QCD Studies at the Tevatron

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for the CDF and DØ Collaborations

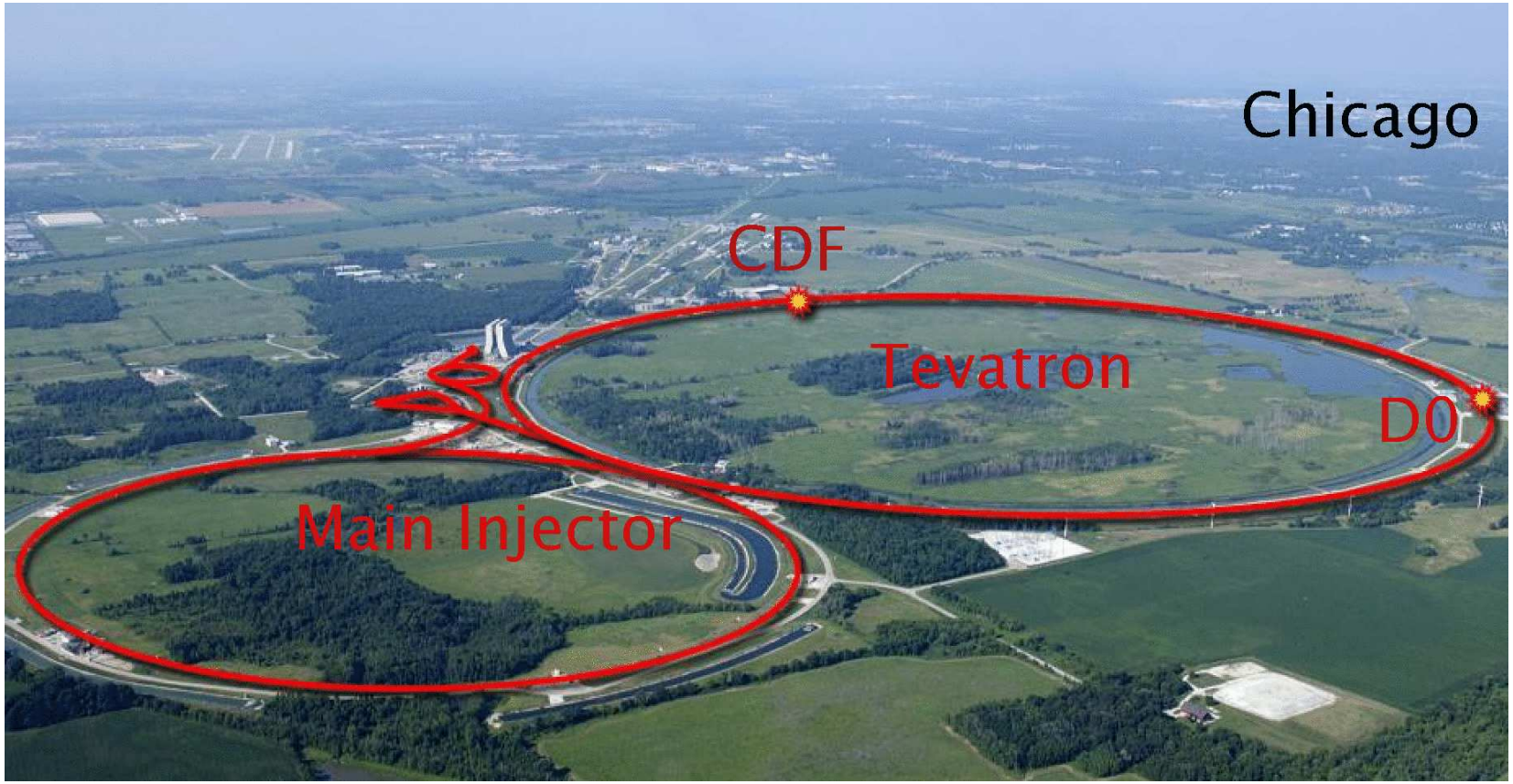
Fermilab

Rencontres de Physique de La Vallee d'Aoste
February 26th, 2008

Outline

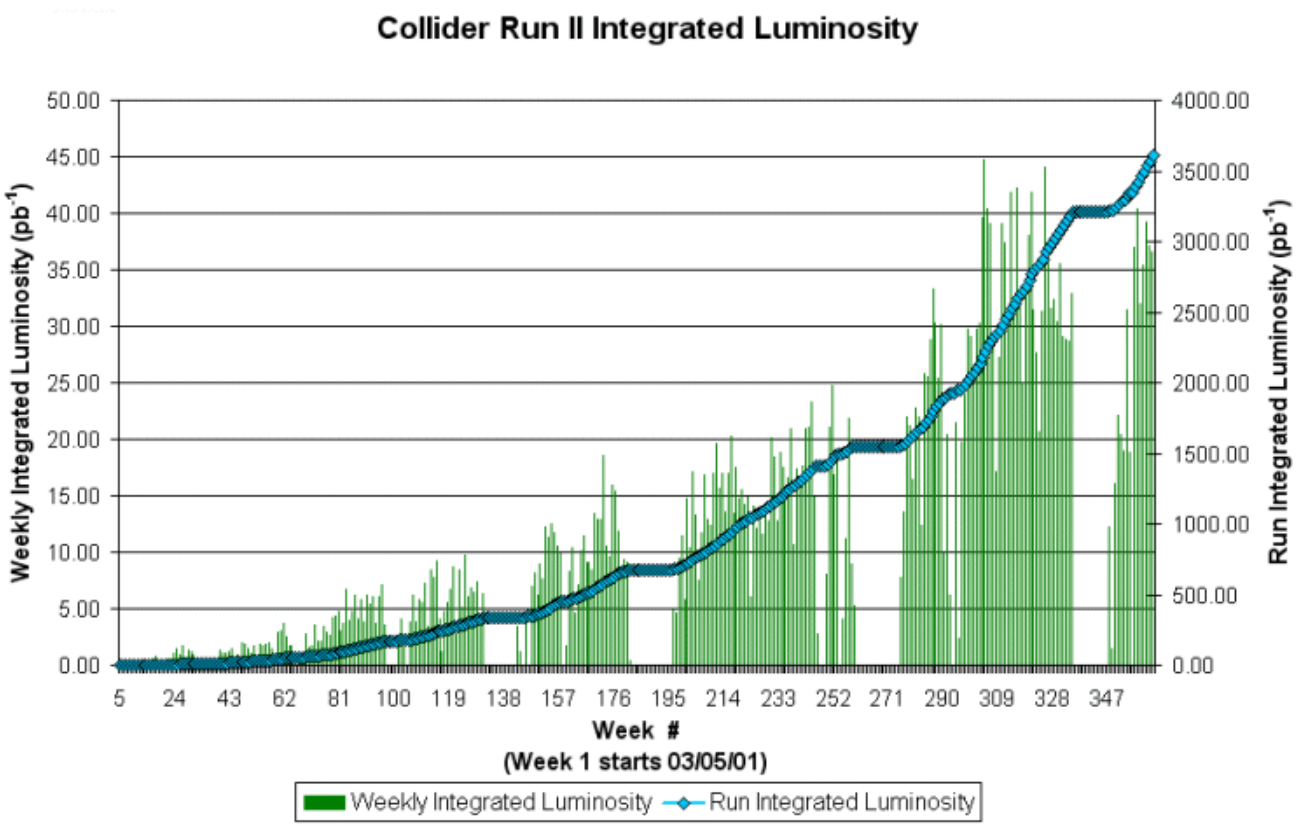
1. Introduction
   - The FNAL Tevatron
   - The CDF and DØ Experiments
   - QCD Jet Production
2. Recent QCD Results
   - Jet Cross Sections
   - Underlying Event Studies at CDF
   - Vector Boson + Jet Production
3. Summary and Conclusions

FNAL: Fermi National Accelerator Lab



The Tevatron currently provides the highest energy proton-antiproton collisions in the world: $\sqrt{s} = 1.96$ TeV

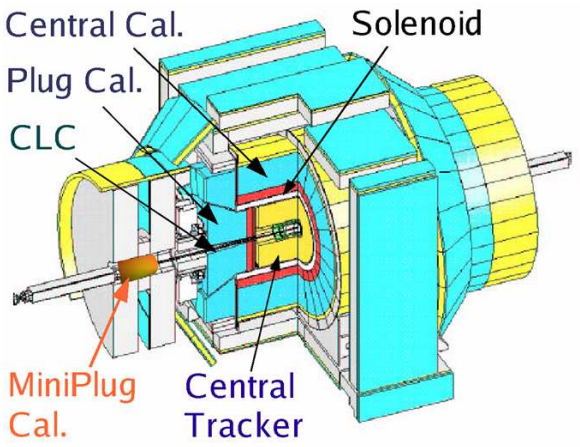
Tevatron Performance

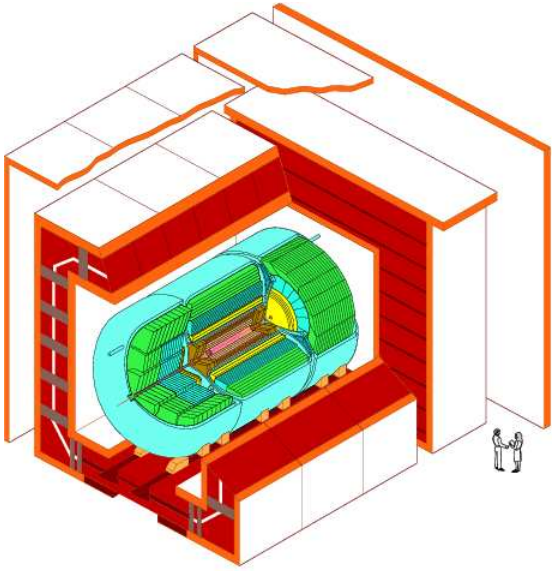


About 3 fb^{-1} of integrated luminosity recorded by CDF and DØ
(More than 30 $\times$ the Run I integrated luminosity)
Expect $6 - 8$ fb^{-1} by end of 2009!

The CDF and DØ Experiments

CDF detector:





DØ Detector

The jet measurements discussed here rely on several components of the general-purpose CDF and DØ detectors:

- Luminosity measurement
- Silicon vertex detector
- Central tracking chamber
- Electromagnetic Calorimeters: Jets, e, and γ
- Hadronic Calorimeters: Jets
- Muon chambers

Tevatron Public Results

CDF Public Page
http://www-cdf.fnal.gov/physics/physics.html
DØ Public Page
http://www-d0.fnal.gov/Run2Physics/WWW/results.htm

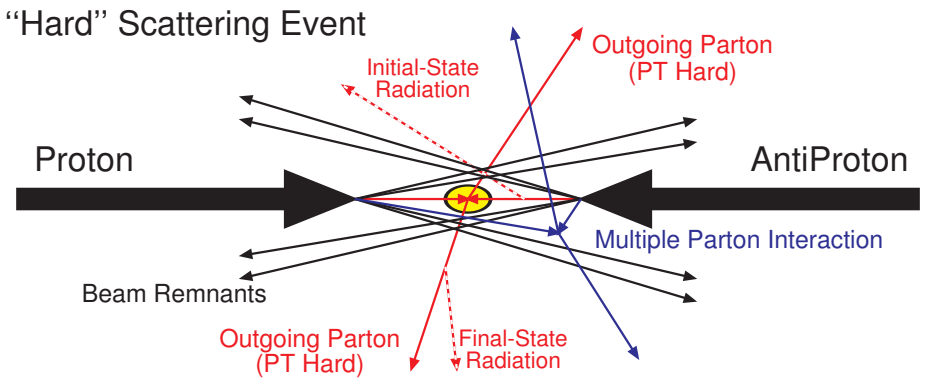
Many other Tevatron results to be presented this week:

- On Wednesday :
  - Electroweak results
  - Precision Top quark mass
  - Top properties
  - Single Top searches
- On Thursday :
  - B states
  - CPV and B_s
- On Friday :
  - Higgs searches
  - SUSY searches
  - Other exotic searches
- On Saturday :
  - Project X

Jet Production at the Tevatron

Model of hadronic collisions :

- Perturbative components:
  - 2→2 'hard' scattering
  - Initial and final state radiation (parton shower)
- Non-perturbative contributions:
  - Underlying event
    - Beam-beam remnants
    - Multiple parton interactions
  - Hadronization effects

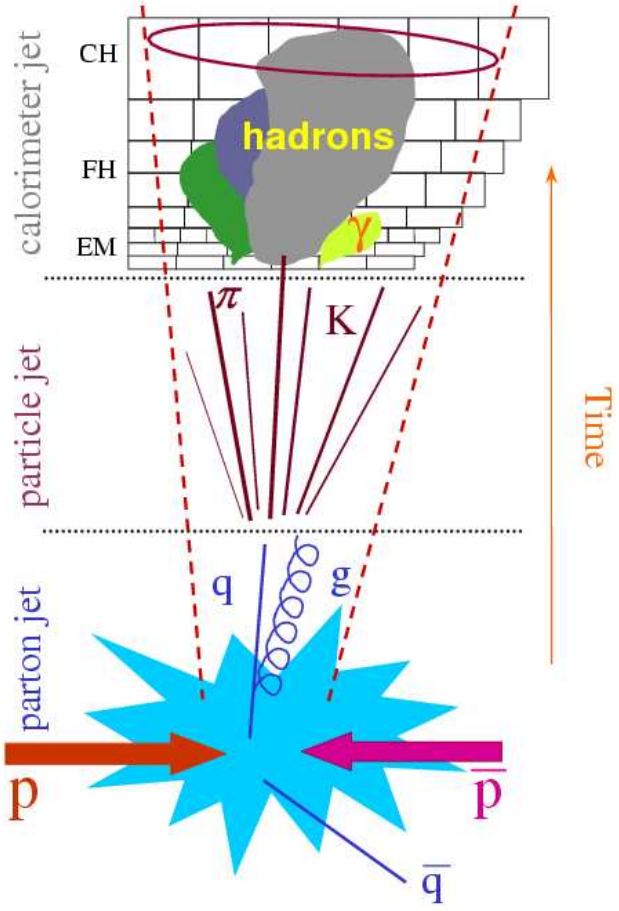


Simple model of hadronic collision

Jet Production at the Tevatron

QCD color-confinement and detector effects make the picture more complicated

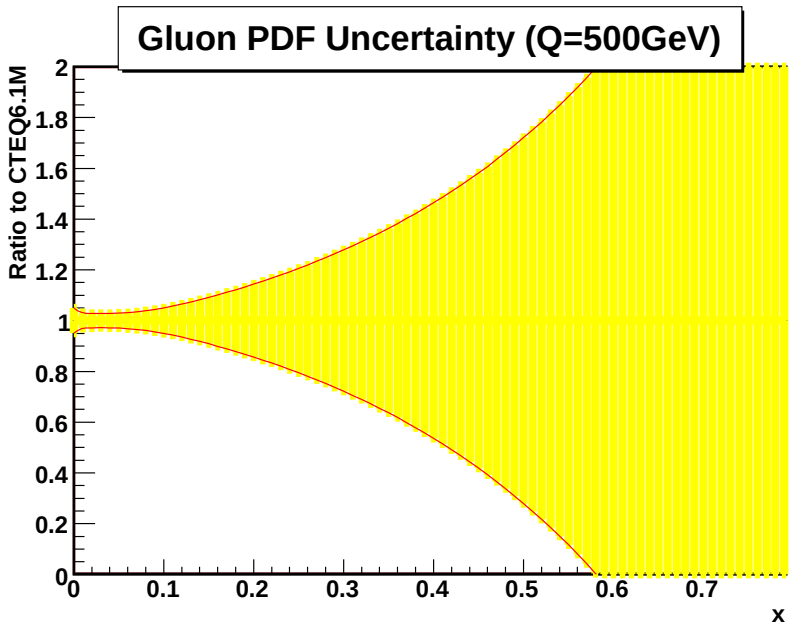
- Colored partons hadronize into color neutral hadrons.
- Particles from the components of proton-antiproton collision are indistinguishable.
- Jet clustering algorithms combine the particle energies from the event to form jets.
  ➜ Cone jet algorithms cluster jets based on their separation in rapidity-ϕ space.



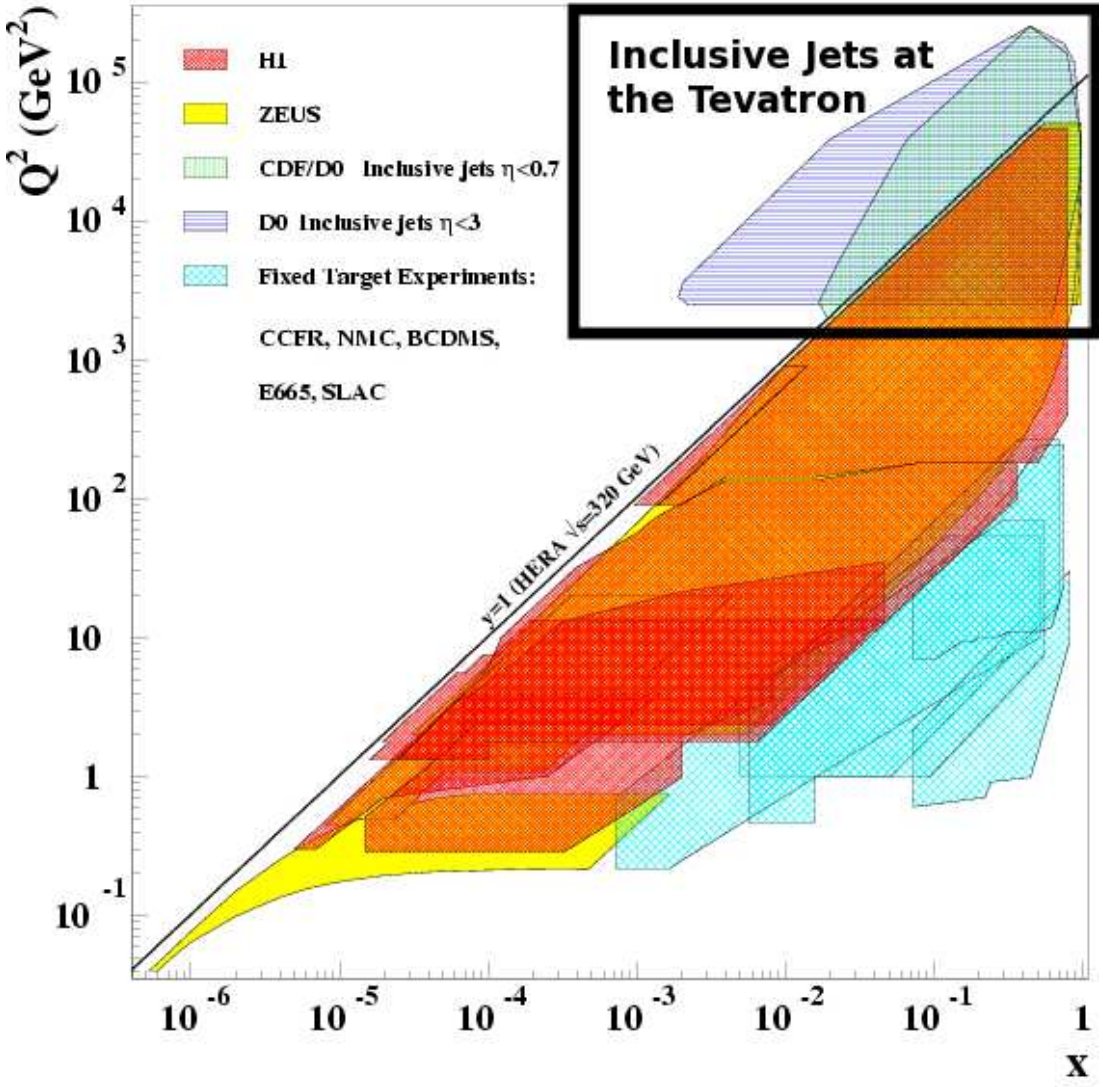
Jet Cross Sections

Motivation:

- Theoretically simple
  $\longrightarrow$ fundamental test of pQCD.
- Measurement over 8 orders of magnitude in cross section.
- Wide P_T range
  $\longrightarrow$ probes running of α_s.
- Probe distance scale of order $10^{-19}m$.
- Sensitive to new physics
  $\longrightarrow$ quark substructure.
- Probe large x
  $\longrightarrow$ constrain gluon PDFs.



Jet Cross Sections at the Tevatron

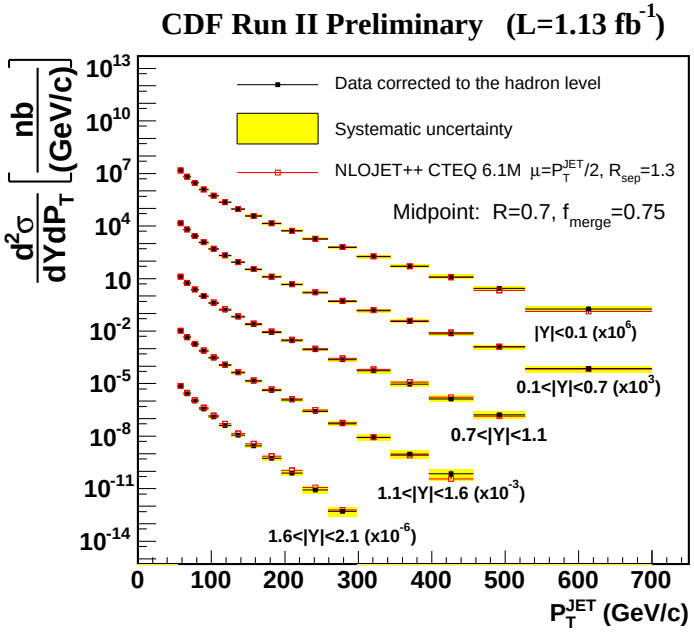


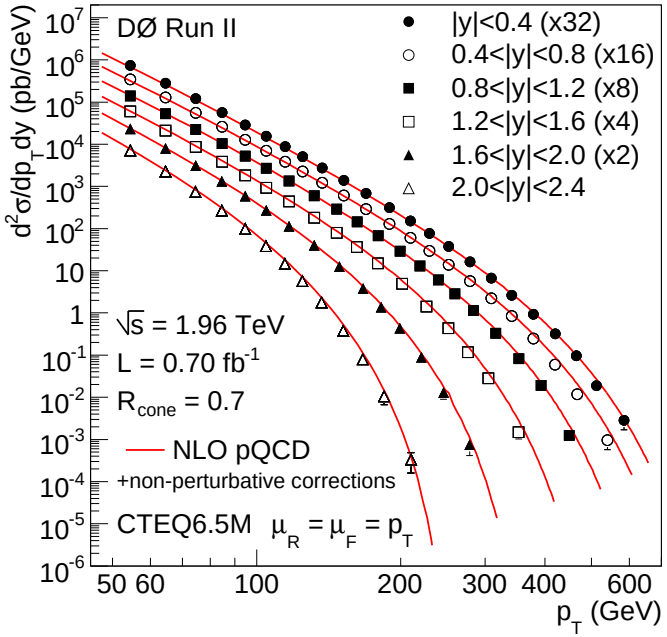
Benefit of including the forward region:

- High x but low Q^2
- Less sensitive to BSM physics
  ➜ Constraints on PDFs

CDF and DØ: Jet Cross Section Distributions

Inclusive jet cross sections using the Midpoint clustering algorithm

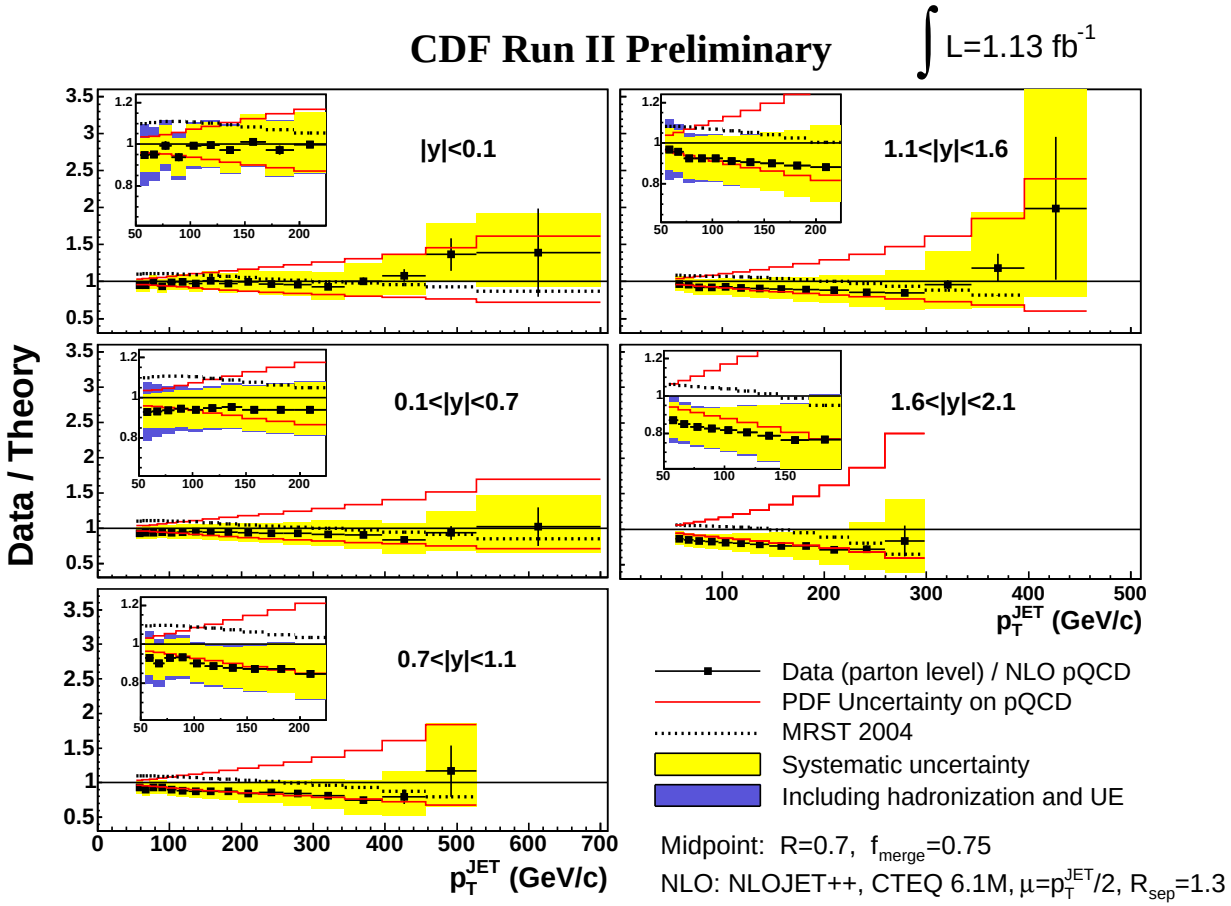




- Compare to CTEQ6.1M PDFs
- Five rapidity regions ($|y| < 2.1$)

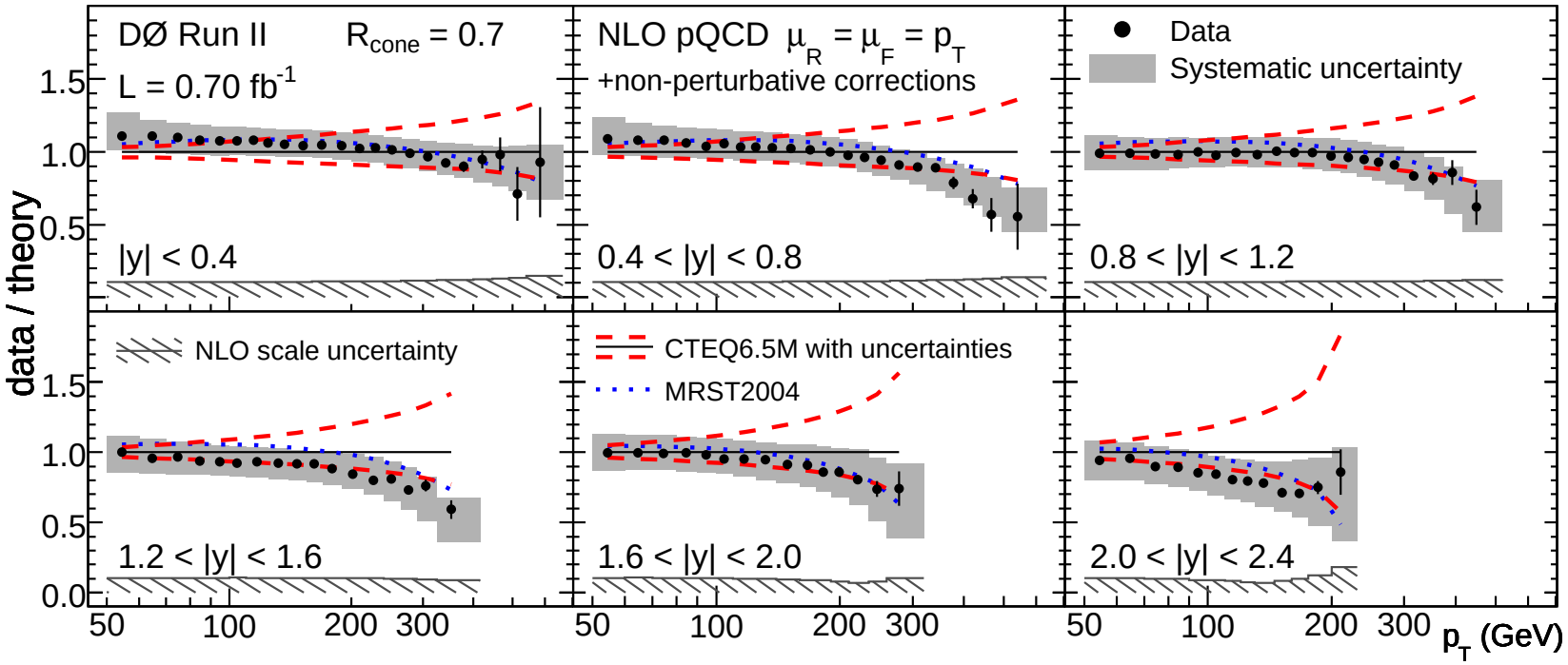
- Compare to CTEQ6.5M PDFs
- Six rapidity regions ($|y| < 2.4$)

CDF: Jet Cross Section Ratio to NLO pQCD



- Reasonable agreement with NLO
- Systematics are smaller at high y than PDF errors

DØ: Jet Cross Section Ratio to NLO pQCD

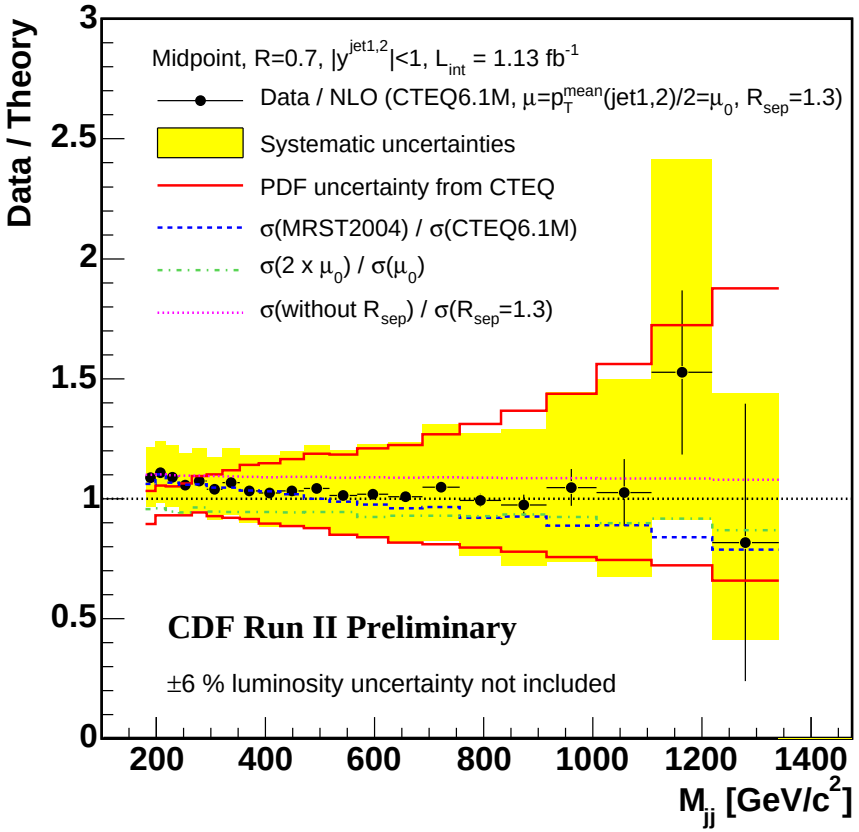


- Recently reduced JES systematic below 2 % over full P_T range.
  ➜ Stronger constraints on PDFs
- CDF and DØ observe similar trends at high rapidity.

CDF:Dijet Mass Cross Section

- Used to set limits on:
  - excited quarks
  - massive gluons
  - Z' and W'
- See S. Pronko's talk on Friday :

"Exotics Searches at the Tevatron"



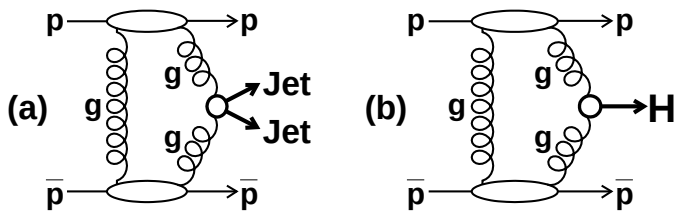
Nice agreement with NLO PQCD predictions.

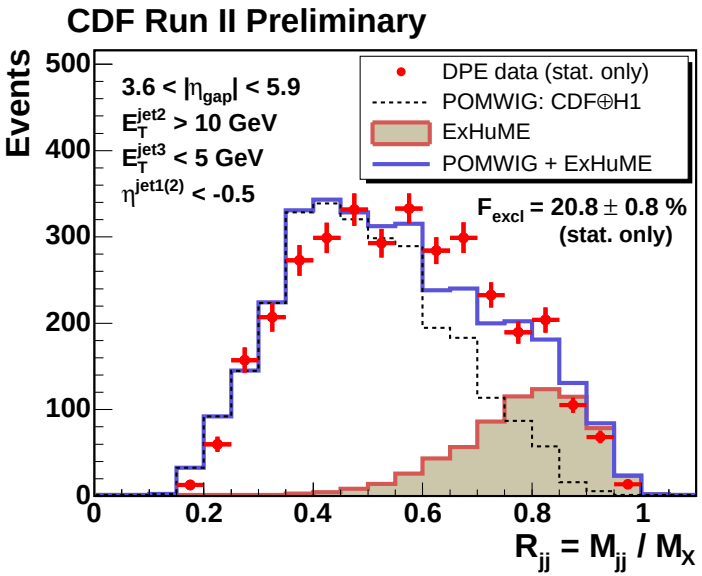
CDF:Exclusive Dijet Cross Section

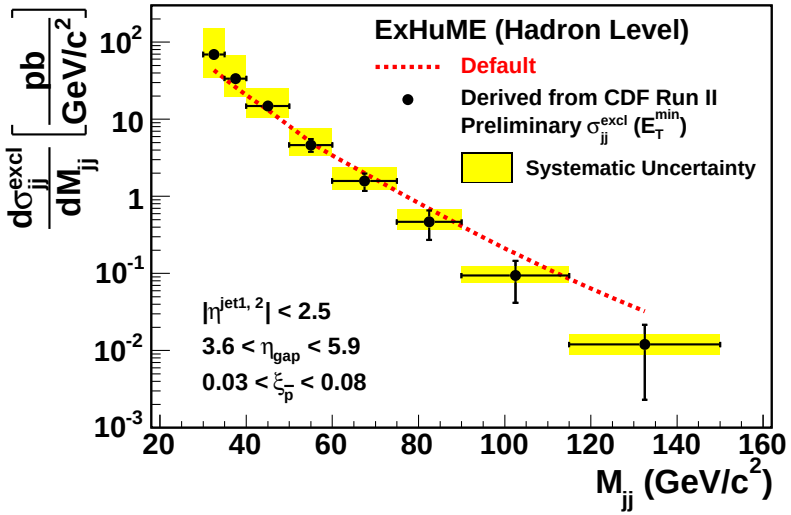
First observation of exclusive dijet production at the Tevatron!

$$p + \bar{p} \rightarrow \bar{p}' + 2jets + rapidity\ gap$$

- Calibration channel for exclusive Higgs production at the LHC
  ➜ Similar theoretical calculation
- Double Pomeron Exchange
- Use Di-jet mass fraction $R_{jj} \equiv M_{jj}/M_X$

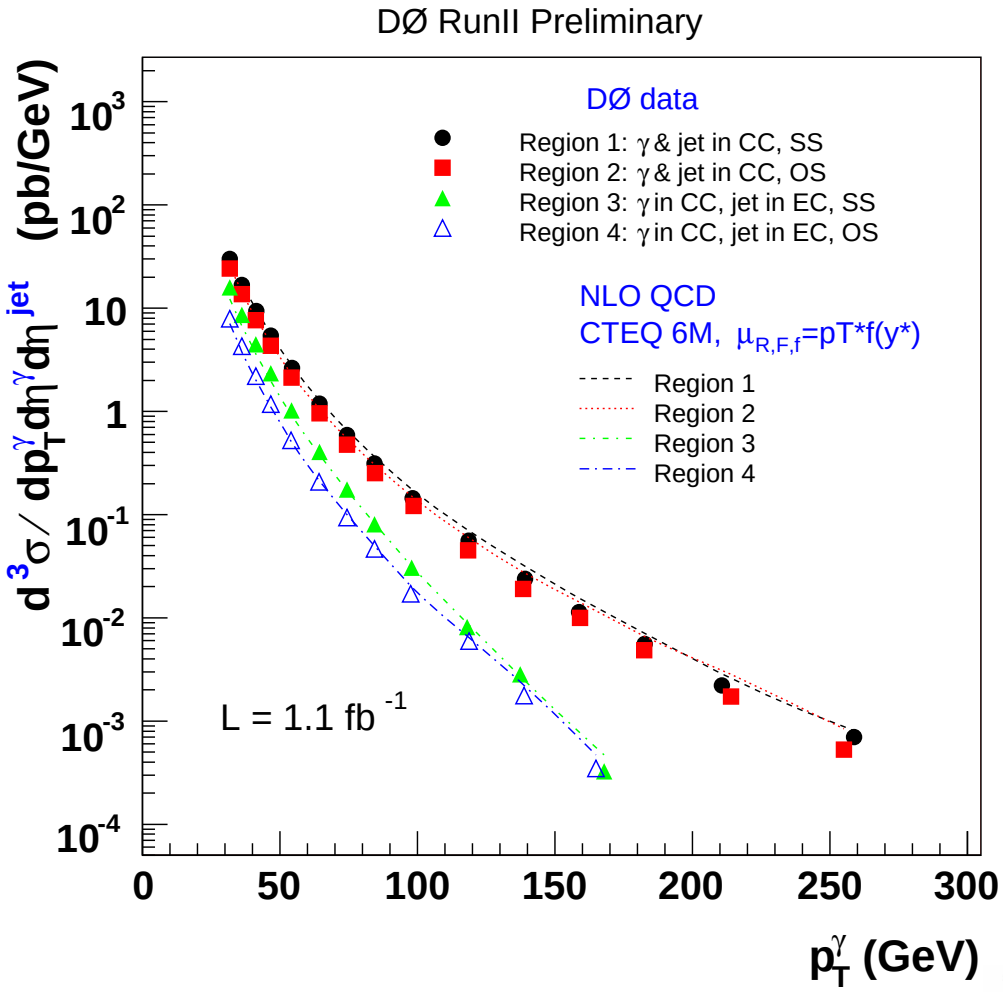






DØ: Triple Differential γ + Jet Cross Section

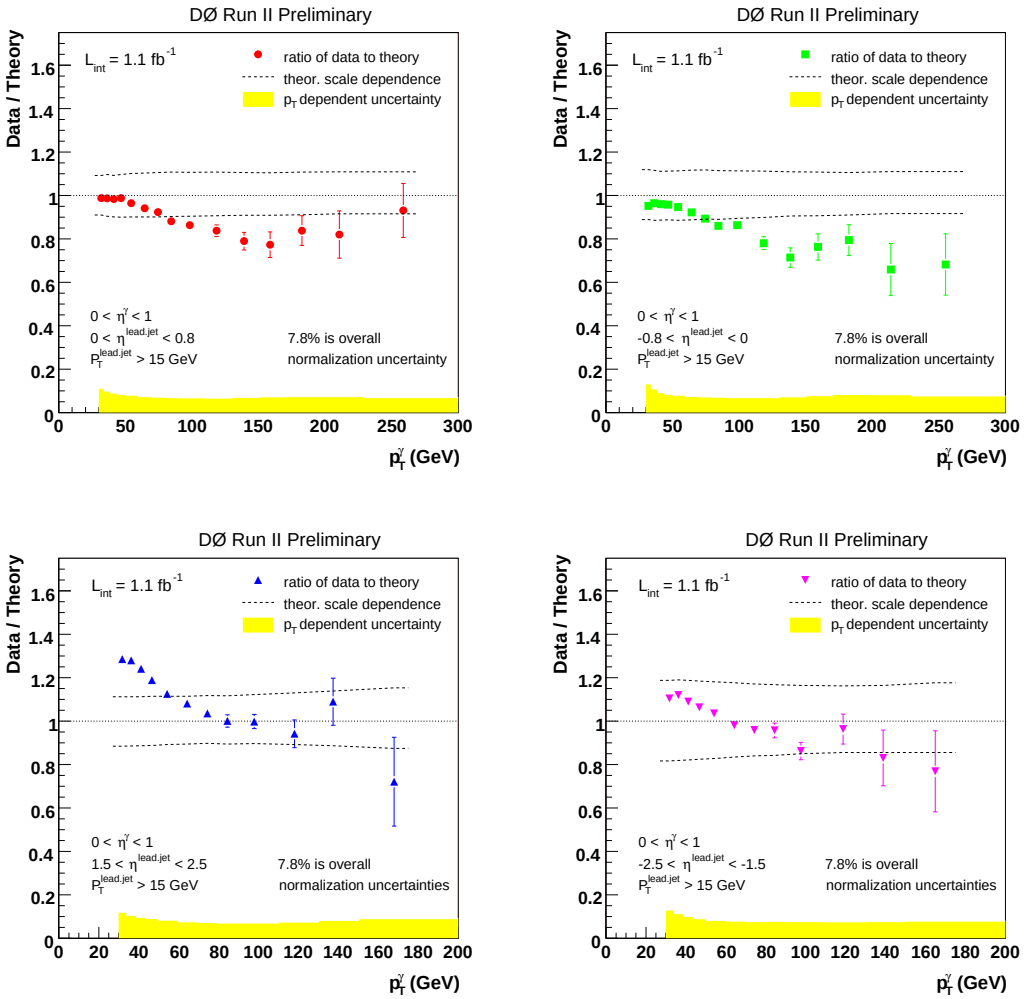
- $\frac{d^3\sigma}{dp_T^\gamma d\eta^\gamma d\eta^{jet}}$
- $30 < dp_T^\gamma < 300\ GeV$
- 4 γ and jet η regions
- NLO QCD (JetPhoX)
- scales = p_T^γ
- Significantly extends x and Q^2 range of previous measurements
- Previous inclusive γ measurements observed mediocre agreement



Test NLO predictions over a large x and Q^2 range

DØ: Triple Differential γ + Jet Cross Section

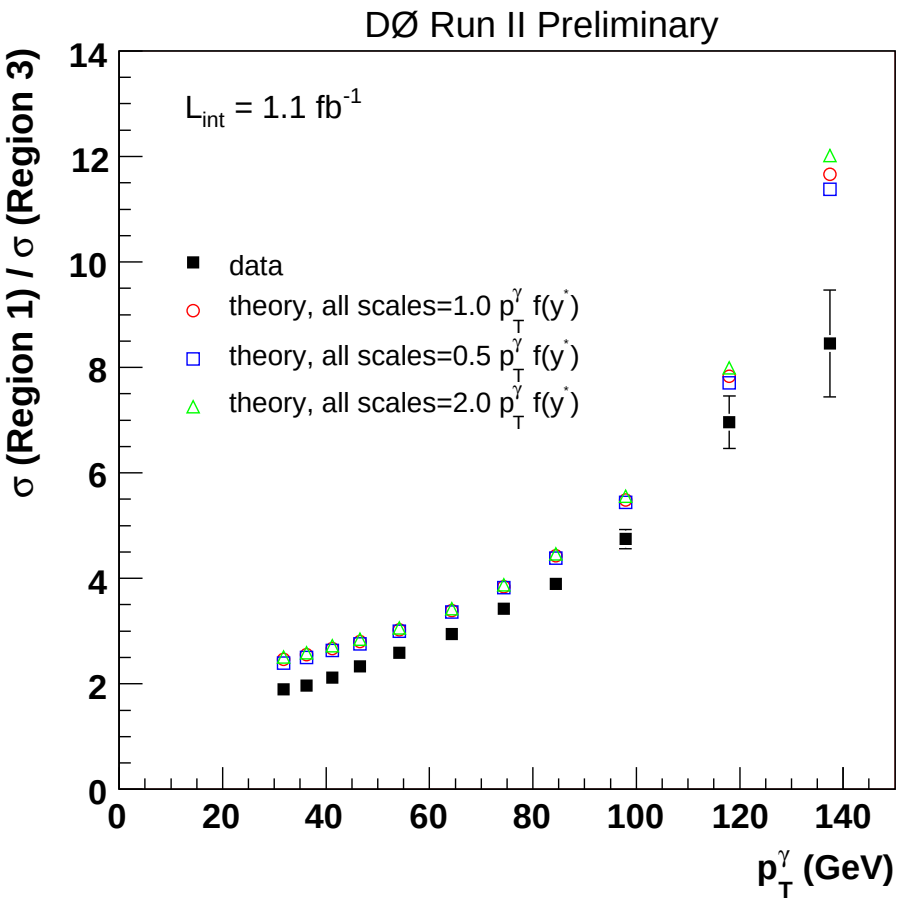
- Theoretical scale variations can not describe all four regions
- Data are outside CTEQ6.1 error bands
- Structure in central result similar to previous results from UA2, CDF , and DØ



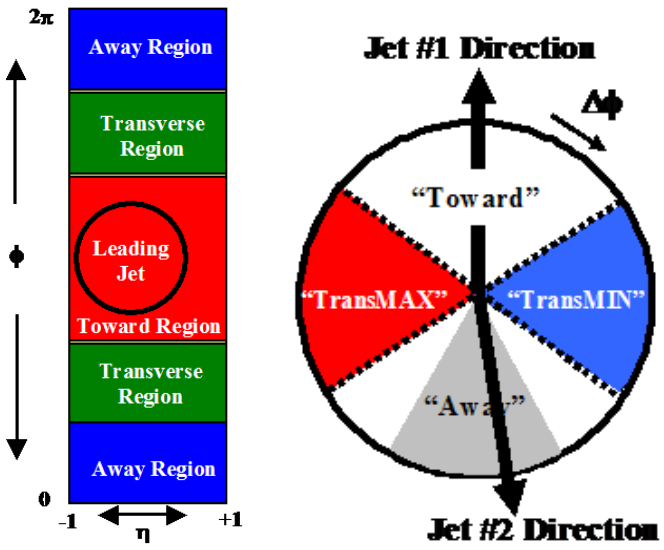
$\gamma+$ jet : Ratios between regions

Ratios:

- All photons are central
  ➜ Systematics largely cancel in ratio
  ➜ Total experimental uncertainty $<$ 9 %
- Shapes are reproduced by theory
- Quantitative disagreement

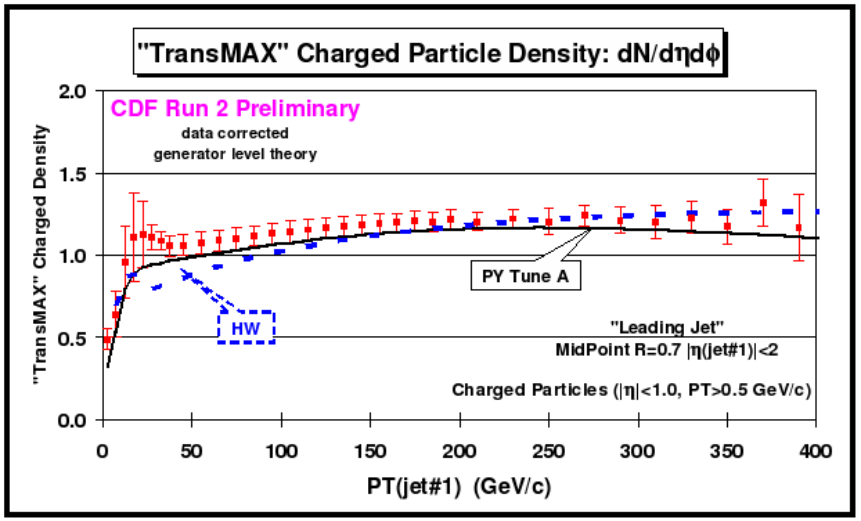


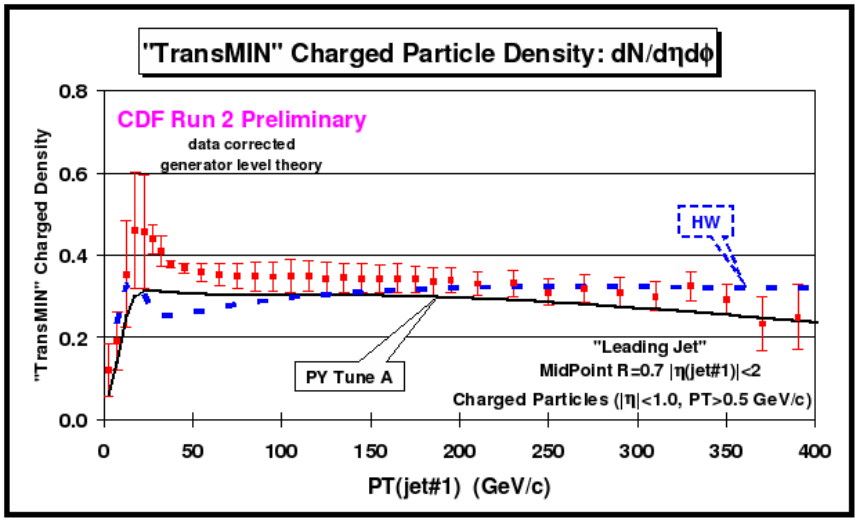
CDF: Studies of the Underlying Event



- Goal : Publish many distributions to help theorists tune MC models
- Use *leading jet* and *back-to-back* topologies to study the UE event
- The *transverse* regions (*TransMAX* and *TransMIN*) are sensitive to the UE observables. Defined as regions with MAX(MIN) densities on event by event basis
- *Leading jet*, *(*Back-to-back),*(*Back-to-back exclusive di-jet) and other topologies are used to isolate various components of the collider event

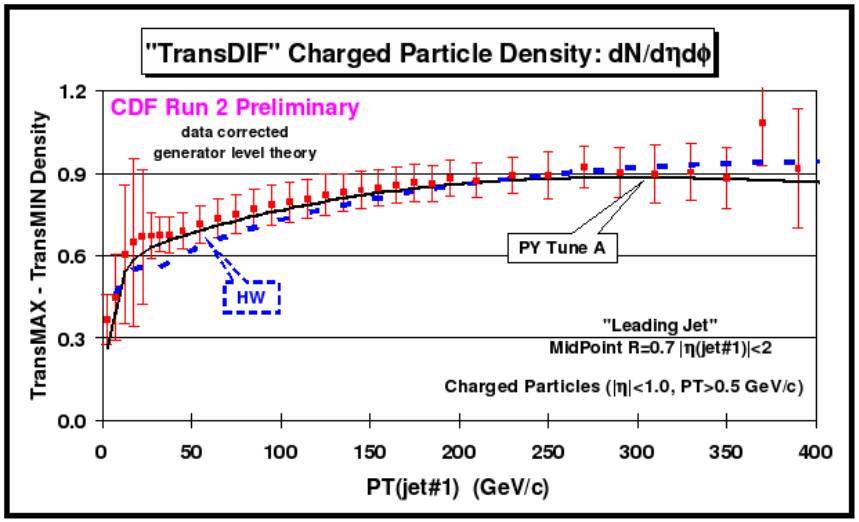
UE example : “Leading Jet” Charge Particle Density





TransDIF = TransMAX - TransMIN

- Taking the difference isolates the “hard” component of UE
- *TransDIF* better modeled by PYTHIA and HERWIG



Boson + Jets Production

- Important background for searches:
  - ➜ SUSY searches in MET+jets channel
- Vector Boson + b-jet also crucial to many searches:
  - ➜ Single Top quark
  - ➜ Higgs WH
  - ➜ Higgs ZH

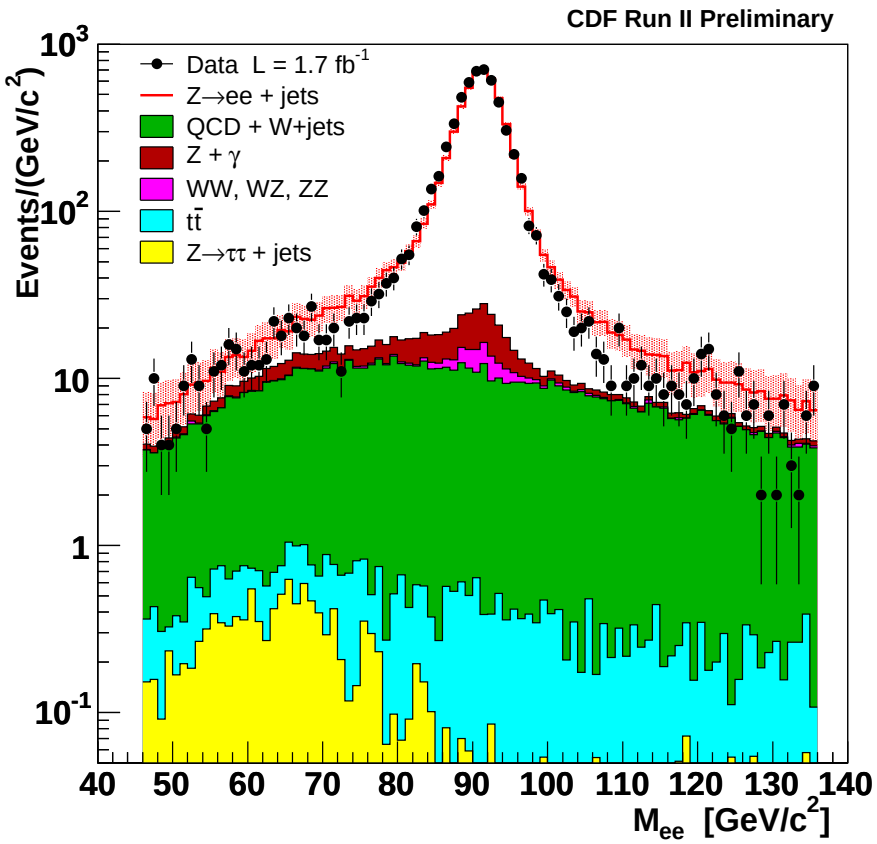
CDF: Z + jet cross section

Motivation:

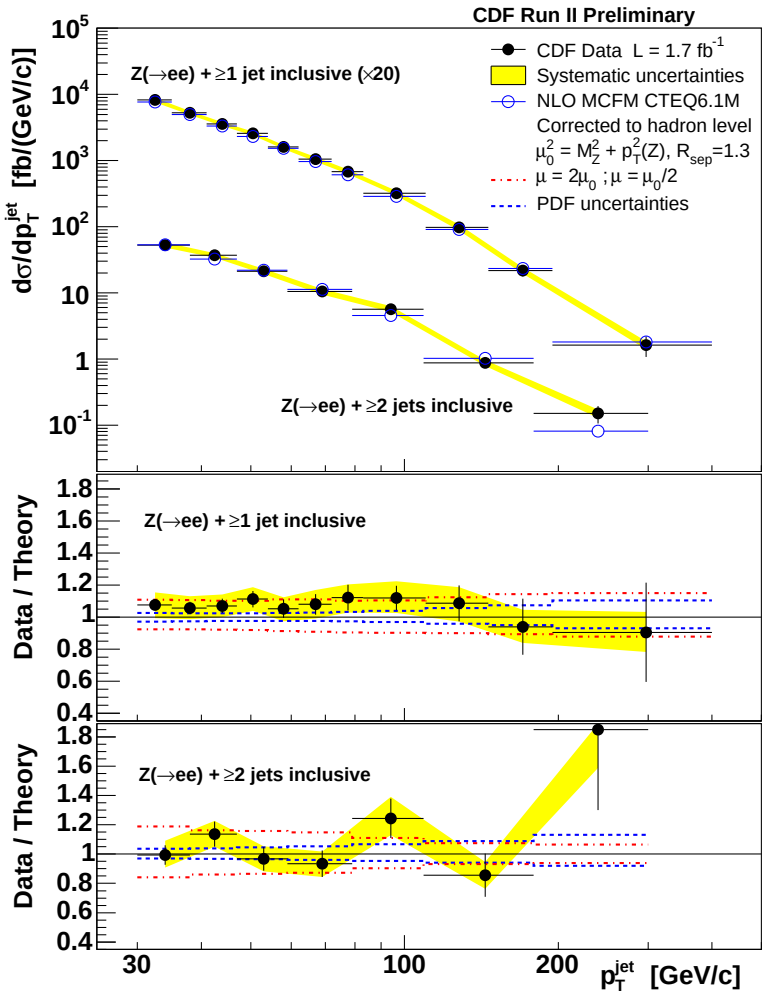
- Test of pQCD
- Important background for SUSY searches

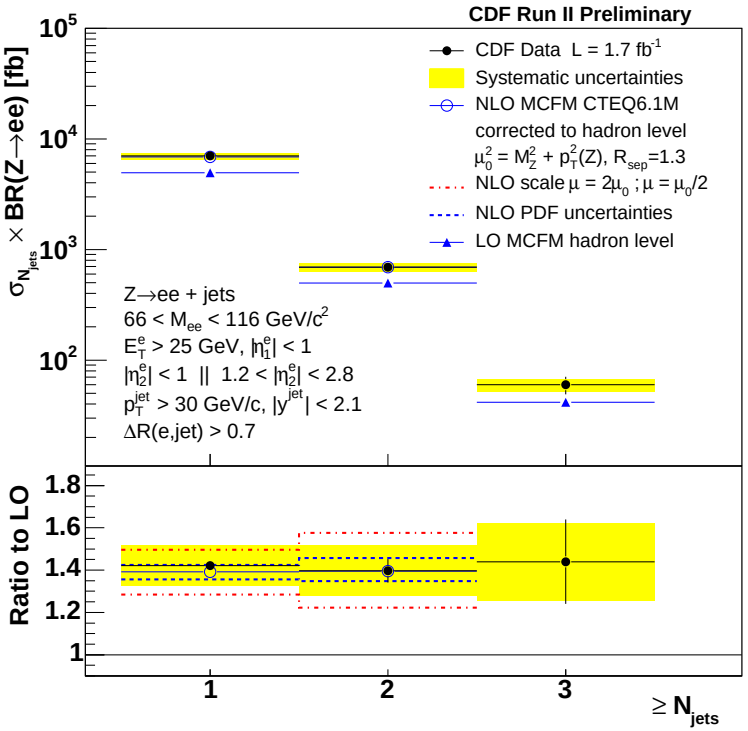
Method:

- Select $Z \rightarrow ee$ events



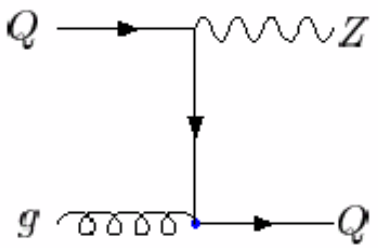
CDF: Z + jet cross section

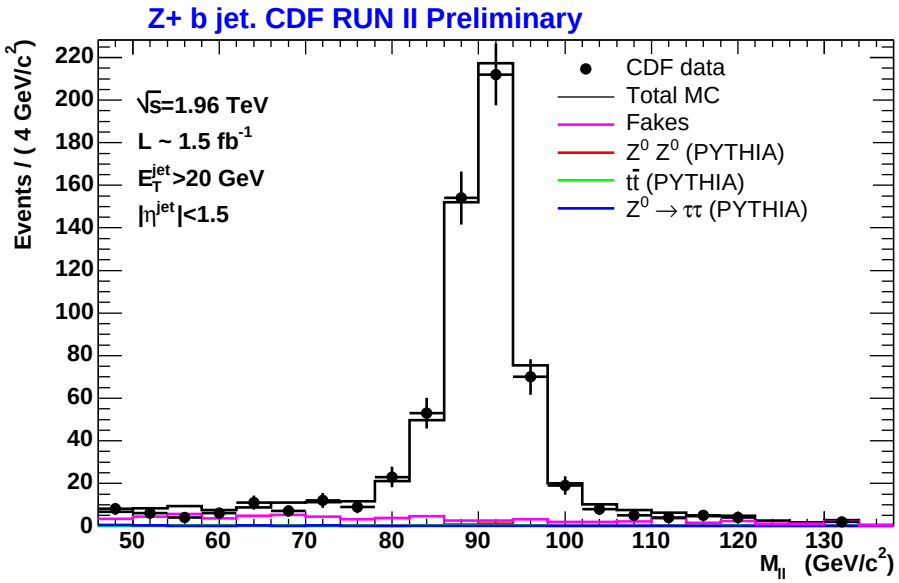




- NLO agrees well with data
- LO-NLO scale factor flat with jet multiplicity

CDF: Z + b-jet cross section





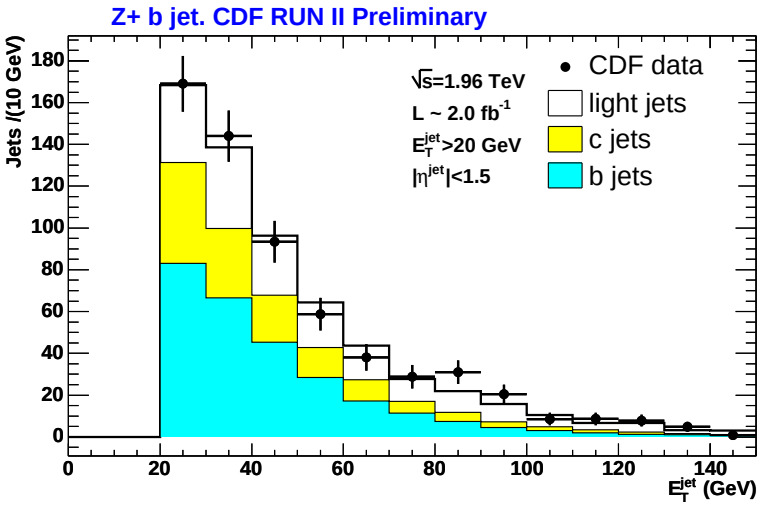
Motivation:

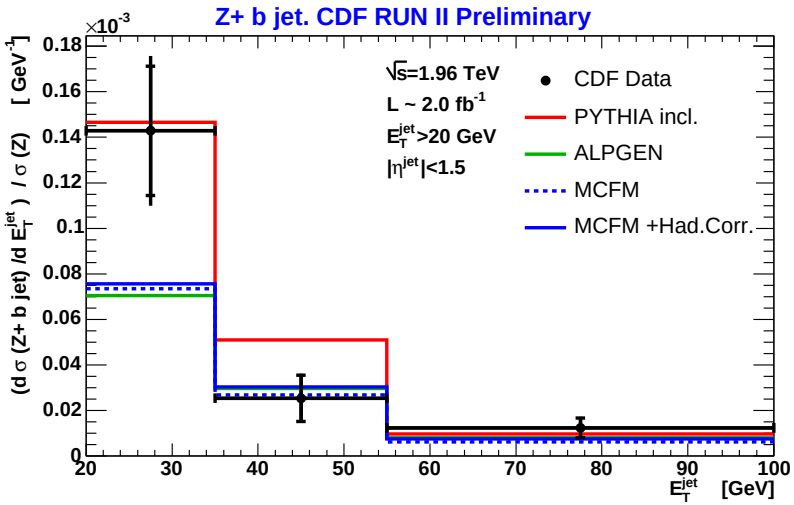
- Probe heavy flavor content of the proton
- Important background for Single Top, ZH, and SUSY Higgs.

Method:

- Select $Z \rightarrow \mu\mu$ and $Z \rightarrow ee$ events
- Use b-vertex mass to separate b,c, and light quark components.

CDF: Z + b-jet cross section



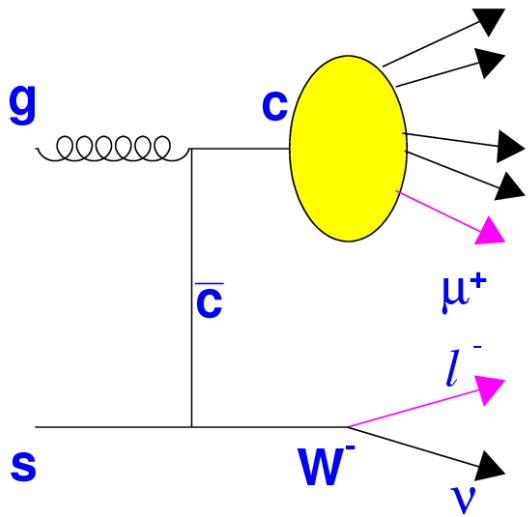


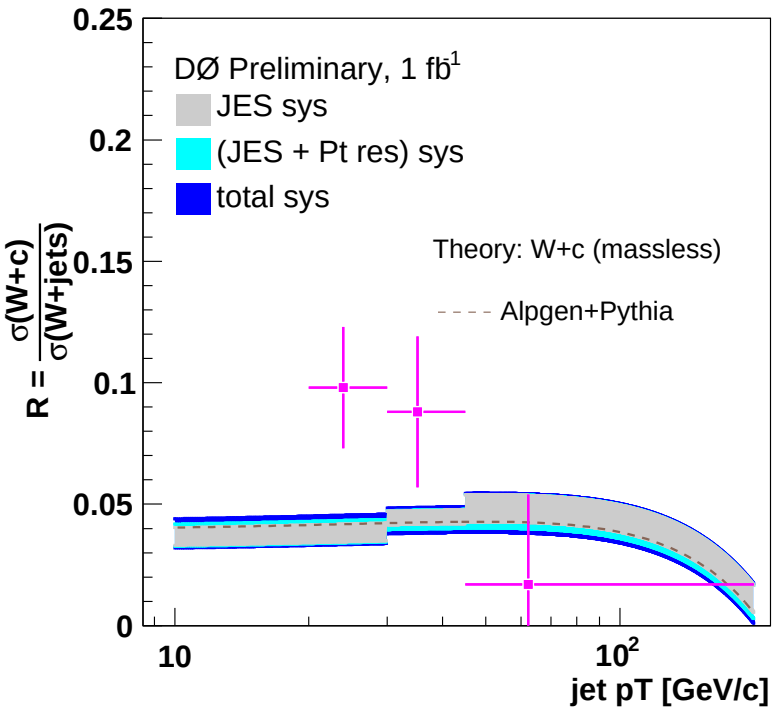
	CDF Data	PYTHIA	ALPGEN	NLO +U.E+hadr.
$\sigma(Z + b\,\text{jet})$	$0.86_{\pm 0.14 \pm 0.12}$ pb	–	–	0.53 pb
$\sigma(Z + b\,\text{jet})/\sigma(Z)$	$0.336_{\pm 0.053 \pm 0.041}$%	0.35%	0.21%	0.23%
$\sigma(Z + b\,\text{jet})/\sigma(Z + \text{jet})$	$2.11_{\pm 0.33 \pm 0.34}$%	2.18%	1.45%	1.71%

Analysis also produced other kinematic distributions to understand where each MC performs better.

DØ: W + c-jet cross section

- Test s-quark content of proton
- Important background for stop-quark and Higgs searches



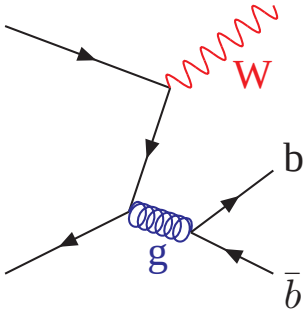


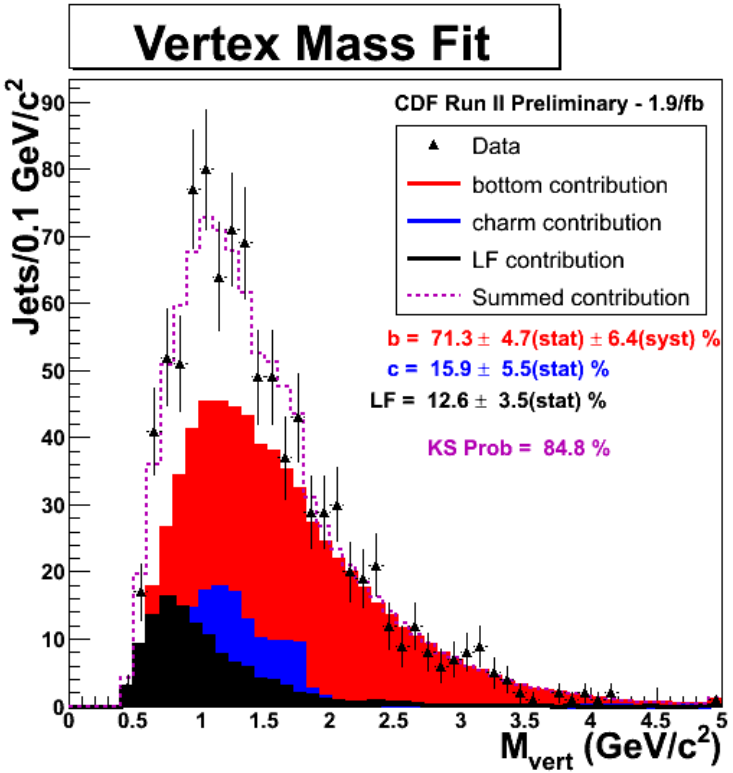
Reasonable agreement with SM prediction of Alpgen

- ID W's with e or μ
- c-quark tagged with μ
- c and W oppositely charged

CDF: W + b-jet cross section

This is the dominant background for Single-Top and WH production!!





Phase space definition :

- e or μ with :
  - $P_T > 20\ GeV/c$
  - $|\eta| < 1.1$
- ν with $P_T > 25\ GeV/c$
- 1 or 2 jets with :
  - $P_T > 20\ GeV/c$
  - $|\eta| < 2.0$

$\sigma_{W+b-jets} \times Br(W \rightarrow l\nu) = 2.74 \pm 0.27(stat) \pm 0.42(syst)\ pb$

Summary

Measurements from the Tevatron Run II are defining a new level of QCD precision measurements in hadron-hadron collisions.

- **The Tevatron has a rich program** : Jet cross sections, W+jets, Z+jets, b-jets, UE studies and much more..
- **Inclusive Jets** : CDF and DØ report nice agreement with NLO.
- **W/Z + heavy flavor** cross sections have been measured
- **Even more** : γ + heavy flavor, diphoton cross section, fragmentation studies, jet and b-jet shapes ..

CDF and DØ are testing and constraining pQCD and also measuring cross sections of important background processes.

BACKUP

BACKUP

Jet Finding Algorithms

Clustering algorithms that 'map' the complex collider event onto "jets".

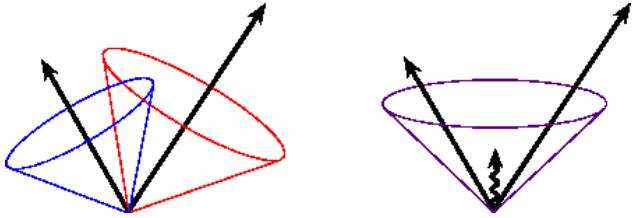
- Desired properties
  - Same algorithm at parton, hadron, and detector level
  - Infrared and collinear safe
  - Fully specified and easy to use
  - Independent of detector geometry/granularity
- 2 types of algorithms employed at CDF
  - Cone algorithm: group particles based on separation in $Y - \phi$ space. (Midpoint algorithm)
  - K_T algorithm: group particles based on their relative transverse momenta
    (and separation in $Y - \phi$ space).

NOTE: Different algorithms produce different observables. Midpoint and K_T are not expected to produce the same result.

The Midpoint Jet Clustering Algorithm

A basic cone algorithm was used in Run I (JetClu):

- Start with *seed* towers.
  (calorimeter towers with energy above given threshold)
- Cluster towers within the cone radius.
- Iterate to find stable cone.
- Sensitive to 'soft' radiation.



Midpoint algorithm replaced JetClu for Run II at CDF.

- Add extra *seeds* at the midpoint between all stable cones.
- Check for an additional stable cone at the midpoint between all stable cones.
- Less sensitive to 'soft' radiation.

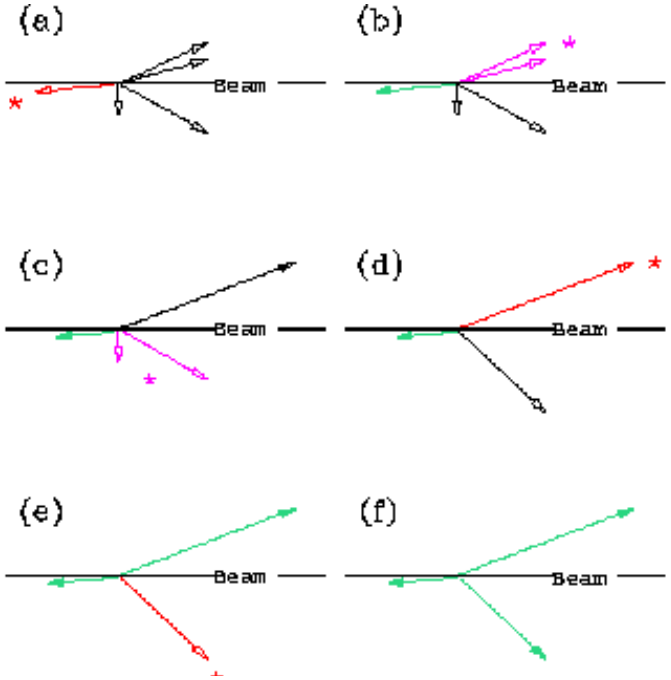
The K_T Algorithm

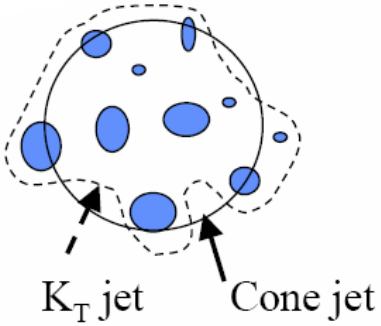
1) Construct
for each particle and pair of particles:
$d_{ij} \equiv min(P^2_{T\,i}, P^2_{T\,j}) \times \frac{\Delta R^2}{D^2}$ and $d_i \equiv P^2_{T\,i}$
2) Start with $min(d_{ij}, d_i)$:
- If
a d_i is the smallest, promote it to a jet.
- If
a d_{ij} is the smallest, combine particles.

3) Iterate until all particles are in a jet.

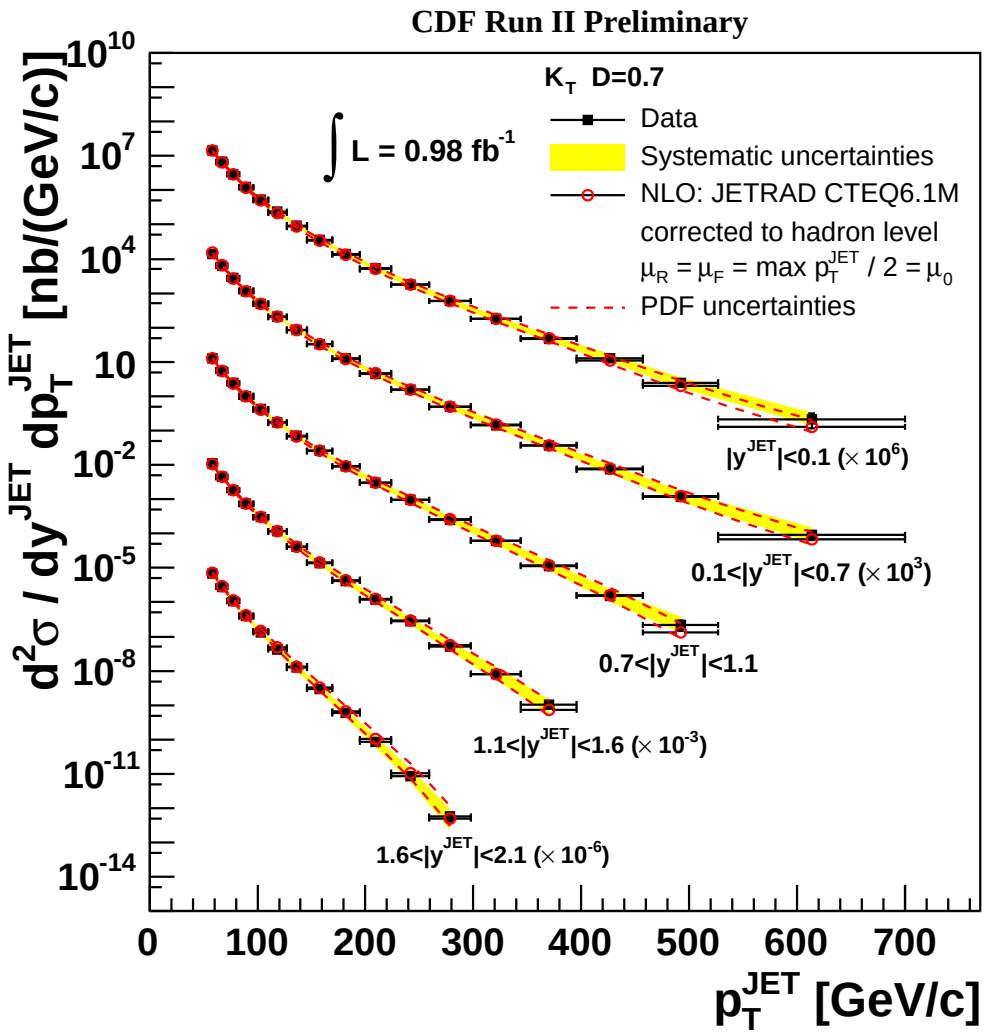
K_T Algorithm is theoretically preferred.
- Infrared and
collinear safe to all orders in pQCD.

K_T has been used successfully at e+e- and ep colliders. It is relatively new to the hadron-hadron collider environment.

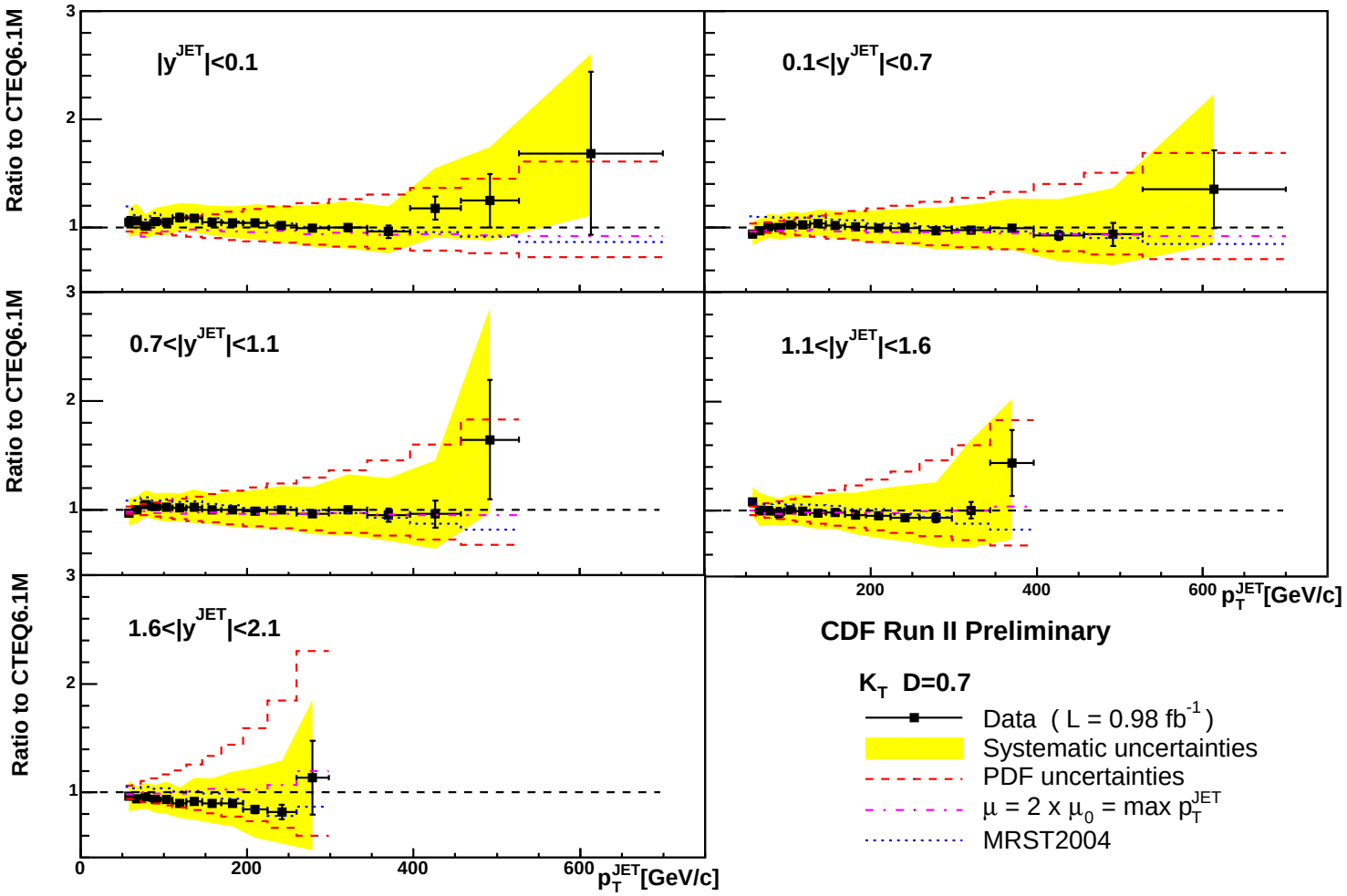




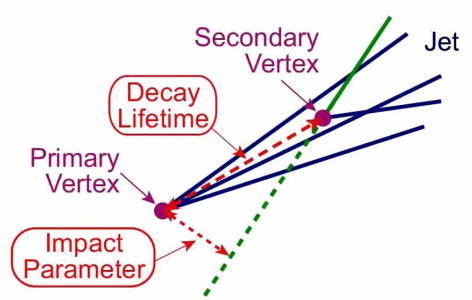
CDF: K_T Cross Section Distributions



CDF: K_T Ratio to NLO pQCD



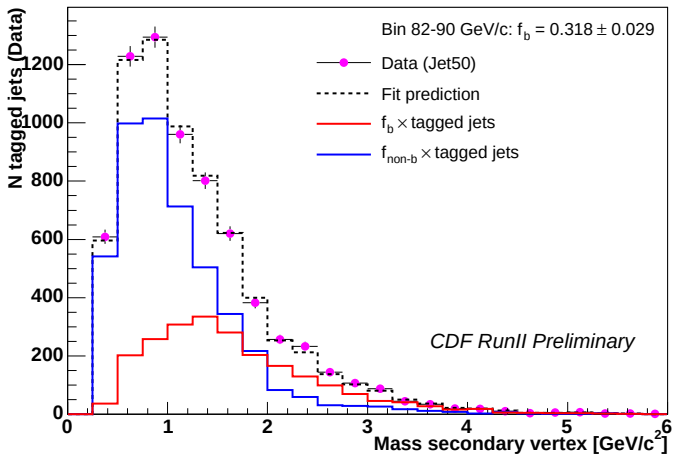
b-tagging



- b-hadrons decay in about 450 μm
- Secondary vertices reconstructed via the SVT
- b-jets are tagged via the secondary vertex
- Tagging Efficiency:
  - $\sim$ 50 % for 50 GeV jets
  - $\sim$ 25 % for 350 GeV jets

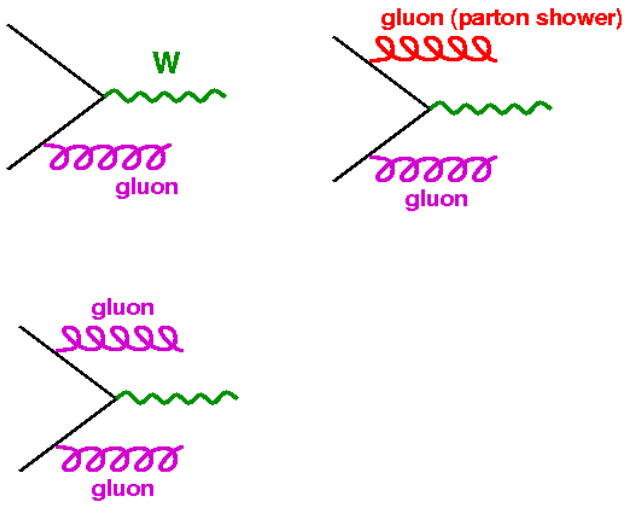
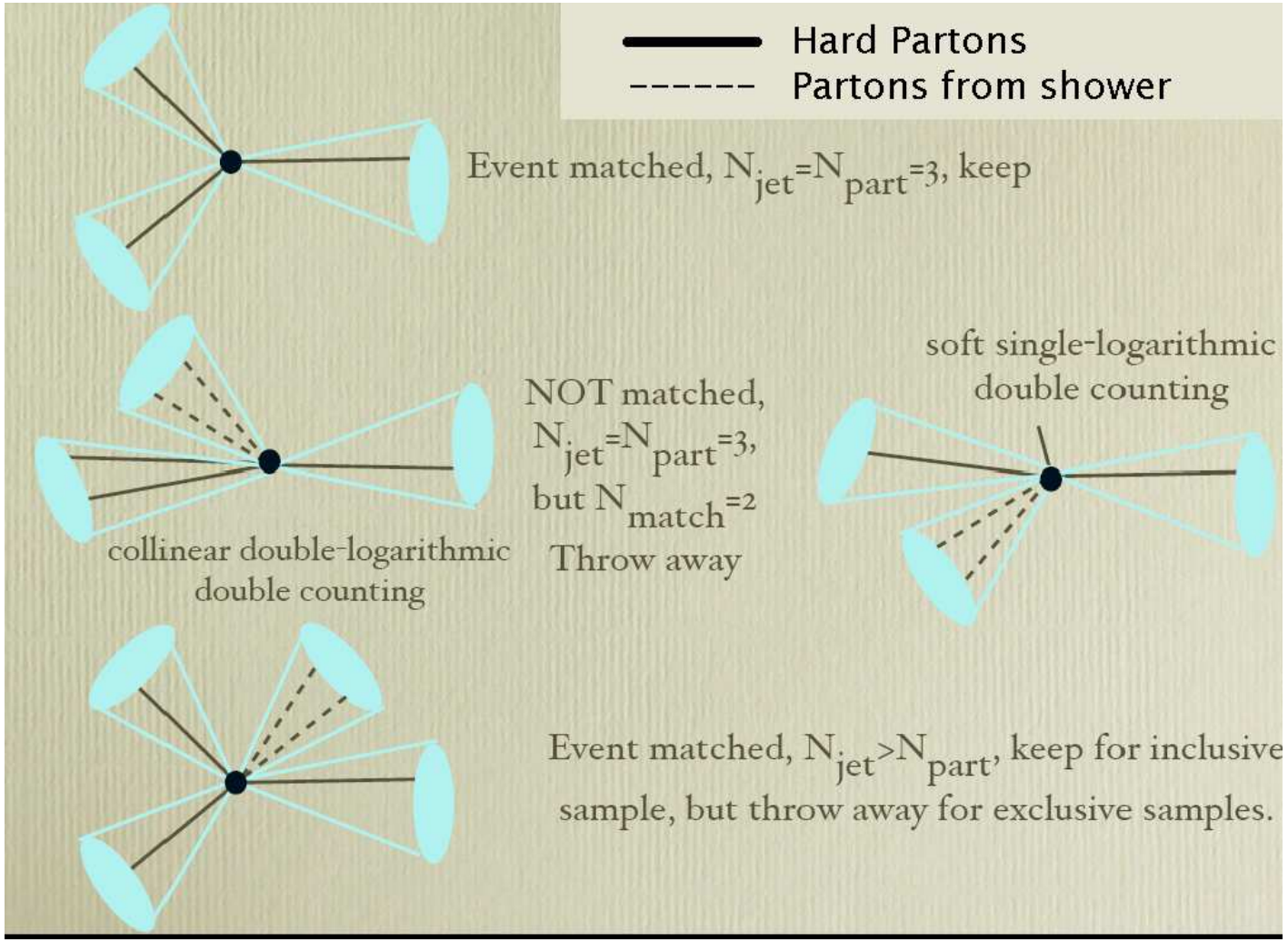
Motivation:

- test of pQCD
- Many backgrounds from b-jets:
  - Top quark physics
  - Low mass SM and SUSY Higgs searches



Beyond Leading-Order

- Leading order MC not reliable for high P_T multi-parton final states
  - MC@NLO : NLO rates for QCD
  - MCFM : NLO parton level MC
  - Alpgen : Leading order with many final state partons
- Need matching schemes to parton shower to avoid double counting
  - MLM Matching
  - CKKW
  - Mrenna-Richardson
- Alpgen + MLM matching provides exclusive N-jet rates.



Matching Example