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RECENT RESULTS ON JET PHYSICS

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ABSTRACT

The study of jets gives insight into Quantum Chromodynamics and serves as a tool to search for physics not described by the Standard Model. Measurements of high energy jet cross sections probe the structure of protons and look for signatures of parton structure. Recent results on jet structure and jet cross sections from the Tevatron and HERA are discussed in this talk. Measurements of subjet structure and cross section ratios are reported. All measurements are compared with leading-order or next-to-leading-order QCD and with current parton distribution functions.

1 Introduction

Results on jet physics and α_s that have been published or have been released as preliminary results in the last six months are reviewed in these proceedings.

Because there are far too many results released to discuss them all, and because the majority of recent results have come from accelerators with initial state protons at the Tevatron and HERA, the discussion is limited to collaborations at these two accelerators. First some of the developments in jet analysis and some experimental details will be described. Then, new results regarding jet characteristics will be discussed. Finally, many cross section measurements will be presented.

2 Theoretical and Experimental Considerations

2.1 Jet Analysis Developments

There have been several recent developments in experimental and theoretical Quantum Chromodynamics (QCD) that have led to improved comparisons between the experimental results and theoretical predictions. Theoretical predictions are nearing a new level of sophistication in two key areas. First, a great deal of work has focused on estimating the uncertainties in the parton distribution functions (PDFs). Currently, an experimenter performs a comparison between data and theory by using many different PDF sets. This is not a valid measure of the uncertainty of the predictions. Accurate estimations of the PDF uncertainties will assist in meaningful comparison between data and theory. Second, there has been some recent progress toward next-to-next-to-leading order calculations (NNLO) of jet cross sections. There have also been improvements in experimental techniques. Collaborations at the Tevatron are providing a meaningful estimate of systematic uncertainty in the form of a covariance matrix. By quantifying the correlations in the error matrix, it is possible to make meaningful χ^2 comparisons between the data and predictions, and to quantify the level of agreement between the two. Other refinements are being developed which will standardize jet algorithms and definitions, making it easier to compare results from different experiments. These developments are not yet complete, but they are already having an impact on the quantitative comparison of data and theory. They have the potential of transforming the way that QCD is quantitatively tested. Although they will not play a major role in the remainder of this paper, they serve as a context to place these and future results.

3 Jet Definitions

Experimental collaborations at the Tevatron have historically used a simple cone algorithm to define jets. A cone algorithm uses 4-vectors to find the center of a jet, then defines the jet as all particles in a cone of radius $\mathcal{R} = \sqrt{(\Delta\phi^2) + (\Delta\eta^2)}$ around that central axis, where ϕ is the azimuthal angle and $\eta = -\ln[\tan(\theta/2)]$ where θ is the polar angle with respect to the proton beam. Complications arise in this algorithm because jets that overlap must be either merged or split. In addition, a theoretical parameter, $\mathcal{R}_{\rm sep}$, is used to decide if different partons should be merged into one experimentally measured jet. For most analysis, the partons are merged if $\mathcal{R}_{\rm sep} < 1.3$.

Another algorithm for reconstructing jets, used for many years at e^+e^- colliders, has recently been adopted for use at Fermilab. This k_T algorithm [1] has many advantages compared to the cone algorithm. It is infrared safe, it can be applied in the same manner to partons, particles, energy clusters, or tracks, and it allows subjets to be defined within a jet. The algorithm combines particles, or energy clusters, into a single entity if their relative k_T is smaller than some scaling parameter, D, where $D = 1.0$ in the current analysis. This algorithm also allows subjets within a jet to be defined with a resolution parameter $y_{\rm cut}$, which prevents clusters with relatively large k_T separation, but still within D, from being merged.

Reconstructed jet energies must be corrected for a number of effects. The calorimeter response function restores the energy lost in cracks and uninstrumented regions of the calorimeter, as well as lost due to the non-linearity of the detector. Also, the average energy deposited from noise and the underlying event must be removed from the jet energy. Finally, energy which is lost outside the cone of $R = 0.7$ must be restored. These corrections are collectively referred to as the jet energy scale.

4 Jet and Event Quantities

The number of jets produced in $p\overline{p}$ events is measured by the DØ collaboration. [2] Jets are required to have $E_T > 20$ GeV. Predictions from QCD do a good job of predicting the number of jets at high E_T, but not such a good job at low E_T as shown in Fig. 1. Data is compared with the Pythia Monte Carlo, and is normalized to the 2-jet data above 40 GeV. This discrepancy may be due to the DGLAP showering model used by Pythia which suppresses events with a large number of jets, suggesting a higher order, or BFKL-augmented prediction might provide better agreement.

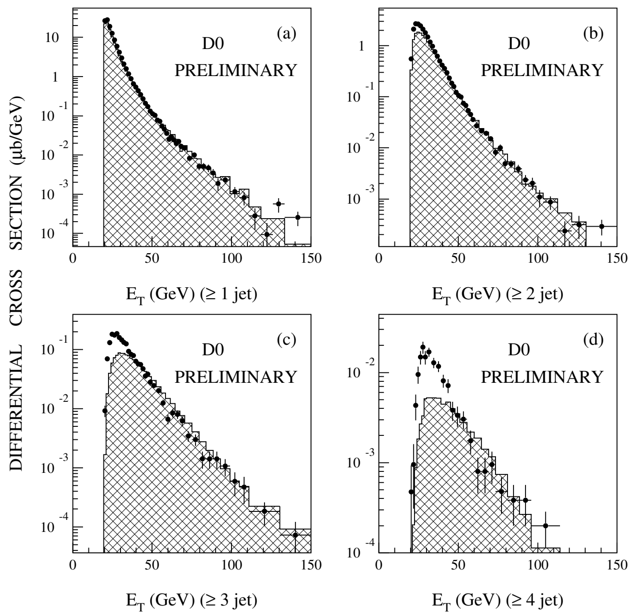

Figure 1: *Production cross sections for events with different numbers of jets. The energy of the highest E_T jet is plotted.*

The DØ collaboration has made a measurement of the subjet multiplicity using the k_T jet algorithm. [3] Perturbative and resummed calculations predict that gluon jets should have a higher subjet multiplicity than quark jets, on average. The subject multiplicity M can be expressed as

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

where f_g is the fraction of gluons in the final state determined from a Monte Carlo simulation, and M_g and M_Q are the extracted subjet multiplicities of gluon and quark jets, respectively. Monte Carlo studies indicate that M_g and M_Q are independent of $\sqrt{s}$, and this result is used to combine data taken at

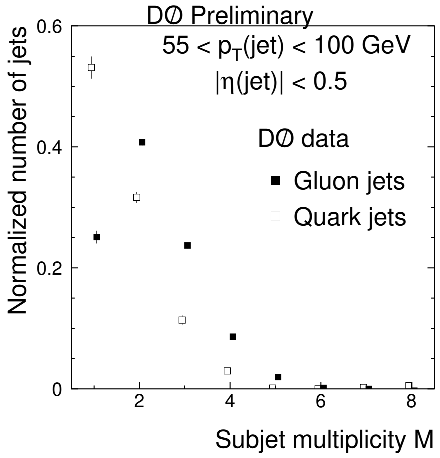

Figure 2: *Subjet multiplicities for quark and gluon jets.*

$\sqrt{s} = 630$ and 1800 GeV. The subjet multiplicity measured in the data is shown in Fig. 2. Taking the ratio, DØ finds

$$R = \frac{\langle M_g \rangle - 1}{\langle M_Q \rangle - 1} = 1.85 \pm 0.15 \text{ (stat)} \ {}^{+0.22}_{-0.16} \text{ (sys)}$$

which agrees with the prediction from the Herwig Monte Carlo of 1.91 ± 0.16.

The subjet multiplicity has also been measured by the Zeus collaboration. [4] The data is unfolded using the Ariadne Monte Carlo and the comparison of data and Monte Carlo is made at the hadron level. The average number of subjets $\langle n_{\rm sbj} \rangle$ in each jet is determined from the data. As Fig. 3 shows, this quantity is sensitive to the strong coupling α_s. The value extracted from this analysis is

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

where the major systematic uncertainty are from the jet energy scale and the hadronization model, and the major theoretical uncertainty is from the variation of the renormalization scale.

5 Cross Sections

Measurements of the the jet production cross section have the potential of answering many questions regarding QCD such as: How well are PDFs known?

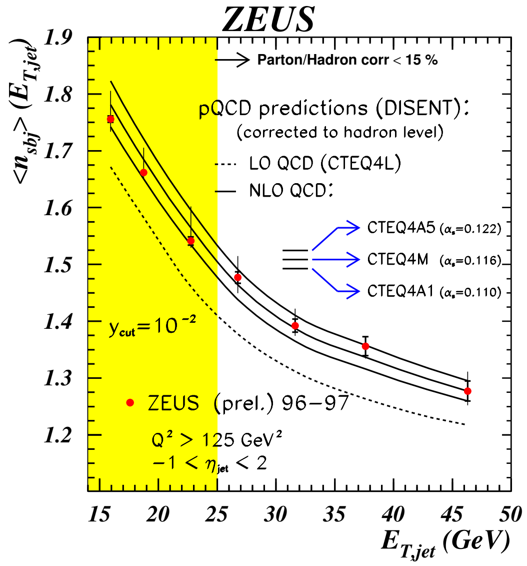

Figure 3: *Average number of subjets per jet as a function of E_T of the jet.*

Are quarks composite particles? What are the appropriate scales for QCD? What is the value of α_s? What is the soft parton structure of the proton? Are NLO calculations sufficient? In addition, QCD serves as a background when searching for signals from unknown physics, so QCD cross sections must be well known in the search for any new physics. Consequently, it is extremely important to accurately measure jet production cross sections.

Experimentally, cross section measurements basically count the number of events of a certain type using corrections for experimental inefficiencies. The triple differential cross section for jet production is written as,

$$\begin{aligned}\frac{E\ d^3\sigma}{dp^3} &= \sum x_1 F(x_1) x_2 F(x_2) \frac{d\sigma}{dt}(ab \to cX) \\ &= \frac{1}{2\pi E_T} \frac{N}{\Delta E_T\ \Delta\eta\ \varepsilon\ \mathcal{L}}\end{aligned}$$

where the first term shows the theoretical cross section including the PDFs ($F(x)$), the fraction of momentum carried by the parton (x), and the parton hard scattering ($\frac{d\sigma}{dt}$), and the second term shows the experimentally determined cross section including the number of found events (N), the detector and selection efficiency (ε), and the integrated luminosity ($\mathcal{L}$).

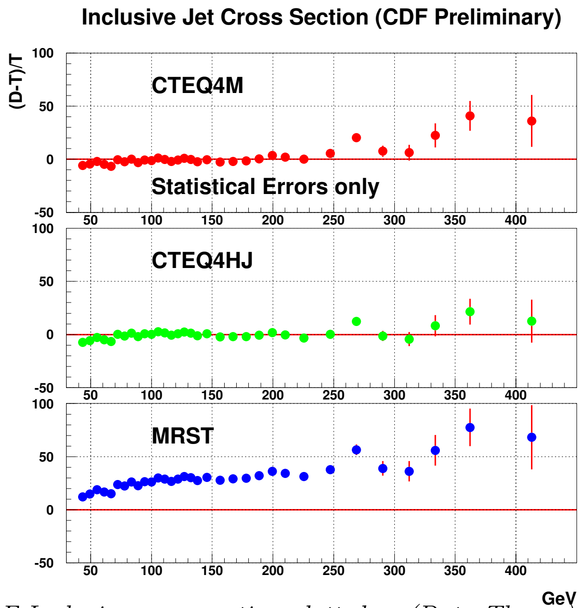

Figure 4: *CDF Inclusive cross section plotted as (Data-Theory)/Theory. of the jet.*

The CDF collaboration has recently completed a measurement of the inclusive jet cross section [5] for the pseudorapidity region $01. < |\eta| < 0.7$ using a cone algorithm to define jets. The results are in agreement with current PDFs as shown in Fig. 4. The default MRST predictions are certainly not normalized correctly. We will see this effect in a number of analyses in these proceedings. However, χ^2 fits for MRST are comparable to those for CTEQ because the correlated uncertainty on the data allows the overall normalization to fluctuate.

The inclusive jet cross section using a cone algorithm has also been measured by the DØ collaboration. [6] This result covers a large region of phase space because it measures the cross section in five pseudorapidity regions as shown in Fig. 5. A plot of (data-theory)/theory for two different PDFs is shown in Fig. 6. The largest systematic uncertainty comes from the jet energy scale. The MRST is not correctly normalized but the probability that the theory matches the data, determined from a complete covariance matrix, does not rule out MRST. The χ^2 probabilities for these, and other PDFs are shown in Table 1. The results from this analysis are currently being incorporated into the latest global PDF fits.

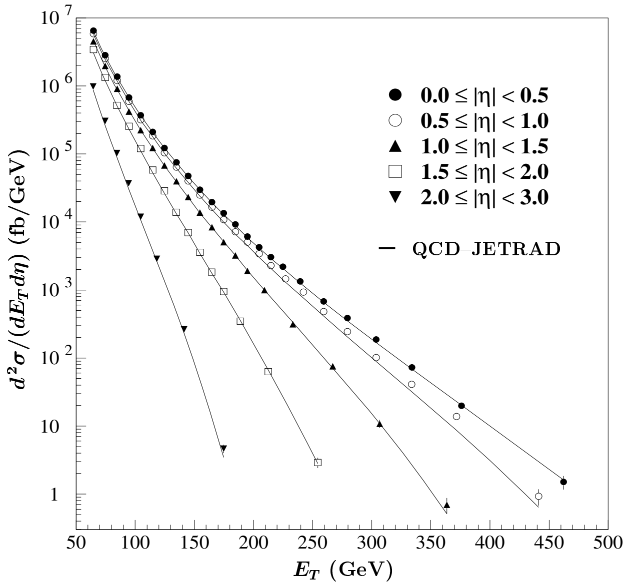

Figure 5: *DØ inclusive jet cross section.*

Table 1: *Probabilities that theory matches data for the DØ inclusive jet measurement using different PDFs.*

PDF	χ^2	χ^2/dof	Prob
CTEQ3M	122	1.35	0.01
CTEQ4M	92	1.03	0.41
CTEQ4HJ	59	0.66	0.99
MRST	114	1.26	0.05
MRSTgD	156	1.73	¡0.01
MRSTgU	85	0.95	0.63

The DØ collaboration has also measured the inclusive jet cross section using the k_t algorithm to find jets. [7] Comparison of data and theory is shown in Fig. 7. No PDF is ruled out based on the χ^2 probabilities of 31% for MRST,

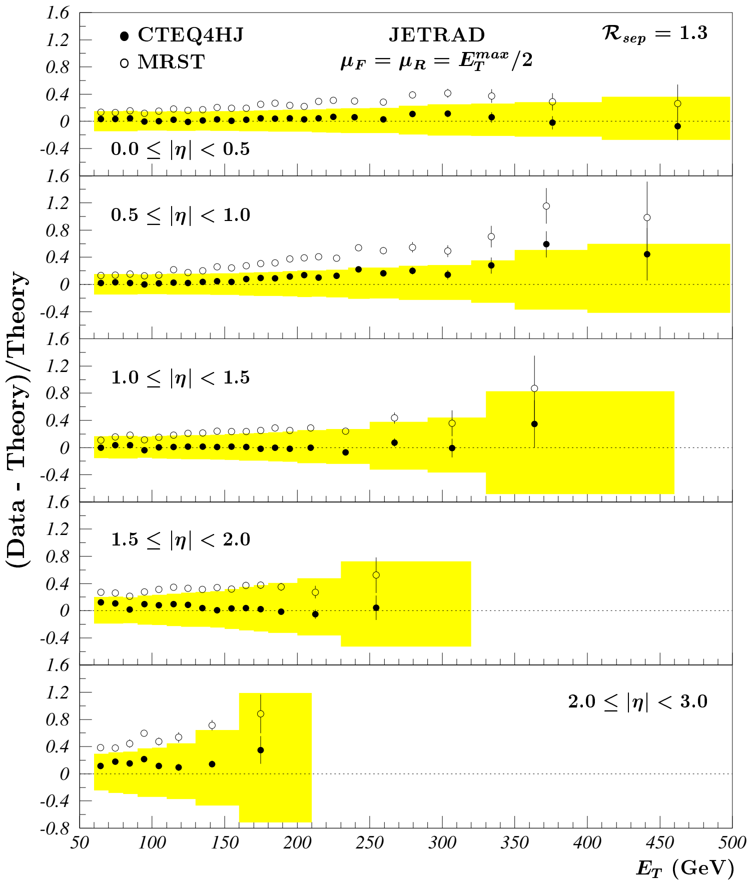

Figure 6: *DØ inclusive jet cross section compared to different PDFs.*

15% for CTEQ4M, and 29% for CTEQ4HJ.

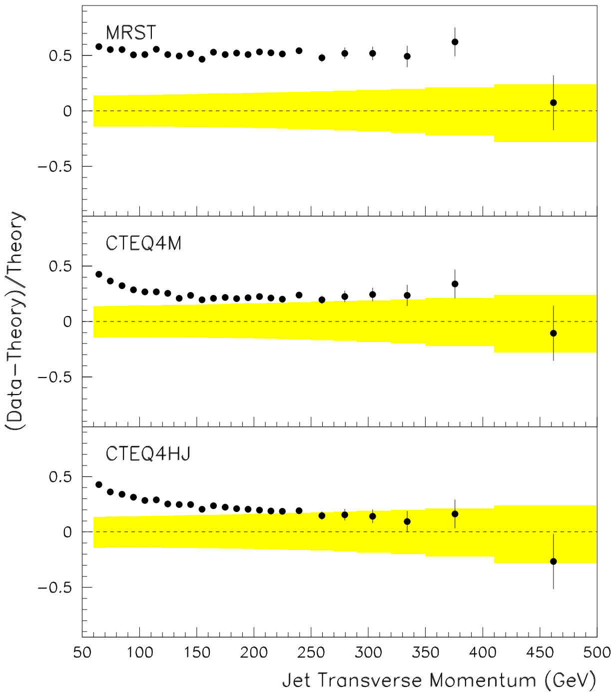

Figure 7: *DØ inclusive jet cross section using k_T algorithm compared to different PDFs.*

The measured jet cross section can be used to extract the strong coupling, α_s. To third order in α_s, the cross section can be written as

$$\frac{d\sigma}{dE_T} = \alpha_s X^0[1 + \alpha_s k_1]$$

where X^0 and k_1 are determined from JETRAD. The CDF collaboration has extracted the value of α_s using this formalism and an $\overline{\mathrm{MS}}$ scheme. [8] Jets are found with a jet cone algorithm with $R_{\mathrm{sep}} = 1.3$, and α_s is extracted in 33 different E_T regions between 30 and 450 GeV. The largest experimental uncertainties in this measurement come from modeling the underlying event at low E_T and from the fragmentation model and calorimeter energy scale at high E_T. Theoretical uncertainties of about 5% each come from adjusting the renormalization scale between $E_T/2$ and $2E_T$, and from changing the PDF. The measured value of α_s at M_Z is

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

The Zeus collaboration has also measured the inclusive jet cross section and extracted a value for α_s from the measurement. [9] Fig. 8 shows the cross section as a function of pseudorapidity. The theory does not agree with the data for points above ≈ 0.5. Using the full phase space covered by the Zeus measurement, α_s is measured to be

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

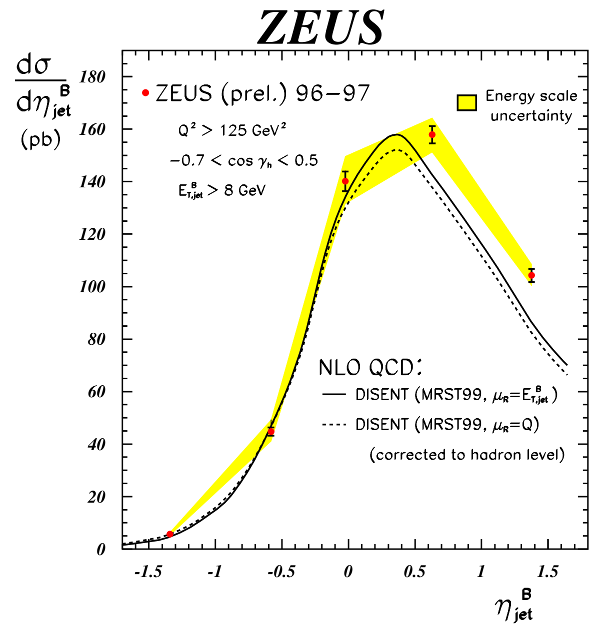

Figure 8: *The inclusive jet cross section.*

The number of jets produced in $p\overline{p}$ collisions is a function of the number of hard gluons radiated. Measuring the ratio of three jet production to two jet production investigates QCD gluon radiation and minimized experimental

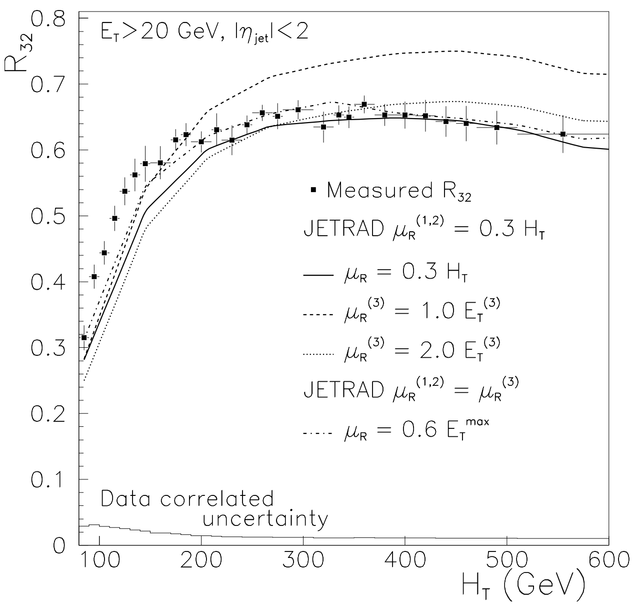

Figure 9: *The ratio of 3 jet production to 2 jet production in the DØ detector.*

systematic uncertainties. The three jet cross section also allows the opportunity to investigate scale differences at the gluon emission vertex. The DØ collaboration has measured the ratio

$$R_{32} = \frac{\sigma_3(p\overline{p} \rightarrow 3 + \mathrm{jets})}{\sigma_2(p\overline{p} \rightarrow 2 + \mathrm{jets})}$$

as a function of H_T where H_T is the sum over the E_T of each jet in the event. [10] Four different selections are used to identify jets. Three of them require $|\eta| < 3$ with E_T of each jet greater than 20, 30, and 40 GeV, respectively. The fourth selection requires $|\eta| < 2$ with E_T of each jet greater than 20. The latter selection shows the greatest sensitivity to the renormalization scale and is plotted in Fig. 9. The curves in the figure show the effect of changing the renormalization scale. Because there are strongly correlated point-to-point uncertainties in the data, satisfactory agreement exists between the theory and the data even though the curves do not visually overlap all of the data points. In general, the scale prescriptions which assign the same scale to all three jets give a better fit than those that assign a softer scale to the softest jet.

The ratio of jet cross sections at different center-of-mass energies provides

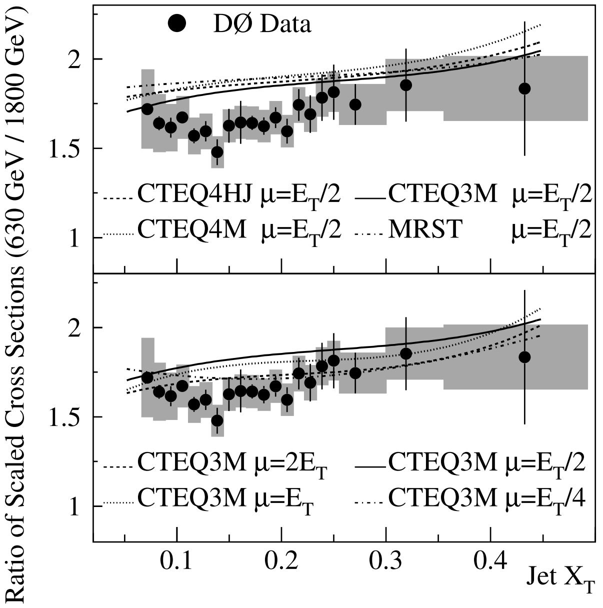

Figure 10: *The ratio* $\sigma_s(630GeV)/\sigma_s(1800GeV)$.

a powerful tool for probing QCD. The ratio allows substantial reduction in theoretical and experimental uncertainties due to cancellations in correlated systematic errors which emphasizes the role of scaling behavior and higher order contributions to the cross section. The DØ collaboration measures the ratio of the scaled dimensionless cross section $\sigma_s = (E_T^3/2\pi)(d^2\sigma/dE_T d\eta)$ as a function of $x_T = E_T/(\sqrt{s}/2)$. [11] Fig. 10 shows the ratio $\sigma_s(630GeV)/\sigma_s(1800GeV)$. The plots show that there is a discrepancy between NLO QCD and data in the region between $.1 < x_T < .25$. As shown in the top plot, changing the PDF used does has little effect on correcting this discrepancy. The bottom plot shows that varying the renormalization scale has a larger effect, but does still not bring the data and theory into complete agreement.

A measurement of the production of two jets (dijet production) provides precise information about the initial state partons. The CDF collaboration has made a measurement of the dijet production cross section using a cone of $R = 0.7$ to define the jets. [12] Each jet must have $E_T > 10$ GeV. The jet with the most energy is constrained to have $0.1 < |\eta| < 0.7$, while the other jet is

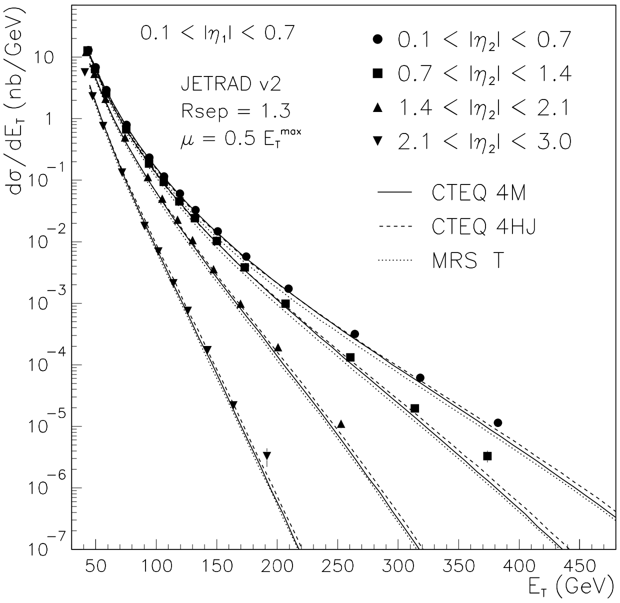

Figure 11: *The CDF di-jet production cross section.*

found in one of four pseudorapidity regions: $0.1 < |\eta| < 0.7$, $0.7 < |\eta| < 1.4$, $1.4 < |\eta| < 2.1$, or $2.1 < |\eta| < 3.0$. The cross section is shown as a function of E_T in Fig. 11.

The Zeus collaboration has made a measurement of the dijet production cross section at HERA. [13] The leading jet is required to have $E_T > 8$ GeV and the other jet must have $E_T > 5$ GeV. Results of this measurement is shown in Fig. 12 as R_{2+1}, the ratio of the production cross section of two jet events to the total jet production cross section. The dijet measurement can be used to extract the value of α_s. The cross section ratio is parameterized as $R_{2+1}(M_Z) = A_1\alpha_s(M_Z) + A_2\alpha_s^2(M_Z)$. A fit to the data is shown in Fig. 13 and the value extracted for α_s is

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

These proceedings have included a measurement of $\alpha_s(M_Z)$ using three different Zeus analyses: inclusive jet production, subjets, and dijet production. A synopsis of those results, along with the PDG value of α_s is shown in Fig. 14.

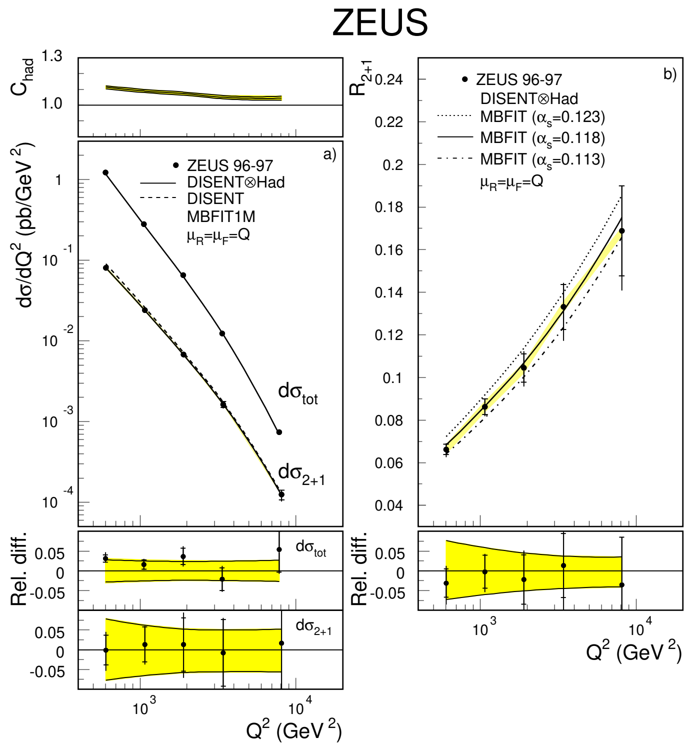

Figure 12: *Production cross section for dijet events.*

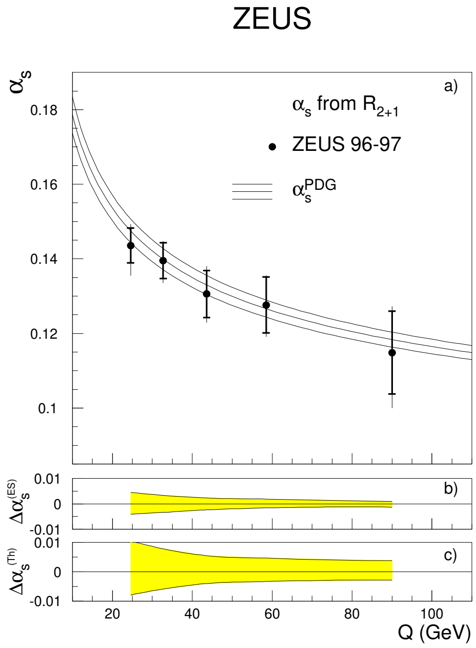

Figure 13: *The value of α_s extracted from the Zeus dijet measurement.*

6 Conclusions

There has been a growing sophistication in jet physics analysis over the last few years. Improvements include the use of complete error analysis including correlations in the systematic uncertainty when comparing data and theory, the use of new jet algorithms, better corrections to the jet energies, and refinements to the PDFs. This growing sophistication has brought the study of jets to a higher level of precision than ever before.

Results that have been produced in the last six months have been discussed. In general, the results agree with NLO QCD and currently available PDFs. Cross section measurements are being used to refine PDFs, particularly in the high E_T region. A few minor discrepancies between data and NLO QCD exist in the very low E_T region for multiple jet production, and in the ratio of the jet production cross section at different center-of-mass energies.

The study of jets should continue to provide fruitful developments. The high E_T region has the potential of revealing quark compositeness or other unknown physics. The low E_T region can reveal soft parton distributions in

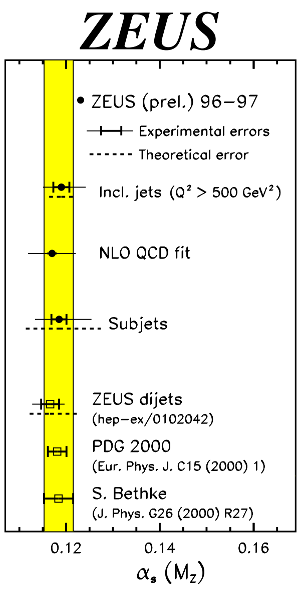

Figure 14: *Values of α_s measured by the Zeus collaboration.*

the proton. In addition, theoretical refinements such as next-to-next-to-leading order calculations and PDF improvements will be necessary for further precision studies. These studies are important, not only to probe QCD processes, but also because QCD serves as a background to possible new discoveries. A thorough understanding of QCD is necessary for future discoveries.

7 Acknowledgments

I would like to thank the DØ, CDF, and Zeus collaborations for the results used in this talk. In particular, I thank John Krane, Anwar Ahmad Bhatti, Frank Chlebana, and Matthew Wing for their assistance in pointing me to people, plots, and analyses useful for these proceedings and for the talk at Physics in Collisions, 2001. I also thank Soo-Bong Kim and the other organizers for a fine conference.

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