Recent Results on Jet Physics and α_s

XXI Physics in Collision Conference

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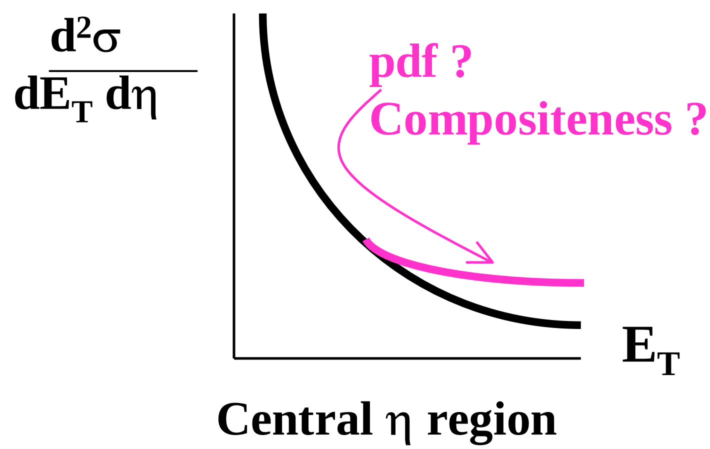
Outline

- Introduction and Experimental Considerations
- Jet and Event Characteristics
  - Low E_T Multijet Studies
  - Subjet Multiplicities
- Cross Sections
  - Three-to-Two Jet Ratio
  - Ratio at Different Center-of-Mass Energies
  - Inclusive Production
  - DiJet Production

Motivation for Studying Jets

- Investigates pQCD
  - Compare with current predictions
  - pQCD is a background to new processes
- Investigates parton distribution functions (PDFs)
  - Initial state for all proton collisions
- Investigates physics beyond the Standard Model



Developments in Jet Physics

(with proton initial states)

Inclusion of error estimates in the PDFs

calculation of virtual corrections → Progress toward NNLO predictions

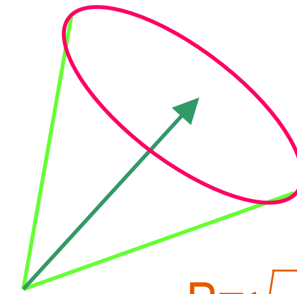
covariance matrices → More rigorous treatment of experimental errors

jet algorithms workshop → More consistent E_T calculations between experiments at the Tevatron

Cone Definition of Jets

Centroid found with 4-vector addition

- Cone Definition
  R=0.7 in $\eta-\phi$



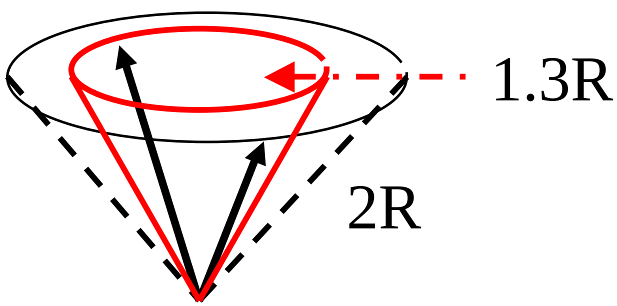
$R=\sqrt{\eta^2 + \varphi^2}$

$\eta = -\ln[\tan(\theta/2)]$

- Merging and splitting of jets required if they share energy

- R_{sep} required to compare theoretical predictions to data

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



k_T Definition of Jets

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

$$d_{ii} = {}^{i}E_T^2$$

min(d_{ii}, d_{ij}) = d_{ij} $\Rightarrow$ Merge

min(d_{ii}, d_{ij}) = d_{ii} $\Rightarrow$ Jet

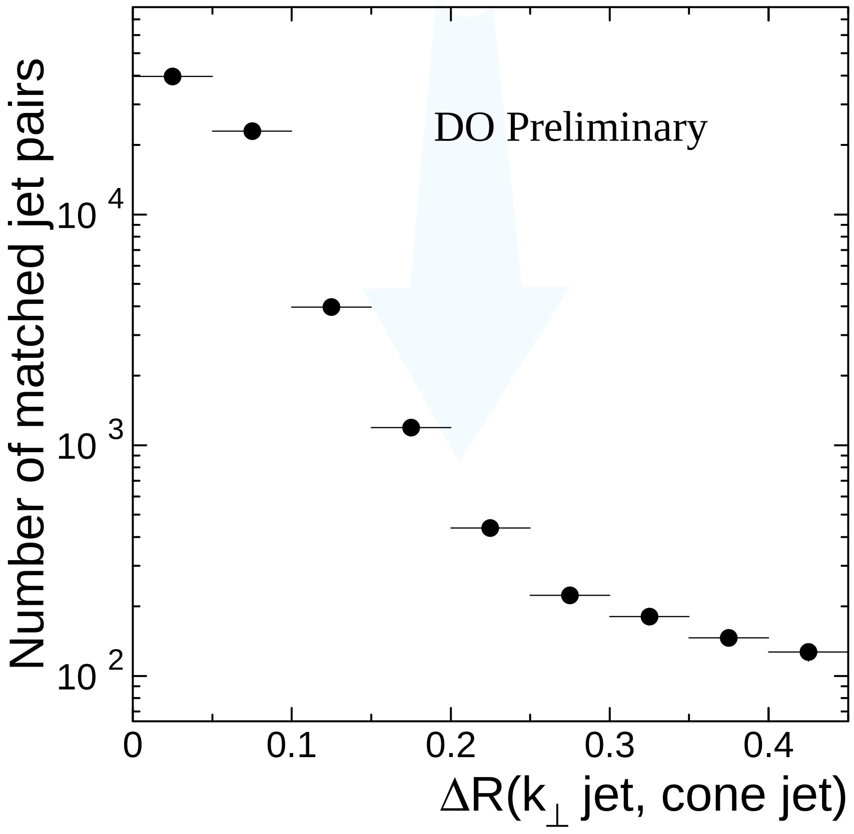
- k_T Definition

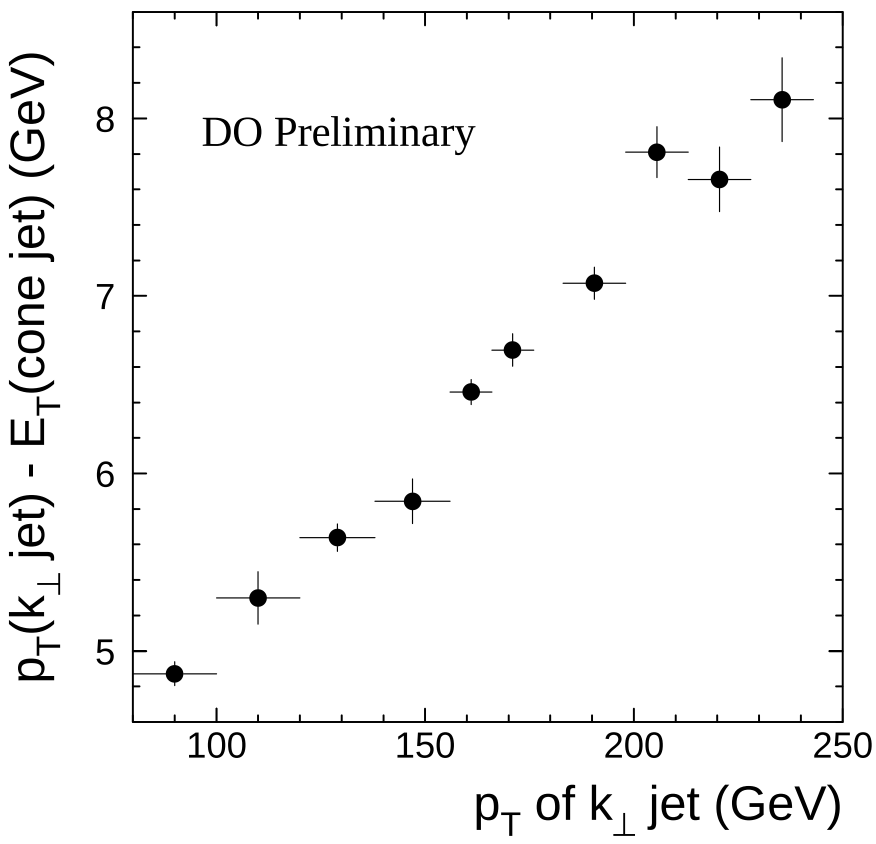
  cells/clusters are combined if their relative k_T^2 is “small” (D=1.0 or 0.5 is a scaling parameter)

- Infrared Safe
- Same definition for partons, Monte Carlo and data
- Allows subjet definitions

k_T and Cone Algorithm

- Use CTEQ4M and Herwig
- Match k_T jets with cone jets





99.9% of Jets have $\Delta R<0.5$

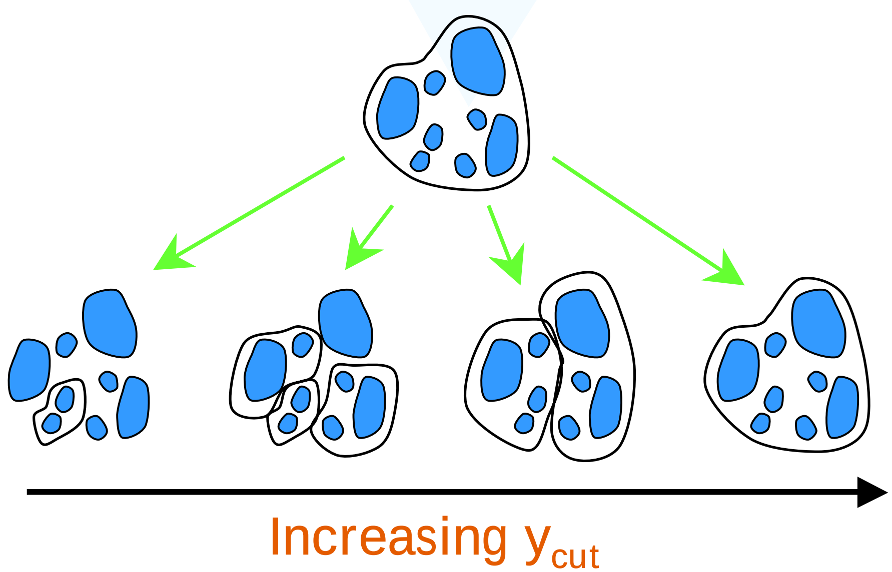
p_T of k_T algorithm is slightly higher

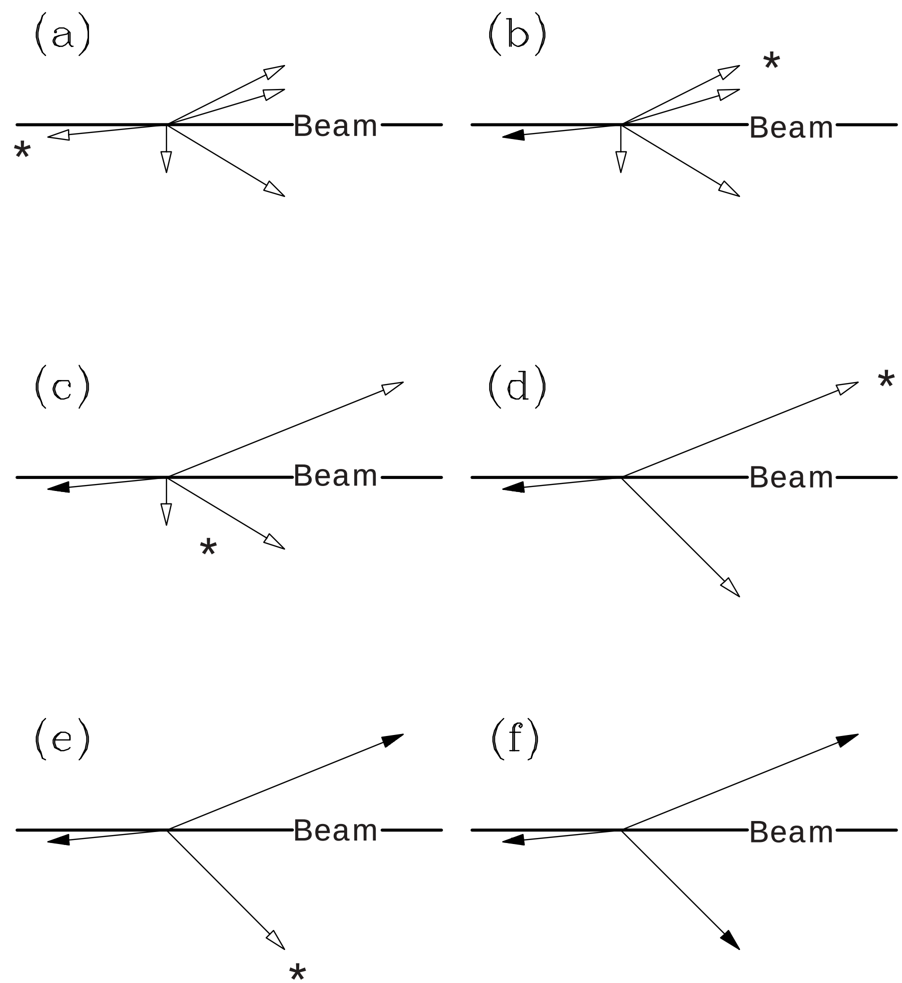
k_T Algorithm and Subjets

For subjets, define "large" k_T

$$\min({}^{i}E_T^2,\ {}^{j}E_T^2)\,\frac{\Delta \mathbf{R}_{ij}^2}{D^2} > y_{\text{cut}}\,E_T^2(\text{jet})$$

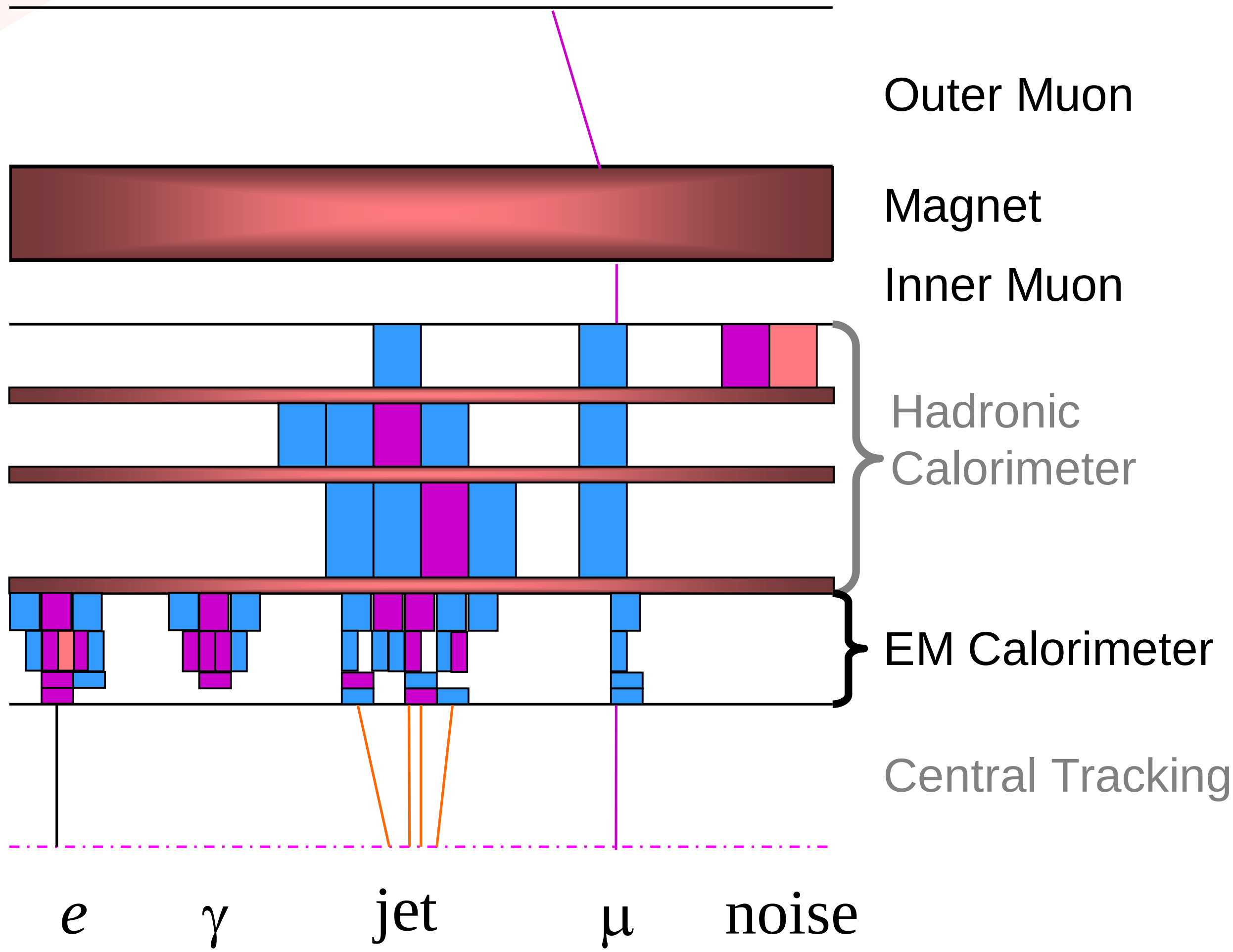
$(y_{cut} = 10^{-3})$





Jet Selection Criteria

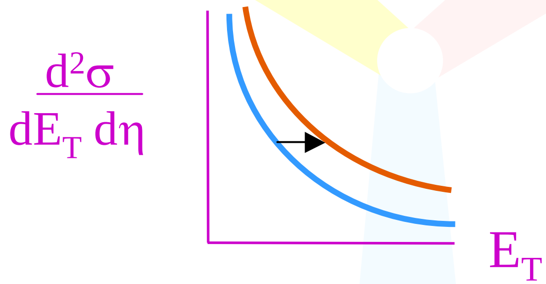
Typical selections
- on EM fraction,
- hot cells,
- missing E_T,
- vertex position,
- etc.



> 97% efficient

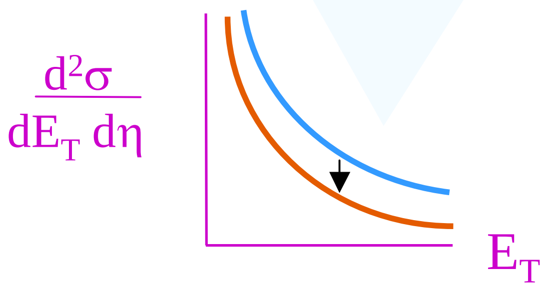
> 99% pure

Jet Energy Corrections



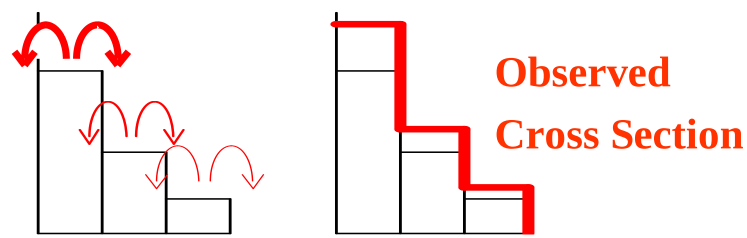
- Response functions
- Noise and underlying event
- "Showering"

no distinction between jets of different kinds



- Resolutions: Uncertainty on E_T Estimated with dijet balancing or simulation

Important for cross section measurement



Jet and Event Quantities

- Low E_T Multijet Studies
- Subjet Multiplicity

DØ Low E_T Multijet events

At high-E_T, NLO QCD does quite well, but the number of jets at low-E_T does not match as well.

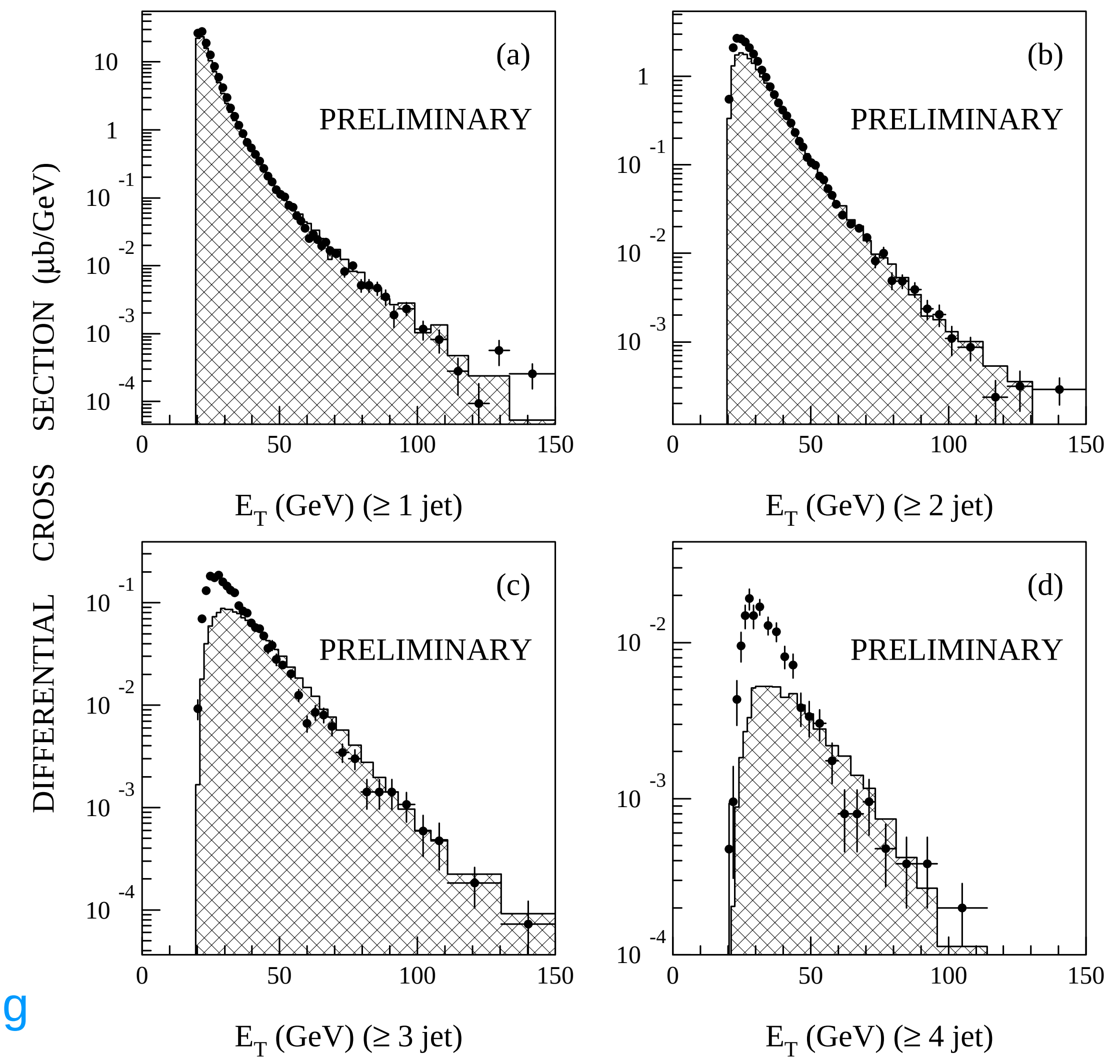
(Comparison with Pythia)

Each jet's E_T>20 GeV.

Theory normalized to 2-jet data >40 GeV.

Looking also at Jetrad and Herwig

E_T of Leading Jet

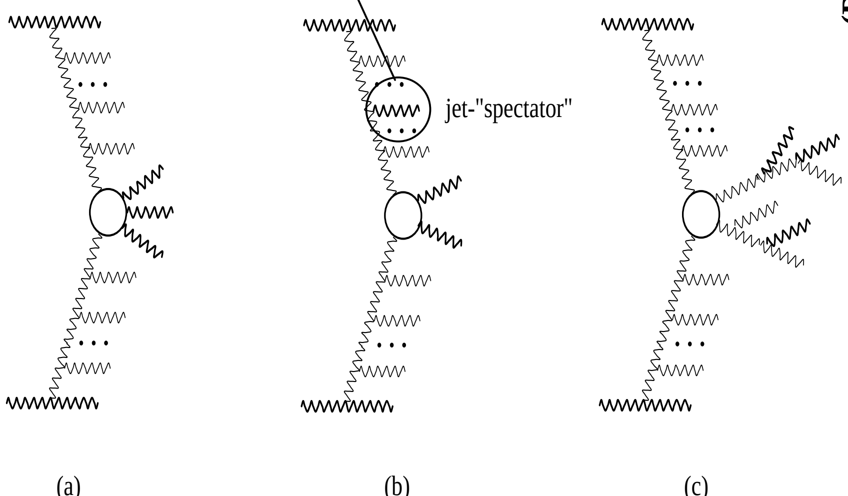


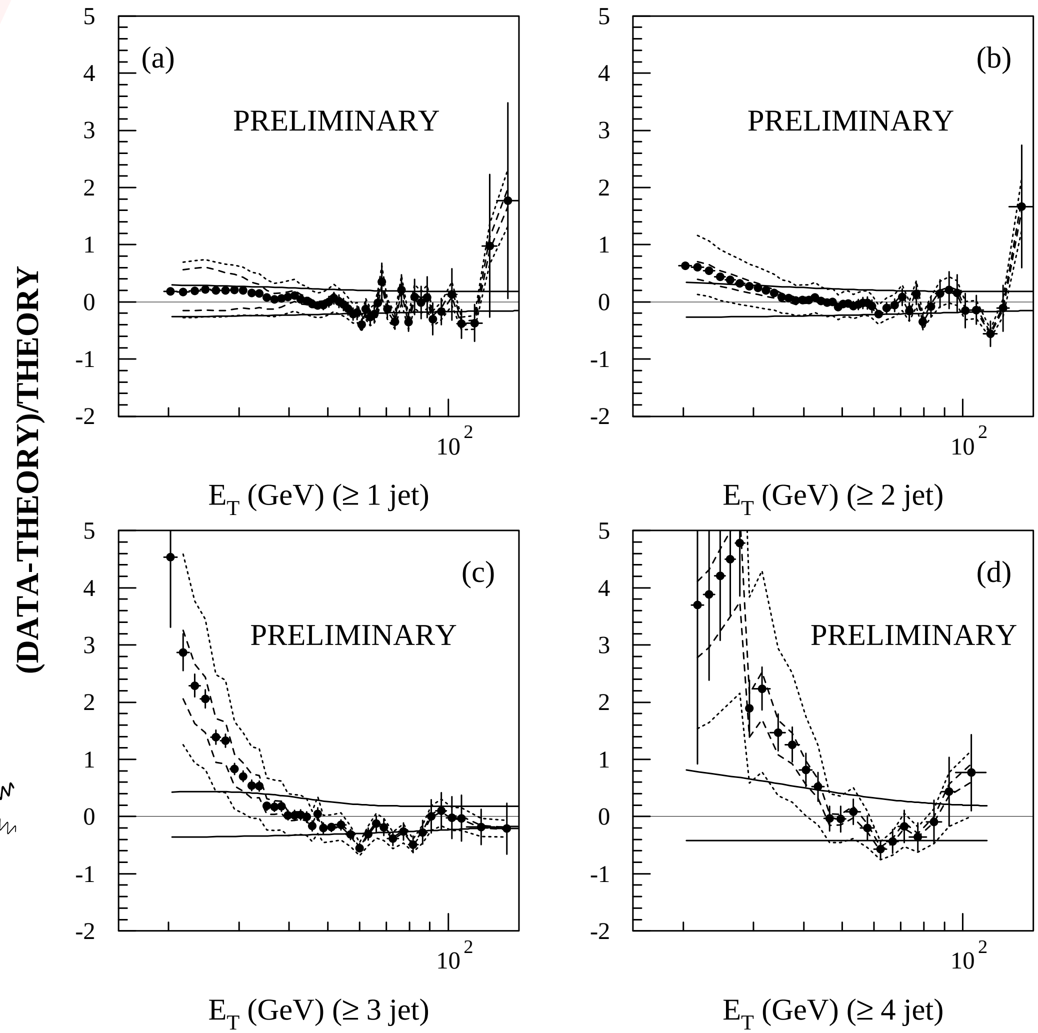
DØ Low E_T Multijet events

- Strong p_T ordering in DGLAP shower evolution may suppress "spectator jets" in Pythia

- BFKL has diffusion in $\log(p_T)$

THREE JETS PRODUCTION





DØ Subjet Multiplicity Using K_T Algorithm

- Perturbative and resummed calculations predict that gluon jets have higher subjet multiplicity than quark jets, on average.

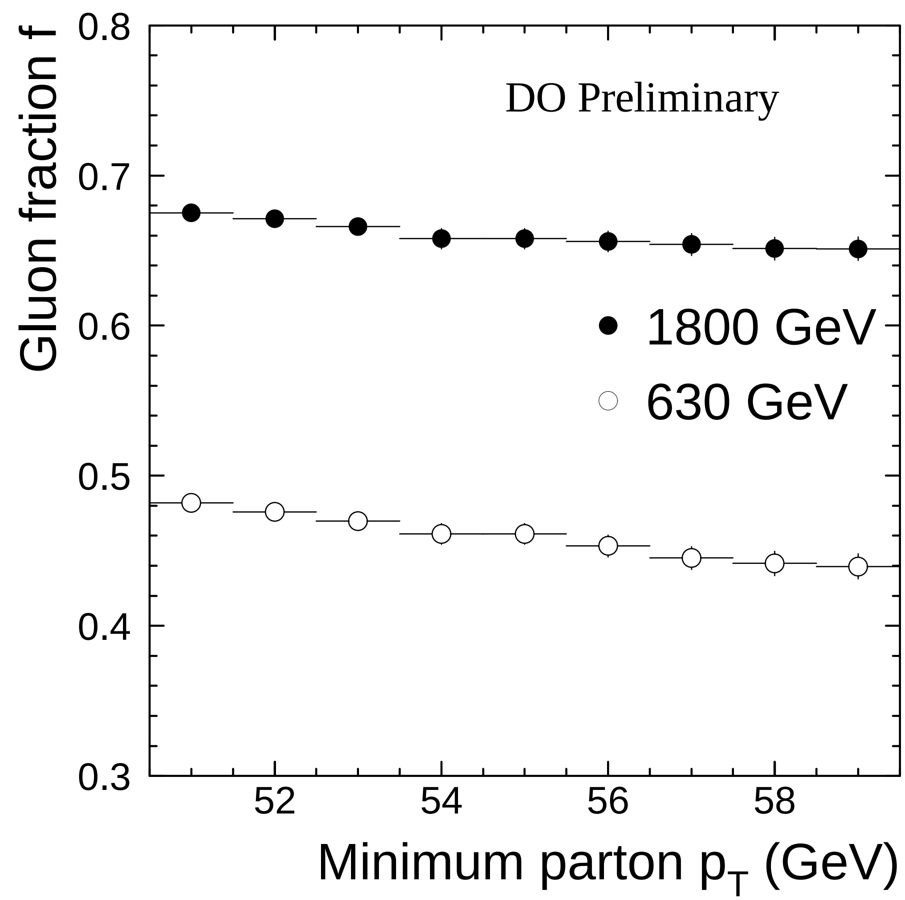
- Linear Combination:

Mean Jet Multiplicity

$$\langle M \rangle = f_g M_g + (1-f_g) M_Q$$

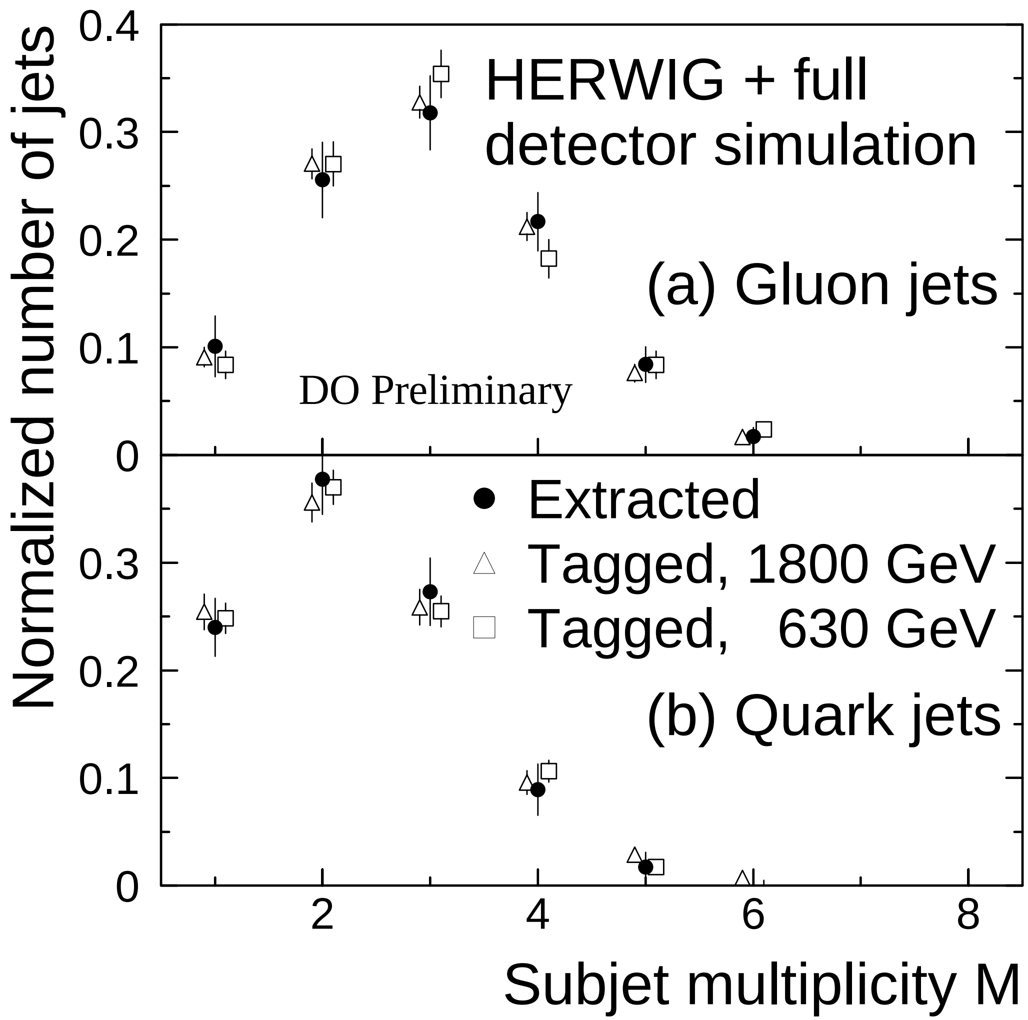
Gluon Jet Fraction *Quark Jet Fraction*

Monte Carlo



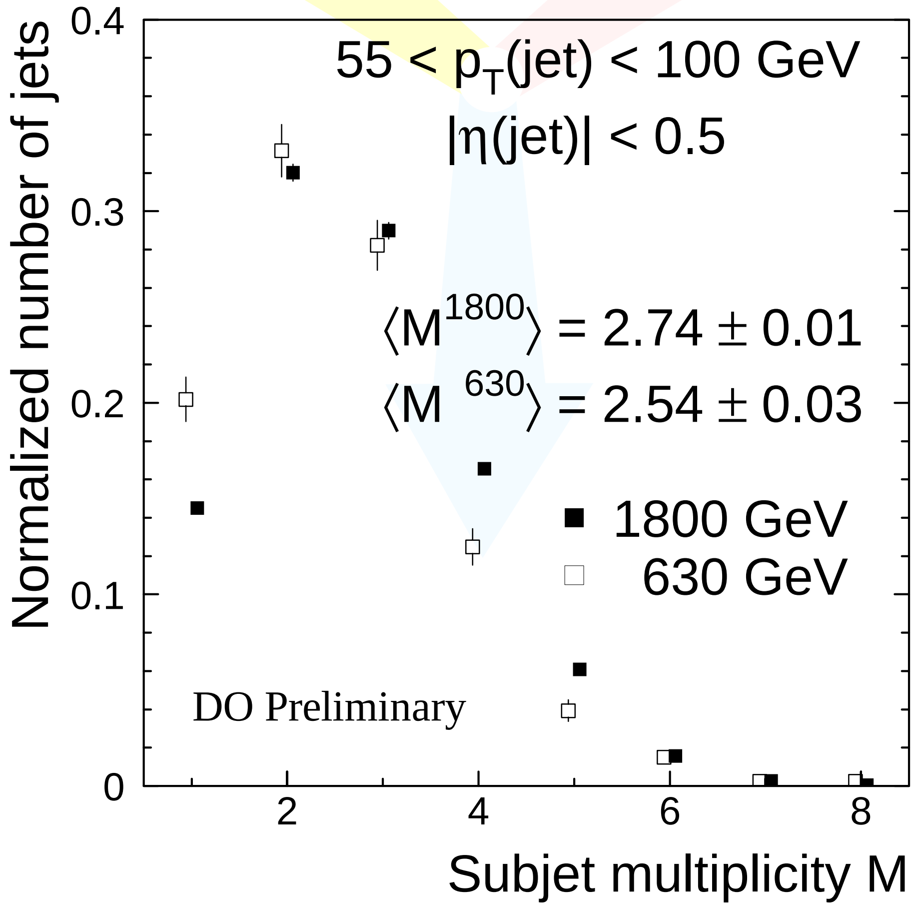
DØ Subjet Multiplicity Using K_T Algorithm

- Assume M_g, M_Q independent of $\sqrt{s}$
- Measure M at two $\sqrt{s}$ energies and extract the g and Q components

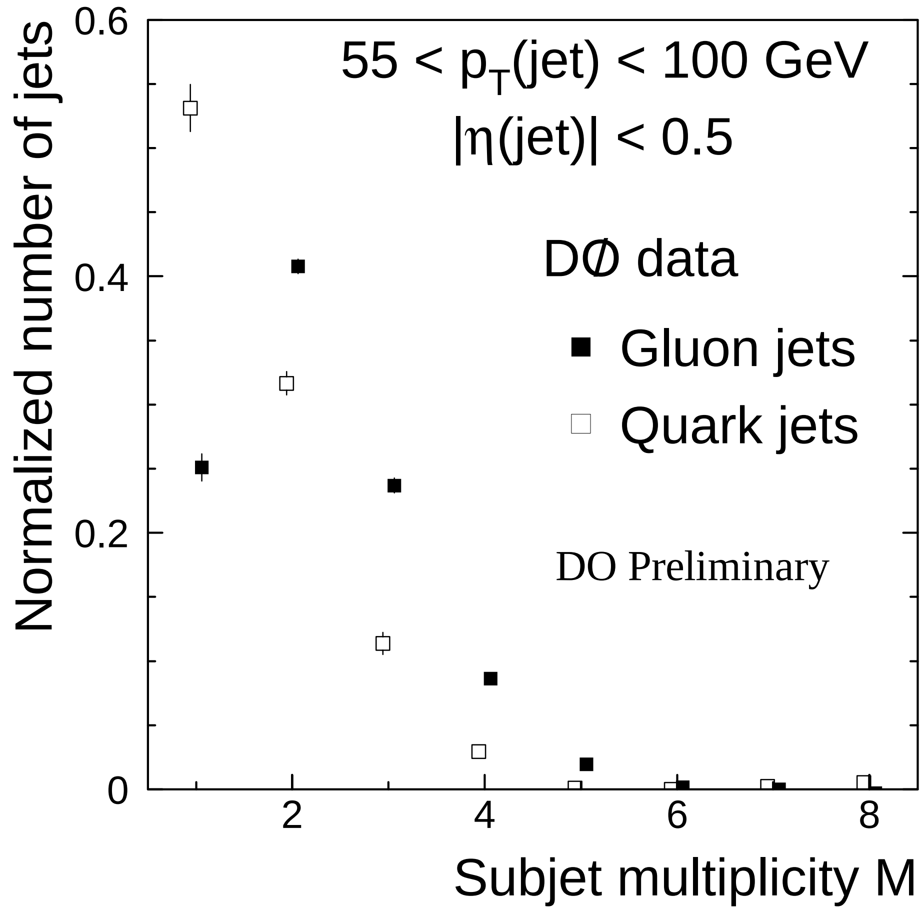


DØ Subjet Multiplicity Using K_T Algorithm

Raw Subjet Multiplicities



Extracted Quark and Gluon Mutiplicities



Higher M $\Rightarrow$ more gluon jets at 1800 GeV

DØ Subjet Multiplicity Using K_T Algorithm

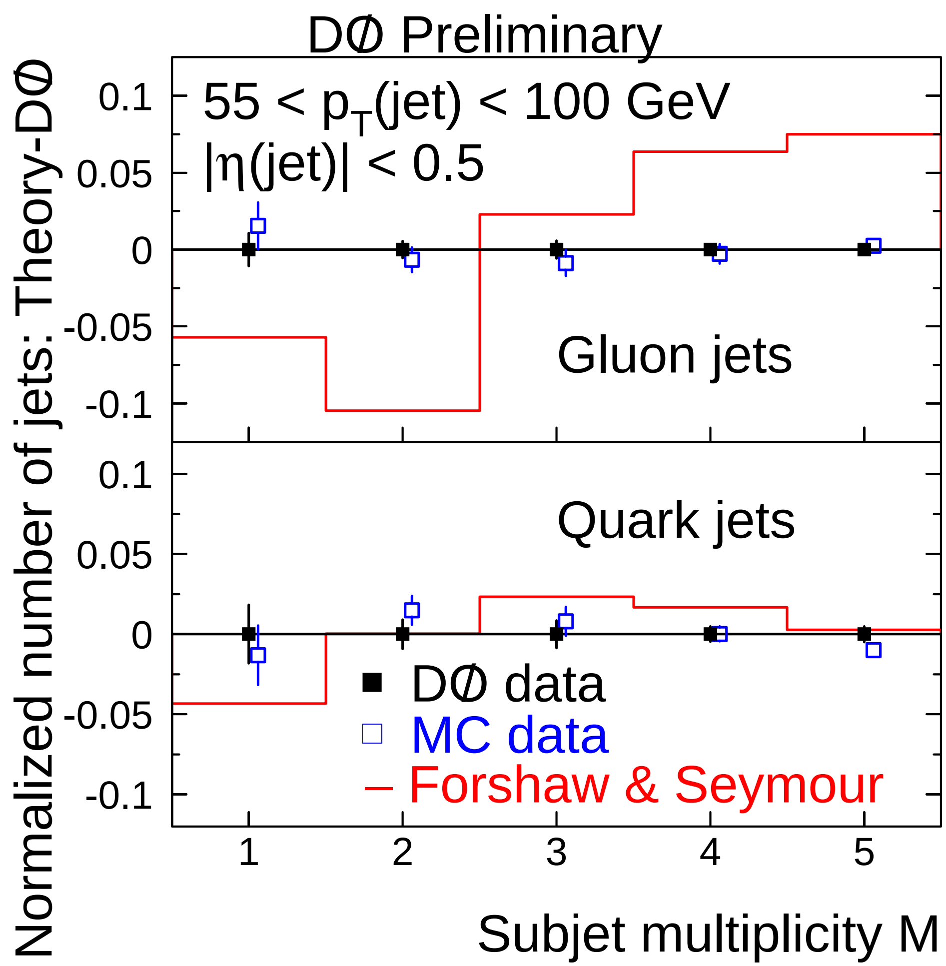
$$R \equiv \frac{\langle M_g \rangle - 1}{\langle M_Q \rangle - 1}$$

$$R = 1.84 \pm 0.15\,(\text{stat})\ ^{+0.22}_{-0.16}\,(\text{syst})$$

HERWIG prediction =1.91±0.16(stat)

Largest uncertainty comes from the gluon fractions in the PDFs

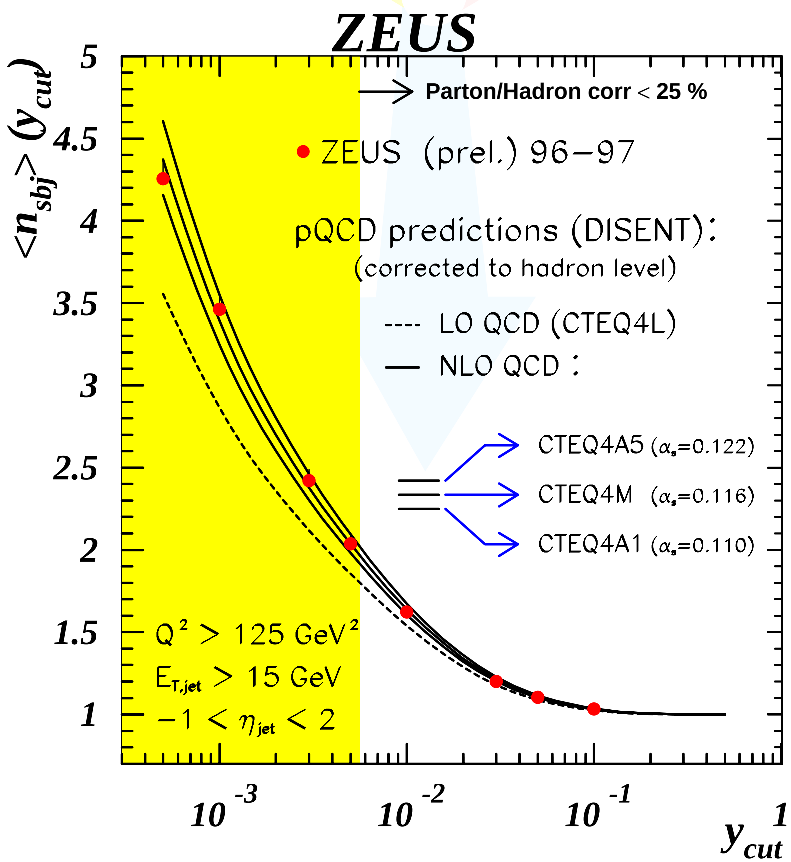
Coming soon as a PRD

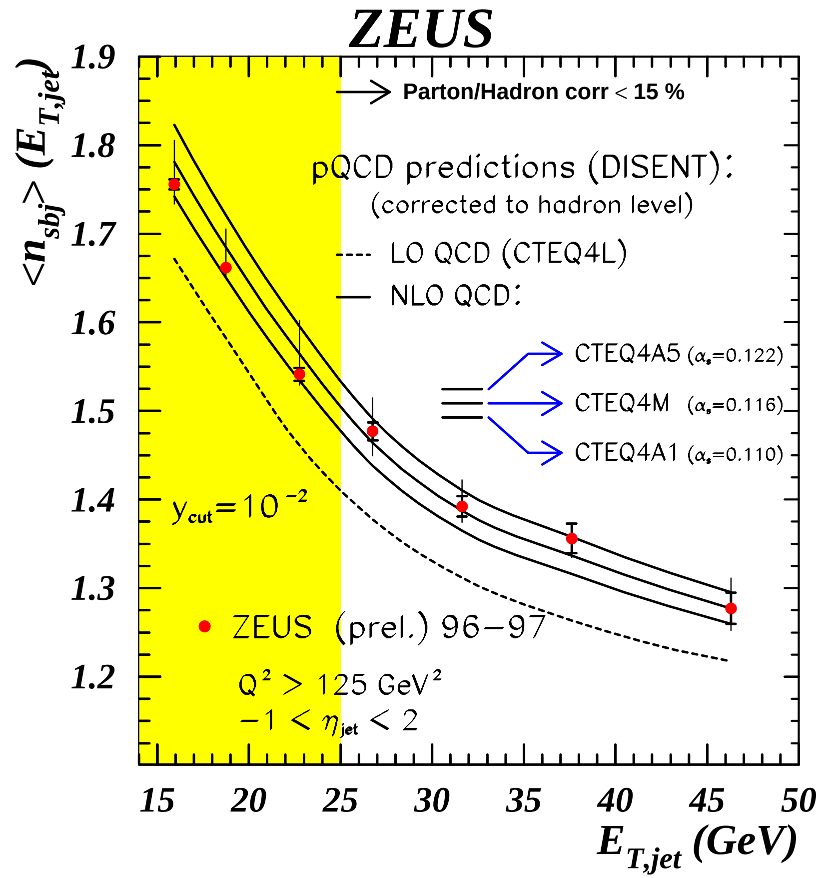


ZEUS Subjet Multiplicity

- Comparison at hadron level
- Unfolded using Ariadne MC

$$\langle n_{sbj} \rangle = \frac{1}{N_{jet}} \sum_{k=1}^{N_{jet}} (n_{sbj})_k$$



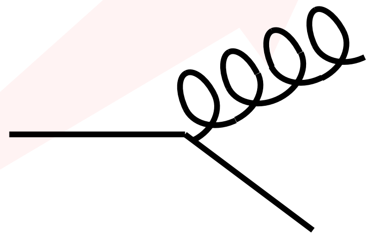


NLO QCD describes data

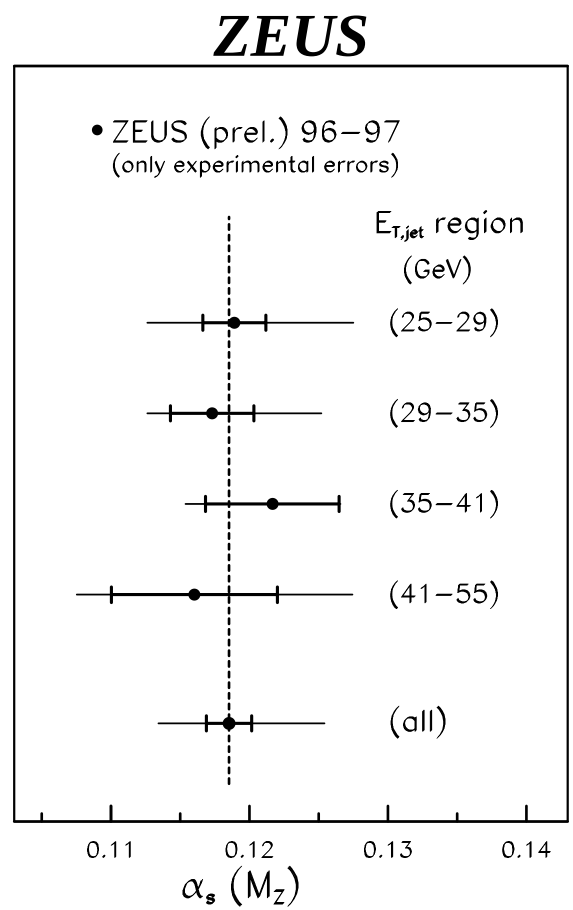
Sensitive to α_s

α_s from ZEUS Subjets

$\langle n_{sub}\text{-}1 \rangle \Rightarrow$



$\Rightarrow$ Proportional to α_s



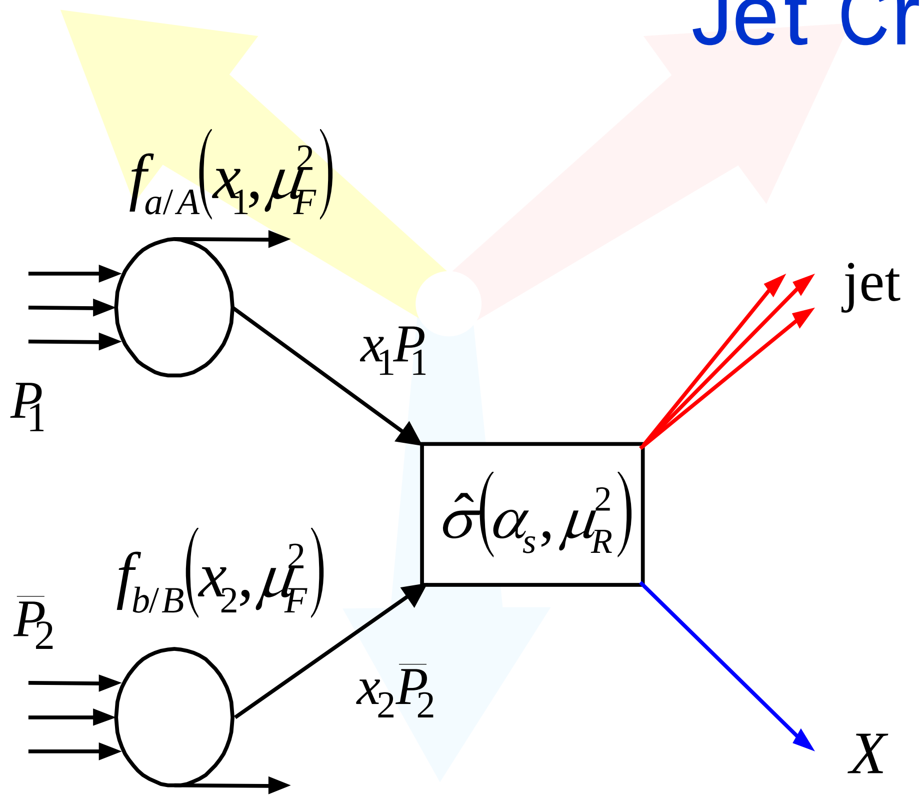
- Major Systematic Errors
  - Model dependence (2-3%)
  - Jet energy scale (1-2%)
- Major Theoretical Errors
  - Variation of renormalization scale

$$\alpha_s(M_Z) = 0.1185 \pm 0.0016\,(\text{stat})\ {}^{+0.0067}_{-0.0048}\ (\text{syst})\ {}^{+0.0089}_{-0.0071}\ (\text{th})$$

Cross Sections

- Inclusive cross sections
  - Rapidity dependence
  - K_T central inclusive
- R_{32}
- 630/1800 ratio of jet cross sections
- Di-Jets
- α_s Conclusions

Jet Cross Sections

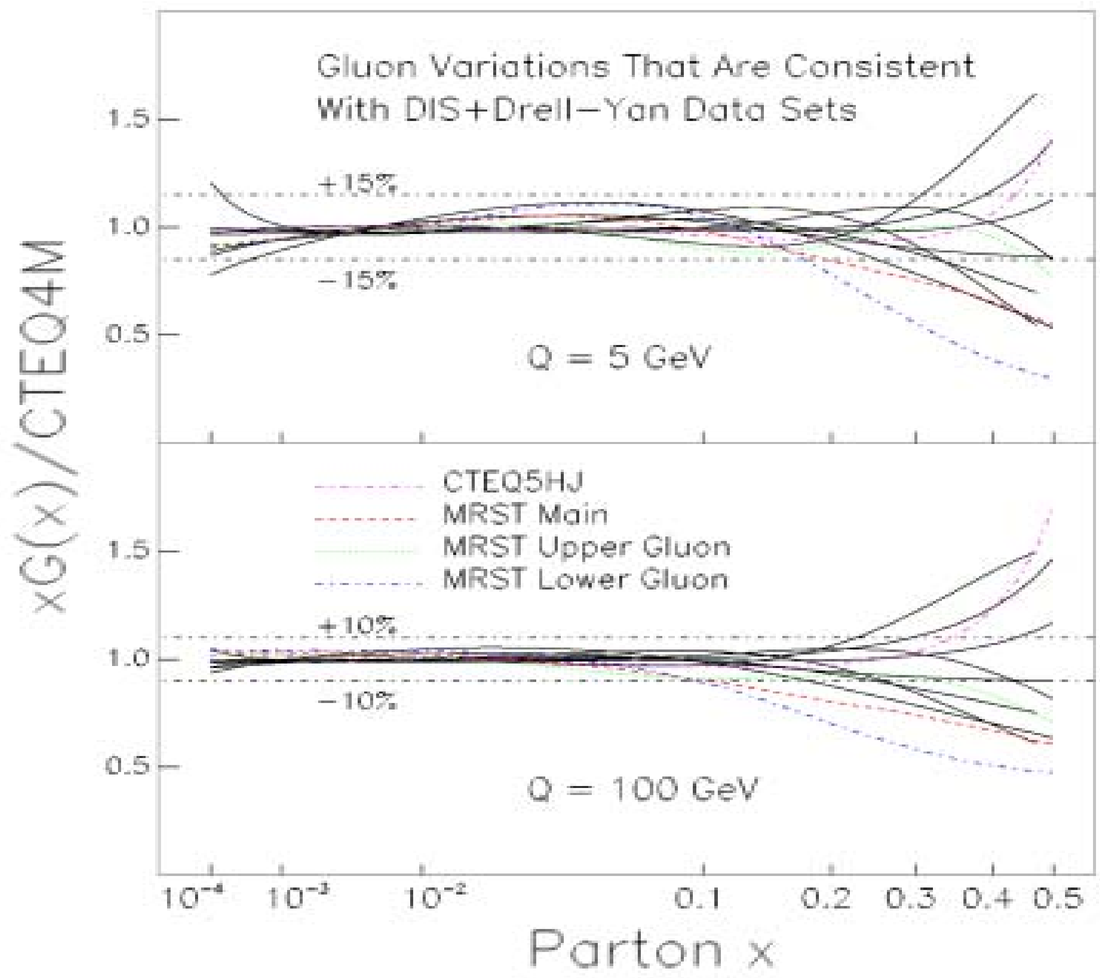


- How well are pdf's known?
- Are quarks composite particles?
- What are appropriate scales?
- What is the value of α_s?
- Is NLO (α_s^3) sufficient?

$$\sigma(p\bar{p} \to \mathrm{jet} + X) = \sum_{abcX} \int dx_1 dx_2 \; f_{a/A} f_{b/B} \; \hat{\sigma}(ab \to cX)$$

CTEQ Gluon Distribution Studies

- Momentum fraction carried by quarks is very well known from DIS data
- Fairly tight constraints on the gluon distribution except at high x
- Important for high E_T jet production at the Tevatron and direct photon production



Experimental Differential Cross Section

$$\frac{E\, d^3\sigma}{dp^3} = \sum x_1 F(x_1)\; x_2 F(x_2)\; \frac{d\hat{\sigma}}{d\hat{t}}(ab \to cX)$$

← Theoretical cross section

$$= \frac{d^3\sigma}{d\cos\theta\; dx_1 dx_2}$$

← Physics variables are θ and x

$$= \frac{d^3\sigma}{dE_T^2\; d\eta} = \frac{1}{2\pi E_T}\frac{d^2\sigma}{dE_T\; d\eta}$$

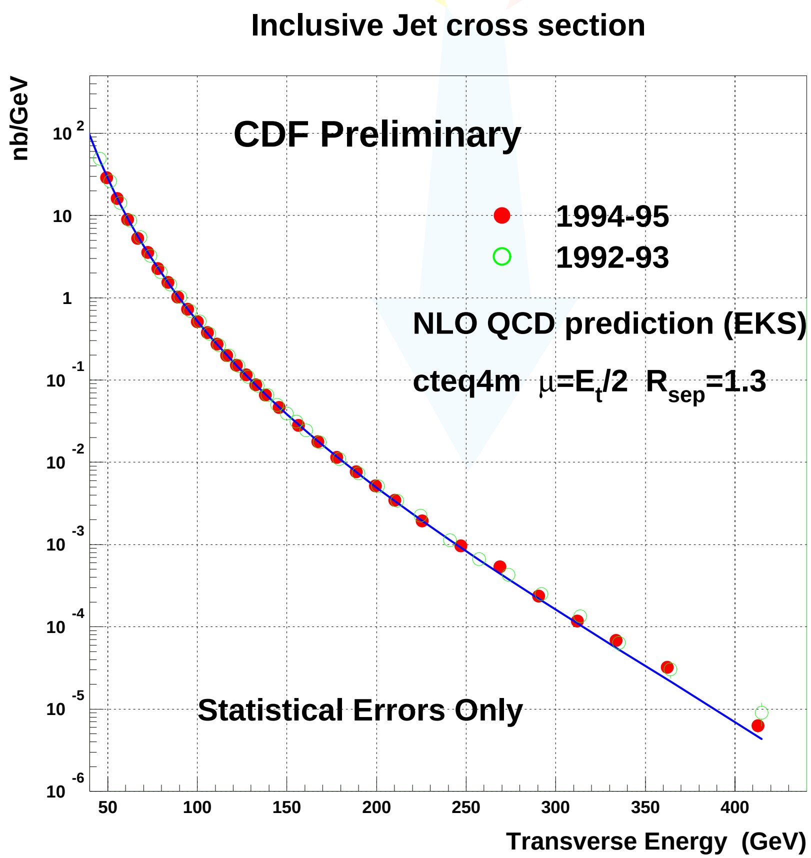
← Detector measures E_T and η

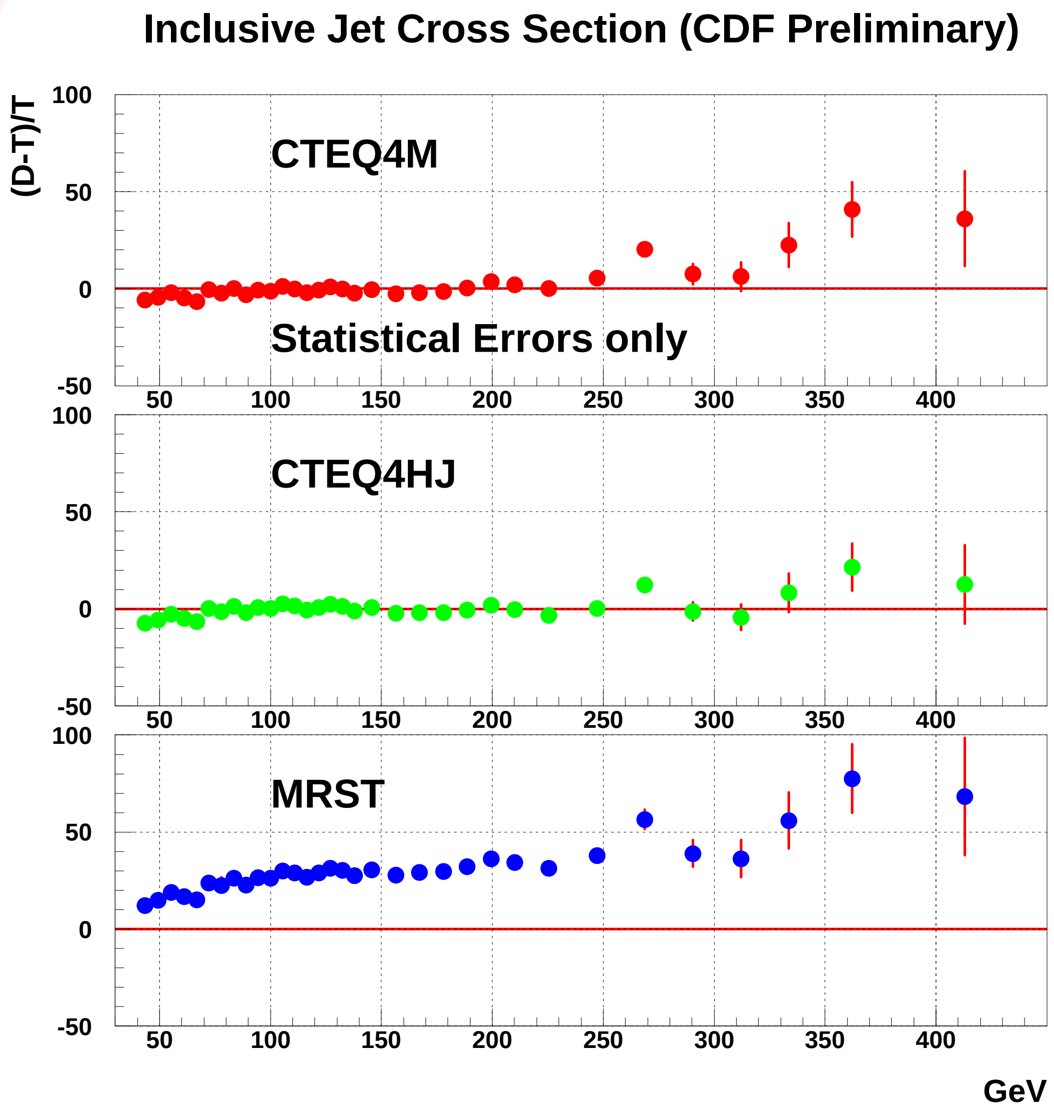
$$= \frac{1}{2\pi E_T}\frac{N}{\Delta E_T\; \Delta\eta\; \varepsilon \int L\, dt}$$

← Counting experiment with detector inefficiencies

CDF Inclusive Jet Cross Section

- $0.1 < |\eta| < 0.7$
- Complete χ^2 calculation

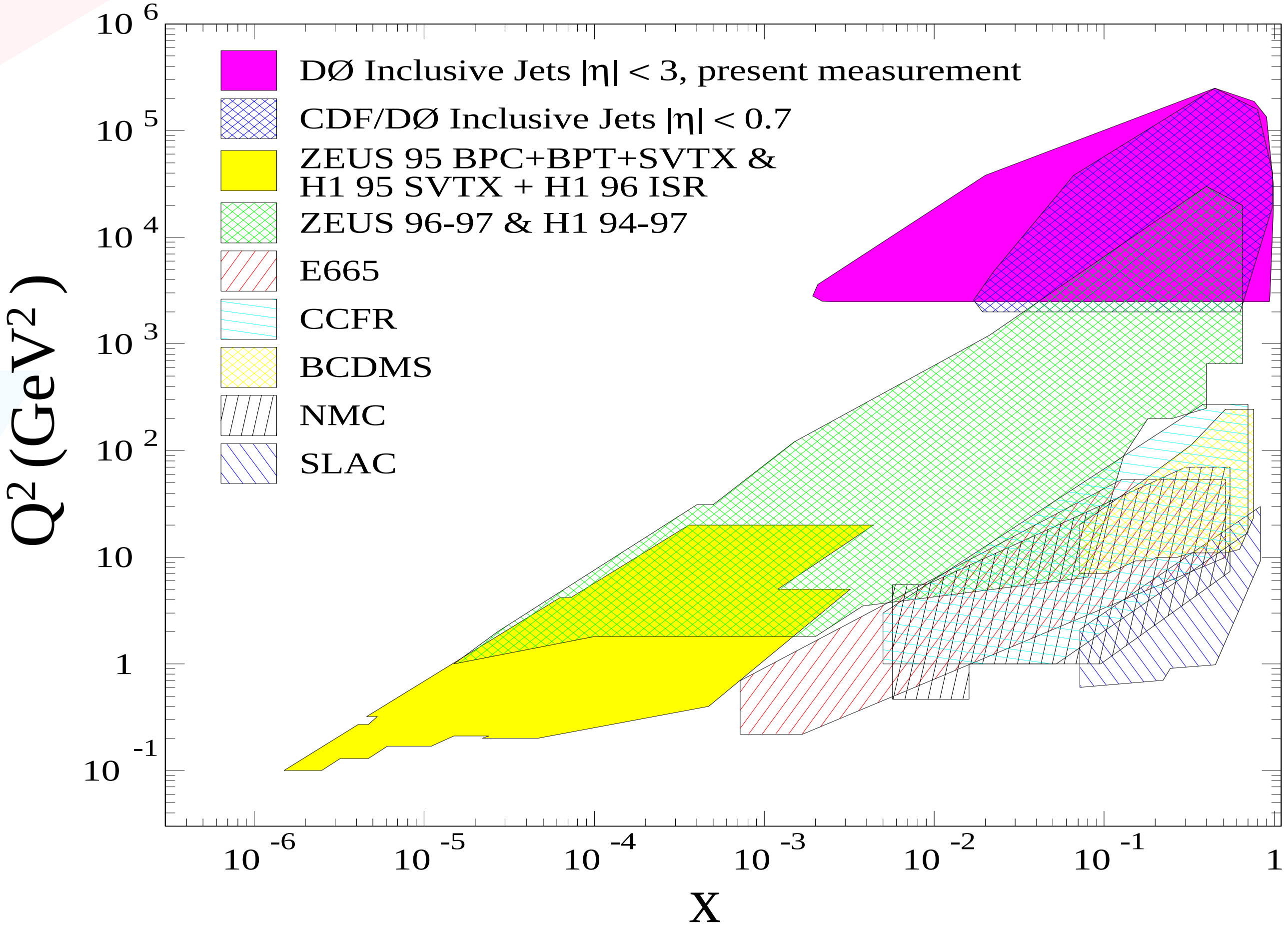




PRD 64, 032001 (2001)

x-Q^2 Measured Parameter Space

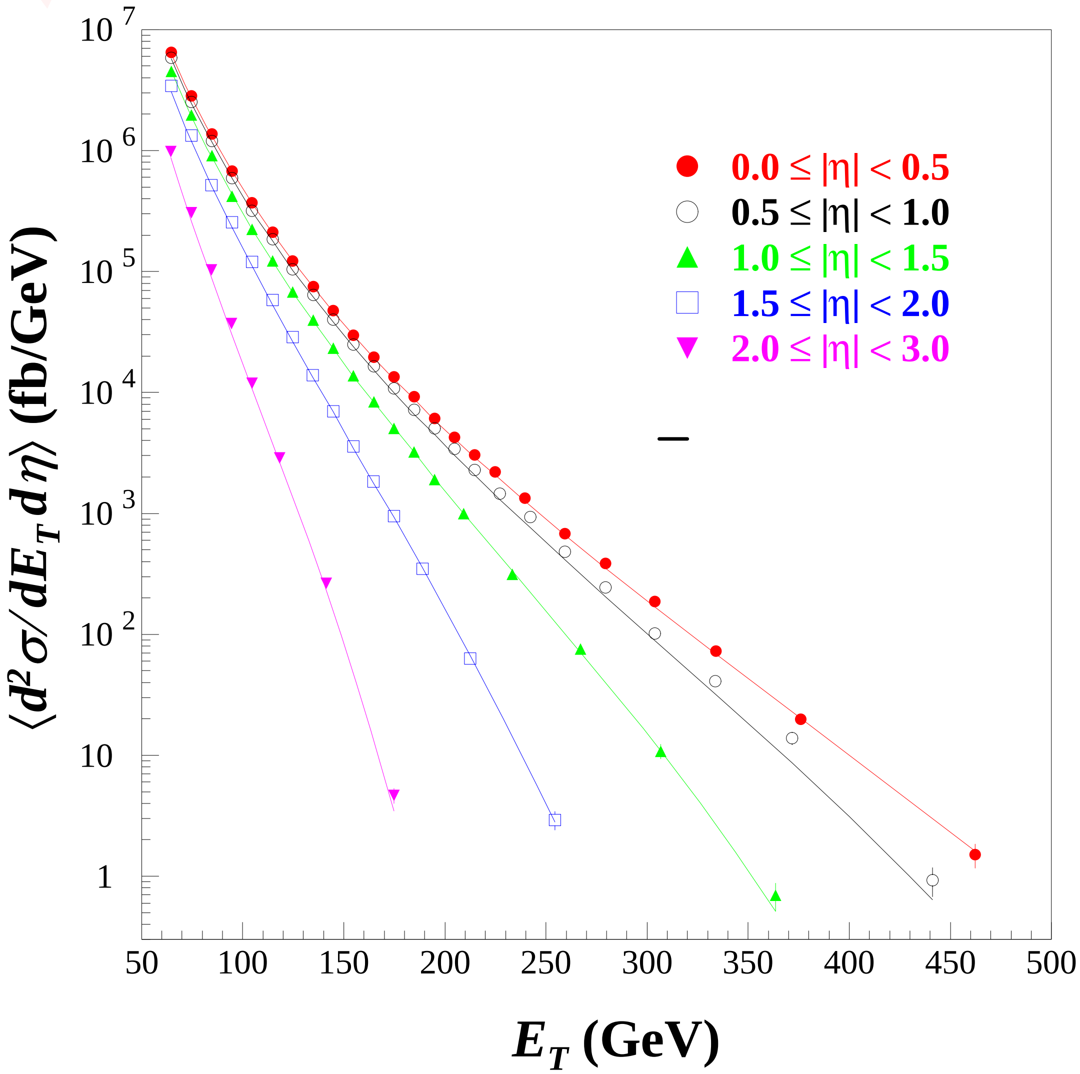
From DØ Inclusive Cross Section Measurement



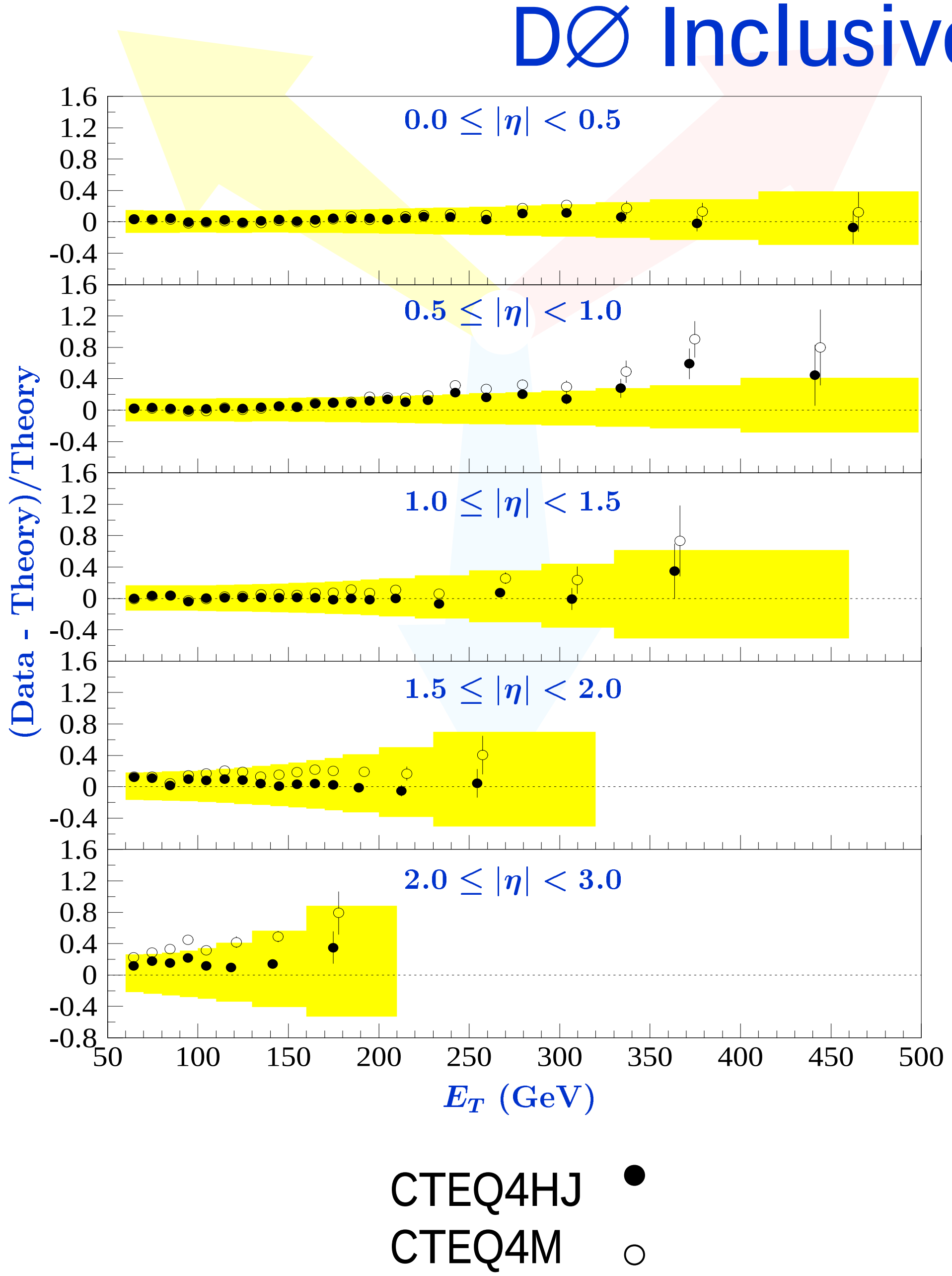
DØ Inclusive Jet Cross Section

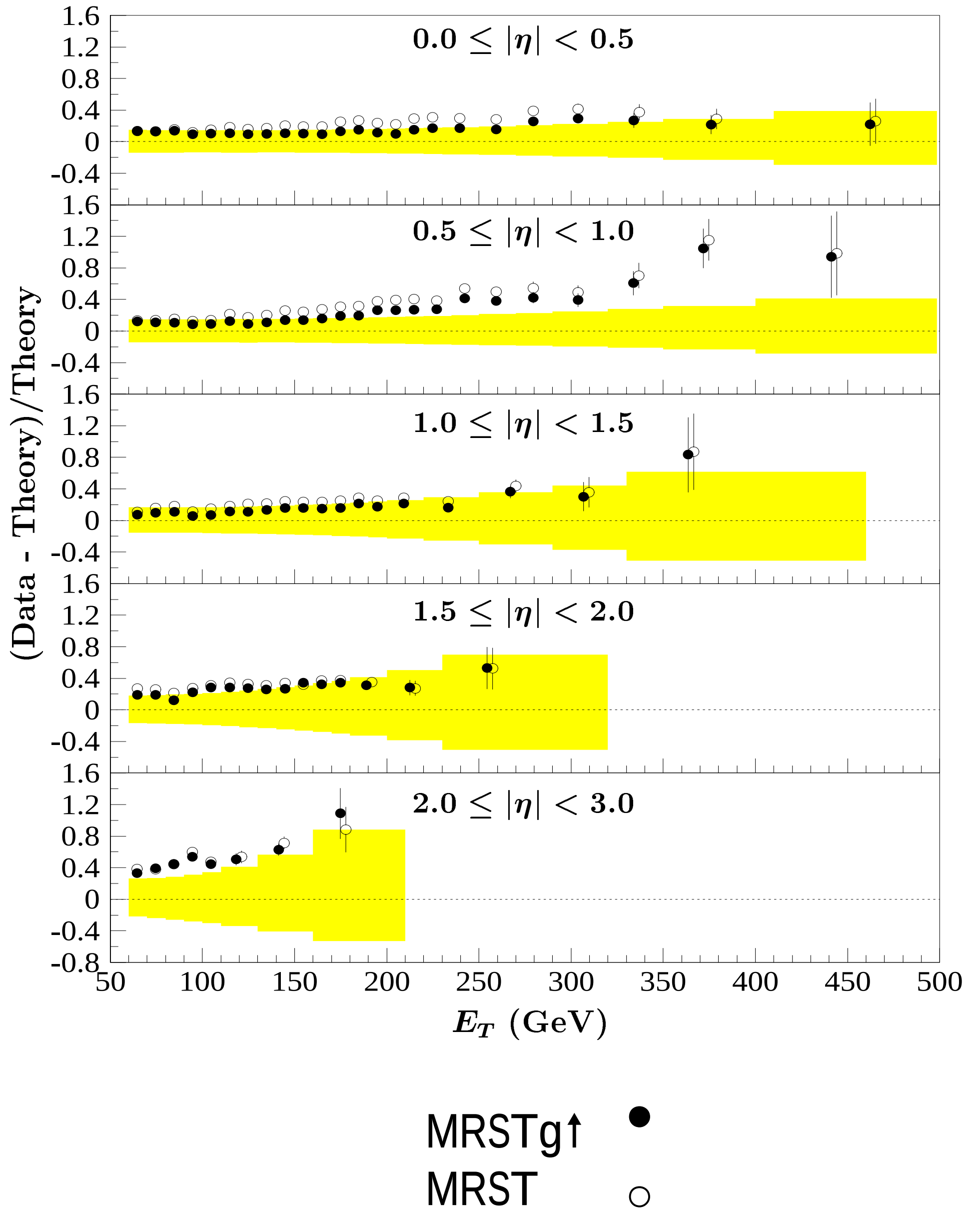
- Five rapidity regions
- Largest systematic uncertainty due to jet energy scale
- Curves are CTEQ4M

PRL 86, 1707 (2001)



DØ Inclusive Jet Cross Section





Gluon PDF Conclusions

PDF	$\chi 2$	$\chi 2/\mathrm{dof}$	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

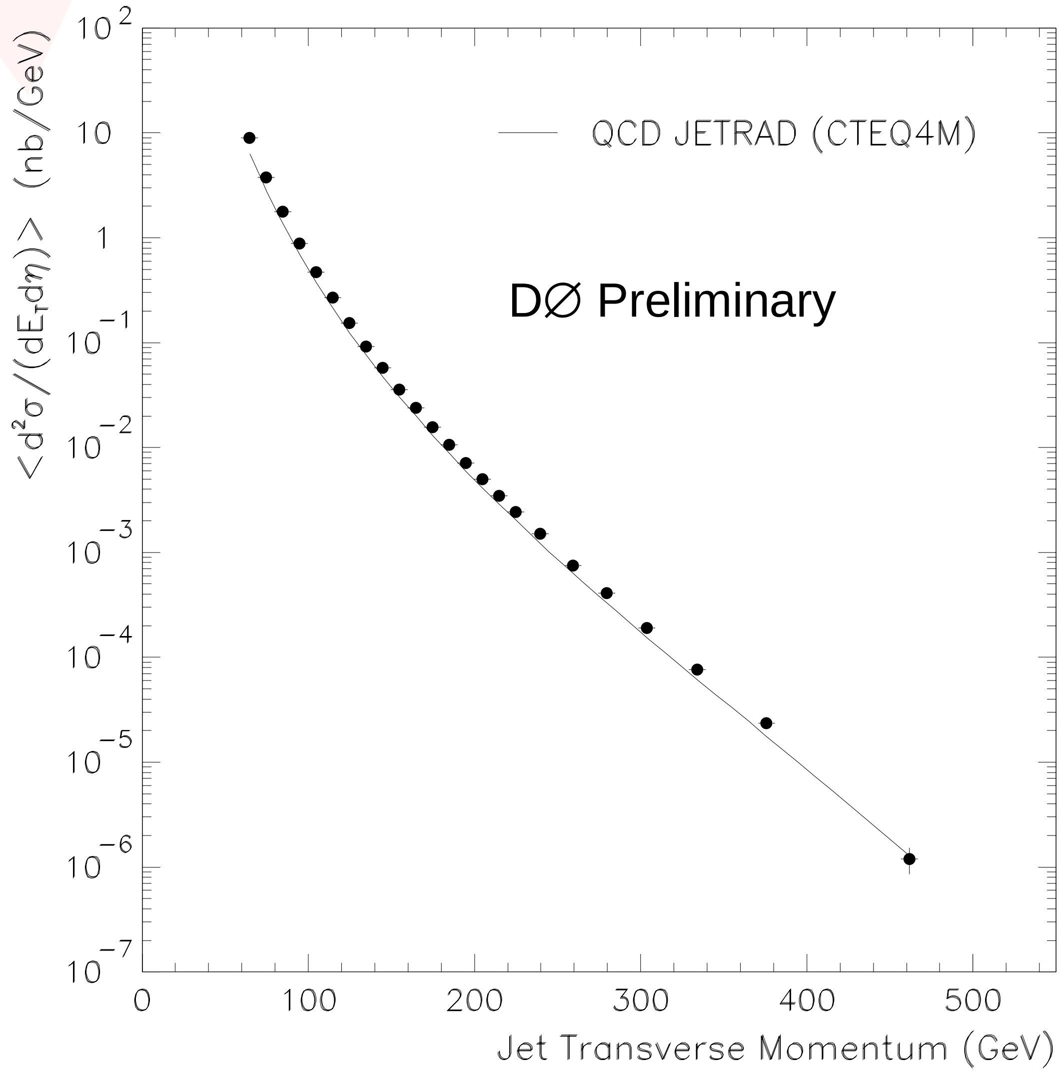
- χ^2 determined from complete covariance matrix
- Best constraint on gluon PDF at high x
- Currently being incorporated in new global PDF fits

Inclusive Cross Section Using K_T Algorithm

$-0.5 < \eta < 0.5$

$D = 1.0$

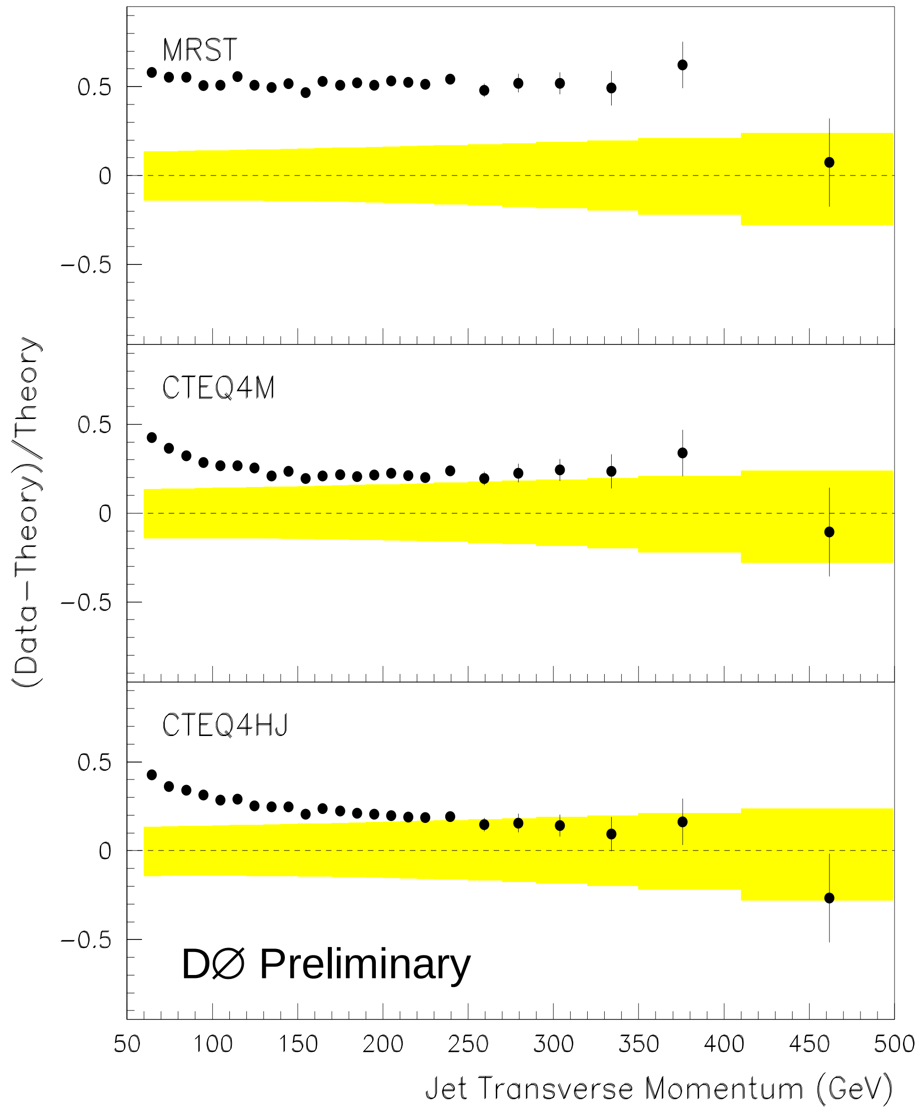
- Predictions IR and UV safe
- Merging behavior well-defined for both experiment and theory



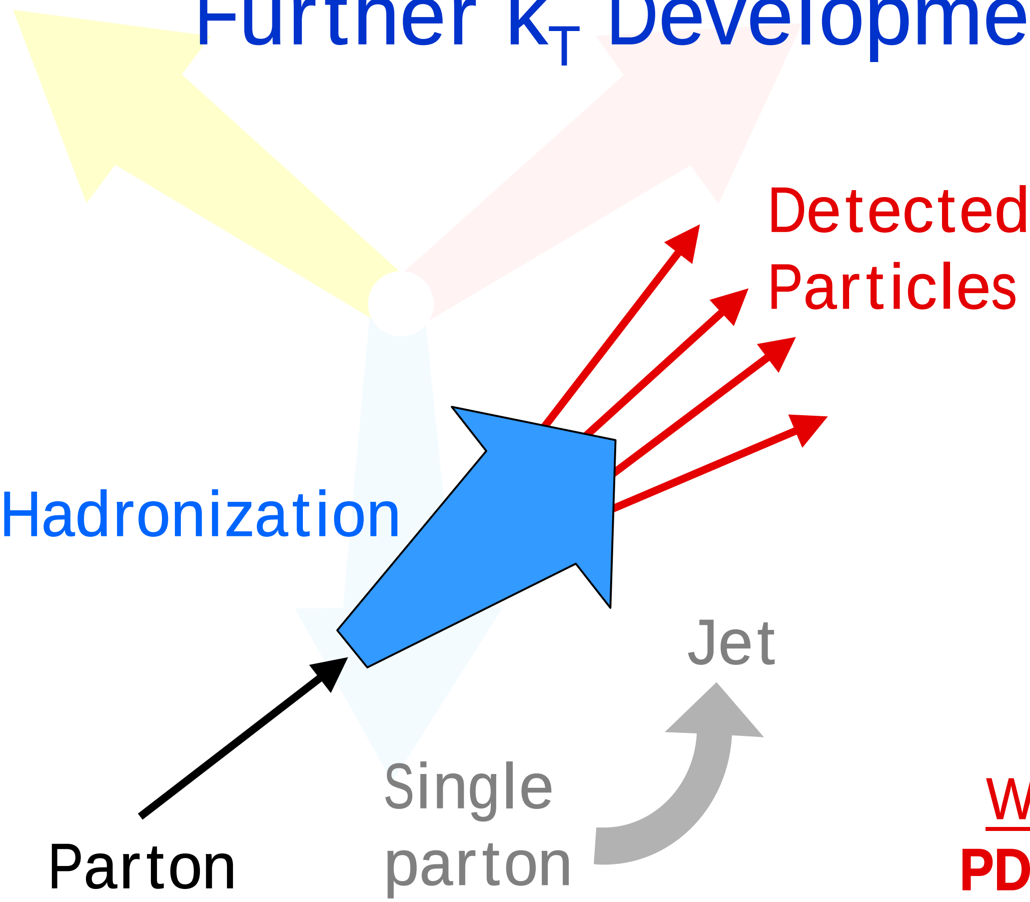
Comparison with Theory

- Normalization differs by 20% or more
- No statistically significant deviations of predictions from data
- When first 4 data points ignored, probabilities are 60-80%

PDF	χ/dof	Prob
MRST	1.12	31
MRSTg↑	1.38	10
MRSTg↓	1.17	25
CTEQ3M	1.56	4
CTEQ4M	1.30	15
CTEQ4HJ	1.13	29



Further k_T Developments (since PIC 2001)



With hadronization correction

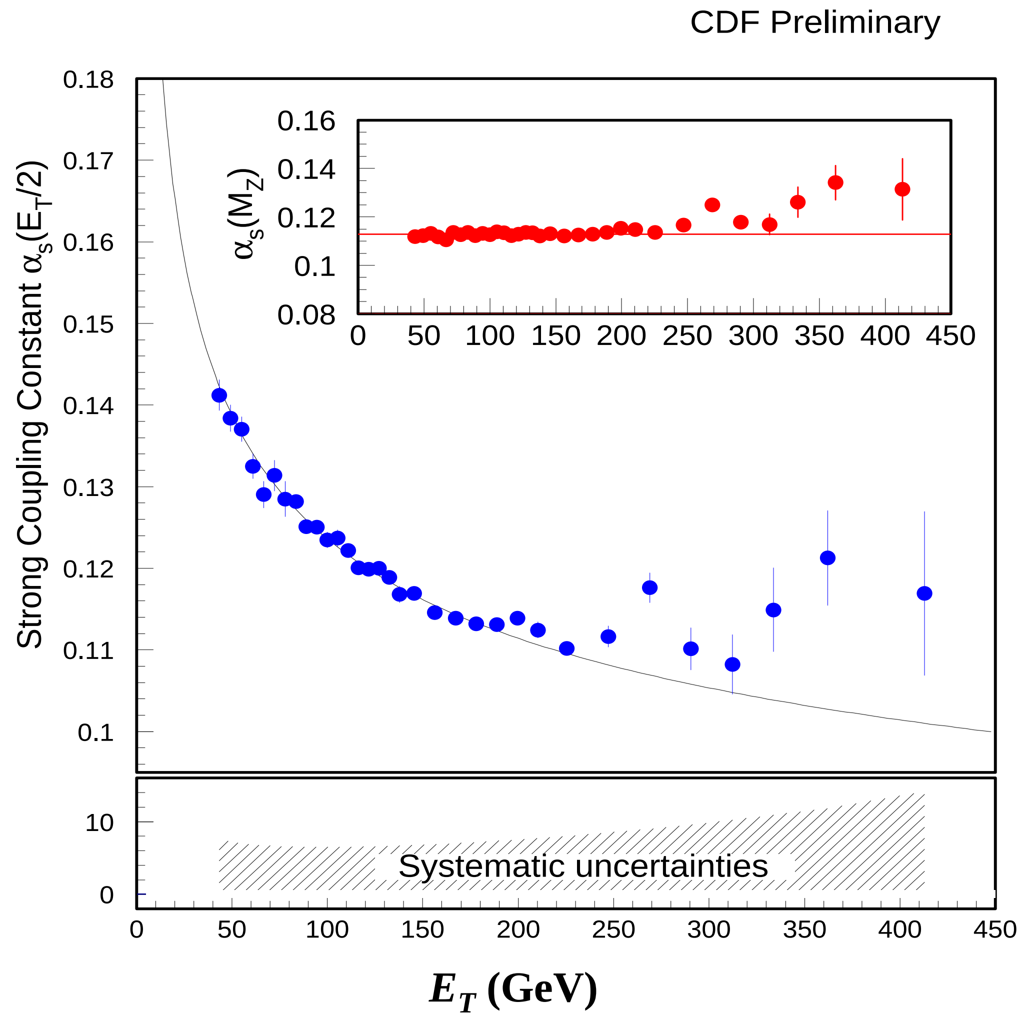
PDF	χ/dof	Prob
MRST	0.86	71
CTEQ4M	1.06	44

Correction for hadronization explains low E_T behavior

CDF α_s from Inclusive Cross Section

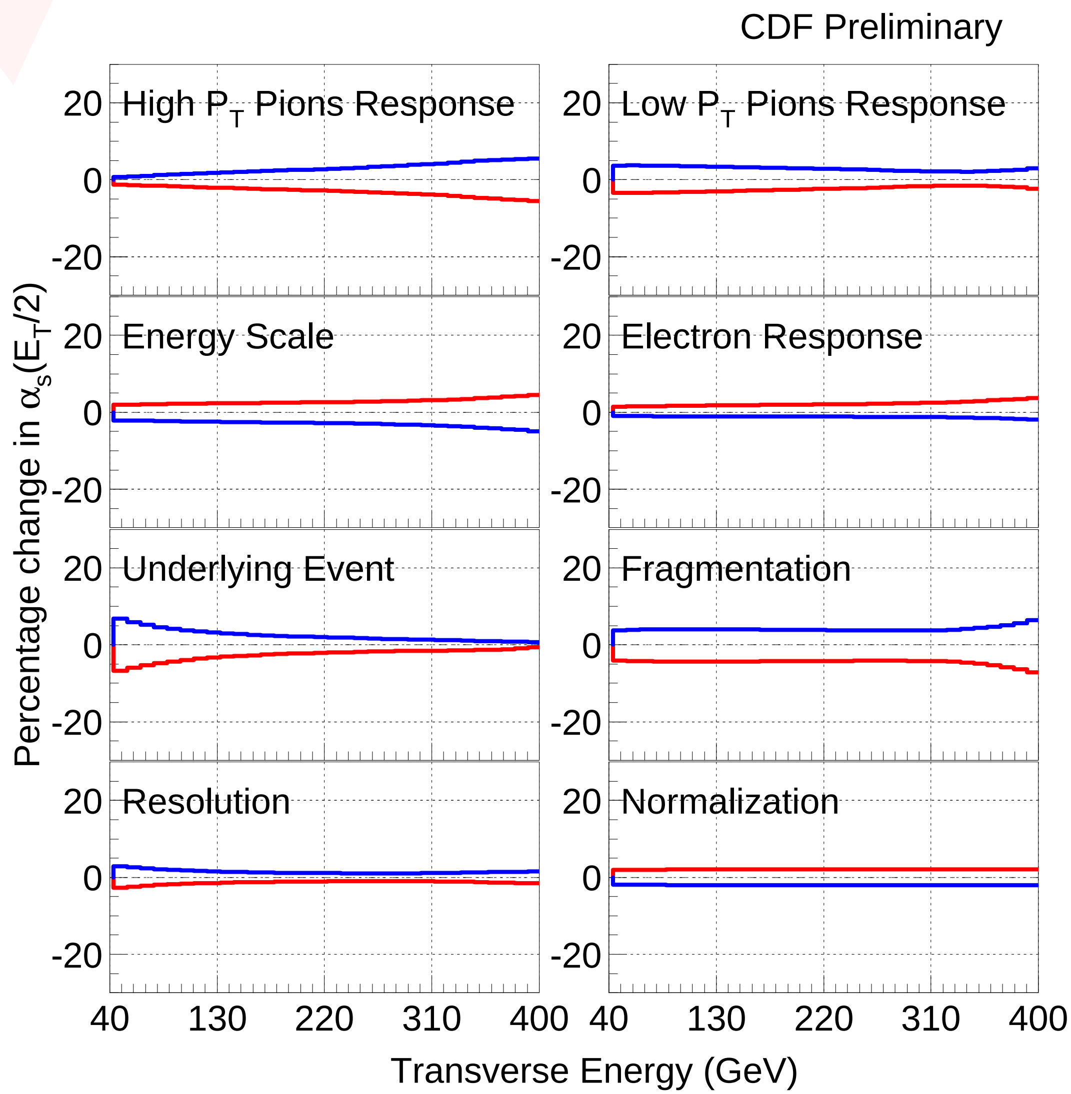
$$\frac{d\sigma}{dE_T} = \alpha_s^2(\mu_R) X^{(0)}(\mu_R, \mu_F)[1 + \alpha_s(\mu_R) k_1(\mu_R, \mu_F)]$$

- $\alpha_s{}^2 X^{(0)}$ is LO prediction
- $\alpha_s{}^3 X^{(0)} k_1$ is NLO prediction
- $X^{(0)}$ and k_1 determined from JETRAD
- $\overline{\mathrm{MS}}$ scheme used
- Jet cone algorithm used with R_{sep} = 1.3
- α_s determined in 33 E_T bins



CDF α_s from Inclusive Cross Section

- Experimental systematic uncertainty
- Largest at low E_T is underlying event
- Largest at high E_T is fragmentation and pion response



CDF α_s from Inclusive Cross Section

μ scale is the major source of theoretical uncertainty

$E_T/2 < \mu < 2E_T$

PDF affects α_s

CTEQ4M minimizes χ^2

Theoretical uncertainties each ~ 5%

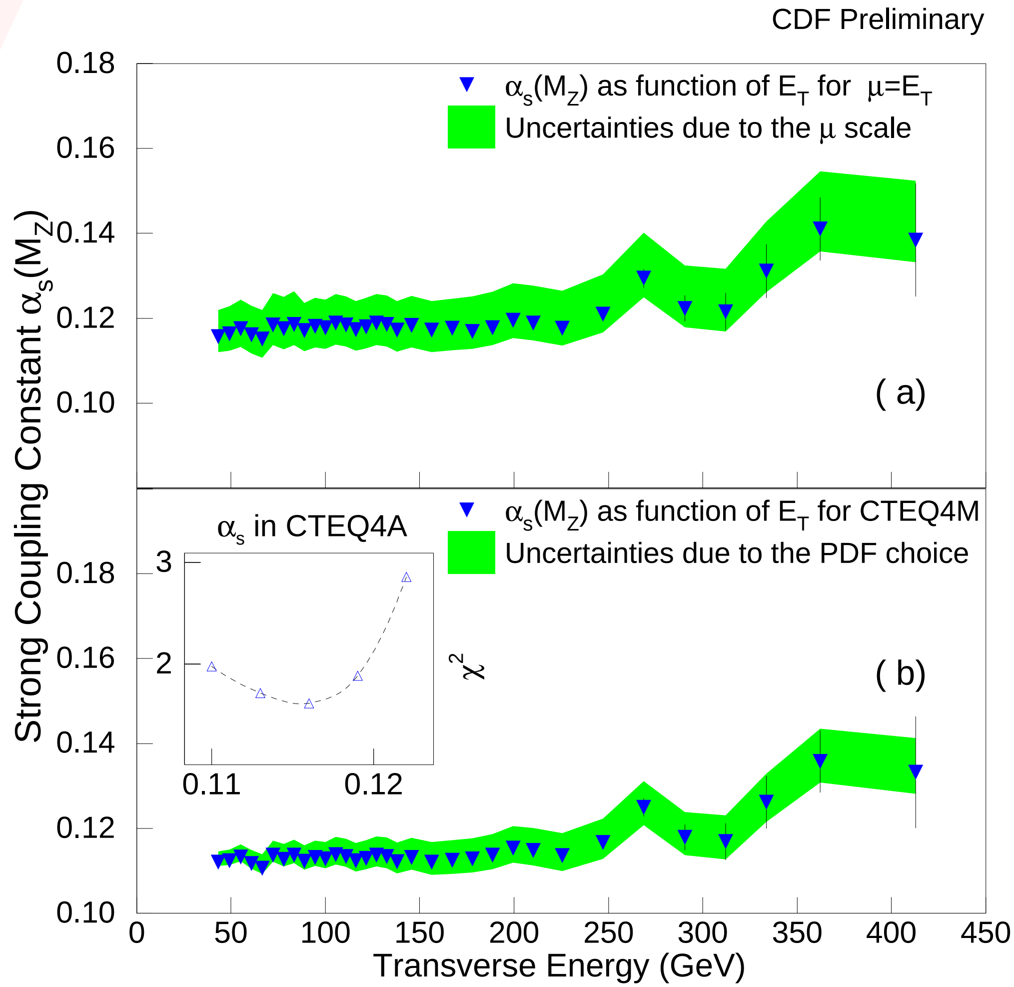
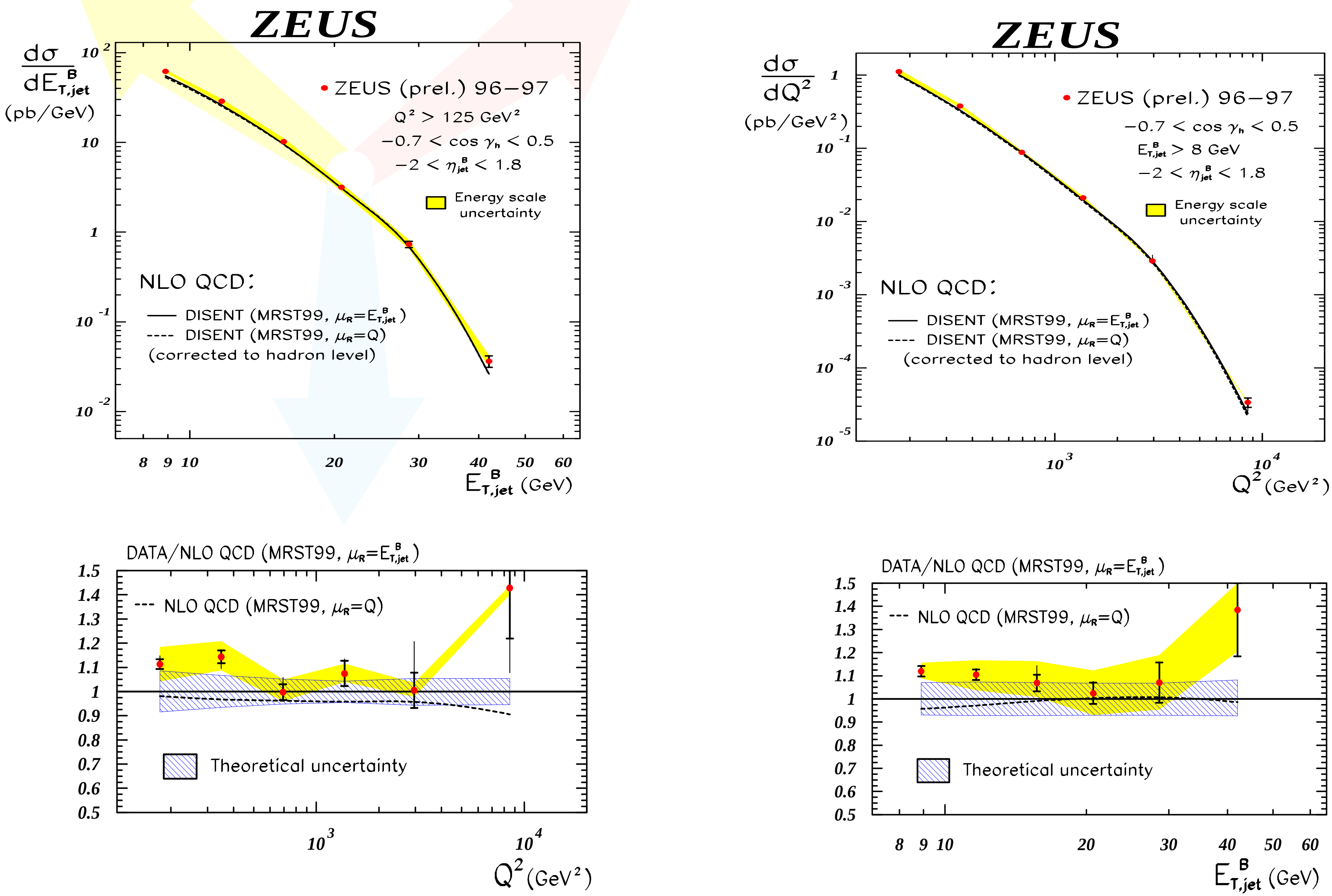


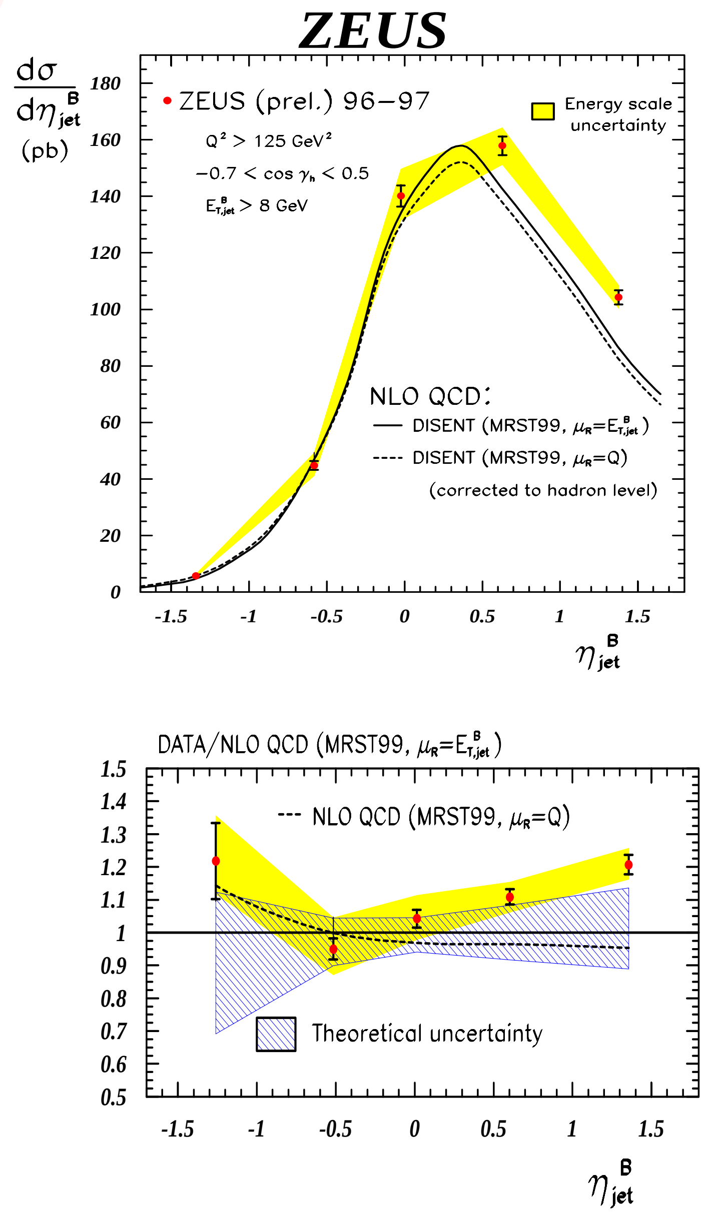
FIG. 3. Uncertainties due to the renormalization scale (a) and parton distribution functions (b). The inset shows the variation of χ^2 for the CTEQ4A PDF family, with minimal value corresponding to CTEQ4M PDF set (input α_s=0.116).

$$\alpha_s(M_Z) = 0.1129 \pm 0.0001\,(\text{stat})\,{}^{+0.0078}_{-0.0089}\,(\text{exp. syst})$$

ZEUS Inclusive Jet Production



ZEUS Inclusive Jet Production



Measured cross section slightly above NLP pQCD in forward section

ZEUS Inclusive Jet Production

α_s Results:

Uses various fits of $d\sigma/dQ^2$ and $d\sigma/dE_T$

Full phase-space

$$\alpha_s(M_Z) = 0.1241 \pm 0.0009\,(\text{stat})\,^{+0.0043}_{-0.0038}\,(\text{exp})\,^{+0.0053}_{-0.0036}\,(\text{th})$$

High-Q^2 region (Q^2>500 GeV^2)

$$\alpha_s(M_Z) = 0.1190 \pm 0.0017\,(\text{stat})\,^{+0.0049}_{-0.0023}\,(\text{exp})\,^{+0.0026}_{-0.0026}\,(\text{th})$$

High-E_T region (>14 GeV)

$$\alpha_s(M_Z) = 0.1206 \pm 0.0015\,(\text{stat})\,^{+0.0058}_{-0.0045}\,(\text{exp})\,^{+0.0041}_{-0.0030}\,(\text{th})$$

R_{32}: Motivation and Method

- Study the rate of soft jet emission (20-40 GeV)
  - QCD multijet production - background to interesting processes
  - Predict rates at future colliders
- Improve understanding of the limitations of pQCD
  - Identify renormalization sensitivity
  - Does the introduction of additional scales improve agreement with data ?
- Measure the Ratio

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

- with H_T

$$H_T = \sum_{\text{jets}} E_T$$

- for all jets with
  - $E_T > 20, 30, 40$ GeV for $\eta<3$ and $E_T > 20$ GeV for $\eta<2$

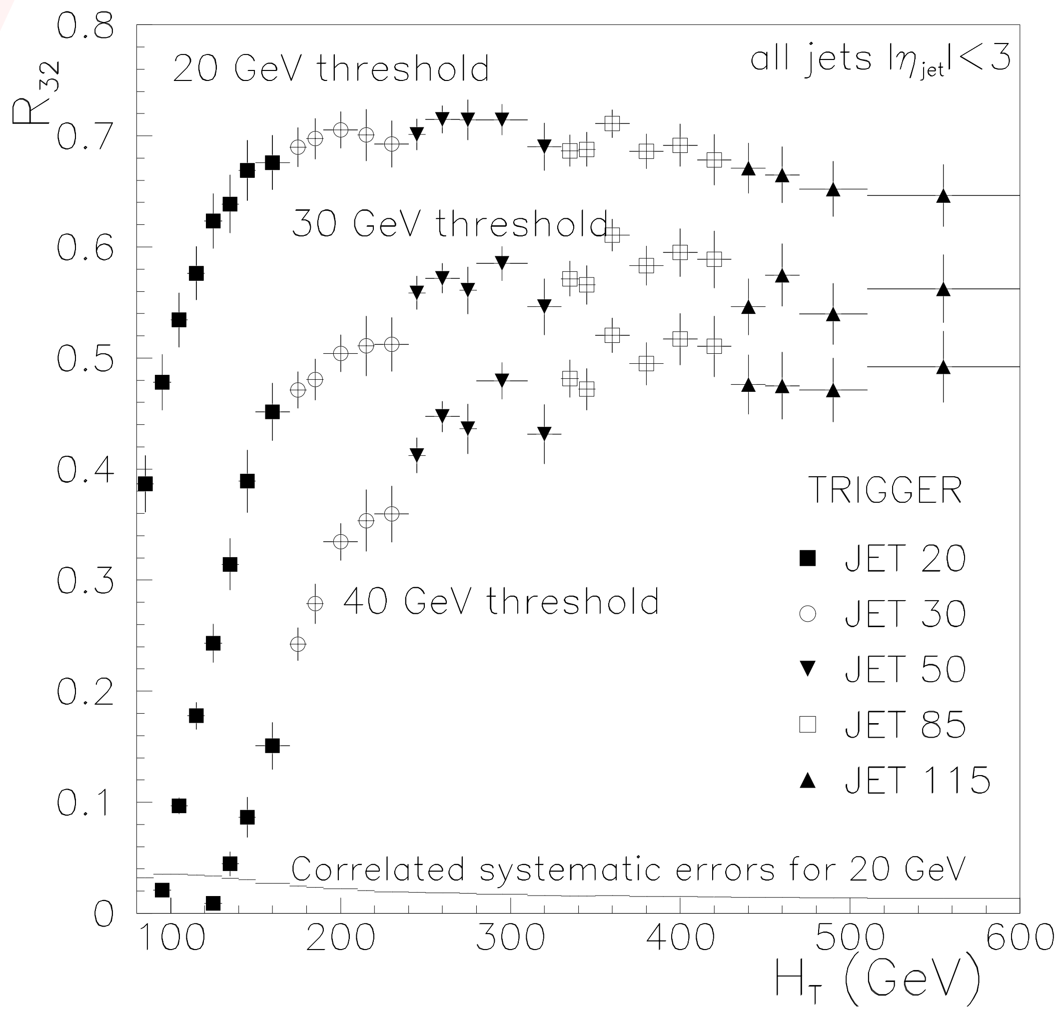
Inclusive R_{32}

Features:

- Rapid rise H_T<200GeV
- Levels off at high H_T

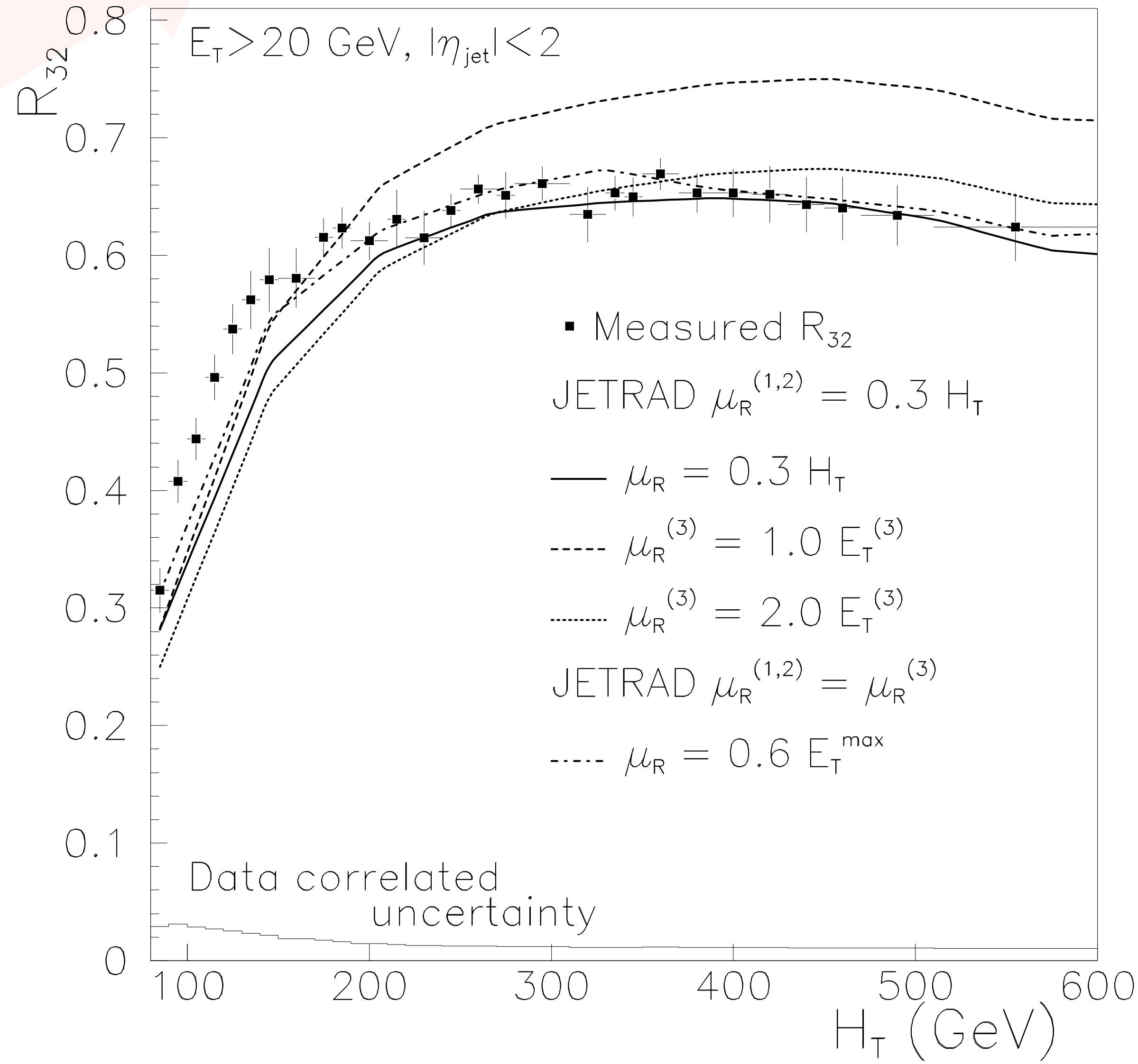
Interesting:

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



R_{32} Sensitivity to Renormalization Scale

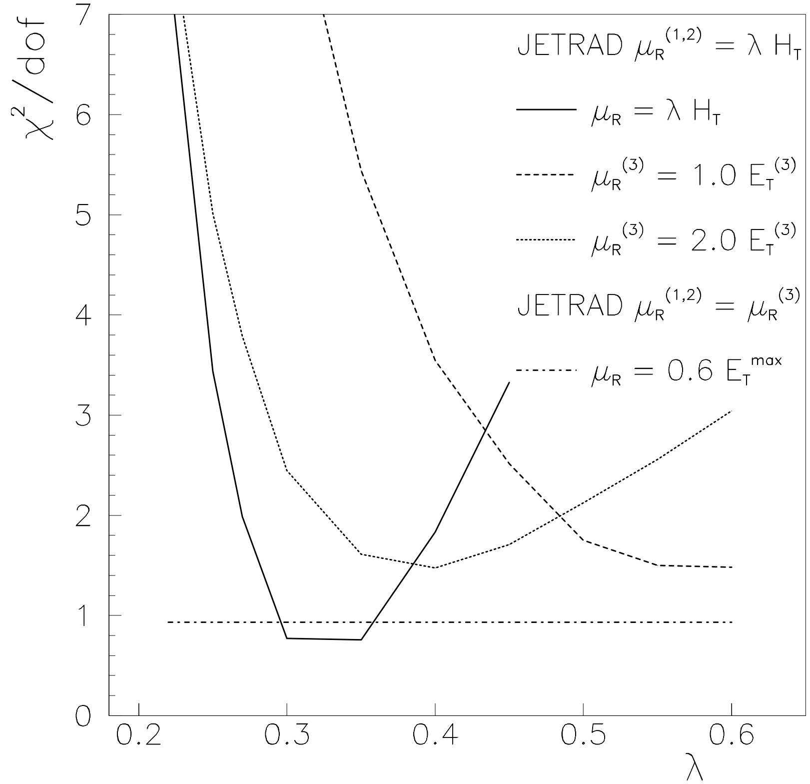
E_T>20 GeV, η<2 show greatest sensitivity to scale



R_{32} Results

- Jet emission best modeled using the same scale
  - i.e. the hard scale for all jets
- Best scale is that which minimizes χ^2 for all criteria
  - $\mu_R = 0.6 E_T^{max}$, for 20 GeV thresholds
  - $\mu_R = \lambda H_T$, $\lambda \approx .3$ for all criteria
- Introduction of additional scales unnecessary.

$E_T > 20$ GeV, $\eta < 2$



PRL 86, 1955 (2001)

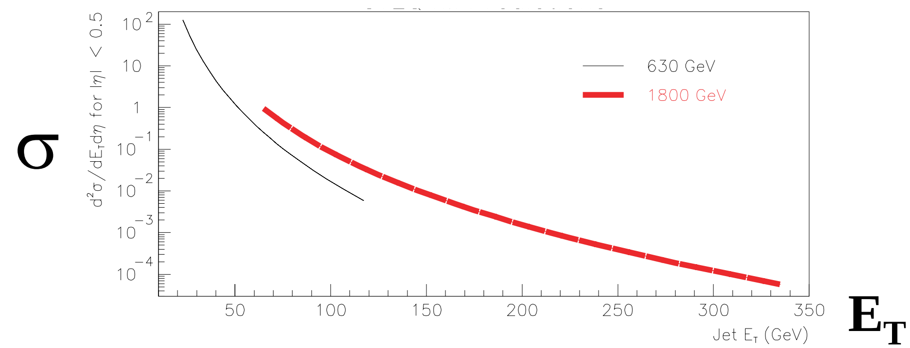
DØ Cross Section Ratio: $\sigma(630)/\sigma(1800)$ vs x_T

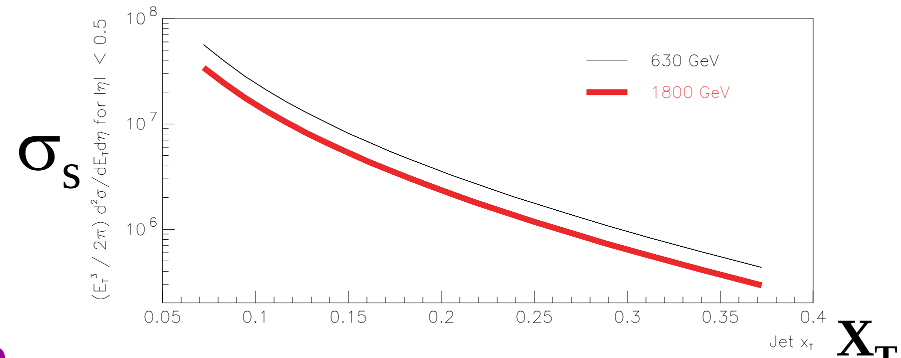
Ratio of the scale invariant cross sections :

$$\sigma_s = (E_T^3/2\pi)\,(d^2\sigma/dE_T d\eta)$$

$$\text{vs} \qquad X_T = E_T / (\sqrt{s}/2)$$

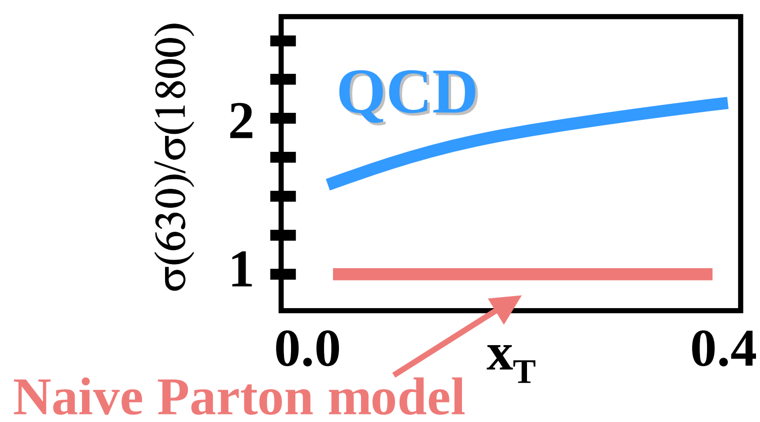
at different cm energies (630 and 1800 GeV)





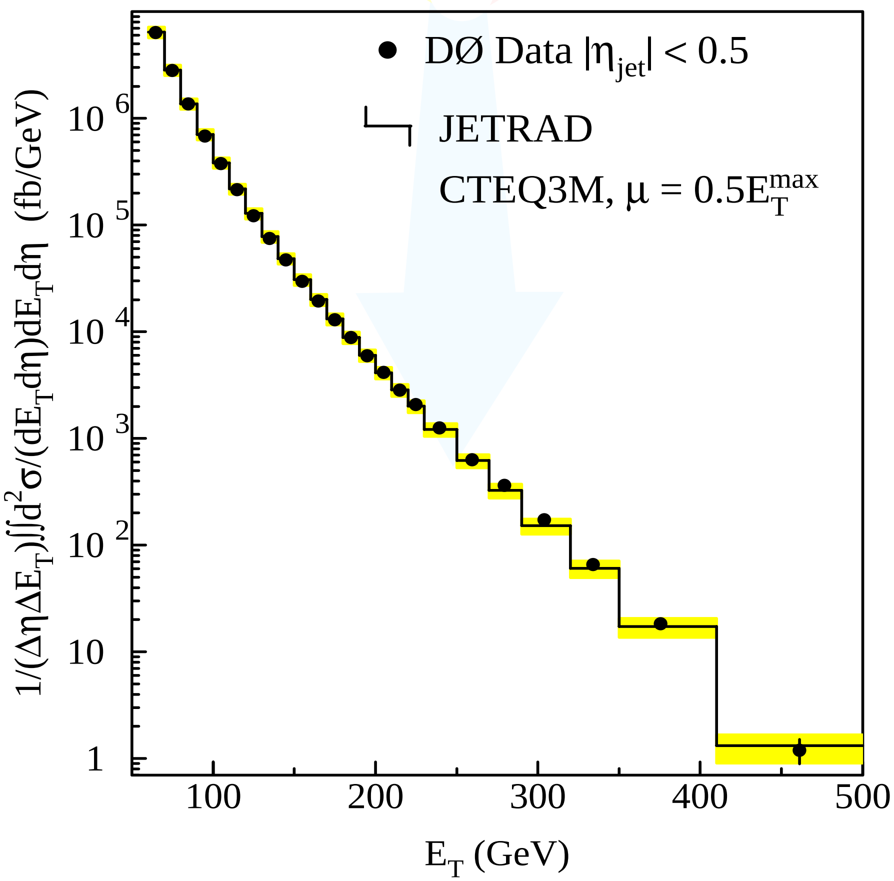
Ratio allows substantial reduction in uncertainties (in theory and experiment). May reveal:

- **Scaling behavior**
- **Terms beyond LO (α_s^2)**

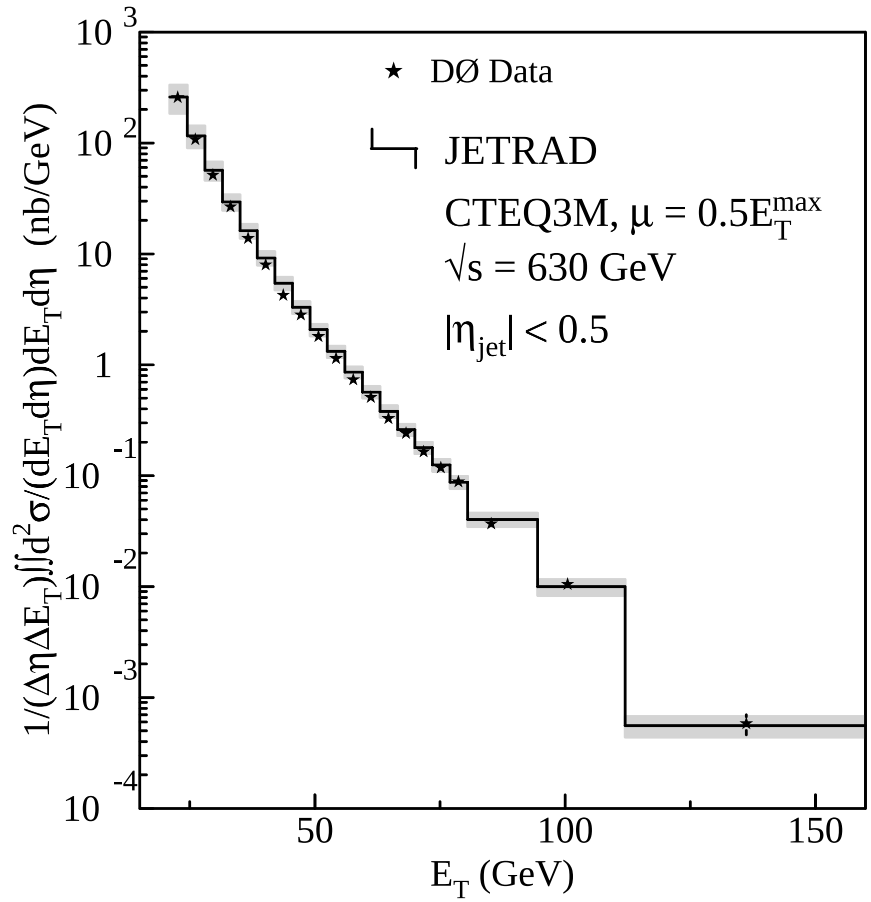


DØ Inclusive Cross Section

$\sqrt{s}$ = 1800 GeV



$\sqrt{s}$ = 630 GeV

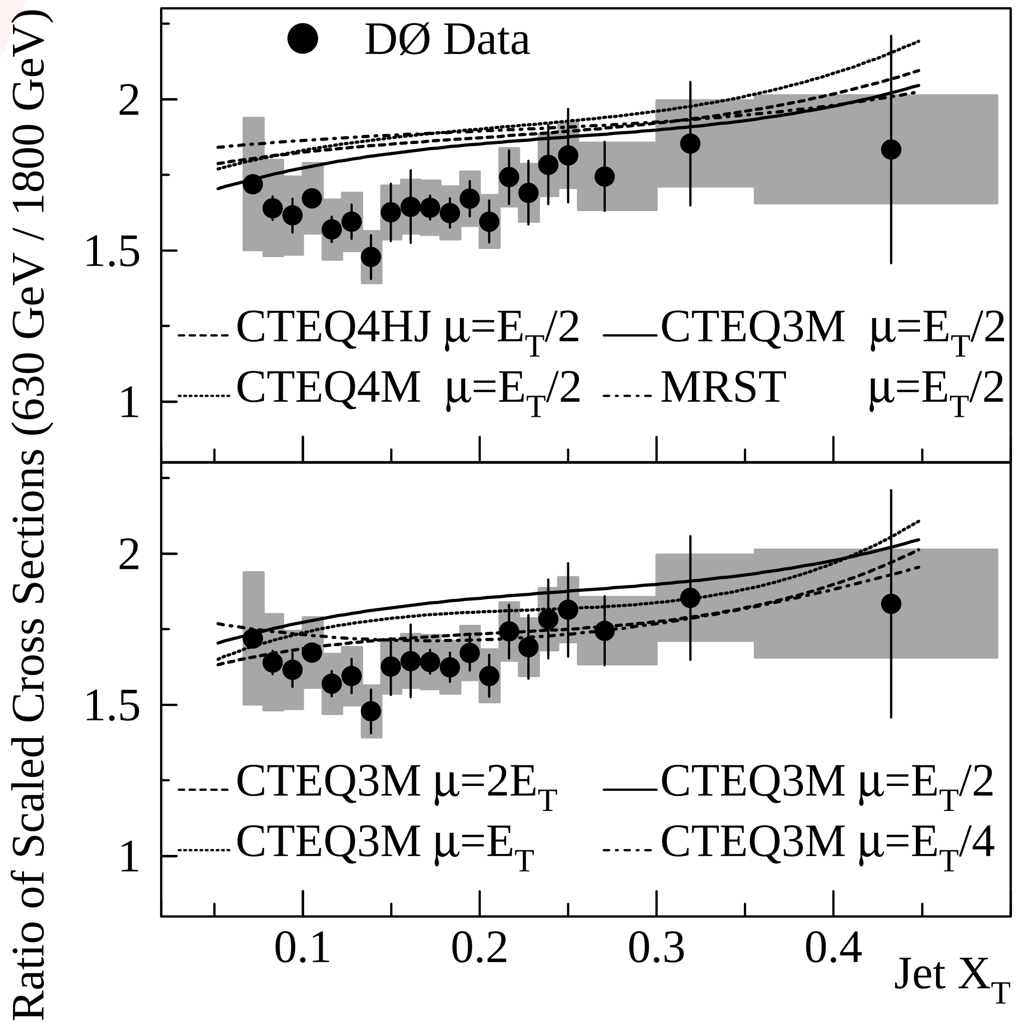


Cross Section Ratio

$\sigma(630)/\sigma(1800)$ is 10-15% below NLO QCD predictions

- **Top plot:** varying choice of pdf has little effect
- **Bottom plot:** varying μ_R scale is more significant
- Better agreement where μ_R different at 630 and 1800 (unattractive alternative !)

Higher order terms will provide more predictive power!



Published in PRL 86, 2523 (2001)

CDF DiJet

Provides precise information about initial state partons

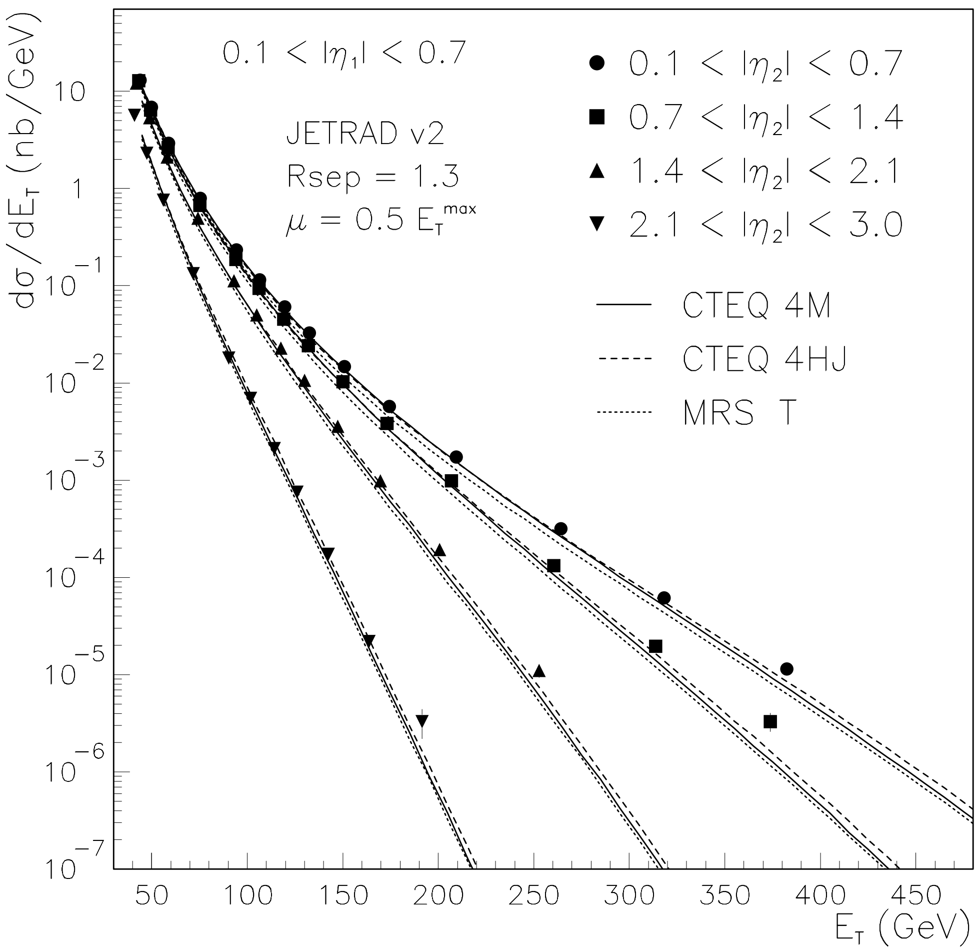
Cone of R=0.7

Both Jets: E_T>10 GeV

Jet 1: 0.1<|η|<0.7

Jet 2: Four η regions

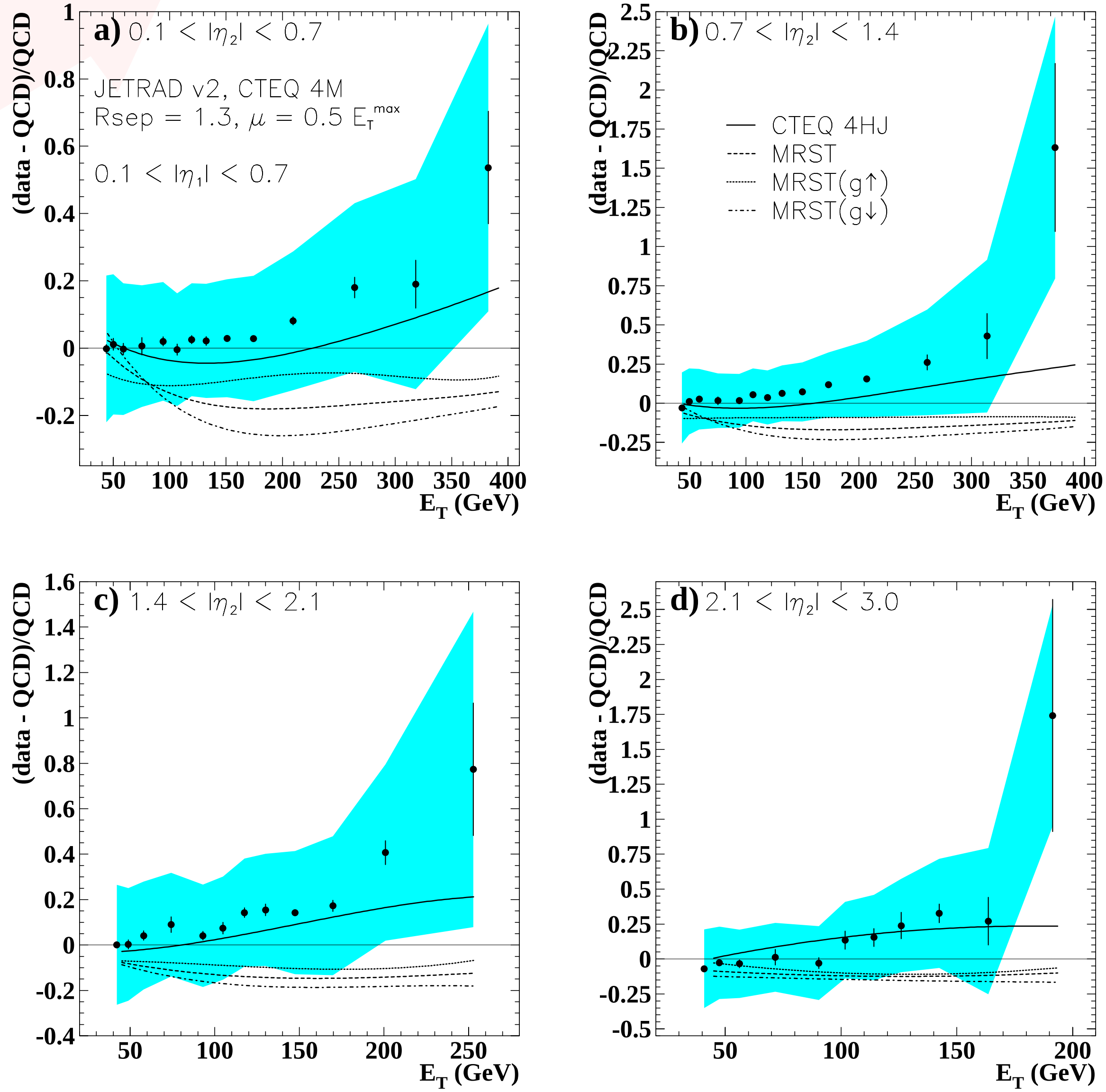
0.1<|η|<0.7
0.7<|η|<1.4
1.4<|η|<2.1
2.1<|η|<3.0



CDF DiJet Cross Section

PDF	χ^2/dof
MRST	2.68
MRST↑	3.63
MRST↓	4.49
CTEQ4M	2.88
CTEQ4HJ	2.43

All < 1% Probability

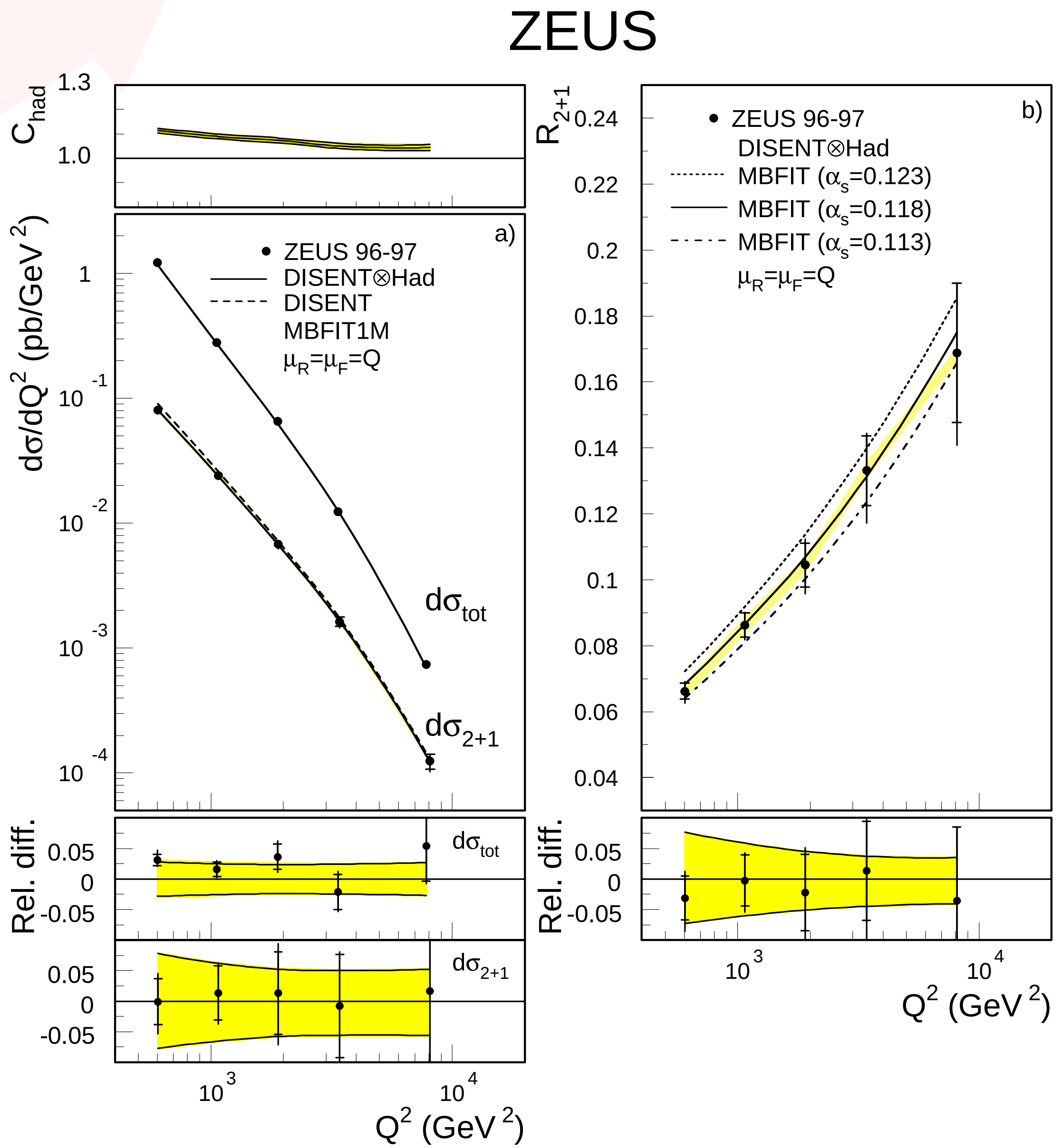


ZEUS DiJet

k_T algorithm used

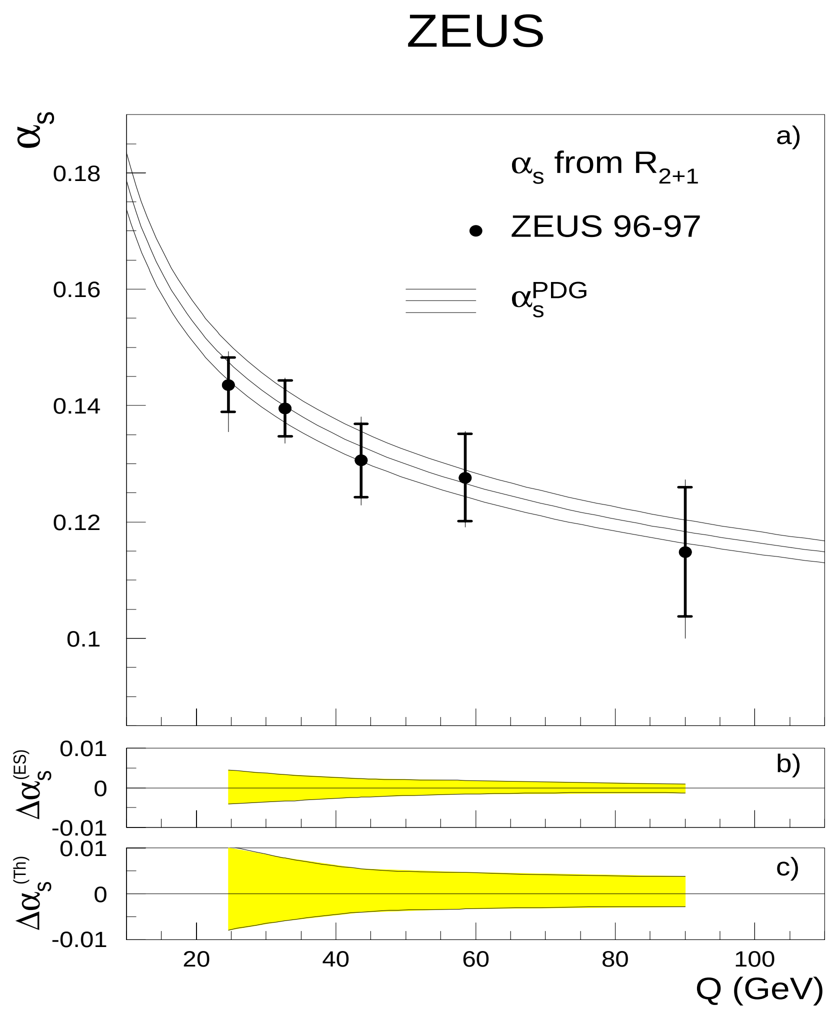
$$R_{2+1} = \frac{d\sigma_{2+1}/dQ^2}{d\sigma_{tot}/dQ^2}$$

- E_T > 8 GeV (leading)
- E_T > 5 GeV (other)
- $-1<\eta<2$ (leading)
- $470<Q^2<20000$ GeV^2



Phys Lett B507, 70 (2001)

ZEUS DiJet



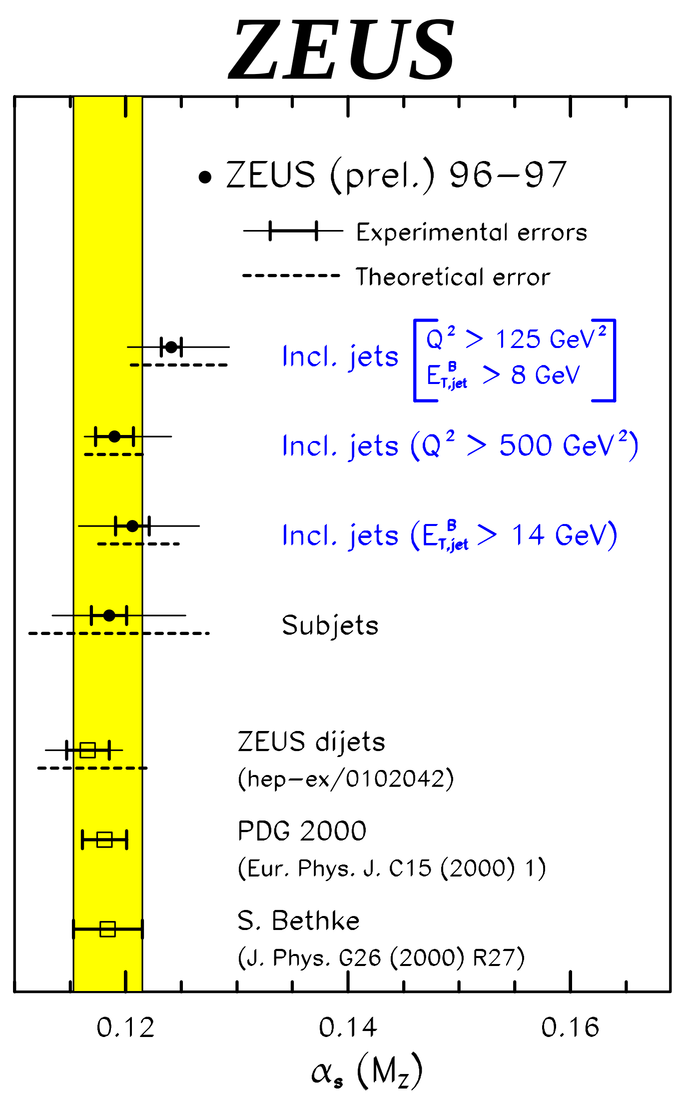
R_{2+1} parameterized as:

$$R_{2+1}(M_Z) = A_1\alpha_s(M_Z) + A_1\alpha_s^2(M_Z)$$

$$\alpha_s(M_Z) = 0.1166 \pm 0.0019\,(\text{stat})\ {}^{+0.0024}_{-0.0033}\,(\text{exp})\ {}^{+0.0057}_{-0.0044}\,(\text{th})$$

ZEUS α_s Summary

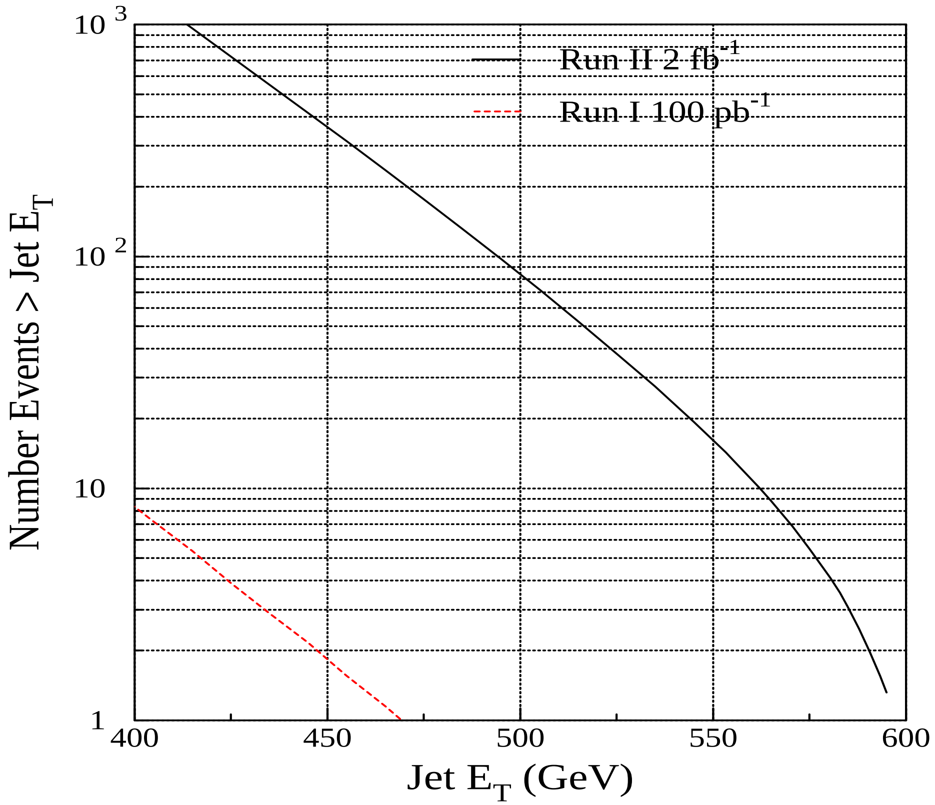
- Dijets has lowest total error of all Zeus measurements.
- All measurements consistent with PDG value of 0.1185±20



Tevatron Run II

Run II: E_{cm} = 1.96 TeV, $\int\mathcal{L} \rightarrow$ 2fb^{-1}
expect: ~100 events E_T > 490 GeV
and ~1K events E_T > 400 GeV

Run I: E_{cm} = 1.8 TeV, $\int\mathcal{L} \approx$ 0.1fb^{-1}
yielded 16 Events E_T> 410 GeV



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

Conclusions from Jet Physics

- Growing sophistication in jet physics analysis
  - Error matrices
  - New jet algorithms
  - Better corrections
  - PDF refinements
- Results generally agree with NLO QCD and PDF's
  - Cross section measurements will continue to refine PDF's
  - α_s measurements agree with PDG
  - Low E_T physics still require theoretical refinements
- Jet physics should continue to provide fruitful developments
  - High E_T region can reveal compositeness and other new physics
  - Low E_T region reveals soft parton distributions in proton
  - NNLO and other theoretical refinements needed
  - Results needed for "discovery" measurements