Search for Single Top Quark Production at DØ in Run II

M. Agelou,1 B. Andrieu,2 P. Baringer,3 A. Bean,3 D. Bloch,4 E.E. Boos,5 V. Bunichev,5 E. Busato,2 L. Christofek,3 B. Clément,4 L.V. Dudko,5 T. Gadfort,6 A. García-Bellido,6 G. Gaudio,6 D. Gelé,4 P. Gutierrez,7 A.P. Heinson,8 S. Jabeen,3 S. Jain,7 A. Juste,9 D. Kau,10 M. Kopal,7 J. Mitrevski,11 J. Parsons,11 P.M. Perea,8 E. Perez,1 H.B. Prosper,10 A. Quadt,12 V.I. Rud,5 R. Schwienhorst,13 M. Strauss,7 B. Vachon,9 M. Warsinsky,12 and G. Watts6

1DAPNIA/SPP, CEA, Saclay
2Universités Paris VI and VII
3University of Kansas
4IReS de Strasbourg
5Moscow State University
6University of Washington
7University of Oklahoma
8University of California, Riverside
9Fermi National Accelerator Laboratory
10Florida State University
11Columbia University
12Universität Bonn
13Michigan State University

We present a search for single top quarks in two production modes, $s$-channel $tb$ and $t$-channel $tqb$, separately and combined. The search is performed in the electron+jets and muon+jets decay channels, with either a soft-muon tagged jet (SLT), a secondary-vertex tagged jet (SVT), or a jet-lifetime-probability tagged jet (JLIP) to indicate the presence of a $b$-jet and thus improve the signal:background ratio. We use between 158 and 169 pb$^{-1}$ of Run II data, depending on the analysis channel, collected between August 22, 2002 and September 7, 2003. The data are reconstructed with p14.03.00 – p14.06.00 code releases. The resulting 95% confidence level upper limits are 19 pb ($s$-channel), 25 pb ($t$-channel), and 23 pb ($s+t$ channels).

Preliminary Results for Summer 2004 Conferences
NOTE

Gray side bars represent changes since version 3.0, given to the Editorial Board on July 1, 2004. See version 3.0 for the gray side bars that denote changes since version 2.4 from April 204.
Contents

1. Introduction 7
   1.1. Single Top Quark Production at the Tevatron 7
       1.1.1. Overview of the Top Quark 7
       1.1.2. Single Top Quark Production 7
       1.1.3. Physics with Single Top Quarks 11
       1.1.4. Status of Single Top Searches 12
   1.2. Backgrounds to Single Top Signals 12
       1.2.1. Overview of the Backgrounds 12
       1.2.2. Overview of the Background Measurement Methods 13
   1.3. Analysis Discussion 16
       1.3.1. Overview of the Analysis 16
       1.3.2. Goals of the Analysis 16

2. Software Packages 17
   2.1. Event Reconstruction: RECO, TMBfixer 17
   2.2. MC Generators and the Detector Simulation Chain 17
   2.3. The Top_Analyze Package 17
   2.4. Final Analysis Packages
       2.4.1. TopDORoot_Analysis and TopDORoot_Singletop 18
       2.4.2. Other Analysis Packages 18
   2.5. Event Selection: Random Grid Search 18
   2.6. Analysis Tools: Limits Package 18

3. Data and Monte Carlo Event Samples 19
   3.1. The Run II p14 Data 19
       3.1.1. Electron Channel Signal and Background Data 19
       3.1.2. Muon Channel Signal and Background Data 19
       3.1.3. 3JETS_LOOSE Multijet Data 20
       3.1.4. ALLJETS Multijet Data 20
       3.1.5. Dielectron Data 21
       3.1.6. Dimuon Data 21
   3.2. Monte Carlo Event Samples 22
       3.2.1. Single Top Signal Samples 22
       3.2.2. \( t\bar{t} \) Background Samples 23
       3.2.3. \( Z\rightarrow\mu\mu \) Background Sample 23
       3.2.4. Post-Matrix-Element Processing 23
       3.2.5. Monte Carlo Sample Statistics 24
   3.3. The Output Root-Tuples from Top_Analyze 24

4. Integrated Luminosity 25

5. Trigger Selection 26
   5.1. Electron and Muon Channel Triggers 26
       5.1.1. \( e+jets \) Triggers 26
       5.1.2. \( \mu+jets \) Triggers 26
   5.2. Application of the Trigger Thresholds to Monte Carlo 27

6. Event Reconstruction 28
   6.1. Primary Vertex 28
       6.1.1. Primary Vertex Reconstruction and Identification 28
       6.1.2. Identification Efficiency Corrections for MC Primary Vertices 28
   6.2. Electrons 29
       6.2.1. Electron Reconstruction and Identification 29
       6.2.2. Energy Scale Corrections for MC Electrons 29
       6.2.3. Identification Efficiency Corrections for MC Electrons 30
   6.3. Muons 31
       6.3.1. Muon Reconstruction and Identification 31
6.3.2. Energy Scale Corrections for MC Muons 32
6.3.3. Identification Efficiency Corrections for MC Muons 32

6.4. Jets 33
  6.4.1. Jet Reconstruction 33
  6.4.2. Jet Energy Scale Corrections 33
  6.4.3. Correction for a Tagging Muon and its Neutrino 33
  6.4.4. Identification 33
  6.4.5. Energy Smearing for MC Jets 34

6.5. Neutrinos 35
  6.5.1. Reconstruction and Corrections 35

7. B-Jet Tagging 36
  7.1. b-Tagging Terminology 36
  7.2. Taggability 37
  7.3. SLT b-tagging algorithm 39
    7.3.1. SLT Algorithm 39
    7.3.2. SLT Flavor-Inclusive Tag-Rate Functions 39
  7.4. SVT b-Tagging algorithm 41
    7.4.1. SVT Algorithm 41
    7.4.2. SVT Flavor-Dependent Tag-Rate Functions for MC 41
    7.4.3. SVT Flavor-Inclusive Tag-Rate Functions for W+Jets 45
  7.5. JLIP Tagger 47
    7.5.1. JLIP Algorithm 47
    7.5.2. JLIP Flavor-Dependent Tag-Rate Functions for MC 49
    7.5.3. JLIP Flavor-Inclusive Tag-Rate Functions for W+Jets 51
  7.6. Scale Factors for Flavor-Inclusive Tag-Rate Functions 54

8. Preselection Cuts 58
  8.1. Data Quality 58
  8.2. Trigger 58
  8.3. Primary Vertex 58
  8.4. Isolated Lepton 58
  8.5. Additional Isolated Leptons 59
  8.6. Good Jets 59
  8.7. Bad Jets and Noise Jets 60
  8.8. Missing Transverse Energy 61
  8.9. Mismeasured Missing Transverse Energy 62
    8.9.1. Misreconstructed Tracks 62
    8.9.2. Misreconstructed Leptons and Jets 62

9. Preselected Event Samples 65

10. The Final Selection 65

11. Final Event Samples 66

12. Systematic Uncertainties 67
  12.1. Uncertainties from Monte Carlo Normalization 67
    12.1.1. Integrated Luminosity 67
    12.1.2. Theory Cross Sections 67
    12.1.3. Experimental Cross Section 67
    12.1.4. Branching Fractions 67
  12.2. Uncertainties from Monte Carlo Modeling 68
    12.2.1. Triggers 68
    12.2.2. Primary Vertex Identification 68
    12.2.3. Electron Identification 68
    12.2.4. Muon Identification 69
    12.2.5. Muons from b Decays 69
    12.2.6. SLT Veto 69
1. INTRODUCTION

1.1. Single Top Quark Production at the Tevatron

1.1.1. Overview of the Top Quark

The top quark, discovered by the Tevatron CDF and DØ collaborations [1, 2] is the heaviest elementary particle found so far. The direct top quark mass (pole mass) measurement by CDF and DØ using Run I data gives $M_t = 178.0 \pm 4.3$ GeV [3], which is in spectacular agreement with the result from the electroweak data analysis by LEP and SLC [4], $179.3^{+1.1}_{-0.9}$ GeV. Despite the fact that the top quark is so heavy, it is predicted to be a point like particle in the Standard Model (SM). The top quark is much heavier than all other quarks and its mass is not far from the electroweak scale, and the top Yukawa coupling $\lambda_t = 2^{3/4}G_F^{3/2}m_t$ is numerically very close to unity. Because of these and other unusual top quark properties, one expects that a study of top quark physics might reveal details of the electroweak symmetry breaking mechanism. It has been argued [5, 6] that new physics might lead to measurable deviations from the Standard Model values that are first manifested in the top sector.

The top quark decay width, $\Gamma_t/|V_{tb}|^2 = 1.39$ GeV at the pole mass, has been calculated in the SM to second order QCD [7] and first order EW [8] corrections including the $W$-boson and $b$-quark masses. Since the CKM matrix element $V_{tb}$ is close to unity in the SM, the top decay lifetime $\tau_t \approx 0.4 \times 10^{-24}$ s is much smaller than the typical time for formation of QCD bound states, since $\tau_{QCD} \approx 1/\Lambda \approx 3 \times 10^{-24}$ s. Therefore, the top quark decays long before it can hadronize [9], and it thereby provides a very clean source of fundamental information. In particular, the angular distributions of the top quark decay products are mainly determined by the momentum and spin state of the top quark itself and are not smeared out by hadronization effects.

Top quarks at the Tevatron have been detected in the pair production mode through strong QCD interactions. However, the SM predicts that top quarks should also be produced singly through electroweak interactions. Single top production mechanisms and related top quark physics have been the subject of many studies [10].

1.1.2. Single Top Quark Production

There are three main processes of single top production at hadron colliders. Each of the processes may be characterized by the virtuality $Q_W^2$, that is, the four-momentum squared, of the participating $W$ boson:

- **$t$-channel and $u$-channel $W$-exchange ($Q_W^2 < 0$)**: This process, $p\bar{p} \rightarrow t\bar{q}b+X$, has the largest cross section of the three processes. It includes a $2 \rightarrow 2$ part with a $b$ quark from the proton sea in the initial state, and a dominant $2 \rightarrow 3$ part, where an extra $b\bar{b}$ antiquark appears in the final state explicitly. Historically, $t$-channel production has also been referred to as $W$-gluon fusion for the $2 \rightarrow 3$ diagrams, since the $b\bar{b}$ antiquark in the final state arises from a gluon splitting to $b\bar{b}$. We refer to the $t$-channel process as “$tqb$,” which includes $tqb$, $\bar{t}qb$, $tq$, and $\bar{t}q$.

- **$s$-channel $W$-exchange ($Q_W^2 > 0$)**: This process, $p\bar{p} \rightarrow t\bar{b}+X$, has a predicted rate at the Tevatron Run II of about 44% of the $t$-channel rate. Although the process should be observable at the LHC, it has a cross section about 25 times smaller there than the
$t$-channel one, and will therefore be easier to study at the Tevatron. We refer to the $s$-channel process as \textquotedblleft $tb$,\textquotedblright which includes both $t\bar{b}$ and $\bar{t}b$.

- Real $W$ production ($Q_w^2 = m_{W}^2$): $tW$-process. A single top quark appears in association with a real $W$-boson. This process has a negligible cross section at the Tevatron \cite{14} because the gluon parton density is small.

In Fig. 1, representative Feynman diagrams are shown for the $t$- and $s$-channel single top production processes at the leading and next-to-leading orders. Diagrams 1.1 and 2.1 give the LO contributions, diagrams 1.2 and 2.2 represent examples of the NLO loop contributions, and diagrams 1.3, 1.4 and 2.3, 2.4 give examples of the NLO tree parts. Note that diagram 1.4 is the most important $2 \to 3$ tree level part where an extra $b\bar{b}$ antiquark appears in the final state explicitly.

![Representative Feynman diagrams for $t$- and $s$-channel single top production processes.](image)

The NLO rates at the Tevatron Run II ($\sqrt{s} = 1.96$ TeV) for the $s$- and $t$-channel single top modes have been calculated in \cite{15–17}. Results for cross sections are shown in Table 1. The errors include components for the choice of scale and for the uncertainties on the parton distribution functions, but not for the top quark mass uncertainty.

<table>
<thead>
<tr>
<th>Process</th>
<th>Cross Section [pb]</th>
</tr>
</thead>
<tbody>
<tr>
<td>$s$-channel ($tb$)</td>
<td>$0.88^{+0.07}_{-0.06}$</td>
</tr>
<tr>
<td>$t$-channel ($tqb$)</td>
<td>$1.98^{+0.23}_{-0.18}$</td>
</tr>
<tr>
<td>$tW$-production</td>
<td>$0.093 \pm 0.024$</td>
</tr>
</tbody>
</table>

**TABLE 1**: Total cross sections for single top quark production at $\sqrt{s} = 1.96$ TeV with $m_t = 175$ GeV.
Figure 2 shows the transverse momenta and pseudorapidities for the partons in our Monte Carlo models of the $s$-channel and $t$-channel single top processes, after decay of the top quark and $W$ boson.

![Figure 2: Distributions of transverse momenta (left column), pseudorapidity times lepton charge (center column), and pseudorapidity (right column) for the final-state partons in $s$-channel single top events (upper row) and $t$-channel (lower row). The plots show $t$ and $t'$ combined.](image)

Figure 3 shows how the combination of the $2\rightarrow 2$ process with the $2\rightarrow 3$ process in the $t$-channel [19] produces the wide-but-central rapidity distribution of the low-$p_T$ $b$ quark shown in the last plot of Fig. 2. The combination is achieved by using the $2\rightarrow 2$ process when $p_T(b) \leq 10$ GeV, and using the $2\rightarrow 3$ process when $p_T(b) > 10$ GeV. This creates NLO distributions for this process.

![Figure 3: The transverse momentum and rapidity distributions of the low-$p_T$ $b$ quark produced with the top quark in the $t$-channel from the $2\rightarrow 2$ and $2\rightarrow 3$ processes and their combination.](image)
We explain here a little more about the main single top production modes, based on material published in Ref. [14]. Figure 4 shows the leading order single top cross sections as a function of the top quark mass. The search described in this note is for the s-channel mode shown in Fig. 4(a) and the t-channel mode shown in Fig. 4(b). One can see that for the s-channel, the 2→2 process dominates the total cross section, whereas for the t-channel, the 2→3 process is more important than the simpler 2→2 part. (One should note that this figure is from a leading-order calculation, not a NLO one as is being used in our signal MC model. The Feynman diagrams included in this figure do not include those with loops from Fig. 1 although all other types are included.)

![Diagram](https://via.placeholder.com/150)

**FIG. 4:** Single top quark cross sections at the Tevatron with √s = 1.8 TeV, versus top quark mass: (a) s-channel production pp → t\bar{b} + t\bar{b}; (b) t- and u-channel production pp → t\bar{q} + t\bar{q}b; (c) pp → tW + tWb; and (d) the total single top and antitop cross section pp → t + \bar{t} + X. The resummed next-to-leading order t\bar{t} cross section of Ref. [20] is shown as the uppermost line in (d), for comparison with single top production (at leading order).

Figure 5 shows that there are two different diagrams for the 2→3 process for t-channel production, and it also shows how they destructively interfere with each other. The diagram containing g→t\bar{t} is not always shown when discussing single top quark production, but is always present for the t-channel. It does not have a Wtb coupling in the production vertex, and thus dilutes slightly the ability of this channel to probe the Wtb vertex.

![Diagram](https://via.placeholder.com/150)

**FIG. 5:** (a) Feynman diagrams for t-channel W-gluon fusion (q'g→t\bar{q}\bar{b}). (b) t-channel cross section for the 2→3 process versus top quark mass, showing the contributions from each of the Feynman diagrams in (a), and the large destructive interference between the two processes.
1.1.3. Physics with Single Top Quarks

Single top quark production provides several new possibilities to study and to measure top quark properties that cannot be performed by studying only $t\bar{t}$ pair production. Single top quark measurements allow direct measurement of the CKM matrix element $V_{tb}$, and can provide verification of the unitarity of the CKM matrix. It is worthwhile to briefly review the problem (see [18]). $V_{tb}$ is known indirectly from the unitarity of the CKM matrix,

$$|V_{ub}|^2 + |V_{cb}|^2 + |V_{tb}|^2 = 1$$

to very high precision [21]:

$$0.9990 \leq |V_{tb}| \leq 0.9993 \quad (90\% \text{ confidence level}).$$

There will be no way to directly measure $|V_{tb}|$ at colliders to this precision. However, the assumption of unitarity in the indirect determination of $V_{tb}$ is very strong. If one relaxes this assumption, then $|V_{tb}|$ becomes virtually unconstrained [21]:

$$0.08 \leq |V_{tb}| \leq 0.9993 \quad (90\% \text{ CL}).$$

A measurement of the ratio of top decays into $b$ quarks and of top decays into all quarks does not yield a measurement of $V_{tb}$ without the assumption of unitarity. Indeed, top quark pair production at the Tevatron has been used with this assumption [22] to measure

$$\frac{B(t \to Wb)}{B(t \to Wq)} = \frac{|V_{tb}|^2}{|V_{td}|^2 + |V_{ts}|^2 + |V_{tb}|^2} = 0.94^{+0.31}_{-0.24}.$$  

If one does not assume three generations, then it follows only that

$$|V_{tb}| \gg |V_{ts}|, |V_{td}|.$$  

Therefore one of the purposes of a direct measurement of $V_{tb}$ is to verify that 3-generation unitarity is valid.

The single top quark is produced through a left-handed interaction and therefore it is expected to be highly polarized. Since no hadronization occurs, spin correlations survive in the final decay products. Hence, single top quark production offers an opportunity to observe the polarization and to test the corresponding highly remarkable SM predictions. It has been shown [23] that the top quark spin in each event follows the direction of the down-type quark momentum in the top quark rest frame. This is the direction of the initial $\bar{d}$-quark for the $s$-channel, and mostly the direction of the final $d$-quark for $t$-channel single top production. It has been pointed out [24] that the above result follows directly from the properties of the polarized top decays when single top production is considered as top quark decay going “backwards in time.” The decay differential width of a polarized top quark to a bottom quark and two leptons or two light quarks is given by a very simple formula in the Standard Model

$$\frac{1}{\Gamma} \frac{d\Gamma}{d\cos \theta_{fp}} = \frac{1}{2} (1 + K_f \cos \theta_{fp}^*),$$

where $\theta_{fp}$ is the angle between the momentum direction of one of the final fermions $f$ in the top rest frame and the direction of the top quark polarization vector. The coefficients $K_f$ are equal to 1 for the down-type fermions $l^+, d$ and $s$ quarks, and to $-0.31$ for the up-type
fermions $\nu$, $u$ and $c$ quarks [25]. This means that the down-type fermions are the best top quark spin analyzers. The NLO corrections do not change this property significantly. NLO corrections to the lepton factor $K_l$ are very small, $-0.0015\alpha_s$ [26] and to the quark factor $K_{d,s}$ they are about $-6\%$ [27].

From consideration of single top production as a decay going “backwards in time”, one can easily conclude that the best variable to observe maximal top spin correlations between single top production and subsequent decay is the angle between the aforementioned $d$-quark direction in the production processes and the charged lepton (or $d$, $s$-quark) direction from the top decay in the top rest frame.

Finally, measurements of the charged-current couplings of the top quark may probe any nonstandard structure of the couplings and therefore provide hints of new physics. Especially any deviation in the $(V-A)$ structure of the $Wtb$ coupling would lead to a violation of the spin correlation properties [14]. A survey of all new physics scenarios which have been studied using single top quark production is not the subject of this note and we refer the reader to some review articles [5, 6, 18] and references therein.

1.1.4. Status of Single Top Searches

In Run I, the accumulated statistics of about 90 pb$^{-1}$ was not enough to observe single top production, and the first limits on the cross sections have been presented by both the D$ar{O}$ [11, 12] and CDF [13] collaborations. At the 95% confidence level, the D$ar{O}$ limit on the $s$-channel is 17 pb and the CDF limit is 18 pb. At the same confidence level, the limit on the $t$-channel production cross section is 22 pb by D$ar{O}$ and 13 pb by CDF. CDF also published a combined limit of 14 pb.

In Run II, one expects significantly higher statistics and much better $b$-tagging, and therefore a discovery of electroweak top quark production at the Tevatron.

1.2. Backgrounds to Single Top Signals

1.2.1. Overview of the Backgrounds

The main problem for a single top search is the very large background. The situation is significantly different from top pair production not just because of the smaller production rate but more importantly because of the smaller multiplicity of final particles (leptons or jets) and the lower production threshold. As a result, signal to background ratios are far smaller for single top compared with top pair production. Therefore, extracting the signal from the backgrounds is significantly more complicated in a single top search.

The final-state signature of a single top quark event is characterized by a high-$p_T$ centrally produced isolated lepton ($e^\pm$ or $\mu^\pm$) and missing transverse energy ($E_T$) from a neutrino from the decay of the $W$ boson from the top quark decay, together with two or three jets. One of the jets comes from a high-$p_T$ central $b$ quark from the top quark decay. Processes that can share this final state include $W+$jets events, $tt$, $bb$, multijet events with a jet misidentified as an electron, and some smaller contributions from $Z+$jets and diboson events.

- $W+$jets events form the dominant part of the background. The cross section for $W+2$jets is over 1000 pb [28, 29] with $Wbb$ contributing about 1% of this.
- $tt$ production (NNLO cross section $= 6.77 \pm 0.42$ pb, for $m_t = 175$ GeV, $Q^2 = m_t^2$ [30]).
This process has a larger multiplicity of final particles than single top events. However, when some of the jets or a lepton are missed, the kinematics of the remaining particles are very similar to those of the signal.

- $bb$ production (resummed NLO cross section $= 58 \, \mu b$, for $\sqrt{s} = 1.8$ TeV [31]). This process contributes to the background when one of the $b$’s decays semileptonically and the electron or muon is mistaken for one from a $W$ boson decay. The background in the electron channel is very small. In the muon channel, $bb$ events form a background when the muon travels wide of its jet, or when the jet is not reconstructed.

- Multijet events form a background in the electron channel when a jet is misidentified as an electron. The probability of such misidentification is rather small, about $10^{-4}$, but the $\geq 3$ jet cross section is so large that the overall contribution is significant.

- $Z$/Drell-Yan+jets production can mimic the single top signals in two ways. There are two isolated leptons ($e^+e^-$ or $\mu^+\mu^-$) in the final state, but if one is not reconstructed, then this results in missing transverse energy, which reconstructs as a $W$ boson when combined with the other lepton. For the second way that $Z$/DY+jets events create a background, there are two muons in the final state. One accidentally overlaps a jet and is thereby identified as a tagging muon from a semileptonic $b$ decay.

- $WW$, $WZ$, and $ZZ$ processes are the electroweak part of the $W$+jets and $Z$+jets backgrounds. The cross sections are a few picobarns each. This electroweak part of the $W$+jets and $Z$+jets processes has different kinematics than the $W$+(QCD-)jets part.

To put these various backgrounds in perspective, we give here the percentage of the total background that each component contributes after identifying at least one $b$ jet in each event and after applying preselection cuts (which keep only events with the right set of final state objects and reject mismeasured events). $W$+jets events (including most $Z$+jets and dibosons) form 61–72% of the total background, depending on the decay channel and $b$ identification method, $tt$ contributes 20–25%, $bb$ contributes 10–16% to the muon decay channels, multijet events contribute 7–18% in the electron decay channels, and $Z\rightarrow\mu\mu$+jets adds 11% to the muon-tagged muon channel background.

1.2.2. Overview of the Background Measurement Methods

The most powerful tool we have for reducing the backgrounds in this analysis is to identify whether jets originate from $b$ quarks. A $b$-quark is present in all top quark decays, but $W$+jets and multijet events are expected to have only a very small fraction of $b$-quark jets.

We use three different algorithms for $b$ jet tagging: (i) “Soft-Lepton Tagger” (SLT), which identifies a muon associated with a jet. The muon is expected to come from a semileptonic $B$ hadron decay or the cascade charm decay; (ii) Secondary-Vertex Tagger, “SVT,” a track-vertex reconstruction algorithm; and (iii) Jet-Lifetime-Probability Tagger “JLIP,” a track impact-parameter based algorithm. The SVT and JLIP algorithms are referred to as lifetime taggers.

Figure 6 illustrates the methods we have applied for measuring the various backgrounds in the single top search. The methods are almost the same for the electron and muon decay channels. In order to be able to combine the results from the soft-lepton-tag searches with the lifetime-tag searches, we reject events in the lifetime-tag analyses that have a muon-tagged jet. This ensures orthogonality of the analyses before combining them to calculate the final cross section limits.
Since the “$W$+jets” background shown in Fig. 6 is measured from data, it includes all sources of background with a real isolated lepton (electron or muon), with real or mismeasured missing transverse energy. That is, it includes $W$+jets (including light jets, charm jets, and bottom jets), $Z$+jets (where the $Z$ boson decays to $ee$ or $\mu\mu$ and one of the leptons is not found, creating fake missing transverse energy), and the diboson processes $WW$, $WZ$, and $ZZ$.

The fake-lepton backgrounds are multijet events in the electron channel where a jet is misidentified as an electron, or $b\bar{b}$ events in the muon channel where one or both $b$’s decays to a muon and one of the muons is not associated with a jet, thus faking an isolated muon assumed to be from a $W$ boson. (In many other analyses in D0, these backgrounds are known as “QCD”.)

$t\bar{t}$ production contributes as a background both in the $l$+jets and in the dilepton decay channels. We normalize these MC backgrounds to the NNLO cross section [30, 55].

The $Z\rightarrow\mu\mu$ background is only seen in the $\mu$+jets/$\mu$ analysis channel, where one of the muons from the $Z$ decay is coincidentally aligned with an initial state jet. This background is not included in the “$W$+jets” measurement since both muons are properly reconstructed, and because 100% of the events have a muon-tagged jet, whereas only about 0.1% of the $W$+jets and $Z$+jets events described above have a muon-tagged jet. We normalize this MC background to the number of $Z\rightarrow\mu\mu+2$jets events observed in data.

We have chosen to measure the $W$+jets backgrounds using data, with flavor-inclusive tag-rate functions also determined from data. This method was used in Run I for the published $t\bar{t}$ cross section measurements and for the first Run I single top quark search. It is also being used in Run II for the $t\bar{t}$/SLT analyses. It is a simple and elegant method, with very few components to the systematic error, and an expected overall error smaller than a totally MC-based method. We cannot use the methods used in the $t\bar{t}$ topological analyses because of the jet-multiplicity-inclusive nature of our analysis (for Berends’ scaling), and because of low statistics after tagging leading to a large uncertainty (for the second-matrix method). We decided not to use the MC-based method used in the $t\bar{t}$ lifetime tagging analyses because it is complex and requires many corrections and a detailed understanding of the MC samples.
We use a flavor-inclusive tag-rate function derived on a multijet sample to predict the tagged $W+$jets event yield. The production mechanisms for jets are similar in multijet events and in $W+$jet events: they are dominated by gluons splitting into jets. An example Feynman diagram for $W+2$ jet production is shown in Fig. 7.

![Feynman diagram for $W+2$ jet production](image)

FIG. 7: Representative Feynman diagram for $W+2$ jet production (from [47]).

The Run II $t\bar{t}\to e+$jets and $t\bar{t}\to \mu+$jets analyses have applied our SVT flavor-inclusive tag-rate functions to their untagged $W+$jets data samples as a cross check of their MC method and found results for the tagged $W+$jets backgrounds consistent with the MC method [35]. They have not compared the size of the errors between the two methods. This cross-checking between data-plus-tag-rate functions method and the MC method was also performed in the Run I single top analysis and the two sets of measurements were found to be in agreement.

A study was performed in Run I to verify the assumption that the heavy-flavor content of multijet events is the same as in $W+$jets events, within some quantified uncertainty. The results of the study are shown in Fig. 8.

Peter Tamburello [36] applied a flavor-inclusive tag-rate function very similar to one of ours to nine HERWIG-generated multijet, $\gamma+$jets, $Z+$jets, and $W+$jets samples, and found agreement within 10% for all samples between predicted and observed tag rates (apart from the $Z+\geq 1$jet sample). This study indicates that the heavy flavor fraction in multijet events is within 10% of that in $W+$jets events at tree level.

![Test of the Run I SLT tag-rate functions on various HERWIG version 5.8 Monte Carlo samples](image)

FIG. 8: Test of the Run I SLT tag-rate functions on various HERWIG version 5.8 Monte Carlo samples. Note the $W+1$jet sample is a separate process from just $W$ production, but the $Z+1$jet process was not available, and the measurement is from an inclusive $Z$ sample.

Please see a review talk [37] by A. Heinson from 1/20/04 that compares the various methods used to measure the $W+$jets backgrounds for more information on the decision to measure the $W+$jets background using data.
1.3. Analysis Discussion

1.3.1. Overview of the Analysis

The analysis is structured in three distinct steps. We define the following sets of events:

- **“Skimmed”** — all Common Samples Group’s data that pass the Top Group’s skimming selections EMQCD and MUQCD, and all Monte Carlo events
- **“Preselected”** — MC events and skimmed data that pass preselection
- **“Final”** — all preselected events that pass the final event selection

The preselected and final categories are also identified as:

- **“Tagged”** — events with at least one tagged jet
- **“Untagged”** — events with no tagged jets
- **“Pretagged”** — events before tagging is applied (i.e., = tagged + untagged)

Tagging acronyms from the B-ID Group are used in this note:

- **“SLT”** — Soft-lepton tagging (i.e., a muon in a jet)
- **“SVT”** — Secondary-vertex tagging
- **“JLIP”** — Jet-lifetime-probability tagging
- **“SLV”** — Soft-lepton-tag veto (for the SVT and JLIP analyses)

1.3.2. Goals of the Analysis

This analysis note covers the first search for single top quark production at DØ in Run II. Many decisions about the scope of the analysis have been made which reduce the signal sensitivity somewhat in order to get results completed within a few months of starting the analysis. These aspects will be addressed after this first stage of the analysis and review are complete. Our goals for this analysis are:

1. Set an upper limit on the production cross sections of:
   - $s$-channel single top, $p\bar{p} \rightarrow tb + X$
   - $t$-channel single top, $p\bar{p} \rightarrow tqb + X$
   - combined single top, $p\bar{p} \rightarrow t + X$ ($X \neq t, W$)

2. Learn the limitations of the methods chosen and the gains of those not implemented so that we can improve the analysis in the future.

3. Write general analysis software and document the analysis, so we can build on it rapidly in preparation for observation of single top quark production in the future.
2. SOFTWARE PACKAGES

2.1. Event Reconstruction: reco, TMBfixer

The data were reconstructed with reco versions p14.03.00, p14.03.01, p14.03.02, p14.05.00, p14.05.02, and p14.06.00. These different versions are similar enough not to make any expected differences to the analysis. The p14 thumbnail (TMB) fixer was run on the data by the Common Samples Group. This package remakes CalDataChunk, correcting for the shared energy problems that are not fixed in p14, fixes the so-called Tower 2 problem, performs a correction for a calorimeter cable swap, and (unfortunately) adds the “massless gaps ×2 bug. It remakes the primary vertex with two-pass vertexing, fixes ChargedParticle extrapolation to the Central Preshower detector and to the associated vertices, remakes muons, taus, jets, EM objects, and missing $E_T$, and finally makes a new ThumbNailChunk and writes out a new TMB file. The fixed TMB files are used for Common Samples Group skimming. Post-TMBfixer corrections now in the d0correct package were implemented in the Top_Analyze package before d0correct became available.

2.2. MC Generators and the Detector Simulation Chain

The single top signal samples were generated with SingleTop, a package based on CompHEP. For the $s$-channel process, this uses a leading order simulation, which has been shown to produce almost the same distributions as next-to-leading order. For the $t$-channel process, a next-to-leading-order simulation is used. Both the $s$- and $t$-channel simulations include all spin information in the production and decay by generating all the $2\to4$ and $2\to5$ diagrams (i.e., including the decay to the $t$ quark and $W$ boson).

The $t\bar{t}$ samples were generated with ALPGEN version 1.3, a leading-order generator that includes the spins of the particles by using a full $2\to6$ calculation.

All samples were processed through PYTHIA 6.203, which added the underlying event (Rick Field’s Tune A parametrization with CTEQ5L), TAUOLA with Particle Data Book 2002 tau decay branching fractions was used to decay taus, although the ancient DØ defaults were accidentally used for the $t\bar{t}$ MC samples. The differences are mostly in the hadronic decays.

We used EVTGEN from p15 to decay the following $b$ hadrons: $B^0, B^+, B^0_s, B^+_c$, and $\Lambda_b$. PYTHIA added initial-state and final-state radiation to the events.

The single top generator-level event samples were processed with d0GSTAR, d0SIM, and reco at GridKa with p14.05.01 for the $s$-channel and reco p14.05.02 for the $t$-channel. The $t\bar{t}$ samples were processed on the official MC farms with p14.05.01. Monte Carlo minimum bias events were added to the hard scatter, with the number of events taken from a Poisson distribution with a mean of 0.8 events (chosen to match the average instantaneous luminosity in the data sample). The $s$-channel single top sample has 0.5 average minimum bias events overlaid, owing to a mistake when the events were processed. We do not expect this difference with the other samples to have any noticeable effect on the analysis.

2.3. The Top_Analyze Package

For this analysis, all data and MC events were processed with the Top Group’s Top_Analyze package. The version was “Nefertiti_hitfities” from February 2004. The package applies the jet energy scale calibration, smears energies of electrons, muons, jets, and missing transverse energy, applies DØ standard particle ID, corrects missing transverse energy for isolated muons, and writes out the events in a root-tuple format (“TopDØRoot”) for subsequent analysis steps.
2.4. Final Analysis Packages

There are four final analysis packages, each set up to do similar things in parallel for different analysis channels.

2.4.1. TopDORoot_Analysis and TopDORoot_Singletop

TopDORoot_Analysis is a framework designed to provide an analysis infrastructure which allows for base functionality such as cut application, histogramming and data skimming. This analysis code reads the Top_Analyze trees (output root-tuples) but it is developed using d0root objects. The conversion is made automatically as the code inherits from the Top_Analyze-tree-to-d0root converter. Details on the use of this package can be found at: http://www-clued0.fnal.gov/~ggaudio/SingleTopAnalysisFramework.html

The TopDORoot_Singletop package applies the preselection cuts, and writes out new Top_Analyze-format root-tuples for events that pass. It applies all correction factors to calculate a weight for each event, and the weight’s error. The correction factors include those that make MC simulated events look like data (trigger thresholds, particle ID efficiency corrections, etc.) and those that convert the event to a fractional acceptance and yield (branching fraction and cross section, initial number of events and integrated luminosity). The package also calculates the probability for each event to be tagged, and this probability forms part of the event weight.

These packages are used in the $l$+jets/SVT analysis channels.

2.4.2. Other Analysis Packages

There are three additional packages which read in the Top_Analyze root-tuples and perform the same tasks as TopDORoot_Analysis. These allow independent cross checks between each step of the calculations. These packages are used in the $e$+jets/SLT, $\mu$+jets/SLT, and $l$+jets/JLIP analysis channels.

2.5. Event Selection: Random Grid Search

We use the Random Grid Search package [38] developed in Run I to optimize cuts on final variables. This is run as part of the TopDORoot package, coupled to the limits package described next, such that the optimization can be performed on the expected cross section limit.

2.6. Analysis Tools: Limits Package

We calculate cross section upper limits using a Root package provided by Tom Junk, which applies a modified frequentist approach to the calculation, known as the “confidence limit (CL) method” [39]. This is the method commonly used by the LEP experiments, and is in use for some of DØ’s new-phenomena analyses. We also use Bayesian limit setting code based on the Run I Single Top analysis. Both of these programs are implemented in the cvs package top_statistics.
3. DATA AND MONTE CARLO EVENT SAMPLES

3.1. The Run II p14 Data

We use data selected using two different methods. The first part of our dataset was selected using Top Group skims before the Common Samples Group (CSG) set up collaboration-wide event selection. The second part of the dataset comes from the CSG skims.

3.1.1. Electron Channel Signal and Background Data

We start with data from the Top Group skim “ETRACK” selected from data reconstructed with p14.03.00, p14.03.01, p14.03.02, and p14.05.02. The skim definition is:

- **ETRACK**: \( \geq 1 \text{ EM (ID}=10 \text{ or } 11) \) with \( E_T > 12 \text{ GeV} \) and \( \geq 1 \text{ track with } p_T > 10 \text{ GeV} \) and \( \Delta \phi(\text{EM,track}) < 0.4 \)

(An EM object ID of 10 means a calorimeter cluster has been found that is consistent with an EM object. A value of \pm 11 means that the calorimeter cluster has a matched track. +11 means an electron and −11 means a positron, based on the direction of curvature of the track in the central magnetic field.)

The second part of the dataset comes from an “event tags” skim defined by the Top Group for the Common Samples Group skimming. This was run on data reconstructed with p14.05.00, p14.05.02(DST), and p14.06.00. “DST” means that this dataset was re-reconstructed starting from the “data summary tapes” format from the first pass of reco, whereas the other samples were re-reco’d starting from the “raw” data format files. The skim definition is:

- **SKIM_EM1TRK**: \( \geq 1 \text{ EM (ID}=10 \text{ or } 11) \) with \( E_T > 8 \text{ GeV} \) and \( \geq 1 \text{ track with } p_T > 5 \text{ GeV} \) and \( \Delta \phi(\text{EM,track}) < 0.1 \)
- **SKIM_TOP_ETRACK**: \( \geq 1 \text{ EM (ID}=10 \text{ or } 11) \) with \( E_T > 12 \text{ GeV} \) and \( \geq 1 \text{ track with } p_T > 8 \text{ GeV} \) and \( \Delta \phi(\text{EM,track}) < 0.1 \)

SKIM_TOP_ETRACK was run on data that passed SKIM_EM1TRK.

These selections result in \(5,730,465\) “EMQCD” events, where EMQCD is the name of this dataset within the Top Group.

3.1.2. Muon Channel Signal and Background Data

We start with data from the Top Group skim “MUTRACK” selected from data reconstructed with p14.03.00, p14.03.01, p14.03.02, and p14.05.02. The skim definition is:

- **MUTRACK**: \( \geq 1 \text{ medium muon and } \geq 1 \text{ central track with } p_T > 12 \text{ GeV} \). Either the track and the muon are matched in Reco \((nseg = 3)\) or \( \Delta \phi(\text{muon,track}) < 0.4 \)

The second part of the dataset comes from an “event tags” skim defined by the Top Group for the Common Samples Group skimming. This was run on data reconstructed with p14.05.00, p14.05.02(DST), and p14.06.00. The skim definition is:

- **SKIM_1MULOOSE**: \( \geq 1 \text{ loose muon with } \max(\text{local-}p_T, \text{global-}p_T) > 8 \text{ GeV} \)
- **SKIM_TOP_MUTRACK**: \( \geq 1 \text{ loose muon with global } p_T > 12 \text{ GeV} \) if it has a central matched track, or local \( p_T > 8 \text{ GeV} \) if it does not. The track must match within \( \Delta \phi(\text{MU,track}) < 0.4 \)
(Local-$p_T$ is the transverse momentum of the muon measured in the muon spectrometer. This is only used if there is no matched central track. Global-$p_T$ is the muon’s transverse momentum as measured in the central tracking system, with much better resolution than is possible in the spectrometer.)

SKIM\_TOP\_MUTRACK was run on data that passed SKIM\_1MULOOSE.

These selections result in $755,742$ “MUQCD” events, where MUQCD is the name of this dataset within the Top Group.

### 3.1.3. 3JETS\_LOOSE Multijet Data

The first part of the data used to measure inclusive tag-rate functions for the lifetime tags SVT and JLIP comes from a Common Samples Group’s skim for data reconstructed with p14.03.00, p14.03.01, p14.03.02, and p14.05.02. The skim definition is:

- **SKIM\_NP**: Either the MHT30\_3CJT5 or the Level 1 3CJT5 triggers fired.

MHT30\_3CJT5 has conditions at Levels 1, 2, and 3, and is unprescaled. 3CJT5 has no Level 2 or 3 requirements, but is prescaled.

The second part of the dataset comes from an “event tags” skim defined by the Top Group for the Common Samples Group skimming. This was run on data reconstructed with p14.05.00, p14.05.02(DST), and p14.06.00. The skim definition is:

- **SKIM\_NP**: Either the MHT30\_3CJT5 or the Level 1 3CJT5 triggers fired.
- **SKIM\_TOP\_3JET**: Jets 1,2, and 3 with $p_T > 8$ GeV and $|\eta| < 4.6$ and Level 1 trigger 3CJT5.

SKIM\_TOP\_3JET was run on data that passed SKIM\_NP.

These selections result in $1,065,154$ “3JETS\_LOOSE” events for measuring the flavor-inclusive tag-rate functions.

### 3.1.4. ALLJETS Multijet Data

This data is used to measure the inclusive tag-rate functions for muon tagging (SLT), and to cross check the inclusive tag-rate functions for the lifetime taggers. The first part of the data comes from a Top Group skim for data reconstructed with p14.03.00, p14.03.01, p14.03.02, and p14.05.02. The skim definition is:

- **ALLJETS**: Passes the 4JT12 trigger and has at least four jets (“JCCB” definition) and sum of JCCB jets’ $E_T = H_T > 100$ GeV.

The second part of the dataset comes from an “event tags” skim defined by the Top Group for the Common Samples Group skimming. This was run on data reconstructed with p14.05.00, p14.05.02(DST), and p14.06.00. The skim definition is:

- **SKIM\_3JET**: Jet 1 has $E_T > 20$ GeV, and jets 2 and 3 have $E_T > 15$ GeV, and all three jets have $|\eta| < 2.6$
- **SKIM\_TOP\_ALLJETS**: Jet 1 with $E_T > 20$ GeV, Jets 2 and 3 with $E_T > 15$ GeV, Jet 4 $E_T > 8$ GeV, and $|\eta| < 2.6$ for Jets 1, 2, and 3. The total scalar energy $H_T$ is $> 100$ GeV, and the events must pass at least one of the following list of triggers: “4JT10” “4JT12” “3J15\_2J25\_PVZ” “3JT15\_PVZ”

SKIM\_TOP\_ALLJETS was run on data that passed SKIM\_3JET.

These selections result in $6,144,925$ “ALLJETS” events.
3.1.5. **Dielectron Data**

We use dielectron data for various cross checks. It comes from the Common Samples Group’s skim of data from all reconstruction versions, defined as:

- **SKIM\_2EM**: \( \geq 2 \) EM’s (\(|\text{ID}| = 10 \text{ or } 11\)) with \( E_T > 7 \text{ GeV} \)

This selection results in **1,556,581 “DIEM\_EXTRALOOSE” events**.

3.1.6. **Dimuon Data**

We use dimuon data for various cross checks. It comes from the Common Samples Group’s skim of data from all reconstruction versions, defined as:

- **SKIM\_2MU**: \( \geq 2 \) loose muons

This selection results in **332,707 “DIMU” events**.
3.2. Monte Carlo Event Samples

We would like to emphasize two things about our MC event samples. First, none of them are affected by the “multi-parton interactions” (MPI) bug that affects most of the Top Group’s MC samples at the moment. In this bug, the MPI, also known as the underlying event, was turned off (by one of the ALPGEN authors) between ALPGEN and PYTHIA. Our samples have proper MPI simulation, with the latest parameters tuned to Tevatron data.

Second, our simulation of the single top signal events is state-of-the-art. It reproduces the kinematic distributions from the full NLO calculations, and contains all spin information in the production and decay. In Run I, we had a full LO simulation, with no spin information in the top quark decays. (In comparison, CDF are using PYTHIA and HERWIG to simulate single top production, as they did in Run I, and these generators do not reproduce even the LO kinematics properly [40]. They also do not include spin information required to model the angular distributions correctly.)

3.2.1. Single Top Signal Samples

We use the following signal samples for this analysis:

**Generator Files**
- s-channel single top (tb)
  - /rooms/hall/stop2/output_tb_enbb/generator
  - /rooms/hall/stop2/output_tb_munbb/generator
- t-channel single top (tqb)
  - /rooms/hall/stop2/output_tqb_enbqb/generator
  - /rooms/hall/stop2/output_tqb_munbqb/generator

**TMB Files from RECO**
- s-channel single top (tb)
  - /rooms/barbershop/projects/p14.05.01/singletop/enbb
  - /rooms/barbershop/projects/p14.05.01/singletop/munbb
- t-channel single top (tqb)
  - /rooms/barbershop/projects/p14.05.02/singletop/enbqb
  - /rooms/barbershop/projects/p14.05.02/singletop/munbqb

The events were generated with the SingleTop generator, based on CompHEP. Each sample includes both top and antitop contributions, in equal parts. The top quarks decay to \(Wb\) and the \(W\) bosons decay to \(e\) and \(\tau\) or to \(\mu\) and \(\tau\). The \(\tau\)'s decay to either \(e\) or \(\mu\) with PDB 2002 branching fractions. No parton-level cuts were applied when the events were generated. The CTEQ6M PDF set was used. The scales for production were \(Q^2 = M_{\text{top}}^2\) for the s-channel samples and \(Q^2 = (M_{\text{top}}/2)^2\) for the t-channel samples. These choices correspond to where the LO and NLO cross section calculations are equal. For these samples, \(M_{\text{top}} = 175\) GeV and \(\sqrt{s} = 1.96\) TeV.
3.2.2. $t\bar{t}$ Background Samples

We use the following samples to model the top pair background for this analysis:

TMB Files from RECO

$t\bar{t}\rightarrow l+\text{jets}$
- `topwg_alpgen_pythia_ttbar-l+jets_175GeV-TuneA_0.8mb_p14.05.01tmb_11100`
- `topwg_alpgen_pythia_ttbar-ll_175GeV-TuneA_0.8mb_p14.05.01tmb_11101`

The $t\bar{t}$ samples were generated with Alpgen v.1.3. The top quarks decay to $Wb$, the $W$ bosons decay either to quark-antiquark pairs or to $e$, $\mu$, and $\tau$, and the $\tau$'s decay to anything, with the ancient DØ default $\tau$ branching fractions. (This was a bug introduced into the new samples with Tune A underlying event. The branching fractions should have been the PDB 2002 ones.)

No parton-level cuts were applied when the events were generated. The CTEQ6.1M PDF set was used. The scale for production was $Q^2 = M_{\text{top}}^2$. For these samples, $M_{\text{top}} = 175$ GeV and $\sqrt{s} = 1.96$ TeV.

3.2.3. $Z\rightarrow\mu\mu$ Background Sample

We use the following sample to model the background from $Z+\text{jet}$ production in the $\mu+\text{jets}/\text{SLT}$ channel, where the $Z$ boson decays into two muons and one of the muons is reconstructed within a jet:

TMB Files from RECO

$Z\rightarrow\mu\mu+\text{jets}$
- `topwg_alpgen_pythia_zdyjj-mass2-TuneA_0.8mb_p14.05.01tmb_11729`

There are 48,450 events in the sample.

3.2.4. Post-Matrix-Element Processing

For both the single top signal samples and $t\bar{t}$ background samples, after the four-vectors for the final state partons are calculated by the matrix element generators, this information is fed into Pythia which adds the following things to the simulation: (i) underlying event with Rick Field’s Tune A parameters; (ii) initial-state and final-state radiated gluons; (iii) showering of the final state partons into jets; and it calls (iv) Tauola to decay the $\tau$s, and (v) Evtgen to decay the $B$ hadrons. Pythia version 6.203 was used, with CTEQ5L for the scales of the underlying event and showering.
3.2.5. Monte Carlo Sample Statistics

Table 2 summarizes the cross sections, branching fractions, initial numbers of events, and integrated luminosities of the Monte Carlo event samples.

<table>
<thead>
<tr>
<th>Event Type</th>
<th>Cross Section [pb]</th>
<th>Branching Fraction</th>
<th>Number of Events</th>
<th>Int. Lum. [fb⁻¹]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Signals</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(tb\to e^+\text{jets} )</td>
<td>0.88 ± 0.14</td>
<td>0.1309 ± 0.0026</td>
<td>32,000</td>
<td>278</td>
</tr>
<tr>
<td>(tb\to \mu^+\text{jets} )</td>
<td>0.88 ± 0.14</td>
<td>0.1304 ± 0.0026</td>
<td>31,000</td>
<td>270</td>
</tr>
<tr>
<td>(tqb\to e^+\text{jets} )</td>
<td>1.98 ± 0.30</td>
<td>0.1309 ± 0.0026</td>
<td>32,500</td>
<td>125</td>
</tr>
<tr>
<td>(tqb\to \mu^+\text{jets} )</td>
<td>1.98 ± 0.30</td>
<td>0.1304 ± 0.0026</td>
<td>31,500</td>
<td>122</td>
</tr>
<tr>
<td>Backgrounds</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(t\bar{t}\to l^+\text{jets} )</td>
<td>6.77 ± 1.22</td>
<td>0.4444 ± 0.0089</td>
<td>48,500</td>
<td>16</td>
</tr>
<tr>
<td>(t\bar{t}\to l^-\bar{l} )</td>
<td>6.77 ± 1.22</td>
<td>0.1111 ± 0.0089</td>
<td>47,000</td>
<td>63</td>
</tr>
<tr>
<td>(Z\to \mu\mu^+\text{jets} )</td>
<td>—</td>
<td>—</td>
<td>48,450</td>
<td>—</td>
</tr>
</tbody>
</table>

TABLE 2: The cross sections, branching fractions, initial numbers of events, and integrated luminosities of the Monte Carlo event samples. Note that the \(Z\to \mu\mu\) sample is scaled to the cross section measured in data, thus no cross section or branching fraction values are given.

3.3. The Output Root-Tuples from Top_Analyze

After running Top_Analyze on the data and MC TMB files, we end up with the following top tree root-tuples used as input to the preselection stage of the analysis:

**Signal and background data**
- /rooms/cafe/SingleTop_SKIMS/Data/Electron_Jets
- /rooms/cafe/SingleTop_SKIMS/Data/Muon_Jets
- /rooms/cafe/SingleTop_SKIMS/Data/3JetsLoose
- /rooms/cafe/SingleTop_SKIMS/Data/Zuu
- /rooms/cafe/SingleTop_SKIMS/Data/Z_ee_mumu
- /prj_root/1001/top_write/top_analyzed_data/Nefertiti/ALLJETS

**Signal and background MC**
- /rooms/cafe/SingleTop_SKIMS/MonteCarlo/Electron_Jets
- /rooms/cafe/SingleTop_SKIMS/MonteCarlo/Muon_Jets
- /work/broglie-clued0/agensou/top_analyze_Nefertiti/zjj_hitfitres
4. INTEGRATED LUMINOSITY

All single top analyses use the standard Top Group data skims, and, as such, takes advantage of the Top Group luminosity calculation. A brief description is related below, more details can be found in Section X.B of Ref. [41].

The electron and muon single-top channels use the Top Group’s EMQCD and MUQCD skims. The luminosity calculation is performed for each file on which Top_Analyze has been run. Simple cross checks are done to ensure no Top_Analyzed files were missed.

Early versions of the trigger changed rapidly, which creates problems for trigger efficiency calculations. Because of this trigger consideration, and because of the data quality, both the EMQCD and MUQCD samples begin with run 162458, which is the start of trigger list 8.2.

The raw recorded luminosity for EMQCD is 180.23 pb$^{-1}$ and for MUQCD it is 181.62 pb$^{-1}$. The difference is due, presumably, to the live time of the triggers. Good-run lists and bad-luminosity-block rejection are then applied. The criteria are different for the $e$ and $\mu$ channels and also for the lifetime-tagging and soft-lepton-tagging analyses. Table 3 gives a summary of which good-run lists were used and which bad-luminosity blocks were rejected.

<table>
<thead>
<tr>
<th>Sample</th>
<th>Tag Method</th>
<th>Good-Run Lists</th>
<th>Bad-Lumi-Block Lists</th>
<th>Integrated Luminosity (pb$^{-1}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>EMQCD</td>
<td>Soft Lepton</td>
<td>Good Muon, Other Detectors</td>
<td>Jet/MET, Ring of Fire</td>
<td>156.24</td>
</tr>
<tr>
<td>EMQCD</td>
<td>Lifetime</td>
<td>Other Detectors</td>
<td>Jet/MET, Ring of Fire</td>
<td>168.68</td>
</tr>
<tr>
<td>MUQCD</td>
<td>Soft Lepton</td>
<td>Good Muon, Other Detectors</td>
<td>Jet/MET, Ring of Fire</td>
<td>158.39</td>
</tr>
<tr>
<td>MUQCD</td>
<td>Lifetime</td>
<td>Good Muon, Other Detectors</td>
<td>Jet/MET, Ring of Fire</td>
<td>158.39</td>
</tr>
</tbody>
</table>

TABLE 3: The good-run lists and bad-luminosity-block lists used for the calculation of integrated luminosity and event rejection for each of the analyses described in this note.

The “Good Muon” run list requires the muon chambers to be graded “reasonable” in the run quality database. The “Other Detectors” list requires that the SMT and the CFT not be marked “bad.” The Jet/MET bad-luminosity-block list with T42 version 5.1 can be found on the CALGO group’s web page. Finally the Ring of Fire bad luminosity block list can also be found on the CALGO group’s web page, and version 21-OCT-2003 of that list was used.

The Top Group has taken a snapshot of the good-runs database and the bad-luminosity-block list. The group has authored a package, top_dq (dq = data quality) which contains all of the lists used as input to the calculation, a resulting bad-luminosity-block list, and code to aid analyzers in rejecting events in luminosity blocks marked as bad. The bad-luminosity-block list is produced as a by-product of the integrated luminosity determination. The cvs version of this package we used is v00-04-02.
5. TRIGGER SELECTION

5.1. Electron and Muon Channel Triggers

The trigger requirements used by each analysis channel are summarized in Table 4. Details of these triggers can be found in Section III.C of Ref. [41], including plots of the turn-on curves for each trigger at Levels 1, 2, and 3. The package used to apply these turn-on curves to our MC events is “top_trigger” v00-20-03.

<table>
<thead>
<tr>
<th>Final State</th>
<th>Trigger List</th>
<th>Trigger Name</th>
<th>Level 1</th>
<th>Level 2</th>
<th>Level 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>e+jets</td>
<td>v12</td>
<td>E1.SHT15.L2J20</td>
<td>CEM(1,11)</td>
<td>—</td>
<td>ELE.SHT(1,15),JET(2,20)</td>
</tr>
<tr>
<td></td>
<td>v8.2-v11</td>
<td>EM15.2J15</td>
<td>CEM(1,10),CJT(2,5)</td>
<td>EM(.85,10),JET(2,10)</td>
<td>ELE.LOOSE_SH_T(1,15),JET(2,15)</td>
</tr>
<tr>
<td>µ+jets</td>
<td>v12</td>
<td>MU.JT25.L2M0</td>
<td>MUL1PTXATXX,CJT(1,3)</td>
<td>MUON(1,med),JET(1,10)</td>
<td>JET(1,25)</td>
</tr>
<tr>
<td></td>
<td>v8.2-v11</td>
<td>MU.JT20.L2M0</td>
<td>MUL1PTXATXX,CJT(1,5)</td>
<td>MUON(1,med)</td>
<td>JET(1,20)</td>
</tr>
</tbody>
</table>

TABLE 4: Definitions of the triggers used in the single top analyses for the electron and muon channels.

Studies have been performed that indicate an increase in the signal acceptance obtained by combining more than one specific trigger. However, owing to time constraints for this analysis, only one specific trigger per trigger list version for each channel was considered at this time. Simulation of the trigger performance based on the per-object trigger efficiencies applied to Monte Carlo events becomes extremely complex when more than one trigger is considered.

5.1.1. e+jets Triggers

Trigger list version 12 has been used to record data since May 2003. For this subset of data, events must satisfy the specific trigger E1.SHT15.L2J20. At Level 1, events must contain at least one electromagnetic trigger tower with transverse energy above 11 GeV (CEM(1,11)). There are no Level 2 requirements. At Level 3, events must contain at least one electron defined with a tight shower shape cut and $E_T > 15$ GeV (ELE.SHT(1,15)). In addition, at least two Level 3 jets with $E_T > 20$ GeV must be present in the event (JET(2,20)).

For data recorded using trigger list versions 8.2 to 11 during the period of August 2002 to July 2003, events are required to have fired the specific trigger EM15.2J15. At Level 1, events must contain at least one electromagnetic trigger tower with energy greater than 10 GeV (CEM(1,10)) and two calorimeter jet trigger towers with energy above 5 GeV (CJT(2,5)). At Level 2, events must contain at least two jets with $E_T > 10$ GeV (JET(2,10)) and at least one electromagnetic object with $E_T > 10$ GeV and electromagnetic fraction greater than 0.85 (EM(.85,10)). One loose electron satisfying a transverse shower shape and with $E_T > 15$ GeV (ELE.LOOSE_SH_T(1,15)) must be present at Level 3 in addition to two jets with $E_T > 15$ GeV (JET(2,15)).

5.1.2. µ+jets Triggers

In trigger list version 12, events must pass the specific trigger MU.JT25.L2M0. At Level 1, the single muon trigger based on the muon scintillators is required to have fired (mul1ptxatxx) in addition to one calorimeter jet trigger tower with $E_T > 3$ GeV (CJT(1,3)). At Level 2,
events must contain one medium muon and one jet with $E_T > 10$ GeV, and at Level 3 they
must have one jet with $E_T > 25$ GeV.

Trigger requirements defined in trigger list version 8.2 to 11 are similar to the one used in
version 12. At Level 1, events must fire the single muon trigger mu1ptxatxx and contain at
least one calorimeter trigger tower with $E_T > 5$ GeV. At Level 2, there must be at least one
medium muon. At Level 3, events must contain at least one jet with $E_T > 20$ GeV.

5.2. Application of the Trigger Thresholds to Monte Carlo

The trigger simulator TRIGSIM has not yet been shown to adequately reproduce the online
trigger behavior. The overall trigger efficiencies are instead calculated using single-object
(electron, muon, jet, etc.) trigger efficiency curves measured on data and applied to Monte
Carlo events. Details of the method and its implementation can be found in Section III.B of
Ref. [41] and Ref. [42].

As an example, we show the turn-on curves for the L3 electron tool ELE_LOOSE_SH_T in
Figure 9. This is a Level 3 tool with tight shower shape requirements used in trigger list
versions 8-11. The extrapolated turn-on curve used in the analysis for a trigger threshold
of 15 GeV. Also shown in the figure are the turn-on curves obtained from $Z \rightarrow ee$ data for
thresholds of 25 GeV and 35 GeV, together with their corresponding fits. The functional
form used in the fitting of the data is:

   Double_t turnon(Double_t *x, Double_t *par)
   {
     Double_t arg = 0;
     arg = (x[0] - par[0])/ (TMath::Sqrt(2)*par[1]);
     Double_t fitval = 0.5*par[2]*(1+TMath::Erf(arg));
     return fitval;
   }

FIG. 9: Comparison of the extrapolated electron trigger turn-on curve with two turn-on curves derived from data
and their corresponding fits (blue data points and blue lines). The black line corresponds to the turn-on curve for
the L3 electron tool ELE_LOOSE_SH_T at a trigger threshold of 15 GeV, which is the threshold applied in the signal
trigger EM15_2JT15. The data turn-on curves are for offline electron thresholds of 25 GeV and 35 GeV for trigger
list versions 8-11.

The average efficiencies of the trigger for preselected $tb \rightarrow e+$-jets and $tqb \rightarrow e+$-jets events
are 85.5% and 84.7% respectively, and for preselected $tb \rightarrow \mu+$-jets and $tqb \rightarrow \mu+$-jets events,
the average efficiencies are 89.3% and 88.2% respectively. (These numbers are given just for
illustration and are not used in the analysis.) The errors from the trigger simulation are
given in Section 12.2.1.
6. EVENT RECONSTRUCTION

6.1. Primary Vertex

6.1.1. Primary Vertex Reconstruction and Identification

Precise determination of the primary vertex position is crucial for all $b$-tagging algorithms. Primary vertex reconstruction and selection are explained in Section IV of Ref. [41], here only a brief overview is given. Top-Analyze uses the primary vertex selected by d0root after a two-step reconstruction and a probabilistic selection. See Ref. [43] for a detailed explanation and performance information.

Primary vertices are reconstructed by fitting tracks with $p_T > 0.5$ GeV, at least two SMT hits and with distance-of-closest-approach (DCA) significance from the beam spot $S_{BS}$ less than four. The beam spot position is previously calculated around $(0,0)$ in the transverse plane using a loose DCA-significance cut. The fitting procedure begins with the highest $p_T$-track and forms clusters of tracks by adding new tracks less than 2 cm away in $z$ from the center of the cluster. The list of reconstructed vertices is then parsed to select the primary vertex, the result of a hard scatter, by constructing the probability for each vertex to originate from a minimum bias interaction. Vertices from minimum bias interactions have lower-$p_T$ tracks than hard scatter vertices. The vertex with the lowest minimum bias probability is selected as the primary vertex.

The following identification requirements are applied to the selected primary vertex in both the electron and muon channels at the preselection level:

- Number of tracks attached to the primary vertex: $N_{\text{tracks}} \geq 3$
- Fiduciality of the primary vertex: $|z_{\text{vertex}}| < 60$ cm

The second cut ensures good primary vertex quality by requiring it to lie within the SMT.

6.1.2. Identification Efficiency Corrections for MC Primary Vertices

The efficiencies for reconstructing a primary vertex vary slightly between Monte Carlo events and data. We correct the MC reconstruction efficiency to make it match data with the following factors:

- Electron channel primary vertex correction factor = $1.008 \pm 0.006$
- Muon channel primary vertex correction factor = $0.997 \pm 0.008$

Measurement of these factors is described in Ref. [45].
6.2. Electrons

6.2.1. Electron Reconstruction and Identification

There are three steps for electron identification: find a calorimeter cluster, match a track, and apply a likelihood cut. A detailed description of all elements of electron identification can be found in Section V of Ref. [41]. The criteria are:

**Loose Isolated-EM Object**

- EM fraction of calorimeter cluster $F_{EM} > 0.9$
- Isolation = $(E_{Total}(R < 0.4) - E_{EM}(R < 0.2))/E_{EM}(R < 0.2) < 0.15$
- Eight-variable H-matrix $\chi^2 < 75$
- Transverse energy $E_T > 15$ GeV
- Detector pseudorapidity $|\eta^{det}| < 1.1$ (CC)

**Tight Isolated-Electron**

- Passes all loose-EM criteria
- Track match: $|\Delta\phi(EM, track)| < 0.05$ radians, $|\Delta\eta(EM, track)| < 0.05$
- Vertex cut: $|\Delta z(track, primary vertex)| < 1$ cm
- Seven-variable likelihood $L > 0.75$ (CC)

The likelihood variables are: (i) $F_{EM}$, (ii) $\chi^2_{HMTx8}$, (iii) $E_{cal}^{track}/p_T^{track}$, (iv) Probability $\chi^2$ of the track match, (v) Distance of closest approach between the track and the primary vertex in the $(x,y)$ plane, (vi) $N_{tracks}(\Delta R (track, matched track) < 0.05)$, and (vii) $\sum p_T$ of tracks in $\Delta R < 0.4$ cone around the matched track.

6.2.2. Energy Scale Corrections for MC Electrons

A comparison between the dielectron invariant mass distributions for $Z\rightarrow ee$ events in MC and data shows that the position of the $Z$ peak is shifted in MC from that in data, and that the electron energy resolution in MC is better than in data. We correct the electromagnetic energy scale for MC electrons and smear their energies to make them have the same energy and resolution as electrons in data by applying a correction function, parametrized as:

$$E' = E \times [\alpha + \text{Gaussian}(0, \sigma = \alpha S)]$$

where $\alpha$ is the scale factor and $S$ is the smearing parameter.

The values for the scale and the over-smearing parameter are obtained using a Kolmogorov-Smirnov test for different categories of the MC electron, based upon its position in the detector. These measurements are described in Ref. [44]. The values for $\alpha$ and $S$ are listed in Table 5.
### Table 5

<table>
<thead>
<tr>
<th>MC Electron Type</th>
<th>Scale $\alpha$</th>
<th>Smearing $S$</th>
</tr>
</thead>
<tbody>
<tr>
<td>CC (fiducial)</td>
<td>1.003</td>
<td>0.045</td>
</tr>
<tr>
<td>CC (not fiducial)</td>
<td>0.950</td>
<td>0.115</td>
</tr>
</tbody>
</table>

The scale and over-smearing parameters for MC electrons in the central 80% of a calorimeter module (“fiducial”), and for those within 0.02 radians of an intermodule crack (“not fiducial”).

#### 6.2.3 Identification Efficiency Corrections for MC Electrons

The efficiencies for finding an EM cluster in data, and for it passing cluster identification, track match, and likelihood, as well as the methods used to evaluate them are given in Section V of [41]. All efficiencies are measured using $Z \rightarrow ee$ data. The electron-ID cuts are also applied to MC electrons, but the corresponding efficiencies are mostly over-estimated. We therefore correct for this bias by applying a correction factor to MC electrons:

\[
\varepsilon_{e-ID} = \varepsilon_{\text{Data, Cluster}} \times \varepsilon_{\text{MC, EMF, Isol}} \times \varepsilon_{\text{Data, Trackmatch}} \times \varepsilon_{\text{MC, Trackmatch}} \times \varepsilon_{\text{Data, Track-PV}} \times \varepsilon_{\text{MC, Track-PV}} \times \varepsilon_{\text{Data, Likelihood}} \times \varepsilon_{\text{MC, Likelihood}}
\]

\[
= 0.960 \times 0.997 \times 0.913 \times 0.991 \times 0.891 \times 0.957
\]

\[
= 0.869 \pm 0.021
\]
6.3. Muons

6.3.1. Muon Reconstruction and Identification

There are three steps for muon identification: find a track in the spectrometer, make sure it is not a cosmic ray, and check its isolation from the nearest jet. A detailed description of all elements of muon identification can be found in Section VI of Ref. [41]. In the Run II DØ spectrometer, we can reconstruct muons out to $|\eta^{\text{det}}| = 2$. The three identification steps are split into the following groups:

**Muon ID = “$|n_{\text{seg}}| = 3$ Medium Muon”**
- At least 2 wire hits in the A layer
- At least 1 scintillator hit in the A layer
- At least 2 wire hits in the BC layers
- At least 1 scintillator hit in the BC layers
  (except for central muons with $< 4$ wire hits in the BC layers)

**Loose Cosmic-Ray Rejection**
- $|\Delta t(\text{A layer scint}, t_0)| < 10$ ns
- $|\Delta t(\text{BC layer scints}, t_0)| < 10$ ns

**Tight Cosmic-Ray Rejection**
- Passes loose cosmic-ray rejection cuts
- Central track $\chi^2 < 4$
- $|\text{DCA}(x, y)_{\text{sig}}| < 3\sigma$
- $|\Delta z(\text{central track, primary vertex})| < 1$ cm

**Loose-Isolation from a Jet**
- $R(\muon, \text{jet}) > 0.5$

**Tight-Isolation from a Jet**
- Passes loose-isolation criterion
- Track halo isolation = $\sum_{\text{tracks}} p_T/p_T(\mu) < 0.06$ in $\Delta R(\text{track, muon track}) < 0.5$ cone
- Calorimeter halo isolation = $\sum_{\text{cells}} E_T/p_T(\mu) < 0.08$ in $0.1 < \Delta R(\text{cal-cells, muon cal-track}) < 0.4$ cone

For our analysis:

**Muon from $W$ decay = “Isolated muon”**
- Passes all criteria listed above
- $p_T > 15$ GeV

**Muon from $b$ decay = “Tagging muon”**
- Passes $|n_{\text{seg}}| = 3$ medium criteria
- Passes the loose cosmic ray rejection criteria
- $\Delta R(\muon, \text{jet}) \leq 0.5$
- $p_T > 4$ GeV

Because a central matched-track is not required for a tagging muon, its kinematic information can come from the muon spectrometer information (after correcting for the energy loss in the calorimeter). However, if there is one with $\chi^2 < 100$, then the muon’s kinematic parameters come from the central track.
6.3.2. Energy Scale Corrections for MC Muons

A comparison between the dimuon invariant mass distributions for $Z \rightarrow \mu\mu$ events in MC and data shows that the position of the $Z$ peak is shifted in MC from that in data, and that the muon energy resolution in MC is better than in data. We correct the energy scale for MC muons and smear their energies to make them have the same energy and resolution as muons in data by applying a correction function, parametrized as:

$$\frac{1}{p_T} = \frac{1}{\alpha} + [\text{Gaussian}(0, \sigma = S)]$$

where $\alpha$ is the scale factor and $S$ is the smearing parameter.

The values for the scale and the smearing parameter are obtained using a Kolmogorov Smirnov test, resulting in:

- Scale = $\alpha = 0.991$
- Smearing = $S = 0.0023$ GeV$^{-1}$

These measurements are fully described in Section VI.D of Ref. [41].

6.3.3. Identification Efficiency Corrections for MC Muons

The efficiencies for finding an $|nseg|=3$ medium muon that passes the cosmic ray cuts and isolation criteria are described in Section VI of [41]. The muon-ID cuts are applied to MC muons, but the corresponding efficiencies are mostly over-estimated. We therefore correct for this bias by applying a correction factor to MC muons. The isolated muon corrections are calculated with $Z \rightarrow \mu\mu$ data and MC, and the tagging muon correction is calculated with $J/\psi \rightarrow \mu\mu$ data and MC.

$$\varepsilon_{\text{isol-\mu-ID}} = \frac{\varepsilon_{\text{Z Data}}}{\varepsilon_{\text{Z MC}}} \times \frac{\varepsilon_{\text{Z TrackMatch}}}{\varepsilon_{\text{Z TrackMatch}}} \times \frac{\varepsilon_{\text{Z DCA}}}{\varepsilon_{\text{DCA}}_{\text{sig}}} \times \frac{\varepsilon_{\text{Z Track-PV}}}{\varepsilon_{\text{Track-PV}}} \times \frac{\varepsilon_{\text{Z TightIsol}}}{\varepsilon_{\text{TightIsol}}}$$

$$= 1.010 \times 0.960 \times 0.990 \times 0.997 \times 0.899$$

$$= 0.860 \pm 0.054$$

$$\varepsilon_{\text{tag-\mu-ID}} = \frac{\varepsilon_{\text{J/\psi Data}}}{\varepsilon_{\text{J/\psi MC}}} \times \frac{\varepsilon_{\text{J/\psi MediumID}}}{\varepsilon_{\text{MediumID}}}$$

$$= 1.025 \pm 0.006$$

The value for $\varepsilon_{\text{Z Data}}/\varepsilon_{\text{Z MC}}$ is slightly different here than in the $t\bar{t}$ analyses because this correction factor is parametrized as a function of $\eta^{\text{det}}$ and the $\eta^{\text{det}}$ distributions of the muons in each production mode are not identical.
6.4. Jets

6.4.1. Jet Reconstruction

We reconstruct jets using the “improved legacy cone algorithm” [46] with radius $R=0.5$. The jets are reconstructed with the “t42” algorithm applied. This algorithm is designed to reduce coherent noise in the calorimeter by suppressing cells with weak signals if they do not have at least one neighboring cell with a strong signal. (This algorithm was developed and successfully used in the H1 experiment.) The definition of a strong signal is one greater than $4\sigma$ above the noise level, and the neighboring cells must have signal greater than $2\sigma$ above the noise to be kept (hence the name). Negative energy cells are also rejected. We remove jets from the list if $\Delta R$(loose EM object, jet) $\leq 0.5$. The loose EM object has $E_T > 15$ GeV.

6.4.2. Jet Energy Scale Corrections

We use JETCORR 5.1 to apply the jet energy scale corrections. We use the version measured from jets reconstructed with the “t42” algorithm. The purpose of the jet energy scale corrections is to convert raw jet energies from D0reco into particle-level energies. Nonuniformities in the calorimeter readout are thus reduced, together with corrections for out-of-cone showering and for the difference in calorimeter response to electrons and pions.

We measure the uncertainty from the jet energy scale for the Monte Carlo samples, to quantify how well the model matches the data. This source of uncertainty thus contributes to the signal acceptance error and to the error on the $t\bar{t}$ backgrounds. Details of the method and results of the measurements are given in Section 12.2.11.

6.4.3. Correction for a Tagging Muon and its Neutrino

When a heavy flavor hadron has a muon and neutrino in the decay chain, some energy is carried out of the calorimeter, leaving the calorimeter-only measurement of the particle energy lower than it should be. We add back to the jet momentum the momentum from the muon and some approximation to the neutrino, and properly account for the energy deposited in the calorimeter by the muon so as not to double count it. This is done in Top_Analyze.

6.4.4. Identification

We identify jets that have been well-reconstructed via the following requirements:

**Bad Jets Cuts**

- $0.05 < \text{Fraction of jet } E_T \text{ in the EM calorimeter layers} < 0.95$
- Fraction of jet $E_T$ in the coarse hadronic calorimeter layers $< 0.4$
- Ratio of $E_T$’s of hottest cell in jet to next-hottest cell $< 10$
- Smallest number of towers that make up 90% of the jet $E_T, n_{90} > 1$

**Noise Jets Cut**

- For a given jet, the scalar sum of the trigger tower’s $E_T$ inside the jet’s cone, divided by the jet $E_T$ and by one minus the fraction of jet $E_T$ in the coarse hadronic calorimeter layers must be $> 0.4 \ (|\eta^{\text{det}}| < 0.8, 1.5 < |\eta^{\text{det}}|) \ or \ > 0.2 \ (0.8 \leq |\eta^{\text{det}}| \leq 1.5)$. This cut is known as “L1 confirmation.”
6.4.5. Energy Smearing for MC Jets

The reconstructed fully-corrected energy of jets from the D0GSTAR simulation of the detector performance does not match that seen in data. Specifically, the jet energy resolution is too good and there is a small offset not corrected by the jet energy scale package. Therefore, in Top-Analyze, we smear the energies of the MC jets to make the resolution match the data. The smearing functions used should be, but are not yet, described in Section VII of Ref. [41].

We summarize here how the jet energy smearing is done. The jets are divided into four pseudorapidity regions:

- $|\eta^{\text{det}}| < 0.5$
- $0.5 \leq |\eta^{\text{det}}| < 1.0$
- $1.0 \leq |\eta^{\text{det}}| < 1.5$
- $1.5 \leq |\eta^{\text{det}}| < 10.0$

The jet $E_T$ resolution is given by:

$$\sigma = \sqrt{N^2/E_T^2 + S^2/E_T + C^2}$$

This resolution has been measured in both data and MC, and the parameters $N$, $S$, and $C$ are given in Table 6.

| Constant  | $|\eta^{\text{det}}|$ Region |
|-----------|-----------------|
|           | 0.0–0.5 | 0.5–1.0 | 1.0–1.5 | 1.5–10.0 |
| Data      |         |         |         |         |
| $N$       | 5.05    | 9.00 $\times 10^{-9}$ | 2.24 | 6.42 |
| $S$       | 0.753   | 1.20    | 0.924  | 4.50 $\times 10^{-10}$ |
| $C$       | 0.0893  | 0.0870  | 0.135  | 0.0974 |
| Monte Carlo|         |         |         |         |
| $N$       | 4.26    | 4.61    | 3.08   | 4.83 |
| $S$       | 0.658   | 0.621   | 0.816  | 5.13 $\times 10^{-7}$ |
| $C$       | 0.0436  | 0.0578  | 0.0729 | 0.0735 |

TABLE 6: The resolution parameters for jets in data and MC.

The width of the smearing Gaussian is found by comparing the data and MC resolutions:

$$\sigma_{\text{smear}} = \sqrt{\sigma_{\text{data}}^2 - \sigma_{\text{MC}}^2}$$

The $E_x$, $E_y$, $E_z$, and resulting $E_T$ and $E$ of each MC jet, and $E_T$, are smeared by a Gaussian of width $\sigma_{\text{smear}}$ in Top-Analyze. Thus the MC jet resolution is made to match that seen in data.
6.5. Neutrinos

6.5.1. Reconstruction and Corrections

We measure only the transverse momentum of the neutrino in the event, as the opposite of the vector sum of all the energy deposited in the calorimeter. A detailed description of the procedure can be found in section VII of Ref. [41].

This calorimeter-only missing transverse energy ($E_T^{\text{cal}}$) is then corrected for the presence of electrons, photons, jets, and muons in the event.

- **Electrons and photons.** The calorimeter cluster energy for EM candidates (see Sec. 6.2) is subtracted from $E_T^{\text{cal}}$ and then the EM-scale corrected energy is added.

- **Jets.** The response part of the jet energy scale correction applied to good jets (see Sec. 6.4) is also applied to the missing transverse energy, as explained in Sec. VII of Ref. [41]. This quantity is called $E_T^{\text{JES}}$.

- **Muons.** The momentum of track-matched muons (see Sec. 6.3) is subtracted from the missing transverse energy vector, correcting for the energy deposited in the calorimeter by the muon. This correction is done for isolated muons.
7. **B-JET TAGGING**

A $b$-quark is present in all top quark decays (rare decays of the top quark occur < 0.1% of the time in the SM, and are not considered in this analysis). Multijet events with a misidentified-lepton and $W+$jets events, however, are expected to have a small proportion of $b$-quarks. The $b$-tagging algorithms described in this section are used to differentiate between jets that contain $b$-quarks and those that do not.

Two of the algorithms (SVT and JLIP) rely completely on the tracks in the event. Since tracking efficiencies in high-activity environments like jets are higher in MC than in data, we have to define procedures to calculate the proper tagging efficiencies and fake rates in Monte Carlo, separately for each tagger.

The taggers described in this section are: (i) Soft-Lepton Tagger “SLT,” which looks for a muon associated with a jet. The muon is expected to come from a $B$ hadron decay or the cascade charm decay; (ii) Secondary-Vertex Tagger, “SVT,” a track-vertex reconstruction algorithm; and (iii) Jet-Lifetime-Probability Tagger “JLIP,” a track impact-parameter based algorithm. The SVT and JLIP algorithms are referred to as lifetime taggers.

### 7.1. $b$-Tagging Terminology

We provide a short vocabulary list for those not familiar with $b$ tagging.

- **Tagging Algorithm** These algorithms, or *taggers*, are designed to differentiate between jets that originate from heavy-flavor quarks ($b$ quarks) and those that originated from light quarks or gluons. Three different tagging algorithms are used in this analysis, SLT, SVT, and JLIP. They are applied directly to the signal data and to multijet background data, and the SLT algorithm is also applied directly to MC events.

- **Tagging Efficiency** This is the average number of jets per event that are tagged by a tagging algorithm. Tagging efficiencies are not used in the single-top analyses. *(TRF Event Weights are used instead, see below.)*

- **Taggability** This is a jet quality cut applied before a lifetime tagging algorithm is used on signal data or on multijet background data. Jets in the untagged $W+$jets data sample are also checked for their taggability before the flavor-inclusive lifetime tag-rate functions are applied (see below). For a calorimeter jet to be considered taggable, there must be at least two good-quality tracks close to it. Taggability is defined in detail in Section 7.2.

- **Taggability-Rate Functions** These give the average probability that a jet is taggable as a function of the jet’s $E_T$ and $\eta$. There are two taggability-rate functions in this analysis, one for the electron channel and one for the muon channel, described in Section 7.2. These functions are measured using data and are applied to MC before the flavor-dependent tag-rate functions are applied. Tracking and related variables are not well simulated by the MC model, and so the taggability algorithm cannot be applied directly to MC jets.

- **Tag-Rate Functions (TRFs)** These give the average probability that a taggable jet passes a tagging algorithm as a function of the jet’s $E_T$ and $\eta$. “TRF” is a generic term — there are two different types of TRFs used in this analysis, listed below. The probability for a jet to be tagged is the product of the value of the taggability-rate function (if needed) and the value of the tag-rate function.
- **Flavor-Dependent TRFs** These are applied to MC jets to determine their probability to be tagged. For each jet, one finds the closest MC particle. Depending on the type of particle found, a heavy-flavor TRF, charm TRF, or light-quark TRF is applied to the jet as a function of its $E_T$ and $\eta$. The light-quark TRF (which includes $u, d, s$, and gluons) is a mistag rate since there is no heavy flavor present. The heavy-flavor and light-quark TRFs are determined from data. The charm TRF is determined from a combination of data and MC events. There is one set of flavor-dependent TRFs for each of the lifetime taggers.

- **Flavor-Inclusive TRFs** These are used to predict the heavy-flavor content of the $W+$jets data samples. There is one flavor-inclusive TRF for each of the three tagging algorithms, derived from suitable multijet data samples. These TRFs do not separate out the fraction of tags from $b$’s, $c$’s, or light quarks and gluons, but provide an inclusive measurement with the components in the right proportions.

- **TRF Event Weight** Each MC and data event in the single top analyses is assigned a weight, a number between 0 and 1, which are summed to get the acceptances and yields. For MC, the weight includes all correction factors to make the MC look like data, including the probability for the event to have at least one $b$-tagged jet, the TRF event weight. For data, the $b$-tagged probability enters into the weight for the $W+$jets background. The probability for each jet in the event to be tagged is determined from the taggability-rate functions and the tag-rate functions. The advantage of calculating a weight for each event rather than just multiplying the total number of events by the average probability for an event to have at least one tagged jet is that the $E_T$ turn-on curve and $\eta$ fiducial region are properly modeled. Without the event weights, the shapes of distributions of variables such as $H_T$ would be incorrect.

### 7.2. Taggability

Good tagging efficiency depends on more than the heavy flavor content of the jets. Even run conditions, in particular, can affect the tag rate. This is born out of the noise problems that DO’s calorimeter has experienced. The $B$-ID Group has thus factored the efficiency into two parts: a heavy-flavor-sensitive component and a jet-quality-sensitive component. The first is the traditional *tagging* efficiency and the second is *taggability*.

A taggable jet requires two tracks within a cone of 0.5 in $\Delta R$. One track has $p_T > 1.0$ GeV and the other has $p_T > 0.5$ GeV. Both tracks must have at least one SMT hit, an $xy$ distance-of-closest-approach (DCA) of $< 0.2$ cm, and a $z$ DCA of $< 0.4$ cm. Each jet is tested for taggability before the lifetime tagging algorithms are applied. The test is not needed for the soft lepton tagger as having a soft muon in the jet already provides a jet-quality requirement.

For the case of Monte Carlo, because the tracking efficiency is different to that in data, a *taggability-rate function* is utilized. This function is calculated centrally by the Top Group and is used by all the $b$-tagging based analyses. The taggability is determined separately as a function of jet $E_T$ and $\eta$, assuming that they are independent, by dividing the number of taggable jets by the total number of good jets. The lepton and jet quality cuts in the analysis change the jet distributions in the preselected samples. In order to compensate for this, the above generated taggability function is run on both the $e+$jets and $\mu+$jets samples and then rescaled to match the actual number of taggable jets. For the electron sample, this change is 1%, and for the muon sample, it is 5%. The resulting scaled functions are used to calculate taggability in the MC. The systematic uncertainty on this procedure is taken as the statistical uncertainly in each bin.
Figure 10 shows the resulting taggability functions and their uncertainty for the electron and muon channels.

FIG. 10: Jet taggability as a function of jet $E_T$ and $\eta$ for the $e$+jets (left) and $\mu$+jets (right) samples used in the Top Production subgroup. Curves indicate the fit and its 1 $\sigma$ error band.

See Section 20 for a complete description of the top group taggability and cross checks. This section has been copied from the top group b-tagging cross section note (in final stages of preparation).
7.3. SLT \( b \)-tagging algorithm

According to the measured branching fractions \[56\] for an admixture of \( B \) hadrons to decay to a muon either directly or via a cascade charm or tau decay, 21\% of our \( b \)-jets are expected to include a muon in their decay chain. (The components are 10.95\% for \( b \rightarrow c \rightarrow \mu \), 1.6\% for \( b \rightarrow \bar{c} \rightarrow \mu \), and 2.48\% \times 17.36\% for \( b \rightarrow \tau \) and \( \tau \rightarrow \mu \) plus a small contribution from \( b \rightarrow c \rightarrow \tau \rightarrow \mu \) and a few small subtractions to avoid double counting.) The SLT \( b \)-tagging algorithm identifies \( b \)-jets by finding a muon in the jet.

7.3.1. SLT Algorithm

A jet is considered to be a \( b \)-jet by the SLT algorithm if at least one muon is found that satisfies the criteria listed in Section 6.3.1. The average probability to tag at least one jet in an event using the SLT algorithm is measured using the MC samples. The results are presented in Table 7. They are not used in the analysis but are presented to show the effectiveness of the technique.

(It is interesting to compare these values with those found in the Run I single top analysis, where \( \sim 11\% \) of \( s \)-channel events had a muon tag, \( \sim 7\% \) of \( t \)-channel events had a muon tag, and \( \sim 15\% \) of \( t\bar{t} \) events had a muon tag (\( l \)-jets and dileptons combined) after preselection cuts. The improvement probably comes from the extension of the muon \( |\eta| \) region from 1.7 to 2.0, although there are many other differences in the muon ID that affect the reconstruction efficiency and fake rate.)

<table>
<thead>
<tr>
<th>Percentage of Preselected Events with an SLT Tag</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electron Channel</td>
</tr>
<tr>
<td><strong>Signals</strong></td>
</tr>
<tr>
<td>( tb )</td>
</tr>
<tr>
<td>( t\bar{q}b )</td>
</tr>
<tr>
<td><strong>Backgrounds</strong></td>
</tr>
<tr>
<td>( t\bar{t} \rightarrow l+\text{jets} )</td>
</tr>
<tr>
<td>( t\bar{t} \rightarrow ll )</td>
</tr>
</tbody>
</table>

Table 7: Percentage of preselected single top and \( t\bar{t} \) events that have a tagging muon in them.

We use direct SLT tagging (i.e., finding a muon in a jet) for the signal data, multijet background samples, and for the MC signals and backgrounds. No tag-rate functions are needed in any of these cases.

7.3.2. SLT Flavor-Inclusive Tag-Rate Functions

We use flavor-inclusive tag-rate functions to measure the tagged \( W+\text{jets} \) background by applying them to untagged \( W+\text{jets} \) data. For the SLT algorithm, these functions are determined using the ALLJETS data sample. The details are described in Ref. \[47\]. The tag-rate probability is parametrized as a function of the jet \( E_T \), \( \eta \), and \( \phi \). We assume that the \( \phi \) dependence, described by a histogram obtained from the data, can be factorized out, and therefore this function is:

\[
\text{TRF}(E_T, \eta^{\text{det}}, \phi^{\text{det}}) = A(E_T, \eta^{\text{det}}) \cdot B(\phi^{\text{det}})
\]
The function $A(E_T, \eta^{\text{det}})$ is parametrized as an analytical function of $E_T$ obtained by a fit to the data, in bins of $\eta$. Jan Stark, who measured the TRFs for SLT, found good agreement on the closure tests for the TRFs: the predicted number of tags in the ALLJETS sample agrees with the actual number of tags, and also when applying the ALLJETS TRF to the 3JETS\_LOOSE sample, good agreement is seen. Finally, we tested the SLT TRF on a data sample dominated by $W$ events. We apply the following cuts to the preselected data sample: $H_T < 200 \text{ GeV}$ to remove top events, and electron likelihood $> 0.95$ (instead of 0.75) to reject multijet events with a misidentified electron. Table 8 shows the results. Equivalent numbers for $Z$ events with two or more jets are also given. The $Z$ events have been selected by asking for two EM-objects, each with a track match spatial $\chi^2 < 1$ and with an invariant mass within 20 GeV of the $Z$ mass. The same criteria on the jets as for the preselected sample have also been used. (Note, we do not expect the TRFs to be valid for $W+1$jet or $Z+1$jet samples, since the heavy-flavor fractions will be rather different in these than in the sample on which the TRFs were derived. For example, not so much $g\rightarrow b\bar{b}$ will be present, as this often produces two ISR $b$-jets.)

<table>
<thead>
<tr>
<th>Tagging Efficiencies with SLT-TRF and with SLT on W+jets and Z+jets Data</th>
<th>Predicted</th>
<th>Observed</th>
</tr>
</thead>
<tbody>
<tr>
<td>$W+2$jets</td>
<td>$(0.89 \pm 0.02)%$</td>
<td>$(0.7 \pm 0.2)%$</td>
</tr>
<tr>
<td>$W+\geq 3$jets</td>
<td>$(1.37 \pm 0.07)%$</td>
<td>$(2.0 \pm 0.8)%$</td>
</tr>
<tr>
<td>$W+\geq 2$jets</td>
<td>$(1.01 \pm 0.02)%$</td>
<td>$(1.0 \pm 0.3)%$</td>
</tr>
<tr>
<td>$Z+\geq 2$jets</td>
<td>$(0.93 \pm 0.05)%$</td>
<td>$(2.0 \pm 0.8)%$</td>
</tr>
</tbody>
</table>

**TABLE 8**: Tagging efficiencies using SLT in the electron channel, obtained from a $W$+jets control sample and from a $Z$+jets sample by applying the TRF (Predicted) or by measuring directly the tagging efficiency in these samples (Observed) for different good-jet multiplicities.

The agreement between the observed and predicted tagging efficiencies for the inclusive $W$+jets sample is within the statistical uncertainties.
7.4. SVT b-Tagging algorithm

The secondary vertex b-quark tagger (SVT) looks for track-vertices displaced from the primary vertex. Details of the algorithm can be found in the certification DØ Note [48]; the single top analysis is using the certified BID algorithm SVT TIGHT and the B-ID Group’s flavor-dependent tag-rate functions. The “TIGHT” set of cuts has been tuned to obtain the lowest probability of the three tune options for a light quark mistag, at 0.025%. The following sections give a brief description of the algorithm, and an overview of how it is used.

7.4.1. SVT Algorithm

The SVT algorithm is fully described in the certification note [48]. A simple $V_0$-removal algorithm (developed for the CSIP b-tagging algorithm) is applied to the tracks first. This removes most $K_s$’s, $\Lambda$’s, and photon-conversions. Tracks are then required to have two SMT hits, $p_T > 1.0$, impact parameter significance $> 3.5$, and a track $\chi^2 > 10$. A simple cone jet-algorithm is used to cluster the tracks into track-jets, and then a Kalman filter algorithm is used to find vertices with the tracks in each track-jet. The decay length, $L_{xy}$, and its error, $\sigma_{L_{xy}}$, the distance between the primary vertex and the found secondary vertex, is calculated, taking into account the error on the primary vertex. If the decay length significance $L_{xy}/\sigma_{L_{xy}}$ is more than 7.0, then the found vertex is considered a tight tag. A calorimeter jet is considered tagged if $\Delta R < 0.5$, where $\Delta R$ is the distance between the jet axis and the line joining the primary vertex and the secondary vertex.

7.4.2. SVT Flavor-Dependent Tag-Rate Functions for MC

All SVT efficiencies are calculated on data with the exception of the charm efficiency, which has a small input from MC. As noted above, the following is more fully described in the SVT certification note [48].

To calculate the probability for a jet in MC to be tagged, a tag-rate function is used. The tag probability for a particular jet depends on a number of things. For example, its $p_T$, its $\eta$, and, of course, if the jet originates from a b-quark, c-quark, or from neither of these. The SVT tag-rate functions are parametrized in jet $\eta$ and $E_T$. Separate functions are determined for bottom jets, charm jets, and light quark jets. The rest of this section outlines the procedure used to calculate the three SVT tag-rate functions.

7.4.2.1. SVT Bottom-Flavor Jet Tagging

The SVT tag-rate function for b quarks is derived from data: a muon+jets sample with $p_T(\mu) > 8$ GeV. Three methods are used to determine the heavy-flavor content and thus the tagging rate for b jets.

- **Muon $p_T^{rel}$ Single-Tag Fit.** $p_T^{rel}$ shapes for b-quarks, c-quarks and light quarks are determined from MC samples. The b-quark content is determined using these fits and the SVT tag-rate of the away jet.
- **Muon $p_T^{rel}$ Double-Tag Fit.** Similar to the previous method, but both the muon-jet and the away-jet are required to be tagged. Though statistics are lower, the $p_T^{rel}$ fits are more stable.
**System 8.** A set of eight nonlinear equations that play two tagging algorithms off each other (SLT and SVT).

The muon $p_T^{rel}$ shapes in data are fitted to the MC-generated shapes to determine the $b$-quark content. There are nine different shapes for light quark jets, charm quark jets, and $b$-quark jets — each flavor is split by both jet $E_T$ and also jet $\eta$. Sample plots can be found in Figure 11.

![Figure 11: $p_T^{rel}$ templates used to fit the muon-in-jet data. Left plots: light-quark templates approximated by using a tracks-in-jet trigger (or EMQCD) data; middle plots: $c$-quark templates from $Z\rightarrow c\bar{c} \rightarrow \mu$ and $t\bar{t}$ Monte-Carlo simulations; right plots: $b$-quark templates from $Z\rightarrow b\bar{b} \rightarrow \mu$ and $t\bar{t}$ Monte-Carlo simulations. For each flavor, the templates are subdivided according to the muon $p_T$ and jet $E_T$ range.](image)

The left-hand plot in Figure 12 shows the performance of the SVT\_Tight algorithm on $b$-jets as a function of the jet $E_T$ for each method for all values of $\eta$. The final tag rate is the weighted average of the three methods. The systematic uncertainty on the TRF is taken to be the spread between the three results. The right-hand plot in Figure 12 shows the same thing, but as a function of jet $\eta$. This uncertainty is about 6.5% in the central region.
The tag rate derived above is for jets with a muon nearby. This is a side effect of the $p_T(\mu) > 8$ GeV cut discussed above. To determine the TRF for hadronic jets without a nearby muon, a scale factor is derived from Monte Carlo. A TRF is derived for $b$-quark jets with and without a close by muon, and the ratio of these factors is used to scale the TRFs determined from data.

The uncertainty on the scale factor is taken to be the uncertainty on the two MC tag-rate functions that are input to the scale factor. The two are added in quadrature. Unfortunately, only a small amount of $b \rightarrow \mu X$ MC was available, and as a result, this TRF forms the largest contribution to the overall flavor-dependent TRF systematic error. It is as high as 9% in some regions. This measurement will be updated by the $B$-ID group before publication.

![Figure 12: The $b$-quark tag rate for the SVT_Tight tagging algorithm as a function of jet $E_T$ (left plot) and $\eta$ (right plot) as measured on data. The weighted average of the three methods (described in the text) is used to calculate the tag-rate function, and the spread is used to determine the error associated with using the tag-rate function. The gray band has been drawn to guide the eye. These rates are averaged over all values of $\eta$.](image)

7.4.2.2. SVT Charm-Flavor Jet Tagging

An effective method of determining the charm quark tagging rate in data has not yet been found. To get around this, the charm and $b$-tagging ratio from Monte Carlo is used to scale the $b$-quark tag rate determined from data. The average ratio of $b/c$ TRFs in MC is 0.25. The ratio is calculated bin-by-bin (in jet $E_T$ and $\eta$) when it is used to calculate the probability that a charm jet gets tagged.

7.4.2.3. SVT Light-Flavor Jet Tagging

The light-quark tag-rate function is also calculated from data. The calculation employs negatively tagged jets.

Light-quark tags are assumed to be mostly from tracking effects (resolution, reconstruction, etc.). The tagging algorithm normally requires a reconstructed secondary vertex to be in front of the primary vertex (along the jet axis). However, tags due to track misreconstruction and resolution will originate as often behind as in front of the primary vertex. Secondary vertices tagged and reconstructed behind the primary vertex are called negative tags, those in front are called positive tags.

The light-quark tag-rate function is mostly a parametrization of the negative tags in the sample. Monte Carlo is used to correct for two biases. First, a jet that contains a gluon splitting to two $b$-quarks is more likely to have a negative tag than light quarks in general. Second, owing to the way a negative tag is defined — a positively tagged jet cannot have a
negative tag as well — a small positive bias must be corrected.

The light-flavor tag-rate function is parametrized in $E_T$ only, but in three bins of $\eta$ (CC, ICD, and EC). Closure plots that show the efficacy of this method can be found in the certification note [48].

The negative tag rate is calculated on two data samples, an unbiased jet-trigger sample, and the EMQCD sample. The average of the two is taken and the spread is used as an error. Figure 13 shows the negative tag-rate as a function of jet $E_T$ in the CC, EC, and ICR $\eta$ regions.

**FIG. 13:** The negative tag rate in the CC, EC, and ICR $\eta$ regions as a function of jet $E_T$ for the SVT.TIGHT tagging algorithm.

### 7.4.2.4. Using the SVT Flavor-Dependent Tag-Rate Functions

The TRFs, derived as described above, are applied to the single top and $t\bar{t}$ Monte Carlo as part of determining the acceptances. The procedure is straightforward. First, for each jet in the event (with $E_T > 15$ GeV and $|\eta| < 3.4$) a taggability-rate function is applied.

Next, each jet’s lineage is determined. If the jet contains a $B$ meson within $\Delta R < 0.5$ of the jet axis it is labeled a $b$-quark jet. If a $D$ meson is within $\Delta R < 0.5$ of the jet axis, it is labeled a $c$-quark jet. If neither of the two are close by, the jet is labeled a light-quark jet. The probability determined from the appropriate TRF is then applied. The taggability and tagging probability are multiplied together to determine the probability of the MC jet being tagged ($P_{\text{jet-tag}}$).

The probability for at least one jet in the event to be tagged is one minus the probability of no jet being tagged:

$$P_{\text{event-tag}} = 1 - \prod_{\text{jets}} (1 - P_{\text{jet-tag}})$$

This number is used as part of the event weight for MC events, similar to the procedure used for a trigger weight. Table 9 gives the overall tagging efficiencies in the various Monte Carlo samples. These efficiencies are determined after all preselection cuts have been made and the trigger weighting has been applied to each event.
<table>
<thead>
<tr>
<th>Percentage of Tagged Events with SVT</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
</tr>
<tr>
<td><strong>Electron Channel</strong></td>
</tr>
<tr>
<td>Signals</td>
</tr>
<tr>
<td>$t\bar{b}$</td>
</tr>
<tr>
<td>$t\bar{q}b$</td>
</tr>
<tr>
<td>Backgrounds</td>
</tr>
<tr>
<td>$t\bar{t} \rightarrow l + jets$</td>
</tr>
<tr>
<td>$t\bar{t} \rightarrow ll$</td>
</tr>
</tbody>
</table>

TABLE 9: Percentage of preselected single top and $t\bar{t}$ events that have at least one SVT-tagged jet.

### 7.4.3. SVT Flavor-Inclusive Tag-Rate Functions for W+Jets

Modeling the $W+\text{jets}$ background entirely with Monte Carlo is difficult, especially when it is important to get heavy flavor contributions correct. We therefore derive inclusive tag-rate functions that can be applied to the untagged preselected data sample in order to evaluate the residual tagged $W+\text{jets}$ background. The inclusive TRFs are built from a multijet sample, 3JETS_LOOSE, which has kinematics similar to the preselected data sample. We make the assumption that the fraction of jets with heavy flavor is the same in the $W+\text{jets}$ background and the multijet sample for events with the same jet multiplicity and at least two jets.

We use the 3JETS_LOOSE data skim to calculate the flavor-inclusive TRFs since, unlike the ALLJETS sample, the 3JETS_LOOSE sample agrees well with our preselected data sample as seen in the distributions for the number of good jets, the number of tracks associated with a jet, the total scalar energy $H_T$, and the $E_T$ of all good jets, shown in Fig. 14.

The flavor-inclusive TRF is defined as the ratio of the number of tagged jets to the number of pretagged taggable jets as a function of the jet $E_T$ and $\eta^{\text{det}}$. We use the ratio directly from the $(E_T, \eta^{\text{det}})$ histogram shown in Fig 15. Also shown in Fig 15 is the $(E_T, \eta^{\text{det}})$ histogram containing the errors on the TRFs. Since we use ratios to obtain the TRFs, we are not sensitive to the jet-$E_T$ thresholds in the 3JETS_LOOSE sample or to variations in the jet energy scale.

To obtain the tagged $W+\text{jets}$ background, the TRF is applied to the untagged preselected data sample in a similar way as described in Section 7.4.2.4. The probability for at least one jet in the event to be tagged is one minus the probability of no jet being tagged:

$$P_{\text{event-tag}} = 1 - \prod_{\text{jets}}(1 - P_{\text{jet-tag}})$$

This number is used as part of the overall event weight. To validate use of the TRF, various closure plots have been produced to compare the observed distributions (as obtained using the tagger) to the predicted ones (as obtained using the TRF). These are discussed in Section 7.6, along with a scale factor that must be applied to account for the varying heavy-flavor content as a function of number of jets.
FIG. 14: Distributions of the number of good jets, the number of tracks associated with a jet, the $H_T$, and the $E_T$ of all good jets, for the preselected MUQCD (cyan), preselected EMQCD (magenta), 3JETS_LOOSE (green), and the ALLJETS (red) samples.

FIG. 15: The two-dimensional ($E_T, \eta^{det}$) histograms showing the inclusive tag-rate functions (left) and the corresponding errors (right) obtained using the 3JETS_LOOSE sample.
7.5. JLIP Tagger

A comprehensive description of the JLIP tagger and its performance can be found in Ref. [49]. Here, we summarize the method and its application for this analysis.

7.5.1. JLIP Algorithm

The decay of a long-lived particle such as a $B$ hadron, produces a jet of tracks with large impact parameters, which is not the case for particles originating from the primary interaction. The JLIP method to tag $b$-quark jets is based on this difference. For each taggable jet, the probability that all matched tracks originate from the interaction point is computed. Jets with long lived decays can thus be selected.

The impact parameter, $IP$, of a charged particle track is the minimal distance between the estimated primary interaction point and the track trajectory. Impact parameters are computed in the plane transverse to the beam axis. The $IP$ value is given a positive (negative) sign if the perigee coordinate along the track trajectory is found downstream (upstream) with respect to the primary vertex, $PV$.

For each track matched to a jet, the significance is defined as the signed $IP$ divided by its error:

$$S = IP / \sigma_{IP}.$$ 

As explained in [49], the $\sigma_{IP}$ errors have been calibrated as a function of three different track properties:

- the number of reconstructed SMT and CFT hits
- the $p_{\text{scat}} = p \sin \theta^{3/2}$ value of the track, where the $p_{\text{scat}}$ dependence of the $IP$ resolution describes multiple-scattering effects in the detector
- the number of tracks attached to the primary vertex

Typically, the intrinsic resolution for tracks with at least three SMT hits and seven CFT hits reaches an asymptotic value of about 20 $\mu$m in the data (for $p_{\text{scat}} > 10$ GeV).

Tracks originating from a $V^0$ candidate are rejected using an algorithm provided by the CSIP group [50]. The algorithm rejects $K_s^0$'s, $\Lambda$'s, and photon conversions. In order to further reduce the $V^0$ contribution, only charged particles with $p_T > 1$ GeV and $|IP| < 0.15$ cm were considered.

The distribution of the negative track significance, denoted impact parameter resolution function $R(S_{IP})$, is mainly determined by tracks coming from the PV, including scatters in the detector material and tracks with wrong hit associations, while the contribution of tracks coming from decays of long-lived particles is small. Multijet data and Monte Carlo events have been used to parametrize $R(S_{IP})$ as the sum of four Gaussian functions. A total of 29 categories of tracks, depending on the number of SMT and CFT hits, and the $|\eta|$, $\chi^2$ and $p_T$ values of the tracks, have been considered to define the range of $R$ parametrization. These track samples were adjusted to describe as much as possible the geometric and tracking effects, while keeping a reasonable number of events in each category.

For tracks with a positive significance, by means of a normalized integration, the resolution function can be converted into a probability for these tracks to originate from the primary interaction point:

$$P_{trk}(S_{IP}) = \frac{\int_{-50}^{-|S_{IP}|} R(s)ds}{\int_{-50}^{0} R(s)ds}.$$
By definition, tracks from the PV have a flat distribution of $P_{trk}(S)$ between 0 and 1, while tracks from decays of long-lived particles exhibit a significant peak at small probability values.

All $N_{trk}^+$ ($N_{trk}^-$) tracks in the jet with a positive (negative) $IP$ significance can be used to compute a jet lifetime (JLIP) probability $P_{jet}^+$ ($P_{jet}^-$):

$$P_{jet}^\pm = \Pi^\pm \times \sum_{j=0}^{N_{trk}^\pm-1} \frac{(- \log \Pi^\pm)^j}{j!} \text{ with } \Pi^\pm = \prod_{i=1}^{N_{trk}^\pm} P_{trk}(S_{IP>0}^i) .$$

The corresponding distributions are shown in Fig. 16 for multijet data and simulated jets of different flavors, and for positive and negative $IP$ values.

FIG. 16: JLIP probability in p14 jet trigger data and QCD Monte Carlo simulations of different flavors, for positive (light, yellow) and negative (dark, green) $IP$ values
7.5.2. JLIP Flavor-Dependent Tag-Rate Functions for MC

Applying a cut on $P^+_\text{jet}$, the $b$-tagging efficiency is defined as the ratio of the number of tagged $b$ jets to the number of taggable $b$ jets. A similar definition is used for each quark flavor. A “tight” working point is chosen by selecting jets with $P^+_\text{jet} < 0.004$. This JLIP cut corresponds to an average mistag rate of about 0.003 in the multijet data (see Ref. [49]).

7.5.2.1. JLIP Bottom-Flavor Jet Tagging

We use Monte Carlo event samples of $t\bar{t}$, $Z$, $W+$jets, and QCD to estimate tagging efficiencies as a function of the jet $E_T$ and $|\eta|$, as shown in Fig. 17.

![Fig. 17: b-tagging and c-tagging efficiencies (tight probability cut) as functions of jet $E_T$ and $|\eta|$ for various processes in the p14 simulation.](image)

The $b$-tagging efficiencies are also determined with data. We use three methods on muon-in-jet data, which is naturally enriched in $b$ content, to estimate the $b$-tagging efficiency. Two of the methods rely on a fit to the $p_{T\text{rel}}$ distribution of the muon, the $p_{T\text{rel}}$ variable being the transverse momentum of the muon relative to the jet axis. The third method (SystemD, or System8) is a counting method [51] associated with the resolution of a system of eight equations with eight unknowns. It mainly relies on real data, with few Monte Carlo inputs. The results are presented in Fig. 18.

The $b$-tagging efficiency is larger in the simulation than in the data, and it is thus necessary to calibrate the Monte Carlo $b$-tagging efficiencies to those measured in the data according to a scale factor $SF_b$ defined as:

$$SF_b = \frac{\varepsilon_{\text{data}}_{b\rightarrow\mu}}{\varepsilon_{\text{MC}}_{b\rightarrow\mu}}$$

This correction factor is shown in Fig. 19 as a function of the jet $E_T$ and $|\eta|$. The calibrated MC $b$-tagging efficiency for inclusive decays that can be used in a $b$-tagging analysis is given by:

$$\varepsilon_b = \varepsilon_{\text{MC}}^{b} \times SF_b$$

where $\varepsilon_{\text{MC}}^{b}$ is the inclusive $b$-tagging efficiency in Monte Carlo.
FIG. 18: $E_T$ and $|\eta|$ dependence of the $b$-tagging efficiency in muon-in-jet data for a tight probability cut.

FIG. 19: $SF_b$ scale factor, ratio of the $b$-tagging efficiencies measured in muon-in-jet data and simulation, as a function of the jet $E_T$ and $|\eta|$ for a tight probability cut.

7.5.2.2. JLIP Charm-Flavor Jet Tagging

For $c$ tagging, we assume that $SF_c = SF_b$ and define analogously the calibrated MC tagging efficiency for inclusive $c$ decays:

$$\varepsilon_c = \varepsilon_c^{MC} \times SF_c$$

7.5.2.3. JLIP Light-Flavor Jet Tagging

The negative impact parameter of tracks in jet data can be used to evaluate the probability to tag light-quark jets (denoted mistag rate). However, this negative tag rate has to be corrected to the residual presence of $c$-quark and $b$-quark jets in these events by means of two scaling factors derived from MC. Consequently, the light mistag rate is estimated as:

$$\varepsilon_{\text{tight}} = \varepsilon_{\text{data}} \cdot F_{hf} \cdot F_{lt},$$

where

- $\varepsilon_{\text{data}}$ is the negative tag rate in jet trigger (or EMQCD) data
• $F_{hf} = \frac{\varepsilon_{QCD_{light}}}{\bar{\varepsilon}_{QCD_{all}}}$ is the ratio between the number of negative tagged jets from light quarks over the total number of negative tagged jets in the QCD Monte Carlo. It is smaller than 1 if heavy-flavor jets are present.

• $F_{ll} = \frac{\varepsilon_{QCD_{light}}}{\varepsilon_{QCD_{light}}}$ is the ratio between the number of positive tagged jets from light quarks over the number of negative tagged jets from light quarks in the QCD Monte Carlo. It is sensitive to long-lived hadron decays in light-quark jets.

The corrected mistag rates for a tight probability cut, parametrized as a function of $E_T$(jet) and $|\eta$(jet)| are shown in Fig. 20.

7.5.2.4. JLIP Flavor-Dependent Tag-Rate Functions for MC

In order to be able to predict the number of tagged events from a specific process, we have to parametrize the probability to tag a jet originating from a defined quark flavor. Taking into account the previous calibrated tagging efficiencies, this parametrization is performed as a function of two appropriate variables: jet $E_T$ and $\eta$. A two-dimensional parametrization denoted tag-rate function (TRF) is derived from the one-dimensional ones assuming that they are fully uncorrelated. These exclusive TRFs for $b$, $c$ and light-quark jets denoted $\text{TRF}_{b,c,l}(E_T, \eta)$ are represented in Fig. 21 for the tight probability cut.

7.5.3. JLIP Flavor-Inclusive Tag-Rate Functions for $W$+Jets

For the JLIP tagger, the flavor-inclusive tag-rate functions for the $W$+jets background are derived in a manner similar to that for the SVT tagger (see Section 7.4.3) using the 3JETS_LOOSE sample. But in this case, instead of using the ($E_T, \eta^{det}$) histogram directly, a two-dimensional ($E_T, \eta^{det}$) parametrization is done to obtain the inclusive TRF. This function is shown in Fig. 22. Here also we make the assumption that the heavy-flavor content of the multijet sample is similar to the one in $W$+jets events. To validate the parametrization, various closure plots have been produced to compare the observed distributions to the predicted ones. Figures 23 show comparisons of the prediction from the inclusive TRF with the JLIP tagger for the jet multiplicity, jet $E_T$, and $\eta^{det}$ distributions. While the observed and predicted distributions agree within the uncertainty for jet $E_T$ and $\eta^{det}$, a noticeable difference can be seen in the jet multiplicity distribution.
FIG. 21: Flavor-dependent JLIP tag-rate functions ($E_T, \eta$) for $b$-quark jets, $c$-quark jets and light-quark jets, after the tight probability cut.

FIG. 22: Flavor-inclusive JLIP tag-rate function ($E_T, \eta_{\text{det}}$) derived from the multijet sample after the tight probability cut.
FIG. 23: Comparisons between the number of tagged events and the number of expected events from applying the inclusive TRFs for jet multiplicity, jet $E_T$, and jet $\eta^\text{det}$. 
7.6. Scale Factors for Flavor-Inclusive Tag-Rate Functions

As can be seen in Figs. 23 (above) and 24 (below, left two plots), the flavor-inclusive tag-rate functions (TRFs) vary in their effectiveness at reproducing the observed number of tags in multijet events for different jet multiplicities. We correct the TRFs to account for these small variations, caused by differences in the heavy-flavor content of the data for each jet multiplicity. The correction factors are used event-by-event to rescale the TRFs, depending on the jet multiplicity of each event. This is done only for the TRFs of the lifetime taggers SVT and JLIP. The flavor-inclusive TRF for SLT was derived from a different multijet sample (with higher jet multiplicity) and no evidence is seen for jet multiplicity dependence in this case. The correction factors are assumed to be dependent on the heavy-flavor fraction of the data samples and not on features of the tagging algorithms, and they are therefore expected to be the same for the SVT and JLIP algorithms. We describe here their derivation using the SVT algorithm.

As discussed in Section 7.4.3, the flavor-inclusive TRFs are calculated using the 3JETS_LOOSE data. The TRF is the number of tagged jets divided by the number of taggable jets in each bin of a two-dimensional histogram in jet $E_T$ and $\eta^{\text{jet}}$. The TRF is then applied to each jet in the untagged $W+$jets data sample, and a factor is calculated for the event to have at least one tagged jet. This factor is rescaled for the ratio of pretagged to untagged events, and then included in the event weight.

The simplest way to test the efficacy of a TRF is to compare the TRF prediction with the results from the tagger on the sample used to derive the TRF. This procedure (a closure test) should give the same number of tags as the TRF predicts.

Figure 24 shows the TRF-tagger closure plots for the distributions of the numbers of good jets and the $H_T$ of all good jets for the 3JETS_LOOSE sample (left two plots). We observe that the TRF prediction is slightly higher than the tagger in the 2-jet bin and lower than the tagger in the higher jet-multiplicity bins. We observe similar behavior in the ALLJETS data sample. That is, the TRF prediction is lower than the tagger when the number of good jets is greater than two. This is illustrated in the right two plots of Fig. 24. Both of these samples are dominated by QCD, and thus we expect the heavy flavor to come solely from QCD. The 3JETS_LOOSE TRF, therefore, should be able to predict the heavy flavor content of the ALLJETS sample.

![Figure 24](image)

**FIG. 24:** Distributions of the number of good jets, and the $H_T$ of all good jets for the 3JETS_LOOSE data sample for the left two plots and for the ALLJETS data sample for the right two plots. The points show the number of events when the SVT tagger is used directly, and the histogram shows the number of events when the TRF is applied.

The small difference in flavor composition in different jet multiplicity bins can be understood when considering the contributing physics processes: while hard-scatter processes...
are relevant in 2-jet events, gluon-splitting is more important for 3-or-more jet events. Also see the relevant Feynman diagrams in Ref. [47].

We expect similar effects to be present in $W$+jets events, and rather than try to predict this with a complete MC simulation, we have chosen to empirically scale the TRF so that it matches the two jet-data samples. Both $N_{\text{jets}}$ and $H_T$ are possibly correlated with the change in heavy-flavor processes. Indeed, closure plots for both are fairly unconvincing if the correction is not applied. Though we only rescale by $N_{\text{jets}}$, both $N_{\text{jets}}$ and $H_T$ dependences were explored.

Best results are obtained if we apply a scale factor to the TRF for each event, based upon the good-jet multiplicity of that event such that the number of events predicted by the TRF is reduced in the 2-jets bin, and is increased in the higher jet-multiplicity bins (we do not feel we have the statistics to do a simultaneous correction in $H_T$).

In Fig. 25, the scale factor required for the TRF is shown as a function of the good jet multiplicity, without any cut on the $H_T$ of all good jets, and in an $H_T$ window of 150–200 GeV, for the 3JETS_LOOSE sample and the ALLJETS sample. The choice of the above $H_T$ window is motivated by the distribution shown in Fig 14 where we observe that the distribution is falling in the region $150 < H_T < 200$ GeV for all four samples. We then choose the following two scale factors based upon the good-jet multiplicity of that event:

$$0.965 \pm 0.05, \quad \text{if} \ N_{\text{good-jets}} = 2,$$

$$1.180 \pm 0.05, \quad \text{if} \ N_{\text{good-jets}} > 2.$$  

We assign a systematic uncertainty of 5% to account for differences in the measured scale factor between the 3JETS_LOOSE and the ALLJETS samples, as well as the $H_T$ dependence of the scale factors.

![Fig. 25: The scale factor required for the TRF as a function of the number of good jets, without any cut on the $H_T$ of all good jets (left), and with 150 GeV < $H_T$ < 200 GeV (right).](image)

In Fig. 26, we show distributions for the number of good jets, the $E_T$, the $H_T$, and the $\eta^{\text{det}}$ of all good jets in the 3JETS_LOOSE sample, before and after scaling the TRFs. The points show the distribution with the SVT tagger used directly, the solid histogram shows the distribution with the scaled TRF, and the dotted histogram shows the distribution with the unscaled TRF. Figure 27 shows the corresponding distributions for the ALLJETS sample. These two figures show that the scaled TRF is in better agreement with the tagger than the unscaled TRF.
FIG. 26: Distributions of the number of good jets, and the $H_T$, $E_T$, and $\eta^{\text{det}}$ of all good jets for the 3JETS_LOOSE sample. The points show the distribution with the SVT tagger used directly, the solid histogram shows the distribution with the scaled TRF, and the dotted histogram shows the distribution with the unscaled TRF.

FIG. 27: Distributions of the number of good jets, and the $H_T$, $E_T$, and $\eta^{\text{det}}$ of all good jets for the ALLJETS sample. The points show the distribution with the SVT tagger used directly, the solid histogram shows the distribution with the scaled TRF, and the dotted histogram shows the distribution with the unscaled TRF.
Tables 10 and 11 show a comparison of applying the inclusive TRF for the SVT and JLIP taggers to various data samples before and after scaling with the observed number of tagged events in those samples. The different samples considered are the 3JETS_LOOSE sample, the ALLJETS sample, a Z sample, and two W samples. The W samples have been derived from the preselection samples with additional cuts to remove QCD background and $t\bar{t}$. The $W\rightarrow e+\geq 2\text{jets}$ sample is derived from the preselected EMQCD sample and has the additional requirements that the electron likelihood be $> 0.95$ and $H_T < 200$ GeV. The $W\rightarrow \mu+\geq 2\text{jets}$ sample is derived from the preselected MUQCD sample and has the additional requirement that the reconstructed transverse mass of the W boson ($M^W_T$) be $> 20.0$ GeV and $H_T < 200$ GeV. Here, $H_T$ refers to the scalar sum of the $E_T$ of the lepton, $E_T$ and the two leading jets.

<table>
<thead>
<tr>
<th>Data Sample</th>
<th>Predicted (TRF) Unscaled</th>
<th>Predicted (Tagger) Scaled</th>
<th>Observed (Tagger) Unscaled</th>
<th>Difference $(\text{Obs} - \text{Pred})$ Unscaled</th>
<th>Difference $(\text{Obs} - \text{Pred})$ Scaled</th>
</tr>
</thead>
<tbody>
<tr>
<td>3JETS_LOOSE</td>
<td>2,111</td>
<td>2,023</td>
<td>2,027</td>
<td>−4.2%</td>
<td>0.2%</td>
</tr>
<tr>
<td>ALLJETS</td>
<td>4,174</td>
<td>4,907</td>
<td>5,431</td>
<td>23.0%</td>
<td>9.7%</td>
</tr>
<tr>
<td>$Z\rightarrow ee/\mu\mu+\geq2\text{jets}$</td>
<td>17.6</td>
<td>18.0</td>
<td>20</td>
<td>12.0%</td>
<td>10.9%</td>
</tr>
<tr>
<td>$W\rightarrow e+\geq 2\text{jets}$</td>
<td>39.0</td>
<td>39.9</td>
<td>40</td>
<td>2.5%</td>
<td>0.3%</td>
</tr>
<tr>
<td>$W\rightarrow \mu+\geq 2\text{jets}$</td>
<td>30.9</td>
<td>31.6</td>
<td>27</td>
<td>−14.4%</td>
<td>−17.9%</td>
</tr>
</tbody>
</table>

**TABLE 10:** Comparison of the inclusive SVT tag-rate functions with requiring a tag in the same sample for five different data samples, showing the effects of the scaling factors.

<table>
<thead>
<tr>
<th>Data Sample</th>
<th>Predicted (TRF) Unscaled</th>
<th>Predicted (Tagger) Scaled</th>
<th>Observed (Tagger) Unscaled</th>
<th>Difference $(\text{Obs} - \text{Pred})$ Unscaled</th>
<th>Difference $(\text{Obs} - \text{Pred})$ Scaled</th>
</tr>
</thead>
<tbody>
<tr>
<td>3JETS_LOOSE</td>
<td>944</td>
<td>986</td>
<td>973</td>
<td>3.0%</td>
<td>−1.3%</td>
</tr>
<tr>
<td>ALLJETS</td>
<td>4,025</td>
<td>4,747</td>
<td>4,956</td>
<td>18.8%</td>
<td>4.2%</td>
</tr>
<tr>
<td>$Z\rightarrow ee/\mu\mu+\geq2\text{jets}$</td>
<td>14.6</td>
<td>14.9</td>
<td>20</td>
<td>27%</td>
<td>25.5%</td>
</tr>
<tr>
<td>$W\rightarrow e+\geq 2\text{jets}$</td>
<td>36.9</td>
<td>37.6</td>
<td>40</td>
<td>7.8%</td>
<td>6.0%</td>
</tr>
</tbody>
</table>

**TABLE 11:** Comparison of the inclusive JLIP tag-rate functions with requiring a tag in the same sample for five different data samples, showing the effects of the scaling factors. The test on the 3JETS_LOOSE sample was done for 50,000 events, while the test on the ALLJETS sample was done for 100,000 events.

For all samples considered, the agreement is better after scaling, except for the $W\rightarrow \mu+\geq 2\text{jets}$ sample. However, even for that sample the inclusive TRF still agrees with the found number of tags within the statistical uncertainty.

The general agreement within uncertainty for these samples shows that the inclusive TRF can be used to predict the tag rate of $W+$-jet events in the final signal sample. We assign a systematic uncertainty to the flavor-inclusive TRF of 20% based on these results.
8. PRESELECTION CUTS

The preselection cuts are designed to remove misreconstructed events and to keep only those that have the same final state objects in them as expected in the signals. The cuts are described here. The particle ID criteria and other variables have been described in more detail in the Luminosity, Triggers, and Event Reconstruction sections earlier in this note. Unless explicitly noted, all cuts are on corrected quantities. The jet energy scale corrections, for example, are applied before cuts on jet $E_T$'s are made.

8.1. Data Quality

All data events must be within a good run for JET/MET, and a good luminosity block. If muons are used in the analysis, then the events must also be in a “reasonable” muon run. Duplicate events are removed from the samples.

8.2. Trigger

All events must pass the following triggers:

Electron Channel
- EM15_JT15 (trigger lists v.8.2 to v.11)
- E1_SHT15_JT20 (trigger list v.12)

Muon Channel
- MU_JT25_L2M0 (trigger lists v.8.2 to v.11)
- MU_JT20_L2M0 (trigger list v.12)

8.3. Primary Vertex

We require the primary vertex to be within the Silicon Microstrip Tracker and to have enough tracks associated with it to be properly reconstructed:
- $N_{\text{tracks}} \geq 3$
- $|z_{\text{vertex}}| < 60 \text{ cm}$

8.4. Isolated Lepton

Each event must have exactly one isolated primary electron or muon that passes the tight selection cuts:

Loose Isolated-EM Object
- EM fraction of calorimeter cluster > 0.9
- Isolation = $E_{\text{Total}}(R < 0.4) - E_{\text{EM}}(R < 0.2))/E_{\text{EM}}(R < 0.2) < 0.15$
- Eight-variable H-matrix $\chi^2 < 75$
- Detector pseudorapidity $|\eta^{\text{det}}| < 1.1$ (CC)
- Transverse energy $E_T > 15 \text{ GeV}$
Tight Isolated Electron
- Passes all loose-EM criteria
- Track match: $|\Delta \phi(\text{EM, track})| < 0.05$ radians, $|\Delta \eta(\text{EM, track})| < 0.05$
- Vertex cut: $|\Delta z(\text{track, primary vertex})| < 1$ cm
- Seven-variable likelihood $\mathcal{L} > 0.75$ (CC)

Loose-Isolated Muon
- $|n_{\text{seg}}| = 3$ medium muon
- $|\Delta t(\text{A layer, } t_0)| < 10$ ns
- $|\Delta t(\text{BC layers, } t_0)| < 10$ ns
- Central track $\chi^2 < 4$
- $|\text{DCA}(x, y)_{\text{signif}}| < 3\sigma$
- $|\Delta z(\text{central track, primary vertex})| < 1$ cm
- $\Delta R(\text{muon, jet}) > 0.5$

Tight-Isolated Muon
- Passes all loose-isolated muon criteria
- Transverse momentum $p_T > 15$ GeV
- Track halo isolation = $|\sum_{\text{tracks}} p_T / \mu (< 0.06$ in $\Delta R(\text{track, muon track}) < 0.5$ cone)
- Calorimeter halo isolation = $|\sum_{\text{cells}} E_T / \mu (< 0.08$ in $0.1 < \Delta R(\text{cal-cells, muon cal-track}) < 0.4$ cone

8.5. Additional Isolated Leptons

Events with additional isolated loose leptons are removed from the preselected samples to reduce the backgrounds from $t\bar{t}$, $WW$, $WZ$, and $Z/\gamma$ decays to dileptons.

Note that photons are included in the loose isolated EM object definition since no central track is required. Note also that there is no $p_T$ requirement on a loose isolated muon, events with extra muons of any $p_T$ are rejected.

8.6. Good Jets

Good jets in data pass all the bad-jets and noise-jets cuts:

Bad Jets Cuts
- $0.05 < \text{Fraction of jet } E_T \text{ in the EM calorimeter layers} < 0.95$
- Fraction of jet $E_T$ in the CH calorimeter layers $< 0.4$
- Ratio of $E_T$’s of hottest cell in jet to next-hottest cell $< 10$
- Smallest number of towers that make up 90% of the jet $E_T$, $n90 > 1$

Noise Jets Cut
- For a given jet, the scalar sum of the trigger tower’s $E_T$ inside the jet’s cone, divided by the jet $E_T$ and by one minus the fraction of jet $E_T$ in the coarse hadron calorimeter layers must be $> 0.4$ ($|\eta_{\text{det}}| < 0.8, 1.5 < |\eta_{\text{det}}|$) or $> 0.2$ ($0.8 \leq |\eta_{\text{det}}| \leq 1.5$)
In addition, we require the following:

**Leading Good Jet**
- \( E_T > 25 \text{ GeV} \)
- \( |\eta^{\text{det}}| < 2.5 \)

**Additional Good Jets**
- \( E_T > 15 \text{ GeV} \)
- \( |\eta^{\text{det}}| < 3.4 \)

**Good Jet Multiplicity**
- \( 2 \leq N_{\text{goodjets}} \leq 4 \)

The \( E_T \) cuts reduce the sensitivity of the analysis to the jet reconstruction turn-on differences between MC and data. Setting a maximum number of jets reduces the sensitivity of the analysis to the weaknesses of simulating multiple ISR and FSR jets with *pythia*.

### 8.7. Bad Jets and Noise Jets

“Bad jets” are defined in a similar manner to Run I analyses and their sources are well understood. However, throughout the data-taking period for this analysis, the calorimeter experienced excess noise or pile-up from unknown sources. We use the t42 algorithm (see Section 6.4.1) to reduce the number of jets reconstructed from 3d-isolated low energy or noisy cells. Jets reconstructed from such calorimeter cells are known as “noise” jets. Only a very small fraction of jets fail the bad jets requirements. However, a much larger fraction fail the noise-jets cut, and this fraction rises as the good-jet multiplicity increases. For the remainder of this subsection, we use the term “noise jets” to refer to both bad jets and noise jets, to avoid having to say “bad jets or noise jets” each time we refer to them.

Figure 28 shows four \( E_T \) distributions for events with: (i) 0 noise jets and \( \geq 2 \) good jets (open red squares), (ii) 1 or 2 noise jets and \( \geq 2 \) good jets (solid magenta squares), (iii) 0 noise jets and 4 good jets (open black circles), and (iv) \( \geq 3 \) noise jets and \( \geq 2 \) good jets (solid blue triangles). The fact that the distributions for (ii) and (iii) are very similar and not very different from (i) is a clear indication that there is no problem with events with one or two noise jets. The fact that distribution (iv) is very different from the others is an indication that there is a problem in events with three or more noise jets.

![Figure 28: Distribution of \( E_T \) for two different calorimeter L1 trigger \( \eta^{\text{det}} \) coverage periods: before Run 172359 with \( |\eta^{\text{det}}| < 2.4 \) (left plot) and after Run 172359 with \( |\eta^{\text{det}}| < 3.2 \) (right plot). Open red squares represent the distribution of \( E_T \) in events with 0 noise jets, solid magenta squares events with 1 or 2 noise jets, open black circles events with 0 noise jets and 4 good jets, and solid blue triangles events with > 2 noise jets. A few simple cuts were applied: \( |z_{\text{vertex}}| < 60 \), one electron in CC or EC with \( E_T > 15 \text{ GeV} \), di-EM veto, \( N_{\text{goodjets}} \geq 2 \) and \( E_T^{\text{goodjets}} > 15 \text{ GeV} \).](image-url)
To say this in other words, if we do not make a distinction between good jets and noise jets, the four $E_T$ distributions are for events with: (i) $\geq 2$ jets, (ii) $\geq 3$ jets, (iii) 4 jets, and (iv) $\geq 5$ jets. While (i), (ii), and (iii) have similar shapes, (iv) is very different. Since we cannot see how the inclusion of a 5th jet could so dramatically change the $E_T$ distribution, we prefer to conclude that events in (iv) are events with real noise jets and we discard these events.

We therefore make the following jet-based event quality requirement:

- $N_{\text{noisejets}} \leq 2$

Keeping events with one or two noise jets rather than rejecting all events with any noise jets in them significantly reduces data-MC differences from non-application of the L1 confirmation cut, which cannot be applied directly to MC events. The L1 calorimeter trigger tower confirmation cut changed in $\eta_{\text{det}}$ during the data-taking period, complicating determination of a possible correction factor for MC events. Further investigation shows that by allowing up to two noise jets present in events, the efficiency becomes greater than 99%, and therefore no correction factor is necessary, as shown in Fig. 29 by the green points (including those at an efficiency of 1, where no error bar is shown).

Our signal events have a neutrino in them from the decay of the $W$ boson from the top quark decay. Consequently, we apply the following thresholds to the missing transverse energy:

- $E_T^{\text{JES}} > 15 \text{ GeV}$, $E_T > 15 \text{ GeV}$

where $E_T^{\text{JES}}$ is the jet-energy-scale corrected missing transverse energy in the calorimeter, and $E_T$ is $E_T^{\text{JES}}$ that has also been corrected for the energy of isolated and tagging muons. We cut on $E_T$ both with and without the muon corrections to reduce our sensitivity to mismeasured muon momentum in the backgrounds (in particular in misidentified-lepton multijet events).
8.9. Mismeasured Missing Transverse Energy

8.9.1. Misreconstructed Tracks

Sometimes an object’s track is misreconstructed and as a consequence its transverse momentum is poorly measured. Particularly in the case of muons, this can lead to meaninglessly large values of missing transverse energy, which damage beyond repair the possibility to understand the kinematics of these events. To remove these problematic events from the analysis, we require:

- $E_T < 200$ GeV

8.9.2. Misreconstructed Leptons and Jets

Often, a low-$E_T$ electron is really a jet that happens to pass the electron ID criteria. The difference between the electron reconstruction and jet reconstruction algorithms leads to a small amount of missing transverse energy along the same direction as the electron. For muons, sometimes the track momentum is measured too high or too low, and this also leads to a small amount of missing transverse energy along the direction of the muon or back-to-back with it. Jets can have their energy mismeasured or miscalibrated, and this most often happens to attribute to the jet more energy than it really had. (Perhaps two close low-energy jets are merged into one with the cone algorithm.) In this situation, a small amount of missing transverse energy is generated back-to-back with the jet.

These sources of mismeasurement are difficult to model in the background measurement, and since there is very little signal acceptance in these kinematic regions, we clean up the analysis significantly and efficiently by making so-called “triangle cuts” to reject events with mismeasured $E_T$.

The triangle cuts are applied to both data and Monte Carlo events, and are defined as follows:

**Electron Channel**
- $|\Delta \phi(\text{electron, } E_T)|$ versus $E_T$: $|\Delta \phi|$ from 0.0 to 1.5 when $E_T = 0$ GeV, and $E_T$ from 0 to 35 GeV when $|\Delta \phi| = 0$ (SLT, SVT, and JLIP analyses)
- $|\Delta \phi(\text{electron, } E_T)|$ versus $E_T$: $|\Delta \phi|$ from 0.0 to 1.0 when $E_T = 0$ GeV, and $E_T$ from 0 to 80 GeV when $|\Delta \phi| = 0$ (SVT and JLIP analyses only)
- $|\Delta \phi(\text{leading jet, } E_T)|$ versus $E_T$: $|\Delta \phi|$ from 1.5 to $\pi$ when $E_T = 0$ GeV, and $E_T$ from 0 to 35 GeV when $|\Delta \phi| = \pi$
- $|\Delta \phi(\text{second leading jet, } E_T)|$ versus $E_T$: $|\Delta \phi|$ from 1.5 to $\pi$ when $E_T = 0$ GeV, and $E_T$ from 0 to 35 GeV when $|\Delta \phi| = \pi$

**Muon Channel**
- $|\Delta \phi(\text{muon, } E_T)|$ versus $E_T$: $|\Delta \phi|$ from 0.0 to 1.5 when $E_T = 0$ GeV, and $E_T$ from 0 to 35 GeV when $|\Delta \phi| = 0$
- $|\Delta \phi(\text{muon, } E_T)|$ versus $E_T$: $|\Delta \phi|$ from 2.0 to $\pi$ when $E_T = 0$ GeV, and $E_T$ from 0 to 50 GeV when $|\Delta \phi| = 0$
- $|\Delta \phi(\text{leading jet, } E_T)|$ versus $E_T$: $|\Delta \phi|$ from 1.5 to $\pi$ when $E_T = 0$ GeV, and $E_T$ from 0 to 35 GeV when $|\Delta \phi| = \pi$
The $\Delta \phi$ versus $E_T$ distributions are shown for the $s$-channel and $t$-channel signals and for the misidentified-lepton background data in the preselected pretagged samples in Figs. 30 through 34. The positions of the triangle cuts are shown superposed.

FIG. 30: Distributions of the opening angle between the electron and $E_T$ versus $E_T$, for the misidentified-electron background data and for $s$-channel and $t$-channel signals. The $E_T$ and triangle cuts are shown. The small-area cut is for the SLT, SVT, and JLIP analyses; the large-area cut is for the SVT and JLIP ones only, as explained below.

FIG. 31: Distributions of the opening angle between the highest-$E_T$ jet and $E_T$ versus $E_T$, for the misidentified-electron background data and for $s$-channel and $t$-channel signals. The $E_T$ and triangle cuts are shown.

FIG. 32: Distributions of the opening angle between the second-highest-$E_T$ jet and $E_T$ versus $E_T$, for the misidentified-electron background data and for $s$-channel and $t$-channel signals. The $E_T$ and triangle cuts are shown.

There are different triangle cuts for the opening angle between the electron and the $E_T$ depending on the tagging method of the analysis for the following reason. The smaller triangle cut is chosen to reject the mismeasured multijet background described above. The triangle exclusion region was enlarged for the lifetime tagger analyses because an additional source of background was found in this region. It consists of real low-$E_T$ electrons, and fairly large aligned $E_T$, not just above threshold, and three jets (although sometimes two or four), and one of the jets is tagged. The additional rejected events all have $M_W^T < 10$ GeV. They are not included in our multijet with a misidentified-lepton background model as they have real electrons. They are not included in our $W$+jets background model as the flavor-inclusive tag-rate functions do not include tags in events with real isolated leptons. There
are approximately 10 of these events with an SVT tag and approximately 14 of them with a JLIP tag above background expectations of a few events. We tested the electron and jets in the events with the tau-ID neural network tool [52], but only one of them was consistent with a $Z \rightarrow \tau \tau$ hypothesis. We also inspected the EM fraction of the jets to see whether any of the events might be $Z \rightarrow ee$ events with an electron misidentified as a jet.

FIG. 33: Distributions of the opening angle between the muon and $\slashed{E}_T$ versus $\slashed{E}_T$, for the misidentified-muon background data and for s-channel and t-channel signals. The $\slashed{E}_T$ and triangle cuts are shown.

FIG. 34: Distributions of the opening angle between the highest-$E_T$ jet and $\slashed{E}_T$ versus $\slashed{E}_T$, for the misidentified-muon background data and for s-channel and t-channel signals. The $\slashed{E}_T$ and triangle cuts are shown.

However, this was not strongly indicated. Our best guess at this time is that these events are $bb \rightarrow e$, or $Z \rightarrow ee$ with a multijet minimum bias event with close primary vertices. The choice of the wrong primary vertex for the jets could increase the probability for reconstructing a lifetime tag in a jet, especially for the JLIP algorithm, which only requires one large-DCA track. Since we do not have a model for this background to include in our background measurement before the Moriond deadline, we choose to exclude this region of phase space from our analyses in the electron channel lifetime tagger analyses. The effect is not seen with an SLT tag, nor in the muon channel (but in the latter case, the initial triangle cut is tighter than for the electron channel, which may mask such events from the analysis, and also the $bb$ background is included in our background model).
9. PRESELECTED EVENT SAMPLES

After the preselection described in the previous section, we obtain the “preselected” event samples. The statistics of the preselected pretagged samples are given in Table 12.

<table>
<thead>
<tr>
<th>The Pretagged Preselected Event Samples</th>
<th>Electron Channel</th>
<th>Muon Channel</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>SLT</td>
<td>SVT</td>
</tr>
<tr>
<td>Signals</td>
<td></td>
<td></td>
</tr>
<tr>
<td>MC $t\bar{t}$</td>
<td>10,148</td>
<td>8,154</td>
</tr>
<tr>
<td>MC $tb$</td>
<td>10,139</td>
<td>8,762</td>
</tr>
<tr>
<td>MC $t\bar{t}b$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Backgrounds</td>
<td></td>
<td></td>
</tr>
<tr>
<td>MC $t\bar{t}\rightarrow l+\text{jets}$</td>
<td>5,320</td>
<td>4,502</td>
</tr>
<tr>
<td>MC $t\bar{t}\rightarrow ll$</td>
<td>5,951</td>
<td>4,882</td>
</tr>
<tr>
<td>MC $Z\rightarrow \mu\mu+\text{jets}$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Untagged $W+\text{jets}$ data</td>
<td>3,194</td>
<td>3,063</td>
</tr>
<tr>
<td>Mis-Id'd $l$ data</td>
<td>24,189</td>
<td>13,288</td>
</tr>
<tr>
<td>Signal data</td>
<td>3,252</td>
<td>3,160</td>
</tr>
</tbody>
</table>

TABLE 12: Numbers of events for the electron and muon channels after preselection but before tagging. The SLT, SVT, and JLIP electron-channel samples have the small triangle cut, the SVT and JLIP electron channel samples also have the large triangle cut. The SVT and JLIP samples have an SLT-veto applied. The numbers given for the $W+\text{jets}$ samples are for untagged events.

10. THE FINAL SELECTION

We have chosen to place a cut on one simple variable, common to all analysis channels, to reject background after preselection while keeping most of the signal acceptance. Many variables, singly and in combinations, were tested with the Random Grid Search package, using the expected cross section limit as the criterion on which to determine the best variables and cut points for each channel. The result of these studies was somewhat of a surprise to us. The best results are obtained by cutting only on one variable that has discriminating power between the $W+\text{jets}$ background (and somewhat for the multijet backgrounds with a misidentified isolated lepton), with no rejection of the $t\bar{t}$ background needed.

The final selection for this stage of the analysis is:

- $H_T(\text{lepton}, \slashed{E}_T, \text{jet1, jet2}) > 150$ GeV

Figure 35 shows the distribution of $H_T$ for the combination of electron and muon channels for two different tagger combinations: SVT and SLT as well as JLIP and SLT. The misidentified lepton background as well as the $W+\text{jets}$ background both have significantly lower $H_T$ than the $s$- and $t$-channel single top signals. The cut on $H_T$ was chosen to reject these two large background sources.

The next stage of the analysis will involve making an alternative final selection using sets of neural networks. Optimization of these networks is in progress.
FIG. 35: Distribution of $H_T$ for the different signal and background sources, normalized to unit area for the combined electron and muon channel samples. The plot on the left shows the combination of SVT and SLT, the plot on the right the combination of JLIP and SLT.

11. FINAL EVENT SAMPLES

After the final selection described in the previous section, we obtain the “final” event samples. The statistics of the final pretagged samples are given in Table 13.

<table>
<thead>
<tr>
<th>The Pretagged Final Event Samples</th>
<th>Electron Channel</th>
<th>Muon Channel</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>SLT</td>
<td>SVT</td>
</tr>
<tr>
<td><strong>Signals</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>MC $t \bar{t}$</td>
<td>9,243</td>
<td>7,352</td>
</tr>
<tr>
<td>MC $tq \bar{b}$</td>
<td>9,116</td>
<td>7,813</td>
</tr>
<tr>
<td><strong>Backgrounds</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>MC $t \bar{t} \to t + jets$</td>
<td>5,279</td>
<td>4,458</td>
</tr>
<tr>
<td>MC $t \bar{t} \to t\tau$</td>
<td>5,788</td>
<td>4,731</td>
</tr>
<tr>
<td>MC $Z \to \mu \mu + jets$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Untagged $W$+jets data</td>
<td>1,896</td>
<td>1,796</td>
</tr>
<tr>
<td>Mis-ID’d $l$ data</td>
<td>16,226</td>
<td>7,158</td>
</tr>
<tr>
<td>Signal data</td>
<td>1,950</td>
<td>1,862</td>
</tr>
</tbody>
</table>

TABLE 13: Numbers of events for the electron and muon channels after the final selection but before tagging. The numbers given for the $W$+jets samples are for untagged events.
12. SYSTEMATIC UNCERTAINTIES

12.1. Uncertainties from Monte Carlo Normalization

12.1.1. Integrated Luminosity

D0 uses a total inelastic cross section that is an average of results from CDF and E811. The uncertainty on the integrated luminosity is [53]:

• Integrated luminosity error = ±6.5%

12.1.2. Theory Cross Sections

The single top and \( t\bar{t} \) samples are normalized with the calculated cross sections to obtain the event yields. The errors on these cross sections (including the uncertainty from \( \Delta m_{\text{top}} = 5.1 \, \text{GeV} \)) are [54, 55]:

- Signal cross section errors:
  - \( s\)-channel \((tb) = \pm 16\% \)
  - \( t\)-channel \((tqb) = \pm 15\% \)

- Background cross section error:
  - \( t\bar{t} = \pm 18\% \)

The single top cross sections and their errors do not of course enter into the final cross section limit calculations. Only the \( t\bar{t} \) cross section and error are used. We give the single top values since they are used when quoting the expected number of signal events.

12.1.3. Experimental Cross Section

The \( Z\rightarrow\mu\mu \) sample is normalized to the number of \( Z\rightarrow\mu\mu+2\text{jets} \) events observed in data. The error on this normalization factor is:

• \( Z\rightarrow\mu\mu \) background normalization error = ±16%

12.1.4. Branching Fractions

We use the single top and \( t\bar{t} \) MC samples, which have been forced to decay into selected channels, to calculate acceptances of the total production cross section. The errors on the branching fractions used to convert from partial to full cross sections are [56]:

• Branching fraction error = ±2%
12.2. Uncertainties from Monte Carlo Modeling

12.2.1. Triggers

We apply an efficiency correction factor for all Monte Carlo samples calculated for each object in the event that is also present in the trigger definition. The error on this correction is measured using the MC samples by varying the object trigger turn-on curves by ±1σ and recalculating the acceptances. There is a separate error for each signal and background sample in each of the electron and muon channels. The percentage change in acceptances are given in Table 14.

<table>
<thead>
<tr>
<th>Systematic Errors on MC Acceptances and Yields from the Trigger Thresholds</th>
<th>Electron Channels</th>
<th>Muon Channels</th>
</tr>
</thead>
<tbody>
<tr>
<td>Event Type</td>
<td>SLT</td>
<td>SVT</td>
</tr>
<tr>
<td>Preselection</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Signals</td>
<td>MC $tb$</td>
<td>11.3</td>
</tr>
<tr>
<td></td>
<td>MC $tqb$</td>
<td>11.8</td>
</tr>
<tr>
<td>Backgrounds</td>
<td>MC $t\bar{t}l+jets$</td>
<td>8.6</td>
</tr>
<tr>
<td></td>
<td>MC $t\bar{t}ll$</td>
<td>8.2</td>
</tr>
<tr>
<td></td>
<td>MC $Z\rightarrow\mu\mu+jets$</td>
<td>26.9</td>
</tr>
<tr>
<td>Final Selection</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Signals</td>
<td>MC $tb$</td>
<td>11.0</td>
</tr>
<tr>
<td></td>
<td>MC $tqb$</td>
<td>10.4</td>
</tr>
<tr>
<td>Backgrounds</td>
<td>MC $t\bar{t}l+jets$</td>
<td>8.6</td>
</tr>
<tr>
<td></td>
<td>MC $t\bar{t}ll$</td>
<td>8.0</td>
</tr>
<tr>
<td></td>
<td>MC $Z\rightarrow\mu\mu+jets$</td>
<td>26.9</td>
</tr>
</tbody>
</table>

TABLE 14: The percentage change in acceptance of MC signals and backgrounds from varying the trigger efficiency by ±1σ.

12.2.2. Primary Vertex Identification

We correct the MC events for a slight difference in reconstruction efficiency for the primary vertex between MC and data. The error on this correction factor is:

- Electron channel primary vertex error = 0.6%
- Muon channel primary vertex error = 0.8%

12.2.3. Electron Identification

We apply the electron ID criteria directly to MC electrons, but the resulting efficiency is slightly different to that found in data. We correct for this difference, and the error on the correction factor is:

- Electron ID error = ±2.4% (CC)
12.2.4. Muon Identification

We apply the muon ID criteria directly to MC muons, but the resulting efficiency is slightly different to that found in data. We correct for this difference, and the error on the correction factor is:

- Isolated muon ID error = ±6.3%
- Tagging muon ID error = ±0.6% (SLT analyses only)

12.2.5. Muons from b Decays

The modeling of tagging muons in PYTHIA is assigned a systematic error based on the 2003 Particle Data Book error on the value for the branching fraction of an admixture of B mesons to a muon, \( B(b \rightarrow \mu) = (10.95^{+0.29}_{-0.25})\% \):

- MC tagging muons modeling error per muon = ±2.6% (SLT analyses only)

12.2.6. SLT Veto

When the SVT and JLIP analyses veto MC events with a tagging muon in order to keep the analysis channels orthogonal, the uncertainties on producing and reconstructing an MC tagging muon contribute to an error on the SLT veto for the lifetime tagging channels. That is, the SLT veto error is the addition in quadrature of the tagging muon ID error and the \( B \) decay to muon error:

- SLT veto error = ±2.7% (SVT and JLIP analyses only)

12.2.7. Jet Fragmentation

There is some variation between different models of jet fragmentation in Herwig, Pythia, etc. This difference contributes an uncertainty to our modeling of the MC jets. In our analysis, we use the measurement from the Run I \( t\bar{t} \) alljets analysis for the error from modeling the jet fragmentation, adjusted for the jet multiplicity (as we did for the published Run I single top measurements). This results in:

- MC fragmentation modeling error
  - \( tb, tqb, t\bar{t} \rightarrow l\bar{l} = \pm 5\% \)
  - \( t\bar{t} \rightarrow l + \text{jets} = \pm 7\% \)

(The Top Group does not have any ALPGEN+HERWIG or COMPHEP+HERWIG MC samples with which to measure this error in Run II. There are technical problems for doing this.)

12.2.8. Calorimeter Level 1 Trigger \( \eta \) Coverage

The calorimeter Level 1 trigger changed its readout from \( |\eta^{\text{det}}| \leq 2.4 \) to \( |\eta^{\text{det}}| \leq 3.2 \) while data analyzed for this result was being collected. This effect is important and must be understood because a "good jet" requires a matching Level 1 calorimeter tower. Other Top Group analyses use jets out to \( |\eta^{\text{det}}| \leq 2.4 \) only, and are thus not affected by this change. This single top search uses jets out to \( |\eta^{\text{det}}| = 3.4 \) because the \( t \)-channel production is expected to have a significant number of forward jets.
A Level 1 calorimeter tower is required to be within $\Delta R < 0.5$ of every reconstructed jet considered for this analysis. This requirement was implemented collaboration-wide to reduce the number of noise-related jets. The Level 1 calorimeter trigger readout has always been good to $|\eta^\mathrm{det}| < 2.4$, but was extended to $|\eta^\mathrm{det}| < 3.2$ at about the time the experiment started taking data with the v12 trigger list. This means that jets in the region $2.4 < |\eta^\mathrm{det}| < 3.4$ taken in the pre-v12 era will be falsely labeled as noise jets, and good events may not survive the $N_{\text{good-jets}} > 2$ cut. On the other hand, events with a large number of jets (in particular $t\bar{t}$) may now survive the $N_{\text{good-jets}} \leq 4$ cut.

To understand how this change affects the acceptance, the analysis was re-run with a jet $|\eta^\mathrm{det}| < 2.4$ requirement and the acceptance re-calculated. The effect needs to be measured only for the Monte Carlo samples. The data-derived backgrounds, misidentified-lepton multijet events and $W$+jets events, automatically take this effect into account. Table 15 shows the change in acceptance for $s$-channel and $t$-channel single top, and for $t\bar{t}$ decaying to lepton+jets and dileptons. The table also shows a integrated-luminosity-weighted scale factor that could perhaps be applied to each channel's acceptance. Approximately 75% of the integrated luminosity was gathered using pre-v12 trigger lists and the remaining 25% using the v12 trigger list. Exact numbers vary due to trigger effects and are not quoted here, though they are used to calculate the scale factors.

<table>
<thead>
<tr>
<th>Event Type</th>
<th>Electron Channel</th>
<th>Muon Channel</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Signals</td>
<td></td>
<td></td>
</tr>
<tr>
<td>MC $t\bar{b}$</td>
<td>$-0.95%$</td>
<td>$0.998$</td>
</tr>
<tr>
<td>MC $t\bar{q}b$</td>
<td>$-3.56%$</td>
<td>$0.991$</td>
</tr>
<tr>
<td>Backgrounds</td>
<td></td>
<td></td>
</tr>
<tr>
<td>MC $t\bar{t} \rightarrow l + \text{jets}$</td>
<td>$1.95%$</td>
<td>$1.005$</td>
</tr>
<tr>
<td>MC $t\bar{t} \rightarrow ll$</td>
<td>$-0.19%$</td>
<td>$1.000$</td>
</tr>
</tbody>
</table>

**Table 15:** The percentage change in acceptance of MC signals and backgrounds from reducing the jet $|\eta^\mathrm{det}|$ range to 2.4, and possible integrated-luminosity-weighted scale factors to correct for the change.

We have decided not to apply the scale factors to our Monte Carlo event sets as the calculation shown above does not fully model the problem. Instead, we take the maximum difference of the scale factors from unity as the uncertainty on our MC acceptances:

- Calorimeter L1 trigger $|\eta^\mathrm{det}|$ coverage = $\pm 4\%$

### 12.2.9. Jet Reconstruction and ID

We have considered assigning a separate systematic uncertainty to Monte Carlo events to cover differences between Monte Carlo and data in jet reconstruction and identification efficiencies. Most of this difference, however, comes from the Level 1 trigger confirmation requirement, and as we already have an uncertainty to account for that (see Section 12.2.8), we are thus not assigning a separate uncertainty for jet reconstruction and ID efficiency differences.
12.2.10. Jet Energy Resolution

The systematic error from the jet energy resolution uncertainty is measured by raising or lowering the jet smearing by one sigma. The resulting shifts in the yield after preselection vary 0.5% and 2%.

Since these small values for the jet energy resolution themselves have a large uncertainty due to the limited Monte Carlo statistics, we use a fixed value for all channels and all sources.

- Jet energy resolution = ±2%

12.2.11. Jet Energy Scale

The systematic error from the jet energy scale uncertainty is measured by raising or lowering the jet energy scale correction by one sigma. The percentage changes in acceptances of the MC signals and backgrounds are given in Table 16. These values are used as the systematic errors on the acceptances from the jet energy scale. The values are set to be the larger of the two absolute values from the two shifts, rather than averaging them, to be conservative.

<table>
<thead>
<tr>
<th>Event Type</th>
<th>Electron Channels</th>
<th>Muon Channels</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>SLT</td>
<td>SVT</td>
</tr>
<tr>
<td>Preselection Signals</td>
<td>MC $t\bar{b}$</td>
<td>3.5</td>
</tr>
<tr>
<td></td>
<td>MC $tq\bar{b}$</td>
<td>3.4</td>
</tr>
<tr>
<td>Backgrounds</td>
<td>MC $t\bar{t} \rightarrow l+\text{jets}$</td>
<td>4.4</td>
</tr>
<tr>
<td></td>
<td>MC $t\bar{t} \rightarrow ll$</td>
<td>2.4</td>
</tr>
<tr>
<td></td>
<td>MC $Z \rightarrow \mu\mu+\text{jets}$</td>
<td>13.2</td>
</tr>
<tr>
<td>Final Selection Signals</td>
<td>MC $t\bar{b}$</td>
<td>4.8</td>
</tr>
<tr>
<td></td>
<td>MC $tq\bar{b}$</td>
<td>6.1</td>
</tr>
<tr>
<td>Backgrounds</td>
<td>MC $t\bar{t} \rightarrow l+\text{jets}$</td>
<td>4.1</td>
</tr>
<tr>
<td></td>
<td>MC $t\bar{t} \rightarrow ll$</td>
<td>3.0</td>
</tr>
<tr>
<td></td>
<td>MC $Z \rightarrow \mu\mu+\text{jets}$</td>
<td>13.2</td>
</tr>
</tbody>
</table>

TABLE 16: The percentage change in acceptance of MC signals and backgrounds from varying the jet energy scale.

12.2.12. Flavor-Dependent Tag-Rate Functions

The weight applied to each Monte Carlo jet when applying the flavor-dependent tag-rate functions is a combination of a taggability-rate function, the actual flavor-dependent TRF, and an inclusive/$\mu$ jet ratio. The systematic error described here is the combination of the error on each of the two rate functions and the scale factor, added in quadrature.

The total uncertainty associated with the flavor-dependent tag-rate functions is evaluated by raising and lowering the tag-rate by one standard deviation for both taggability and the tag-rate function, and then determining the new event tagging probability.
The largest contribution to the tagging systematic is the inclusive/μ jet ratio; it is slightly larger than 9% for central jets with a $E_T > 40$ GeV.

The uncertainty is set to be the larger of the two absolute values from the upwards and downwards shifts. The results are given in Table 17. The $B$-ID group provided the tag-rate functions and their associated errors. The derivation is detailed in D0 Notes dedicated to the taggers and their certification [48, 49].

<table>
<thead>
<tr>
<th>Event Type</th>
<th>Preselection SVT</th>
<th>Preselection JLIP</th>
<th>Final Selection SVT</th>
<th>Final Selection JLIP</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Signals</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>MC $tb$</td>
<td>6.5</td>
<td>9.7</td>
<td>6.9</td>
<td>9.9</td>
</tr>
<tr>
<td>MC $tqb$</td>
<td>7.5</td>
<td>11.6</td>
<td>8.0</td>
<td>11.9</td>
</tr>
<tr>
<td><strong>Backgrounds</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>MC $t\bar{t} \rightarrow l+\text{jets}$</td>
<td>6.6</td>
<td>9.1</td>
<td>6.9</td>
<td>9.3</td>
</tr>
<tr>
<td>MC $t\bar{t} \rightarrow ll$</td>
<td>6.7</td>
<td>9.7</td>
<td>7.1</td>
<td>9.9</td>
</tr>
<tr>
<td><strong>Signals</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>MC $tb$</td>
<td>6.6</td>
<td>9.7</td>
<td>7.0</td>
<td>9.9</td>
</tr>
<tr>
<td>MC $tqb$</td>
<td>7.6</td>
<td>11.6</td>
<td>8.1</td>
<td>11.9</td>
</tr>
<tr>
<td><strong>Backgrounds</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>MC $t\bar{t} \rightarrow l+\text{jets}$</td>
<td>6.6</td>
<td>9.1</td>
<td>6.9</td>
<td>9.3</td>
</tr>
<tr>
<td>MC $t\bar{t} \rightarrow ll$</td>
<td>6.7</td>
<td>9.7</td>
<td>7.1</td>
<td>9.9</td>
</tr>
</tbody>
</table>

TABLE 17: The percentage change in acceptance of MC signals and backgrounds from varying the flavor-dependent tag-rate functions.

### 12.3. Summary of Monte Carlo Systematic Uncertainties

Tables 18, 19, 20, 21, and 22 show a summary of the Monte Carlo systematic uncertainties for the $s$-channel $tb$, $t$-channel $tqb$, and $tb+tqb$ combined signal samples as well as the $t\bar{t} \rightarrow l+\text{jets}$ and $t\bar{t} \rightarrow ll$ background samples. The tables can be used to see the correlation between the various samples and channels for each uncertainty. The systematic uncertainty is assumed to be fully correlated within a given line in each table, and for lines with the same name in different tables. For example, the “Luminosity” uncertainty is fully correlated between all MC samples and all channels.

Each table also shows the combined systematic uncertainty for each channel, as well as the total uncertainty, combining statistical and systematic uncertainties. The combined uncertainties are the sum in quadrature of the individual components. Since the luminosity and cross section do not enter into the acceptance calculation, those components are not included when calculating the overall uncertainty for the acceptances of $s$-channel $tb$, $t$-channel $tqb$, and $tb+tqb$ combined. The last line in tables 18, 19, and 20 shows the total uncertainty on the signal acceptances.
## Percentage Errors on the $s$-Channel $tb$ Yields

<table>
<thead>
<tr>
<th>Uncertainty</th>
<th>Electron Channels</th>
<th>Muon Channels</th>
<th>Preselection</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>SLT</td>
<td>SVT</td>
<td>JLIP</td>
</tr>
<tr>
<td>Luminosity</td>
<td>6.5</td>
<td>6.5</td>
<td>6.5</td>
</tr>
<tr>
<td>$tb$ cross section</td>
<td>16</td>
<td>16</td>
<td>16</td>
</tr>
<tr>
<td>Branching fraction</td>
<td>2</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>Trigger</td>
<td>11.3</td>
<td>12.4</td>
<td>8.55</td>
</tr>
<tr>
<td>Primary vertex</td>
<td>0.6</td>
<td>0.6</td>
<td>0.6</td>
</tr>
<tr>
<td>Electron ID</td>
<td>2.4</td>
<td>2.4</td>
<td>2.4</td>
</tr>
<tr>
<td>Isolated muon ID</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Tagging muon ID</td>
<td>0.6</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$b\to\mu$ decay</td>
<td>2.6</td>
<td></td>
<td></td>
</tr>
<tr>
<td>SLT-veto</td>
<td></td>
<td>2.7</td>
<td>2.7</td>
</tr>
<tr>
<td>Jet fragmentation</td>
<td>5</td>
<td>5</td>
<td>5</td>
</tr>
<tr>
<td>L1 eta coverage</td>
<td>4</td>
<td>4</td>
<td>4</td>
</tr>
<tr>
<td>Jet energy resolution</td>
<td>2</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>Jet energy scale</td>
<td>3.51</td>
<td>3.71</td>
<td>2.8</td>
</tr>
<tr>
<td>Flavor-dependent TRFs</td>
<td></td>
<td>6.54</td>
<td>9.73</td>
</tr>
<tr>
<td>Combined uncertainties</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Syst. yield uncertainty</td>
<td>22.4</td>
<td>23.9</td>
<td>23.2</td>
</tr>
<tr>
<td>Stat. uncertainty</td>
<td>2.4</td>
<td>1.16</td>
<td>1.16</td>
</tr>
<tr>
<td>Total yield uncertainty</td>
<td>22.5</td>
<td>23.9</td>
<td>23.2</td>
</tr>
<tr>
<td>Total acceptance uncertainty</td>
<td>14.4</td>
<td>16.6</td>
<td>15.5</td>
</tr>
</tbody>
</table>

### Final Selection

| Combined Uncertainties          |      |     |     |      |     |     |              |
| Syst. yield uncertainty         | 22.6| 24.6| 22.8| 22.5| 26.3| 25.1|              |
| Stat. uncertainty               | 2.4 | 1.21| 1.21| 2.5 | 1.37| 1.37|              |
| Total yield uncertainty         | 22.6| 24.6| 22.8| 22.5| 26.3| 25.1|              |
| Total acceptance uncertainty    | 14.6| 17.5| 14.9| 14.4| 19.8| 18.3|              |

TABLE 18: Errors in percent on the $s$-channel $tb$ yields, for each analysis channel, shown separately and combined.
<table>
<thead>
<tr>
<th>Uncertainty</th>
<th>Preselection</th>
</tr>
</thead>
<tbody>
<tr>
<td>Luminosity</td>
<td>6.5</td>
</tr>
<tr>
<td>$tqb$ cross section</td>
<td>15.0</td>
</tr>
<tr>
<td>Branching fraction</td>
<td>2.0</td>
</tr>
<tr>
<td>Trigger</td>
<td>11.8</td>
</tr>
<tr>
<td>Primary vertex</td>
<td>0.6</td>
</tr>
<tr>
<td>Electron ID</td>
<td>2.4</td>
</tr>
<tr>
<td>Isolated muon ID</td>
<td>—</td>
</tr>
<tr>
<td>Tagging muon ID</td>
<td>0.6</td>
</tr>
<tr>
<td>$b\rightarrow\mu$ decay</td>
<td>2.6</td>
</tr>
<tr>
<td>SLT-veto</td>
<td>—</td>
</tr>
<tr>
<td>Jet fragmentation</td>
<td>5.0</td>
</tr>
<tr>
<td>L1 eta coverage</td>
<td>4.0</td>
</tr>
<tr>
<td>Jet energy resolution</td>
<td>2.0</td>
</tr>
<tr>
<td>Jet energy scale</td>
<td>3.5</td>
</tr>
<tr>
<td>Flavor-dependent TRFs</td>
<td>—</td>
</tr>
<tr>
<td>Combined uncertainties</td>
<td></td>
</tr>
<tr>
<td>Syst. yield uncertainty</td>
<td>21.9</td>
</tr>
<tr>
<td>Stat. uncertainty</td>
<td>3.0</td>
</tr>
<tr>
<td>Total yield uncertainty</td>
<td>22.1</td>
</tr>
<tr>
<td>Total acceptance uncertainty</td>
<td>14.9</td>
</tr>
<tr>
<td>Final Selection</td>
<td></td>
</tr>
<tr>
<td>Syst. yield uncertainty</td>
<td>21.8</td>
</tr>
<tr>
<td>Stat. uncertainty</td>
<td>3.0</td>
</tr>
<tr>
<td>Total yield uncertainty</td>
<td>22.0</td>
</tr>
<tr>
<td>Total acceptance uncertainty</td>
<td>14.7</td>
</tr>
</tbody>
</table>

TABLE 19: Errors in percent on the $t$-channel $tqb$ yields for each analysis channel, shown separately and combined.
## Percentage Errors on the Combined $tb+tqb$ Yields

<table>
<thead>
<tr>
<th>Uncertainty</th>
<th>Electron Channels</th>
<th>Muon Channels</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>SLT</td>
<td>SVT</td>
</tr>
<tr>
<td><strong>Preselection</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Luminosity</td>
<td>6.5</td>
<td>6.5</td>
</tr>
<tr>
<td>$tb+tqb$ cross section</td>
<td>15.4</td>
<td>15.4</td>
</tr>
<tr>
<td>Branching fraction</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>Trigger</td>
<td>11.6</td>
<td>12.6</td>
</tr>
<tr>
<td>Primary vertex</td>
<td>0.6</td>
<td>0.6</td>
</tr>
<tr>
<td>Electron ID</td>
<td>2.4</td>
<td>2.4</td>
</tr>
<tr>
<td>Isolated muon ID</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>Tagging muon ID</td>
<td>0.6</td>
<td>—</td>
</tr>
<tr>
<td>$b\rightarrow mu$ decay</td>
<td>2.6</td>
<td>—</td>
</tr>
<tr>
<td>SLT-veto</td>
<td>—</td>
<td>2.7</td>
</tr>
<tr>
<td>Jet fragmentation</td>
<td>5</td>
<td>5</td>
</tr>
<tr>
<td>L1 eta coverage</td>
<td>4</td>
<td>4</td>
</tr>
<tr>
<td>Jet energy resolution</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>Jet energy scale</td>
<td>3.42</td>
<td>5.22</td>
</tr>
<tr>
<td>Flavor-dependent TRFs</td>
<td>—</td>
<td>7.14</td>
</tr>
<tr>
<td><strong>Combined uncertainties</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Syst. yield uncertainty</td>
<td>22.1</td>
<td>24.1</td>
</tr>
<tr>
<td>Stat. uncertainty</td>
<td>3.84</td>
<td>1.65</td>
</tr>
<tr>
<td>Total yield uncertainty</td>
<td>22.4</td>
<td>24.1</td>
</tr>
<tr>
<td>Total acceptance uncertainty</td>
<td>14.9</td>
<td>17.4</td>
</tr>
</tbody>
</table>

| **Combined Uncertainties**           |     |     |      |     |     |      |
| Syst. yield uncertainty              | 22.1| 24.5| 23.0 | 22.6| 26.8| 25.5 |
| Stat. uncertainty                    | 3.84| 1.72| 1.72 | 3.98| 1.94| 1.94 |
| Total yield uncertainty              | 22.4| 24.6| 23.1 | 23.0| 26.9| 25.6 |
| Total acceptance uncertainty         | 14.9| 18.0| 16.0 | 15.7| 21.0| 19.4 |

TABLE 20: Errors in percent on the combined $tb+tqb$ yields for each analysis channel, shown separately and combined.
<table>
<thead>
<tr>
<th>Uncertainty</th>
<th>Preselection</th>
<th>Muon Channels</th>
<th>Electron Channels</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>SLT</td>
<td>SVT</td>
<td>JLIP</td>
</tr>
<tr>
<td>Luminosity</td>
<td>6.5</td>
<td>6.5</td>
<td>6.5</td>
</tr>
<tr>
<td>$t\bar{t}$$\rightarrow$$l$$+$$jets$ cross section</td>
<td>18</td>
<td>18</td>
<td>18</td>
</tr>
<tr>
<td>Branching fraction</td>
<td>2</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>Trigger</td>
<td>8.55</td>
<td>8.15</td>
<td>4.54</td>
</tr>
<tr>
<td>Primary vertex</td>
<td>0.6</td>
<td>0.6</td>
<td>0.6</td>
</tr>
<tr>
<td>Electron ID</td>
<td>2.4</td>
<td>2.4</td>
<td>2.4</td>
</tr>
<tr>
<td>Isolated muon ID</td>
<td>—</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>Tagging muon ID</td>
<td>0.6</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>$b$$\rightarrow$$mu$ decay</td>
<td>2.6</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>SLT-veto</td>
<td>—</td>
<td>2.7</td>
<td>2.7</td>
</tr>
<tr>
<td>Jet fragmentation</td>
<td>7</td>
<td>7</td>
<td>7</td>
</tr>
<tr>
<td>L1 eta coverage</td>
<td>4</td>
<td>4</td>
<td>4</td>
</tr>
<tr>
<td>Jet energy resolution</td>
<td>2</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>Jet energy scale</td>
<td>4.38</td>
<td>2.05</td>
<td>6.4</td>
</tr>
<tr>
<td>Flavor-dependent TRFs</td>
<td>—</td>
<td>6.6</td>
<td>9.14</td>
</tr>
<tr>
<td><strong>Combined uncertainties</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Syst. yield uncertainty</td>
<td>23.3</td>
<td>23.8</td>
<td>24.5</td>
</tr>
<tr>
<td>Stat. uncertainty</td>
<td>3.1</td>
<td>1.55</td>
<td>1.55</td>
</tr>
<tr>
<td>Total yield uncertainty</td>
<td>23.5</td>
<td>23.9</td>
<td>24.5</td>
</tr>
</tbody>
</table>

| **Final Selection**             |              |               |                |              |               |                |
| Syst. yield uncertainty         | 23.3         | 23.8          | 24.4           | 22.7         | 24.1          | 25.6           |
| Stat. uncertainty               | 3.1          | 1.56          | 1.56           | 3.5          | 1.71          | 1.71           |
| Total yield uncertainty         | 23.5         | 23.8          | 24.5           | 23.0         | 24.2          | 25.6           |

TABLE 21: Errors in percent on the $t\bar{t}$$\rightarrow$$l$$+$$jets$ yields for each analysis channel, shown separately and combined.
<table>
<thead>
<tr>
<th>Uncertainty</th>
<th>Electron Channels</th>
<th>Muon Channels</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>SLT</td>
<td>SVT</td>
</tr>
<tr>
<td><strong>Preselection</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Luminosity</td>
<td>6.5</td>
<td>6.5</td>
</tr>
<tr>
<td>$t\bar{t}\rightarrow ll$ cross section</td>
<td>18</td>
<td>18</td>
</tr>
<tr>
<td>Branching fraction</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>Trigger</td>
<td>8.17</td>
<td>9.41</td>
</tr>
<tr>
<td>Primary vertex</td>
<td>0.6</td>
<td>0.6</td>
</tr>
<tr>
<td>Electron ID</td>
<td>2.4</td>
<td>2.4</td>
</tr>
<tr>
<td>Isolated muon ID</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>Tagging muon ID</td>
<td>0.6</td>
<td>—</td>
</tr>
<tr>
<td>$b\rightarrow mu$ decay</td>
<td>2.6</td>
<td>—</td>
</tr>
<tr>
<td>SLT-veto</td>
<td>—</td>
<td>2.7</td>
</tr>
<tr>
<td>Jet fragmentation</td>
<td>5</td>
<td>5</td>
</tr>
<tr>
<td>L1 eta coverage</td>
<td>4</td>
<td>4</td>
</tr>
<tr>
<td>Jet energy resolution</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>Jet energy scale</td>
<td>2.37</td>
<td>4.38</td>
</tr>
<tr>
<td>Flavor-dependent TRFs</td>
<td>—</td>
<td>6.68</td>
</tr>
<tr>
<td><strong>Combined uncertainties</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Syst. yield uncertainty</td>
<td>22.4</td>
<td>24.1</td>
</tr>
<tr>
<td>Stat. uncertainty</td>
<td>2.6</td>
<td>1.49</td>
</tr>
<tr>
<td>Total yield uncertainty</td>
<td>22.5</td>
<td>24.1</td>
</tr>
<tr>
<td><strong>Final Selection</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Syst. yield uncertainty</td>
<td>22.4</td>
<td>24.1</td>
</tr>
<tr>
<td>Stat. uncertainty</td>
<td>2.6</td>
<td>1.5</td>
</tr>
<tr>
<td>Total yield uncertainty</td>
<td>22.5</td>
<td>24.2</td>
</tr>
</tbody>
</table>

TABLE 22: Errors in percent on the $t\bar{t}\rightarrow ll$ yields for each analysis channel, shown separately and combined.
Table 23 lists the uncertainties associated with the $Z \rightarrow \mu\mu + \text{jets}$ yield estimate. Since the $Z \rightarrow \mu\mu + \text{jets}$ MC sample is normalized directly to the $Z \rightarrow \mu\mu + \text{jets}$ yield in the data rather than through cross section and luminosity, uncertainties related to MC normalization don’t apply. In particular, those uncertainties that are related to MC-data efficiency differences which are relevant for the $t\bar{t}$ and single top samples do not apply in this case. Only the jet energy scale and trigger uncertainties are considered because only those can have different effects for the $Z$ selection and the preselection. Cuts that are made in preselection such as $E_T$ and triangle cuts are not made when selecting the $Z + \text{jets}$ normalization sample.

<table>
<thead>
<tr>
<th>Uncertainty</th>
<th>SLT Preselection</th>
<th>Final Selection</th>
</tr>
</thead>
<tbody>
<tr>
<td>Normalization</td>
<td>13.2</td>
<td></td>
</tr>
<tr>
<td>Trigger</td>
<td>26.9</td>
<td></td>
</tr>
<tr>
<td>Jet energy scale</td>
<td>15.7</td>
<td></td>
</tr>
<tr>
<td>Combined uncertainty</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total yield uncertainty</td>
<td>33.8</td>
<td>33.8</td>
</tr>
</tbody>
</table>

**TABLE 23**: Errors in percent on the $Z \rightarrow \mu\mu + \text{jets}$ yield for the muon channel with SLT channel, shown separately and combined.
12.4. Uncertainties from the Background Measurement Methods

12.4.1. Electron and Muon Fake Probabilities

We assign a constant value systematic uncertainty of ±0.5 (approximately 50%) to the fake-electron probability (see Section 15.3.1.1) to account for variations as a function of different kinematic variables (see for example Figure 36).

Similarly, we assign a constant value systematic uncertainty of ±0.3 (approximately 30%) to the fake-muon probability for the same reasons (see Section 15.4).

12.4.2. Rescaling the Tagged Misidentified-Lepton Backgrounds

The uncertainty associated with the scale factor for the tagged misidentified-lepton background includes the uncertainties from the estimate of the number of misidentified lepton events in the loose-lepton sample from the matrix method, the uncertainty on the fake-lepton probability, and the statistical uncertainty from the size of the tagged orthogonal fake-lepton sample.

The uncertainty on the number of fake-lepton events in the pretagged sample is determined by propagating the individual uncertainties according to the matrix method equation (see Section 15.3). This uncertainty is then added in quadrature with the statistical uncertainty from the tagged orthogonal fake-lepton sample.

The resulting uncertainty for this background alone is shown in Table 24 for each analysis channel.

| Systematic Errors on Misidentified-Lepton Background Yields from Normalization of the Samples |
|-----------------------------------------------|----------------|----------------|----------------|
| | Electron Channels | Muon Channels |
| | SLT | SVT | JLIP | SLT | SVT | JLIP |
| Background | Mis-ID’d lepton | 56 | 57 | 57 | 36 | 36 | 36 |

TABLE 24: The percentage change in yield of the misidentified-lepton backgrounds from the sample normalization.

12.4.3. Flavor-Inclusive Tag-Rate Functions for W+jets Backgrounds

There are several contributions to the uncertainty on the W+jets backgrounds from the use of tag-rate functions. These include: (i) the difference in the fraction of jets with heavy flavor between the multijet samples the tag-rate functions are measured from and the W+jets samples they are applied to; (ii) the fit of the functions to the data (for SLT and JLIP, SVT uses histograms with no fitting); (iii) the statistics in the histograms (SVT); (iv) the spread of TRF weights distribution (as the TRF weights are not constant, the error on their sum depends on the width of the distribution and the size of the untagged sample). We have measured the uncertainties from all these components; all are small apart from the first one. We determine the error from the difference in the fraction of heavy flavor from the closure tests of the TRF on the 3JETS_LOOSE sample and from applying it to the ALLJETS, EMQCD, MUQCD, DIEL, and DIMU data samples and comparing the predicted tagged fractions with the actual tagged fractions. The largest error seen is ±20%, and rather than try to combine these cross check errors (which would reduce the error from this source since
the independent measurements are all consistent), and with the small components from error sources (ii), (iii) and (iv), we take the uncertainty from the use of tag-rate functions as this largest value:

- Flavor-inclusive tag-rate functions = ±20%

For the SVT and JLIP taggers, we add (in quadrature) an uncertainty of ±5% to this to account for the uncertainties on the scale factors in the 2-jets bin and the 3-jet and 4-jet bins. (We will treat this source of uncertainty in more detail, and separately for each tagger, after the Moriond analysis is complete. We expect it will go down.)

12.4.4. Rescaling the Tagged W+Jets Backgrounds

The systematic uncertainty on the scale factor for the W+Jets background is the sum in quadrature of the uncertainty on the number of W+Jets events in the tight sample as predicted by the matrix method and the systematic uncertainty for the inclusive TRF.

Table 25 shows the overall uncertainty for the W+Jets background alone.

<table>
<thead>
<tr>
<th>Background</th>
<th>Electron Channels</th>
<th>Muon Channels</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>SLT</td>
<td>SVT</td>
</tr>
<tr>
<td>W+jets</td>
<td>23.3</td>
<td>21.9</td>
</tr>
</tbody>
</table>

TABLE 25: The percentage change in yield of the W+jets backgrounds from the sample normalization.

12.4.5. Correlation between the Data Background Uncertainties

The uncertainties on the expected numbers of W+jets and misidentified-lepton multijet events are anti-correlated, since the measurements of these numbers both use the numbers of W+jets and misidentified-lepton events found in the pretagged sample via the matrix method (see Section 15). This is taken into account when calculating upper bounds on the signal cross sections by considering the W+jets and the misidentified-lepton multijet backgrounds together. The full derivatives of the expressions for the numbers of W and misidentified-lepton events in the pretagged samples are propagated into the expression giving the final W+jets plus mis-ID’d lepton event yield. The formula for this can be found in Ref. [58].

Table 26 shows the overall uncertainty for the sum of the W+jets and misidentified-lepton backgrounds. As expected from the anti-correlation, the relative uncertainty on the sum of the two backgrounds is much smaller than the uncertainty on the individual contributions.

<table>
<thead>
<tr>
<th>Background</th>
<th>Electron Channels</th>
<th>Muon Channels</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>SLT</td>
<td>SVT</td>
</tr>
<tr>
<td>W+jets + Mis-ID’d $l$</td>
<td>16.0</td>
<td>19.2</td>
</tr>
</tbody>
</table>

TABLE 26: The percentage change in yield of the combined W+jets and misidentified-lepton backgrounds, taking correlations into account.
13. OVERVIEW OF THE FINAL CALCULATIONS

We set limits on single top quark production using data and MC events that pass the preselection criteria given in Section 8 and where at least one jet is identified as originating from a $b$ quark by one of the algorithms described in Section 7. By construction, a jet cannot be tagged simultaneously by the SLT and the SVT or JLIP taggers, since these analyses apply an SLT-veto to maintain channel orthogonality.

The numbers of observed events in the various analysis channels are compared to the corresponding expectations from background processes to derive upper bounds on the numbers of single top events in the data, produced via the: (i) $s$-channel ($tb$) process, (ii) $t$-channel ($tqb$) process, and (iii) combined $tb+tqb$ processes. These upper bounds are translated into upper limits on the relevant cross sections.

For a given signal cross section $\sigma_{\text{sig}}$, the expected yields of signal events in each analysis channel are determined by:

$$Y^{\text{sigMC}} = A^{\text{sigMC}} \mathcal{L} \sigma_{\text{sig}}$$

where the acceptances $A^{\text{sigMC}}$ are calculated from signal Monte Carlo events as explained in Section 14.

The backgrounds consist mainly of:

- $t\bar{t}$ production leading to events with one or two leptons and several jets in the final state; this contribution is measured using Monte Carlo events, with the yields given in Section 15.2.

- When determining the upper bound on the $s$-channel ($t$-channel) production cross section, single top production via the $t$-channel ($s$-channel) process is included as part of the background, and the corresponding expected yield is obtained from Monte Carlo as described in Section 15.2.

- $Z\rightarrow\mu\mu$+jets events; this background contributes only in the $\mu$+jets/$\mu$ channel when one muon coincidentally overlaps with a jet in the event and fakes a $b$-tag; it is described in Section 15.2.

- Multijet events where a jet is misidentified as an electron, or a muon from a $b$ decay is misidentified as one from a $W$ decay; this background is measured using data, as explained in Sections 15.3 and 15.4.

- $W$+jets events; this contribution, which includes $Z$+jets events where one lepton is not reconstructed, and diboson events, is measured using data, as described in Section 15.5.
14. ACCEPTANCES FOR MONTE CARLO SIGNALS

14.1. Acceptance Calculation

This section describes the determination of the single top s-channel, t-channel, and combined acceptances. These are used as input into the limit calculation. (The same method is applied later for the $t\bar{t}$ background calculations.)

The signal acceptance is defined as:

$$A^{\text{sigMC}} = \frac{B}{N_{\text{initial}}} \sum_{N_{\text{preselect}}} \varepsilon_{\text{trigger}} \varepsilon_{\text{correction}} \varepsilon_{b-\text{tagging}}$$

where:

- $B$ is the branching fraction for each MC sample, given in Table 2. The error on $B$ is $\pm 2\%$, see Section 12.1.4.
- $N_{\text{initial}}$ is the number of events in each MC sample before any cuts are applied. The numbers are given in Table 2.
- $\varepsilon_{\text{trigger}}$ is the trigger efficiency for each event, described in Section 5.2. The errors are between 4% and 27%, depending on the analysis channel, see Section 12.2.1.
- $\varepsilon_{\text{correction}}$ is the product of the correction factors described in Section 14.2 that account for differences between MC events and data.
- $\varepsilon_{b-\text{tagging}}$ is the probability for each event to have at least one $b$-tagged jet. The soft lepton tagging method is described in Section 7.3.1, and the flavor-dependent tag-rate functions are described in Section 7.4.2 (SVT) and 7.5.2 (JLIP). The errors are between 7% and 12%, depending on the analysis channel, see Section 12.2.12.

14.2. Acceptance Correction Factors

The Monte Carlo simulation, even after smearing, does not model the data well enough to be able to use acceptance calculations directly from the MC. We apply the following correction factors to each MC event so that the MC reconstruction efficiency matches that found in data:

- $\varepsilon_{\text{vertex}} = (100.8 \pm 0.6)\%$ ($e+$jets), $= (99.7 \pm 0.8)\%$ ($\mu+$jets). Described in Section 6.1.2.
- $\varepsilon_{e-\text{ID}} = (86.9 \pm 2.1)\%$. Used only in the $e+$jets analyses. Described in Section 6.2.3.
- $\varepsilon_{\text{isol}\mu-\text{ID}} = (86.0 \pm 5.4)\%$. Used only in the $\mu+$jets analyses. Described in Section 6.3.3.
- $\varepsilon_{\text{tag}\mu-\text{ID}} = (102.5 \pm 0.6)\%$. Used only in the SLT analyses. Described in Section 6.3.3.

14.3. Acceptance Uncertainties

In addition to the uncertainties on $B$, $\varepsilon_{\text{trigger}}$, $\varepsilon_{\text{correction}}$, and $\varepsilon_{b-\text{tagging}}$, the signal acceptance uncertainties also include the following components:

- $\varepsilon_{b-\mu} = \pm 2.6\%$. Needed only for the SLT analyses, described in Section 12.2.5.
- $\varepsilon_{\text{SLT-veto}} = \pm 2.7\%$. Needed only for the SVT and JLIP analyses, described in Section 12.2.6.
- $\varepsilon_{\text{jet-frag}} = \pm 5\%$ ($tb$, $tqb$, $t\bar{t}\rightarrow ll$, $Z\rightarrow \mu\mu$), $\pm 7\%$ ($t\bar{t}\rightarrow ll+$jets). Needed for all analyses, described in Section 12.2.7.
• $\varepsilon_{\text{L1Cal-}\eta} = \pm 4\%$. Needed for all analyses, described in Section 12.2.8.
• $\varepsilon_{\text{JER}} = \pm 2\%$. Needed for all analyses, described in Section 12.2.10.
• $\varepsilon_{\text{JES}} = \pm$ between 2\% and 13\%. Needed for all analyses, described in Section 12.2.11.

14.4. Monte Carlo Signal Acceptances

Table 27 shows the results of the acceptances calculated for the $s$-channel, $t$-channel, and the combined $s+t$-channel.

<table>
<thead>
<tr>
<th>Percentage Acceptances of Single Top Signals</th>
<th>SLT</th>
<th>SVT</th>
<th>JLIP</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Electron Channel</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$tb$</td>
<td>0.487 ± 0.012 ± 0.064</td>
<td>1.286 ± 0.015 ± 0.200</td>
<td>1.299 ± 0.015 ± 0.187</td>
</tr>
<tr>
<td>$tqb$</td>
<td>0.304 ± 0.009 ± 0.044</td>
<td>0.961 ± 0.011 ± 0.171</td>
<td>0.974 ± 0.011 ± 0.168</td>
</tr>
<tr>
<td>$tb+tqb$</td>
<td>0.360 ± 0.007 ± 0.033</td>
<td>1.061 ± 0.009 ± 0.144</td>
<td>1.074 ± 0.009 ± 0.134</td>
</tr>
<tr>
<td><strong>Muon Channel</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$tb$</td>
<td>0.445 ± 0.011 ± 0.057</td>
<td>1.012 ± 0.013 ± 0.186</td>
<td>1.012 ± 0.013 ± 0.182</td>
</tr>
<tr>
<td>$tqb$</td>
<td>0.270 ± 0.008 ± 0.042</td>
<td>0.716 ± 0.009 ± 0.146</td>
<td>0.757 ± 0.010 ± 0.157</td>
</tr>
<tr>
<td>$tb+tqb$</td>
<td>0.324 ± 0.006 ± 0.032</td>
<td>0.807 ± 0.008 ± 0.135</td>
<td>0.836 ± 0.007 ± 0.141</td>
</tr>
<tr>
<td><strong>Final Selection</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$tb$</td>
<td>0.475 ± 0.011 ± 0.063</td>
<td>1.299 ± 0.015 ± 0.200</td>
<td>1.218 ± 0.015 ± 0.167</td>
</tr>
<tr>
<td>$tqb$</td>
<td>0.295 ± 0.009 ± 0.043</td>
<td>0.897 ± 0.011 ± 0.164</td>
<td>0.907 ± 0.011 ± 0.150</td>
</tr>
<tr>
<td>$tb+tqb$</td>
<td>0.350 ± 0.007 ± 0.032</td>
<td>0.993 ± 0.009 ± 0.142</td>
<td>1.002 ± 0.009 ± 0.117</td>
</tr>
</tbody>
</table>

TABLE 27: Acceptances of the Monte Carlo signals for the preselection cuts. The values are given as a percentage of the total cross section for each process. The first component of the error is from the MC statistics, and the second is the systematic contribution, which dominates.
15. EVENT YIELDS FOR SIGNALS AND BACKGROUND

15.1. Definition of Yield

Throughout this note, we define the term “yield” to mean the number of events predicted in the data we have collected, after all corrections have been applied and corresponding to the luminosity in a given channel. (We avoid calling this a “number of events” explicitly, since we reserve the phrase to refer to the count of events in the MC or data samples, before application of the correction and normalization factors. Thus we avoid a common and sometimes confusing ambiguity in terminology.)

15.2. Monte Carlo Signal and Background Yields

15.2.1. Monte Carlo Yield Calculation for Top Samples

We calculate the yields for \( t\bar{b} \), \( t\bar{q}b \), and \( t\bar{t} \) expected in the integrated luminosity of the Run II data set as follows:

\[
\text{Yield} = Y^{\text{MC}} = A^{\text{MC}} \cdot L \cdot \sigma
\]

where the acceptance \( A^{\text{MC}} \) has been derived in Section 14.1, and the normalization terms are:

- \( L \) is the integrated luminosity of the electron or muon channel signal data
- \( \sigma \) is the theoretical cross section for each MC process

The relative errors on the yield are calculated thus:

\[
\text{Yield statistical error} = \Delta Y^{\text{MC}}_{\text{stat}} = \Delta A^{\text{MC}}_{\text{stat}}
\]

\[
\text{Yield systematic error} = \Delta Y^{\text{MC}}_{\text{syst}} = \sqrt{\left(\Delta A^{\text{MC}}_{\text{syst}}\right)^2 + (\Delta L)^2 + (\Delta \sigma)^2}
\]

and

- \( \Delta A^{\text{MC}}_{\text{stat}} \) is the relative statistical error for the samples after preselection (see Section 14.1)
- \( \Delta A^{\text{MC}}_{\text{syst}} \) is the relative systematic error on the acceptance (see Section 14.1)
- \( \Delta L \) is the relative error on the integrated luminosity (see Section 12.1.1)
- \( \Delta \sigma \) is the relative error on the theoretical cross section (see Section 12.1.2)

15.2.2. Monte Carlo Yield Calculation for \( Z \rightarrow \mu\mu \)

\( Z \rightarrow \mu\mu + \text{jets} \) events contribute to the background if one of the muons is mis-identified as a tagging muon. We calculate the yield for this \( Z \rightarrow \mu\mu + \text{jets} \) background in a similar manner to that described for the top samples, but instead of normalizing to the integrated luminosity, theoretical cross section, and branching fraction, we normalize this background to the number of \( Z \rightarrow \mu\mu + 2\text{to}4 \text{jets} \) events observed in data [47].

To evaluate this background component, we start from a Monte Carlo \( Z \rightarrow \mu\mu + \text{jets} \) sample and apply all of the preselection cuts. This gives the number of Monte Carlo \( Z \rightarrow \mu\mu \) events passing preselection cuts, \( N_{\text{tag,MC}}^{Z \rightarrow \mu\mu} \).
For the normalization, we start from the same Monte Carlo $Z\rightarrow\mu\mu+$jets sample, but instead of applying preselection cuts, we select events that contain two isolated muons ($p_T > 15\,\text{GeV}$) passing our muon ID criteria (section 6.3.1). We also require between 2 and 4 jets. This gives the number of Monte Carlo $Z\rightarrow\mu\mu$ events in the $Z$ sample, $N_{Z,MC}^{Z\rightarrow\mu\mu}$. We also apply the same $Z$ selection cuts (two isolated muons and 2-4 jets) to the full dataset. In the data sample thus selected we fit the peak in the invariant mass distribution of the $\mu\mu$ pair to a Gaussian plus an exponential background. The yield of data $Z\rightarrow\mu\mu$ events thus obtained is given by $Y_{Z,\text{data}}^{Z\rightarrow\mu\mu}$.

The yield for the $Z\rightarrow\mu\mu+\text{jets}$ background events after preselection, ($Y_{\text{tag, data}}^{Z\rightarrow\mu\mu}$) is calculated from these numbers as

$$Y_{\text{tag, data}}^{Z\rightarrow\mu\mu} = N_{\text{tag, MC}}^{Z\rightarrow\mu\mu} \times \frac{Y_{Z,\text{data}}^{Z\rightarrow\mu\mu}}{N_{Z,\text{MC}}^{Z\rightarrow\mu\mu}}.$$

The result of this measurement is:

- $Z\rightarrow\mu\mu$ normalization factor $\frac{Y_{Z,\text{data}}^{Z\rightarrow\mu\mu}}{N_{Z,\text{MC}}^{Z\rightarrow\mu\mu}} = 1.34 \pm 0.21$

which is a 16% error.

15.2.3. Monte Carlo Event Yields

Table 28 shows the event yields for the Monte Carlo signal and background samples, with the statistical and systematic errors, in the electron and muon channels after preselection cuts and $b$-tagging.
<table>
<thead>
<tr>
<th></th>
<th>Electron Channel</th>
<th>Muon Channel</th>
<th>Preselection</th>
<th>Final Selection</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Signals</td>
<td>Signals</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>$tb$</td>
<td>$tb$</td>
<td>$tb$</td>
<td></td>
</tr>
<tr>
<td></td>
<td>$0.67 \pm 0.02 \pm 0.15$</td>
<td>$0.62 \pm 0.02 \pm 0.13$</td>
<td>$1.41 \pm 0.02 \pm 0.36$</td>
<td>$1.41 \pm 0.02 \pm 0.35$</td>
</tr>
<tr>
<td></td>
<td>$tqb$</td>
<td>$0.85 \pm 0.03 \pm 0.19$</td>
<td>$2.24 \pm 0.03 \pm 0.59$</td>
<td>$2.37 \pm 0.03 \pm 0.63$</td>
</tr>
<tr>
<td></td>
<td>$tb + tqb$</td>
<td>$1.47 \pm 0.03 \pm 0.28$</td>
<td>$3.65 \pm 0.03 \pm 0.86$</td>
<td>$3.78 \pm 0.04 \pm 0.90$</td>
</tr>
<tr>
<td>Backgrounds</td>
<td>$t\bar{t} \rightarrow l + jets$</td>
<td>$6.09 \pm 0.21 \pm 1.46$</td>
<td>$14.77 \pm 0.25 \pm 3.56$</td>
<td>$14.90 \pm 0.25 \pm 3.81$</td>
</tr>
<tr>
<td></td>
<td>$\bar{t} \bar{t} \rightarrow ll$</td>
<td>$1.96 \pm 0.06 \pm 0.44$</td>
<td>$4.42 \pm 0.07 \pm 1.11$</td>
<td>$4.43 \pm 0.07 \pm 1.13$</td>
</tr>
<tr>
<td></td>
<td>$Z \rightarrow \mu \mu + jets$</td>
<td>$10.73 \pm 3.66$</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>$t\bar{t} \rightarrow l + jets$</td>
<td>$7.05 \pm 0.22 \pm 1.64$</td>
<td>$18.93 \pm 0.29 \pm 4.50$</td>
<td>$19.26 \pm 0.30 \pm 4.70$</td>
</tr>
<tr>
<td></td>
<td>$\bar{t} \bar{t} \rightarrow ll$</td>
<td>$2.67 \pm 0.07 \pm 0.60$</td>
<td>$5.18 \pm 0.08 \pm 1.25$</td>
<td>$5.22 \pm 0.08 \pm 1.24$</td>
</tr>
<tr>
<td></td>
<td>$Z \rightarrow \mu \mu + jets$</td>
<td>$10.29 \pm 3.48$</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**TABLE 28:** Event yields from the Monte Carlo signal and background samples with the statistical and systematic errors.
15.3. Misidentified-Electron Background Yields

The background from multijet events with a jet misidentified as an isolated electron is measured using data. We abbreviate the name of this background to “fake-\(e\).” There are four steps needed to measure the fake-\(e\) background:

1. We determine the number of pretagged fake-\(e\) events in the pretagged preselected signal-data using the “matrix method.”
2. An independent pretagged sample is selected that consists mainly of fake-\(e\) events. This is known as the “orthogonal fake-\(e\) sample.”
3. We normalize the orthogonal fake-\(e\) sample to the number of pretagged fake-\(e\) events found in step 1.
4. The \(b\)-tagging algorithms are applied to the normalized orthogonal sample to obtain the tagged fake-\(e\) background.

The following four subsections describe these steps.

15.3.1. Number of Fake-\(e\) Events in the Pretagged Preselected Data

We use the matrix method to divide the pretagged preselected signal-data into two parts: events with a misidentified electron and those with a real electron. Misidentified electrons are from multijet events, while real electrons are mostly from \(W +\) jets events, with a very small fraction from \(t\bar{t}\) and single top. The matrix method and its error calculation are explained in detail in Ref. [58].

To apply the matrix method, we start from the EMQCD dataset and select from it a sample of good pretagged events containing a loose electromagnetic object (the “loose-\(e\) sample”), and a subsample of events from that sample that contain a tight electron (the “tight-\(e\) sample”). The tight-\(e\) sample is the main pretagged preselected signal-data sample used in this analysis.

**Loose-\(e\) Sample**

- Passes all preselection criteria
- Passes the loose-\(e\) identification criteria (EM fraction, isolation, \(H\)-matrix \(\chi^2\), transverse energy, and \(|\eta^{\text{det}}|\))
- Passes the tight-electron identification criteria (track match, vertex cut) except that the likelihood cut is not applied
- \(N_{\text{loose-}\text{-}\text{EM}} = 8,604\) events (SLT), \(6,195\) events (SVT and JLIP)

**Tight-\(e\) Sample**

- Passes all loose-\(e\) sample criteria
- Passes the electron likelihood cut: \(\mathcal{L} > 0.75\)
- \(N_{\text{tight-}\text{-}\text{e}} = 3,252\) events (SLT), \(3,160\) events (SVT and JLIP)

(The SLT numbers are slightly larger than the lifetime-tagger ones because the \(E_T\) triangle cut is tighter in the lifetime-tagger analyses.)
The matrix method calculation is based on the following two equations:

\[
N_{\text{loose-EM}} = N_{\text{loose-EM}}^{\text{fake-e}} + N_{\text{loose-EM}}^{\text{real-e}}
\]
\[
N_{\text{tight-e}} = N_{\text{tight-e}}^{\text{fake-e}} + N_{\text{tight-e}}^{\text{real-e}}
\]

where

- \(N_{\text{loose-EM}}^{\text{fake-e}}\) is the number of events with a fake electron in the loose-EM sample (multijet events)
- \(N_{\text{loose-EM}}^{\text{real-e}}\) is the number of events with a real electron in the loose-EM sample (W+jets, \(t\bar{t}\), and single top events, where “W+jets” includes Z+jets and diboson events as usual in this analysis)
- \(N_{\text{tight-e}}^{\text{fake-e}}\) is the number of events with a fake electron in the tight-e sample
- \(N_{\text{tight-e}}^{\text{real-e}}\) is the number of events with a real electron in the tight-e sample
- \(\varepsilon_{\text{fake-e}}\) is the probability for an event with a fake electron to pass from the loose-EM sample into the tight-e one, also known as the “fake-electron probability”
- \(\varepsilon_{\text{real-e}}\) is the probability for an event with a real electron to pass from the loose-EM sample into the tight-e one, also known as the “real-electron probability”

Solving these two simultaneous equations gives:

\[
N_{\text{loose-EM}}^{\text{fake-e}} = \frac{\varepsilon_{\text{real-e}} N_{\text{loose-EM}}^{\text{loose-EM}} - N_{\text{tight-e}}}{\varepsilon_{\text{real-e}} - \varepsilon_{\text{fake-e}}}
\]
\[
N_{\text{loose-EM}}^{\text{real-e}} = \frac{N_{\text{tight-e}} - \varepsilon_{\text{fake-e}} N_{\text{loose-EM}}^{\text{loose-EM}}}{\varepsilon_{\text{real-e}} - \varepsilon_{\text{fake-e}}}
\]

We apply the matrix method event-by-event to take account of a nonconstant parametrization of \(\varepsilon_{\text{fake-e}}\). We use the values of \(\varepsilon_{\text{fake-e}}\) and \(N_{\text{loose-EM}}^{\text{fake-e}}\) summed over the events to determine the number we are trying to measure, \(N_{\text{tight-e}}^{\text{fake-e}}\).

**15.3.1.1. Determination of the Fake-Electron Probability**

In previous top pair production analyses, the probability \(\varepsilon_{\text{fake-e}}\) that an EM object originating from a jet faked an electron (i.e., that it passed the electron likelihood cut) was determined as a constant value obtained from data with low missing transverse energy (< 15 GeV say), which is dominated by fake-e events. It was then assumed that the fake probability is the same in this region as in the signal region with high missing transverse energy (> 15 GeV). We have found that this assumption is not valid for our analysis.

Figure 36 shows the fake-electron probability \(\varepsilon_{\text{fake-e}}\) for the preselected data sample (except for the \(E_T\) cut) as a function of the fully corrected missing transverse energy. The fake-electron probability increases when \(E_T\) goes to very low values. This effect must be a function of how the likelihood is defined. This increase makes it difficult to use the same strategy as before and a new method has been developed to overcome the problem.

A new background sample is formed by applying all the preselection cuts except for the triangle cuts, which are inverted, i.e., events are kept if they fail at least one of the three triangle cuts. As a reminder, the triangle cuts exclude events above the main \(E_T\) cut threshold.
when the $E_T$ and electron are aligned, or when the $E_T$ and the first or second jets are back-to-back. Events selected in this way are expected to show the same behavior as the fake-e background in the signal region and can thus be used to determine the fake-electron probability. We observe in this sample that the fake-electron probability depends strongly on the transverse momentum of the loose-EM object, as shown in Fig. 37.

The dependence of $\varepsilon_{\text{fake-e}}$ on the transverse energy of the loose-EM object has been parametrized by the following function:

$$
E_T^{\text{loose-EM}} < 25 \text{ GeV} : \quad \varepsilon_{\text{fake-e}} = -0.012(E_T^{\text{loose-EM}} - 25) + 0.075
$$

$$
E_T^{\text{loose-EM}} \geq 25 \text{ GeV} : \quad \varepsilon_{\text{fake-e}} = 0.075
$$

The error on $\varepsilon_{\text{fake-e}}$, obtained from variation of the function choice, is:

- Error on the fake-electron probability = ±0.5

To illustrate the difference in the fake-e background prediction between using a fixed value for $\varepsilon_{\text{fake-e}}$ and using the new parametrization, we plot in Fig. 38 the electron transverse energy for pretagged preselected data (solid black circles) and the sum (open black histogram) of the fake-e background (brown shaded histogram) and of a $W+$jets MC background sample.
normalized to the prediction of the matrix method. (This MC sample is not used elsewhere in the analysis, just for illustration in these plots. The important part of the plots to consider is the shape of the brown shaded fake-$e$ histogram and the agreement between background model and data in the low transverse energy region.) The left plot shows the fake-$e$ background calculated with a constant fake-electron probability. The right plot shows the same background calculated with the new parametrized fake-electron probability. The agreement between the sum of the backgrounds and the data is better in the very low $E_{T}^{e}$ region in the right-hand plot, and the shape of the fake-$e$ background there is more natural.

FIG. 38: Electron transverse energy distributions of the pretagged preselected signal-data (solid black circles) and the sum (open black histogram) of the fake-$e$ background (brown shaded histogram) and of a $W+$jets MC background sample, for a constant fake-electron probability (left plot) and for the new $E_{T}^{e}$-parametrized fake-electron probability (right plot).

15.3.1.2. Determination of the Real-Electron Probability

The real-electron probability $\varepsilon_{\text{real}-e}$ is simply the probability for a real electron in the loose-EM sample to pass the likelihood cut. We have measured this efficiency in a sample of $Z\rightarrow ee$ data and found it to be:

$$\varepsilon_{\text{real}-e} = 0.891 \pm 0.006$$

15.3.1.3. Matrix Method Results

Applying the matrix method, we obtain the following results for the numbers of fake-electron events in the pretagged preselected data samples:

$$N_{\text{fake}-e}^{\text{tight}} = 514 \pm 278 \text{ (SLT)}, \quad 283 \pm 158 \text{ (SVT and JLIP)}$$

The SVT/JLIP number is smaller than the SLT one because the pretagged preselected sample is smaller to start with. A tighter electron-$E_{T}$ triangle cut has been applied, and an SLT-veto. The tighter triangle cut preferentially removes a region with more fake electrons in it than the remaining region, so the difference between these two numbers is relatively large.
15.3.2. Selecting the Orthogonal Fake-Electron Sample

Starting from the EMQCD data, we create a sample consisting of mainly multijet events with a misreconstructed EM-object, and no good tight electrons in the sample. It is orthogonal to the tight-\(e\) sample.

**Orthogonal Fake-\(e\) Sample**

- Passes all preselection criteria
- Passes the loose-EM criteria (EM fraction, isolation, H-matrix \(\chi^2\), transverse energy, and \(|\eta^{\text{det}}|\))
- (NB, not required to pass the tight-electron criteria of a track match or a vertex cut)
- Passes a tight inverted electron likelihood cut \(L < 0.05\)
- \(N_{\text{orthog-pretag}}^{\text{fake-\(e\)}} = 24,189\) events (SLT), = 13,288 events (SVT and JLIP)

15.3.3. Normalizing the Orthogonal Fake-Electron Sample

The orthogonal fake-\(e\) sample is normalized to the number of fake-electron events in the pretagged preselected signal-data sample using the following normalization factor:

\[
\frac{F_{\text{pretag}}}^{\text{fake-\(e\)}} = \frac{N_{\text{tight-\(e\)}}^{\text{fake-\(e\)}}}{N_{\text{orthog-pretag}}^{\text{fake-\(e\)}}} = \frac{514}{24,189} = 0.021 \pm 0.011 \text{ (SLT)}
\]

\[
= \frac{283}{13,288} = 0.021 \pm 0.012 \text{ (SVT and JLIP)}
\]

Note, these values are weighted averages of the individual scale factors, given here to show the average size of the rescaling. In the analysis, we rescale the weight of each event by its own scale factor appropriate for the value of \(\varepsilon_{\text{fake-\(e\)}}\) for that event. (\(\varepsilon_{\text{fake-\(e\)}}\) is a function of \(E_T^{\text{loose-EM}}\), as described in Section 15.3.1.1.)

15.3.4. Tagged Misidentified-Electron Yields

We apply each of the three \(b\)-tagging algorithms to the orthogonal fake-\(e\) data sample and normalize it as described above to obtain the tagged misidentified isolated-electron background yields. The results are given in the first and third rows of Table 29.

The numbers in the second row of Table 29 are the results of a cross check calculation. The matrix method is applied to the tagged preselected data instead of to the pretagged preselected data. The loose-EM data sample in this case has had \(b\) tagging applied, and the electron likelihood is applied to this tagged sample to get a new tight-\(e\) sample. The results are consistent within errors with the main method. We expect the main method to give smaller errors than the cross check one, particularly after final selection cuts have reduced the tight-\(e\) data sample down to a handful of events.

Figure 39 shows a histogram of the transverse mass of the reconstructed \(W\) boson in the pretagged preselected data sample. The result of applying the matrix method in each bin is also shown. The fake-\(e\) distribution is shown by the brown error bars, the real-\(e\) distribution is in green, and the data are solid black circles. This plot shows that application of this method produces a distribution of the fake-\(e\) background that has a reasonable shape and
TABLE 29: Event yields from the misidentified-electron backgrounds with statistical and systematic errors (first and third rows). The second row has been calculated using a different method as a cross check, as described in the text.

is mainly at low-$M_W^T$ as expected. We do not use the shapes of these distributions in our analysis, only the integrals of the brown (fake-$e$) and green (real-$e$) regions.

FIG. 39: Distribution of the transverse mass of the reconstructed $W$ boson, showing the results of applying the matrix method bin-by-bin for the pretagged preselected sample.
15.4. Misidentified-Muon Background Yields

Multijet events are an important background source in the muon channel. These events look like signal ones when a muon from a heavy flavor decay is separated from its accompanying jet and passes the isolation requirement misidentifying it as a muon from a $W$ decay. The muon can appear isolated if it travels wide of its jet, or if the jet is not reconstructed, for example if the jet $E_T$ is less than 15 GeV. We abbreviate the name of this background to “fake-$\mu$.” It should be understood that the muon in this case is real, but the isolation is fake. However, this abbreviated notation is convenient. The same method is used to measure the fake-$\mu$ background as was used for the fake-$e$ background, see Section 15.3.

15.4.1. Number of Fake-$\mu$ Events in the Pretagged Preselected Data

We use the matrix method to divide the pretagged preselected signal-data into two parts: events with a misidentified isolated muon and those with a real isolated muon. Misidentified isolated muons are mainly from $b\bar{b}$ events with some $c\bar{c}$ contribution, while real isolated muons are mostly from $W$+jets events, with a very small fraction from $t\bar{t}$ and single top.

The matrix method and its error calculation are explained in detail in Ref. [58].

To apply the matrix method, we start from the MUQCD dataset and select from it a sample of good pretagged events containing a loose muon (the “loose-$\mu$ sample”), and a subsample of events from that sample that contain a tight-isolated muon (the “tight-$\mu$ sample”). The tight-$\mu$ sample is the main pretagged preselected signal-data sample used in this analysis.

**Loose-$\mu$ Sample**

- Passes all preselection criteria
- Passes the loose-$\mu$ identification criteria ($|nseg| = 3$ medium muon, loose and tight cosmic ray cuts)
- Passes the loose-isolation cut: $\Delta R > 0.5$
- $N_{\text{loose-$\mu$}} = 5,241$ events (SLT), $= 5,131$ events (SVT and JLIP)

**Tight-$\mu$ Sample**

- Passes all loose-$\mu$ sample criteria
- Passes the tight-isolation cuts: track halo isolation $< 0.06$, calorimeter halo isolation $< 0.08$
- $N_{\text{tight-$\mu$}} = 2,429$ events (SLT), $= 2,379$ events (SVT and JLIP)

The matrix method calculation is based on the following two equations:

\[
\begin{align*}
N_{\text{loose-$\mu$}} &= N_{\text{fake-$\mu$}} + N_{\text{real-$\mu$}} \\
N_{\text{tight-$\mu$}} &= N_{\text{fake-$\mu$}} + N_{\text{real-$\mu$}} \\
&= \varepsilon_{\text{fake-$\mu$}} N_{\text{loose-$\mu$}} + \varepsilon_{\text{real-$\mu$}} N_{\text{loose-$\mu$}}
\end{align*}
\]
where

- \( N_{\text{loose-}\mu}^{\text{fake-}} \) is the number of events with a fake-isolated muon in the loose-\( \mu \) sample (multijet events)
- \( N_{\text{loose-}\mu}^{\text{real-}} \) is the number of events with a real-isolated muon in the loose-\( \mu \) sample (W+jets, \( tt \), and single top events, where “W+jets” includes Z+jets and diboson events as usual in this analysis)
- \( N_{\text{tight-}\mu}^{\text{fake-}} \) is the number of events with a fake-isolated muon in the tight-\( \mu \) sample
- \( N_{\text{tight-}\mu}^{\text{real-}} \) is the number of events with a real-isolated muon in the tight-\( \mu \) sample
- \( \varepsilon_{\text{fake-}\mu} \) is the probability for a event with a fake muon to pass from the loose-\( \mu \) sample into the tight-\( \mu \) one, also known as the “fake-muon probability”
- \( \varepsilon_{\text{real-}\mu} \) is the probability for an event with a real-isolated muon to pass from the loose-\( \mu \) sample into the tight-\( \mu \) one, also known as the “real-muon probability”

Solving these two simultaneous equations gives:

\[
N_{\text{loose-}\mu}^{\text{fake-}} = \frac{(\varepsilon_{\text{real-}\mu} N_{\text{loose-}\mu}^{\text{fake-}} - N_{\text{tight-}\mu}^{\text{fake-}})}{(\varepsilon_{\text{real-}\mu} - \varepsilon_{\text{fake-}\mu})}
\]
\[
N_{\text{loose-}\mu}^{\text{real-}} = \frac{(N_{\text{tight-}\mu}^{\text{fake-}} - \varepsilon_{\text{fake-}\mu} N_{\text{loose-}\mu}^{\text{fake-}})}{(\varepsilon_{\text{real-}\mu} - \varepsilon_{\text{fake-}\mu})}
\]

We apply the matrix method on the whole sample at once since \( \varepsilon_{\text{fake-}\mu} \) is a constant. We use the values of \( \varepsilon_{\text{fake-}\mu} \) and \( N_{\text{loose-}\mu}^{\text{fake-}} \) summed over the events to determine the number we are trying to measure, \( N_{\text{tight-}\mu}^{\text{fake-}} \).

15.4.1.1. Determination of the Fake-Muon Probability

The probability for a loose-isolated muon to fake a tight-isolated one is measured in a sample of data with the same topology as our signal data, but which consists mainly of \( bb \) multijet events. The preselection cuts are applied to the MUQCD data sample, except that the the tight-isolation cuts are not applied and the missing transverse energy requirement is reversed, \( E_T < 15 \text{ GeV} \). The fake-muon probability is defined as the number of events in this sample passing the tight-isolation cuts divided by the total number of events. The fake rate is found to be:

\[ \varepsilon_{\text{fake-}\mu} = 0.096 \pm 0.030 \]

15.4.1.2. Determination of the Real-Muon Probability

The real-muon probability \( \varepsilon_{\text{real-}\mu} \) is simply the probability for a muon from a \( W \) decay in the loose-\( \mu \) sample to pass the tight-isolation cuts. We have measured this efficiency in a sample of \( Z \rightarrow \mu\mu \) data and found it to be:

\[ \varepsilon_{\text{real-}\mu} = 0.861 \pm 0.032 \]

15.4.1.3. Matrix Method Results

Applying the matrix method, we obtain the following results for the numbers of fake-muon events in the pretagged preselected data samples:
\[ N_{\text{tight-\(\mu\)}}^{\text{fake-\(\mu\)}} = 244 \pm 86 \text{ (SLT)}, \quad = 256 \pm 144 \text{ (SVT and JLIP)} \]

15.4.2. Selecting the Orthogonal Fake-Muon Sample

Starting from the MUQCD data, we create a sample consisting of mainly multijet events with a nonisolated muon, and with no good tight-isolated muons in the sample. It is orthogonal to the tight-\(\mu\) sample, which always has an tight-isolated muon in each event.

**Orthogonal Fake-\(\mu\) Sample**

- Passes all preselection criteria
- Passes the muon ID and the loose and tight cosmic-ray rejection criteria
- (NB, not required to pass the loose-isolation \(\Delta R\) cut)
- Passes inverted tight-isolation cuts on the muon, track halo isolation > 0.08, calorimeter halo isolation > 0.06
- \(N_{\text{orthog-pretag}}^{\text{fake-\(\mu\)}} = 3,017\) events (SLT), = 2,780 events (SVT and JLIP)

15.4.3. Normalizing the Orthogonal Fake-Muon Sample

The orthogonal fake-\(\mu\) sample is normalized to the number of fake-muon events in the pretagged preselected signal-data sample using the following normalization factor:

\[ F_{\text{pretag}}^{\text{fake-\(\mu\)}} = \frac{N_{\text{tight-\(\mu\)}}^{\text{fake-\(\mu\)}}}{N_{\text{orthog-pretag}}^{\text{fake-\(\mu\)}}} = \frac{244}{3,017} = 0.081 \pm 0.029 \text{ (SLT)} \]

\[ = \frac{256}{2,780} = 0.092 \pm 0.052 \text{ (SVT and JLIP)} \]

15.4.4. Tagged Misidentified-Muon Yields

We apply the SLT and SVT \(b\)-tagging algorithms to the orthogonal fake-\(\mu\) data sample and normalize it as described above to obtain the tagged misidentified isolated-muon background yields. The results are given in the first and third rows of Table 30.

The numbers in the second row of Table 30 are the results of a cross check calculation. The matrix method is applied to the tagged preselected data instead of to the pretagged preselected data. The loose-\(\mu\) data sample in this case has had \(b\) tagging applied, and the muon tight-isolation is applied to this tagged sample to get a new tight-\(\mu\) sample. The results are consistent within errors with the main method. We expect the main method to give smaller errors than the cross check one, particularly after final selection cuts have reduced the tight-\(\mu\) data sample down to a handful of events.

Figure 40 show a histogram of the transverse mass of the reconstructed \(W\) boson in the pretagged preselected samples. The result of applying the matrix method in each bin is also shown. The fake-\(\mu\) distribution is shown by the brown error bars, the real-\(\mu\) distribution is shown by the green error bars, and the data are solid black circles. This plot shows that application of this method has produced a distributions of the fake-\(\mu\) background that has
a reasonable shape and is mainly at low-$M_T^{W}$ as expected. We do not use the shape of this distribution in our analysis, only the integrals of the brown (fake-$\mu$) and green (real-$\mu$) regions.

<table>
<thead>
<tr>
<th></th>
<th>SLT</th>
<th>SVT</th>
<th>JLIP</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Preselection</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fake-$\mu$ yield</td>
<td>4.9 ± 1.7</td>
<td>13.3 ± 4.7</td>
<td>14.0 ± 5.0</td>
</tr>
<tr>
<td>Cross check</td>
<td>5.5 ± 2.1</td>
<td>12.7 ± 4.8</td>
<td>14.5 ± 5.2</td>
</tr>
<tr>
<td><strong>Final Selection</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fake-$\mu$ yield</td>
<td>3.4 ± 1.2</td>
<td>7.0 ± 2.5</td>
<td>6.2 ± 2.2</td>
</tr>
</tbody>
</table>

TABLE 30: Event yields from the misidentified-muon backgrounds with statistical and systematic errors (first and third rows). The second row has been calculated using a different method as a cross check, as described in the text.

FIG. 40: Distribution of the transverse mass of the reconstructed $W$ boson, showing the results of applying the matrix method bin-by-bin for the pretagged preselected sample.
The background from $W+$-jets, $Z+$-jets with a lost lepton, $WW$, $WZ$, and $ZZ$ events is measured using data. We abbreviate the name of this background to “$W+$-jets.” There are four steps needed to measure the $W+$-jets background:

1. We determine the number of pretagged real-$l$ events ($l = e$ or $\mu$) in the pretagged preselected signal-data using the “matrix method.”

2. An untagged preselected sample is chosen that consists mainly of $W+$-jets events. This is known as the “untagged $W+$-jets sample.”

3. We normalize the untagged $W+$-jets sample to the number of pretagged real-$l$ events found in step 1.

4. Flavor-inclusive tag-rate functions are applied to the normalized untagged sample to obtain the tagged $W+$-jets background.

The following four subsections describe these steps.

### 15.5.2. Number of Real-$l$ Events in the Pretagged Preselected Data

Applying the matrix method, we obtain the following results for the numbers of real-electron and real-muon events in the pretagged preselected data samples:

$$
N_{\text{real}-e}^{\text{tight}} = 2,737 \pm 284 \text{ (SLT)}, \quad = 2,877 \pm 168 \text{ (SVT and JLIP)}
$$

$$
N_{\text{real}-\mu}^{\text{tight}} = 2,177 \pm 100 \text{ (SLT)}, \quad = 2,123 \pm 153 \text{ (SVT and JLIP)}
$$

### 15.5.3. Selecting the Untagged $W+$-Jets Samples

Starting from the EMQCD and MUQCD data, we apply all the preselection cuts. We then select only events where none of the jets is tagged by the relevant $b$-tagging algorithm for the analysis in question. These samples are orthogonal to the tagged preselected signal-data samples. We make the assumption that these untagged preselected samples are 100% $W+$-jets events (including $Z+$-jets and dibosons). That is, we assume the top content ($tb$, $tqb$, and $t\bar{t}$) is negligible. We test this assumption by measuring the percentage of top events in the untagged samples and find about 3% of the events are top quark ones, so the assumption is reasonable. The numbers of events in these samples are:

$$
N_{\text{notag}}^{\text{real}-e} = 3,194 \text{ events (SLT)}, \quad = 3,063 \text{ events (SVT)}, = 3,045 \text{ events (JLIP)}
$$

$$
N_{\text{notag}}^{\text{real}-\mu} = 2,372 \text{ events (SLT)}, \quad = 2,279 \text{ events (SVT)}, = 2,288 \text{ events (JLIP)}
$$
15.5.4. Normalizing the Untagged W+Jets Samples

The untagged W+jets samples are normalized to the number of real-lepton events in the pretagged preselected signal-data sample:

$$F_{\text{pretag}} = \frac{N_{\text{tight}-e}}{N_{\text{notag}}} = \frac{2.452}{2.838} = 0.864 \pm 0.086 \text{ (SLT)}$$

$$F_{\text{pretag}} = \frac{N_{\text{tight}-\mu}}{N_{\text{notag}}} = \frac{2.177}{2.372} = 0.918 \pm 0.042 \text{ (SLT)}$$

15.5.5. Tagged W+Jets Yields

We apply each of the three flavor-inclusive tag-rate functions to the untagged W+jets data samples and normalize them as described above to obtain the tagged W+jets background yields. Derivation and application of the tag-rate functions to determine the probability that at least one jet in an event is tagged is described in Sections 7.3.2, 7.4.3, and 7.5.3. The results are given Table 31.

<table>
<thead>
<tr>
<th></th>
<th>W+Jets Background Event Yields</th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>SLT</td>
<td>SVT</td>
<td>JLIP</td>
<td></td>
</tr>
<tr>
<td><strong>Electron Channel</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>W+jets yield</td>
<td>27.8 ± 6.5</td>
<td>65.8 ± 14.4</td>
<td>82.2 ± 18.0</td>
<td></td>
</tr>
<tr>
<td><strong>Muon Channel</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>W+jets yield</td>
<td>23.6 ± 4.9</td>
<td>51.2 ± 11.0</td>
<td>63.3 ± 13.7</td>
<td></td>
</tr>
<tr>
<td><strong>Electron Channel</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>W+jets yield</td>
<td>20.2 ± 4.7</td>
<td>41.9 ± 9.2</td>
<td>58.8 ± 12.9</td>
<td></td>
</tr>
<tr>
<td><strong>Muon Channel</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>W+jets yield</td>
<td>19.0 ± 3.9</td>
<td>41.4 ± 8.9</td>
<td>53.8 ± 11.6</td>
<td></td>
</tr>
</tbody>
</table>

TABLE 31: Event yields from the W+jets samples with the statistical and systematic errors.
15.6. Combined $W$+Jets and Misidentified-Lepton Background Yields

When determining the uncertainty on the sum of the background contributions from $W$+jets and misidentified-lepton multijet events, the correlation of uncertainties from the matrix method have to be taken into account.

This has the beneficial result that when the two backgrounds are combined, much of the large uncertainties cancel out because they are anticorrelated.

15.6.1. Combining Uncertainties for $W$+Jets and Misidentified-Lepton Yields

Let us define the backgrounds:

- $N_{\text{real}}^{l}$ is the tagged $W$+jets yield (which includes $Z$+jets with a lost lepton, and diboson events), i.e., events with a real lepton.
- $N_{\text{fake}}^{l}$ is the misidentified-lepton yield.
- $l$ refers to electrons or muons.

The sum of these two backgrounds for each channel is:

$$N_{\text{tag}}^{l} = N_{\text{tag}}^{\text{real}} + N_{\text{tag}}^{\text{fake}}$$

and the two parts are calculated thus:

$$N_{\text{tag}}^{\text{real}} = F_{\text{pretag}}^{\text{real}} \times \sum_{N_{\text{notag}}} P_{\text{tag}}$$

$$N_{\text{tag}}^{\text{fake}} = F_{\text{pretag}}^{\text{fake}} \times N_{\text{orthog-tag}}^{\text{fake}}$$

where

- $F_{\text{pretag}}^{\text{real}}$ is the normalization factor from the matrix method for the real-lepton $W$+jets sample (see Section 15.5):

$$F_{\text{pretag}}^{\text{real}} = \frac{N_{\text{tight-tag}}^{l}}{N_{\text{notag}}}$$

- $N_{\text{notag}}^{\text{real}}$ is the size of the untagged real-lepton $W$+jets sample.
- $P_{\text{tag}}$ is the probability to tag each untagged $W$+jets event, calculated using the flavor-inclusive tag-rate functions.
- $F_{\text{pretag}}^{\text{fake}}$ is the normalization factor from the matrix method for the fake-lepton sample (see Section 15.3):

$$F_{\text{pretag}}^{\text{fake}} = \frac{N_{\text{tight-tag}}^{l}}{N_{\text{orthog-pretag}}}$$

- $N_{\text{orthog-tag}}^{\text{fake}}$ is the size of the tagged orthogonal fake-lepton sample.

The uncertainty on the summed background, $\Delta N_{\text{tag}}^{l}$, is calculated according to Gaussian error propagation. The absolute error is given by:

$$\Delta N_{\text{tag}}^{l} = \sqrt{\left(\Delta N_{\text{tag}}^{\text{real}}\right)^2 + \left(\Delta N_{\text{tag}}^{\text{fake}}\right)^2}$$
The uncertainties on these two samples are anticorrelated because both depend on a scale factor from the matrix method normalization. This can be seen as follows.

The uncertainty on the number of $W$+jets events is given by:

$$\Delta N_{\text{real-}l}^{\text{tag}} = \sqrt{\left(F_{\text{real-}l}^{\text{pretag}}\right)^2 \times \left(\Delta N_{\text{notag}}^{\text{real-}l}\right)^2 + \left(\Delta F_{\text{pretag}}^{\text{real-}l}\right)^2 \times \left(N_{\text{notag}}^{\text{real-}l}\right)^2}$$

where the uncertainty on the tagging probability $P_{\text{tag}}$ is included into the uncertainty on the normalization factor $F_{\text{pretag}}^{\text{real-}l}$.

The uncertainty on the number of misidentified-lepton events is given by:

$$\Delta N_{\text{fake-}l}^{\text{tag}} = \sqrt{\left(F_{\text{fake-}l}^{\text{pretag}}\right)^2 \times \left(\Delta N_{\text{orthog-tag}}^{\text{fake-}l}\right)^2 + \left(\Delta F_{\text{pretag}}^{\text{fake-}l}\right)^2 \times \left(N_{\text{tag}}^{\text{fake-}l}\right)^2}$$

The uncertainty on the real-lepton normalization factor is given by:

$$\Delta F_{\text{pretag}}^{\text{real-}l} = F_{\text{pretag}}^{\text{real-}l} \sqrt{\left(\Delta N_{\text{notag}}^{\text{real-}l} / N_{\text{notag}}^{\text{real-}l}\right)^2 + \left(\Delta N_{\text{tag}}^{\text{real-}l} / N_{\text{tag}}^{\text{real-}l}\right)^2 + (\Delta P_{\text{tag}})^2}$$

and the uncertainty on the fake-lepton scale factor is given by:

$$\Delta F_{\text{pretag}}^{\text{fake-}l} = F_{\text{pretag}}^{\text{fake-}l} \sqrt{\left(\Delta N_{\text{orthog-tag}}^{\text{fake-}l} / N_{\text{orthog-tag}}^{\text{fake-}l}\right)^2 + (\Delta N_{\text{tag}}^{\text{fake-}l} / N_{\text{tag}}^{\text{fake-}l})^2}$$

where:

- $N_{\text{tight-}l}$ is the matrix method output for the real-lepton content in the tight-lepton sample
- $N_{\text{notag}}^{\text{real-}l}$ is the number of events in the untagged $W$+jets sample
- $\Delta P_{\text{tag}}$ is the uncertainty from the flavor-inclusive tag-rate functions
- $N_{\text{tight-}l}^{\text{real-}l}$ is the matrix method output for the fake-lepton content in the tight-lepton sample
- $N_{\text{orthog-tag}}^{\text{fake-}l}$ is the number of events in the pretagged orthogonal fake-lepton sample
- $\Delta N_{\text{tight-}l}^{\text{real-}l} / N_{\text{tight-}l}^{\text{real-}l}$ is the relative uncertainty on the real-lepton content in the tight sample, given by the Matrix Method
- $\Delta N_{\text{tight-}l}^{\text{fake-}l} / N_{\text{tight-}l}^{\text{fake-}l}$ is the relative uncertainty on the fake-lepton content in the tight sample, given by the Matrix Method

As these equations show, the number of real-lepton $W$+jets events is proportional to the matrix method output for the pretagged sample $N_{\text{tight-}l}^{\text{real-}l}$, and the number of misidentified-lepton events $N_{\text{tag}}^{\text{fake-}l}$ is proportional to the matrix method output for the pretagged sample $N_{\text{tight-}l}^{\text{fake-}l}$. The sum of these two is fixed to the number of events in the tight-lepton sample:

$$N_{\text{tight-}l}^{\text{real-}l} + N_{\text{tight-}l}^{\text{fake-}l} = N_{\text{tight-}l}^{l}$$

which means that their uncertainties are anticorrelated. Hence the uncertainties $\Delta N_{\text{tag}}^{\text{real-}l}$ and $\Delta N_{\text{tag}}^{\text{fake-}l}$ are also to a large extent anticorrelated. More details about the uncertainty calculation in the matrix method can be found in Ref. [58].

Because of this, the largest uncertainty in the combined $W$+jets and fake-lepton yield is due to the uncertainty of the flavor-inclusive tag-rate functions. That uncertainty only applies to the $W$+jets yield.
15.6.2. Combined $W + \text{Jets}$ and Misidentified-Lepton Yields

The results of adding up the two yields and their uncertainties are given Table 32. As expected from the propagation of uncertainties, the overall uncertainty is lower than the sum of the individual contributions.

<table>
<thead>
<tr>
<th>Background</th>
<th>SLT</th>
<th>SVT</th>
<th>JLIP</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Preselection</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Electron Channel</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$W + \text{jets} + \text{fake-}l$ yield</td>
<td>36.1 ± 5.8</td>
<td>72.4 ± 13.9</td>
<td>89.8 ± 17.4</td>
</tr>
<tr>
<td><strong>Muon Channel</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$W + \text{jets} + \text{fake-}l$ yield</td>
<td>28.4 ± 4.8</td>
<td>64.5 ± 11.0</td>
<td>77.3 ± 13.6</td>
</tr>
<tr>
<td><strong>Final Selection</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Electron Channel</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$W + \text{jets} + \text{fake-}l$ yield</td>
<td>25.7 ± 4.1</td>
<td>45.8 ± 8.8</td>
<td>62.2 ± 12.5</td>
</tr>
<tr>
<td><strong>Muon Channel</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$W + \text{jets} + \text{fake-}l$ yield</td>
<td>22.4 ± 3.9</td>
<td>48.4 ± 8.8</td>
<td>60.0 ± 11.4</td>
</tr>
</tbody>
</table>

**TABLE 32**: Event yields from the $W + \text{jets}$ and fake-lepton samples with the combined errors.
15.7. Signal Data Event Yields

15.7.1. Signal Data Yield Calculation

The event yield in the Run II data is obtained as follows:

\[ \text{Yield} = \gamma_{\text{sigdata}} = \frac{N_{\text{sigdata,cuts,tag}}}{1} \]

\[ \text{Yield statistical error} = \Delta \gamma_{\text{stat}} = \sqrt{\frac{N_{\text{sigdata,cuts,tag}}}{1}} \]

where \( N_{\text{sigdata,cuts,tag}} \) is the number of events remaining after the preselection cuts and \( b \) tagging. There is no systematic error on the signal data yield. We can use Gaussian statistics for the error as the yields after preselection cuts are quite high.

15.7.2. Signal Data Yields

Table 33 shows the event yields and errors, in the electron and muon channels of the Run II data, after the preselection cuts and \( b \) tagging.

<table>
<thead>
<tr>
<th>Signal Data Yields in Run II Data</th>
<th>( b ) tagging</th>
<th>Muon Channel</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electron Channel</td>
<td>Preselection</td>
<td></td>
</tr>
<tr>
<td>SLT</td>
<td>58(^{+8.7}_{-7.6})</td>
<td>97(^{+10.8}_{-9.8})</td>
</tr>
<tr>
<td>SVT</td>
<td>( 48^{+8.0}_{-6.9} )</td>
<td>( 92^{+10.6}_{-9.6} )</td>
</tr>
<tr>
<td>JLIP</td>
<td>( 91^{+10.5}_{-9.5} )</td>
<td></td>
</tr>
<tr>
<td>Muon Channel</td>
<td>Final Selection</td>
<td></td>
</tr>
<tr>
<td>SLT</td>
<td>54(^{+8.4}_{-7.3})</td>
<td>63(^{+9.9}_{-7.9})</td>
</tr>
<tr>
<td>SVT</td>
<td>( 75^{+9.7}_{-8.7} )</td>
<td>( 70^{+9.4}_{-8.4} )</td>
</tr>
<tr>
<td>JLIP</td>
<td>( 70^{+9.4}_{-8.4} )</td>
<td></td>
</tr>
</tbody>
</table>

TABLE 33: Event yield in the electron and muon channels after the preselection and final cuts and \( b \) tagging.
15.8. Combined Signal and Background Event Yields

15.8.1. The Combined Yields

Table 34 shows the numbers of events for each of the signals, combinations of signals, and backgrounds, after preselection and after final selection, both with $b$ tagging. We show the $W$+jets and multijet misidentified-lepton backgrounds combined as most of their uncertainties are 100% anticorrelated, and we use the backgrounds combined like this in the cross section limit calculations.

<table>
<thead>
<tr>
<th>Signal and Background Event Yields in Run II Data</th>
<th>Electron Channel (CC)</th>
<th>Muon Channel</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>SLT</td>
<td>SVT</td>
</tr>
<tr>
<td><strong>Preselection</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Signals</td>
<td></td>
<td></td>
</tr>
<tr>
<td>MC $tb$</td>
<td>0.67 ± 0.15</td>
<td>1.91 ± 0.44</td>
</tr>
<tr>
<td>MC $tq$</td>
<td>0.94 ± 0.21</td>
<td>3.21 ± 0.78</td>
</tr>
<tr>
<td>MC $tb$+$tq$</td>
<td>1.61 ± 0.31</td>
<td>5.12 ± 1.10</td>
</tr>
<tr>
<td><strong>Backgrounds</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>MC $\bar{t}\ell$--$l$+jets</td>
<td>7.05 ± 1.66</td>
<td>19.04 ± 4.54</td>
</tr>
<tr>
<td>MC $\bar{t}\ell$--$\ell\ell$</td>
<td>2.69 ± 0.61</td>
<td>5.27 ± 1.27</td>
</tr>
<tr>
<td>MC $Z\rightarrow\mu\mu$+jets</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td>$W$+jets + fake-$l$ data</td>
<td>36.13 ± 5.79</td>
<td>72.45 ± 13.89</td>
</tr>
<tr>
<td>Sum of bkgds for $tb$</td>
<td>46.8 ± 6.3</td>
<td>100.0 ± 15.2</td>
</tr>
<tr>
<td>Sum of bkgds for $tq$</td>
<td>46.5 ± 6.2</td>
<td>98.7 ± 15.1</td>
</tr>
<tr>
<td>Sum of bkgds for $tb$+$tq$</td>
<td>45.9 ± 6.2</td>
<td>96.8 ± 15.1</td>
</tr>
<tr>
<td>Signal data</td>
<td>$58^{+8.7}_{-7.6}$</td>
<td>$97^{+10.8}_{-9.8}$</td>
</tr>
<tr>
<td><strong>Final Selection</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Signals</td>
<td></td>
<td></td>
</tr>
<tr>
<td>MC $tb$</td>
<td>0.65 ± 0.14</td>
<td>1.79 ± 0.43</td>
</tr>
<tr>
<td>MC $tq$</td>
<td>0.91 ± 0.20</td>
<td>3.00 ± 0.73</td>
</tr>
<tr>
<td>MC $tb$+$tq$</td>
<td>1.57 ± 0.30</td>
<td>4.79 ± 1.05</td>
</tr>
<tr>
<td>Backgrounds</td>
<td></td>
<td></td>
</tr>
<tr>
<td>MC $\bar{t}\ell$--$l$+jets</td>
<td>7.05 ± 1.66</td>
<td>18.93 ± 4.51</td>
</tr>
<tr>
<td>MC $\bar{t}\ell$--$\ell\ell$</td>
<td>2.67 ± 0.60</td>
<td>5.18 ± 1.25</td>
</tr>
<tr>
<td>MC $Z\rightarrow\mu\mu$+jets</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td>$W$+jets + fake-$l$ data</td>
<td>25.70 ± 4.14</td>
<td>45.76 ± 8.85</td>
</tr>
<tr>
<td>Sum of bkgds for $tb$</td>
<td>36.3 ± 4.8</td>
<td>72.9 ± 10.8</td>
</tr>
<tr>
<td>Sum of bkgds for $tq$</td>
<td>36.1 ± 4.7</td>
<td>71.7 ± 10.7</td>
</tr>
<tr>
<td>Sum of bkgds for $tb$+$tq$</td>
<td>35.4 ± 4.7</td>
<td>69.9 ± 10.5</td>
</tr>
<tr>
<td>Signal data</td>
<td>$54^{+8.4}_{-7.3}$</td>
<td>$63^{+9.0}_{-7.9}$</td>
</tr>
</tbody>
</table>

TABLE 34: Summary of the yields of signal and background events in the electron and muon channels in the Run II data, with combined errors. The summed background for an individual single top production mode includes the other single top mode as part of that background.
15.9. Studies of the Event Yields

The figures in this section show distributions of various interesting variables for the five single top analysis channels. Each plot shows a summed histogram of all background contributions plus the expected single top signal, and the signal data. The individual contributions are (from the bottom up on each plot): misidentified-lepton multijet events in brown, $W$+jets (including $Z$+jets and dibosons) in green, $t\bar{t}\rightarrow l +$jets in red, $t\bar{t}\rightarrow ll$ in pink, $t$-channel ($tqb$) single top in light blue, and $s$-channel ($tb$) single top in dark blue. The data is shown by black solid circles and/or black error bars.

The figures on the following pages show for each analysis channel for a cross-check data sample, for the full dataset after preselection, and after final selection ($H_T > 150$ GeV): the jet multiplicity in exclusive multiplicity bins, the transverse mass of the reconstructed $W$ boson, and the $H_T$ of the event, defined as the scalar sum of the transverse energies of the lepton, neutrino, and two highest transverse-energy jets.
FIG. 41: Distributions of the number of good jets (top row), the transverse mass of the $W$ boson (middle row), and the scalar sum of the transverse energy of the electron, neutrino, and two highest-$E_T$ jets (bottom row), with the SLT tagger. The first column shows results after preselection, the second shows results after final selection (preselect + $H_T > 150$ GeV). Note, the statistics are too low to show useful plots for the mainly $W$+jets cross-check sample.
FIG. 42: Distributions of the number of good jets (top row), the transverse mass of the W boson (middle row), and the scalar sum of the transverse energy of the electron, neutrino, and two highest-\textit{E}_T jets (bottom row), with the SVT tagger. The left column shows results for a mainly W+jets cross-check sample (preselection + ≥2 jets + \textit{H}_T < 200 GeV). The central column shows results after preselection. The third column shows results after final selection (preselection + \textit{H}_T > 150 GeV).
FIG. 43: Distributions of the number of good jets (top row), the transverse mass of the $W$ boson (middle row), and the scalar sum of the transverse energy of the electron, neutrino, and two highest-$E_T$ jets (bottom row), with the JLIP tagger. The left column shows results for a mainly $W+\text{jets}$ cross-check sample (preselection $+ =2\text{jets} + H_T < 200$ GeV). The central column shows results after preselection. The third column shows results after final selection (preselection $+ H_T > 150$ GeV).
Distributions for the $\mu$+jets/SLT Analysis

FIG. 44: Distributions of the number of good jets (top row), the transverse mass of the $W$ boson (middle row), and the scalar sum of the transverse energy of the isolated muon, neutrino, and two highest-$E_T$ jets (bottom row), with the SLT tagger. The first column shows results after preselection, the second shows results after final selection (preselect + $H_T > 150$ GeV). The $Z$+jets background is shown in yellow. Note, the statistics are too low to show useful plots for the mainly $W$+jets cross-check sample.
Distributions for the $\mu$+jets/SVT Analysis

FIG. 45: Distributions of the number of good jets (top row), the transverse mass of the $W$ boson (middle row), and the scalar sum of the transverse energy of the isolated muon, neutrino, and two highest-$E_T$ jets (bottom row), with the SVT tagger. The left column shows results for a mainly $W$+jets cross-check sample (preselection + $\geq$2 jets + $H_T < 200$ GeV). The central column shows results after preselection. The third column shows results after final selection (preselection + $H_T > 150$ GeV).
FIG. 46: Distributions of the number of good jets (top row), the transverse mass of the $W$ boson (middle row), and the scalar sum of the transverse energy of the muon, neutrino, and two highest-$E_T$ jets (bottom row), with the JLIP tagger. The left column shows results for a mainly $W$+jets cross-check sample (preselection + $2$ jets + $H_T < 200 \text{ GeV}$). The central column shows results after preselection. The third column shows results after final selection (preselection + $H_T > 150 \text{ GeV}$).
16. CROSS SECTION LIMITS FROM THE COUNTING EXPERIMENTS

Upper bounds on the single top production cross-section are calculated using two different methods: the modified frequentist method (also sometime referred as the CLs method) and a purely Bayesian method.

While both methods yield 95% cross section limits, it is important to emphasize that the concept of a Confidence Level has slightly different statistical meaning in each method and the results are therefore not expected to be exactly identical.

16.1. Modified Frequentist Method

16.1.1. Method for Calculating the Limits

The general procedure to test the degree to which the observed data are compatible with the existence of both signal and background or background only can be summarized as follows. The first step consists of choosing observables in the experiment sensitive to both hypotheses. A test statistic (or estimator) is then constructed based on these observables in order to discriminate between the two hypotheses. Finally, in order to make a statement about the compatibility of the data with respect to the two different hypotheses, a criterion of acceptance or rejection of the signal must be defined.

In this note, the observable used to calculate an upper limit on the production cross section of single top events is the total number of events in each channel studied. The test statistic used to discriminate between the signal plus background ($H_1$) and the background only hypothesis ($H_0$) is the likelihood ratio defined as,

$$Q(x) = \frac{L(x; H_0)}{L(x; H_1)}$$

where $x$ corresponds to a given experimental result.

The method used in this note to calculate the cross section limits is the so-called Modified Frequentist approach (or also sometime referred to as the CLs method) [39].

For any monotonically increasing test statistics ($X$), the confidence in the background plus signal hypothesis ($CL_{s+b}$) is given by the probability that the estimator be less than or equal to the value observed in the experiment ($X_{obs}$),

$$CL_{s+b} = P_{s+b}(X \leq X_{obs}),$$

where

$$P_{s+b}(X \leq X_{obs}) = \int_{-\infty}^{X_{obs}} dP_{s+b}$$

The quantity $dP_{s+b}$ is the probability density function of the test statistic for experiments with signal and background events.

Similarly, the confidence in the background only hypothesis is in general given by

$$CL_b = P_b(X \leq X_{obs}),$$

where

$$P_b(X \leq X_{obs}) = \int_{-\infty}^{X_{obs}} dP_b$$
The quantity $\frac{dP}{dX}$ is the probability density function of the test statistic for background only experiments.

In the modified frequentist approach, the quantity $CL_s$ is defined as

$$CL_s = \frac{CL_{s+b}}{CL_b}.$$ 

This quantity, although not itself a confidence level but rather a ratio of confidences, is used to exclude the existence of signal events at a fixed confidence level $CL$ given that

$$CL \geq 1 - CL_s.$$ 

16.1.2. Treatment of Systematic Uncertainties

The estimated systematic uncertainties on the background estimates and signal acceptances are described in Sections 12 and 15.

Systematics uncertainties are treated as either fully correlated or uncorrelated. Each uncertainty that appears in the tables in Section 12.3 is treated as fully correlated between all channels. Uncertainties that are treated as uncorrelated are given different names in those tables. Correlations between different analysis channels and background sources are fully taken into account.

Uncertainties are taken into account in the limit calculations by performing a large number of Monte Carlo experiments. For each experiment, a new set of “smeared” signal and background rates are obtained and from these distributions, the number of signal and background event for this particular Monte Carlo experiment are generated.

16.1.3. Expected Cross Section Limits — Modified Frequentist

Based on the background estimates and signal acceptances, expected upper limits on the production cross section of single top events are calculated. The expected upper bounds with and without taking into account systematics uncertainties are summarized in Tables 35 and 36 after the preselection and in Tables 37 and 38 after the final cuts are applied.

16.1.4. Measured Cross Section Limits — Modified Frequentist

The 95% Confidence Level upper limits on the production cross section of single top events with and without taking into account the systematics uncertainties on the background estimates and signal acceptance are summarized in Tables 40 and 39 after the preselection and in Tables 42 and 41 after the final cut is applied.
### 95% CL Expected Upper Limits on the Single Top Production Cross Sections

After Preselection, **Without Systematics**, Modified Frequentist

<table>
<thead>
<tr>
<th>Channel</th>
<th>Electron</th>
<th>Muon</th>
<th>$e + \mu$</th>
<th>$e + \mu$ with SLT</th>
</tr>
</thead>
<tbody>
<tr>
<td>s-channel</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>SLT</td>
<td>19.4</td>
<td>21.7</td>
<td>14.2</td>
<td></td>
</tr>
<tr>
<td>SVT</td>
<td>9.9</td>
<td>12.5</td>
<td>7.5</td>
<td>6.5</td>
</tr>
<tr>
<td>JLIP</td>
<td>10.7</td>
<td>13.7</td>
<td>8.4</td>
<td>6.9</td>
</tr>
<tr>
<td>t-channel</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>SLT</td>
<td>32.0</td>
<td>34.3</td>
<td>22.7</td>
<td></td>
</tr>
<tr>
<td>SVT</td>
<td>13.4</td>
<td>17.8</td>
<td>10.3</td>
<td>9.1</td>
</tr>
<tr>
<td>JLIP</td>
<td>14.3</td>
<td>18.2</td>
<td>11.1</td>
<td>9.5</td>
</tr>
<tr>
<td>s- and t-channel</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>SLT</td>
<td>25.7</td>
<td>29.2</td>
<td>18.8</td>
<td></td>
</tr>
<tr>
<td>SVT</td>
<td>12.0</td>
<td>15.2</td>
<td>9.4</td>
<td>8.3</td>
</tr>
<tr>
<td>JLIP</td>
<td>12.9</td>
<td>16.2</td>
<td>10.0</td>
<td>8.5</td>
</tr>
</tbody>
</table>

**TABLE 35**: The 95% confidence level expected upper limits on the production cross section (in pb) of single top events without taking into account systematic uncertainties, after the preselection cuts are applied, using the Modified Frequentist method.

### 95% CL Expected Upper Limits on the Single Top Production Cross Sections

After Preselection, **With Systematics**, Modified Frequentist

<table>
<thead>
<tr>
<th>Channel</th>
<th>Electron</th>
<th>Muon</th>
<th>$e + \mu$</th>
<th>$e + \mu$ with SLT</th>
</tr>
</thead>
<tbody>
<tr>
<td>s-channel</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>SLT</td>
<td>27.8</td>
<td>32.8</td>
<td>23.4</td>
<td></td>
</tr>
<tr>
<td>SVT</td>
<td>19.0</td>
<td>22.9</td>
<td>18.4</td>
<td>18.0</td>
</tr>
<tr>
<td>JLIP</td>
<td>22.2</td>
<td>26.2</td>
<td>21.4</td>
<td>19.8</td>
</tr>
<tr>
<td>t-channel</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>SLT</td>
<td>44.7</td>
<td>53.8</td>
<td>38.2</td>
<td></td>
</tr>
<tr>
<td>SVT</td>
<td>27.1</td>
<td>33.6</td>
<td>25.6</td>
<td>25.8</td>
</tr>
<tr>
<td>JLIP</td>
<td>30.3</td>
<td>36.8</td>
<td>29.0</td>
<td>28.2</td>
</tr>
<tr>
<td>s- and t-channel</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>SLT</td>
<td>37.0</td>
<td>45.3</td>
<td>31.5</td>
<td></td>
</tr>
<tr>
<td>SVT</td>
<td>23.3</td>
<td>28.8</td>
<td>22.4</td>
<td>22.6</td>
</tr>
<tr>
<td>JLIP</td>
<td>26.5</td>
<td>31.1</td>
<td>25.8</td>
<td>24.7</td>
</tr>
</tbody>
</table>

**TABLE 36**: The 95% confidence level expected upper limits on the production cross section (in pb) of single top events taking into account systematic uncertainties, after the preselection cuts are applied, using the Modified Frequentist method.
### 95% CL Expected Upper Limits on the Single Top Production Cross Sections After Final Selection, **Without Systematics**, Modified Frequentist

<table>
<thead>
<tr>
<th>Channel</th>
<th>$e$</th>
<th>$\mu$</th>
<th>$e + \mu$</th>
<th>with SLT</th>
</tr>
</thead>
<tbody>
<tr>
<td>s-channel</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>SLT</td>
<td>17.8</td>
<td>20.5</td>
<td>12.9</td>
<td></td>
</tr>
<tr>
<td>SVT</td>
<td>9.0</td>
<td>11.6</td>
<td>6.9</td>
<td>6.0</td>
</tr>
<tr>
<td>JLIP</td>
<td>10.1</td>
<td>13.2</td>
<td>7.6</td>
<td>6.6</td>
</tr>
<tr>
<td>t-channel</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>SLT</td>
<td>29.5</td>
<td>33.9</td>
<td>21.3</td>
<td></td>
</tr>
<tr>
<td>SVT</td>
<td>12.2</td>
<td>16.5</td>
<td>9.5</td>
<td>8.7</td>
</tr>
<tr>
<td>JLIP</td>
<td>13.6</td>
<td>17.4</td>
<td>10.4</td>
<td>9.2</td>
</tr>
<tr>
<td>s- and t-channel</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>SLT</td>
<td>23.6</td>
<td>27.7</td>
<td>17.8</td>
<td></td>
</tr>
<tr>
<td>SVT</td>
<td>10.4</td>
<td>14.6</td>
<td>8.5</td>
<td>7.5</td>
</tr>
<tr>
<td>JLIP</td>
<td>11.7</td>
<td>15.8</td>
<td>9.4</td>
<td>8.0</td>
</tr>
</tbody>
</table>

**TABLE 37**: The 95% confidence level expected upper limits on the production cross section (in pb) of single top events without taking into account systematic uncertainties, after the final selection cut is applied, using the Modified Frequentist method.

### 95% CL Expected Upper Limits on the Single Top Production Cross Sections After Final Selection, **With Systematics**, Modified Frequentist

<table>
<thead>
<tr>
<th>Channel</th>
<th>$e$</th>
<th>$\mu$</th>
<th>$e + \mu$</th>
<th>with SLT</th>
</tr>
</thead>
<tbody>
<tr>
<td>s-channel</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>SLT</td>
<td>24.8</td>
<td>30.6</td>
<td>21.0</td>
<td></td>
</tr>
<tr>
<td>SVT</td>
<td>16.2</td>
<td>21.0</td>
<td>15.9</td>
<td>15.7</td>
</tr>
<tr>
<td>JLIP</td>
<td>18.7</td>
<td>24.5</td>
<td>18.3</td>
<td>17.2</td>
</tr>
<tr>
<td>t-channel</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>SLT</td>
<td>40.5</td>
<td>52.4</td>
<td>35.7</td>
<td></td>
</tr>
<tr>
<td>SVT</td>
<td>22.2</td>
<td>30.6</td>
<td>22.0</td>
<td>22.1</td>
</tr>
<tr>
<td>JLIP</td>
<td>25.2</td>
<td>32.8</td>
<td>24.9</td>
<td>24.7</td>
</tr>
<tr>
<td>s- and t-channel</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>SLT</td>
<td>32.9</td>
<td>42.1</td>
<td>28.1</td>
<td></td>
</tr>
<tr>
<td>SVT</td>
<td>18.7</td>
<td>26.6</td>
<td>19.1</td>
<td>19.3</td>
</tr>
<tr>
<td>JLIP</td>
<td>22.7</td>
<td>29.7</td>
<td>22.4</td>
<td>21.5</td>
</tr>
</tbody>
</table>

**TABLE 38**: The 95% confidence level expected upper limits on the production cross section (in pb) of single top events taking into account systematic uncertainties, after the final selection cuts are applied, using the Modified Frequentist method.
### 95% CL Measured Upper Limits on the Single Top Production Cross Sections

**After Preselection, Without Systematics, Modified Frequentist**

<table>
<thead>
<tr>
<th>Channel</th>
<th>Electron</th>
<th>Muon</th>
<th>$e + \mu$</th>
<th>$e + \mu$ with SLT</th>
</tr>
</thead>
<tbody>
<tr>
<td>s-channel</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>SLT</td>
<td>34.0</td>
<td>21.7</td>
<td>20.7</td>
<td></td>
</tr>
<tr>
<td>SVT</td>
<td>9.4</td>
<td>15.8</td>
<td>8.0</td>
<td>8.5</td>
</tr>
<tr>
<td>JLIP</td>
<td>10.1</td>
<td>10.8</td>
<td>6.9</td>
<td>6.9</td>
</tr>
<tr>
<td>t-channel</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>SLT</td>
<td>54.5</td>
<td>36.6</td>
<td>34.4</td>
<td></td>
</tr>
<tr>
<td>SVT</td>
<td>12.9</td>
<td>22.9</td>
<td>11.5</td>
<td>12.2</td>
</tr>
<tr>
<td>JLIP</td>
<td>13.9</td>
<td>14.8</td>
<td>9.4</td>
<td>9.9</td>
</tr>
<tr>
<td>s- and t-channel</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>SLT</td>
<td>47.4</td>
<td>30.9</td>
<td>30.0</td>
<td></td>
</tr>
<tr>
<td>SVT</td>
<td>12.3</td>
<td>21.0</td>
<td>11.4</td>
<td>11.8</td>
</tr>
<tr>
<td>JLIP</td>
<td>13.2</td>
<td>13.7</td>
<td>9.1</td>
<td>9.6</td>
</tr>
</tbody>
</table>

**TABLE 39:** The 95% confidence level measured upper limits on the production cross section (in pb) of single top events, without taking into account systematic uncertainties, after preselection cuts, using the Modified Frequentist method.

### 95% CL Measured Upper Limits on the Single Top Production Cross Sections

**After Preselection, With Systematics, Modified Frequentist**

<table>
<thead>
<tr>
<th>Channel</th>
<th>Electron</th>
<th>Muon</th>
<th>$e + \mu$</th>
<th>$e + \mu$ with SLT</th>
</tr>
</thead>
<tbody>
<tr>
<td>s-channel</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>SLT</td>
<td>43.1</td>
<td>32.8</td>
<td>30.8</td>
<td></td>
</tr>
<tr>
<td>SVT</td>
<td>18.3</td>
<td>27.1</td>
<td>18.9</td>
<td>20.2</td>
</tr>
<tr>
<td>JLIP</td>
<td>21.7</td>
<td>22.5</td>
<td>19.7</td>
<td>19.9</td>
</tr>
<tr>
<td>t-channel</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>SLT</td>
<td>69.7</td>
<td>57.4</td>
<td>51.1</td>
<td></td>
</tr>
<tr>
<td>SVT</td>
<td>26.7</td>
<td>39.2</td>
<td>26.6</td>
<td>28.7</td>
</tr>
<tr>
<td>JLIP</td>
<td>29.8</td>
<td>32.2</td>
<td>26.9</td>
<td>28.5</td>
</tr>
<tr>
<td>s- and t-channel</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>SLT</td>
<td>59.6</td>
<td>47.6</td>
<td>43.5</td>
<td></td>
</tr>
<tr>
<td>SVT</td>
<td>23.8</td>
<td>35.2</td>
<td>24.8</td>
<td>26.8</td>
</tr>
<tr>
<td>JLIP</td>
<td>27.0</td>
<td>29.2</td>
<td>24.9</td>
<td>26.2</td>
</tr>
</tbody>
</table>

**TABLE 40:** The 95% confidence level measured upper limits on the production cross section (in pb) of single top events, taking into account systematic uncertainties, after preselection, using the Modified Frequentist method.
### 95% CL Measured Upper Limits on the Single Top Production Cross Sections After Final Selection, Without Systematics, Modified Frequentist

<table>
<thead>
<tr>
<th>Channel</th>
<th>Electron</th>
<th>Muon</th>
<th>$e + \mu$ with SLT</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>s-channel</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>SLT</td>
<td>42.4</td>
<td>22.6</td>
<td>26.7</td>
</tr>
<tr>
<td>SVT</td>
<td>6.3</td>
<td>15.4</td>
<td>5.9</td>
</tr>
<tr>
<td>JLIP</td>
<td>7.0</td>
<td>9.1</td>
<td>4.3</td>
</tr>
<tr>
<td><strong>t-channel</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>SLT</td>
<td>68.1</td>
<td>38.1</td>
<td>43.9</td>
</tr>
<tr>
<td>SVT</td>
<td>8.9</td>
<td>22.0</td>
<td>8.4</td>
</tr>
<tr>
<td>JLIP</td>
<td>9.6</td>
<td>12.5</td>
<td>6.1</td>
</tr>
<tr>
<td><strong>s- and t-channel</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>SLT</td>
<td>59.4</td>
<td>32.0</td>
<td>38.1</td>
</tr>
<tr>
<td>SVT</td>
<td>8.2</td>
<td>20.7</td>
<td>8.2</td>
</tr>
<tr>
<td>JLIP</td>
<td>8.6</td>
<td>11.8</td>
<td>5.9</td>
</tr>
</tbody>
</table>

TABLE 41: The 95% confidence level measured upper limits on the production cross section (in pb) of single top events, without taking into account systematic uncertainties, after the final cuts are applied, using the Modified Frequentist method.

### 95% CL Measured Upper Limits on the Single Top Production Cross Sections After Final Selection, With Systematics, Modified Frequentist

<table>
<thead>
<tr>
<th>Channel</th>
<th>Electron</th>
<th>Muon</th>
<th>$e + \mu$ with SLT</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>s-channel</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>SLT</td>
<td>51.3</td>
<td>33.1</td>
<td>35.6</td>
</tr>
<tr>
<td>SVT</td>
<td>13.1</td>
<td>24.8</td>
<td>14.7</td>
</tr>
<tr>
<td>JLIP</td>
<td>15.2</td>
<td>18.9</td>
<td>14.2</td>
</tr>
<tr>
<td><strong>t-channel</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>SLT</td>
<td>83.8</td>
<td>56.3</td>
<td>59.3</td>
</tr>
<tr>
<td>SVT</td>
<td>18.1</td>
<td>37.1</td>
<td>20.3</td>
</tr>
<tr>
<td>JLIP</td>
<td>20.5</td>
<td>27.1</td>
<td>19.8</td>
</tr>
<tr>
<td><strong>s- and t-channel</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>SLT</td>
<td>70.7</td>
<td>47.2</td>
<td>50.6</td>
</tr>
<tr>
<td>SVT</td>
<td>16.6</td>
<td>32.8</td>
<td>18.7</td>
</tr>
<tr>
<td>JLIP</td>
<td>19.2</td>
<td>24.4</td>
<td>18.0</td>
</tr>
</tbody>
</table>

TABLE 42: The 95% confidence level measured upper limits on the production cross section (in pb) of single top events, taking into account systematic uncertainties, after the final cut is applied, using the Modified Frequentist method.
16.2. Bayesian Method

We also use a Bayesian method to obtain an upper limit on the single top cross section. This is implemented as follows. We start with the relation:

\[ y_{\text{pred}} = a_{\text{sigMC}} l \sigma + \sum_{s=1}^{N} y_s = a' \sigma + \sum_{s=1}^{N} y_s \]

- \( y_{\text{pred}} \) is the predicted number of events seen in the signal data from both single top signal and backgrounds, given the single top cross section \( \sigma \).
- \( a_{\text{sigMC}} \) is the acceptance of the single top signal
- \( l \) is the integrated luminosity
- \( \sigma \) is the cross section of the single top signal mode
- \( y_s \) is the yield of background events, \( s \) is the index over background sources (\( s = 1 \) to \( N \))
- \( a' = a_{\text{sigMC}} \times l \), is the effective luminosity

The Poisson probability for observing \( Y_{\text{obs}} \) events is:

\[
P(Y_{\text{obs}}|y_{\text{pred}}) = P \left( Y_{\text{obs}}|\sigma, a', \sum_{s=1}^{N} y_s \right) = \frac{\exp \left( -y_{\text{pred}} \right) \ (y_{\text{pred}})^{Y_{\text{obs}}} \ Y_{\text{obs}}!}{Y_{\text{obs}}!}
\]

- \( Y_{\text{obs}} \) is the actual number of events observed in the data

We represent our prior knowledge of the parameters by the product of a flat prior for the cross section and a multivariate Gaussian for the effective luminosity and backgrounds. The measured values of the effective luminosity and backgrounds are used to build the mean and their errors are used to construct the error matrix for the multi-variate Gaussian. We take into account all correlations between the errors. The prior probability is thus:

\[
P(y_{\text{pred}}) = \text{Prior} \left( \sigma, a', \sum_{s=1}^{N} y_s \right) = \text{Prior} (\sigma) \times \text{Prior} \left( a', \sum_{s=1}^{N} y_s \right)
\]

\[
\text{Prior} (\sigma) = P(\sigma) = \text{constant}, \ 1/\sigma_{\text{max}}, 0 < \sigma < \sigma_{\text{max}}
\]

0, otherwise

where \( \sigma_{\text{max}} \) is chosen sufficiently large such that the posterior probability for \( \sigma > \sigma_{\text{max}} \) is negligible.

\[
\text{Prior} \left( a', \sum_{s=1}^{N} y_s \right) = P \left( a', \sum_{s=1}^{N} y_s \right) = \text{Gaussian}(c, C, \Sigma_C),
\]

\[
c = \begin{pmatrix} a' \\ y_1 \\ y_2 \\ \vdots \\ y_N \end{pmatrix}, \quad C = \begin{pmatrix} A' = A_{\text{sigMC}} L \\ \vdots \\ \vdots \\ \vdots \\ Y_N \end{pmatrix}
\]
\( c \) is termed the “parameter” matrix which is a column vector of dimension \((N + 1)\)

- \( C \) is the corresponding column vector of measured values (determined using MC or data) and is the mean of the multi-variate Gaussian. It has dimension \( N+1 \), where \( N \) is the number of background sources.

- \( \Sigma_C \) is the error matrix for the multi-variate Gaussian. It is symmetrical and has dimension \( N+1 \). It takes into account all correlations between the acceptance and backgrounds.

Bayes’ theorem gives the posterior probability:

\[
\text{Post} (y_{\text{pred}}|Y_{\text{obs}}) = \frac{P (Y_{\text{obs}}|y_{\text{pred}}) P (y_{\text{pred}})}{\int y_{\text{pred}} P (Y_{\text{obs}}|y_{\text{pred}}) P (y_{\text{pred}}) \, dy_{\text{pred}}}
\]

which we integrate over the nuisance parameters \( a', y_1, y_2, \ldots, y_N \) (“marginalize”) to obtain:

\[
\text{Post} (\sigma|Y_{\text{obs}}) = \int a' \int y_1 \int y_2 \cdots \int y_N \frac{P (Y_{\text{obs}}|\sigma, a', \sum_{s=1}^{N} y_s) P (\sigma) P (a', \sum_{s=1}^{N} y_s)}{\int \int \cdots \int}
\]

The multidimensional integral over the acceptance and backgrounds is done by importance-sampled Monte Carlo integration with 5,000 samples for each calculation.

An upper limit \((\sigma_{95})\) on the cross section \( \sigma \) is obtained by solving:

\[
\int_{0}^{\sigma_{95}} \text{Post} (\sigma|Y_{\text{obs}}) = 0.95
\]

### 16.3. Matrices for the Error Correlations

We can calculate error matrices and cross section limits for a number of combinations of measurements. There are three production modes of single top to be considered:

- s-channel \( tb \)
- t-channel \( tqb \)
- combined \( tb+tqb \)

There are two decay modes:

- electron channel
- muon channel

and three search modes based on which tagging algorithm is used:

- SLT
- SVT
- JLIP
The simplest calculation is for one production mode with one decay channel and one search mode, of which there are 18 combinations. The error matrices in this case have dimension \((N+1)\) where \(N\) is the number of background sources per production mode per decay channel per search mode. One can then combine search modes, or decay channels. The error matrices in that case will have dimension \(\sum_{i=1}^{M} N_i + M\), where \(M\) is the total number of decay channels and search modes in the combination, and \(N_i\) is the number of background sources in each channel or mode.

The errors on the acceptance and backgrounds are divided into several components such that all correlations can be taken into account. We show here how the error matrix could be calculated with reference to the \(s\)-channel signal in the electron decay mode with the SVT tagger.

Background from \((W + \text{jets}) + \text{QCD} = Y_1 \pm dY_1\)

Background from \(t\bar{t} \rightarrow l + \text{jets} = Y_2 \pm dY_2\)

Background from \(t\bar{t} \rightarrow ll = Y_3 \pm dY_3\)

Background from \(tq\bar{b} = Y_4 \pm dY_4\)

Acceptance \times \text{Luminosity} = A' \pm dA'

\[
Y_1 = 45.76 \\
Y_2 = 18.93 \\
Y_3 = 5.176 \\
Y_4 = 2.995
\]

\[
A' = A^{tb} \times \mathcal{L} = 0.01209 \times 168.68 = 2.039
\]

The parameter matrix, \(C\), for this example is:

\[
C = \begin{pmatrix}
    p_1 \\
    p_2 \\
    p_3 \\
    p_4 \\
    p_5
\end{pmatrix} = \begin{pmatrix}
    45.76 \\
    18.93 \\
    5.176 \\
    2.995 \\
    2.039
\end{pmatrix},
\]

The error matrix in this case is:

\[
\Sigma_C = \begin{pmatrix}
    c_{11} & c_{12} & c_{13} & c_{14} & c_{15} \\
    c_{21} & c_{22} & c_{23} & c_{24} & c_{25} \\
    c_{31} & c_{32} & c_{33} & c_{34} & c_{35} \\
    c_{41} & c_{42} & c_{43} & c_{44} & c_{45} \\
    c_{51} & c_{52} & c_{53} & c_{54} & c_{55}
\end{pmatrix}
\]

where \(c_{ij} = p_i p_j \sum_{k=1}^{m} f_{ik} f_{jk}\), where \(f_{i(j)k}\) is the fractional error from the \(k^{th}\) component of error for the \(i^{th}\) (\(j^{th}\)) source. The components for acceptance and MC backgrounds are listed in Section 12.3 while the components for data background sources are given in table 26.
16.3.1. Expected Cross Section Limits — Bayesian

Based on the above procedure, expected upper limits on the production cross section of single top events are calculated. The expected upper bounds with and without taking into account systematics uncertainties are summarized in Tables 43 and 44 after the preselection and in Tables 45 and 46 after the final cuts are applied.

16.3.2. Measured Cross Section Limits — Bayesian

The 95% Confidence Level upper limits on the production cross section of single top events with and without taking into account the systematics uncertainties on the background estimates and signal acceptance are summarized in Tables 48 and 47 after the preselection and in Tables 50 and 49 after the final cut is applied. The plots for the posterior probability density as a function of the signal cross section are shown in Figs. 47–51 for various combinations of decay channels and search modes after the final cut. The effects of systematics uncertainties are included.
<table>
<thead>
<tr>
<th>Channel</th>
<th>Electron</th>
<th>Muon</th>
<th>$e + \mu$ with SLT</th>
</tr>
</thead>
<tbody>
<tr>
<td>s-channel</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>SLT</td>
<td>20.0</td>
<td>21.8</td>
<td>14.2</td>
</tr>
<tr>
<td>SVT</td>
<td>9.9</td>
<td>12.4</td>
<td>7.5</td>
</tr>
<tr>
<td>JLIP</td>
<td>10.5</td>
<td>13.3</td>
<td>8.1</td>
</tr>
<tr>
<td>t-channel</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>SLT</td>
<td>32.0</td>
<td>35.9</td>
<td>23.0</td>
</tr>
<tr>
<td>SVT</td>
<td>13.1</td>
<td>17.5</td>
<td>10.2</td>
</tr>
<tr>
<td>JLIP</td>
<td>14.0</td>
<td>17.7</td>
<td>10.7</td>
</tr>
<tr>
<td>s- and t-channel</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>SLT</td>
<td>26.8</td>
<td>29.8</td>
<td>19.2</td>
</tr>
<tr>
<td>SVT</td>
<td>11.8</td>
<td>15.4</td>
<td>9.1</td>
</tr>
<tr>
<td>JLIP</td>
<td>12.6</td>
<td>15.9</td>
<td>9.6</td>
</tr>
</tbody>
</table>

TABLE 43: The 95% confidence level expected upper limits on the production cross section (in pb) of single top events, without taking into account systematic uncertainties, after the preselection cuts are applied, using the Bayesian method.

<table>
<thead>
<tr>
<th>Channel</th>
<th>Electron</th>
<th>Muon</th>
<th>$e + \mu$ with SLT</th>
</tr>
</thead>
<tbody>
<tr>
<td>s-channel</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>SLT</td>
<td>29.5</td>
<td>35.5</td>
<td>24.7</td>
</tr>
<tr>
<td>SVT</td>
<td>20.9</td>
<td>25.5</td>
<td>20.2</td>
</tr>
<tr>
<td>JLIP</td>
<td>23.3</td>
<td>28.7</td>
<td>22.8</td>
</tr>
<tr>
<td>t-channel</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>SLT</td>
<td>47.1</td>
<td>59.0</td>
<td>40.4</td>
</tr>
<tr>
<td>SVT</td>
<td>28.4</td>
<td>36.7</td>
<td>27.9</td>
</tr>
<tr>
<td>JLIP</td>
<td>31.9</td>
<td>39.4</td>
<td>31.3</td>
</tr>
<tr>
<td>s- and t-channel</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>SLT</td>
<td>39.3</td>
<td>48.1</td>
<td>33.5</td>
</tr>
<tr>
<td>SVT</td>
<td>24.8</td>
<td>31.1</td>
<td>24.2</td>
</tr>
<tr>
<td>JLIP</td>
<td>28.0</td>
<td>34.4</td>
<td>27.3</td>
</tr>
</tbody>
</table>

TABLE 44: The 95% confidence level expected upper limits on the production cross section (in pb) of single top events, taking into account systematic uncertainties, after the preselection cuts are applied, using the Bayesian method.
95% CL Expected Upper Limits
on the Single Top Production Cross Sections
After Final Selection, Without Systematics, Bayesian

<table>
<thead>
<tr>
<th>Channel</th>
<th>Electron</th>
<th>Muon</th>
<th>$e + \mu$ with SLT</th>
</tr>
</thead>
<tbody>
<tr>
<td>s-channel</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>SLT</td>
<td>18.4</td>
<td>20.9</td>
<td>13.3</td>
</tr>
<tr>
<td>SVT</td>
<td>9.1</td>
<td>11.9</td>
<td>7.0</td>
</tr>
<tr>
<td>JLIP</td>
<td>9.9</td>
<td>12.8</td>
<td>7.6</td>
</tr>
<tr>
<td>t-channel</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>SLT</td>
<td>29.4</td>
<td>34.4</td>
<td>21.5</td>
</tr>
<tr>
<td>SVT</td>
<td>12.1</td>
<td>16.9</td>
<td>9.6</td>
</tr>
<tr>
<td>JLIP</td>
<td>13.2</td>
<td>17.2</td>
<td>10.2</td>
</tr>
<tr>
<td>s- and t-channel</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>SLT</td>
<td>24.6</td>
<td>28.5</td>
<td>17.9</td>
</tr>
<tr>
<td>SVT</td>
<td>10.8</td>
<td>14.8</td>
<td>8.5</td>
</tr>
<tr>
<td>JLIP</td>
<td>11.8</td>
<td>15.4</td>
<td>9.1</td>
</tr>
</tbody>
</table>

TABLE 45: The 95% confidence level expected upper limits on the production cross section (in pb) of single top events, without taking into account systematic uncertainties, after the final selection cuts are applied, using the Bayesian method.

95% CL Expected Upper Limits
on the Single Top Production Cross Sections
After Final Selection, With Systematics, Bayesian

<table>
<thead>
<tr>
<th>Channel</th>
<th>Electron</th>
<th>Muon</th>
<th>$e + \mu$ with SLT</th>
</tr>
</thead>
<tbody>
<tr>
<td>s-channel</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>SLT</td>
<td>26.0</td>
<td>33.1</td>
<td>22.4</td>
</tr>
<tr>
<td>SVT</td>
<td>17.8</td>
<td>23.6</td>
<td>17.4</td>
</tr>
<tr>
<td>JLIP</td>
<td>19.8</td>
<td>26.3</td>
<td>19.5</td>
</tr>
<tr>
<td>t-channel</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>SLT</td>
<td>41.6</td>
<td>55.7</td>
<td>36.6</td>
</tr>
<tr>
<td>SVT</td>
<td>24.0</td>
<td>35.2</td>
<td>23.8</td>
</tr>
<tr>
<td>JLIP</td>
<td>27.2</td>
<td>36.6</td>
<td>26.8</td>
</tr>
<tr>
<td>s- and t-channel</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>SLT</td>
<td>34.6</td>
<td>44.9</td>
<td>30.0</td>
</tr>
<tr>
<td>SVT</td>
<td>20.7</td>
<td>29.2</td>
<td>20.4</td>
</tr>
<tr>
<td>JLIP</td>
<td>23.7</td>
<td>31.6</td>
<td>23.2</td>
</tr>
</tbody>
</table>

TABLE 46: The 95% confidence level expected upper limits on the production cross section (in pb) of single top events, taking into account systematic uncertainties, after the final selection cuts are applied, using the Bayesian method.
### 95% CL Measured Upper Limits on the Single Top Production Cross Sections

**After Preselection, ** **Without Systematics, Bayesian**

<table>
<thead>
<tr>
<th>Channel</th>
<th>Electron</th>
<th>Muon</th>
<th>$e + \mu$ with SLT</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>s-channel</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>SLT</td>
<td>33.6</td>
<td>21.8</td>
<td>21.0</td>
</tr>
<tr>
<td>SVT</td>
<td>8.9</td>
<td>15.5</td>
<td>8.0</td>
</tr>
<tr>
<td>JLIP</td>
<td>9.7</td>
<td>10.1</td>
<td>6.4</td>
</tr>
<tr>
<td><strong>t-channel</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>SLT</td>
<td>54.4</td>
<td>36.2</td>
<td>34.8</td>
</tr>
<tr>
<td>SVT</td>
<td>12.4</td>
<td>22.5</td>
<td>11.4</td>
</tr>
<tr>
<td>JLIP</td>
<td>13.3</td>
<td>13.9</td>
<td>8.9</td>
</tr>
<tr>
<td><strong>s- and t-channel</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>SLT</td>
<td>47.0</td>
<td>30.9</td>
<td>30.2</td>
</tr>
<tr>
<td>SVT</td>
<td>11.9</td>
<td>20.9</td>
<td>11.1</td>
</tr>
<tr>
<td>JLIP</td>
<td>12.8</td>
<td>13.1</td>
<td>8.6</td>
</tr>
</tbody>
</table>

**TABLE 47:** The 95% confidence level measured upper limits on the production cross section (in pb) of single top events, without taking into account systematic uncertainties, after preselection cuts, using the Bayesian method.

### 95% CL Measured Upper Limits on the Single Top Production Cross Sections

**After Preselection, ** **With Systematics, Bayesian**

<table>
<thead>
<tr>
<th>Channel</th>
<th>Electron</th>
<th>Muon</th>
<th>$e + \mu$ with SLT</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>s-channel</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>SLT</td>
<td>44.6</td>
<td>35.3</td>
<td>33.9</td>
</tr>
<tr>
<td>SVT</td>
<td>19.8</td>
<td>29.1</td>
<td>19.7</td>
</tr>
<tr>
<td>JLIP</td>
<td>22.5</td>
<td>24.7</td>
<td>20.9</td>
</tr>
<tr>
<td><strong>t-channel</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>SLT</td>
<td>70.2</td>
<td>59.2</td>
<td>56.5</td>
</tr>
<tr>
<td>SVT</td>
<td>27.6</td>
<td>42.6</td>
<td>27.5</td>
</tr>
<tr>
<td>JLIP</td>
<td>31.4</td>
<td>34.7</td>
<td>29.3</td>
</tr>
<tr>
<td><strong>s- and t-channel</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>SLT</td>
<td>61.2</td>
<td>49.9</td>
<td>47.7</td>
</tr>
<tr>
<td>SVT</td>
<td>25.1</td>
<td>38.0</td>
<td>25.2</td>
</tr>
<tr>
<td>JLIP</td>
<td>28.6</td>
<td>31.2</td>
<td>26.8</td>
</tr>
</tbody>
</table>

**TABLE 48:** The 95% confidence level measured upper limits on the production cross section (in pb) of single top events, taking into account systematic uncertainties, after preselection, using the Bayesian method.
95% CL Measured Upper Limits on the Single Top Production Cross Sections
After Final Selection, **Without Systematics**, Bayesian

<table>
<thead>
<tr>
<th>Channel</th>
<th>Electron</th>
<th>Muon</th>
<th>$\mu^+\mu^-$</th>
<th>with SLT</th>
</tr>
</thead>
<tbody>
<tr>
<td>s-channel</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>SLT</td>
<td>42.3</td>
<td>22.5</td>
<td>26.6</td>
<td></td>
</tr>
<tr>
<td>SVT</td>
<td>6.2</td>
<td>14.8</td>
<td>5.9</td>
<td>7.7</td>
</tr>
<tr>
<td>JLIP</td>
<td>6.6</td>
<td>8.4</td>
<td>4.3</td>
<td>5.8</td>
</tr>
<tr>
<td>t-channel</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>SLT</td>
<td>68.5</td>
<td>37.5</td>
<td>44.1</td>
<td></td>
</tr>
<tr>
<td>SVT</td>
<td>8.6</td>
<td>21.7</td>
<td>8.5</td>
<td>11.0</td>
</tr>
<tr>
<td>JLIP</td>
<td>9.1</td>
<td>11.6</td>
<td>6.1</td>
<td>8.0</td>
</tr>
<tr>
<td>s- and t-channel</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>SLT</td>
<td>59.0</td>
<td>32.1</td>
<td>38.1</td>
<td></td>
</tr>
<tr>
<td>SVT</td>
<td>8.2</td>
<td>20.1</td>
<td>8.2</td>
<td>10.8</td>
</tr>
<tr>
<td>JLIP</td>
<td>8.7</td>
<td>10.9</td>
<td>5.8</td>
<td>8.0</td>
</tr>
</tbody>
</table>

TABLE 49: The 95% confidence level measured upper limits on the production cross section (in pb) of single top events, without taking into account systematic uncertainties, after the final cuts are applied, using the Bayesian method.

95% CL Measured Upper Limits on the Single Top Production Cross Sections
After Final Selection, **With Systematics**, Bayesian

<table>
<thead>
<tr>
<th>Channel</th>
<th>Electron</th>
<th>Muon</th>
<th>$\mu^+\mu^-$</th>
<th>with SLT</th>
</tr>
</thead>
<tbody>
<tr>
<td>s-channel</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>SLT</td>
<td>53.4</td>
<td>34.6</td>
<td>40.1</td>
<td></td>
</tr>
<tr>
<td>SVT</td>
<td>14.0</td>
<td>27.3</td>
<td>14.4</td>
<td>19.0</td>
</tr>
<tr>
<td>JLIP</td>
<td>15.8</td>
<td>20.6</td>
<td>14.9</td>
<td>21.9</td>
</tr>
<tr>
<td>t-channel</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>SLT</td>
<td>81.0</td>
<td>58.9</td>
<td>67.3</td>
<td></td>
</tr>
<tr>
<td>SVT</td>
<td>19.5</td>
<td>40.9</td>
<td>19.6</td>
<td>24.5</td>
</tr>
<tr>
<td>JLIP</td>
<td>22.1</td>
<td>29.3</td>
<td>21.0</td>
<td>30.3</td>
</tr>
<tr>
<td>s- and t-channel</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>SLT</td>
<td>72.2</td>
<td>49.4</td>
<td>57.3</td>
<td></td>
</tr>
<tr>
<td>SVT</td>
<td>17.6</td>
<td>36.0</td>
<td>18.0</td>
<td>23.3</td>
</tr>
<tr>
<td>JLIP</td>
<td>20.0</td>
<td>26.1</td>
<td>19.0</td>
<td>30.4</td>
</tr>
</tbody>
</table>

TABLE 50: The 95% confidence level measured upper limits on the production cross section (in pb) of single top events, taking into account systematic uncertainties, after the final cut is applied, using the Bayesian method.
FIG. 47: Posterior probability density versus the signal cross section for the electron, muon and the \( e + \mu \) decay channels using the SLT tagger. The three different plots are for the signal cross section in the \( s \)-channel, \( t \)-channel and the \( s \)- and \( t \)-channels.

FIG. 48: Posterior probability density versus the signal cross section for the electron, muon and the \( e + \mu \) decay channels using the SVT tagger. The three different plots are for the signal cross section in the \( s \)-channel, \( t \)-channel and the \( s \)- and \( t \)-channels.

FIG. 49: Posterior probability density versus the signal cross section for the electron, muon and the \( e + \mu \) decay channels using the JLIP tagger. The three different plots are for the signal cross section in the \( s \)-channel, \( t \)-channel and the \( s \)- and \( t \)-channels.
FIG. 50: Posterior probability density versus the signal cross section for the combined $e + \mu$ decay channels using the SVT tagger, the SLT tagger and the SVT and SLT taggers. The three different plots are for the signal cross section in the $s$-channel, $t$-channel and the $s$- and $t$-channels.

FIG. 51: Posterior probability density versus the signal cross section for the combined $e + \mu$ decay channels using the JLIP tagger, the SLT tagger and the JLIP and SLT taggers. The three different plots are for the signal cross section in the $s$-channel, $t$-channel and the $s$- and $t$-channels.
17. SUMMARY

We have performed a search for electroweak production of single top quarks in the
electron+jets and muon+jets decay channels. The measurements use \( \sim 156 \) to \( 167 \text{ pb}^{-1} \)
of data from Run II of the Fermilab Tevatron collider collected at a center of mass energy of
1.96 TeV with the DØ detector between August 2002 and September 2003. We use events
with a tagging muon in a jet, or a lifetime tag (SVT or JLIP algorithms) to identify the
presence of a \( b \) jet, and select events with a simple preselection and a cut on the total scalar
energy of the lepton, \( E_T \), and two highest-\( E_T \) jets to set an upper limit at the 95% confidence
level on the cross section for the \( s \)-channel process \( p\bar{p} \rightarrow tb + X \) of 19 pb. The upper limit
for the \( t \)-channel process \( p\bar{p} \rightarrow tqb + X \) is 25 pb, and for the combined process \( tb+tqb \), we
find the limit to be 23 pb.

18. ACKNOWLEDGMENTS

We would like to thank the following collaborators and theorist colleagues for their help
during this analysis: Gregorio Bernardi, Marumi Kado, Bob Kehoe, Nikolaos Kidonakis,
Lisa Shabalina, Jan Stark, Marek Zielinski, and Zack Sullivan.

We would also like to thank the editorial board for their careful review and helpful
comments and suggestions: Harry Weerts (chair), Neil Cason, Sean Mattingly, Bob
McCarthy, Silke Nelson, and Ariel Schwartzman.

19. APPENDIX OF PLOTS

The following sets of histograms use a consistent color coding scheme and consistent stacking
order. The colors and order (from top to bottom) are:

- Blue for \( s \)-channel \( tb \) signal
- Cyan for \( t \)-channel \( tqb \) signal
- Magenta for \( tt \rightarrow ll \) background
- Red for \( tt \rightarrow l+jets \) background
- Green for \( W+jets \) background
- Brown for misidentified lepton background

The data are shown as black points with error bars.
19.1. Pretagged Preselected Signal Data

19.1.1. Electron Channel

Distributions for Electrons after Preselection in Pretagged Data

FIG. 52: Electron distributions in preselected data before tagging.
FIG. 53: Jet distributions in preselected electron-channel data before tagging.
Distributions for Missing Transverse Energy in Pretagged Electron Data after Preselection

FIG. 54: Missing transverse energy distributions, $H_T$, and $M_T(W)$, in preselected electron-channel data before tagging.
19.1.2. Muon Channel

Distributions for Muons after Preselection in Pretagged Data

FIG. 55: Muon distributions in preselected data before tagging.
FIG. 56: Jet distributions in preselected muon-channel data before tagging.
Distributions for Missing Transverse Energy in Pretagged Muon Data after Preselection

FIG. 57: Missing transverse energy distributions, $H_T$ and $M_T(W)$, in preselected muon-channel data before tagging.
FIG. 58: Distributions of the transverse energy of the electron (first row), electron detector eta (second row), electron phi (third row), missing transverse energy (fourth row), and $E_T$ phi (fifth row), with the SLT tagger. The left column shows results after preselection. The right column shows results after final selection (preselection + $H_T > 150$ GeV). There are insufficient SLT events to show the plots for the mainly $W$+jets cross-check sample.
FIG. 59: Distributions of the transverse energy of the highest-$E_T$ jet (first row), jet 1 detector eta (second row), and jet 1 phi (third row), with the fourth through sixth rows showing the same things for jet 2, with the SLT tagger. The left column shows results after preselection. The right column shows results after final selection (preselection + $H_T > 150$ GeV). There are insufficient SLT events to show the plots for the mainly $W$+jets cross-check sample.
FIG. 60: Distributions of the transverse energy of the electron (top row), the highest-$E_T$ jet (middle row), and the second-highest-$E_T$ jet (bottom row), with the SVT tagger. The left column shows results for a mainly $W$+jets cross-check sample (preselection $+ =2$jets $+ H_T < 200$ GeV). The central column shows results after preselection. The third column shows results after final selection (preselection $+ H_T > 150$ GeV).
FIG. 61: Distributions of the transverse energy of the electron (top row), electron detector eta (second row), electron phi (third row), missing transverse energy (fourth row), $E_T$ phi (fifth row), and reconstructed top quark mass (sixth row), with the JLIP tagger. The left column shows results for a mainly $W+$jets cross-check sample (preselection + =2jets + $H_T < 200$ GeV). The central column shows results after preselection. The third column shows results after final selection (preselection + $H_T > 150$ GeV).
FIG. 62: Distributions of the transverse energy of the highest-$E_T$ jet (top row), its detector eta (second row), and its phi (third row), then similarly for Jet 2, with the JLIP tagger. The left column shows results for a mainly $W+\text{jets}$ cross-check sample (preselection $+2\text{jets}+H_T<200$ GeV). The central column shows results after preselection. The third column shows results after final selection (preselection $+H_T>150$ GeV).
The $e^+\text{-jets}/JLIP$ Analysis

FIG. 63: Distributions of the transverse energy of the third-highest-$E_T$ jet (top row), its detector eta (second row), and its phi (third row), then similarly for Jet 4, with the JLIP tagger. The left column shows results for a mainly $W+\text{jets}$ cross-check sample (preselection $+2Jets + H_T < 200$ GeV). The central column shows results after preselection. The third column shows results after final selection (preselection $+ H_T > 150$ GeV).
19.2.2. Muon Channel

The $\mu$+jets/SLT Analysis

FIG. 64: Distributions of the transverse energy of the muon (first row), muon eta (second row), muon phi (third row), missing transverse energy (fourth row), and reconstructed top quark mass (fifth row), with the SLT tagger. The left column shows results after preselection. The right column shows results after final selection (preselection + $H_T > 150$ GeV). There are insufficient SLT events to show the plots for the mainly $W$+jets cross-check sample.
The $\mu$+jets/SLT Analysis

FIG. 65: Distributions of the transverse energy of the highest-$E_T$ jet (first row), Jet 1 detector eta (second row), and similarly for Jet 2, with the SLT tagger. The left column shows results after preselection. The right column shows results after final selection (preselection + $H_T > 150$ GeV). There are insufficient SLT events to show the plots for the mainly $W$+jets cross-check sample.
FIG. 66: Distributions of the transverse energy of the muon (first row), the highest-\(E_T\) jet (second row), the second-highest-\(E_T\) jet (third row), the \(H_T\) of all the jets (fourth row), and the missing transverse energy (fifth row), with the SVT tagger. The left column shows results for a mainly \(W+\)jets cross-check sample (preselection + \(\geq 2\)jets + \(H_T < 200\) GeV). The central column shows results after preselection. The third column shows results after final selection (preselection + \(H_T > 150\) GeV).
FIG. 67: Distributions of the transverse energy of the muon (top row), muon eta (second row), muon phi (third row), missing transverse energy (fourth row), $E_T$ phi (fifth row), and reconstructed top quark mass (sixth row), with the JLIP tagger. The left column shows results for a mainly W+jets cross-check sample (preselection + =2 jets + $H_T < 200$ GeV). The central column shows results after preselection. The third column shows results after final selection (preselection + $H_T > 150$ GeV).
FIG. 68: Distributions of the transverse energy of the highest-$E_T$ jet (top row), its detector eta (second row), and its phi (third row), then similarly for Jet 2, with the JLIP tagger. The left column shows results for a mainly $W$+jets cross-check sample (preselection + $\geq$2 jets + $H_T <$ 200 GeV). The central column shows results after preselection. The third column shows results after final selection (preselection + $H_T > 150$ GeV).
The $\mu$+jets/JLIP Analysis

FIG. 69: Distributions of the transverse energy of the third-highest-$E_T$ jet (top row), its detector eta (second row), and its phi (third row), then similarly for Jet 4, with the JLIP tagger. The left column shows results for a mainly $W$+jets cross-check sample (preselection + $\geq$2jets + $H_T < 200$ GeV). The central column shows results after preselection. The third column shows results after final selection (preselection + $H_T > 150$ GeV).
20. APPENDIX: TOP GROUP TAGGABILITY

This section is lifted from the top group’s draft b-ID cross section note. That note should be released soon and at that time we will remove this from future versions of this note.

Only calorimeter jets satisfying jet identification requirements, with $E_T > 15$ GeV (after JES corrections) and $|\eta| \leq 2.5$ are considered in the definition of taggability.

The taggability per jet is determined from data and parameterized as a function of jet $E_T$ and $\eta$:

$$P_{\text{tagg}}(E_T, \eta) = \frac{\# \text{ taggable jets in } (E_T, \eta) \text{ bin}}{\# \text{ jets in } (E_T, \eta) \text{ bin}}.$$  \hspace{1cm} (1)

A priori we expect taggability to be different in data and Monte Carlo. In Monte Carlo, the taggability is expected to be higher than in data mainly due to an unrealistic description of the tracking detectors (dead detector elements, other inefficiencies, noise, etc) resulting in a higher tracking efficiency (in particular within jets). Therefore, the Monte Carlo taggability must be calibrated to that observed in the data.

According to the b-ID group definition, a calorimeter jet is taggable if it is matched within $\Delta R \leq 0.5$ to a track-jet with the following properties:

- the track-jet consists of at least two tracks; $r-\phi$ track-jet cone is $\Delta R = 0.5$ and $z$ cone is $\Delta z = 2 cm$

- the tracks used to form the track-jet are required to have $p_T > 0.5$ GeV and at least 1 SMT hit in the SMT barrels or F disks

- at least one track in the track-jet is required to have $p_T > 1$ GeV (track seed)

- tracks are required to have $dca < 0.2$ cm and $zdca < 0.4$ cm.

The taggability has been studied using the EMqcd and preselected signal samples. Figure 70 compares taggability as a function of $E_T$ for these three samples. Although it is clearly seen that taggability in the EMqcd sample (black circles in Figure 70) tend to be higher than in both $e+$jets and $\mu+$jets preselected samples the shapes of the distributions are similar. A more detailed comparison of the shapes of $E_T$ and $\eta$ distributions of taggability between EMqcd and signal preselected samples is presented in Figures 71 and 72 where the relative differences of the corresponding distributions are plotted. Distributions are consistent within errors with being independent on jet $E_T$ and $\eta$ but show the difference in absolute normalization about 5%.

Based on the studies presented above the high statistics EMqcd sample is chosen to derive the parameterization of the taggable efficiency since it provides the smallest possible statistical uncertainty and describes the shapes of the taggability in the signal samples reasonably well. Figure 73 shows the jet taggability in EMqcd sample as a function of jet $E_T$ and $\eta$ along with the fit and the $\pm \sigma$ error band. A two-dimensional parameterization is derived from the one-dimensional ones assuming that they are fully uncorrelated.

The closure tests are presented in Figures 74 and 75. The agreement between the observed $E_T$ and $\eta$ distributions of the taggable jets and the ones predicted from the parameterization both in the tails (Fig.74) and in the core of the distribution (Fig.75) proves the validity of this assumption.
Since the average taggability in the EMqcd sample is higher than in signal samples the parameterization obtained in EMqcd sample was corrected to reproduce the number of taggable jets in signal samples in the first jet multiplicity bin, where the contribution from noise jets is expected to be small. The correction factors are found to be 0.984 and 0.958 for $e$-jets and $\mu$-jets, respectively. Fig. 76 shows the taggability as a function of $E_T$ and $\eta$ measured in the preselected $e$-jets and $\mu$-jets signal samples compared to the normalized taggability from EMqcd. Fig. 77 shows taggability as a function of the number of jets in the event measured in the preselected $e$-jets and $\mu$-jets signal samples. The average taggability goes down for higher jet multiplicity, the size of the effect is significantly smaller. We attribute this improvement to the better jet identification criteria, in particular the introduction of Level 1 confirmation, which removes a large fraction of the noisy jets. Further
FIG. 72: Relative difference of taggability in preselected $e+$jets and EMqcd samples as a function of jet $E_T$ and $\eta$.

FIG. 73: Jet taggability as a function of jet $E_T$ and $\eta$ for EMqcd.

FIG. 74: Observed jet taggability and predicted by a two-dimensional parameterization as a function of jet $E_T$ and $\eta$ in the EMqcd sample (log scale).
FIG. 75: Observed jet taggability and predicted by a two-dimensional parameterization as a function of jet $E_T$ and $\eta$ in the EMqcd sample (linear scale).

FIG. 76: Jet taggability as a function of jet $E_T$ and $\eta$ for the preselected $e$+jets (left) and $\mu$+jets (right) signal samples. Curves indicate the fit and its 1 $\sigma$ error band.

tightening L1 confirmation requirement makes the distribution even flatter but it does not seem to fully account for the drop of taggability.

FIG. 77: Jet taggability as a function of number of jets in the event for the preselected $e$+jets (left) and $\mu$+jets (right) signal samples. Blue points correspond to tightened L1 confirmation cut.

Systematic uncertainty on the taggability is evaluated by replacing the parameterizations
derived as explained above by the ones obtained directly on the $e+$jets and $\mu+$jets signal samples. The corresponding $E_T$ and $\eta$ distributions along with the fits and 1 $\sigma$ error band are presented in Fig.78. It is worthwhile to mention that in case of $e+$jets channel taggability measured in EMqcd sample provides a good description of the taggability in the preselected $e+$jets sample for high $E_T$ jets. The normalized EMqcd taggability shown in Fig.76, which provides a better agreement on average, seems to slightly underestimate it for high $E_T$ jets.

\begin{figure}[ht]
\centering
\includegraphics[width=0.4\textwidth]{fig78a}
\includegraphics[width=0.4\textwidth]{fig78b}
\caption{Jet taggability as a function of jet $E_T$ and $\eta$ for the preselected $e+$jets (left) and $\mu+$jets (right) signal samples. Curves indicate the fit and its 1 $\sigma$ error band.}
\end{figure}
[22] T. Affolder et al. [CDF Collaboration], First Measurement of the Ratio $B(t\rightarrow Wb)/B(t\rightarrow Wq)$ and Associated Limit on the CKM Element $V_{ts}$, Phys. Rev. Lett. 86, 3233 (2001).