QCD Results from DØ

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IPPP Workshop on Multiparticle Production in QCD Jets
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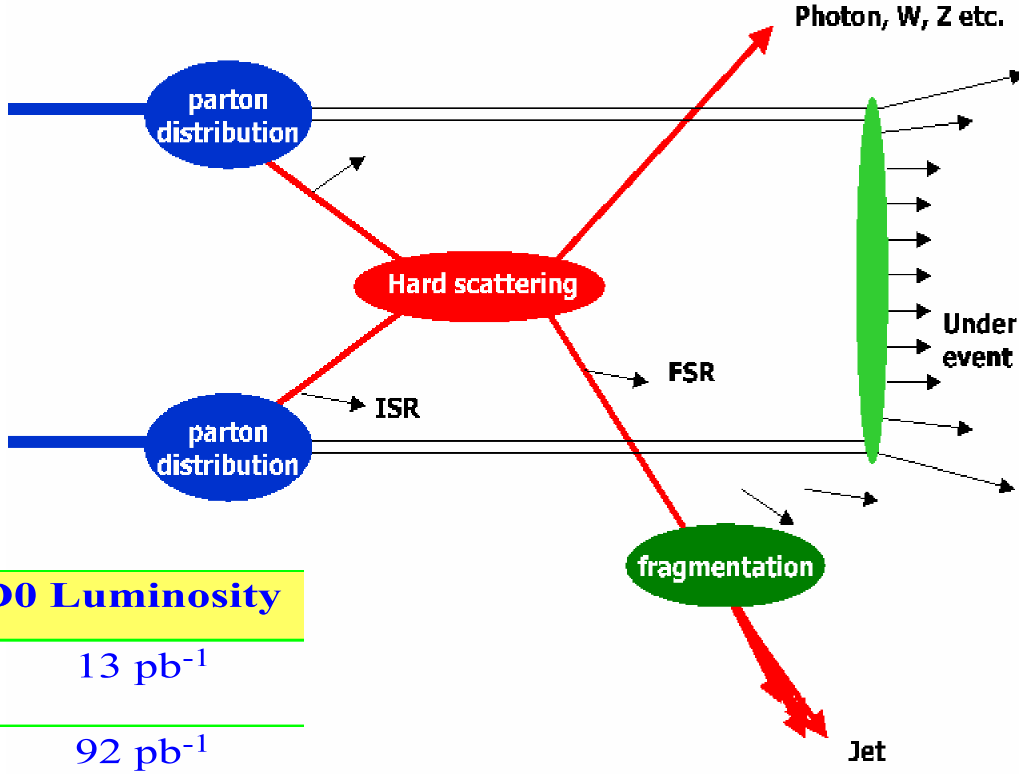
Outline

- Introduction
- Jet Cross Sections
- Multi-jet Production
- BFKL Results
- Quark/Gluon Jet Structure
- Run II Startup
- Conclusions



Data Samples

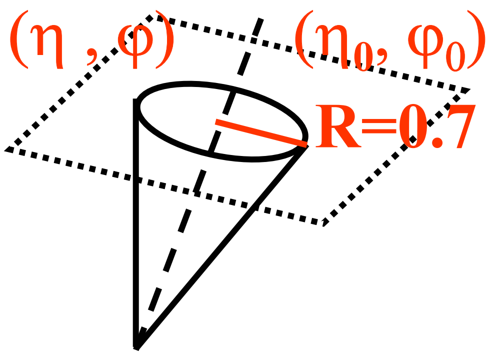
Collider Run	D0 Luminosity
1992-93 @ 1800 GeV	13 pb^{-1}
1994-95 @ 1800 GeV	92 pb^{-1}
Dec 1995 @ 630 GeV	0.5 pb^{-1}

Caveat: This is not the entire D0 Run I QCD program – that is impossible in 20 minutes. For a complete list of results look under

http://www-d0.fnal.gov/Run2Physics/qcd/

Jet Algorithms at Run 1

Fixed Cone Algorithm:

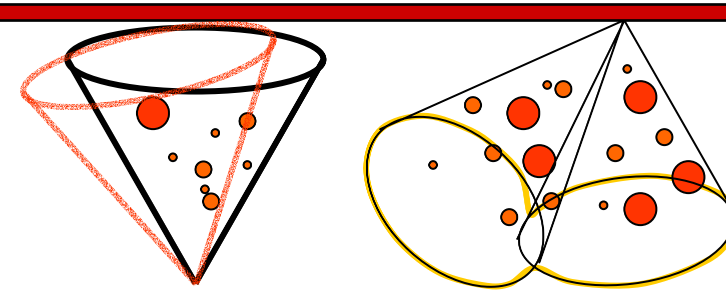


$$\mathbf{E_T} = \sum_{\mathbf{i}} \mathbf{E_{Ti}}$$

$$\eta_{jet} = \frac{\sum_i E_T^i \eta^i}{\sum_i E_T^i}$$

$$\phi_{jet} = \frac{\sum_i E_T^i \phi^i}{\sum_i E_T^i}$$

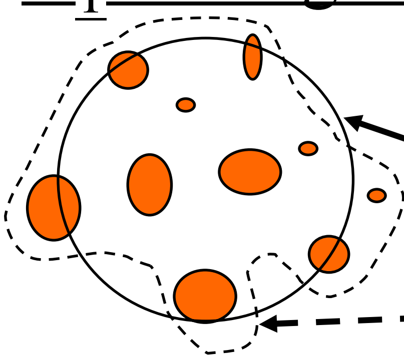
Snowmass



Calorimeter E_T

Jet Seeds

K_T Jet Algorithm:

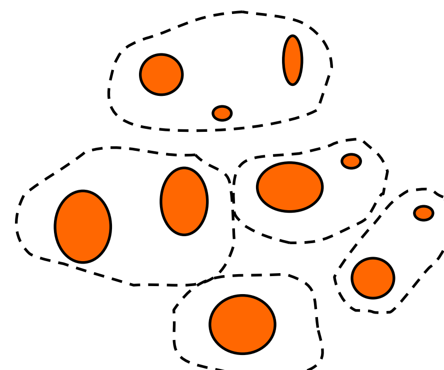


Cone jet

K_T jet (D=1)

$$\vec{\mathbf{p}}_{ij} = \vec{\mathbf{p}}_i + \vec{\mathbf{p}}_j$$

$$\mathbf{E}_{ij} = \mathbf{E}_i + \mathbf{E}_j$$



$$\Delta R_{ij}^2 = (\Delta\eta_{ij})^2 + (\Delta\phi_{ij})^2$$

$$d_{i,j} = \min(E_{T,i}^2, E_{T,j}^2)\frac{\Delta R_{ij}^2}{D^2}$$

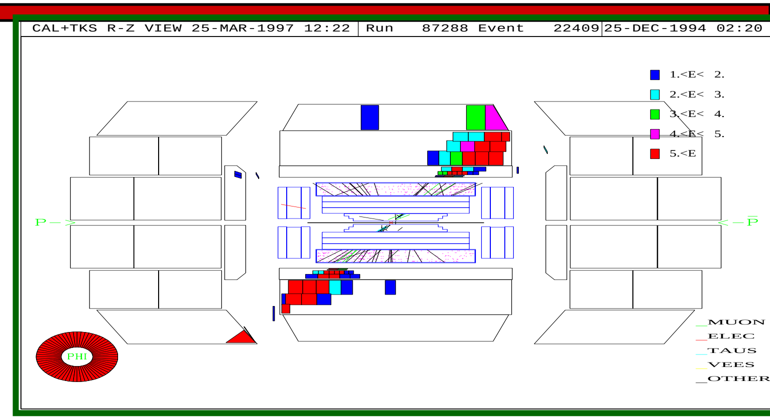
$$> y_{cut} E_{T,Jet}^2$$

resolution parameter

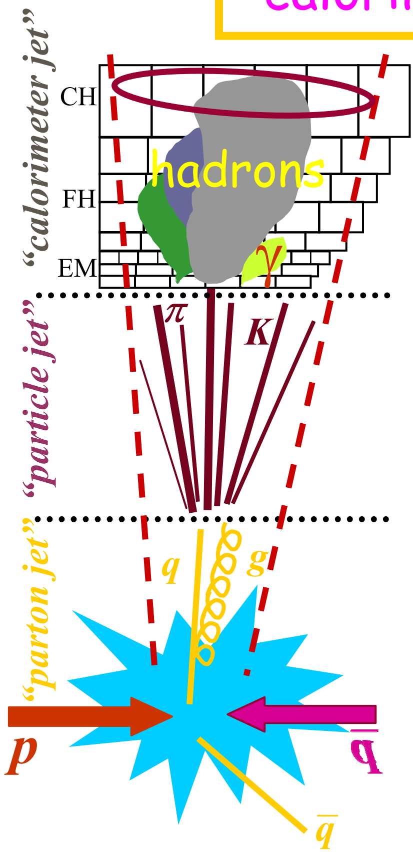
Jet E_T

Jet Selection and Corrections

- ∴ Acceptance cut on interaction vertex Z position
- ∴ Eliminate events with large missing transv energy
- ∴ Apply jet quality cuts



Jet energy scale correction: "calorimeter" → "particle" jet



$$E^{true} = \frac{E^{meas} - E_O}{R_{jet}\, R_{OOC}}$$

E^{true} "True" Jet Energy; particle level

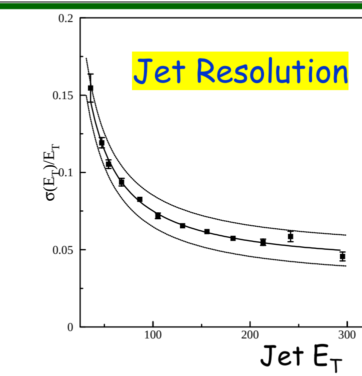
E^{meas} Measured Jet Energy

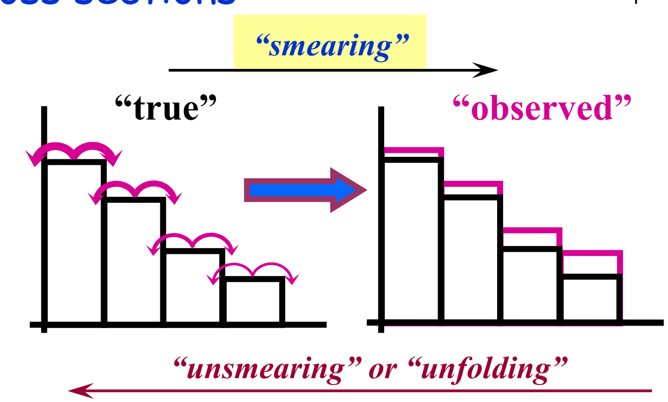
E_O Offset (Ur noise, Mult. Int., pile-up, UE)

R_{jet} Calorimeter Jet Response
Measured in situ using γ – Jet P_T balance

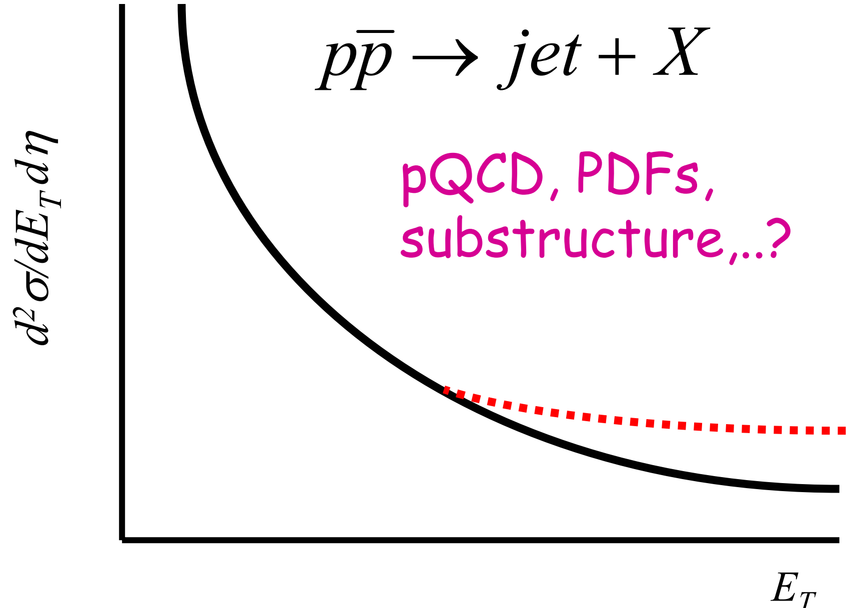
R_{OOC} Out of Cone Calorimeter Showering

Unfold the effects of finite jet energy resolutions from very steeply falling inclusive jet cross sections





Inclusive Jet Cross Section



- How well do we know proton structure (PDFs) ?
- Is NLO (α_s^3) QCD "sufficient" ?
- Are quarks composite ?

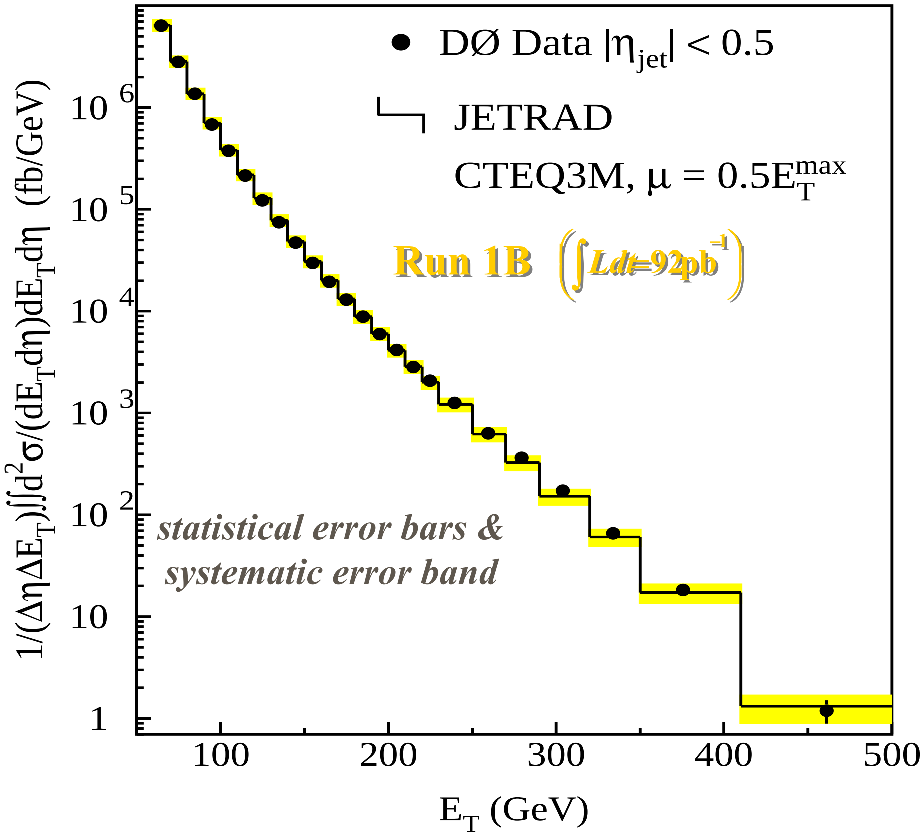
$$\frac{1}{\Delta E_T \Delta\eta} \iint d\eta\, dE_T \frac{d^2\sigma}{dE_T\, d\eta} \longleftrightarrow \frac{N_{jet}}{\Delta E_T \Delta\eta\, \varepsilon \int L dt} \text{ vs. } E_T$$

ΔE_T	$\to$	E_T bin size	ε	$\to$	selection efficiency
$\Delta\eta$	$\to$	η bin size	L	$\to$	inst. Luminosity
N_{jet}	$\to$	# of jets in the bin			

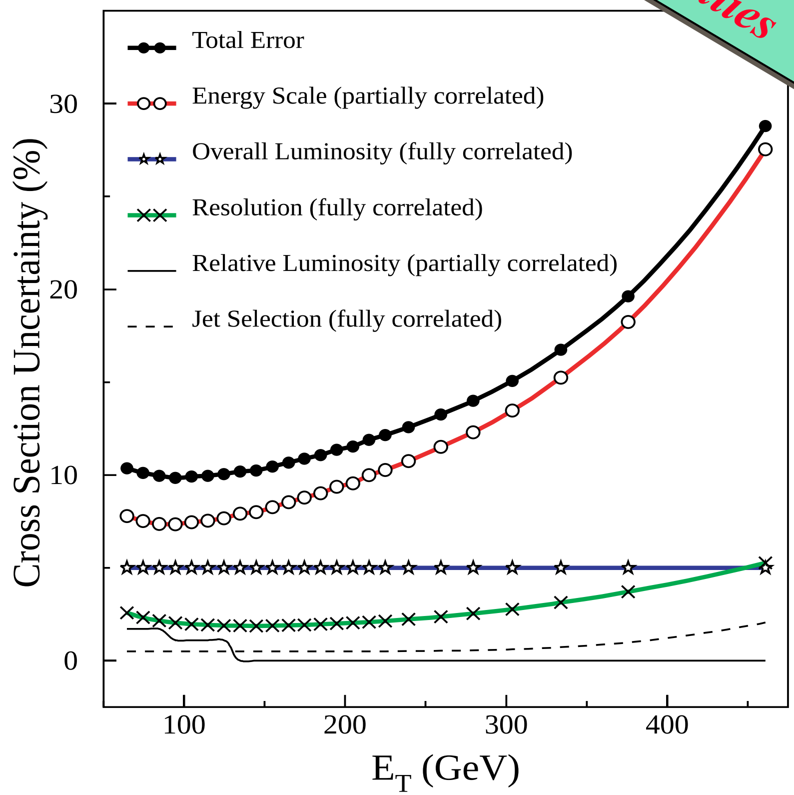
Inclusive Jet Cross Section

PRL:82 2451 (1999)
PRD 64, 032003 (2001)

$\left(\sqrt{s} = 1800\ \text{GeV}\right)$



Uncertainties

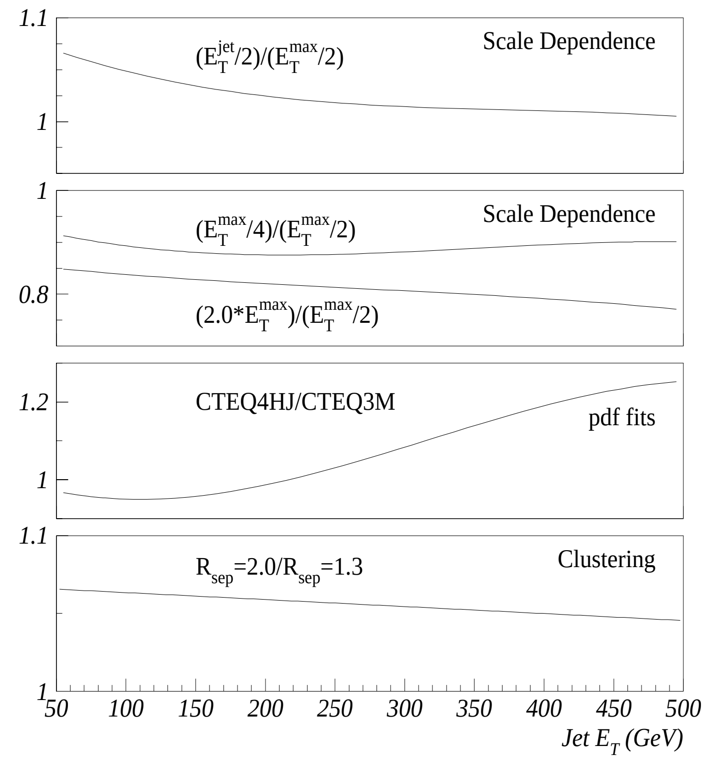


Theory Uncertainties

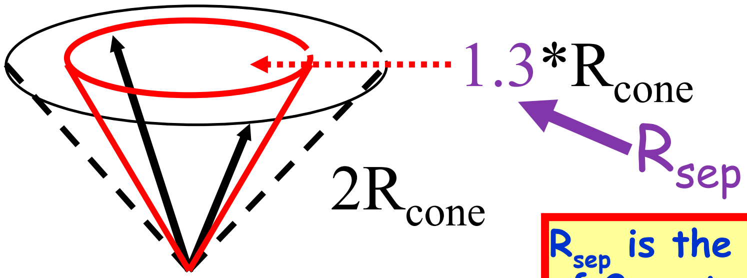
- NLO pQCD predictions (α_s^3):
  - Ellis, et al., Phys. Rev. D, 64, (1990) EKS
  - Aversa, et al., Phys. Rev. Lett., 65, (1990)
  - Giele, et al., Phys. Rev. Lett., 73, (1994) JETRAD

DØ uses: JETRAD
$\mu = 0.5E_T^{Max}$, $R_{sep}=1.3$

CDF uses: EKS
$\mu = 0.5E_T^{Jet}$, $R_{sep}=1.3$

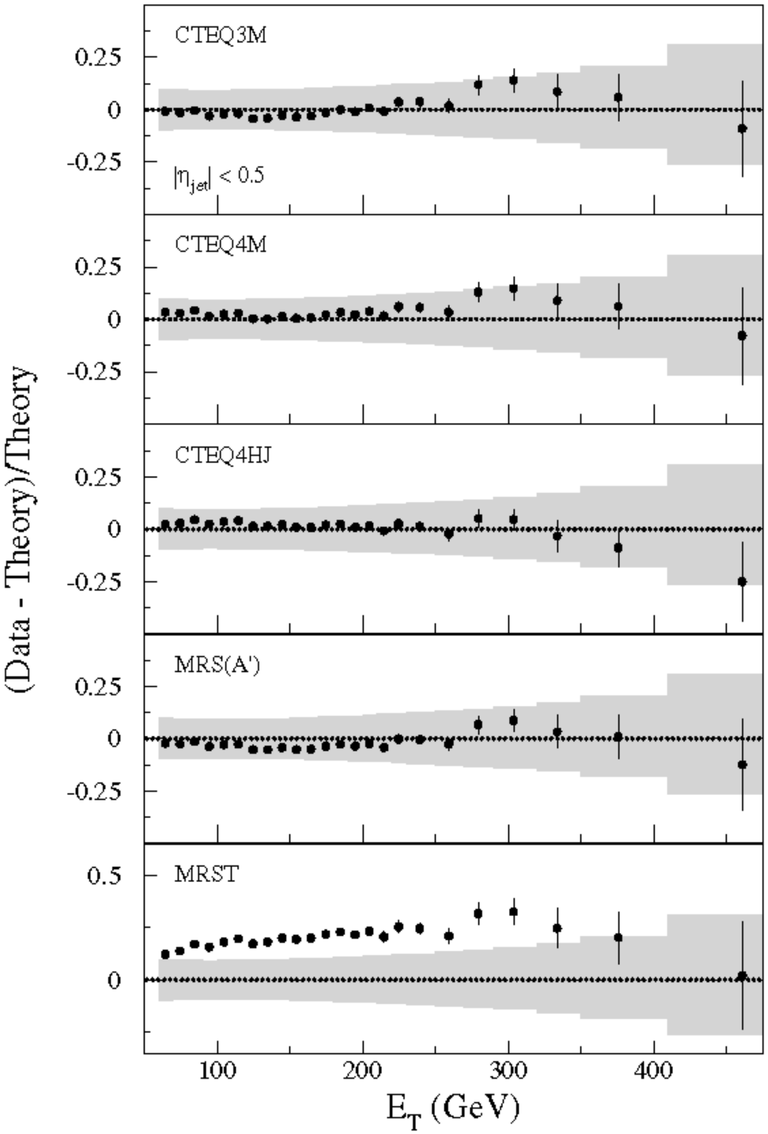


- Choices (hep-ph/9801285, EPJ C5, 687, 1998):
  - ➔ Renormalization Scale (~10%)
  - ➔ PDFs (~20% with E_T dependence)
  - ➔ Clustering Alg. (~5% with E_T dependence)



R_{sep} is the minimum separation of 2 partons to be considered distinct jets

Comparisons to NLO Theory



- No indication of an excess above 350 GeV.
- Good agreement quantitatively as indicated by χ^2 test:

$$\chi^2 = \Sigma\, (D_i - T_i)\, C^{-1}_{ij}\, (D_j - T_j)$$

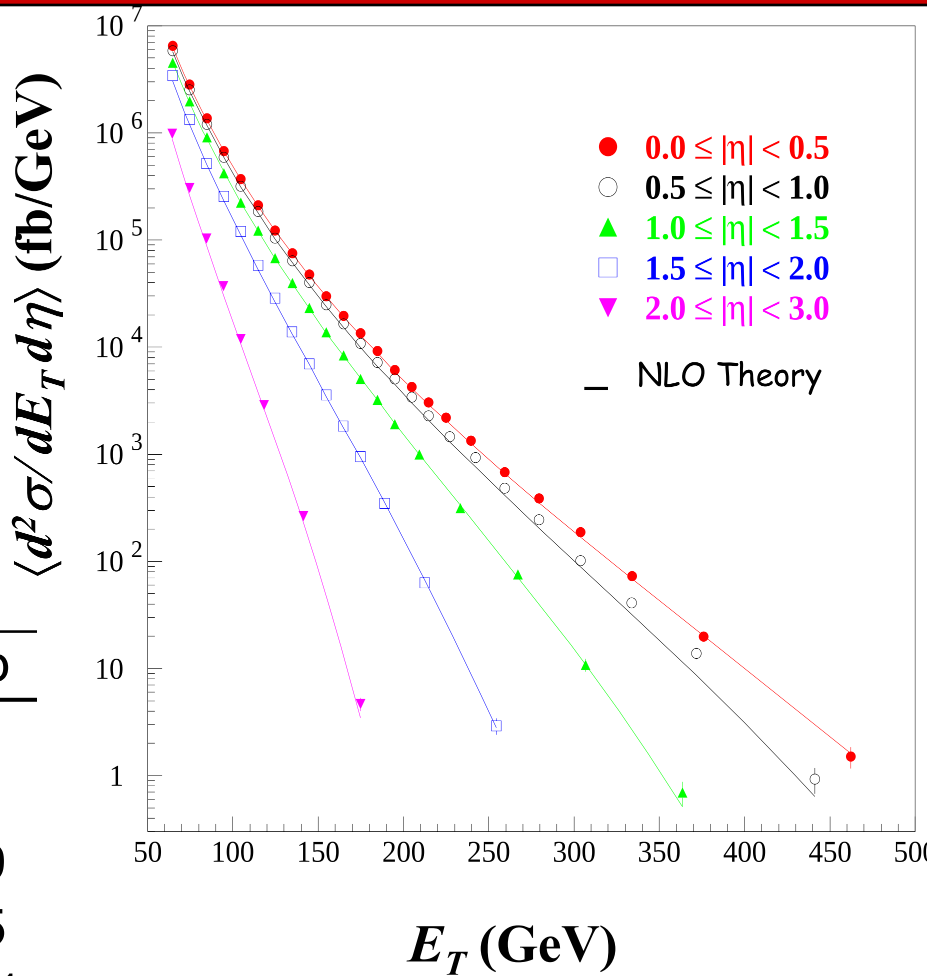
D_i and T_i data and theory, C_{ij} covariance matrix.

	$\lvert\eta\rvert < 0.5$	$0.1 < \lvert\eta\rvert < 0.7$
CTEQ 3M	25.3 (0.39)	32.7 (0.11)
CTEQ4M	20.1 (0.69)	26.8 (0.31)
CTEQ4HJ	16.8 (0.86)	22.4 (0.56)
MRS(A')	20.4 (0.67)	28.5 (0.24)
MRST	25.3 (0.39)	29.6 (0.20)

Rapidity-Dependent Inclusive

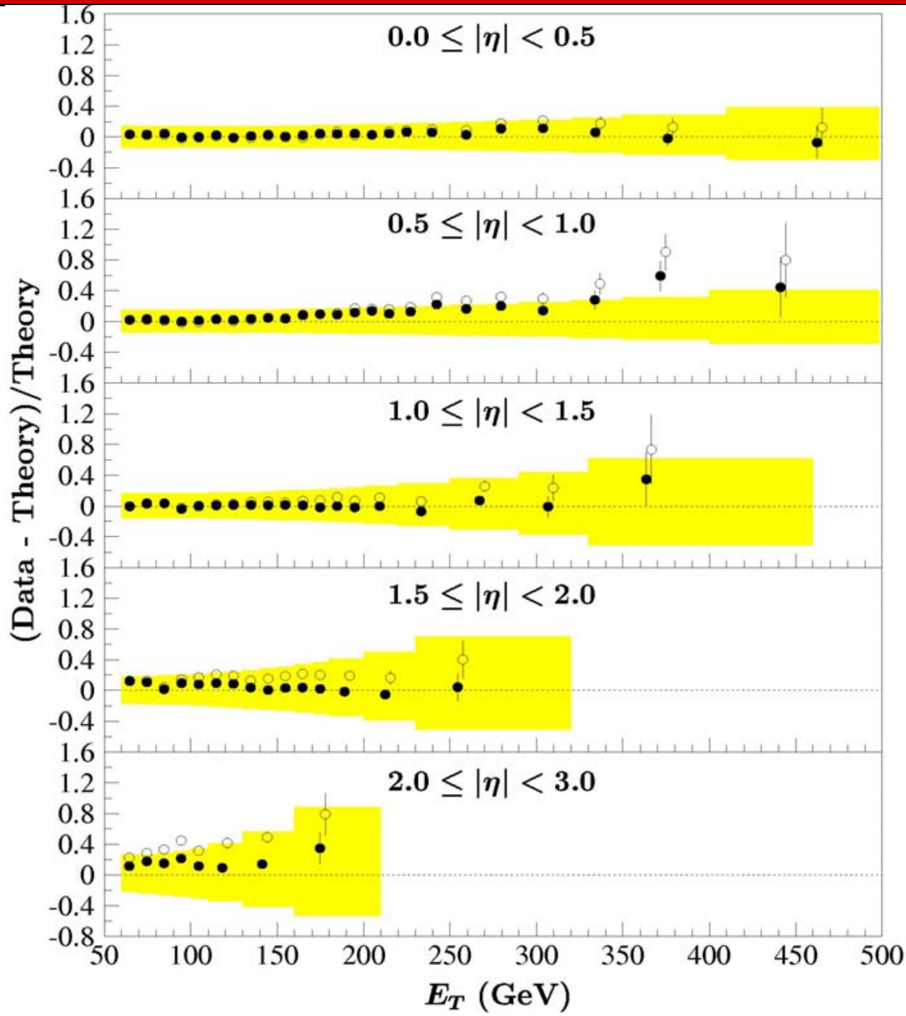
- DØ's most complete cross section measurement
- Uncertainty in theory is larger than uncertainty in data!
- Discriminates between PDF
- MRST to improve gluon determination at large x

PDF	$\chi2$	$\chi2$/dof	Prob
CTEQ3M	121.56	1.35	0.01
CTEQ4M	92.46	1.03	0.41
CTEQ4HJ	59.38	0.66	0.99
MRST	113.78	1.26	0.05
MRSTgD	155.52	1.73	<0.01
MRSTgU	85.09	0.95	0.63

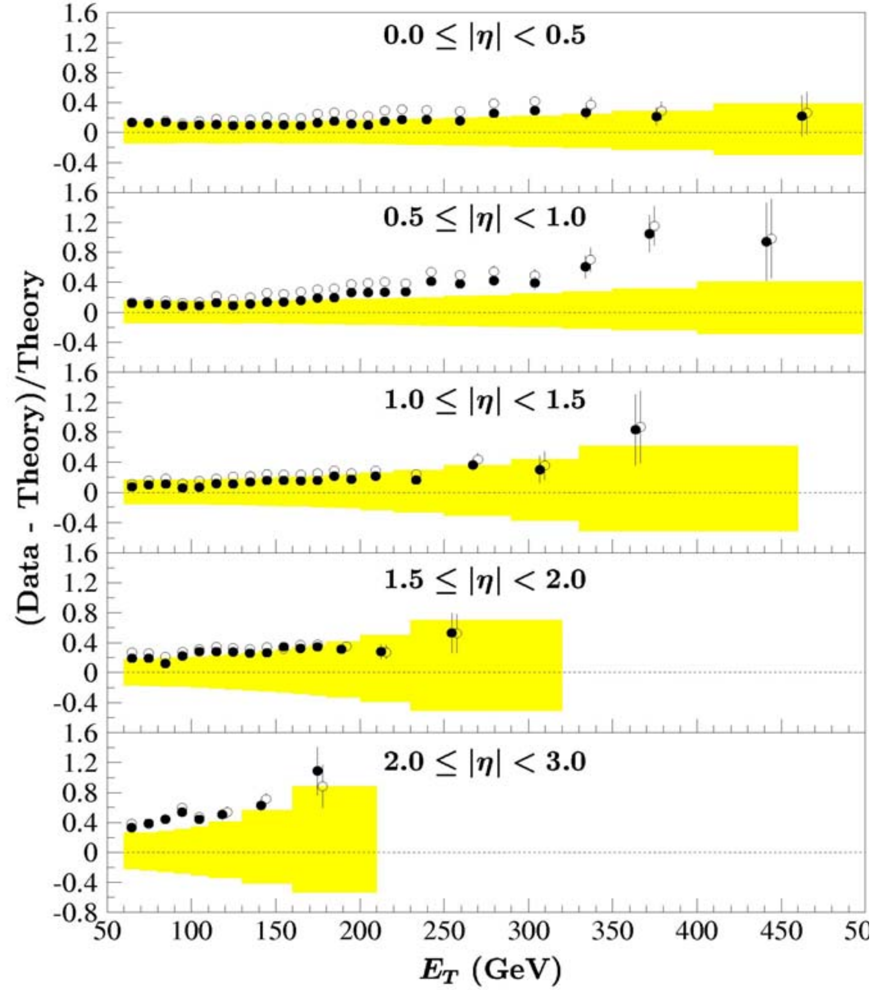


PRL 86, 1707 (2001)

Comparison to NLO Theory

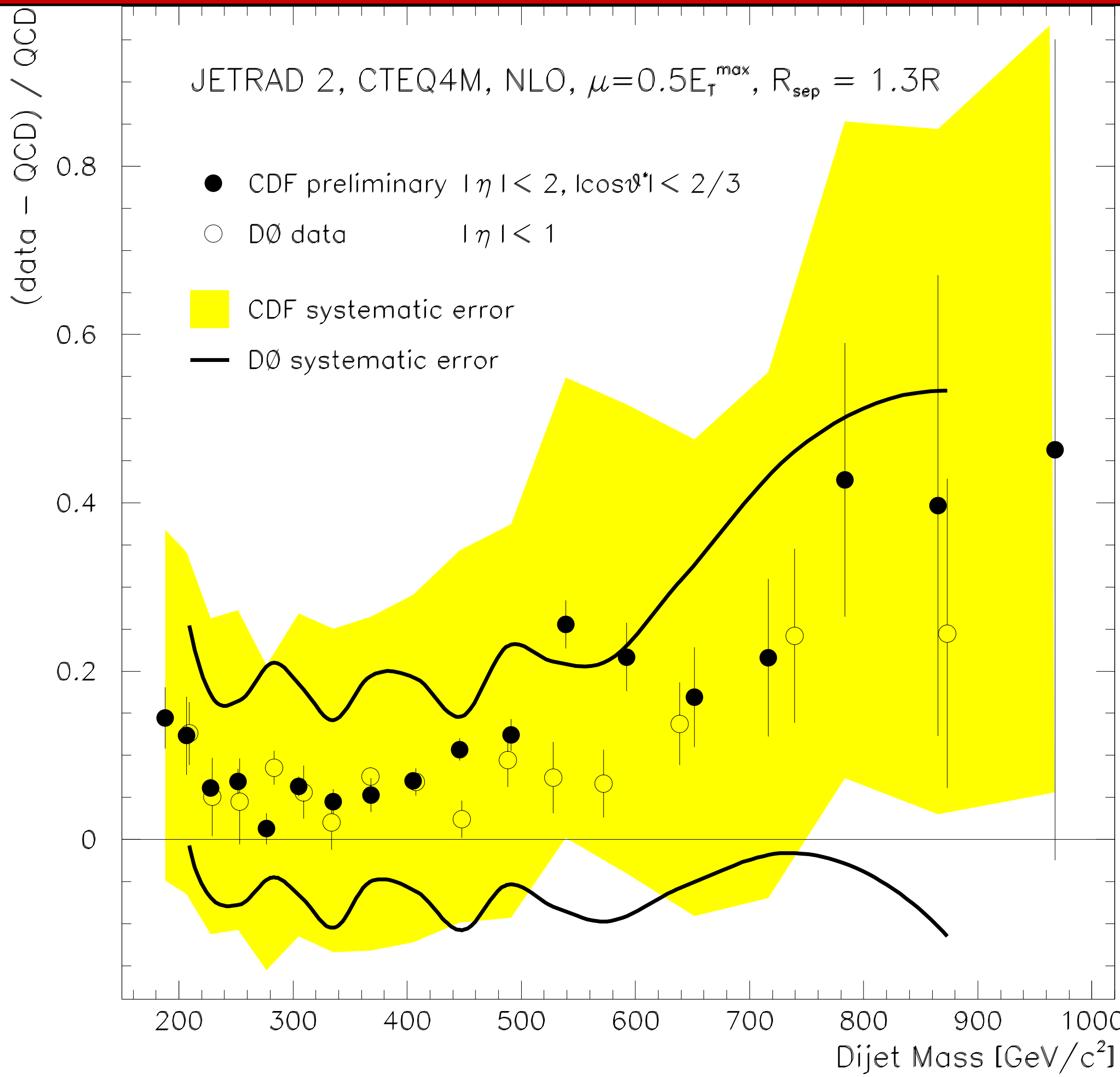


Closed: CTEQ4HJ Open: CTEQ4M



Closed: MRST g↑ Open: MRST

Dijet Mass Spectrum



$$\frac{N_{events}}{L\,\Delta M\,\Delta\eta_1\,\Delta\eta_2}$$

Experiments in excellent agreement.

Different rapidity ranges and very different analysis techniques.

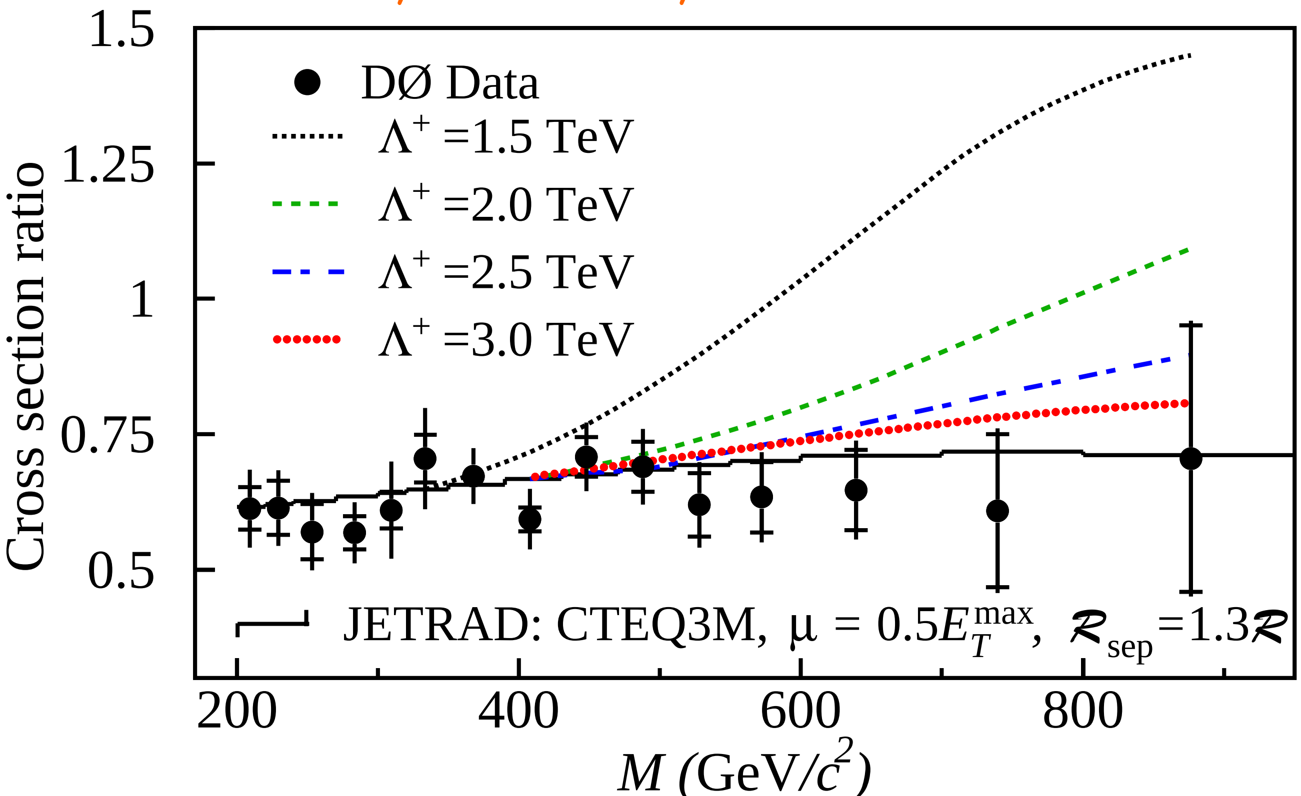
Reasonable agreement with predictions.

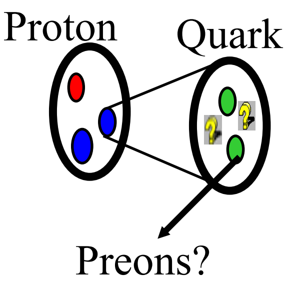
PRL:82 2457 (1999)
PRD 64, 032003 (2001)

Dijet Mass Cross Section Ratio

$\sigma\,(|\eta_{1,2}| < 0.5\,) \,/\, \sigma\,(\,0.5 < |\eta_{1,2}| < 1\,)$ $(\sqrt{s}=1800$ GeV)

PRL 82, 2457-2462, 1999





Theory uncertainty

~ 6% (μ) , 3% (PDF)

Systematic Uncertainty ~ 8%

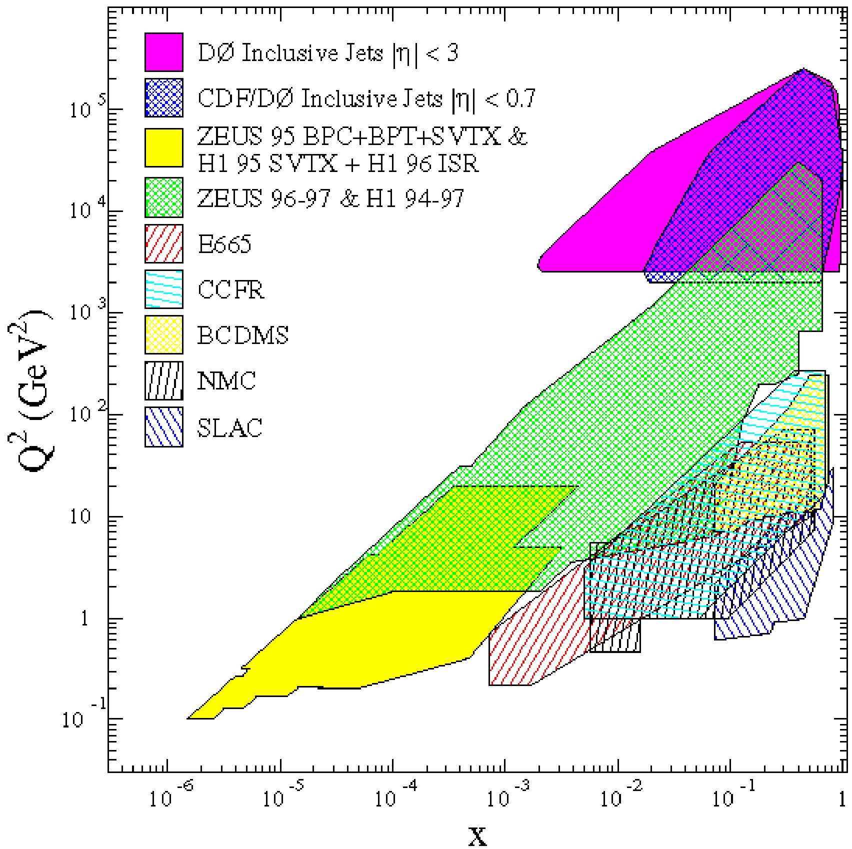
$$L_{qq} = \pm \frac{g^2}{2\Lambda_c^2} \bar{q}_L \gamma^\mu q_L \bar{q}_L \gamma_\mu q_L$$

NLO QCD in good agreement with data

$\Lambda >$ 2.4 - 2.7 TeV (95% confidence level)

What Have We Learned?

- These results extend significantly the kinematic reach of previous studies and are consistent with pQCD calculations over the large dynamic range accessible (|η | < 3).
- Once incorporated into revised modern PDFs, these measurements will greatly improve our understanding of the structure of the proton at large x and Q^2.
- Are gluon distributions at large x enhanced?
  - ➔ factor 20 more data in Run II will extend the reach to higher ET and should make the asymptotic behaviour clearer



Tevatron x-Q^2 reach overlaps and extends reach of DIS

Ratio of Cross Sections

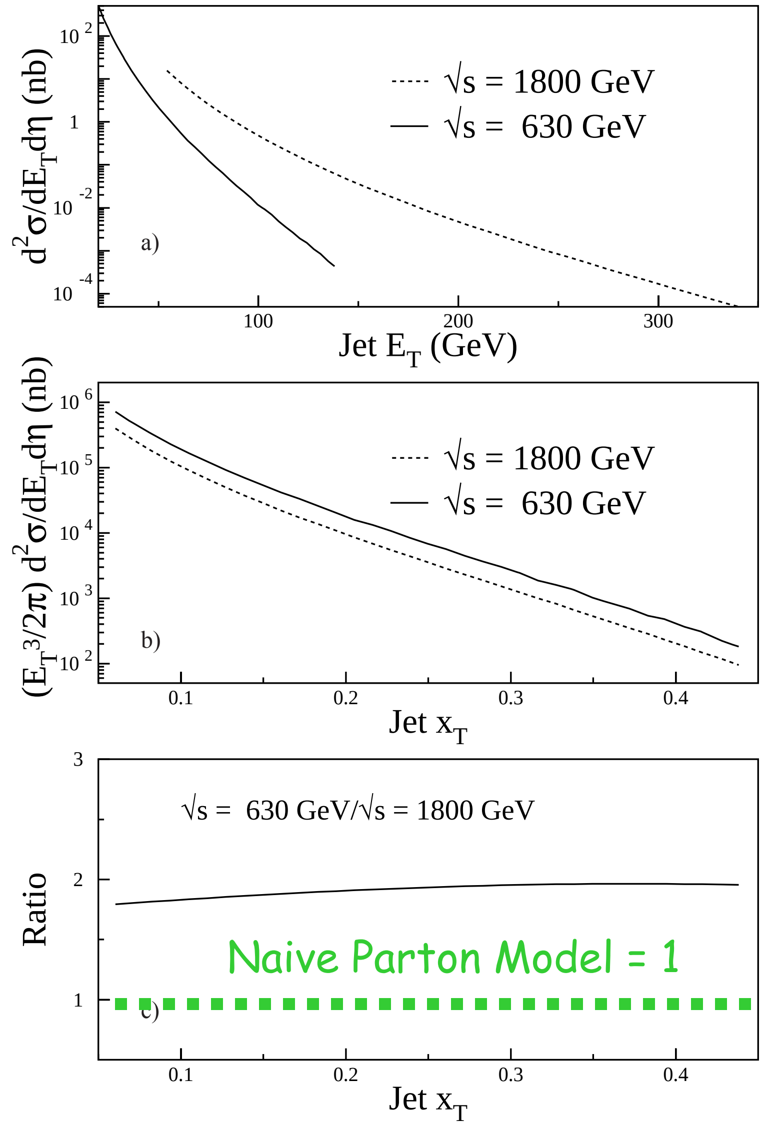
- Express Inclusive Jet Cross Section as dimensionless quantity

$$\boxed{\frac{E_T^3}{2\pi}\frac{d^2\sigma}{dE_T d\eta}}$$

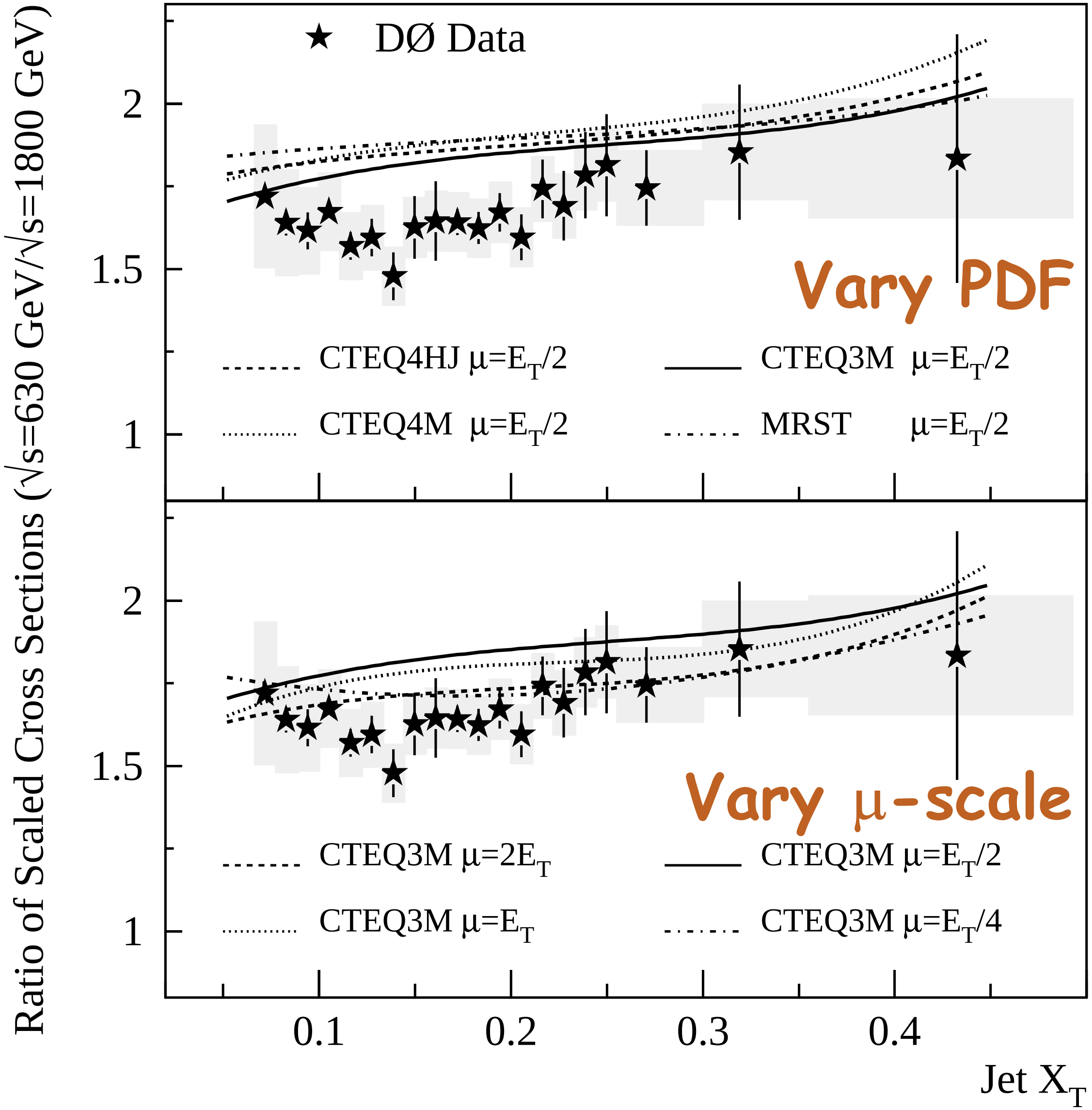
as a function of

$$\boxed{x_T = \frac{2E_T}{\sqrt{s}}}$$

- Various theoretical and experimental uncertainties tend to cancel in the ratio



Ratio of Cross Sections



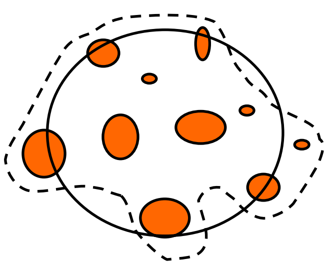
- Phys.Rev.Lett.86, 2523 (2001); hep-ex/0012046
- Data 10-15% below NLO QCD
- Uncertainty due to PDFs reduced in the ratio
- Better agreement with NLO QCD in shape than in normalization

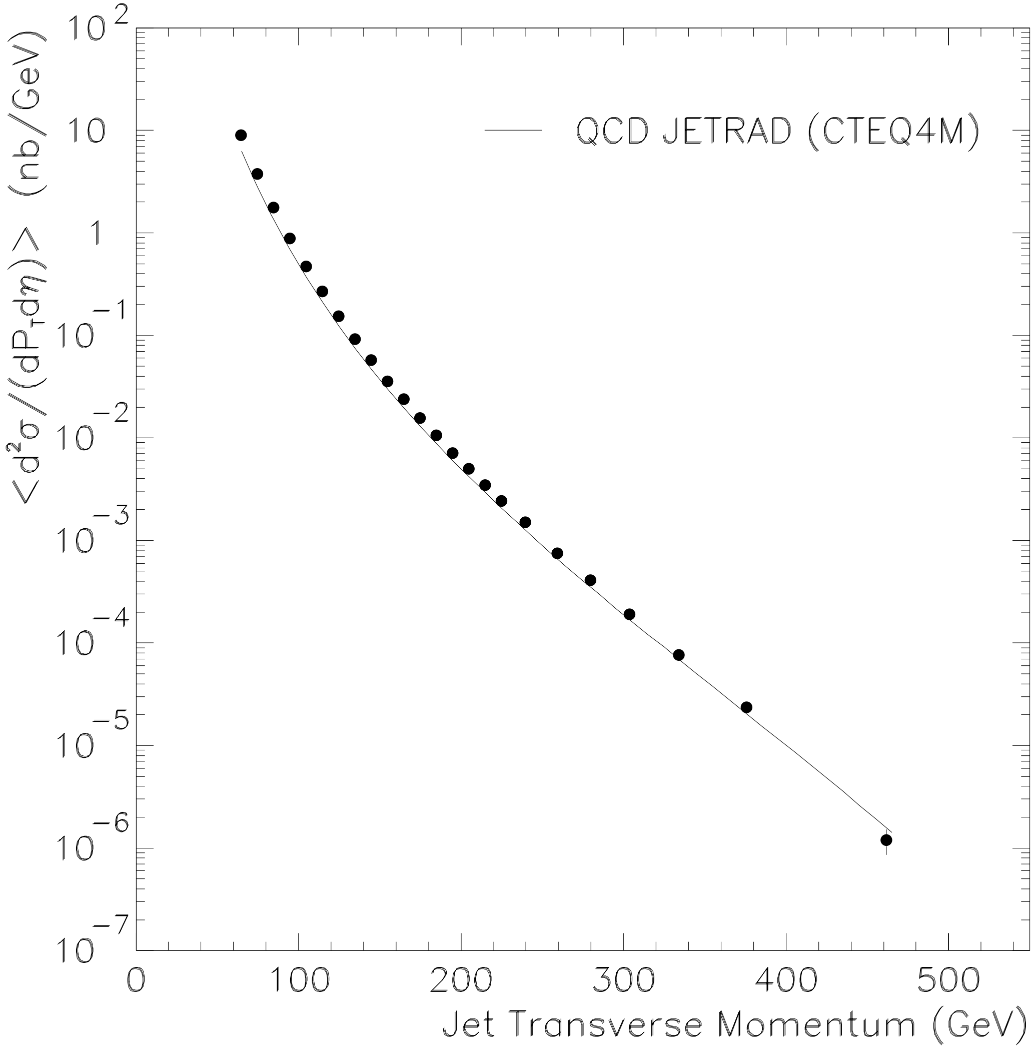
PDF	χ^2 (20 dof)	Prob(%)
CTEQ3M	20.5	42.5
CTEQ4M	22.4	31.9
CTEQ4HJ	21.0	40.0
MRST	22.2	33.0

Jet Cross Section Using K_T

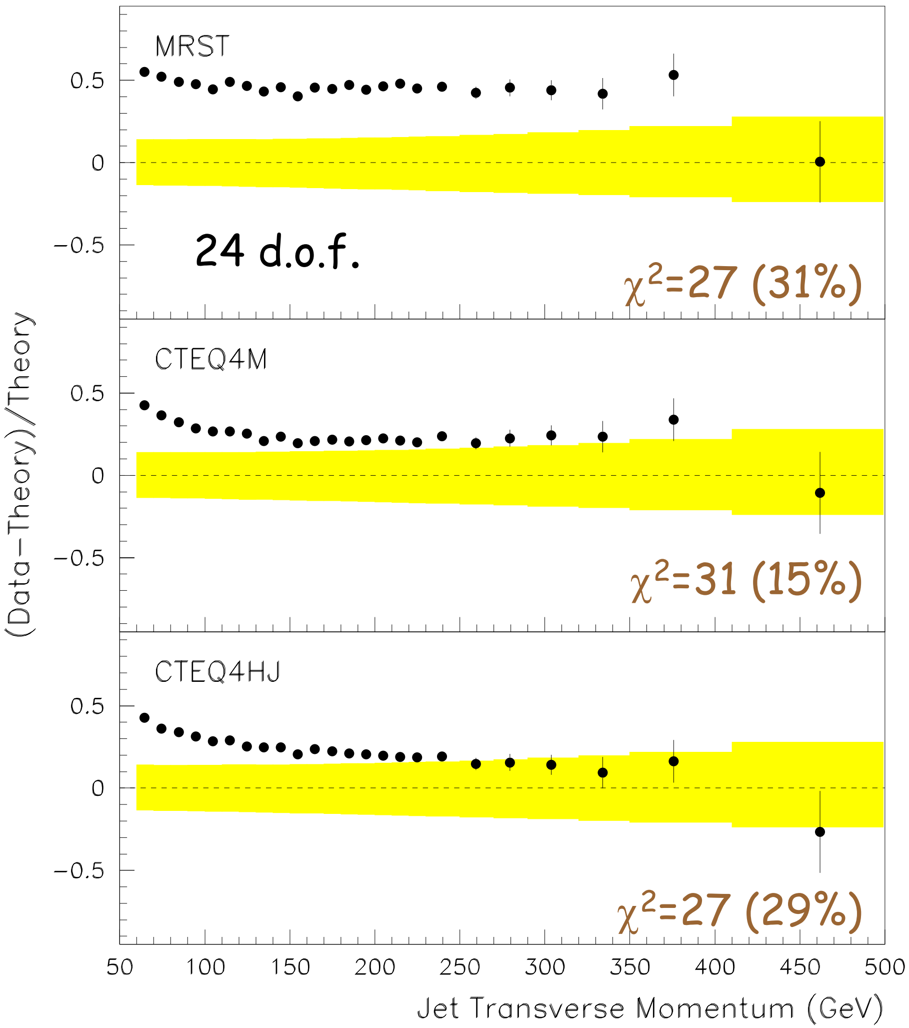
- hep-ex/0106032 (accepted by Phys Lett B)
- The first jet cross section measurement at a hadronic collider using K_T algorithm
- Data: $-0.5 < \eta < 0.5$

  D = 1.0
- Predictions IR and UV safe
- Merging behavior well-defined for both exp. and theory

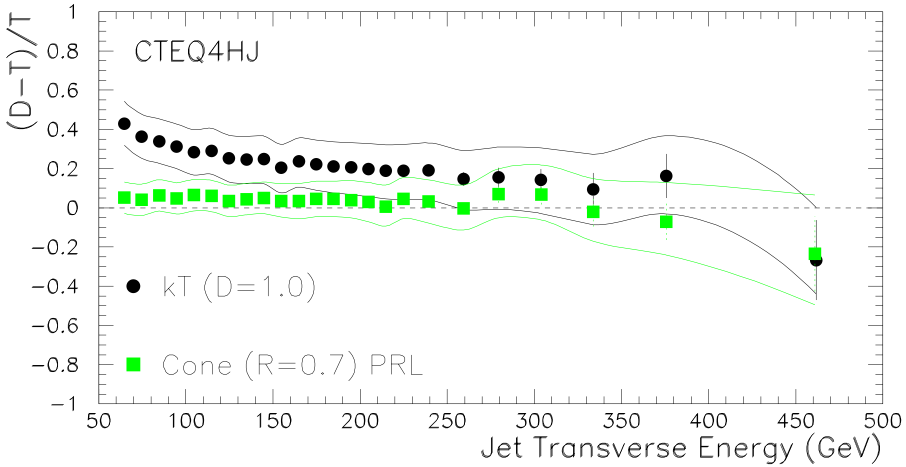




Jet Cross Section Using K_T

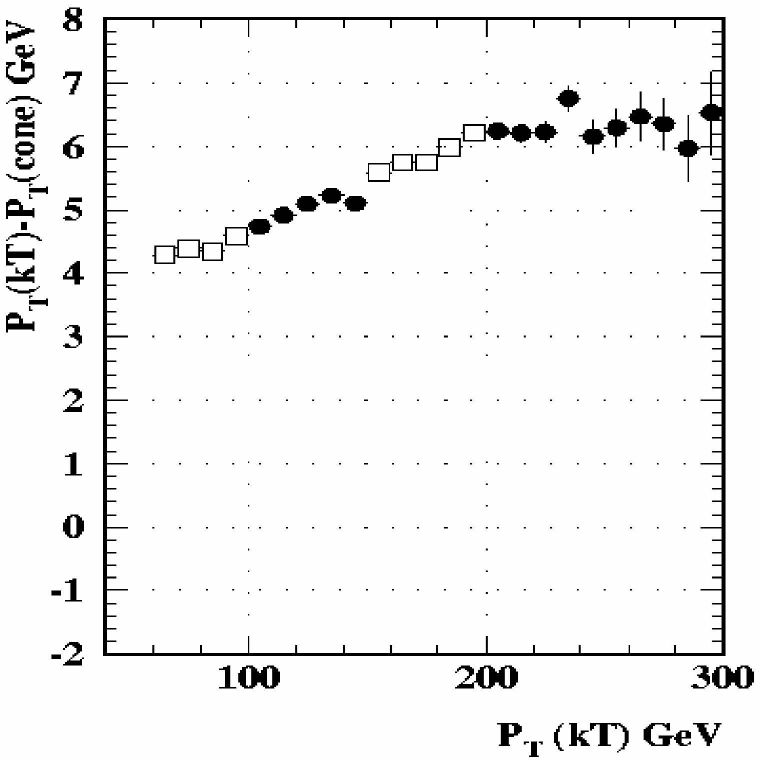


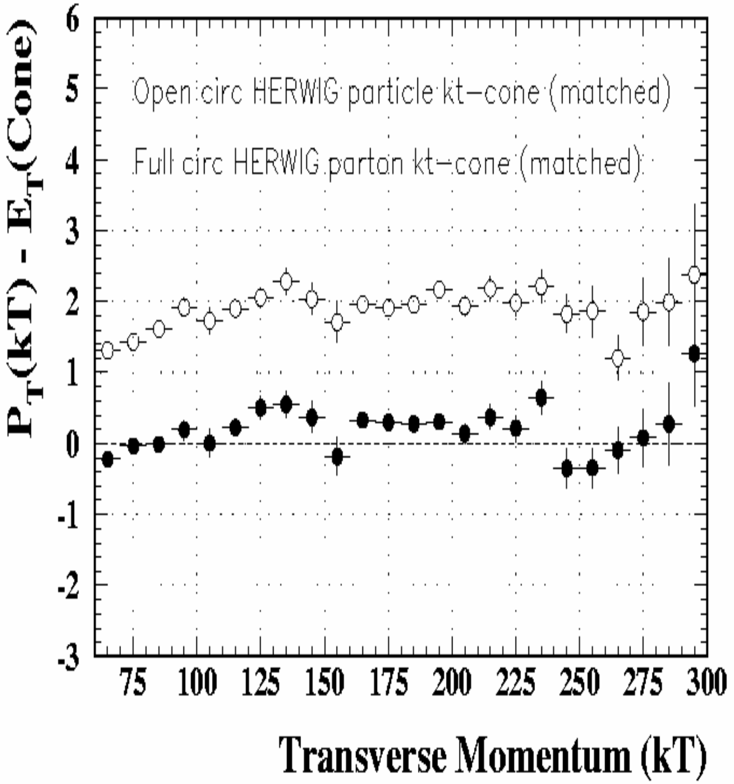
- In NLO QCD, K_T cross section with D=1.0 equals Cone cross section with R=0.7



- Difference with NLO theory mostly at low E_T.

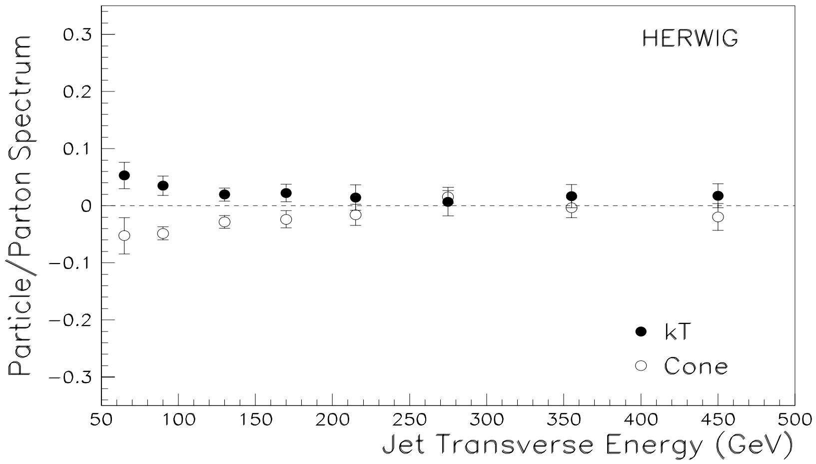
K_T – CONE Jet p_T: Data and MC

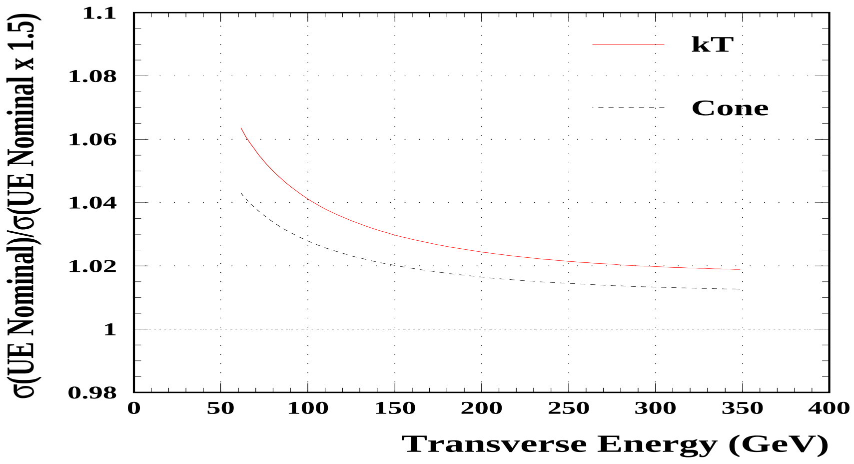




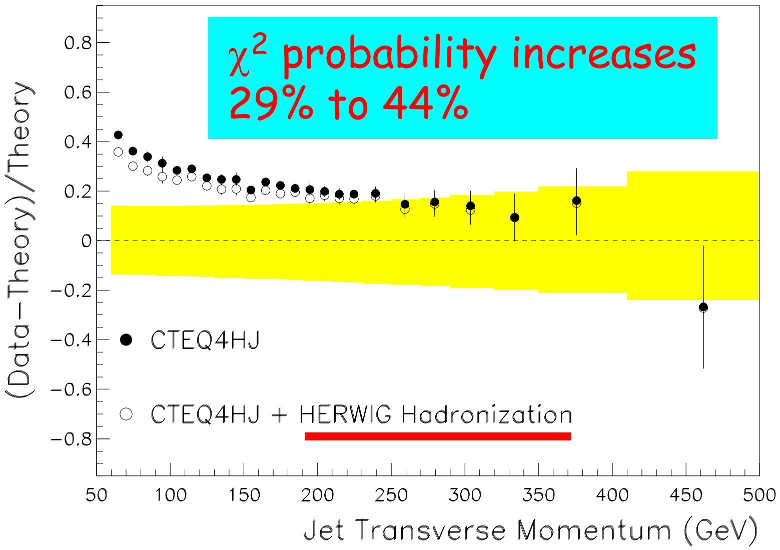
- DØ Run 1 Data
- Herwig MC

More on K_T Jet Cross Section





- The measured K_T and cone cross sections are consistent with each other if the energy difference between K_T and cone jets is taken into account
- K_T and NLO cross section difference can be partially explained by
  - Hadronic Showering effects (parton to particle)
  - Underlying Event uncertainties

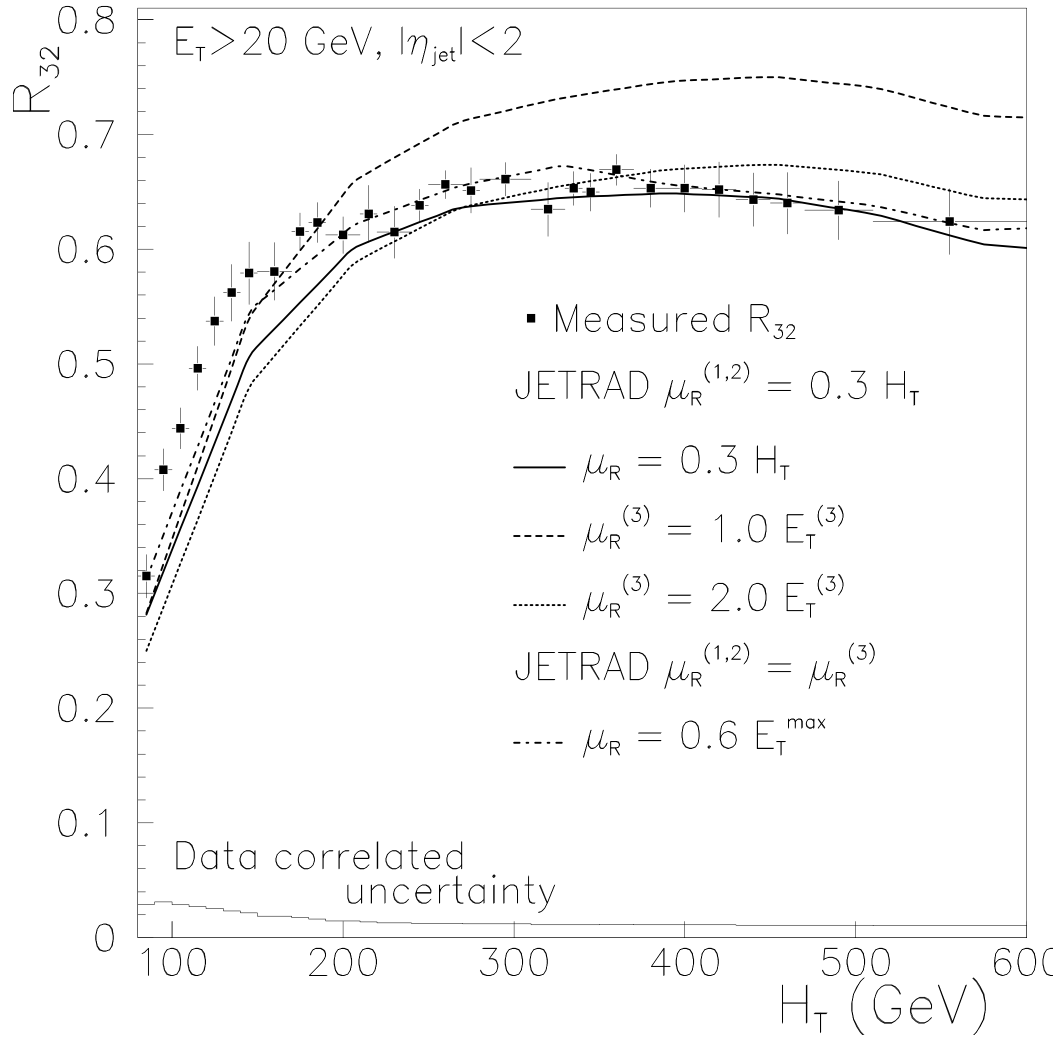


Ratio of Multijet Cross Sections

$$R_{32} = \frac{\sigma_{\geq 3\,\text{Jets}}}{\sigma_{\geq 2\,\text{Jets}}} \quad vs \quad H_T = \sum_{\text{Jets}} E_T$$

- QCD multijet production
  - Background to interesting processes
  - Predict rates at future colliders
- Improve understanding of the limitations of pQCD
  - Prediction is sensitive to choice of renormalization scales
  - Probing the rate of soft gluon emission
- Investigate μ_R scale sensitivity with Jetrad

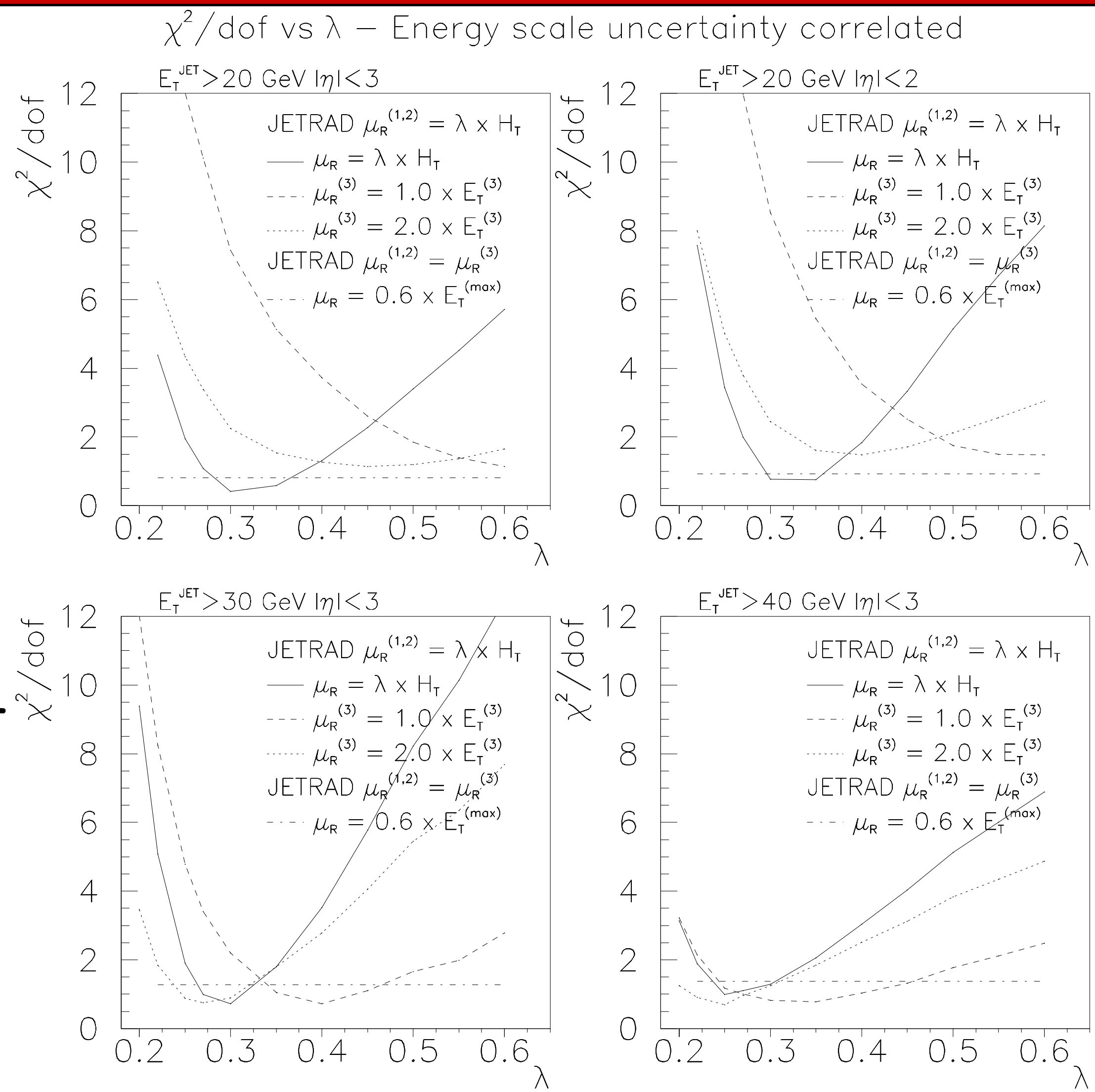
$\mu_R = \lambda H_T$ or $\mu_R = \lambda E_T^{max}$



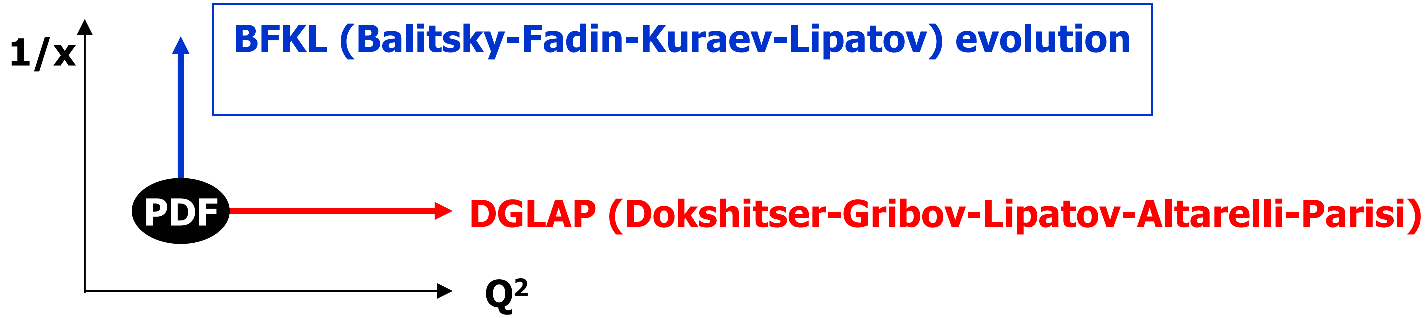
Inclusive R_{32}

- Several formulae for μ_R investigated
- μ_R allowed to differ for jets in the same event - yet agreement not improved
- Single-scales seem better than mixed-scales
- $0.3*H_T$ is most robust
- Need higher order terms for more predictive power

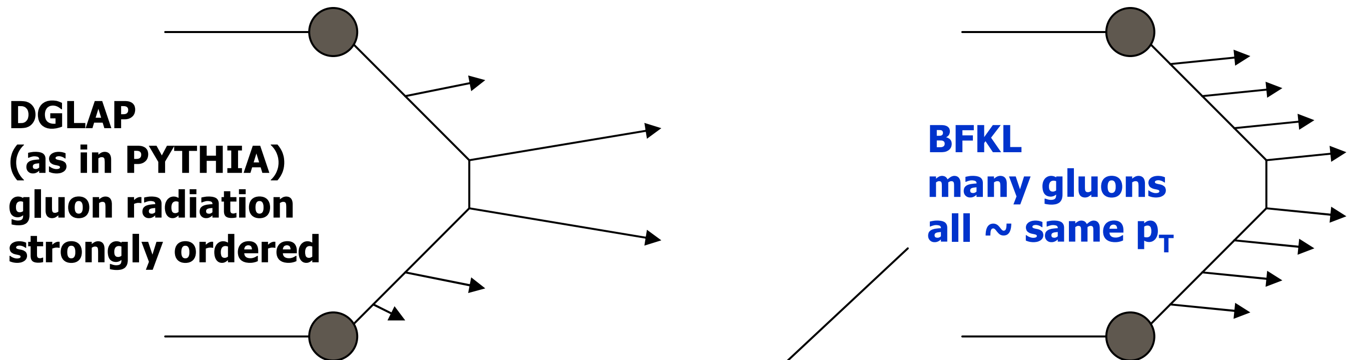
PRL 86, 1955 (2001)



BFKL



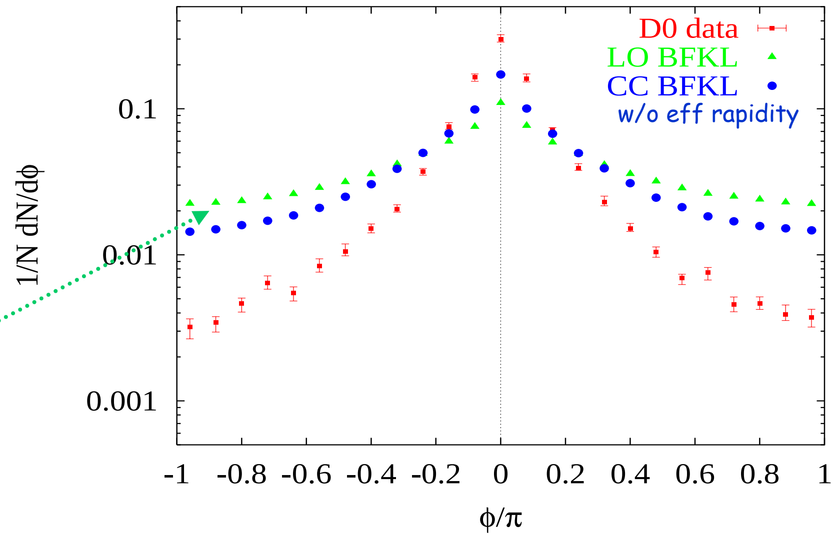
- In hadron-hadron collisions:

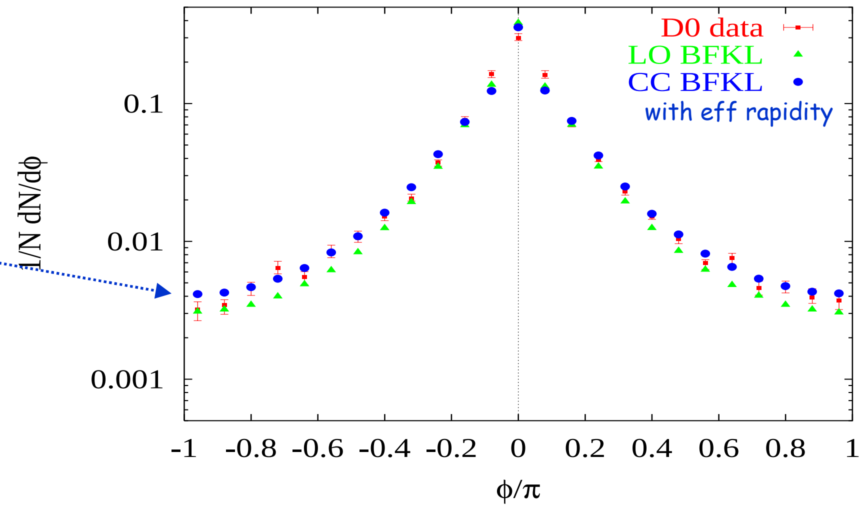


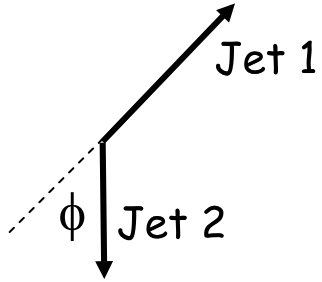
Look at jets widely separated in rapidity, or at low-p_T multi-jet events -- many gluons of comparable p_T can be present
BFKL provides a way to resum the contribution of these gluons

BFKL: Decorrelation of Jets

- Old DØ data (PRL 77, 595 (1996))
- New calculation
  Kwiecinski et al., hep-ph/0105039
- The original BFKL formalism failed to describe azimuthal decorrelation of dijet data
- New calculation: includes subleading effects and uses an *effective* rapidity difference $\hat{y}$ (in place of usual ΔY)
  - ➔ Much better description of tails of the azimuthal distribution





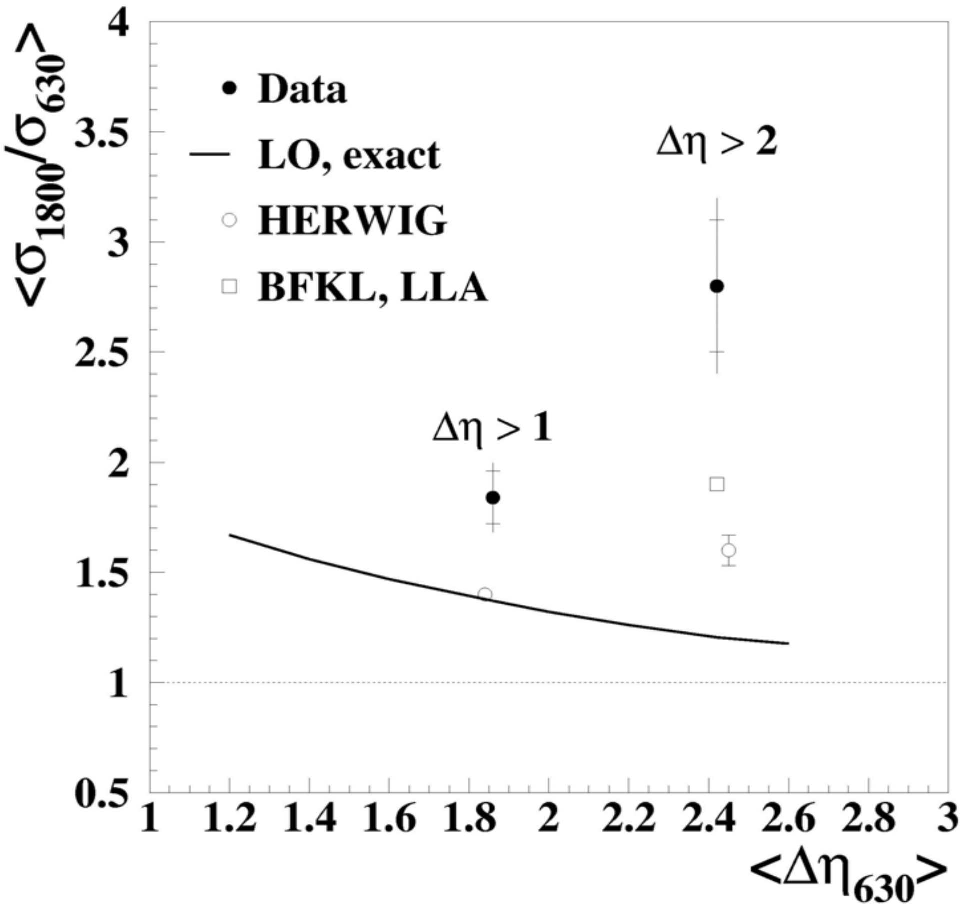


BFKL

- Phys.Rev.Lett. 84, 5722 (2000)
- An attempt to find an observable which displays BFKL behavior
- DØ measurement of 630/1800 GeV cross section ratio at large rapidity separations
  - ➔ $E_T > 20$ GeV, $|\eta| < 3$
  - ➔ use bins such that x and Q^2 are the same in the two datasets but different $\Delta\eta \rightarrow$ A, B

    (Mueller, Navelet)

$$R = e^{(\alpha_{BFKL} - 1)(\Delta\eta_A - \Delta\eta_B)} / \sqrt{\Delta\eta_A / \Delta\eta_B}$$



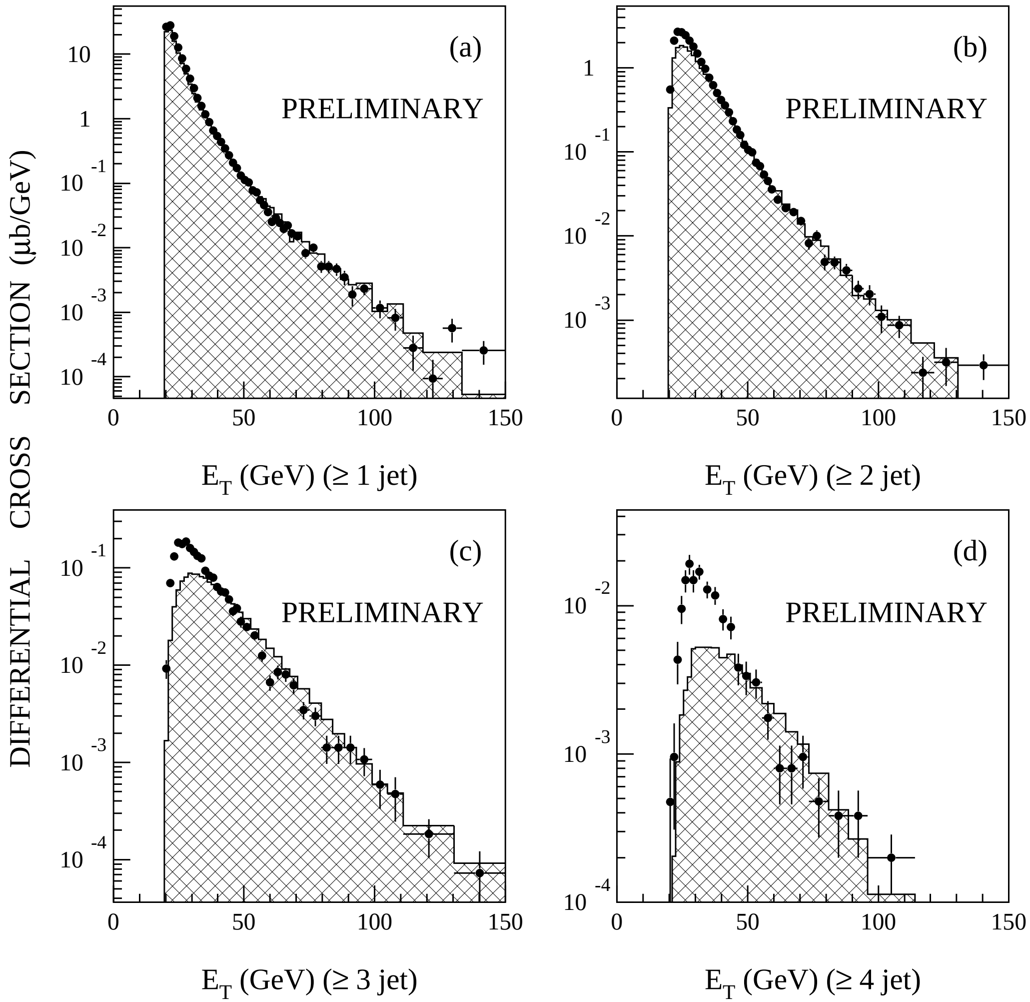
- What's going on here?
  - ➔ data rise stronger than LLA BFKL (and HERWIG)
  - ➔ but is asymptotic BFKL expression applicable?
  - ➔ careful about effects of equal jet E_T cuts, definition of momentum fraction x of incoming partons, and Q^2 restrictions (Andersen, Del Duca, Frixione, Schmidt, Stirling, JHEP 0102, 007 (2001))

Low-E_T Multijet Events

- At high-E_T, QCD does quite well
- But try looking at multi-jets at low-E_T…compare to Pythia
- This region may be sensitive to differences in BFKL and DGLAP descriptions
- Each jet's E_T>20 GeV, $|\eta|$<3
- For 2 jets or more, normalization is off, so correct to >40 GeV spectrum

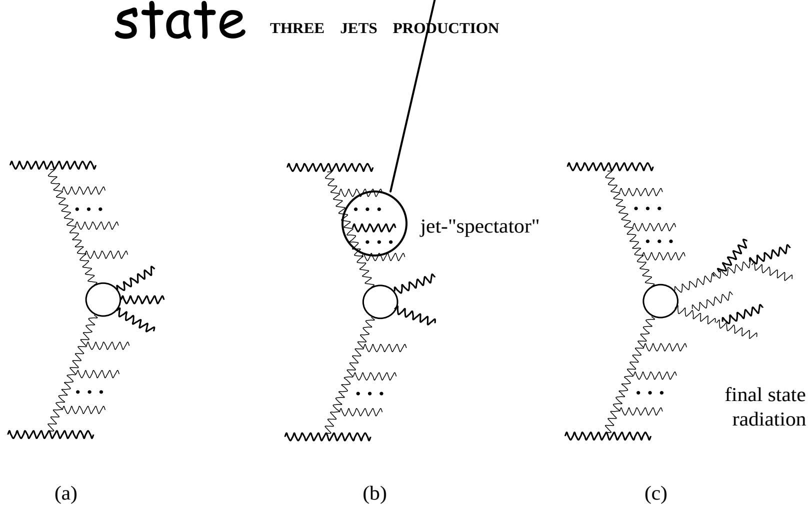
- hep-ex/0106072

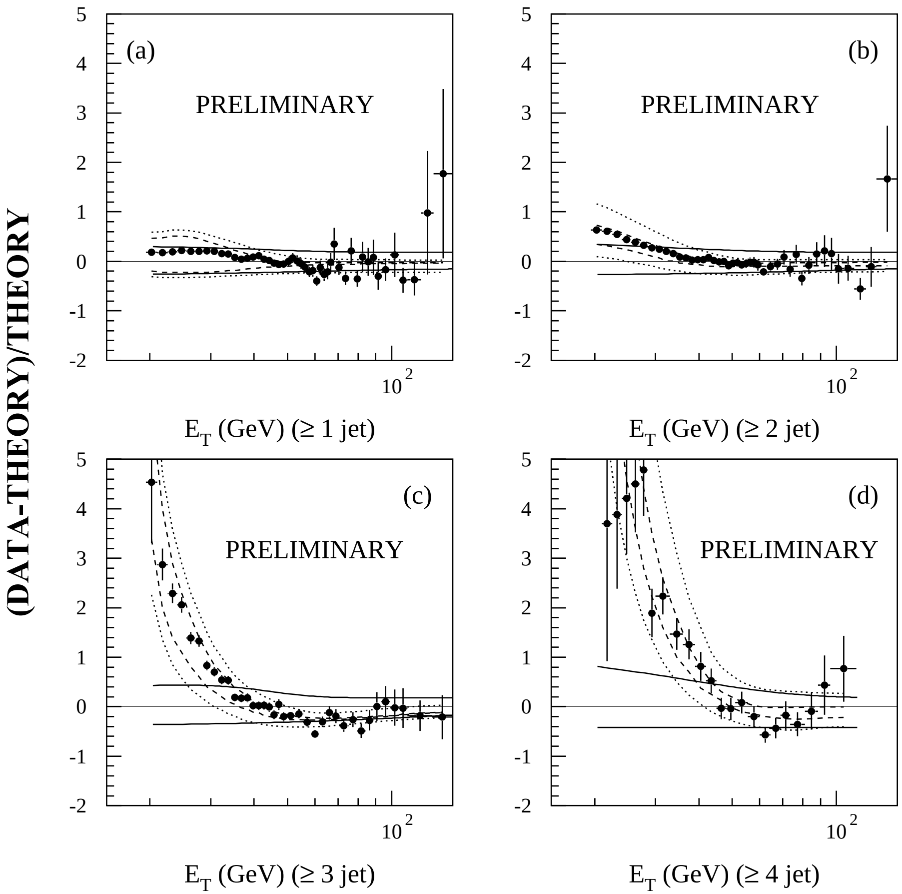
E_T of Leading Jet



DØ Low-E_T Multijet Events

- Strong shape disagreement at low E_T for 3 and 4-jet samples
- Strong p_T ordering in DGLAP suppresses "spectator jets"
- BFKL can enhance radiation of "spectator jets" in initial state

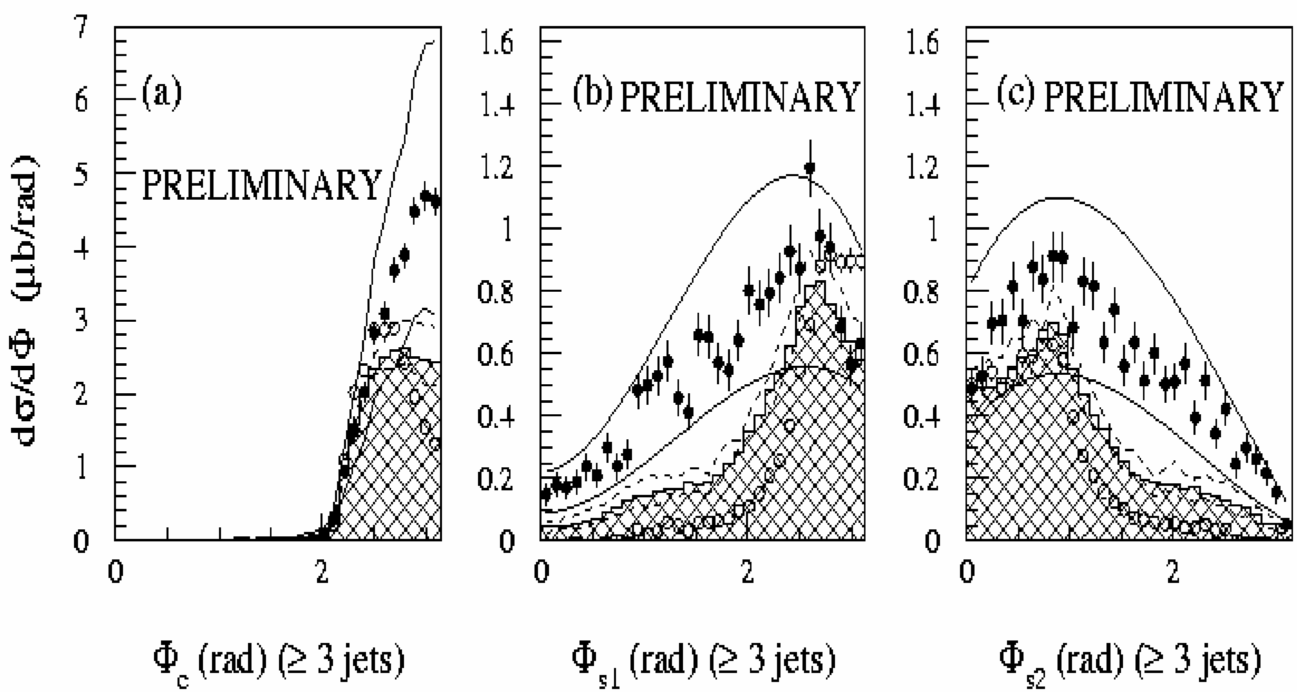




DØ Low ET-Multijet Events

- Spectator jet in inclusive 3-jet event sample:
  - ➔ find a pair of "best balanced" jets – angle ϕ_c
    - distribution more back to back than in Pythia or Jetrad
  - ➔ 3[rd] jet relative to these two – angles ϕ_{s1}, ϕ_{s2} (for $|\pi-\phi_c| <$ 0.4) - less correlation than in Pythia or Jetrad

Data – points
Pythia – hatched
Jetrad – open circles



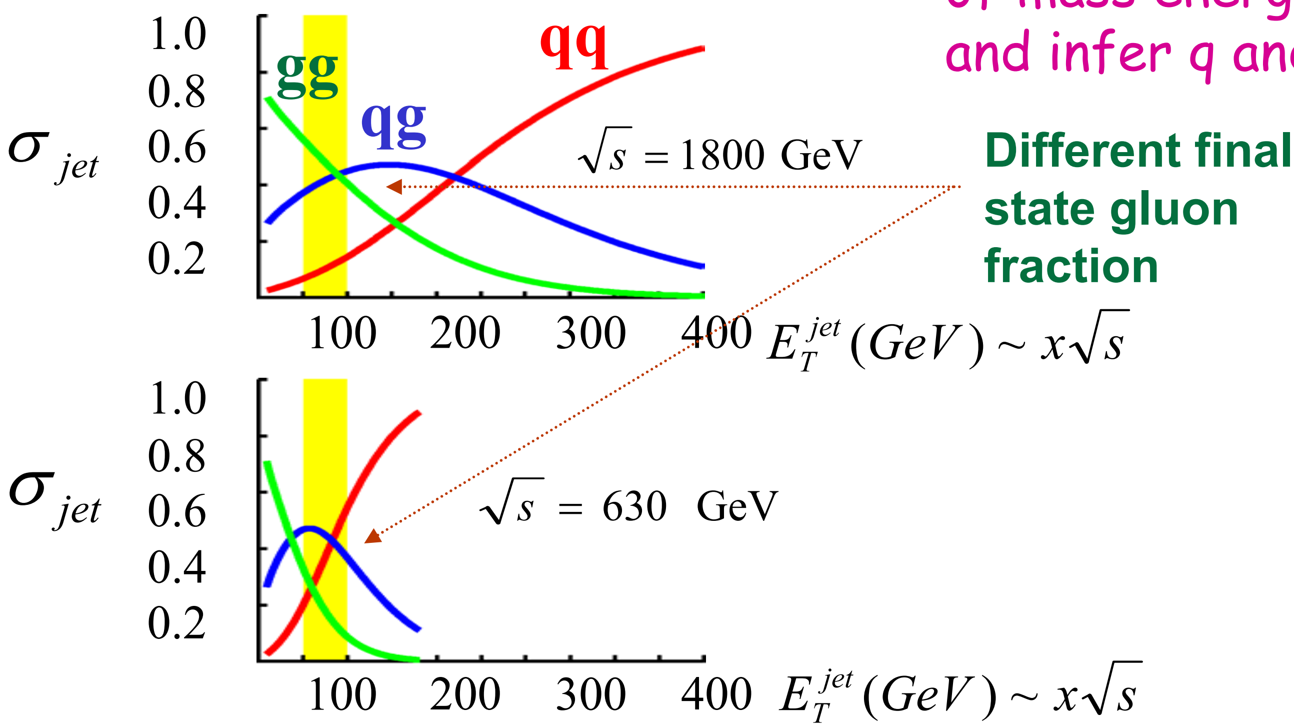
Subjet Multiplicity in Quark & Gluon Jets

Motivation:

- Test of QCD: differences of q & g jets
- Separate q jets from q jets (top, Higgs, W+Jets events)

Method:

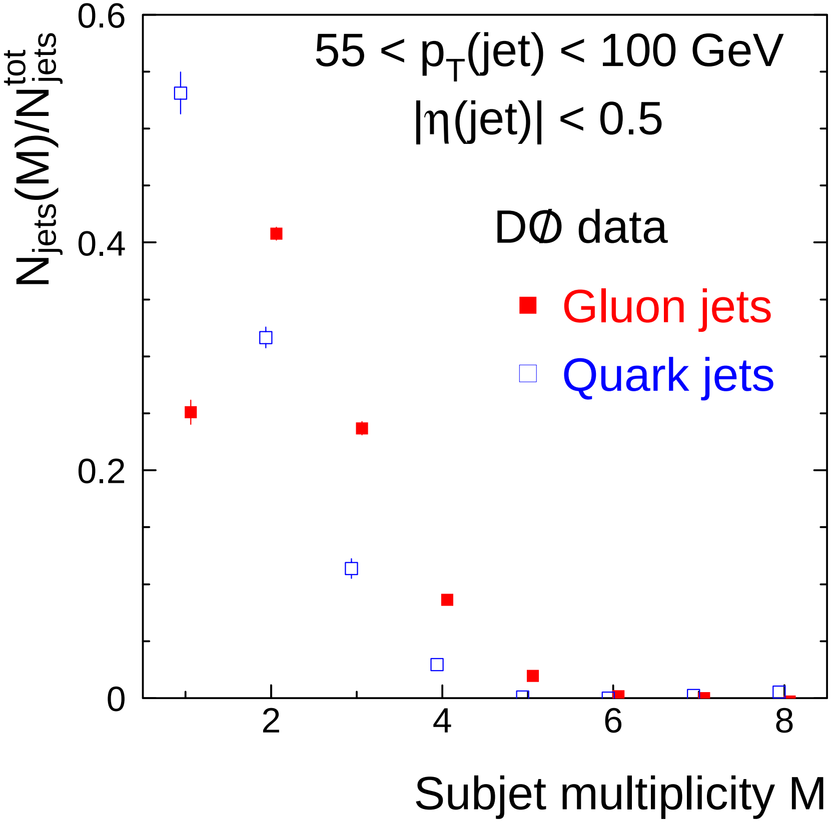
- Select quark enriched & gluon enriched jet samples
- Compare the subjet multiplicity of jets with same E_T and η at center of mass energies 630 and 1800 GeV and infer q and g jet differences



Obtain gluon fractions for both energies from Herwig

(59% gluon jets at 1800 GeV; 33% at 630 GeV)

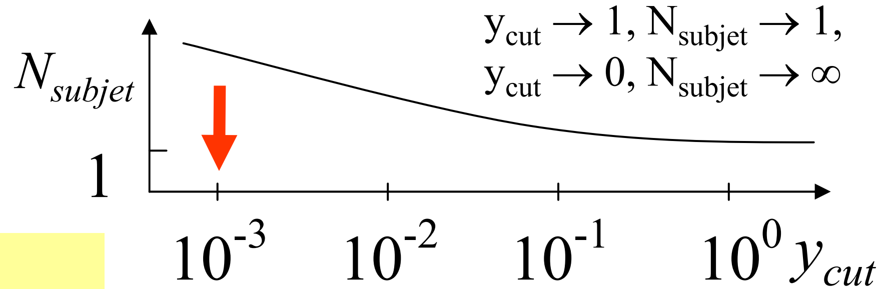
Subjet Multiplicity of Quark/Gluon Jets



- Rerun k_T-algorithm on all 4-vectors merged into jet:
  - ➔ Recombine energy clusters into subjets separated by y_{cut} (a resolution parameter)

$$d_{i,j} = \min(p_{T,i}^2, p_{T,j}^2)\frac{\Delta R_{ij}^2}{D^2} > y_{cut}\, p_{T,Jet}^2$$

- Measure Subjet Multiplicity:

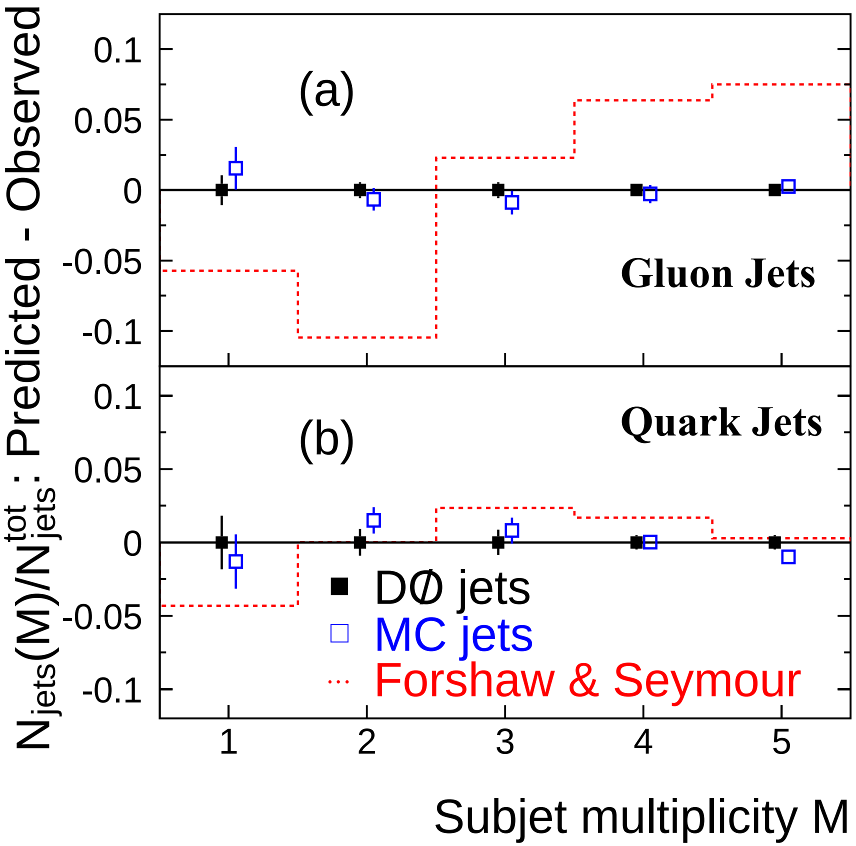


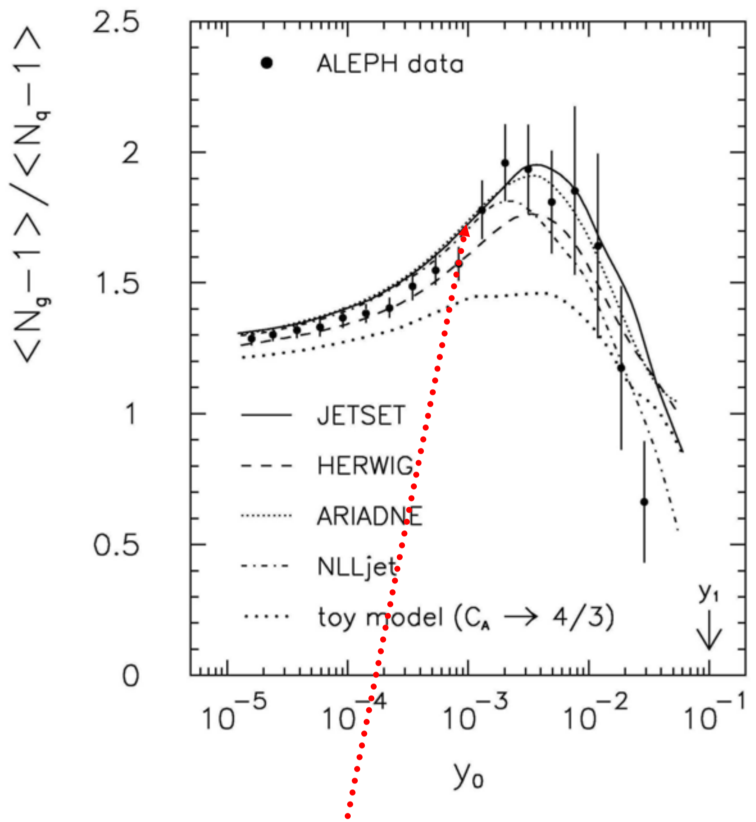
DO data: $R = \dfrac{\langle M_g \rangle - 1}{\langle M_q \rangle - 1} = 1.84 \pm 0.15\,(stat) \pm^{0.22}_{0.18}(sys)$

Herwig: $R = 1.91 \pm 0.16(stat)$

hep-ex/0106040
accepted by PRD

Subjet Multiplicity of Quark/Gluon Jets



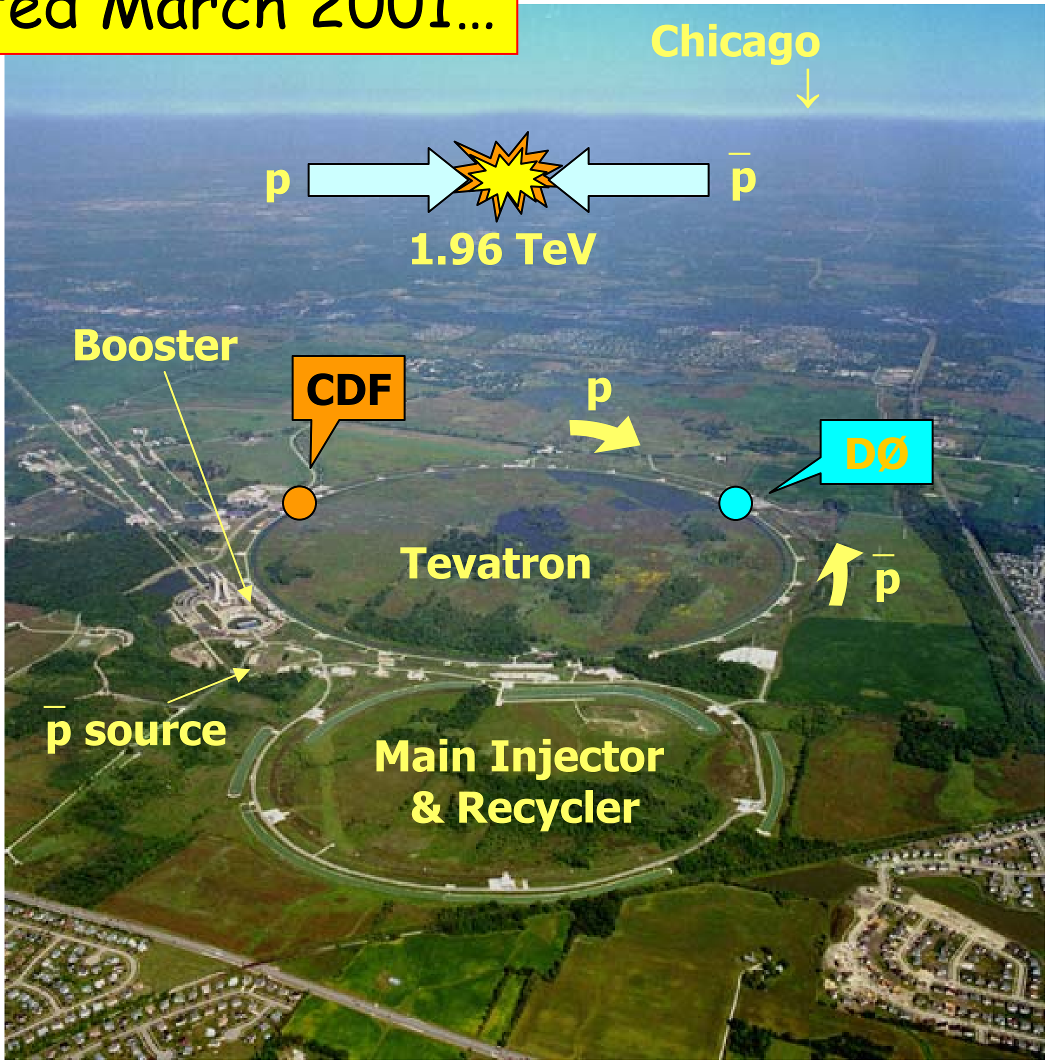


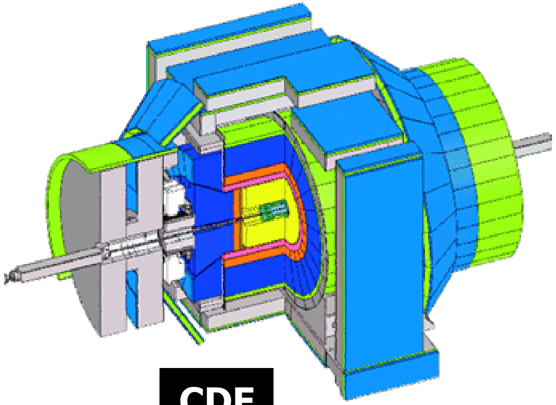
- Nice agreement with Herwig
- Analytic resummed calculation predicts slightly higher multiplicities

Result is consistent with ALEPH measurement for $y_0 \sim 10^{-3}$

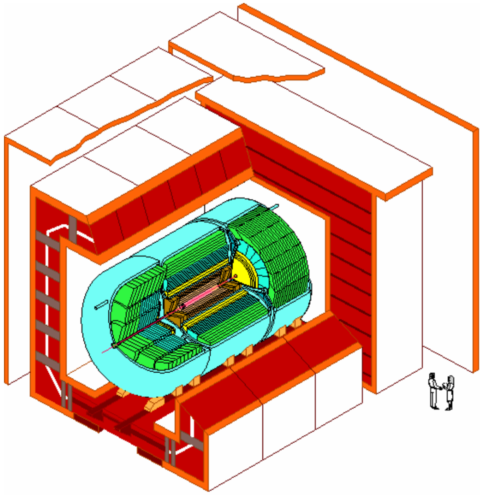
Looking Ahead: Tevatron Run 2

Started March 2001…





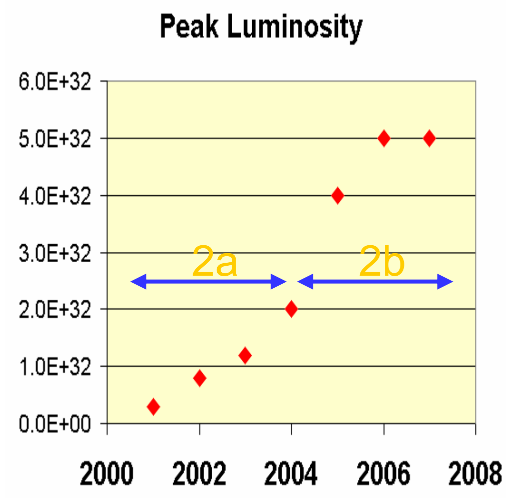
CDF

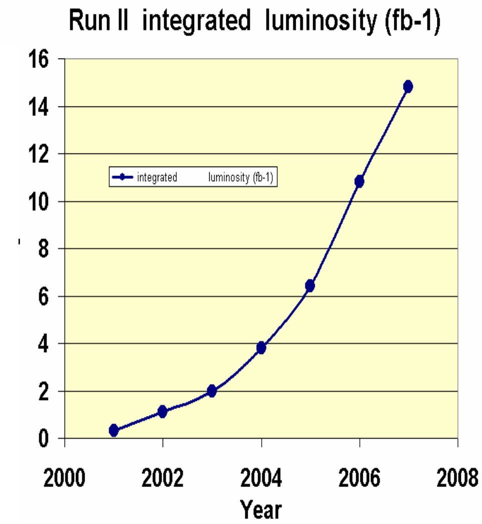


DØ

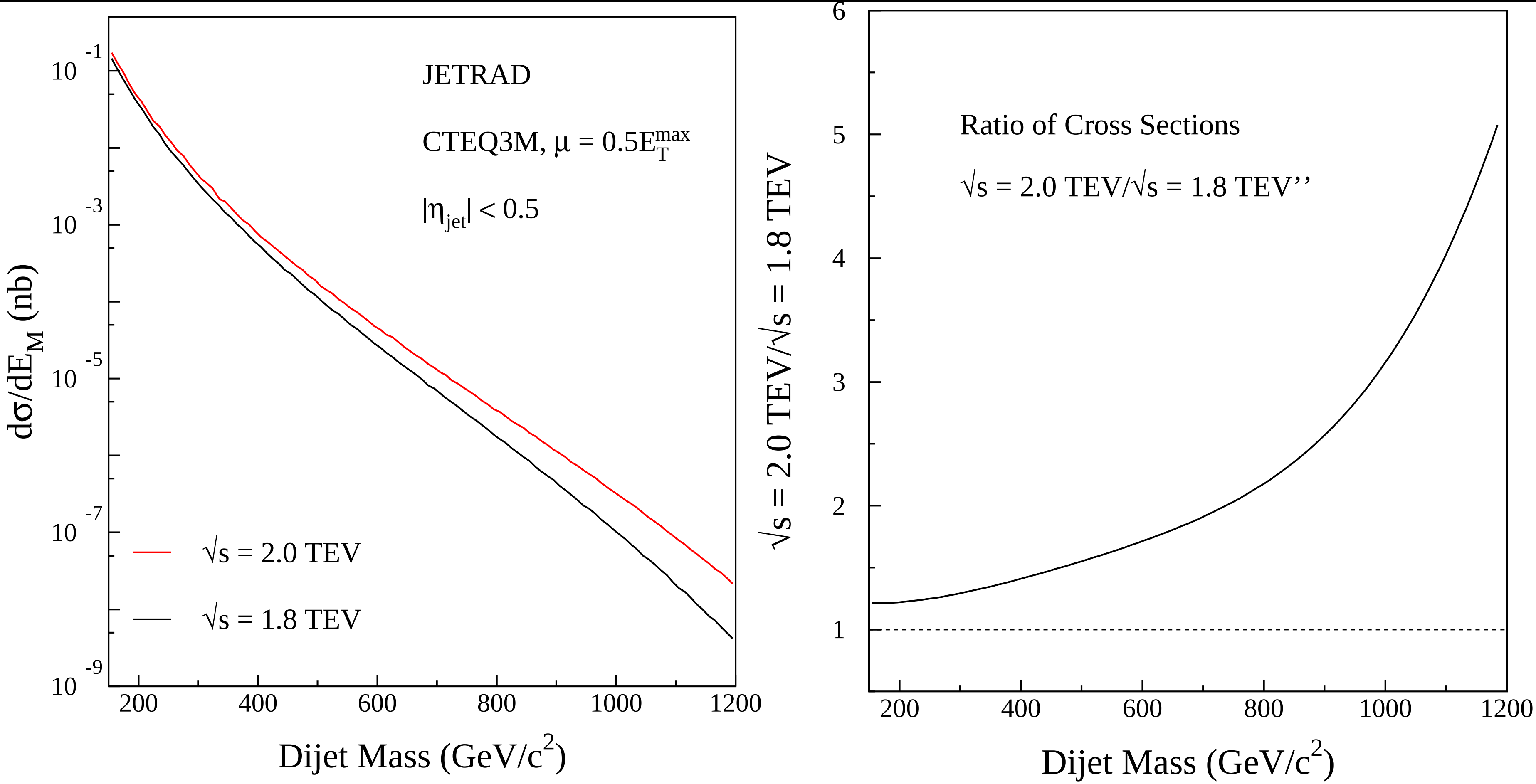
Tevatron timeline

1985	First proton-antiproton collisions
1988-89	First physics run, CDF
1992-96	Run 1: 120 pb^{-1}, 1.8TeV, CDF and DØ
	6 bunches, 3.5 μs between collisions; $L \sim 10^{31}\ cm^{-2}\ s^{-1}$
1995	Top Discovery (D0, CDF)
1996-2001	Major detector upgrades
2001-04 Now	Run 2a: 2 fb^{-1}, 2 TeV
	36 bunches, 396 ns between collisions; $L \sim 2 \times 10^{32}\ cm^{-2}\ s^{-1}$
2004	Short shutdown to install new silicon detectors (+ . . .)
2004-07	Run 2b: ~ 15 fb^{-1} (total)
	99 bunches, 132 ns between collisions; $L \sim 5 \times 10^{32}\ cm^{-2}\ s^{-1}$
2007?	LHC operation starts at CERN





Dijet Mass Spectrum



Dramatic increase in high p_T cross sections
Large gains in statistics

Jets in Run 2

High ET jets:

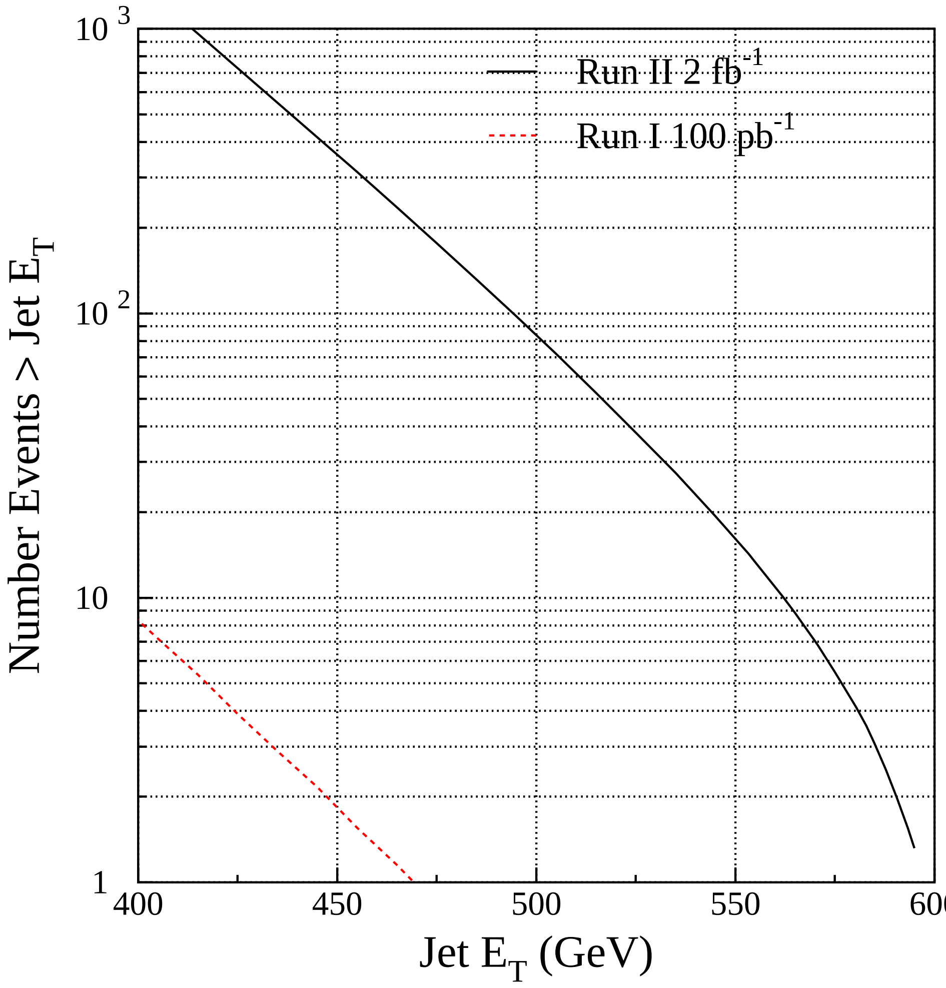
Run 2a:
~100 events ET > 490 GeV
~1K events ET > 400 GeV

Run 1:
16 Events E_T> 410 GeV

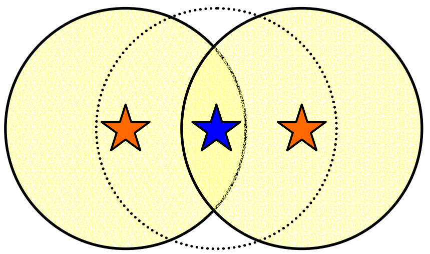
Great reach at high x and Q^2,
the place to look for new physics!

Low ET jets:

Improvements expected from
better tracking measurements



Jet Algorithms in Run 2



- Fermilab Run 2 workshops

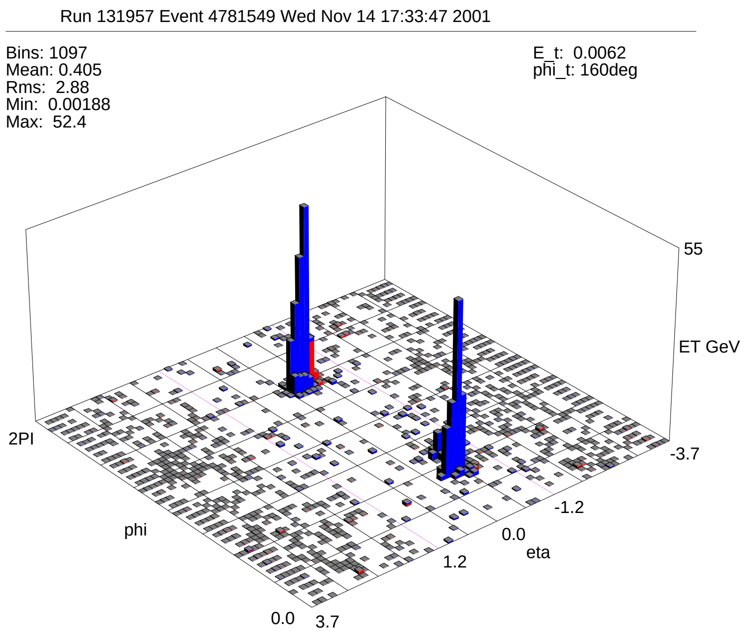
http://theory.fnal.gov/people/ellis/QCDWB/QCDWB.html

- K_T algorithms now in regular use
- New Cone Algorithm
  - Theoretical desires
    - infrared and collinear safety
    - avoid ad hoc parameters (like R_{sep})
    - level independence (parton/particle/detector)
  - Cone algorithm improved by
    - clustering 4-vectors
    - modification of seed choices - midpoints
    - seedless algorithm? In development.
- Experimental tuning
  - Reduce sensitivity to noise, pileup, negative energies

Jet Events

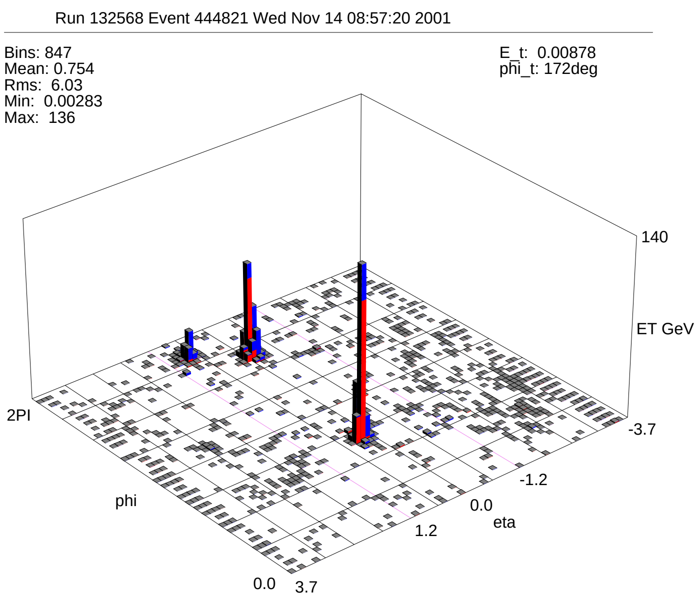
First Look at Run 2 Data

Using R=0.7 Cone Algorithm with Run 1 corrections



3-jet event

- E_T^{jet1}~310GeV
- E_T^{jet2}~240GeV
- E_T^{jet3}~110GeV
- $\not{E}_T$~8GeV



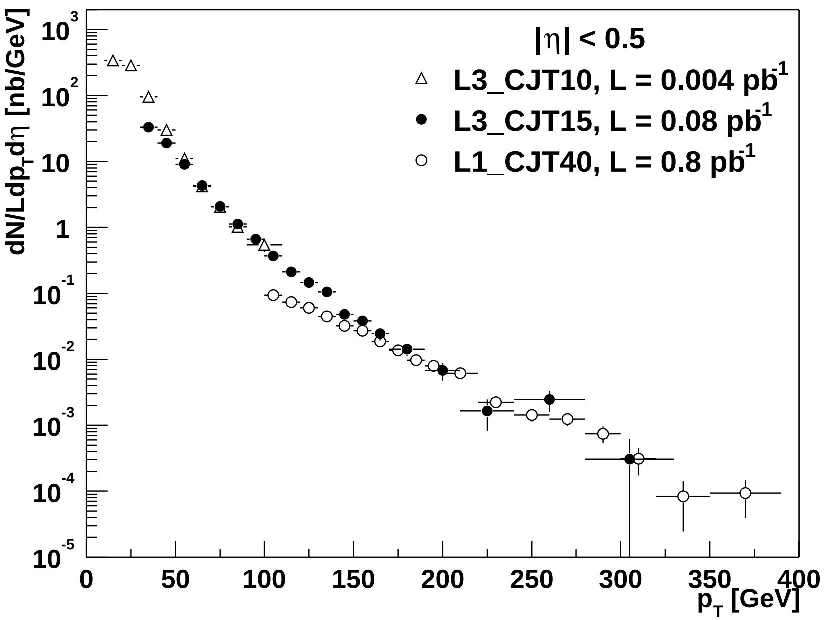
2-jet event

- E_T^{jet1}~230GeV
- E_T^{jet2}~190GeV

Jet Distributions

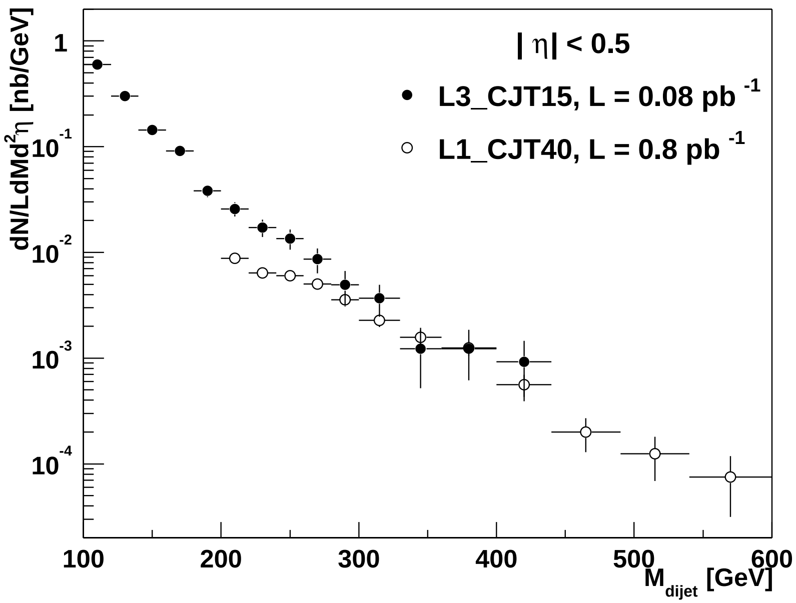
First Look at Run 2 Data

Using R=0.7 Cone Algorithm (energies partially corrected)



Single Jet P_T

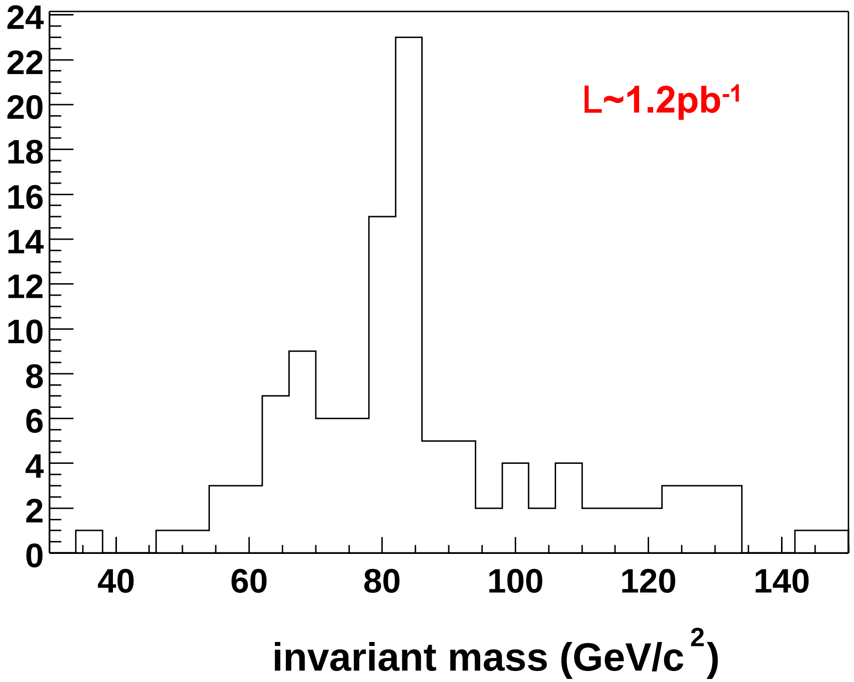
Dijet Invariant Mass



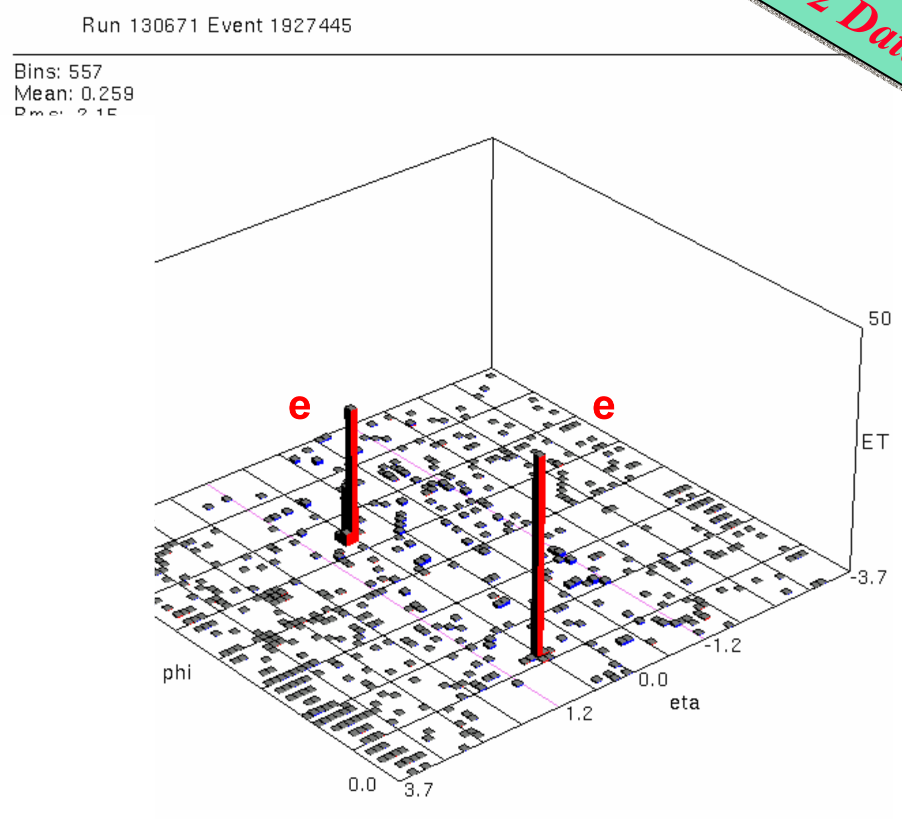
$Z \rightarrow e^+e^-$ Candidates

First Look at Run 2 Data

2 EM objects, E_T > 20 GeV, isolation and shower shape cuts



(uncalibrated energy scale)



Closing Remarks

- **Run 2 at Tevatron has started**
  BIG Opportunity for QCD
- **In most cases QCD predictions work well, especially at moderate to high scales**

  Issues: **Low p_T processes are problematic**
  jets and photons
  underlying event (shall we be subtracting it from Jets?)
  event characteristics
  Should we correct jets for hadronization effects?

- **Experimental results have recently reached or exceeded the accuracy of theoretical predictions**
  need for NNLO calculations for jet production
- **Any suggestions on studies of particular interest?**