Probing QCD and New Physics with Jets at CDF

Kenichi Hatakeyama
Rockefeller University

Southern Methodist University
January 12, 2009

Outline

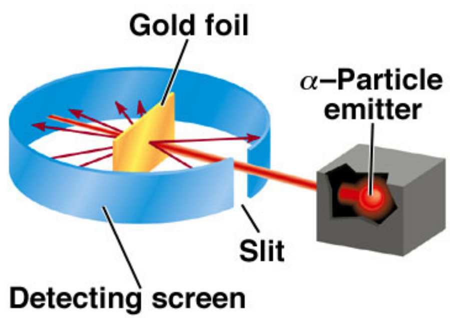
- Introduction
- Tevatron collider and jets in $p\bar{p}$ collisions
- CDF experiment
- Measurement of inclusive jet cross sections
- Search for dijet mass resonances
- Future prospects
- Summary

Particle Physics

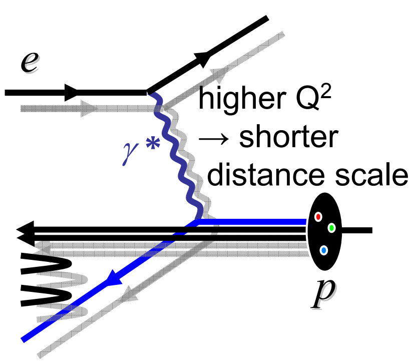
- What are the fundamental building blocks (elementary particles) from which all matter is made?
- What are the interactions between them that govern how they combine and decay?

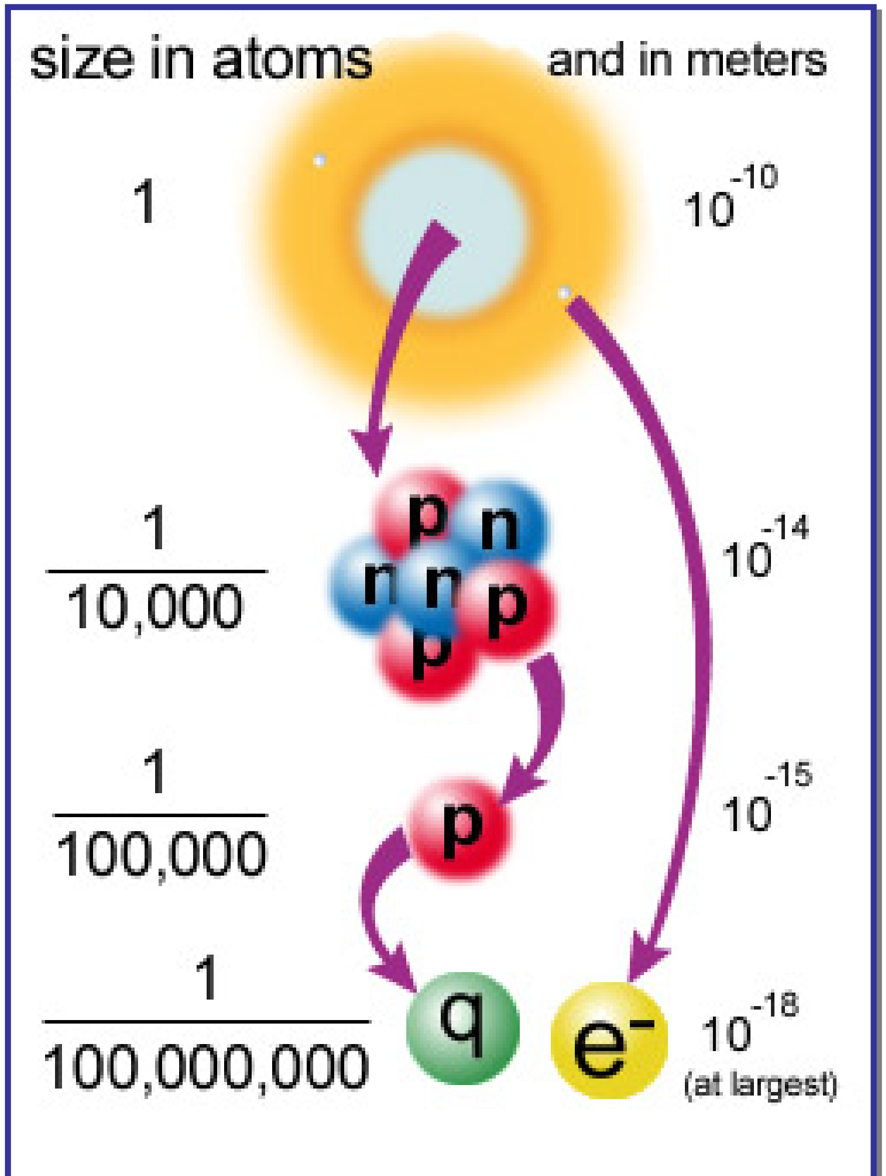
Questions being asked since BC…

Rutherford scattering



Deep inelastic scattering





In 19th century, atoms were considered to be elementary particles.

In 1930's, protons, neutrons, and electrons were considered to be elementary particles.

And, now…

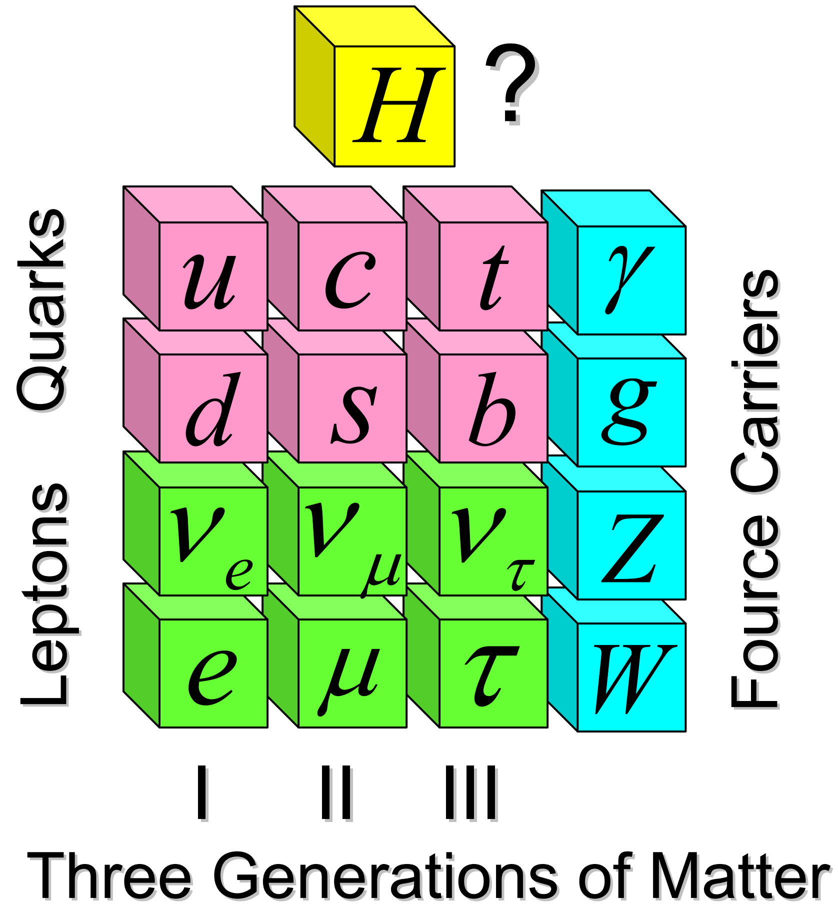
Standard Model

- Our current best answers to these questions are given by the "Standard Model"
- Matter particles
  - Three generations of Quarks and Leptons
- Forces
  - Quantum Chromodynamics (QCD) for strong interactions

    Force carriers: gluons
  - Quantum Electrodynamics (QED) for electroweak interactions

    Force carriers: photons, *W, Z*

And, probably the Higgs boson remains to be discovered…



Are we satisfied with the Standard Model?
Not really…

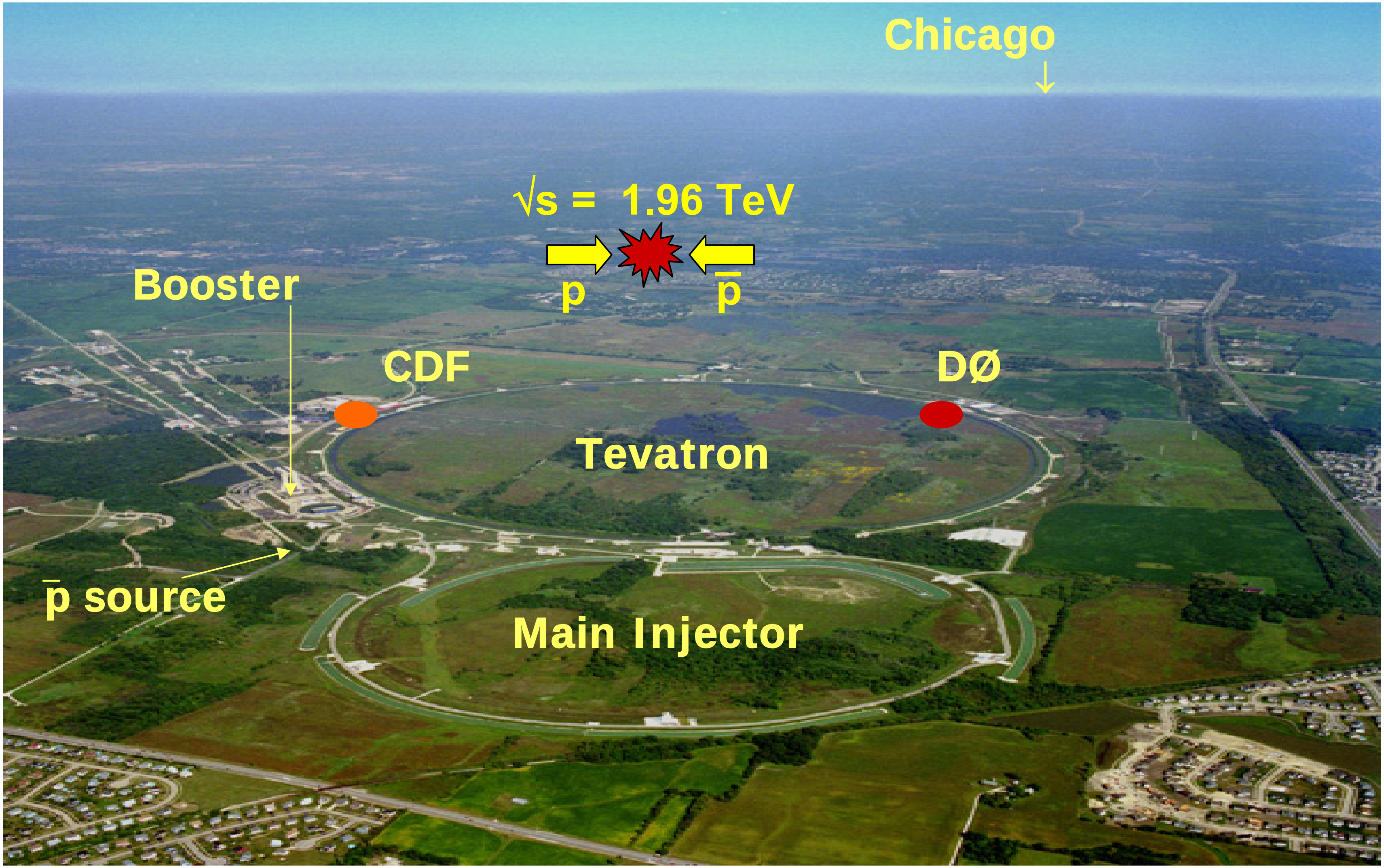
Questions in the Standard Model

- What is the origin of the mass and electroweak symmetry breaking?
  - Is the Higgs mechanism the right answer? Technicolor?
- Can the electroweak and strong forces be unified?
- How can we incorporate gravity into the Standard Model?
  - Why is the gravity so weak compared to other forces?
- Why are there many different kinds of elementary particles?
  - Are the quarks and leptons composite particles?
- What is dark matter?
  - Are there unobserved stable particles?
- What happened to the anti-matter?
- …

➡ Further test Standard Model predictions

➡ Look for undiscovered particles and/or phenomena, which hopefully offer answers to some of these questions

Fermilab Tevatron $\bar{p}p$ Collider

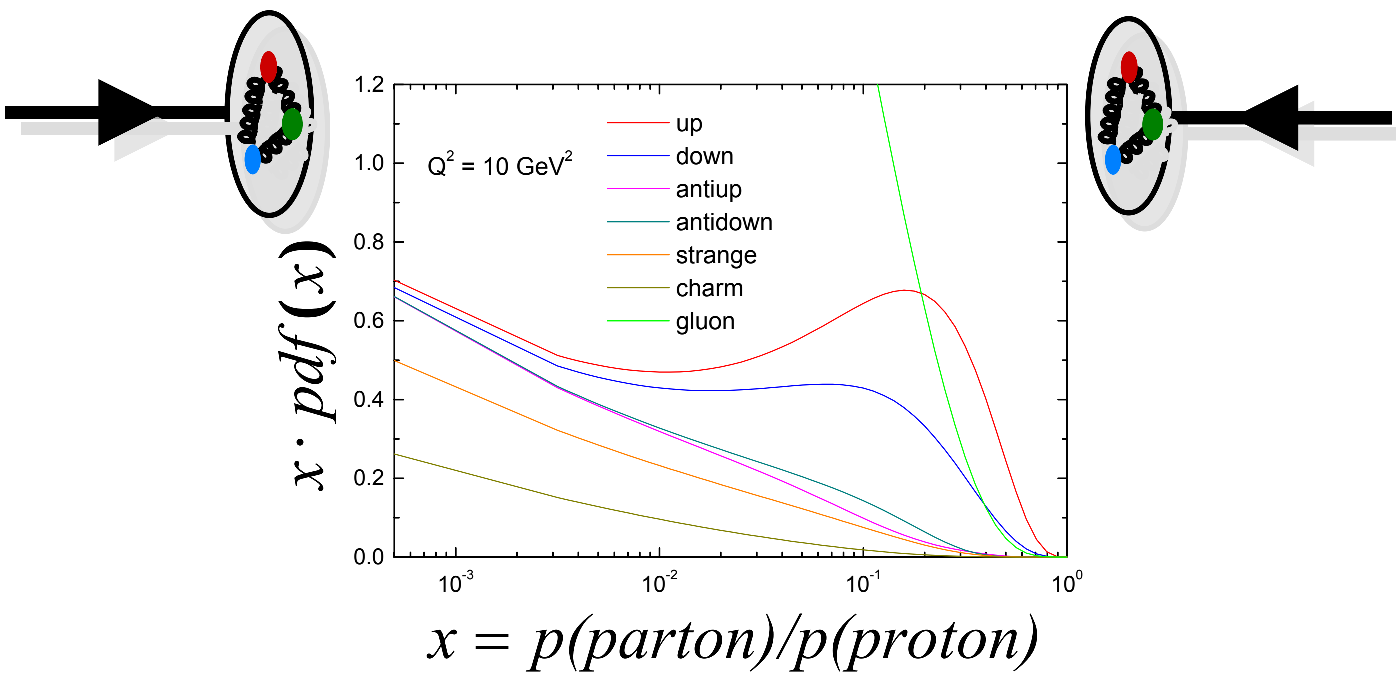


Proton-Antiproton Collision

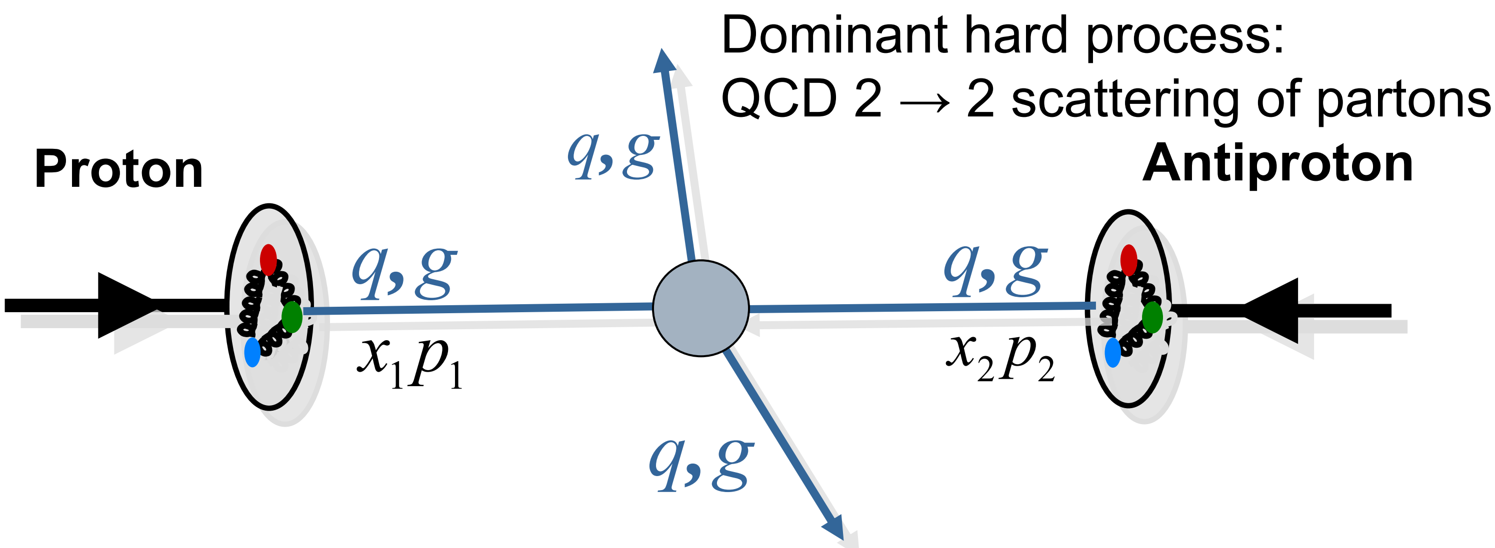
Proton-Antiproton Collision

Partons inside (anti)proton:
Parton Distribution Functions (PDF's)

Proton **Antiproton**



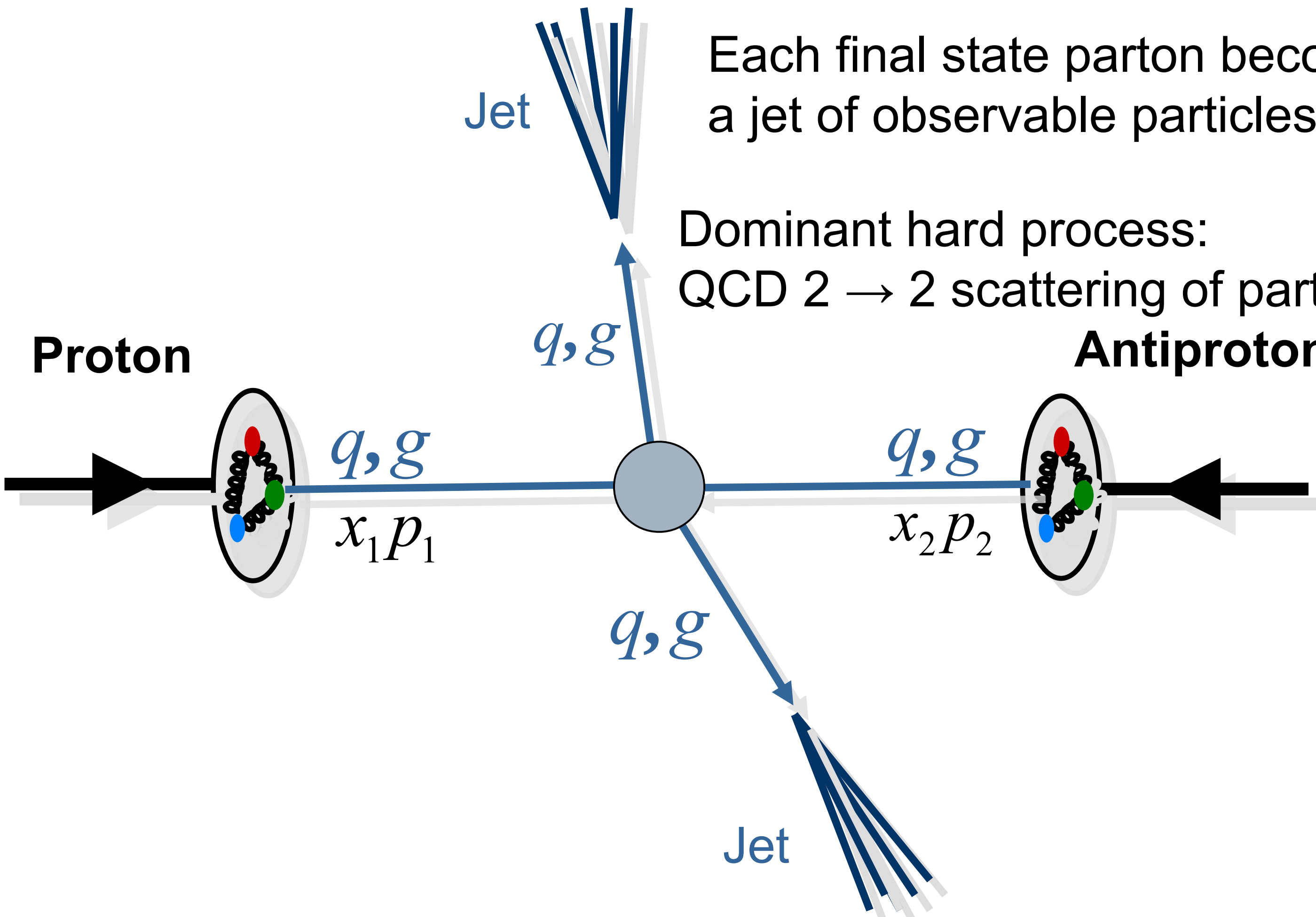
Proton-Antiproton Collision



Proton-Antiproton Collision

Each final state parton becomes a jet of observable particles

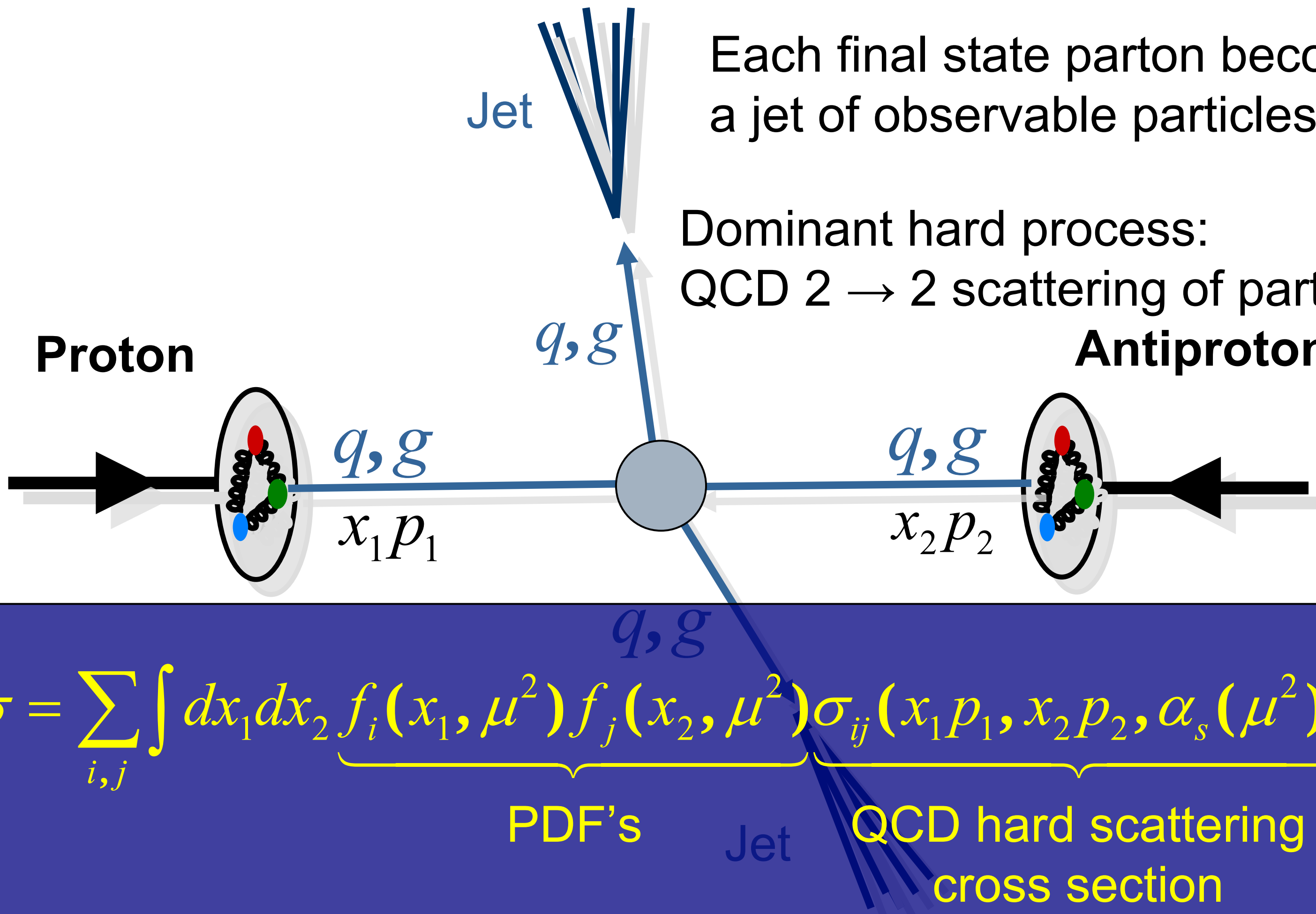
Dominant hard process:
QCD 2 → 2 scattering of partons



Proton-Antiproton Collision

Each final state parton becomes a jet of observable particles

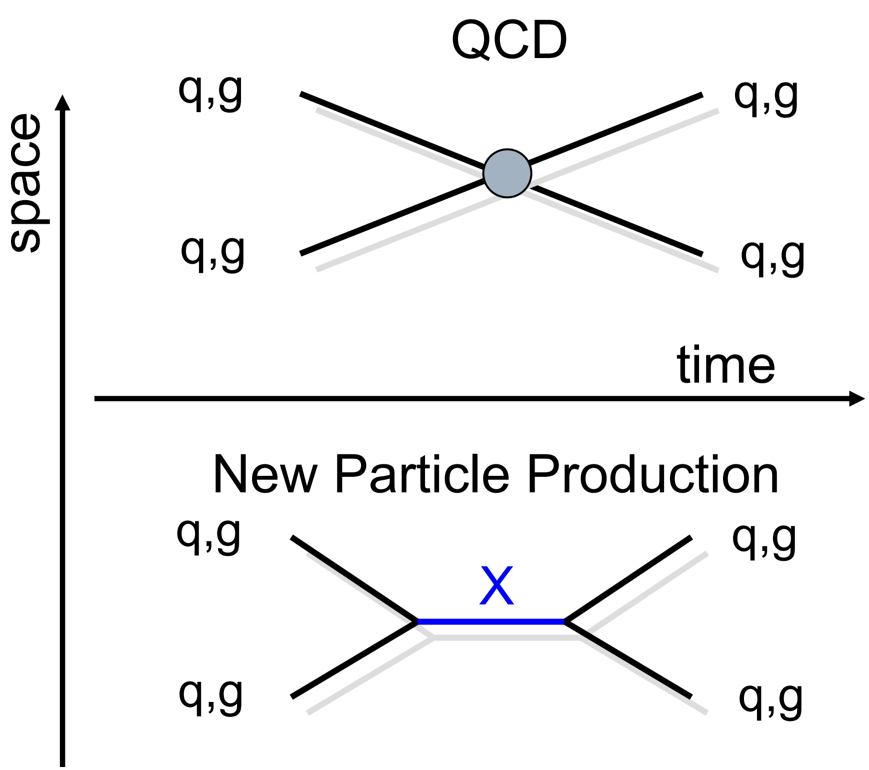
Dominant hard process:
QCD 2 → 2 scattering of partons



$$\sigma = \sum_{i,j} \int dx_1 dx_2 \underbrace{f_i(x_1, \mu^2) f_j(x_2, \mu^2)}_{\text{PDF's}} \underbrace{\sigma_{ij}(x_1 p_1, x_2 p_2, \alpha_s(\mu^2))}_{\text{QCD hard scattering cross section}}$$

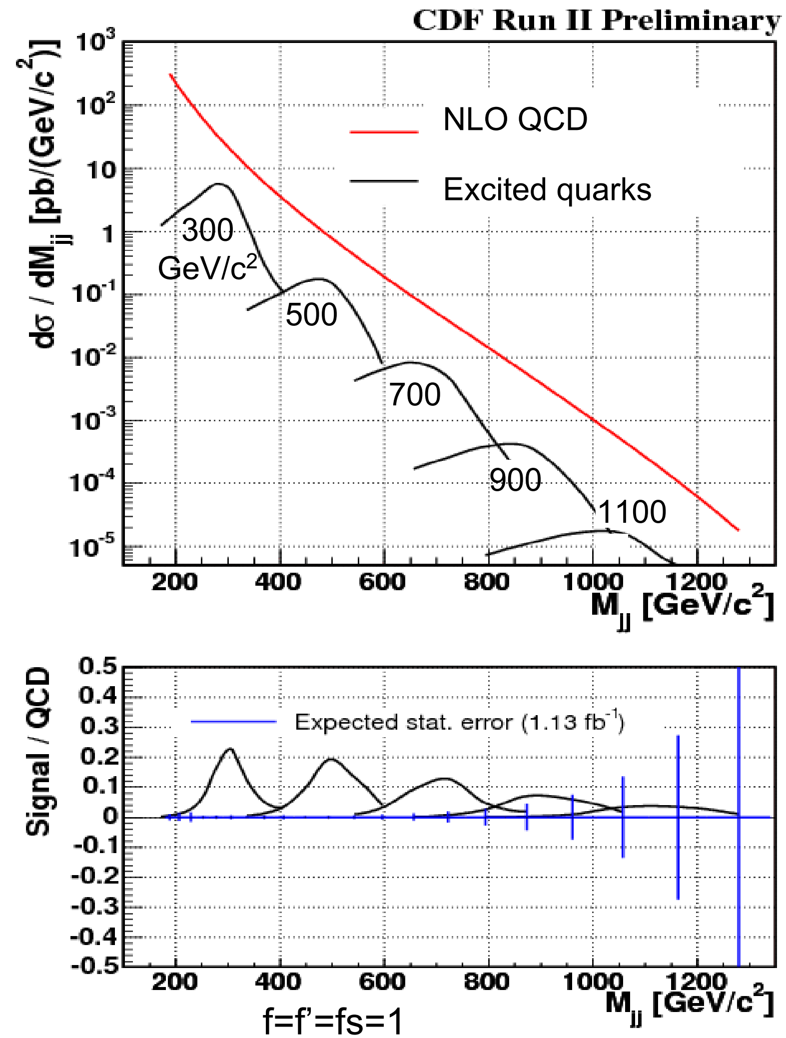
Test QCD predictions and constrain PDF's with jets!

New Physics Searches with Jets (1)



→ dijet mass resonances

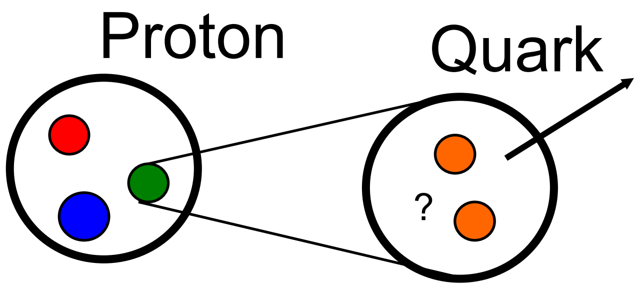
Many new physics models predict new particles decaying into dijets!



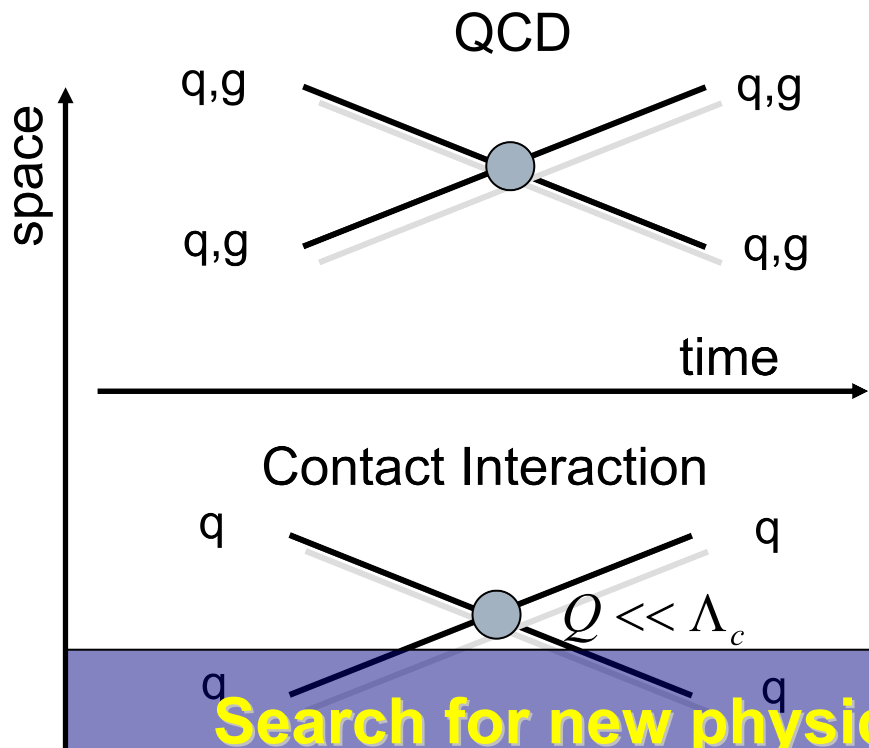
New Physics Searches with Jets (2)

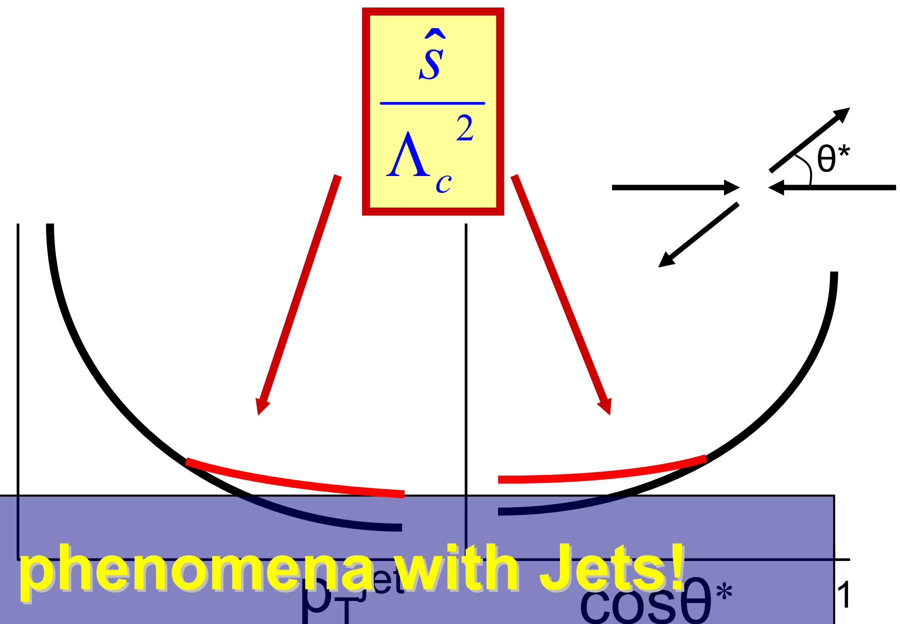
Preons?

$r_{preon} \sim \hbar c / \Lambda_c$ (Λ_c=4 TeV, r ~ 5 ·10^{-20} m)



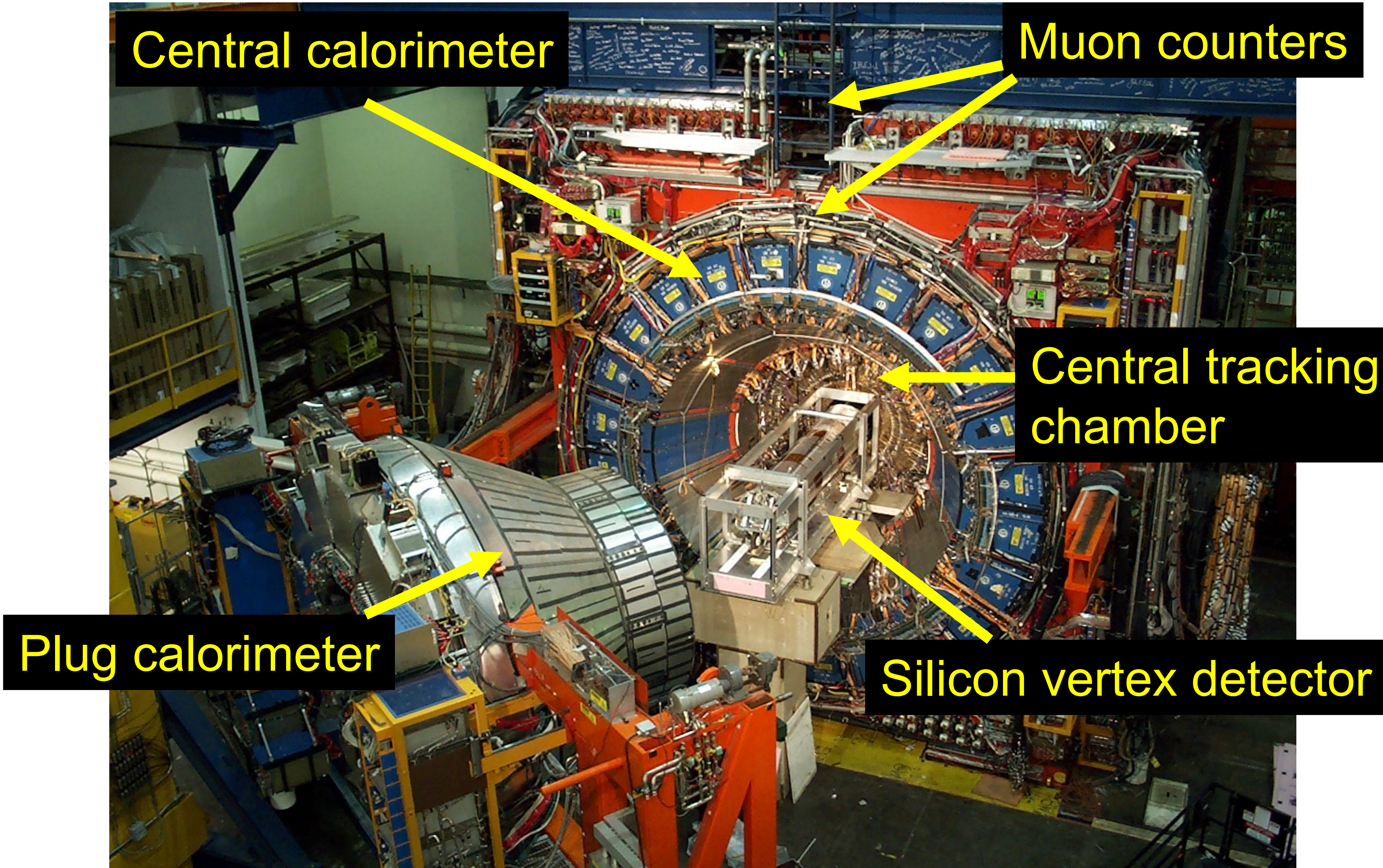
Existence of substructure below Λ_c leads to contact interactions





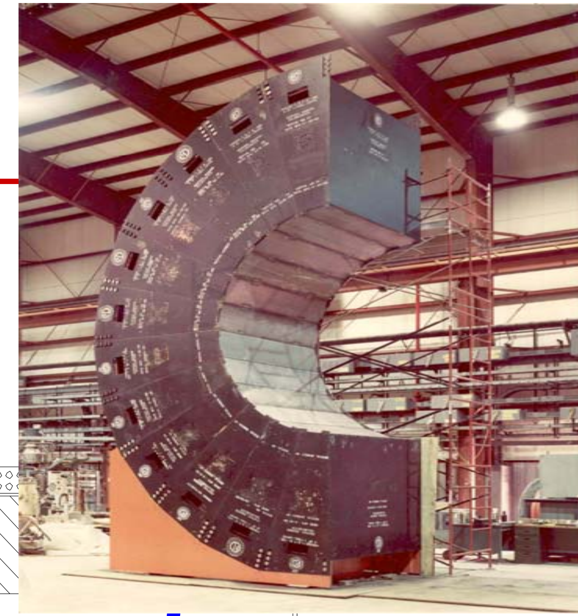
Search for new physics phenomena with Jets!

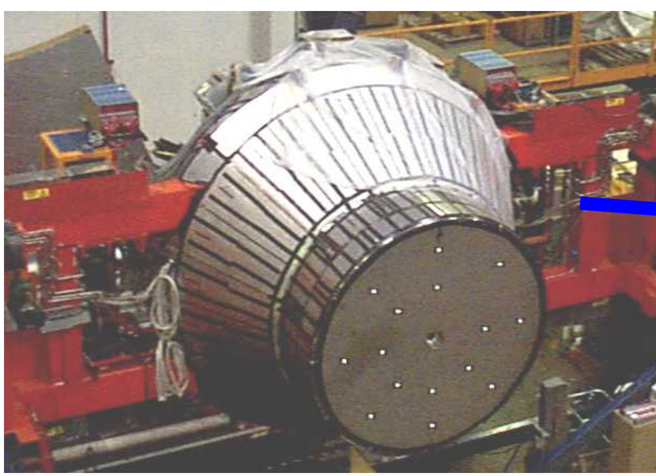
Collider Detector at Fermilab (CDF)

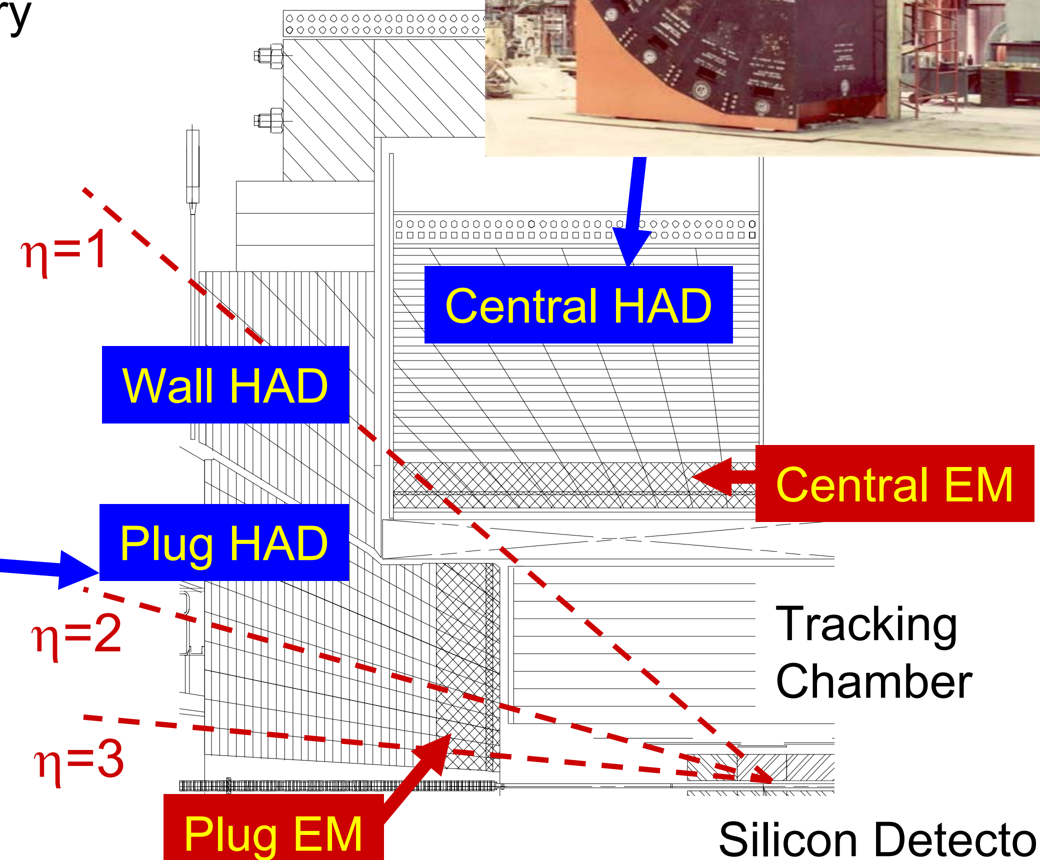


Calorimeters

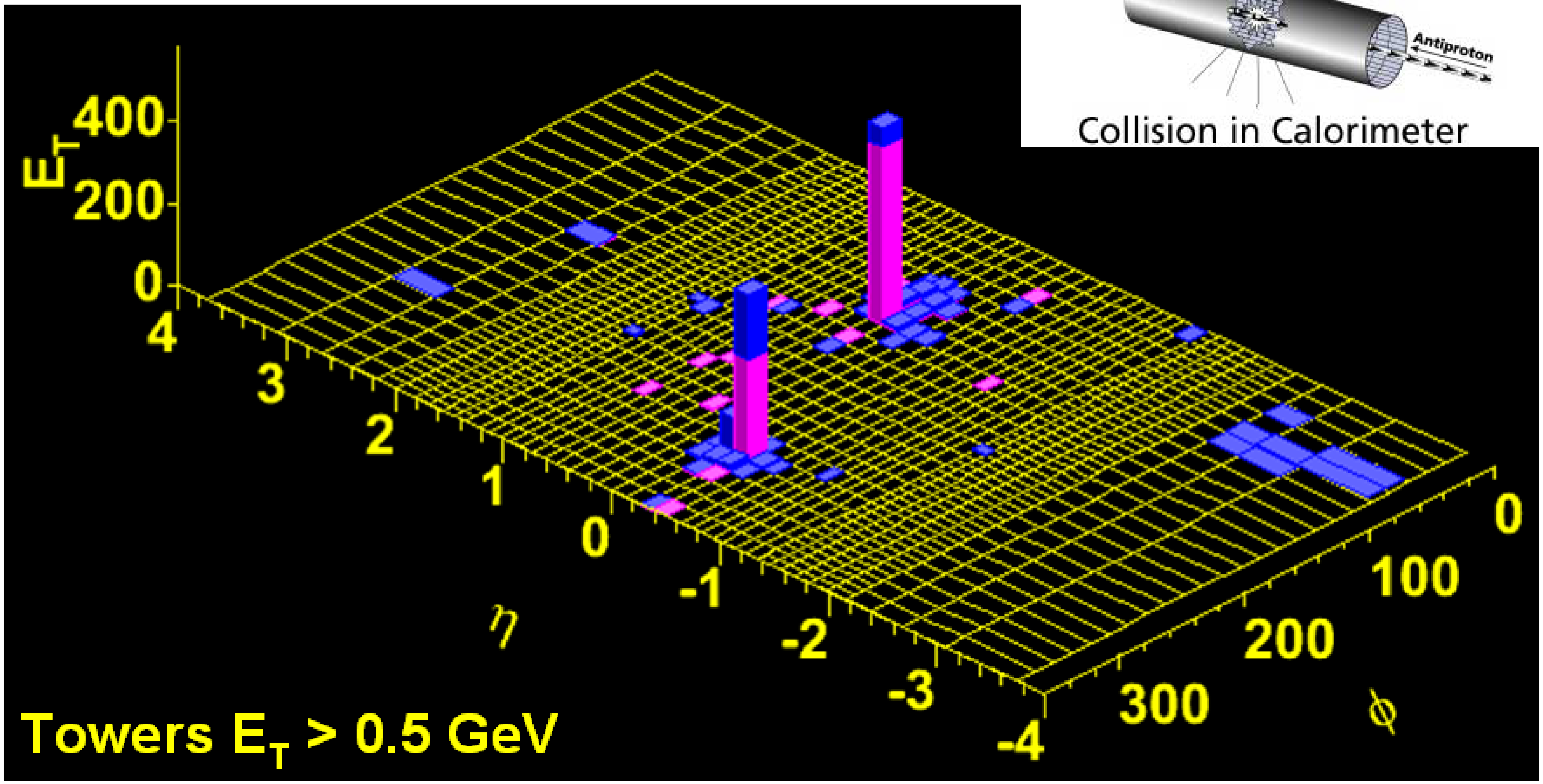
- Sampling calorimeter:
  - Scintillating tiles
  - Lead/iron absorbers
  - Projective tower geometry
- Granularity:
  - $\Delta\eta \sim 0.1$
  - $\Delta\phi = 30^{o}$ (15^{o})

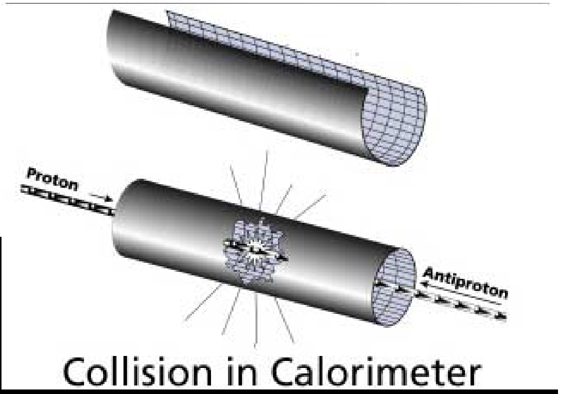






High Mass Dijet Event





Measurement of Inclusive Jet Cross Section

Phys. Rev. D 74, 071103(R) (2006).
Phys. Rev. D 78, 052006 (2008).

Work with C. Group* (U. Florida → FNAL), G. Flanagan* (MSU → Purdue U.),
A. Bhatti (Rockefeller U.), F. Chlebana (FNAL), J. Huston (MSU), G. Latino (INFN)

*) Ph.D. Thesis on this measurement

Inclusive Jet Cross Section

$$\frac{d^2\sigma}{dp_T dy} \leftrightarrow \frac{N_{jet}}{\Delta p_T \cdot \Delta y \cdot \varepsilon \cdot \int L dt} \; vs. \; p_T$$

$\Delta p_T \rightarrow p_T$ *bin size*

$\varepsilon \rightarrow$ *selection efficiency*

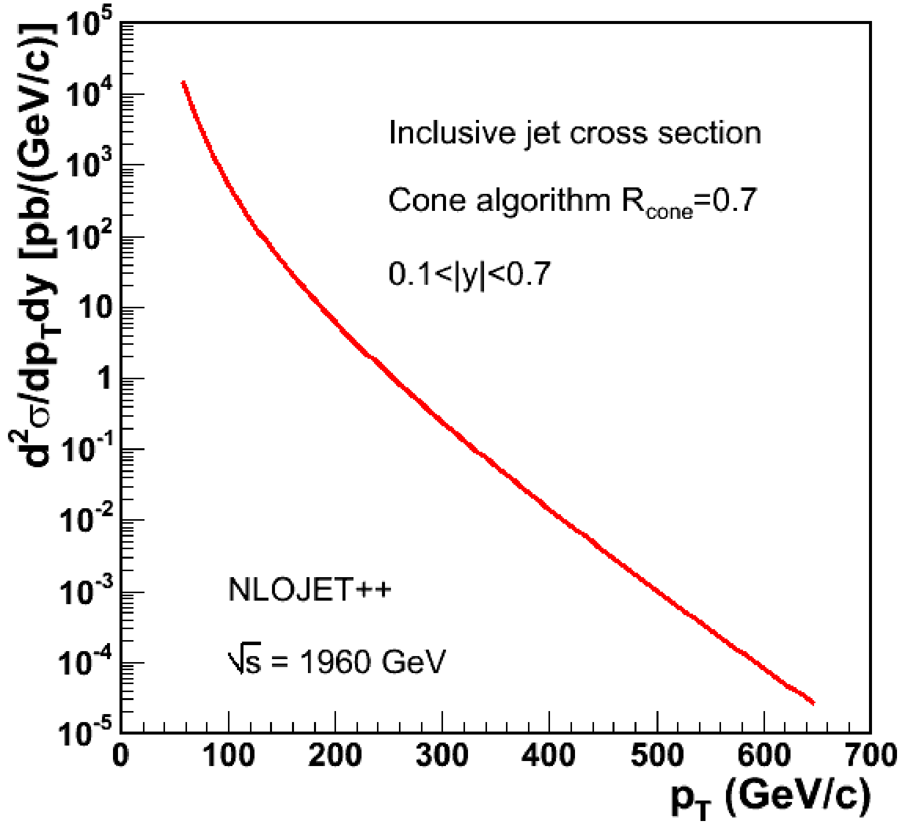
$\Delta y \rightarrow y$ *bin size*

$\int L dt \rightarrow$ *integrated luminosity*

Njet $\rightarrow$ *# of jets in the bin*

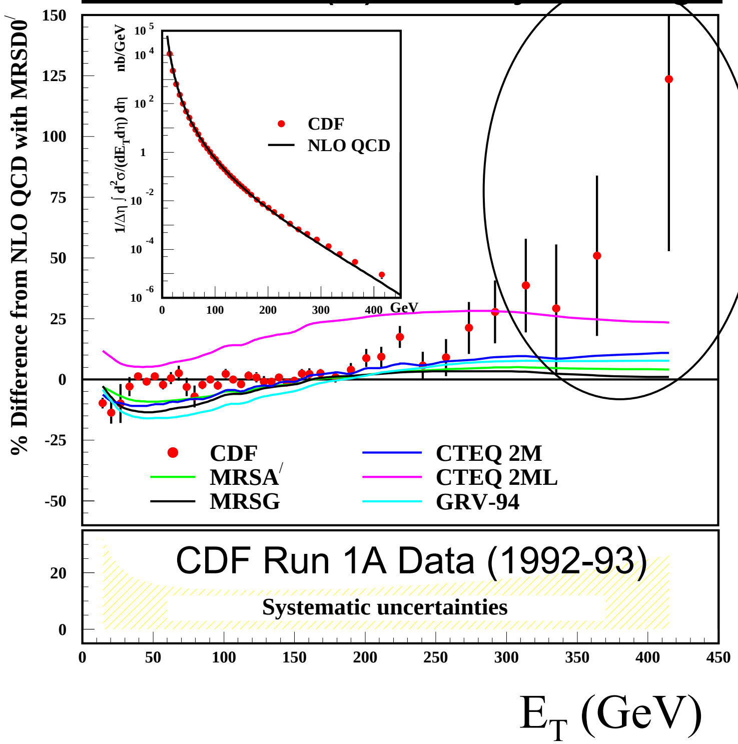
Motivation

- Test QCD predictions over ~8 orders of magnitude in differential cross section
- Probe the running of the strong coupling constant, α_s.
- Sensitive to new physics
  - Probing distance scale of order 10^{-19} m
- Constrain PDF in the proton

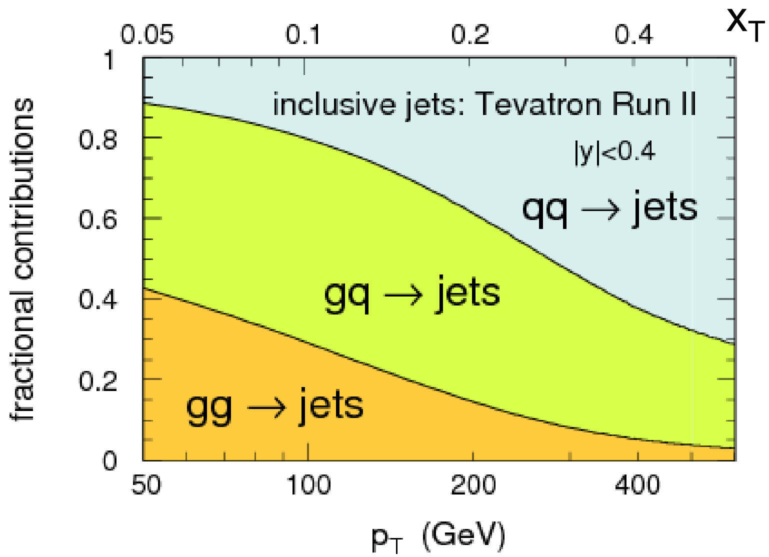


A Little History

Excitement(?) at 10 years ago



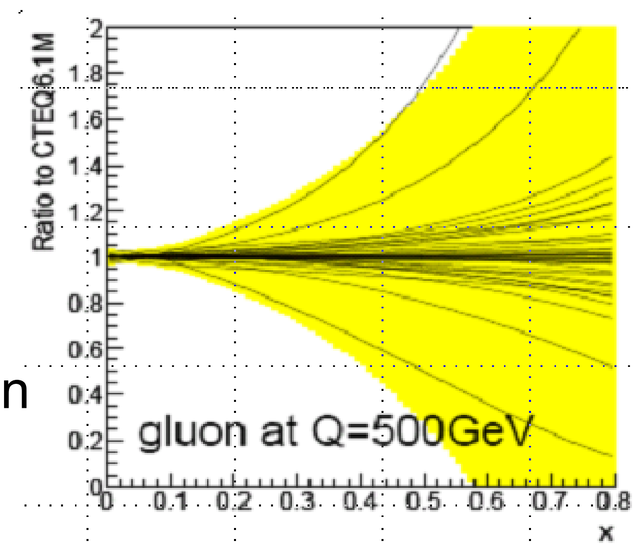
Phys. Rev. Lett. 77, 438 (1996)



High-x gluon not well known

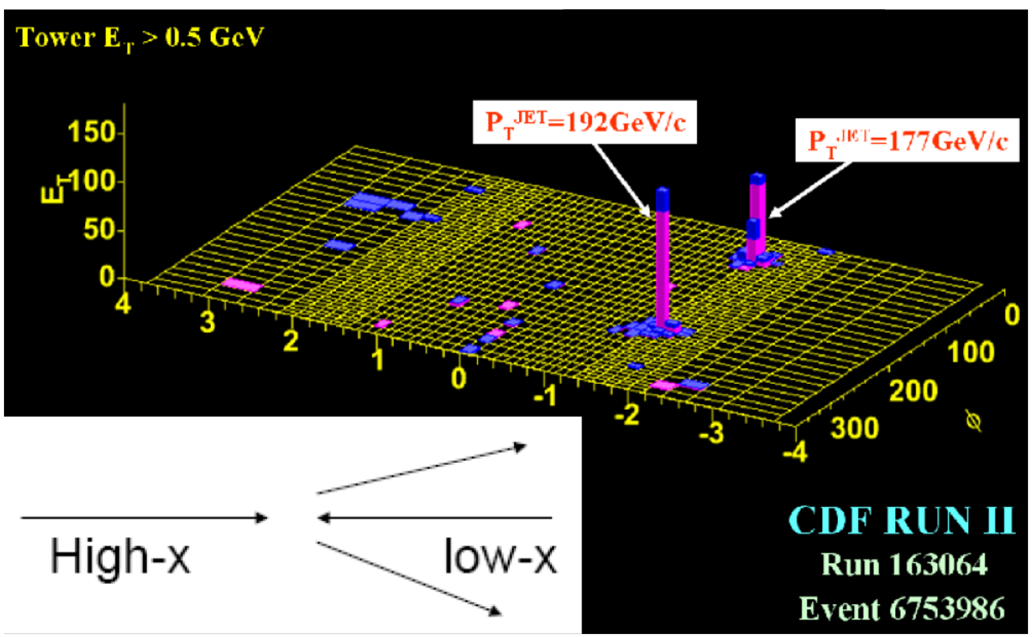
…can be accommodated

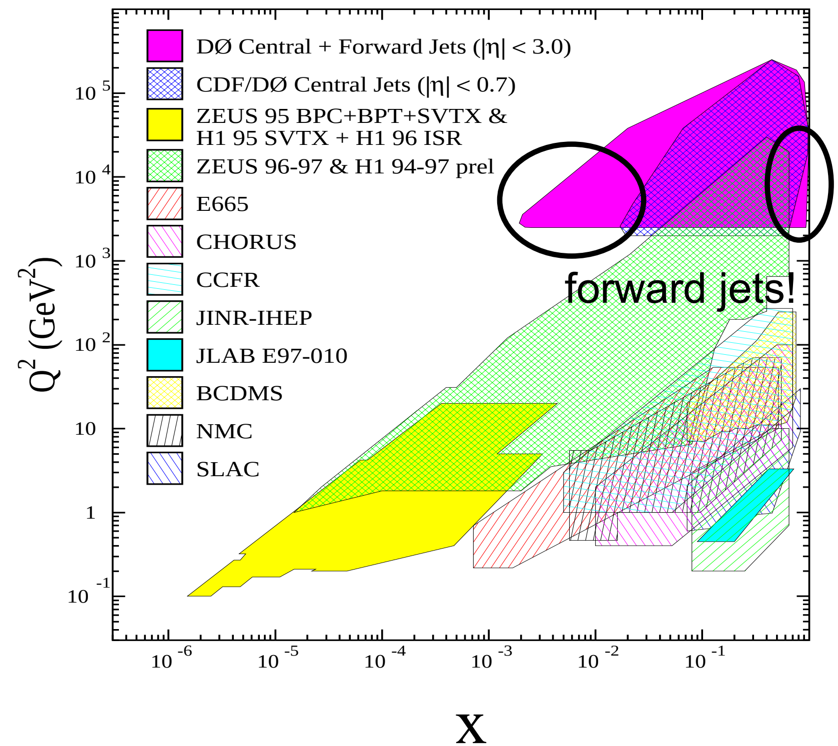
in the Standard Model



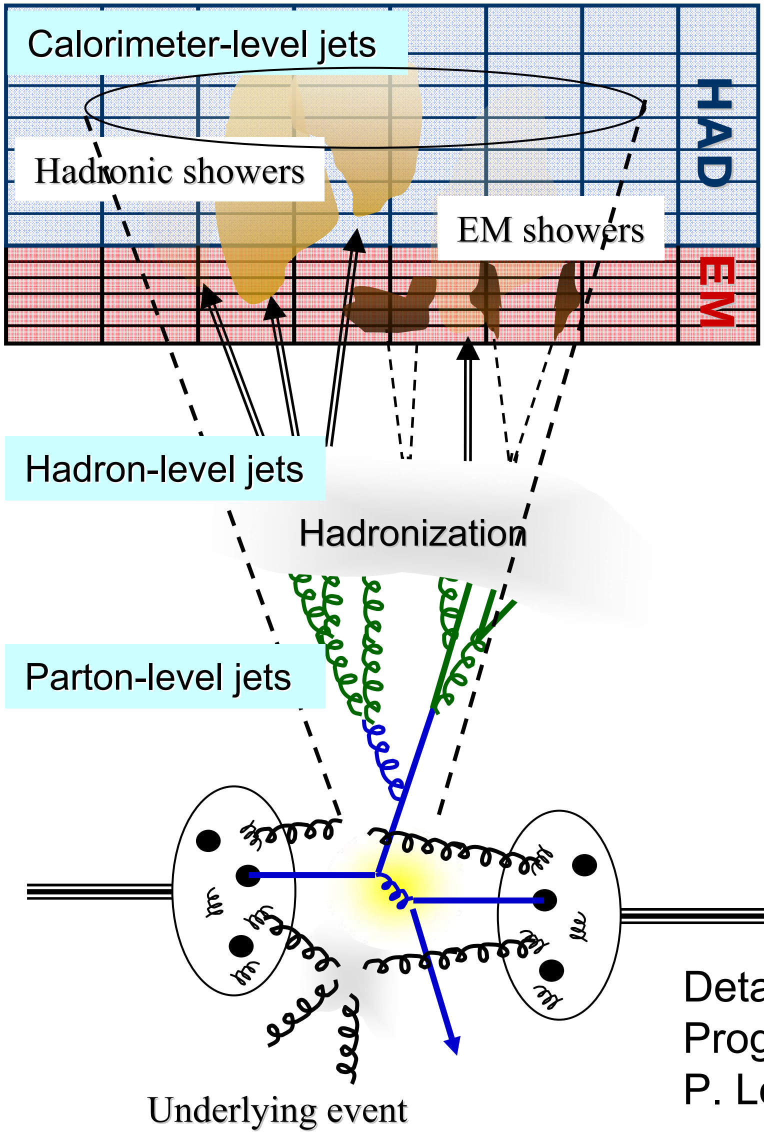
Forward Jets

- Forward jets probe high-x at lower Q^2 (= $-q^2$) than central jets
  - Q^2 evolution given by DGLAP (Dokshitzer-Gribov-Lipatov-Altarelli-Parisi)
  - Essential to distinguish PDF and possible new physics at higher Q^2
- Also, extend the sensitivity to lower x





Jet Production



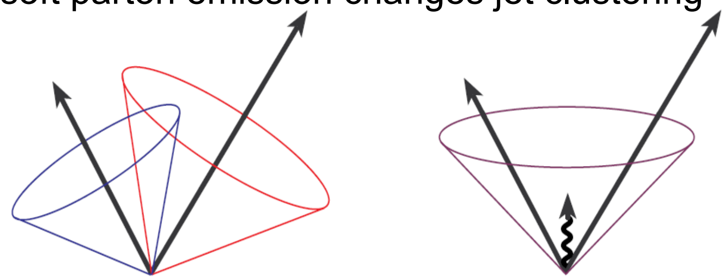
- Jets are collimated sprays of particles (mostly hadrons) originating from quarks/gluons coming from the hard scattering (Jets are experimental signatures of quarks and gluons)
- Unlike photons, leptons etc, jets have to be defined by an algorithm for quantitative studies
- Need a well-defined algorithm that gives close relationship between calorimeter-level jets, hadron-level jets, and parton-level jets

Detailed discussions in e.g. “Jets in hadron-hadron collisions”, Prog. Part. Nucl. Phys. 60, 484, with S. Ellis, J. Huston, P. Loch, M. Tonnesmann,

Jet "Definitions" – Jet Algorithms

Midpoint cone-based algorithm

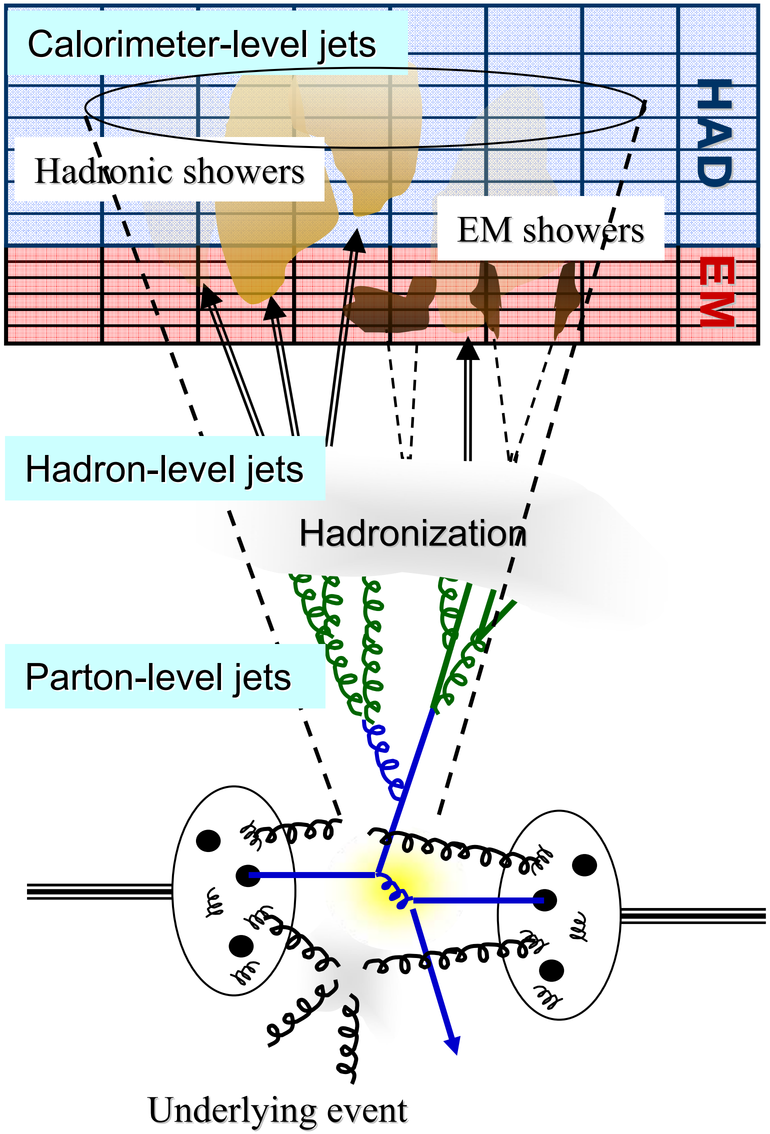
Infrared unsafety:
soft parton emission changes jet clustering



- Cluster objects based on their proximity in y-ϕ space
- Starting from seeds (calorimeter towers/particles above threshold), find stable cones (p_T-weighted centroid = geometric center).
- Seeds have been necessary for speed, however source of infrared unsafety.
- In recent QCD studies, we use "Midpoint" algorithm, i.e. look for stable cones from middle points between two adjacent cones
  → Infrared safety restored up to NNLO
- Stable cones sometime overlap
  → merge cones when overlap > 75%

Jet Corrections:

Calorimeter-level to Hadron-level



$p_T^{jet}(\text{calorimeter}) \neq p_T^{jet}(\text{particles})$:

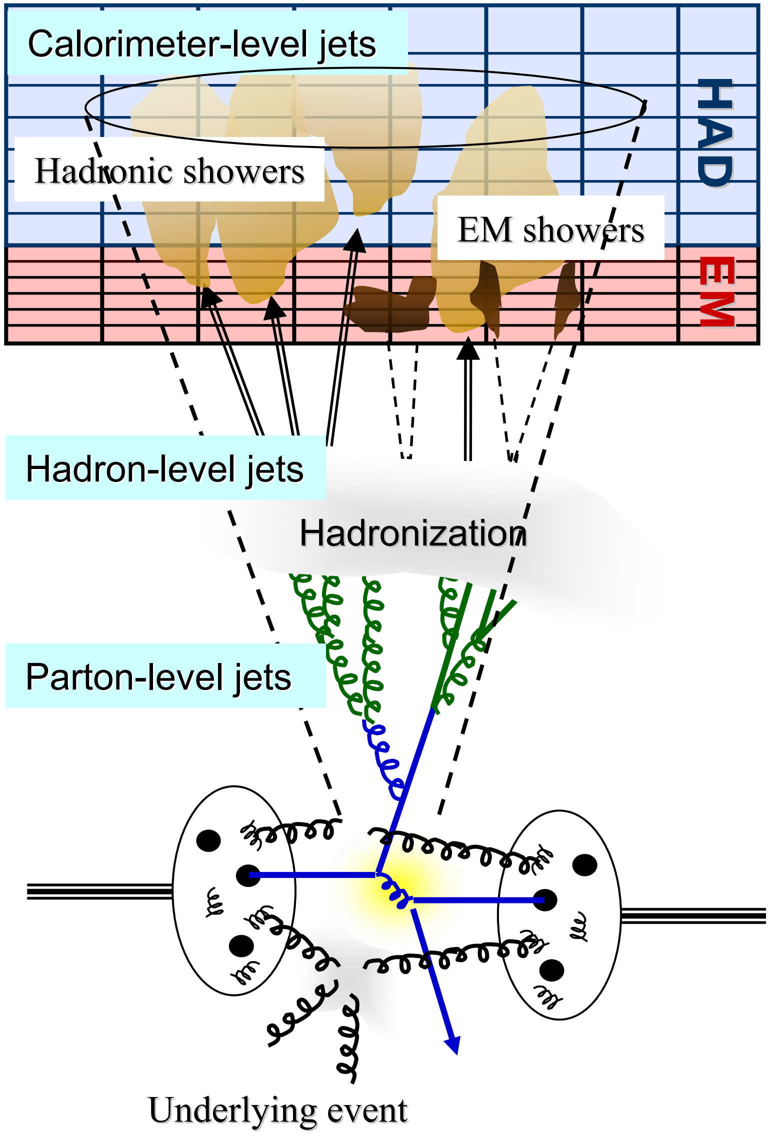
- Calorimeter's non-compensating nature (e/h>1)
- Non-uniformity
- Particles from other $p\bar{p}$ interactions
- Particles below calorimeter noise level
- Particles curved outside the clustering cone due to magnetic field

⇩

Jet Corrections

Jet Corrections:

Calorimeter-level to Hadron-level



Correction Steps:

- Calorimeter non-uniformity
  - Two-jet p_T balance
- Energy from additional $\overline{p}p$ interactions
  - Subtract p_T as function of N(interactions)-1
- Average energy loss and resolution effect in calorimeter energy measurement:
  - Average p_T correction from <p_T(cal)> versus <p_T(had)>
  - Unfolding correction

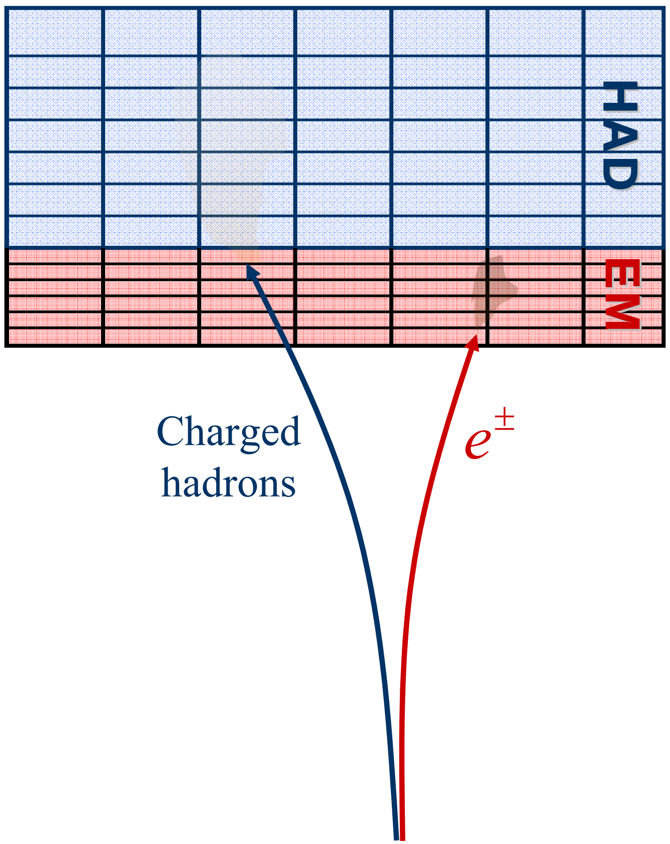
$$U(p_T^{jet}, y^{jet}) = \frac{\sigma(\text{calorimeter} - \text{level jets})}{\sigma(\text{hadron} - \text{level jets})}$$

in MC (jj event generator + detector simulation).

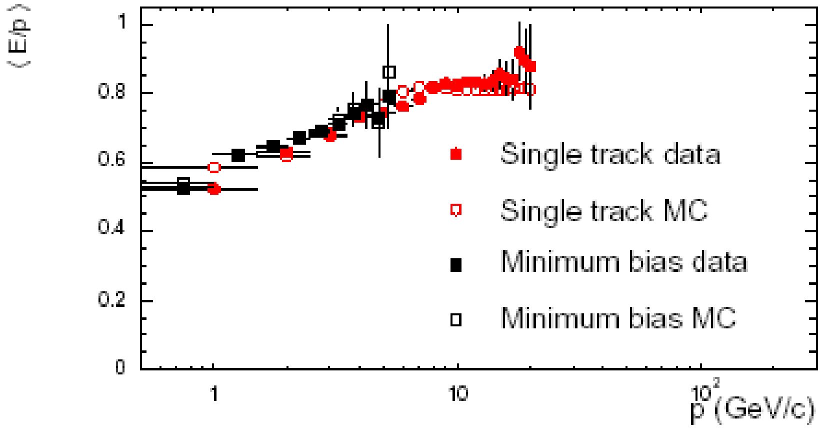
- Shower simulation tuned to data

Calorimeter Response Tuning

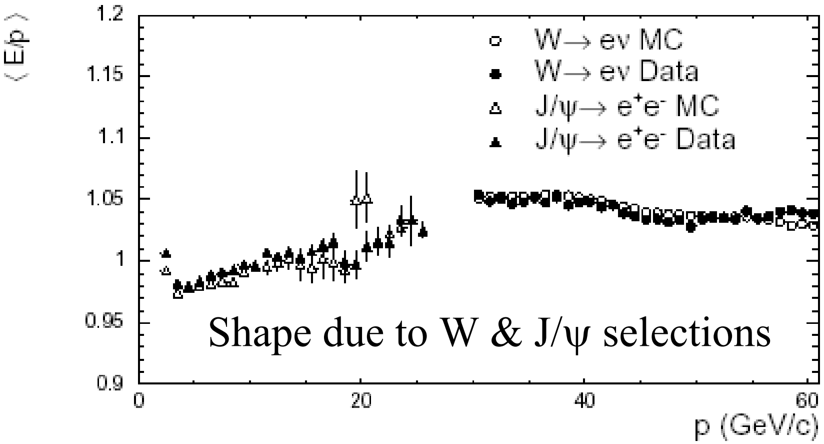
- Tune individual particles' response (E/p)



Charged hadrons ($\pi^\pm$, $K^\pm$, p, …)

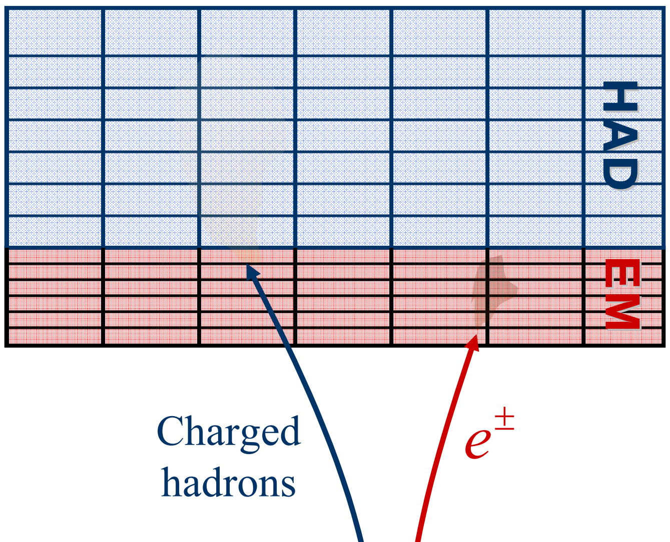


Electromagnetic particles (electrons, photons, π^0, …)

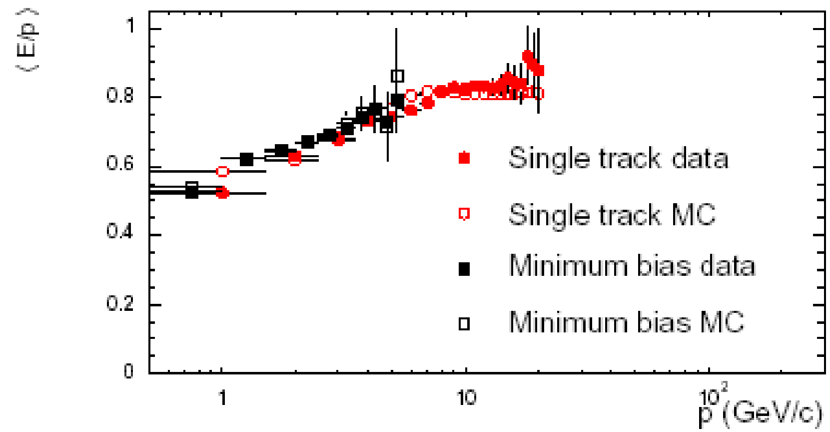


Calorimeter Response Tuning

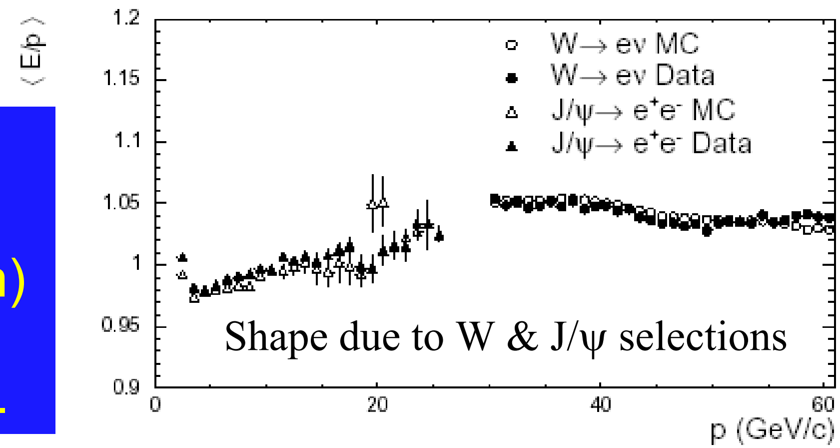
- Tune individual particles' response (E/p)



Charged hadrons ($\pi^{\pm}$, $K^{\pm}$, p, …)



Electromagnetic particles (electrons, photons, π^0, …)



Accuracy of the tuning
→ jet energy scale uncertainty
(2-3% in the central rapidity region)

Nucl. Instrum. Method A 566, 375 (2006).

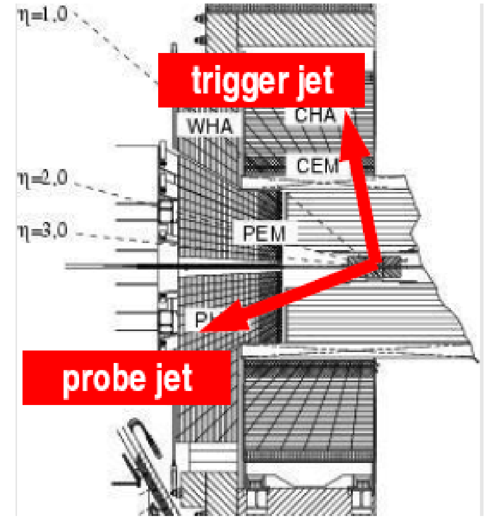
Non-Central Jets

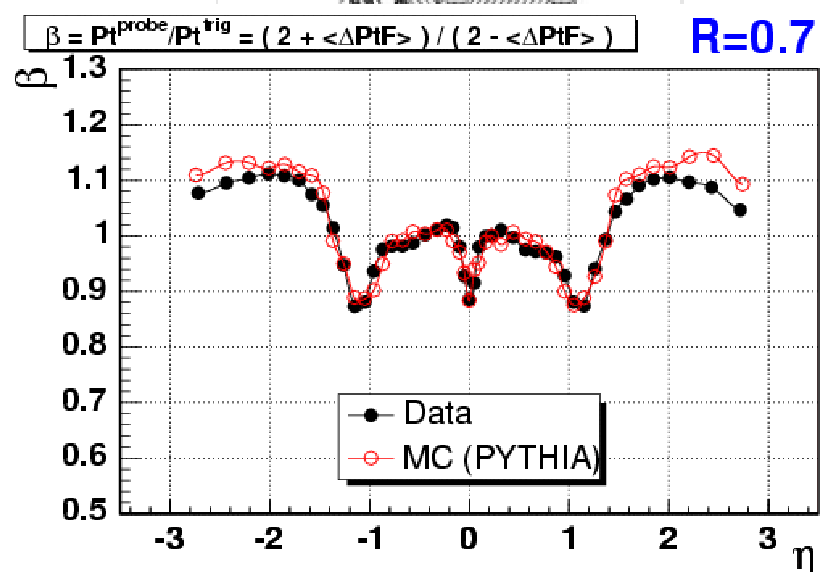
- The single particle response tuning is limited in precision in non-central regions due to detector geometry / limited tracking coverage.
  - **dijet p_T balance method**
- Equalize jets outside the central region to central jets.

Trigger jet: central region
Probe jet: anywhere

$$\Delta p_T f \equiv \frac{\Delta p_T}{p_T^{ave}} = \frac{p_T^{probe} - p_T^{trigger}}{(p_T^{probe} + p_T^{trigger})/2}$$

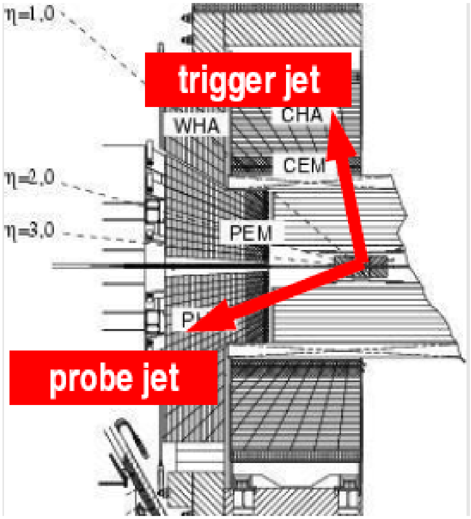
$$\beta \equiv \frac{p_T^{probe}}{p_T^{trigger}} = \frac{2 + \langle \Delta p_T f \rangle}{2 - \langle \Delta p_T f \rangle}$$





Non-Central Jets

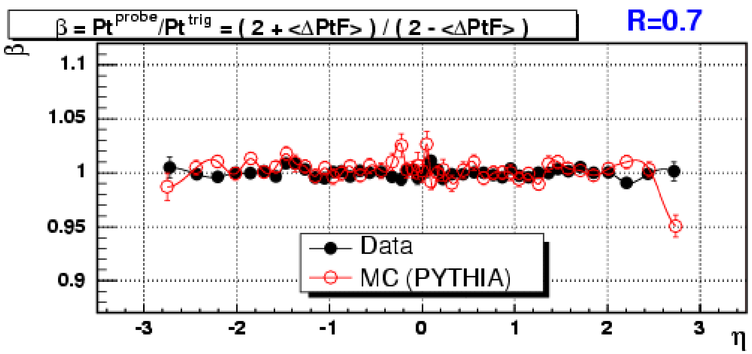
- The single particle response tuning is limited in precision in non-central regions due to detector geometry / limited tracking coverage.
  - **dijet p_T balance method**
- Equalize jets outside the central region to central jets.



Trigger jet: central region
Probe jet: anywhere

$$\Delta p_T f \equiv \frac{\Delta p_T}{p_T^{ave}} = \frac{p_T^{probe} - p_T^{trigger}}{(p_T^{probe} + p_T^{trigger})/2}$$

$$\beta \equiv \frac{p_T^{probe}}{p_T^{trigger}} = \frac{2 + \langle \Delta p_T f \rangle}{2 - \langle \Delta p_T f \rangle}$$



Jet Energy Scale Validations

Jet energy scale is validated with:

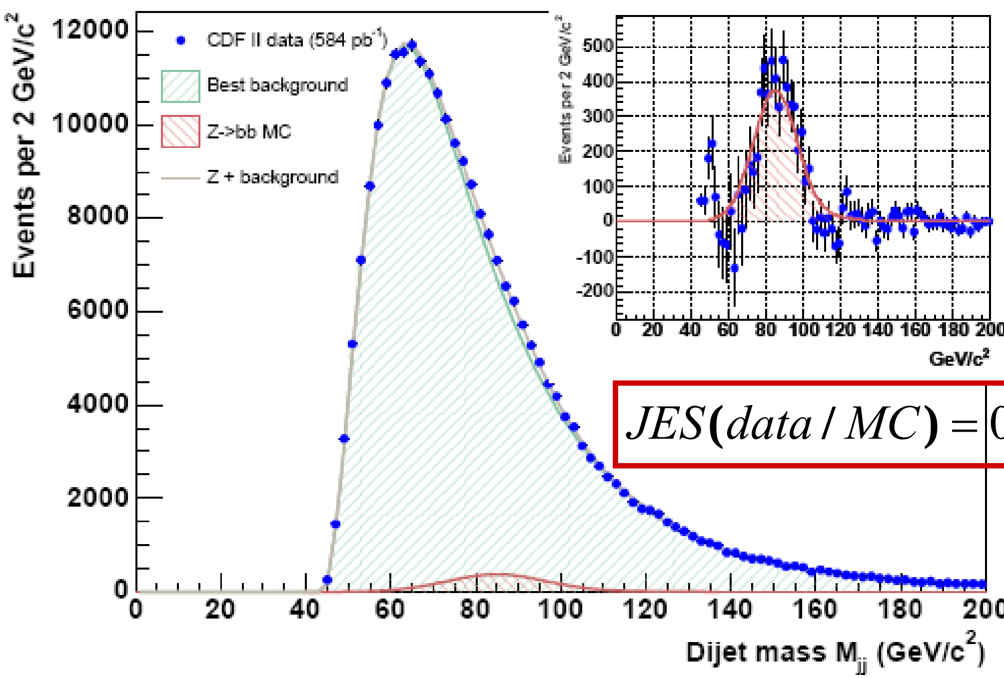
- Photon(Z)-jet p_T balance
- $W \to jj$ in $t\bar{t}$ production

  $$t\bar{t} \to (W\bar{b})(Wb),\ W \to l\nu, W \to jj$$

- $Z \to b\bar{b}$ production

Nucl. Instrum. Meth. A 596, 54-367 (2008)

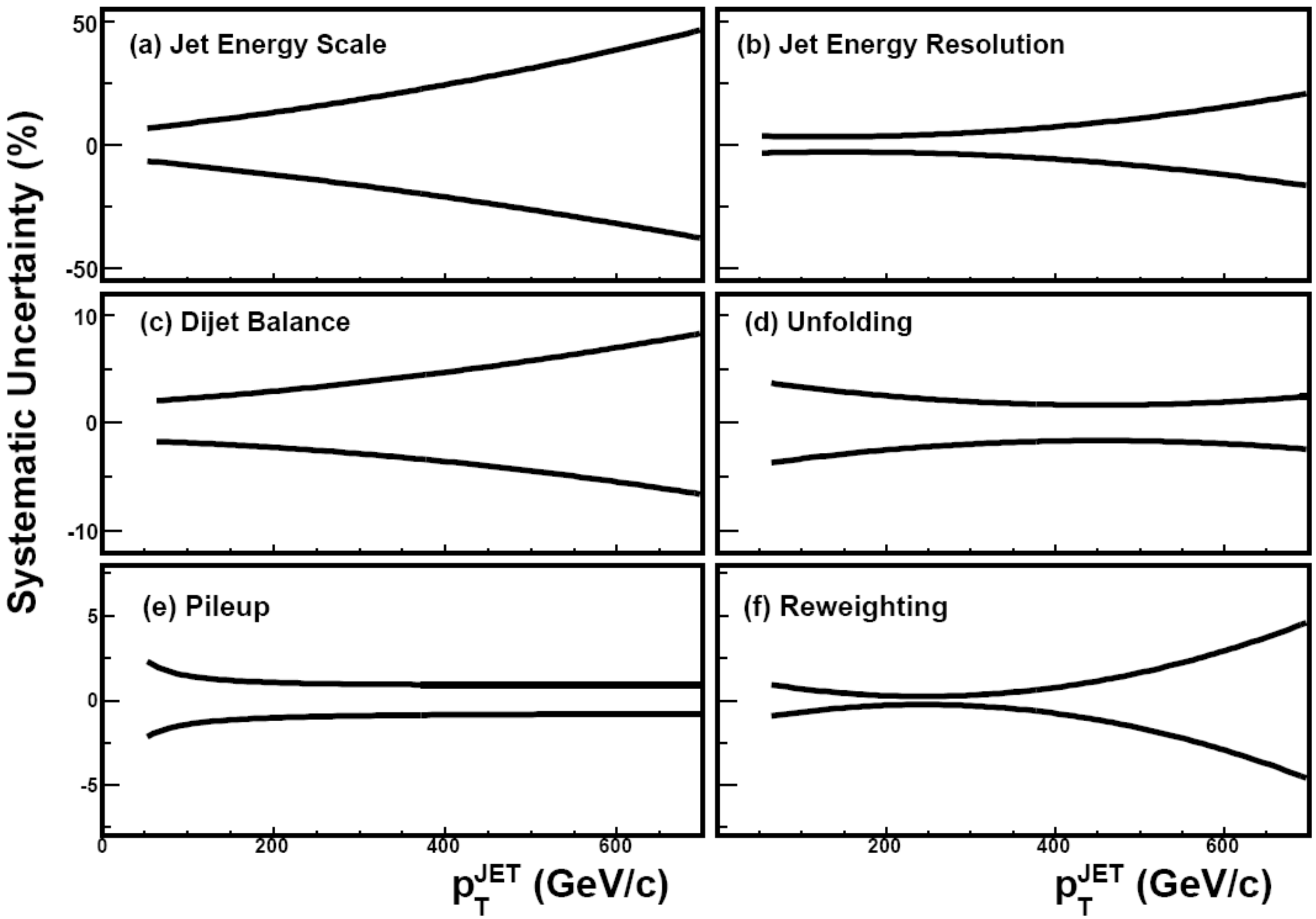
With J. Donini, T. Dorigo (Padova), M. Shochet (Chicago) et. al.



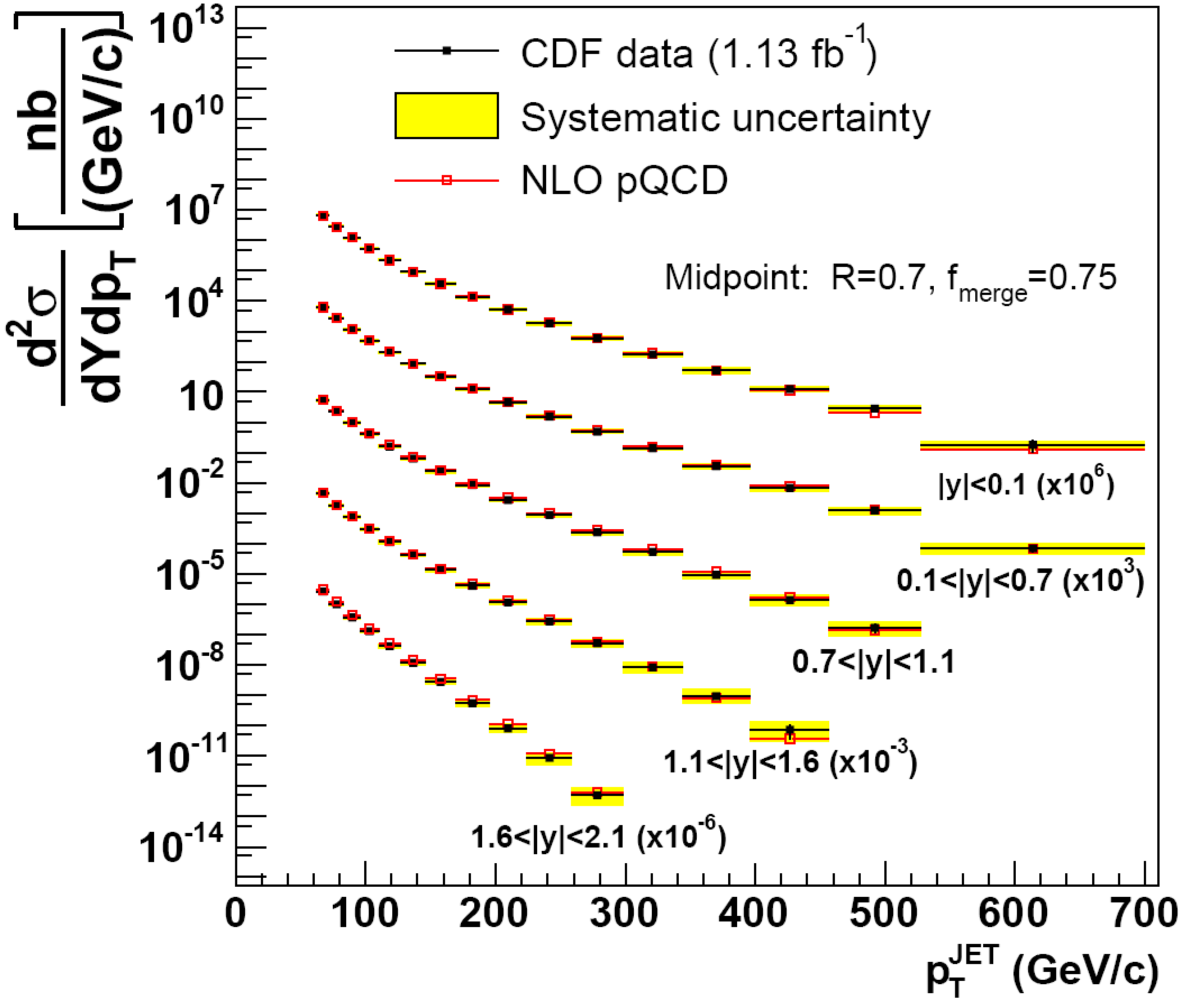
$$\boxed{JES(data/MC) = 0.974 \pm 0.011(stat.)^{+0.017}_{-0.014}(syst.)}$$

Systematic Uncertainties

$0.1<|y^{jet}|<0.7$

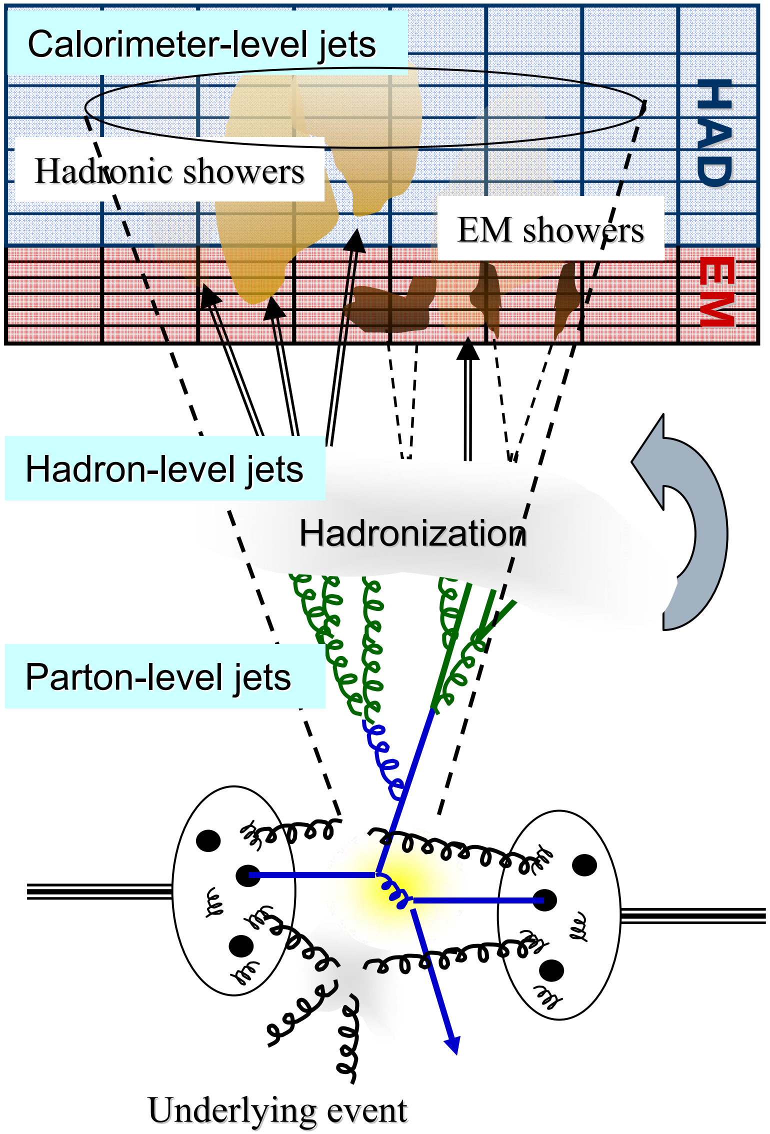


Inclusive Jet Cross Sections



(6% luminosity uncertainty not included)

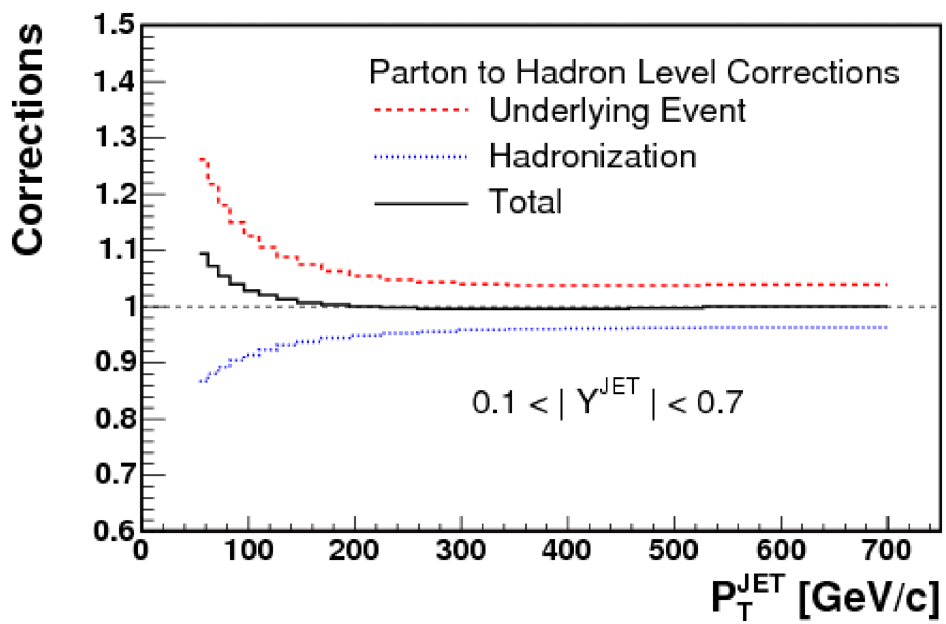
UE & Hadronization Correction



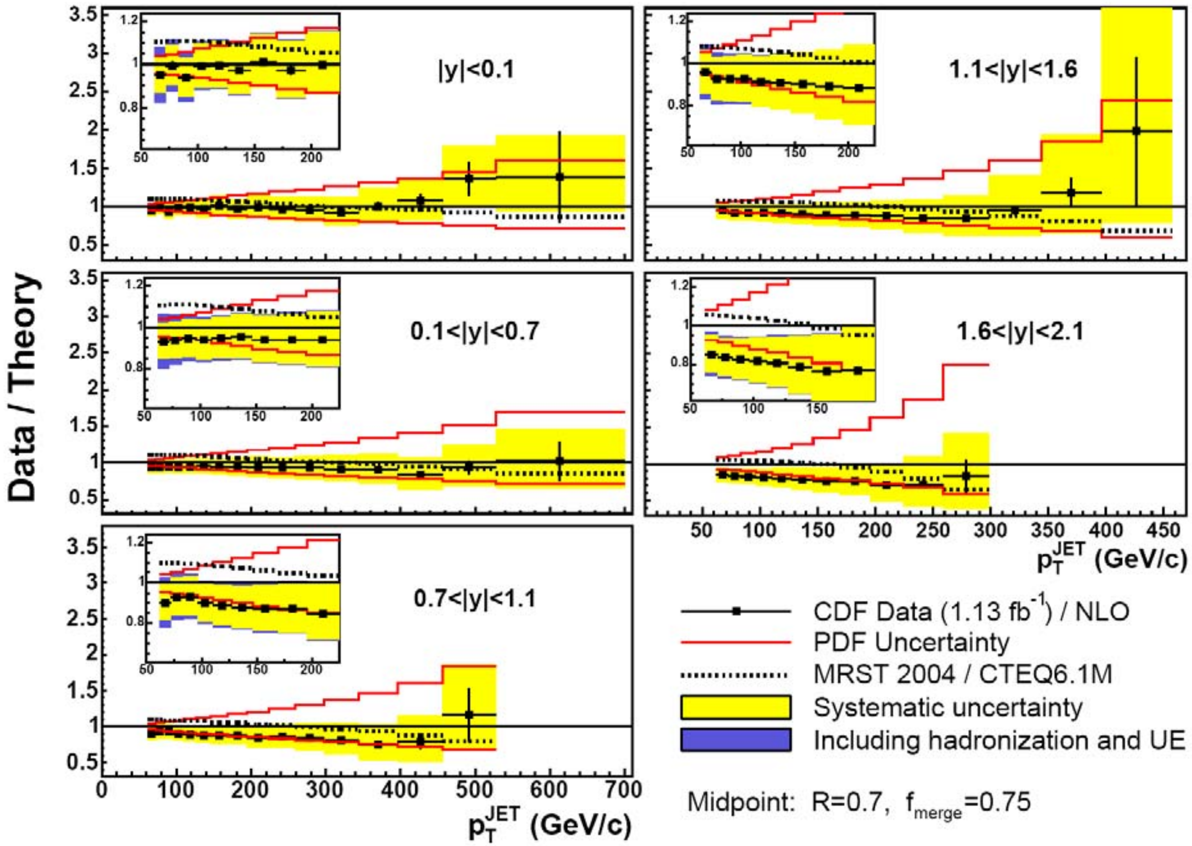
Currently-available state-of-the-art next-to-leading-order QCD predictions do not take into account:

- Underlying event (UE)
- Hadronization

These effects are estimated using Monte Carlo event generator (Pythia) tuned to data.



Inclusive Jets: Data vs QCD Predictions



- Data consistent with QCD predictions in all regions (χ^2/ndf = 94/72)
  - No excess at high p_T in the central region
- Experimental uncertainty in the forward region smaller than PDF uncertainty → further constrain PDFs (next generation of CTEQ PDF)

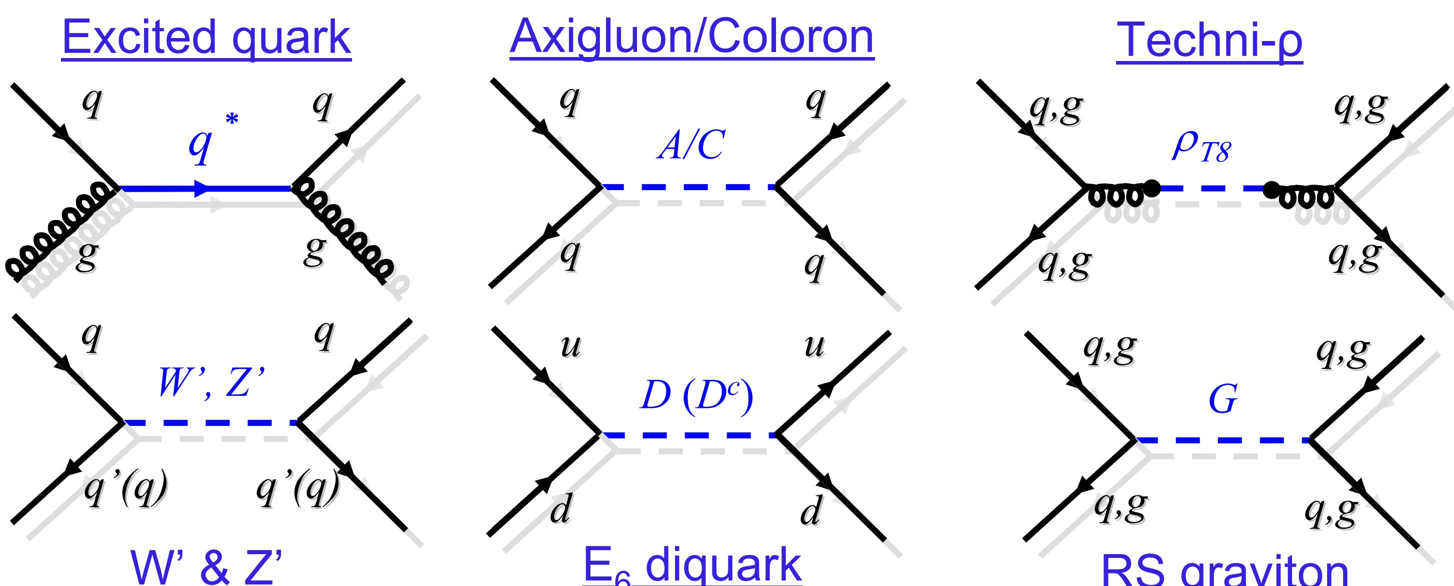
Searches for New Particles Decaying Into Dijets

arXiv:0812.4036 [hep-ex], Submitted to Phys. Rev. D.

Work with A. Bhatti (Rockefeller U.), R. Harris (Fermilab)

Motivation

- Finding a resonance in mass spectrum is a most convincing way to find a new particle.
- The Tevatron is still the world highest energy collider and accumulating more data.
  - Allow us to explore the unprecedented high mass region.
- Dijet Resonances are predicted in many new physics models.



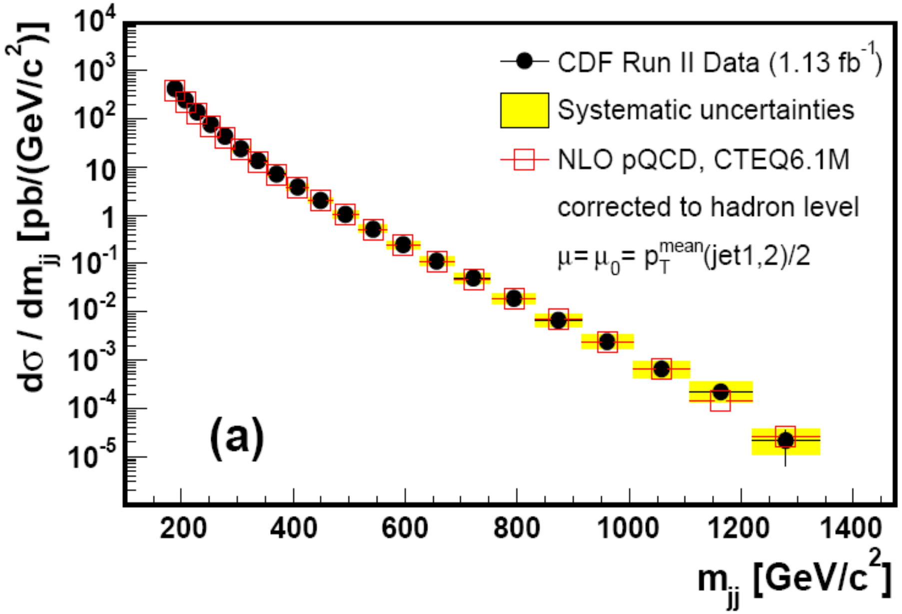
Analysis Strategy

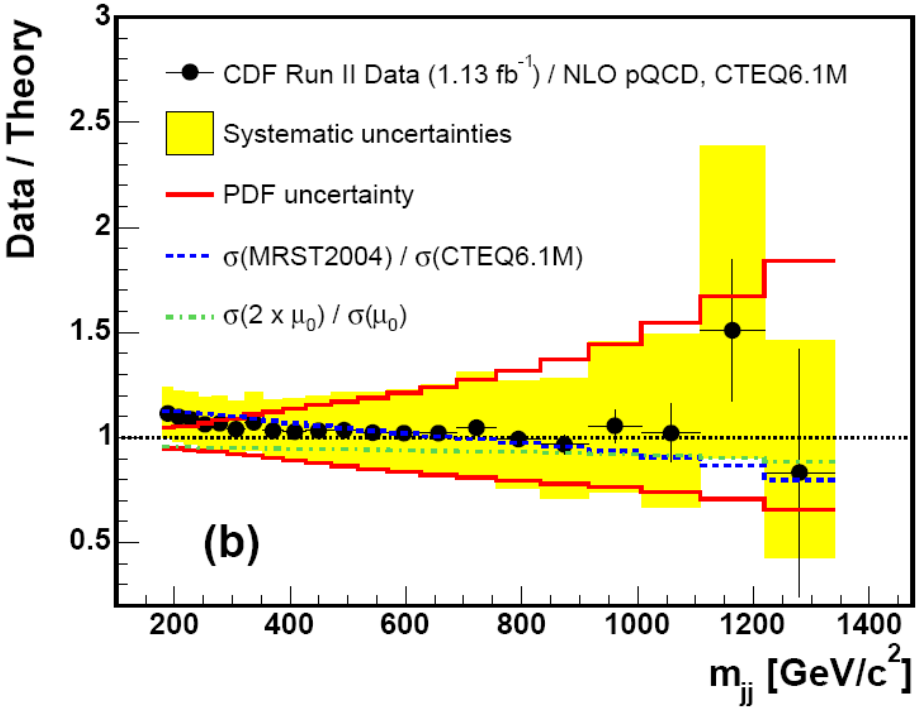
- Use the same strategy as the inclusive jet cross section measurement for forming dijet mass spectrum
  - Jet p_T → Dijet invariant mass
  - Jet cross section → Dijet pair cross section

- Search for a resonant structure over a smooth function fit
  - BG is dominated by QCD dijets
  - Model QCD dijet mass spectrum by a smooth functional form fitted to data rather than relying on the theory prediction(s)
    - Predictions on QCD dijets have large uncertainties
  - Use a function which fits the predictions from Pythia, Herwig event generators, & (N)LO perturbative QCD calculations .

$$\frac{d\sigma}{dm} = p_0 (1-x)^{p1} / x^{p2+p3\log(x)}, \quad x = m/\sqrt{s}$$

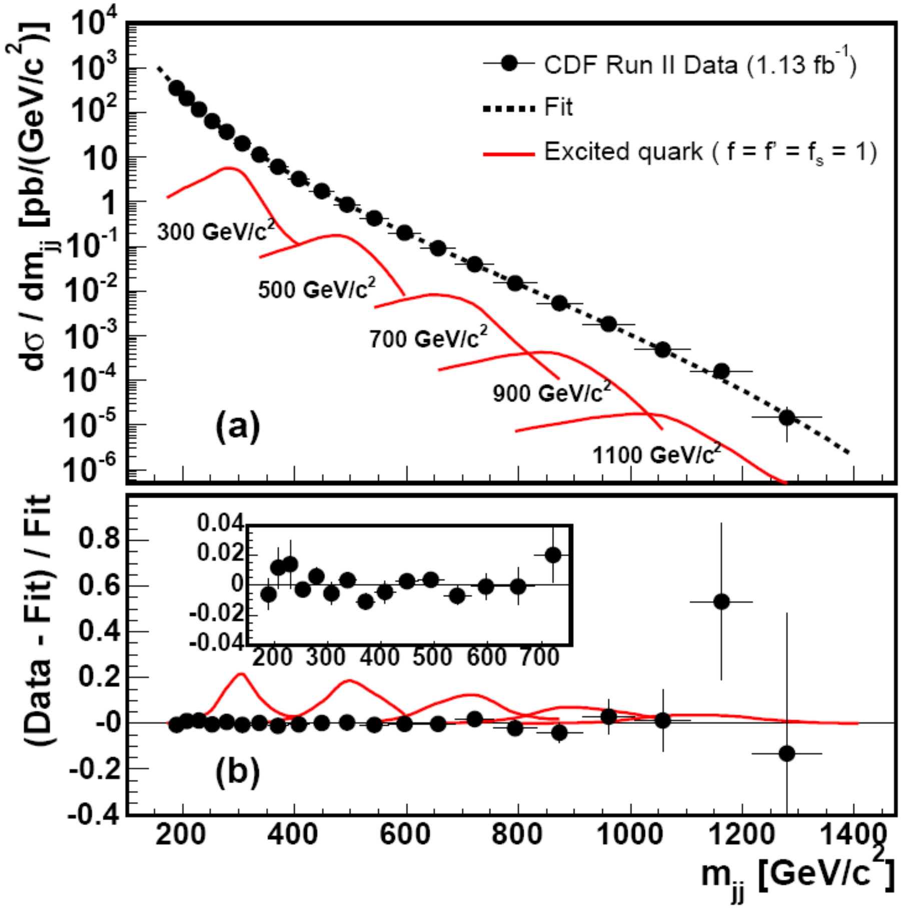
Dijet Mass Differential Cross Section





Consistent with NLO QCD predictions (χ^2/n.d.f.=21/21)

Search for Resonances



Fit form :

$$\frac{d\sigma}{dm} = p_0(1-x)^{p1} / x^{p2+p3\log(x)}, \quad x = m/\sqrt{s}$$

No convincing resonance found in the measured dijet mass spectrum (χ^2/n.d.f.=16/17).

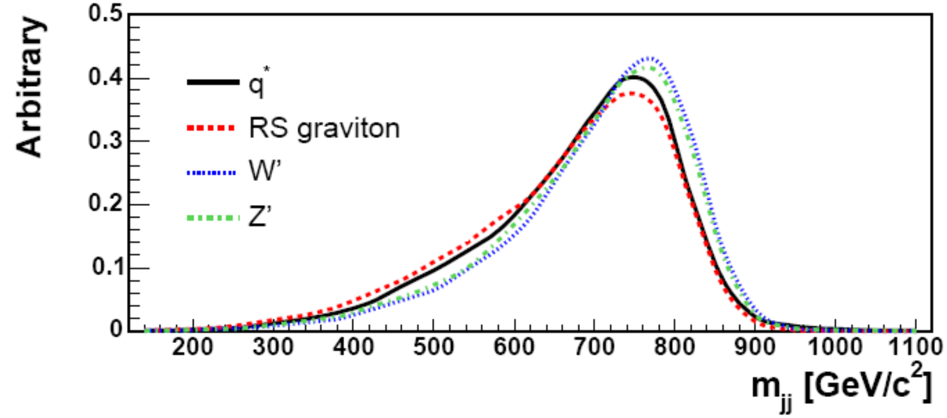
- Set 95% C.L. upper limits on new particle production

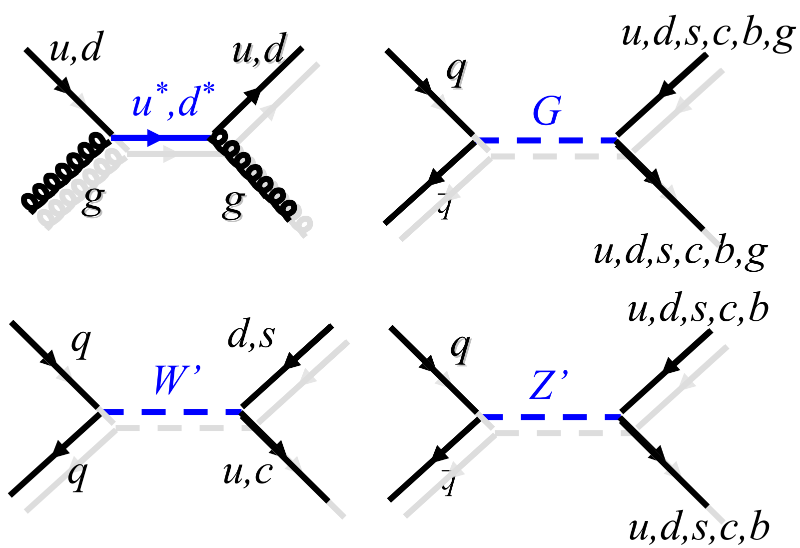
Dijet Resonance Models

- Dijet mass distributions for
  - Excited quark (q*)
  - RS graviton (G)
  - W’
  - Z’

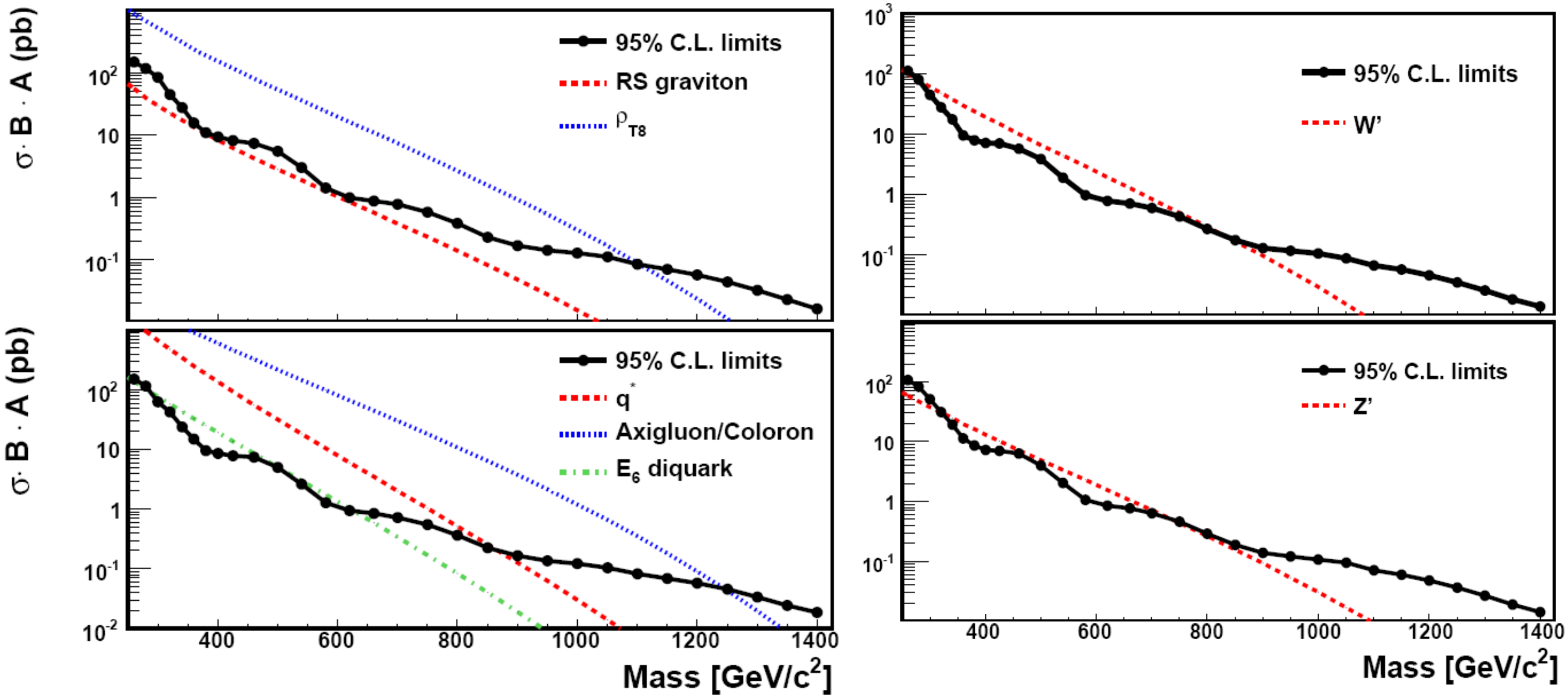
  modeled by Pythia MC.
- Gluons make the dijet mass resonance shape wider.

  (~20% effect on resonance cross section sensitivities)
- Determine 95% CL limits using signal shapes from these four models separately
- For other models, compare predictions with one of these limits that are applicable to each model





Upper Limits @ 95% CL



Dijet resonance models are excluded at the 95% C.L. in the mass region above the black curves.

Exclusions for Resonance Models

Models	Mass Exclusions (GeV/c^2)	
	Existing	This Search
q*	260 < m < 775	260 < m < 870
Axigluon/ coloron	260 < m < 980	260 < m < 1250
ρ_{T8}	260 < m < 480	260 < m < 1100
E_6 diquark	290 < m < 420	290 < m < 630
W'_{SM}	300 < m < 800 (m<1000 from $W' \rightarrow l\nu$)	280 < m < 840
Z'_{SM}	400 < m < 640 (m<889 from $Z' \rightarrow ll$)	320 < m < 740

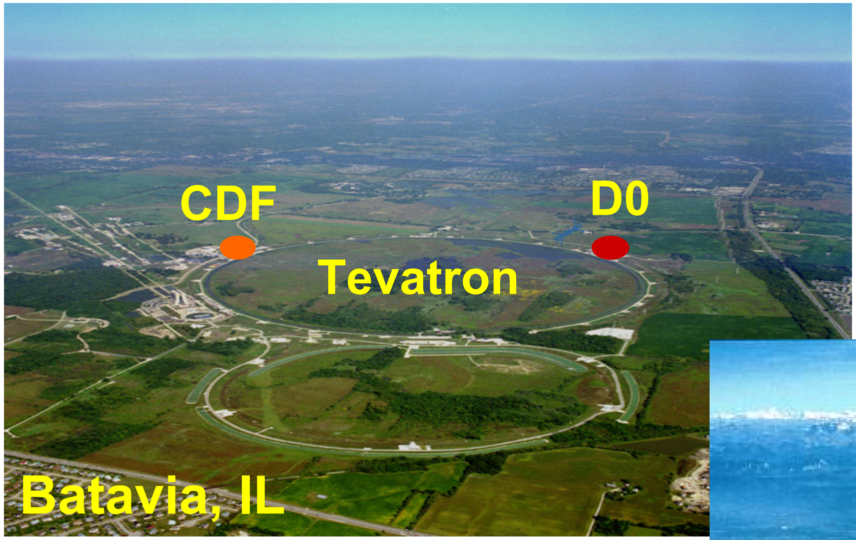
World best limits

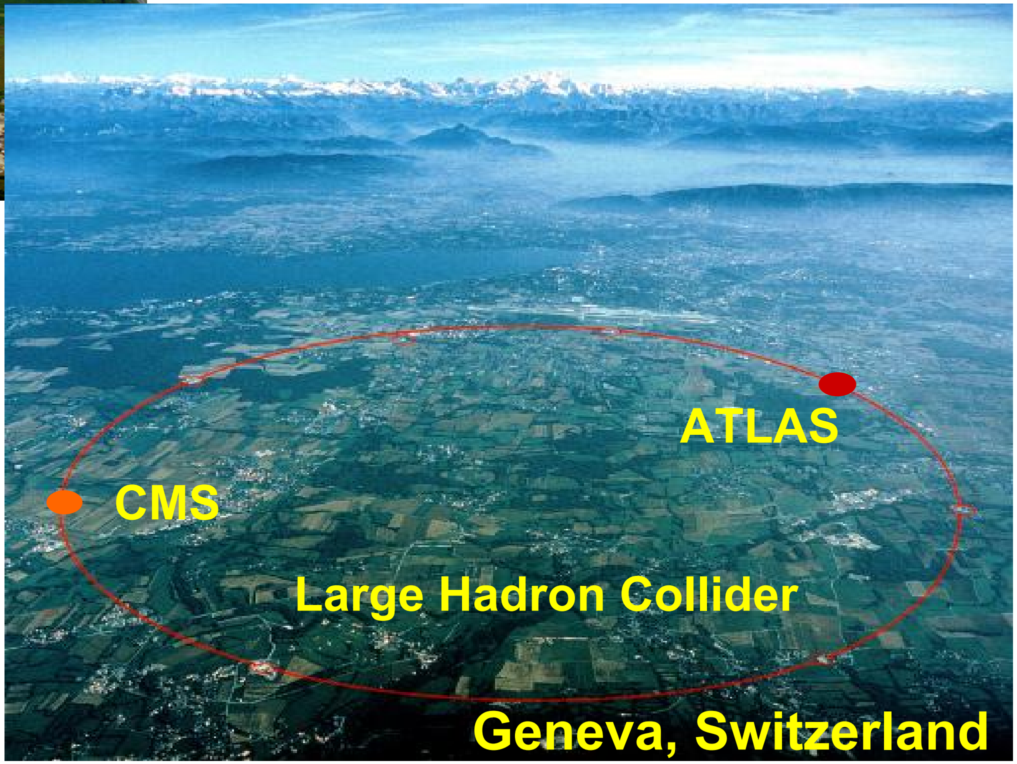
World best limits in jj channel

- Constraining many theoretical models.
- Mass exclusions up to 1.2 TeV/c^2!

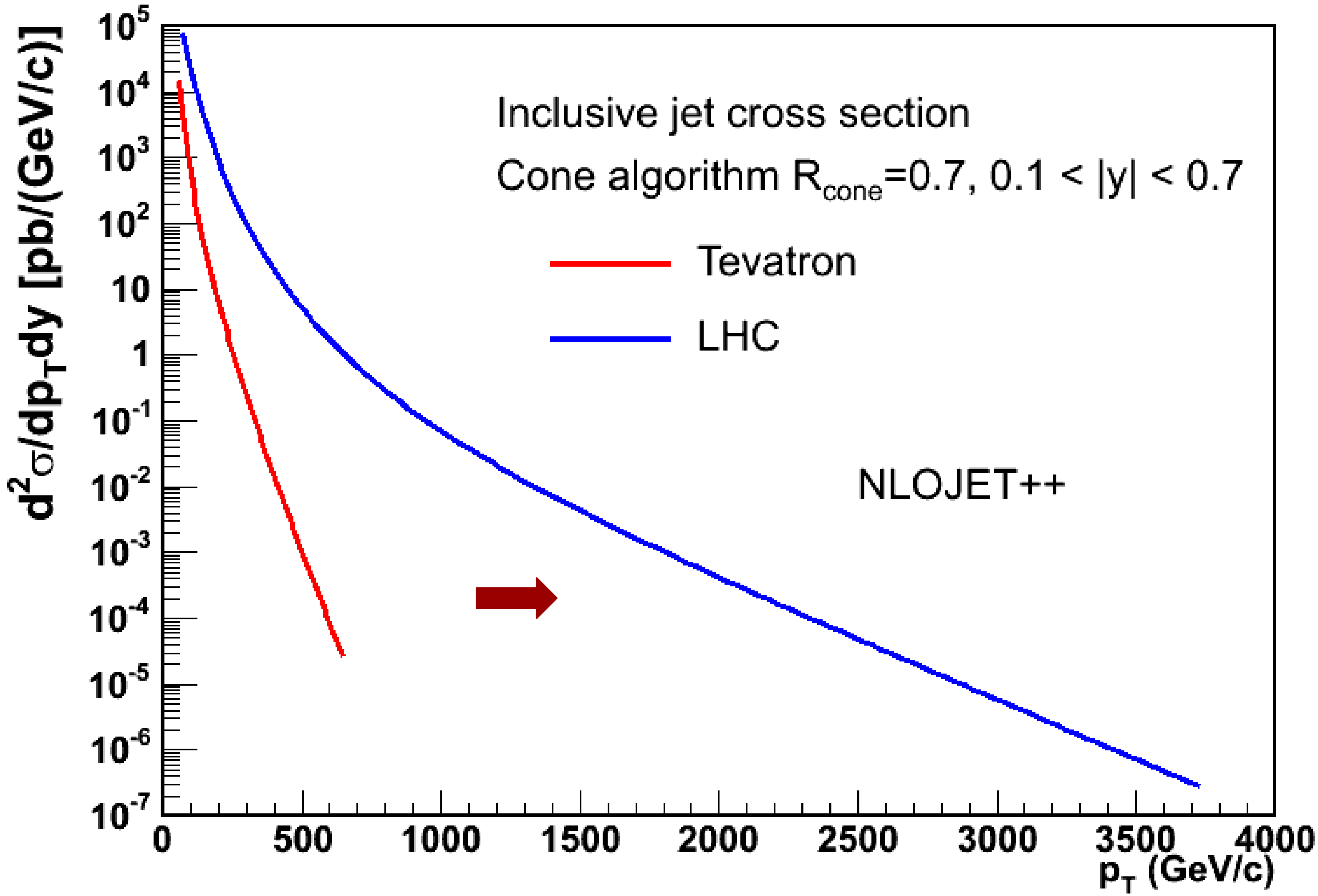
Future Prospects

Tevatron → Large Hadron Collider

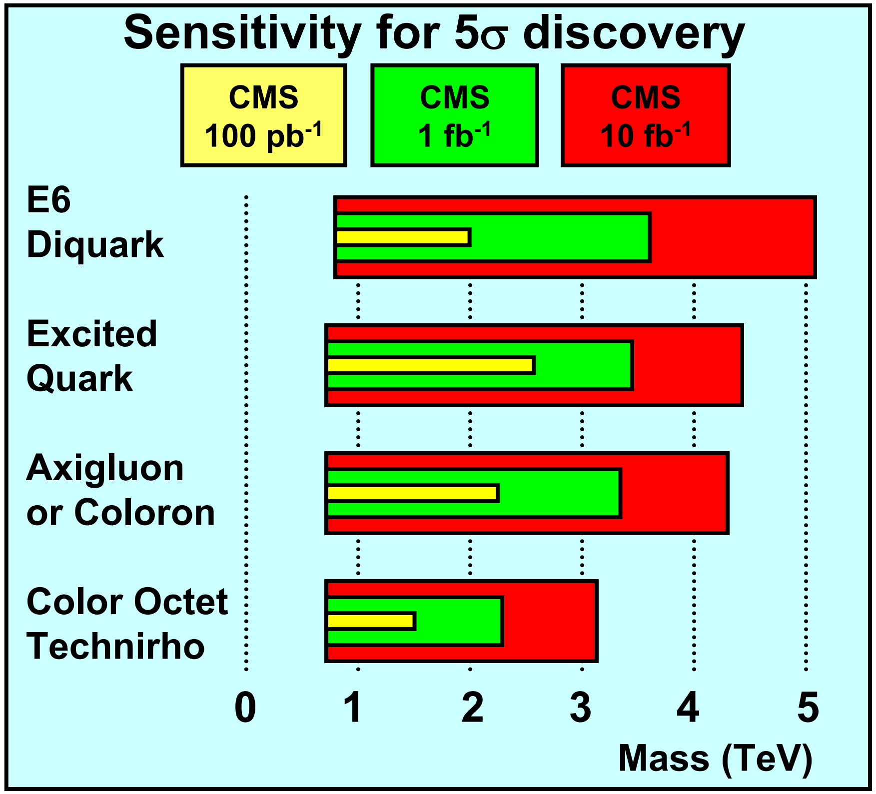


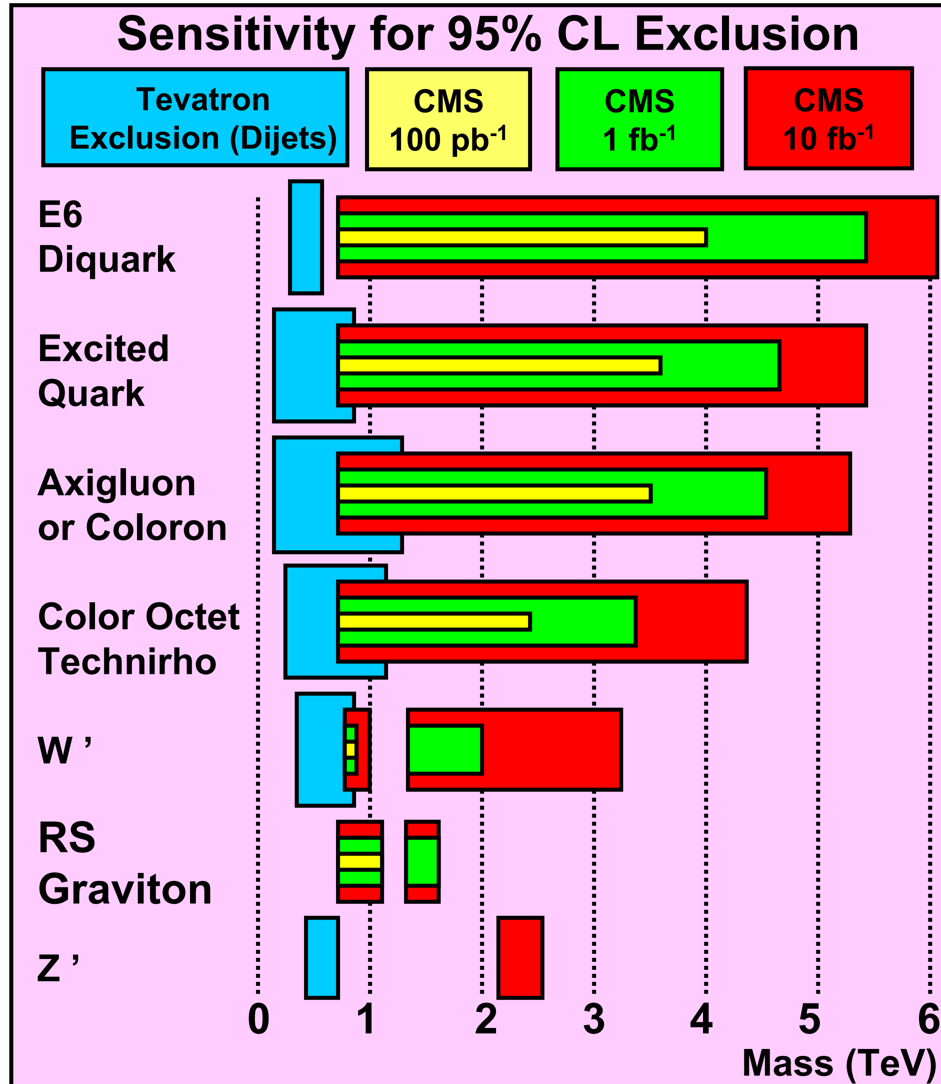


Inclusive Jets at LHC



LHC Sensitivity to Dijet Resonances





- Possibility to discover particles up to 5 TeV/c^2 in 10 fb^{-1} of data
- If the new particles are not there, will extend Tevatron exclusions

From the CMS experiment

More Physics with Jets at LHC

- Higgs boson searches
  - qqH ($H \to \tau\tau \to lj$), qqH ($H \to WW^* \to l\nu jj$), …
- Top quarks
  - High statistics $t\bar{t}$ events great sample to calibrate jets from $W \to jj$
  - New physics searches with top quarks: FCNC, $t\bar{t}$ resonances, …
- Searches for SUSY:
  - Squark/gluino production
    $\to$ missing E_T + multi-jets (+ lepton(s))
- …

Solid understanding of jets will be essential for new discoveries to be made at the LHC.

Summary & Remarks

High energy jets produced by the Tevatron offer great opportunities to:

- Test QCD predictions in the widest kinematic range
- Constrain parton distribution functions (PDFs) in the proton
- Search for new physics beyond the Standard Model

Measurement of the inclusive jet cross sections

- Detailed jet energy scale calibrations (uncertainty < 3%)
- Provide constraints on proton PDFs (especially high-x gluons)

Searches for new particles decaying into dijets

- Significantly extend the limits from the previous searches

The LHC era is approaching:

- We expect new discoveries at the LHC (Higgs?, SUSY?, compositeness?, new symmetries?, something unexpected?), and jets will play a key role.

Let’s get ready for new discoveries!

My Research in the Past

- Selected Publications:
  - Dijet resonance search, arXiv:0812.4036 , submitted to PRD (2008).
  - Measurement of inclusive jets including forward region, PRD (2008).
  - Measurement of $Z \rightarrow b\bar{b}$, NIM A (2008).
  - Jets in hadron-hadron collisions, Prog. Part. Nucl. Phys (2008).
  - Measurement of inclusive jets for central region, PRD-RC (2006).
  - Jet energy scale determination, NIM A (2006).
  - Measurement of inclusive double pomeron exchange, PRL (2004).
  - The CDF MiniPlug calorimeter, NIM A (2003).
  - Diffractive dijets at $\sqrt{s}$ = 630 and 1800 GeV, PRL (2002).
  - Diffractive dijets and diffractive structure function measurement, PRL (2000).

- Service Work:

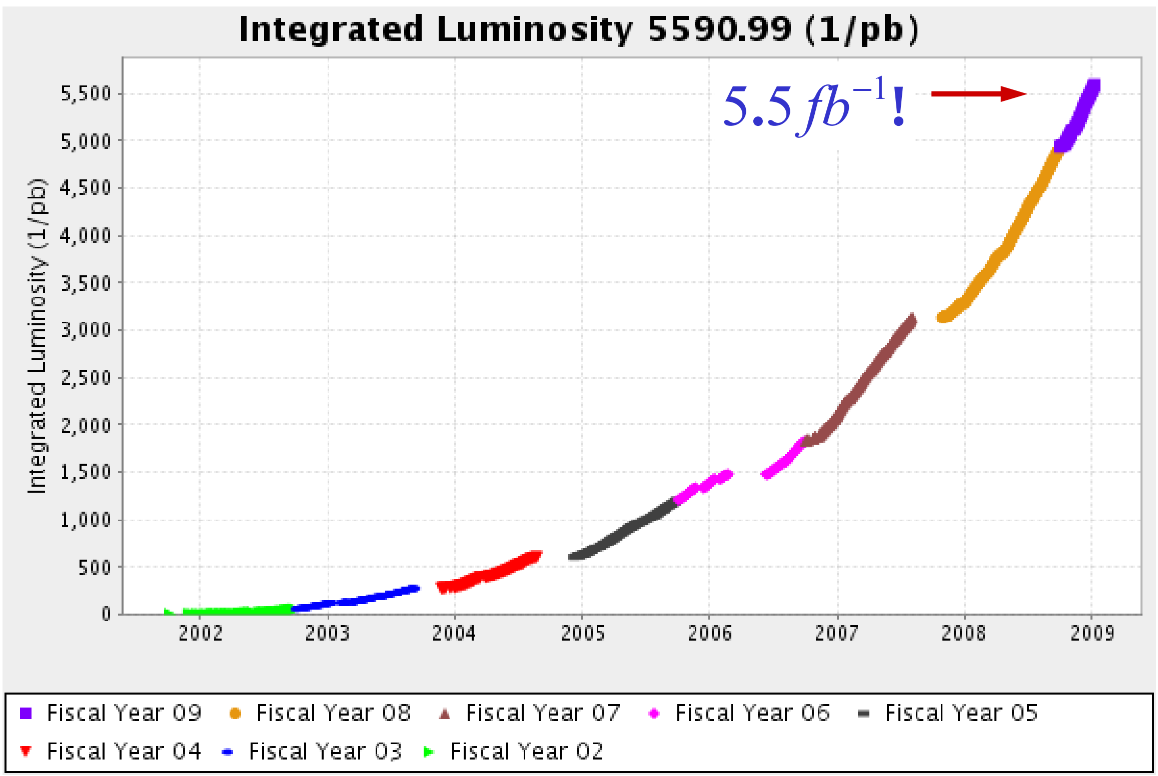
  On CDF
  - QCD physics group convener (Jan. 2007 – Dec. 2008)
  - Jet energy and resolution group convener (Apr. 2005 – Nov. 2006)
  - QCD group Monte Carlo coordinator (Apr. 2005 – Nov. 2006)
  - Offline production coordinator (Aug. 2004 – Jan. 2005)
  - Beam-shower counter maintenance

  On CMS
  - Data quality monitoring for jets and missing E_T (Sep. 2008 -)

Backup Slides

Tevatron Performance & Projection

- Run II (2001-), $\sqrt{s}$ = 1.96 TeV
  - Delivered luminosity now ~ 5.5 fb^{-1}
  - Projection ~ 6.5 fb^{-1} by summer 2009
  - Running by summer 2010, additional 2.5 fb^{-1}

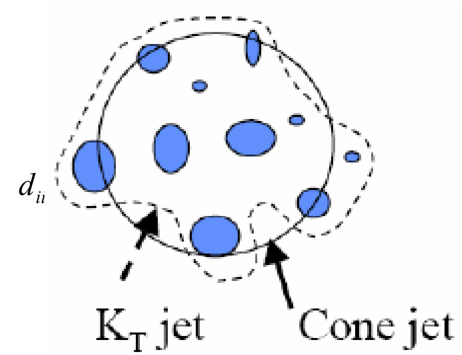


Jet "Definitions" – Jet Algorithms

k_T algorithm

- Cluster objects in order of increasing their relative transverse momentum (k_T)
  - $d_{ii} = p_{T,i}^2, \quad d_{ij} = \min(p_{T,i}^2, p_{T,j}^2)\,\dfrac{\Delta R^2}{D^2}$

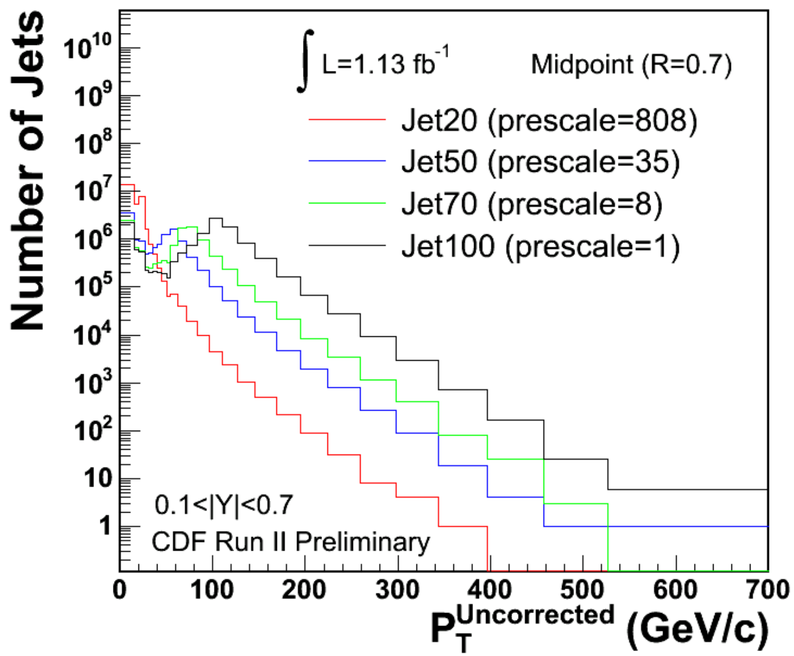
  until all objects become part of jets
- D parameter controls merging termination and characterizes size of resulting jets

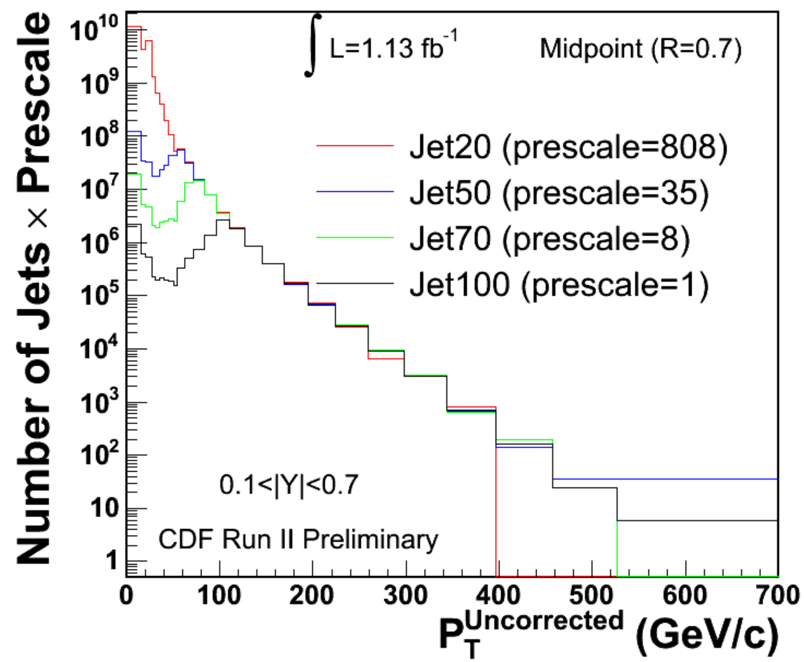


- No issue of splitting/merging. Infrared and collinear safe to all orders of QCD.
- Every object assigned to a jet: concerns about vacuuming up too many particles.
- Successful at LEP & HERA, but relatively new at the hadron colliders
  - More difficult environment (underlying event, multiple $\bar{p}p$ interactions…)

Jet Trigger and Datasets

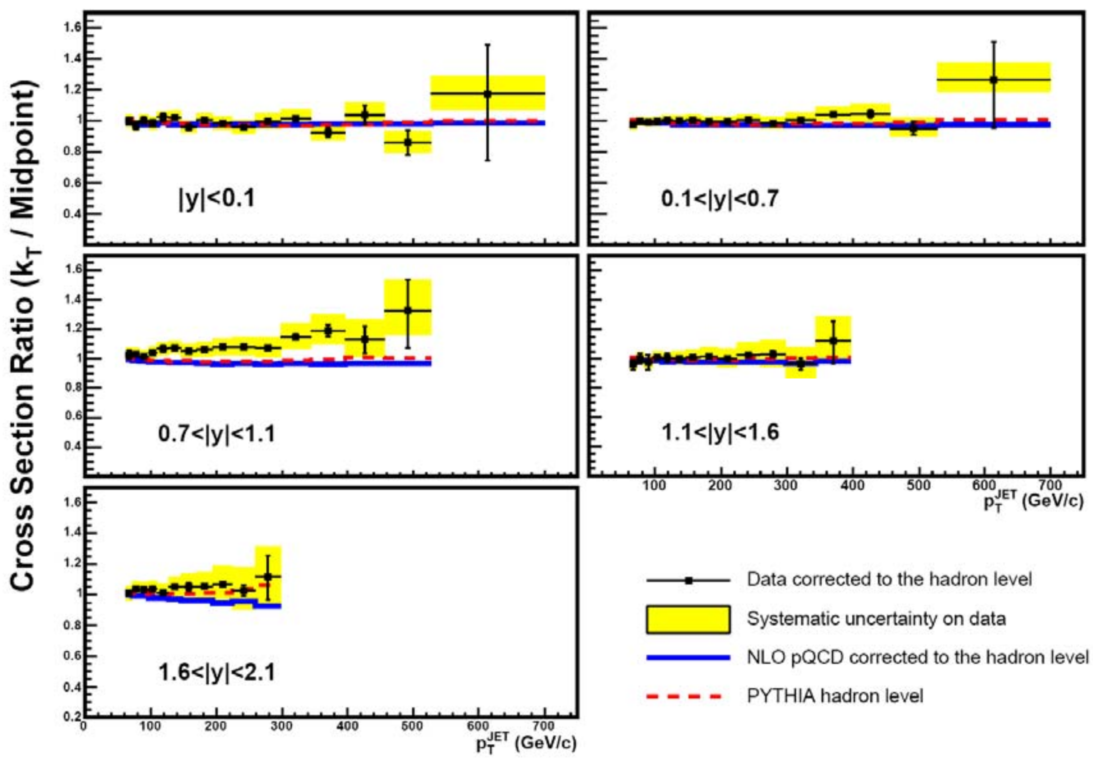
- Jet rate at the Tevatron too high. Collisions recorded only at ~100 Hz.
- Use four different trigger samples
  - Low threshold sample, E_T^{jet}>20 GeV (jet20), w/ prescale ~ 800
    (Only 1 out of 800 events satisfying the trigger requirement is recorded)
  - High threshold sample, E_T^{jet}>100 GeV (jet100), w/o prescale,
    (All events are recorded)
  - For each p_T bin, use highest threshold samples with trigger efficiency > 99.5%.

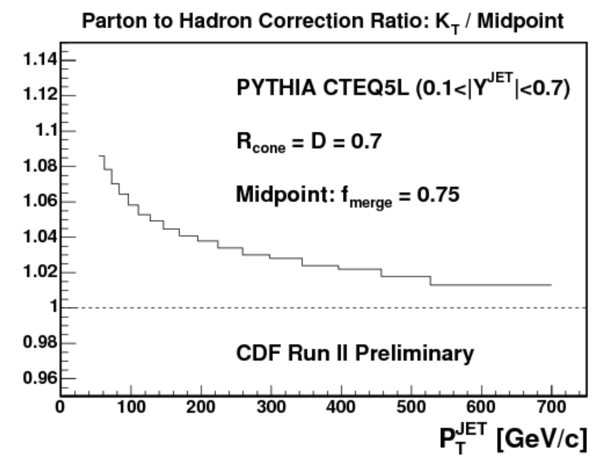




Cone versus k_T Algorithm Results

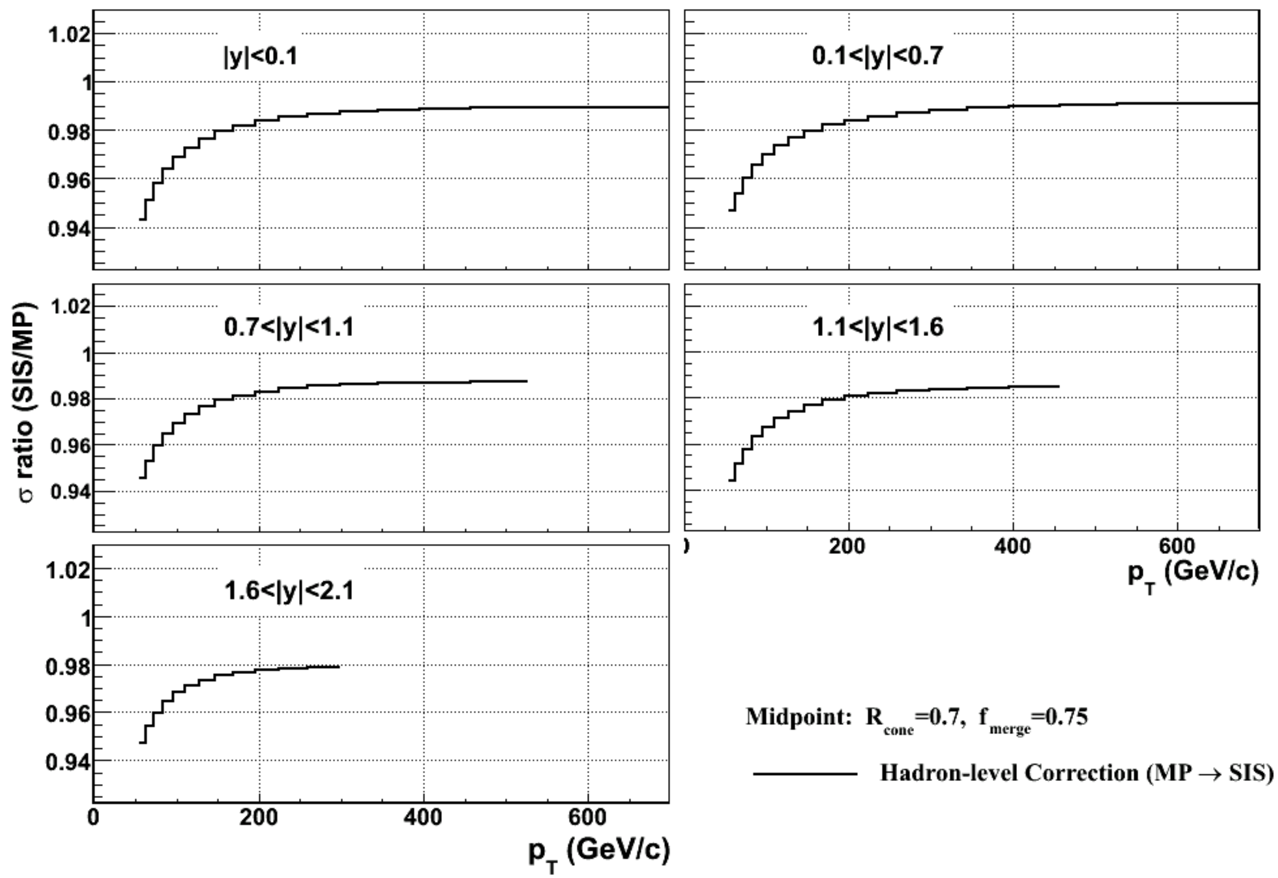
- At the parton level, $\sigma(k_T)<\sigma(\text{cone})$ with $R_{cone}=D$.
  - Cone algorithm tend to merge two energetic clusters with large separation ($>R_{cone}=D$) more than the k_T algorithm.
- Non-pertubative (UE+hadronization) effects larger for k_T algorithm
  - $\sigma(k_T) \sim \sigma(\text{cone})$ at the hadron level.





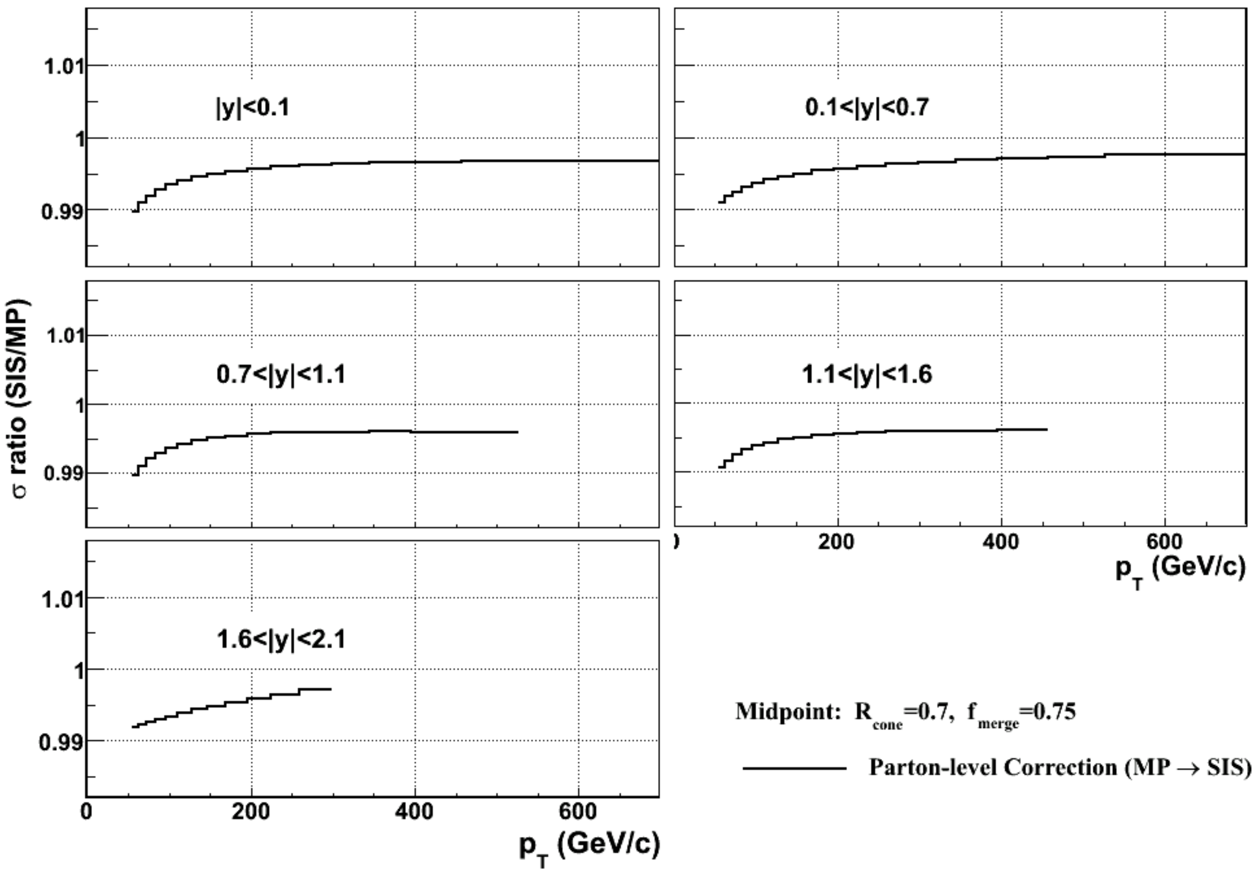
Midpoint vs SIScone: hadron level

- Differences between the currently-used Midpoint algorithm and the newly developed SIScone algorithm in MC at the hadron-level.



Midpoint vs SIScone: parton level

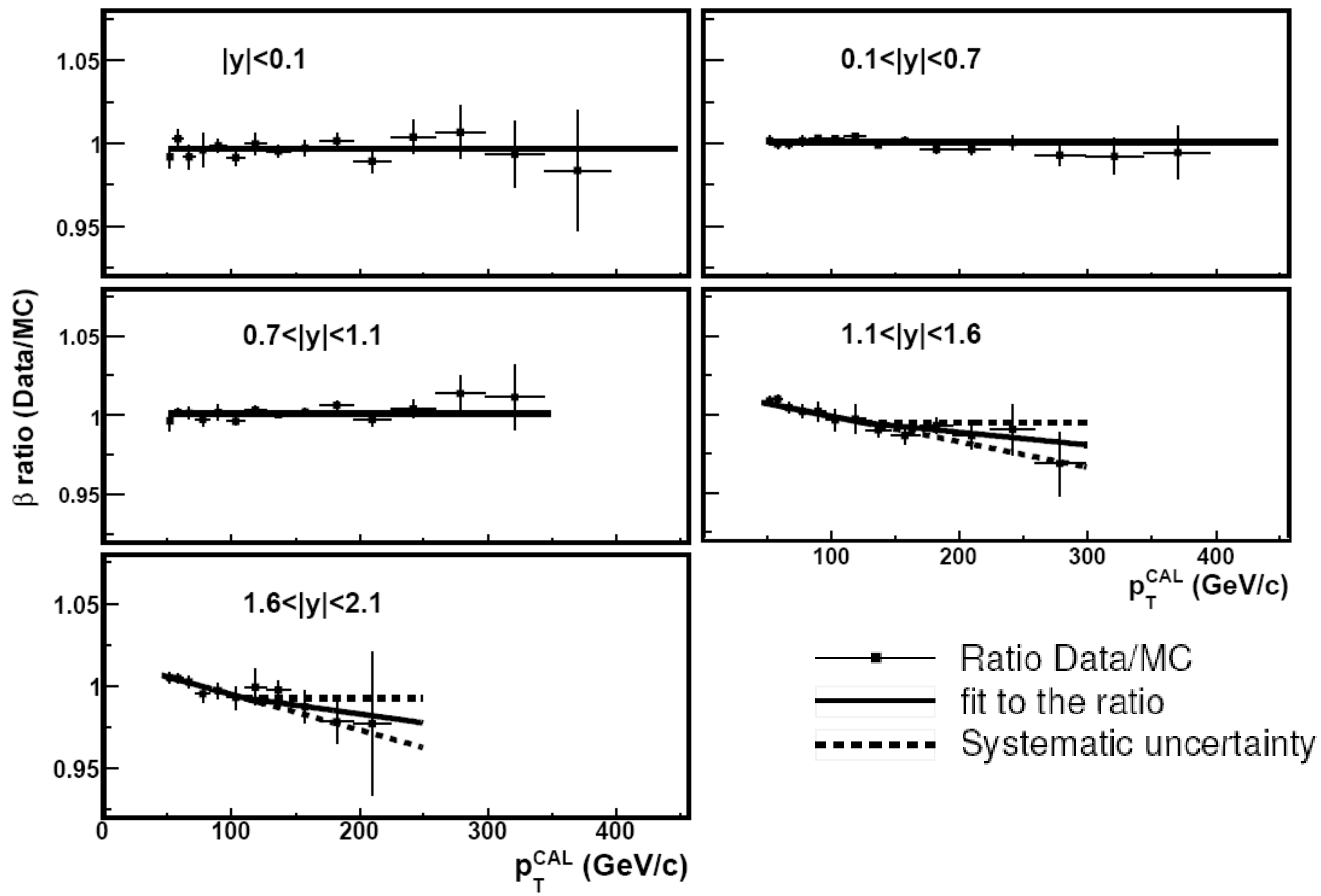
- Differences between the currently-used Midpoint algorithm and the newly developed SIScone algorithm at the parton-level.



Differences < 1% → negligible effects on data-NLO comparisons

Dijet p_T Balance vs Jet p_T

- Dijet p_T balance changes as a function with jet p_T in the forward region → Additional correction!



Jet Energy Resolution: Bisector Method

- The unfolding correction for jet resolution effects is derived from MC simulation.
- The MC simulation has to reproduce the jet energy resolution in data.

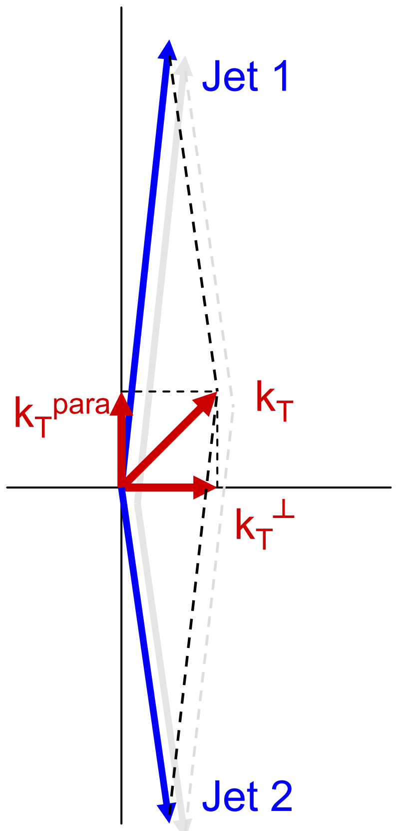
- Use the “bisector” method.

$$k_T^{para} = (p_{T1} - p_{T2})\,\mathbf{sin}(\varphi_{12}/2) \leftarrow$$ detector and physics effects

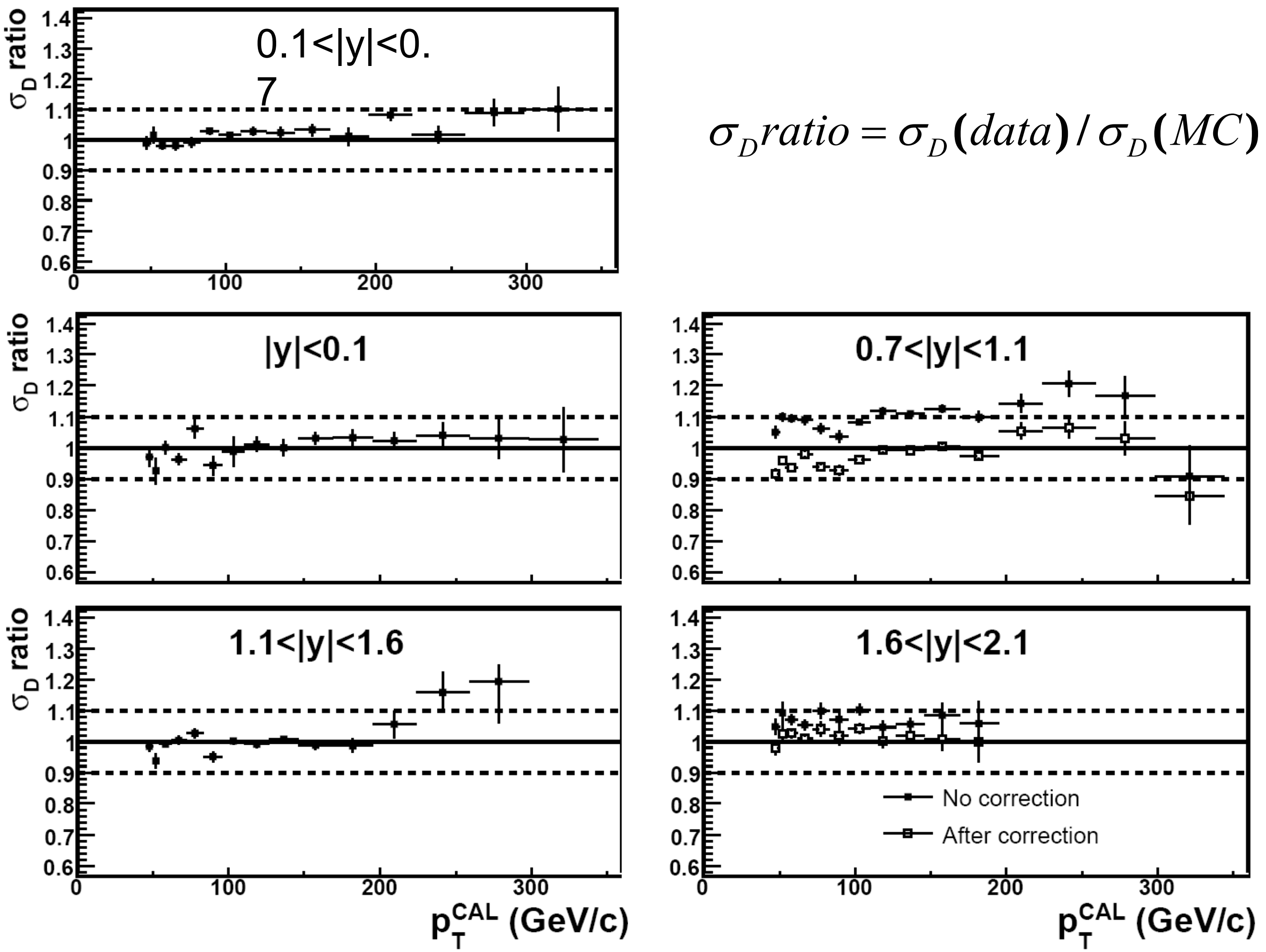
$$k_T^{\perp} = \pm(p_{T1} + p_{T2})\,\mathbf{cos}(\varphi_{12}/2) \leftarrow$$ physics effects

$\sigma_{para}(\sigma_{\perp})$: RMS of $k_T^{para}(k_T^{\perp})$ distribution

$$\sigma_D = \sqrt{\sigma_{para}^2 - \sigma_{\perp}^2} \leftarrow$$ Jet resolution due to detector effects



Jet Energy Resolution: Bisector Method

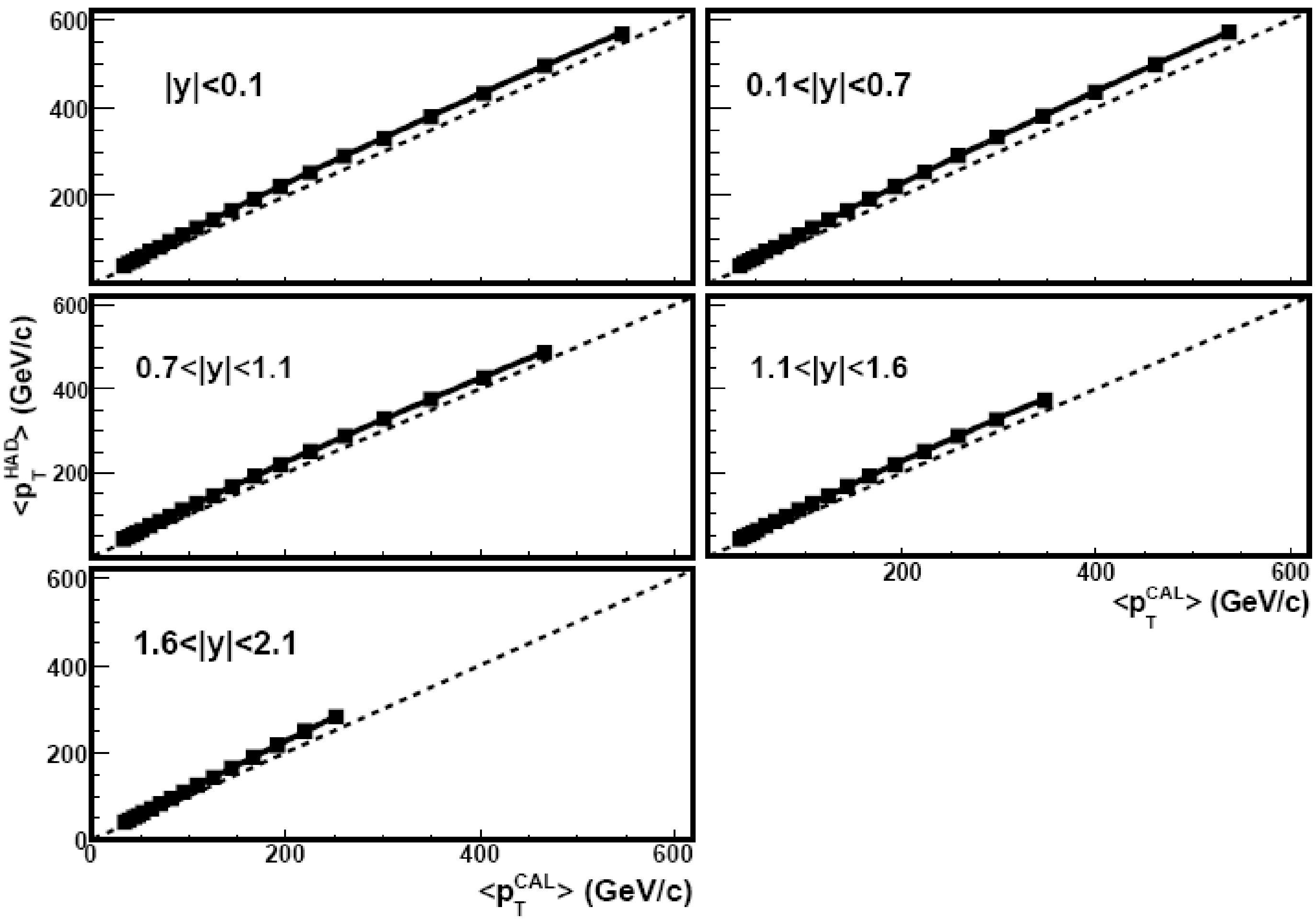


$$\sigma_D ratio = \sigma_D(data)/\sigma_D(MC)$$

In the region where the MC underestimate the resolution, introduce extra smearing.

Average p_T Correction

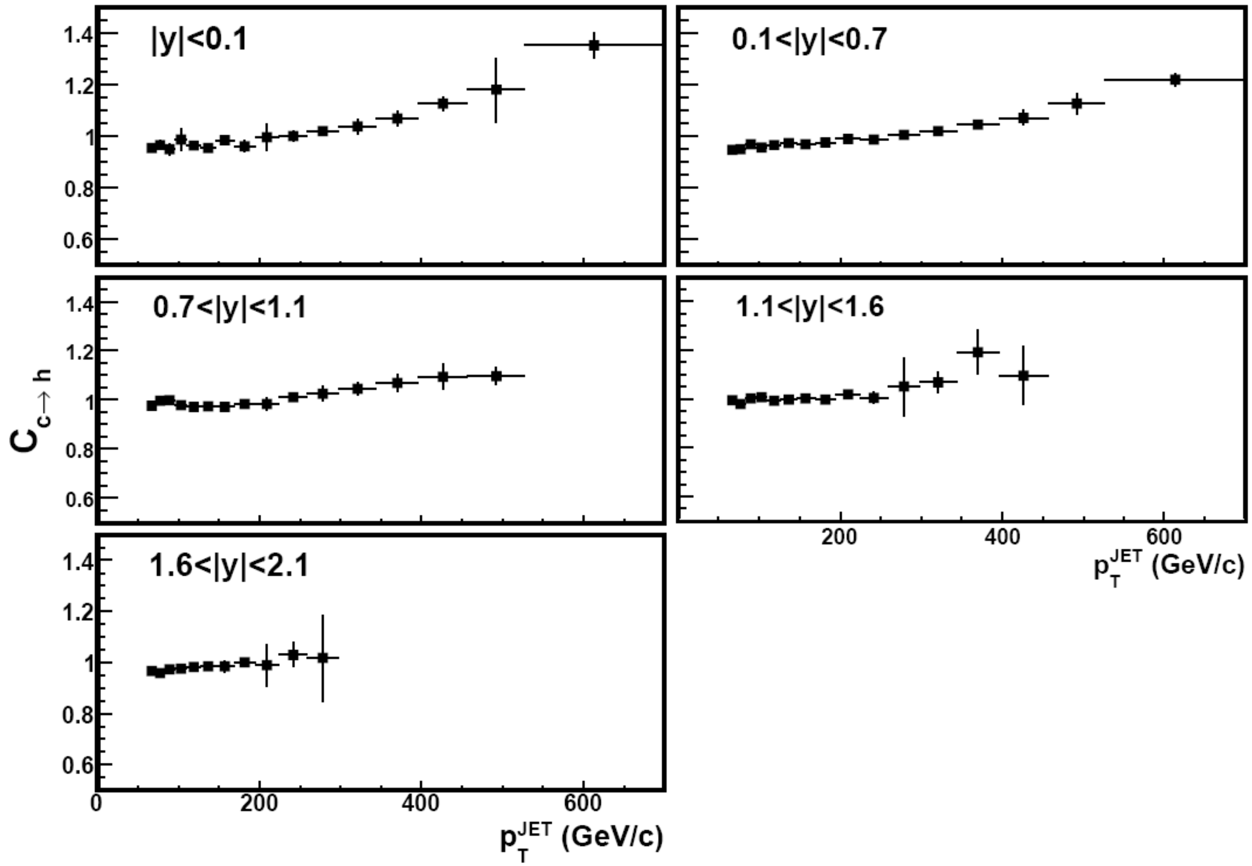
Take $\langle p_T^{CAL} \rangle$ vs $\langle p_T^{HAD} \rangle$ correlation



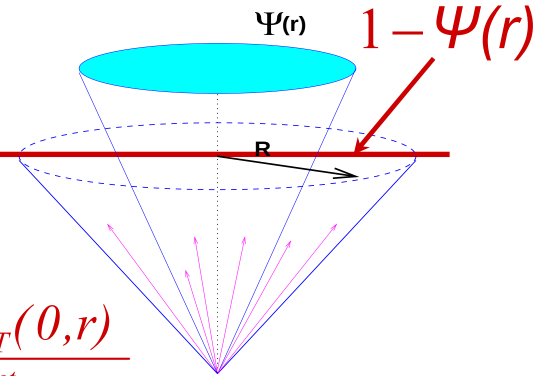
Unfolding Corrections

$$U(p_T^{jet}, y^{jet}) = \frac{N(\text{calorimeter} - \text{level jets})}{N(\text{hadron} - \text{level jets})}$$

Correction for the jet energy resolution effects



Jet Fragmentation Studies



Need to simulate jets properly:

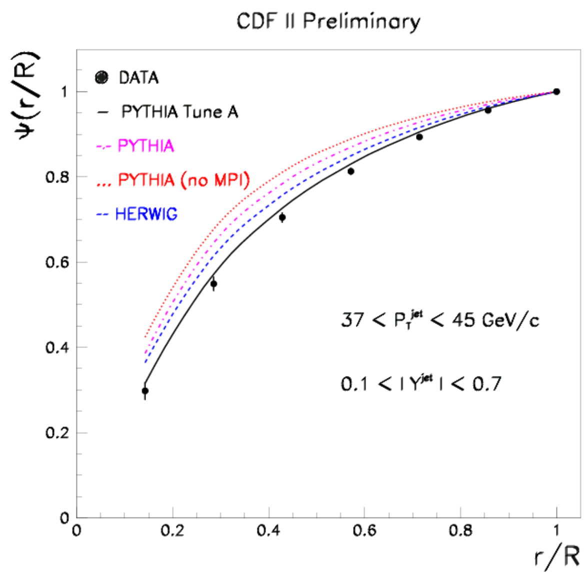
particle composition,
multiplicity, momentum
distribution etc

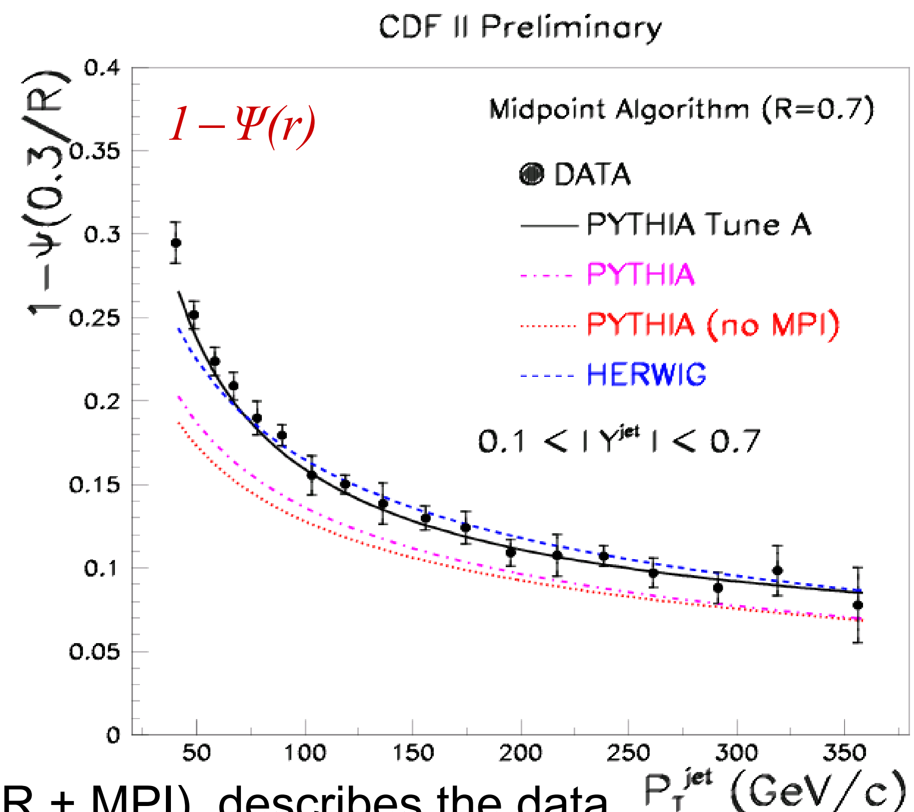
$$\Psi(r) = \frac{1}{N_{jets}} \Sigma_{jets} \frac{p_T(0,r)}{p_T^{jet}(0,R)}$$

e.g. **2 hadrons with $p_T = 50$ GeV/c**

$\neq$ 20 hadrons with $p_T = 5$ GeV/c

due to calorimeter non-linearity



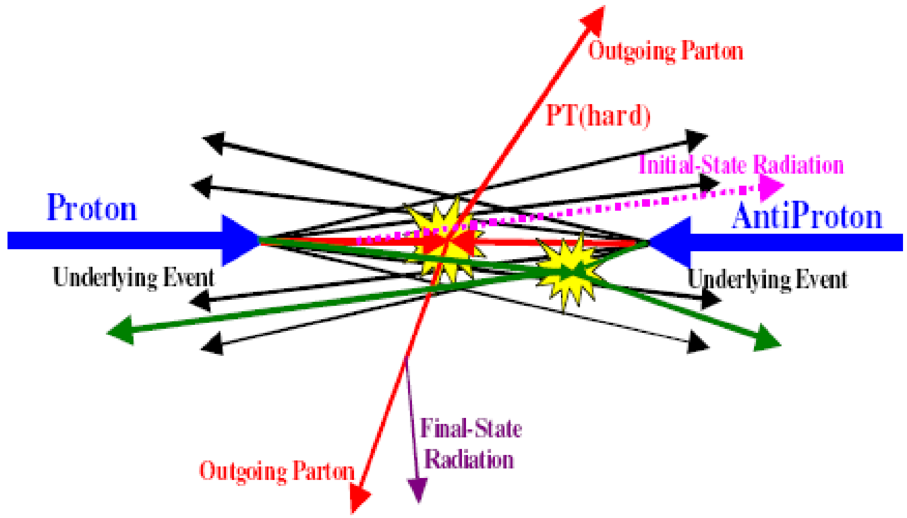


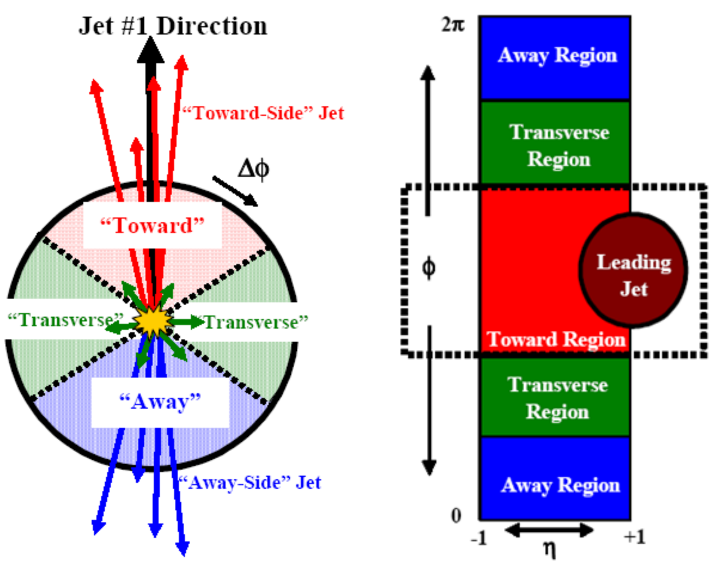
Tuned MC, PYTHIA Tune A (enhanced ISR + MPI), describes the data

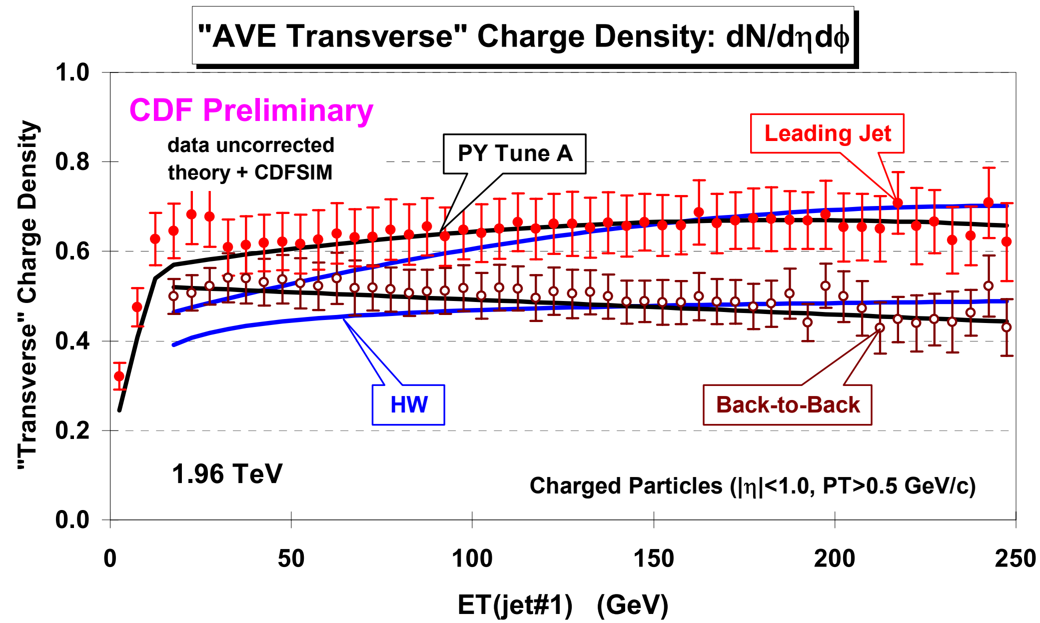
We know how to model the jet fragmentation reasonably well !!

Underlying Event (UE) Tuning

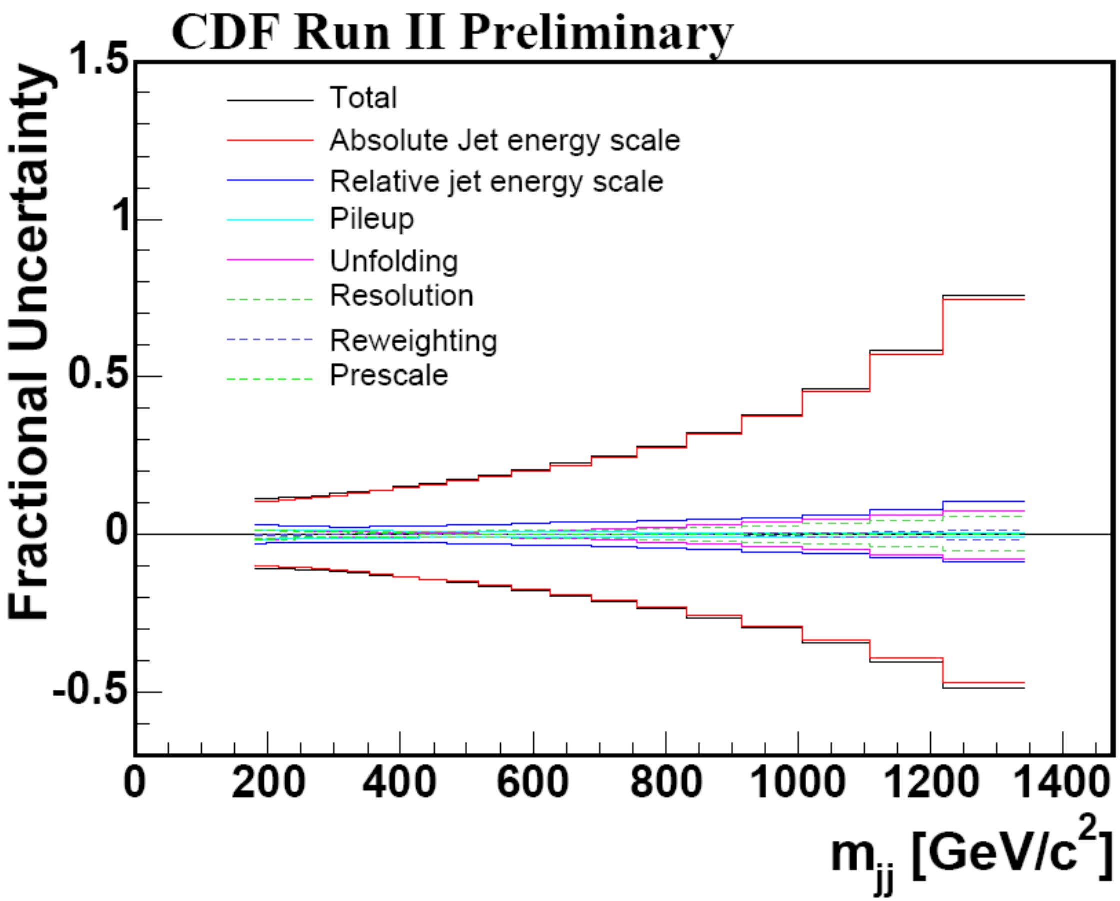
- Underlying Event: particles not associated with the hard scatter
  - Beam remnants
  - Multiple parton interactions (MPI)
  - Initial state soft radiations
- Tune charged particles in MC in the “transverse” region (sensitive to UE) in dijet events







Systematic uncertainty summary



Dominated by jet energy scale uncertainty