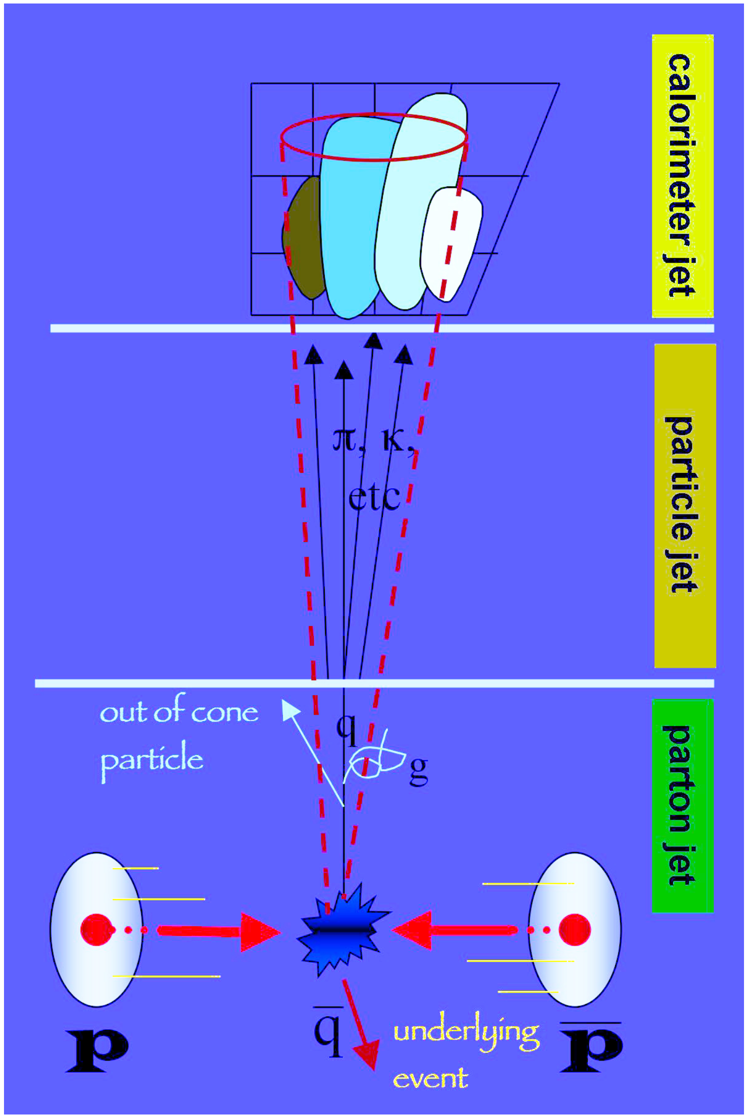
Hard Scattering in Hadron-Hadron Collisions: Physics and Anatomy

Section 4: Production & Identification of Jets

1. Definitions of Basic Physics Processes
2. Anatomy of a Jet
3. Jet-Finding Algorithms
4. Resolutions and Efficiencies
5. Heavy Quark Tagging
6. Example: Quark Substructure

Definitional Issues

- Confinement in QCD ensures that high P_T quarks & gluons undergo
  - Fragmentation -- ie, dissociation into a "jet" of coloured partons
  - Hadronization -- ie, the partons form colourless, observable hadrons
- Study of jets motivated by
  - Understanding QCD
  - Studying of heavy quarks
    - b/c quarks that fragment & hadronize before decay
    - Top quarks that decay before fragmentation/hadronication
  - Searching for new interactions that couple to quarks/gluons
  - Backgrounds to e, μ, γ & τ

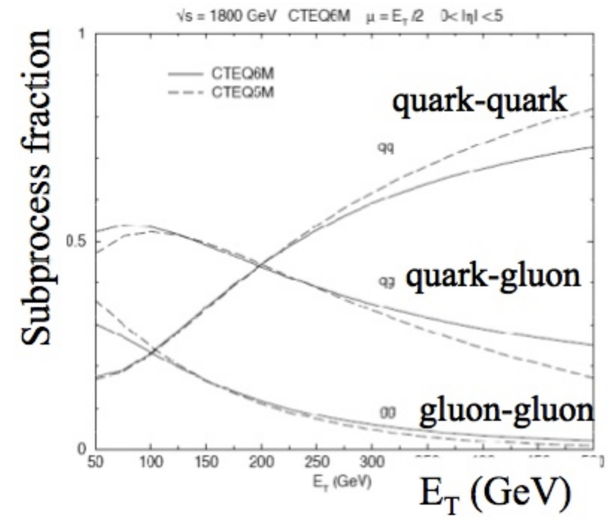


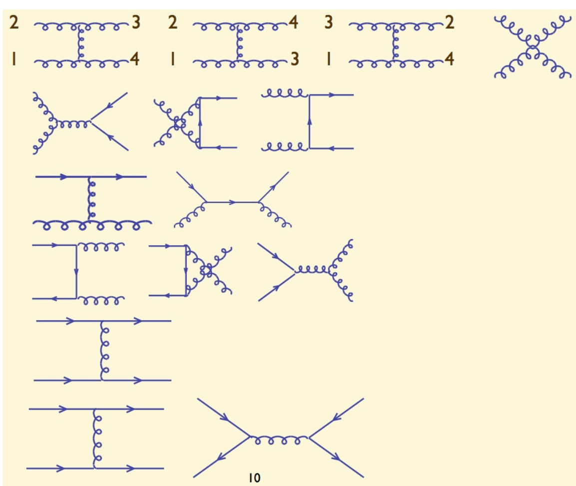
Fundamentals of Jet Physics

- **Basic production mechanism in pQCD starts with**

$$\sigma = \sum_{\substack{partons\ i \\ colour\ j}} C_{ij} \int_0^1 d\tau \int_\tau^1 \frac{dx_1}{\tau} \left[f_1(x_1) f_2(\tau / x_1) \right] \hat{\sigma}(\tau s)$$

  - **Leading-order (LO) diagrams already complex**



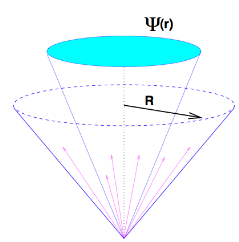


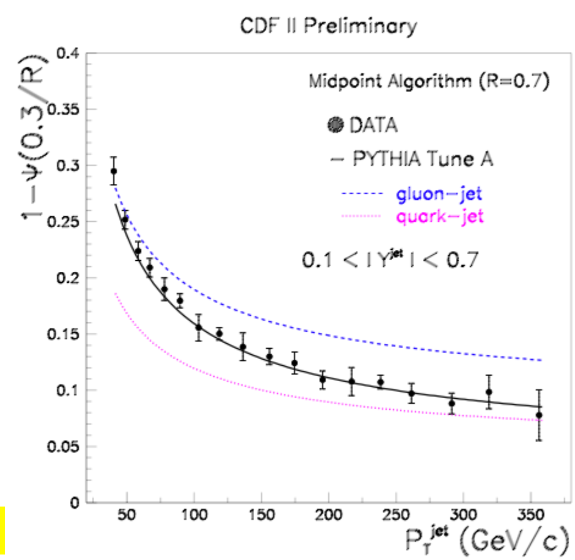
Process	$\bar{\Sigma}\|\mathcal{M}\|^2/g^4$	Numerical value for 90°
$qq' \to qq'$	$\frac{4}{9}\frac{\hat{s}^2+\hat{u}^2}{\hat{t}^2}$	2.22
$q\bar{q}' \to q\bar{q}'$	$\frac{4}{9}\frac{\hat{s}^2+\hat{u}^2}{\hat{t}^2}$	2.22
$qq \to qq$	$\frac{4}{9}\left(\frac{\hat{s}^2+\hat{u}^2}{\hat{t}^2}+\frac{\hat{s}^2+\hat{t}^2}{\hat{u}^2}\right)-\frac{8}{27}\frac{\hat{s}^2}{\hat{u}\hat{t}}$	3.26
$q\bar{q} \to q'\bar{q}'$	$\frac{4}{9}\frac{\hat{t}^2+\hat{u}^2}{\hat{s}^2}$	2.22
$q\bar{q} \to q\bar{q}$	$\frac{4}{9}\left(\frac{\hat{s}^2+\hat{u}^2}{\hat{t}^2}+\frac{\hat{t}^2+\hat{u}^2}{\hat{s}^2}\right)-\frac{8}{27}\frac{\hat{u}^2}{\hat{s}\hat{t}}$	2.59
$q\bar{q} \to gg$	$\frac{32}{27}\frac{\hat{t}^2+\hat{u}^2}{\hat{t}\hat{u}}-\frac{8}{3}\frac{\hat{t}^2+\hat{u}^2}{\hat{s}^2}$	1.04
$gg \to q\bar{q}$	$\frac{1}{6}\frac{\hat{t}^2+\hat{u}^2}{\hat{t}\hat{u}}-\frac{3}{8}\frac{\hat{t}^2+\hat{u}^2}{\hat{s}^2}$	0.15
$gq \to gq$	$\frac{4}{9}\frac{\hat{s}^2+\hat{u}^2}{\hat{s}\hat{u}}+\frac{\hat{u}^2+\hat{s}^2}{\hat{t}^2}$	6.11
$gg \to gg$	$\frac{9}{2}\left(3-\frac{\hat{t}\hat{u}}{\hat{s}^2}-\frac{\hat{s}\hat{u}}{\hat{t}^2}-\frac{\hat{s}\hat{t}}{\hat{u}^2}\right)$	30.4

What Have We Learned?

- **Definition of jets critical**
  - **Much evolution in algorithms**
  - **Driven in large measure by theoretical considerations**
- **Calibration of jets requires data-driven techniques**
  - **Developed several techniques to calibrate *in situ***
  - **Still "work in progress"**
- **Approach to jet-finding and calibration driven by physics**
  - **Best example is comparison between**
    - QCD tests
    - Reconstruction of heavy objects (top and Higgs)
- **Need data to understand jets as backgrounds**
  - **Examples include**
    - Lepton ID
    - MET measurement
    - Heavy quark tagging
  - **Use to "calibrate" MC/simulation**
- **Bottom line: SM Picture of QCD works well**

$$\Psi(r) \equiv \frac{1}{N_{jet}} \sum_{jets} \frac{P_T(0,r)}{P_T(0,R)}$$

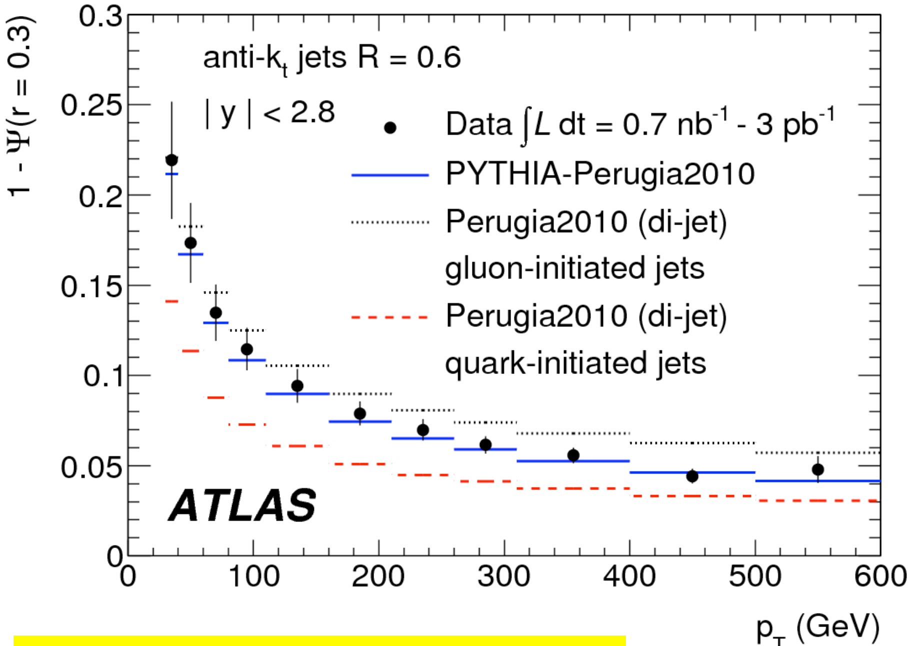




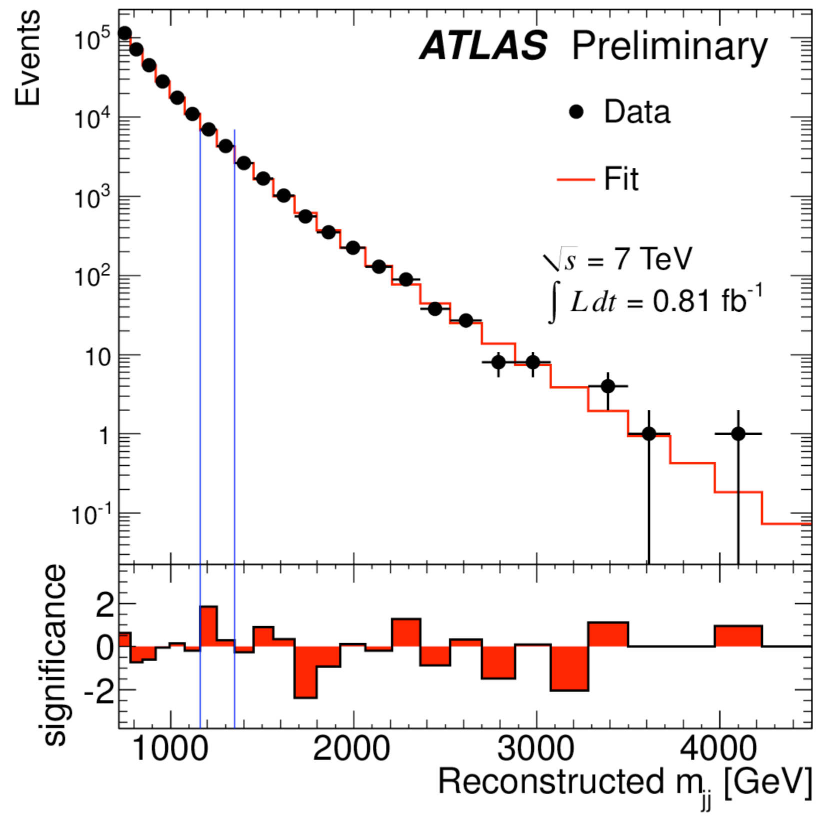
D. Acosta et al. (CDF), Phys. Rev. D 71, 112002 (2005)

LHC Lessons

- LHC studies have reproduced many of these observations
  - **However, much higher jet momenta**
    - Jets with $p_T > 2$ TeV
  - **Focus has been on searches**
    - Looking for resonances in dijet mass
    - Sensitive to excited quarks

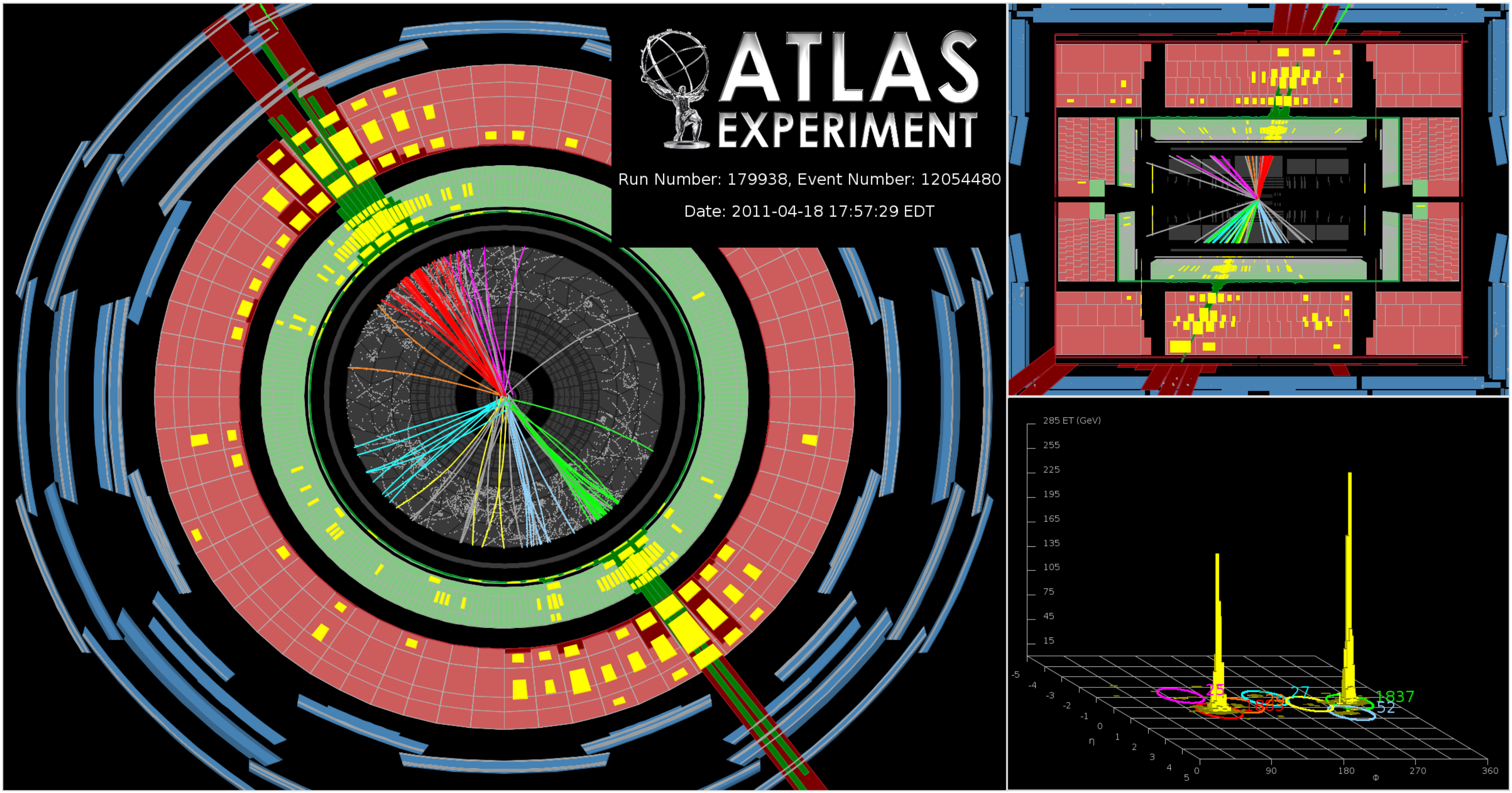


ATLAS Collaboration, Phys. Rev. D 83, 052003 (2011)



ATLAS-CONF-2011-096, 18 July 2011

Highest 2011 Dijet Mass Event



Jet Anatomy

- A jet arises from 2 different physical phenomena
  - Happen at different energy scales
    - Fragmentation of initial parton
      - QCD radiation of a coloured object
      - Creates a "cluster" of coloured partons
      - In principle, not independent of rest of event
      - Energy scale >> 1 GeV
    - Hadronization of "cluster"
      - Formation of colourless objects -- mesons & baryons
      - Responsible for the real observables
      - Energy scale ~ 1 GeV
- Have to worry about
  - What defines a jet (algorithm)?
  - What its properties are (recombination scheme)?

G. Blazey et al., FERMILAB-CONF-00-092-E and hep-ex/0005012, May 2000.

- First, tackle easiest part: What is a jet's observable properties?
  - Assume you have a collection of final state mass-less "particles" detected in calorimeter towers *i*

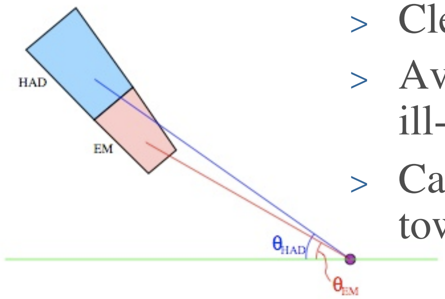
$$\vec{p}_J \equiv \left(E^J, p_x^J, p_y^J, p_z^J\right) \equiv \sum_i \left(E^i, p_x^i, p_y^i, p_z^i\right)$$

$$p_T^J \equiv \sqrt{\left(p_x^J\right)^2 + \left(p_y^J\right)^2}$$

$$M^J \equiv \sqrt{\left(E^J\right)^2 - \left(p^J\right)^2}$$

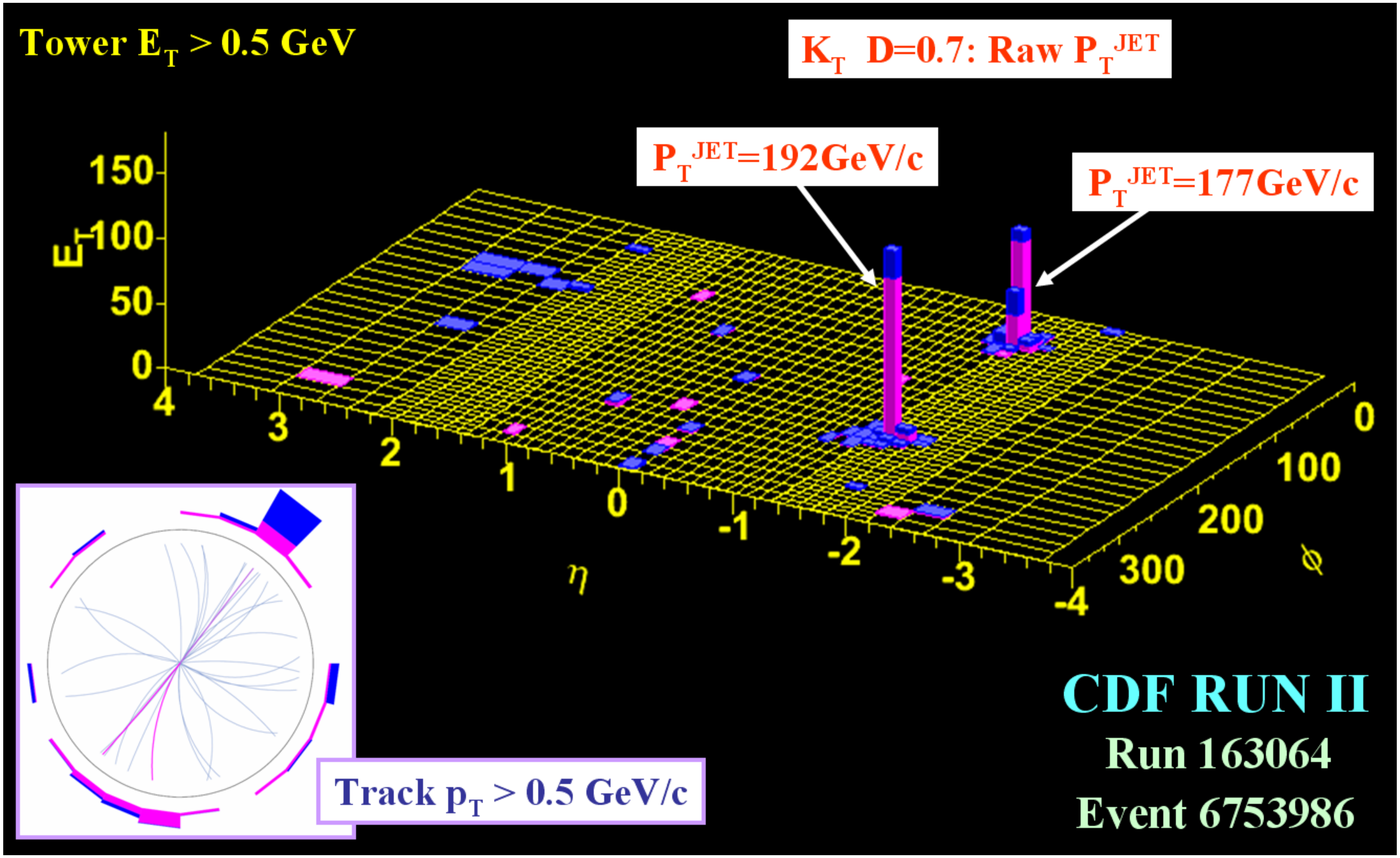
$$y^J \equiv \frac{1}{2}\ln\frac{E^J + p_z^J}{E^J - p_z^J}$$

$$\varphi^J \equiv \tan^{-1} p_y^J \big/ p_x^J$$

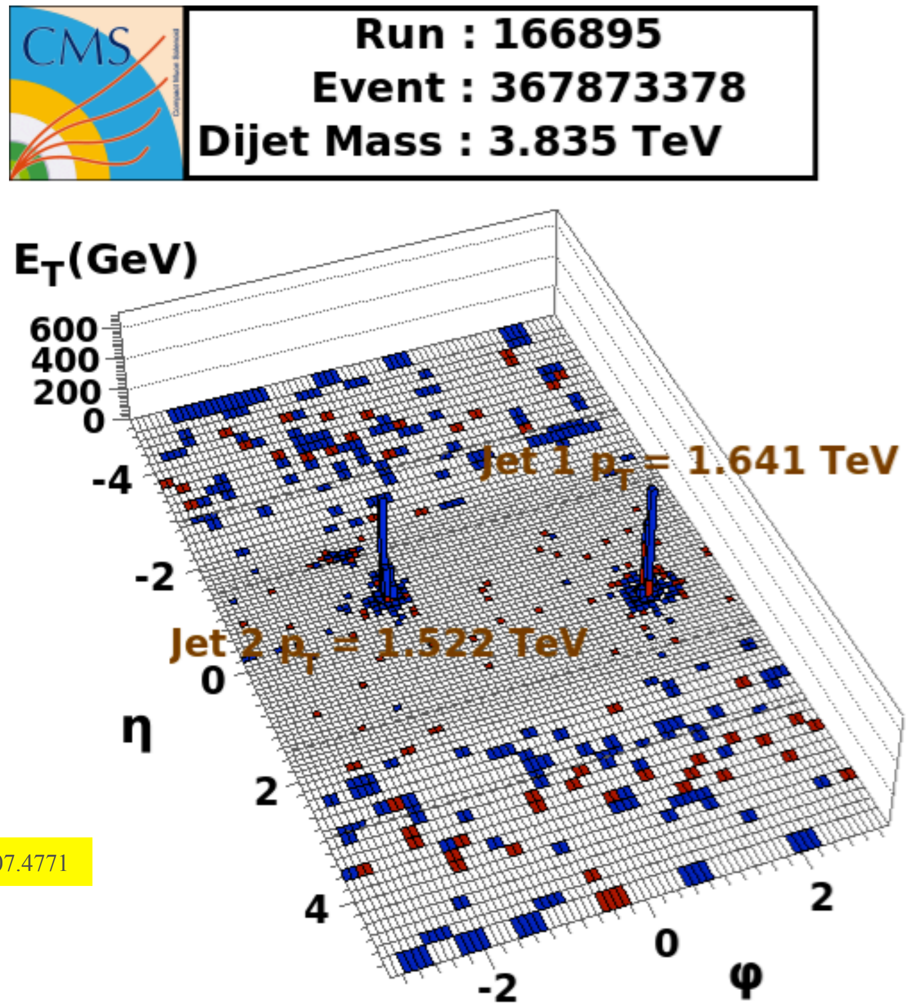


  - Advantages:
    - Clear Lorentz behaviour
    - Avoids use of E_T which has ill-defined definition
    - Can generalize to "cells", towers, charged particles, etc.

A Real Jet Event from CDF



An LHC CMS Jet Event



Highest dijet Mass event Observed by CMS at 7 TeV

CMS Collaboration, hep-ex/1107.4771

Parton Shower Evolution

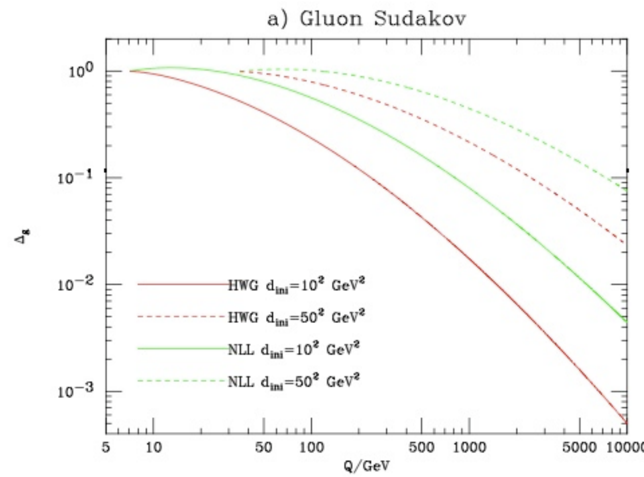
- **Start with a parton (q/g) with virtuality μ^2**
  - **Probability of emission with daughter carrying z fraction of parent momentum**

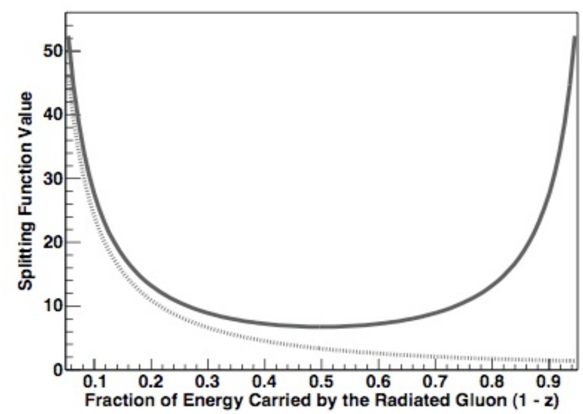
$$d^2 P_a\left(z,\mu^2\right) = \frac{d\mu^2}{\mu^2}\frac{\alpha_s}{2\pi} P_{a\to bc}(z)\, dz$$

  - **Order these using Sudakov factor, relating $\mu^2 \sim Q^2$**

$$P_a^{no}\left(Q^2_{\max}, Q^2\right) = \exp\left(-\int_{Q^2}^{Q^2_{\max}} dQ' \int_{z_{\min}}^{z_{\max}} dz'\, P_a\left(z', Q'^2\right)\right)$$

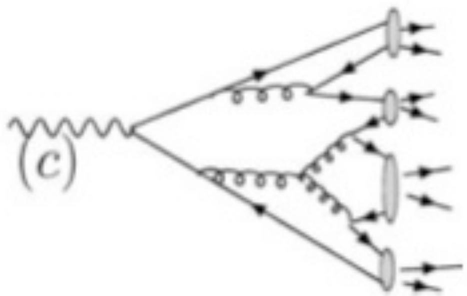
  - **Deal with infrared & collinear divergences**
    - Define minimum $\mu - \mu_0$
  - **Ensure colour coherence of multiple emissions**
    - Typically do this by angular ordering, selective vetoing, etc.
    - Must be respected when hadronization is performed





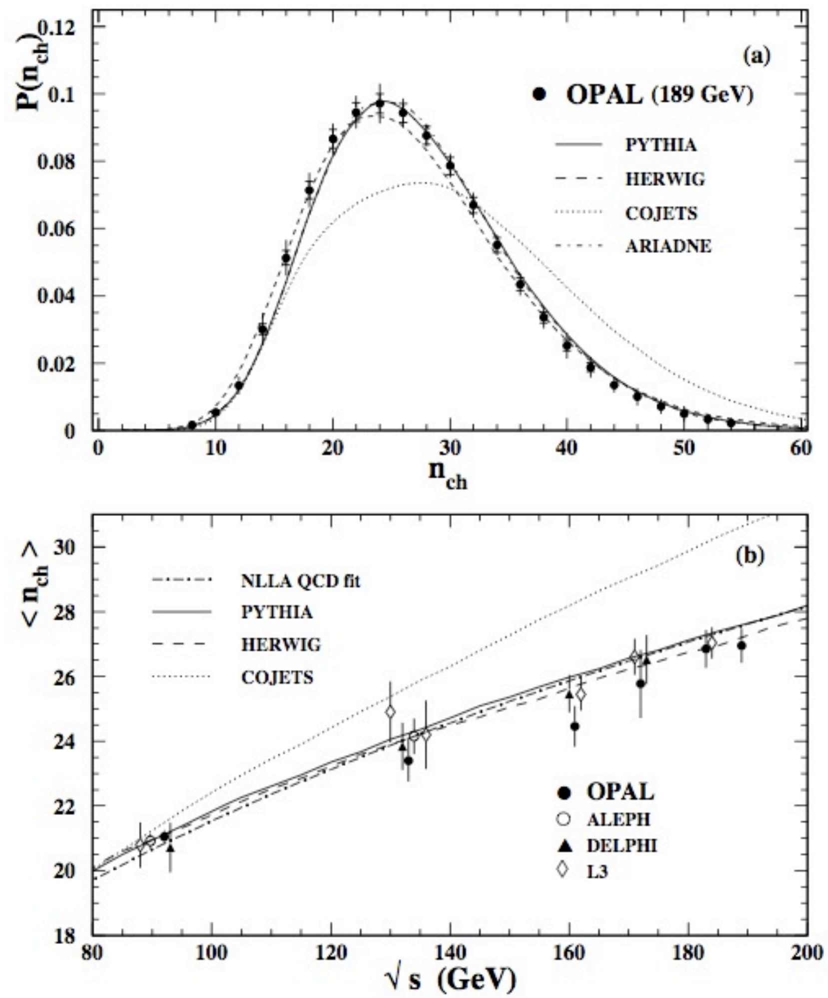
Hadronization of Showers

- **Hadronization is then performed**
  - **Invoke "parton-hadron duality"**
  - **Several models**
    - String fragmentation (eg., PYTHIA)
    - Cluster fragmentation (eg. HERWIG)



  - **Have various parameters that need to be tuned to data**
    - Best constraints from LEP
      - **Tevatron results confirm these, but don't really add much power**
      - **Challenging to measure without significant systematic uncertainties**
    - Remains a source of systematic uncertainty

OPAL, Eur. Phys. J C16, 185 (2000)



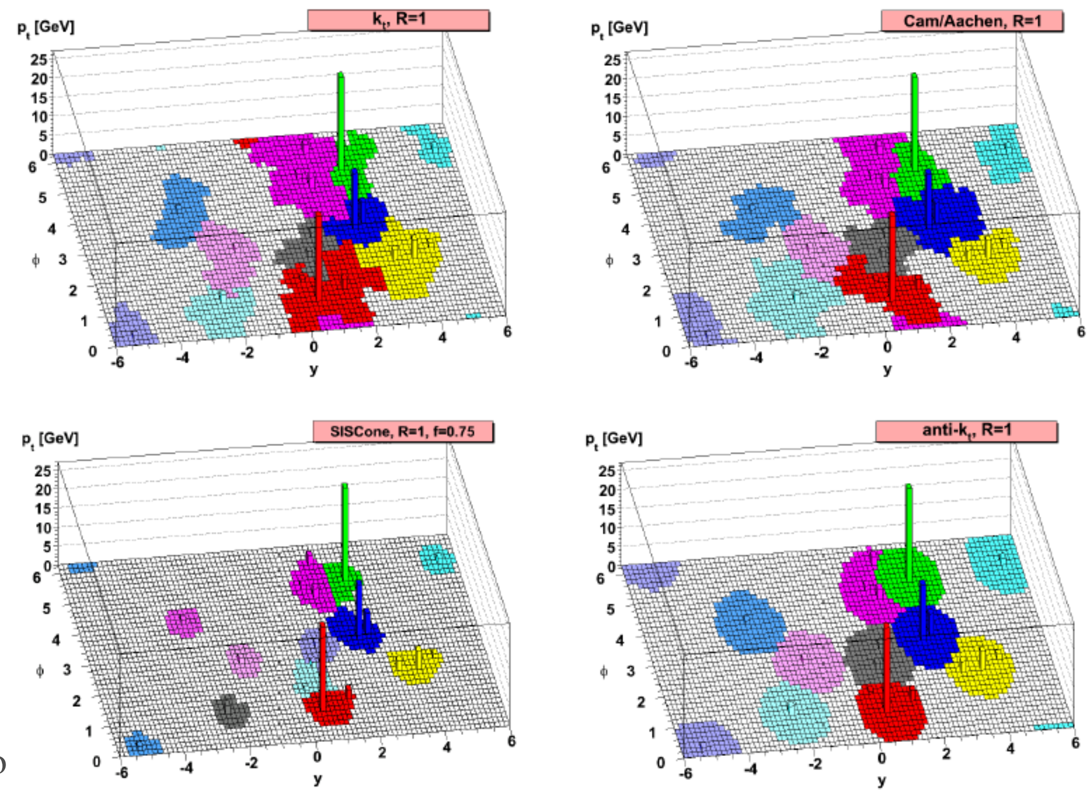
Jet Algorithms

- Jet clustering algorithms have evolved over the last 30 years
  - Goals of any algorithm can be divided into
    - Theoretically motivated:
      - Fully specified
      - Detector independent
      - Theoretically well-behaved
      - Order independent
    - Experimentally motivated:
      - Fully specified
      - Detector independent
      - Optimal resolution and efficiency
      - Ease of calibration
      - Computationally efficient
- Various efforts to develop consistent frameworks
  - Snowmass Accord (1990)
  - Les Houches Accord (1999)
- Raz Alon (see talk below) has done a nice job of summarizing current Jet Algorithm codes
  - Key observations:
    - In principle, prefer some algorithms over others
      - Seedless cone-based algorithms
      - K_T algorithms
    - Computational efficiency is a concern in some cases
      - But largely an issue of optimization
    - Selection of "best" algorithm requires evaluation of ultimate systematic uncertainties
      - Need data, as certain choices will depend on performance of calorimeter
      - Example is noise and pileup
  - Good news is that we are not limited by lack of ideas

R. Alon, http://indico.cern.ch/conferenceDisplay.py?confId=52628

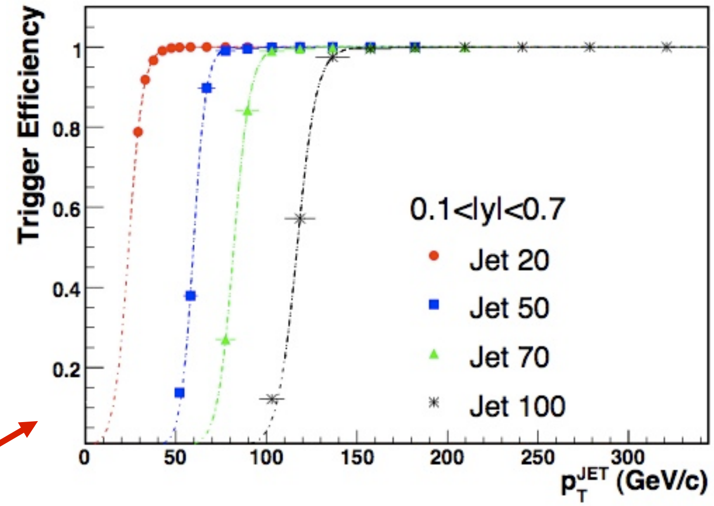
Clustering Effects

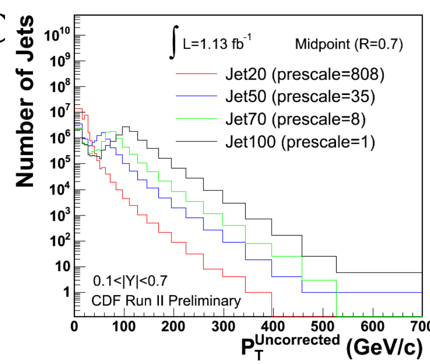
- Illustrate by one example (from ATLAS studies)
  - Compare results of several different algorithms
    - K_T with R=1
    - Angular-ordering (Cam/Aachen)
    - SISCone
    - Anti-K_T
  - Things to be concerned about
    - Cluster sizes determined by data will present challenges to calibrate
    - Cluster merging/splitting will continue to be a challenge
    - Optimization of resolution/ systematic uncertainties will require effort
  - Things not to worry about
    - Angular resolution (though need to check for any biases)!

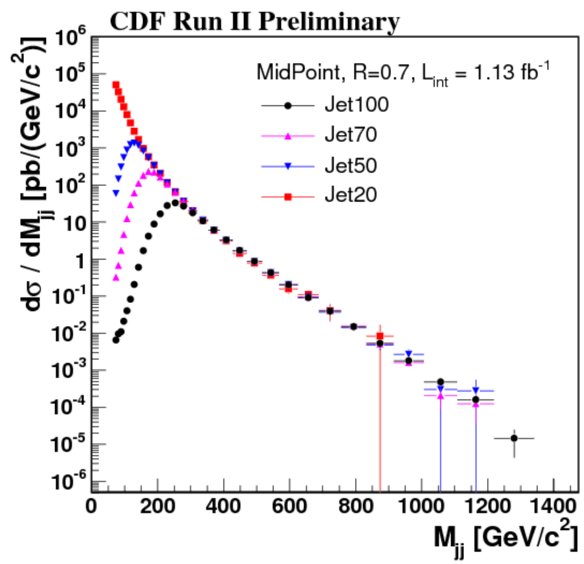


Jet Finding Efficiencies

- Efficiency of finding jets limited primarily by two effects:
  - Detector energy response & resolution
  - Physical size of jets
    - For cone algorithms, these two compete with each other
- Further complicated by the fact that jets are produced with sharply falling spectrum
  - Means that efficiencies become an issue already at the trigger level
  - Manage these at Tevatron & LHC with variety of triggers
    - Prescale lower-energy jet triggers (~10^3)
    - Lower energy jets used primarily for
      - Background studies
      - Calibration







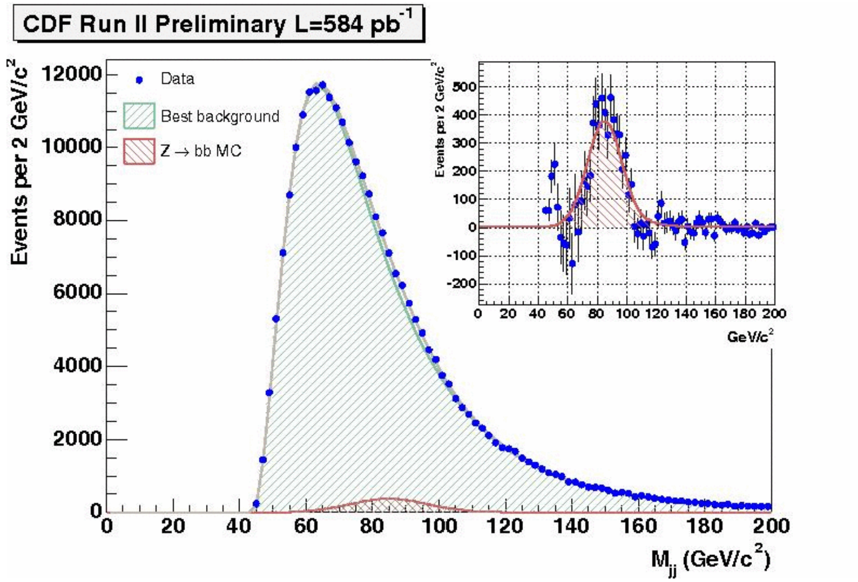
Jet Energy Resolutions

- MC & simulation give estimates of energy resolution
  - **Resolution is determined primarily by convolution of**
    - Intrinsic calorimeter response
    - Jet fragmentation & hadronization effects
    - Jet algorithm + pileup + ….
  - **In reality, need to measure the resolution in data**
- Four *in situ* measurements of resolution developed at Tevatron
  - **γ+jet balancing**
  - **W to qq in top quark decays**
  - **Dijet balancing (more of a constraint than anything else)**
  - **Z to bb decays**
    - Require two jets, each with secondary vertex b-tag
      - **Possible due to L2 vertex trigger**
- CDF: Taking the FWHM ~ 25 GeV/c², obtain

$$\sigma_Z \sim 12\% \; M_Z$$

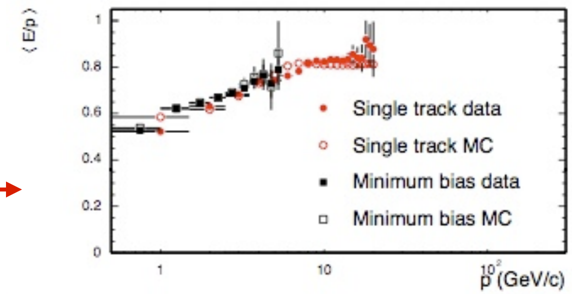
$$\Rightarrow \frac{\sigma}{P_T^J} \sim 17\%$$

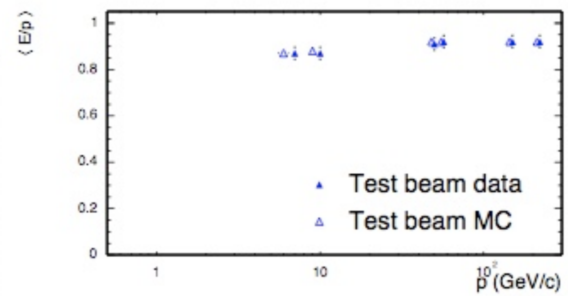
  - **Or about 50% more than intrinsic energy resolution of calorimeter**

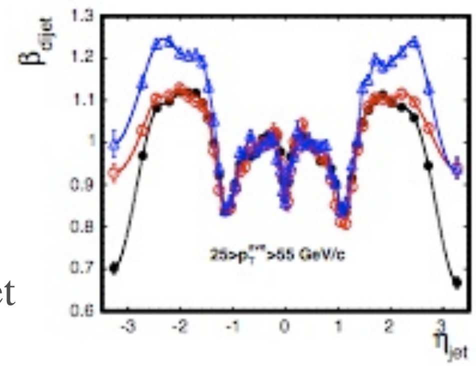


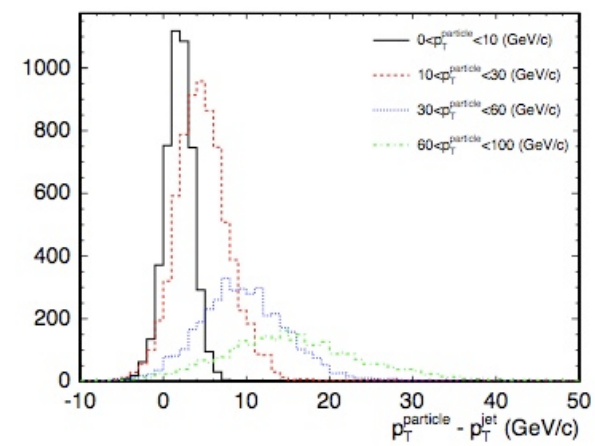
Jet Energy Calibration

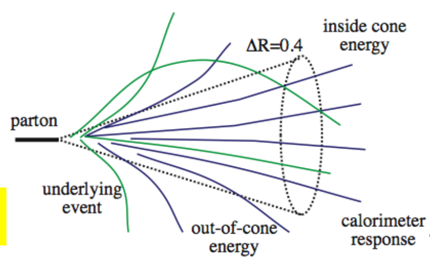
- **To calibrate jet energy scale:**
  - **1. Determine intrinsic response to particles**
    - Combination of in situ measurements & test beam data
  - **2. Dijet balancing to get uniform η response**
    - Primarily dijet data
    - "Tune" MC and simulation
  - **3. Determine absolute response to "particle jet"**
    - Define particle jet as all real particles in cone of jet
    - Account for calorimeter nonlinearity, cracks, etc.
  - **4. Take into account "out-of-cone" effects, multiple interactions**
    - Use combination of MC and data









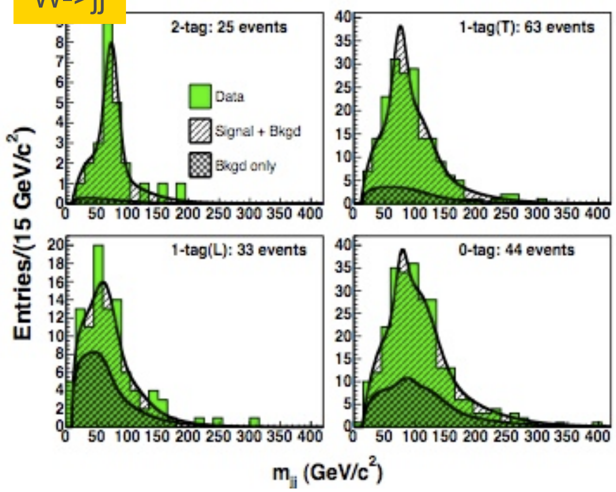


A. Bhatti et al., Nucl. Instrum. Meth. A566, 375 (2006)

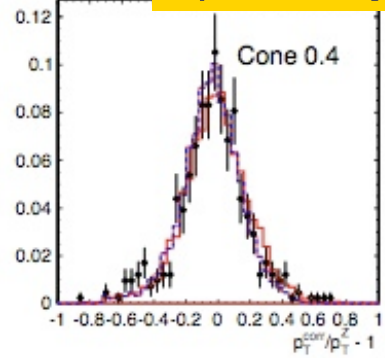
Final Steps in Energy Calibration

- Cross check using, for example,
  - Z+jet & γ+jet balancing
  - Dijet balancing
  - W-> jj in ttbar events

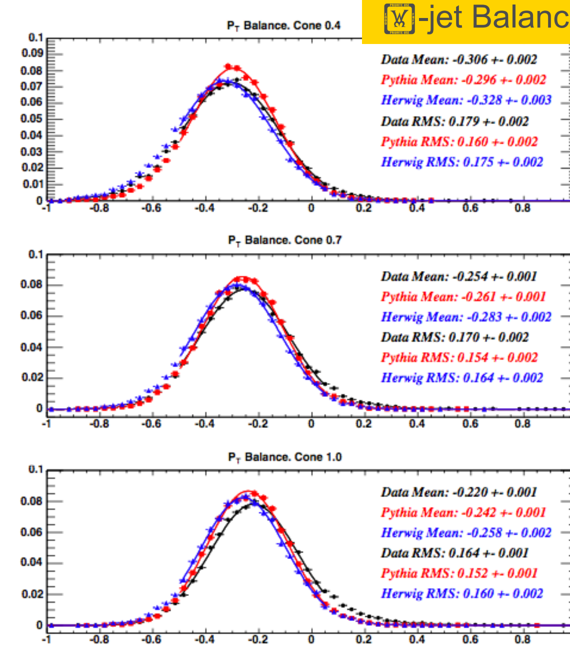
W->jj



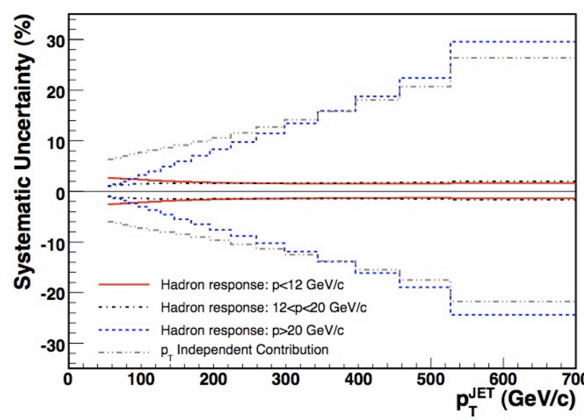
Z-jet Balancing



γ-jet Balancing

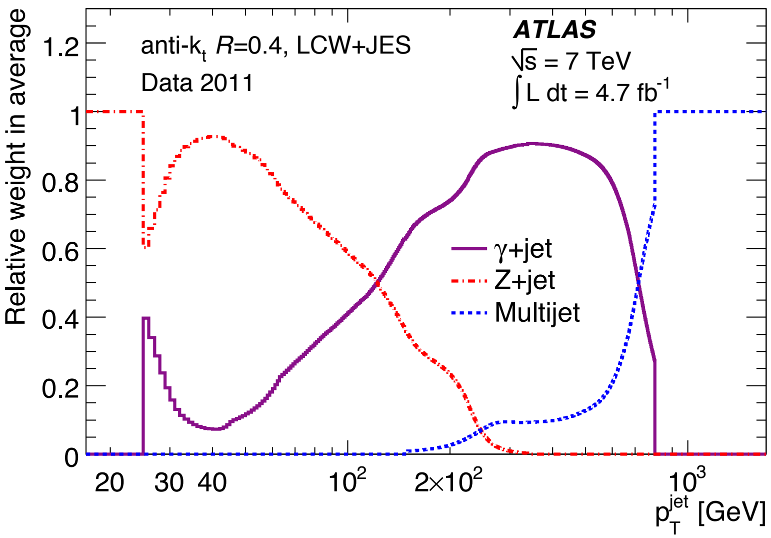


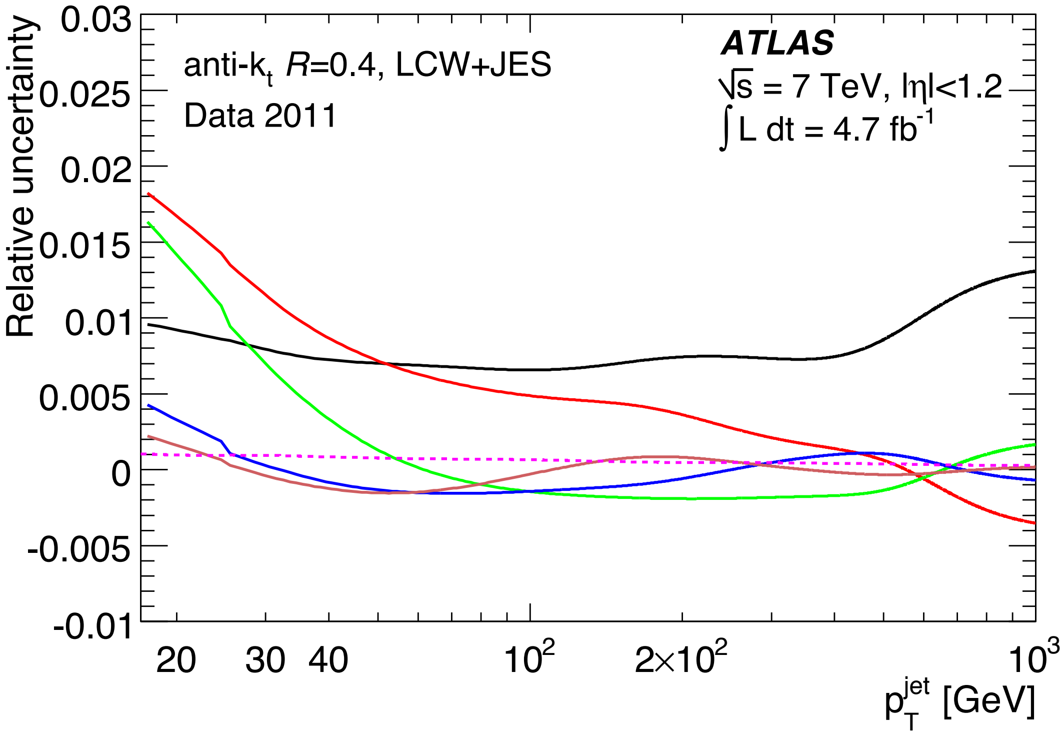
- Estimate systematic uncertainties
  - Estimate each source independently
  - Struggle with the fact that we cannot measure high P_T jet response



ATLAS Jet Calibration

- Used similar techniques
  - Z+jet & γ+jet balancing
  - Dijet balancing
  - Also extended and tested other techniques
  - Have 2 calibration schemes
    - EM+JES
    - LCW+JES

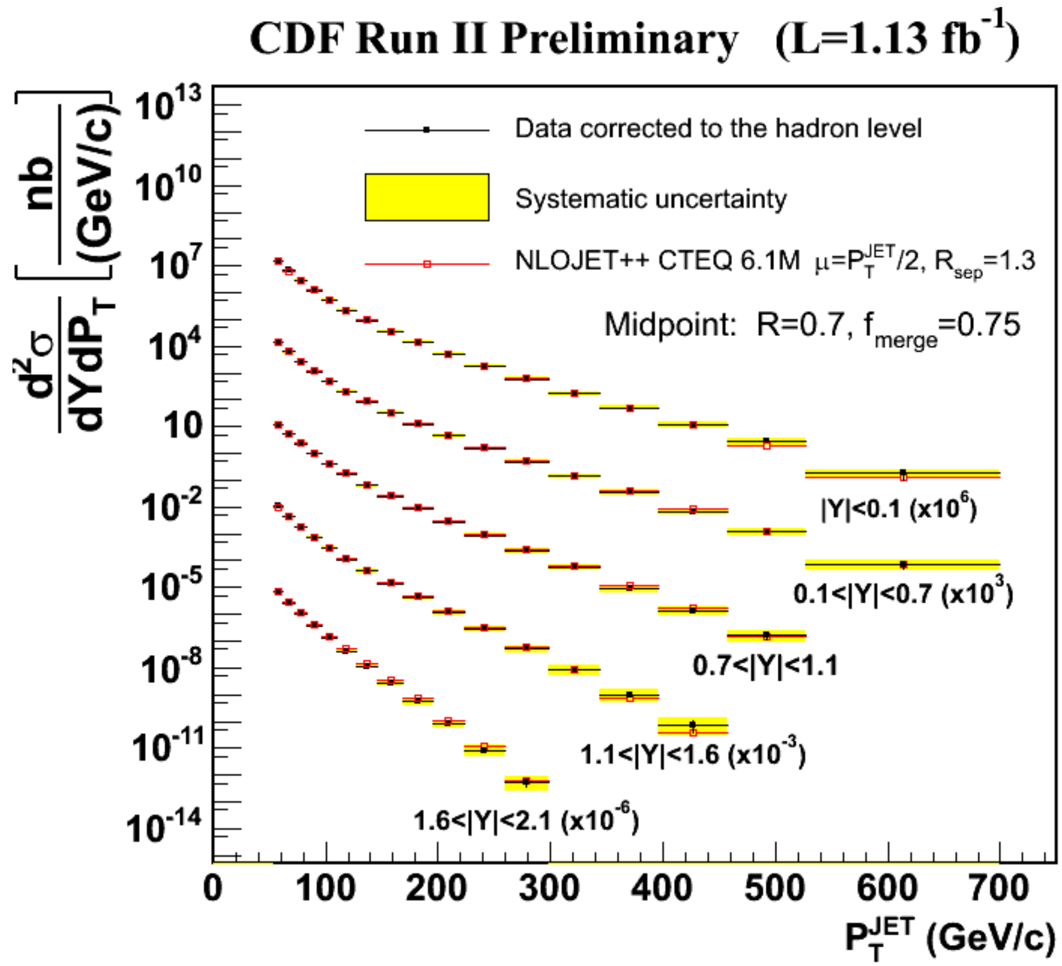




ATLAS Collaboration, Eur. Phys. J. C (2015) 75:17, arXiv:1406.0076

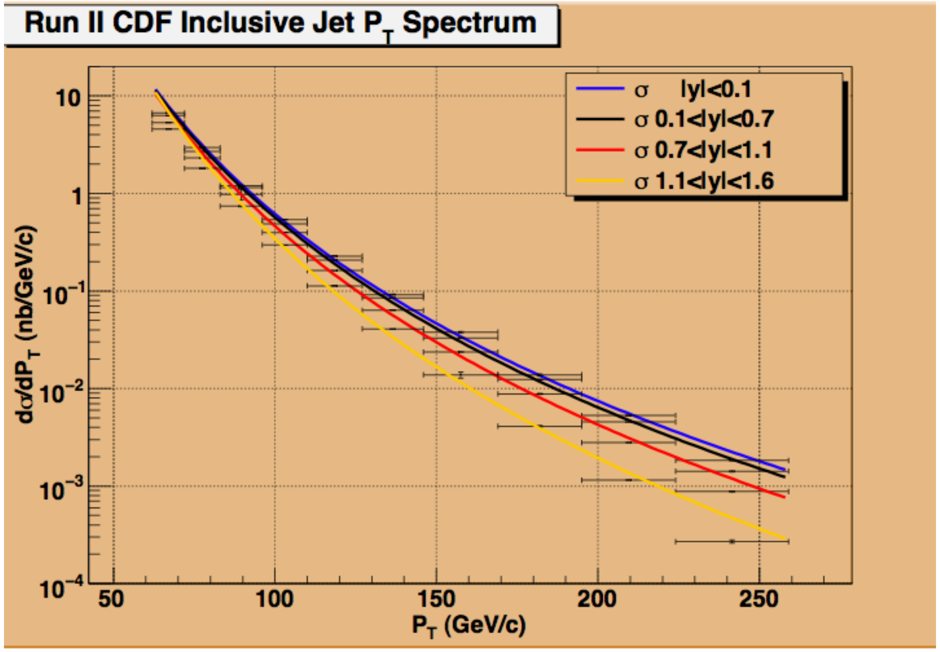
Production Cross Sections

- CDF analysis of ~1.13 fb^{-1} of jet data
  - Used mid-point algorithm with R=0.7, f_{merge}=0.75
  - Data is scaled in plot to avoid overlapping
- Provide a strong test of QCD
  - Theoretically "clean" to model
  - Compare with NLO calculations
    - Fill in details!
  - Generally a trend of small excess of events at higher P_T
  - Not statistically significant given systematic uncertainties



Total Jet Production Rates

- An "Exercise to Reader" – what is total cross section?
  - To answer this question
    - Fit the spectrum in each y bin to power law using ROOT
    - Use fit to extrapolate over various P_T ranges
      - **Was lazy, only did the first four bins**
    - Generally, differential cross section falls with $(P_T)^{-6}$
      - **And gets a little steeper as P_T increases**
      - **Means that higher P_T jets tend to be more central**
- Note large cross section at low P_T
  - This is the source of backgrounds to other objects
  - Also note that these are quite uncertain given the extrapolation!
    - Eg., just changing range of fit
      - **$\Delta\sigma(P_T>10)\sim30\%$**

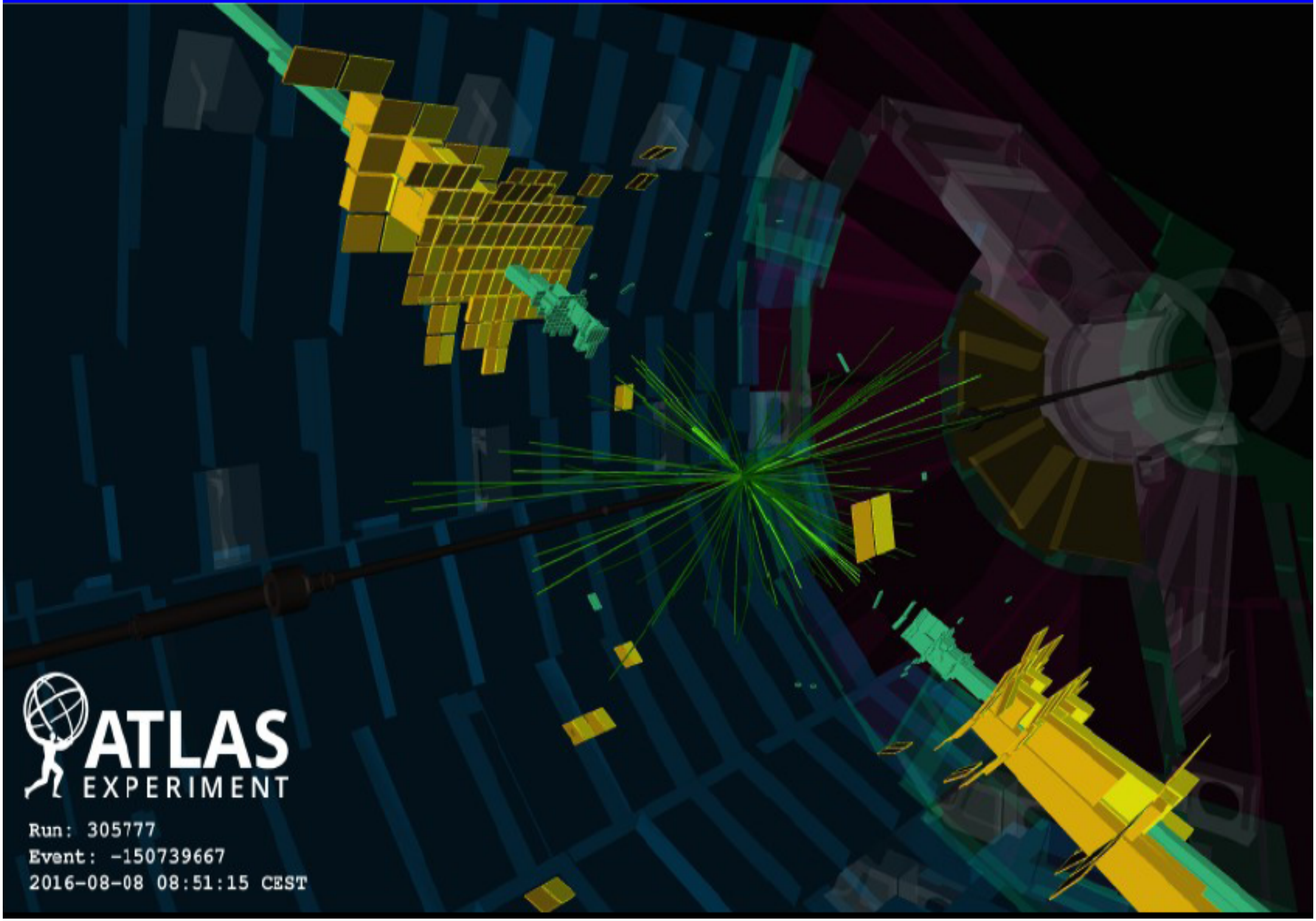


Cross Section (in nb)

	PT > 62 GeV	PT > 30 GeV	PT > 10 GeV
|y| < 0.1	122	5,600	1,800,000
0.1 < |y| < 0.7	111	5,600	2,000,000
0.7 < |y| < 1.1	96	6,100	3,000,000
1.1 < |y| < 1.6	93	8,900	8,900,000
	422	26,200	15,700,000

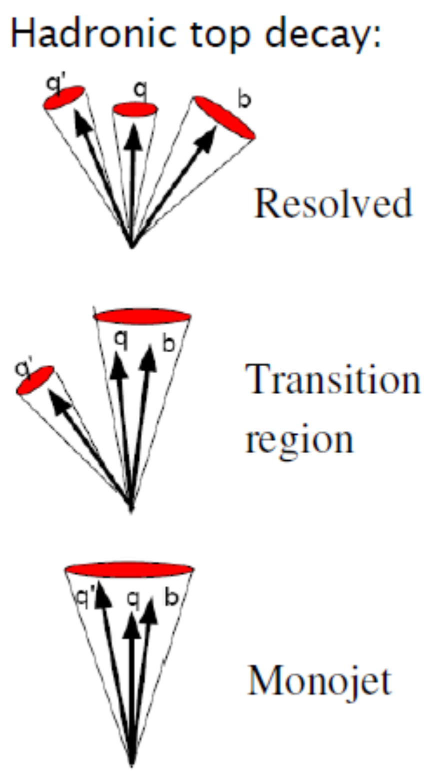
Note: Another ~5-10% in rapidity interval 1.6 < |y| < 2.1

Highest-mass dijet event (8.12 TeV)



Choice of Distance Parameter?

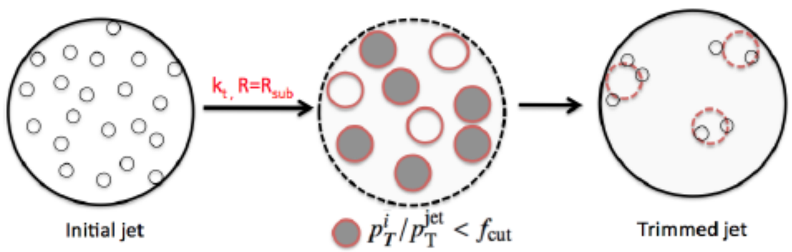
- *anti-k_t* **default algorithm**
  - **Default R=0.4 or 0.5 distance parameter**
  - **Balance between**
    - capturing full parton shower
    - contamination from UE and other jets
- **Large-R jets are used to ensure full containment**
  - **Use *anti-k_t* or *Cambridge-Achen* algorithms**
  - **Have to have some form of pileup correction or mitigation**
- **Test case is top quark decays**
  - **Small-R jets best for "resolved topology"**
  - **But merging is an issue for top quark p_T's $\gtrsim$ 350 GeV**



- **Solution is to use pileup rejection**
  - **Trimming has become a standard approach**
  - **Other strategies have also been studied**
  - **Key is to do it in a theoretically controlled manner**

Trimming!

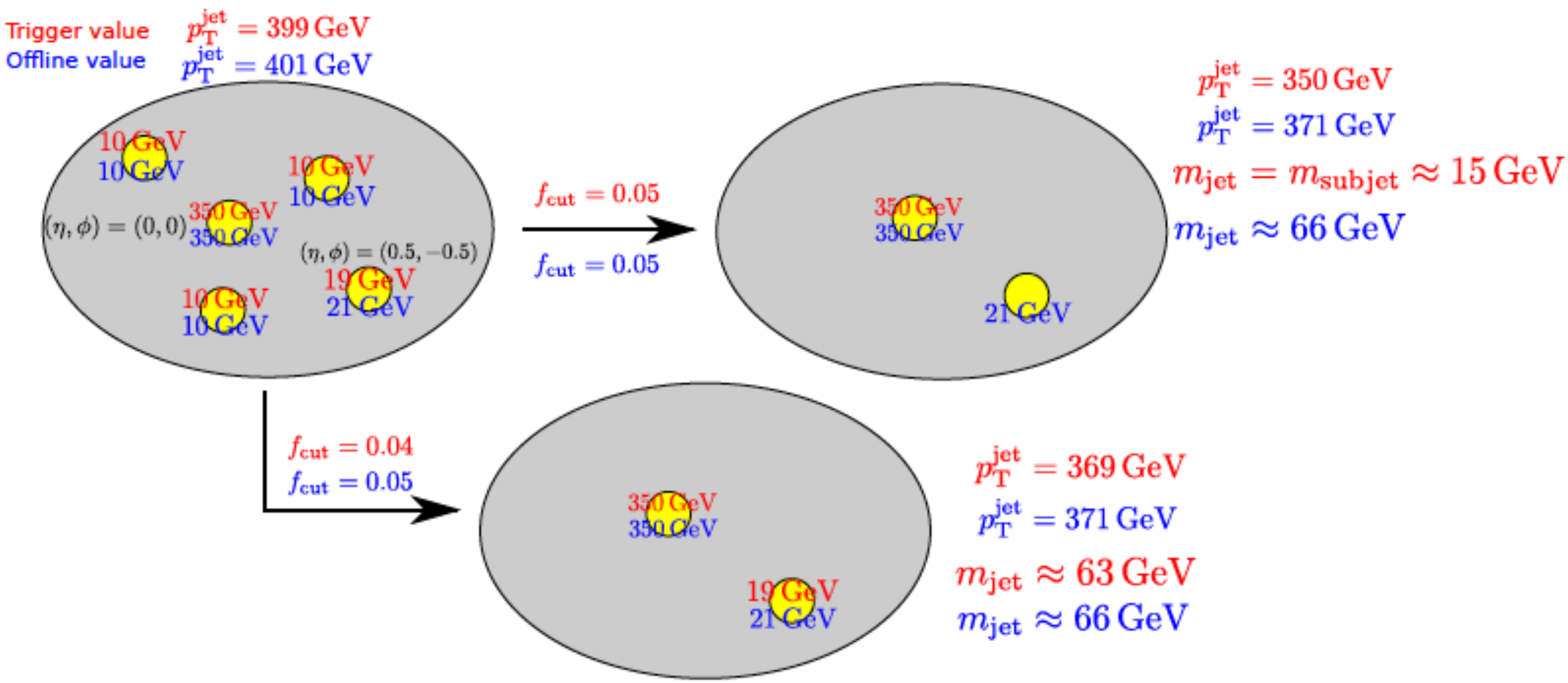
- **Example of how trimming works**



- Trimming: recluster jet into sub-jets of $R_{\mathrm{sub}} = 0.2$
- Only keep subjets with $p_{\mathrm{T}}^{\mathrm{subjet}} / p_{\mathrm{T}}^{\mathrm{jet}} > f_{\mathrm{cut}}$

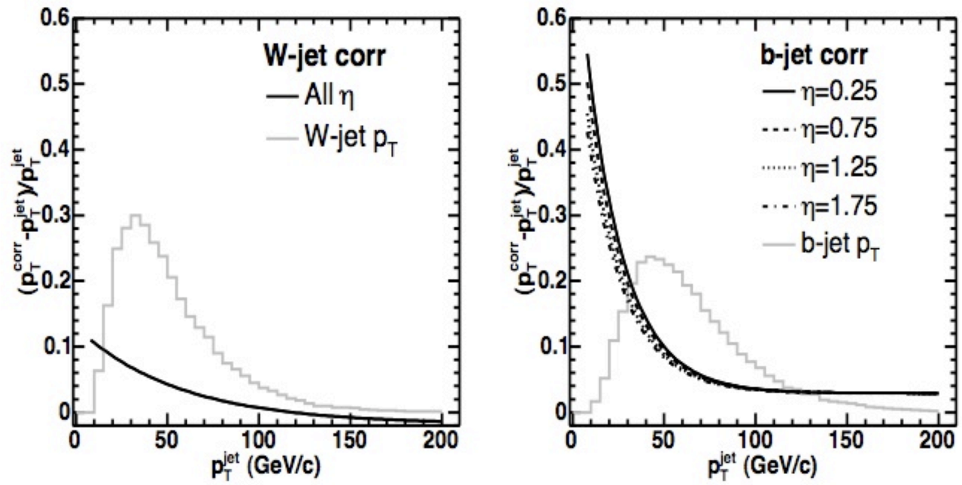
– **Have to choose R_{sub} and f_{cut} judiciously**

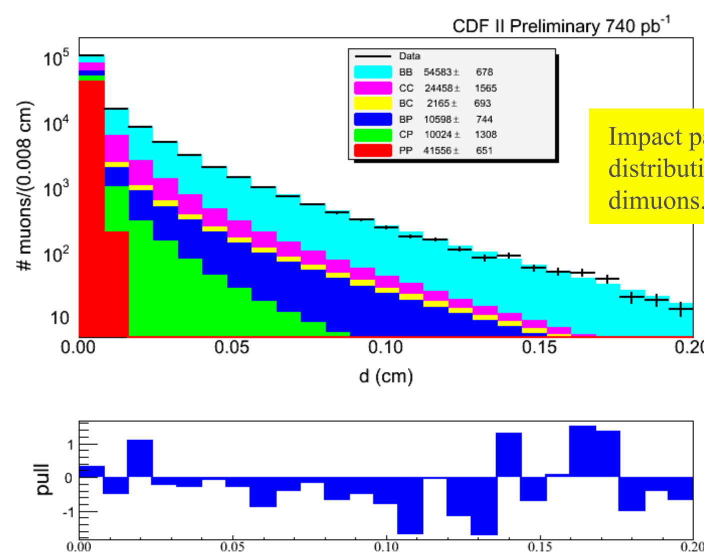
Real Effects of Trimming!



Heavy Quark Jets

- Heavy quarks (b/c) also manifest themselves as jets
  - Different fragmentation process
  - Different hadronization
    - Result in kinematics that differ from light quark & gluon jets
  - “rich” in ν ‘s and charged leptons
    - Used for identification
    - But also affect efficiency and & energy resolution
  - Relatively long lifetimes allow for tagging using secondary vertices
    - Become “standard” technique
- Bottom quarks have been particularly important
  - Essential for top quark studies
  - Result in unique capabilities at hadron colliders
    - Good example is B_s studies

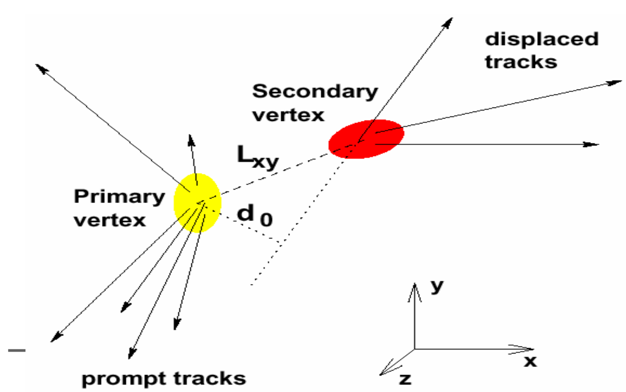




Impact parameter distribution, CDF dimuons.

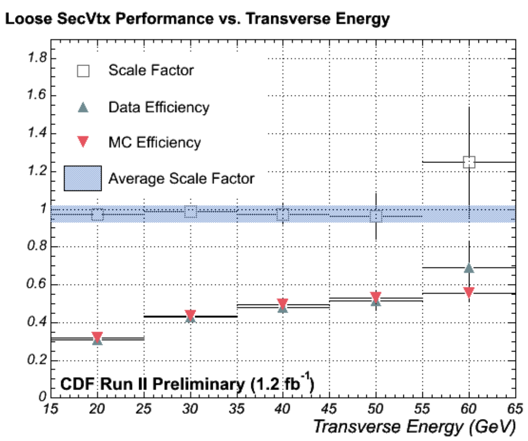
Heavy Flavour Tagging

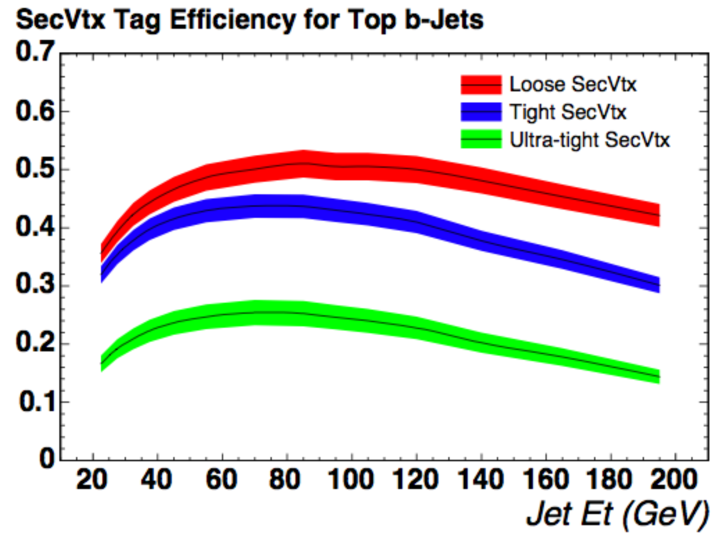
- Heavy flavour tagging has been essential tool at Tevatron
  - Top quark search
  - Search for Higgs
  - Studies of bottom/charm production
- Two methods developed
  - Semileptonic tagging
    - 20% of b's decay inclusively to μ or e
      - Another 20% have leptons from charm decay
    - Challenge is purity of tagging scheme
      - CDF couldn't get fake rates below about 3-4%
  - Secondary vertex tagging most powerful
- Basic strategy is to use well-measured tracks
  - Select those with large impact parameter
    - Typically reconstruct average primary beam position in (x,y)
  - Require 2+ tracks with impact parameter > 2s and high quality
    - Attempt to create a secondary vertex
    - If successful, see if secondary vertex is sufficiently far from primary
      - Tag when secondary vtx found
      - Also "fake tag" when tag found, but in wrong direction

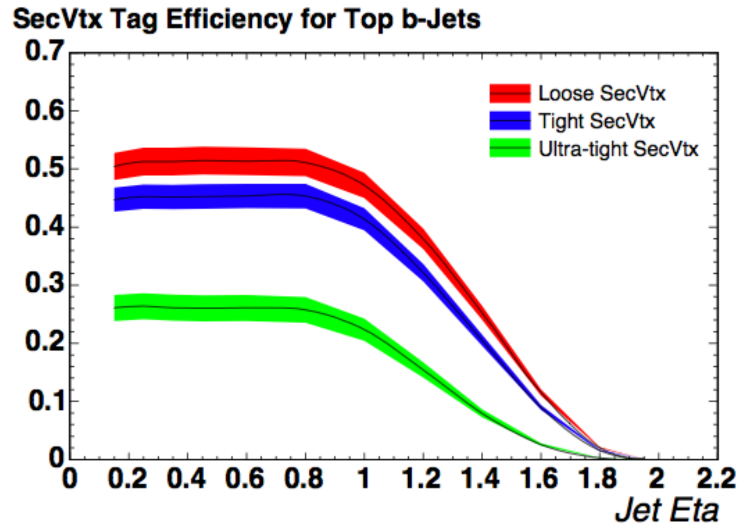


Tagging Efficiencies

- **Tagging efficiency difficult to model via simulation**
  - **Requires excellent knowledge of tracking resolution & efficiency**
  - **Strategy:**
    - Measure efficiency and "mistag" rates in data
      - **Inclusive electrons and muons**
        - **Estimate b quark fraction**
      - **Tag fully reconstructed Bs**
    - Compare with simulation & compute a scale factor
      - **SF = $\varepsilon_{Data}/\varepsilon_{MC}$ ~ 0.95 ± 0.05 for "tight" SECVTX**





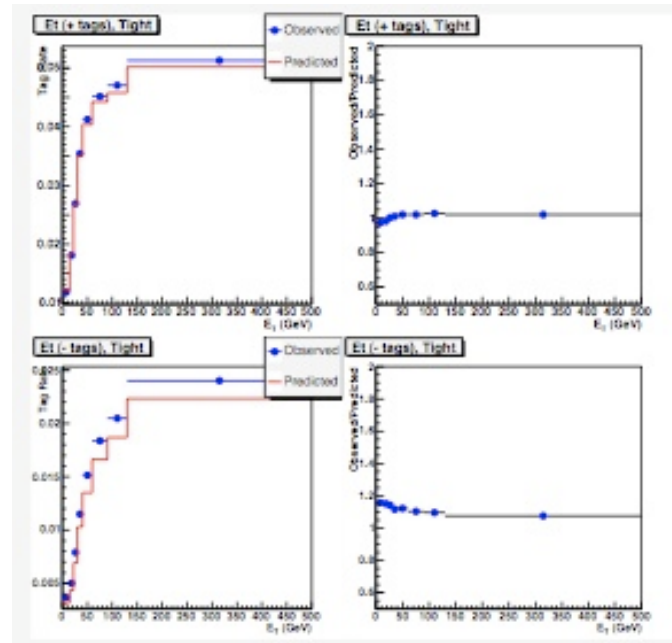


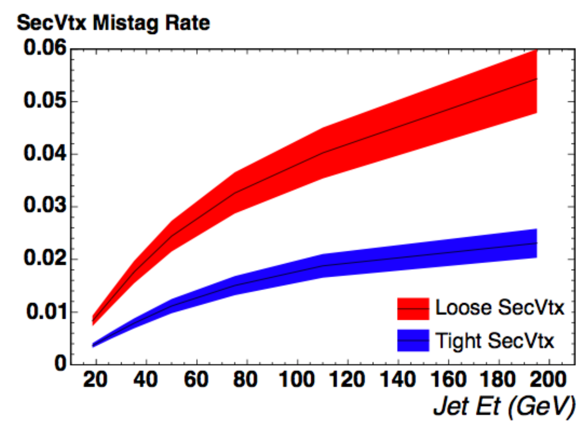
Tagging Fake Rates

- **B tagging fake rates measured from data**
  - **Take samples of dijet data, and then create a "fake matrix"**
    - Function of 6 variables
    - Measure both +ve and -ve tag rates for "taggable jets"
      - **Use -ve tag rates as mistag rate**
    - Apply mistag rate to the jets in data sample before tagging

Variable	Bin Edges
Jet E_T (GeV)	0, 15, 22, 30, 40, 60, 90, 130, 1000
Num Tracks/jet	0, 1, 2, 3, 4, 5, 6, 7, 8 10, 13, 100
$\lvert\eta_{\text{jet}}\rvert$	0.0, 0.4, 0.8, 1.1, 2.4
$n_{\text{PrimaryVertex}}$	1 – 6
$\sum E_t$ (GeV)	0, 80, 140, 220, 1000
z_{prim} (cm)	-25, -10, 10, 25

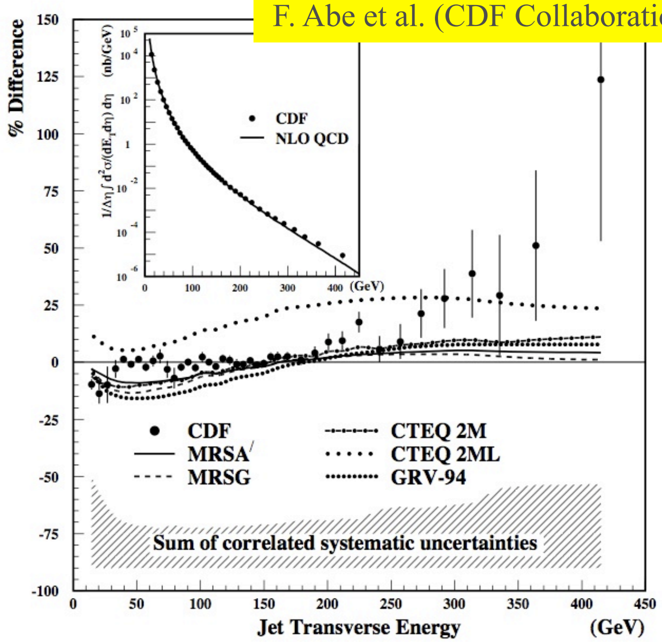
Table 1: Variables and binning used in the mistag matrices.





Example: Quark Substructure

- **Search for quark substructure a long-standing tradition at high energies**
  - **Eichten, Lane & Peskin**
    - PRL 50, 811 (1983)
  - **Introduced "contact term" Λ_C**
  - **CDF obliged in 1996**
    - $\Lambda_C \sim 1.6$ TeV



F. Abe et al. (CDF Collaboration), PRL 77, 438 (1996)

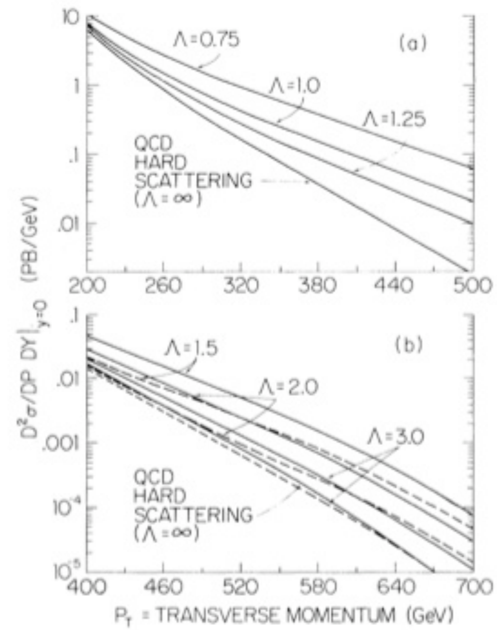


FIG. 3. The jet production cross section (in picobarns/gigaelectronvolt) at rapidity $y = 0$ vs transverse momentum at $\sqrt{s} = 2$ TeV in (a) $\bar{p}p$ collisions and (b) pp collisions for various Λ (in teraelectronvolts). The solid and dashed lines in (b) refer, respectively, to the plus and minus signs in Eq. (5). As a result of a cancellation near $y = 0$, the interference is negligible in (a).

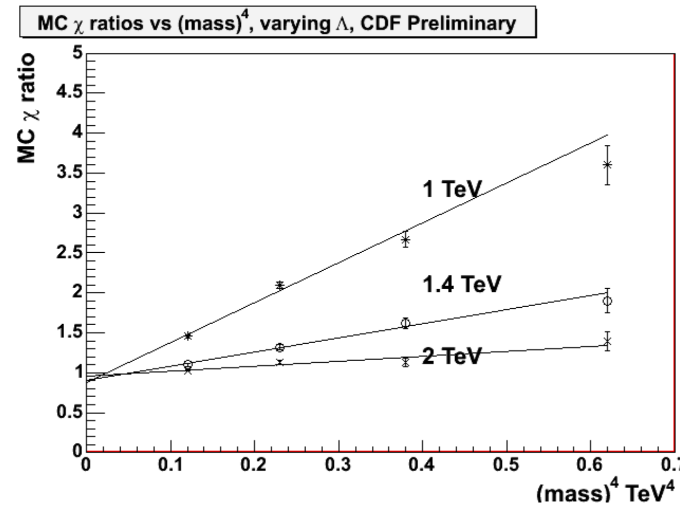
- **Later shown to be described by different PDF behaviour at large x**

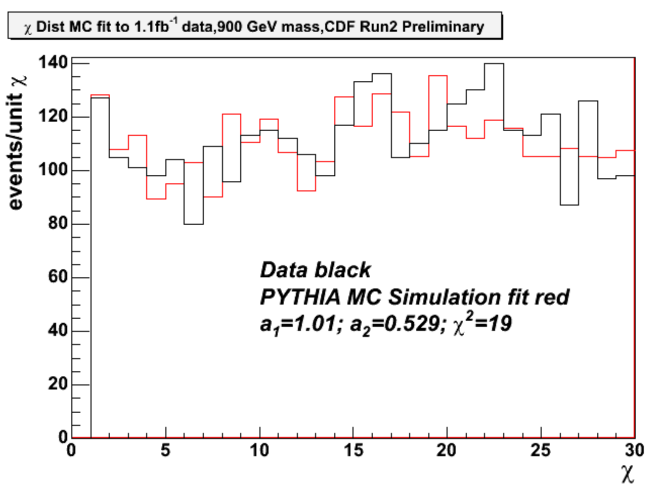
More Sensitive Study

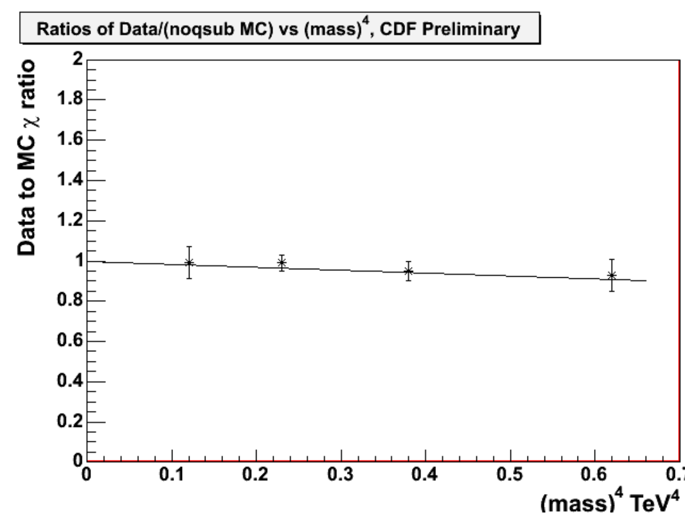
- **Employ angular distribution in dijet scattering**

$$\chi \equiv \exp|\eta_1 - \eta_2|$$

  - **Look at this as a function of dijet invariant mass**
    - 100 GeV mass bins
  - **More sensitive to Λ_C**
    - Less sensitive to PDFs
    - $\Lambda_C > 2.4$ TeV at 95% CL





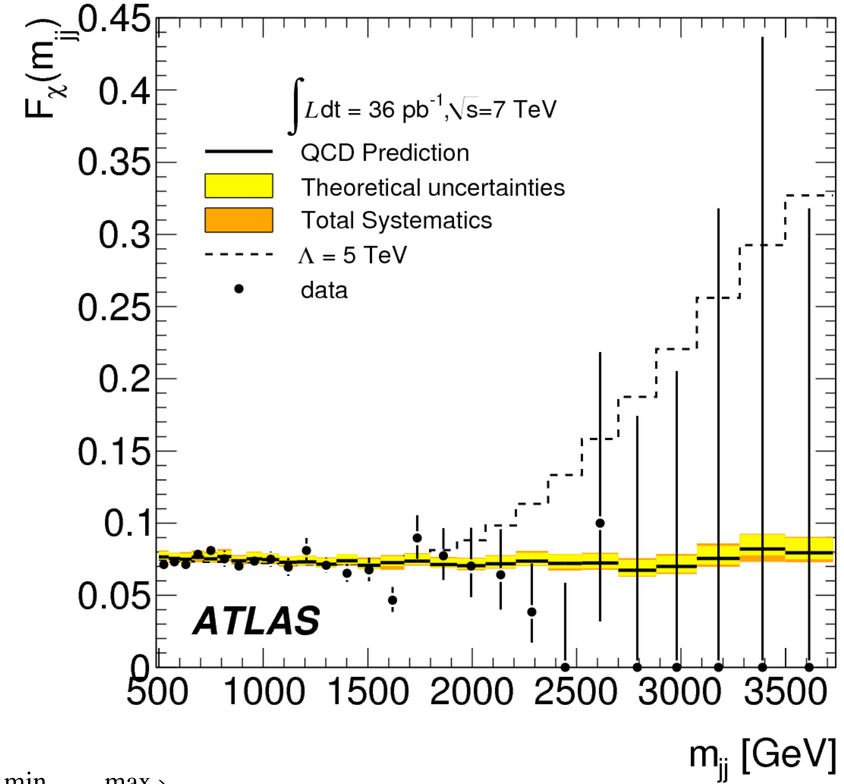


CDF Public Note 9609, November 2008

And Even More Sensitive!

- ATLAS has further improved sensitivity
  - Look at fraction of centrally produced jets relative to larger angular range
  - See behaviour as dijet mass increases
  - Expect QCD background to have flat ratio
- More sensitive to Λ_C
  - $\Lambda_C > 9.5$ TeV at 95% CL

ATLAS Collaboration, New J. Phys. 13,053004 (2011)



$$F_\chi([m_{jj}^{\max} + m_{jj}^{\max}]/2) \equiv \frac{N_{events}(|y^*| < 0.6, m_{jj}^{\min}, m_{jj}^{\max})}{N_{events}(|y^*| < 1.7, m_{jj}^{\min}, m_{jj}^{\max})}$$

$$y^* \equiv \frac{1}{2}(y_1 - y_2)$$