CDF II

DØ

QCD Measurements at the Tevatron

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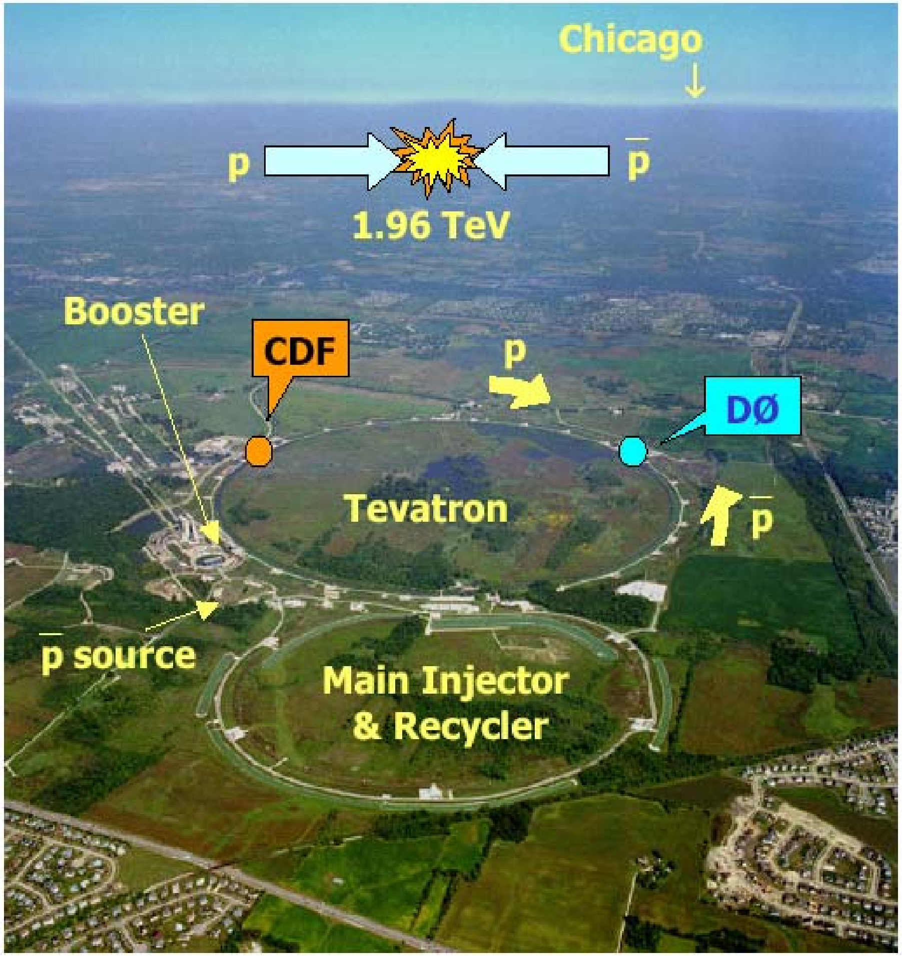
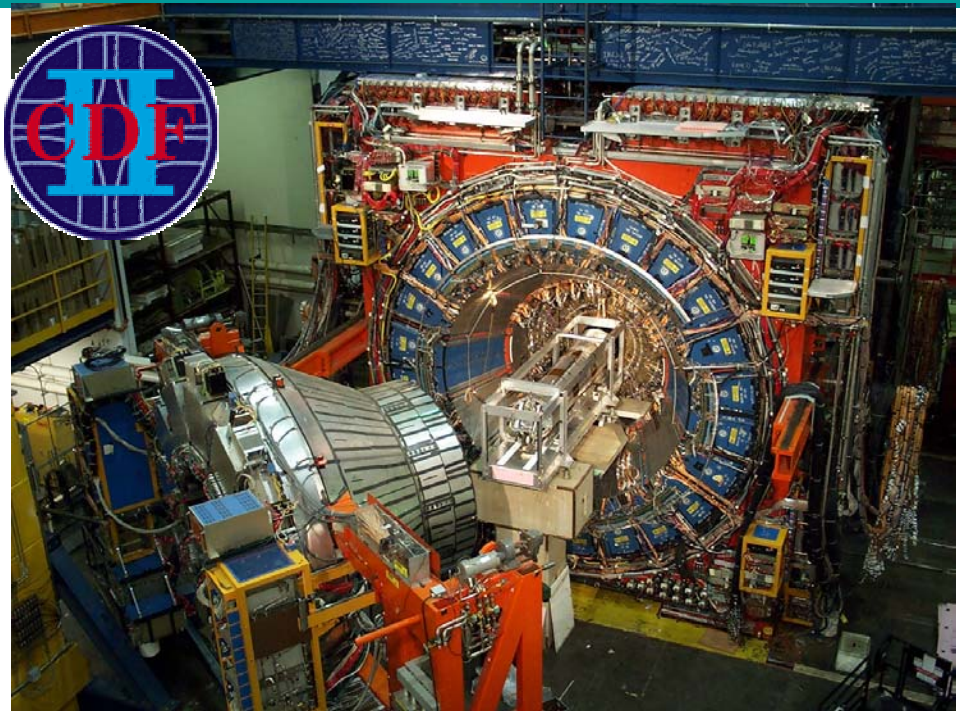
The Tevatron Accelerator

- World's highest energy collider (until 2007)
  - Proton-antiproton Synchrotron
  - Experiments CDF and D0
- Run I (1992-1996)
  - $\sqrt{s}$ = 1.8 TeV
  - 6 x 6 bunches with 3 μs spacing
  - ~100 pb^{-1} int. luminosity
- Major upgrade to accelerator complex
  - Main Injector (x5)
  - Pbar Recycler (x2)
- Run II (2001-2009 ?)
  - $\sqrt{s}$ = 1.96 TeV
  - 36 x 36 bunches with 396 ns spacing
  - Current peak luminosity >15.0 x 10^{31} $cm^{-2}s^{-1}$ = 5 x Run I
  - Aim for 4-9 fb^{-1} int. luminosity in Run II – both experiments have now > 1 fb^{-1} on tape.



CDF and D0 in Run II



Both detectors

- •Silicon microvertex tracker
- •Solenoid
- •High rate trigger/DAQ
- •Calorimeters and muons

L2 trigger on displaced vertices
Excellent tracking resolution

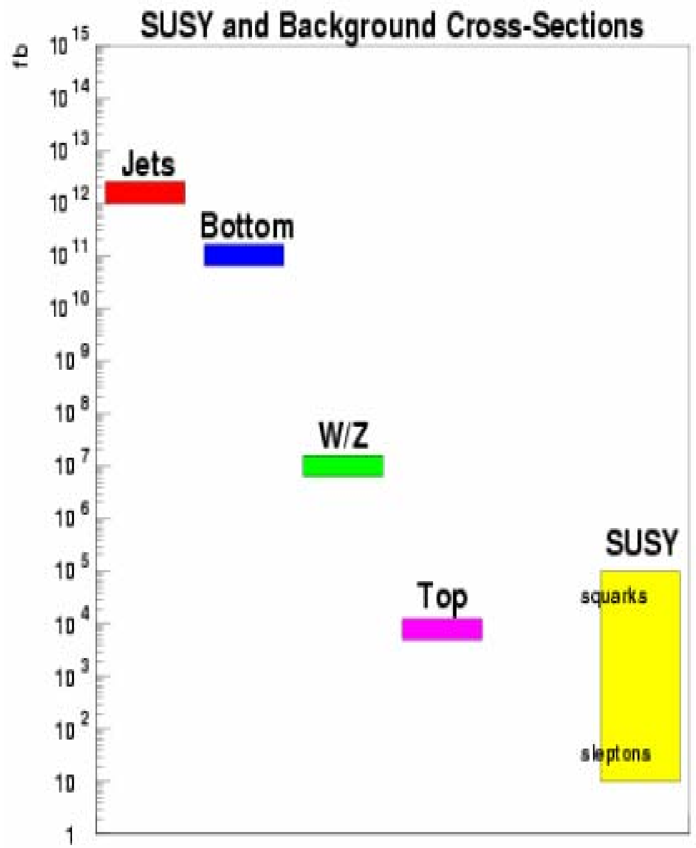
Excellent muon ID and acceptance
Excellent tracking acceptance $|\eta| < 2\text{-}3$

Electroweak And Strong Force

- Quantum field theory is used to describe forces of nature:
  - Unified description of weak and electromagnetic force (Glashow, Salam, Weinberg):
    - Photon
    - W, Z
  - Strong force described by Quantumchromodynamics (QCD)
    - 8 gluons
- Precision measurements test validity of model and calculations
- QCD has unique features:

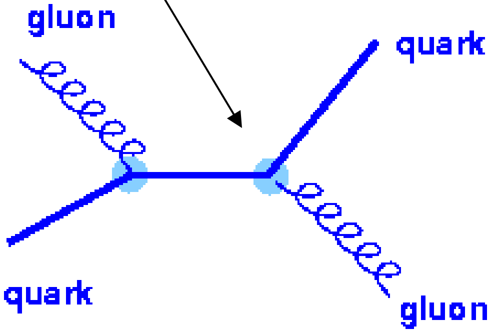
  - Test of the SM and phenomenological models in its own right
- QCD is indeed the ‘strong force’

  - i.e. large cross sections for background towards searches beyond the Standard Model

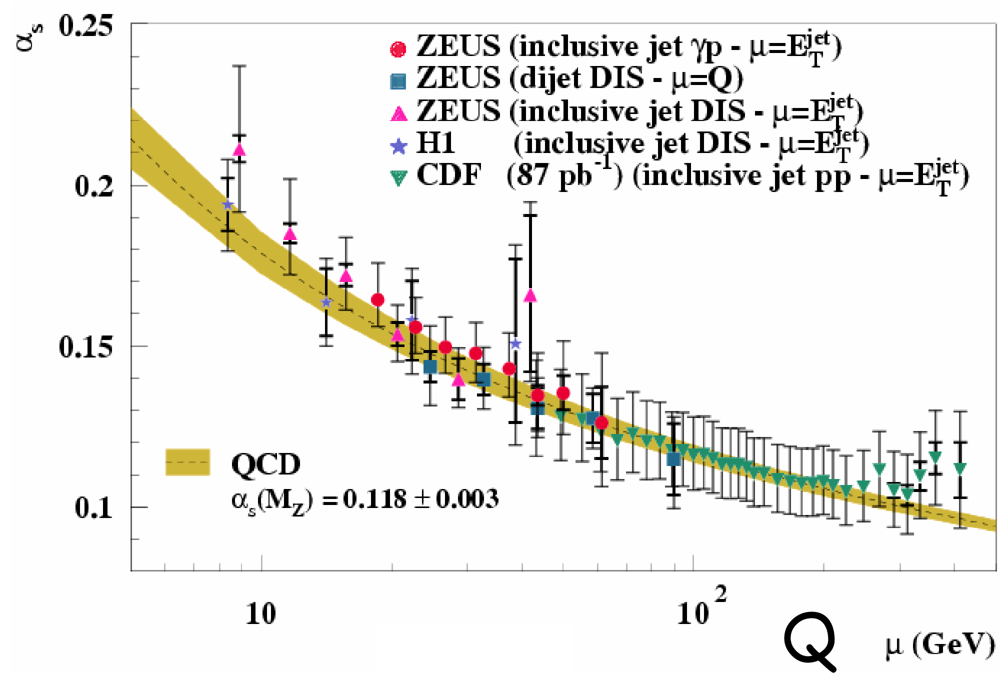


QCD : Asymptotic Freedom & Confinement

$$\alpha_s(Q^2) = \frac{12\pi}{(33-2n_f)\ln\frac{Q^2}{\Lambda^2_{QCD}}}$$



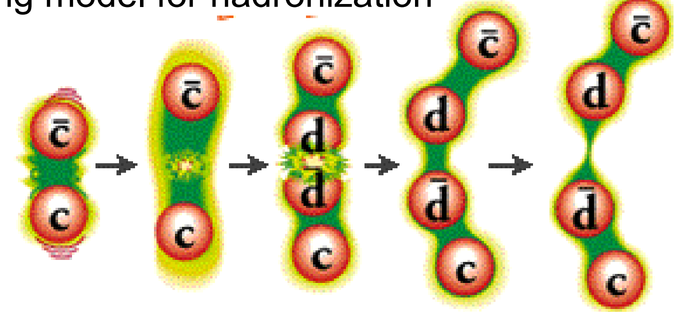
$$\hat{\sigma}_{qg\to qg}$$



At high Q (short distances) perturbation theory can be used to compute partonic cross sections

At low Q (large distances) pQCD breaks down (and we rely on phenomenological models)

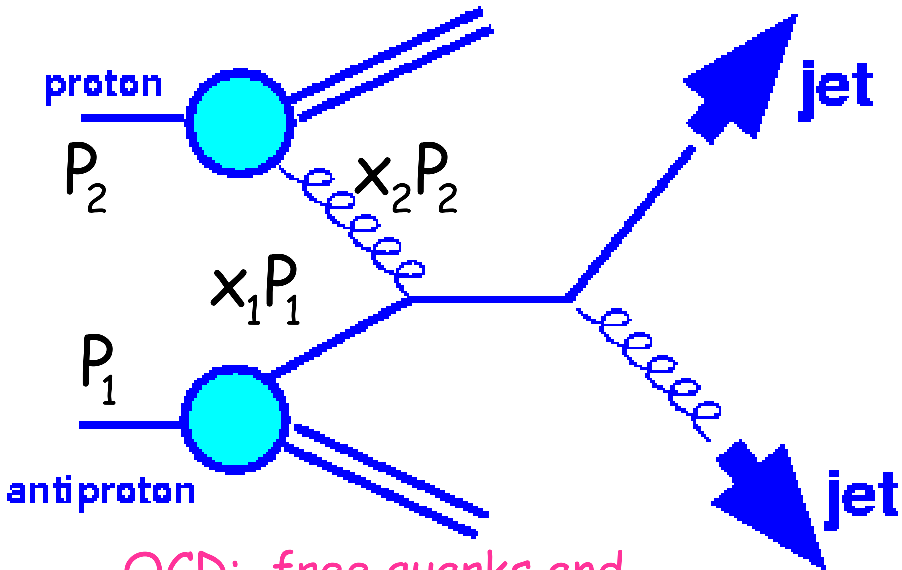
String model for hadronization



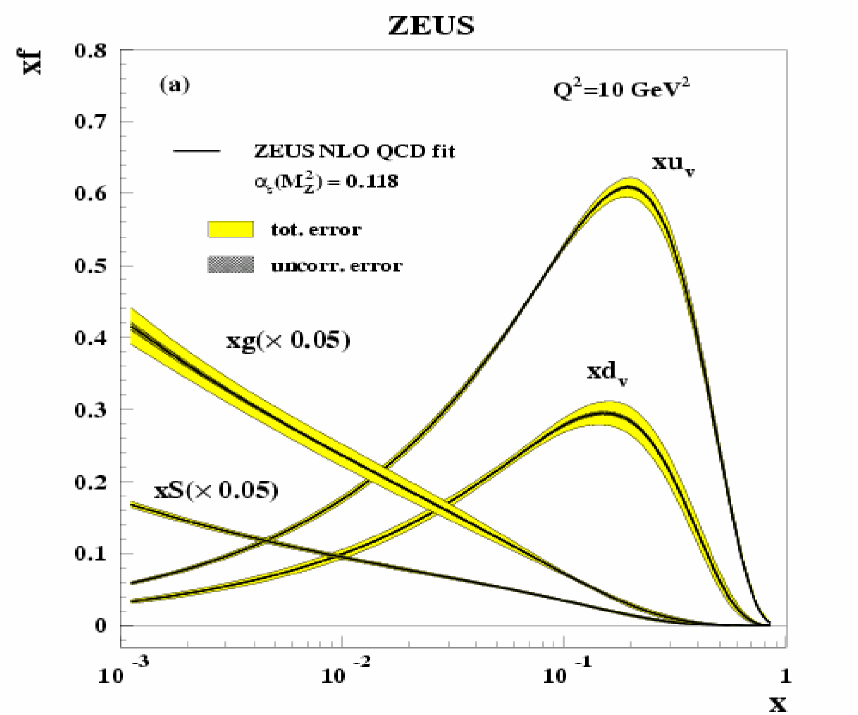
Quarks confined inside hadrons

QCD Factorization

$$\sigma = \sum \int dx_1 dx_2 f_q(x_1, Q^2) f_g(x_2, Q^2) \hat{\sigma}_{qg \to qg}$$



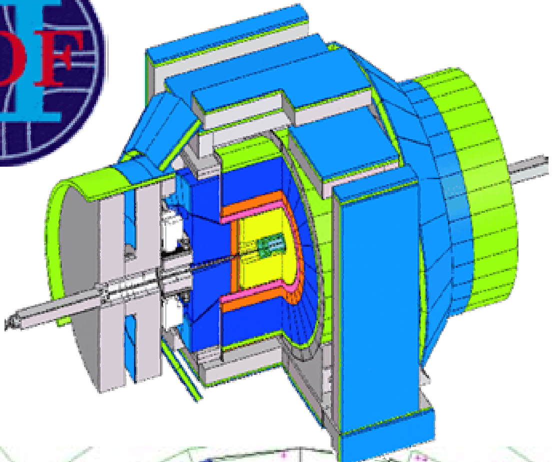
QCD: free quarks and gluons are not allowed…

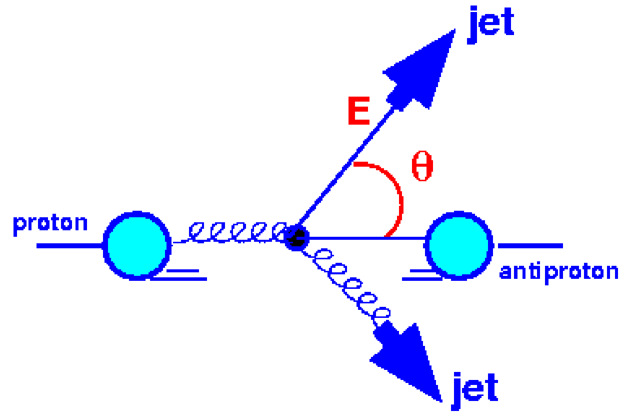


$\hat{\sigma}_{qg \to qg}$ Partonic cross section: calculated to a given order in pQCD

$f_q(x_1, Q^2)$ PDFs of parton inside the proton: needs experimental input (universal → can be used to compute different processes)

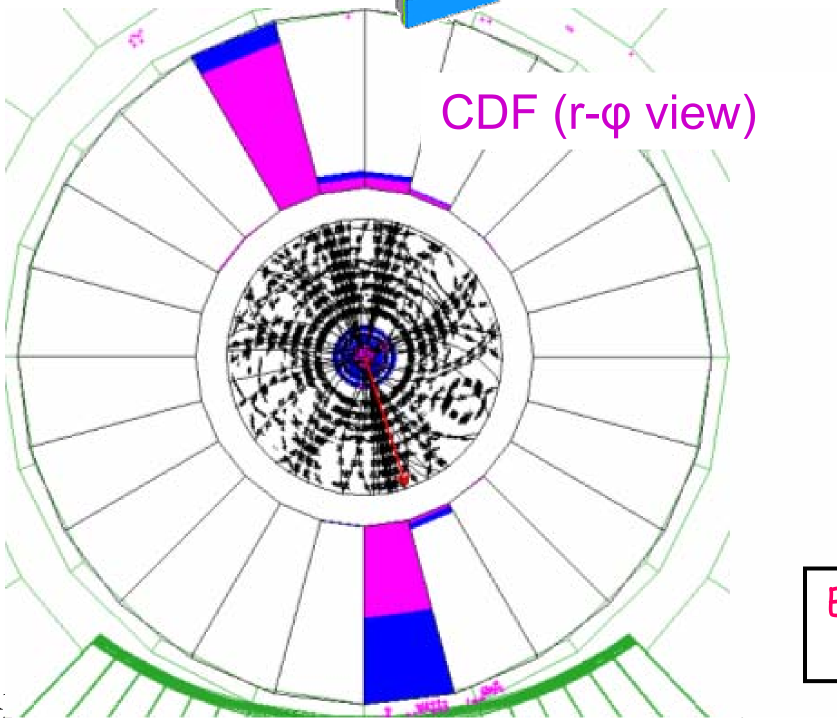
Dijet Event in CDF Detector



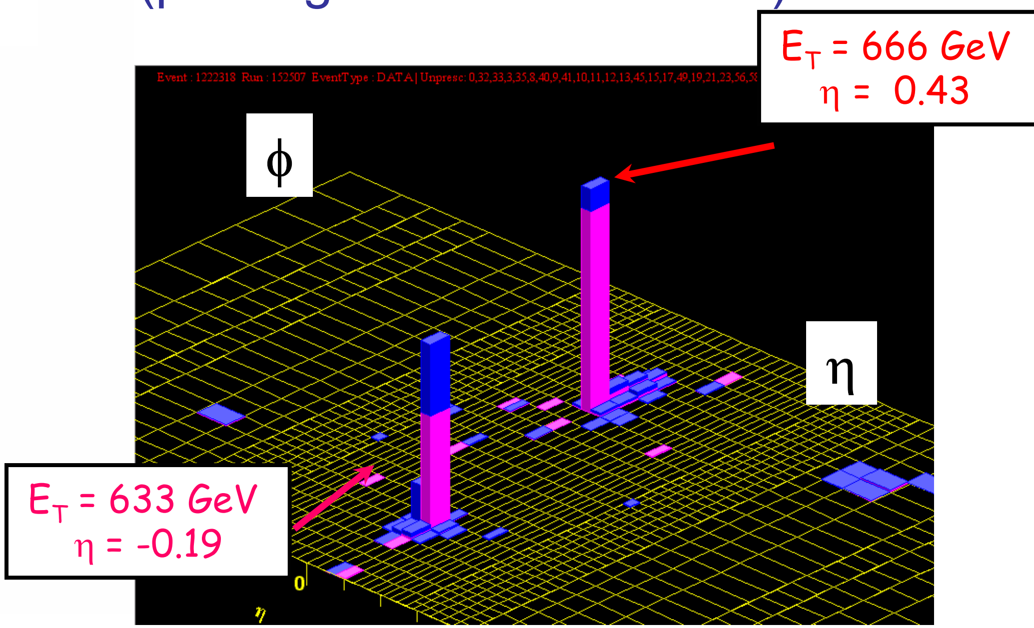


$$\eta = -\ln(\tan\frac{\theta}{2})$$

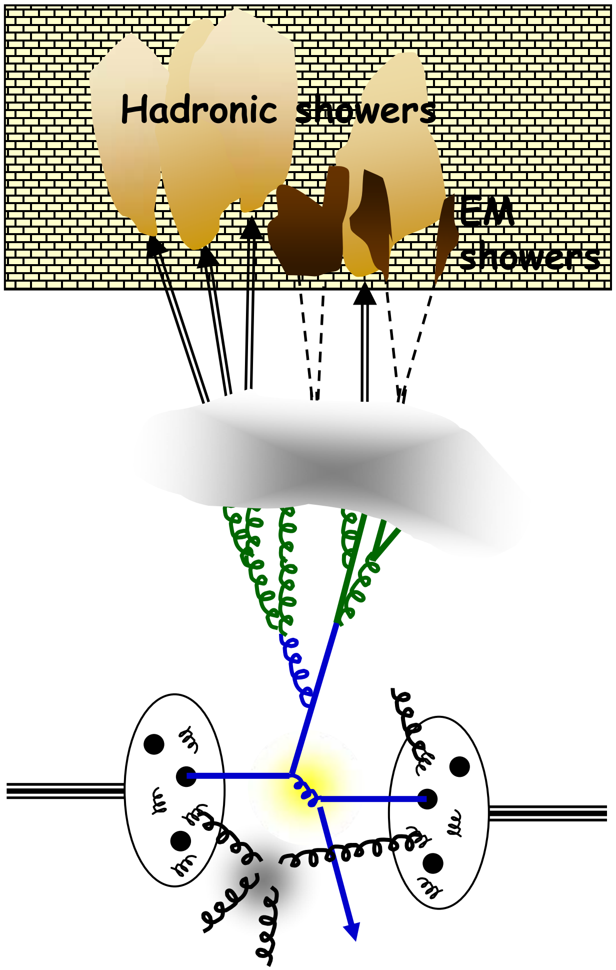
$$E_T = E\sin\theta$$



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



What do we really measure?



- Calorimeter Jets:
  - **Cluster calorimeter towers to jets by a jet algorithm**
  - **Correct for detector resolution and efficiency**
  - **Correct for "pile-up" – extra minimum bias events**
- Hadron Jets:
  - **Cluster (stable) particles in a jet algorithm using MC – correct data for difference of MC particle jet to MC calorimeter jet**
- Parton Jets:
  - **Correct particle level jets for fragmentation effects**
  - **Correct for particles from the 'Underlying Event' (soft initial and final state gluon radiation and beam remnant interactions)**

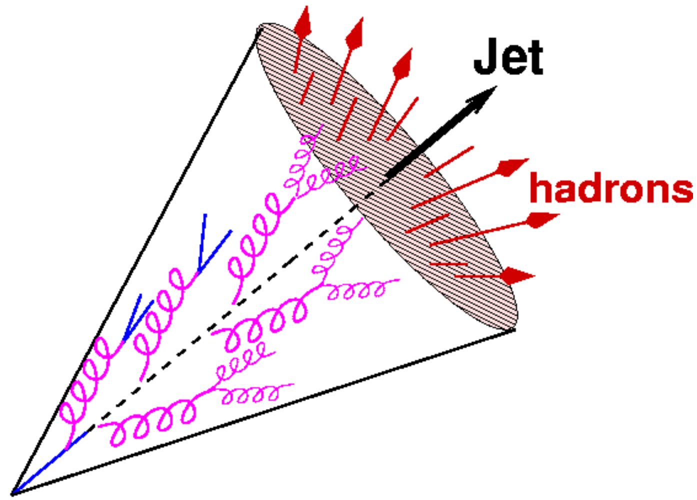
Measurement = PDF + pQCD ME + pQCD Approximation + UE + Had + Algo

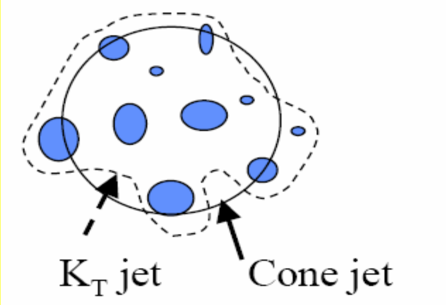
Jet Algorithms

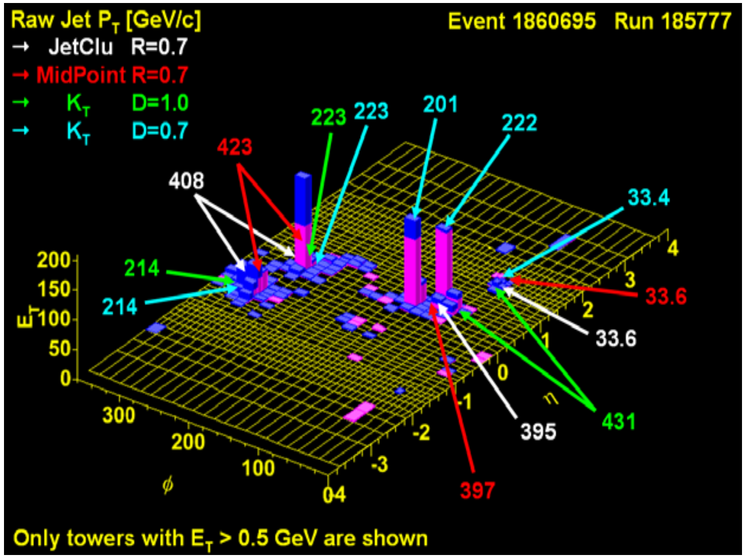
Jets are collimated sprays of hadrons originating from the hard scattering

Appropriate jet search algorithms are necessary to define/study hard physics and compare with theory

Different algorithms correspond to different observables and give different results!







K_T

Cluster particle/towers

Based on their relative p_T

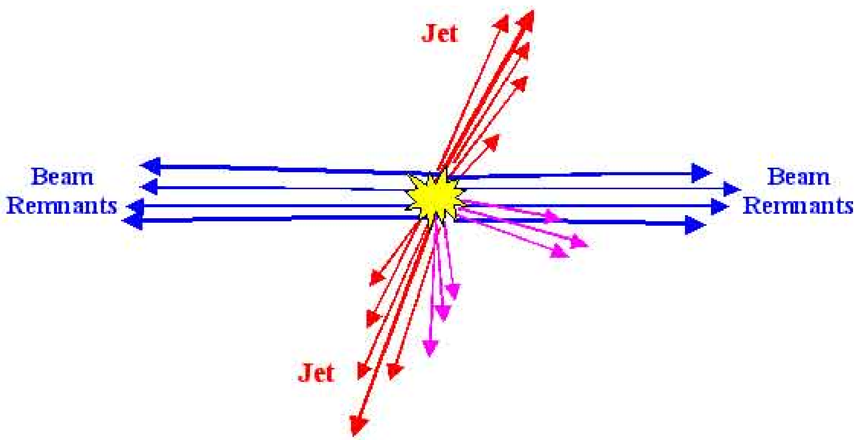
Infrared and coll. safe

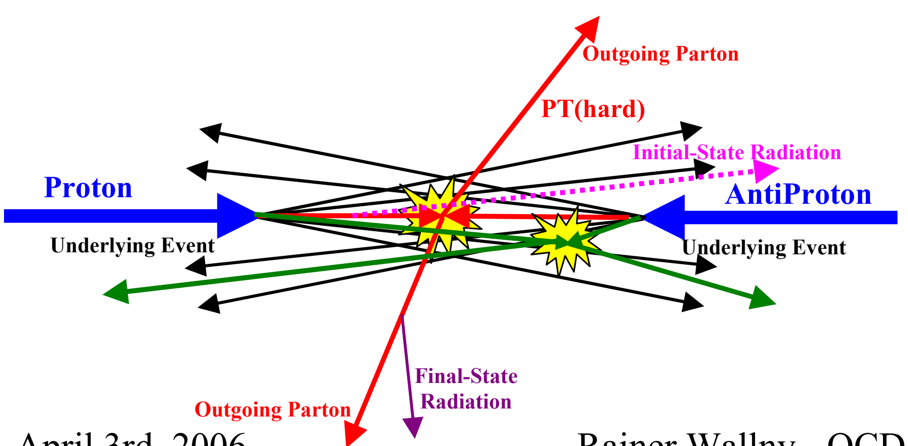
No merging/spitting

MidPoint (cone)

Cluster particle/towers based on their proximity in the η-ϕ plane

The “Underlying Event”





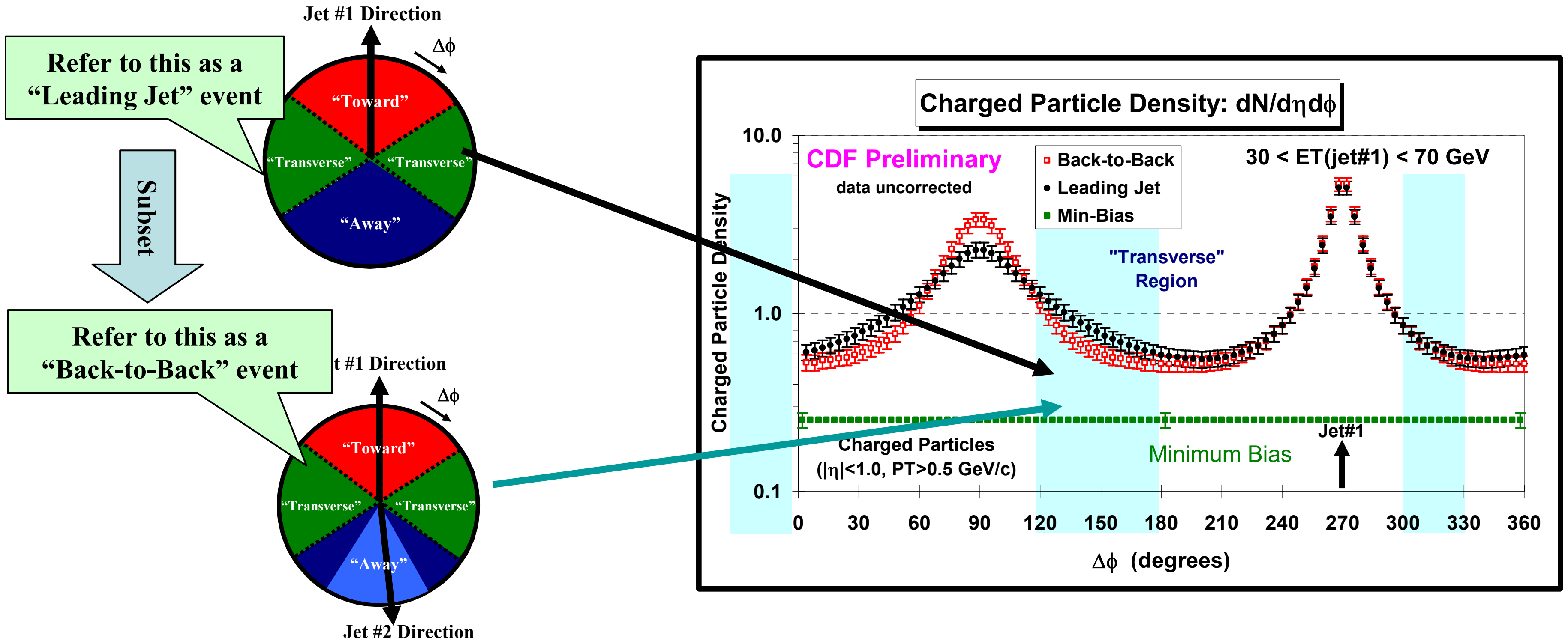
The hard scattering process:

- Outgoing two jets
- hard initial & final state radiation

The “underlying event”:

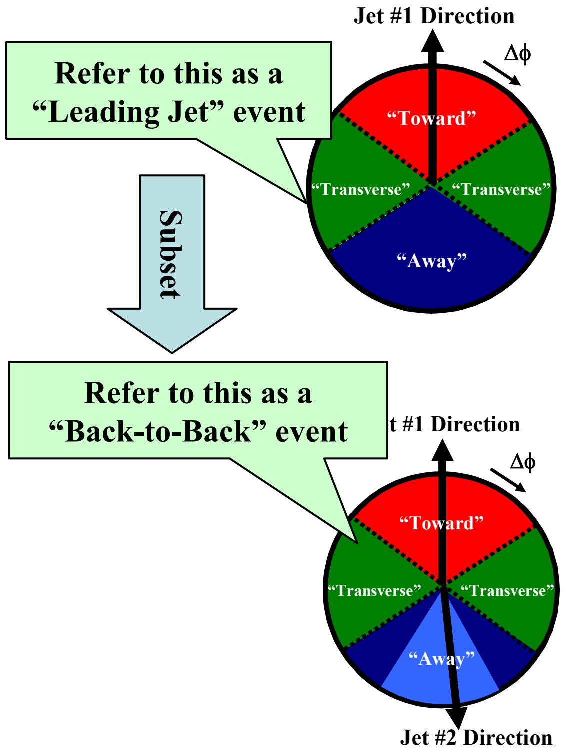
- soft initial & final-state radiation
- the “beam-beam remnants”
- possible multiple parton interactions

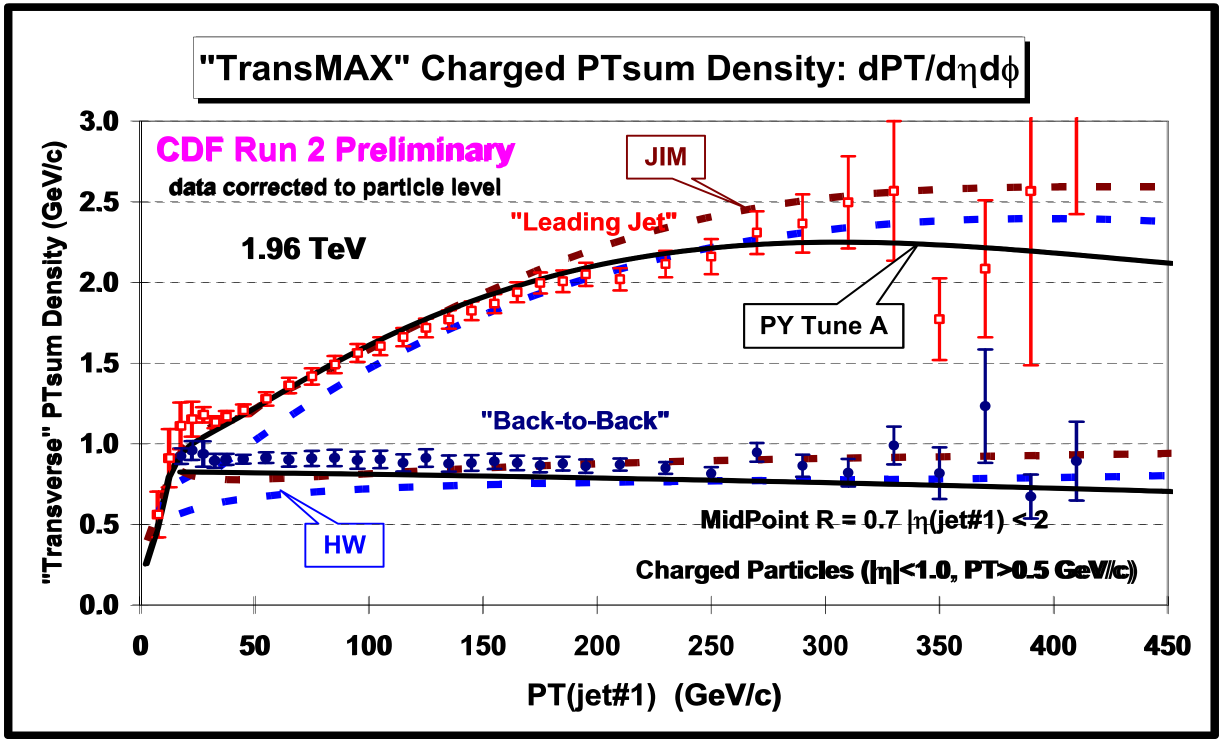
Charged Particle Density
Δφ Dependence



- Examine "transverse" region as defined by the leading jet ($|\eta| < 2$) or by the leading two jets ($|\eta| < 2$).
  - "Back-to-Back" $\Delta\phi_{12} > 150^o$ with almost equal transverse momenta ($P_T(jet\#2)/P_T(jet\#1) > 0.8$)
  - Suppression of hard initial and final state radiation

Monte Carlo Tuning of ‘Underlying Event’



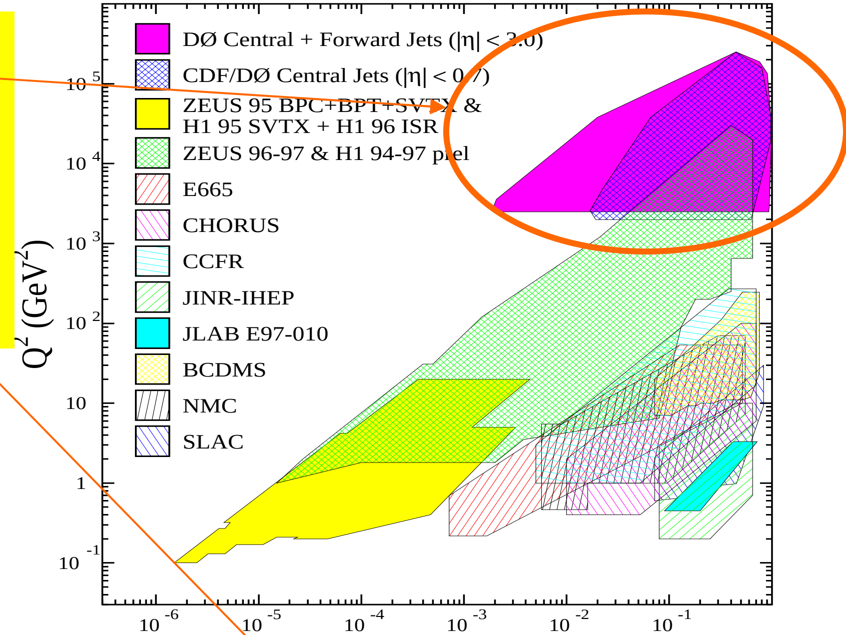


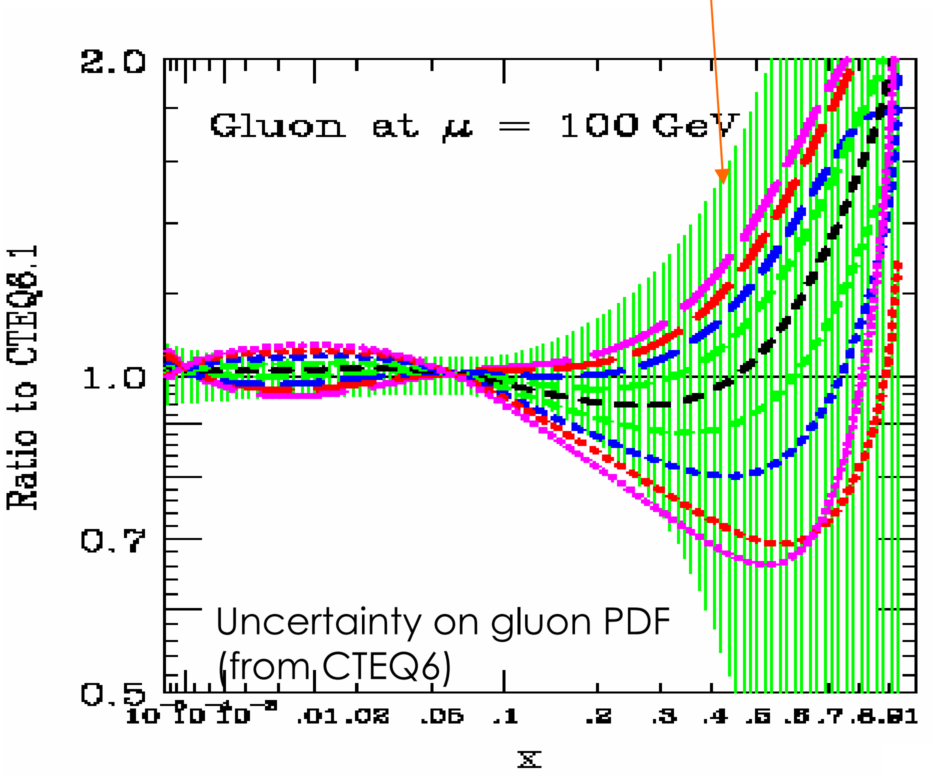
- Pythia (Tune A) tuned to CDF Run I data using charge particle densities in the transverse regions
- Run II data still described well by this Tune (both in ‘Leading Jet’ as well as ‘back to back’ jet events’)
- HERWIG underestimates UE at low pT – no multiple parton scattering present
- Multiple parton scattering added by JIMMY – agreement much better

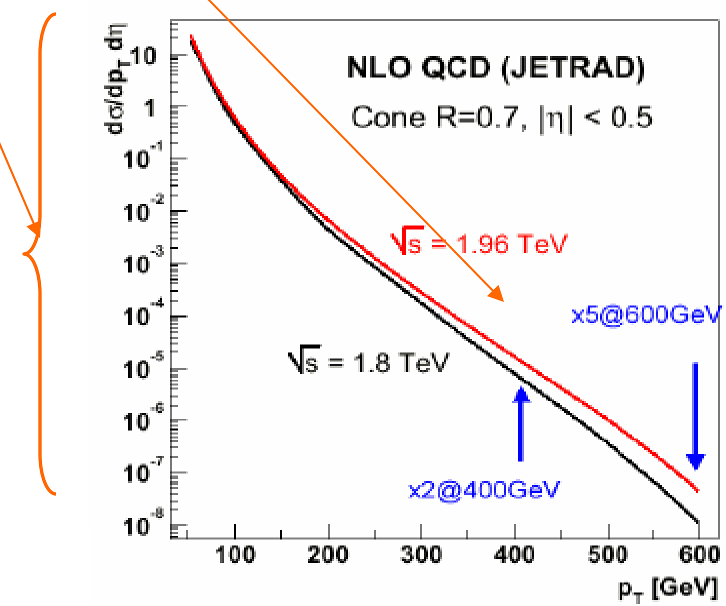
Inclusive Jet Production

Inclusive Jet Production

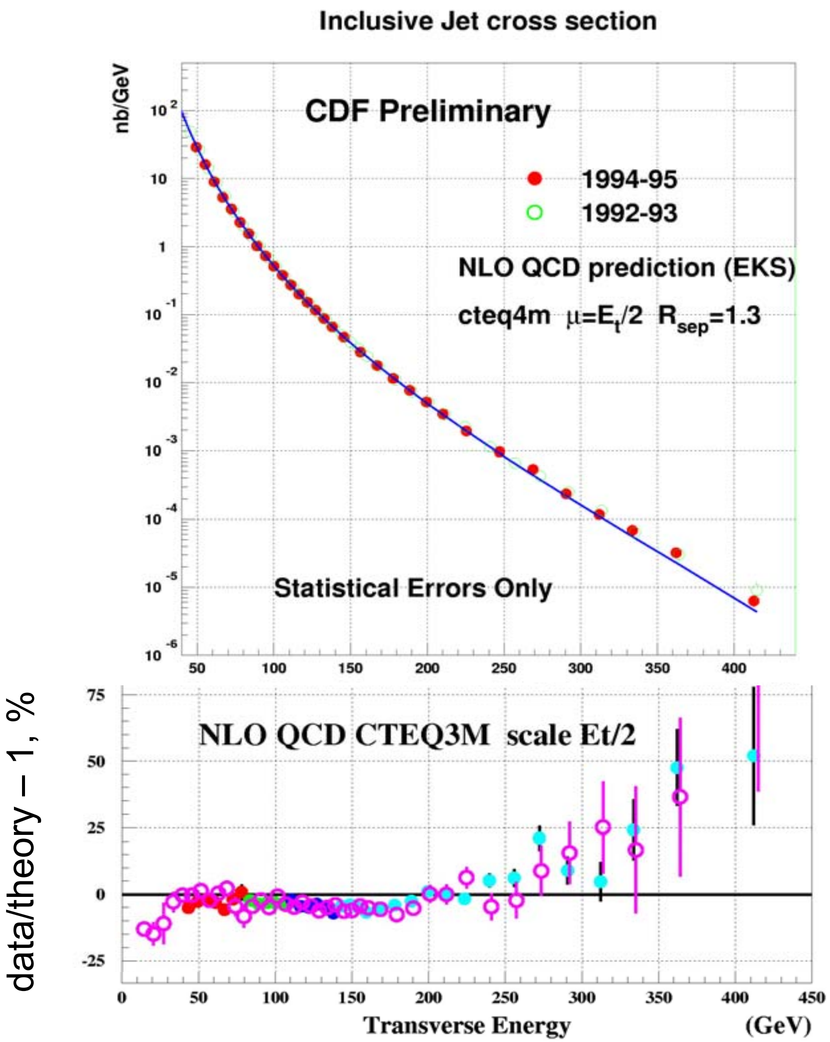
- Probes physics at small distances ≈10^{-19}m
- Higher reach in pT due to increased √s
- Test pQCD over more than 9 decades in σ
- Sensitive to PDF (gluon @ high-x)





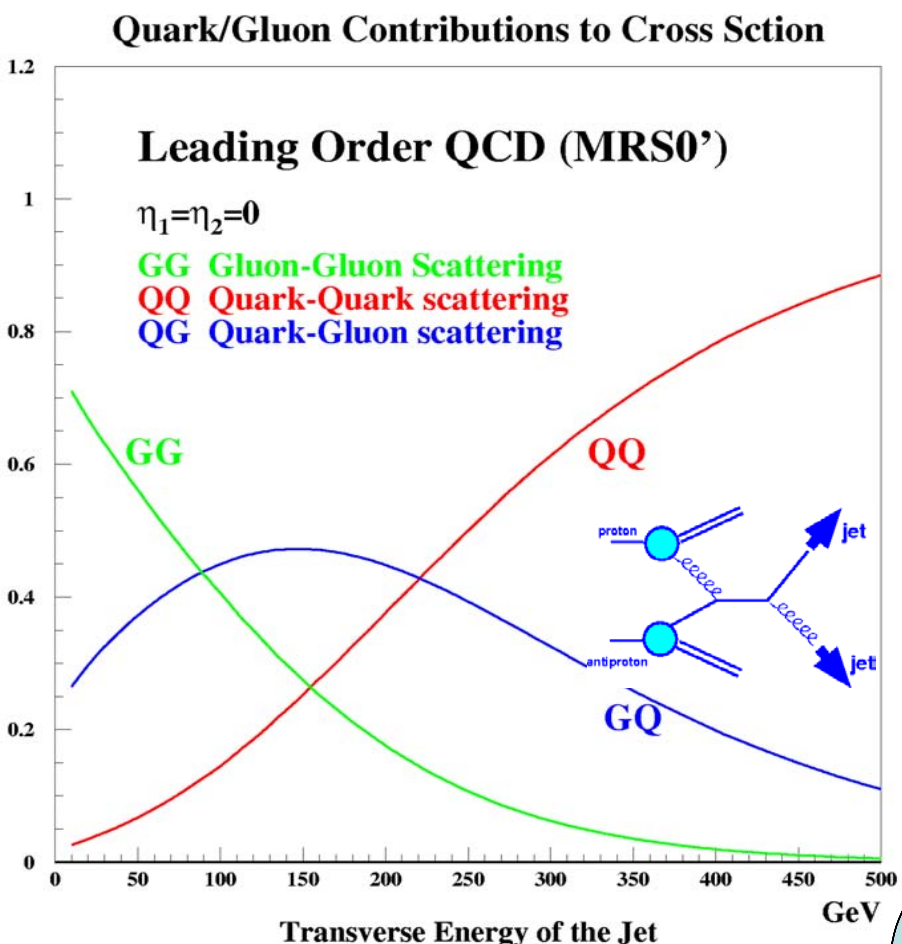


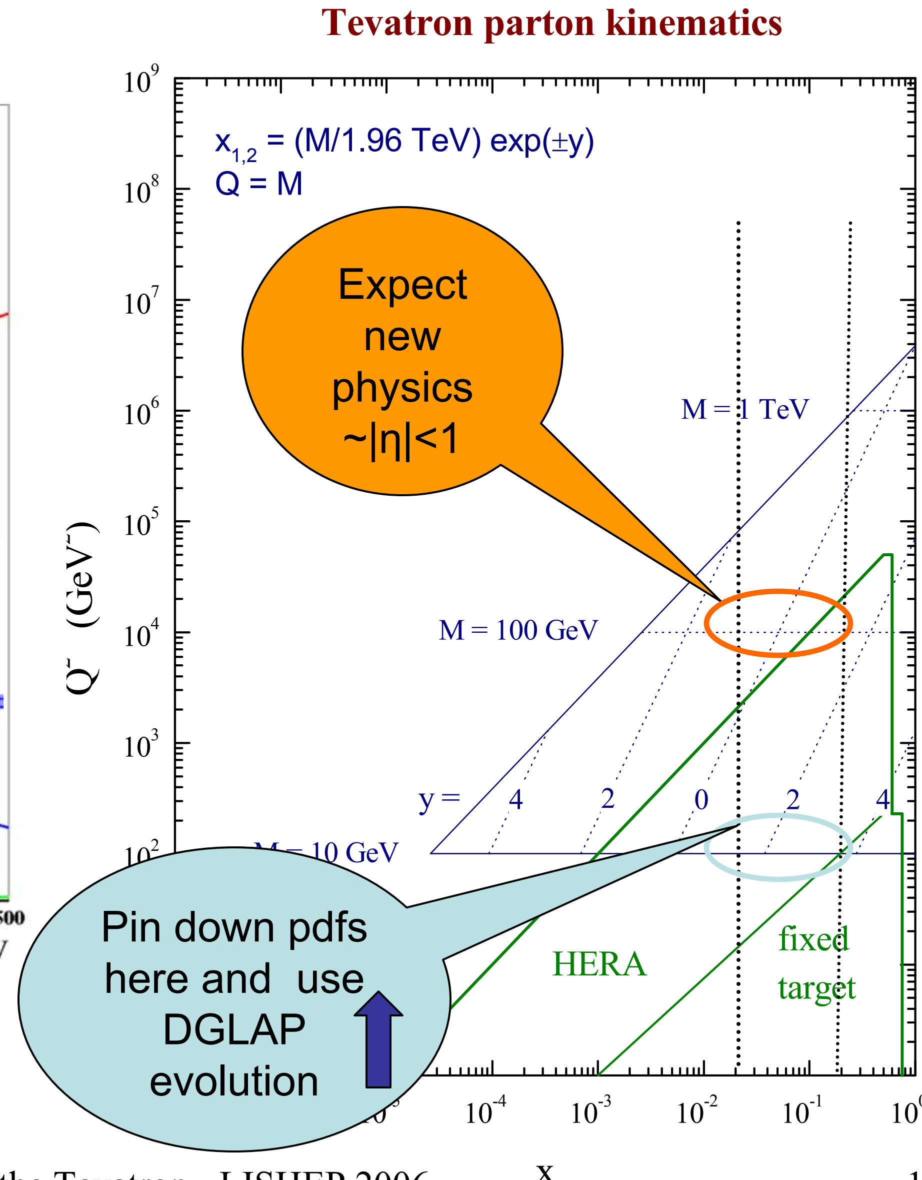
Inclusive Jet Production: Run I legacy



- Run I
  - Cone jet finding algorithm
  - Apparent excess at high pT, but within the overall systematic errors
  - Is it New Physics or parton distribution function effect ?
- Between Run I and Run II
  - Improved machinery of jet finding algorithms:
    - MidPoint Cone Algorithm
    - kT Algorithm

Inclusive Jet Production



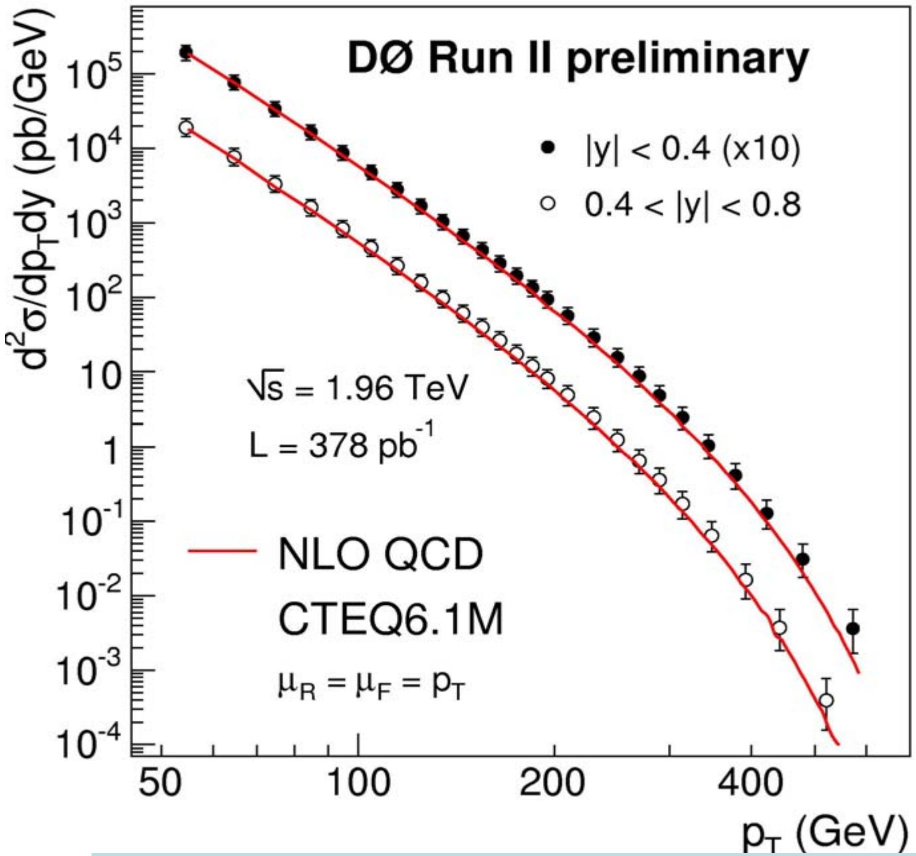


- Gluon contribution significant
- use forward jets to pin down pdfs versus new physics at higher Q^2 in central region

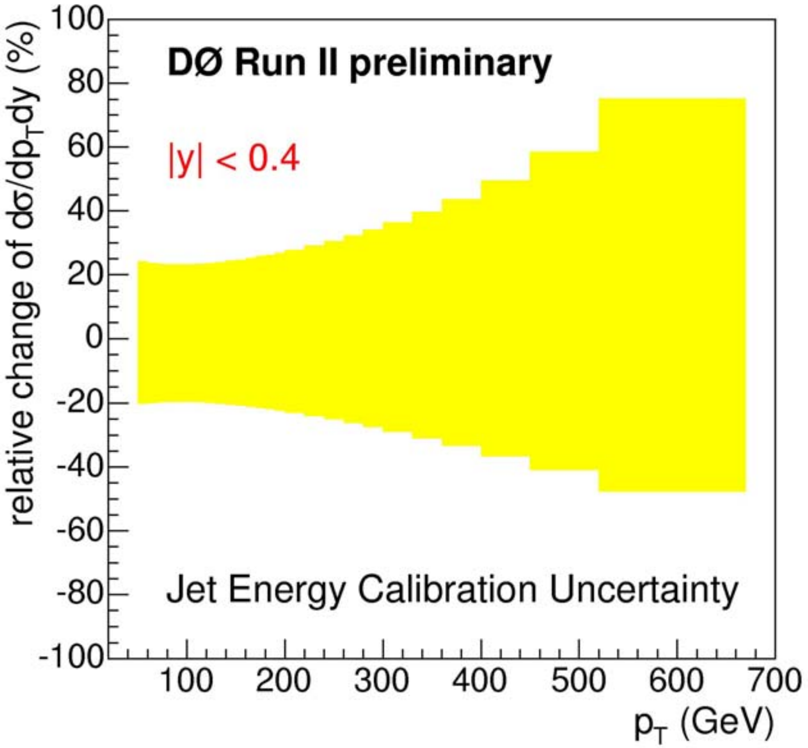
Inclusive Jet Cross Section
(MidPoint algorithm R=0.7)

- 2 regions in rapidity explored
  - $|y^{jet}| < 0.4$
  - $0.4 < |y^{jet}| < 0.8$

L = 380 pb^{-1}



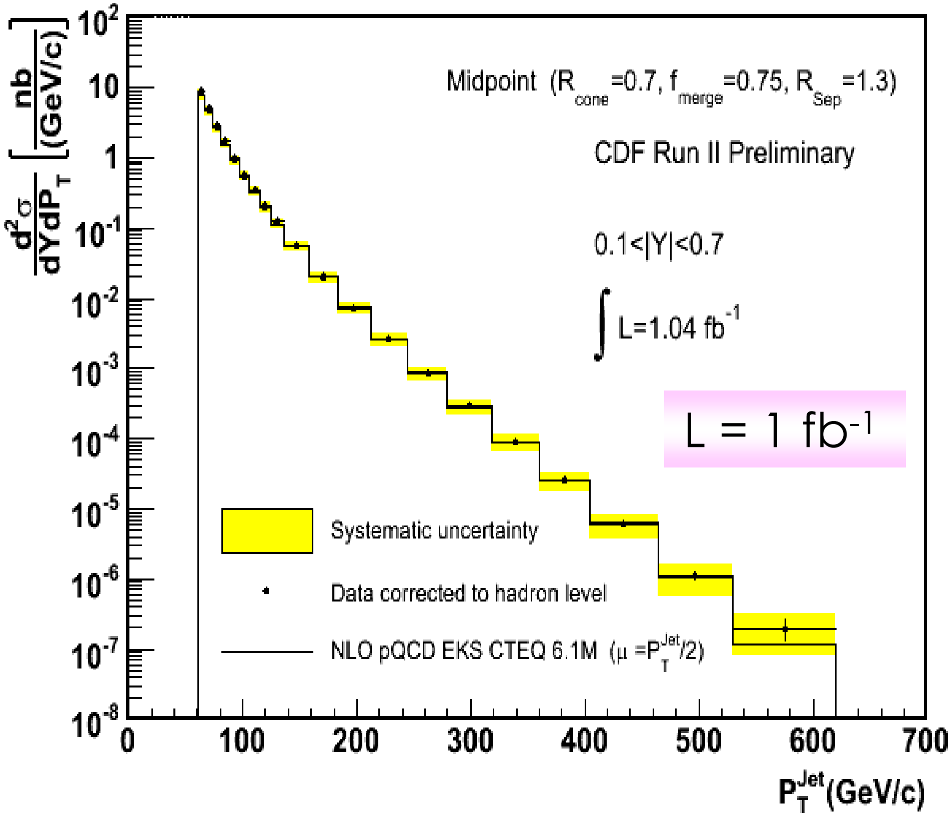
Direct comparison of hadron to parton level (i.e. neglect fragmentation and UE)



Jet energy scale uncertainty ~5%
- ➔ cross section uncertainty of 20-80 %
- ➔ dominant error
- ➔ 770 pb^{-1} update in preparation with improved jet enery scale calibration

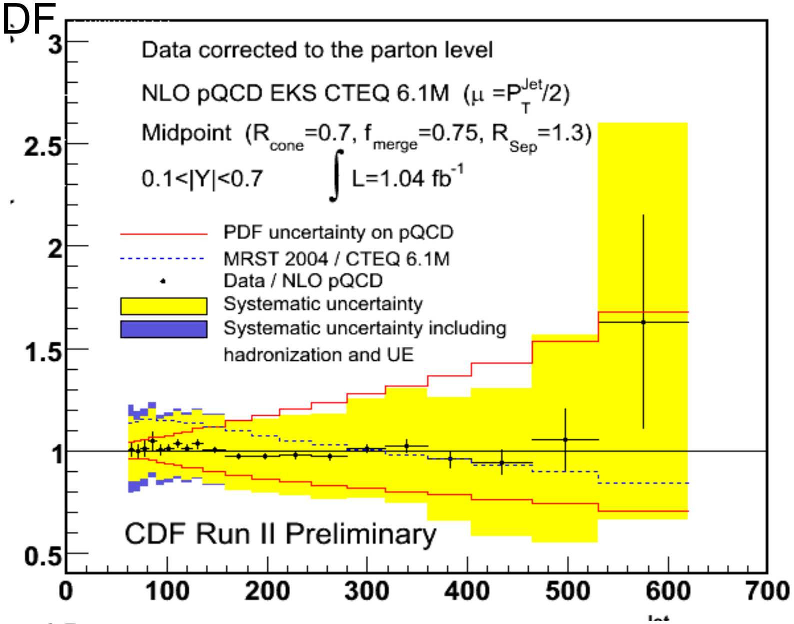
Inclusive Jet Cross Section

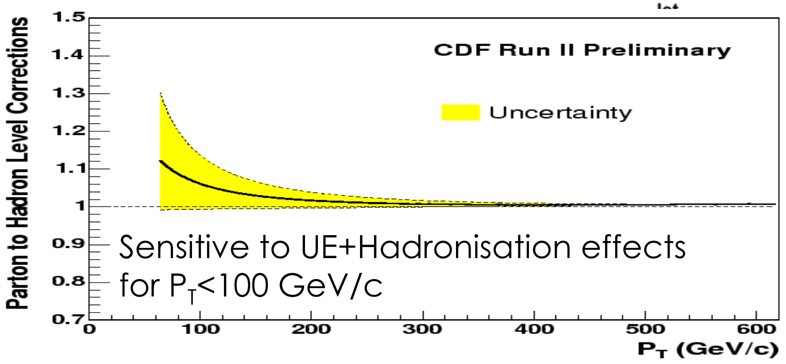
- MidPoint algorithm R = 0.7
- Central jets: $0.1<|y^{jet}|< 0.7$
- More than 8 orders of magnitude covered



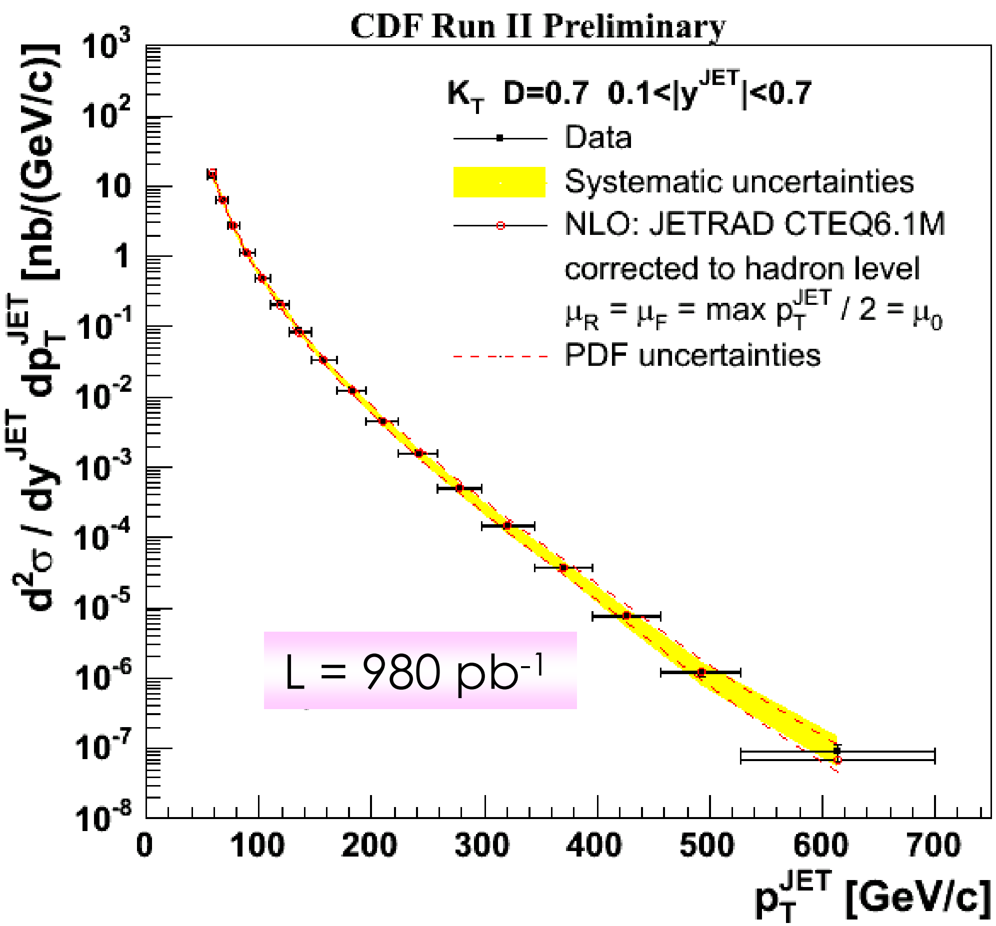
Good agreement with NLO predictions

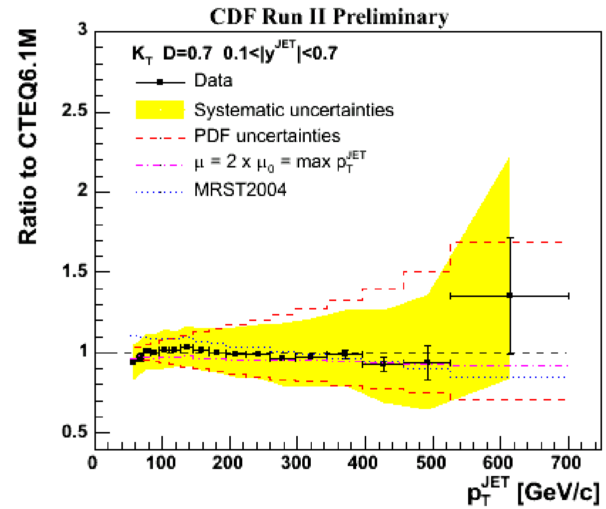
- Data dominated by Jet Energy Scale (JES) uncertainties (2-3%)
- Theory uncertainty dominated by high x gluon PDF

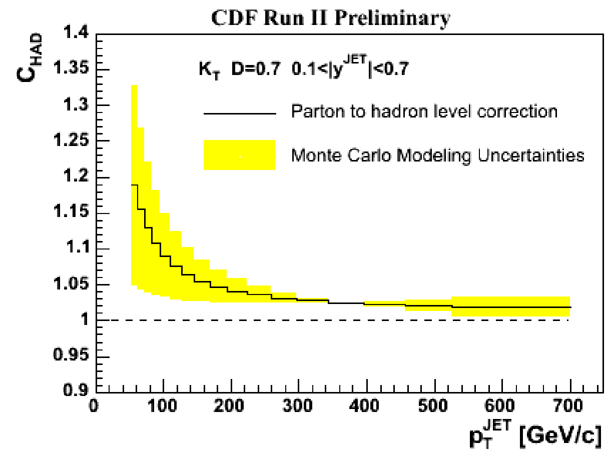




Inclusive Jet Cross Section with kT algorithm





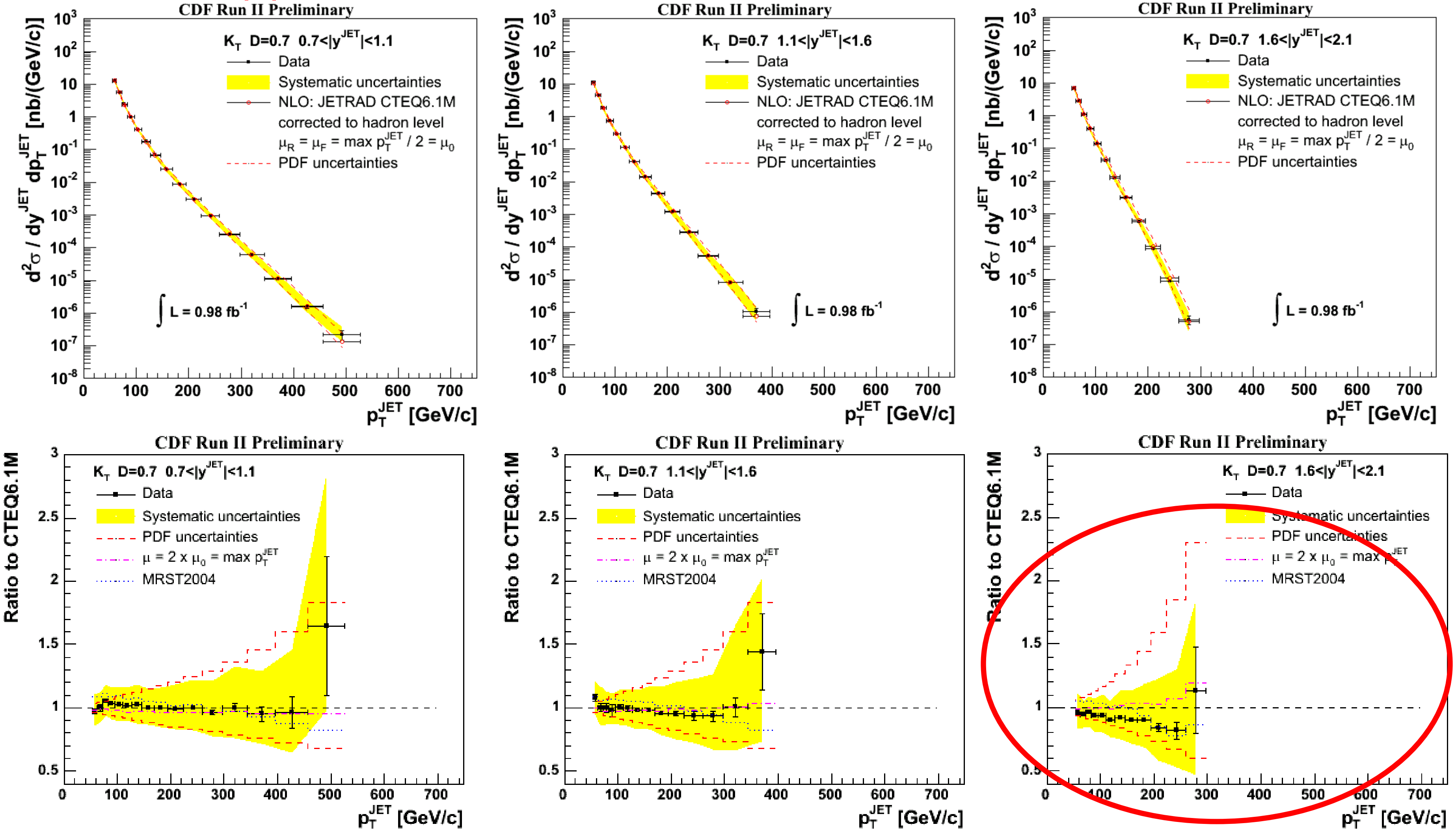


K_T algorithm performs well in hadron collisions (i.e. with an underlying event)

Good agreement with NLO pQCD (both data and theory compared at hadron level)

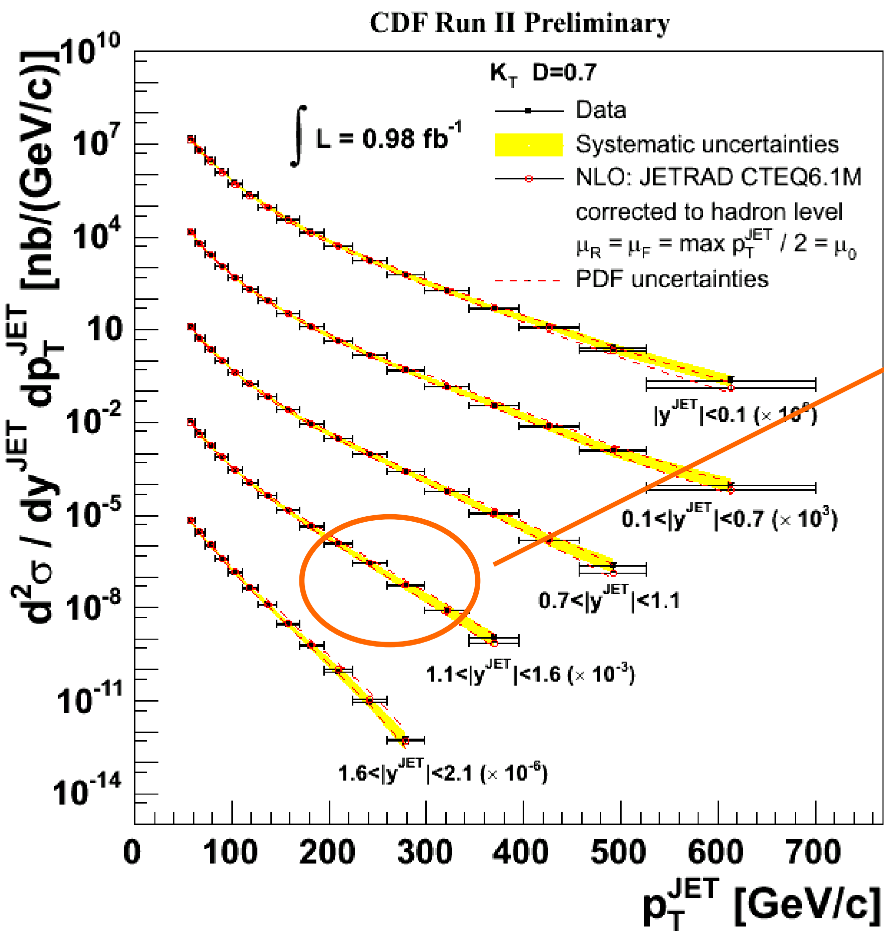
Forward jets (k_T algorithm)

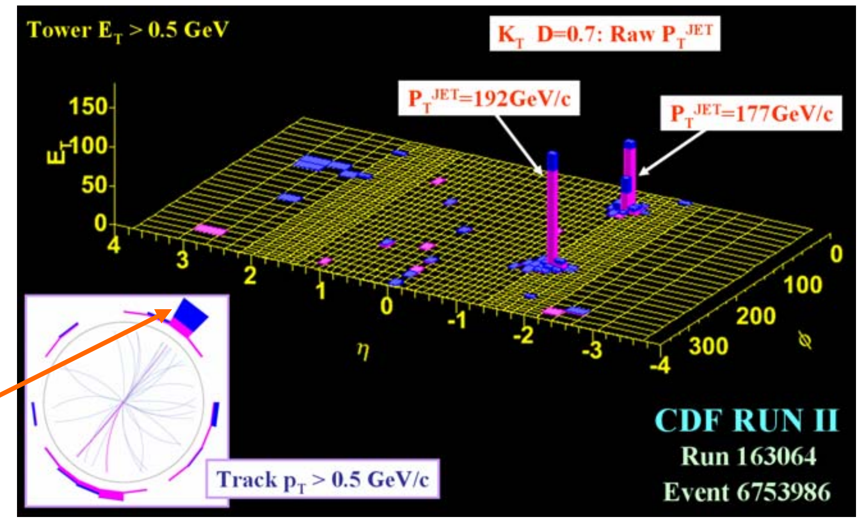
0.7<|Y|<1.1 | **1.1<|Y|<1.6** | **1.6<|Y|<2.1**

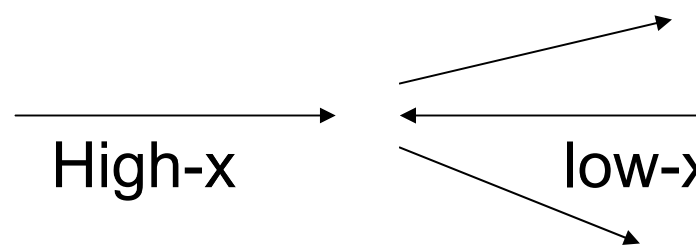


Data will further constrain high x gluon in global fits

High-x Event

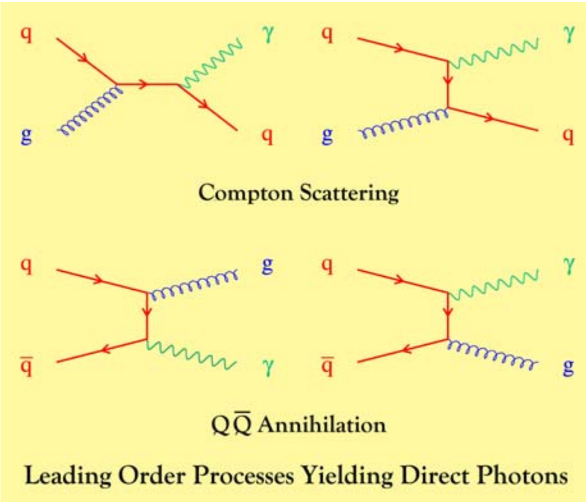


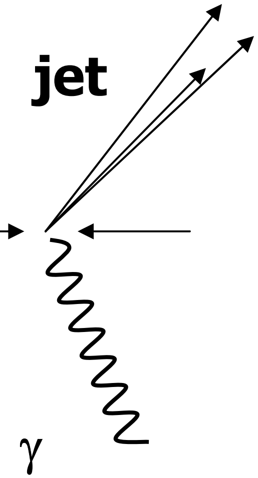


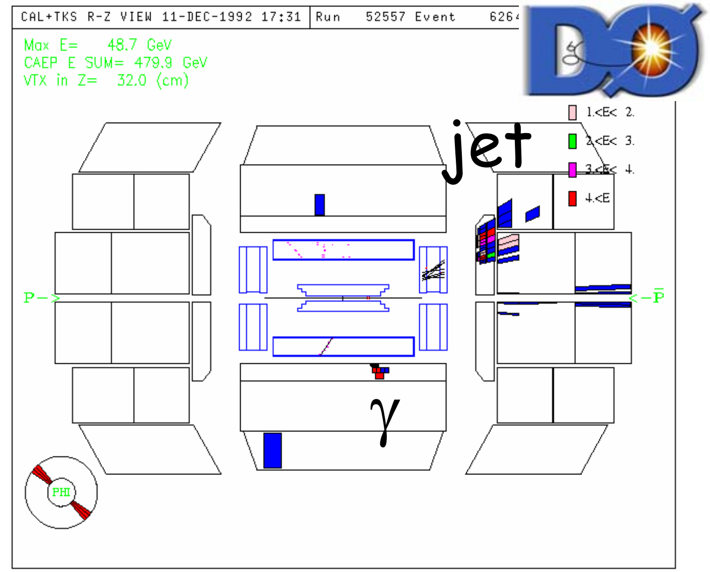


A "Rutherford type" parton backscattering

Direct Photon Production



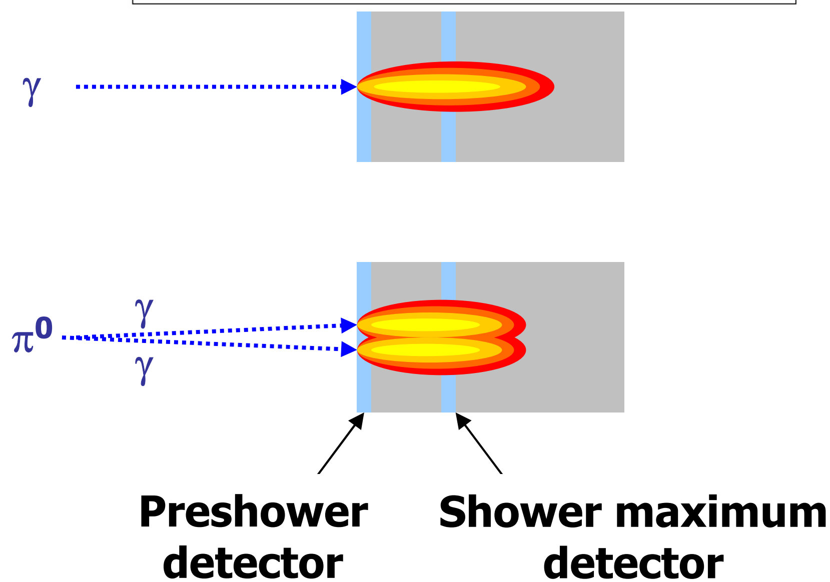




Using prompt photons one can precisely study QCD dynamics:

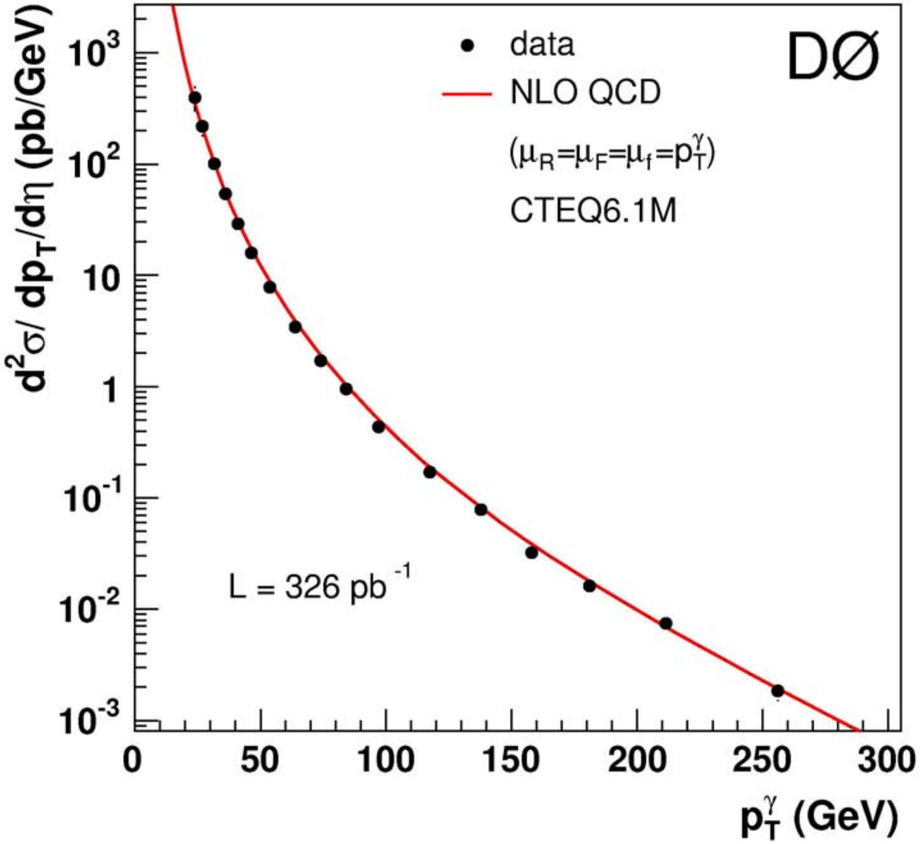
- Well known coupling to quarks
- Give access to lower Pt
- Not dependent on jet energy scale
- constrain of gluon PDF

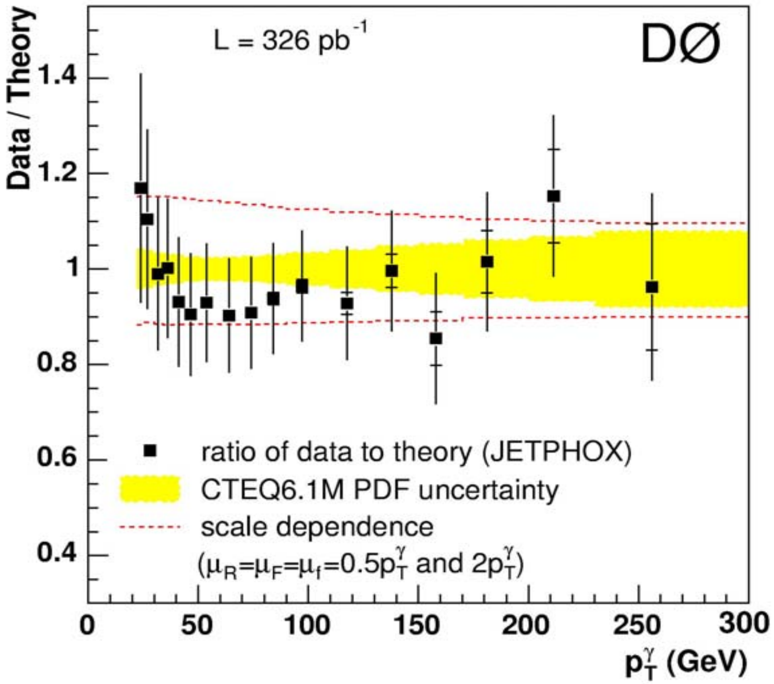
BUT: Experimentally difficult because of large background from π^0 decays



Inclusive γ cross section

- Highest $p_T(\gamma)$ is 442 GeV/c
  - 3 events above 300 GeV/c not displayed



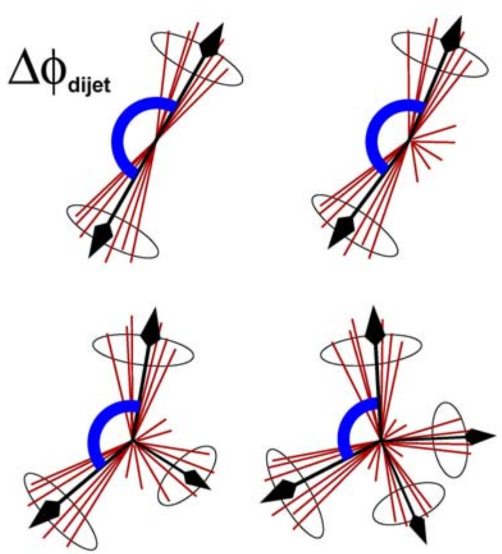


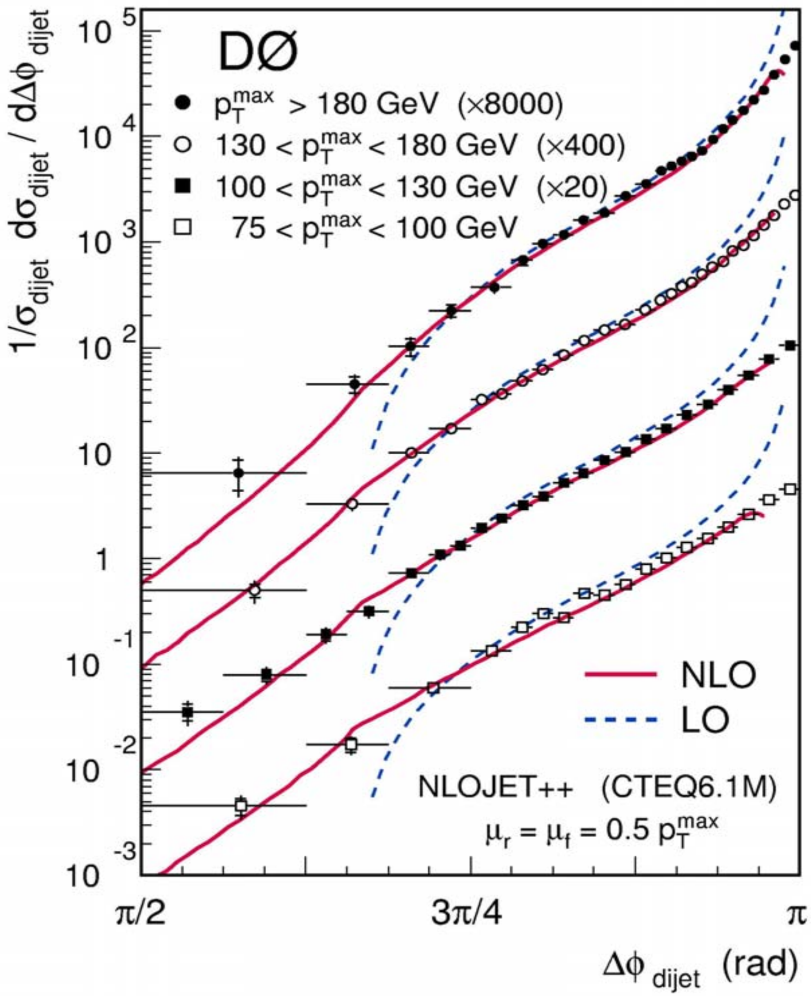
Good agreement with pQCD NLO

- Errors ~20%
- Very promising at ~ fb^{-1} luminosities to constrain gluon PDF at high x

Jet-Jet Correlations

Jet#1-Jet#2 $\Delta\phi$ Distribution



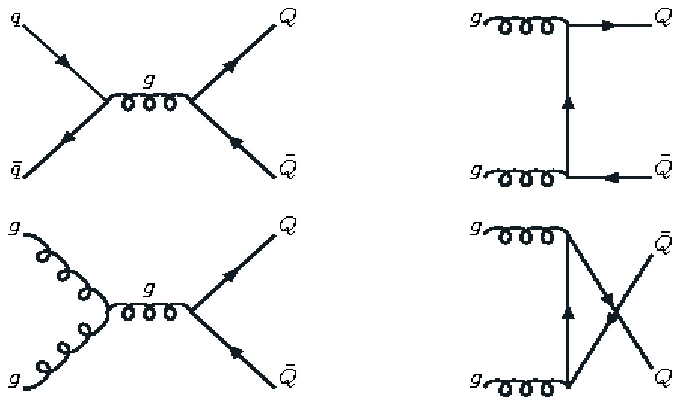


- MidPoint Cone Algorithm (R = 0.7, f_{merge} = 0.5)
- L = 150 pb^{-1} (Phys. Rev. Lett. 94 221801 (2005))
- Data/HERWIG and Data/PYTHIA (increased ISR) agreement good.
- Data/NLO agreement within 5-10% (pdf uncertainty <20%)

Inclusive b-jet Production

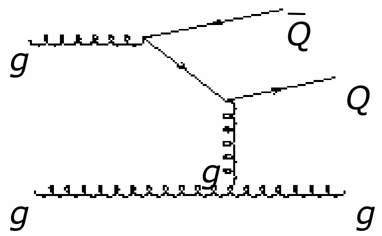
B-quark production in hadron collisions

Leading Order

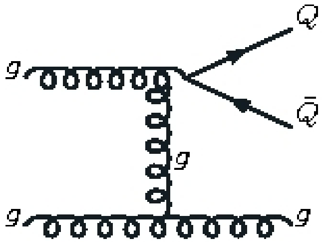


Flavor creation

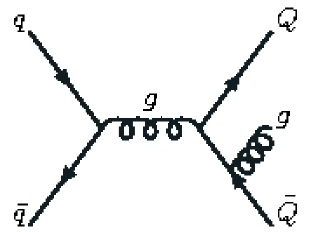
Next to Leading Order



Flavor excitation



Gluon splitting



other radiative corrections..

Experimental inputs are B-Hadrons or b-jets rather than b-quark

Proton structure

$$\frac{d\sigma\left(p\bar{p} \rightarrow BX\right)}{d\,p_T(B)} = \frac{d\sigma\left(q\bar{q}\,/\,gg\,/\,qg \rightarrow bX\right)}{d\,p_T(b)} \otimes F^{p\bar{p}} \otimes D^{b\rightarrow B}$$

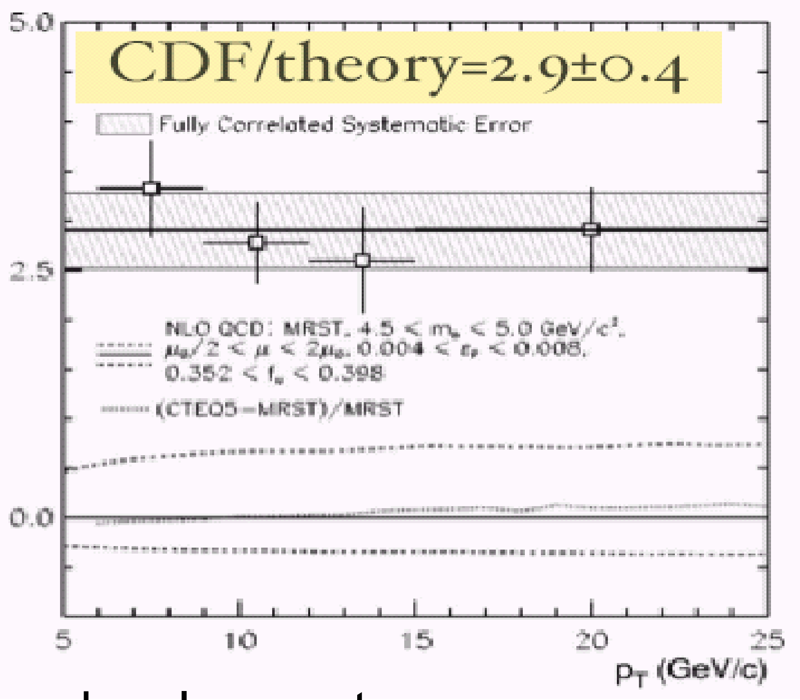
NLO QCD

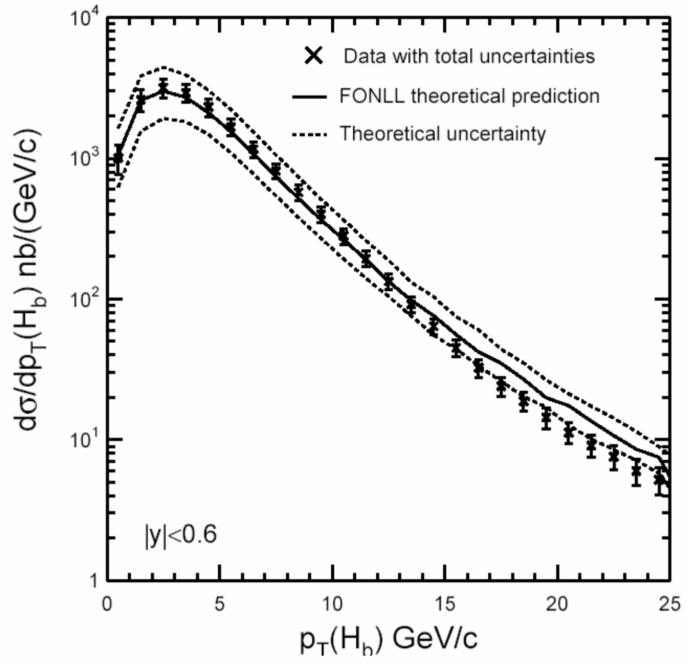
Fragmentation

=> Another stringent test of NLO QCD

Run I Legacy

- In Run I, a factor 3 discrepancy was reported between theory predictions and experimental data by both CDF and DØ in B-hadron cross sections



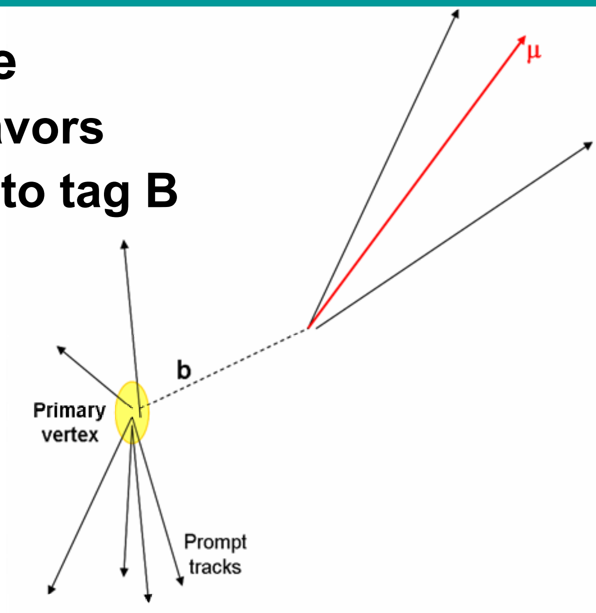


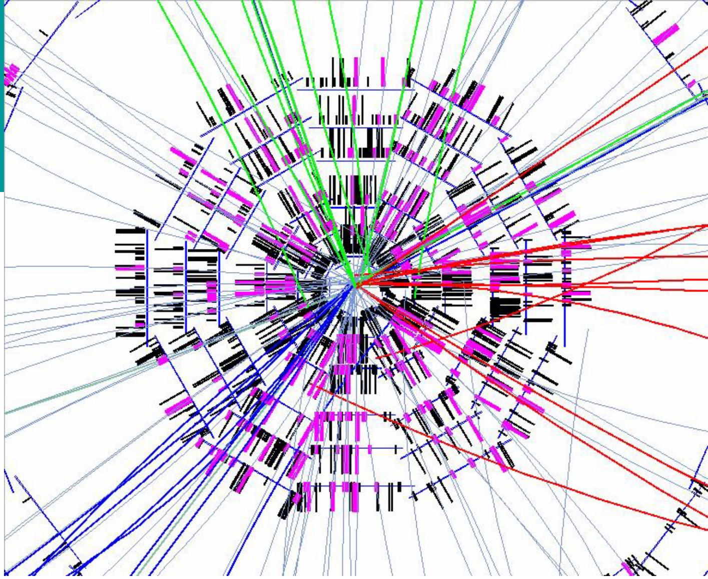
- Recent theory development: FONLL (Cacciari et. al.) – NLO resummed
- very good agreement with more exclusive B-hadron production
- check for more inclusive observable – b-jet production – comparison with NLO only

$$\sigma(p\bar{p} \to H_b X, |y| < 0.6) = 17.6 \pm 0.4(stat)^{+2.5}_{-2.3}(syst)\ \mu\text{b}$$

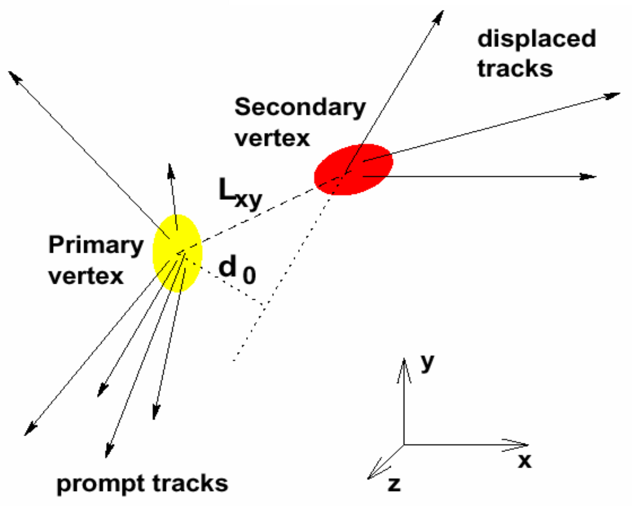
Tagging B hadrons

- **B hadrons are massive**
  - **decay into lighter flavors**
  - **use decay products to tag B**
  - **'Soft Lepton Tag'**





- **B hadrons are long lived**
  - **$c\tau$ ~ 460 μm**
  - **give rise to secondary vertices**
  - **tracks from secondary vertex have non-vanishing impact parameter d_0 at primary vertex**
  - **'Secondary Vertex Tag' & 'Jet probability'**

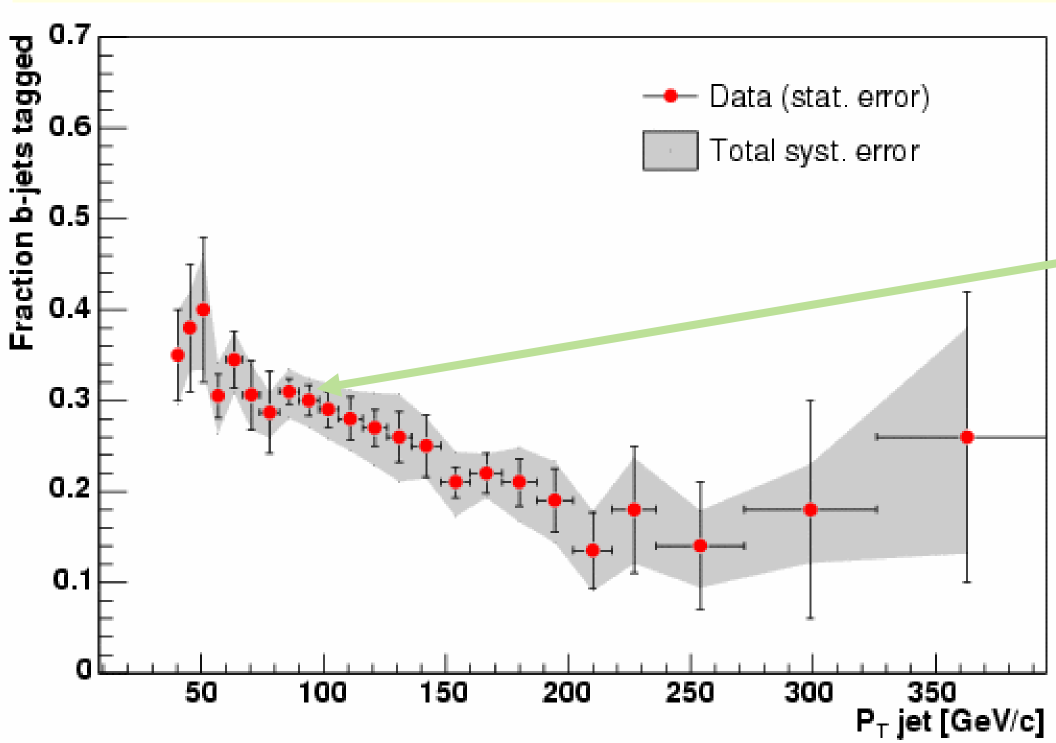


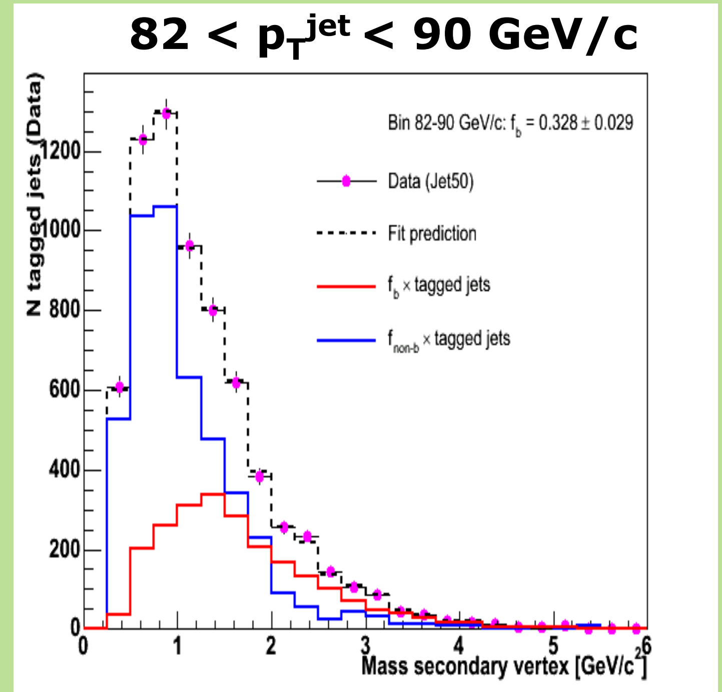
Fraction of tagged b-jets

Extract fraction of b-tagged jets from data using shape of mass of secondary vertex as discriminating quantity

→bin-by-bin as a function of jet p_T

→2 component fit:b and non-b templates (Monte Carlo PYTHIA)

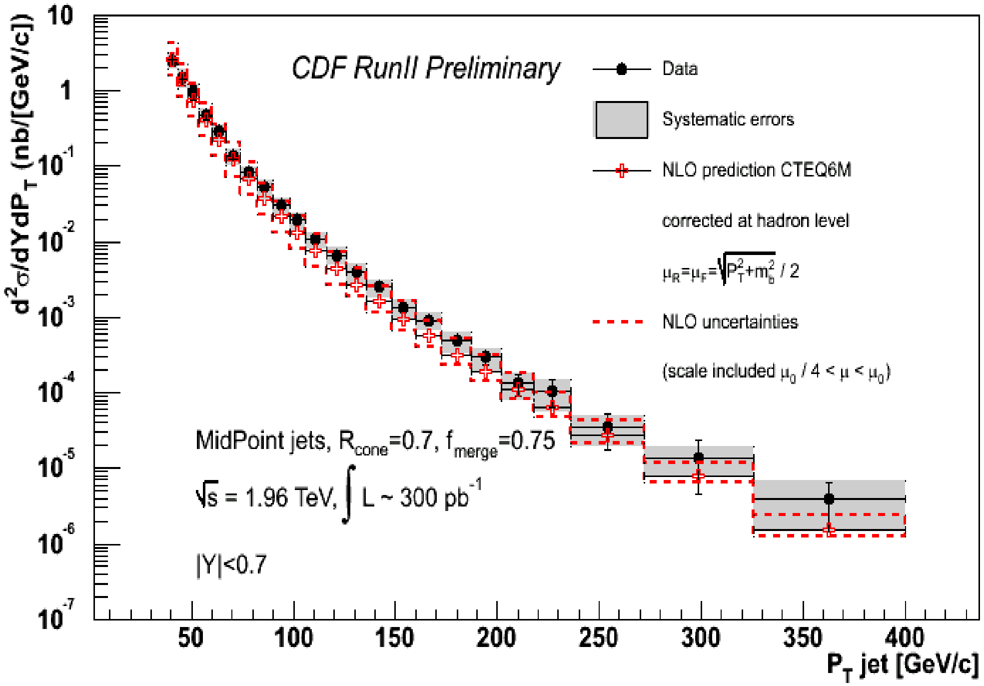


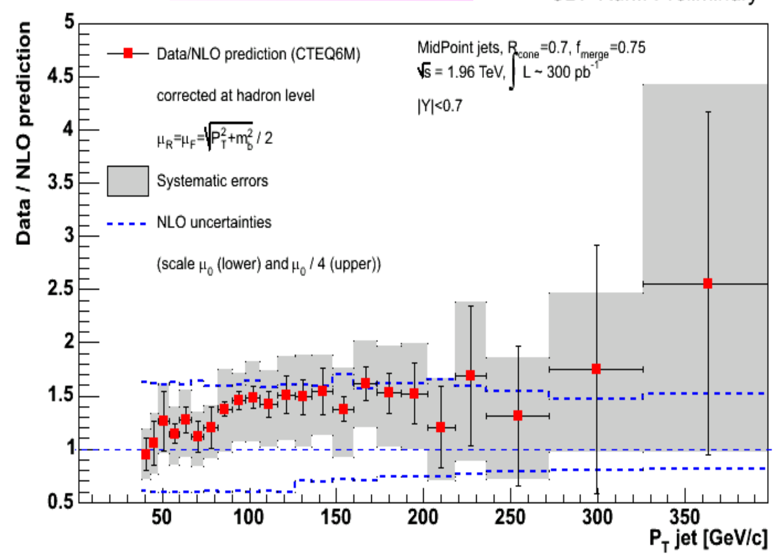


High P_T b-jet cross section

- Beauty production → Test of pQCD
- MidPoint jets: R = 0.7, | y ^{jet} | < 0.7
- Reconstruct secondary vertex from B hadron decays (b-tagging)
- Shape of secondary vertex mass used to extract b-fraction from data

L = 300 pb^{-1}





- More than 6 orders of magnitude covered
- Data systematic uncertainties dominated by Jet Energy Scale and b-fraction uncertainties
- **Main uncertainties on NLO due μ_R/μ_F scales**

Agreement with pQCD NLO within systematic uncertainties
→ Sensitive to high order effect (NNLO)

The b-bbar DiJet Cross-Section

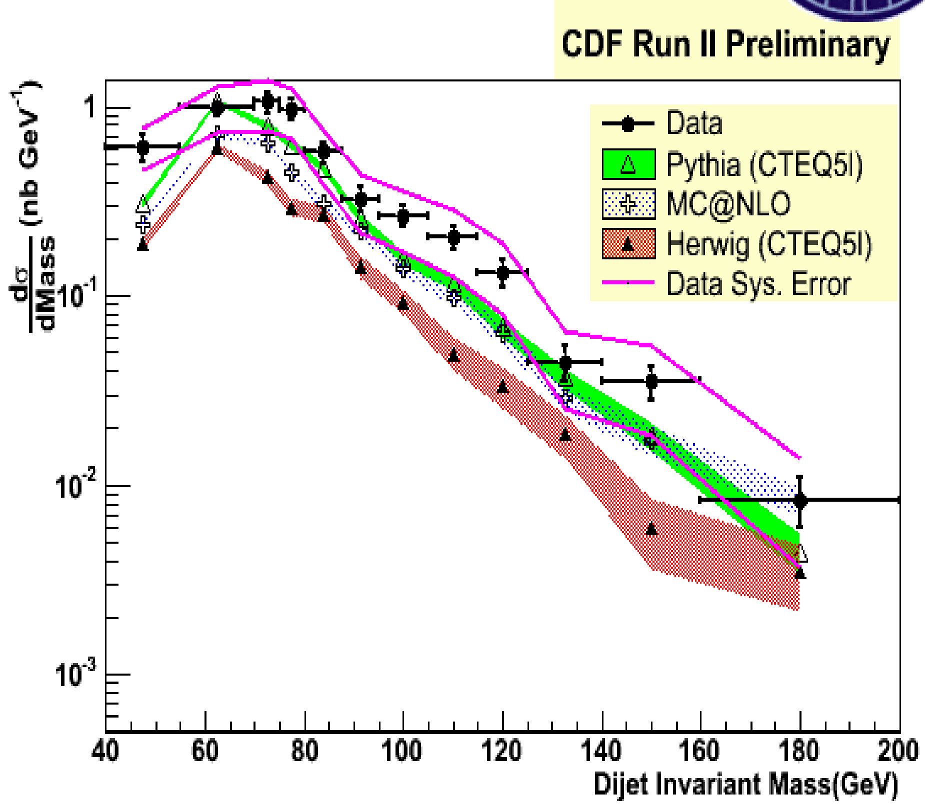
- E_T(b-jet#1) > 30 GeV, E_T(b-jet#2) > 20 GeV, $|\eta$(b-jets)$|$ < 1.2.

Preliminary CDF Results:

$$\sigma_{bb} = 34.5 \pm 1.8 \pm 10.5 \text{ nb}$$

QCD Monte-Carlo Predictions:

PYTHIA Tune A CTEQ5L	38.71 ± 0.62nb
HERWIG CTEQ5L	21.53 ± 0.66nb
MC@NLO	28.49 ± 0.58nb



- Large Systematic Uncertainties:
  - Jet Energy Scale (~20%).
  - b-tagging Efficiency (~8%)
- PYTHIA vs.Data ~ 1.4 flat
  - expect due NLO corrections

The b-bbar DiJet Cross-Section

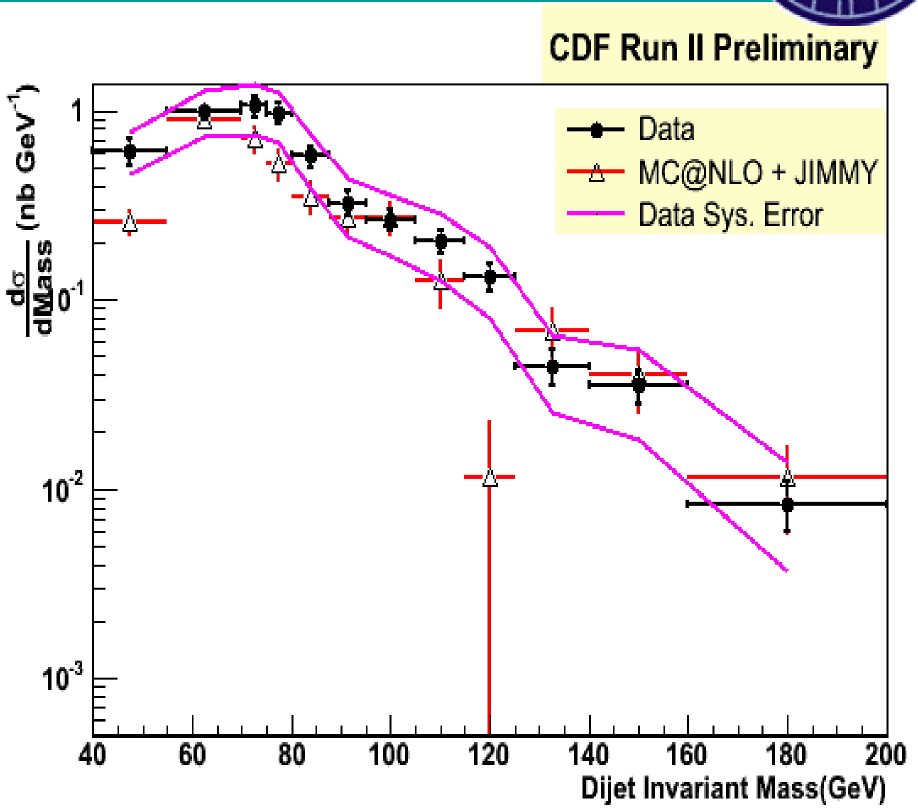
- E_T(b-jet#1) > 30 GeV, E_T(b-jet#2) > 20 GeV, $|\eta$(b-jets)$| < 1.2$.

Preliminary CDF Results:

$$\sigma_{bb} = 34.5 \pm 1.8 \pm 10.5 \text{ nb}$$

QCD Monte-Carlo Predictions:

PYTHIA Tune A CTEQ5L	38.71 ± 0.62nb
HERWIG CTEQ5L	21.53 ± 0.66nb
MC@NLO	28.49 ± 0.58nb
MC@NLO + JIMMY	35.7 ± 2.0 nb

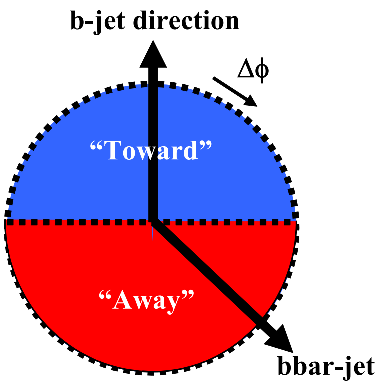


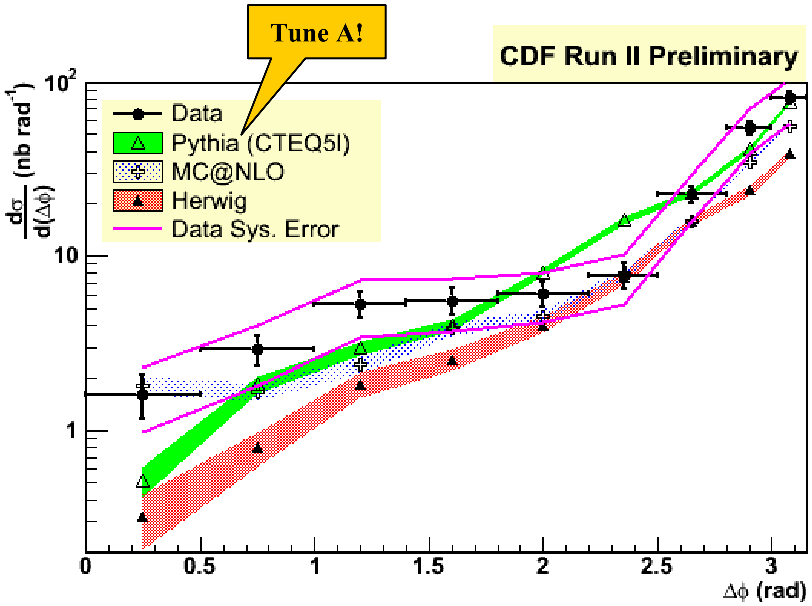
JIMMY: add multiple parton interactions to HERWIG

=> Enhances underlying event and b-cross section

=> Better agreement of NLO calculation with data!

b-bbar DiJet Correlations

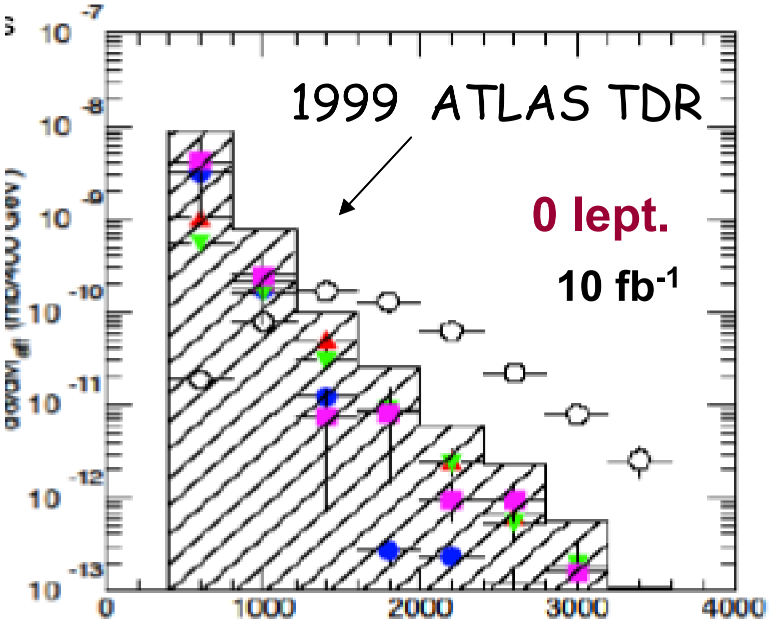




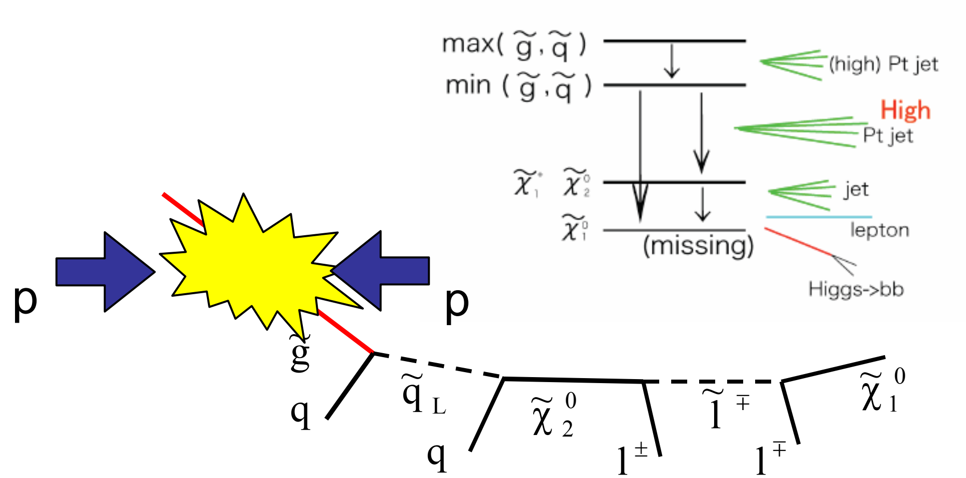
- The two b-jets are predominately "back-to-back"
  - Angular distribution sensitive to fraction of flavor creation (back to back) to gluon splitting and flavor excitation
- Pythia Tune A agrees fairly well with the correlation
  - Run 1b data was used in Pythia Tune A

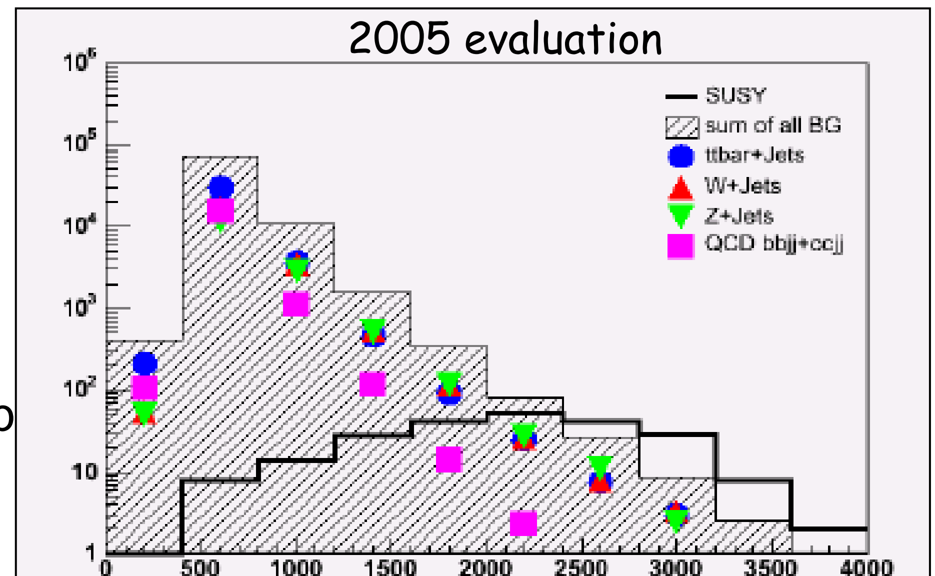
Vector Boson/Jets Final States: Background to Searches

QCD and New Physics



$$M_{eff} = \not{E}_T + \sum_{i=1}^{4}(p_T^{j_i})$$

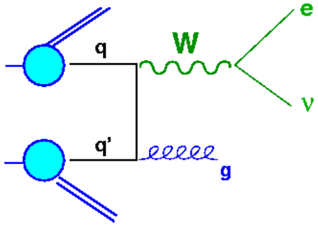


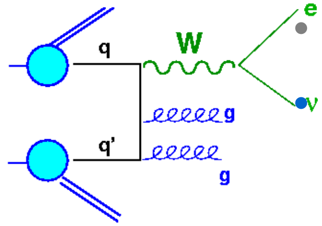


- Preliminary MC studies (1999) suggested prominent SUSY Signal from cascade decays in high p_T multi jets + $\not{E}_T$ sample
- Discovery 'within weeks' after LHC startup
- New W/Z+jet(s) programs (ALPGEN) predict a much harder jet E_t distributions than PYTHIA+PS

M_{eff}

W+jets production



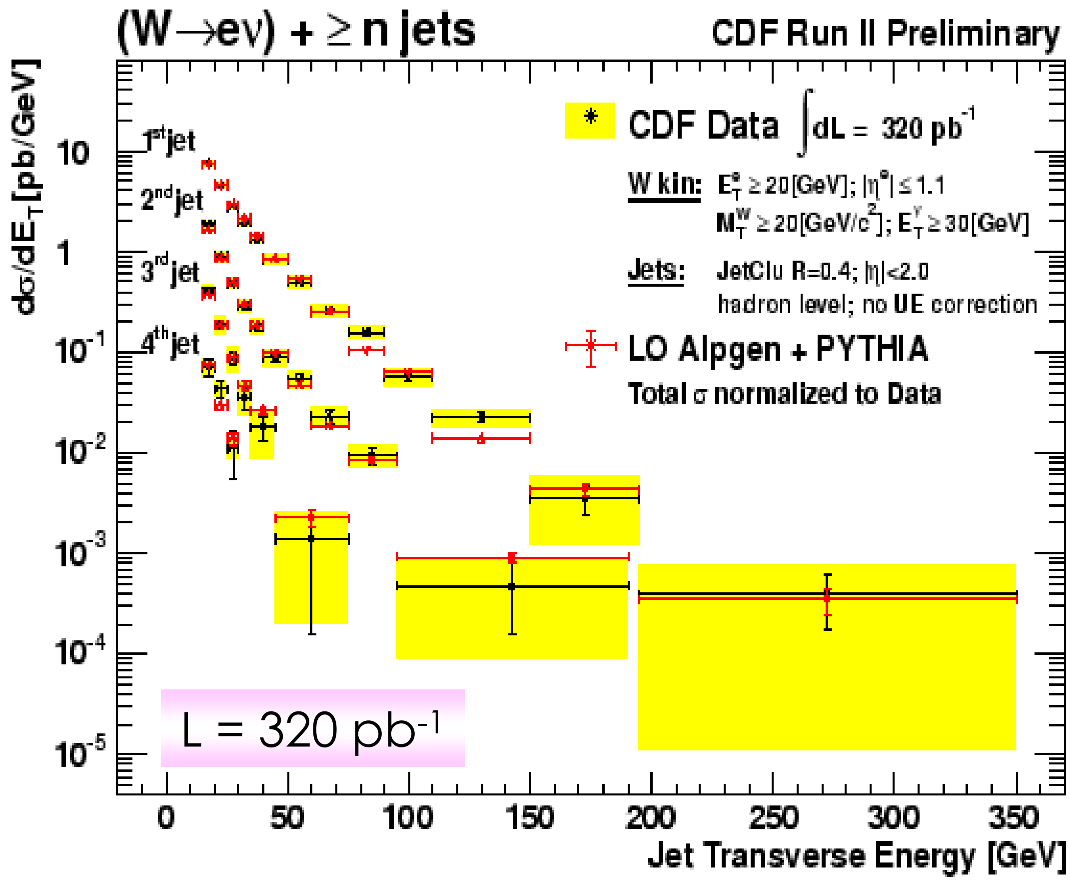


Background to top and Higgs Physics

Testing ground for pQCD in multijet environment

– Key sample to test LO and NLO ME+PS predictions

- Restrict σ_W :
  - $W \rightarrow \nu e$, $|\eta^e| < 1.1$
- JETCLU jets (R=0.4):
  - $E_T^{jets} > 15$ GeV, $|\eta^{jet}| < 2.$
- Uncertainties dominated by background subtraction and Jet Energy Scale



LO predictions normalized to data integrated cross sections

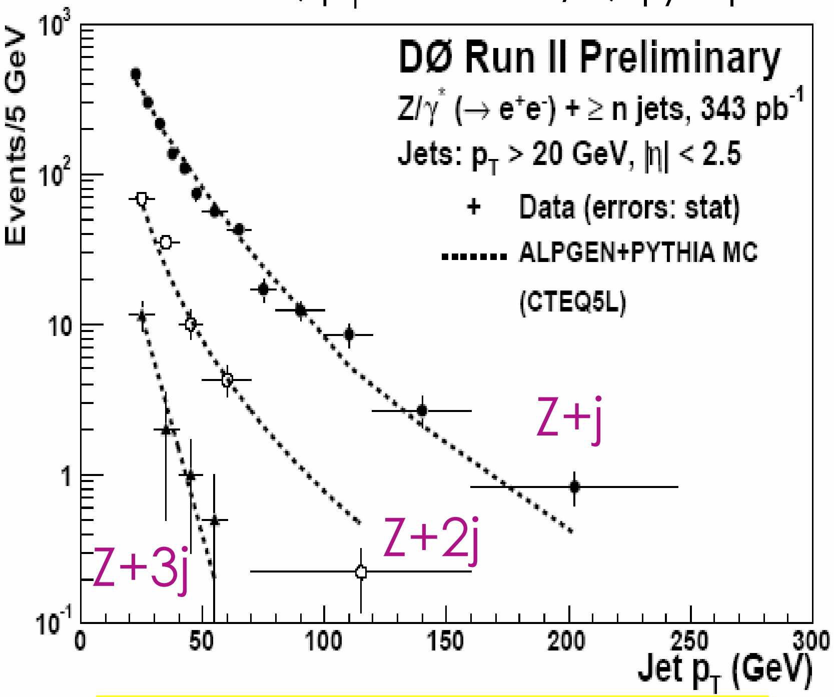
→ **Shape comparison only**

Z+jets production

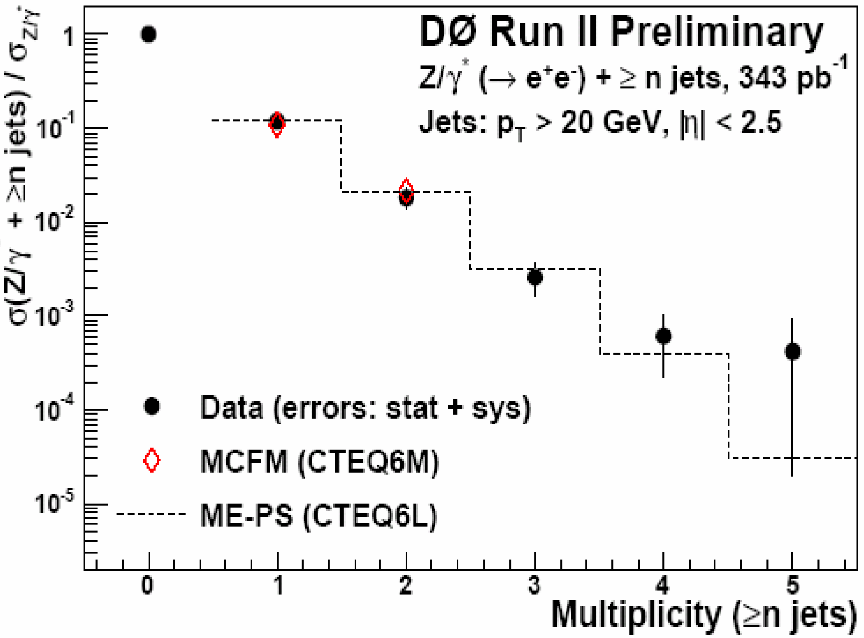
L = 343 pb^{-1}

- Same motivations as W + jets
  $\sigma(Z) \sim \sigma(W) / 10$, but $Z \rightarrow e^+e^-$ cleaner
- Central electrons ($|\eta|<1.1$)
- MidPoint jets:
  - R = 0.5, $p_T > 20$ GeV/c, $|y^{jet}|<2.5$

$$R_n = \frac{\sigma_n}{\sigma_0} = \frac{\sigma[Z/\gamma^*(\rightarrow e^+e^-) + \geq njets]}{\sigma[Z/\gamma^*(\rightarrow e^+e^-)]}$$



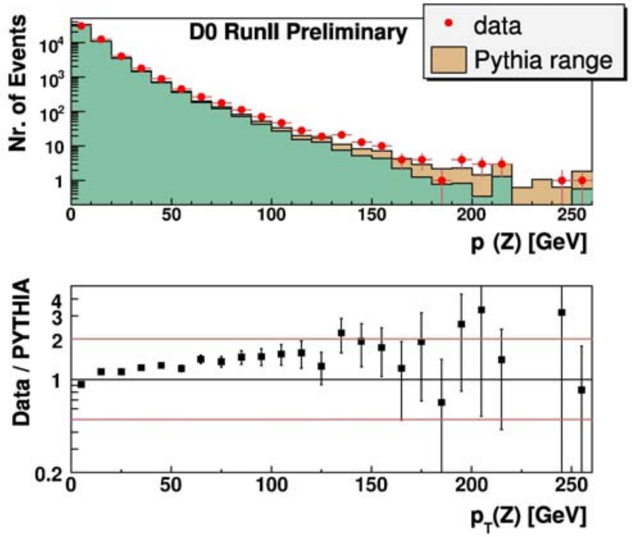
p_T spectra of n^{th} jet distribution

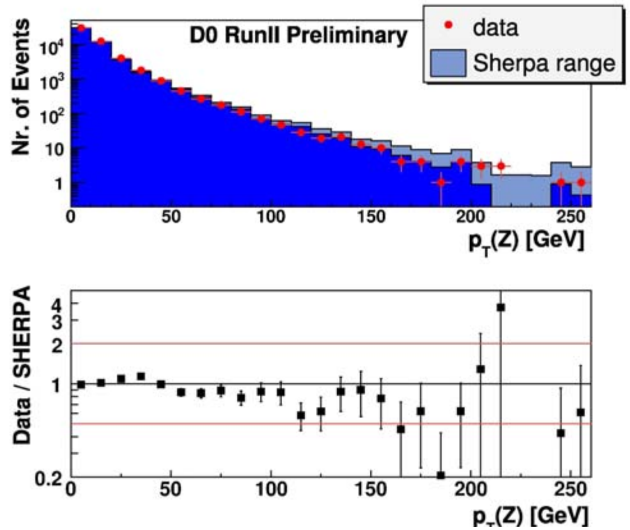


MCFM: NLO for Z+1p or Z+2p → good description of the measured cross sections

ME + PS: with MADGRAPH tree level process up to 3 partons → reproduce shape of N_{jet} distributions (Pythia used for PS)

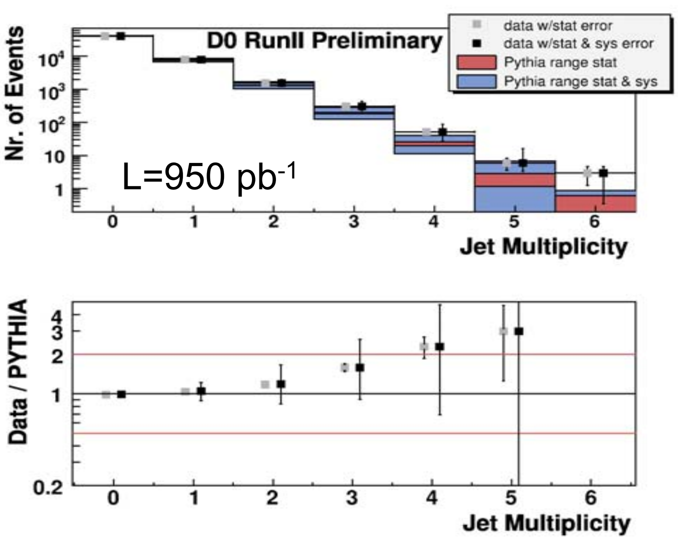
Comparison of Sherpa (ME+PS) and Pythia(PS)

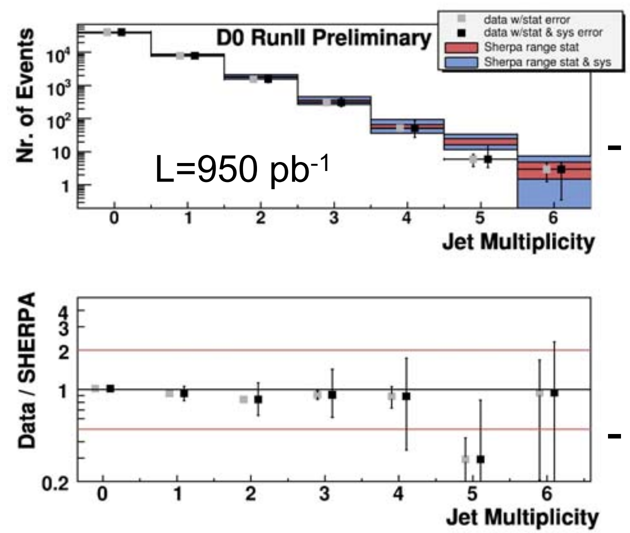




$(Z \rightarrow ee)$+jets

L=950 pb^{-1}





- Pythia tends to under-estimate high pT jets, especially at high jet multiplicity

- Sherpa describes data well up to 4 jets

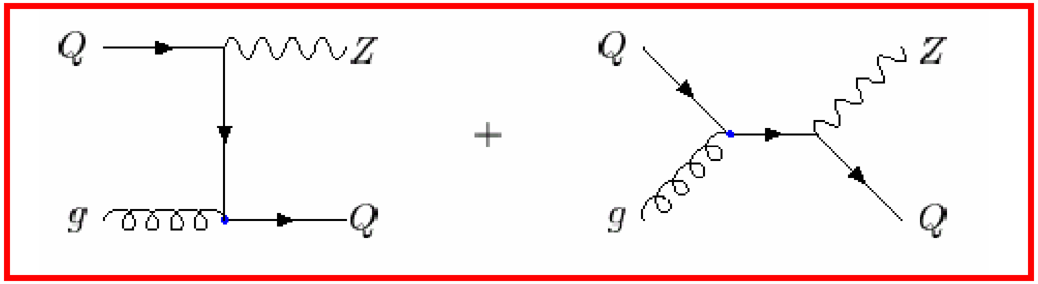
Pythia:Z+1 jets ME Sherpa:Z+≤3 jets ME

Z+b jet production

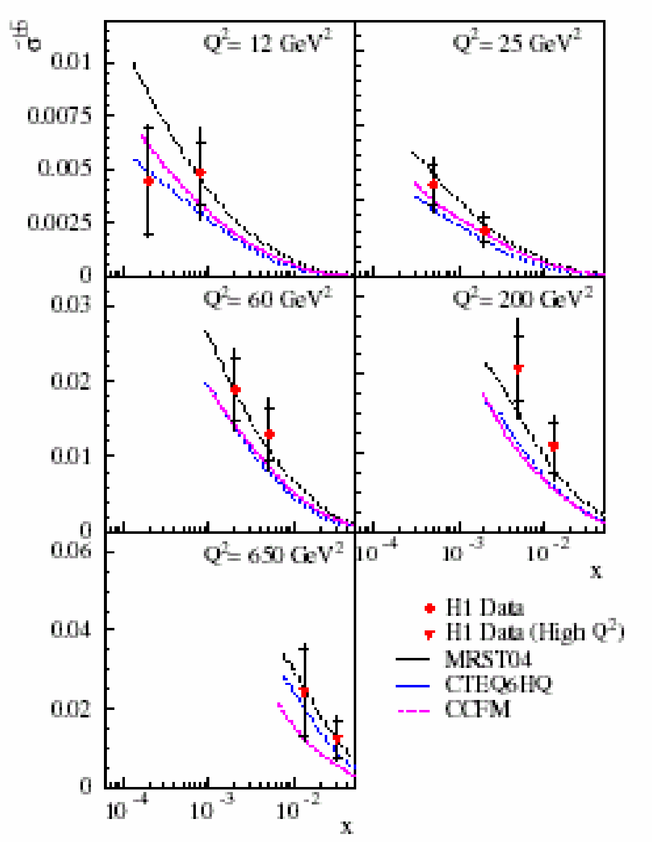
In QCD, Z+b can help constrain b density in the proton

Important background for new physics such as search for ZH Higgs production

+



Probe the heavy flavor content of proton



With HERA F^{bb}_2 data:
CTEQ below MRST by 50% and below data → Z+b jets can help understand this picture

Z+b jets production

Both CDF and D0:

- Leptonic decays for $Z \to e^+e^-, \mu^+\mu^-$
- Z associated with jets
  (CDF: JETCLU, D0: MidPoint) R = 0.7, $|\eta^{jet}|<1.5$, E_T (p_T) >20 GeV
- Look for tagged jets in Z events
- Dominant systematic uncertainty:
  → B-fraction for jet events with 2 heavy quarks.
  → Jet Energy Scale

CDF

L = 335 pb^{-1}

Extract fraction of b-tagged jets from secondary vertex Mass: no assumption on the charm content

$$\sigma(Z+bjet) = 0.96 \pm 0.32 \pm 0.14 pb$$

$$R = \frac{\sigma[Z+bjet]}{\sigma[Z+jet]} = 0.0237 \pm 0.0078(stat) \pm 0.0033(syst)$$

D0

L = 180 pb^{-1}

Assumption on the charm content from theoretical prediction: $N_c=1.69N_b$

$$R = \frac{\sigma[Z+bjet]}{\sigma[Z+jet]} = 0.021 \pm 0.004(stat)^{+0.002}_{-0.003}(syst)$$

Agreement with NLO prediction: $\sigma(Z+bjet) = (0.52 \pm 0.08) pb$ $\quad R = 0.018 \pm 0.004$

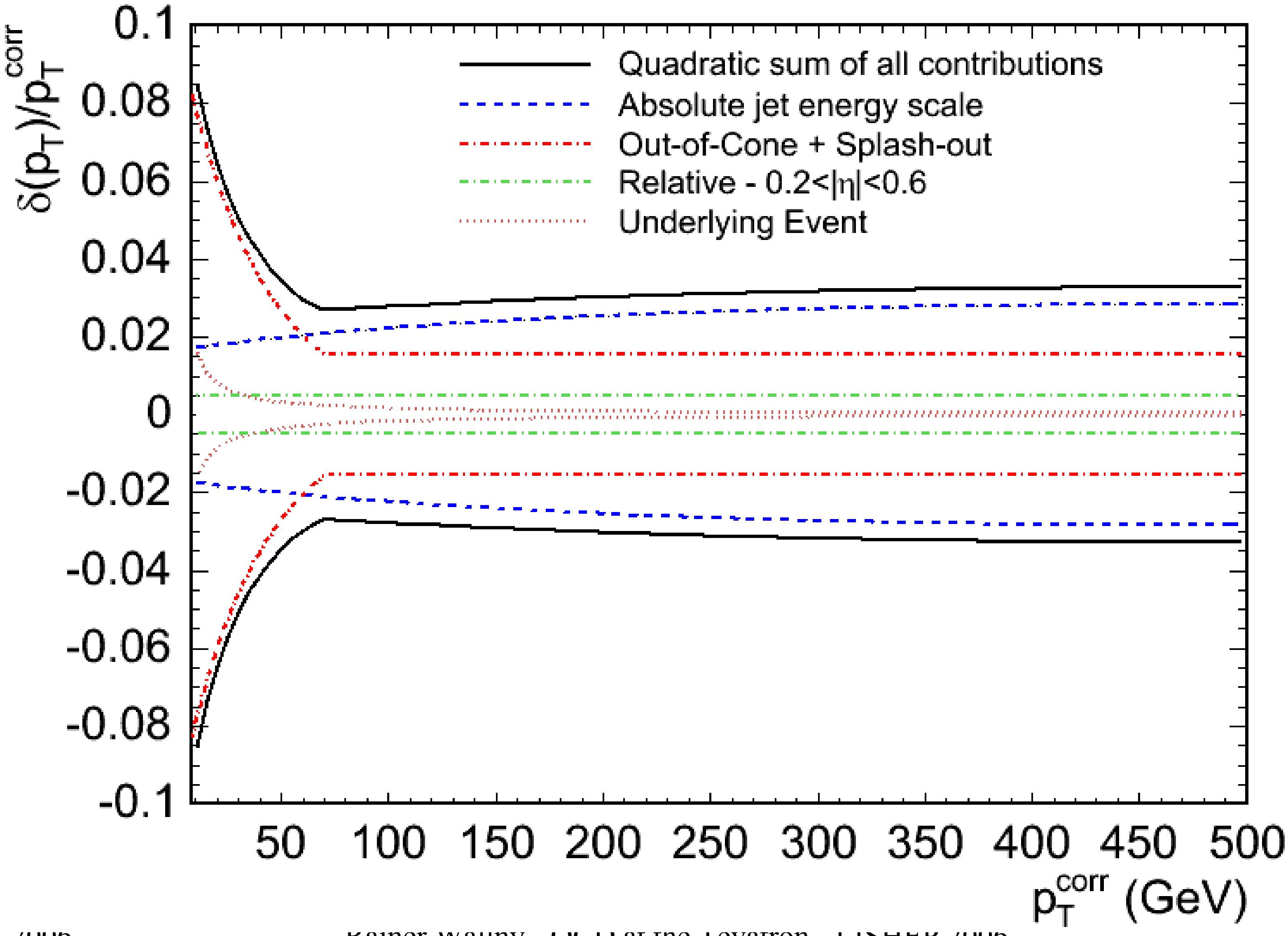
(J. Campbell, K.Ellis)

Conclusions

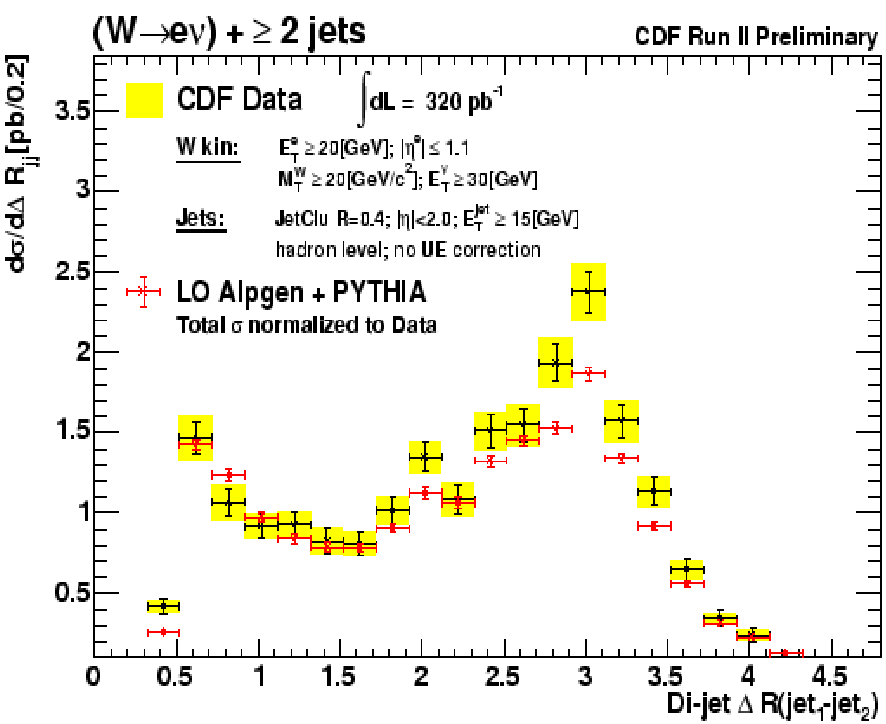
- QCD at the Tevatron is being tested in a vast kinematic range
  - 9 orders of magnitude in inclusive cross section
  - stringent pQCD tests at NLO
  - Input in global PDF fits
- QCD processes (especially jets +vector boson) pose significant background for searches beyond the Standard Model
  - MC tools cannot be blindly relied upon – measuring and testing a very crucial tool for future searches at the High Energy Frontier
  - QCD at the Tevatron provides a crucial testing/calibration ground for these tools (underlying event)
  - ME+PS models show good agreement (ALPGEN, SHERPA, …)
  - real NLO calculations (i.e. MC@NLO, MCFM …) very promising
- CDF and D0 are looking forward into a bright future of ~ fb^{-1} QCD physics at the Tevatron
  - QCD results among the first using the full data sets accumulated so far!

BACKUP

Total JES Uncertainties

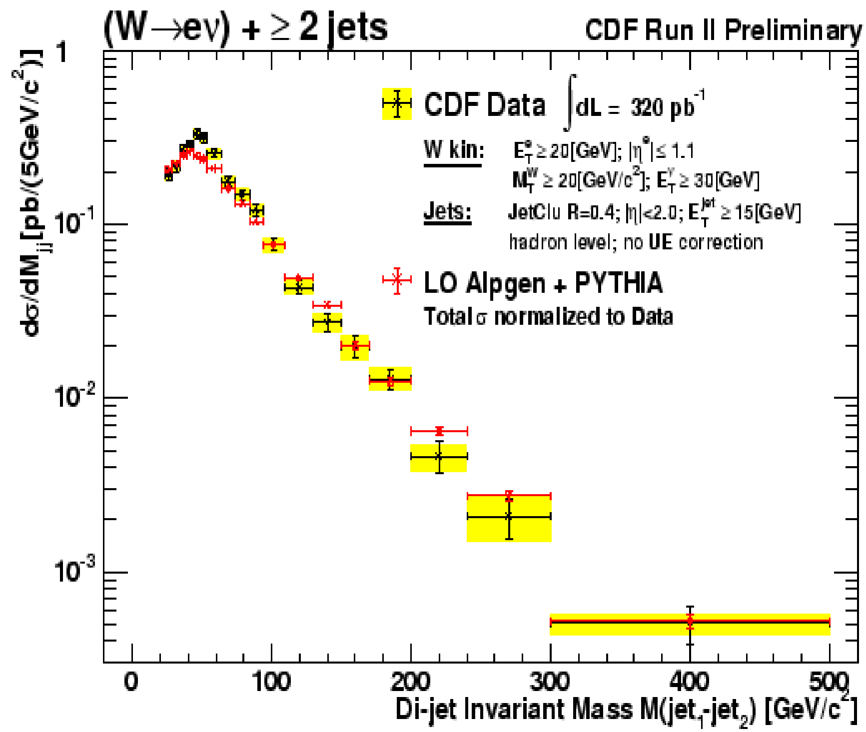


W+jets production



Differential cross section w.r.t. di-jet ΔR in the W+2 jet inclusive sample

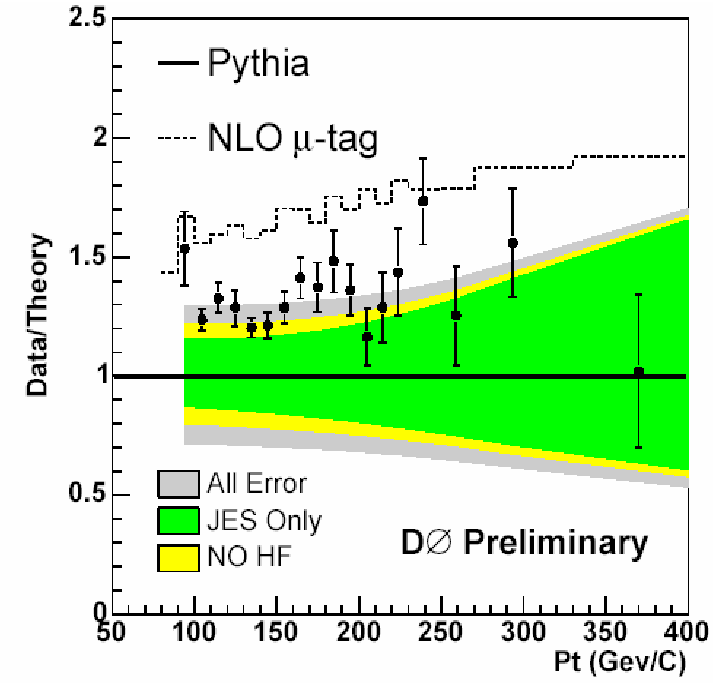
Differential cross section w.r.t. di-jet invariant mass in the W+2 jet inclusive sample



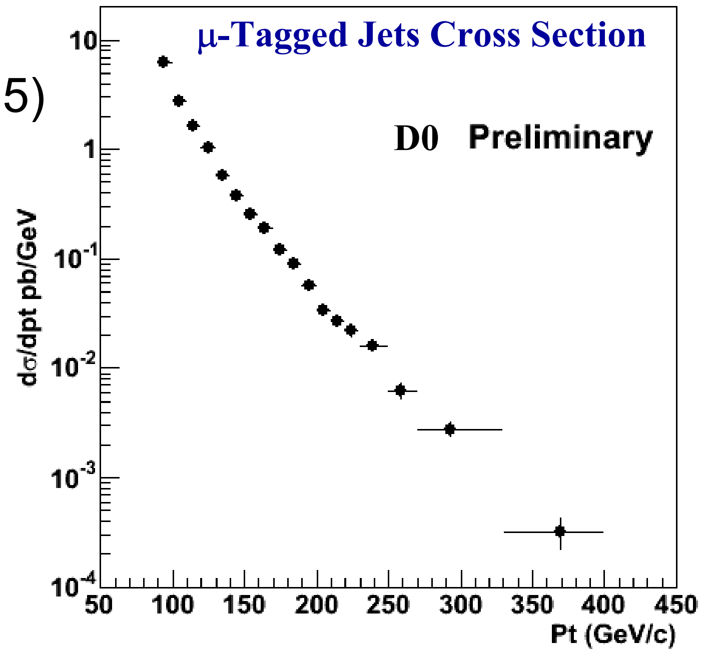
LO predictions normalized to data integrated cross sections

→ **Shape comparison only**

μ-Tagged Jets Correlations



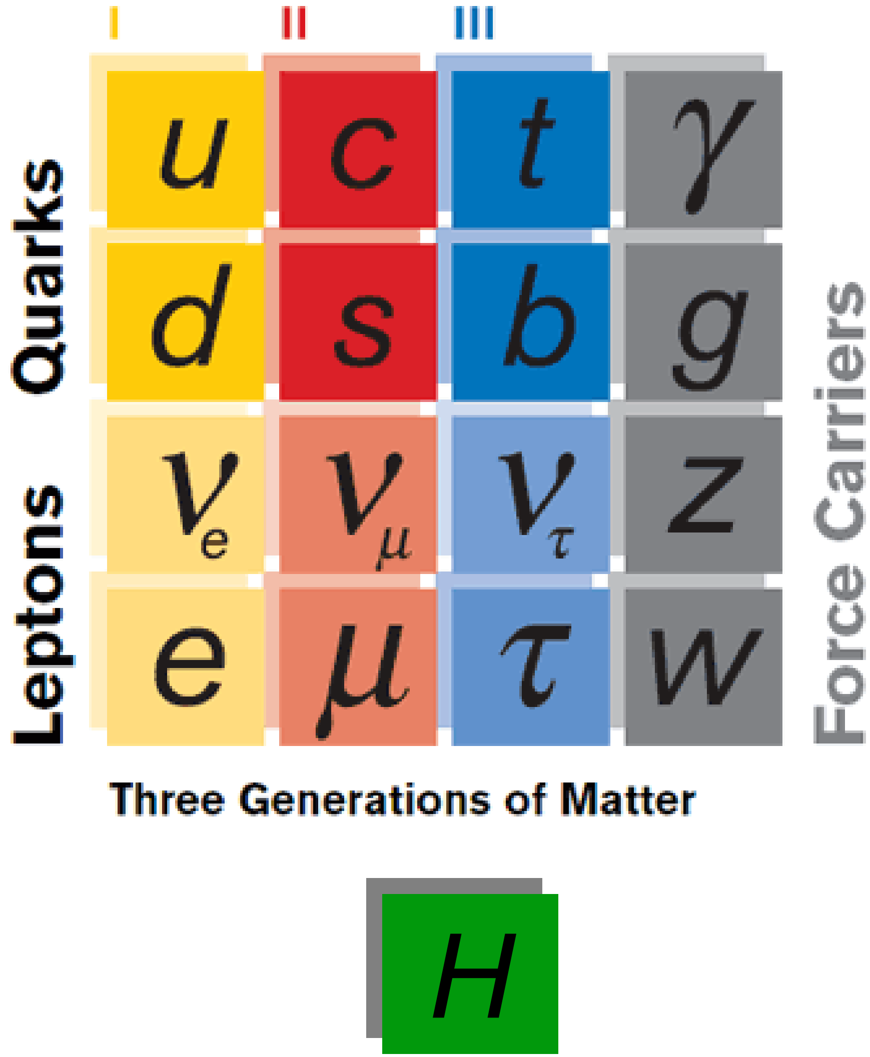
- MidPoint Cone Algorithm (R = 0.5)
- Require muon in R = 0.5.
- L = 300 pb^{-1}
- $|y_{jet}| < 0.5$
- $P_T(m) > 5$ GeV/c



- Searching for muons in jets enhances the heavy flavor content.
- Data/PYTHIA ~ 1.3 flat.

The Standard Model

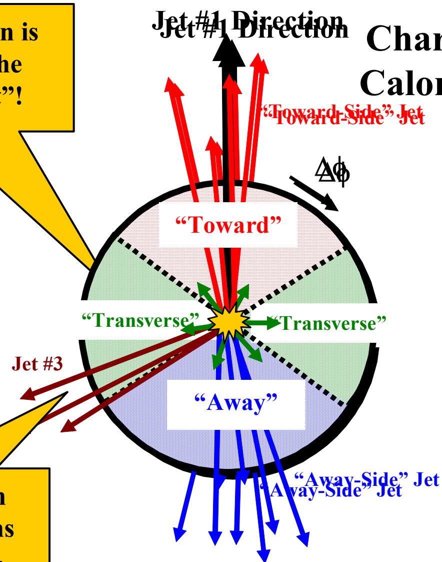
- Matter is made out of fermions:
  - quarks and leptons
  - 3 generations
- Forces are carried by Bosons:
  - Electroweak: γ,W,Z
  - Strong: gluons
- Higgs boson:
  - Gives mass to particles
  - Not found yet



Non-Perturbative Effects

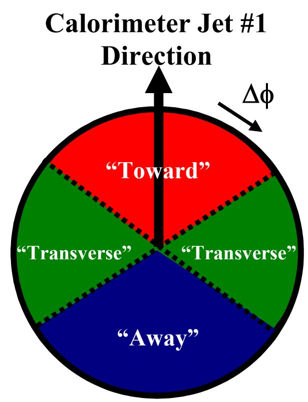
The "Transverse" Region
as defined by the Leading Jet

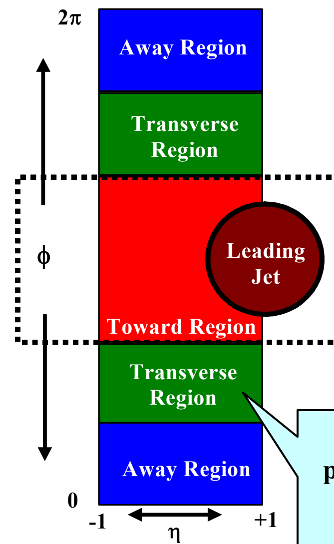
"Transverse" region is very sensitive to the "underlying event"!



"Transverse" region recieves contributions from initial & final-state radiation!

Charged Particles ($p_T > 0.5$ GeV/c, $|\eta| < 1$)
Calorimeter Towers ($E_T > 0.1$ GeV, $|\eta| < 1$)

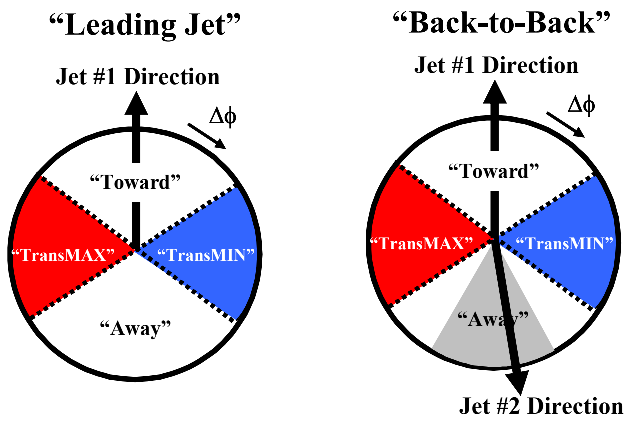


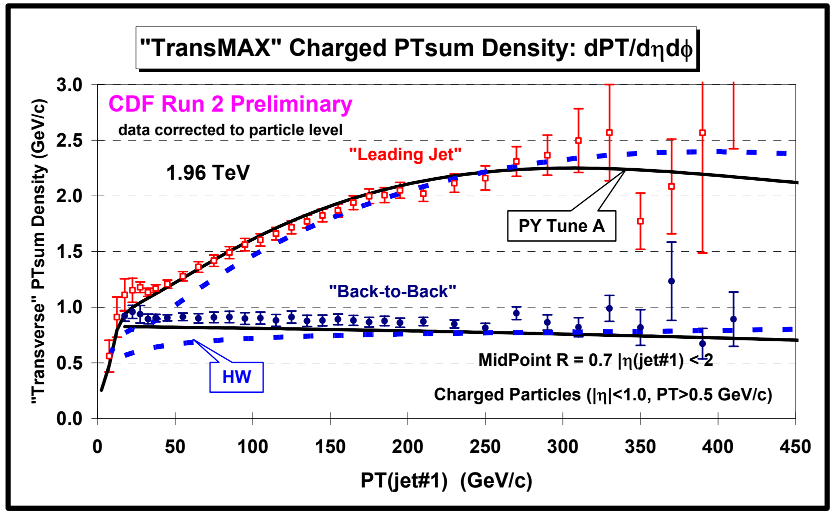


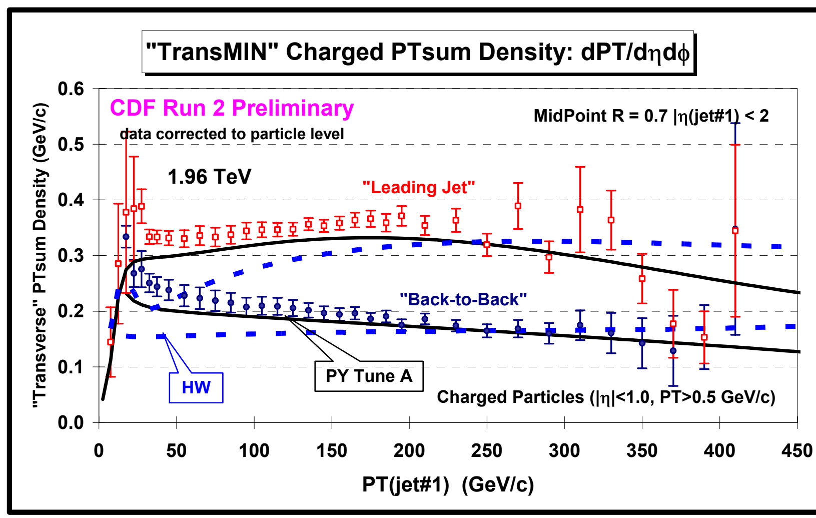
Look at the charged particle density and the ETsum density in the "transverse" region!

- Look at the "transverse" region as defined by the leading calorimeter jet (MidPoint, R = 0.7, f_{merge} = 0.75, $|\eta| < 2$).
- Define $|\Delta\phi| < 60^o$ as "Toward", $60^o < -\Delta\phi < 120^o$ and $60^o < \Delta\phi < 120^o$ as "Transverse 1" and "Transverse 2", and $|\Delta\phi| > 120^o$ as "Away".).
- Study the charged particles ($p_T > 0.5$ GeV/c, $|\eta| < 1$) and form the charged particle density, dNchg/dhdf, and the charged scalar p_T sum density, dPTsum/dηdφ, by dividing by the area in η-φ space.
- Study the calorimeter towers ($E_T > 0.1$ GeV, $|\eta| < 1$) and form the scalar E_T sum density, dETsum/dηdφ.

"TransMAX/MIN" PTsum Density
PYTHIA Tune A vs HERWIG

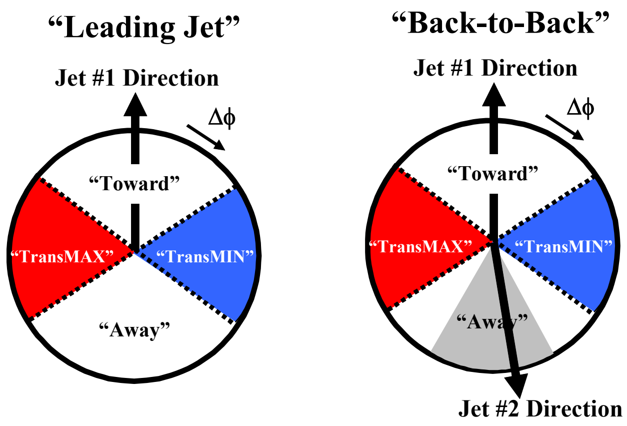


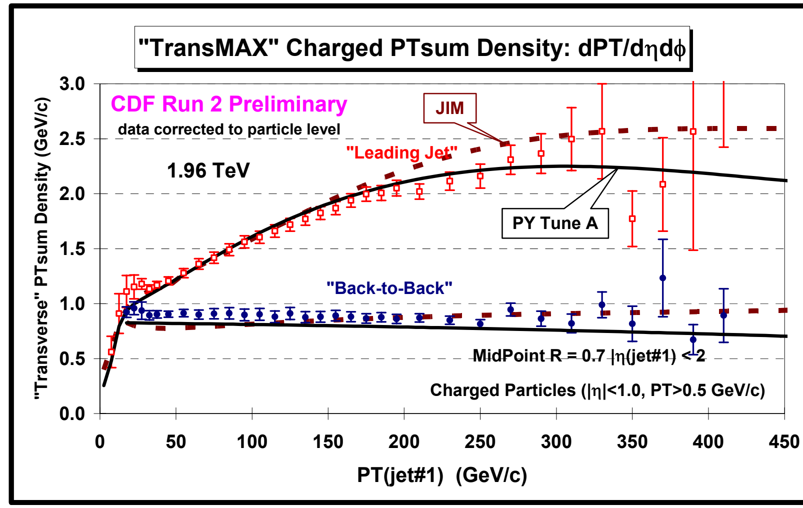


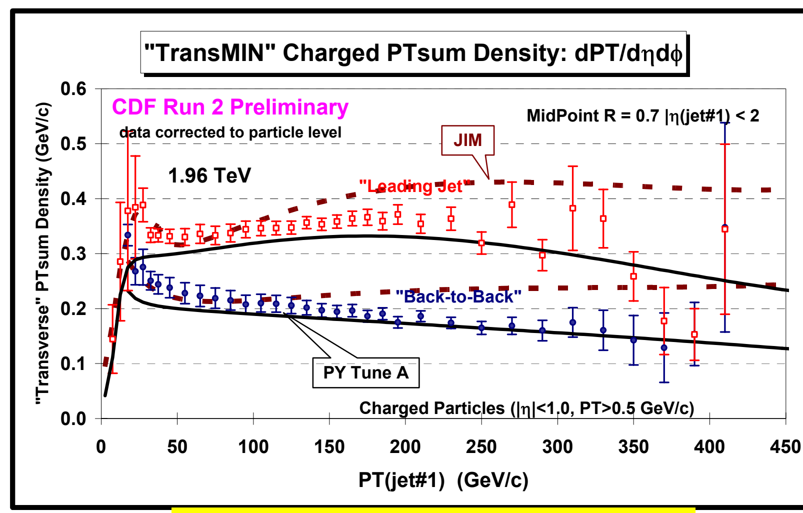


- Order transverse regions according to charged PTsum density, dPTsum/dηdφ, into "transMAX" and "transMIN" region (p_T > 0.5 GeV/c, |η| < 1) versus P_T(jet#1) for "Leading Jet" and "Back-to-Back" events.
- transMAX picks up the hard component
- transMIN picks up beam-beam remnant
- Compare the (*corrected*) data with PYTHIA Tune A (with MPI) and HERWIG (without MPI) at the particle level.

"TransMAX/MIN" PTsum Density
PYTHIA Tune A vs JIMMY





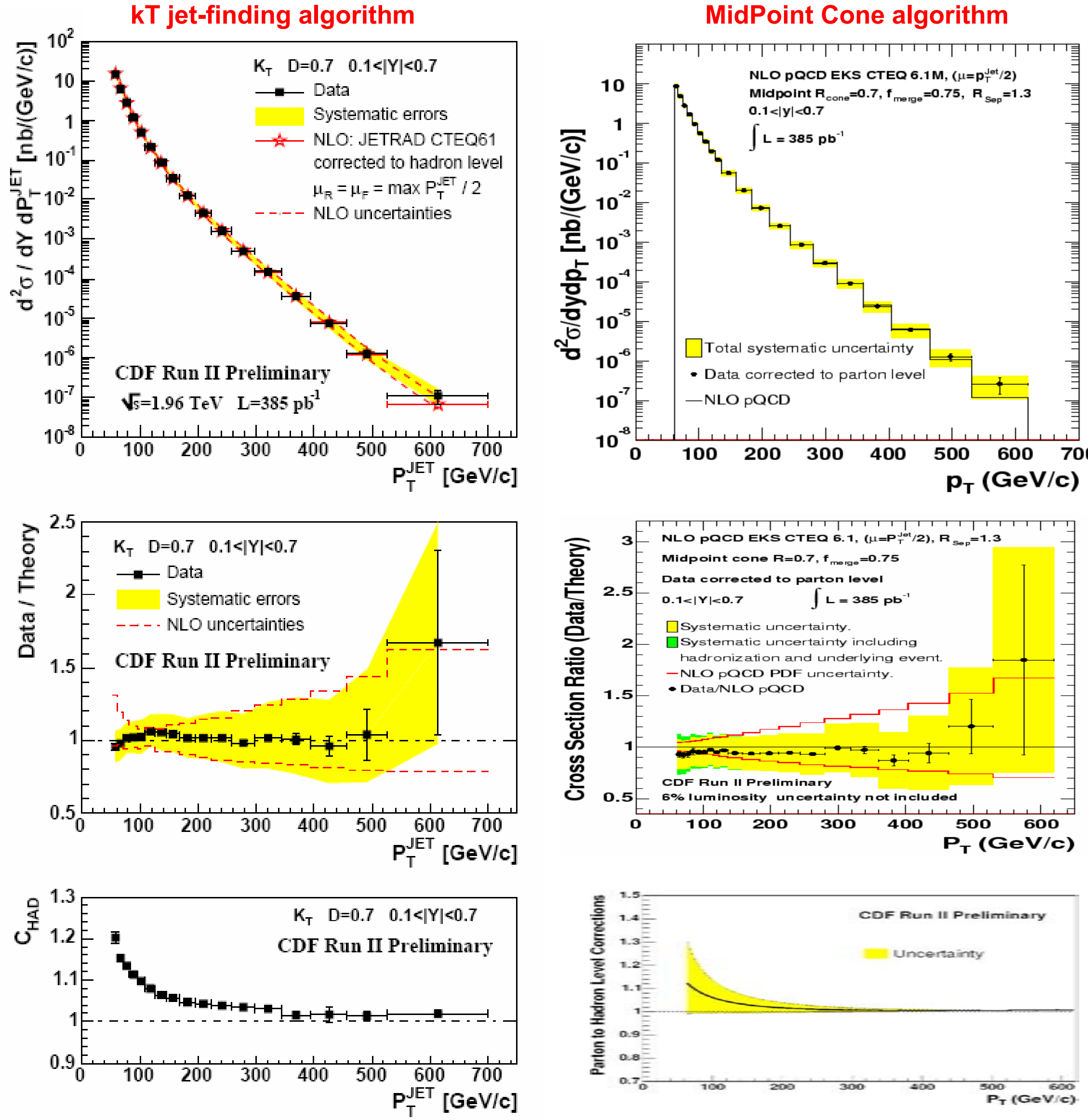


- Order transverse regions according to charged PTsum density, dPTsum/dηdϕ, into "transMAX" and "transMIN" region ($p_T > 0.5$ GeV/c, $|\eta| < 1$) versus P_T(jet#1) for "Leading Jet" and "Back-to-Back" events.
- transMAX picks up the hard component
- transMIN picks up beam-beam remnant
- Compare the (*corrected*) data with PYTHIA Tune A (with MPI) and a tuned version of JIMMY (with MPI) at the particle level.

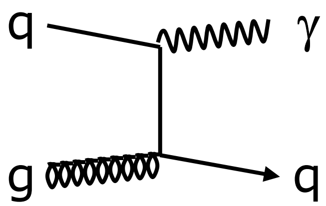
Rick Field, U of Florida

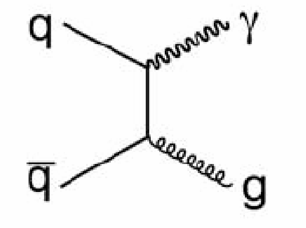
Run II Inclusive Jets: k_T vs MidPoint

- Jet finding algorithms
  - left: kT (D=0.7)
  - right: MidPoint (R=0.7)
  - both for central jets only: 0.1<|Y|<0.7
- Comparison to NLO:
  - both agree with NLO and have similar patterns in Data/Theory
- UE+Had Corrections:
  - UE+Hadronization are phenomenological models, not a theory!
  - matter only for P_T<100
  - k_T algorithm is twice more sensitive



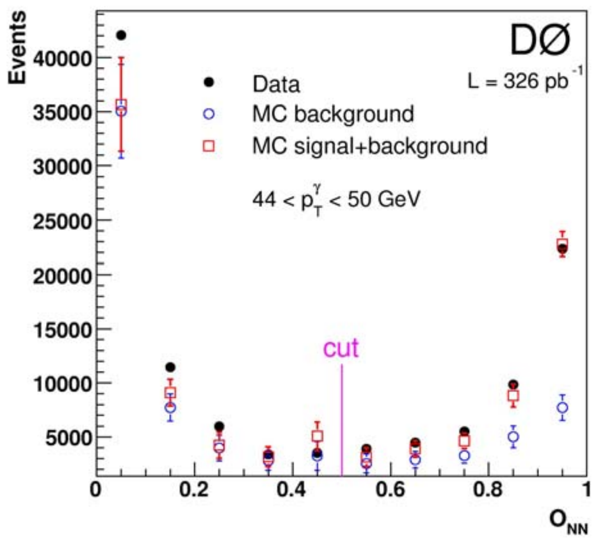
Inclusive γ cross section (D0)





L = 330 pb^{-1}

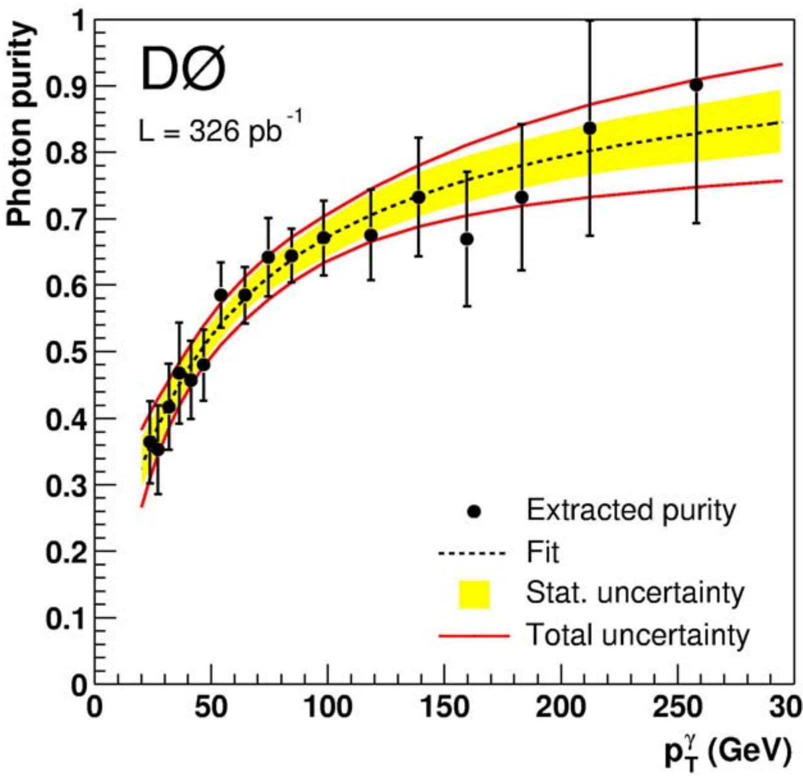
- Separating photons from jet backgrounds is challenging



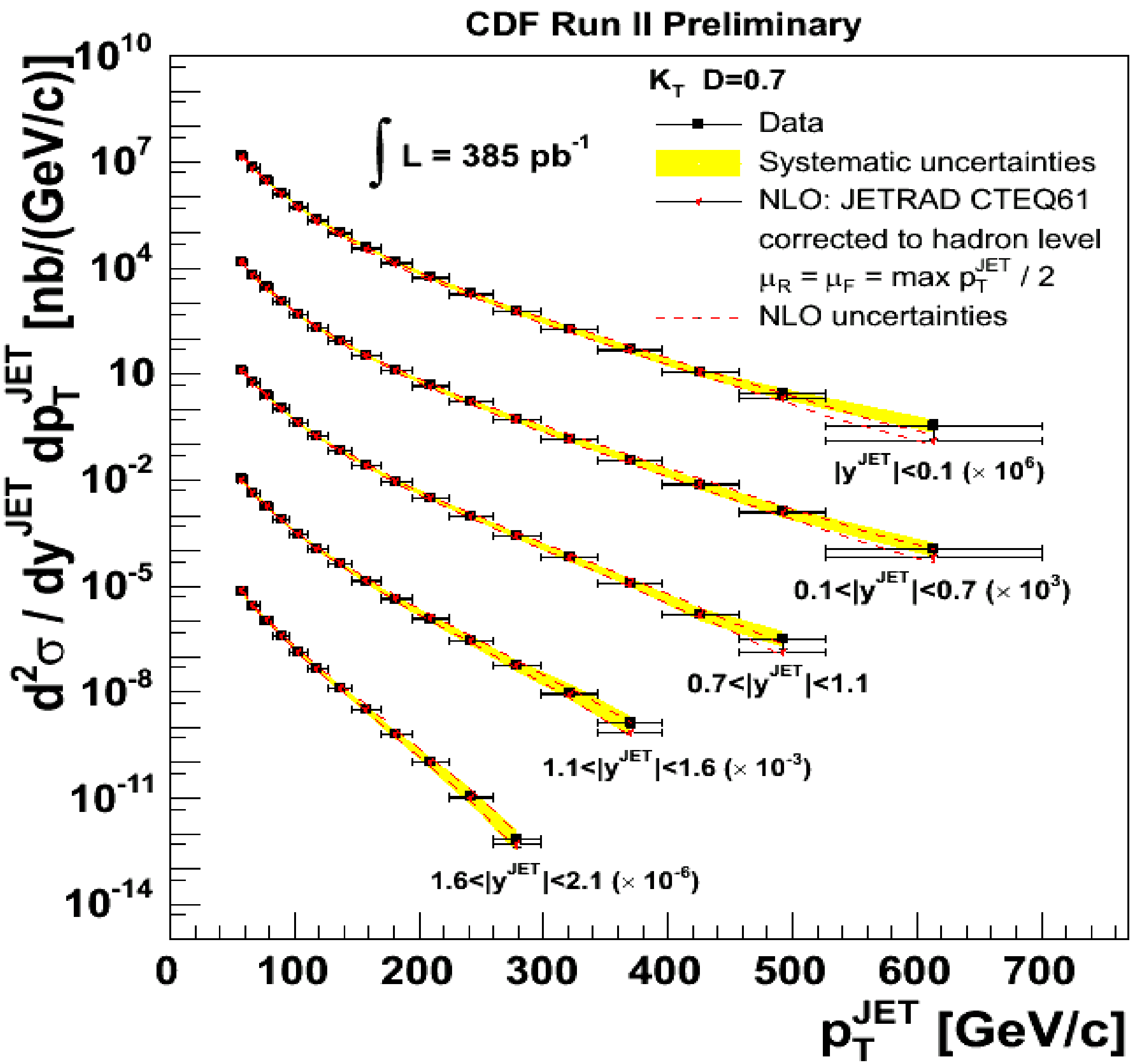
- Use neural network (NN)
  - Track isolation and calorimeter shower shape variables

- Sensitive to PDF and hard scatter dynamics: no need to define "jets"
- Performed for central photons, $|y^g|< 0.9$

No Jet Energy Scale error, use good understanding of EM energy scale
→ purity uncertainties dominates



Forward jets (k_T algorithm ,CDF)

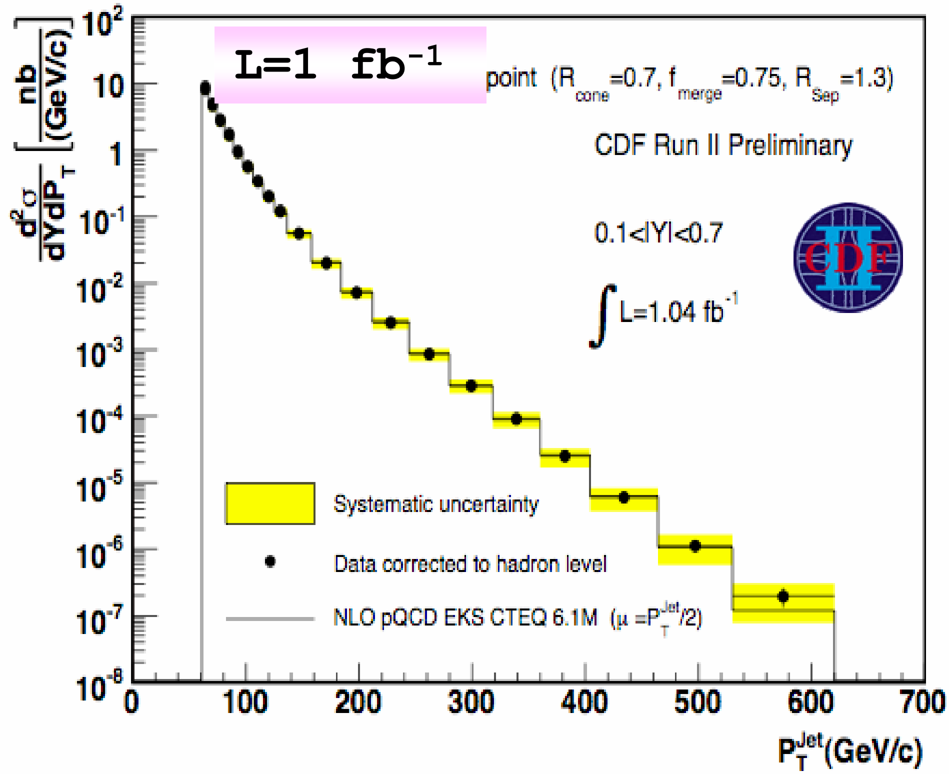


Five regions in jet rapidity explored (D=0.7):

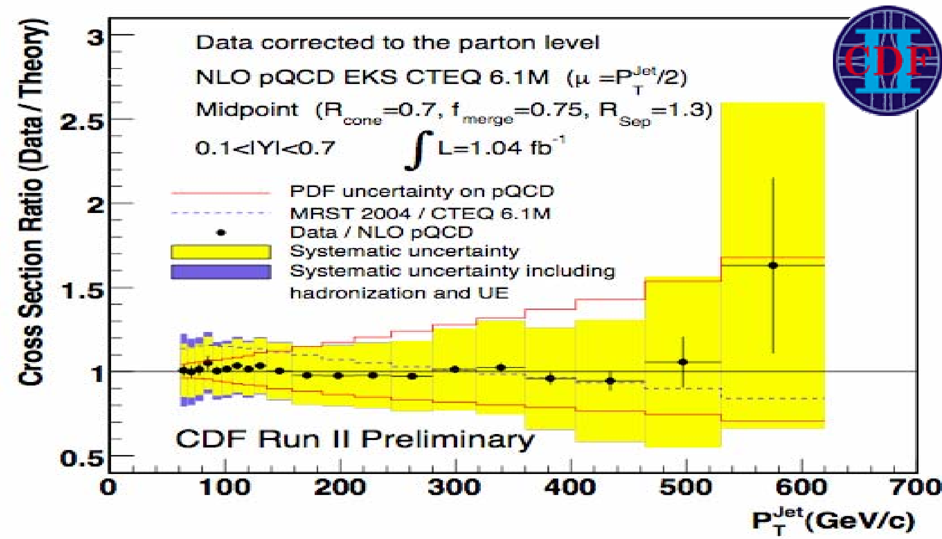
- $|y^{jet}|<0.1$
- $0.1<|y^{jet}|<0.7$
- $0.7<|y^{jet}|<1.1$
- $1.1<|y^{jet}|<1.6$
- $1.6<|y^{jet}|<2.1$

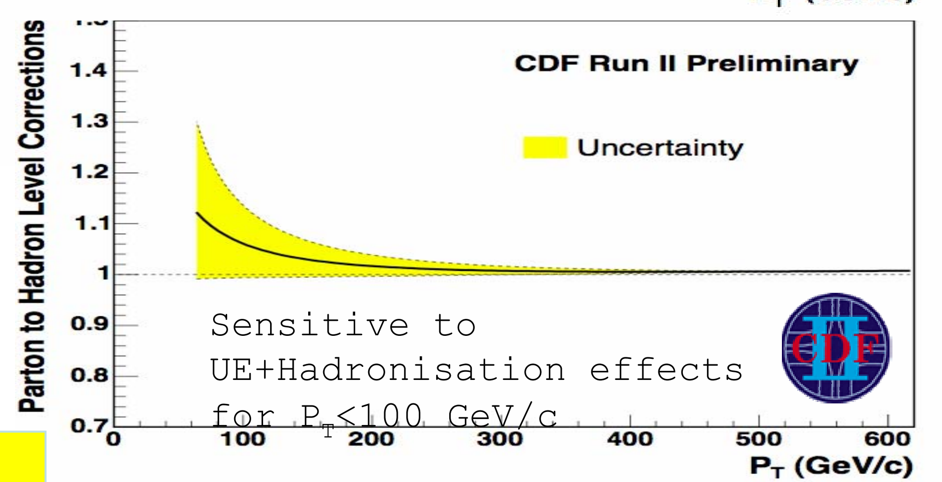
Good agreement with the NLO pQCD for jets up to $|Y|<2.1$

Inclusive Jet Cross Section-CDF (MidPoint algorithm R=0.7)



Central jets: $0.1<|y^{jet}|< 0.7$





- Systematic dominated by Jet Energy Scale uncertainties (2-3%)
- NLO uncertainty due to high x gluon PDF

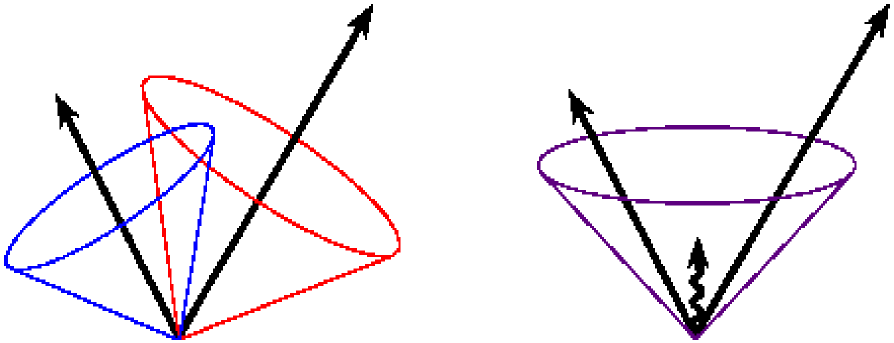
Good agreement with NLO CTEQ6.1M

Notes on Run I Jet Algorithm

$$d\hat{\sigma}_{JET} = d\Phi\,|M|^2\,F_{JET}$$

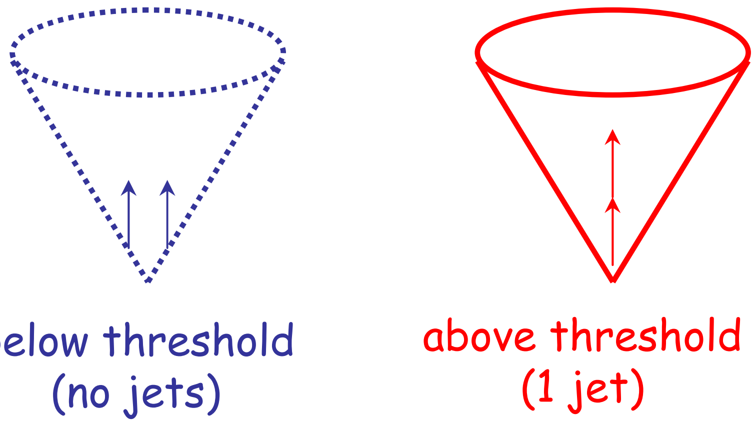
Cone algorithm not infrared safe:

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



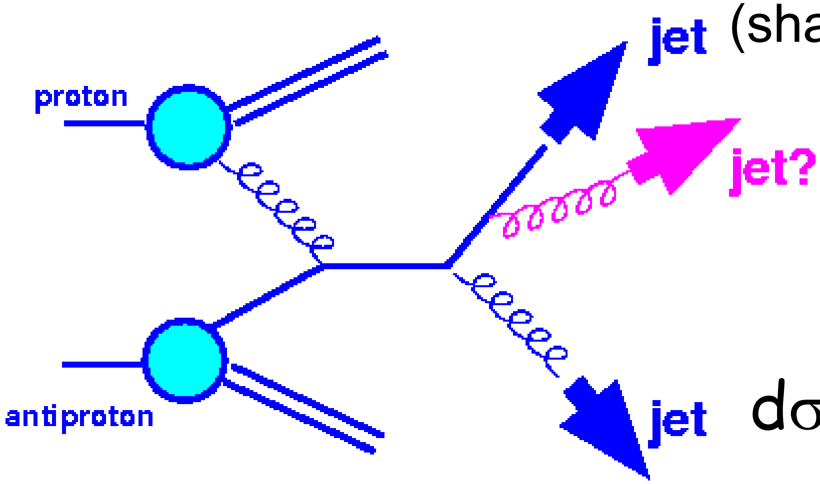
Fixed-order pQCD calculations will contain not fully cancelled infrared divergences:

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

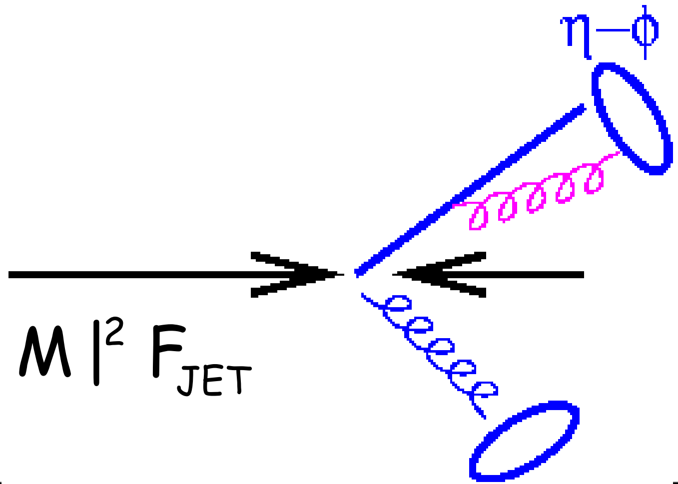
} three partons inside a cone

Cone Algorithm

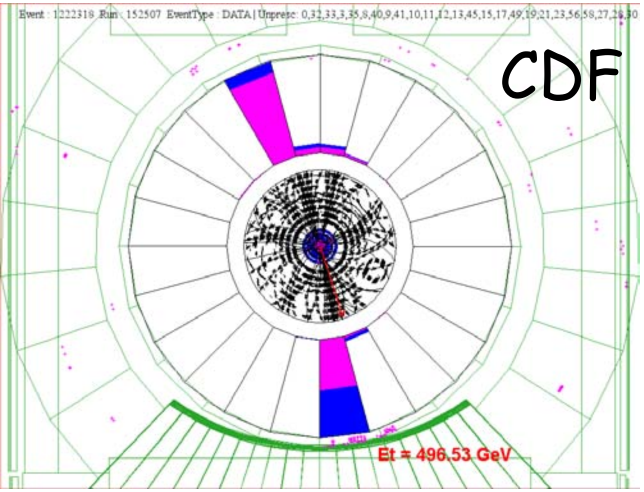
NLO pQCD diagram

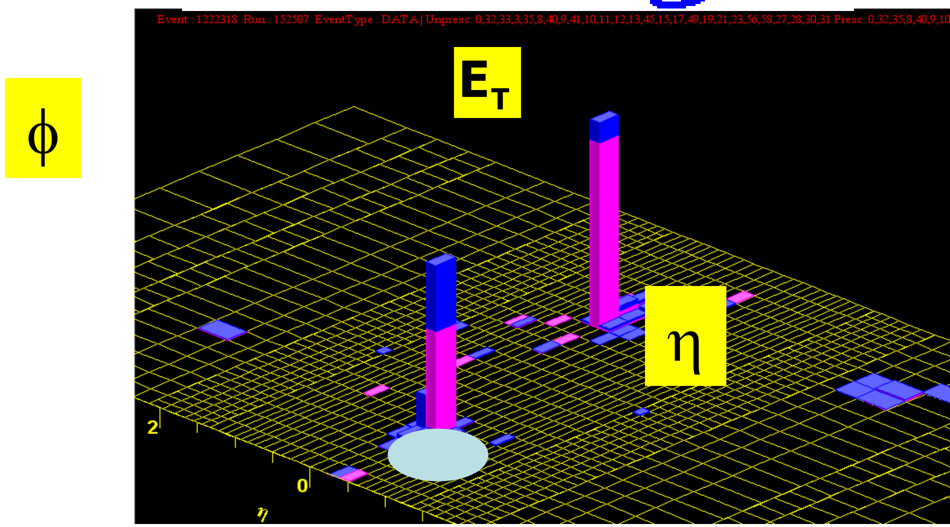


Convenient to define jets in $\eta-\phi$ space
(shape invariant against longitudinal boost)



$$d\hat{\sigma}_{JET} = d\Phi\,|M|^2\,F_{JET}$$





Run I Cone algorithm

1. Seeds with $E_T \geq 1$ GeV

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

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

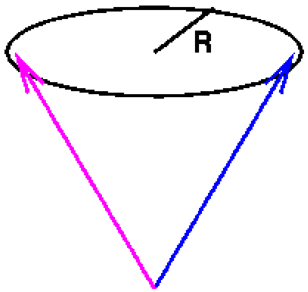
$$\eta^{jet} = \frac{\sum_k E_T^k \cdot \eta_k}{E_T^{jet}}, \quad \phi^{jet} = \frac{\sum_k E_T^k \cdot \phi_k}{E_T^{jet}}$$

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

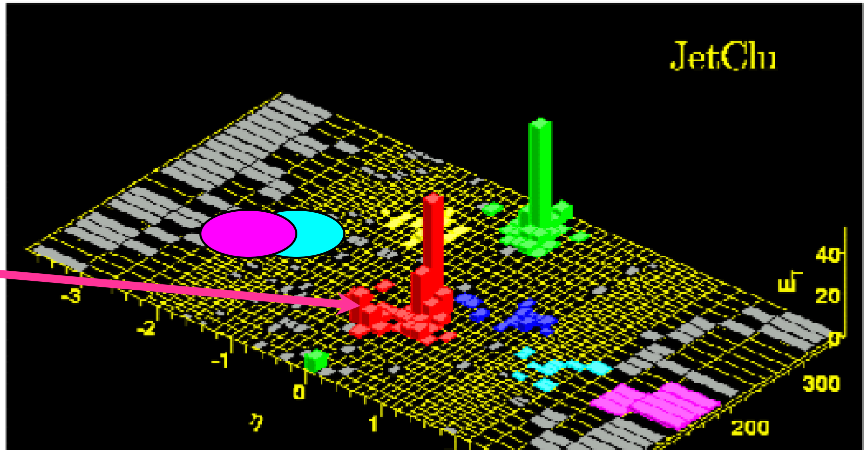
4. Look for possible overlaps

merged if common transverse energy between jets is more than 75 % of smallest jet…..

pQCD NLO does not have overlaps (at most two partons in one jet)

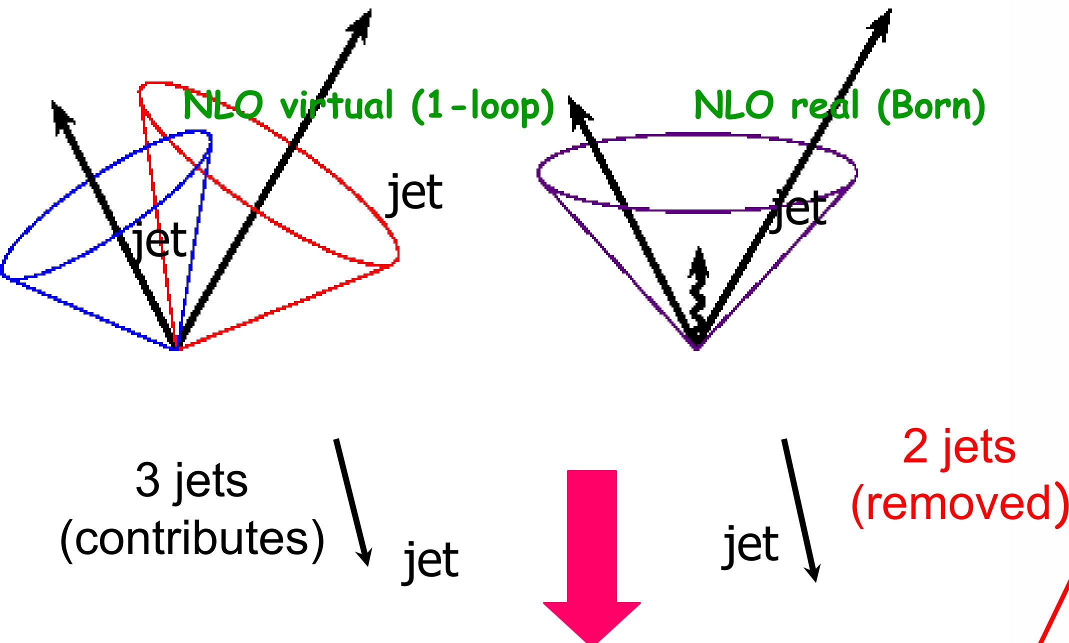


Therefore it uses larger cone R' = Rsep x R to emulate experimental procedure
-> arbitrary parameter



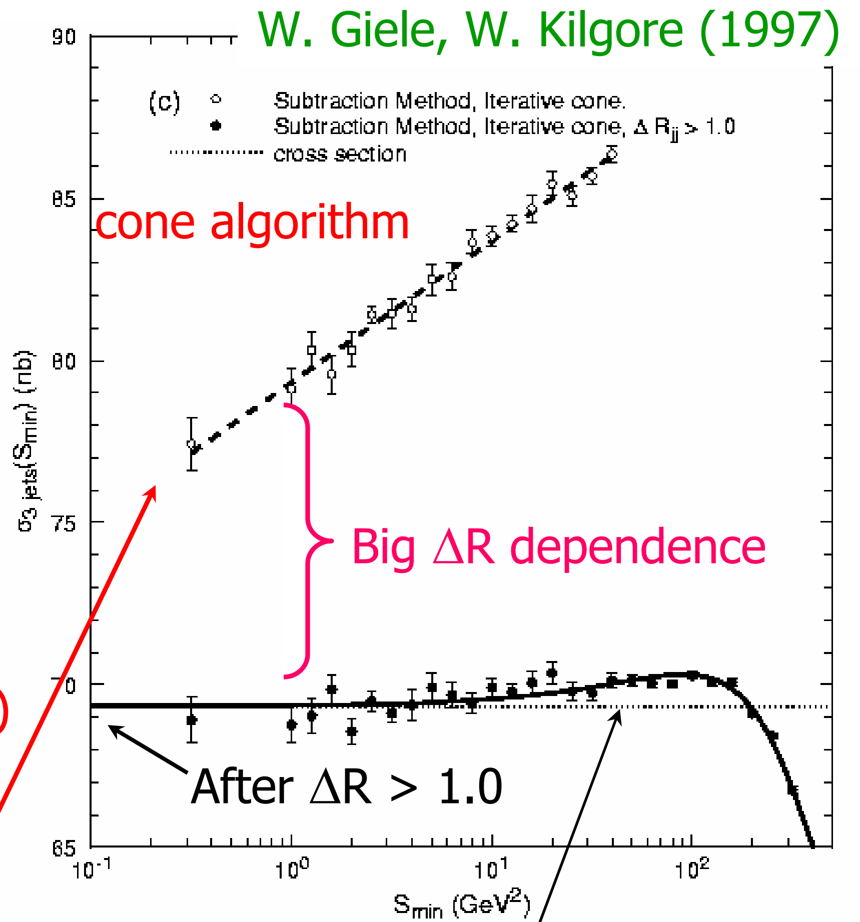
Three-jet Production at NLO

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



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

W. Giele, W. Kilgore (1997)



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

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"

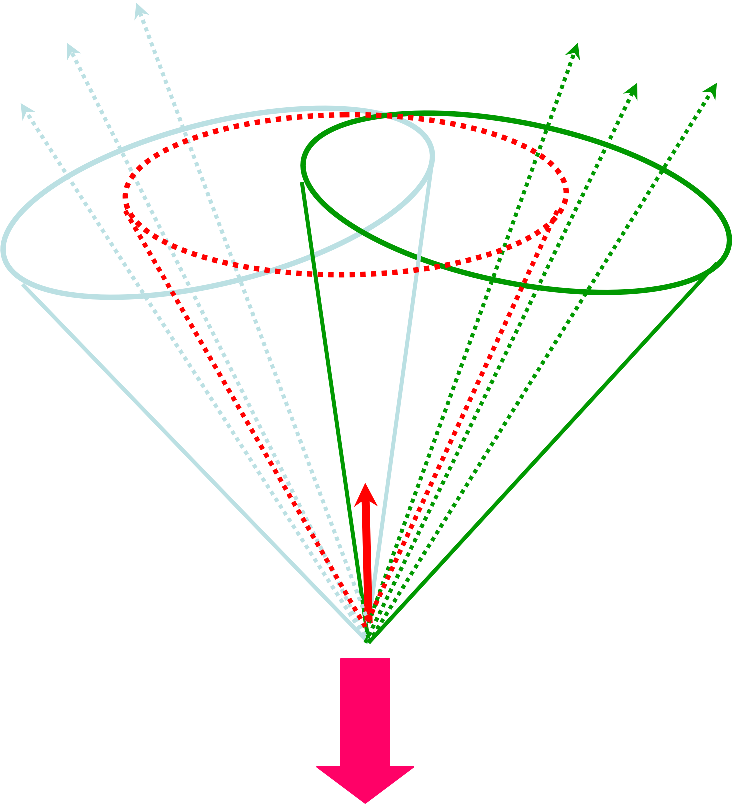
$$E^{jet} = \sum_k E^K, \quad P_i^{jet} = \sum_k P_i^K$$

$$(\text{massive jets} : P_T^{jet}, Y^{jet})$$

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

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

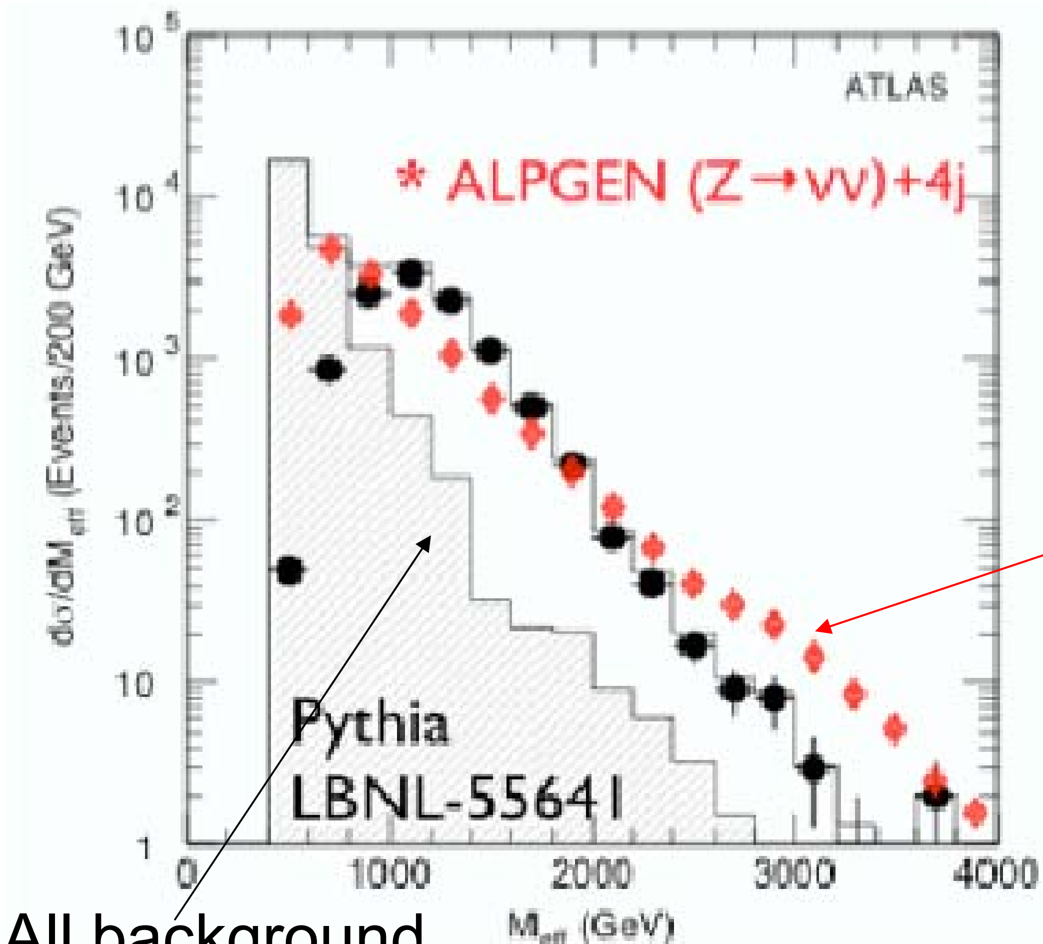
5. Merging/Splitting



Cross section calculable in pQCD

Discovery within a month ?

The SM (QCD) backgrounds are tricky!



F.Gianotti, M. Mangano
hep-ph-0504221

ME+PS (only Z+4 jets)

All background based on PS

Clearly, we need to understand Z/W+jets process