Fermi National Accelerator Laboratory

FERMILAB-Pub-97/290-E
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Measurement of the Differential Cross Section for Events with Large Total Transverse Energy in p$\overline{\text{p}}$ Collisions at $\sqrt{s}$ = 1.8 TeV

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September 1997

Submitted to *Physical Review Letters*

Operated by Universities Research Association Inc. under Contract No. DE-AC02-76CH03000 with the United States Department of Energy

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Distribution

CDF/PUB/JET/PUBLIC/4023

Measurement of the differential cross section for events with large total transverse energy in $p\overline{p}$ collisions at $\sqrt{s} = 1.8$ TeV

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PACS numbers: 13.87Ce,12.38Qk

Abstract

The differential cross section $d\sigma/d\sum E_T^{jet}$ has been measured for events with total transverse energy $\sum E_T^{jet} > 320$ GeV. The results are based on 112 pb^{-1} of $p\overline{p}$ collisions at $\sqrt{s} = 1.8$ TeV collected with the Collider Detector at Fermilab at the Tevatron collider. The data are compared with QCD predictions using various sets of parton distribution functions. The observed cross section at the highest values of total transverse energy is higher than current predictions based on $\mathcal{O}(\alpha_s^3)$ perturbative QCD calculations. The apparent excess is reduced when a new parton distribution function set is used for the QCD predictions. This set was derived in order to reduce a similar excess observed in the inclusive jet cross sections at high jet transverse energies.

Within the framework of perturbative QCD, events with large total transverse energy are expected to be produced in $p\overline{p}$ collisions from hard parton-parton scattering. The outgoing scattered partons manifest themselves as hadronic jets. The lowest order QCD diagrams predict two jets in the final state. Higher order processes can give rise to events with more than two jets. The kinematic properties of events with up to six jets [1, 2, 3] and large total transverse energy have been previously measured by the CDF collaboration at the Tevatron $p\overline{p}$ collider operating at a center-of-mass energy of 1.8 TeV. The kinematic properties of these multijet events are well described by both the HERWIG [4] QCD parton shower Monte Carlo program and the NJETS [5] complete leading order (LO) QCD matrix element Monte Carlo program for $2 \rightarrow N$ scattering. In the present Letter we extend our results by comparing the differential cross section for multijet events with large total transverse energy to predictions from the HERWIG Monte Carlo program and the JETRAD next to leading order (NLO) two-jet Monte Carlo program [6].

The rate of events with with large total transverse energy is of particular interest because the CDF collaboration has recently reported that the inclusive jet differential cross section exhibits an excess at high jet transverse energy ($E_T^{jet} > 200$ GeV) [7] with respect to the current NLO perturbative QCD predictions [8]. Although there are several candidate explanations [9, 10], the origin of the high-E_T^{jet} excess is not at present understood. However, the angular distribution for two-jet events is in good agreement with NLO QCD predictions

[11], suggesting that the high E_T^{jet} excess may have an explanation within the framework of QCD rather than originating from new physics. If this is the case, an excess with respect to NLO QCD predictions should also be observed in the differential cross section for events with large total transverse energy.

The data used in the present analysis were recorded by the CDF experiment over the period 1992 - 1995 and correspond to an integrated luminosity of 112 $\pm$8 pb^{-1}. A full description of the CDF detector can be found in ref. [12]. The analysis described in this Letter exploits the CDF calorimeters which cover the pseudorapidity region $|\eta| < 4.2$, where $\eta \equiv -\ln(\tan\theta/2)$. The calorimeters are constructed in a tower geometry in η - ϕ space (ϕ is the azimuthal angle around the beam line). The towers are 0.1 units wide in η and 15^o wide in ϕ in the central region and 5^o wide at larger η (approximately $|\eta| > 1.2$).

The data were recorded using a trigger that required $\sum E_T^{cluster} > 175$ GeV, where the sum is over all calorimeter clusters found by the hardware trigger processor. To reject backgrounds from cosmic ray interactions, beam halo, and detector malfunctions, the events were required to have (i) total energy less than 2000 GeV, (ii) no significant energy deposited in the hadron calorimeters out-of-time with the proton-antiproton collision, (iii) missing E_T ($\not\!\!E_T$) significance [1] $S \equiv \not\!\!E_T \,/(\sum E_T^{towers})^{1/2} < 6$ GeV$^{1/2}$, where the sum is over all calorimeter towers above a given threshold and (iv) a primary vertex reconstructed with $|z| < 60$ cm. These requirements select 749506 events for further analysis.

Jets are reconstructed using a cone algorithm [13] with radius $R \equiv (\Delta\eta^2 + \Delta\phi^2)^{1/2} = 0.7$. Jet energies are corrected [13] for calorimeter non-linearities, energy lost in uninstrumented regions and energy that falls inside the clustering cone from the fragmentation of partons not associated with the hard scatter. The typical correction is 18% for jets of E_T^{jet} =200 GeV falling to 13% for jets of E_T^{jet} = 400 GeV. We do not correct for energy that falls outside the clustering cone because this is taken into account by the parton shower in the HERWIG Monte Carlo program and also to some degree in the NLO QCD calculations.

We measure the differential cross section for events with large total transverse energy, $d\sigma/d\sum E_T^{jet}$, where the sum is over all jets above a given E_T^{jet} threshold after jet energy corrections have been applied. The cross section has been measured for two different choices of E_T^{jet} threshold, $E_T^{jet} > 20$ GeV and $E_T^{jet} > 100$ GeV . When we refer to both samples together the number in parentheses refers to the $E_T^{jet} > 100$ GeV sample. Events with $\sum E_T^{jet} > 320$ GeV are retained (the trigger is fully efficient for events above this $\sum E_T^{jet}$

threshold for both E_T^{jet} thresholds), yielding a sample of 141041(71611) events.

The measured $\sum E_T^{jet}$ spectrum must be corrected for smearing effects caused by the finite experimental E_T^{jet} resolution. To determine the $\sum E_T^{jet}$ resolution of the detector we have used a sample of HERWIG Monte Carlo events that have been passed through the CDF detector simulation. The $\sum E_T^{jet}$ resolution varies between 8% and 10% over the $\sum E_T^{jet}$ range of interest for both choices of E_T^{jet} threshold.

The predicted $\sum E_T^{jet}$ spectra can be parameterized using the following functional form

$$\frac{d\sigma}{d\sum E_T^{jet}} = A \times (1 - \sum E_T^{jet}/\sqrt{s})^{p_6} \times 10^f, \tag{1}$$

where $f = \sum_{i=1}^{5} p_i \log^i(\sum E_T^{jet})$. We convolute this parameterization with the resolution function and compare it to the observed spectra. The best fits to the observed spectra are obtained with the parameters listed in Table 1 which yield a χ^2 of 30(36) for 28 degrees of freedom. To unsmear the observed spectrum we compare the fitted functional forms before and after they are convoluted with the resolution function. This yields a bin-by-bin unsmearing correction that is applied to the cross-section in each bin of measured $\sum E_T^{jet}$. Typical unsmearing corrections for $\sum E_T^{jet} = 320$ GeV are 1.025(0.97) and for $\sum E_T^{jet} = 900$ GeV are 0.94(0.87). The unsmeared cross sections along with the statistical uncertainties are shown in Fig. 1 and given in Table 2.

The systematic uncertainties on the cross section arise from the following sources:

(a) The uncertainty on the absolute energy scale of the calorimeters. The one standard deviation systematic uncertainty on the energy scale is 5.6% at $E_T^{jet} = 20$ GeV dropping to 3.4% at $E_T^{jet} = 100$ GeV [14]. For jets in the rapidity range $1.4 < |\eta| < 2.4$ there is an additional 2% uncertainty on the energy scale relative to the central calorimeter. To evaluate the uncertainty on the measured differential cross section due to the uncertainty on the energy scale we changed the jet energies by one systematic standard deviation and recalculated the unsmearing correction. Increasing the jet energies by one standard deviation causes the unsmeared cross section to increase by 30(25)% at $\sum E_T^{jet} = 320$ GeV and by 38(34)% at $\sum E_T^{jet} = 900$ GeV. Conversely, decreasing the jet energies by one standard deviation causes the unsmeared cross section to decrease by 24(19)% at $\sum E_T^{jet} = 320$ GeV and by 30(37)% at $\sum E_T^{jet} = 900$ GeV. The uncertainty due to the scale is larger than that reported for the inclusive jet cross section

[8] because we are summing only those jets that pass the E_T^{jet} threshold.

(b) The modeling of the resolution functions. The resolution functions have a non-Gaussian tail due to calorimeter non-linearities and energy lost in uninstrumented regions. To estimate the uncertainty on the measured cross section due to our imperfect knowledge of the tails we have recalculated the unsmearing corrections using Gaussian resolution functions. The unsmeared cross section increases or decreases by up to 15(17)% at $\sum E_T^{jet} = 900$ GeV.

(c) The uncertainty in the luminosity measurement (7%).

The overall systematic uncertainty is obtained by combining the individual contributions in quadrature.

The unsmeared data in Fig. 1 are compared to the predictions from NLO QCD. This is a next-to-leading order $2 \to 2$ calculation using the CTEQ4M parton distribution functions (PDFs) [15] and a renormalization and factorization scale of $\mu = 0.5 \sum E_T^{jet}$. We also compare the data to predictions from the HERWIG parton shower Monte Carlo program [4]. The HERWIG curve was generated using CTEQ2L parton distributions and a scale of $Q^2 = stu/2(s^2+t^2+u^2)$ for the hard $2 \to 2$ process. In Fig. 1 the QCD predictions have been normalized to the data between $\sum E_T^{jet} = 320 - 480$ GeV for both E_T^{jet} thresholds. For $E_T^{jet} > 20$ GeV , this yields a normalization factor of 1.43 for the NLO QCD prediction using the CTEQ4M PDF. The large normalization factor indicates that the NLO $2 \to 2$ calculation is not adequate to describe the rate of events at large $\sum E_T^{jet}$. We note that for $E_T^{jet} > 20$ GeV there are more three-jet events than two-jet events in our $\sum E_T^{jet} > 320$ GeV data sample [2] which suggests that $\mathcal{O}(\alpha_s^4)$ corrections to the NLO $2 \to 2$ calculation may be important. In this sample 31% of the events have more than three jets passing the threshold. For $E_T^{jet} > 100$ GeV the normalization factor of 1.01 for the NLO QCD prediction suggests that the NLO calculation can better describe the data once we are in a region where two-jet events dominate. In this sample 95% of the events have only two jets passing the threshold (this fraction falls to about 78% for $\sum E_T^{jet} > 600$ GeV).

We have studied the effect on the predicted cross-section of varying μ. Using $\mu = 0.25 \sum E_T^{jet}$ we obtain a cross-section that is a factor of 1.26 higher for $E_T^{jet} > 20$ GeV and 1.07 higher for $E_T^{jet} > 100$ GeV . The large change for $E_T^{jet} > 20$ GeV suggests that the higher order corrections are significant while the change seen for $E_T^{jet} > 100$ GeV is typical of NLO calculations. The normalization factor for the HERWIG prediction is large for both choices of E_T^{jet} , namely 1.33(1.39). This is to be expected because although HERWIG includes a parton shower, the underlying hard scattering cross section is only LO $2 \rightarrow 2$. The measured total cross section for $\sum E_T^{jet} > 320$ GeV is $1.34^{+0.44}_{-0.36}$ nb for $E_T^{jet} > 20$ GeV and $0.64^{+0.17}_{-0.15}$ nb for $E_T^{jet} > 100$ GeV . The errors are the one standard deviation systematic uncertainties. The statistical uncertainties are negligible. The total cross section for NLO QCD using the CTEQ4M PDF is 930(630)pb. The total cross sections obtained using the different PDFs are similar.

The observed spectra are harder than the NLO QCD and HERWIG predictions above about 500 GeV for both choices of E_T^{jet} threshold. This effect is similar to the one seen in the inclusive jet cross section [8]. It can be seen more clearly in Fig. 2 where we show the ratio of the data divided by the theoretical predictions. The theory has not been normalized to the data allowing both the normalization and the shape to be compared. The systematic uncertainty is shown relative to the solid circles (NLO QCD and CTEQ4M parton distributions). Comparisons with NLO QCD using the MRSA [16] and GRV94 [17] parton distributions yield similar normalization factors and shapes.

Recently, the CDF high-E_T^{jet} (> 200 GeV) inclusive jet data have been included in the CTEQ4HJ global parton distribution fits [9]. With respect to the predictions using the previous PDFs, an increase of 25-30% in the cross section at high-E_T^{jet} is predicted due to an increase in the gluon density in the proton. Figure 2 shows the data divided by the theoretical predictions for the CTEQ4HJ PDF. The ratio at high $\sum E_T^{jet}$ is reduced by about a factor of 1.25 relative to CTEQ4M for both E_T^{jet} thresholds.

We next compare the excess observed at large $\sum E_T^{jet}$ with the excess previously observed in the inclusive jet cross section at large E_T^{jet}. In the approximation that all events are two-jet events, the inclusive jet cross section should be twice the magnitude of the $\sum E_T^{jet}$ cross section. The $\sum E_T^{jet}$ data sample presented here has no requirement on the η of the jets whereas the measured inclusive jet cross section is limited to jets in the range $0.1 < |\eta| < 0.7$. To make the comparison we recalculate the $\sum E_T^{jet}$ using only those jets that have $E_T^{jet} > 100$ GeV and $0.1 < |\eta| < 0.7$. The NLO QCD prediction calculated using the CTEQ4M PDF yields an integrated excess cross section for $\sum E_T^{jet} > 700$ GeV of 0.36 ± 0.09 pb. In the inclusive jet differential cross section there is an integrated excess of 0.67 ± 0.22 pb above

$E_T^{jet} = 326$ GeV (using the CTEQ3M PDF). Under the assumption that all the events with $\sum E_T^{jet} > 700$ GeV are two-jet events (75% of the events have two jets with $E_T^{jet} > 320$ GeV) then we would expect to see an excess of 0.72 ± 0.18 pb in the inclusive jet cross section which is consistent with the observed excess.

In summary, we have measured the differential cross section ($d\sigma/d\sum E_T^{jet}$) for two different E_T^{jet} thresholds using a sample of events whose kinematic properties have been previously found to be in agreement with predictions from LO QCD. For the $E_T^{jet} > 100$ GeV sample, which is dominated by two-jet events, the observed event rate is well reproduced by the NLO QCD calculation. The $E_T^{jet} > 20$ GeV sample is no longer dominated by two-jet topologies and there is a larger dependence of the predictions on the choice of renormalization and factorization scale. Given this uncertainty, there is reasonable agreement between the data and the predictions. The HERWIG parton shower Monte Carlo underestimates the event rate for both jet thresholds, presumably because the predicted cross section is based on the LO $2 \rightarrow 2$ scattering matrix element. Compared to current NLO QCD predictions these spectra exhibit an excess of events at large $\sum E_T^{jet}$ which is consistent with the excess we have previously reported in the inclusive jet cross section. Use of the new parton distribution functions that include the high-E_T^{jet} jet data decreases the disagreement by about 25%.

We thank the Fermilab Accelerator Division and the technical and support staff of the participating institutions for their vital contributions. This work was supported by the U.S. Department of Energy and the National Science Foundation; the Istituto Nazionale di Fisica Nucleare of Italy; the Ministry of Science, Culture and Education of Japan; the Natural Sciences and Engineering Research Council of Canada; the National Science Council of the Republic of China and the A.P. Sloan Foundation.

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[7] $E_T^{jet} = E^{jet} \sin\theta$ where θ is the polar angle with respect to the beam line and E^{jet} is the jet energy.

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Parameter	$E_T^{jet} > 20$ GeV	$E_T^{jet} > 100$ GeV
p_1	-4.905	-7.490
p_2	0.868	0.864
p_3	-0.099	-0.130
p_4	-0.097	-0.053
p_5	0.013	0.023
p_6	5.586	11.998
A (pb/GeV)	8.030×10^{12}	1.874×10^{17}

Table 1: Parameters for the fit to the unsmeared $\sum E_T^{jet}$ spectra using Eq. (1).

	$E_T^{jet} > 20$ GeV		$E_T^{jet} > 100$ GeV	
Bin (GeV)	$\langle\sum E_T^{jet}\rangle$ (GeV)	$d\sigma/d\sum E_T^{jet}$ (pb/GeV)	$\langle\sum E_T^{jet}\rangle$ (GeV)	$d\sigma/d\sum E_T^{jet}$ (pb/GeV)
$320-360$	337.2	$(1.86 \pm 0.01) \times 10^1$	337.2	$(8.49 \pm 0.04) \times 10^0$
$360-400$	377.4	$(7.90 \pm 0.04) \times 10^0$	377.6	$(3.80 \pm 0.03) \times 10^0$
$400-440$	417.6	$(3.59 \pm 0.03) \times 10^0$	417.6	$(1.84 \pm 0.02) \times 10^0$
$440-480$	457.5	$(1.69 \pm 0.02) \times 10^0$	457.7	$(9.34 \pm 0.15) \times 10^{-1}$
$480-520$	497.7	$(8.10 \pm 0.14) \times 10^{-1}$	497.8	$(4.63 \pm 0.10) \times 10^{-1}$
$520-560$	538.0	$(4.11 \pm 0.10) \times 10^{-1}$	538.3	$(2.63 \pm 0.08) \times 10^{-1}$
$560-600$	577.6	$(2.13 \pm 0.07) \times 10^{-1}$	577.7	$(1.25 \pm 0.05) \times 10^{-1}$
$600-650$	625.6	$(9.21 \pm 0.38) \times 10^{-2}$	625.8	$(6.02 \pm 0.3) \times 10^{-2}$
$650-700$	686.1	$(3.84 \pm 0.24) \times 10^{-2}$	684.6	$(2.68 \pm 0.2) \times 10^{-2}$
$700-800$	749.3	$(1.43 \pm 0.13) \times 10^{-2}$	751.5	$(9.77 \pm 1.03) \times 10^{-3}$
$800-1120$	855.3	$(1.29 \pm 0.18) \times 10^{-3}$	852.3	$(8.74 \pm 1.44) \times 10^{-4}$

Table 2: $d\sigma/d\sum E_T^{jet}$. The $\langle\sum E_T^{jet}\rangle$ is the mean value within a bin and the uncertainties are statistical only.

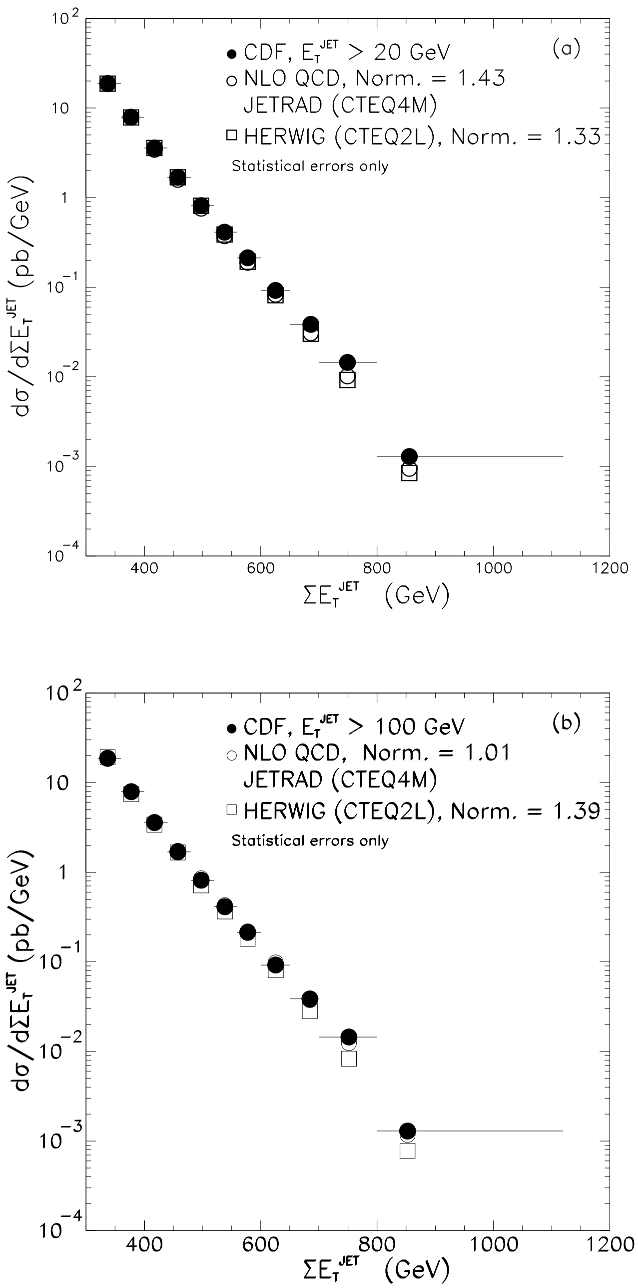

Figure 1: The unsmeared $\sum E_T^{jet}$ differential cross section compared to the predictions from HERWIG and from NLO QCD for (a) $E_T^{jet} > 20$ GeV and (b) $E_T^{jet} > 100$ GeV .

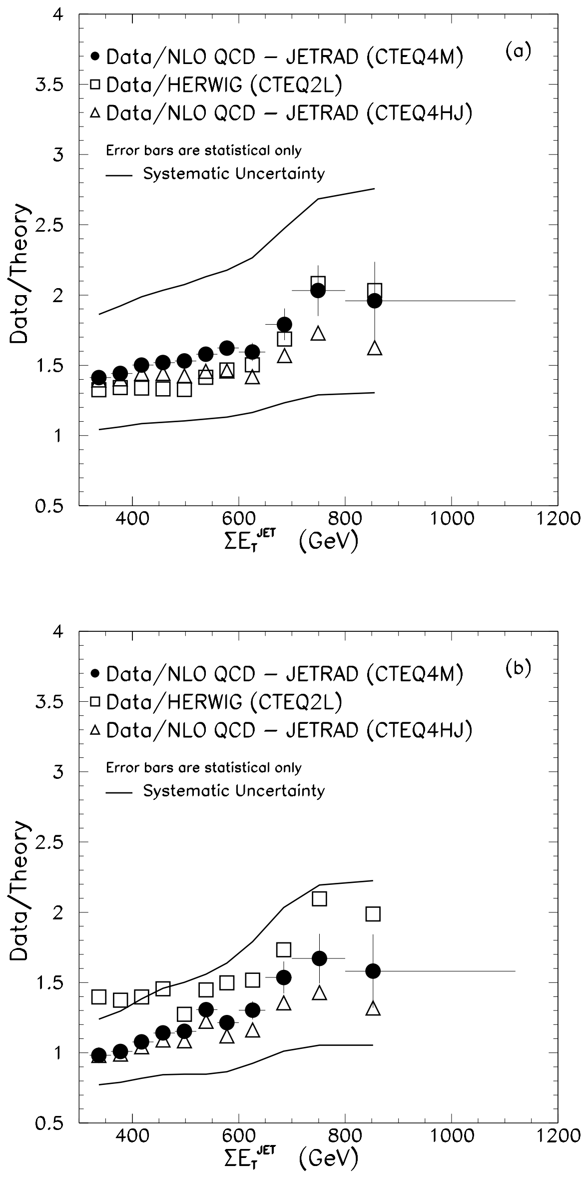

Figure 2: The unsmeared $\sum E_T^{jet}$ cross section divided by HERWIG and by NLO QCD (DATA/THEORY). Each set of points is DATA/THEORY using different parton distributions as indicated on the figure. The error bars are only shown on one set of points for the sake of clarity. The systematic uncertainties are shown with respect to the solid points. (a) $E_T^{jet} > 20$ GeV , (b) $E_T^{jet} > 100$ GeV .