High p_T Jets at the Tevatron

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ABSTRACT: Results are presented from analyses of jet data produced in $p\overline{p}$ collisions at $\sqrt{s}$ = 630 and 1800 GeV collected with the DØ and CDF detectors during the 1994–95 Fermilab Tevatron Collider run. Various measurements of inclusive jet cross sections are presented and comapred with theoretical predictions in several different kinimatic regimes.

1. Introduction

Perturbative QCD (pQCD) predicts the production cross sections at large transverse momentum (p_T) for parton-parton scattering in proton–antiproton ($p\overline{p}$) collisions. The outgoing partons from the parton-parton scattering hadronize to form jets of particles. Calculations of high-p_T jet production involve the folding of parton scattering cross sections with experimentally determined parton distribution functions (PDFs). These predictions have recently improved with next-to-leading-order (NLO) QCD calculations [1, 2, 3] and improved PDFs [4, 5]. In this paper I present several measurements of jet cross sections at $\sqrt{s}$ = 630 and 1800 GeV collected with the DØ and CDF detectors.

In the analyses presented in this paper Jets are reconstructed using an iterative cone algorithm with a fixed cone radius of $\mathcal{R} = 0.7$ in η–ϕ space, where φ is the azimuth. At $\sqrt{s}$ = 1800 GeV these measurements probe the structure of the proton where the interacting partons carry a fraction of the proton momentum, $0.1 \lesssim x \lesssim 0.66$, for momentum transfers (Q) of $2.5 \times 10^3 \lesssim Q^2 \lesssim 2.3 \times 10^5$ GeV^2, where $Q^2 = E_T^2$ and is equivalent to a distance scale of 10^{-4} fm (see Fig. 1).

2. Inclusive Jet Cross Sections

The high p_T behaviour of the inclusive jet cross section has been the subject of much discussion over the last five years. The measured cross sections from CDF [6] and DØ [7]

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[†]The speaker would like to thanks the DØ and CDF collaborations for assistance in preparing this talk.

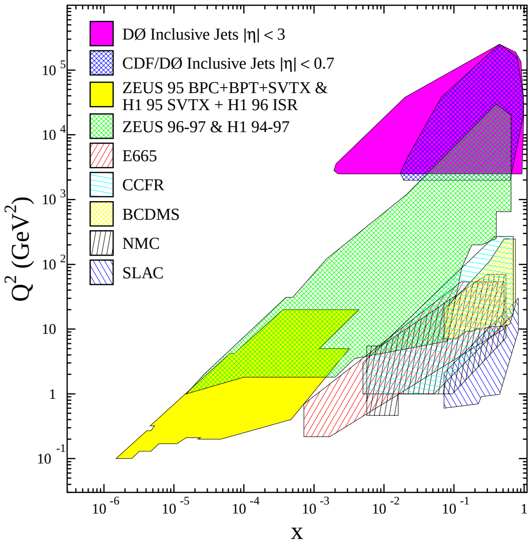

Figure 1: The x and Q^2 range of the data analyzed by the DØ and CDF experiments at $\sqrt{s} = 1.8$ TeV compared with the data used to produce PDFs.

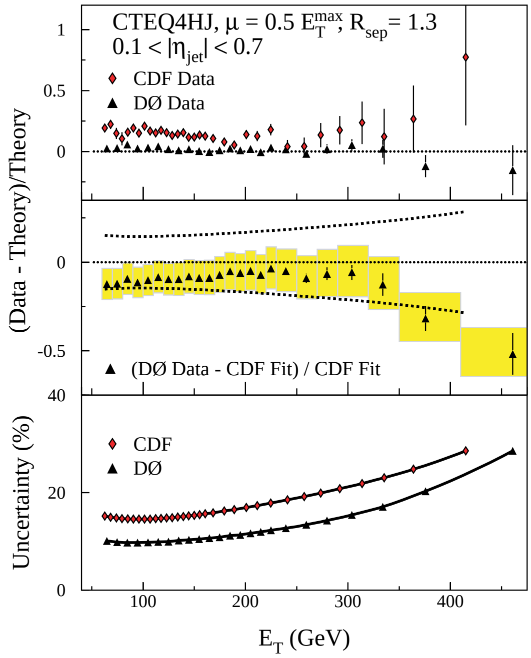

Figure 2: Inclusive Jet Cross Sections for $0.1 < |\eta| < 0.7$ from DØ and CDF compared to the theory prediction JETRAD with the CTEQ4HJ distribution.

are compared with NLO QCD calculations. In order to make direct comparisons with CDF, DØ carried out the analysis in the same rapidity interval as CDF ($0.1 < |\eta| < 0.7$). The results are shown in Fig 2 and show that the two data sets are consistent. A χ^2 comparison [7] between the DØ data and a fit to the CDF data has been carried out resulting in a χ^2 of 30.8 (probability of 16%), representing a reasonable agreement. A quantitative comparison between the theory predictions and the data are carried out they show that the two are consistent and that the prediction calculated with CTEQ4HJ PDF set are in the best agreement. Qualitatively the predictions and the measurements are in good agreement.

DØ has extended the measurement of the inclusive cross section up to $|\eta| < 3$ [8] in five different $|\eta|$ regions. The measurements along with statistical uncertainties, are presented in Fig. 3. The left hand panel of Fig. 3 shows the data compared with JETRAD predictions using the CTEQ4M and CTEQ4HJ PDFs on a linear scale. The error bars are statistical, while the shaded bands indicate one standard deviation systematic uncertainties. The theoretical uncertainties due to variations in input parameters are comparable

PDF	χ^2	χ^2/dof	Probability
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
MRSTg↓	155.52	1.73	<0.01
MRSTg↑	85.09	0.95	0.63

Table 1: The χ^2, χ^2/dof, and the corresponding probabilities for 90 degrees of freedom for various PDFs studied.

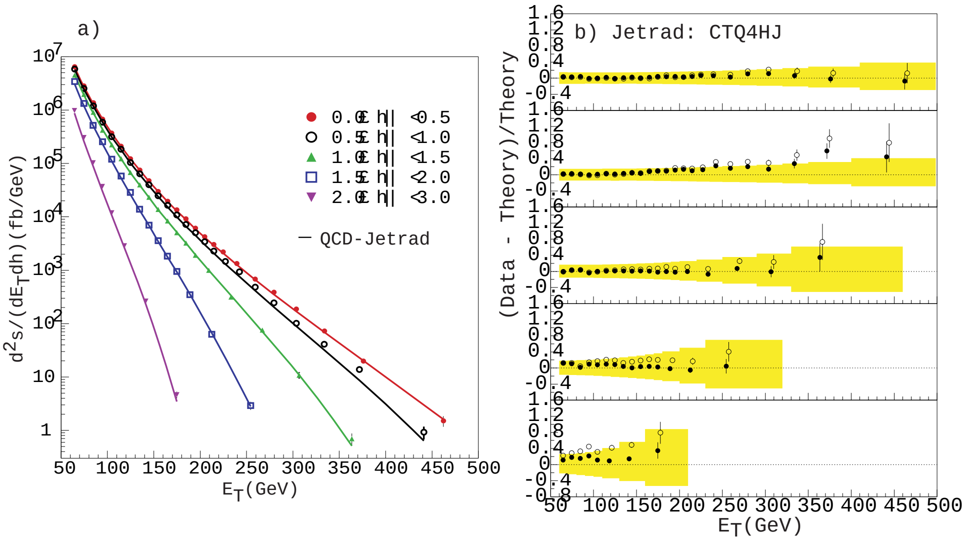

Figure 3: The Inclusive jet cross section measured as of $|\eta|$ compared with the theory prediction JETRAD with the CTEQ4HJ distribution. The right panel shows comparisons with the CTEQ4HJ (•) and CTEQ4M (◦) PDFs

to the systematic uncertainties. The predictions are in reasonable agreement for all of the $|\eta|$ regions. The data and theoretical predictions are compared quantitatively with a χ^2 test incorporating the uncertainty covariance matrix [8, 7] with the resulting χ^2 values given in Table 1 along with the probability of the prediction agreeing for 90 degrees of freedom (dof). In most cases the predictions are in good agreement with the experimental measurements. The data prefer predictions using the CTEQ4HJ, MRSTg↑, and CTEQ4M PDFs. The CTEQ4HJ PDF has enhanced gluon content at large x, favored by previous measurements of inclusive jet cross sections at $|\eta| < 0.7$, relative to the CTEQ4M PDF. The MRSTg↑ PDF includes no intrinsic parton transverse momentum and therefore has effectively increased gluon distributions relative to the MRST PDF. This measurement should place the most stringent constraints on the gluon PDF in the new global PDF fits by the MRST and CTEQ Collaborations.

2.1 Cross Section using the k_T Algorithm

The DØ experiment has also measured the inclusive jet cross section at $\sqrt{s} = 1800$ GeV using an alternative jet clustering algorithm, the k_T algorithm [9, 10]. This recombination algorithm successively merge pairs of nearby objects (partons, particles, or calorimeter towers) in order of increasing relative transverse momentum. A single parameter, D, which approximately characterizes the size of the resulting jets, determines when this merging stops. No splitting or merging is involved because each object is uniquely assigned to a jet. In this analysis a value of $D = 1.0$ is used. This value of D was chosen to give the same theoretical prediction at NLO using the JETRAD PROGRAM as obtained using the cone algorithm with $\mathcal{R} = 0.7$.

The resulting inclusive jet cross section is compared with JETRAD NLO theoretical predictions in Fig. 4. The predictions lie below the data by about 50% at the lowest $p_T$and by $(10 - 20)\%$ for $p_T > 200$ GeV. To quantify the comparison in Fig. 4, the fractional systematic uncertainties are multiplied by the predicted cross section, and a χ^2 comparison, using the full correlation matrix, is carried out. Though the agreement is reasonable (χ^2/dof ranges from 1.56 to 1.12, the probabilities from 4 to 31%), the differences in normalization and shape, especially at low p_T, are quite large. The points at low p_T have the highest impact on the χ^2. If the first four data points are not used in the χ^2 comparison, the probability increases from 29% to 77% when using the CTEQ4HJ PDF.

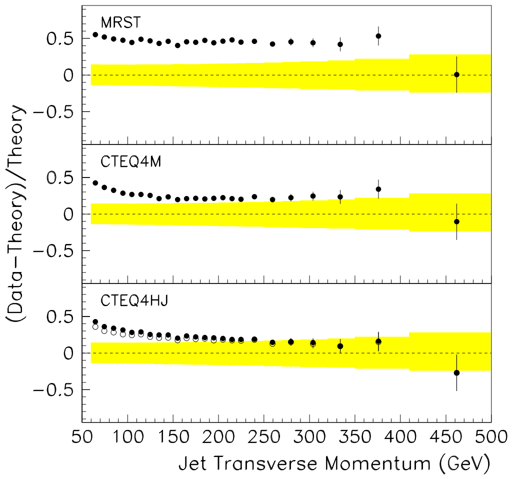

Figure 4: Difference between data and JETRAD pQCD, normalized to the predictions. The shaded bands represent the total systematic uncertainty. In the bottom plot a HERWIG hadronization contribution has been added to the prediction (open circles).

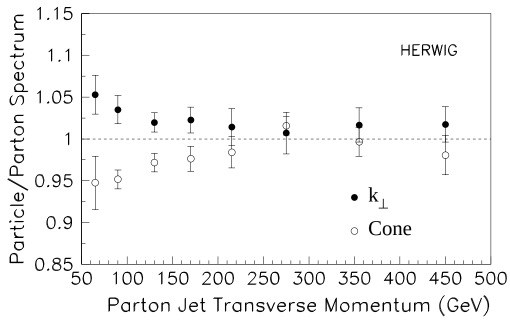

Figure 5: Ratio of particle-level over parton-level HERWIG p_T spectra for jets, as a function of the parton jet transverse momentum.

While the NLO inclusive jet cross section for the k_T ($D = 1.0$) and cone ($R = 0.7$, $\mathcal{R}_{\rm sep}= 1.3$) algorithms for $|\eta| < 0.5$ are within 1%, the measured cross section using k_T is 37% (16%) higher than the previously reported cross section using the cone algorithm at 60 (200) GeV. This difference in the cross sections is consistent with the measured difference in p_T for cone jets matched in $\eta - \phi$ space to k_T jets [9].

This discrepancy may be caused by hadronization effects on both the cross section and the energy measured by the two algorithms. These effects were studied with the HERWIG Monte Carlo event generator [11]. Figure 5 shows the difference in energy for the k_T and cone algorithms for matched jets in the HERWIG simulation. This difference is added to the JETRAD prediction with the CTEQ4HJ PDF, shown in the bottom plot of Fig. 4, which improves the χ^2 probability from 29% to 44%. In addition several of the corrections applied to the two algorithms are independent and could lead to differences which could effect the cross section in similar ways to the observed differences in the cross sections. Further study into these effects will need to be carried out in Run II at the Tevatron.

In general the NLO theoretical predictions are in good agreement with the inclusive jet cross section measured using the k_T algorithm.

2.2 Ratio of Inclusive Jet Cross Sections at $\sqrt{s} = 630$ and 1800 GeV

Both DØ [12] and CDF [13] also measured the inclusive jet cross section at $\sqrt{s} = 630$ GeV. and the ratio taken with the measurement at $\sqrt{s} = 1.8$ TeV as a function of $x_T = 2E_T/\sqrt{s}$. This measurement greatly reduces experimental and theoretical uncertainties. The measurements of CDF [12] and DØ [12] are in agreement for $x_T \approx 0.15$ and diverge at lower values of x_T (Fig. 6 and 7). The measurements lie approximately 10% below the predictions, a two standard deviation fluctuation. This discrepancy has generated a great deal of theoretical interest and may be explained by low E_T non-perturbative effects or different renormalization scales at the two center of mass energies. DØ has made a χ^2 comparison between the measurement and the predictions. The χ^2 values lie in the range 15.1–24 for 20 degrees of freedom (corresponding to probabilities in the range 28% to 77%). The best agreement occurs for extreme choices of renormalization scales: $\mu = (0.25, 2.00)E_T^{\max}$. As expected, there is very little dependence on the choice of PDF. Different renormalization scales can be selected for the different CM energies since there is no explicit theoretical need for identical scales at $\sqrt{s} = 630$ and 1800 GeV [12].

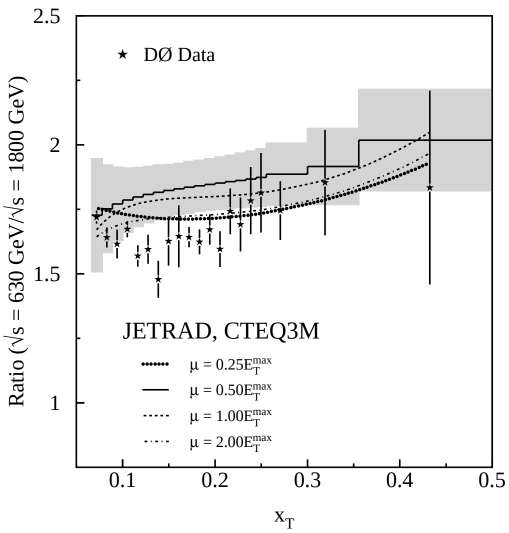

Figure 6: Ratio of jet cross sections at $\sqrt{s} = 1800$ and 630 GeV as a function of $x_T = 2E_T/\sqrt{s}$, as measured by DØ compared to NLO QCD predictions.

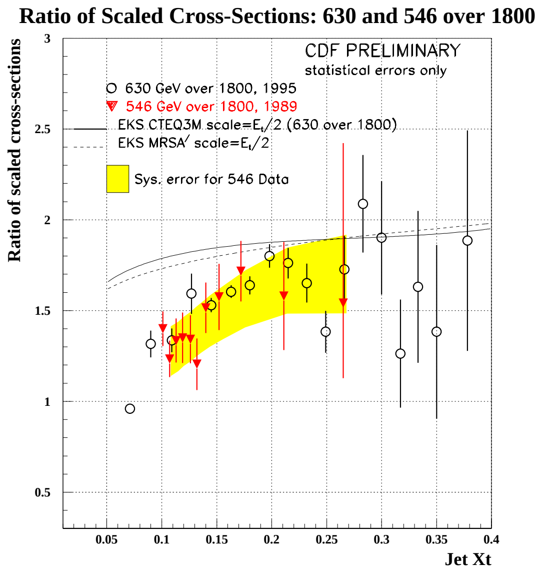

Figure 7: Ratio of jet cross sections as measured by CDF compared to NLO QCD predictions.

3. Multiple Jet Production

The DØ experiment has measured the ratio of inclusive three-jet production to inclusive two-jet production R_{32}, which reflects the rate of gluon emission in QCD jet production processes [14]. This ratio is measured as a function of $H_T = \Sigma E_T$ the sum of the E_T of all jets above a given thresholds of $E_T > 20$, 30, or 40 GeV for $|\eta| \leq 3$ and $E_T > 20$ GeV for $|\eta| \leq 3$. The resulting cross section ratio depicted in Fig. 8. The aim of this analysis is to determine if the theoretical prediction of multi-jet cross sections can be improved by introducing an updated renormalization scale prediction for the gluon emissions. Four different prescriptions were investigated 1) $\mu = \lambda H_T$ for the two leading jets, with three choices for the scale for the emission of the third jet: $\mu = \lambda H_T$, $\mu_3 = E_{T,3}$ the E_T of the third jet in the event, and $\mu_3 = 2E_{T,3}$. 2) $\mu = 0.6H_T$ for all jets in the event. The agreement of the theoretical predictions with all of these choices was tested using a χ^2 comparison (see Fig 9). All of these predictions show the same qualitative behavior, a rapid rise with H_T which is a kinematic threshold effect. The ratio reaches a maximum value approximately at $H_T = 200$ GeV and drops slowly as phase space restrictions begin to take effect.

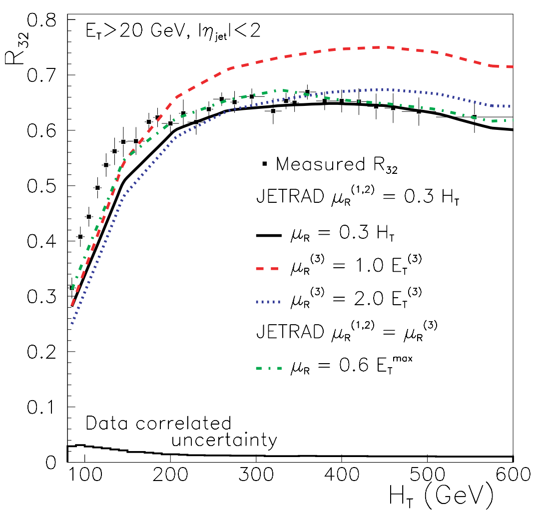

Figure 8: The ratio as a function of H_T, requiring jet $E_T > 20$ GeV and $|\eta| < 2$. Error bars indicate statistical and uncorrelated systematic uncertainties, while the histogram at the bottom shows the correlated systematic uncertainty. The four smoothed distributions show the JETRAD prediction for the renor-malization scales indicated in the legend.

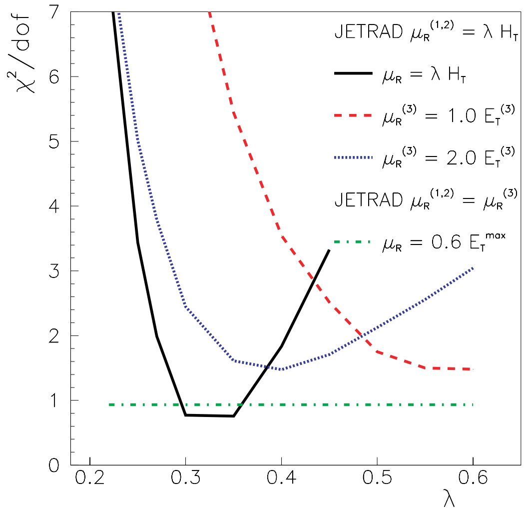

Figure 9: χ^2 per d.o.f. as a function of λ, as shown in the legend, comparing data to JETRAD predictions for several renormalization scales for $E_T > 20$ GeV and $|\eta| < 2$.

The JETRAD prediction assuming a scale $\mu\lambda H_T$ for all jets in the event, provides the best description of the data for λ between 0.30 and 0.35 with a probability of $\approx 80\%$ making this scale choice the most robust of all the renormalization scales studied.

DØ has carried out a study of multiple jet production at low transverse energies ($E_T \geq 20$ GeV) and compared the results with the PYTHIA Monte Carlo event generator [16]. When the predicted PYTHIA cross section is normalized to the observed data cross section for the $\geq$ 2-jet cross section with $E_T > 40$ GeV, there is an excess of events with three or more jets in the event (Fig 10). If these excess events were due to additional initial of final state radiation, it would be expected that the angular distribution of these additional jets would be correlated with the direction of the highest E_T jets in the event. Figure 11 shows the angular distribution for these events and it is clear that the excess events have a different angular distribution than that predicted by the PYTHIA event generator. This suggests that there are jets being produced in the event that are uncorrelated with the other jets. Systematic studies of these jets also show that it is unlikely that they are produced by detector noise or multiple parton interactions.

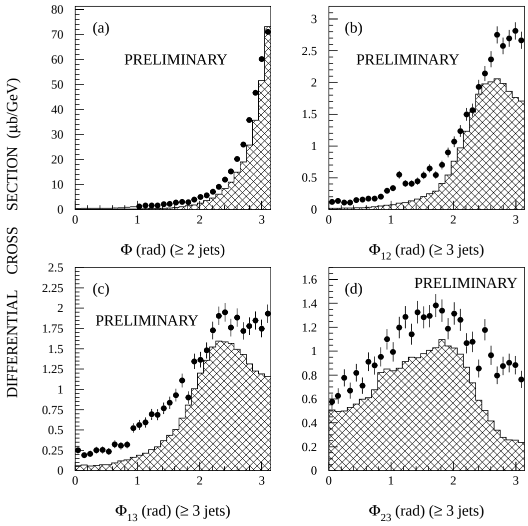

Figure 10: Distributions in the transverse energy of the leading jet for (a) singleinclusive, (b) twojet inclusive, (c) threejet inclusive and (d) fourjet inclusive events. Histograms show the pythia simulation normalized (increased by a factor of 1.3) to the inclusive twojet sample at E_T 40 GeV. Open triangles are normalized herwig results (increased by a factor of 1.6).

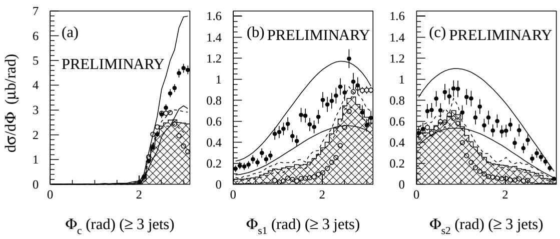

Figure 11: Azimuthal distributions between the leading jets in 3jet events. The data is given by the closed circles (all jets) and by the closed diamonds (the jets overlapped with more than one jet are excluded). Panels (a) show the azimuthal separation between the two jets with the minimum summed transverse momentum. Panel (b) shows the azimuthal separation between the third leading jet and the first jet of the minimum transverse momentum pair. Panels (c) shows the azimuthal separation between the third leading jet and the second jet of the pair. Pythia is given by the histograms and JETRAD is shown by the open circles.

4. Jet Substructure

DØ has used the k_T algorithm to identify sub-jets (or clusters of energy) within jets at $\sqrt{s}$ = 630 and 1800 GeV [9]. If we assume that the multiplicity of subjets for quark jets differs from that of gluon jets, the expected subjet 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 provided by PDFs and Monte Carlo simulation. If we use jets of the same energy ($50 < E_T < 100$ GeV), and the assumption that M_g and M_Q depend only on jet energy (not center-of-mass energy), one extracts the multiplicities characteristic of the two partons. Taking the ratio, DØ finds

$$R = \frac{\langle M_g \rangle - 1}{\langle M_Q \rangle - 1} = 1.91 \pm 0.04(\text{stat}) \pm {}^{0.23}_{0.19}(\text{sys})$$

The prediction from Herwig [11] is $R = 1.86 \pm 0.08(\text{stat})$. Figure 12 provides the spectrum of multiplicities.

5. Conclusion

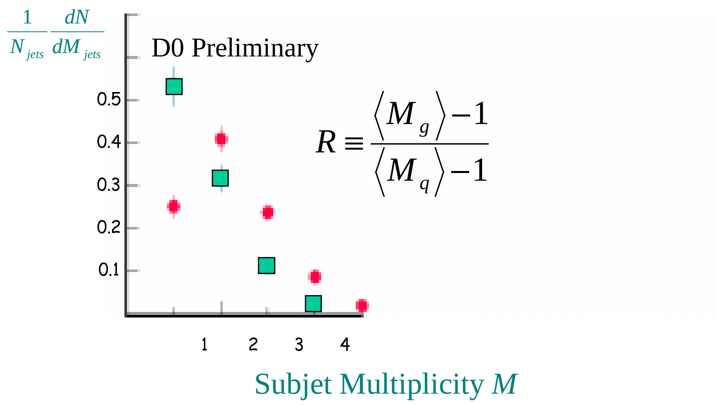

Figure 12: Extracted probabilities of observing M subjets for quark-like jets (squares) and gluon-like jets (circles) at 60 GeV.

Both DØ and CDF have made several high precision measuremenst of jet processes at the Tevatron. In most cases the predictions of QCD are in agreement with the measurements. The major discrepancies are for relatively low transverse momentum processes and in the ratio of cross sections at different center of mass energies. However, these discrepancies occur in areas where either the theory of the measurement has significant uncertainties, and hence, will be areas worth examining at Run II of the Tevatron.

This year, Run II commenced. Both CDF and DØ are still carrying out commissioning work and we expect first results to be available during the Spring conferences in 2002. In the first phase of Run II the experiments expect to collect data samples approaching 2 fb^{-1} which is 20 times the data sample collected previously at $\sqrt{s} = 2000$ GeV. This increased data set and upgrades to both detectors should mean that the significant advances should be made in reducing the systematic uncertainties in all jet measurements and presenting new and intriguing challenges.

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