Fermi National Accelerator Laboratory

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CDF

Measurement of Jet Multiplicity in W Events Produced in $p\bar{p}$ Collisions at $\sqrt{s} = 1.8$ TeV

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Abstract

The W production cross section times the branching ratio for $W \rightarrow l\nu$, $l = e, \mu$ decays has been measured as a function of the associated jet multiplicity. The data have been recorded at the Collider Detector at Fermilab during the 1988-89 run. A recent leading order QCD calculation agrees well with the data up to a jet multiplicity of 4.

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The theory of Quantum chromodynamics (QCD) accounts for associated production of W bosons and hadron jets, first observed at the CERN $p\bar{p}$ collider. The study of the characteristics of the W+jet events provides a strong test of the QCD model. Previous studies made at the CERN and Fermilab colliders [1] indicate a good agreement between data and QCD predictions. A recent tree level calculation allows for the first time to study W+jet topologies up to four jets [2]. Deviations from the predictions in W events with high jet multiplicity could indicate the presence of new physics. We report a measurement of the W cross section times the branching ratio of $W \rightarrow l\nu$, $l = e, \mu$ as function of the associated jet multiplicity. The study is based on samples of $W \rightarrow e\nu$ and $W \rightarrow \mu\nu$ events accumulated at the Collider Detector at Fermilab (CDF) during the 1988-1989 run.

The CDF detector is described in detail elsewhere [3]. The detector elements most relevant to this analysis are briefly described here. The event vertex is located along the beam line by a set of time projection chambers with a resolution of 1 mm. The momenta of charged tracks are measured by a drift chamber (CTC) which is immersed in a 1.4 T axial magnetic field and has a resolution of $\delta P_T/P_T = 0.0011 P_T$ (P_T in GeV/c). Outside the solenoid, the calorimeter is organized in electromagnetic (EM) and hadronic (HAD) compartments with a projective tower granularity $\Delta\eta \times \Delta\phi = 0.1 \times 15^\circ$ up to a pseudorapidity $|\eta| = |\ln(\tan\theta/2)| \leq 1.1$, θ being the polar angle from the proton beam direction, and $\Delta\eta \times \Delta\phi = 0.1 \times 5^\circ$ in the region $1.1 \leq |\eta| \leq 4.2$. Outside the central calorimeter, the region $|\eta| \leq 0.63$ is instrumented with four layers of drift chamber for muon detection (CMU).

The $W \rightarrow l\nu$ candidates, $l = e, \mu$, used in this analysis are selected from data samples of lepton-triggered events by imposing very strict lepton identification criteria [4, 5]. The electron identification is restricted to the kinematic region $|\eta| \leq 1.1$ and $E_T \geq 20$ GeV, where E_T is the electron energy transverse to the beam direction. The muon candidates, detected within the fiducial volume of the CMU, are required to have transverse momentum $P_T \geq 20$ GeV/c. The identification efficiency is estimated to be $\epsilon_e = 84.0 \pm 3.0\%$ for electrons and $\epsilon_\mu = 90.4 \pm 3.8\%$ for muons, after fiducial cuts are applied. A lepton isolation requirement imposes that the total transverse energy contained in an annulus of outer radius $R = (\Delta\eta^2 + \Delta\phi^2)^{\frac{1}{2}} = 0.4$ surrounding the calorimeter tower hit by the lepton be less than 10% of the lepton $E_T(P_T)$. The missing transverse energy vector is defined as

$$\not{\mathbf{E}}_\mathbf{T} = -\sum_i E_T^i \hat{\mathbf{n}}_\mathbf{i}, \quad i = \textit{calorimeter tower number with } \mid \eta \mid \leq 3.6$$

where $\hat{\mathbf{n}}_\mathbf{i}$ is a unit vector perpendicular to the beam axis and pointing to the i-th calorimeter tower. We require $\not{E}_T = \mid \not{\mathbf{E}}_\mathbf{T} \mid \geq 20$ GeV. The selected inclusive W sample consists of 2508 events contributed by the electron sample and 1431 by the muon sample, corresponding respectively to an integrated luminosity of 4.05 ± 0.28 pb^{-1} and 3.54 ± 0.24 pb^{-1}.

Jets have been identified in the calorimeter using a cone algorithm in $\eta - \phi$ space with radius $R = (\Delta\phi^2 + \Delta\eta^2)^{\frac{1}{2}} = 0.7$ [6]. The transverse jet energy is defined as $E_T^{jet} = E^{jet} \sin\theta^{jet}$ where E^{jet} is the sum of the energy deposited in each tower within the clustering cone and θ^{jet} is the polar angle of the jet axis. The jets used in this analysis are within a calorimeter region $|\eta^{jet}| \leq 2.4$ and have observed $E_T^{jet} \geq 10$ GeV. A requirement on the separation between the lepton and the closest jet of $\Delta R \geq 0.7$, intrinsically present in the electron sample, has been imposed on the muon sample for consistency. The E_T^{jet} measured in the detector differs from the transverse energy of the original parton due to detector performance and to fluctuations in fragmentation and in the soft process accompanying the hard interaction. In the following the measured E_T^{jet} is corrected for these effects. In a first step E_T^{jet} is corrected for non-uniformity of calorimeter response as a function of η^{jet} using an η-map of the calorimeter derived by imposing jet balancing on a large statistics sample of two-jet events [6]. Using Monte Carlo events [2], the second step corrects E_T^{jet} back to the transverse energy of the fragmented partons. The jet to parton relation is defined in the following way: the corrected E_T^{jet} of each jet is the transverse energy contained in a cone of radius $R = 0.7$ opened around the reconstructed jet axis at the fragmentation level; the cone contains part or all of the fragments coming from the initial parton hadronization and other particles contributed by the underlying event.

The VECBOS event generator is based on a tree-level matrix element of the W+0,1,2,3,4 jet processes [2]. Monte Carlo $W \rightarrow l\nu$ samples with jet multiplicities up to 4 have been produced requiring parton transverse momenta larger than 8 GeV/c, pseudo-rapidity $\mid \eta \mid < 2.5$ and a separation $\Delta R \geq 0.6$ between partons [7]. These cuts regularize infrared and collinear divergencies in the QCD calculation and have negligible effects in the kinematical region of interest in this analysis. We have used 3 sets of structure functions, DO1, EHLQ1 and MRSB2, and two different renormalization scales , $Q^2 = M_W^2$ and $Q^2 = < P_T >^2$, respectively the W mass squared and the average partonic P_T squared. We estimate an uncertainty of 7% on the cross section associated with the choice of the structure function. The partons generated by VECBOS were hadronized using a Field-Feynman fragmentation function tuned on CDF data [8]. Experimental effects are reproduced by a full detector simulation.

The uncorrected jet E_T spectrum and η distribution of the leading and second to leading jets in the event are shown respectively in Figs. 1a, 1c, 1b and 1d. Electron and muon data are shown together; the Monte Carlo distributions ($Q^2 = < P_T >^2$) are normalized to the exclusive W+1 jet and W+2 jet data samples. The minimum E_T^{jet} cut is 10 GeV on uncorrected energy for both data and simulated events. Data and Monte Carlo show good agreement.

The observed jet multiplicity distribution is related to the W cross section times the branching ratio B for each multiplicity by:

$$\sigma(W + n\ jets)B(W \rightarrow l\nu) = \sigma_n B = \frac{N_n - BG_n}{\epsilon_W\ \epsilon_n^j\ \mathcal{L}}, \quad n = 0 \div 4$$

where N_n is the number of W events containing n jets with corrected $E_T^{jet} \geq 15$ GeV, BG_n is the number of background events with jet multiplicity n (corrected $E_T^{jet} \geq 15$ GeV), ϵ_W and ϵ_n^j are the efficiencies for W and jets respectively and $\mathcal{L}$ is the integrated luminosity. To compare the measured cross section directly to the QCD predictions we define parton-jets in the Monte Carlo samples as cones in the final state centered around the initial parton direction. The transverse energy in the cones must be larger than 15 GeV and the magnitude of the pseudorapidity smaller than 2.4.

The largest background in the W data sample results from W decays to τ and neutrino, followed by the decay of the τ into lepton and neutrino, and from Z bosons decaying to dileptons. The latter background arises due to cracks or limited detector acceptance that cause one of the two leptons to be mismeasured and detected as a large missing energy. Simulated background samples were normalized to the observed events using the estimated acceptances for these topologies. The background contamination is estimated to be $5.5 \pm 0.7\%$ and $13.2 \pm 1.3\%$, respectively for electrons and muons. A second background comes from heavy quark and multijet QCD production, globally referred to as QCD background. In this case the presence of an isolated high P_T lepton and missing energy can be faked due to fluctuations in jet measurement and fragmentation. The amount of QCD background is found by extrapolating the $\not{E}_T$ distribution for isolated leptons into our signal region, using the $\not{E}_T$ shape of the non-isolated leptons [4]. The jet multiplicity distribution arising from the QCD background has been estimated by studying the differences in shape between the multiplicity distributions for isolated and non-isolated low $\not{E}_T$ samples. Correction factors reproducing the effect of the isolation cut have been applied to the shape of the multiplicity distribution for a non-isolated sample in the region $\not{E}_T \geq 20$ GeV. A small contribution from cosmic rays is taken into account for the muon topology containing no jets. The results are shown in Table I.

Details of the W acceptance and the efficiency are in [4, 5]. The values of ϵ_W as function of the jet multiplicity are reported in Table II. The systematic uncertainties of the W acceptance take into account the variations in parton distribution functions, the W P_T and the value of $\sin^2\theta_W$. The uncertainty for the efficiency ϵ_W was obtained by varying each selection cut independently.

For each multiplicity n, ϵ^j_n is defined as the ratio of the number of events that have multiplicity n after reconstruction to the number of events that have been generated with multiplicity n ; the parton-jets must have $E_T \geq 15$ within $|\eta| \leq 2.4$. The reconstructed multiplicity n includes the contributions of processes generating n, $n+1$, $n-1$ parton-jets, normalized to each other according to their cross sections (Table II). The quantity ϵ^j_n also takes into account: 1) jet finding efficiency, 2) fluctuations in the underlying event, 3) the contribution to jet counting by jets with uncorrected measured energy smaller than 10 GeV and corrected energy larger than 15 GeV, 4) smearing of the reconstructed jet axis with respect to the parton direction and 5) overlap between the cones defining the parton jets.

The systematic uncertainties associated with the jet energy scale have been estimated. The systematic uncertainties result mainly from the jet energy scale due to uncertainties on the calorimeter response, fragmentation tuning, underlying event energy falling within the clustering cone and modeling of the single pion response. The uncertainty on the cross sections due to these sources ranges typically from 7% to 15%, increasing with the jet multiplicity. A second relevant uncertainty is contributed by the broad jet energy resolution which smears the E_T^{jet} cut and varies from 2% to 7% of the cross section.

The resulting cross sections with statistical and systematic errors are summarized in Table III. The first two columns report the cross sections times branching ratio measured separately in the muon and electron samples, for a corrected $E_T^{jet} \geq 15$ GeV and a pseudorapidity $|\eta^{jet}| \leq 2.4$. The third column shows the combined value of the electron and muon measurements, $\sigma_n B$ [9]. The systematic uncertainty includes in quadrature contributions from the uncertainty on background, W and jet efficiency, jet energy scale, detector resolution and luminosity measurement. The QCD predictions are also reported in Table III. The errors account for structure functions and fragmentation. Figure 2 shows the combined measured W cross section as function of the multiplicity as well as the absolute QCD predictions for the two different Q^2 scales used.

Summarizing, we have measured the W cross section times branching ratio of $W \to l\nu$, $l = e, \mu$ as a function of an associated jet multiplicity up to 4. The values of $\sigma_n B$ obtained from separate samples of electron and muons are in very good agreement. The total inclusive σB is consistent with our published values [4, 5]. The relative jet rates as well as the shape of the kinematical distributions of the data are well reproduced by QCD. The tree level calculations of the cross sections are sensitive to the choice of the Q^2 scale used for the evaluation of the coupling constant $\alpha(Q^2)$. The dependence on Q^2 increases with the jet multiplicity, since the coupling constant is raised to higher and higher powers. The ratio of the cross sections calculated at the two scales used varies from 1.3 (W+1 jet) to 2.1 (W+4 jets). The data indicate to favor Q^2 scales lower than $Q^2 = M_W^2$ and no significant deviation from the QCD prediction is observed, within the present uncertainties.

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Source		0 jets(%)	1 jets(%)	2 jets(%)	3 jets(%)	4 jets(%)
QCD	e	1.8 ± 0.3	4.7 ± 1.1	5.7 ± 2.7	1.7 ± 3.3	1.7 ± 3.3
	μ	2.5 ± 0.5	3.6 ± 1.3	7.8 ± 3.7	1.7 ± 3.3	1.7 ± 3.3
Total	e	7.3 ± 0.8	10.2 ± 1.3	11.2 ± 2.8	7.2 ± 3.4	7.2 ± 3.4
	μ	16.1 ± 1.4	16.8 ± 1.8	21.0 ± 4.0	14.9 ± 3.5	14.9 ± 3.6

Table I: QCD background in the electron and muon samples for the different jet multiplicities (corrected $E_T^{jet} \geq 15$ GeV). The total backgrounds include the non-signal bosons contribution.

Jet mult.	$\epsilon_W^{electron}(\%)$	$\epsilon_W^{muon}(\%)$	$\epsilon_n^j(\%)$
0	25.5 ± 2.3	15.7 ± 1.0	$100.3^{+3.7}_{-3.7}$
1	25.0 ± 2.5	15.2 ± 1.0	$98.7^{+3.6}_{-3.3}$
2	24.6 ± 2.5	14.4 ± 1.0	$98.8^{+7.2}_{-6.3}$
3	23.1 ± 2.5	13.7 ± 1.0	$95.5^{+8.9}_{-8.7}$
4	22.5 ± 2.5	13.3 ± 1.0	$96.6^{+13.4}_{-14.8}$

Table II: Summary of the efficiencies. Statistic and systematic errors are combined in quadrature.

Jet mult.	$\sigma_n^e B$(pb)	$\sigma_n^\mu B$(pb)	$\sigma_n^{combined} B$(pb)	$\sigma_{QCD}^{M_W^2} B$(pb)	$\sigma_{QCD}^{<P_T>^2} B$(pb)
0	$1810.0 \pm 40.2^{+228.0}_{-228.0}$	$1652.8 \pm 49.5^{+172.7}_{-172.7}$	$1739.8 \pm 31.2^{+287.7}_{-287.7}$	$1753.0 \pm 25.6^{+122.7}_{-122.7}$	
1	$347.2 \pm 17.7^{+48.6}_{-52.3}$	$321.0 \pm 22.2^{+39.1}_{-43.0}$	$336.4 \pm 13.8^{+60.2}_{-63.1}$	$287.4 \pm 3.9^{+20.9}_{-20.9}$	$359.5 \pm 5.2^{-22.7}_{-22.7}$
2	$71.4 \pm 8.0^{+11.9}_{-13.0}$	$86.0 \pm 11.5^{+13.6}_{-15.0}$	$76.1 \pm 6.6^{+17.5}_{-18.3}$	$58.6 \pm 1.8^{+4.5}_{-4.6}$	$91.3 \pm 2.1^{-6.1}_{-8.5}$
3	$15.6 \pm 4.0^{+3.0}_{-3.3}$	$12.6 \pm 4.8^{+2.2}_{-2.5}$	$14.3 \pm 3.1^{+3.2}_{-3.4}$	$11.2 \pm 0.3^{+0.9}_{-1.0}$	$20.4 \pm 1.3^{-1.5}_{-2.2}$
4	$4.2 \pm 2.1^{+1.1}_{-1.1}$	$3.7 \pm 2.6^{+0.9}_{-0.9}$	$4.0 \pm 1.6^{+1.1}_{-1.2}$	$2.0 \pm 0.1^{+0.2}_{-0.3}$	$4.1 \pm 0.3^{-0.3}_{-0.5}$

Table III: W + jets cross section for corrected $E_T^{jet} \geq 15$ GeV measured in electron and muon channel and QCD predictions for two Q^2 scales. The errors are statistic and systematic respectively.

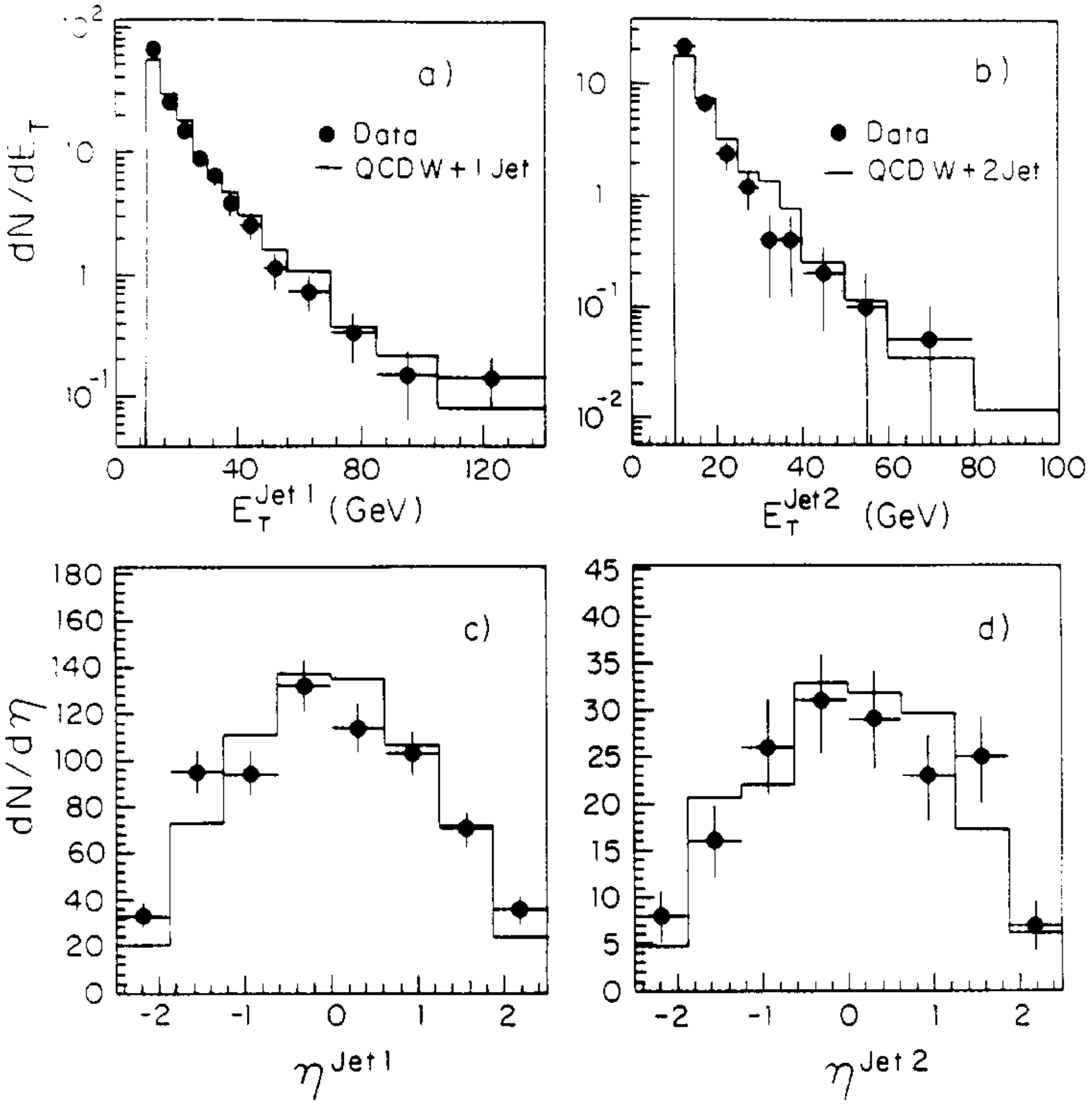

Figure 1. The uncorrected E_T and η exclusive distributions for the leading (1a, 1c) and second to leading jet (1b, 1d). The histogram represents the Monte Carlo predictions after detector simulation. The Q^2 scale used is $Q^2 = < P_T >^2$.

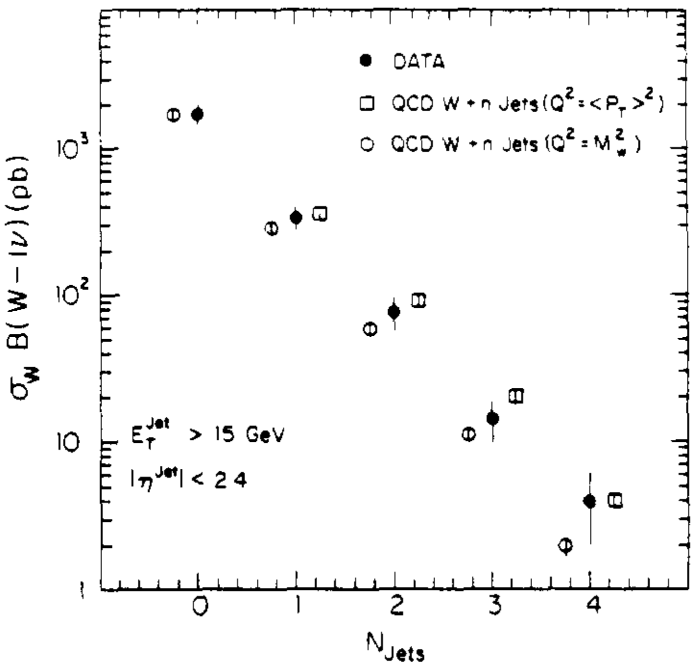

Figure 2. W cross section times leptonic branching ratio for corrected $E_T^{jet} \geq 15$ GeV as a function of jet multiplicity. The data are the combined result of separate measurements in the muon and electron samples. The QCD predictions are estimated at two different Q^2 scales and include hadronization. The jets are clustereded at $R = 0.7$.