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

Peter Loch

University of Arizona

Tucson, Arizona

USA

Preamble

The material presented in this lecture series, which has been designed for ATLAS graduate students at the University of Arizona, is mostly used to explain complex signal features of calorimeters and other detectors we are using to analyze the final states in hadron collider experiments. Its intent is to be educational only, and it most certainly does not represent present evaluations of the actual performance of any of the experiments mentioned. Matter of fact, in some cases older low performance features, long since understood and corrected, are enhanced in the discussion for educational purposes, just to highlight the motivations and tools for the solutions applied. Also, there is a clear bias towards the methodology used by the ATLAS experiment, because I have been involved in this experiment for now 15 years. A serious attempt was made to show only common knowledge or otherwise approved specific material, of course – and to provide citations when available and appropriate.

The more than 200 slides comprising this lecture series would not have been possible to collect without the direct or indirect input from the HERA, Tevatron, and LHC experiment communities, and from colleagues from theory and phenomenology. It is a bit unfortunate that not all the knowledge available today, reflecting the result of hard work of so many people, could be included here. Nevertheless, I like to acknowledge everybody who helped getting us where we are today with the understanding of the detectors and the physics of hadron collisions, in particular with respect to jet reconstruction. I like to recognize and thank the colleagues who, in the last few years, spent nearly endless hours with me discussing topics related to these lectures, and without whom I am sure my own understanding of these subjects would not be as far advanced as it is today. Please find the names on the next slide.

For those of you who are reading these slides, and would like to use them for the purposes they have been put together for, please feel free to do so. Please let me know of any even smallest error or inconsistency, or any improvement concerning the wording and displayed material – thank you for that! I also appreciate suggestions for extension or change of focus, of course. The best way to contact me is by e-mail <loch_AT_physics.arizona.edu>.

Tucson, April 29, 2010

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USA

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Acknowledgements

The following people significantly contributed with their work and ideas to the material of this lecture series – in some case probably without their personal knowledge (yes, I was listening). Also, these are the people who pushed my understanding of the jets in the hadron collider environment in sometimes more or less controversial discussions, which I deeply enjoyed, by issuing relevant comments, or by raising interesting questions. Last but not least I am grateful to the colleagues who invited me to report on jet physics related topics at workshops, conferences, and seminars, either in form of lectures, or as introductory or status talks. Thank you all for this – it helped me a lot to understand the often complex signal features we see in hadron collisions.

Argonne National Laboratory (USA)

Esteban Fullana Torregrosa, Tom LeCompte, Jimmy Proudfoot, Belen Salvachua, Zach Sullivan

Brookhaven National Laboratory (USA)

Ketevi Assamagan, Hong Ma, Frank Paige, Srini Rajagopalan

Carleton University (Canada)

Gerald Oakham, Manuella Vincter

CERN (Switzerland)

David Berge, Tancredi Carli, Daniel Froidevaux, Fabiola Gianotti, Peter Skands, Guillaume Unal

CalTech/Columbia (USA)

David Lopez, K.Perez, Zach Taylor

DESY Hamburg (Germany)

Kerstin Borras, Jörg Gayler, Hannes Jung

Fermi National Laboratory (USA)

W.Giele

Florida State University (USA)

Rick Field

IFAE Barcelona (Spain)

Martine Bosman

INFN Milan (Italy)

Leonardo Carminati, Donatella Cavalli, Silvia Resconi

INFN Pavia (Italy)

Giacomo Polesello

INFN Pisa (Italy)

Paolo Francavilla, Vincent Giangiobbe, Chiara Roda

Lawrence Berkeley National Laboratory/UC Berkeley (USA)

Christian Bauer, Beate Heinemann, Marjorie Shapiro, Jesse Thaler

LPSC Grenoble (France)

Pierre-Antoine Delsart

LPNHE /UPMC Universite de Paris 6 (France)

Bernard Andrieu

LPTHE/UPMC Universite de Paris 6 (France)

Matteo Cacciari, Gavin Salam

Michigan State University (USA)

Joey Huston

Max Planck Institut für Physik München (Germany)

Paola Giovaninni, Andreas Jantzsch, Sven Menke, Horst Oberlack, Guennadi Pospelov, Vladimir Shekelyan, Peter Schacht, Rolf Seuster

Rutherford Appleton Laboratory Didcot (UK)

Monika Wielers

ATLAS

Acknowledgements

Simon Fraser University (Canada)

D.O'Neil , D.Schouten, T.Spreitzer

SLAC (USA)

David Miller, Michael Peskin, Ariel Schwartzman

Universidad de Sonora, Hermosillo (Mexico)

Maria Elena Tejeda-Yeomans

Universität Freiburg (Germany)

Kristin Lohwasser, Iacopo Vivarelli

Universität Heidelberg (Germany)

Victor Lendermann, Pavel Weber

Universität Mainz (Germany)

Sebastian Eckweiler, Stefan Tapprogge

Universität Wuppertal (Germany)

Christian Zeitnitz

University College London (UK)

Jon Butterworth, Mario Campanelli, Adam Davison, S.Dean, N.Kostantinidis, P.Sherwood

University of Arizona (USA)

Ken Johns, Venkat Kaushik, Caleb Lampen, Xiaowen Lei, Prolay Mal, Chiara Paleari, Frederik Rühr, John Rutherfoord, Alexander Savine, Shufang Shu, Michael Shupe

UC Davis (USA)

John Conway

University of Chicago (USA)

Georgios Choudalakis, Frank Merritt

University of Glasgow (UK)

Craig Buttar , Arthur Moraes

University of Oregon (USA)

D.Soper, E. Torrence

University of Oxford (UK)

C.Doglioni, Cigdem Issever

University of Sheffield (UK)

Dan Tovey

University of Toronto (Canada)

Peter Krieger, Richard Teuscher

University of Victoria (Canada)

Frank Berghaus, Michel Lefebvre, Jean-Rafael Lessard, Rob McPherson

University of Washington (USA)

Steve Ellis, Chris Vermillion, Jon Walsh

Not working in HEP anymore…

Levan Babukhadia, Ambreesh Gupta, Kai Voss

… and all the other colleagues whom I may have forgotten and, so I hope, will forgive me for that!

ATLAS

Roadmap

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Introduction

- Sources of jets and missing transverse energy at LHC
- Hadron collision environment

Principles of calorimetry in High Energy Physics

- Interaction of particles and matter
- Calorimeter design principles
- Characteristic features of operating calorimeters in hadron collider experiments

Hadronic final state in high energy hadron collisions

- Characteristic signatures at highest energies
- Experimentalist’s view on partons and particles

What are jets?

- Theoretical guidelines for finding jets
- Jet finding algorithms and jet definition
- Reconstructing jets in the experiment
- Calibrating jets
- Jet substructure reconstruction

Focus on the experimental aspects

- Unfolding hadron collider physics from detector signals
  - Triggering, acceptance, calibration, resolution
- Mostly discussed using the LHC collision experiments (“ATLAS bias”)
  - Accumulation of experiences from previous experiments
  - Occasional highlights from SPS, HERA, Tevatron,…

Lecture style

- Informal
  - Please ask questions – we should have sufficient time!
- Student talks
  - Possibility to present selected aspects (end of semester)

Material

- Some material is private to the ATLAS experiment
  - Mostly used to explain signal features
  - Use only material with publication reference for public talks
- Slides on the web
  - Look for link on http://atlas.physics.arizona.edu/~loch
    - Will try to upload as soon as possible after each session
- Literature
  - Embedded in slides
    - Will extract and put on the web soon!

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Large Hadron Collider

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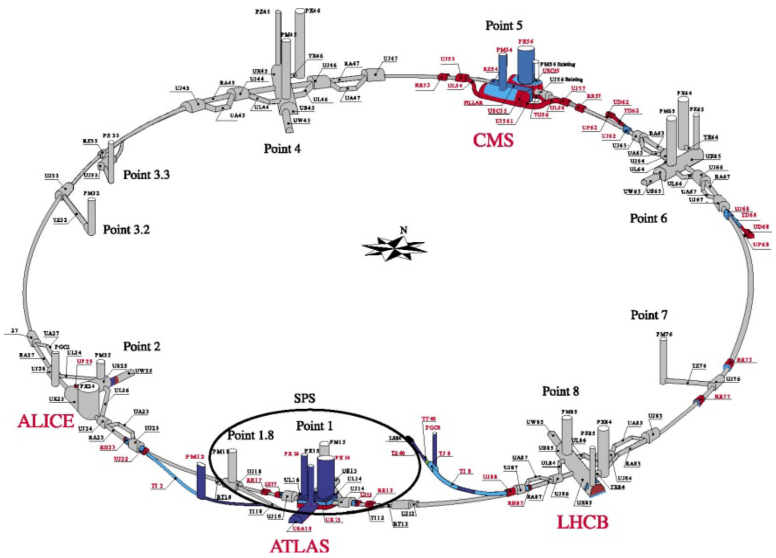

Machine

- Occupies old LEP tunnel at CERN, Geneva, Switzerland & France
- About 27 km long
- 50-100m underground
- 1232 bending magnets
- 392 focusing magnets
- All superconducting
  - ~96 tons of He for ~1600 magnets

Beams (design)

- pp collider
  - 7 TeV on 7 TeV (14 TeV collision energy)
  - Luminosity 10^{34} $cm^{-2}s^{-1}$
  - 2808 x 2808 bunches
  - Bunch crossing time 25 ns (40 MHz)
  - ~20 pp collisions/bunch crossing
- Heavy ion collider (Pb)
  - Collision energy 1150 TeV (2.76 TeV/nucleon)

Proton acceleration chain:
LINAC→Proton Synchrotron Booster (PSB)→Proton Synchrotron (PS)→Super Proton Synchrotron (SPS)→LHC

Pb ion acceleration chain:
LINAC→Low Energy Ion Injector Ring (LEIR)→Proton Synchrotron (PS)→Super Proton Synchrotron (SPS)→LHC

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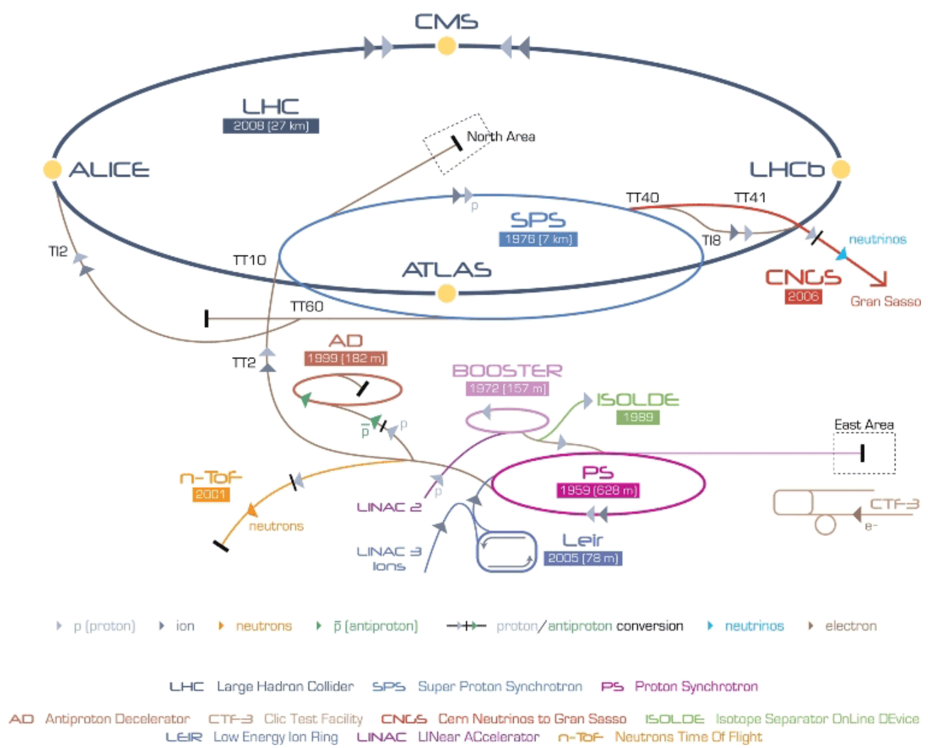

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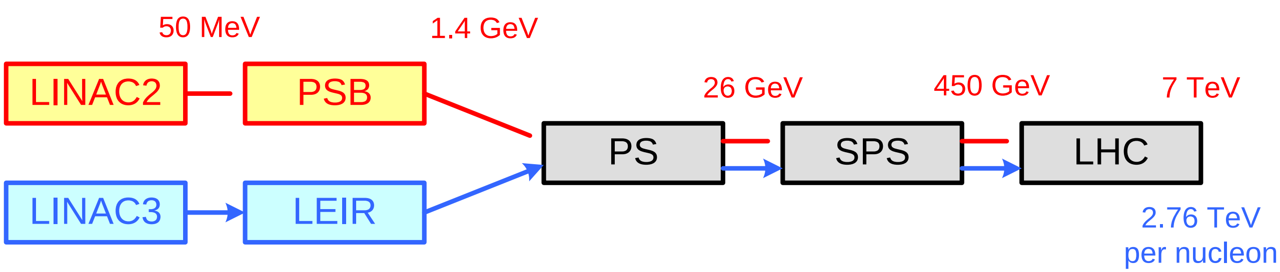

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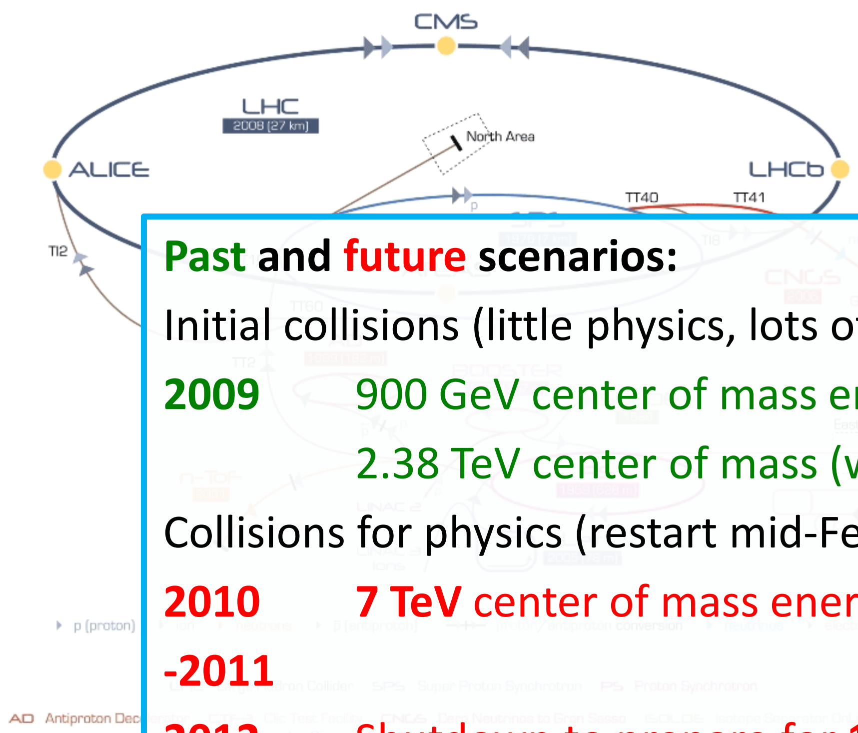

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Past and future scenarios:

Initial collisions (little physics, lots of detector commissioning)

2009 900 GeV center of mass energy

2.38 TeV center of mass (world record)

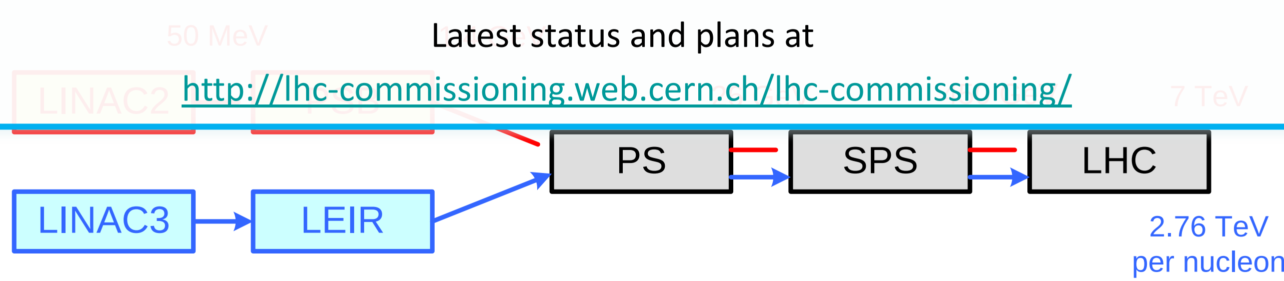
Collisions for physics (restart mid-February 2010)

2010 -2011 **7 TeV** center of mass energy, 10^{29}-10^{32} $cm^{-2}s^{-1}$, up to 1 fb^{-1}

2012 Shutdown to prepare for **14 TeV** center of mass energy

Latest status and plans at

http://lhc-commissioning.web.cern.ch/lhc-commissioning/



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Kinematic Domains @ LHC

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Enormous reach in (x,Q^2)

- Low x at relatively high Q^2
- Mostly unvcovered so far

No experimental data for parton densities

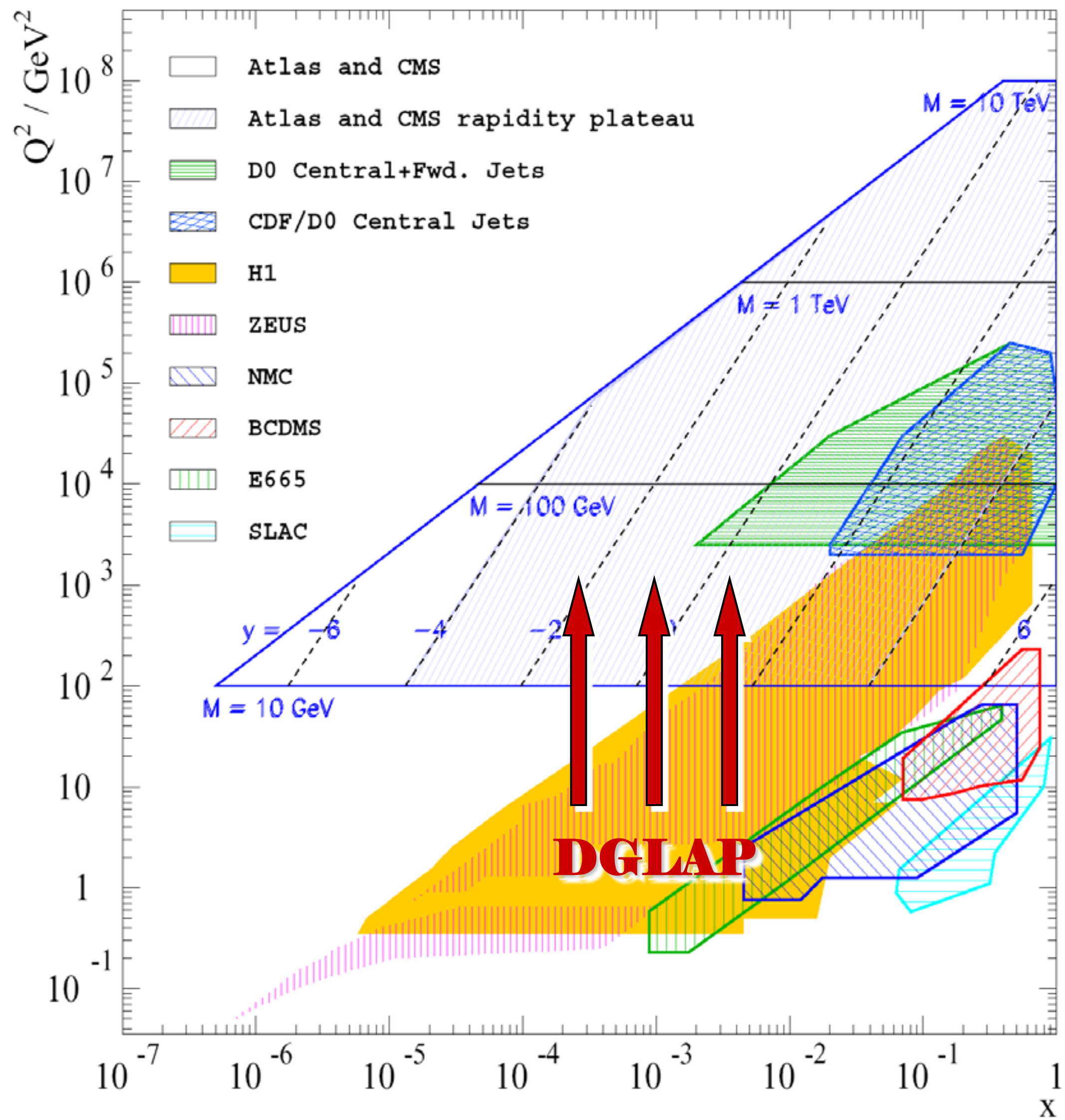
- Validation of proton structure part of LHC physics program
- Must rely on evolution of HERA structure functions

QCD probes whole region

- Di-jet production
- b/c-quark jets
- Prompt photons

$$x_{1,2} = \frac{E_T}{\sqrt{s}}\left(e^{\pm\eta_1} + e^{\mp\eta_2}\right)$$

$$Q^2 \approx 2E_T{}^2 \cosh^2\eta^* \left(1 - \tanh\eta^*\right)$$



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Where do Jets come from at LHC?

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Fragmentation of gluons and (light) quarks in QCD scattering

- Most often observed interaction at LHC

Decay of heavy Standard Model (SM) particles

- Prominent example:

$$t \Rightarrow bW \Rightarrow jjj$$

$$t \Rightarrow bW \Rightarrow l\nu jj$$

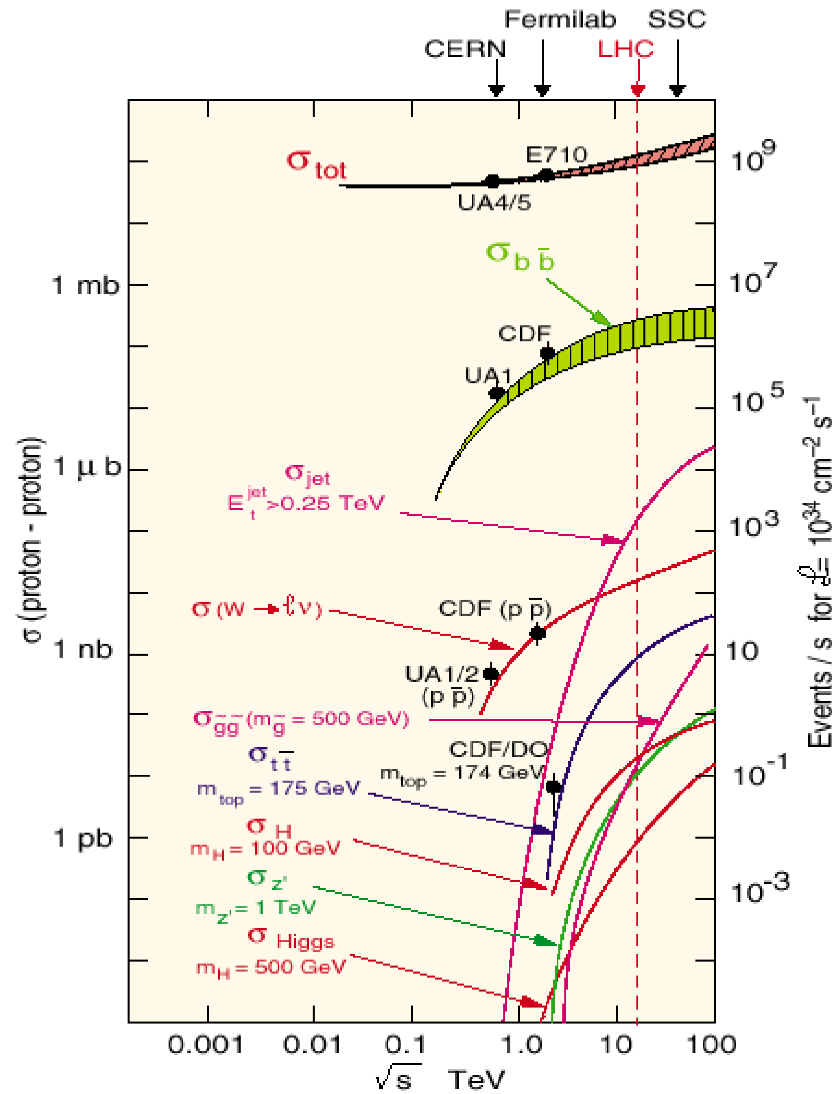
Associated with particle production in Vector Boson Fusion (VBF)

- E.g., Higgs

$$q\tilde{q} \Rightarrow q'\tilde{q}'WW \Rightarrow Hjj$$

Decay of Beyond Standard Model (BSM) particles

- E.g., SUSY



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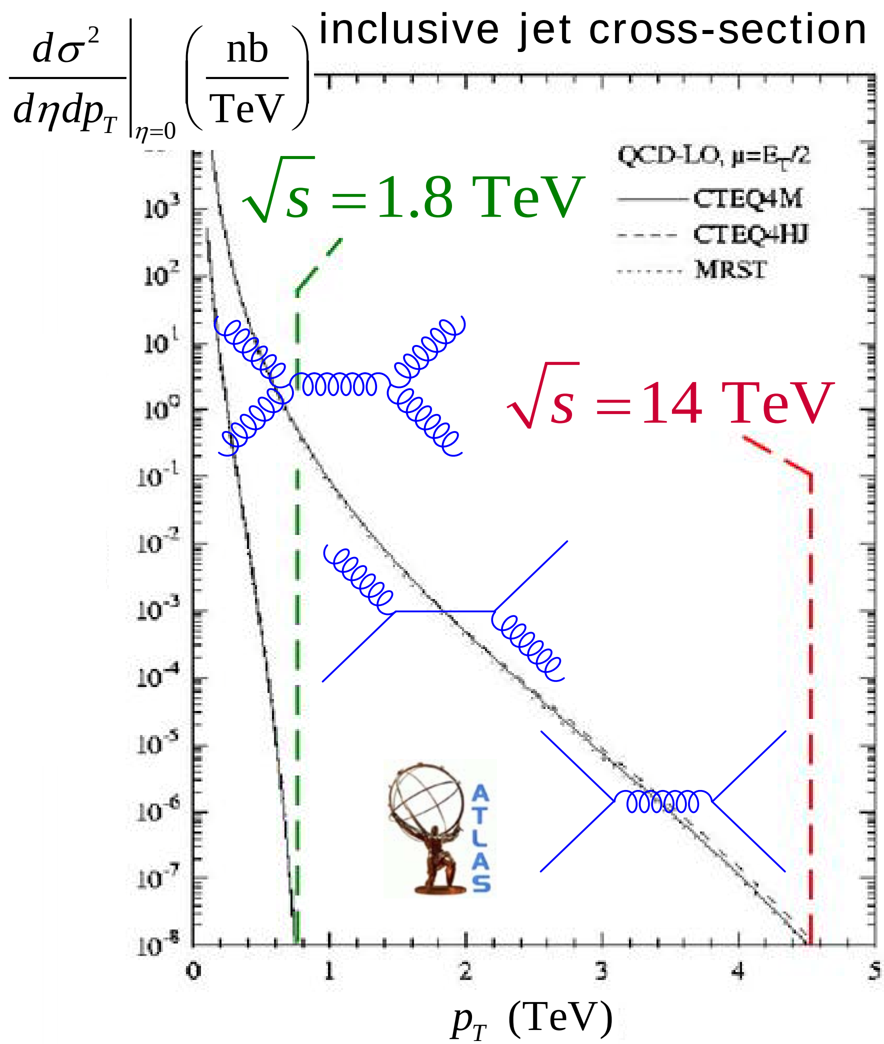

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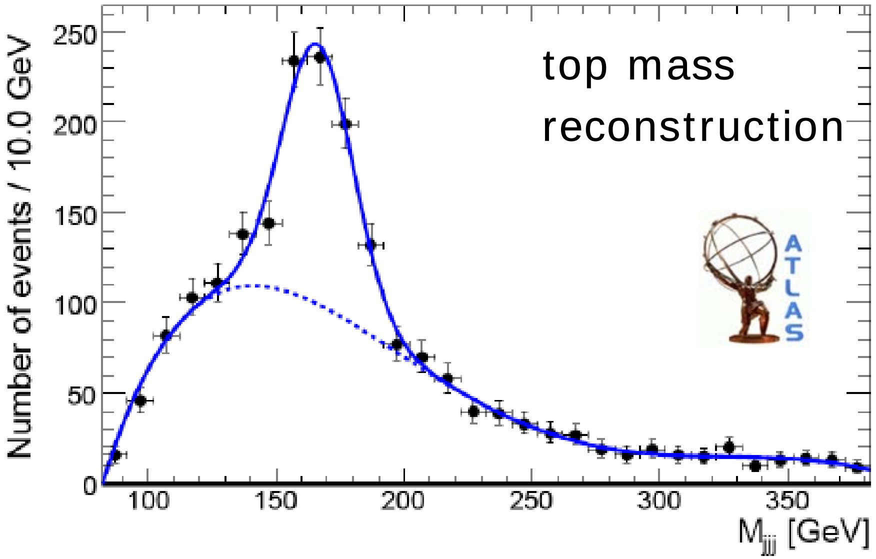

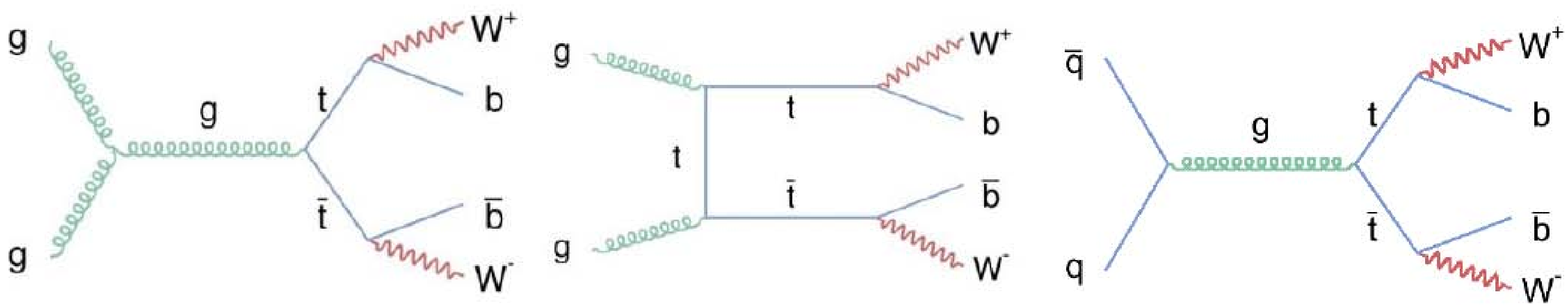

gg→tt 85%

qq→tt 15%

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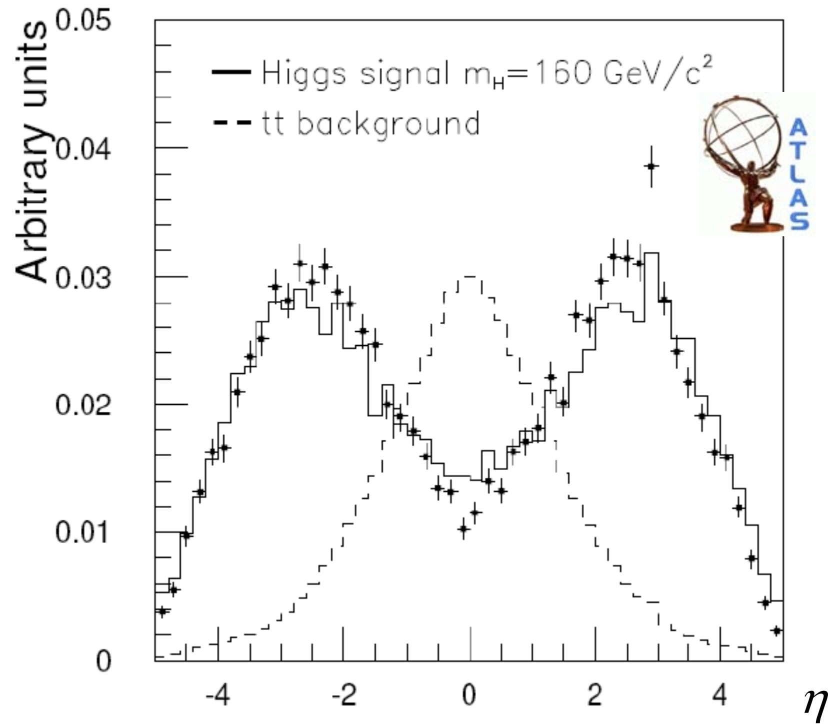

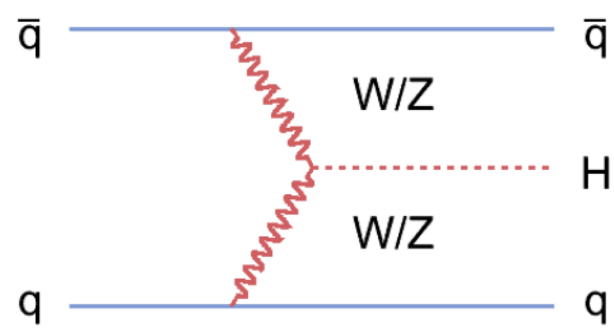

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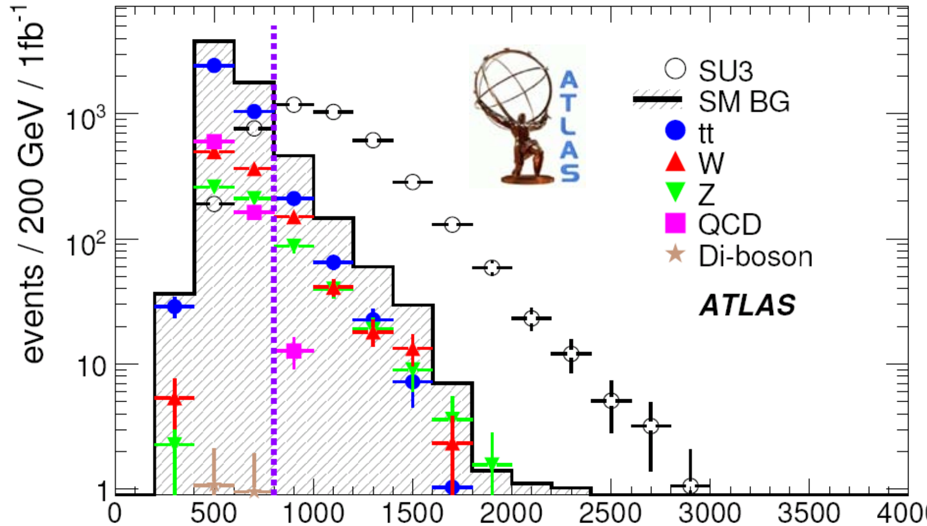
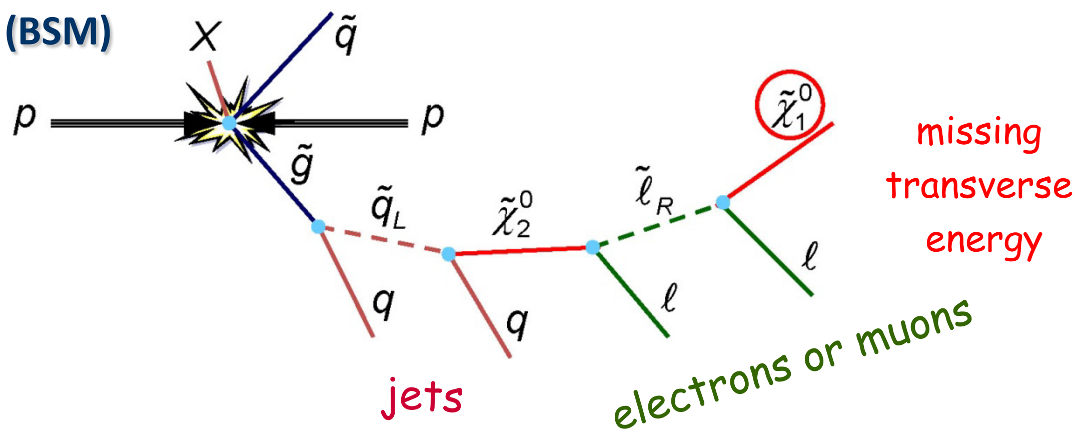


$$M_{eff} = \sum_{\text{jets}} \left| p_{T,j} \right| + \sum_{\text{leptons}} \left| p_{T,\ell} \right| + \not{p}_T$$



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Underlying Event

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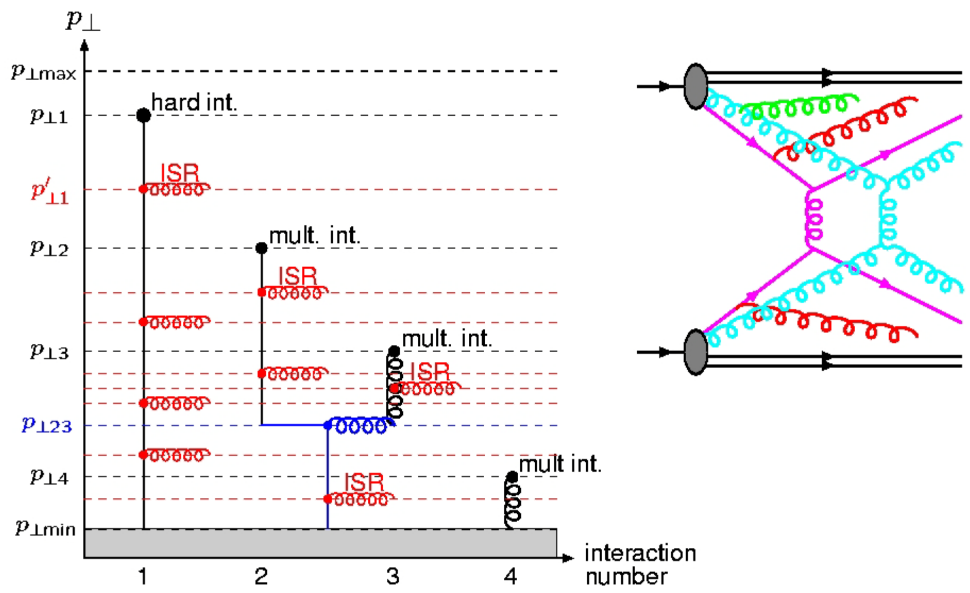
- **Collisions of other partons in the protons generating the signal interaction**
  - Unavoidable in hadron-hadron collisions
  - Independent soft to hard multi-parton interactions
- **No real first principle calculations**
  - Contains low pT (non-pertubative) QCD
    - Tuning rather than calculations
  - Activity shows some correlation with hard scattering (radiation)
    - pTmin, pTmax differences
  - Typically tuned from data in physics generators
- **Carefully measured at Tevatron**
  - Phase space factor applied to LHC tune in absence of data
  - One of the first things to be measured at LHC

Interleaved Multiple Interactions



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Underlying Event

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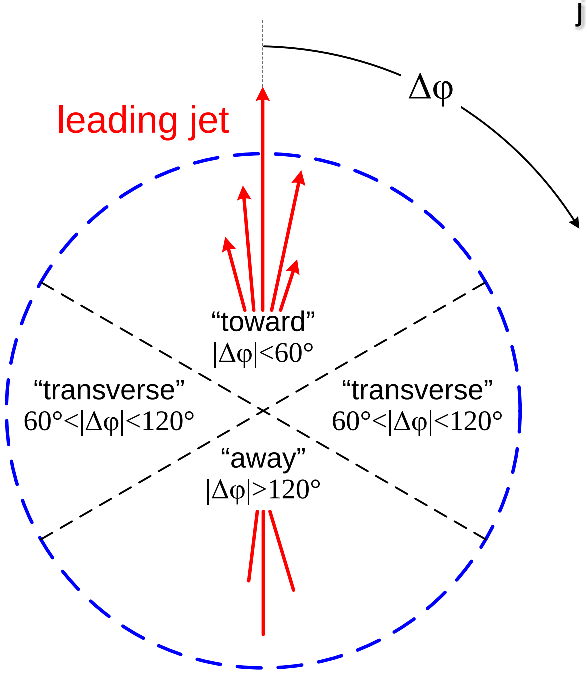
Rick Field's (CDF) view on di-jet events



Look at activity (pT, # charged tracks) as function of leading jet pT in transverse region

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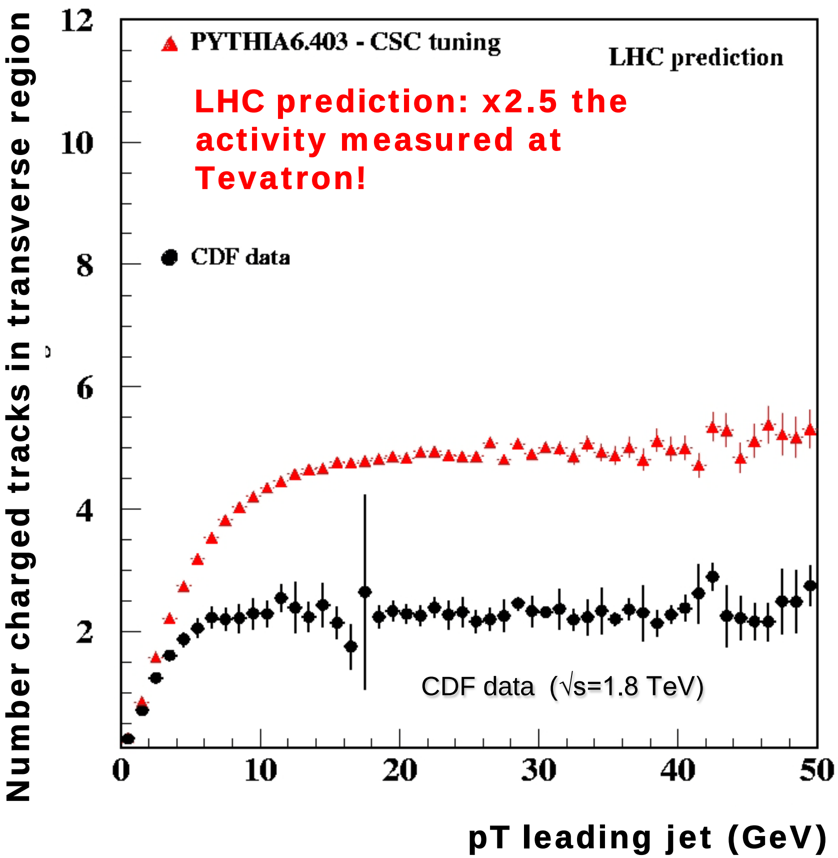
CDF data: Phys.Rev, D, **65** (2002)



Model depending extrapolation to LHC:

$\sim \ln^2 \sqrt{s}$ for PYTHIA

$\sim \ln \sqrt{s}$ for PHOJET

but both agree Tevatron/Sp$\bar{p}$S data!

Pile-Up

Multiple interactions between partons in other protons in the same bunch crossing

- Consequence of high rate (luminosity) and high proton-proton total cross-section (~75 mb)

Statistically independent of hard scattering

- Similar models used for soft physics as in underlying event

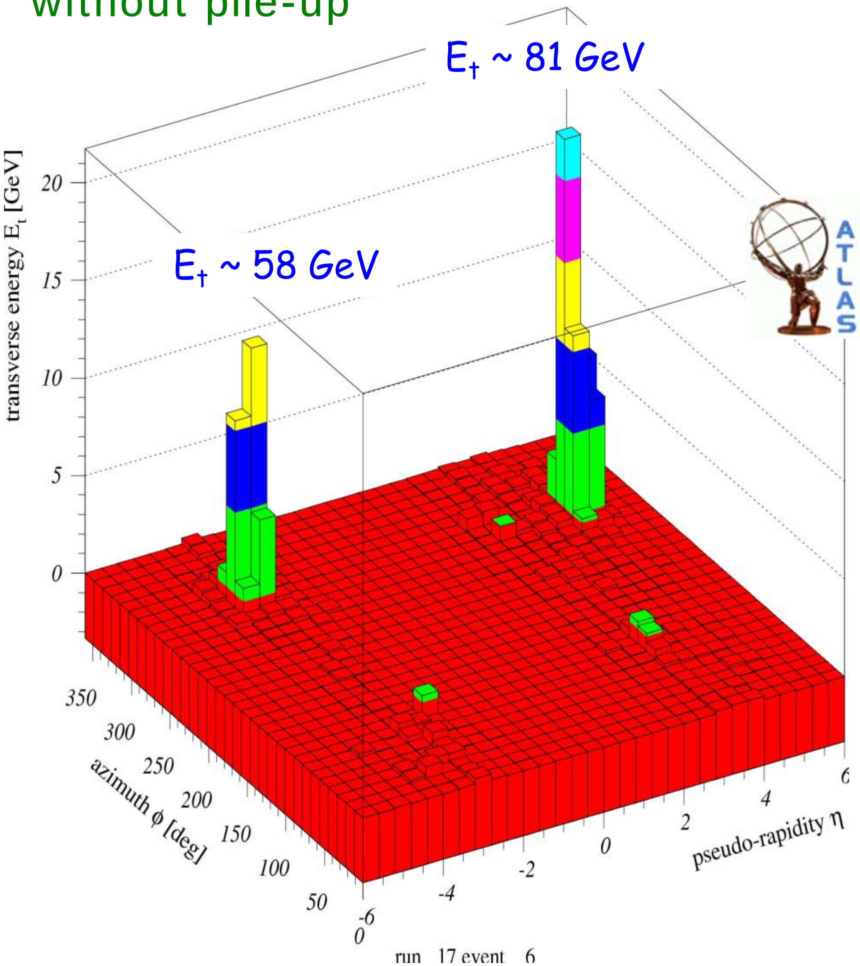
Signal history in calorimeter increases noise

- Signal 10-20 times slower (ATLAS) than bunch crossing rate (25 ns)

Noise has coherent character

- Cell signals linked through past shower developments

without pile-up



Prog.Part.Nucl.Phys. 60:484-551,2008

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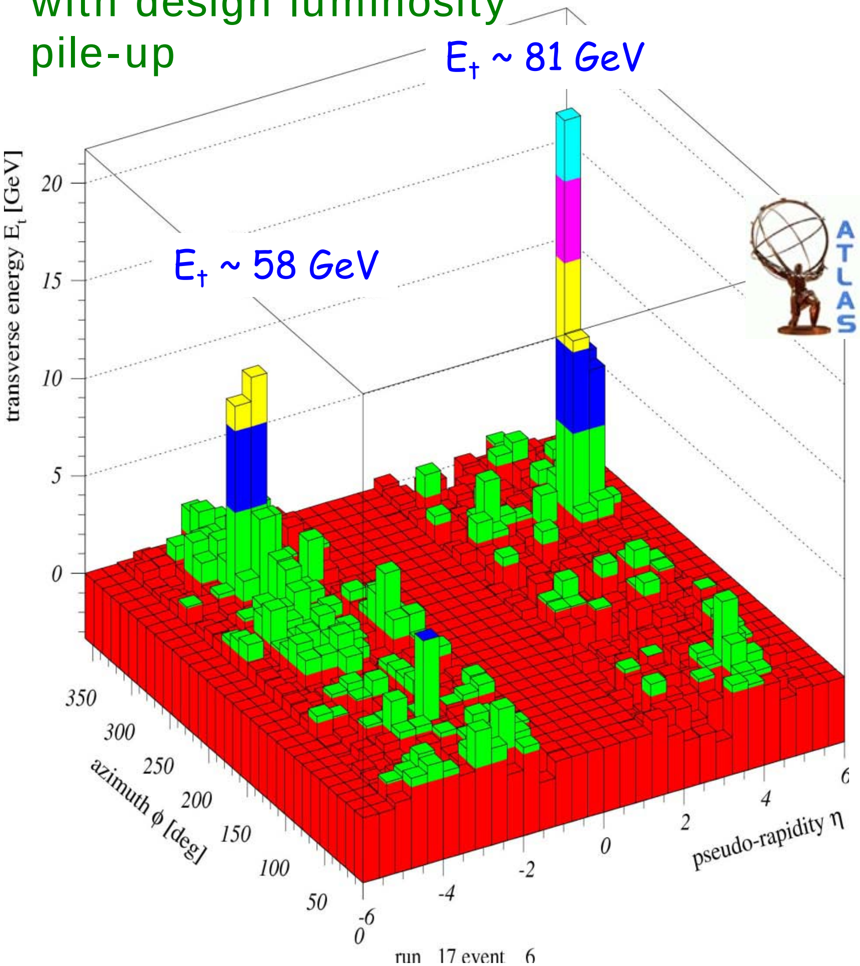
with design luminosity pile-up



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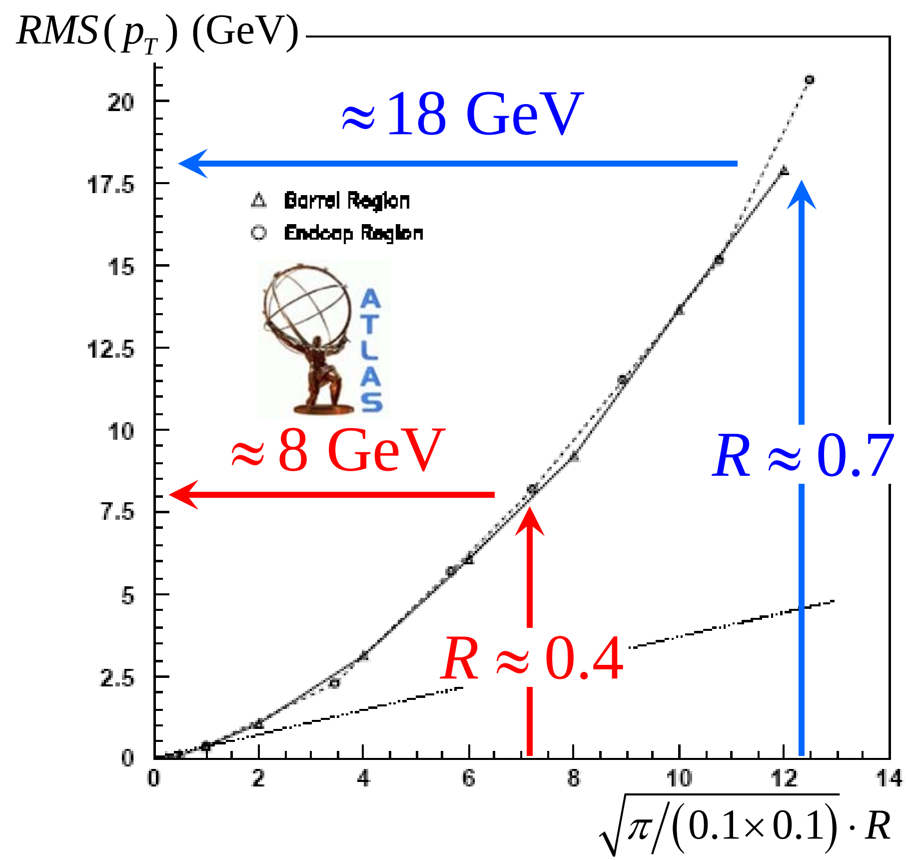

Prog.Part.Nucl.Phys. 60:484-551,2008

Why Is That Important?

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Jet calibration requirements very stringent

- Systematic jet energy scale uncertainties to be extremely well controlled
  - Top mass reconstruction
  - Jet cross-sections
- Relative jet energy resolution requirement
  - Inclusive jet cross-section
  - Di-quark mass spectra cut-off in SUSY

$$\Delta m_{top} < 1 \text{ GeV} \Rightarrow \frac{\Delta E_{\text{jet}}}{E_{\text{jet}}} < 1\%$$

$$\frac{\sigma}{E} = \begin{cases} \frac{50\%}{\sqrt{E(\text{GeV})}} \oplus 3\% & |\eta| < 3 \\ \frac{100\%}{\sqrt{E(\text{GeV})}} \oplus 5\% & |\eta| > 3 \end{cases}$$

Event topology plays a role at 1% level of precision

- Extra particle production due to event color flow
  - Color singlet (e.g., *W*) vs color octet (e.g., gluon/quark) jet source
- Small and large angle gluon radiation
  - Quark/gluon jet differences