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June 1998

Published Proceedings of the 33rd Rencontres de Moriond: QCD and High Energy Hadronic Interactions,
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The Dijet Differential Cross section, $M_{jj}$ and $\alpha_s$

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A preliminary measurement of the inclusive dijet differential cross section obtained from $p\bar{p}$ collisions at $\sqrt{s} = 1.8$ TeV by the CDF collaboration is presented. Results are presented from CDF and DØ for the the dijet mass distribution and compared to QCD calculations. The effect of changing the renormalization scale and the choice of the parton density functions on the predicted cross section is shown. An estimate of $\alpha_s$ is obtained from the inclusive jet data.

1 Introduction

The production of collimated hadronic jets at high energy colliding-beam facilities has proven to be a rich source of tests for QCD, the fundamental theory of the strong interactions. Theoretical developments in both perturbative Next-to-Leading Order (NLO) and shower Monte Carlo calculations now permit rapid calculation of many QCD jet processes with theoretical uncertainties small enough to allow detailed comparison with measured spectra. There are now available numerous parton distribution functions (PDFs) which utilize large ensembles of experimental data from deep inelastic scattering and direct photon production to provide unbiased estimates of the gluon and quark distributions of the nucleon. These PDFs form an essential component of jet production calculations.

Recent measurements of the inclusive jet differential cross section from CDF have indicated an excess of events at high $E_T$ when compared to the QCD predictions with standard parton distributions. This excess has generated a great deal of theoretical interest. Quark substructure would lead to deviations from QCD at high $E_T$. A measurement of dijet angular distributions tests the properties of parton-parton scattering without a strong dependence on the choice of the PDF. Such measurements have been used to set limits on quark compositeness. Another possible explanation for the excess is the gluon distribution being larger than expected at high $x$.

1.1 The Inclusive Dijet Differential Cross Section

Preliminary results for the triple differential jet cross section, $d\sigma/(dE_Td\eta_1d\eta_2)$ are presented by the CDF collaboration. Jets are identified by a cone algorithm with cone radius $R$ defined as $R = \sqrt{(\Delta\phi)^2 + (\Delta\eta)^2} = 0.7$. The transverse energy is calculated from $E_T = E\sin\theta$, where the energy $E$ is the scalar sum of energy in the calorimeter towers within the cone, and $\theta$ is the angle formed by the event vertex, the beam direction and the cone center. Events are collected by on-line identification of at least one jet with transverse energy above thresholds of 20, 50, 70, and 100 GeV. The 20, 50, and 70 GeV samples were prescaled by factors of 1000, 40, and 8
respectively. No prescale was applied to the 100 GeV trigger sample. The data sample presented here correspond to an integrated luminosity of 86 pb$^{-1}$ from $\sqrt{s} = 1.8$ TeV $p\bar{p}$ collisions taken during the 1994-1995 Fermilab Tevatron Collider run. The analysis includes events with at least two reconstructed jets. The trigger jet is required to satisfy $E_T > 40$ GeV and to be within the central pseudorapidity region, $0.1 < |\eta_1| < 0.7$. The probe jet is required to satisfy $E_T > 10$ GeV and to sit in one of four pseudorapidity bins, $0.1 < |\eta_2| < 0.7, 0.7 < |\eta_2| < 1.4, 1.4 < |\eta_2| < 2.1$ or $2.1 < |\eta_2| < 3.0$.

The well-understood response properties of the CDF central calorimeter are utilized to measure the $E_T$ of the trigger jet. The measured energies are corrected for detector resolution and smearing using the same procedure used in the measurement of the inclusive jet cross section. The cross section is measured as a function of the trigger jet’s $E_T$. Four separate distributions are determined corresponding to the four bins of $\eta_2$. The preliminary results are presented in Figure 1 and compared to the calculated cross section determined using JETRAD with several different PDFs. The data are in good quantitative agreement with the QCD predictions except at high $E_T$. The error bars represent the statistical errors. The systematic errors are currently being finalized.

In order to emphasize the high $E_T$ region the cross sections have been scaled by $E^n_T$ using a different exponent for each of the $\eta_2$ bins. The results are shown in Figure 2. Preliminary results from run Ia are also included and are seen to be in good agreement with the run Ib results. The data tend to be higher than that expected from existing PDFs at high $E_T$. The CTEQ4HJ PDF results in a better agreement with the data at high $E_T$.

The $E_T$ and pseudorapidities of the leading jets are related to the momentum fraction, $x$, of the partons involved in the interaction. In leading order the relation is

$$x_1 = \frac{E_T}{\sqrt{s}}(e^{\eta_1} + e^{-\eta_1}); \quad x_2 = \frac{E_T}{\sqrt{s}}(e^{-\eta_1} + e^{-\eta_2}).$$

For fixed $E_T$ and $\eta_1$, different momentum fractions can be selected by requiring that the probe jet lie in different $\eta$ intervals. We define $x_{\text{max}}$ as the maximum of $x_1$ and $x_2$. For a two body process one intuitive choice for the QCD scale of the interaction is

$$Q^2 \sim -\hat{t} = 2E_T^2\cosh^2\eta^* (1 - \tanh \eta^*)$$

The data have been converted from $(E_T, \eta_2)$ bins to $(x_{\text{max}}, \hat{t})$ bins and shown in Figure 3. The high $E_T$ region of the inclusive jet cross section distribution corresponds to high $x$. We also see
that the events occur at high $Q^2$. In contrast to the inclusive jet data which yield information along a line in the $x - Q^2$ plane the dijet data provide information over a region of the $x - Q^2$ plane. The dijet data will prove useful as input in NLO QCD fits to determine new sets of PDFs.

1.2 The Dijet Invariant Mass Distribution

Both CDF and DØ have measured the differential dijet mass cross section, $\Delta d\sigma^2/\Delta M_{jj}d\eta_1d\eta_2$ as a function of the dijet mass. The preliminary CDF measurement is based on $87 \, pb^{-1}$. A cone algorithm with a fixed cone size of $R = 0.7$, is used to reconstruct jets. The two leading jets are required to be within the central region and satisfy $|\eta| < 2$. In order to ensure a high trigger efficiency over the entire dijet mass range both jets are required to satisfy $|\cos \theta^*| < 2/3$ where $\cos \theta^* = \tanh^{-1} \eta^*$ with $\eta^* = (\eta_1 - \eta_2)/2$. Additional cuts were applied to reduce background. The measured jet energies are corrected for detector and smearing effects. The dijet mass is determined from the 4-vector definition

$$M_{jj} = \sqrt{(E_1 + E_2)^2 - (\vec{p}_1 + \vec{p}_2)^2},$$

where $E$ is the jet energy and $\vec{p}$ is the jet momentum.

The DØ measurement requires that both jets satisfy $|\eta| < 1$. The dijet mass is calculated assuming massless jets from

$$M_{jj}^2 = 2E_T^{(1)}E_T^{(2)}(\cosh(\Delta \eta) - \cos(\Delta \phi)).$$

The difference in the calculated mass using the different mass definitions is a few percent. Preliminary results from both experiments are compared to the QCD prediction determined using JETRAD with $\mu = 0.5E_{T}^{\text{max}}$, $R_{\text{sep}} = 1.3$ and the CTEQ4M PDF in Figure 4. The CDF data are shown as squares and has been normalized to the theory prediction in the first six bins. The inner shaded band shows the systematic error on the DØ measurement while the outer band represents the error on the CDF measurement. The shape of the distributions measured by the two collaborations are in excellent agreement.
DØ has split the sample into two $\eta$ regions. The top plot of Figure 5 compares the measured cross section as a function of $M_{jj}$ for $|\eta| < 0.5$ to the theory expectation while the bottom plot shows the results for $0.5 < |\eta| < 1.0$. The data are consistent with the theory predictions however the data tend to be somewhat higher than the expectation at high $E_T$ for the case of more forward jets.

The effect of changing the renormalization scale is shown in Figure 6. The DØ data are used in the ratio (Data-Theory)/Theory where the theory calculation was performed using JETRAD with CTEQ3M and $\mu = 0.5E_T^{max}$. The renormalization scale has been varied from $0.25E_T^{max}$ to $2E_T^{max}$ and compared to the nominal case with $\mu = 0.5E_T^{max}$. The effect of changing the renormalization scale shows up as a shift in the cross section with a slight $M_{jj}$ dependence. The result of changing the PDF is shown in Figure 7. The ratio of (Data-Theory)/Theory is plotted using the DØ data compared to the calculation of JETRAD with CTEQ3M. The difference in the cross section obtained using MRSA', CTEQ4HJ and CTEQ4M PDF is shown. The choice of the PDF can result in significant change in the shape.

**Figure 6:** The DØ data are compared to the QCD predictions of JETRAD with $\mu = 0.5E_T^{max}$. The curves show the effect of changing the renormalization scale from $0.25E_T^{max}$ to $2E_T^{max}$. The jets are required to satisfy $|\eta| < 1$.

**Figure 7:** The DØ data are compared to the QCD predictions of JETRAD using the CTEQ3M PDF. The curves show the change in the cross section obtained using different PDFs. The jets are required to satisfy $|\eta| < 1$.

### 1.3 An Estimate of $\alpha_s$

The CDF collaboration has used the method described by Giele et al.\(^5\) to determine $\alpha_s$ from the inclusive jet data. The NLO QCD inclusive cross section can be expressed as

$$
\frac{d\sigma(E_T)}{dE_T} = \alpha_s^2(\mu_R)A(E_T) + \alpha_s^3(\mu_R)B(E_T).
$$

The constants $A$ and $B$ can be calculated from QCD and assuming a particular PDF set and value of $\alpha_s \equiv \alpha_s(M_Z)$. The program JETRAD was used to determine the coefficients. For each bin in $E_T$ $\alpha_s(E_T)$ is determined and translated to $\alpha_s$ using

$$
\alpha_s(M_Z) = \frac{\alpha_s(\mu_R)}{1 - \alpha_s(\mu_R)L(\lambda)}
$$
with

\[ L(\lambda) = (b_0 + b_1 \alpha_s) \log(\lambda), \tag{7} \]

where \(b_0\) and \(b_1\) are known.

The coupling constant was determined from the measurement of the inclusive jet cross section over the \(E_T\) range of 40 to 250 GeV. The results are shown in Figure 8. The stars show the value of \(\alpha_s(E_T)\) and demonstrate the running of \(\alpha_s\). The circles represent the value of \(\alpha_s\) translated to \(M_Z\) using Equation 6. The error bars represent the statistical errors and the systematic error is shown as the hatched band at the bottom of the plot. The results obtained are dependent on the PDF used to calculate the constants and the value of \(\alpha_s\) used in the calculation. When using CTEQ4M with \(\alpha_s(M_Z) = 0.116\) the value of \(\alpha_s = 0.1152 \pm 0.0001\) is determined.

The same method was used with the dijet data. The result for CTEQ4M is shown in Figure 9 and the CTEQ4HJ result is shown in Figure 10. The error bars represent only the statistical errors. The region over which the data are fit to get extract \(\alpha_s\) is shown in the plots. The CTEQ4HJ PDF results in a better agreement with the data at high \(E_T\). The correlation between \(\alpha_s\) and the gluon distribution makes an independent determination of \(\alpha_s\) difficult.

2 Conclusions

The differential dijet cross section can be used as an input to global QCD fits. Unlike the inclusive jet cross section which provides information along a line in the \(x - Q^2\) plane the dijet differential cross section provides information over a region in the \(x - Q^2\) plane. The extended \(x - Q^2\) coverage allows the possibility to better determine the shape of the PDFs from global QCD fits. The region of most interest is the high \(E_T\) region or equivalently high \(x\) and high \(Q^2\). We have seen that a modified PDF can account for some of the excess of events observed at high \(E_T\).

The dijet mass spectrum is seen to be in agreement with QCD predictions. The shape of the data from CDF and DØ are consistent. We have seen that changing the input parameters to the theory calculation can result in a significant change in the expected cross section.

An estimate of \(\alpha_s\) using the inclusive jet data has been presented. The method is dependent on the choice of the PDF and starting value of \(\alpha_s\) used to determine the constants in Equation 5.
Acknowledgments

We thank the staffs at Fermilab and the collaborating institutions for their contributions to this work, and acknowledge support from the Department of Energy and the National Science Foundation (U.S.A.), Commissariat à l’Energie Atomique (France), State Committee for Science and Technology and Ministry for Atomic Energy (Russia), CNPq (Brazil), Departments of Atomic Energy and Science and Education (India), Colciencias (Columbia), CONACyT (Mexico), Ministry of Education and KOSEF (Korea), and CONICET and UBACyT (Argentina).

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