Jet physics at 2 TeV

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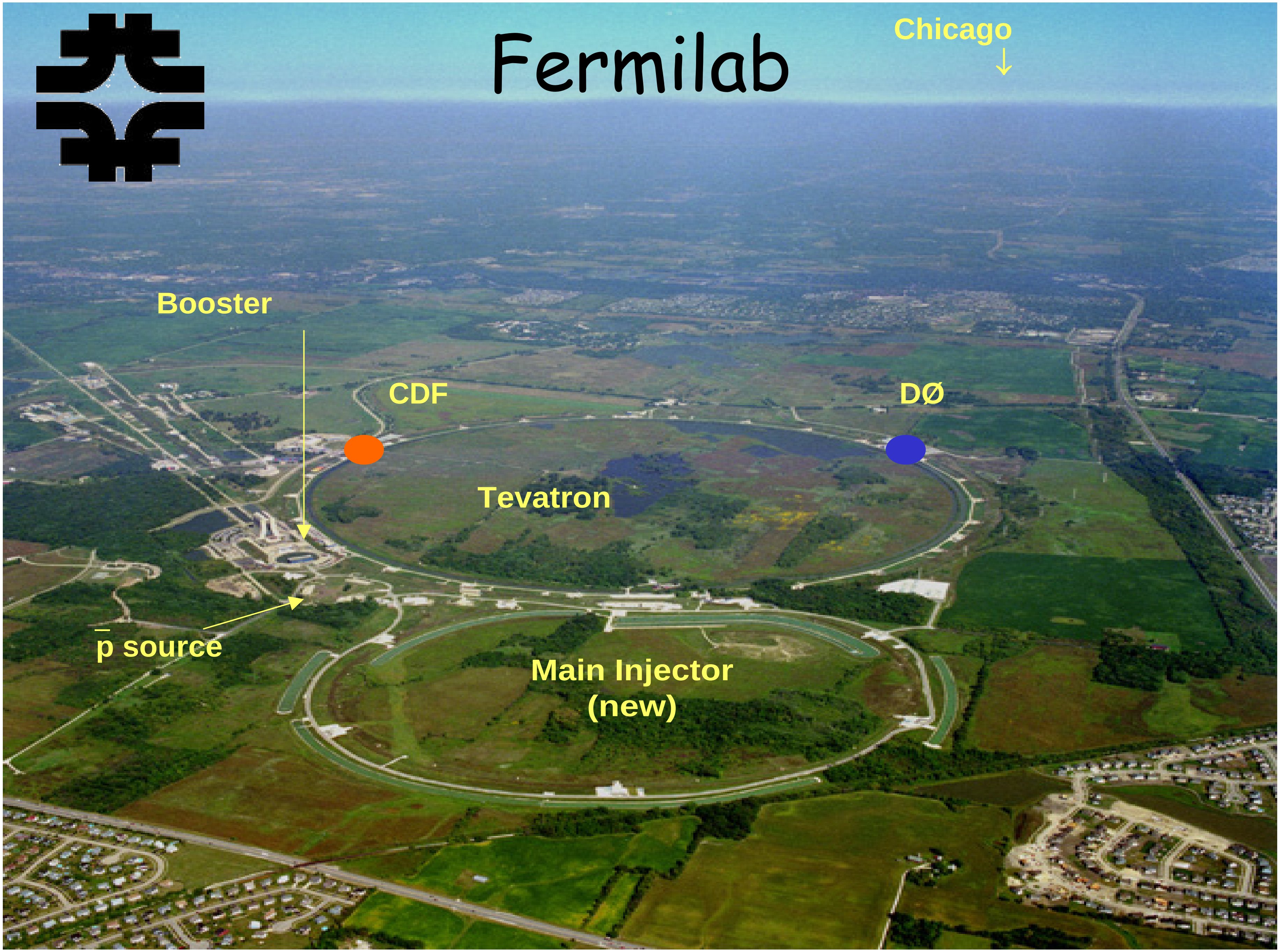
On behalf of CDF & D0 Collaborations

XXIV Physics in Collision Conference, Boston, 2005


Fermilab
Chicago
Booster
CDF
DØ
Tevatron
p̄ source
Main Injector
(new)

Tevatron

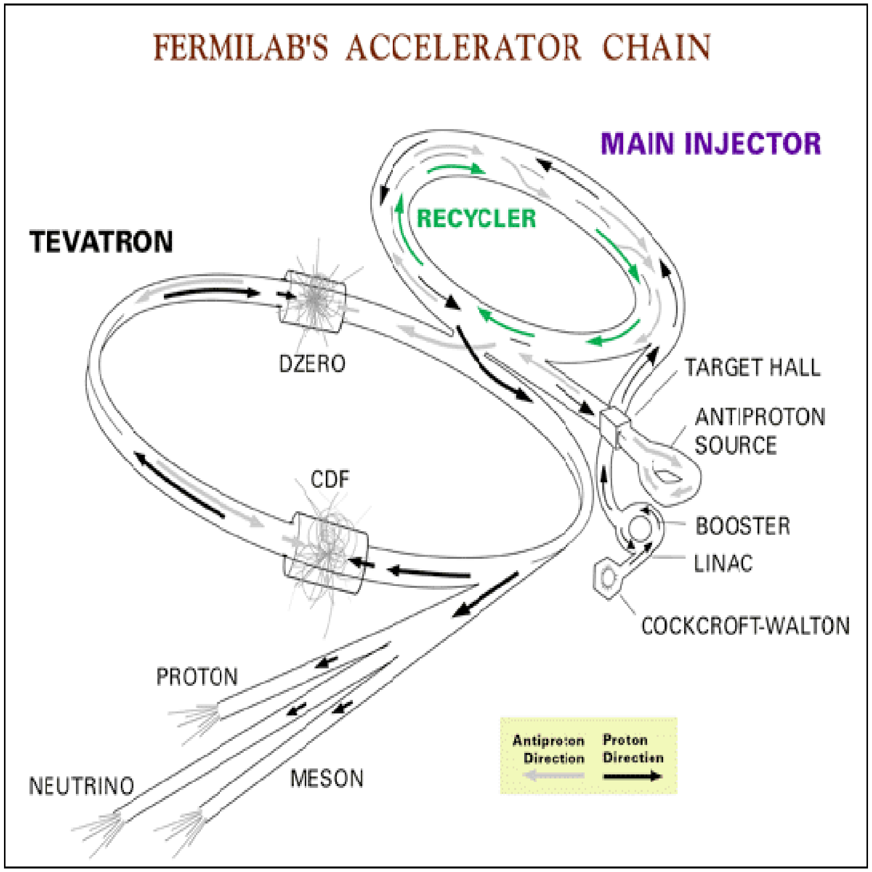
- proton-antiproton collisions

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

- Main injector
  (150 GeV proton storage ring)

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

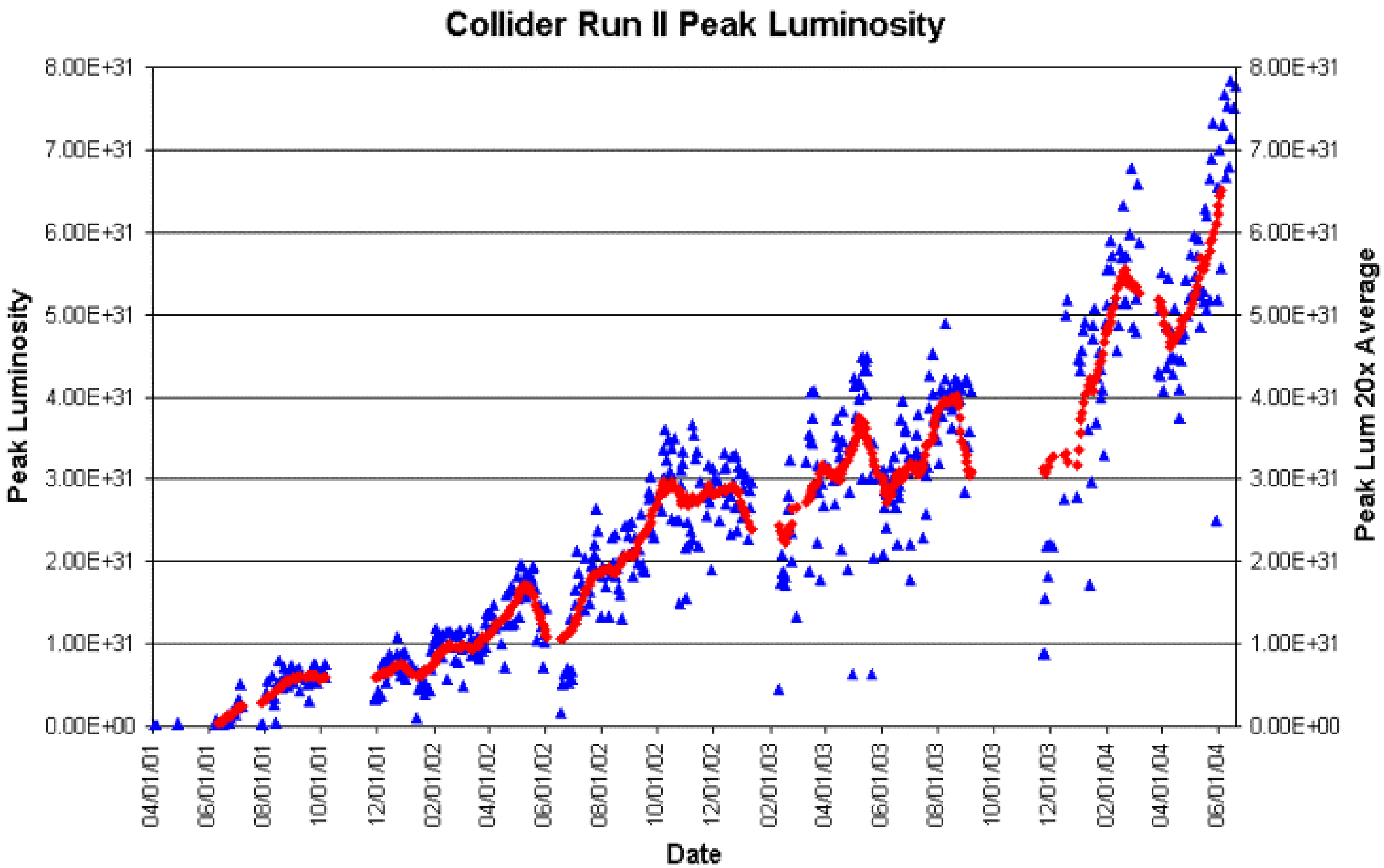
- 36 bunches (396 ns crossing time)



Long Term Luminosity Projection (by end FY2009)

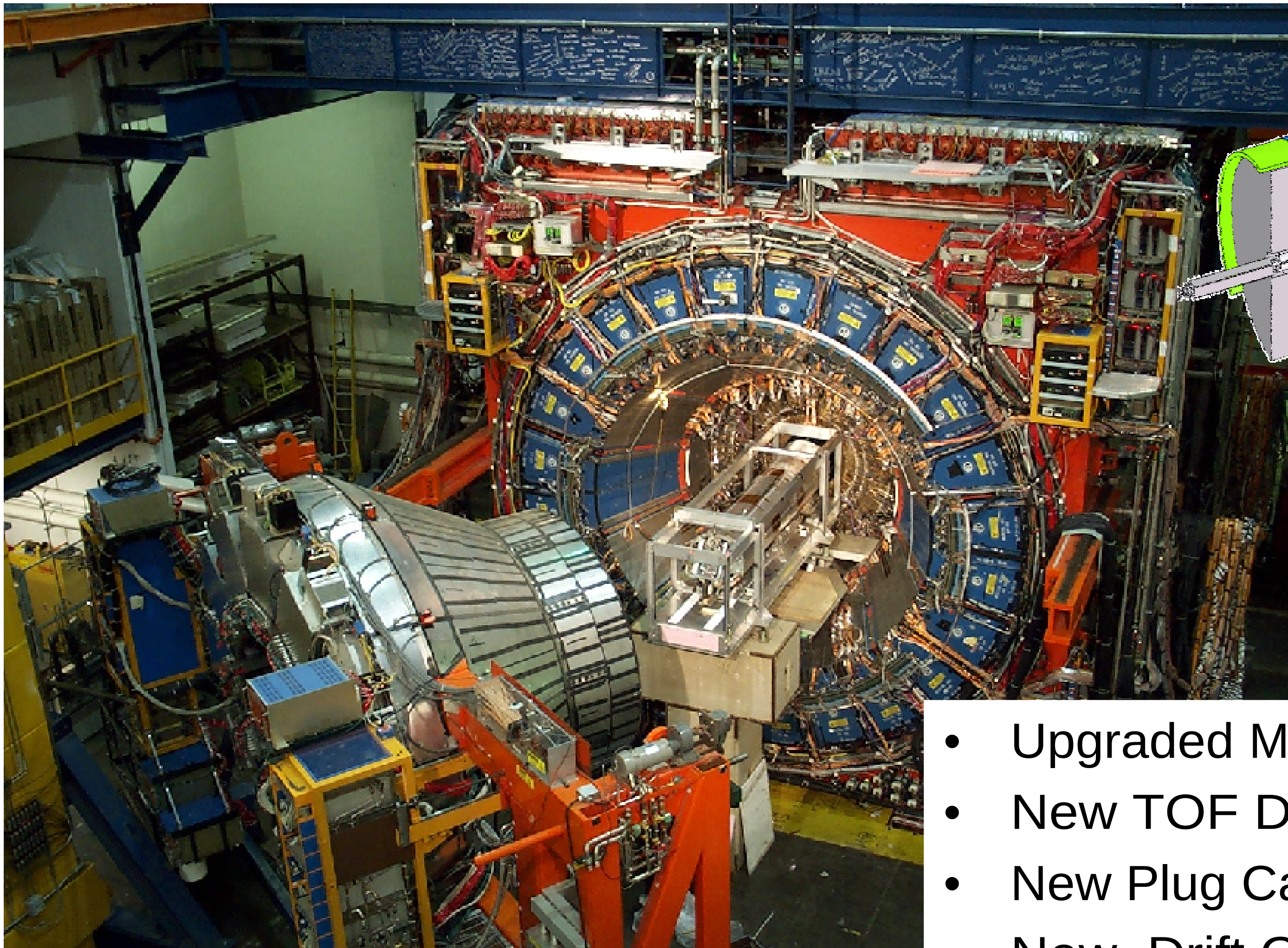
Base Goal -> 4.4 fb-1
Design -> 8.5 fb-1

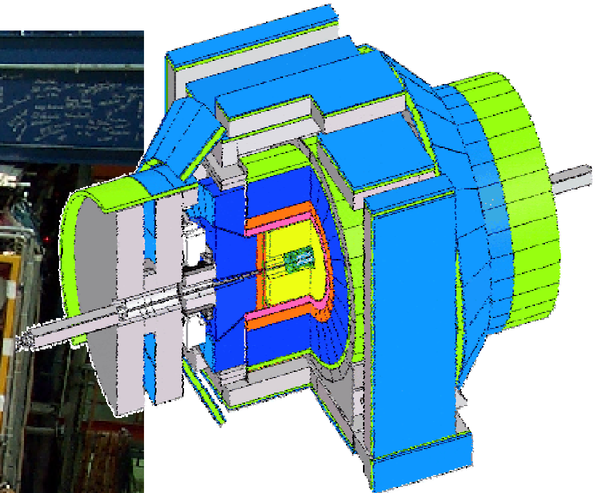
Tevatron Performance



TeVatron plans to deliver 300 pb-1 in FY04

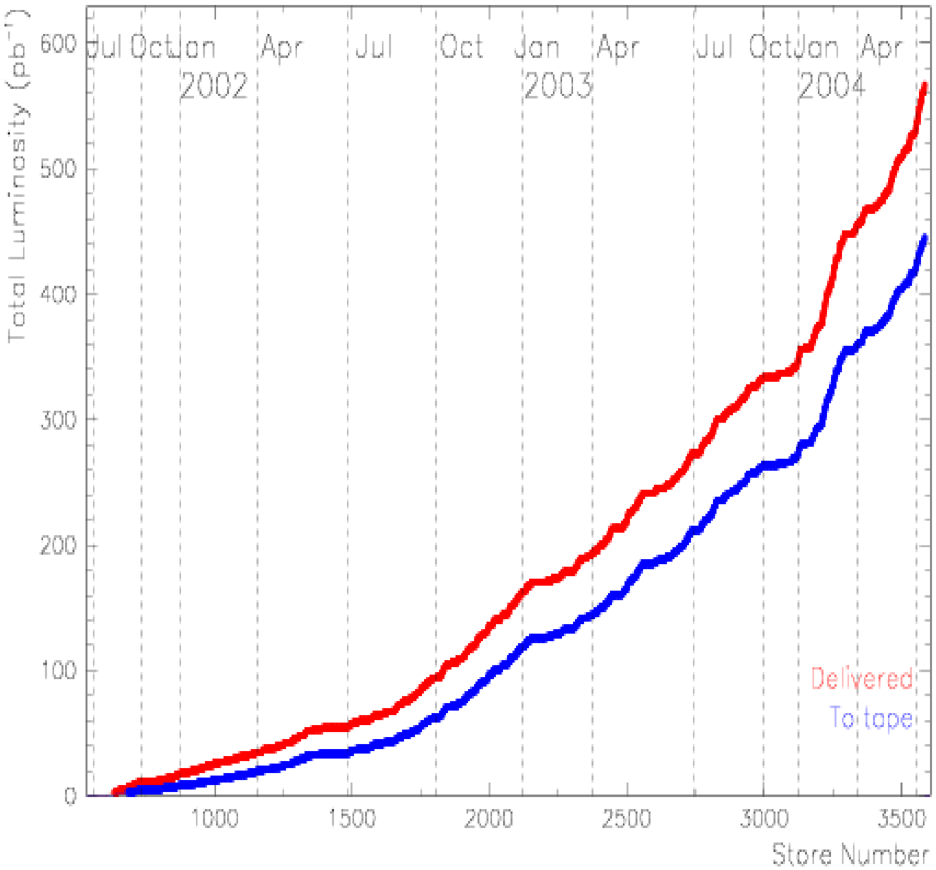
CDF Detector

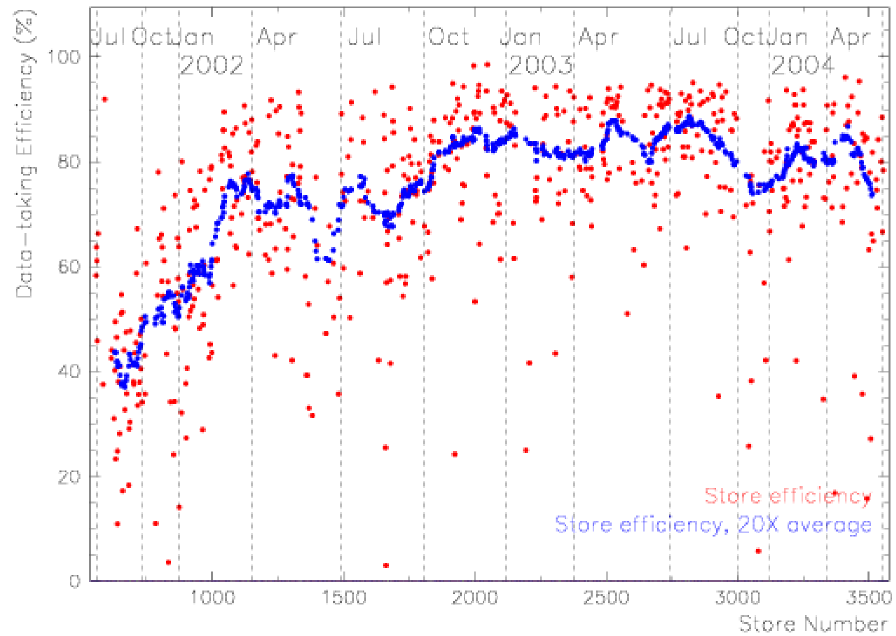




- Upgraded Muon Detectors
- New TOF Detector
- New Plug Calorimeters
- New Drift Chamber
- New Silicon Tracking

CDF Run II Data





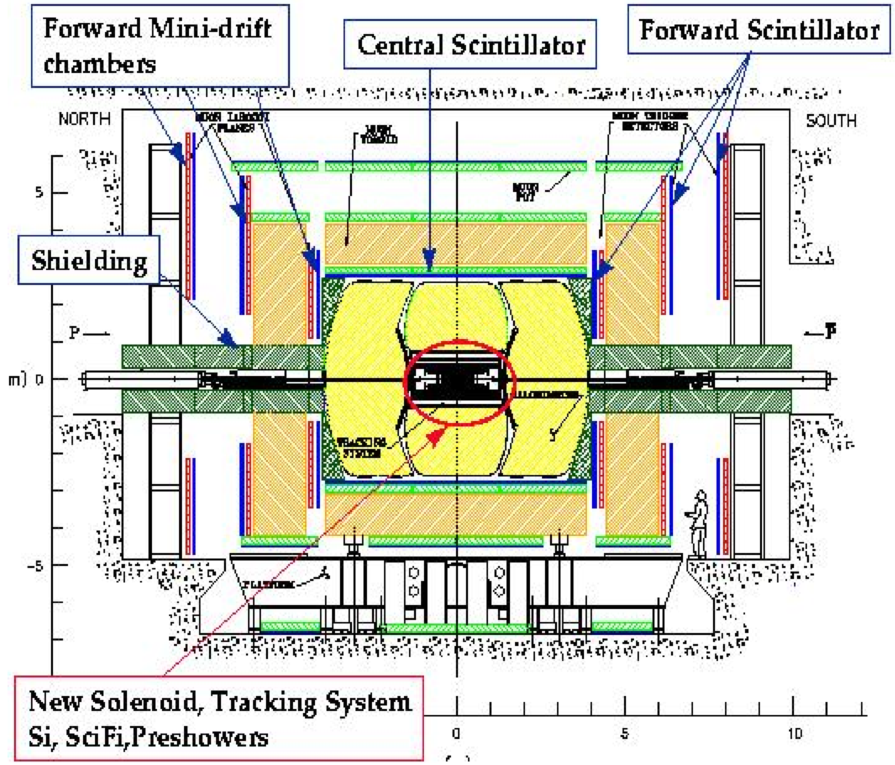
CDF Ef f iciency >80%

CDF -> ~450 pb-1 on tape

DAQ runs with 5% to 10% dead time

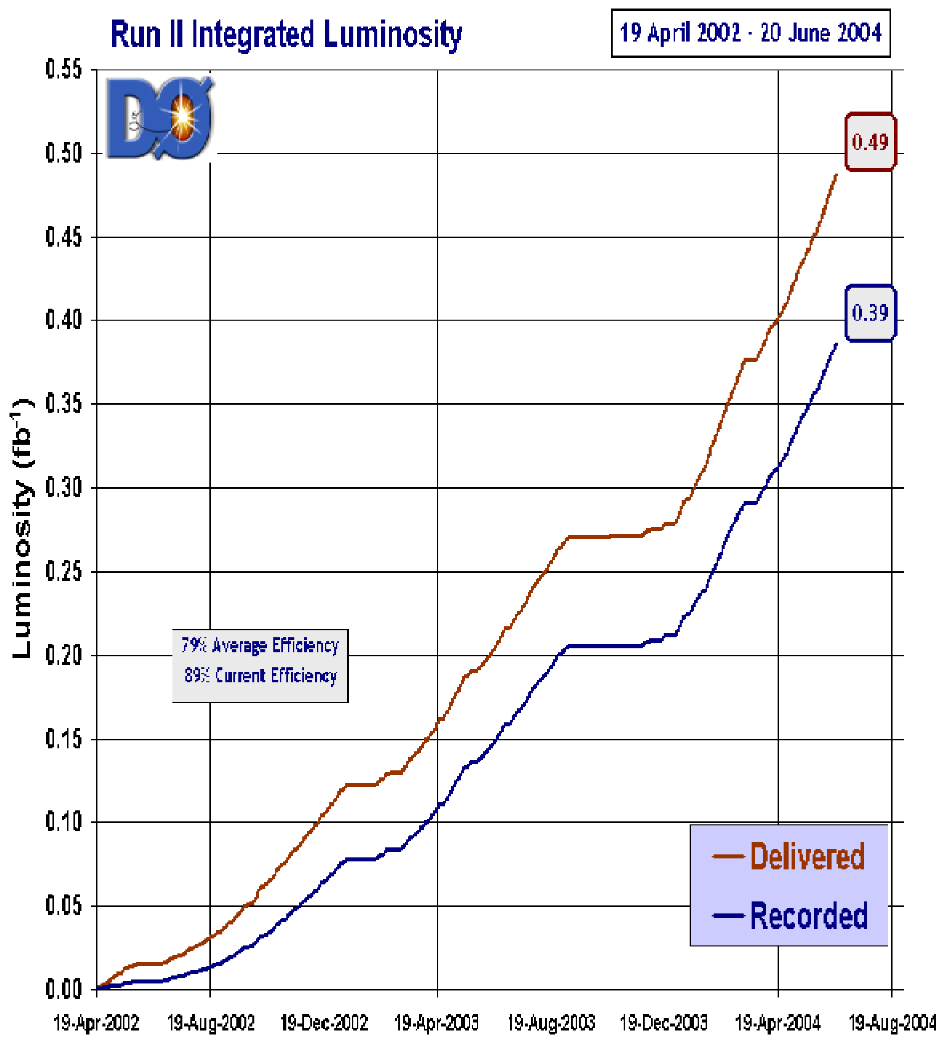
Rest coming from very careful operation of detector's HV due to machine losses (…to preserve silicon & trackers…)

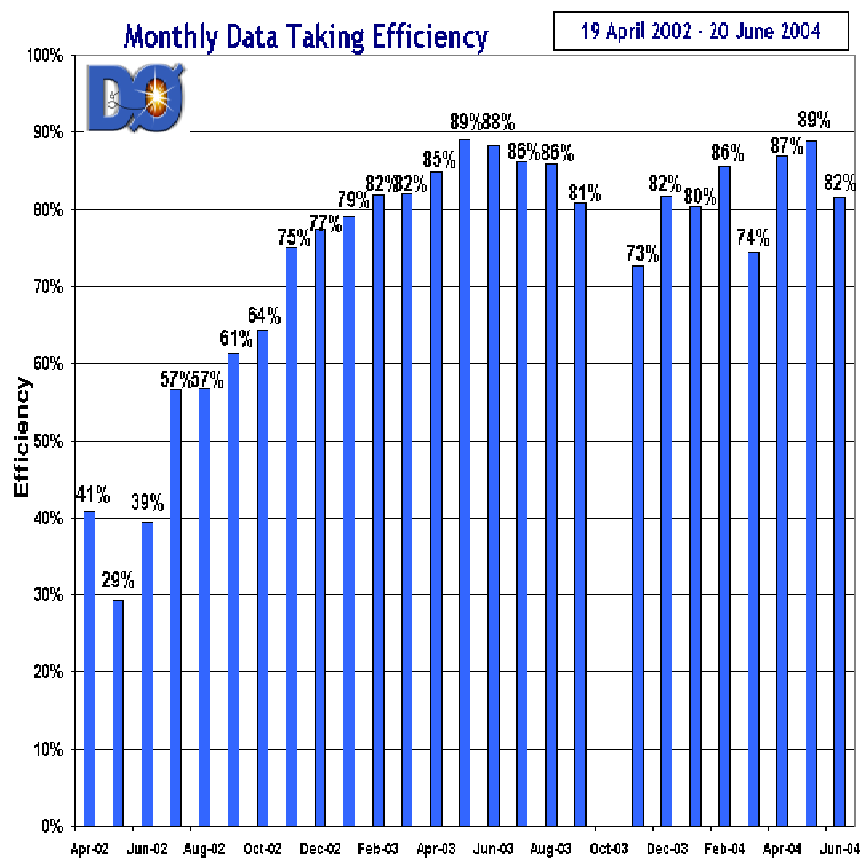
The DØ Detector



- Upgraded muon coverage
- New Tracking System
- New Silicon Micro-vertex
- New Solenoid
- New Pre-showers

DØ Run II Data

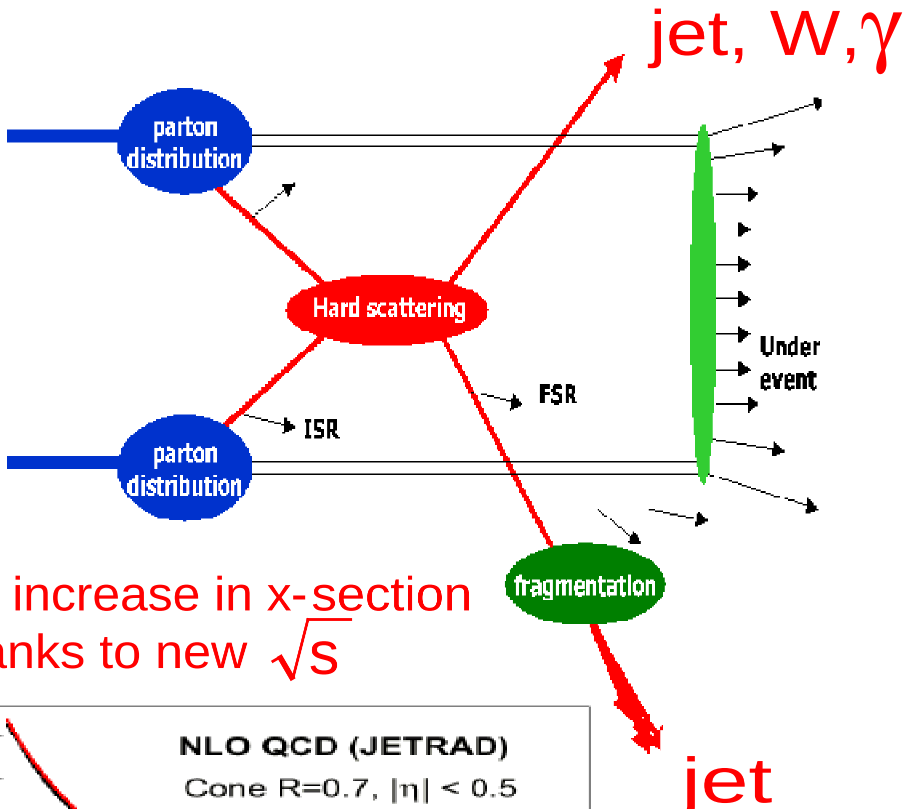




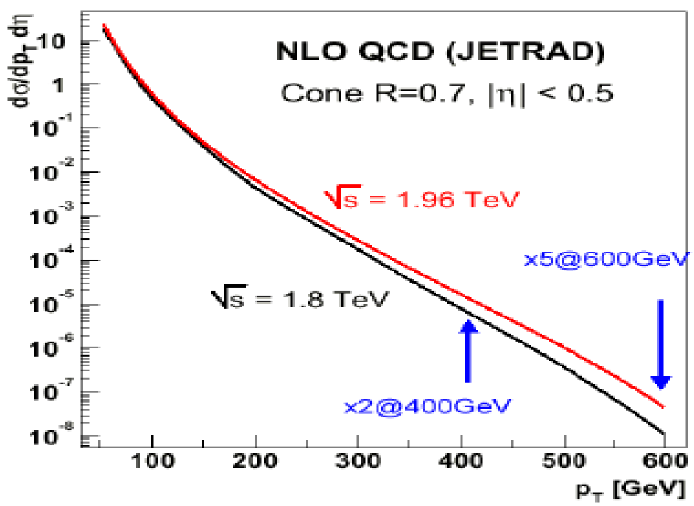
DØ -> ~390 pb-1 on tape

DØ operating well and recording physics quality data with very high efficiency (~ 85%)

Jet Physics at 2 TeV

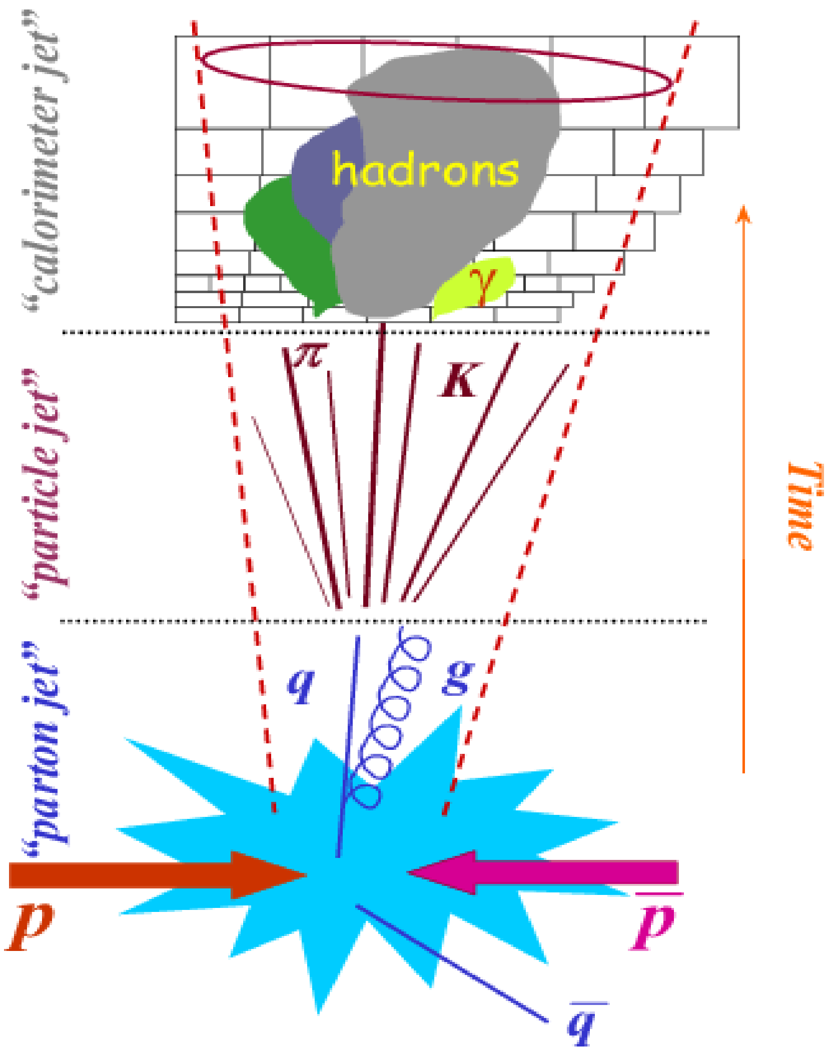


**Big increase in x-section thanks to new $\sqrt{s}$



- Jet Cross Sections**
  - Jet Algorithms
  - Data vs NLO pQCD
  - PDFs uncertainties
  - Soft contributions
- Underlying Event
- Dijet $\Delta\phi$ correlations
- Jet Shapes
- Boson +jet production
- B-jet production

Jet algorithms & physics



- 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 parton shower modeling)
- Precise jet search algorithms necessary to compare with theory and to define hard physics
- Natural choice is to use a cone-based algorithm in η–ϕ space (invariant under longitudinal boost)

Run I -> Cone algorithm

1. Seeds with $E_T > 1$ GeV

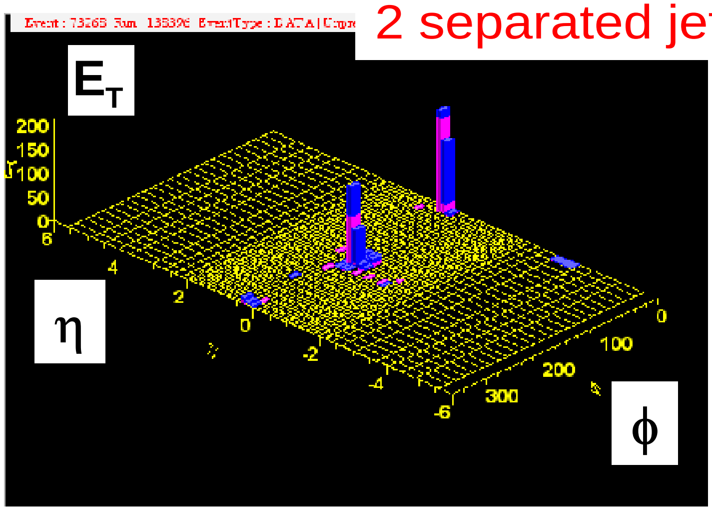
2. Draw a cone around each seed and reconstruct the “proto-jet”

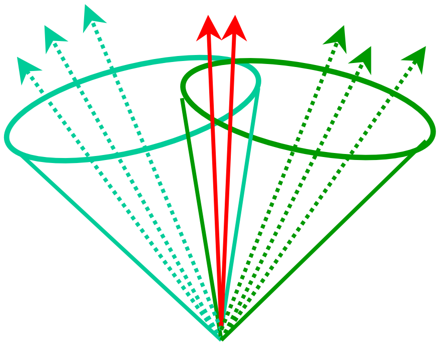
$$E_T^{jet} = \sum_k E_T^K ,$$

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

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

4. Look for possible overlaps

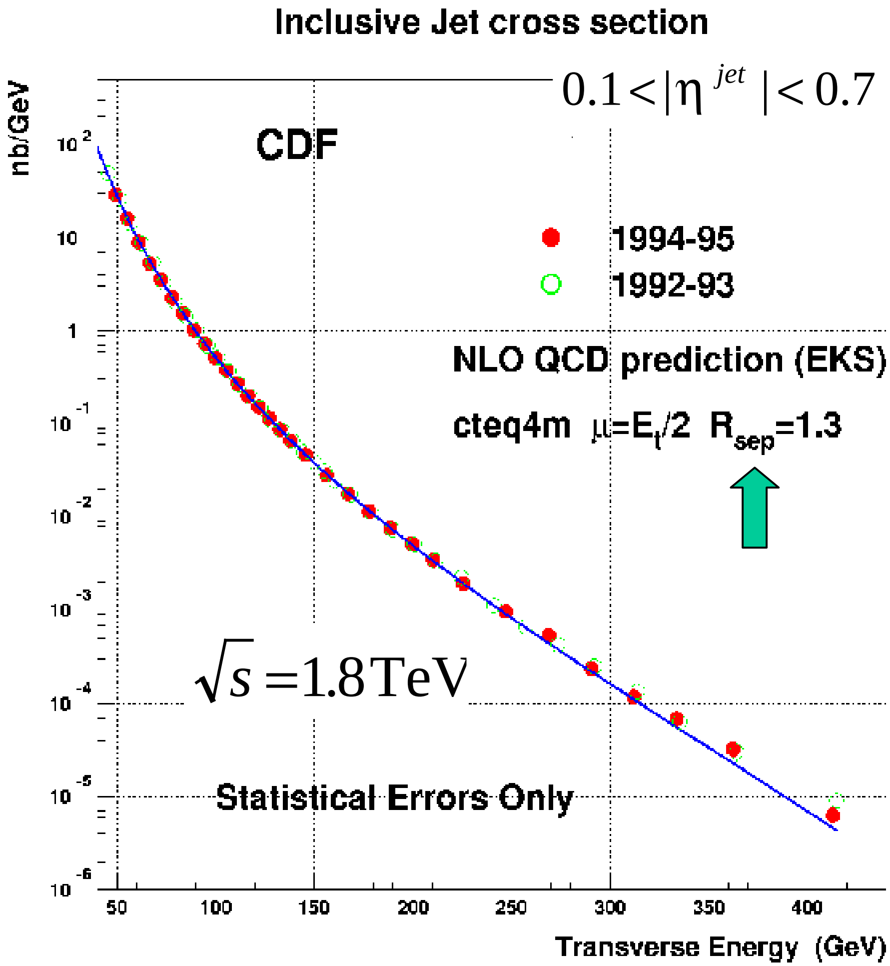


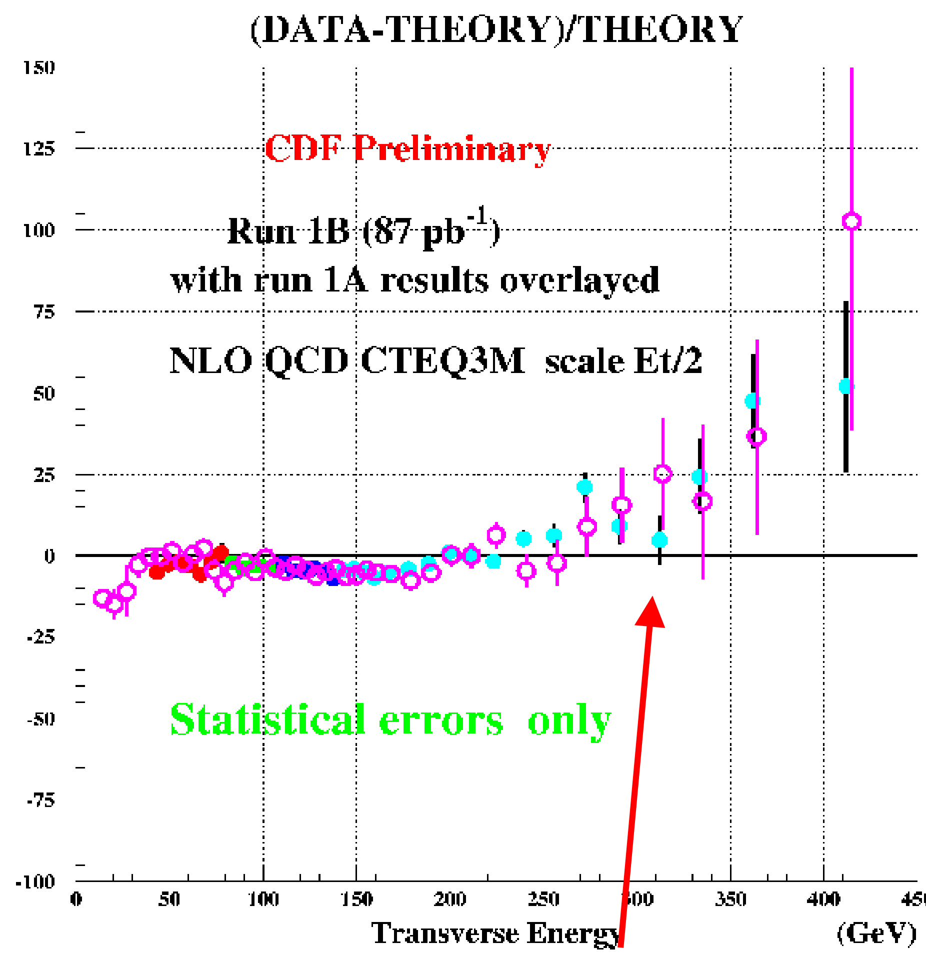


merged if common E_T is more than 75 % of smallest jet

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

Run I Results

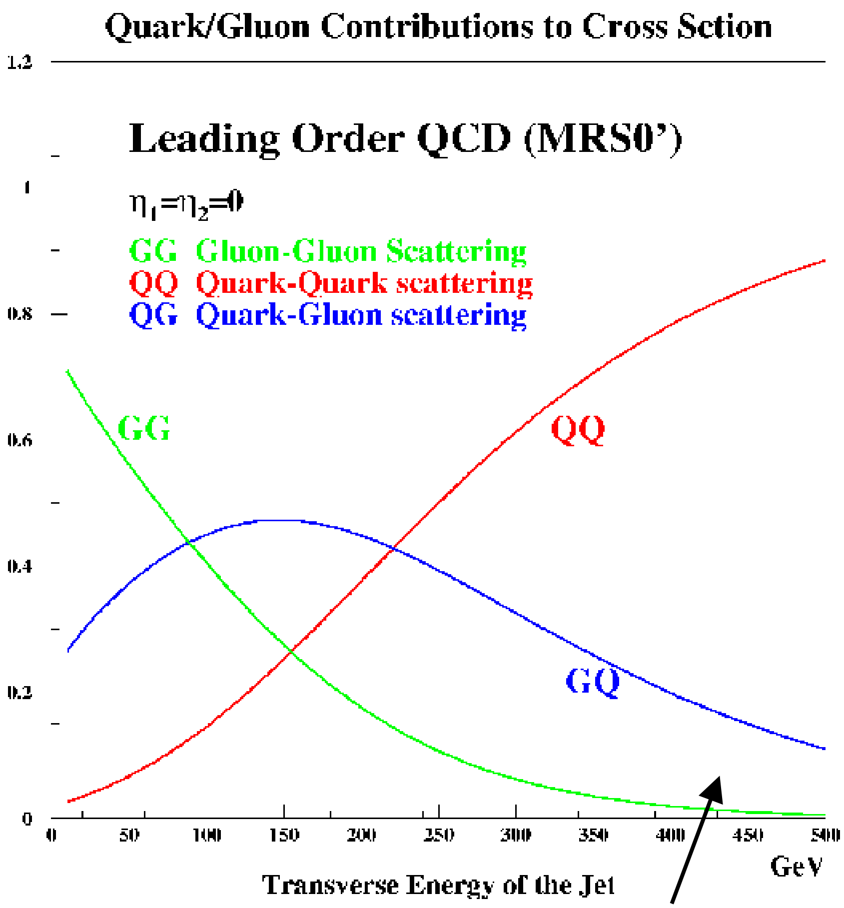


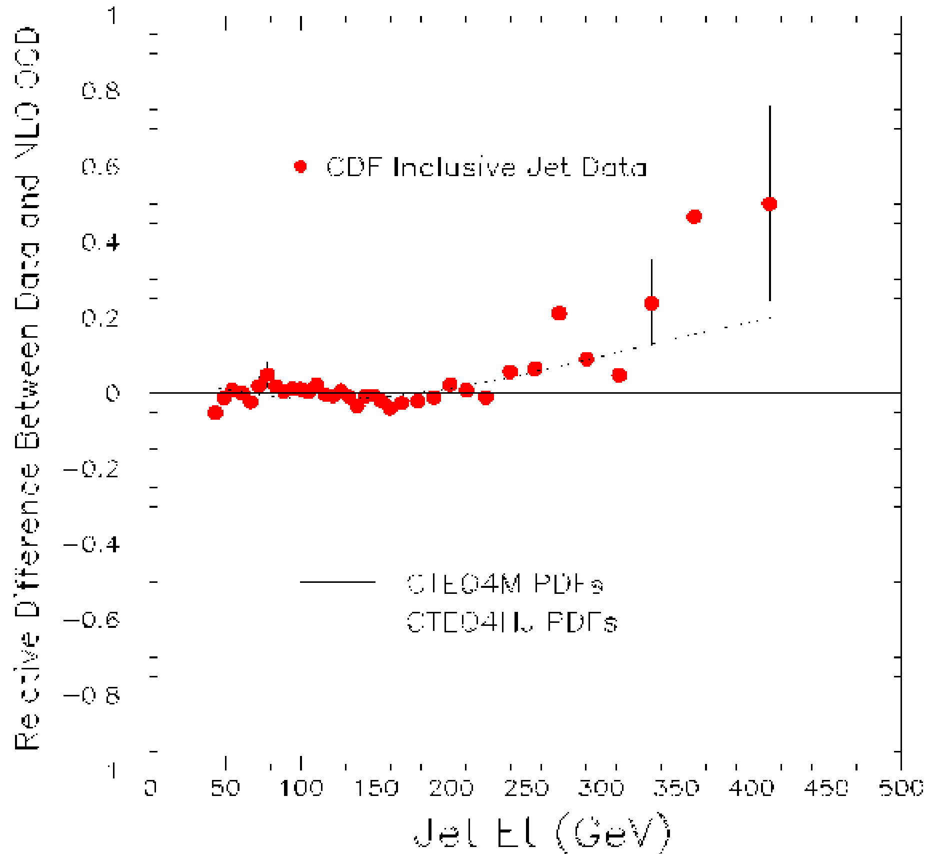


Run I data compared to pQCD NLO

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

gluon density at high-x

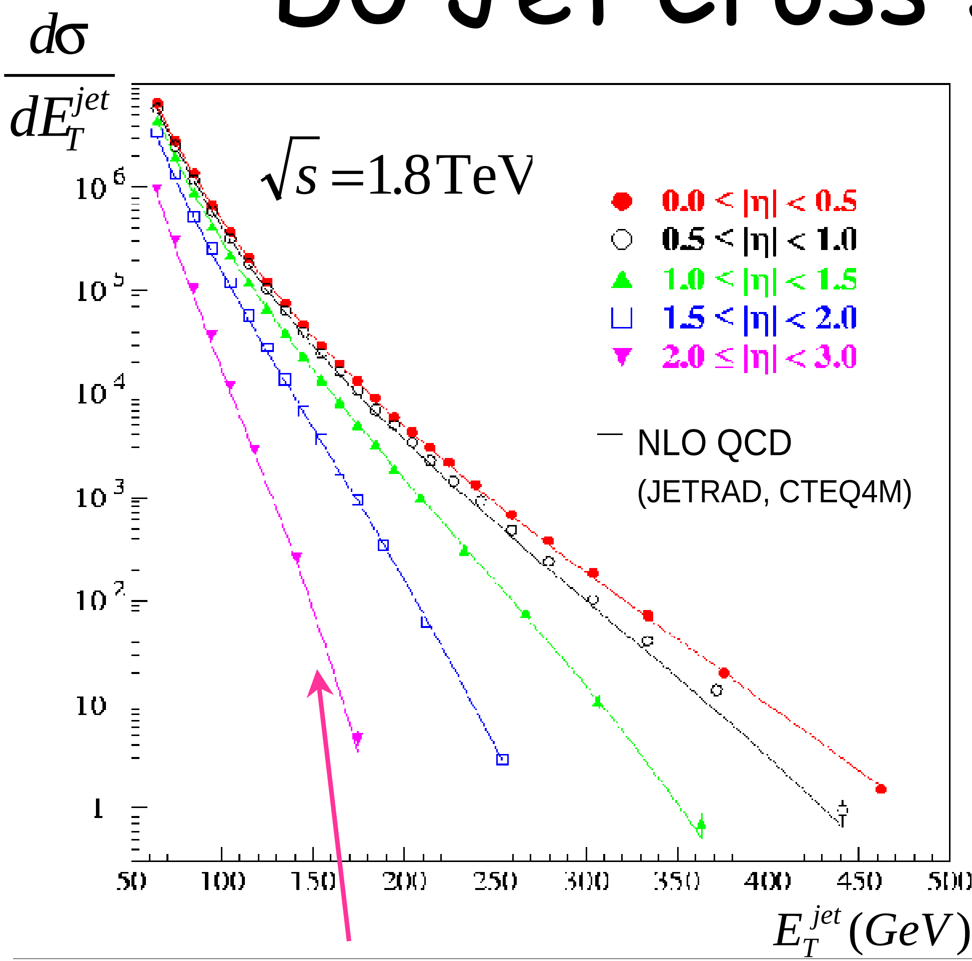


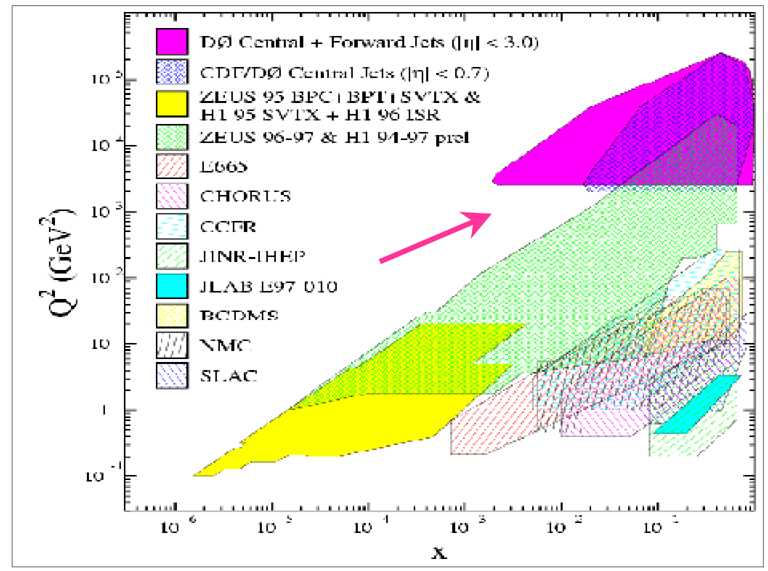


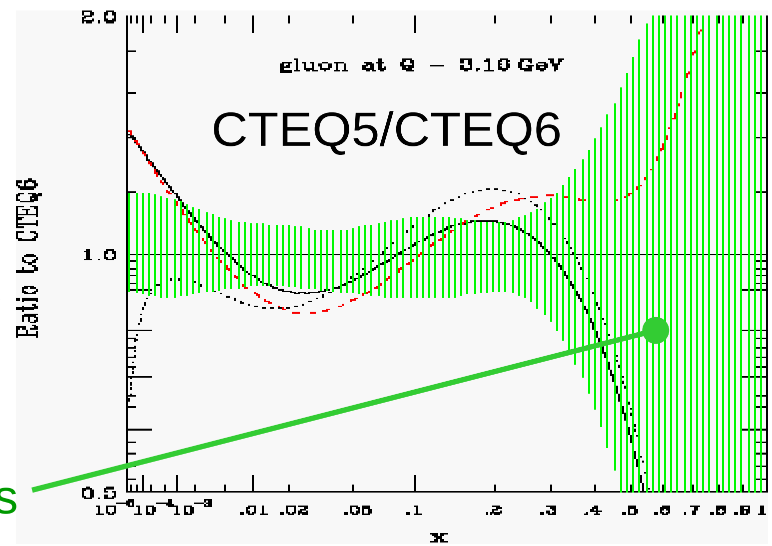
Important gluon-gluon and gluon-quark contributions at high-E_T

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

D0 Jet Cross Section vs η



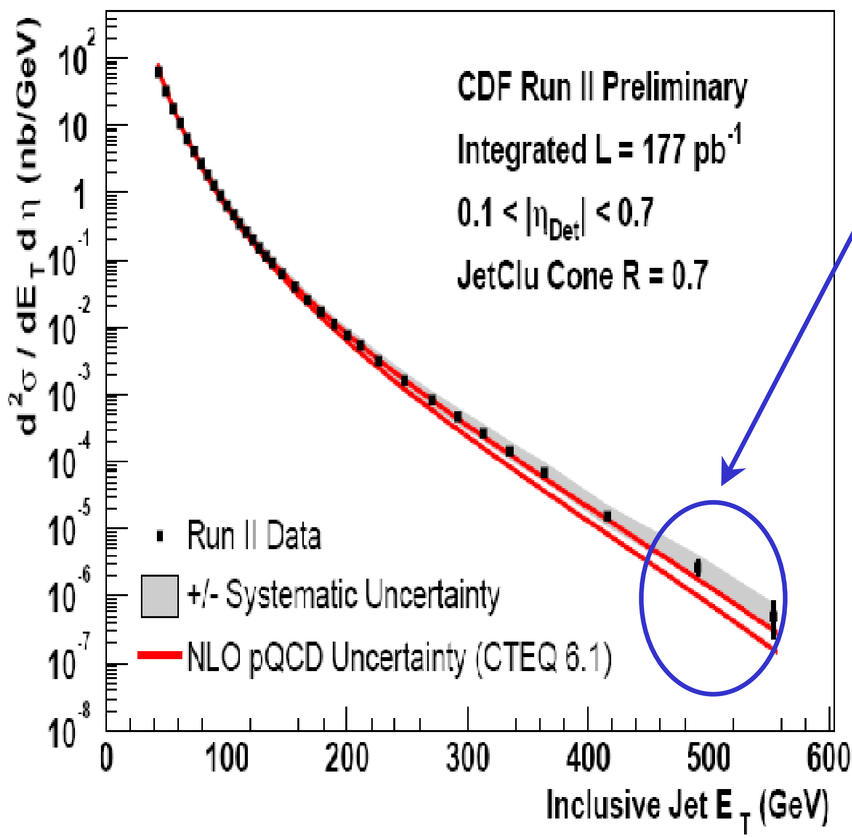




Measurements in the forward region
allow to constrain the gluon distribution

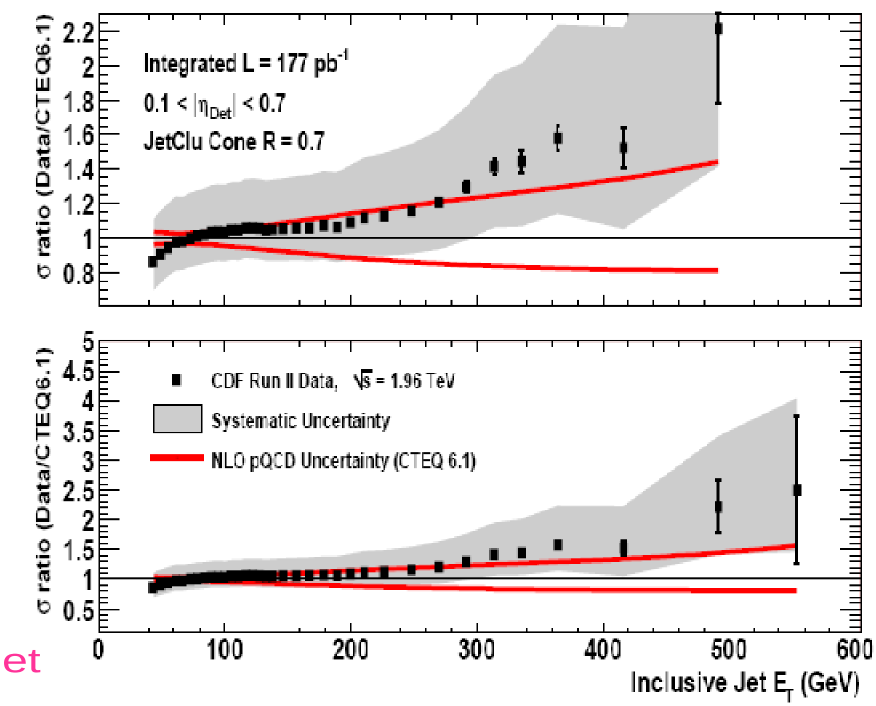
Big uncertainty still remains for high-x gluons

Run II Inclusive Cross Section



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

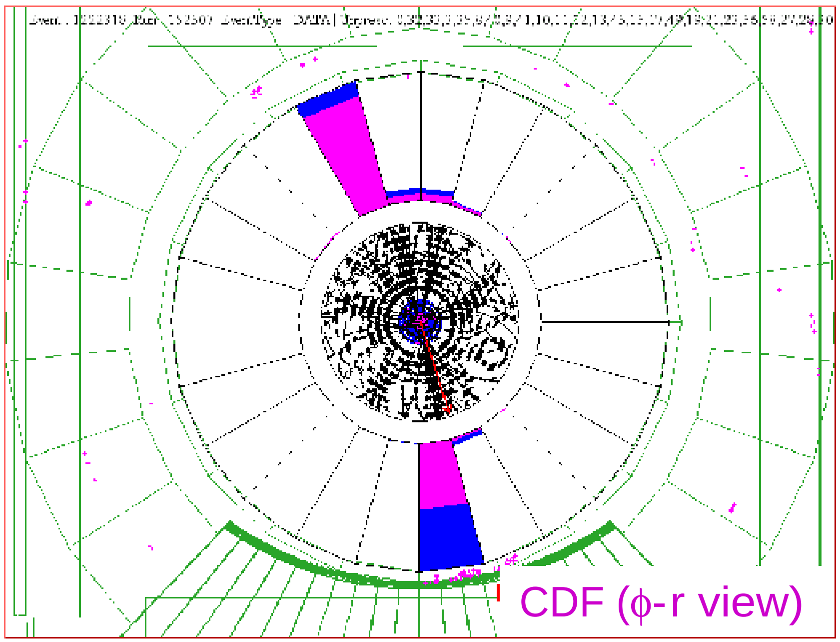
Shape of Data/NLO to be understood



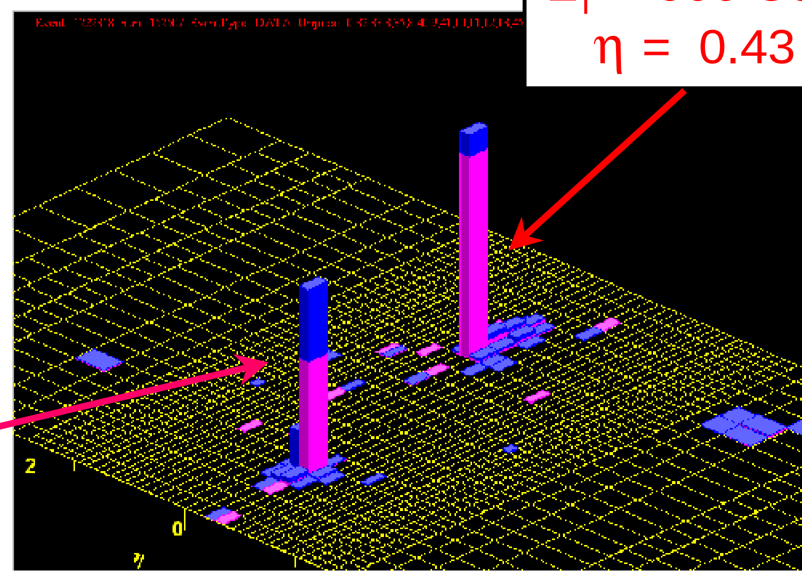
Data dominated by jet energy scale
NLO error mainly from gluon at high x

No hadronization corrections applied to NLO prediction → relevant @ low E_T^{jet}

Highest Mass Dijet Event



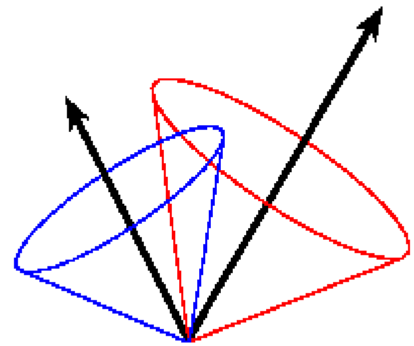
Dijet Mass = 1364 GeV
(probing distance ~10^{-19} m)

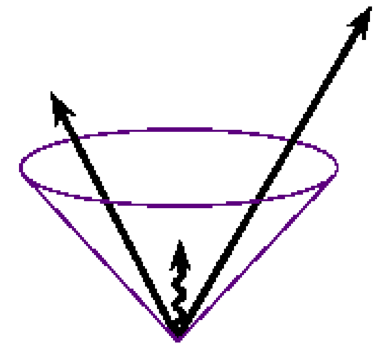


Notes on Run I Jet algorithm

Cone algorithm not infrared safe:

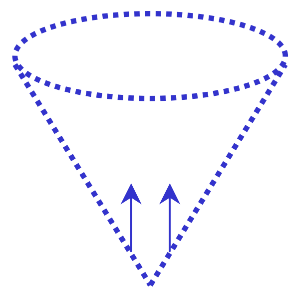
The jet multiplicity changed
after emission of a soft parton



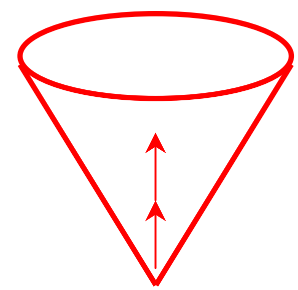


Cone algorithm not collinear safe:

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

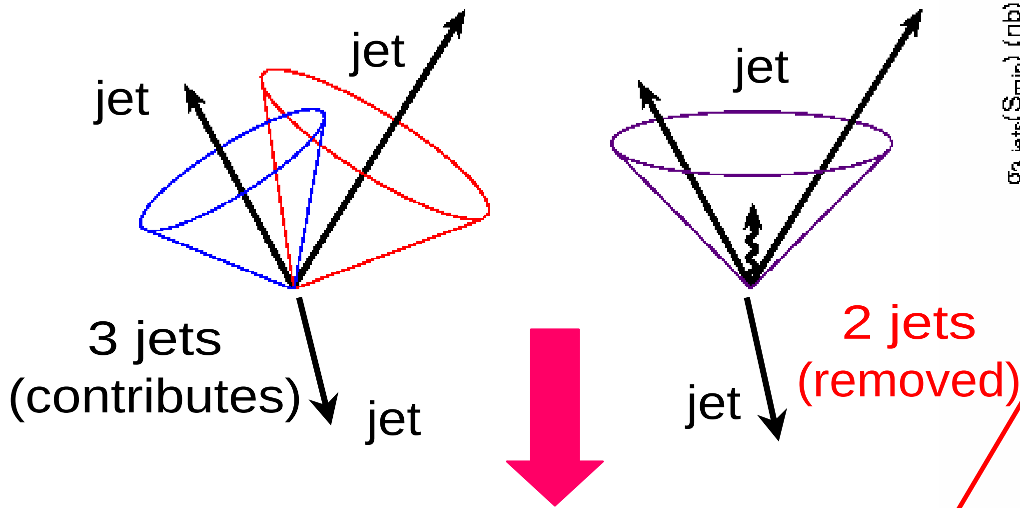
} three partons inside a cone

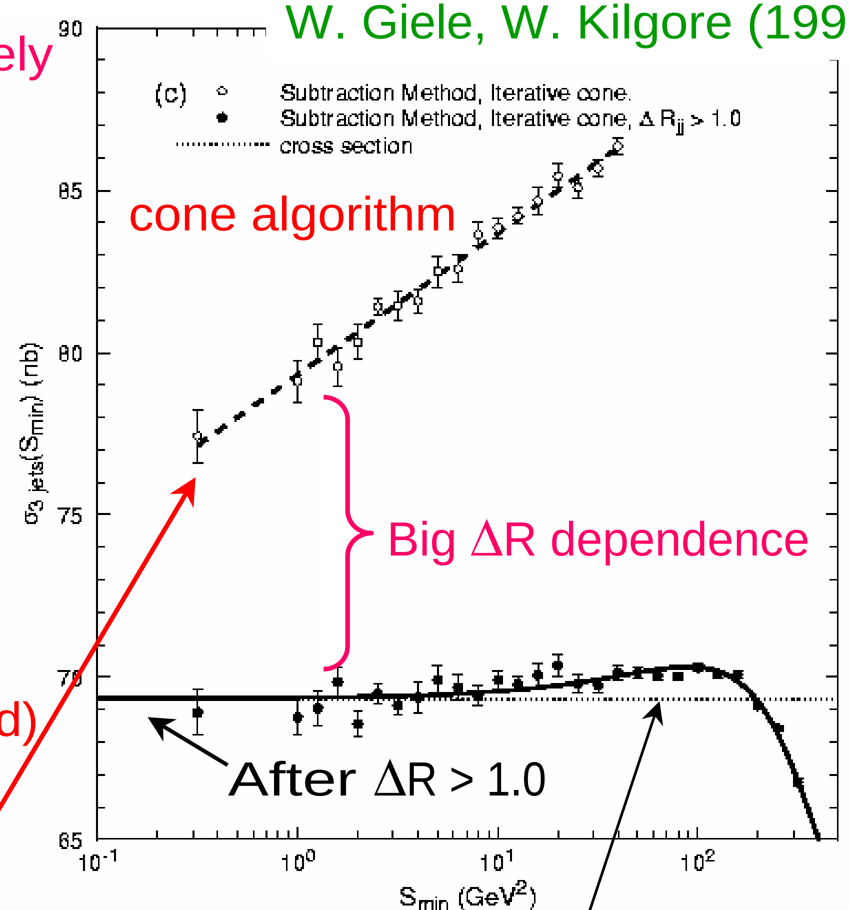
Three-jet Production at NLO

Fixed-order pQCD NLO calculations rely on exact cancellations of collinear and soft singularities between diagrams

W. Giele, W. Kilgore (1997)

NLO virtual (1- loop) **NLO real (Born)**





Infrared/collinear unsafe clustering leads to partial cancellations and introduces logarithmic dependence on soft emission

Slicing method parameter $S_{min} = \min(M_{ij})$
(flat for well defined NLO calculation)

3-jet production vs NLO pQCD

Run I cone (R=0.7)

$E_T^{jet} > 20\,\text{GeV}\,,\ |\eta| < 2.0$

$\sum_{3\ jets} E_T^{jet} > 320\ \ \text{GeV}$

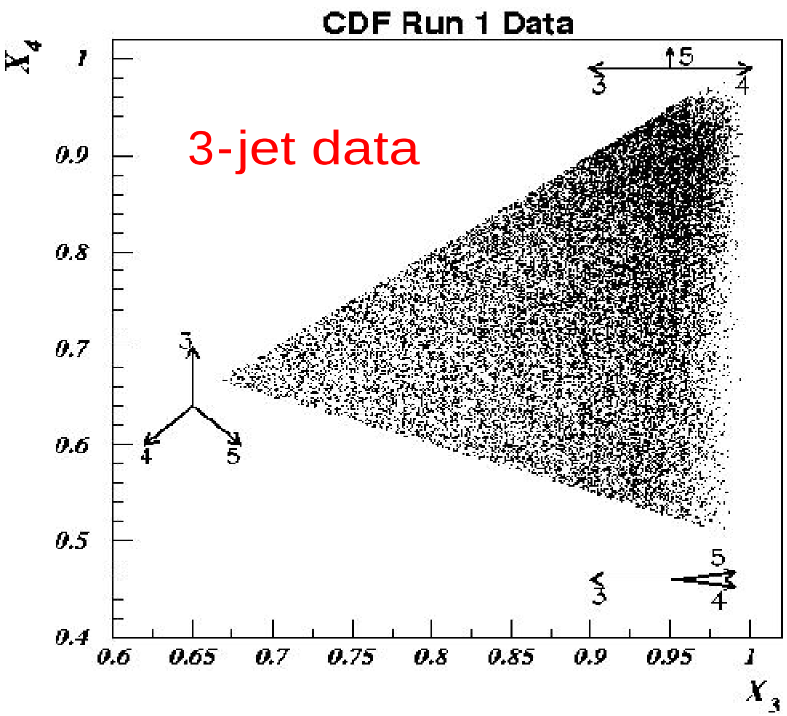
Jet separation $\Delta R > 1.0$

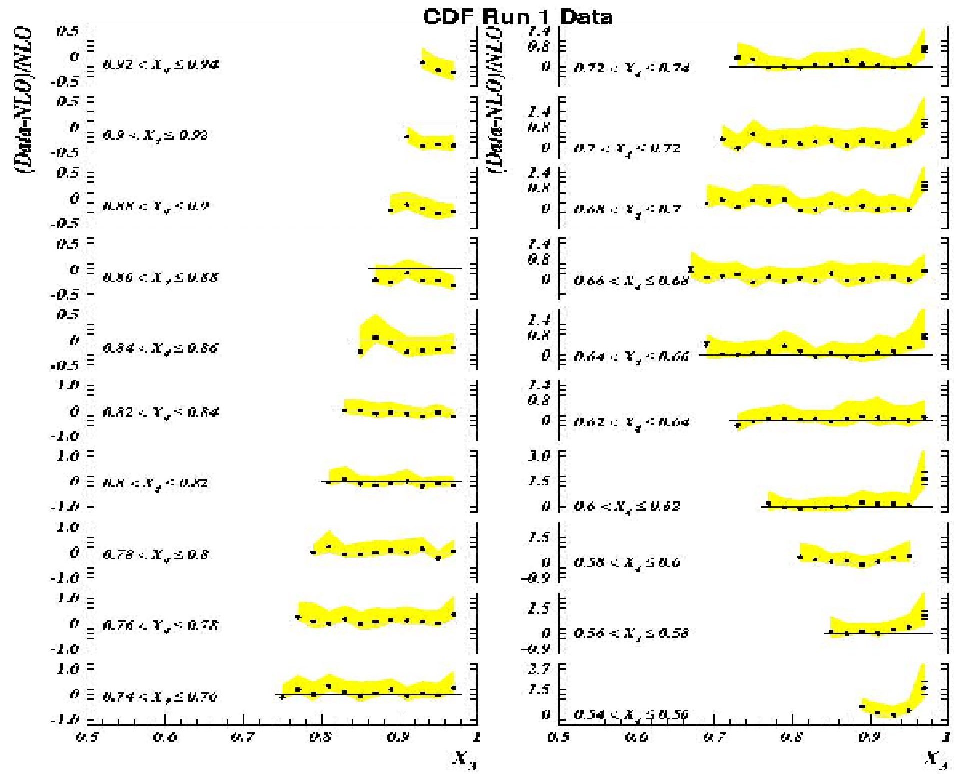
$1+2 \rightarrow 3+4+5$

Dalitz variables in c.m.s of 3-jets

$$X_i = \frac{2 * E_i^{jet}}{M_{3jets}}, \quad i = 3,4,5$$

$$X_3 > X_4 > X_5;\ X_3 + X_4 + X_5 \equiv 2$$





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"

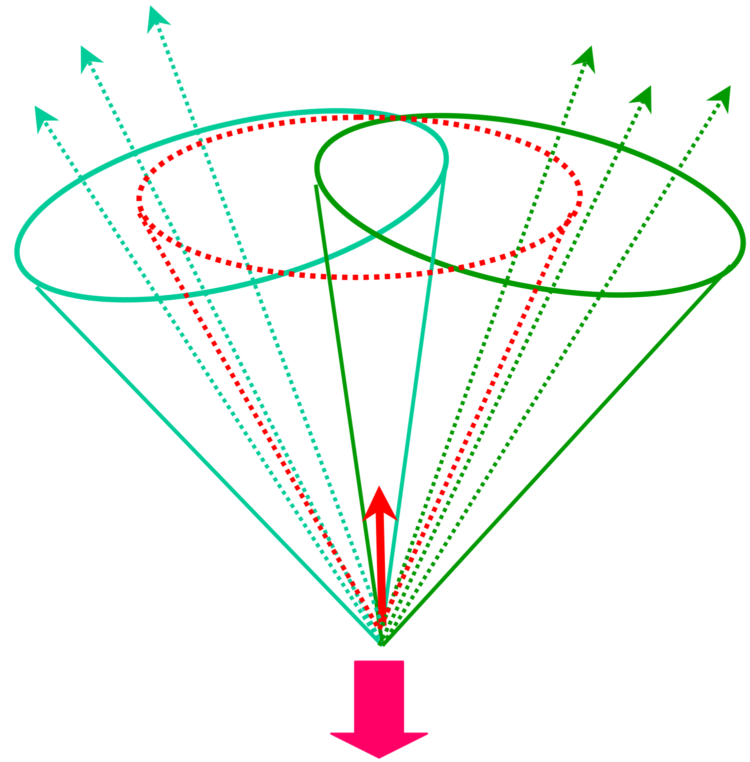
$$E^{jet} = \sum_k E^K, \quad P_i^{jet} = \sum_k P_i^K$$

(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

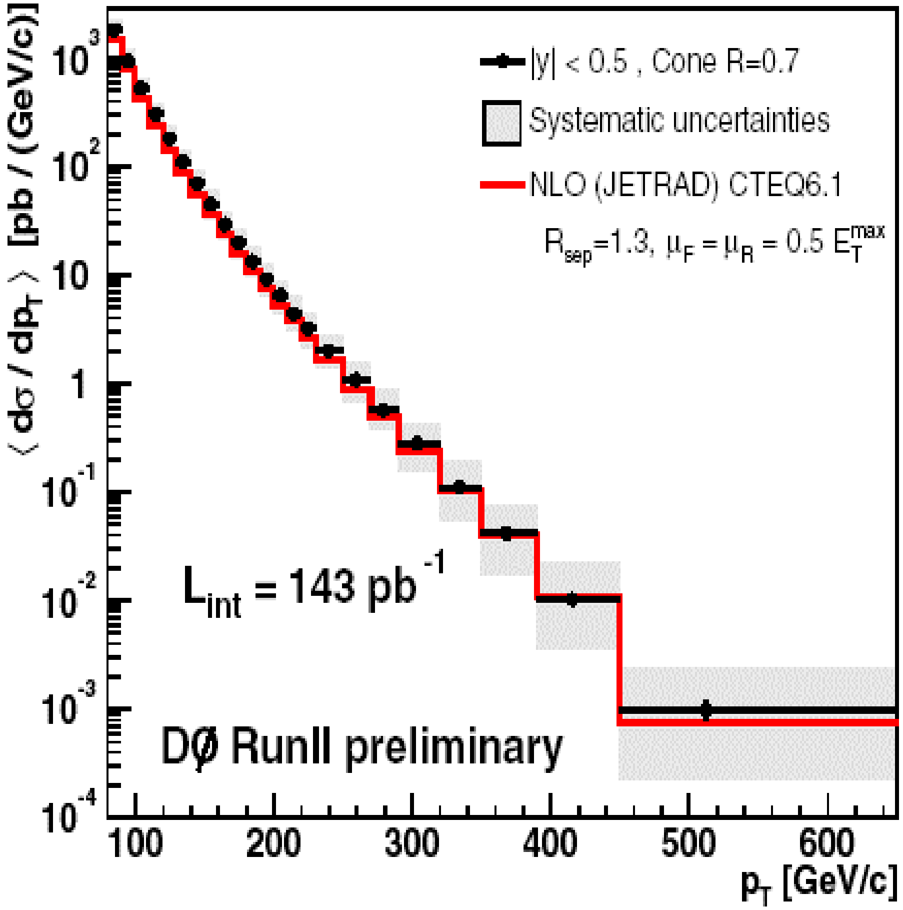
5. Merging/Splitting ⟶



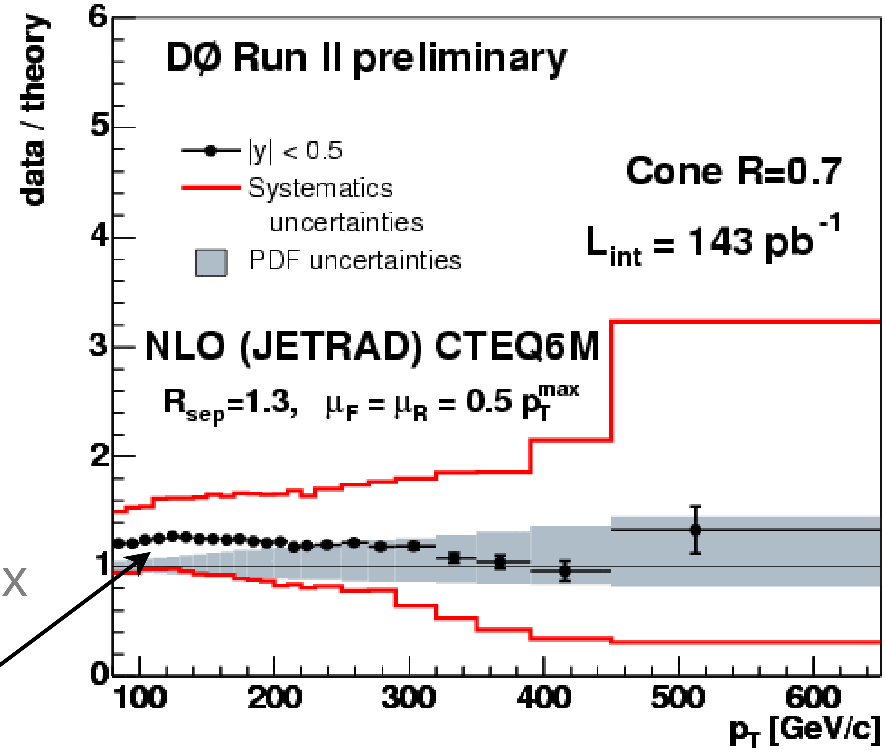
Cross section calculable in pQCD

Arbitrary Rsep parameter still present in pQCD calculation …

Inclusive jet p_T cross section



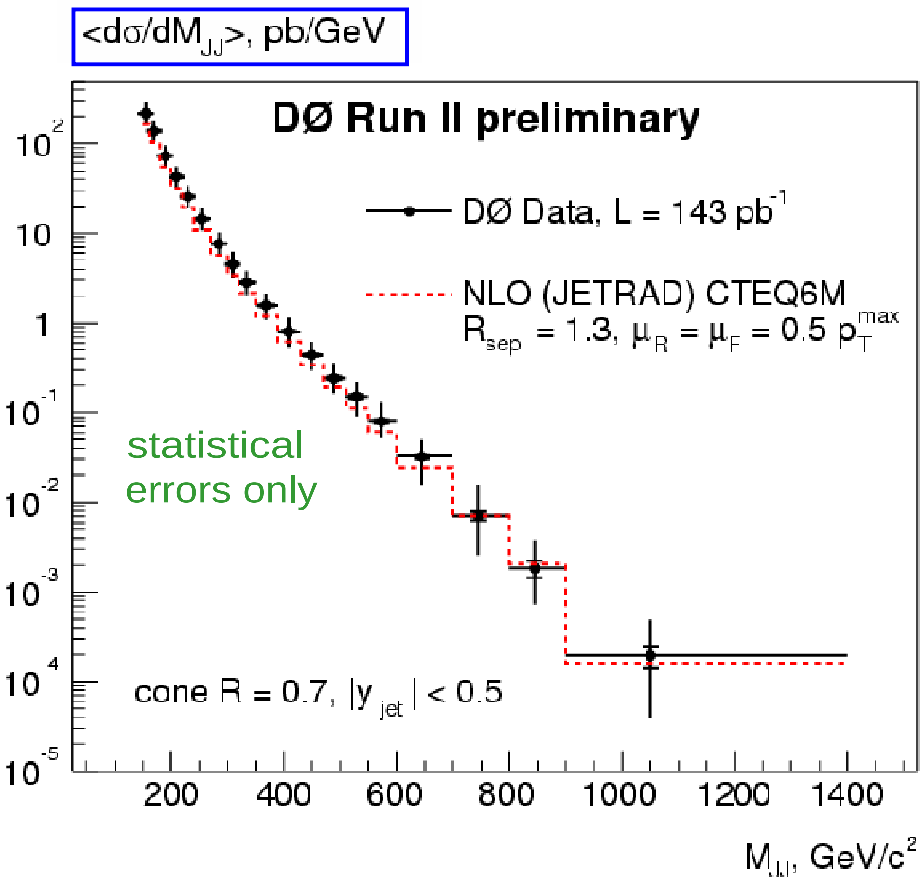
Agreement with theory within systematic uncertainties
(dominated by jet-energy scale)

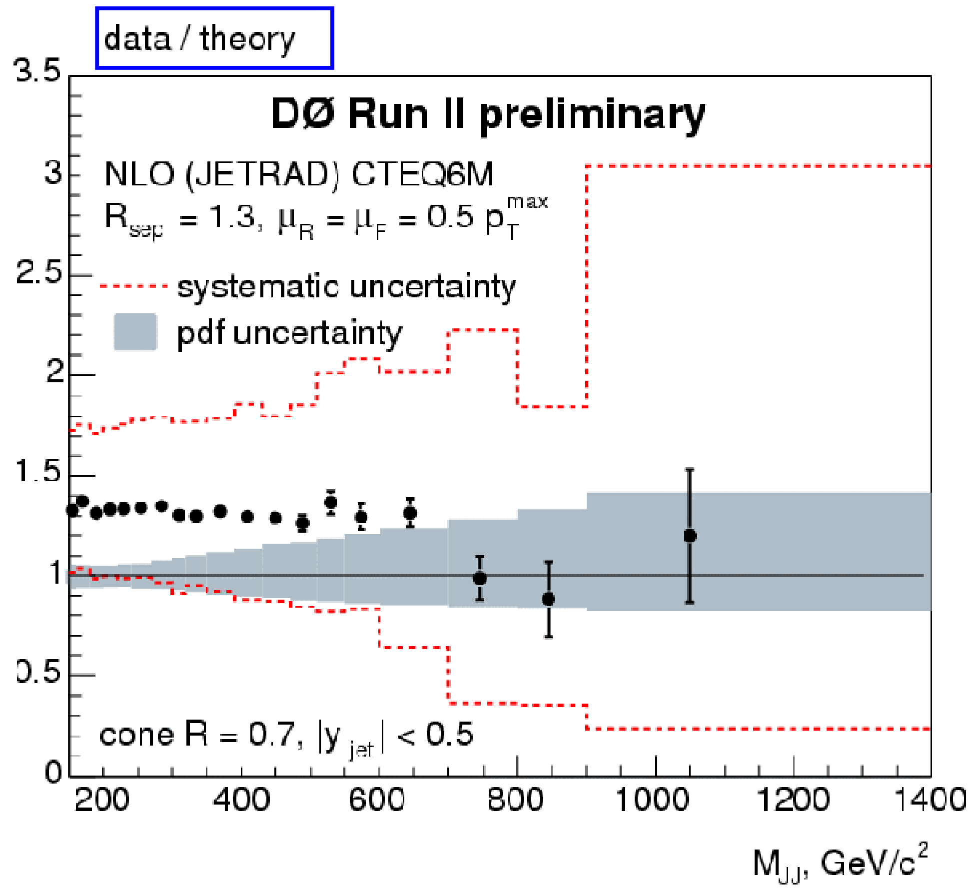


NLO uncertainty due to gluon @ high x

Hadronization Corrections needed ?

Dijet mass cross section

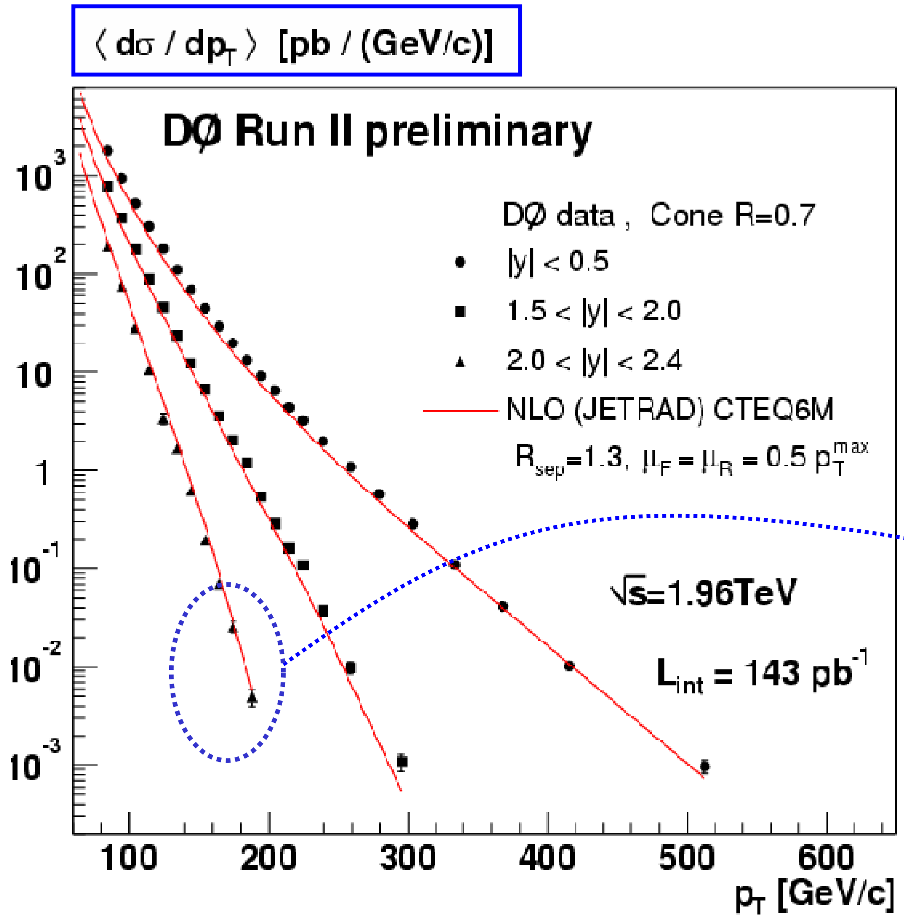


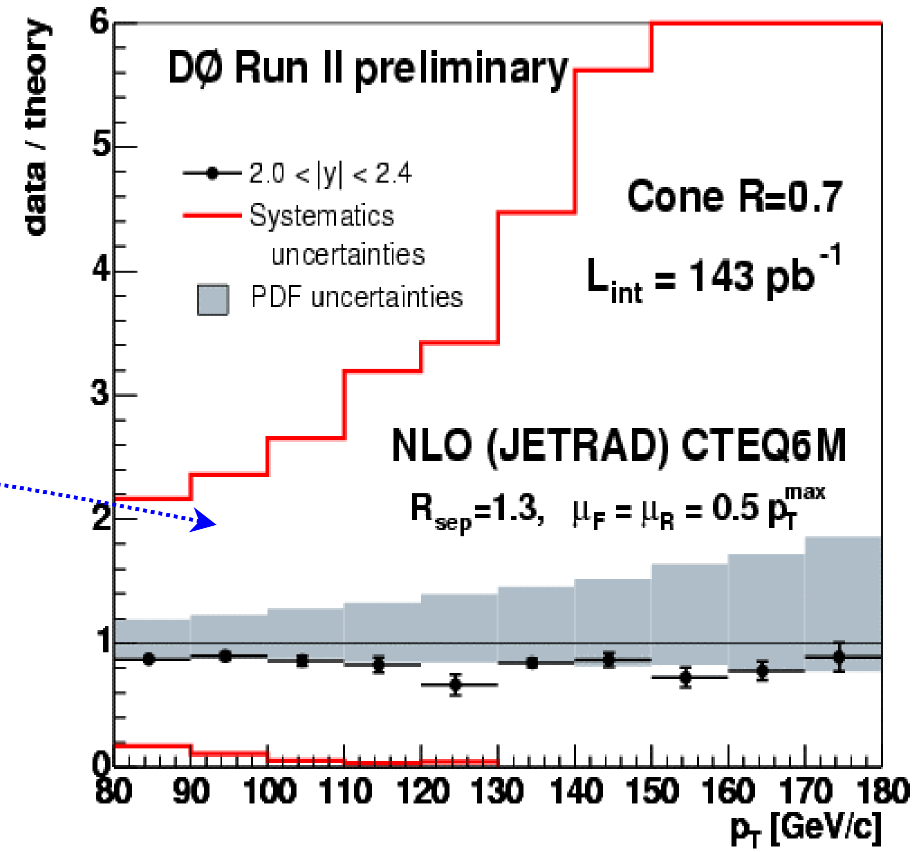


Look for narrow resonance
in Dij et Mass spect r um

data/theory agree within
large systematic errors
(mainly jet-energy scale)

Cross section vs rapidity





Measurements on large |Y| range
Constrain gluon at high x
Good agreement with NLO pQCD

Measurements dominated by uncertainty on the jet energy scale (to be highly improved soon)

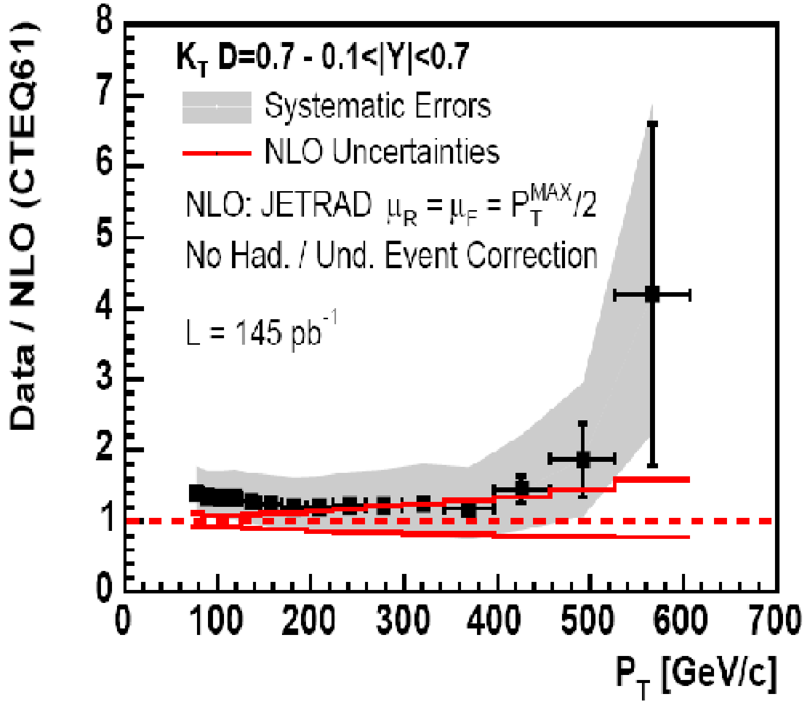
Jet Production with K_T

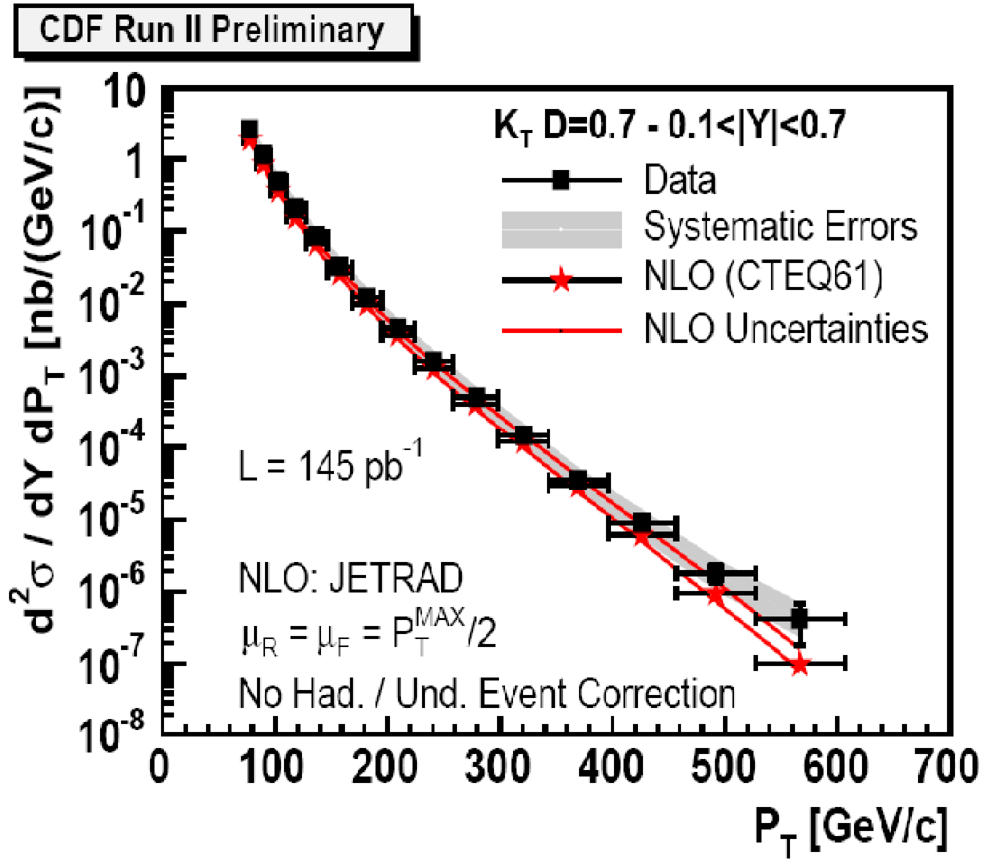
- Inclusive K_T algorithm

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

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

- Infrared/collinear safe (theoretically preferred)
- No merging / splitting





- Reasonable data-theory agreement
- NLO still needs to be corrected for Hadronization / Underlying Event
- High-Pt tail to be watched closely…

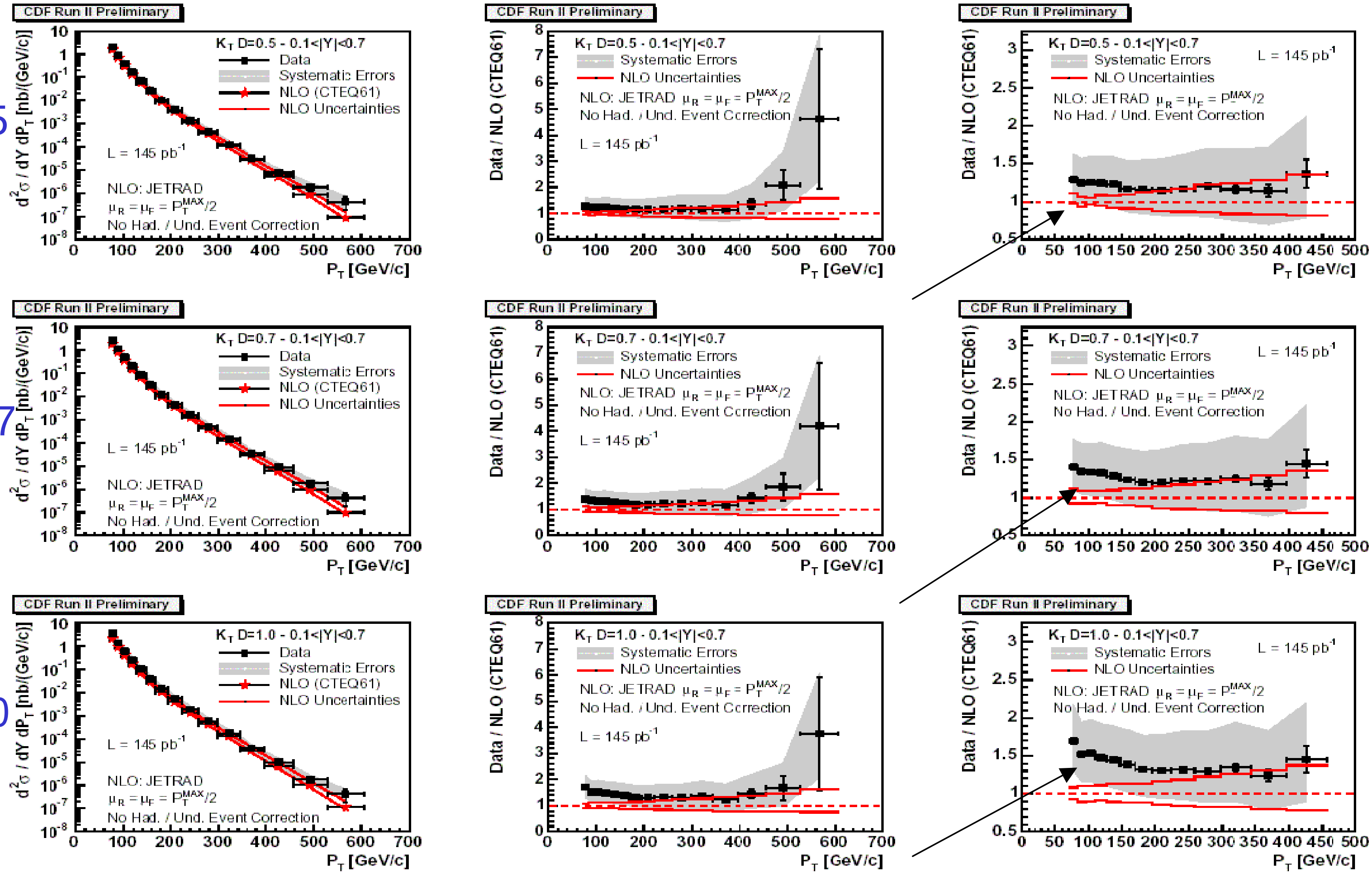
K_T jets vs D

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

D=0.5

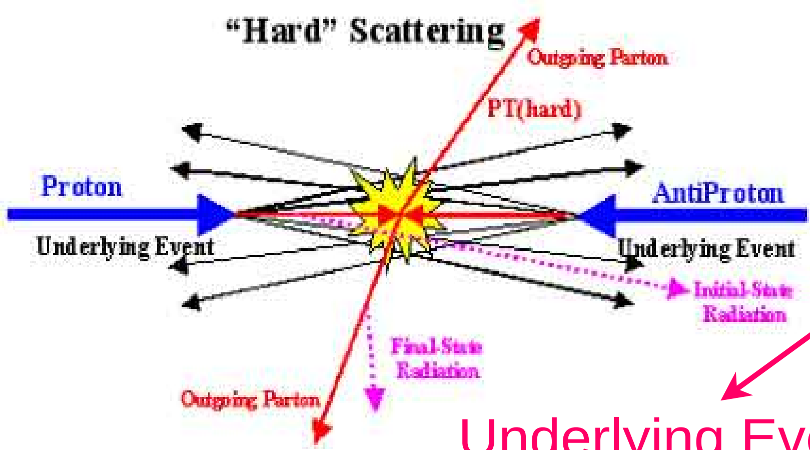
D=0.7

D=1.0



As D increases data departs from pQCD NLO → more soft contributions

Underlying Event & Jet Physics

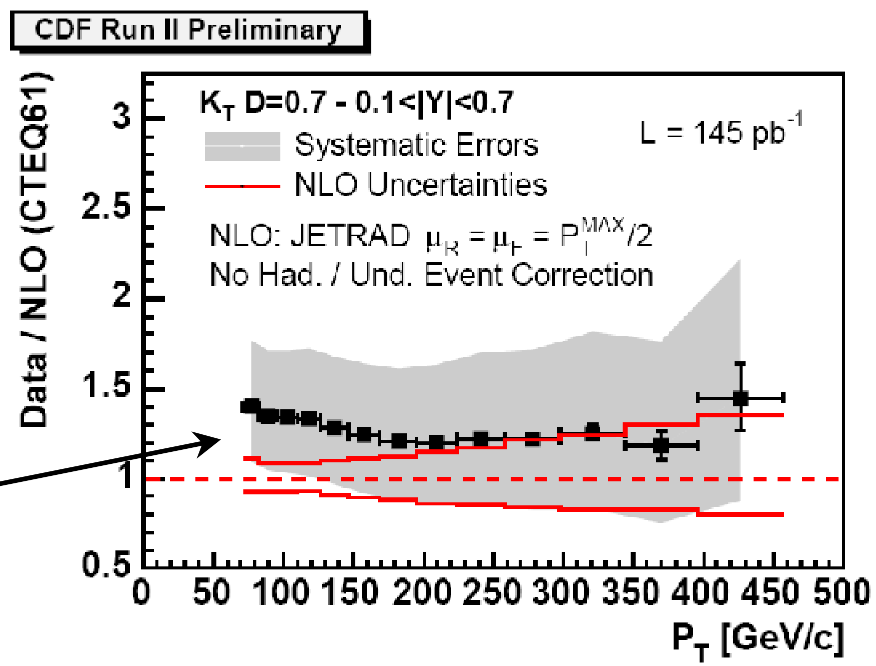


A typical Tevatron dijet event consists of :

- hard interaction
- initial/final gluon radiation
- secondary semi-hard interactions
- interaction between remnants

Underlying Event

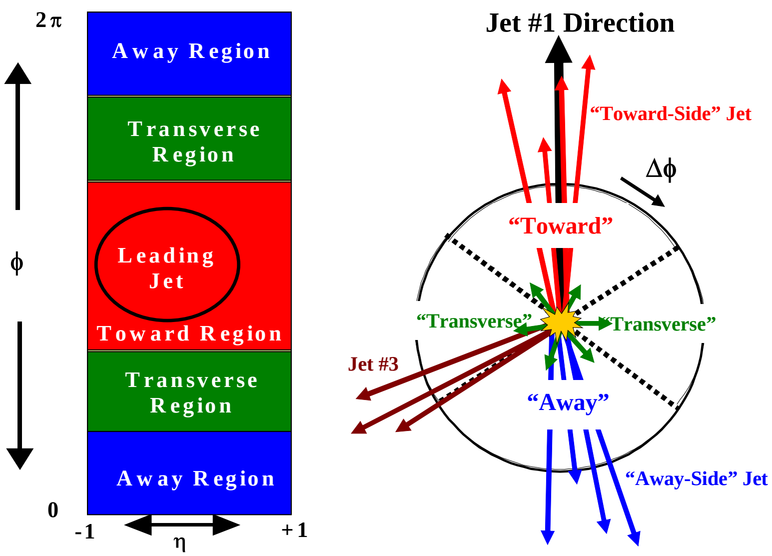
Underlying Event contribution must be removed from the jets before comparing to NLO QCD predictions



Precise jet measurements require good modeling of the underlying event

Interplay between pQCD and non-pQCD physics……

Underlying Event Studies (Run I)

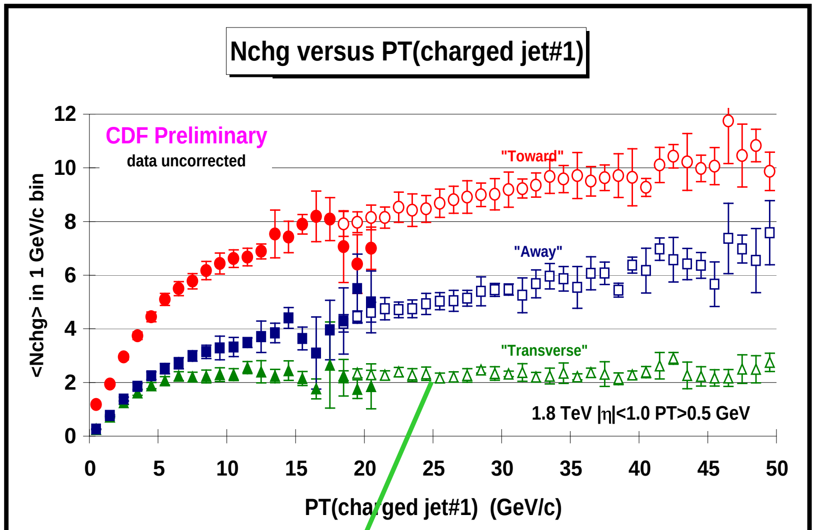


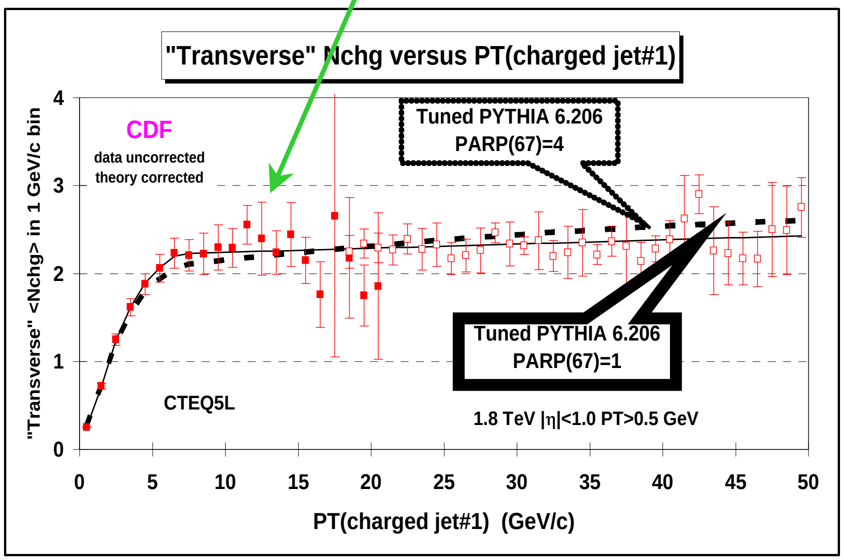
$p_T^{track} > 0.5$ GeV, $|\eta^{track}| < 1$

transverse region sensitive to soft underlying event activity

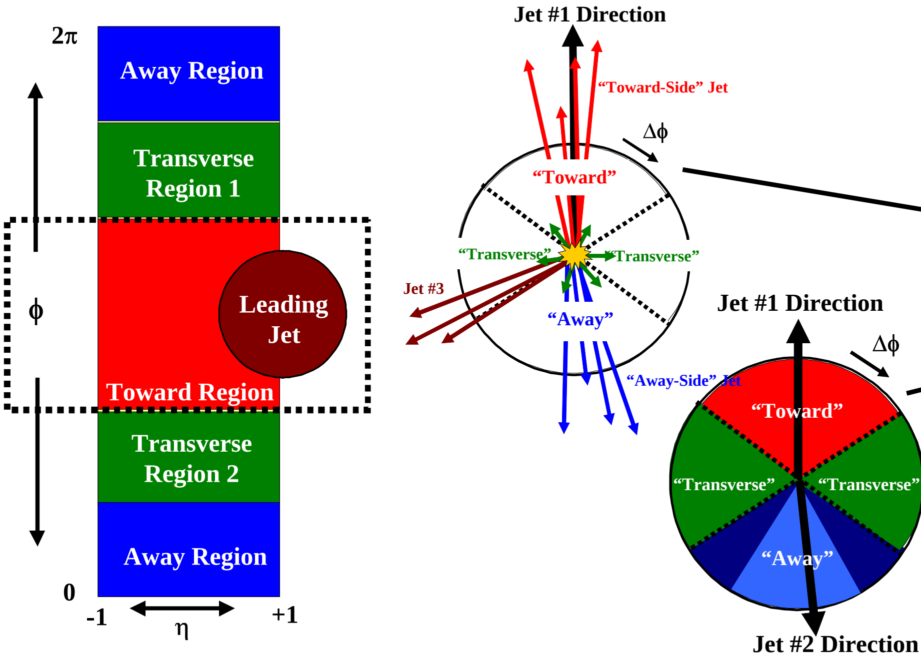
Good description of the underlying event by PYTHIA after tuning the amount of initial state radiation, MI and selecting CTEQ5L PDFs (known as PYTHIA Tune A)

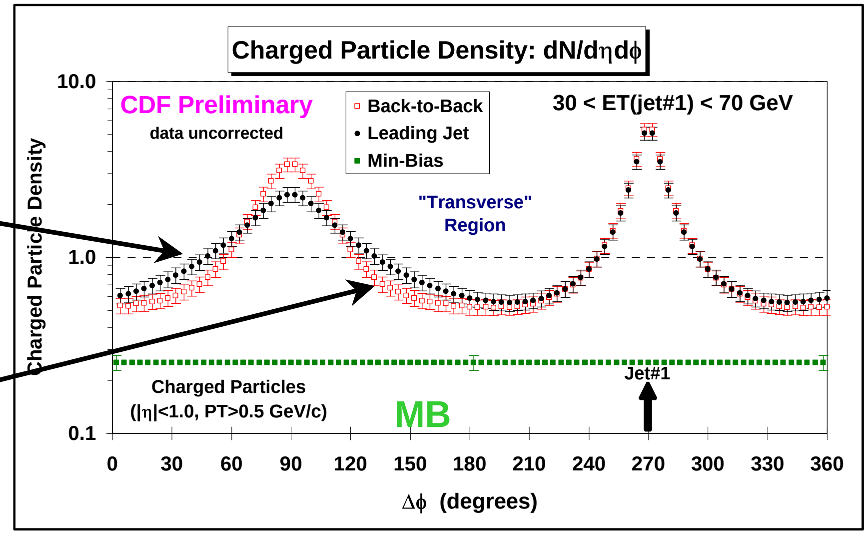
Mean track multiplicity vs leading jet Pt





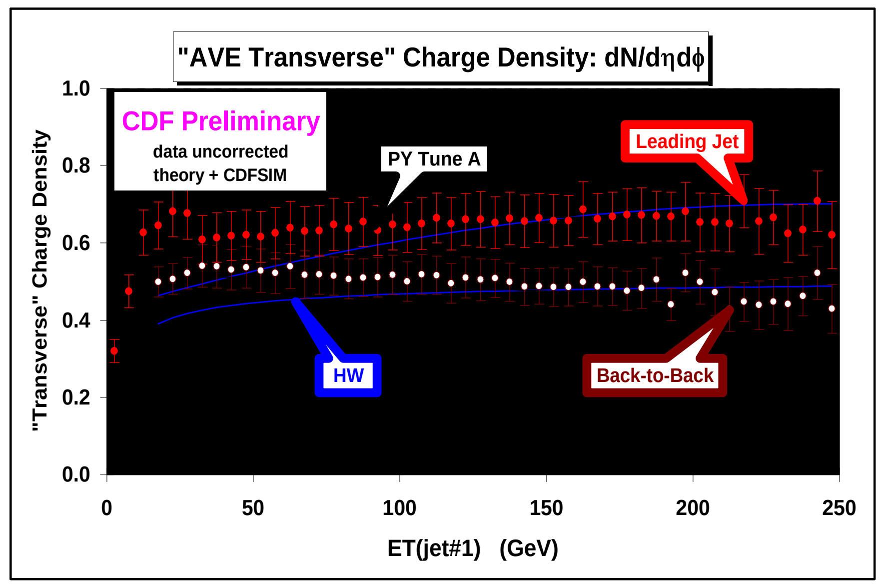
New Underlying Event Studies





Back-to-Back $\left\{ \begin{array}{l} E_T(jet\#2)/E_T(jet\#1) > 0.8 \\ \Delta\phi_{12} > 150^o \end{array} \right.$

Suppresses contribution from additional hard radiation

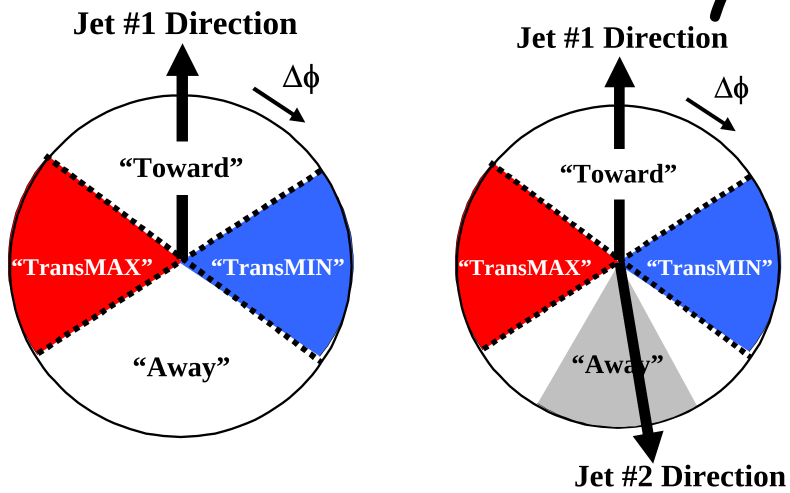


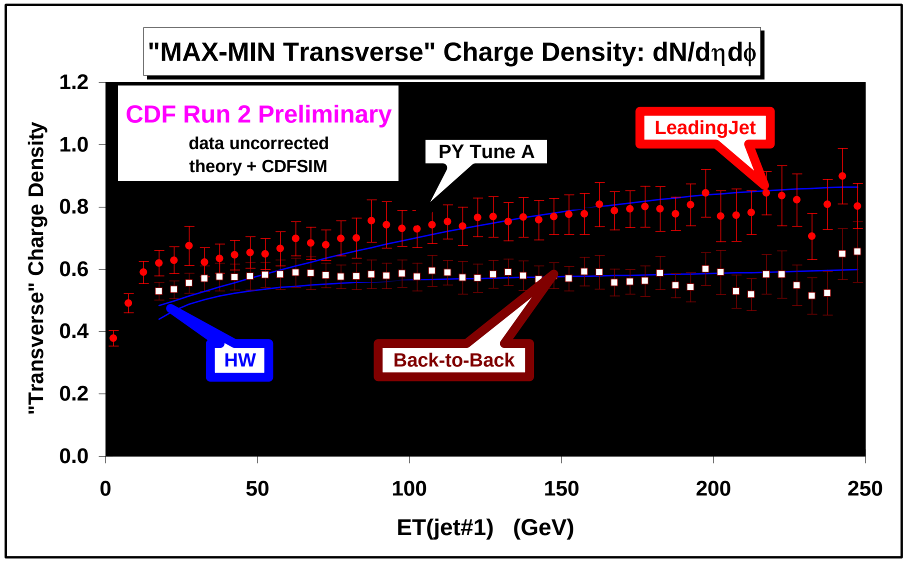
Pythia Tune A describes the data

Herwig underestimates UE activity

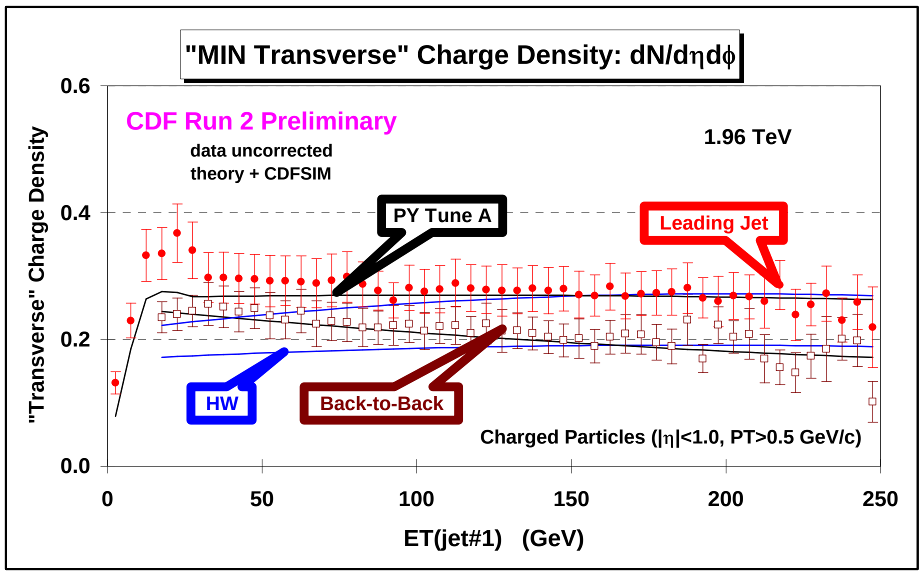
Extended to 250 GeV jets

New Underlying Event Studies



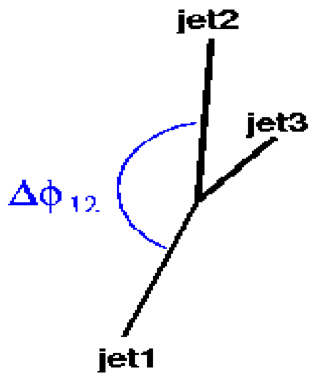


- MAX (MIN) for the largest (smallest) charged particle density in transverse region

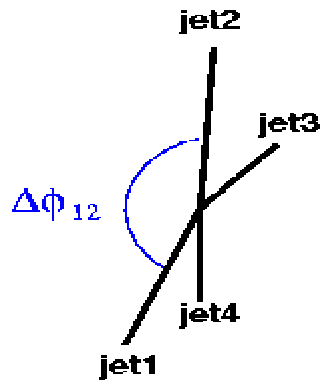


- MAX-MIN sensitive to remaining hard contribution
- MIN specially sensitive to the remnant-remnant contribution

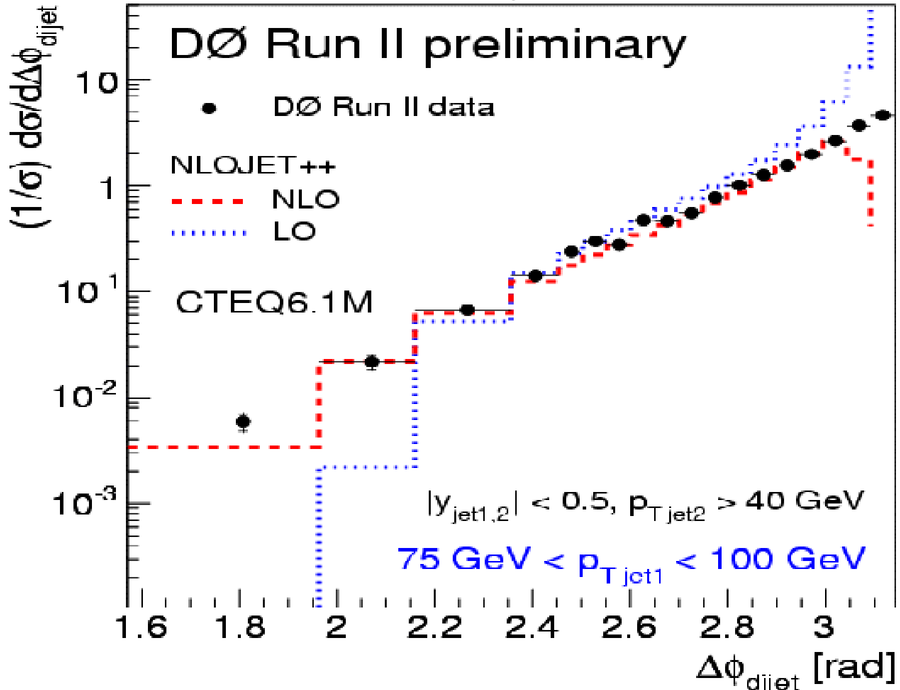
Studies on Δϕ between jets

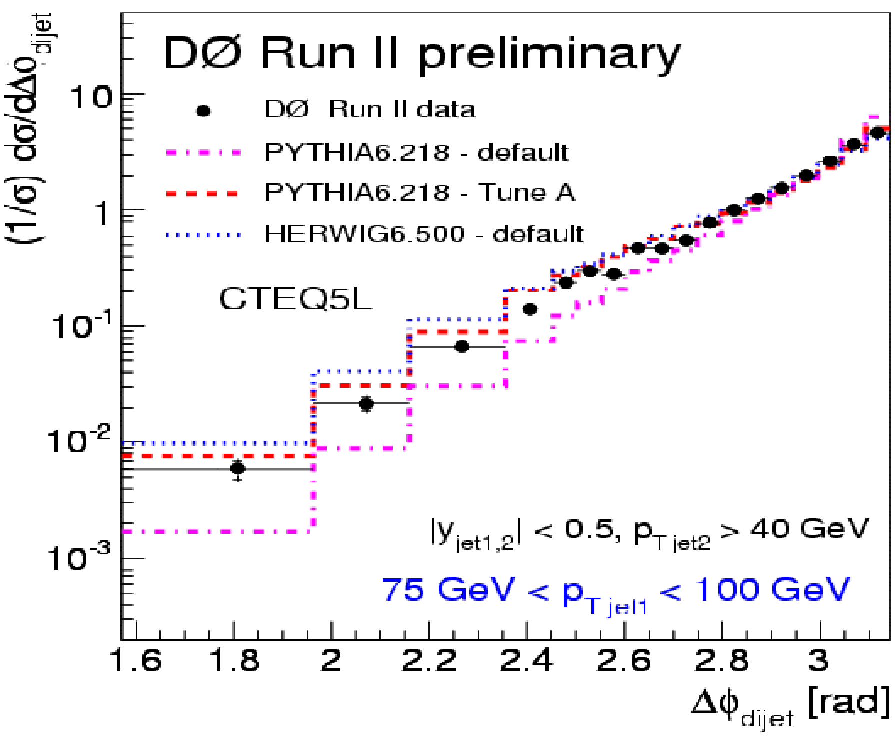


LO in Δϕ



NLO in Δϕ



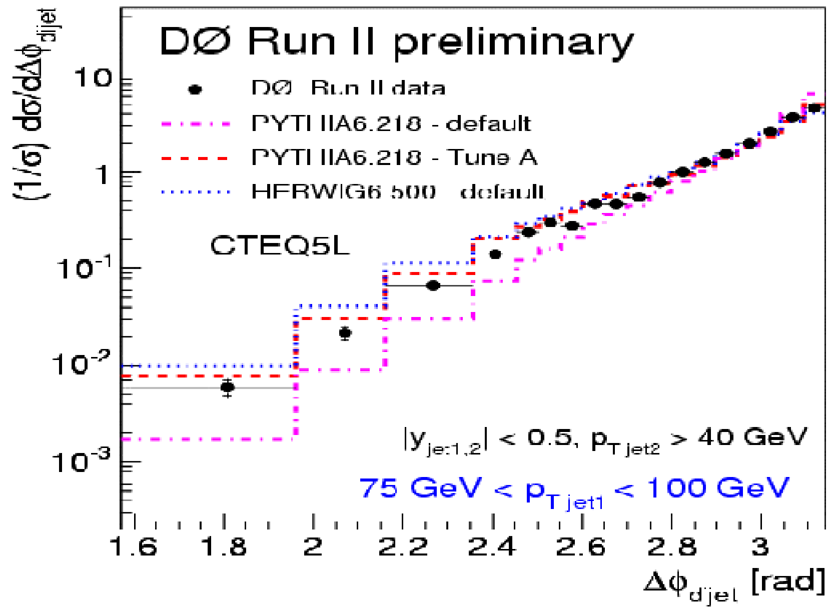


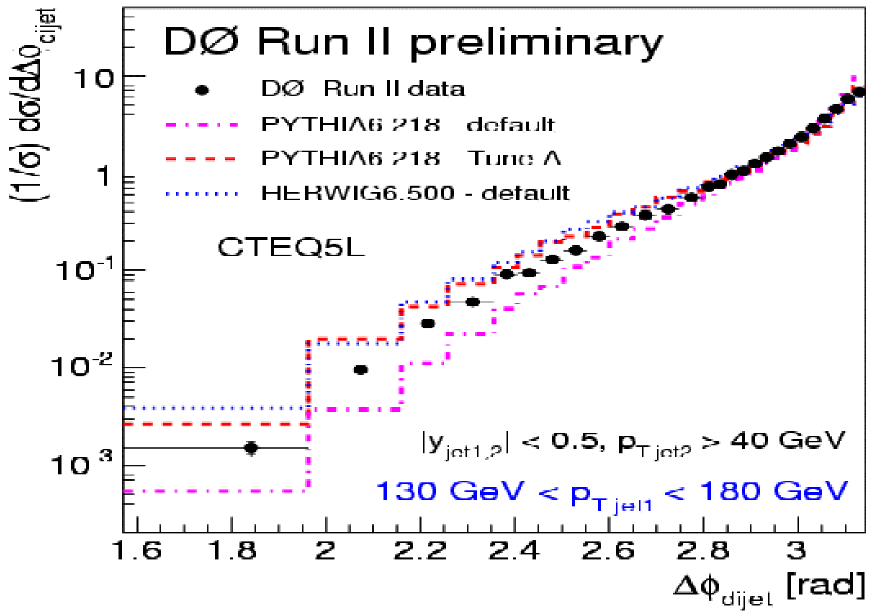
LO limited at hard (Mercedes Star) and soft limits for third emission

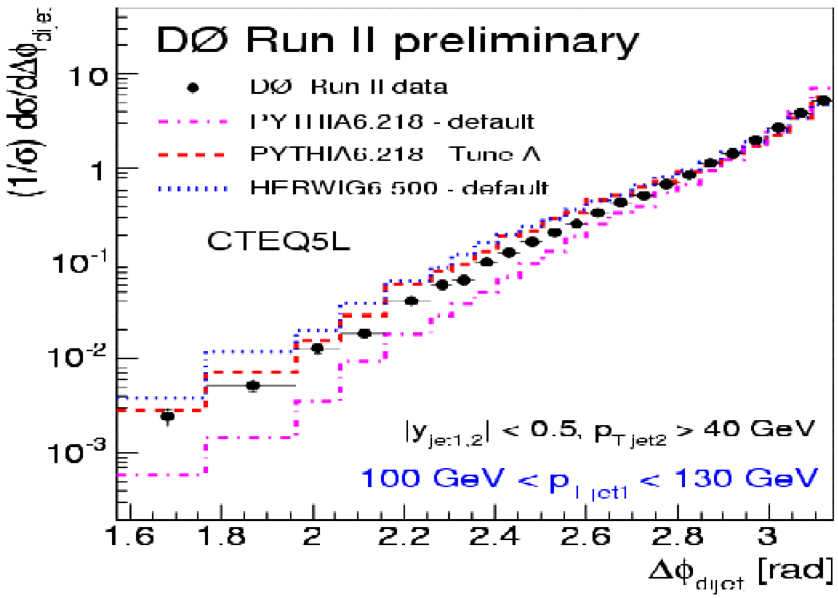
NLO closer to data…however
soft gluon contributions are needed

Parton shower MC approximates the required re-summed calculation

Δφ & soft gluon radiation





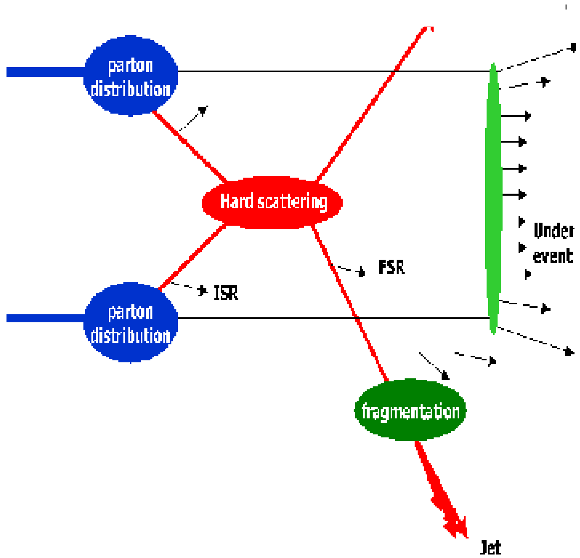


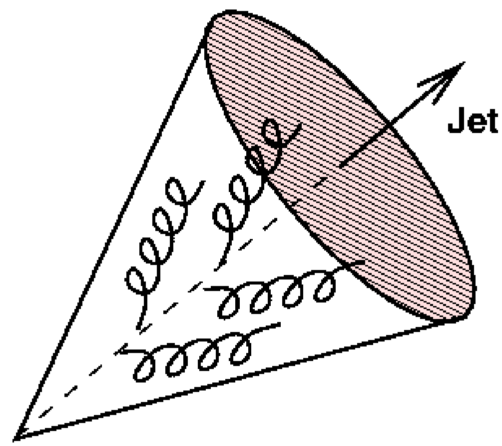
Δφ distribution shows sensitivity to different modeling of parton cascades

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

HERWIG similar to PYTHIA Tune A (underestimates radiation close to leading jets)

Studies on Jet Fragmentation



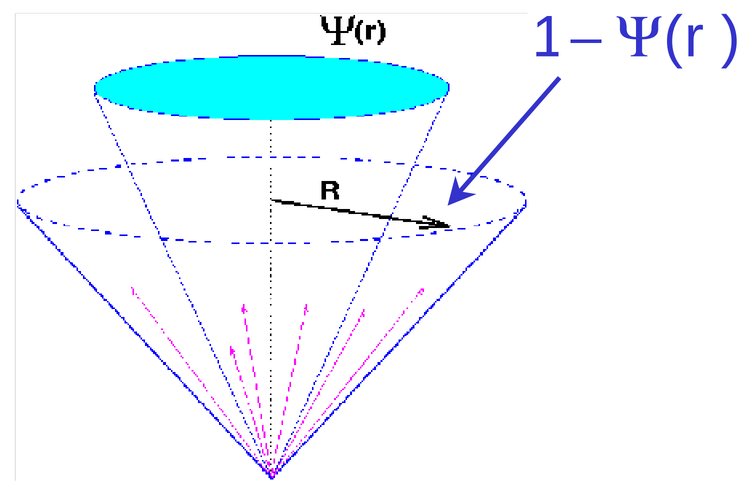


- Jet shape dictated by multi-gluon emission form primary parton

- Test of parton shower models and their implementations

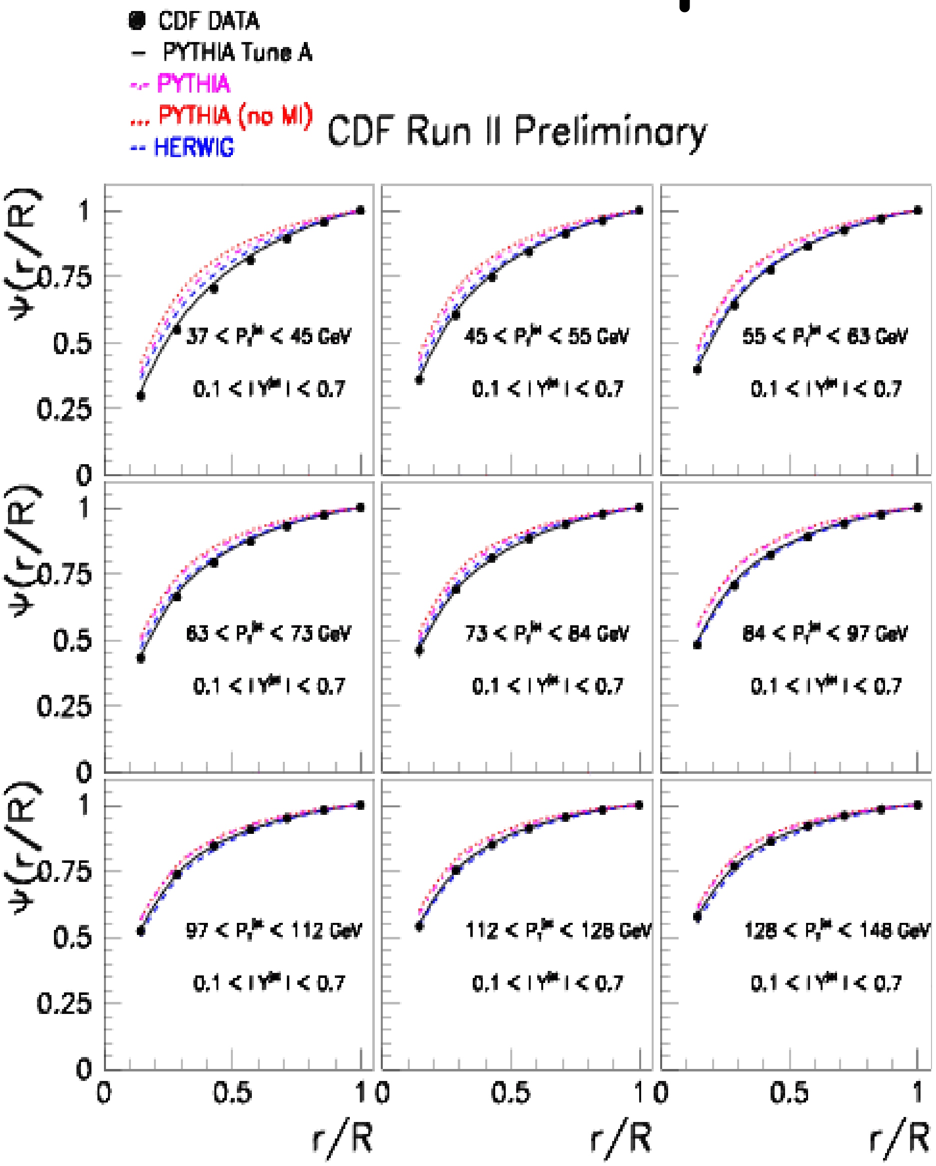
- Sensitive to quark/gluon final state mixture and run of strong coupling

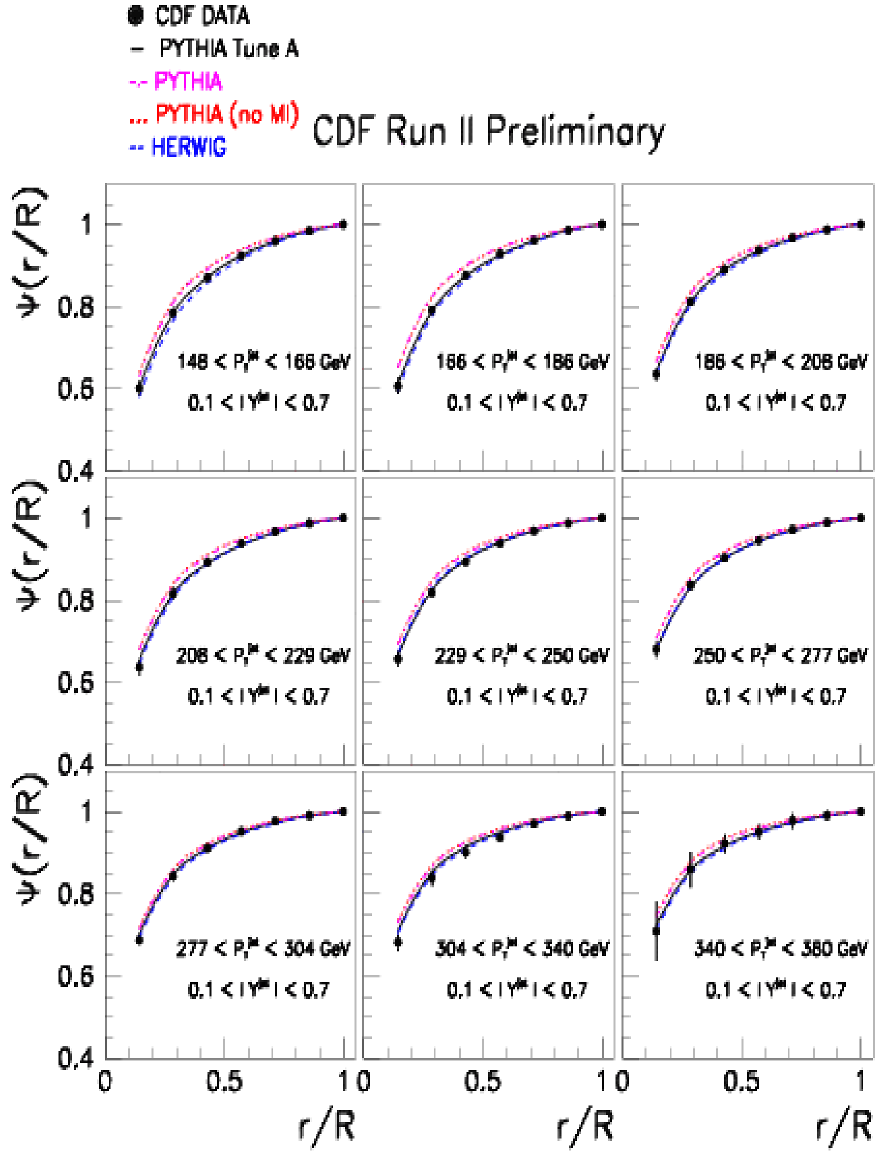
- Sensitive to underlying event structure in the final state



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

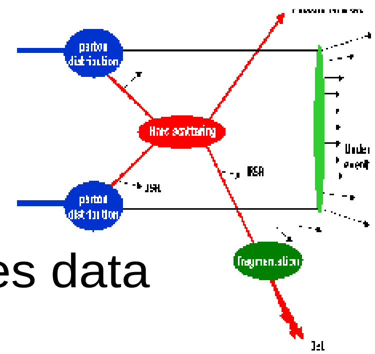
Jet Shapes Measurements



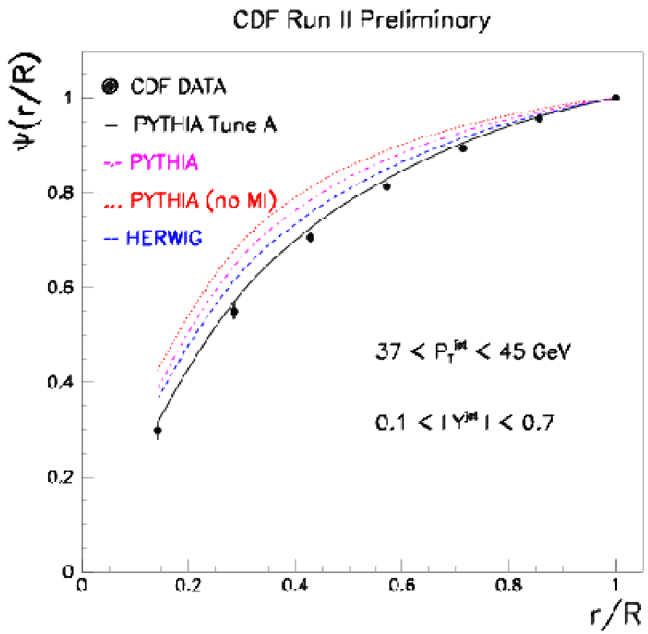


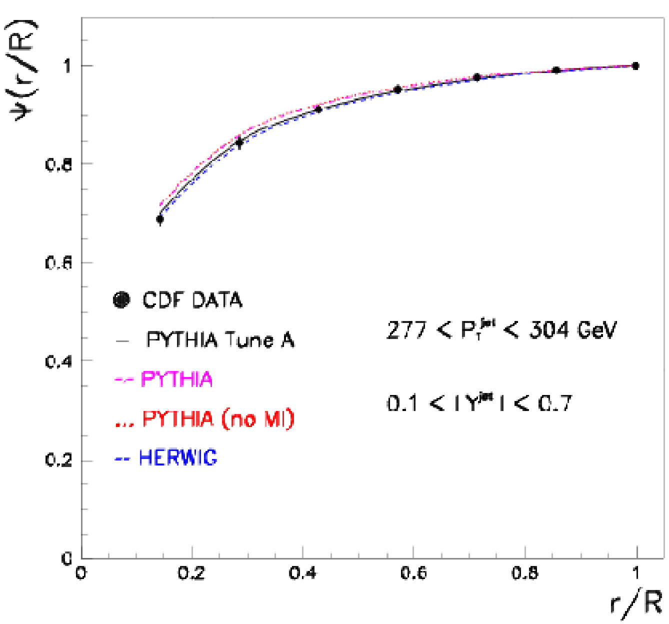
For central jets in the whole range of jet transverse momentum

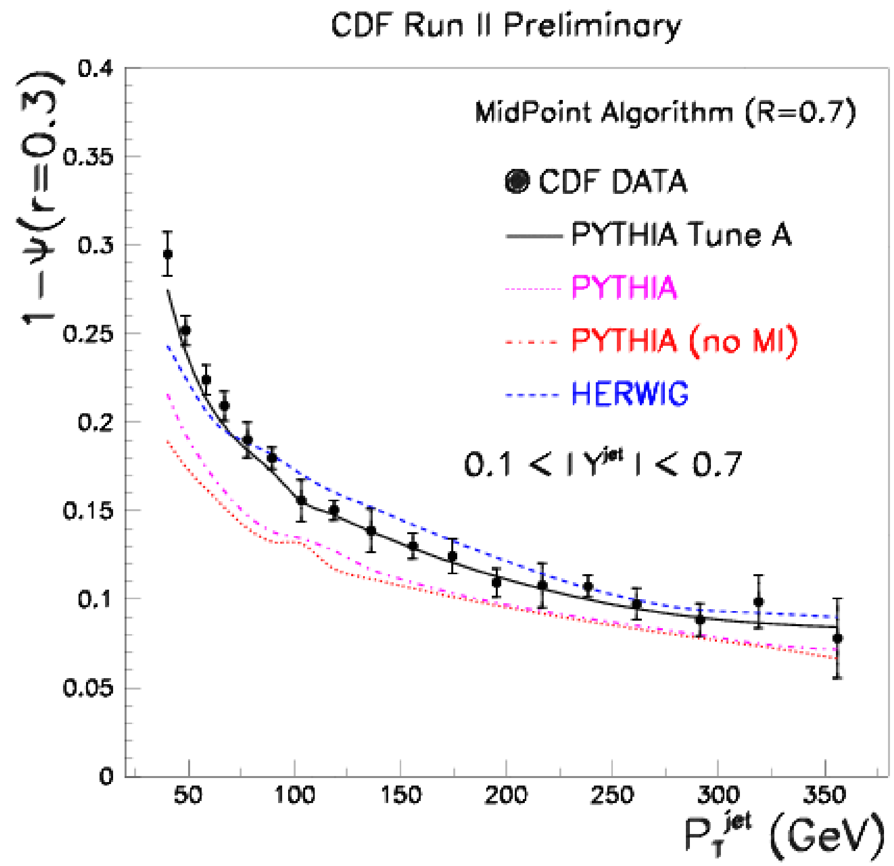
Jet shapes



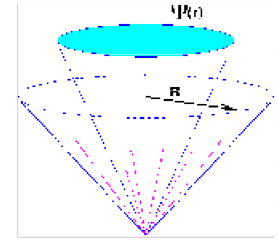
- PYTHIA Tune A → describes data (enhanced ISR + MI tuning)
- PYTHIA default too narrow
- PYTHIA default (w/wo MI) similar
- HERWIG too narrow at low Pt



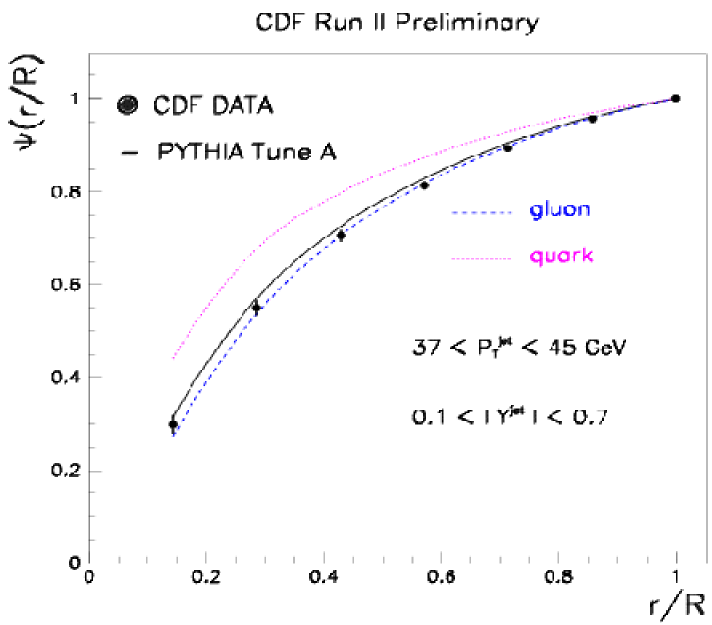


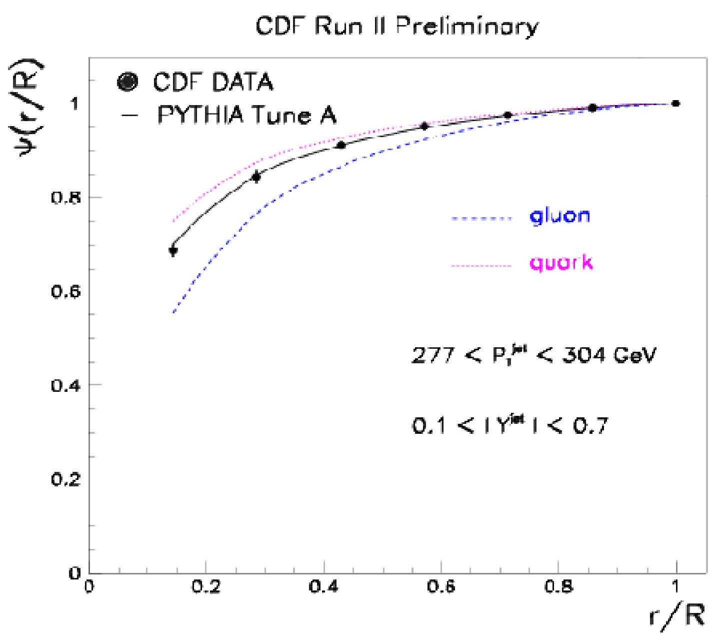


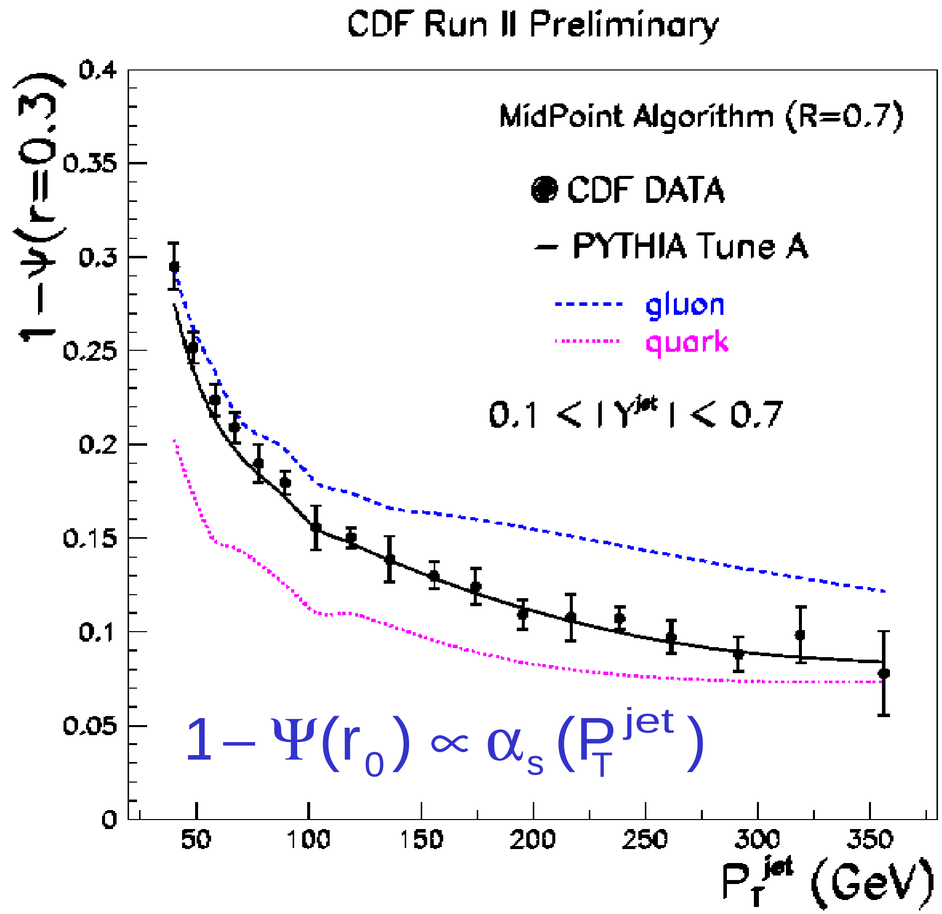
Jet shapes



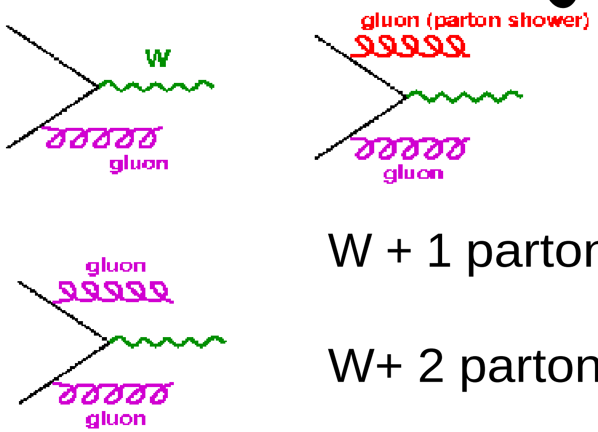
Jet shapes sensitive to the relative amount of quark- and gluon-jets in the final state and the running of strong coupling







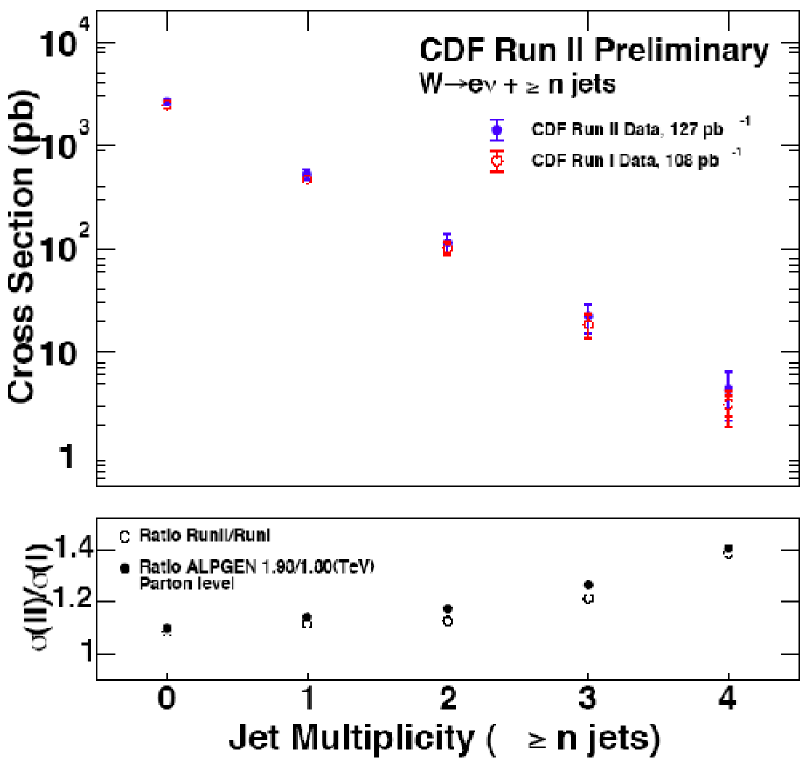
W+jet(s) Production

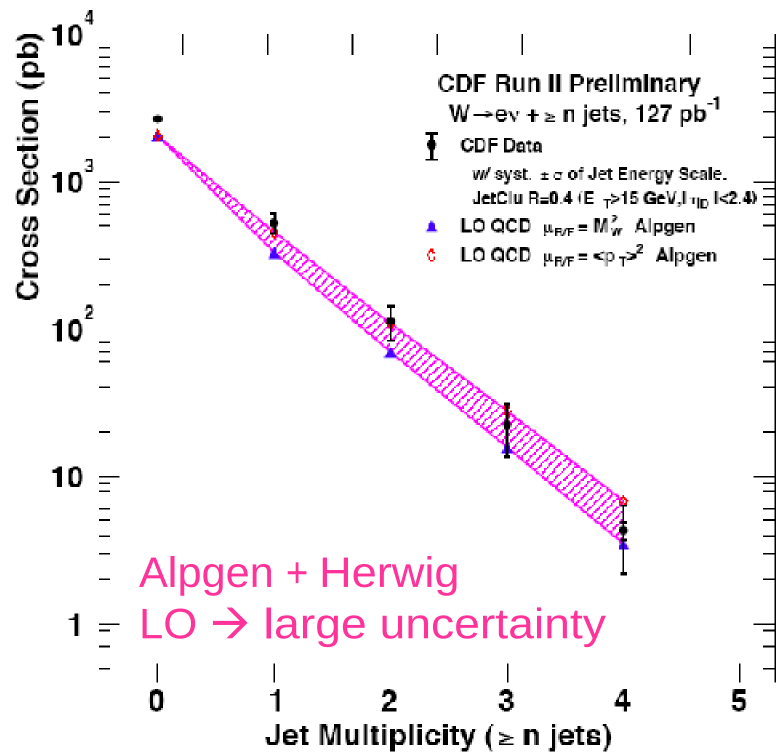


W + 1 parton +PS

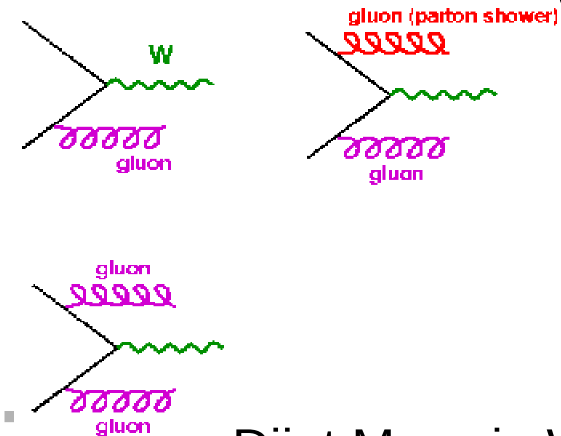
W+ 2 partons

- Background to top and Higgs Physics
- Stringent test of pQCD predictions
- Test Ground for ME+PS techniques
  (Special matching → MLM, CKKW to avoid double counting on ME+PS interface)



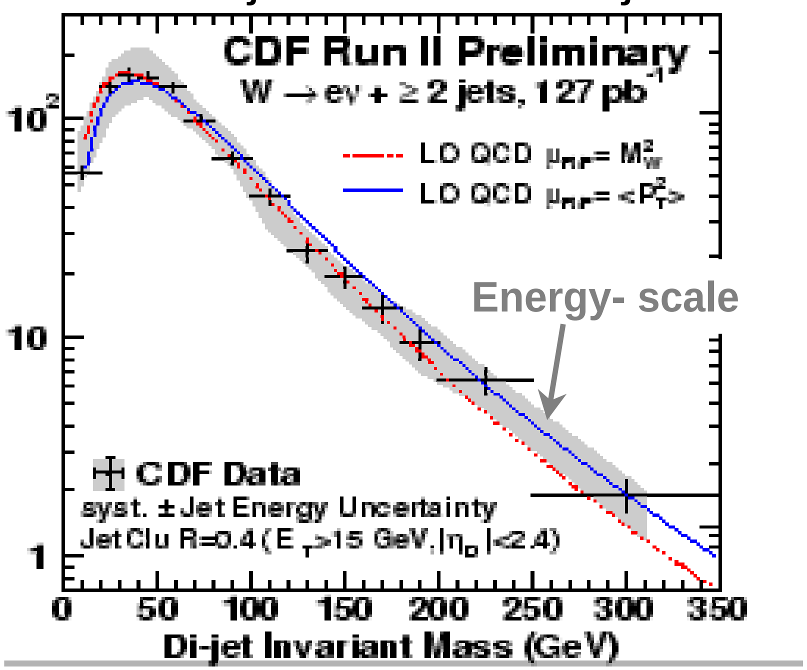


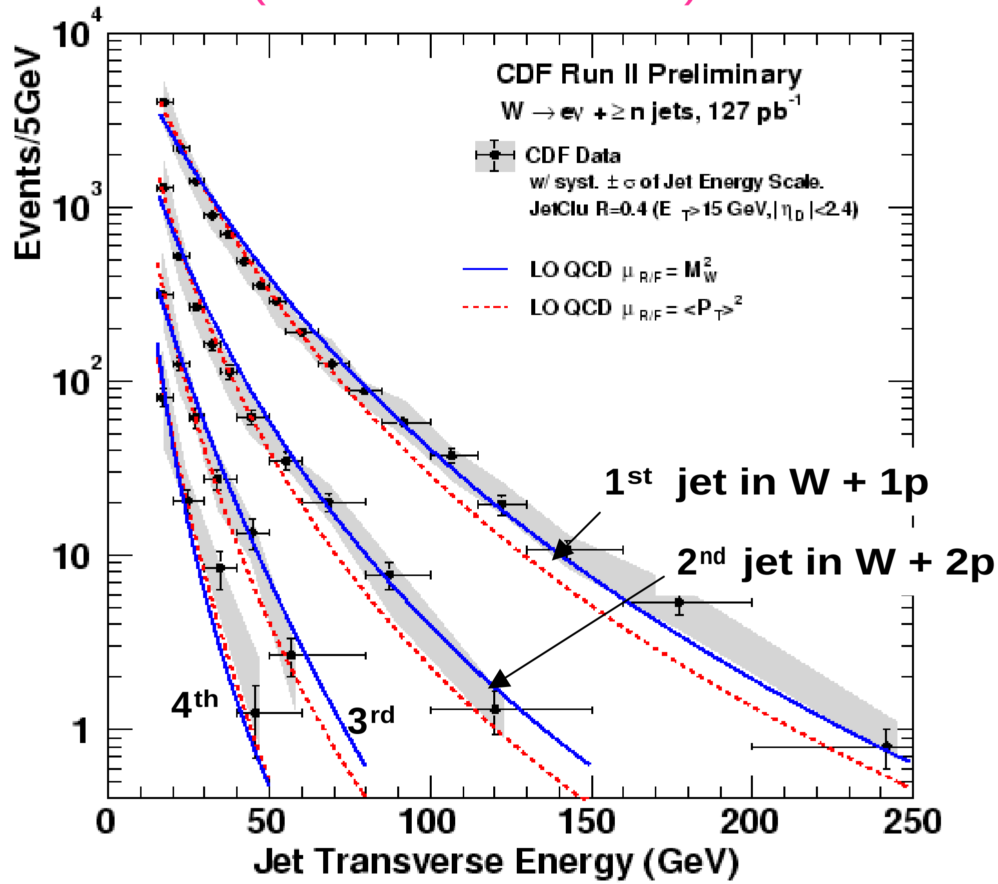
W+ jet(s) Production



ME+PS implementation tested using the N^{th} jet spectrum in W+N^{jet} events (more sensitive one)

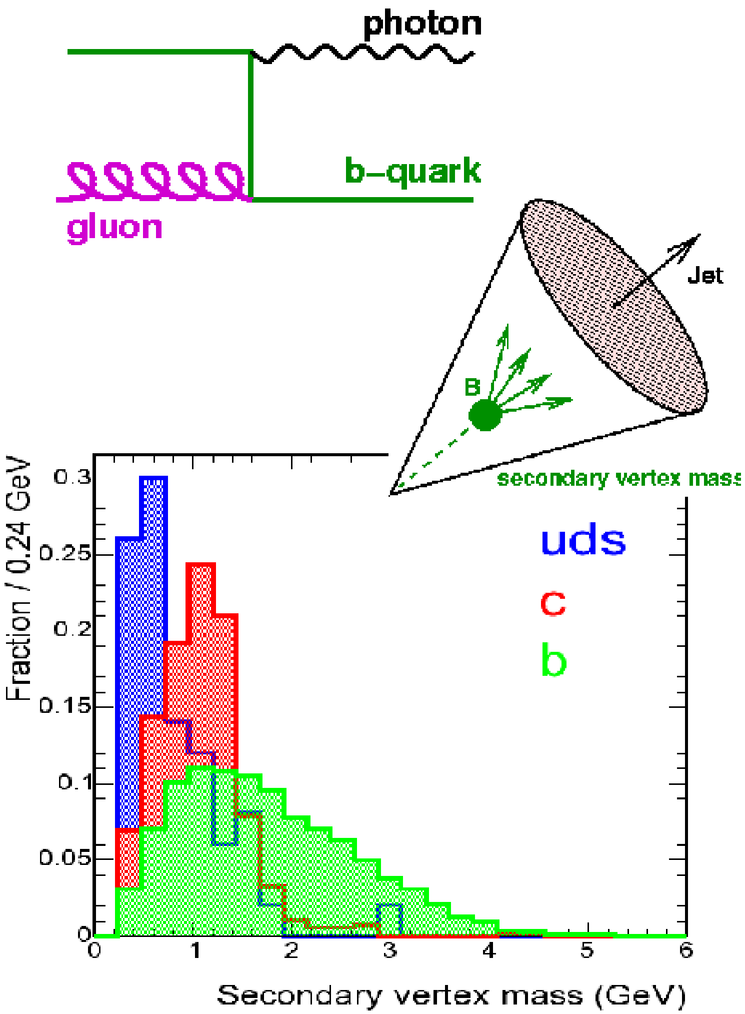
Dijet Mass in W+2jets





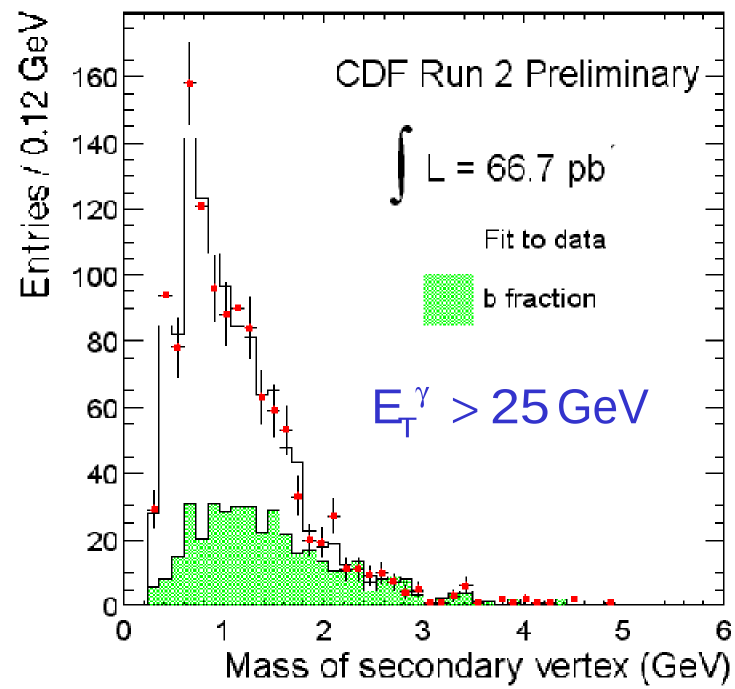
NLO now available for W+2jets

γ+heavy flavour production



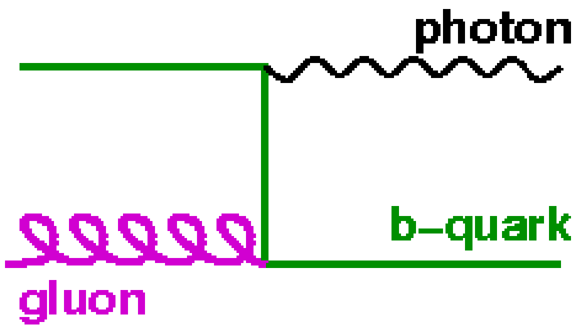
- Probes heavy-quark PDFs
- Background for SUSY (light stop)

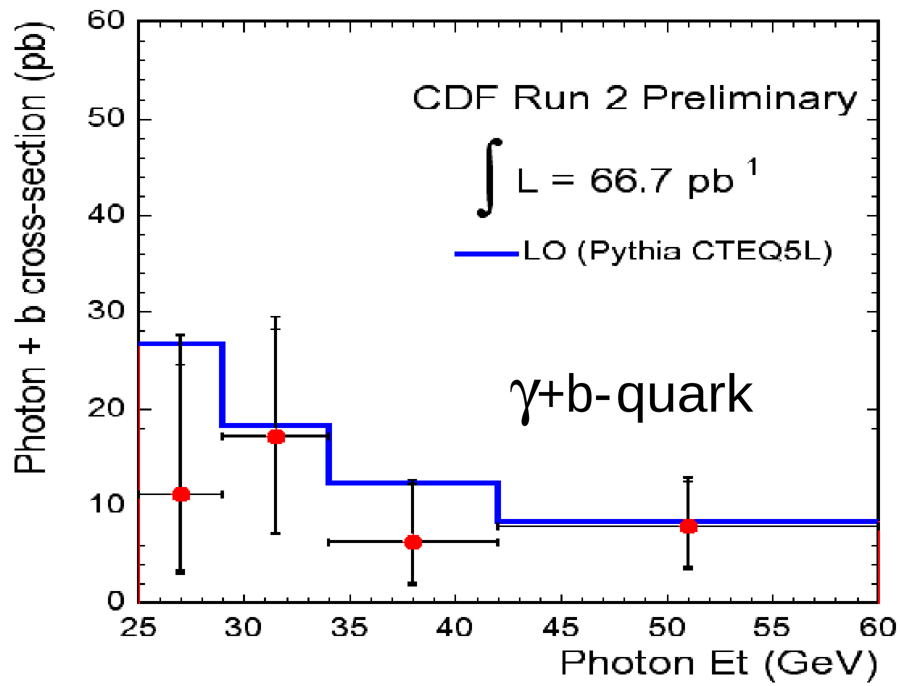
- b/c-quark tag based on displaced vertices
- Secondary vertex mass discriminates flavour

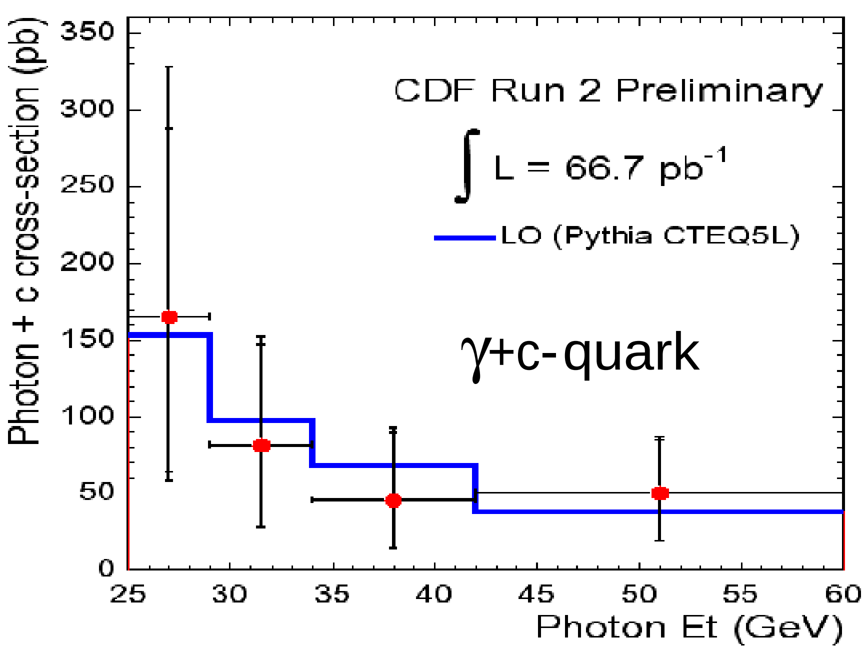


MC templates for b/c & (uds) used to extract b/c fraction in data

γ+heavy flavour production



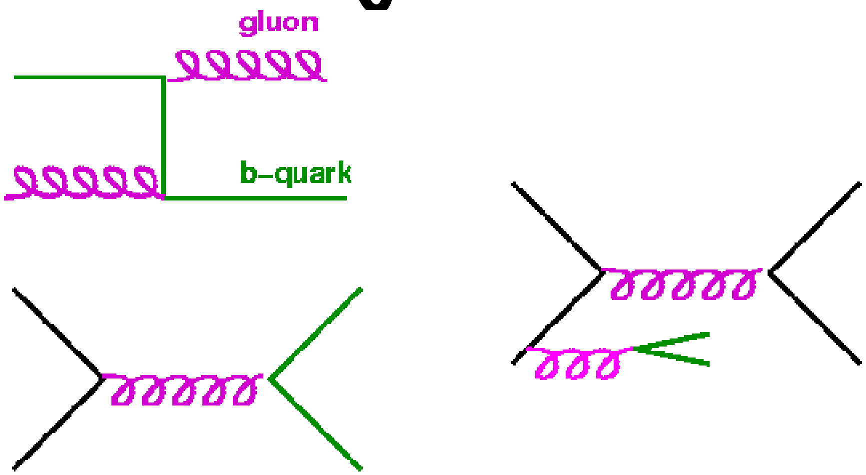


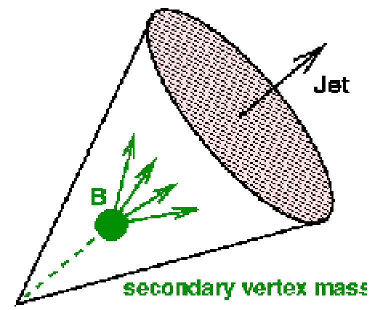


Good agreement with LO pQCD within still very large stat. errors

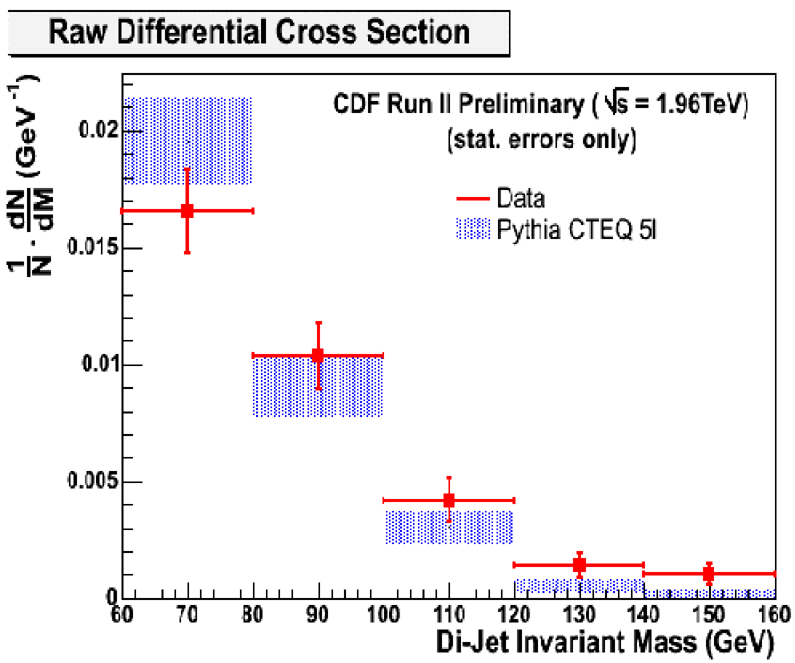
Validates quark flavour separation using secondary vertex mass

B-jet Production (PR plots)

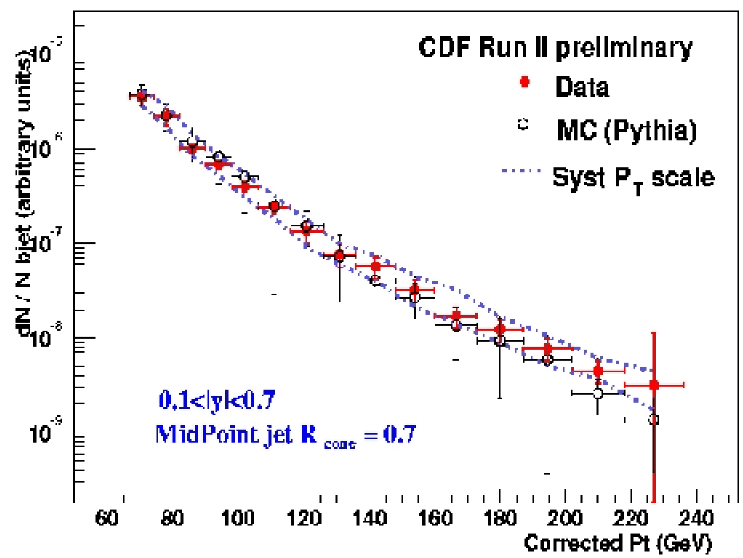




Same technique being used to measure b-jet inclusive and dijet production



(only normalized distributions shown)



Summary & Conclusions

- Very Rich Jet Physics Program at Tevatron
- High luminosity measurements will provide constrains to the gluon PDFs at high x and probe distances of 10^{-19} m
- Run II will explore different jet algorithms
- Studies of soft-gluon radiations are crucial for a proper comparison with pQCD and background estimations
- Studies of Boson + Jets physics and proper understanding of ME+PS matching important for Higgs
- B-jet Physics program just started..cross sections soon..