High P_T Jets at the Tevatron

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DØ Experiment

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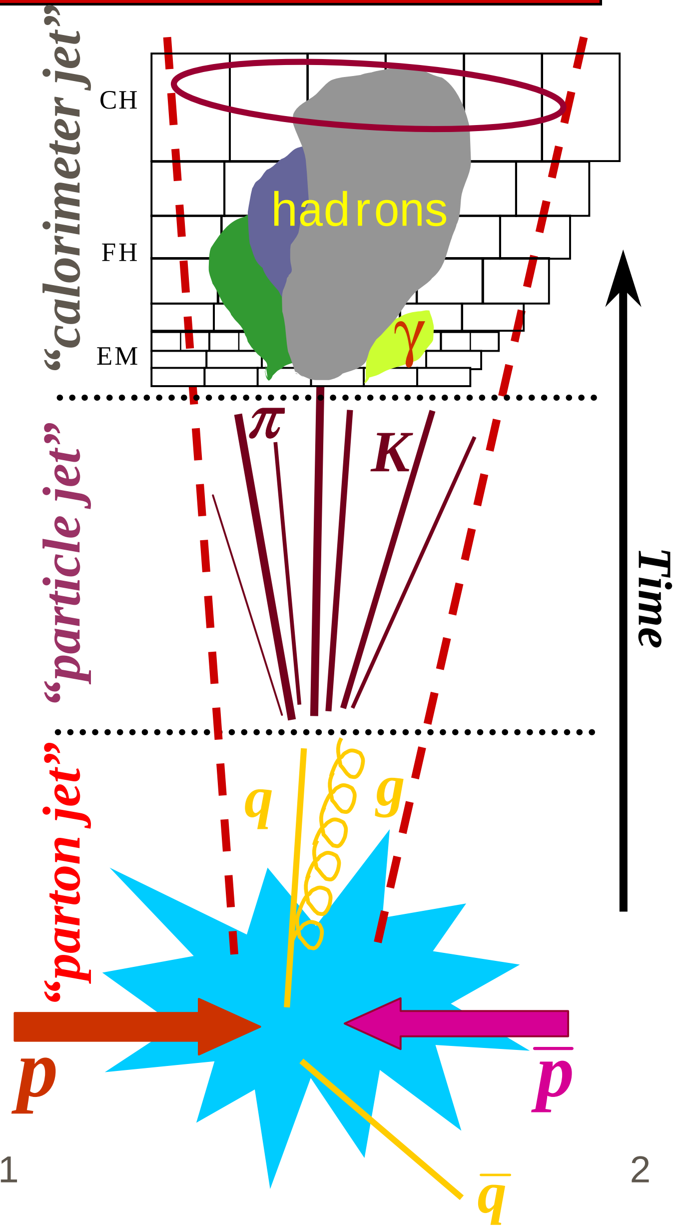
Jets at the Tevatron

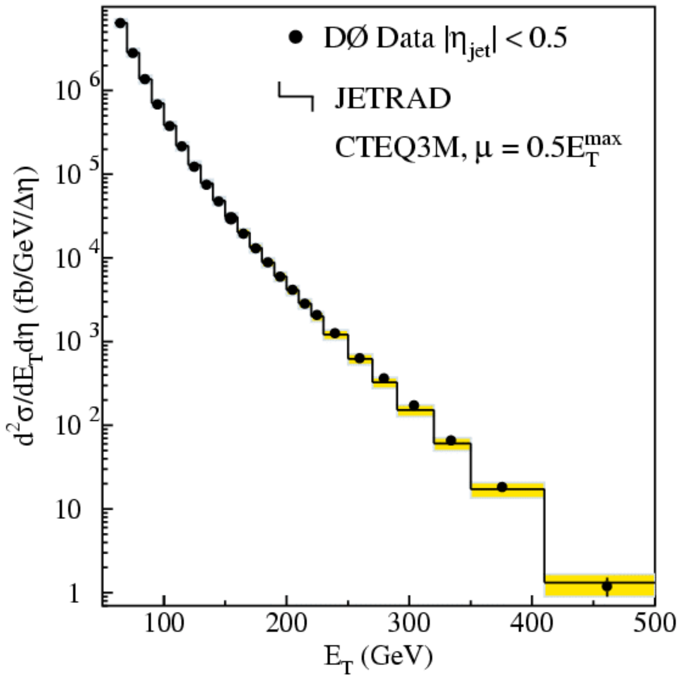
- Mostly Fixed cone-size jets
- Add up towers
- Snowmass Algorithm

$$E_T^{jet} = \sum_{R_i \leq 0.7} E_T^{tower}$$

- Iterative process
- Jet quantities:
  - ➔ E_T, η, ϕ
- Correct to Particles
  - ➔ Do not include underlying event.
  - ➔ Subtract underlying event. Modeled with Minimum Bias event (inelastic scattering)

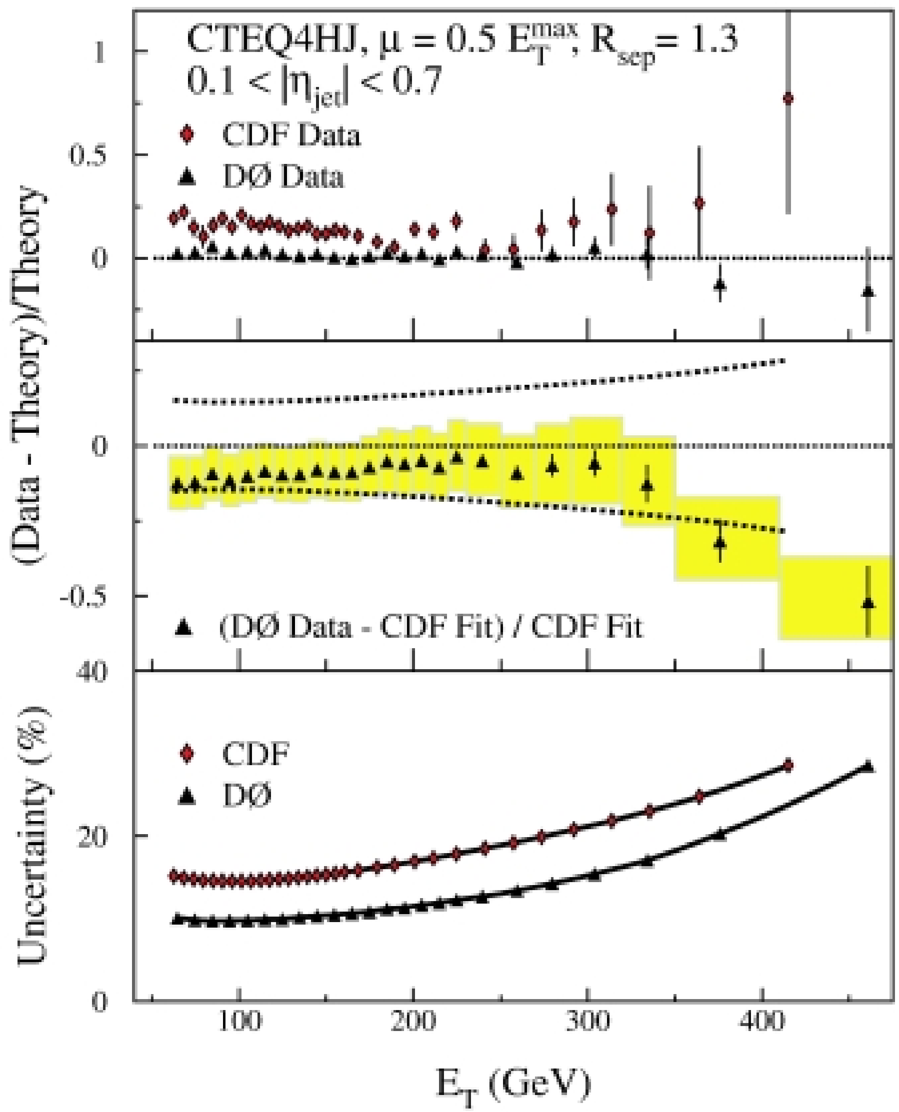


Jet Counting: Inclusive Jet Cross Section



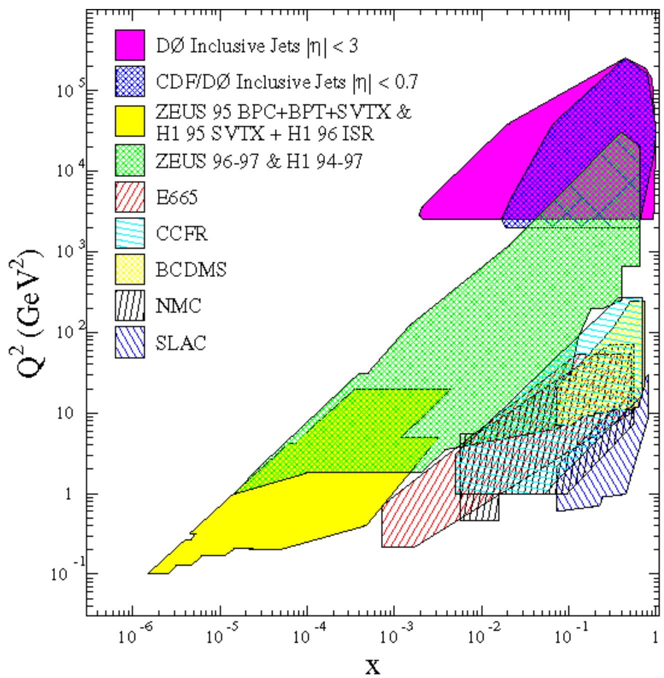
- DØ and CDF Comparison
- **Excellent Agreement**
- If we calculate χ^2 between DØ data and fit to CDF and its uncertainties:

$$\chi^2 = 30.8\ (0.16)$$

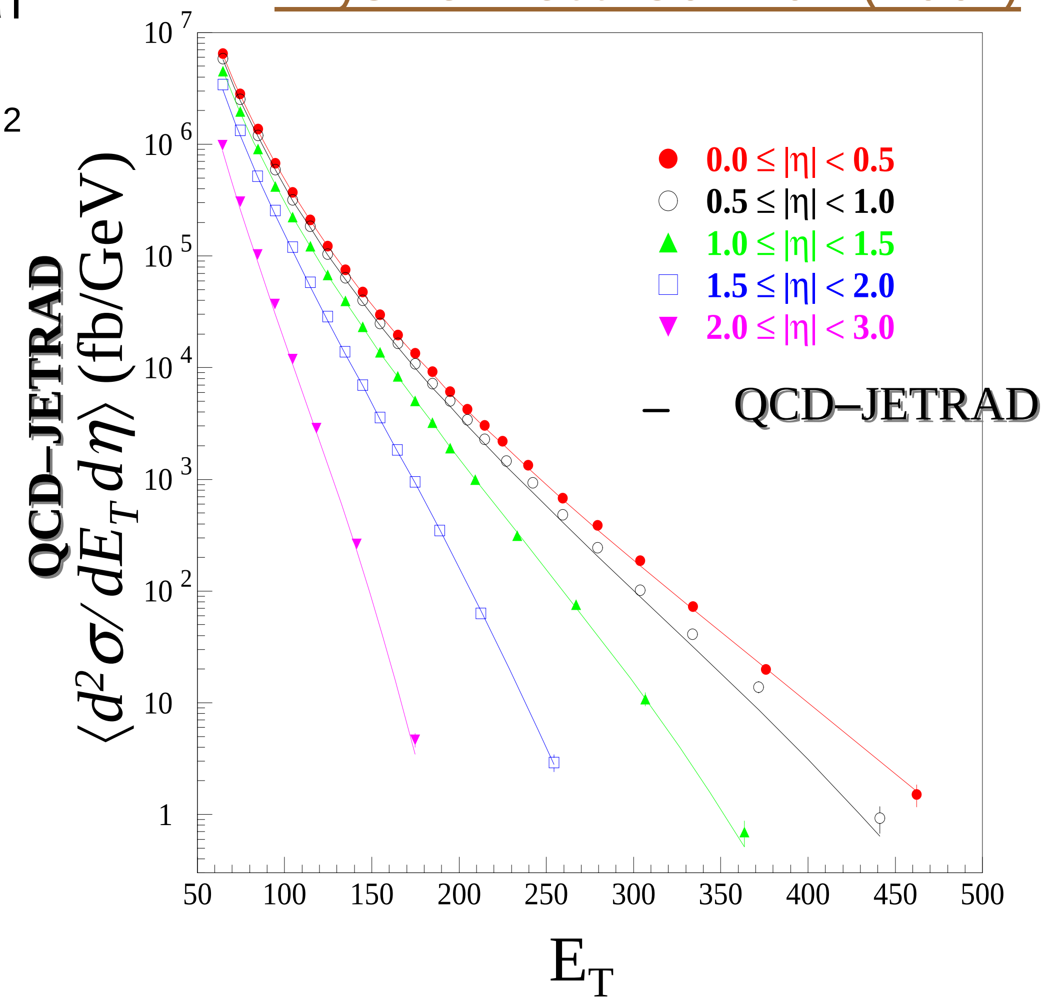


DØ Forward Jets

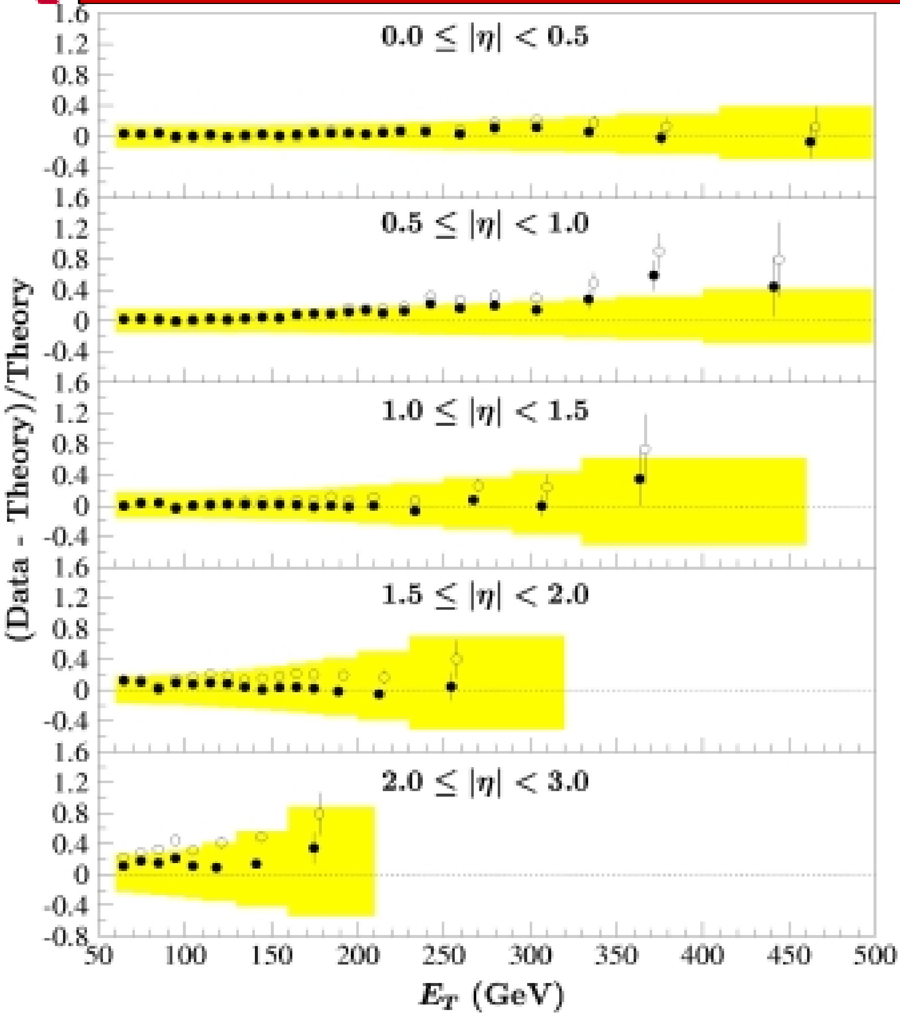
- Measurement extended to |η| < 3.0
- Complements HERA DIS x-Q^2 Range
- Restricts Gluon distribution.



Phys.Rev.Lett. 86 1707 (2001)



Jets: Comparison to Theory



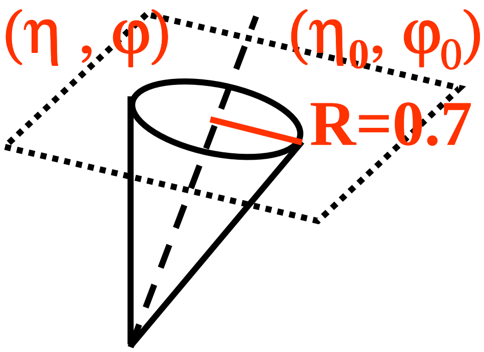
Closed: CTEQ4HJ Open: CTEQ4M

PDF	$\chi 2$	$\chi 2$/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

- 90 data bins
- CTEQ4HJ is best fit
- MRSTgU and CTEQ4M also good fits
- Now being used by CTEQ and MRST groups to fit pdf's
- MRST restrict gluons to 20% uncertainties.

K_T Jet Algorithm

Fixed Cone Algorithm:

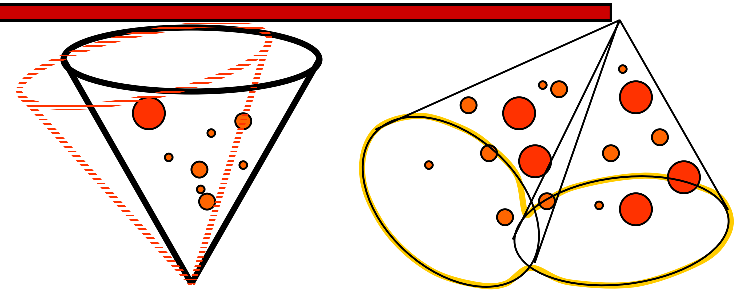


$$E_T = \sum_i E_{Ti}$$

Snowmass

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

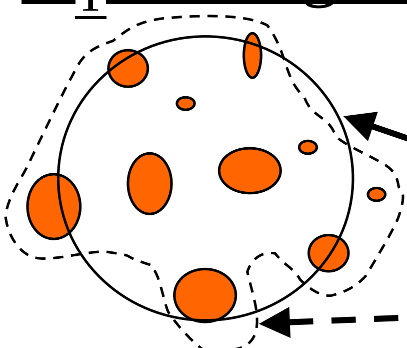
$$\phi_{jet} = \frac{\sum_i E_T^i \phi^i}{\sum_i E_T^i}$$



Calorimeter E_T

Jet Seeds

K_T Jet Algorithm:

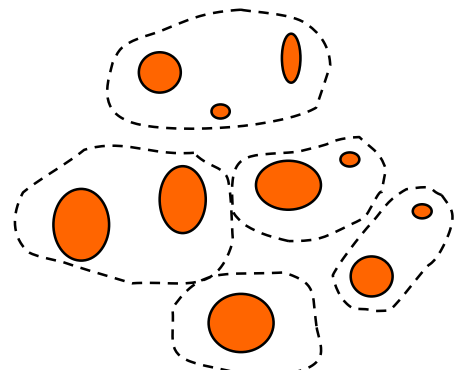


Cone jet

K_T jet (D=1)

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

$$E_{ij} = E_i + E_j$$

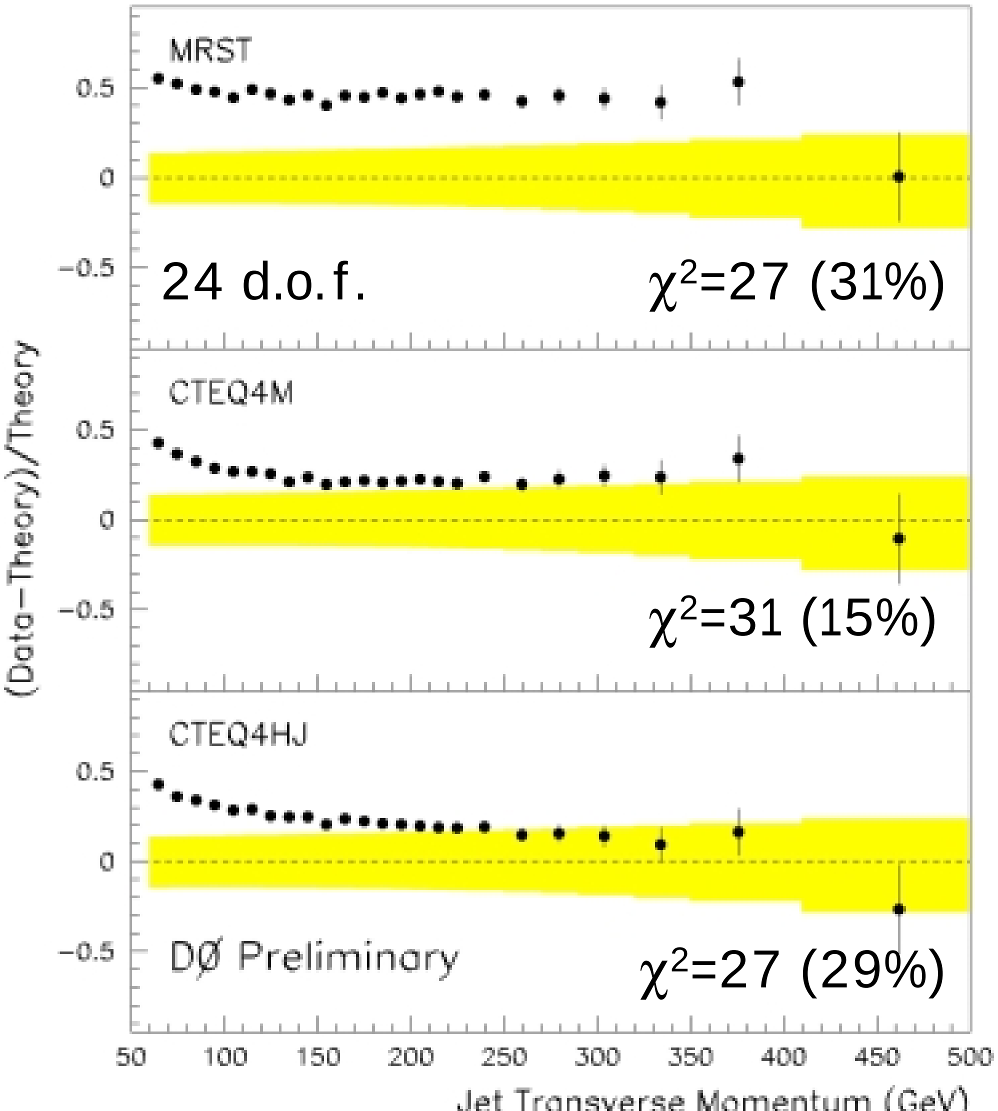


$$d_{i,j} = \min(E_{T,i}^2, E_{T,j}^2)\frac{\Delta R_{ij}^2}{D^2} > y_{cut} E_{T,Jet}^2$$

resolution parameter

Jet E_T

Jet Cross Section using K_T



- K_T with D=1.0, equals NLO cross section with Cone R=0.7
- Energy difference between KT and cone causes difference in cross section
- 1-2 GeV Difference caused by
  - ➔ Hadronic Showering effects (parton to particle)
  - ➔ Underlying Event
  - ➔ Showering
- Difference with theory largest at low E_T.

Ratio of Cross Sections

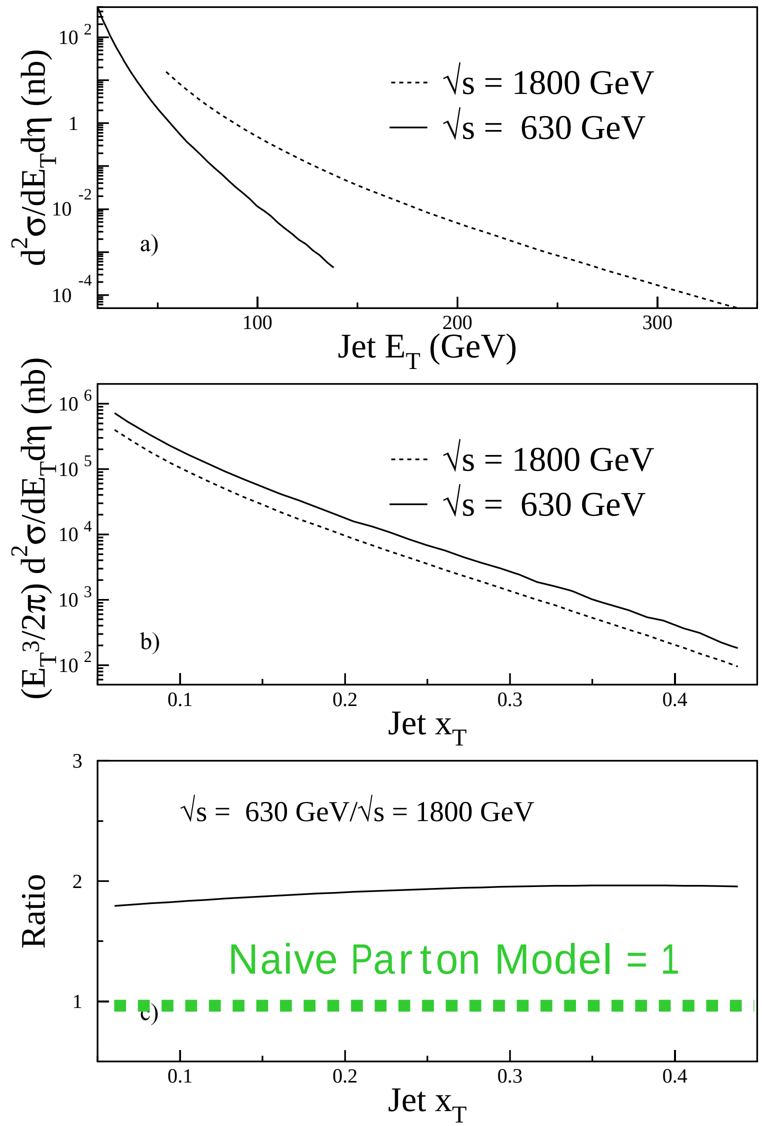
- Express Inclusive Jet Cross Section as dimensionless quantity

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

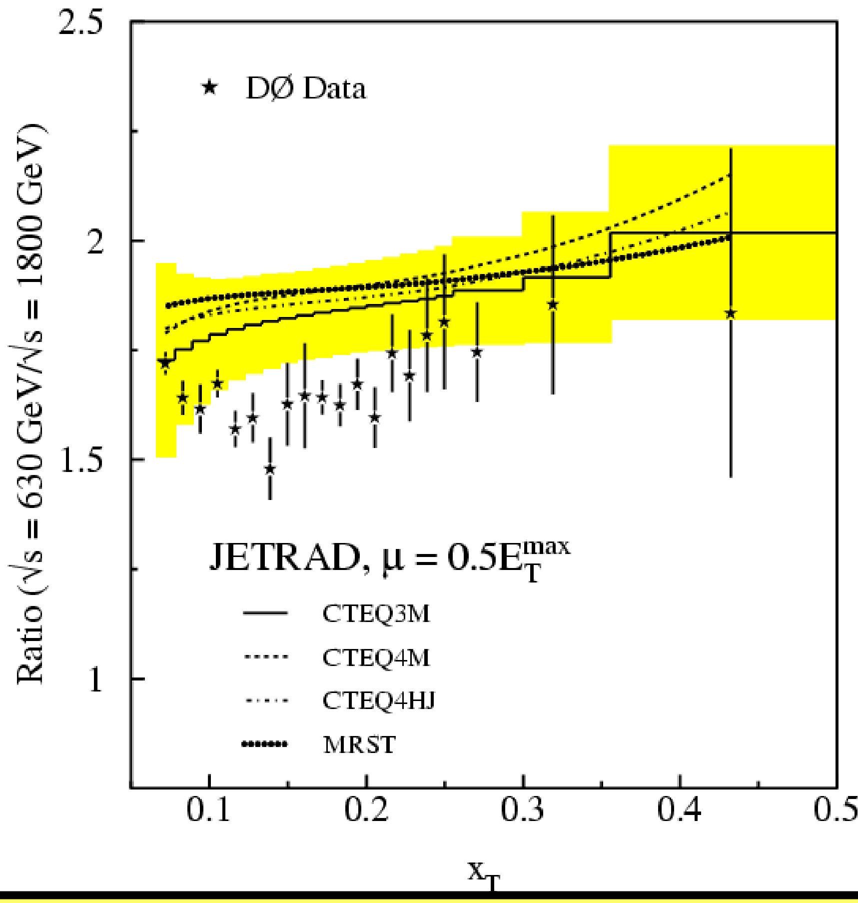
as a function of

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

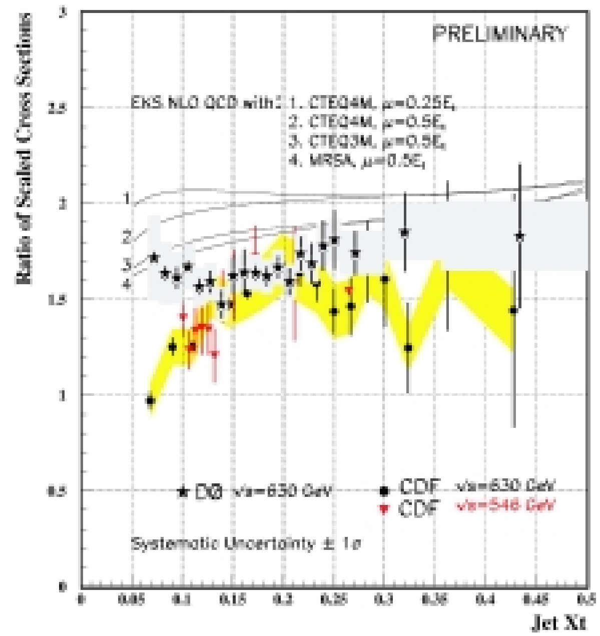
- Theory uncertainties could be reduced to 10%
- Experimental Uncertainties Cancel



Ratio Results



- Comparison with CDF
- Differences might be caused by
  - Fragmentation effects (parton to particle)
  - Underlying Event
  - Hadron Showers in the Calorimeter



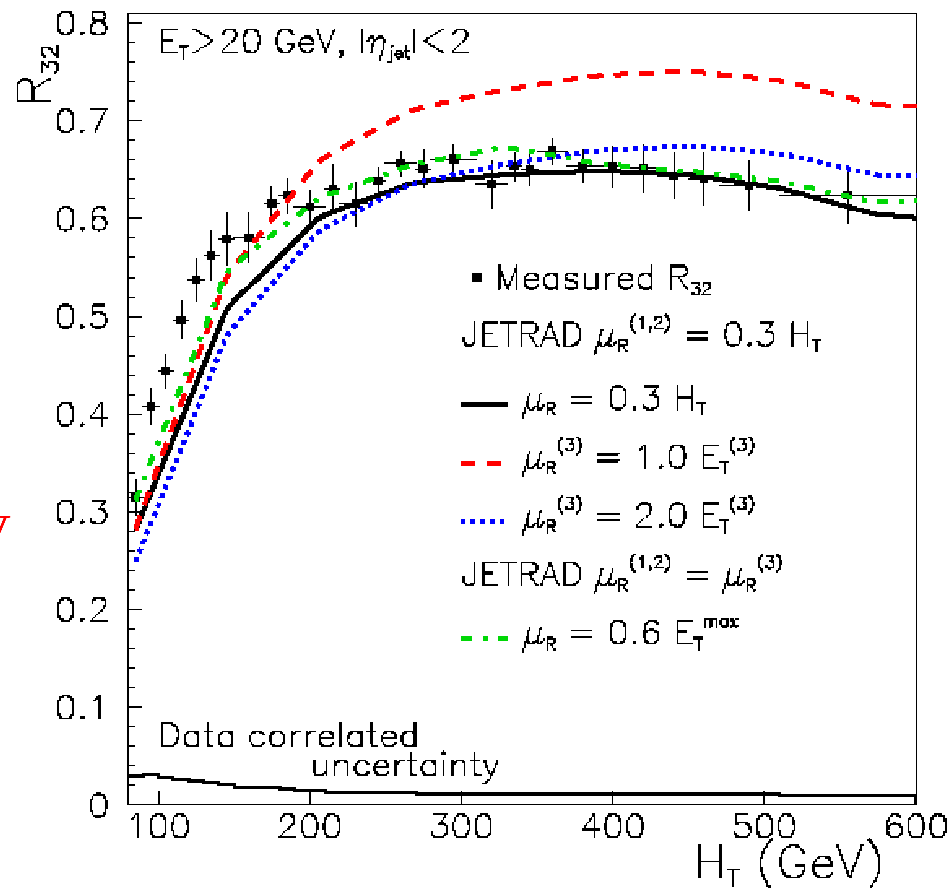
Agreement Probability

(from χ^2 test) with CTEQ4M, CTEQ4HJ, MRST, MRSTGU: **25-80%**

R32: Three Jet vs. Two Jet Cross Section

$$R_{32} = \frac{\sigma_3(p\bar{p} \rightarrow 3+ \text{ jets})}{\sigma_2(p\bar{p} \rightarrow 2+ \text{ jets})} \text{ vs. } H_T$$

- Study scale dependence of additional low E_T jet production.
  - ➔ Do we need different scales for each jet



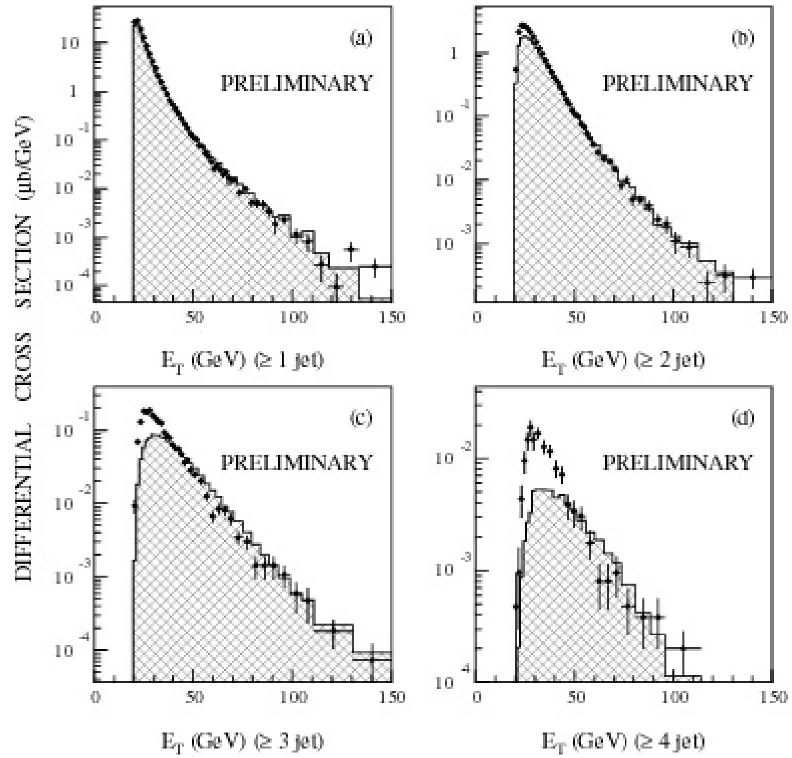
Interesting:

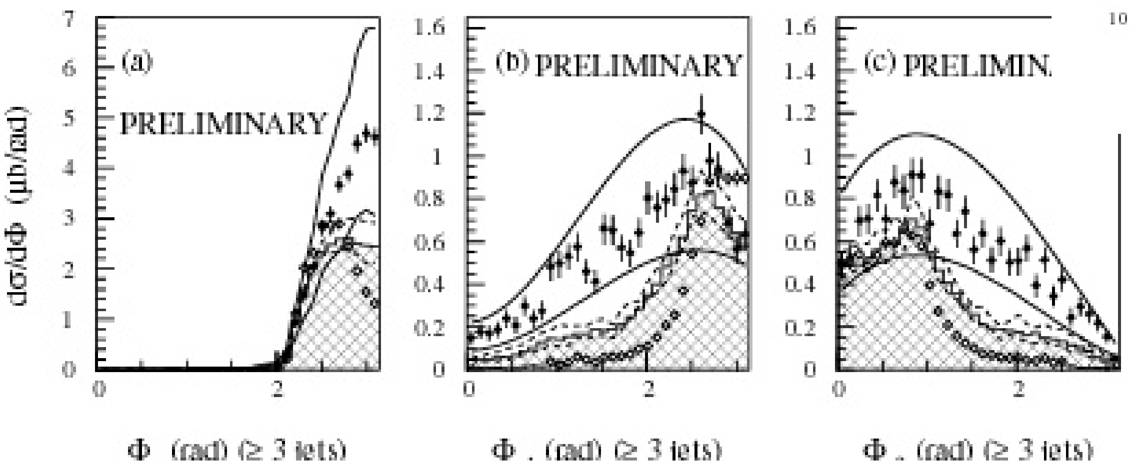
- 70% of high E_T jet events have a third jet above 20 GeV
- 50% have a third jet above 40 GeV

- Jet emission best modeled using the same scale as the hard scale for all jets rather than softer scale for additional jets
  - ➔ χ^2 test used

Low P_T Jet Production

- Compare low ET multi-jet production to Pythia and Jetrad predictions.
- E_T distribution of ≥ 1, 2, 3, and 4 jet events compared with Pythia
  - ➔ Excess of events for ≥ 3 and 4 at low E_T.





Two of the three leading jets are back to back in phi – not typical of three jet events

Subjet Multiplicity in Quark & Gluon Jets

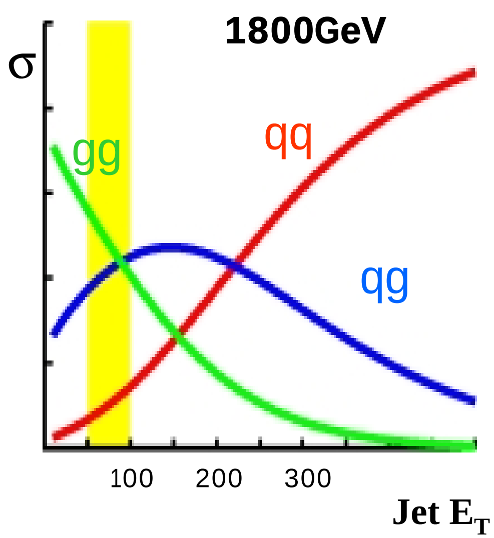
Motivation:

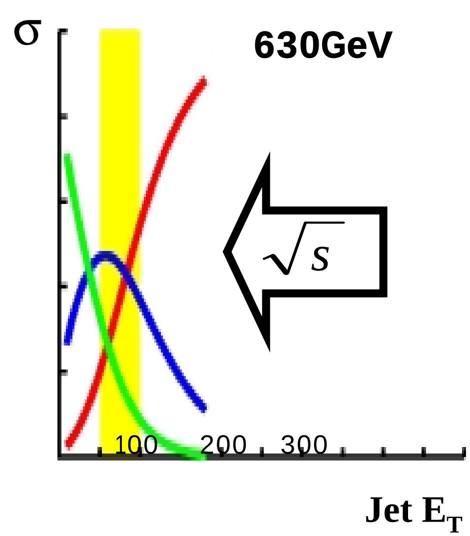
- **Test of QCD (Q & G jets are different)**
- **Separate Q jets from G jets (top, Higgs, W+Jets events)**

Measure the subjet multiplicity in quark and gluon jets

Method:

- **Select quark enriched & gluon enriched jet sample**
- **Compare jets at same (E_T , h) produced at different $\sqrt{s}$ and assume relative q/g content is known**

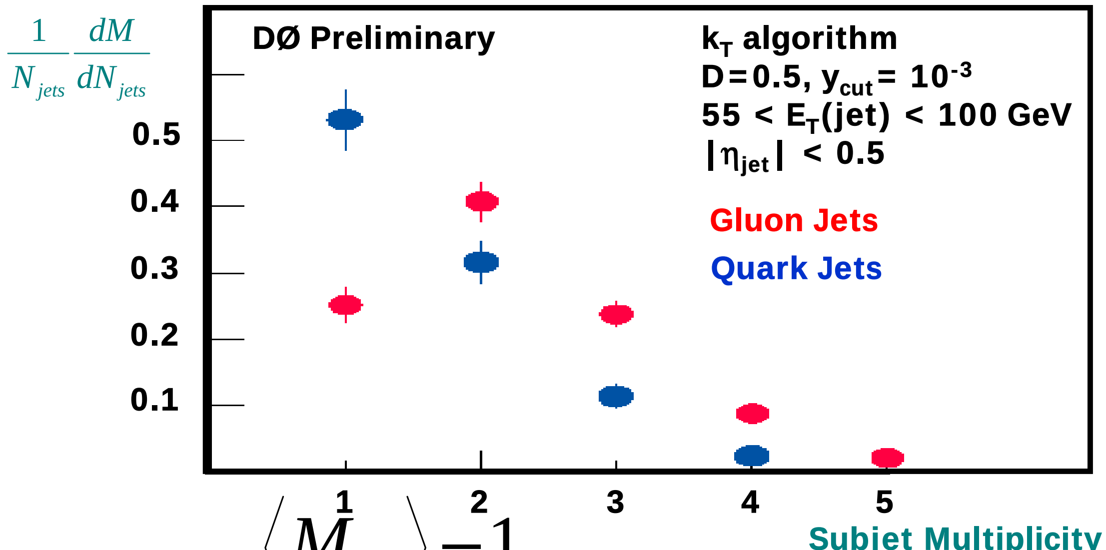




Contributions of different initial states to the cross section for fixed Jet E_T vary with $\sqrt{s}$

Jet Structure at the Tevatron

- Subjets inside jets: perturbative part of fragmentation
- DØ compares 630 to 1800 GeV data at same E_T and η, and infers q and g jet differences

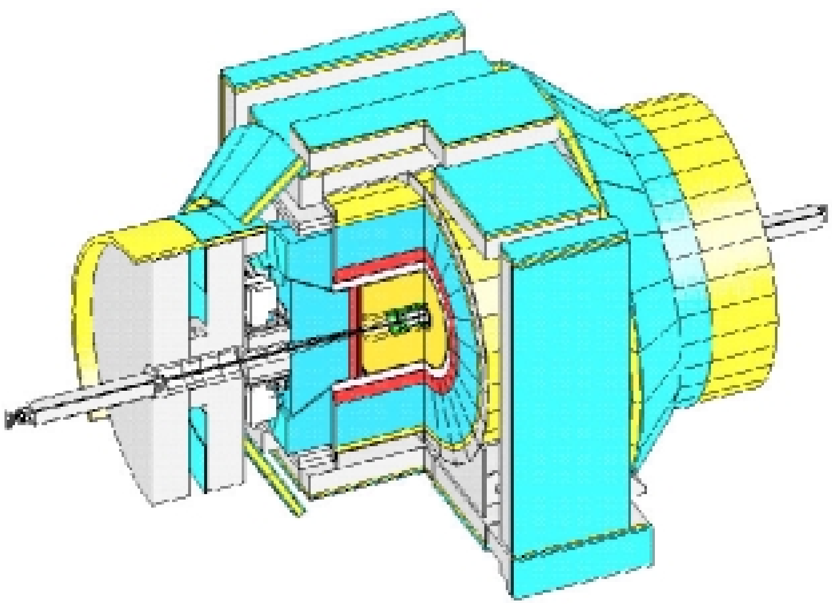


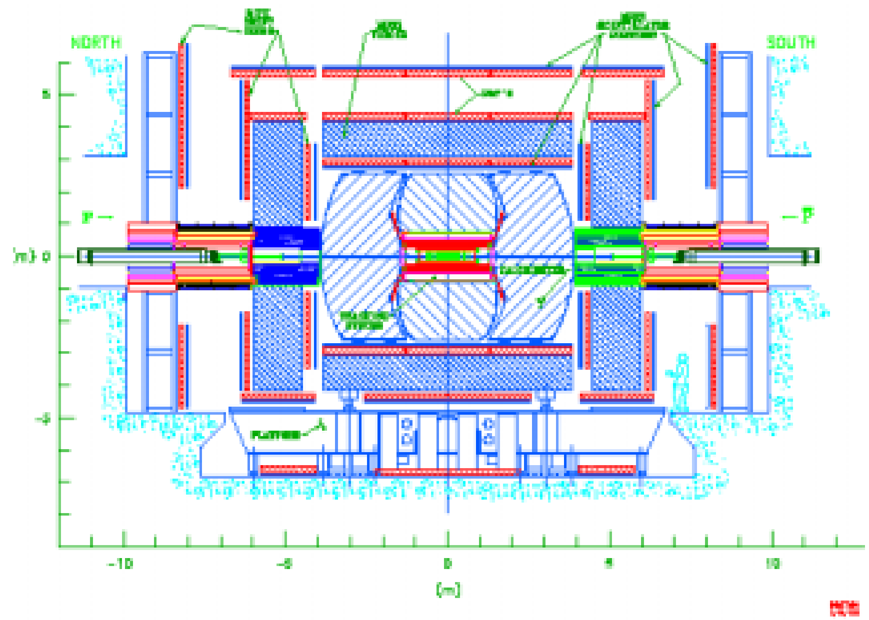
DØ Data $$R = \frac{\langle M_g \rangle - 1}{\langle M_q \rangle - 1} = 1.91 \pm 0.04$$

HERWIG 5.9 $$R = 1.86 \pm 0.04$$

Run II : Commissioning Now – Physics Fall?

$\sqrt{s}$	2.0 TeV	W/Z's	>1M/>50k
Luminosity	2×10^{32}	ttbar	>1k events
$\int L dt$	2-30 fb^{-1}	Higgs	Possible





Upgrades to both detectors: Silicon, Tracking (Drift-CDF, Fibres-DØ) Preshowers, Calorimeter Upgrade – CDF, Muon upgrades, new trigger electronics (bunch spacing), C++ OO code development

Run II: Jets

Run II:

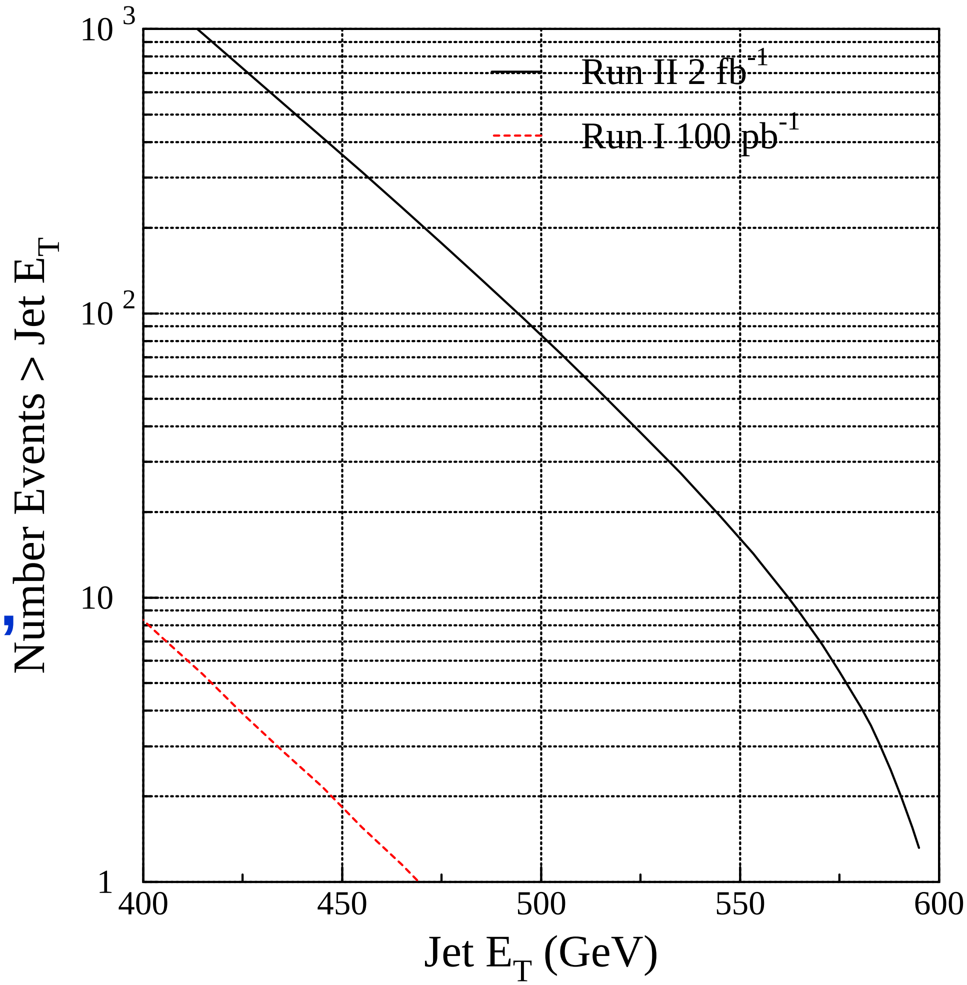
~100 events ET > 490 GeV

~1K events ET > 400 GeV

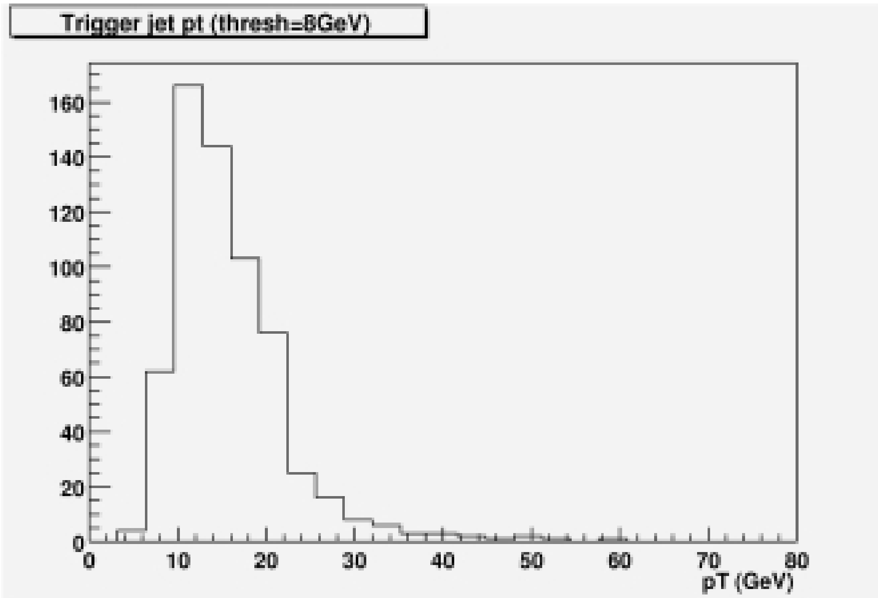
Run I:

16 Events E_T> 410 GeV

Great reach at high x and Q^2, the place to look for new physics, constrain pdf's, test QCD predictions!

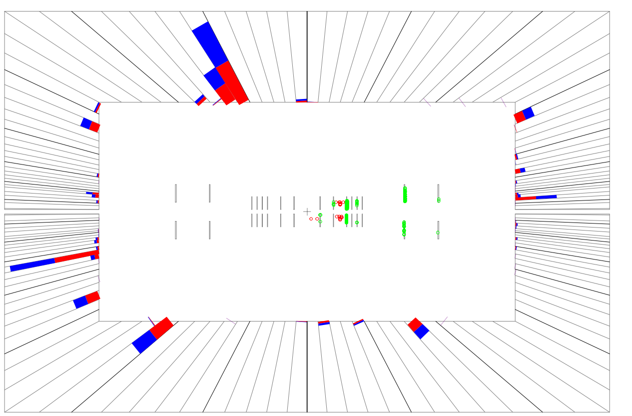


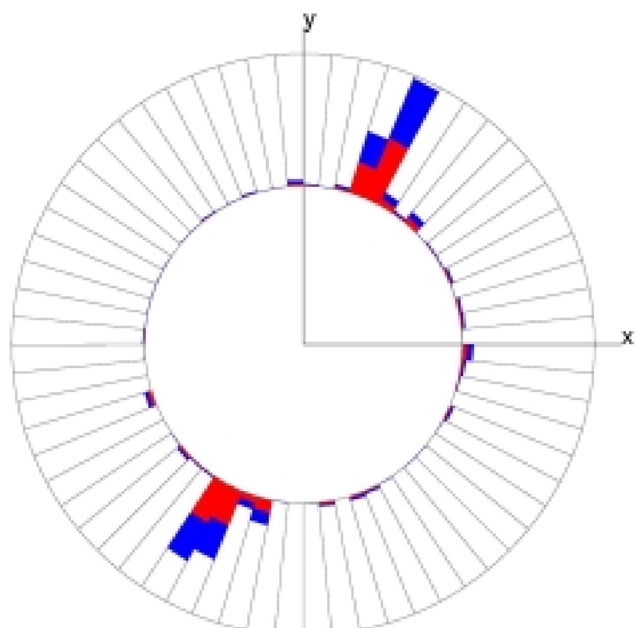
DØ Calorimeter Jets



Jets from June running at DØ.

Jet Trigger of 8 GeV





Closing Remarks

- Run II has started: 1 March 2001
  BIG Opportunity for QCD

- In most cases QCD predictions work exceptionally well.

Exceptions: **Low p_T processes are problematic**

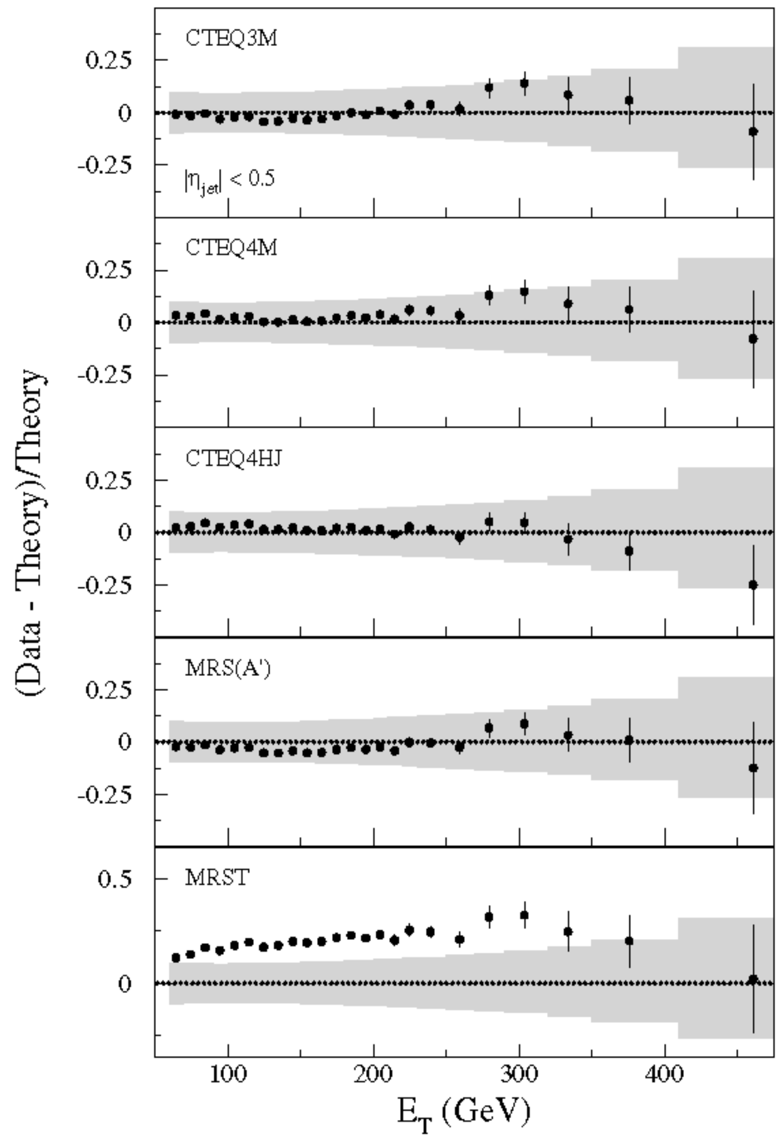
Areas Requiring Study:

- Most discrepancies are at low PT
- Underlying Event Modelling
- Showering Corrections
- Hadronization Effects
- Monte Carlo Simulation

Backup

- Inclusive Jets: DØ Comparisons to NLO Theory
- Comparison to Theory
- Ratio of Cross Sections: CDF
- Ratio of Cross Sections: Renormalization Scale
- Ratio 3 to 2 Jet χ^2 Studies

DØ Comparisons to NLO Theory



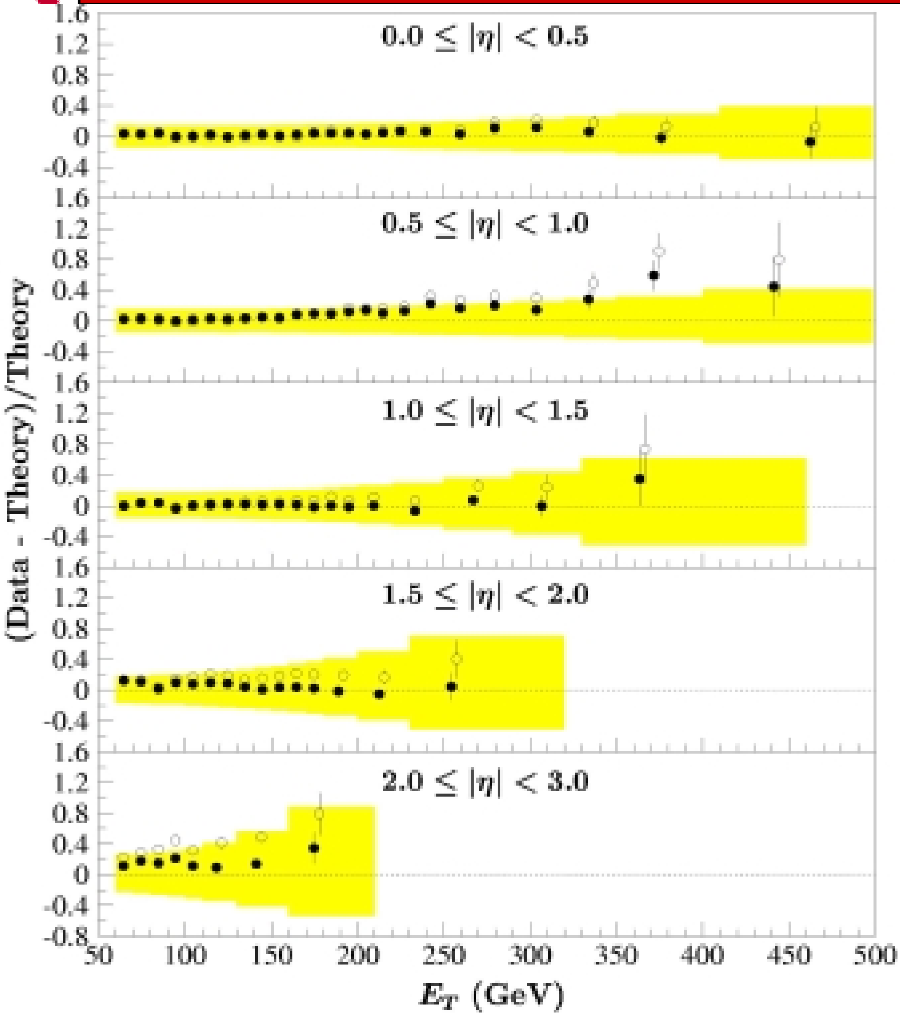
- No indication of an excess above 350 GeV.
- Good agreement quantitatively as indicated by χ^2 test:

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

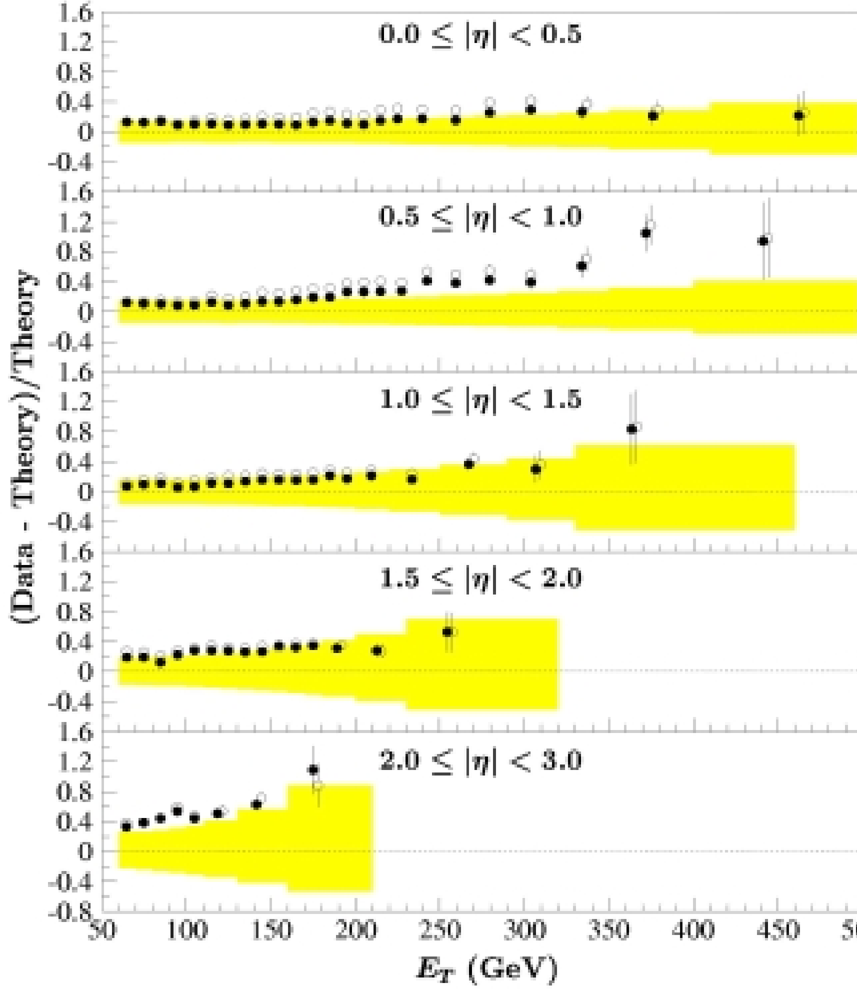
D_i and T_i data and theory, C_{ij} covariance matrix.

	$|\eta| < 0.5$	$0.1 < |\eta| < 0.7$
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)

Comparison to Theory

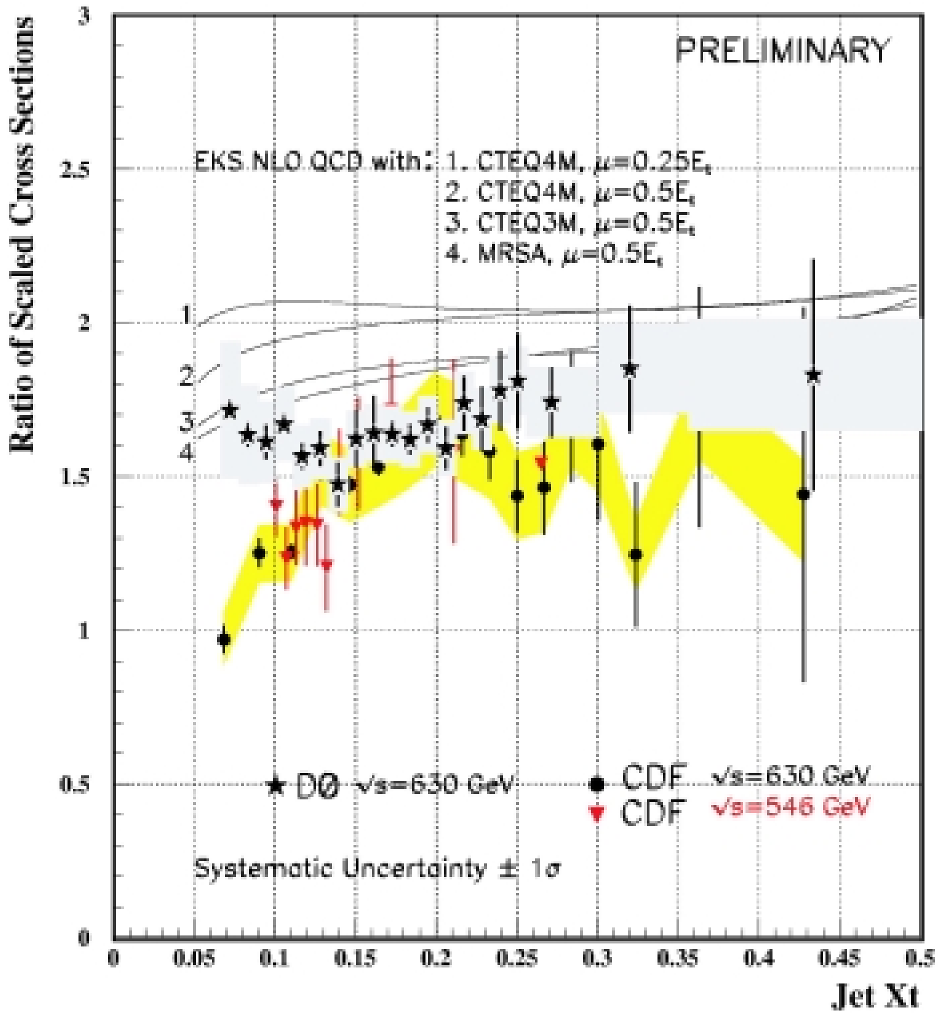


Closed: CTEQ4HJ Open: CTEQ4M



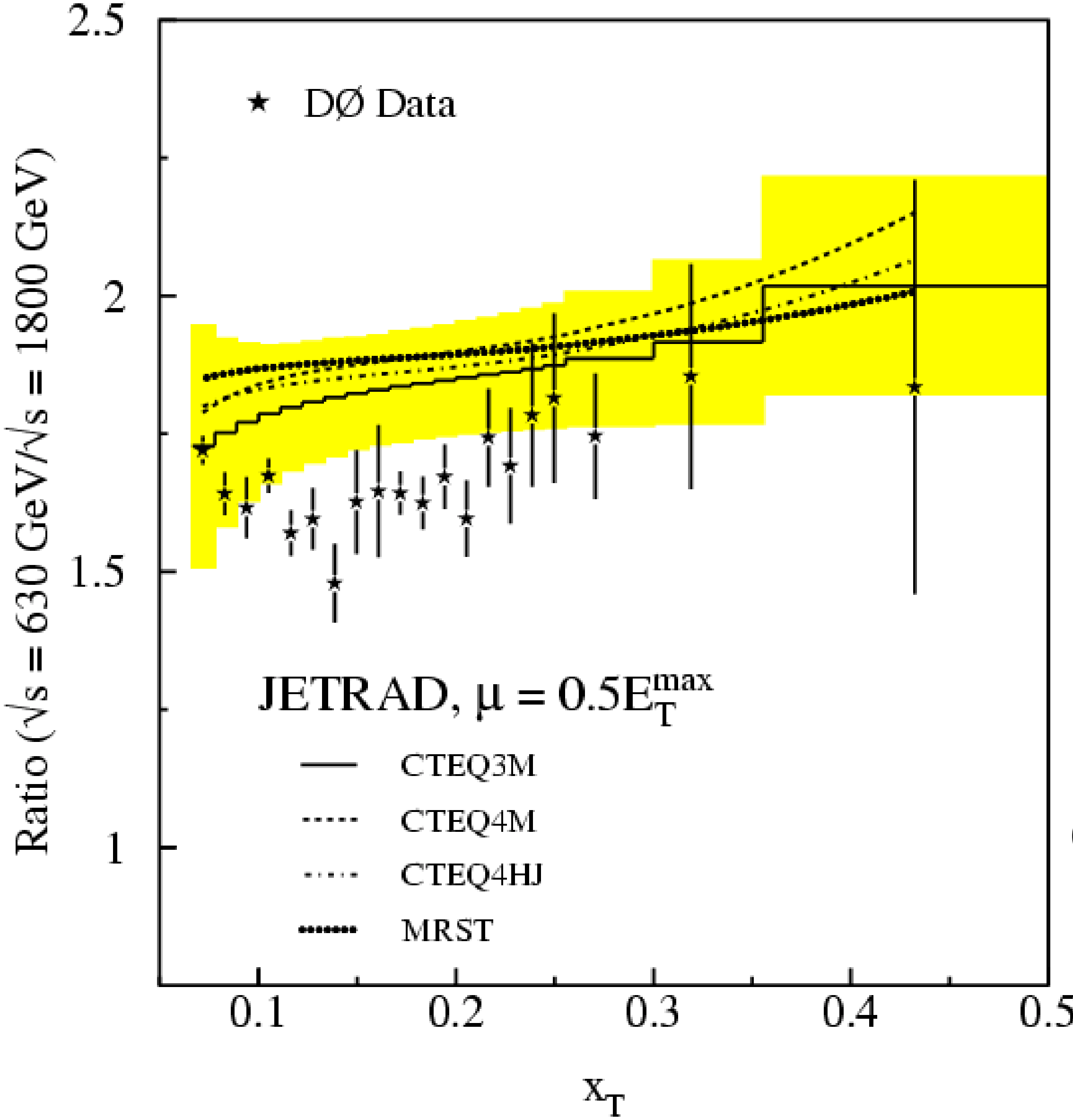
Closed: MRTSg↑ Open: MRST

Ratio Results



- Consistent at high x_T, possible discrepancy at low values
- Differences might be caused by
  - ➔ Hadronic Showering effects (parton to particle)
  - ➔ Underlying Event
  - ➔ Showering
- Difference between experiments largest at low x_T.
- Agreement can be obtained with different renormalization and factorization scales at the two centre of mass energies

Ratio of Cross Sections



- Phys.Rev.Lett.86, 2523 (2001); **hep-ex/0012046**
- Data 10-15% below NLO QCD
- No obvious problem:

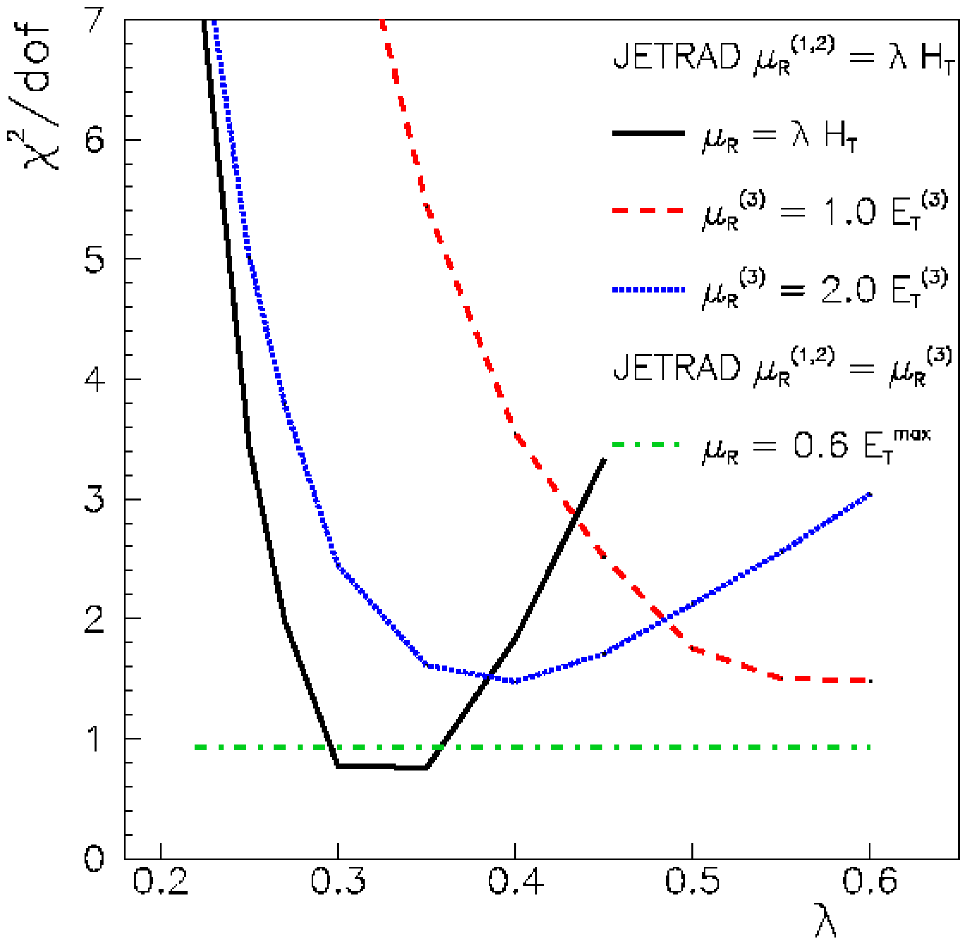
Interesting!

Agreement Probability

(from χ^2 test) with CTEQ4M, CTEQ4HJ, MRST, MRSTGU:

25-80%

Ratio 3 to 2 Jet χ^2 Studies



Results:

•Jet emission best modeled using the same scale ∝ the hard scale for all jets rather than softer scale for additional jets

•Best scale is that which minimizes χ^2 for all criteria

- **$\mu_R=0.6E_T^{max}$**, for 20 GeV thresholds
- **$\mu_R=\lambda H_T$**, $\lambda \approx .3$ for all criteria

•**Introduction of additional scales** to predict the rate of additional jet production **- unnecessary** and leads to poorer agreement with data.

•Need higher order terms for more predictive power !