Studies of jet properties at the Tevatron

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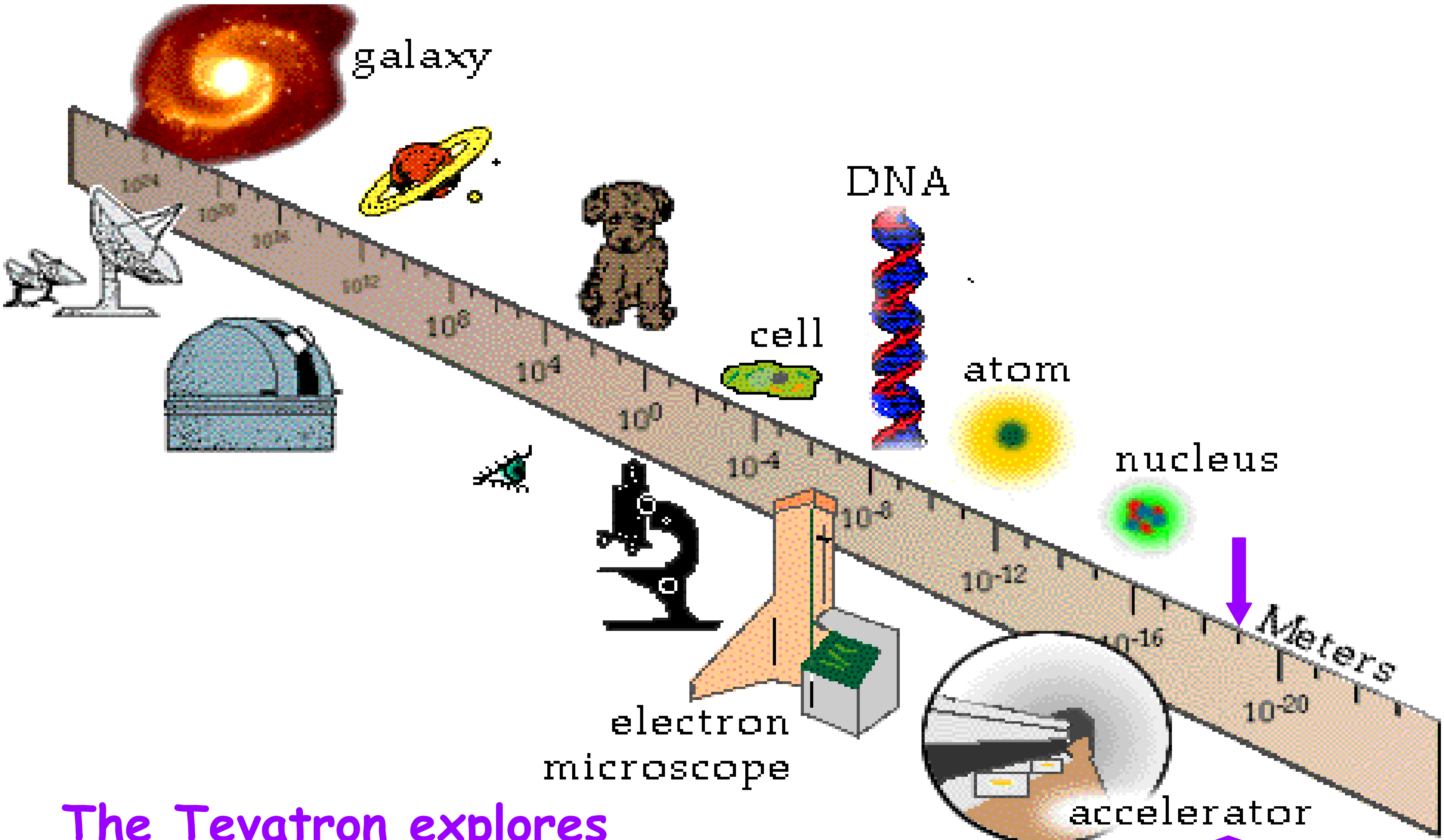
On behalf of CDF & D0 Collaborations

LES RENCONTRES DE PHYSIQUE DE LA VALLEE D'AOSTA
La Thuile, February 27^{th} – March 5^{th} 2005

Structure of Matter & Jets



The Tevatron explores
very small distances → jet production

Tevatron

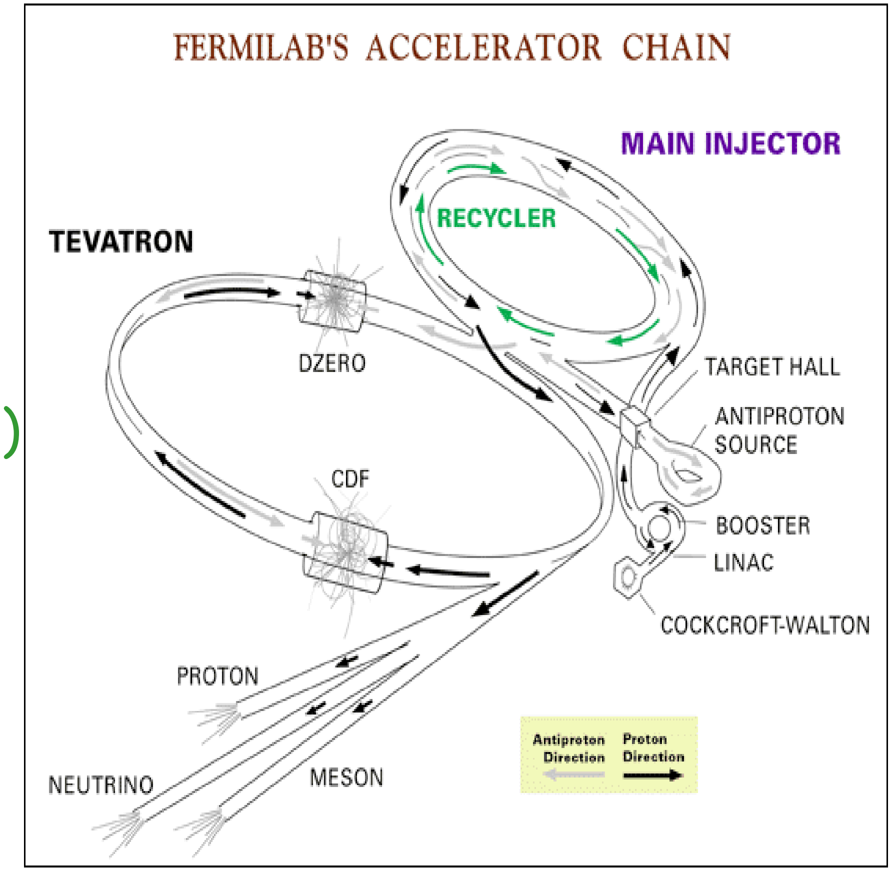
- proton-antiproton collisions

$\sqrt{s} = 1.96$ TeV (Run I $\rightarrow$ 1.8 TeV)

- Main injector
  (150 GeV proton storage ring)

- antiproton recycler (commissioning)
  - Electron cooling this year
  - Operational by Summer'05
  - 40% increase in Luminosity

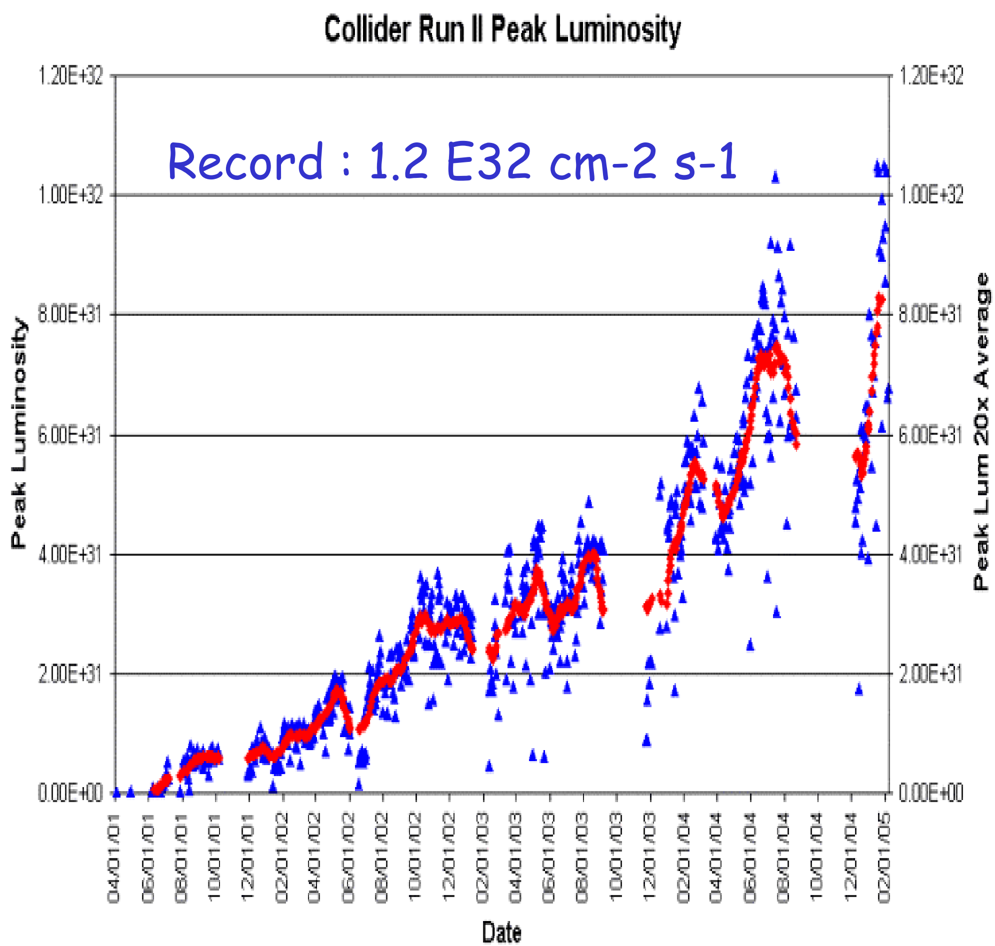
- 36 bunches (396 ns crossing time)

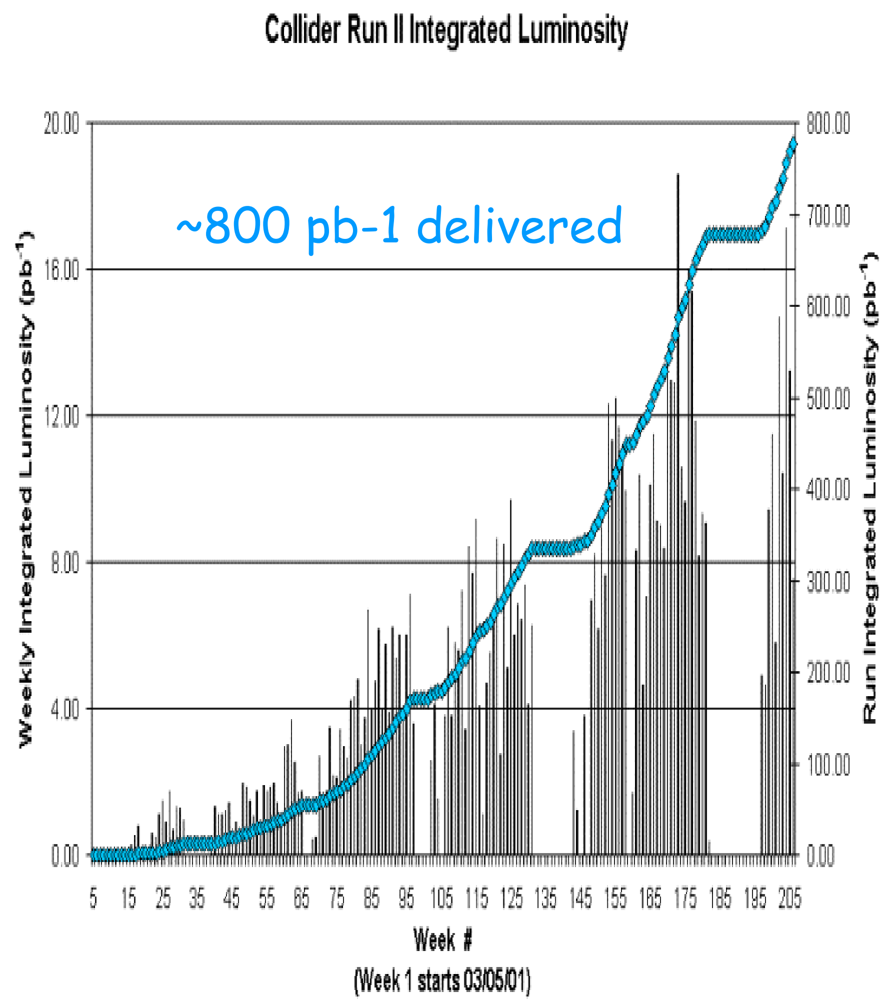


Long Term Luminosity Projection
(by end FY2009)

Base Goal -> 4.4 fb-1
Design -> 8.5 fb-1

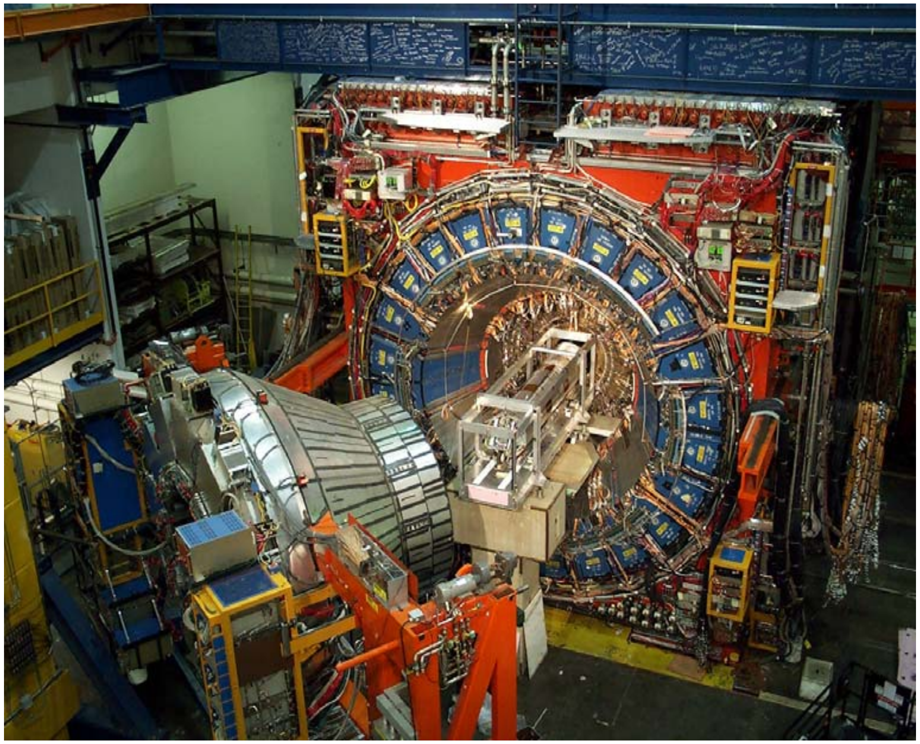
Tevatron Performance





TeVatron delivered more than 350 pb-1 in 2004

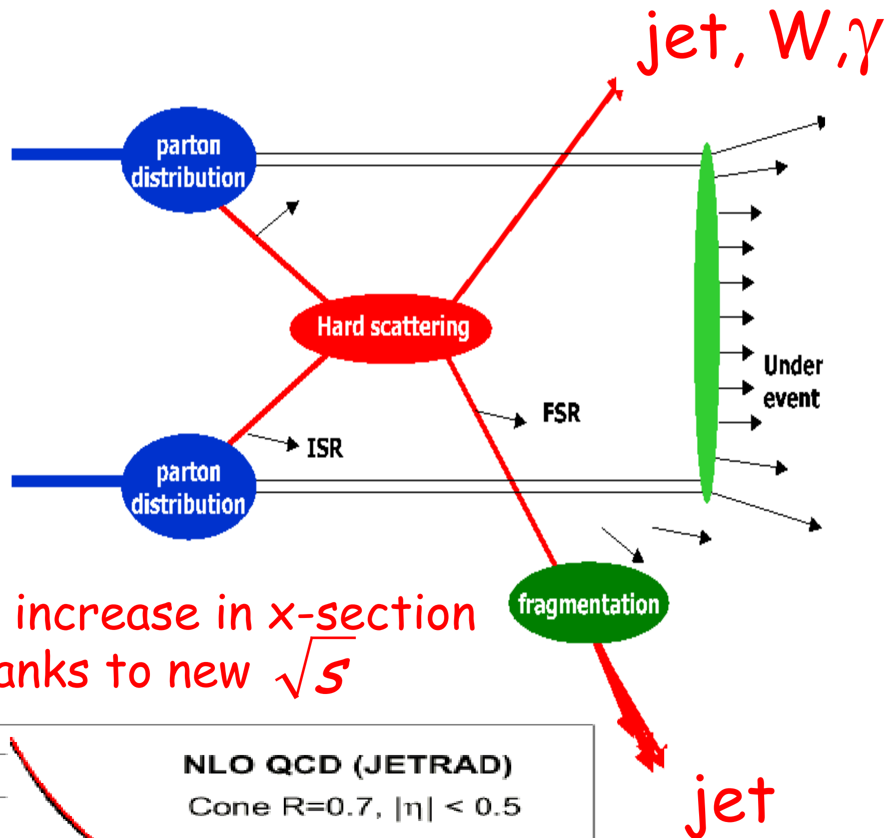
CDF & D0 Detectors



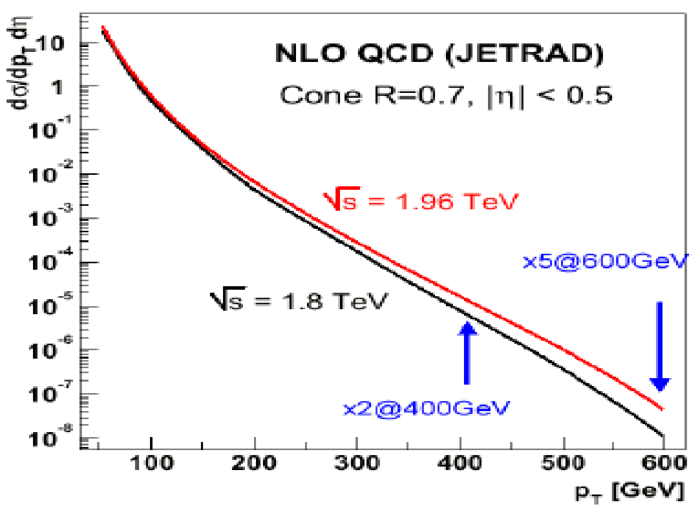
CDF & DØ operating well and recording physics quality data with very high efficiency (80 - 85%)

Both experiments have already collected ~600 pb-1 on tape

Jet Physics at 2 TeV



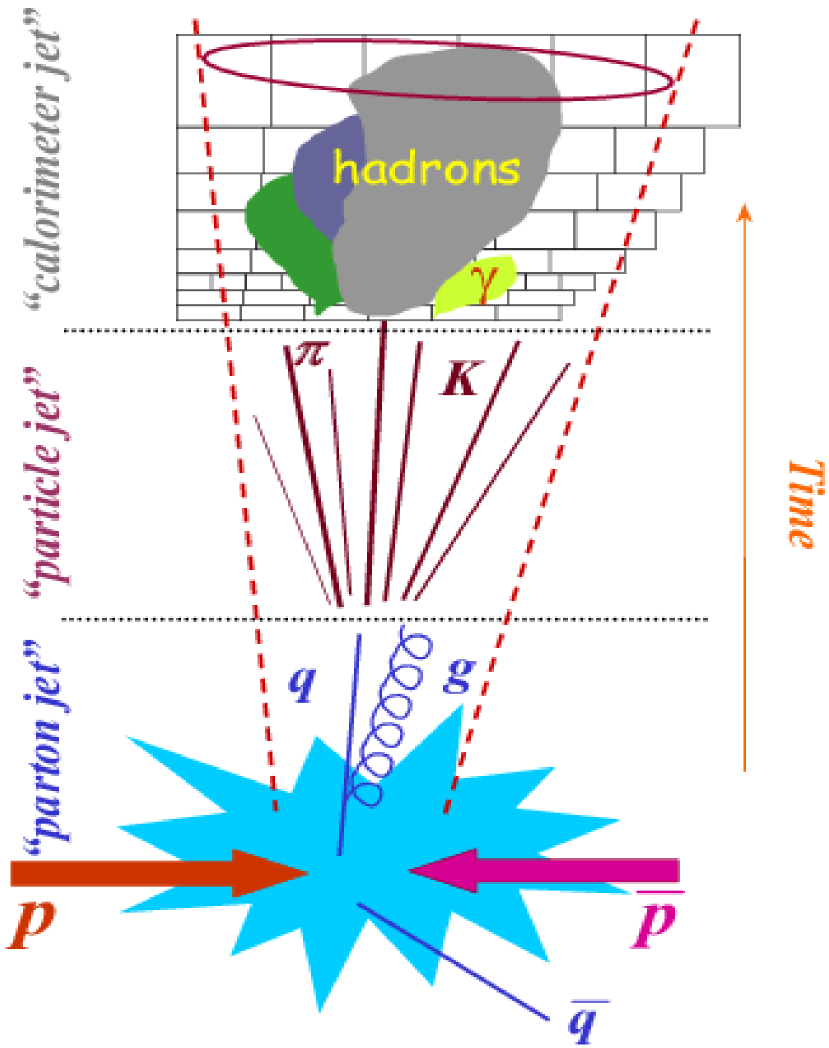
**Big increase in x-section thanks to new $\sqrt{s}$



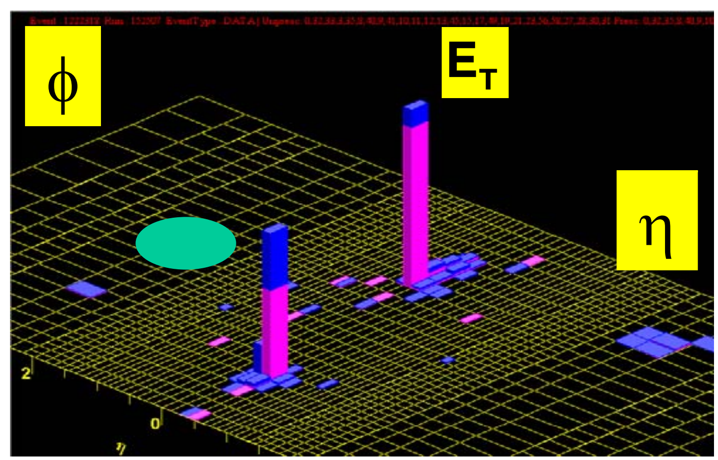
- Jet Cross Sections**
  - Jet algorithms
  - Data vs NLO pQCD
  - PDFs uncertainties
  - Soft contributions
- Underlying Event
- Dijet $\Delta\phi$ decorrelations
- Jet Shapes
- ……………
- ……………

o B-jet Production
o W/Z+Jet(s) Production
o γ+Heavy Quark
o Hard Diffraction

Jet algorithms



- Final state partons are revealed through collimated flows of hadrons called jets
- Measurements are performed at hadron level & theory is parton level (hadron → parton transition will depend on model for gluon shower and fragmentation)
- Precise jet search algorithms necessary to compare with theory and to define hard physics (cone in $\eta - \phi$ space ?)



Run I -> Cone algorithm

1. Seeds with $E_T > 1$ GeV

2. Draw a cone around each seed and reconstruct the "proto-jet"

$$E_T^{jet} = \sum_k E_T^k ,$$

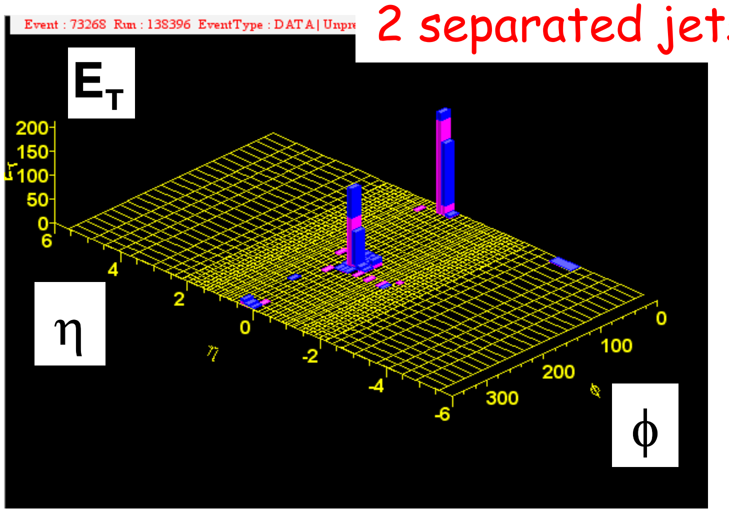
$$\eta^{jet} = \frac{\sum_k E_T^k \cdot \eta_k}{E_T^{jet}}, \quad \phi^{jet} = \frac{\sum_k E_T^k \cdot \phi_k}{E_T^{jet}}$$

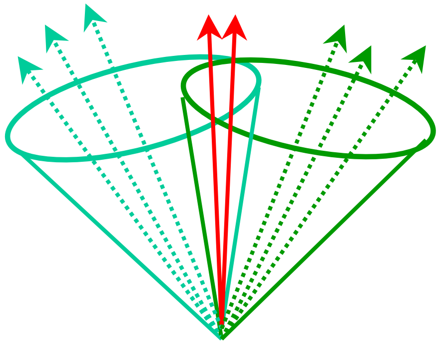
3. Draw new cones around "proto-jets" and iterate until stability is achieved

4. Look for possible overlaps

pQCD NLO uses larger cone R' = Rsep x R
to emulate experimental procedure
-> arbitrary parameter in calculation

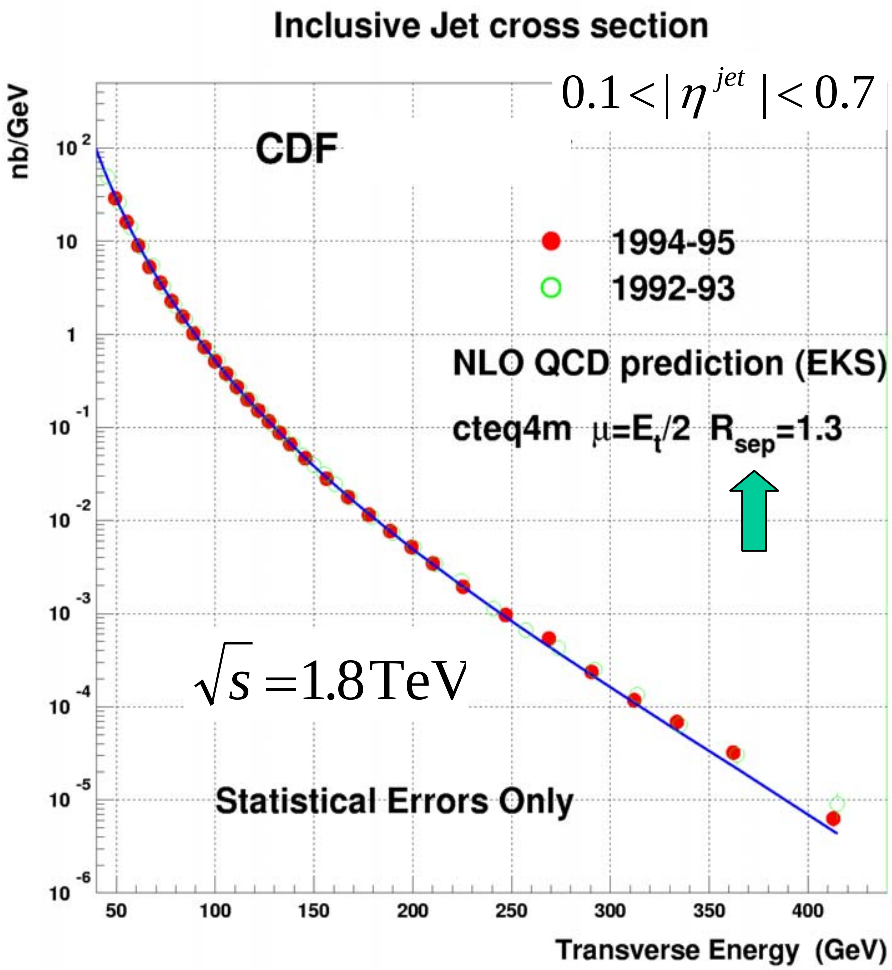
2 separated jets

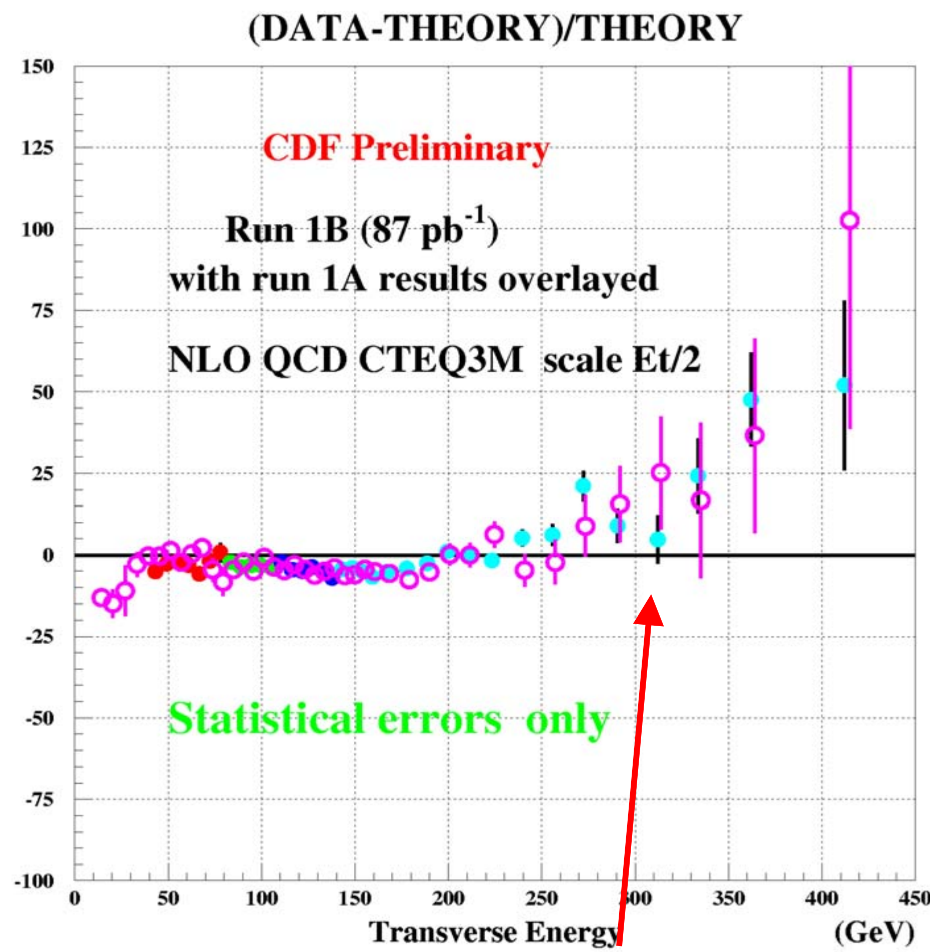




merged if common E_T is more than 75 % of smallest jet

Run I Results

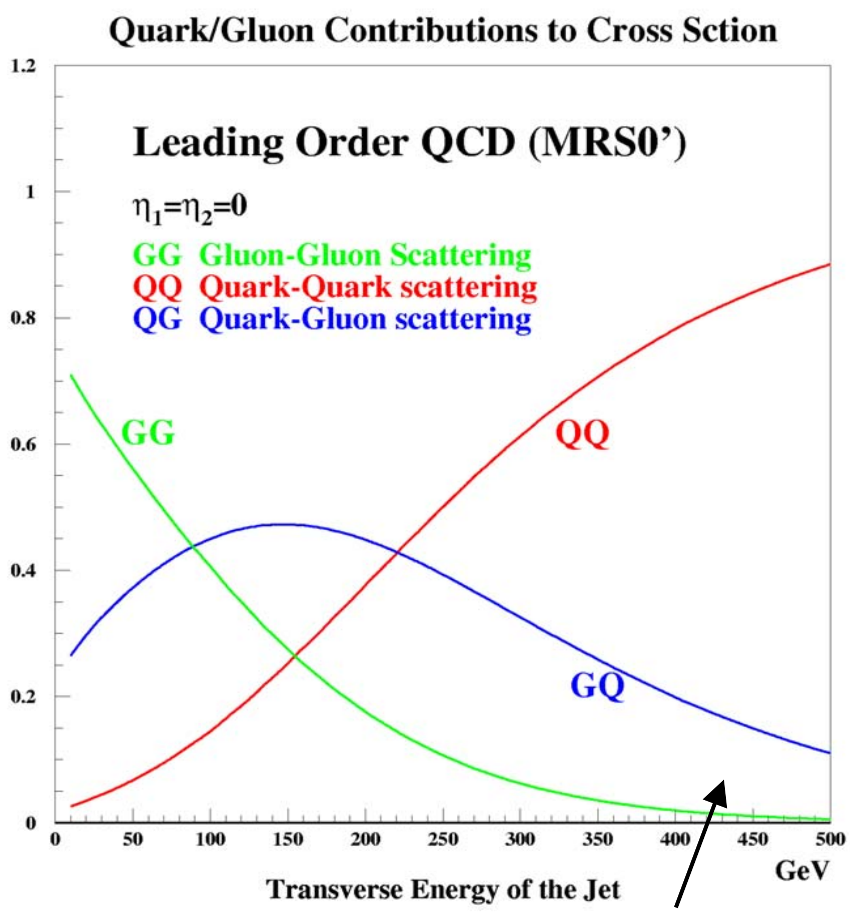


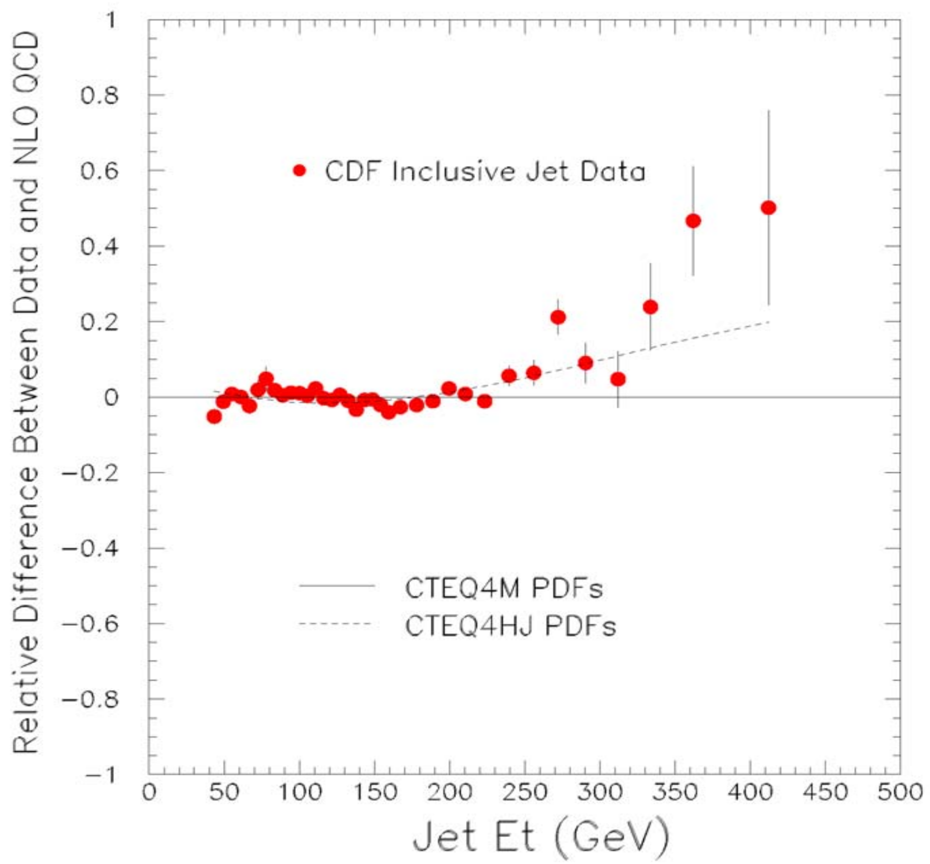


Run I data compared to pQCD NLO

Observed deviation in tail ....
was this a sign of new physics ?

gluon density at high-x

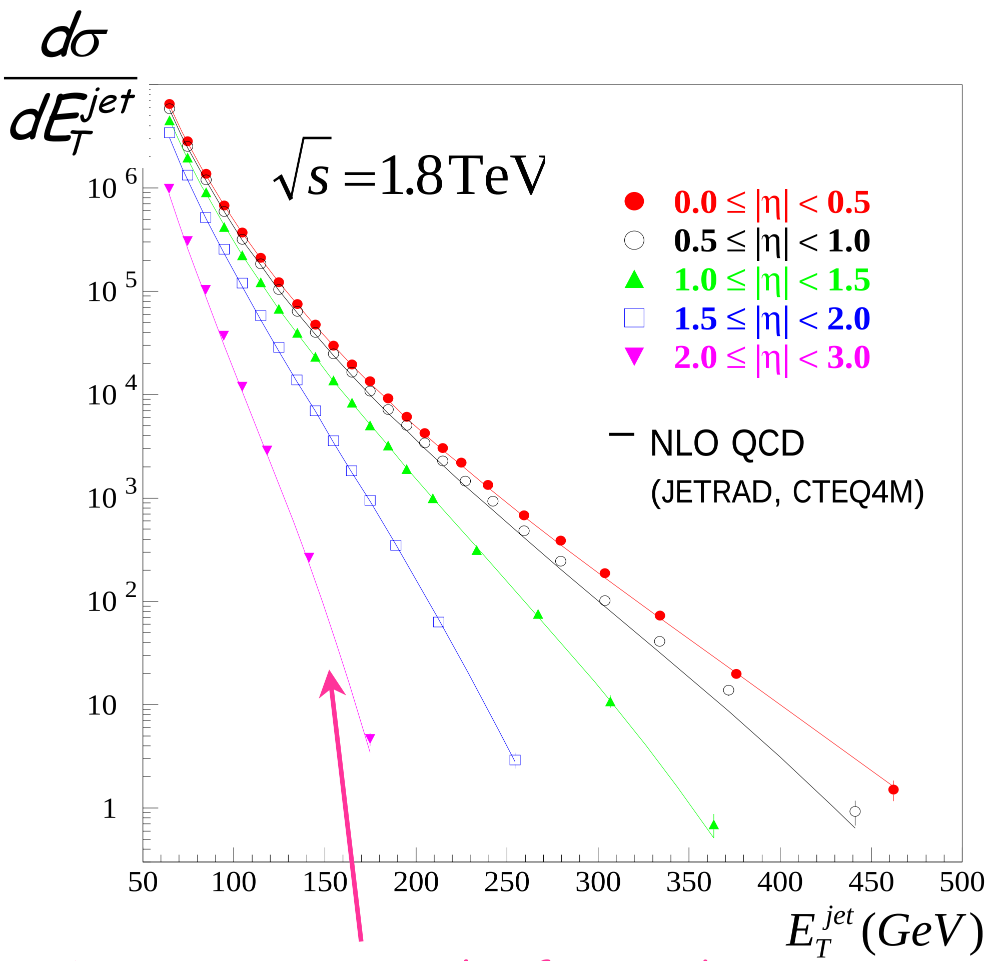


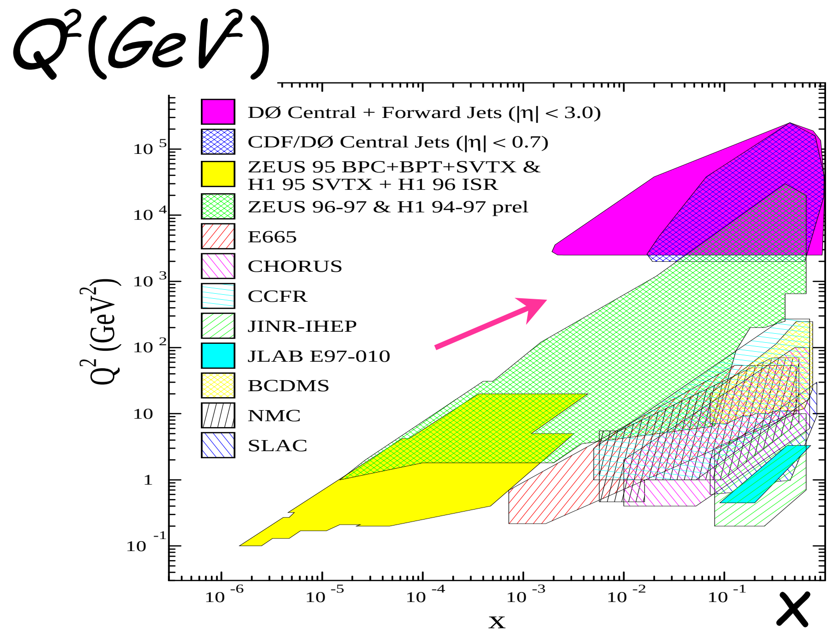


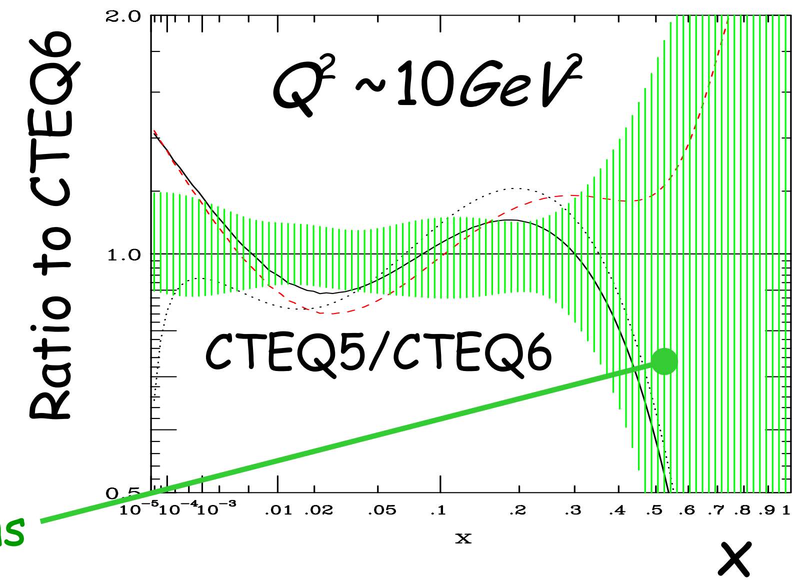
Important gluon-gluon and gluon-quark contributions at high-E_T

Gluon pdf at high-x not well known
…room for SM explanation….

Run I Jet Cross Section vs η



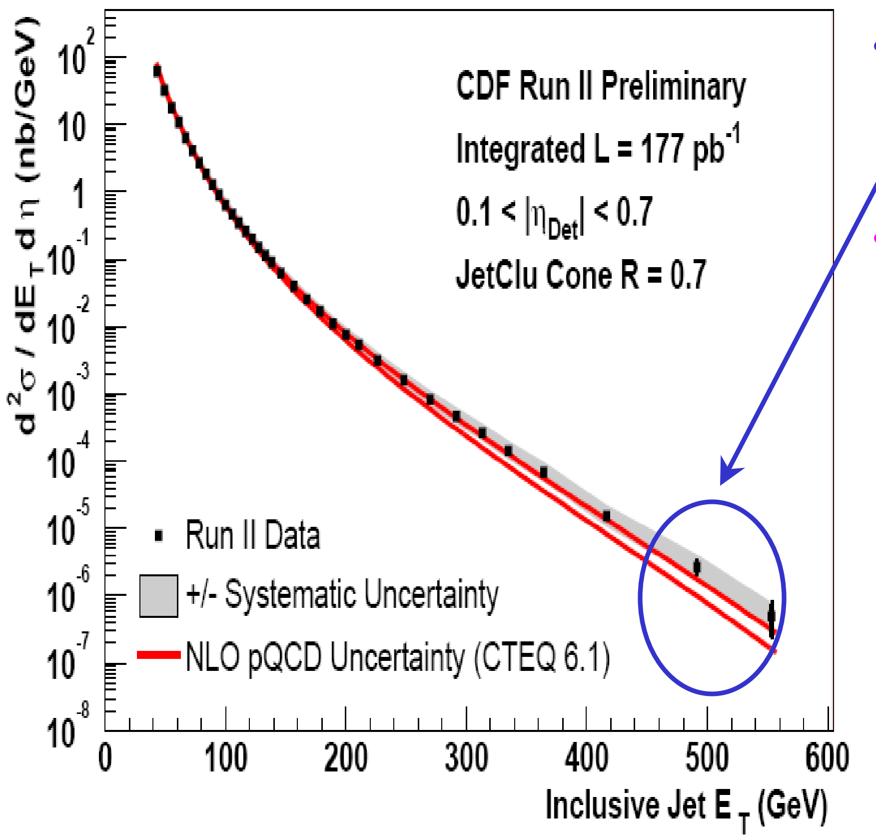




Measurements in the forward region allow to constrain the gluon distribution

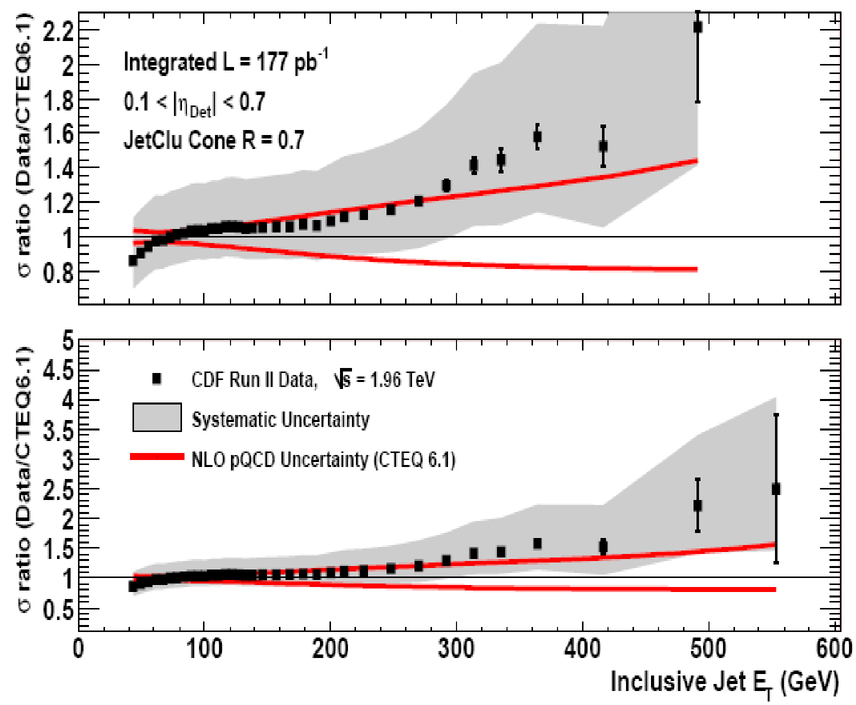
Big uncertainty still remains for high-x gluons

Run II Inclusive Cross Section



- Using Run I cone algorithm & unfolding E_T^{jet} range increased by ~150 GeV
- Comparison with pQCD NLO (JETRAD) (over almost nine orders of magnitude)

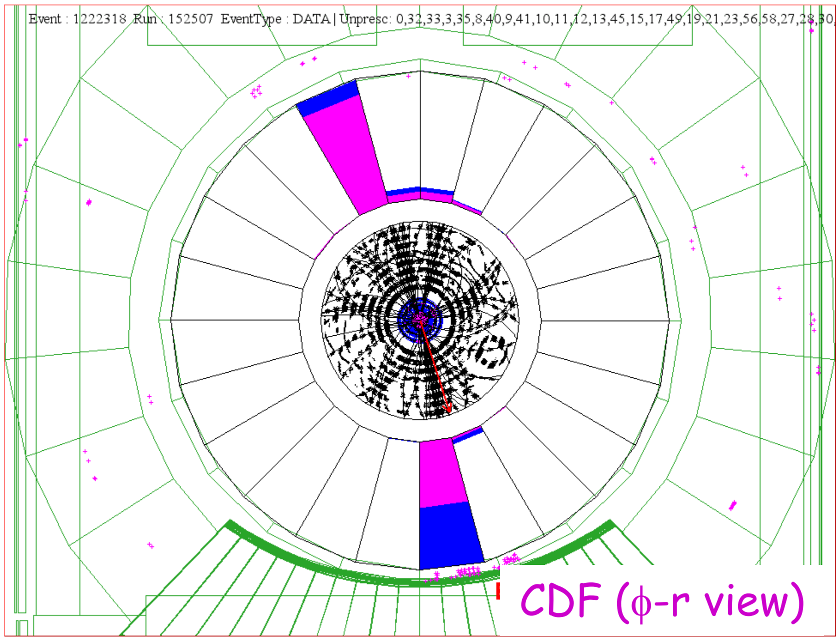
Shape of Data/NLO to be understood



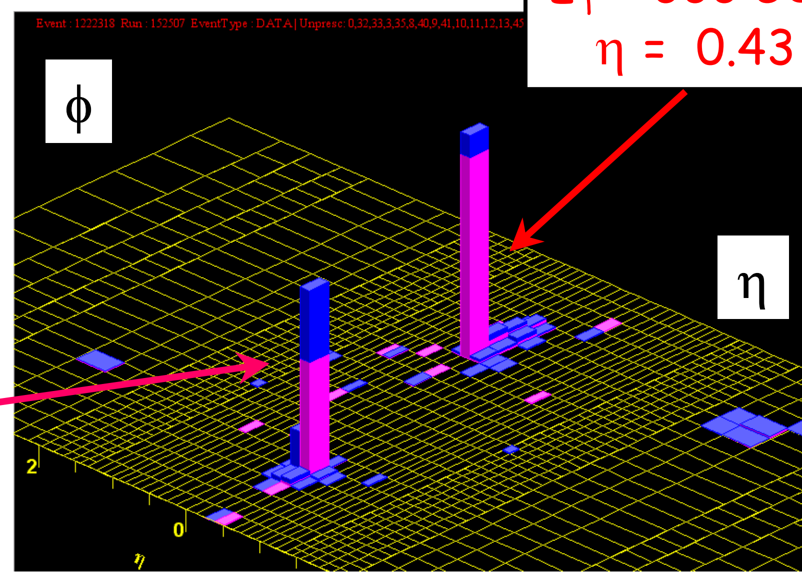
Data errors dominated by a 5% jet energy scale uncertainty

NLO error mainly coming from gluon PDF at high x

Highest Mass Dijet Event


CDF (ϕ-r view)

Dijet Mass = 1.36 TeV
(probing distance ~10^{-19} m)



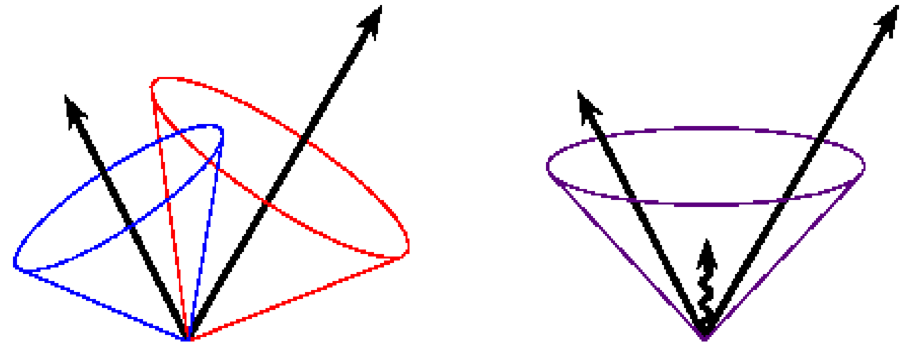
E_T = 633 GeV
η = -0.19

We are looking for a possible quark substructure....

Notes on Run I Jet algorithm

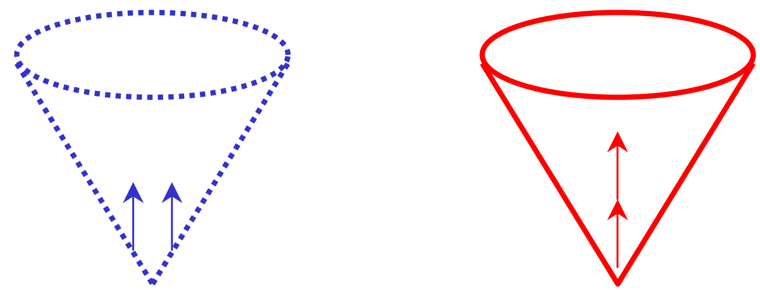
Cone algorithm not infrared safe:

The jet multiplicity changed
after emission of a soft parton



Cone algorithm not collinear safe:

Replacing a massless parton by
the sum of two collinear particles
the jet multiplicity changes



below threshold
(no jets)

above threshold
(1 jet)

Fixed-order pQCD calculations will contain not fully cancelled infrared divergences:

-> Inclusive jet cross section at NNLO
-> Three jet production at NLO
-> Jet Shapes at NLO

} three partons inside a cone

Run II -> MidPoint algorithm

1. Define a list of seeds using CAL towers with $E_T > 1$ GeV

2. Draw a cone of radius R around each seed and form "proto-jet"

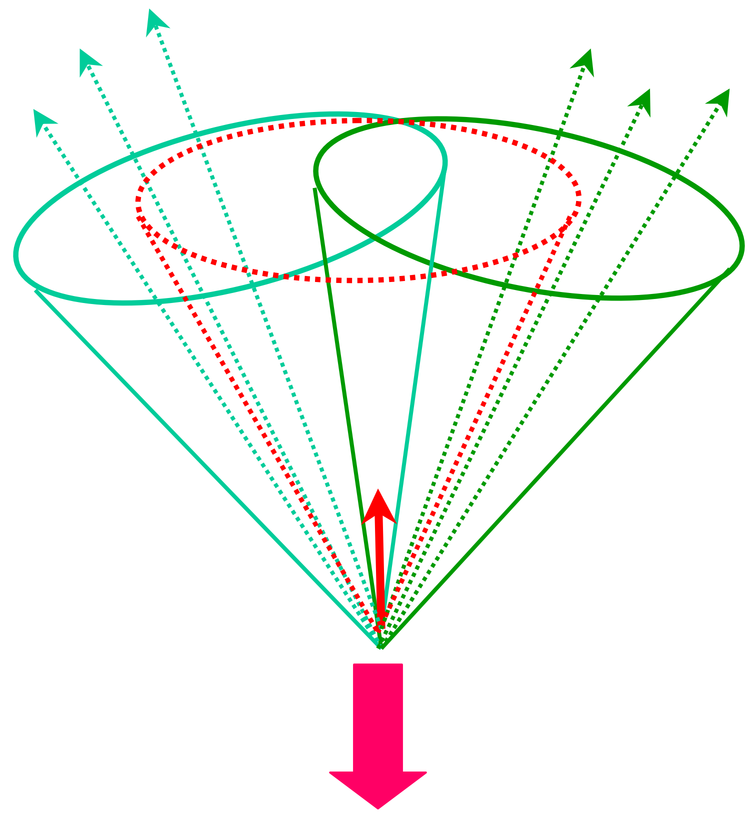
$$E^{jet} = \sum_k E^K, \quad P_i^{jet} = \sum_k P_i^K$$

(massive jets : P_T^{jet}, y^{jet})

3. Draw new cones around "proto-jets" and iterate until stable cones

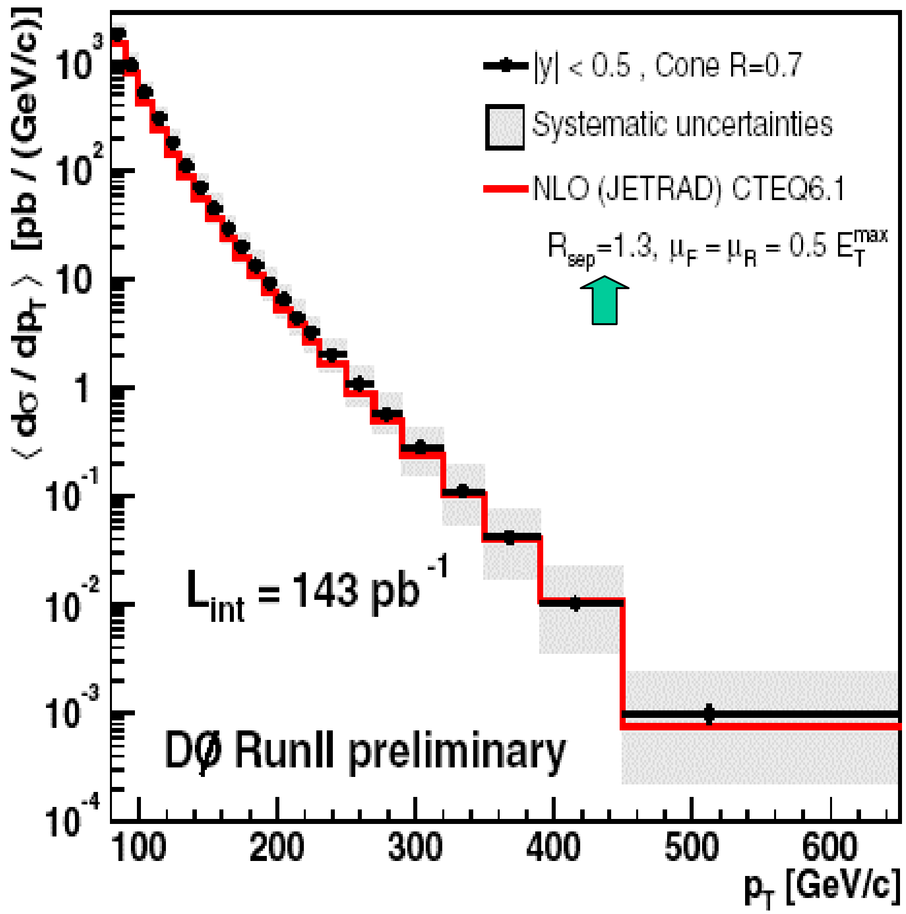
4. Put seed in Midpoint ($\eta - \phi$) for each pair of proto-jets **separated by less than 2R** and iterate for stable jets

5. Merging/Splitting

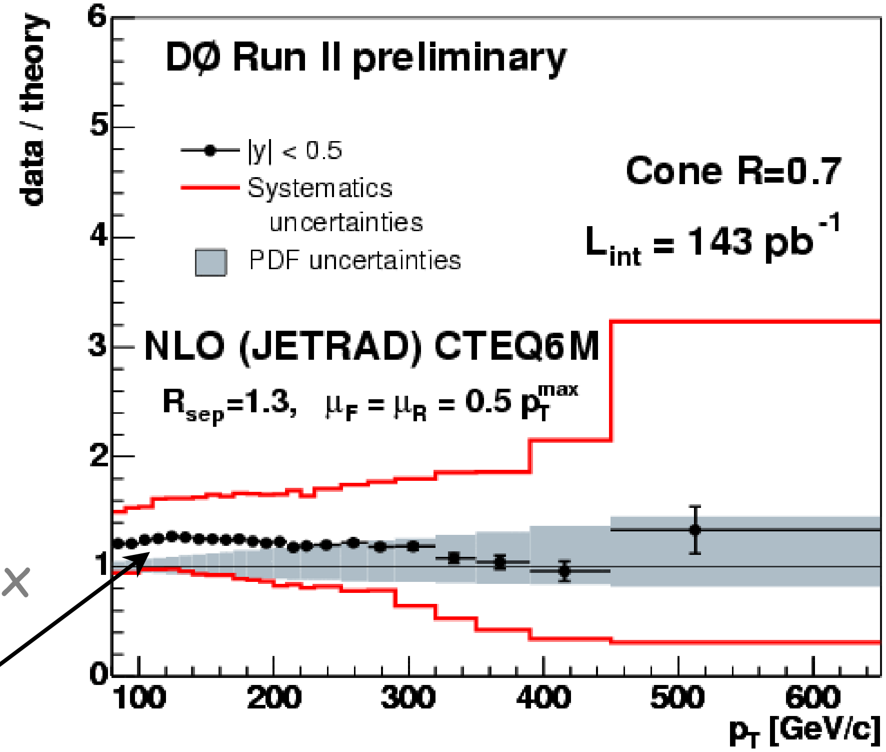


Cross section calculable in pQCD

Inclusive jet p_T cross section



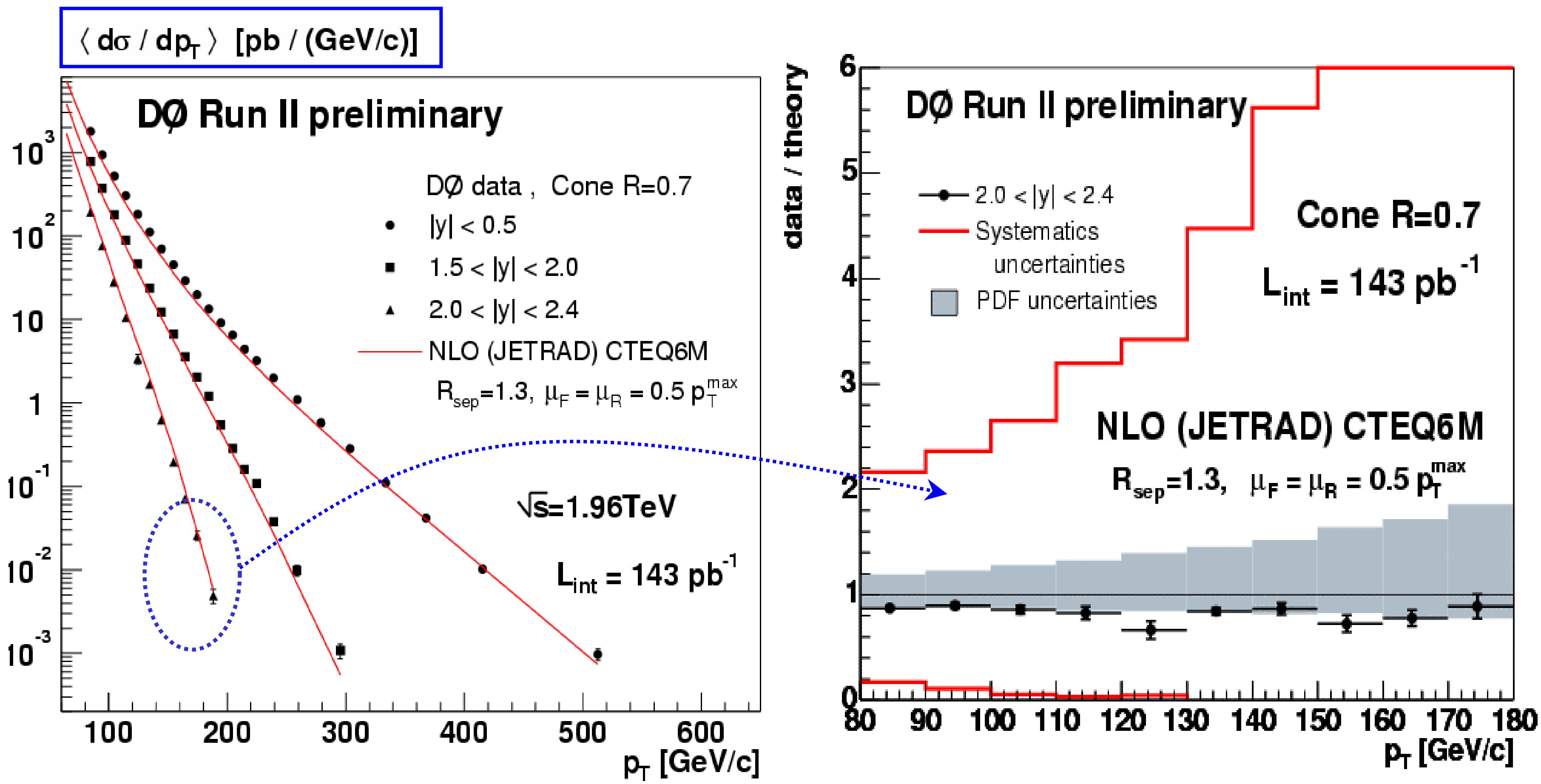
Agreement with theory within systematic uncertainties
(dominated by jet-energy scale)



NLO uncertainty due to gluon @ high x

Hadronization Corrections needed ?

Cross section vs rapidity



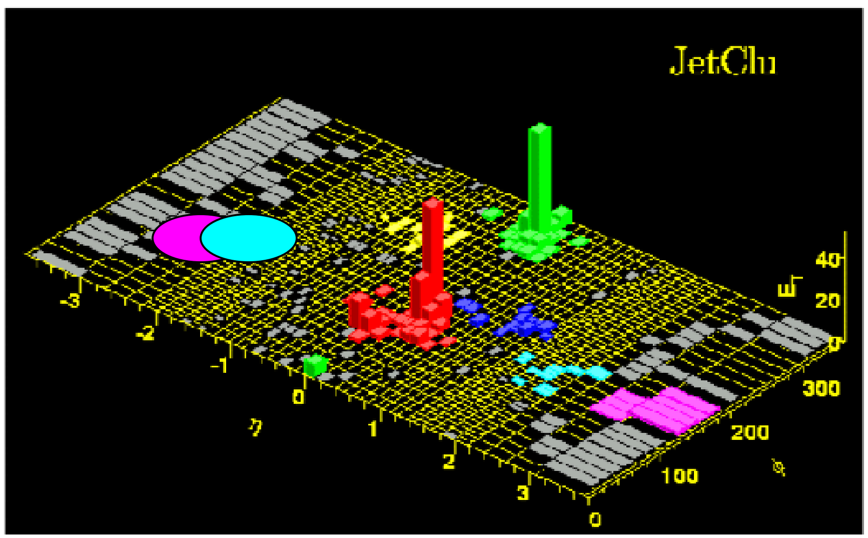
Measurements on large |Y| range help to constrain gluon at high *x*

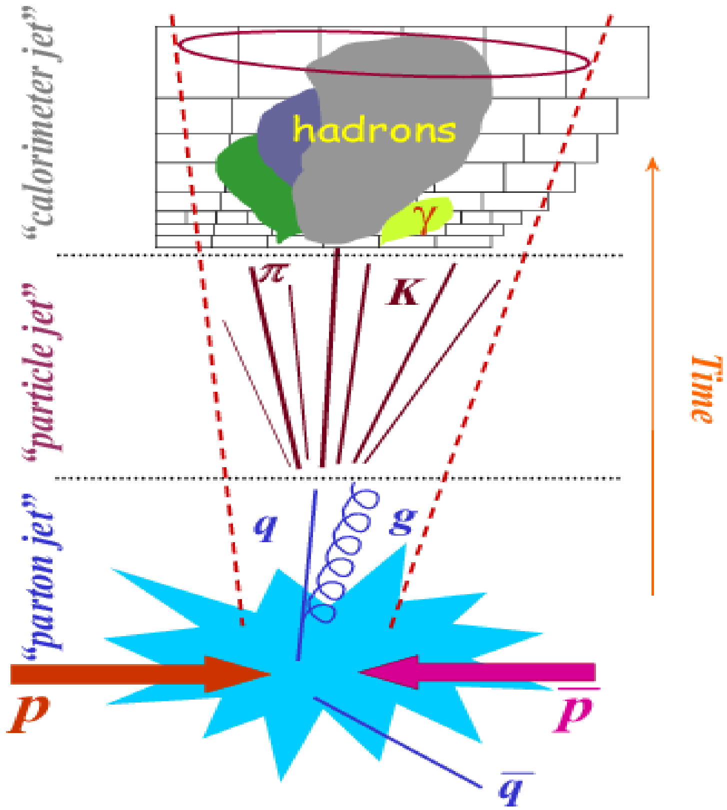
Good agreement with NLO pQCD

Measurement dominated by large uncertainty on the jet energy scale (16 % -> will improve in the near future)

Motivation for the K_T algorithm

- Cone-based algorithms can be modified to be infrared/collinear safe → Midpoint
- Cone-based jet algorithms include an "experimental" prescription to resolve situations with overlapping cones
- This is emulated in pQCD theoretical calculations by an arbitrary increase of the cone size : R → R′ = R * 1.3 ☹





Nature (QCD ?) prefers to separate partons into jets according to their relative transverse momentum

⇩

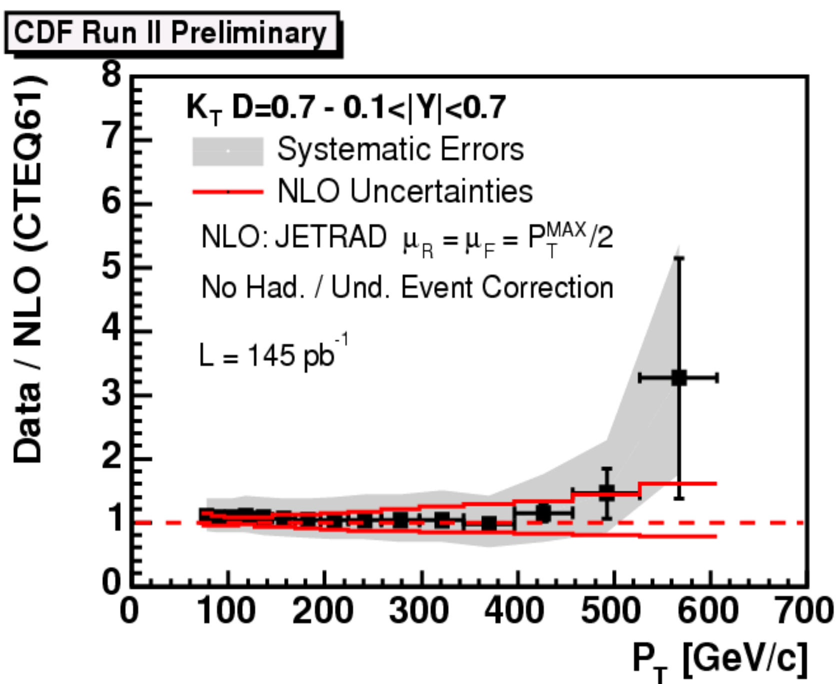
Kt algorithm preferred by theory

Jet Production with K_T

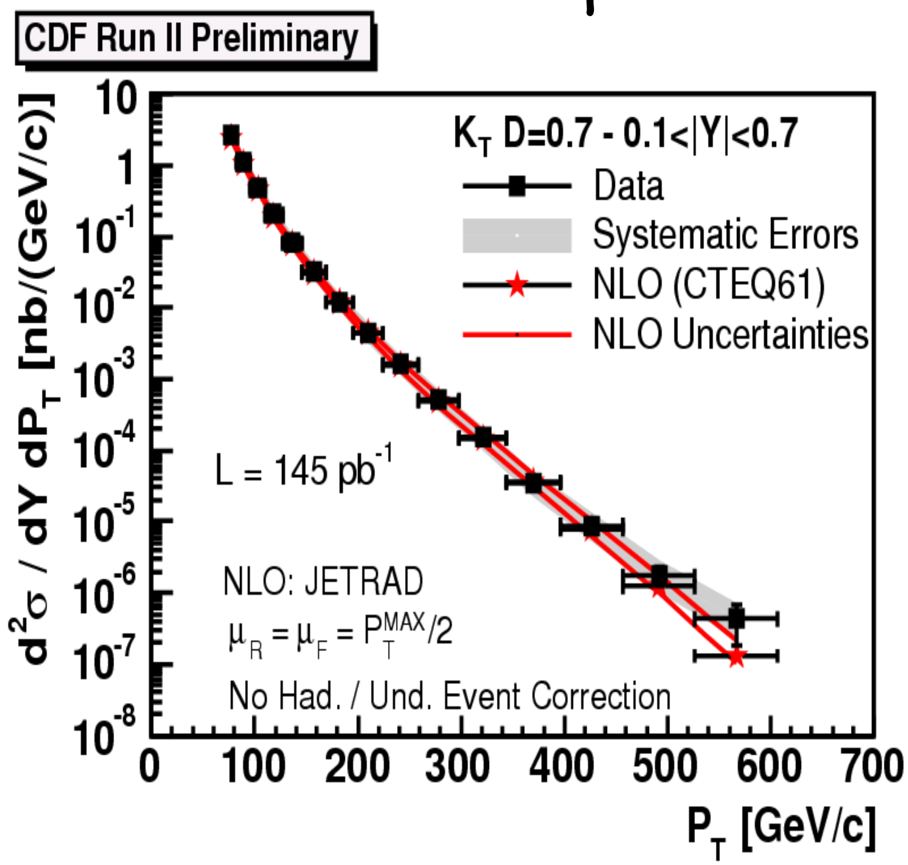
- Inclusive K_T algorithm

$$d_{ij} = \min(P^2_{T,i}, P^2_{T,j}) \frac{\Delta R^2}{D^2}$$

$$d_i = (P_{T,i})^2$$



NLO not corrected for Hadronization & Underlying Event (this will be important at low Pt)



- Good agreement Data vs Theory
- High-Pt tail to be watched closely…
- K_T works in hadron collisions !
  → relevant for LHC strategies

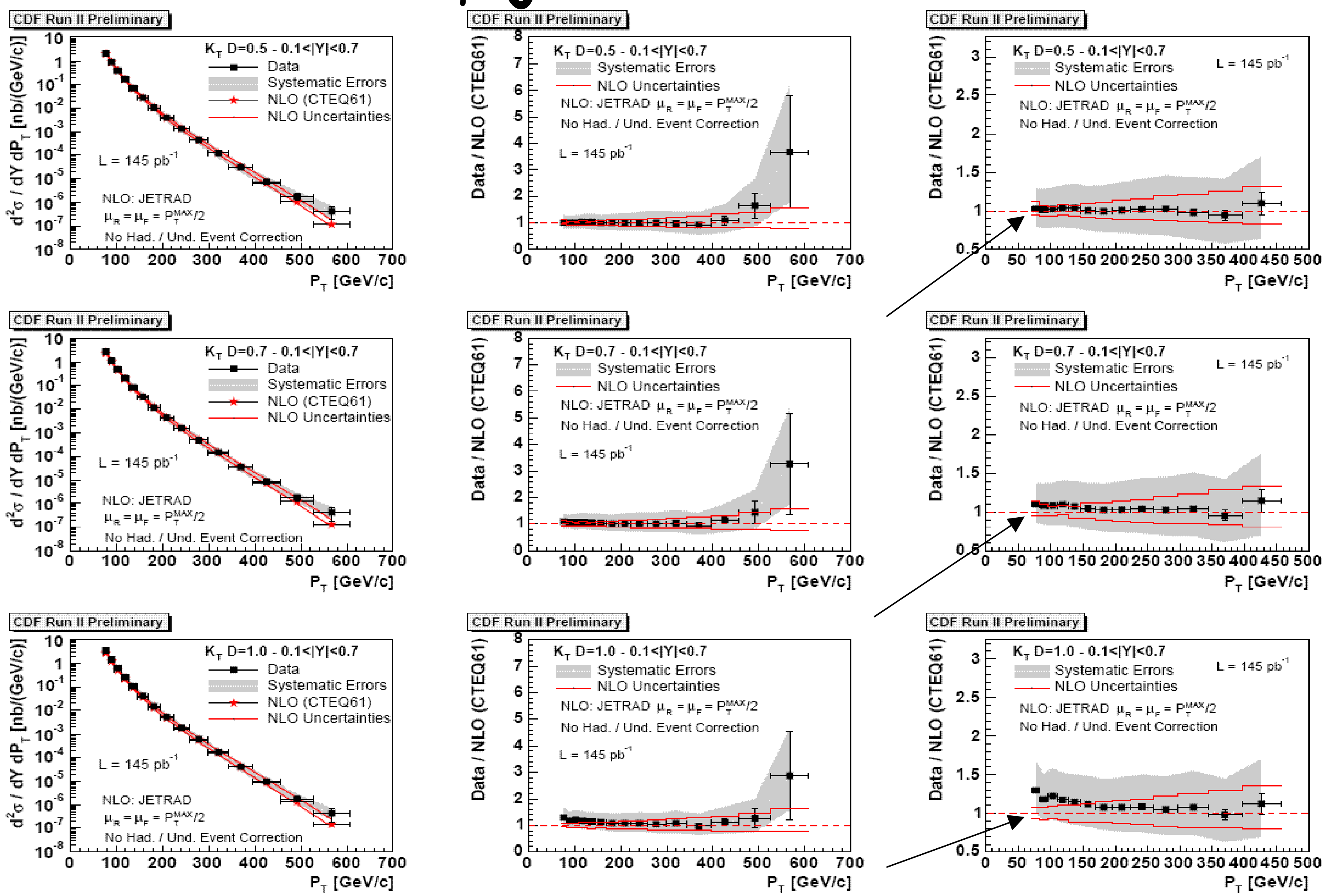
K_T jets vs D

$$d_{ij} = \min(P^2_{T,i}, P^2_{T,j}) \frac{\Delta R^2}{D^2}$$

D=0.5

D=0.7

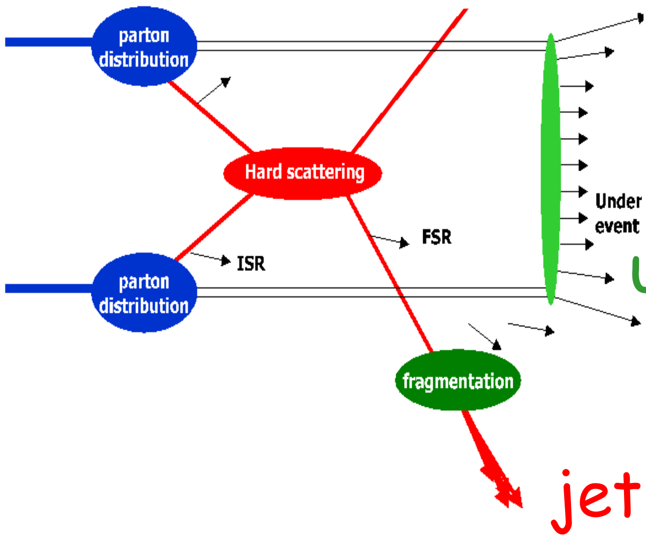
D=1.0



As D increases → more soft contributions (we need a good UE model)

The Underlying Event

jet, γ, W, Z (how important is it?)



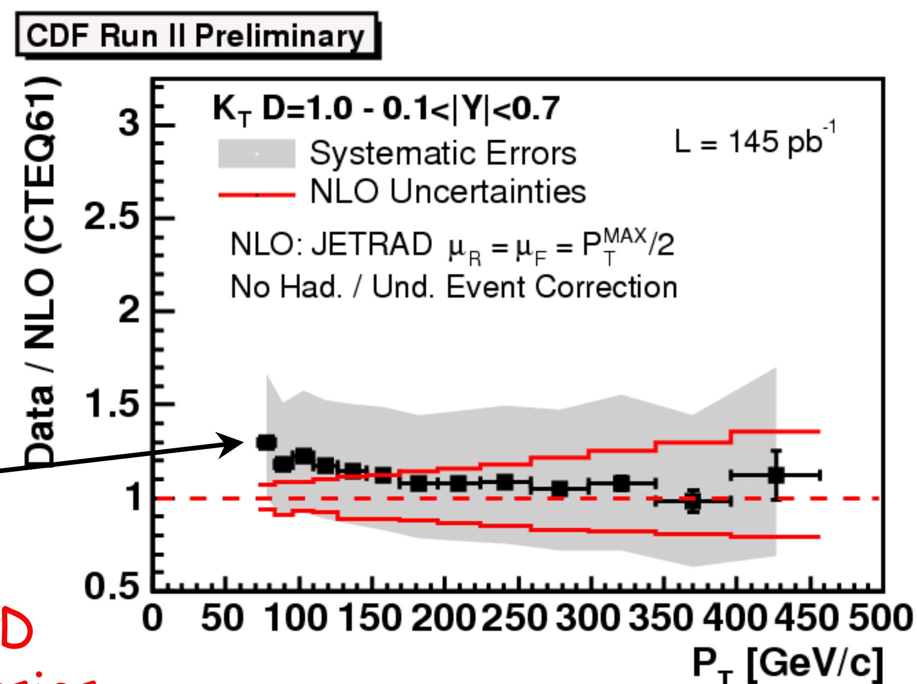
A typical Tevatron event consists of :

- hard interaction

Underlying Event:
- initial soft gluon radiation
- interaction between remnants

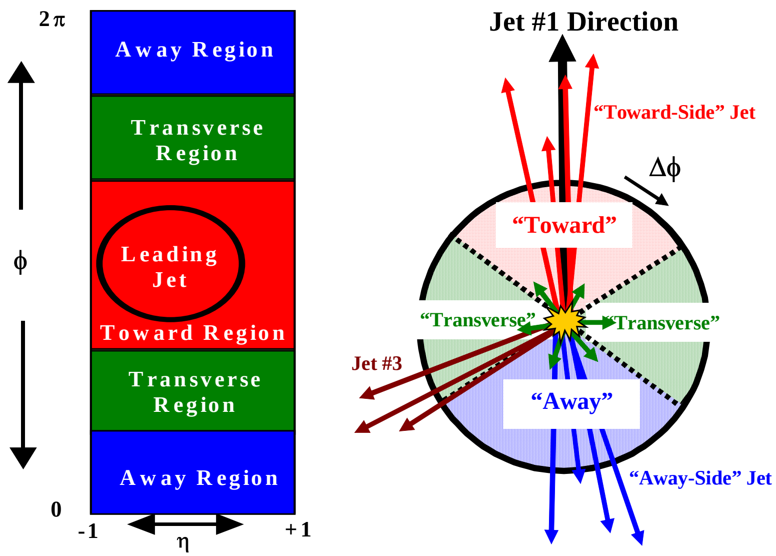
Underlying Event contribution must be removed from the jets before comparing to NLO QCD predictions

Precise measurements at low Pt require good modeling of the underlying event



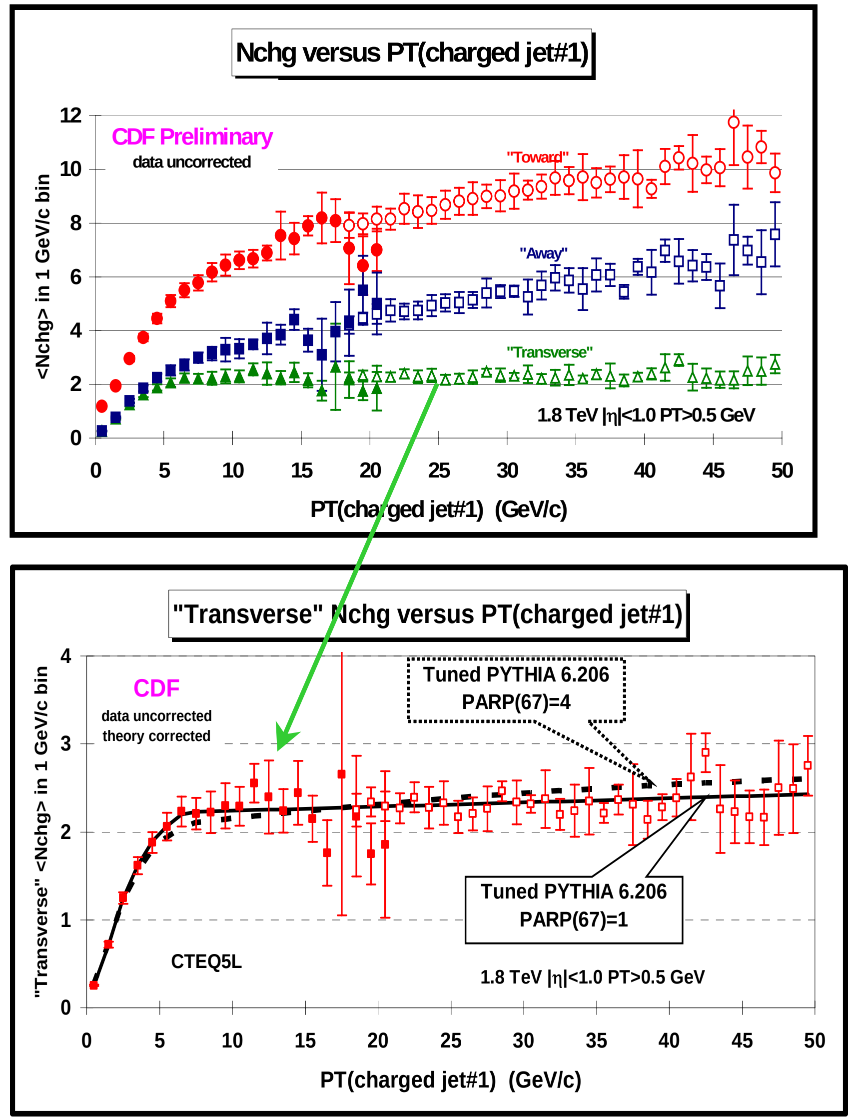
Crucial for a proper estimation of QCD backgrounds in Searches for New Physics…

Underlying Event Studies (Run I)



$p_T^{track} > 0.5\,\text{GeV}, \quad |\eta^{track}| < 1$

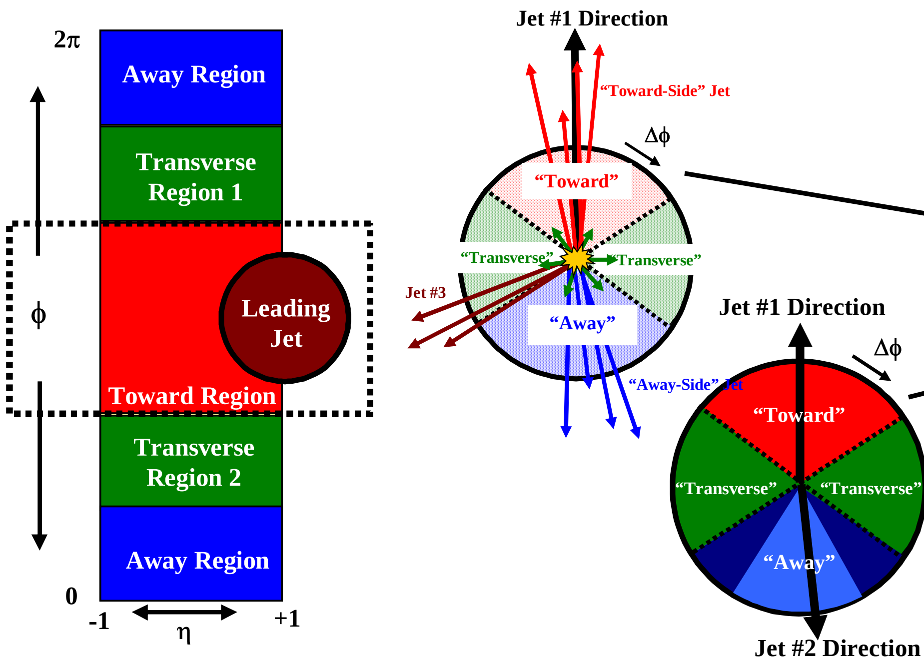
Mean track multiplicity vs leading jet Pt

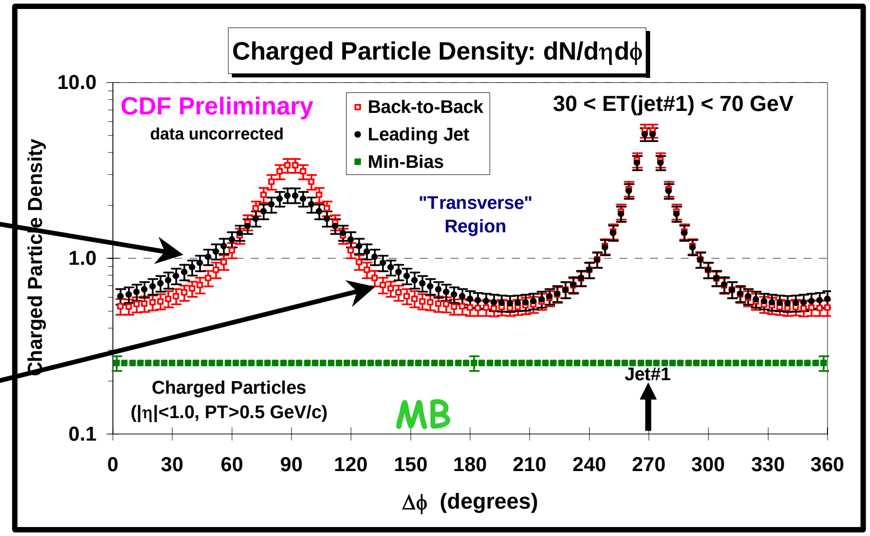


transverse region sensitive to soft underlying event activity

Good description of the underlying event by PYTHIA after tuning the amount of initial state radiation, MPI and selecting CTEQ5L PDFs (known as PYTHIA Tune A)

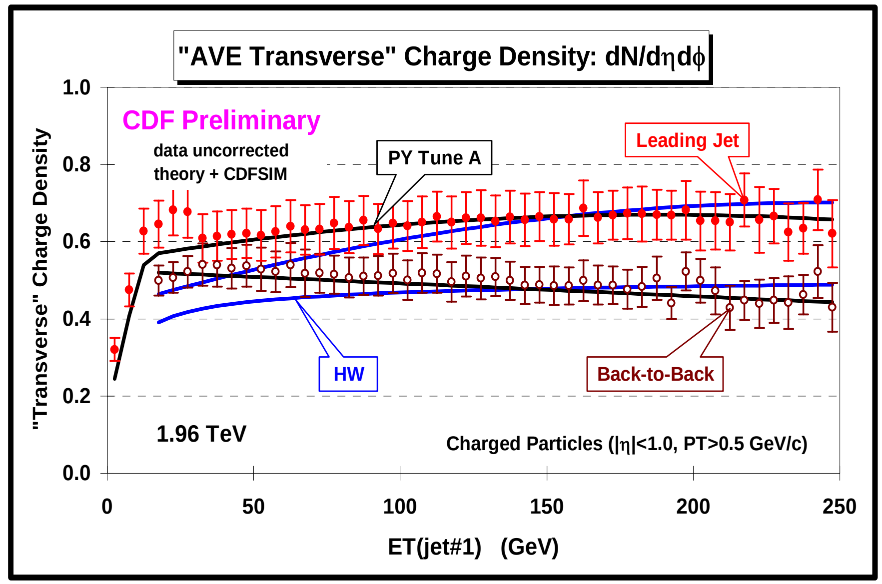
New Underlying Event Studies





Back-to-Back { $E_T(\text{jet\#2})/E_T(\text{jet\#1}) > 0.8$, $\Delta\phi_{12} > 150°$

Suppresses contribution from additional hard radiation



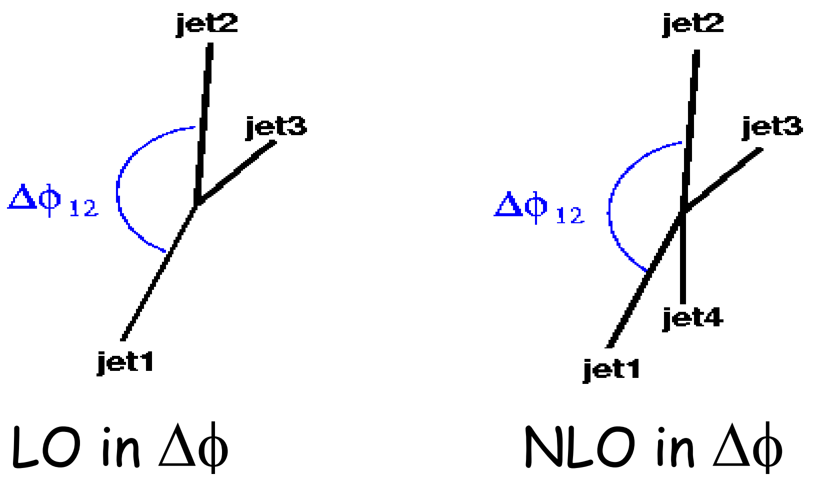
Pythia Tune A describes the data

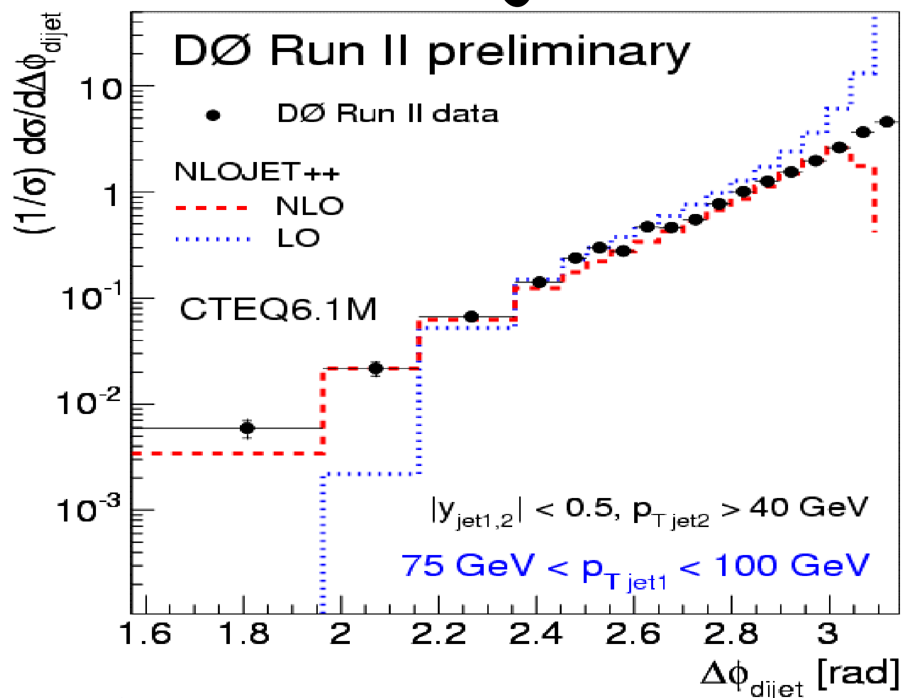
Herwig underestimates UE activity

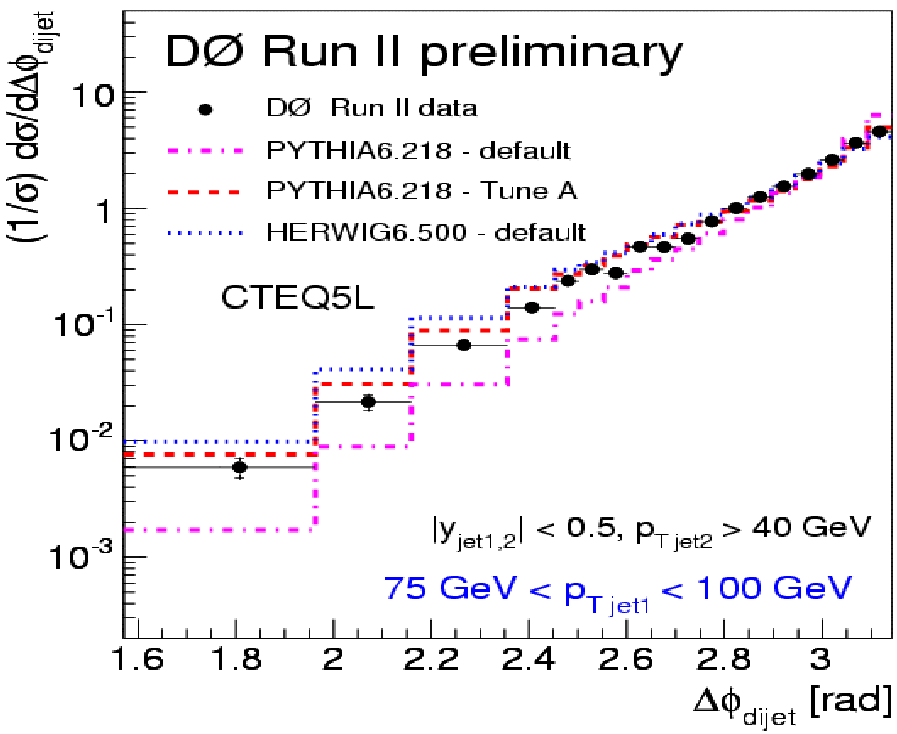
Extended to 250 GeV jets

Submitted to PRL

Studies on Δϕ between jets





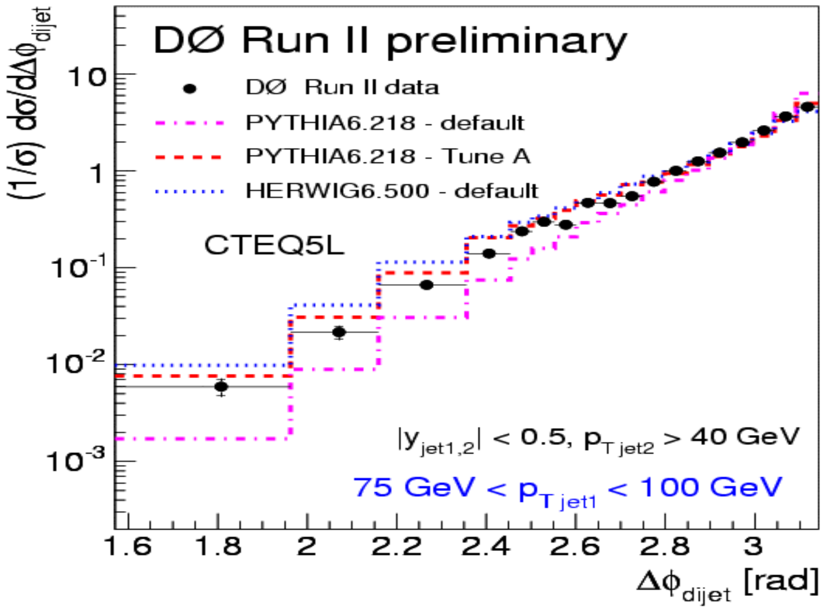


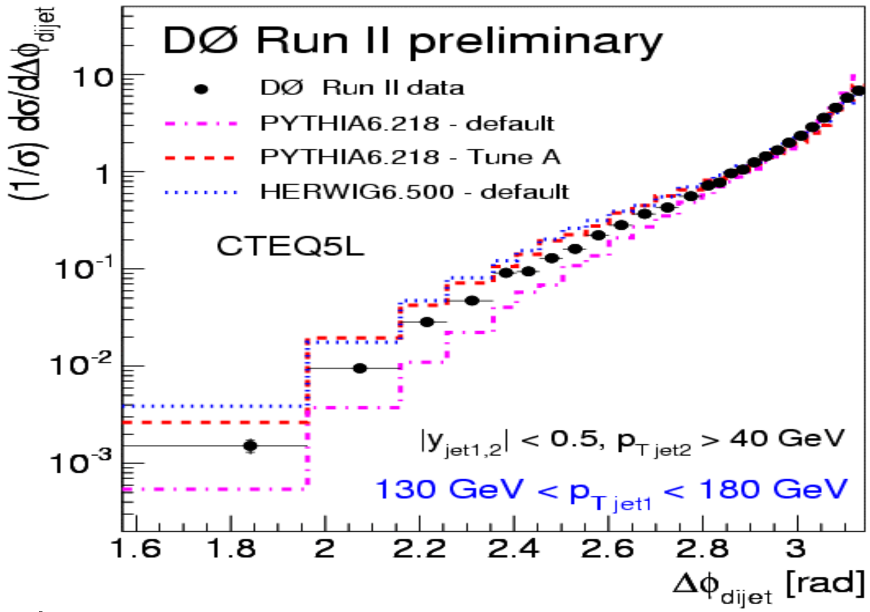
LO limited at hard (Mercedes Star) and soft limits for third emission

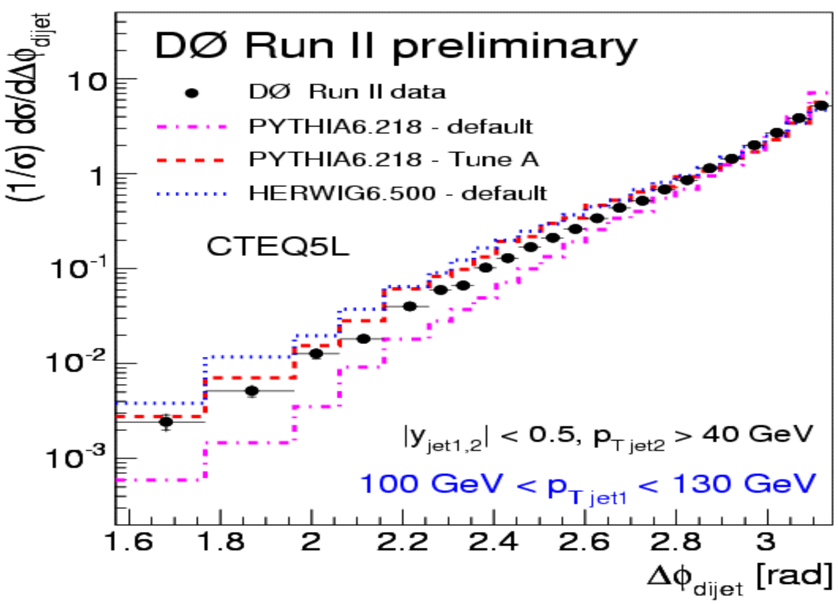
NLO closer to data…however soft gluon contributions are needed

Parton shower MC approximates the required re-summed calculation

Δφ & soft gluon radiation





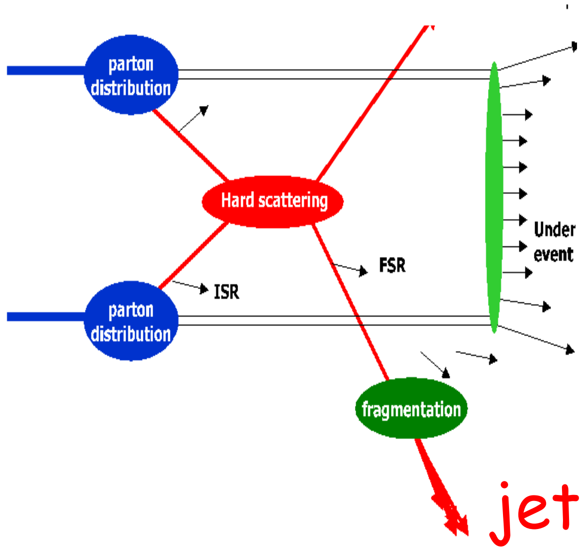


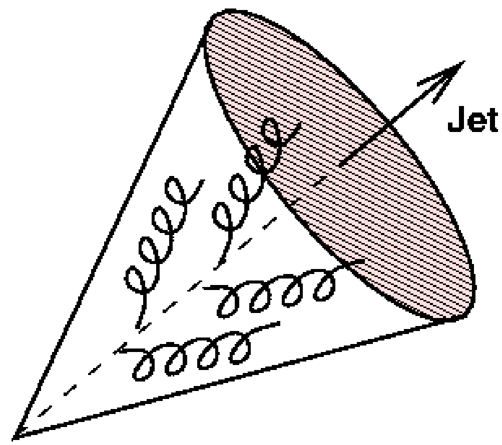
Δφ distribution shows sensitivity to different modeling of parton cascades

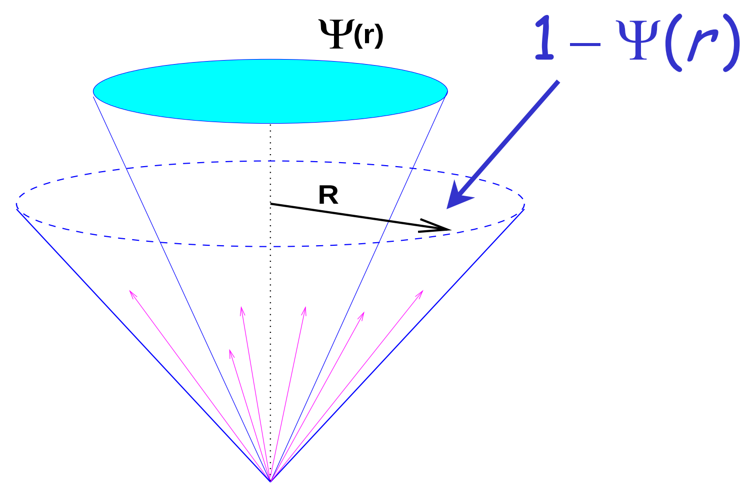
PYTHIA Tune A (enhanced ISR) provides best description across the different regions in jet p_T

HERWIG similar to PYTHIA Tune A

Studies on Jet Fragmentation



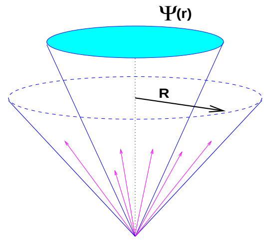




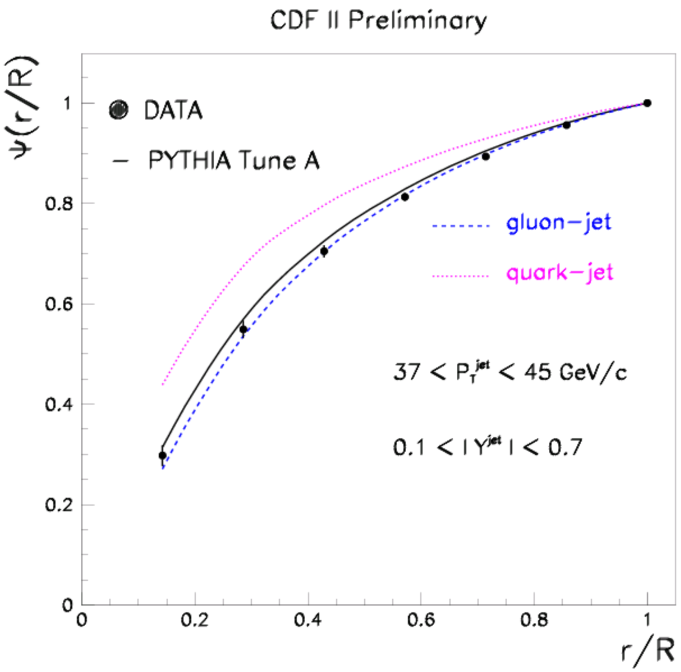
- Jet shape dictated by multi-gluon emission form primary parton
- Test of parton shower models and their implementations
- Sensitive to quark/gluon final state mixture and run of strong coupling
- Sensitive to underlying event structure in the final state

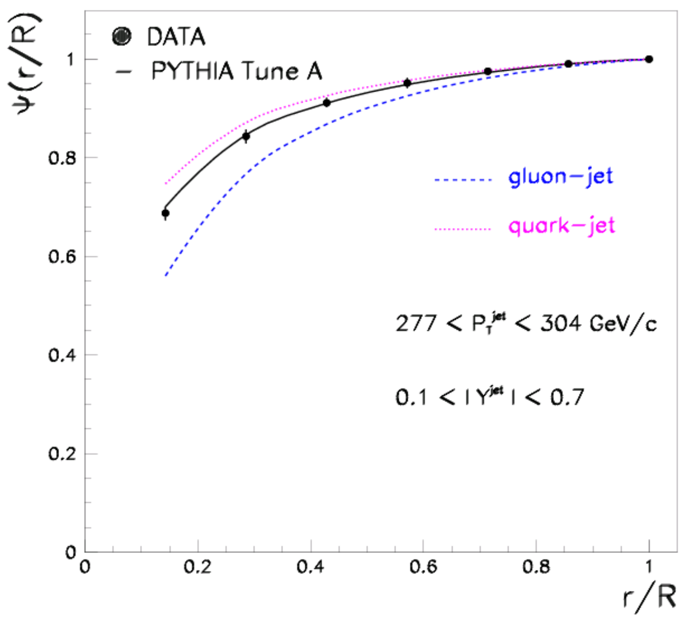
$$\Psi(r) = \frac{1}{N_{jets}} \sum_{jets} \frac{P_T(0,r)}{P_T^{jet}(0,R)}$$

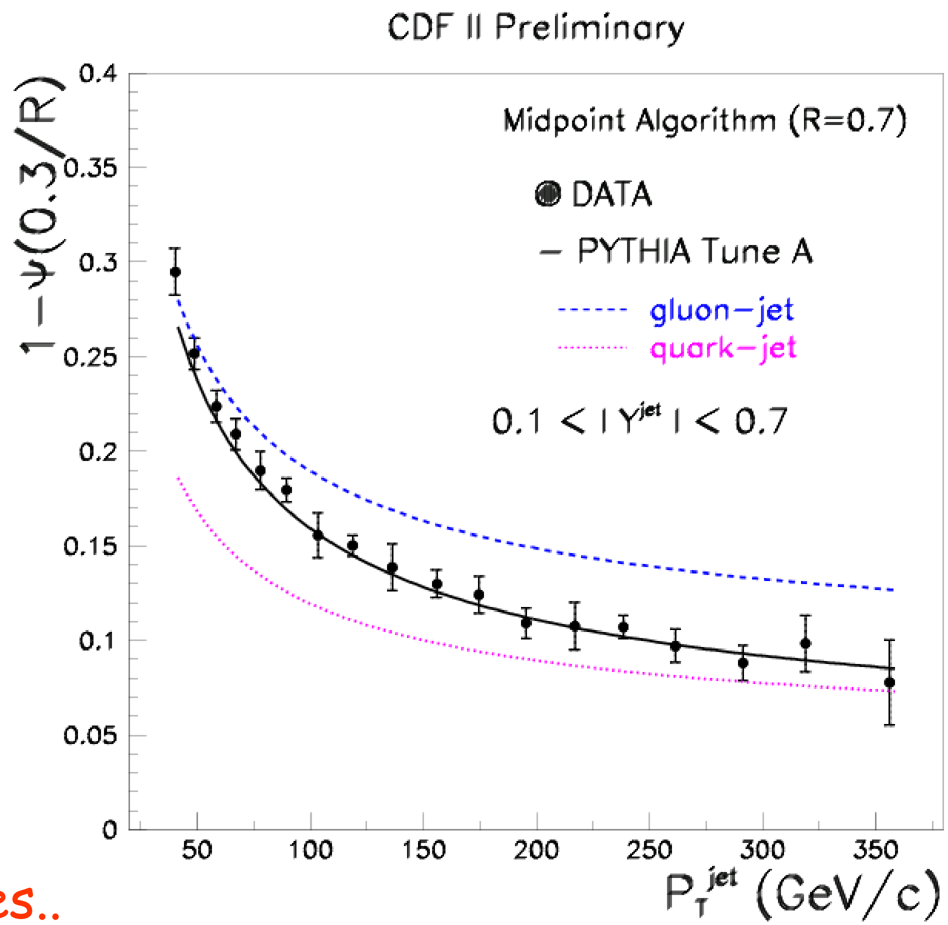
Jet shapes



Jet shapes sensitive to the relative amount of quark- and gluon-jets in the final state and the running of the strong coupling

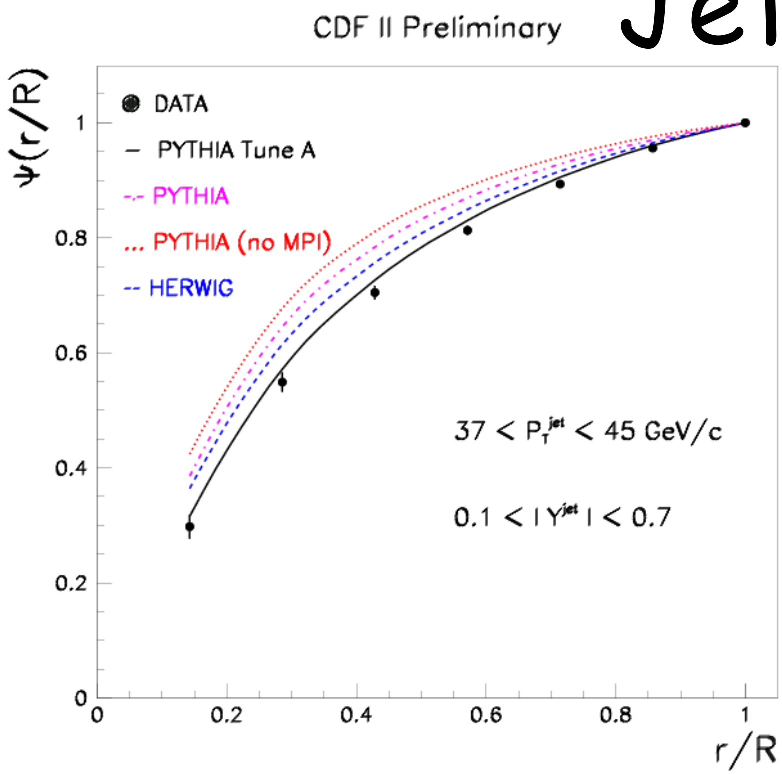


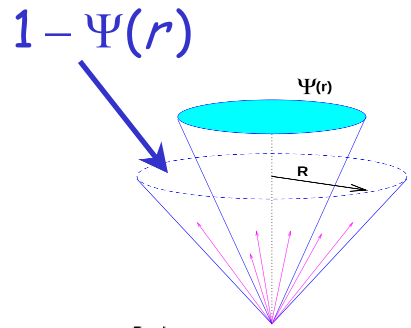


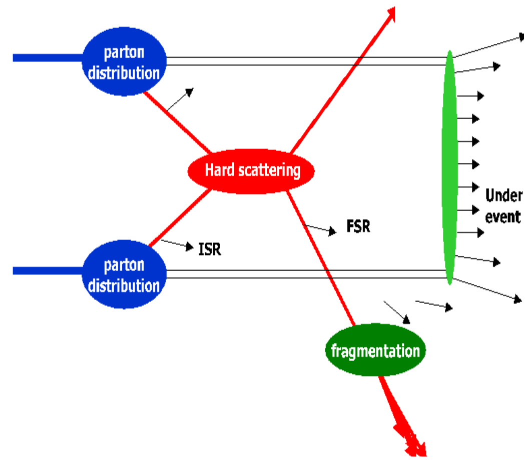


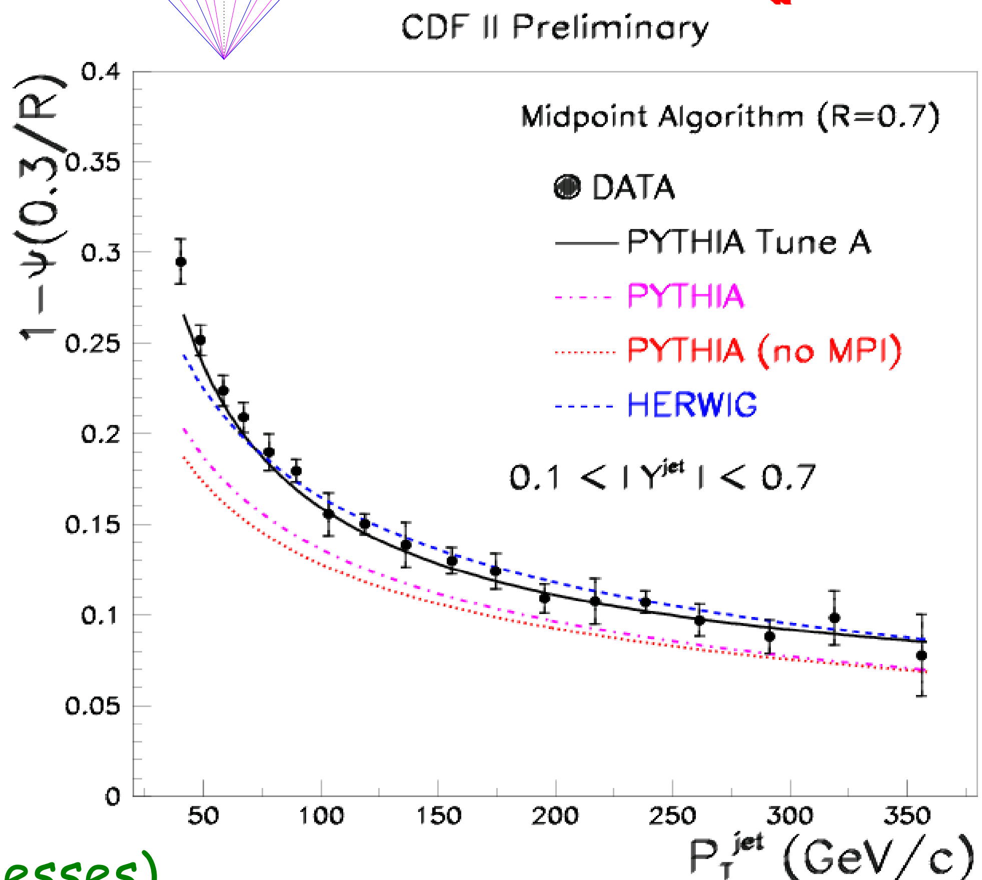
…jets are narrower as Pt increases..

Jet shapes









- PYTHIA Tune A describes the data (enhanced ISR + MPI tuning)
- PYTHIA default too narrow
- MPI are important at low Pt
- HERWIG too narrow at low Pt

We know how to model the UE at 2 TeV (at least for QCD jet processes)

Summary & Conclusions

- Tevatron performance very promising
- High luminosity measurements will provide:
  - Further constraints on the gluon PDFs
  - Probe distances of 10^{-19} m (looking for new physics…)
- Run II explores different jet algorithms
  - K_T works in hadron collisions → relevant for LHC strategies
- Studies on soft-gluon radiation are crucial
  - proper comparison with pQCD NLO
  - QCD background estimations in searches for new physics
- Measurements of the UE in different final states are mandatory
  → Be prepared for the future physics program at the LHC
- Very Rich QCD Physics Program at the Tevatron
  (…I just covered a selected list of topics in this talk….)