Fermi National Accelerator Laboratory

FERMILAB-Conf-92/253-E

QCD Tests with CDF

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September 1992

Published Proceedings *XXVIth International Conference on High Energy Physics,*
Dallas, Texas, August 6 - 12, 1992

Operated by Universities Research Association Inc. under Contract No. DE-AC02-76CHO3000 with the United States Department of Energy

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QCD TESTS WITH CDF *

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Abstract

Measurement of scaling violations, the inclusive photon and diphoton cross sections as well as the photon-jet and jet-jet angular distributions are discussed and compared to leading order and next-to-leading order QCD. A study of four-jet events is described, with a limit on the cross section for double parton scattering. The multiplicity of jets in W boson events is compared to theoretical predictions.

INTRODUCTION

This paper presents a summary of the recent QCD results using the CDF detector[1] and data collected during the 1988-1989 running of the Fermilab proton-antiproton collider. In addition to the 4.4 pb^{-1} collected at $\sqrt{s}$ = 1800 GeV, 8.6 nb^{-1} of data were taken at $\sqrt{s}$ = 546 GeV to allow a measurement of the scaling violations predicted by QCD. Results are presented for the ratio of the scaled jet cross sections, and for the photon and diphoton cross sections. Measurement of the jet-jet and photon-jet angular distributions provide tests of QCD at larger pseudorapdities than are typically included the inclusive cross section measurements. Topological variables of four-jet events are compared to QCD predictions and a limit on the double parton scattering cross section is derived. Finally, a study of jet multiplicity in $W \rightarrow e+\nu$ and $W \rightarrow \mu+\nu$ events is presented.

JET IDENTIFICATION

CDF uses a cone algorithm for jet identification[2], where the radius of the cone is defined as $R=\sqrt{\Delta\eta^2 + \Delta\phi^2}$. The calorimeter energy falling within the cone is summed to give a single four-vector for each jet. Typically, a cone size of R=0.4, 0.7 or 1.0 is used.

Recently, $O(\alpha_s^3)$ calculations[3] for jet production have been performed in which a similar cone algorithm is employed. Cones are drawn around the partons in $\eta-\phi$ space. If two partons happen to fall within the cone they are merged into one "jet". In contrast to leading order calculations, this produces, at the parton level, a dependence of the predicted cross section on the cone size and jet shape. Figure 1 shows the measured cross section as a function of cone size[4].

At the parton level, the jet shape, $\psi(r)$, is

*Supported by the U.S. Dept. of Energy, contract number DE-AC02-76CH03000.

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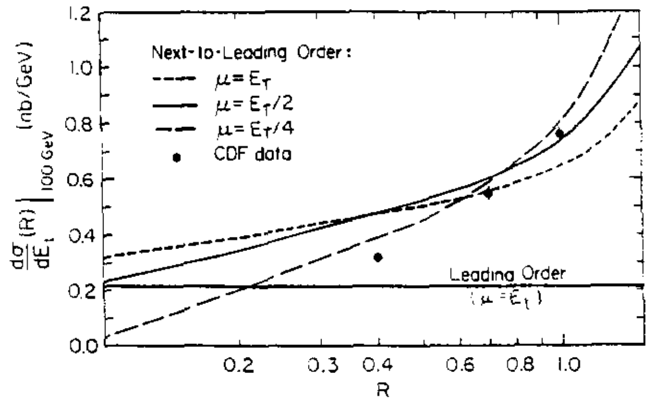

Figure 1. Inclusive Jet Cross section for 100 GeV Jets for cone sizes R = 0.4, 0.7, and 1.0.

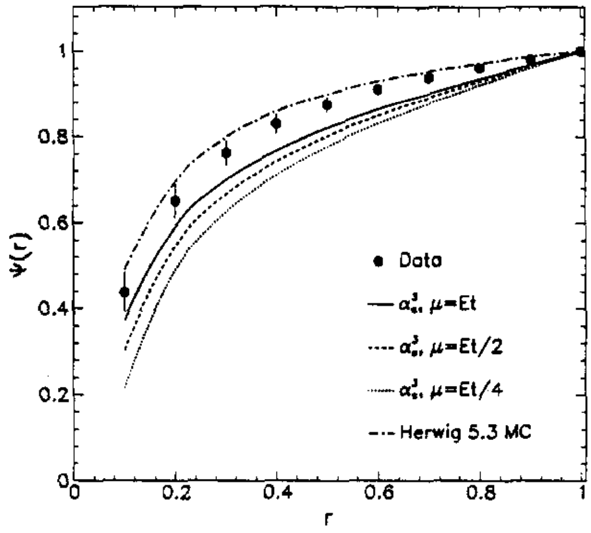

Figure 2. Jet shape for 100 GeV jets compared to next-to-leading order predictions.

defined as the fraction of energy falling within a cone of radius r, normalized to the energy within a cone of R=1.0 and averaged over many events.

Experimentally, $\psi(r)$ is defined as the sum of the P_T of tracks falling within a cone of radius r, around the calorimeter cluster centroid, and normalized to the total track P_T within a cone of radius 1.0. Figure 2 shows the jet shape for 100 GeV jets[5], compared to $O(\alpha_s^3)$calculations.

INCLUSIVE JET CROSS SECTION

With the data taken at $\sqrt{s}$ = 546 and 1800 GeV, CDF is in a unique position to test the predictions of QCD for scaling of the jet cross sections. Previously, it was necessary to compare results from different experiments, and thus the systematic errors would not cancel, or such a large change (more than a factor of 3) in center of mass energy was not possible.

Without QCD evolution, the naive parton model predicts that the scaled jet cross section, $\sigma' = P_T^4(Ed^3\sigma/dp^3)$, will be independent of $\sqrt{s}$ when plotted as a function of the variable $X_T = 2P_T/\sqrt{s}$. Thus, the ratio of the scaled cross sections as measured at $\sqrt{s}$=546 and 1800 GeV should be 1. However, when evolution of the structure functions and of α_s are included in the theory, exact scaling is broken, and this ratio is expected to have an average value (at CDF energies) of about 1.8.

The measurement of the inclusive jet cross section at $\sqrt{s}$ =1.8 TeV has been discussed in Reference [4] and is in good agreement with QCD predictions. Similar techniques were used in the analysis of the $\sqrt{s}$=546 GeV data. The systematic errors for the two samples and the ratio are shown in Figure 3. Notice that the systematic error is greatly reduced in the ratio of the cross sections.

Figure 4 shows the ratio of the scaled jet cross sections as measured by CDF. The band indicates the size of $\pm 1\sigma$ of systematic uncertainty. To determine the significance of the result we form an average value for the data and theory over the X_T range 0.101-0.265. We observe a 1.5-2.4 σ difference between QCD and the data, where the range comes from different choices of structure functions and renormaliza-

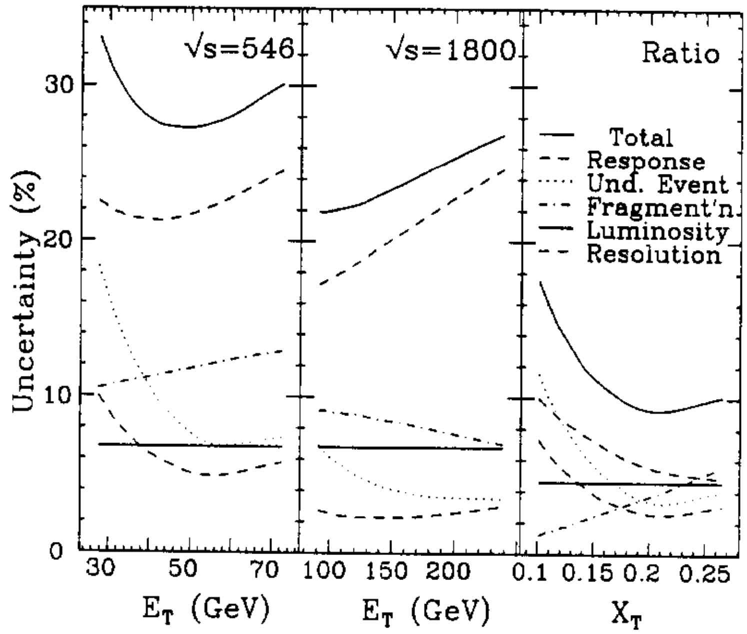

Figure 3. Systematic errors for the scaled jet cross sections at $\sqrt{s}$ = 546 and 1800 GeV.

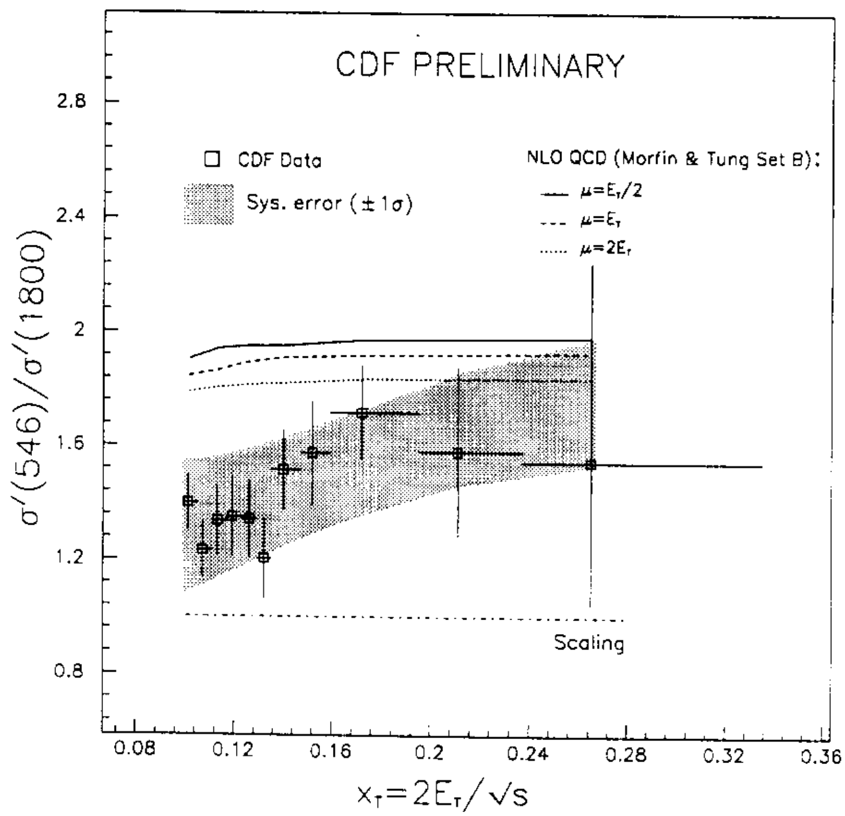

Figure 4. Ratio of the scaled jet cross sections at $\sqrt{s}$ = 546 and 1800 GeV.

tion scale. Scaling is excluded by the data at the 95% confidence level.

INCLUSIVE PHOTON CROSS SECTION

Photons produced directly from the hard collision provide a probe of the gluon structure functions and an energy measurement which is free from the effects of fragmentation. Photon identification at CDF is described in Reference [6]. Separation of photons from the background (mainly π^0s) is accomplished through the comparison of the shower profiles from the data with shower profiles from test beam electrons.

Figure 5 shows the photon P_T spectrum as measured by CDF[6]. The theoretical predictions are all next-to-leading order and the renormalization scale is P_T . The data seems to have a steeper slope at low P_T than the theoretical predictions. The effect of higher order terms, bremsstrahlung diagrams and new structure functions[7] are under study. At present, the range in the predictions from different choices of renormalization scale and the disagreement between theory and data in the low P_T region, preclude the separation of the effects of different gluon structure functions.

The production of di-photon events provides another test of QCD and is an important background to Higgs$\rightarrow \gamma\gamma$ for the SSC. Events with two photons were identified using similar cuts to the single photon analysis except the E_T cut was 10 GeV on each photon[8]. Figure 6 shows the measured di-photon cross section compared to the theoretical predictions. Each photon is entered in the plot.

ANGULAR DISTRIBUTIONS

QCD predicts that the jet-jet angular distribution is dominated by Rutherford-like t-channel gluon exchange (spin 1). The photon-jet final state is expected to be relatively flat since it is dominated by t-channel quark ex-

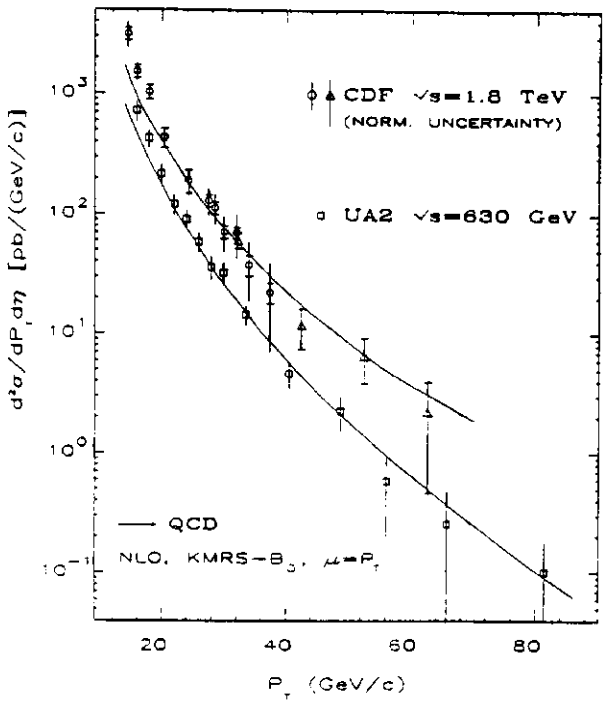

Figure 5. Inclusive Photon Cross section

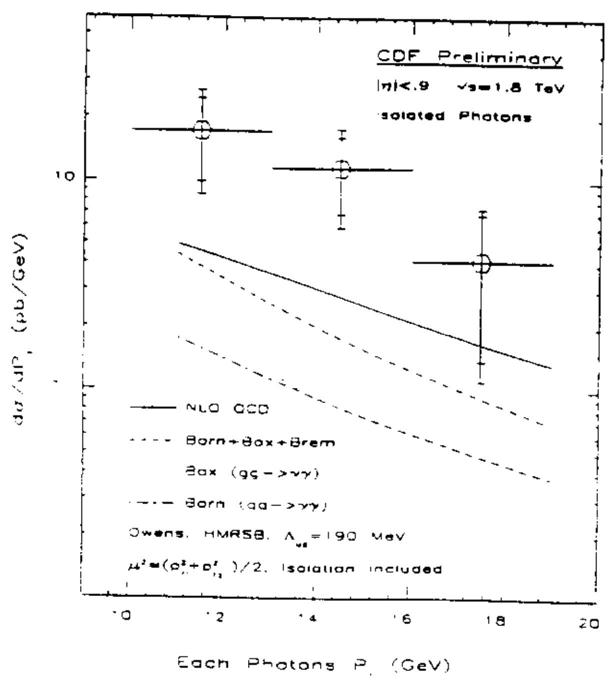

Figure 6. Di-Photon Cross section.

change (spin 1/2). This is directly reflected in the angular distribution.

The cross section for dijet events can be written in terms of the mass, M_{JJ}, the center-of-mass scattering angle, θ^*, and longitudinal boost of the dijet system, $\eta_{boost} = (\eta_1 + \eta_2)/2$, where η_1 and η_2 are the pseudorapidities of the two highest E_T jets[9]. The dijet mass of an event is calculated using the four-vectors of the leading two jets. The scattering angle is related to η_1 and η_2 by the equations $\eta^* = (\eta_1 - \eta_2)/2$ and $\cos\theta^* = \tanh\eta^*$.

Similarly, in photon-jet events, the variables η^* and $\cos\theta^*$ are defined using the pseudorapidities of the photon, η_γ, and the jet, η_{jet}. The jet is defined as the vector sum of the jets which fall in a 120° cone opposite to the photon direction in ϕ. To avoid uncertainties associated with the measurement of the jet energy, the invariant mass of the photon-jet system is calculated using the P_T of the photon and η^*: $M_{\gamma,jet} = 2P_{T,\gamma} cosh\eta^*$.

In the comparisons to theoretical predictions, the jet-jet angular distribution is plotted in terms of the variable $\chi = e^{2|\eta^*|}$. For t-channel exchange, which dominates at large η^* , the $dN/d\chi$ spectrum is expected to be flat and thus insensitive to smearing effects. In addition, the signal of quark compositeness would show up as a peak at low χ.

Figure 7 shows the data[9] compared to $O(\alpha_s^2)$ and $O(\alpha_s^3)$ calculations[10] for HMRSB structure functions. The data and the theoretical curves are normalized to unit area. Four sets of Morfin-Tung structure functions were tested (S, B1, B2 and E); they gave the same confidence levels to within 2%. From this data a limit on the quark compositeness energy scale of Λ_c >1000 GeV has been derived.

Figure 8 shows photon-jet angular distribution compared to leading order and next-to-leading order QCD calculations. The dijet angular distribution as previously measured[11] by CDF has also been included since it was measured at low mass (M_{jj} ≥148 GeV) and thus is closer than the current dijet data to the mass used in the photon-jet measurement. Although the statistics are limited, the photon-jet data appears to be flatter than the dijet data as expected from the spin of the propagators.

FOUR-JET EVENTS

QCD predicts that the dominant mechanism for the production of four-jet events is a 2→2 parton interaction plus double gluon bremsstrahlung. An alternative hypothesis is that four-jet events could be produced by double parton interactions in which two partons in each of the incoming hadrons collide and produce two di-jet events. The double parton scattering events are expected to have two sets of well balanced dijets, randomly oriented with respect to one another. In double bremsstrahlung events, the 3rd and 4th highest E_T jets are expected to be found preferentially near the leading two jets. Topological variables are used to compare the data to the theoretical predictions. Figure 9 shows plots of the cosine of the angle between each jet pair, compared to a leading order four-jet QCD Monte Carlo[12]. Clearly the data is well described by the theoretical predictions.

Using variables sensitive to the double-dijet structure of the events, the data is fit to an admixture of QCD double bremsstrahlung and double parton scattering predictions. It was found that the best fit corresponded to a small contribution (5.2%, 2σ from 0) from double parton scattering. From this we derive a limit on the double parton scattering cross section of σ_{DP} <0.12 μb for partons with E_T > 18 GeV at the 95% confidence level. To compare between experiments the limit is usually quoted in terms of the effective cross section $\sigma_{eff} \equiv \sigma_{dijet}^2/2\sigma_{DP}$, where σ_{dijet} is the

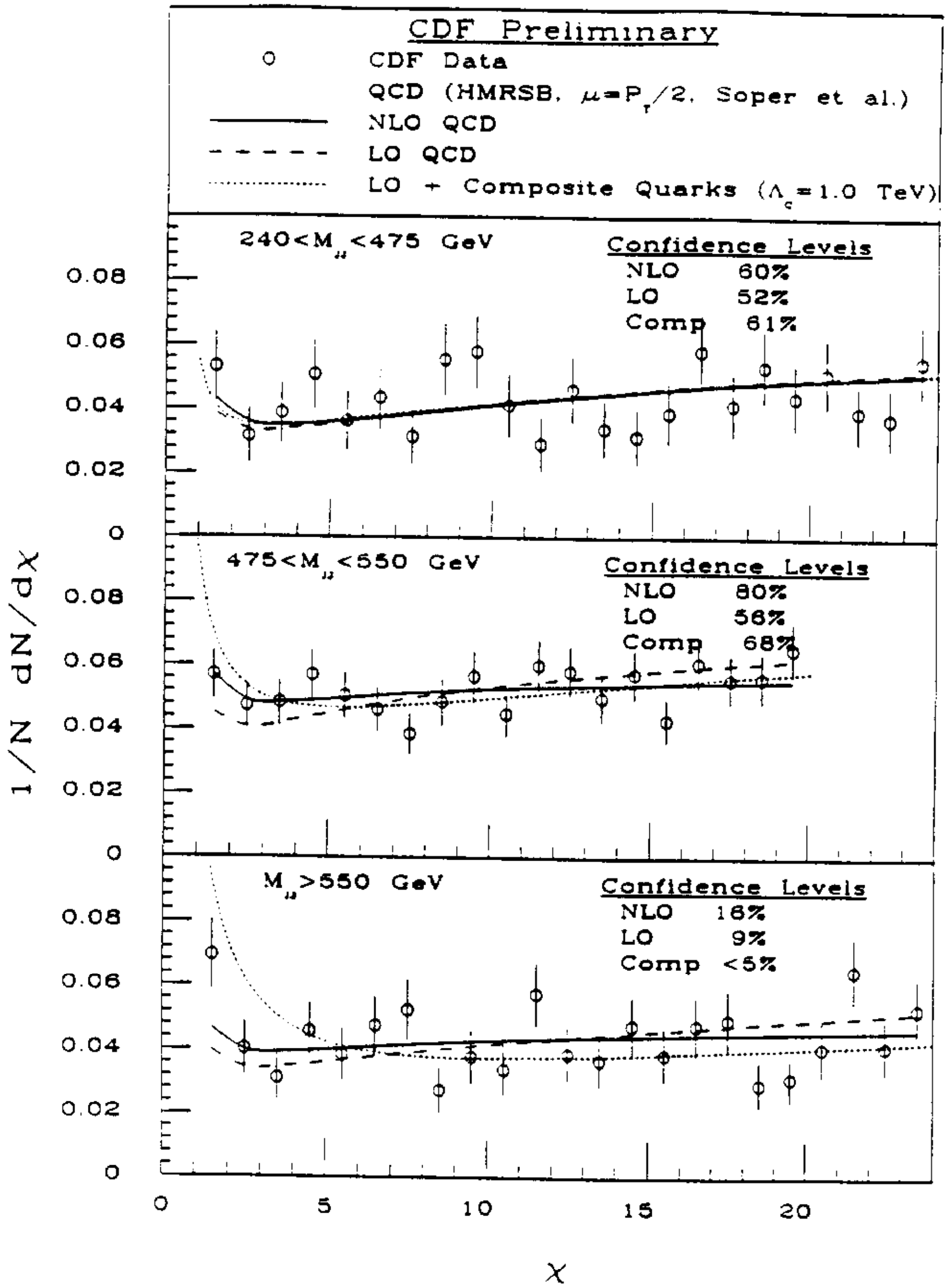

Figure 7. Dijet angular distribution.

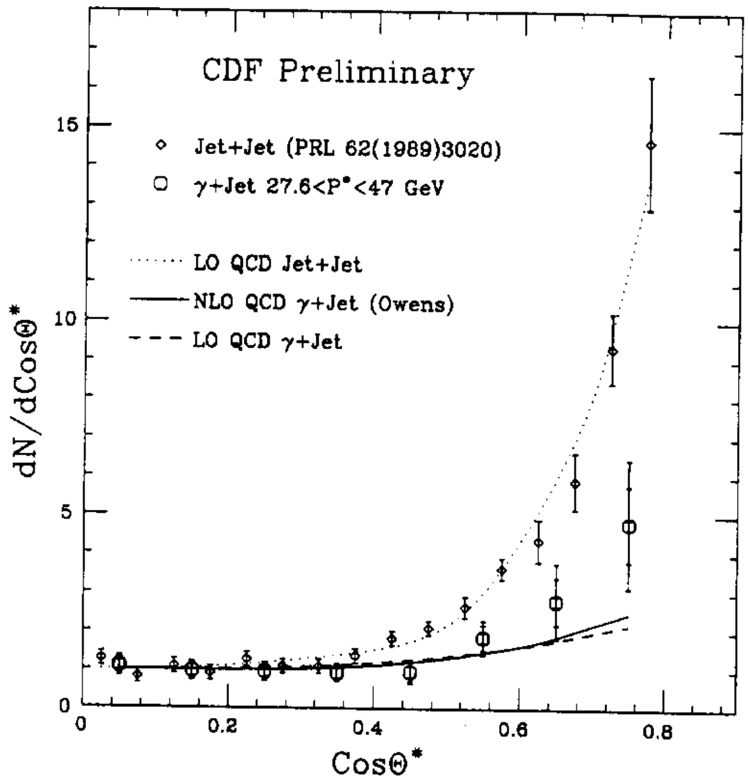

Figure 8. Photon-jet angular distribution.

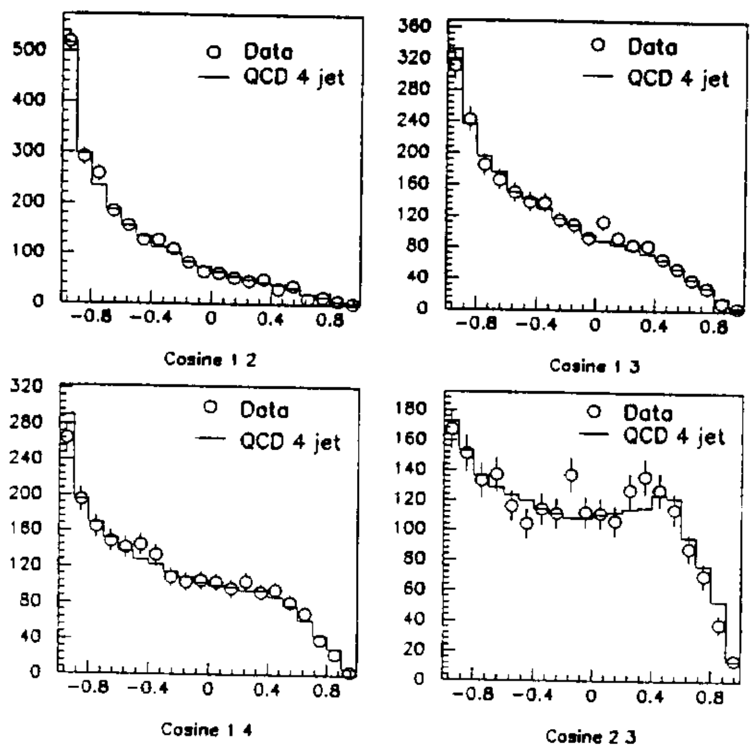

Figure 9. Angular separation between jets in four-jet events compared to QCD.

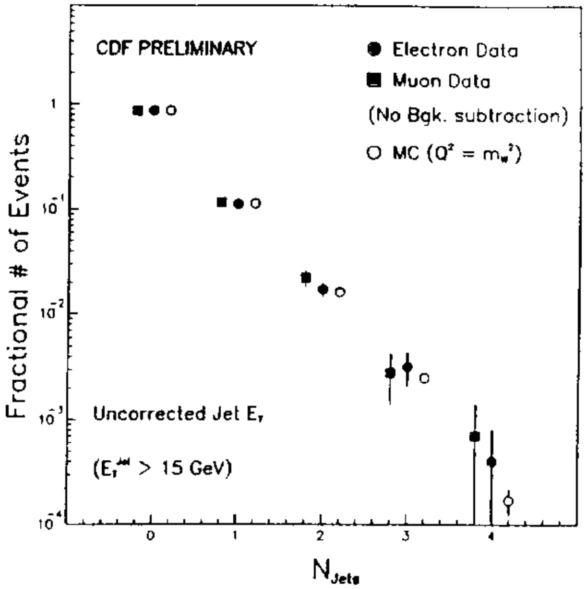

Figure 10. Jet multiplicity in W events for electron and muon W-decays.

dijet cross section. Our limit is $\sigma_{eff} > 3.9$ mb at the 95% confidence level.

JET MULTIPLICITY IN W-BOSON EVENTS

A measurement of the jet multiplicity in high P_T W events provides another test of QCD. Events with a vector boson plus jets are one of the major backgrounds in the search for the top and the Higgs. Events in which the W decays into a electron + neutrino or a muon + neutrino are selected using the standard CDF cuts as described in Reference [13]. The leptons are restricted to the central region ($|\eta| < 1.1$ for electrons and $|\eta| < 0.6$ for muons) while the jets are allowed to be further forward, $|\eta| < 2.4$. A total of 4.05 pb^{-1} of electron data and 3.54 pb^{-1} of muon data was collected. Figure 10 shows the jet mulitiplicity distribution in W events compared to Monte Carlo parton level calculations[14] plus full detector simulation. The theory shows good agreement with the data.

CONCLUSIONS

The inclusive jet cross section has been measured by CDF at two center-of-mass energies: $\sqrt{s} = 546$ GeV and 1800 GeV. The ratio of the scaled jet cross sections is a measure of the scaling violations predicted by QCD. The data has been found to consistant with QCD at the 1.5-2.4σ level and the hypothesis of exact scaling has been ruled out at the 95% confidence level.

Cross sections for direct photons and diphotons have been measured. Some disagreements with the theory have been observed, but the effect of new structure functions, higher order terms and bremsstrahlung are still under study.

The dijet and photon-jet angular distributions have been measured and are well described by the theoretical predictions. A compositeness limit of $\Lambda_c > 1000$ GeV has been derived from the dijet data.

Leading order QCD provides a good description of the four-jet data. Preliminary limits on the double parton scattering cross section of $\sigma_{DP} < 0.12\mu b$ and $\sigma_{eff} > 3.9$ mb have been derived. Finally, the multiplicity of jets in W events has been measured, and is in good agreement with QCD.

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