Fermi National Accelerator Laboratory

FERMILAB-Conf-96/275-E

CDF

W and Z Boson Plus Jets Production at CDF

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September 1996

Published Proceedings of the *XIth Topical Workshop on ppbar Collider Physics*, Padova, Italy, May 27-June 1, 1996.

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

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CDF/Pub/Jet/Public/3760

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The CDF Collaboration

We have studied the production properties of W and Z bosons at CDF, and have measured the jet multiplicity cross sections and various kinematic distributions. We find good agreement with leading order QCD predictions with added gluon radiation and simulated parton fragmentation.

Tevatron collider events that contain either a W or a Z boson provide a particularly clean dataset for testing QCD and for looking for new and interesting physics. The heavy boson insures that the parton-level process involves a large momentum transfer (Q^2), and therefore is calculable using perturbative QCD. The leptonic decays of these bosons are easy to identify. We study the production of jets in these events to test the QCD calculations. Furthermore, once we understand the calculations, we can then look for deviations from QCD to look for new and interesting physics. For example, top quarks decay into W's and jets, dibosons will show up in W and Z plus jets, and a heavy Higgs is expected to produce W's plus jets. Other new and unexpected physics might also show up in this channel. A thorough understanding of the QCD production of W and Z bosons, in addition to improving our understanding of QCD, will help look for and study these other physics phenomena.

The W and Z boson samples each have separate advantages. The Z sample is particularly clean, with low backgrounds and with both lepton decay products well measured. The W sample has higher backgrounds and the longitudinal momentum of the neutrino from leptonic decays cannot be measured, but many more W bosons are produced than Z's, so the statistical uncertainties are much smaller.

This analysis is done with 108 pb^{-1} of $\bar{p}p$ data collected by the CDF collaboration during Fermilab Run 1, from 1992 to 1995. W and Z boson events are identified by looking for their electronic decays. We use a common selection criteria for a good central electron with transverse energy Et $>$ 20 GeV from the boson decay [1] to aid in the comparison between the W and Z samples. The Z sample is then selected by requiring a second electron with looser cuts that forms an invariant mass with the first electron that is within 15 GeV of the nominal Z mass of 91 GeV. These criteria select 6708 $Z \to e^+e^-$ candidate events from a 106 pb^{-1} subsample. Events are W candidates if they have a

Published Proceedings XI Topical Workshop on $p\bar{p}$ Collider Physics, Padova, Italy, May 27-June 1, 1996

Table 1: Raw jet multiplicities for both the $W^{\pm} \rightarrow e^{\pm}\nu$ and $Z \rightarrow e^{+}e^{-}$ datasets.

	$W(e\nu)$	$Z(ee)$
≥ 0 jets	51431	6708
≥ 1 jets	11144	1310
≥ 2 jets	2596	279
≥ 3 jets	580	57
≥ 4 jets	126	11

missing Et greater than 30 GeV and if they are not Z candidates. The missing Et is calculated using corrected jet and electron energies, and with a correction factor applied to the unclustered energy. A total of 51431 W candidates are selected by these criteria. Note that for both the W and the Z candidates, the electrons are required to be separated from the jets in the event (described below) by at least $\Delta R > 0.52$, where $R = \sqrt{\Delta\phi^2 + \Delta\eta^2}$. Here ϕ is the azimuthal angle about the beam direction and η is the pseudorapidity.

In order to test QCD, we examine the jets in the boson events. We cluster the jets with a cone size of $R = 0.4$ and correct the jet Et for underlying-event energy, out-of-cone energy, and energy from additional interactions in the same beam crossing. We then select events with $E_t > 15$ GeV and $\eta > 2.4$ (assuming the interaction were at the center of the detector). Jets that are separated by less than 1.3 times the cone size of 0.4 are merged, but this is a rare occurrence. The raw jet multiplicities for the W and Z datasets are shown in Table 1.

We calculate the cross sections for the different jet multiplicities by measuring the ratio of the number of events with $\geq n$ jets with the number of events in the inclusive sample (i.e. ≥ 0 jets). We multiply this ratio by the inclusive cross section and the appropriate ratio of efficiencies to get σ_n (the cross section for events with $\geq n$ jets). This procedure minimizes the systematic uncertainty in the measurement. The ratio of efficiencies are determined from a sample of Z events where the electrons from the Z decay are removed, and a Monte Carlo simulation is used to redecay the boson many times with the same momentum but different decay angles. This gives a realistic estimate of the electron overlap with jets.

There are two types of background in this analysis: boson candidate events that either are not bosons or were not produced directly by QCD, and jet which either are not jets, or did not come from the interaction which produced the boson. The first type of background affects the measurement of the cross sections, while the second type of background affects the jet multiplicity

distribution without affecting the total number of events.

The largest background to the bosons comes from QCD events faking the W and Z signatures. We determine the size of this background by studying the isolation distributions of the electrons. Electrons from W or Z boson decays are expected to be isolated, while many of the fake electrons from QCD are not isolated. We estimate the number of QCD background events by assuming that the electron isolation is independent of the invariant mass (for Z's) or the missing E_T (for W's), measuring the QCD background in a region where no signal is expected, and extrapolating into the signal region. We find small backgrounds for the Z sample, ranging from 1% for the inclusive events to 4% for events with 3 or more jets. The QCD backgrounds in the W sample are higher, ranging from 3% for all events to 24% for events with 4 or more jets. Other backgrounds to the W sample, such as the contribution from top quark decays, are much smaller and we estimate these using Monte Carlo events which are processed through a detector simulation and our analysis code.

A significant fraction of events in these data samples have additional interactions in the same beam crossing with the interaction that produced the heavy boson. We apply corrections, based upon the number of high-multiplicity vertices, to the jet energies that remove on average the energy from these additional interactions. However, some of these additional interactions have jets that pass our selection criteria by themselves. We count the number of these jets in a minimum-bias data sample, and normalize with the number of high-multiplicity vertices. We correct the cross sections and the differential distributions for these extra jets. The corrections for these extra jets range from 3% to 5%. There is a similar contribution from direct photons which are treated as jets, although these corrections have only been applied to the Z sample at this point.

The resulting cross sections as a function of jet multiplicity for both W and Z bosons are shown in Figure 1. Also shown in this Figure are the QCD predictions. We obtain these leading-order matrix-element predictions from the VECBOS [2] Monte Carlo program using MRSA′ or CTEQ3M structure functions (which give results which are indistinguishable within the errors of the measurement), two-loop α_s evolution, a factorization scale of $Q^2 = M^2 + P_t^2$, and a renormalization scale varying from a low of $Q^2 =< P_t >^2$ to a high of $Q^2 = M^2 + P_t^2$. Simulated events are produced from the parton-level events by including gluon radiation and hadronic fragmentation using the HERWIG [3] shower simulation algorithm.

The lower $Q^2 =< P_t >^2$ gives results that are closer to the measurement, but the variation with jet multiplicity differs from the data. The predictions with $Q^2 = M^2 + P_t^2$ give a constant ratio with the data, which is approximately

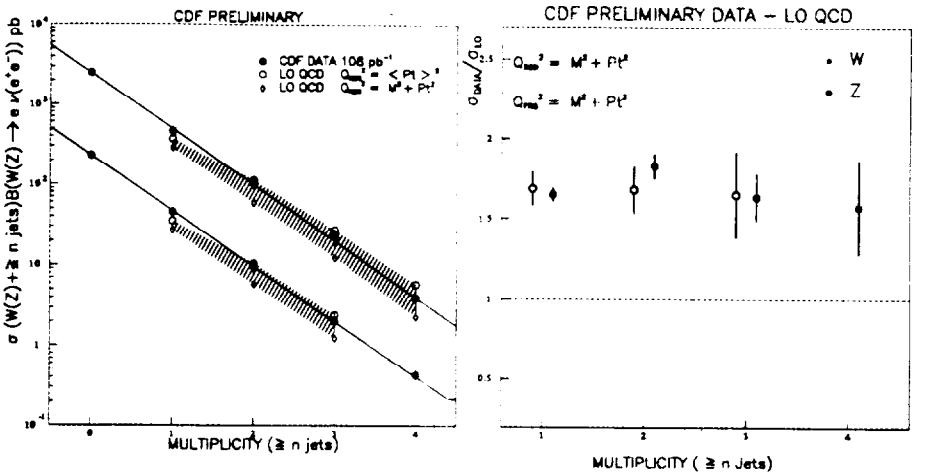

Figure 1: The solid circles are the measured W (top) and Z (bottom) cross sections for $\geq n$ jets. The band indicates the range of QCD predictions as the Q^2 for the renormalization scheme is changed from a low of $Q^2 =< P_t >^2$ (top of band) to a high of $Q^2 = M^2 + P_t^2$ (bottom of band). The fragmentation scale for the Monte Carlo points is $Q^2 = M^2 + P_t^2$. The plot on the right shows the ratio of the data to the prediction with renormalization $Q^2 = M^2 + P_t^2$. This is constant, and similar for both W's and Z's.

1.7 times larger than the prediction. The behavior is remarkably similar for the W and Z bosons. We do not simulate the electron nor do we apply boson selection criteria to make these QCD cross section predictions.

In addition to the jet multiplicity cross sections, we have also examined a number of jet production properties in the boson events. We correct the differential plots of these different production properties for the QCD background and the background caused by jets from extra interactions. The Z boson distributions are corrected for photons treated as jets, and the W boson distributions are corrected for contributions from top quark decays. We compare these to QCD calculations using the same programs used for the cross section calculation, with the exception that the electrons are simulated and the boson selection cuts are applied. The plots showing the E_T distributions of the first three jets (ordered by E_T) are shown in Figure 2. Figure 3 shows the separation between the highest two E_T jets in Z and W events with two or more jets.

The relative sizes and shapes of the different contributions to the W dataset can be seen in Figure 4, which shows the jet-jet invariant mass for events with two or more jets. The bottom plot includes some contributions to the W sample from sources other than direct QCD W production. Note that events with fewer jets have significantly less background and top contribution than

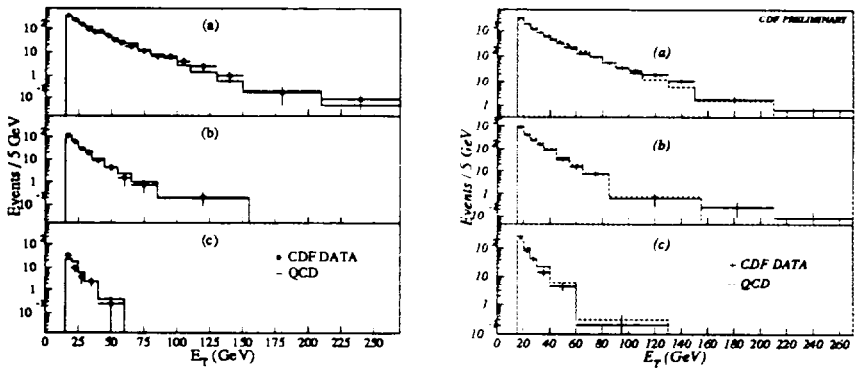

Figure 2: The E_T of the first (a), second (b), and third (c) highest E_T jets in events with ≥ 1, ≥ 2, and ≥ 3 jets, respectively. The left plot has Z events while the right plot has W events.

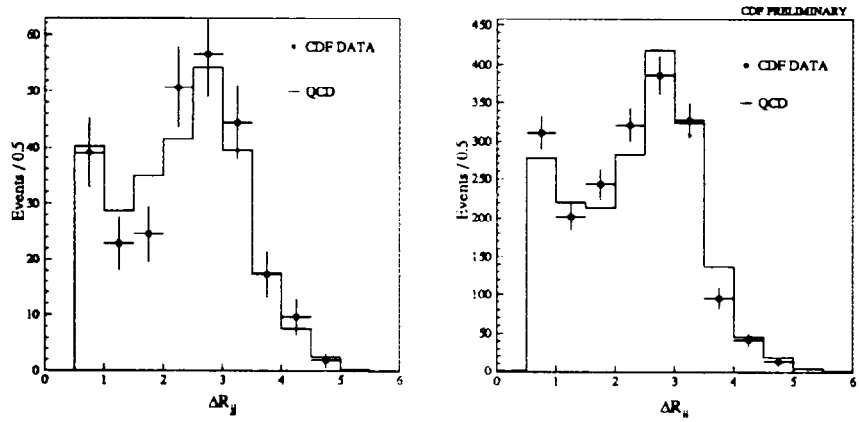

Figure 3: The angular distance between jets in Z (left) and W (right) events with ≥ 2 jet.

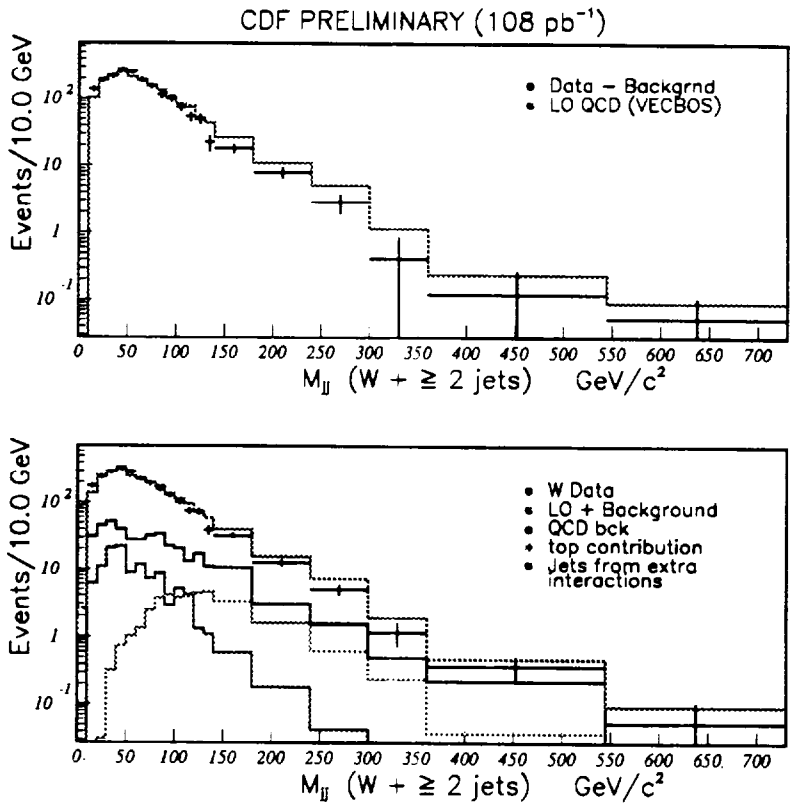

Figure 4: The invariant mass of the two highest E_T jets in W events with ≥ 2 jets. The top plot compares background-subtracted data to leading order (LO) QCD predictions, while the bottom plot compares raw data to the sum of the LO QCD prediction and contributions from backgrounds and top quark decays.

the events with two or more jets shown here.

This paper contains an analysis of jet production properties associated with $Z \rightarrow e^+e^-$ and $W^\pm \rightarrow e^\pm\nu$ events selected from 108 pb^{-1} of $\overline{p}p$ collisions at a center of mass energy of 1.8 TeV. Comparisons are made between the data and LO parton matrix elements with HERWIG-simulated fragmentation to determine the reliability of this QCD calculation. The QCD-predicted jet production properties are in reasonable agreement with the measured spectra.

Acknowledgments

We thank the Fermilab staff and the technical staffs of the participating institutions for their vital contributions. We also thank Walter Giele, Vernon Barger, Nigel Glover, and Tim Stelzer for many useful discussions. This work was supported by the U.S. Department of Energy and National Science Foundation; the Italian Istituto Nazionale di Fisica Nucleare; the Ministry of Education, Science and Culture 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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