Introduction to Hadronic Final State Reconstruction in Collider Experiments (Part XIII)

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CMS Factorized Jet Calibration

**Factorized calibration allows use of collision data**

CMS sequence applies factorized scheme with required and optional corrections

**Required corrections can initially be extracted from collision data**
- Average signal offset from pile-up and UE can be extracted from minimum bias triggers
- Relative direction dependence of response can be corrected from di-jet pT balance
- The absolute pT scale correction can be derived from prompt photon production

**Optional corrections refine jet calibration**
- Use jet by jet calorimeter or track observables to reduce fluctuations
- Includes energy fractions in EMC, track pT fractions, underlying event corrections using jet areas, flavor dependencies and others...
- May need very good simulations!

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**Diagram:**

- **Required Corrections**:
  - Reconstructed Jets
  - Offset
  - Rel: \( \eta \)
  - Abs: \( p_T \)

- **Optional Corrections**:
  - EMF
  - Flavor
  - UE
  - Parton

- **Calibrated Jets**

**Correct CaloJets to have same pT as GenJet on average**

**Corrections back to parton level quantities**
optional

data driven

MC

ATLAS JES Correction Model for First Data
PileUp subtraction

**Goal:**
Correct in-time and residual out-of-time pile-up contribution to a jet on average

**Tools:**
Zero bias (random) events, minimum bias events

**Measurement:**
Et density in $\Delta \eta \times \Delta \phi$ bins as function of 
# vertices
TopoCluster feature (size, average energy as function of depth) changes 
as function of # vertices

**Remarks:**
Uses expectations from the average Et flow for a given instantaneous luminosity
Instantaneous luminosity is measured by the # vertices in the event
Requires measure of jet size (AntiKt advantage)

**Concerns:**
Stable and safe determination of average

Note that magnitude of correction depends on calorimeter signal processing & definition – application easier to see for tower based jets!
Balancing jet $p_T$ with electromagnetic system

Truth from collision
- Based on idea that electromagnetic particles are well measured
- Limits accuracy to precision of photon or electron signal reconstruction

Provides interaction (parton) level reference
- Note that simulation based approaches use particle level reference

Can use direct photon production
- Kinematic reach for jet $p_T \sim 200-400$ GeV for 1% precision – depends on center of mass energy
- Relatively large cross-section
- Background from QCD di-jets – one jet fluctuates into $\pi^0$ faking photon

Can also use $Z$+jet(s)
- Cross-section suppressed, but less background – two electron final state cleaner
- Can also use two muon final state

Note specific physics environment
- Underlying event different from other final states
  - Less radiation in photon/Z hemisphere
- Often only good reference for quark jets
  - Narrow jets in lower radiation environment

Prompt (direct) photon production:
- $gq \rightarrow \gamma q$  \hspace{1em} QCD Compton scattering  \hspace{1em} (~ 95% of $\sigma^\text{tot}_\gamma$)
- $q\bar{q} \rightarrow \gamma g$  \hspace{1em} annihilation

Balance photon with (mostly) quark jet $p_T$ to validate or constrain $p_{T,\text{reco,jet}}$
Balancing jet $p_T$ with electromagnetic system

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Z-boson + jet production:

balance $Z$ pT reconstructed from decay leptons with quark jet pT to validate or constrain $p_T^{\text{reco}, \text{jet}}$
Absolute response

Goal:
Correct for energy (pT) dependent jet response

Tools:
Direct photons, Z+jet(s),...

Measurement:
pT balance of well calibrated system (photon, Z) against jet in central region

Remarks:
Usually uses central reference and central jets (region of flat response)

Concerns:
Limit in precision and estimates for systematics w/o well understood simulations not clear
Needs corrections to undo out-of-cone etc. to compare to particle level calibrations

ratio test variable ($\kappa = \gamma, Z$):

$$f_{\text{absolute}}(\zeta_{\text{probe}}) = \left[ 1 + \frac{p_{T,\text{reco,jet}} - p_{T,\kappa}}{p_{T,\kappa}} \right]^{-1}$$

with

$$\zeta_{T,\text{probe}} = \begin{cases} p_{T,\kappa} & \text{reference pT} \\ p_{T,\kappa} + p_{T,\text{reco,jet}} & \text{average pT} \\ E' = p_{T,\kappa} \cosh \eta_{\text{reco,jet}} & \text{expected jet energy} \end{cases}$$

(rotate to reconstructed jet variables with numerical inversion)

relative projection along reference pT:

$$\frac{\mathcal{P}}{p_{T,\kappa}} = \frac{p_{T,\text{reco,jet}} \cos \theta (\tilde{p}_{T,\text{reco,jet}}, \tilde{p}_{T,\kappa})}{p_{T,\kappa}} = \frac{\tilde{p}_{T,\text{reco,jet}} \cdot \tilde{p}_{T,\kappa}}{p_{T,\kappa}^2}$$

correction from $$\mathcal{P} + 1 \equiv 0$$ for well calibrated jets:

$$f_{\text{absolute}}(\zeta_{\text{probe}}) = \left[ \frac{p_{T,\kappa}}{\mathcal{P}} \right]$$
Photon+jet(s)

Well measured electromagnetic system balances jet response

- Central value theoretical uncertainty ~2% limits precision
  - Due to photon isolation requirements
- But very good final state for evaluating calibrations
- Can test different correction levels in factorized calibrations
  - E.g., local hadronic calibration in ATLAS

Limited pT reach for 1-2% precision
- 25->300 GeV within 100 pb⁻¹

Z+jet(s)

Similar idea, but less initial statistics
- Smaller reach but less background
Photon+jet(s)

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Z+jet(s)

Similar idea, but less initial statistics

Smaller reach but less background
In-situ calibration validation handle

Precise reference in ttbar events

Hadronically decaying W-bosons

Jet calibrations should reproduce W-mass

Note color singlet source

No color connection to rest of collision – different underlying event as QCD

Also only light quark jet reference

Expected to be sensitive to jet algorithms

Narrow jets perform better – as expected

Simulated di-jet invariant mass ($M_{W,\text{reco}}$) spectrum for $kT$ jets with $R = 0.4$ (narrow jets) in $t\bar{t}$ final states at $\sqrt{s} = 14$ TeV
**W boson mass from two jets**

Clean event sample can be accumulated quickly

Original studies for center of mass energy of 14 TeV and luminosity of $10^{33}$ cm$^{-2}$s$^{-1}$

~130 clean events/day in $t\bar{t}$bar

Angular and energy scale component in reconstruction

Energy scale dominant

**Invariant mass from decay jets:**

$$M_{W,\text{reco}} = \sqrt{2E_{\text{jet},1}E_{\text{jet},2}(1 - \cos \theta_{\text{jet1,jet2}})}$$

Bias from angular mismeasurement:

$$\mathcal{K}(\cos \theta_{\text{jet1,jet2}}) = \frac{1 - \cos \theta_{\text{parton1,parton2}}}{1 - \cos \theta_{\text{jet1,jet2}}} \approx 1$$

is small

**arXiv:0901.0512 [hep-ex]**
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Bias from angular mismeasurement:

$$\kappa(\cos \theta_{\text{jet,1,jet,2}}) = \frac{1 - \cos \theta_{\text{parton},1,\text{parton},2}}{1 - \cos \theta_{\text{jet,1,jet,2}}} \approx 1$$

is small $\rightarrow$ major contribution from energy scale:

$$M_{W,\text{PDG}} = \sqrt{2\kappa(E_{\text{jet,1}})E_{\text{jet,1}}\kappa(E_{\text{jet,2}})E_{\text{jet,2}}\kappa(\cos \theta_{\text{jet,1,jet,2}})(1 - \cos \theta_{\text{jet,1,jet,2}})}$$

$$= \sqrt{2\kappa(E_{\text{jet,1}})E_{\text{jet,1}}\kappa(E_{\text{jet,2}})E_{\text{jet,2}}(1 - \cos \theta_{\text{jet,1,jet,2}})}$$

$$= \sqrt{\kappa(E_{\text{jet,1}})\kappa(E_{\text{jet,2}})} \cdot M_{W,\text{reco}}$$

Simple rescaling method assuming energy independent scale shift $\rightarrow \kappa(E_{\text{jet,1}}) = \kappa(E_{\text{jet,2}}) = \kappa$ works reasonably well
W mass from templates

Produce W mass distribution templates

- Use parton or particle level simulations
- Smear with JES and resolution variations
- Store W mass distributions as function of smearing parameters

Find response and resolution smearing parameters

- Find best fit template

\[ \chi^2 = \int \left( \mathcal{T}_{\alpha\beta}(M_W) - \mathcal{R}(M_W) \right)^2 \left( \sigma_{\mathcal{T}_{\alpha\beta}(M_W)}^2 + \sigma_{\mathcal{R}(M_W)}^2 \right) dM_W = \min \]

stability of fit tested by subdividing total sample into 16 "measurements" (770 pb\(^{-1}\) → 16 × 48 pb\(^{-1}\)):
Boosted $W$

- pT boost reduces angle between decay jets

- Reconstructed mass underestimates true $W$ mass

- See example below for $W$ boosted into the ATLAS end-cap calorimeter region

Pile-up can add energy to the system

- Not an improvement of the measurement – accidental and thus uncorrelated jet energy shifts lead to shift in reconstructed mass

\[
\frac{M_{W,PDG}}{M_{W,reco}} = \frac{10^{34} \text{ cm}^{-2} \text{s}^{-1}}{\sqrt{s} = 14 \text{ TeV}}
\]

\(|\eta_W| \approx 1.8\)

\(\sim 290 \text{ GeV}\)

\(\sim 611 \text{ GeV}\)
Data Driven JES Corrections: Direction

**Di-jet balance**

- Calibrate jet in “golden” reference region
  - Use e.g. photon pT balance
  - Use this jet as “truth” reference
- Balance pT with jet in more complex calorimeter region
  - Note: relative energy resolution of reference jet can be worse than probe jet – more forward jet has more energy at same pT
  - Resolution bias needs to be controlled
- Apply corrections to all jets at given direction
  - Need to understand topology – additional soft jet contribution
- Can also be used to measure jet energy resolution
  - Need to consider phase space sharing with possible additional soft jets

**Multi-jet balance**

- Validation of very high pT jets
  - In-situ calibrations with photons etc. only reaches 200-300 GeV (pT)
  - But need to validate very high pT jet scale as well
- Bootstrap approach
  - Find multi-jet events with one hard jet in non-validated phase-space
  - Balance hard jet with several well calibrated lower pT jets (e.g., from photons)
  - Look for more harder jets and use scale corrections from lower pT jets (bootstrap corrections)
- Note that errors evolve from low to high pT
  - Hard to achieve O(1%) precision
  - Likely need simulation based approach
Correct direction-dependent jet response

Establish absolute scale in “golden region” of the detector
- Balancing pT of a central (lower energy) jet with a more forward (higher energy) jet
- Avoid biases by compensating reference jet response first

Determine direction dependent correction factors
- Use pT asymmetry measure for back-to-back jet
- Careful – resolution bias due to different jet energy ranges can still be present!

Jet energy resolution from di-jet pT balance

Select event topology
- Di-jets back-to-back in azimuth
- Same rapidity region
- Similar pT

Use asymmetry measure to calculate jet energy resolution
- Width of the distribution of A

Understand soft radiation contribution

pT balance approach (DØ)
- Use di-jet energy resolution dependence on third jet pT as scale to unfold radiation contribution

kT balance approach (UA2, CDF)
- Determination of radiation contribution using bisector decomposition

Diagram:
- Electromagnetic scale jet response
- Asymmetry measure:
  \[ A = \frac{p_{T,\text{reco}}^{\text{probe}} - p_{T,\text{reco}}^{\text{reference}}}{(p_{T,\text{reco}}^{\text{probe}} + p_{T,\text{reco}}^{\text{reference}})/2} = \frac{p_{T,\text{reco}}^{\text{probe}} - p_{T,\text{reco}}^{\text{reference}}}{p_{\text{average}}^{T,\text{reco}}} \]

Correction factors (use numerical inversion):

\[ c(p_{T,\text{reco}}^{\text{average}}, \eta_{\text{probe}}) = \frac{2 - A(p_{T,\text{reco}}^{\text{average}}, \eta_{\text{probe}})}{2 + A(p_{T,\text{reco}}^{\text{average}}, \eta_{\text{probe}})} \Rightarrow c(p_{T,\text{reco}}^{\text{probe}}, \eta_{\text{probe}}) \]
Correct direction-dependent jet response

Establish absolute scale in “golden region” of the detector

- Balancing \( p_T \) of a central (lower energy) jet with a more forward (higher energy jet)
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Understand soft radiation contribution

- \( p_T \) balance approach (DØ)
  - Use di-jet energy resolution dependence on third jet \( p_T \) as scale to unfold radiation contribution
- \( kT \) balance approach (UA2, CDF)
  - Determination of radiation contribution using bisector decomposition

\[
A = \frac{p_{T,\text{jet1}} - p_{T,\text{jet2}}}{p_{T,\text{jet1}} + p_{T,\text{jet2}}} = \frac{2p_{T,\text{average}}}{p_{T,\text{reco}}} = \frac{p_{T,\text{reco}}^\text{jet1} - p_{T,\text{reco}}^\text{jet2}}{2p_{T,\text{reco}}^\text{average}}
\]

\( p_T \) resolution for jets in same \( \eta \) region with similar \( p_T \):

\[
\frac{\sigma_{p_T}}{p_{T,\text{reco}}^\text{average}} = \sqrt{2\sigma_A} \approx \frac{\sigma_E}{E}
\]

Resolution is symmetrized by randomly computing \( p_{T,\text{reco}}^\text{jet1} - p_{T,\text{reco}}^\text{jet2} \) or \( p_{T,\text{reco}}^\text{jet2} - p_{T,\text{reco}}^\text{jet1} \) for each event
Correct direction-dependent jet response

Establish absolute scale in “golden region” of the detector

Balancing pT of a central (lower energy) jet with a more forward (higher energy jet)
Avoid biases by compensating reference jet response first

Determine direction dependent correction factors

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Jet energy resolution from di-jet pT balance

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Same rapidity region
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Determination of radiation contribution using bisector decomposition

determine clean di-jet resolution by linear extrapolation of

$$\frac{\sigma_{p_T}(p_{T,\text{reco},\text{jet}3} < p_{T,\text{threshold}}, p_{T,\text{average}})}{p_T},$$

typically with $p_{T,\text{threshold}} \geq p_{T,\text{min}} = (7-10)$ GeV, implied by calorimeter jet reconstruction, to

$p_{T,\text{reco},\text{jet}3} = 0$:

$$\lim_{p_{T,\text{reco},\text{jet}3} \to 0} \frac{\sigma_{p_T}(p_{T,\text{reco}}^{\text{average}})}{p_T}$$

fit has some bias problems due to phase space limitations at low $p_{T,\text{reco}}^{\text{average}}$ together in the presence of $p_{T,\text{min}}$
Di-jet balance

Correct direction-dependent jet response

Establish absolute scale in “golden region” of the detector

- Balancing $p_T$ of a central (lower energy) jet with a more forward (higher energy jet)
- Avoid biases by compensating reference jet response first

Determine direction dependent correction factors

- Use $p_T$ asymmetry measure for back-to-back jet
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Jet energy resolution from di-jet $p_T$ balance

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Understand soft radiation contribution

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$k_T$ balance approach (UA2, CDF)

- Determination of radiation contribution using bisector decomposition

resolution correction factor from

$$\mathcal{K}(p_T^{\text{average}}) = \mathcal{K}(p_{T,\text{reco}})$$

$$\lim_{p_{T,\text{reco},\text{jet}3} \to \infty} \frac{\sigma_{p_T}}{p_{T,\text{reco}}} (p_{T,\text{reco},\text{jet}3} < 10 \text{ GeV}, p_{T,\text{reco}})$$

such that

$$\left(\frac{\sigma_{p_T}}{p_{T,\text{reco}}}\right)_{\text{corrected}} = \mathcal{K}(p_{T,\text{reco}}) \frac{\sigma_{p_T}}{p_{T,\text{reco}}} (p_{T,\text{reco},\text{jet}3} < 10 \text{ GeV}, p_{T,\text{reco}})$$

with a parameterization of the $p_T$ dependence of the correction by

$$\mathcal{K}(p_{T,\text{reco}}) = a + b \cdot \log p_{T,\text{reco}}$$

The detailed documentation of this approach, including a full systematic evaluation and discussion of the low $p_T$ bias using ATLAS simulations, is available to ATLAS members only in:

E. Hughes, D. Lopez, A. Schwartzman,
Correct direction-dependent jet response

Establish absolute scale in “golden region” of the detector

Balancing pT of a central (lower energy) jet with a more forward (higher energy jet)

Avoid biases by compensating reference jet response first

Determine direction dependent correction factors

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Jet energy resolution from di-jet pT balance

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Width of the distribution of A

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Determination of radiation contribution using bisector decomposition

$\vec{k}_{T,\psi}$ most sensitive to calorimeter resolution effects:

$\sigma_{\psi}^2 = \sigma_{E,\text{calo}}^2 + \sigma_{\text{radiation,||}}^2$, with $\sigma_{E,\text{calo}} \gg \sigma_{\text{radiation,||}}$

$\vec{k}_{T,\eta}$ most sensitive to (gluon) radiation effects:

$\sigma_{\eta}^2 = \sigma_{\text{radiation,\perp}}^2$

(ignoring effects from angular resolution, underlying event, out of cone losses)

Assume radiation is random wrt jet directions:

$\sigma_{\text{radiation,\perp}}^2 = \sigma_{\text{radiation,||}}^2 \Rightarrow \sigma_{E,\text{calo}}^2 = \sqrt{\sigma_{\psi}^2 - \sigma_{\eta}^2}$
Di-jet balance

**Correct direction-dependent jet response**

Establish absolute scale in “golden region” of the detector

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\[ \sigma_\eta \approx \text{const} \sigma_\psi \left( \frac{p_{T,\text{average}}}{p_{T,\text{min}}} \right), \text{ and} \]

as expected!
Dangerous background for W+n jets cross-sections etc.

Lowest pT jet of final state can be faked or misinterpreted as coming from underlying event or multiple interactions

Extra jets from UE are hard to handle

No real experimental indication of jet source

Some correlation with hard scattering?

Jet area?

No separate vertex

Jet-by-jet handle for multiple proton interactions

Match tracks with vertices to calorimeter jet

Calculate track pT fraction from given vertex

Classic indicator for multiple interactions is number of reconstructed vertices in event

Tevatron with RMS(z_vertex) \(\sim 30\) cm

LHC RMS(z_vertex) \(\sim 8\) cm

If we can attach vertices to reconstructed jets, we can in principle identify jets not from hard scattering

Limited to pseudorapidities within 2.5!
Track jets

Find jets in reconstructed tracks
~60% of jet pT, with RMS ~0.3 –
not a good kinematic estimator

Dedicated 3-dim jet algorithm
Cluster track jets in pseudo-rapidity, azimuth, and
delta(ZVertex)

Match track and calorimeter jet
Helps response!
Other Sources Of JES Uncertainties

Longitudinal jet energy leakage

Dangerous – can changes jet $p_T$ cross-section shape at high $p_T$
Fake compositeness signal

Correlated with muon spectrometer hits

Not strong correlation expected
Insufficient for precise JES
Will likely not produce reconstructed tracks, only

Helps to tag suspicious jets
Suppress suspicious events/jets

Careful – real muon may be inside jet
$b$ decay
Should produce track – cleaner signal inside jet

Also background for missing transverse energy!
Effect of calibration on inclusive jet cross-section

One the first physics results expected from ATLAS & CMS

CMS PAS SBM-07-001
Extras
QCD Dominates Cross-sections

The graph illustrates the cross-sections for various processes at different energy scales, with a focus on the LHC. The Processes include:

- $\sigma_{bb}$
- $\sigma_{W \rightarrow t\bar{t}}$
- $\sigma_{gg}(m_g = 500 \text{ GeV})$
- $\sigma_{tt}$
- $\sigma_H$
- $\sigma_{Z'}$
- $\sigma_{\text{Higgs}}$
- $\sigma_{Z_{SM} \rightarrow 3\gamma}$
- $Z_{SM} \rightarrow 2\gamma$
- SUSY $qg+qg+gg$
- $Z \rightarrow \gamma\gamma$
- $H_{SM} \rightarrow Z^0 \rightarrow 4\mu$
- $H_{SM} \rightarrow \gamma\gamma$
- $H_{SM} \rightarrow 2Z^0 \rightarrow 4\mu$
- $Z_{ARL} \rightarrow 2\ell$
- $Z_{SM} \rightarrow 2\ell$

The LHC input and output scales are indicated, with the rate in events per year and the energy in TeV. The graph shows a logarithmic scale for the cross-sections, with typical values ranging from $10^{-9}$ to $10^9$ barns.
Jet physics

High transverse momentum jets quickly accessible!
100,000 jets with \( p_T > 1 \text{ TeV} \) at 1 fb\(^{-1}\)

Early attempt at inclusive cross-section

Most likely jet origin changes with \( p_T \) and direction

\( 0.0 < |\eta| < 1.0 \)

\( 4.0 < |\eta| < 5.0 \)

1. \( gg \)
2. \( gq \)
3. \( qq \)
4. \( qq' \)
5. \( \overline{q}q \)
6. \( \overline{q}q' \)
Neglecting orders in ME calculations

K-factor NLO-LO can be significant

Much smaller effect of scale variations in NLO

PDF uncertainties

Diven by gluon structure function uncertainties

Especially at higher pT

Plot shows error PDFs in various regions

CTEQ 6.1 family
QCD swamps trigger and acquisition band width

Highly prescaled low pT triggers
Trigger rates follow cross-section for \( pT > \sim 300 \) GeV

Depending on luminosity

Need to understand trigger bias effect on cross-section measurement

Low pT problematic due to efficiency and purity issues anyway!
Safe pT > \sim 60-80 \) GeV

\[ L = 10^{31} \text{cm}^{-2} \text{s}^{-1} \]

\[ \begin{array}{c|c|c|c|c|c}
 pT (GeV) & 60 & 70 & 80 & 90 & 100 \\
 Efficiency (%) & 100 & 100 & 100 & 100 & 100 \\
\end{array} \]
Fake Jets

Average number of jets in minimum bias events estimates fake jet reconstruction rate as function of pT threshold

no pileup!
Extracting PDFs

From inclusive jet cross-sections
Measure cross-section in regions of pseudo-rapidity
Statistical error quickly reduced
Trigger, JES more important

Preliminary indications suggest that ATLAS data can constrain the high x-gluon.

Systematic uncertainties are uncorrelated, 10fb^{-1}=1 year of nominal data-taking