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# Production of W and Z Bosons at the Tevatron

N. Varelas
For the CDF and D0 Collaborations

*University of Illinois at Chicago*
*Chicago, Illinois 60607*

*Fermi National Accelerator Laboratory*
*P.O. Box 500, Batavia, Illinois 60510*

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# Production of $W$ and $Z$ Bosons at the Tevatron

N. Varelas

Department of Physics, University of Illinois at Chicago, Chicago, Illinois 60607, USA

*for the CDF and DØ Collaborations*

## Abstract

We present recent results on measurements of the transverse momentum distribution of $W$ and $Z$ bosons, the angular distribution of electrons from $W$ decays, and on color coherence effects in $W$+jets events from $p\overline{p}$ collisions at $\sqrt{s}$ = 1.8 TeV at the Fermilab Tevatron Collider. The data are compared to perturbative QCD calculations.

## 1. Transverse momentum distribution of $W$ and $Z$ bosons

At Tevatron energies, $W$ and $Z$ bosons are produced in $p\overline{p}$ collisions primarily by head on collisions of $q\overline{q}$ constituents of the proton and antiproton without any transverse momentum ($p_T$). Consequently, the fact that observed $W$ and $Z$ bosons have finite $p_T$ is attributed to initial state gluon emission. At low $p_T$ ($p_T << Q$, where $Q$ is the vector boson mass), multiple soft gluon emission is expected to dominate the cross section. A soft gluon resummation technique is therefore used in order to make reliable QCD predictions. On the other hand, conventional perturbation theory provides a good approximation in the other regime of $p_T >> Q$ [1]. A prescription has been proposed for matching the low and high $p_T$ regions to provide a continuous prediction for all $p_T$ [2, 3]. Thus, a measurement of the transverse momentum distribution may be used to check the soft gluon resummation calculations in the low $p_T$ range, and to test the perturbative QCD calculations at high $p_T$. When $p_T$ approaches $\Lambda_{QCD}$, $\alpha_s$ becomes large and the perturbative calculation is no longer valid. In order to account for the non-perturbative contribution, a phenomenological form factor must be invoked, which contains several parameters that must be tuned to data.

CDF and DØ [4, 5, 6] measure the differential $d\sigma/dp_T$ distribution for $W$ and $Z$ bosons decaying to electrons. The data agree with the combined QCD perturbative and resummation calculations [2, 3], as can be seen in Fig. 1 for the $W$ data, and in Fig. 2 for the $Z$ data. Figure 3 compares the DØ $Z$ data to the fixed-order perturbative QCD [1] and the resummation calculation [3] in terms of a percentage difference from the prediction. A strong disagreement at low-$p_T$ is observed. This is due to the divergence of the $\mathcal{O}(\alpha_s^2)$ calculation at $p_T$= 0, and a significant enhancement of the cross section relative to the prediction at moderate values of $p_T$. This disagreement confirms the presence of contributions from soft gluon emission, which are accounted for in the resummation formalisms.

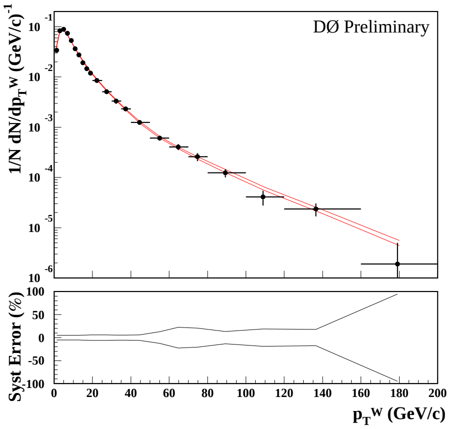

**Figure 1.** The $W$ boson transverse momentum spectrum, showing the DØ result (solid points) with statistical uncertainty. The theoretical calculation by Arnold and Kauffman [2], smeared for detector resolutions, is shown as two lines corresponding to the $\pm 1\sigma$ variations of the uncertainties in the detector modeling. The fractional systematic uncertainty on the data is shown as a band in the lower portion of the plot.

DØ used their $Z$ data to measure the non-perturbative parameter $g_2$. The prediction was smeared with the known detector resolutions, and the result fitted to the $Z$ $d\sigma/dp_T$ data

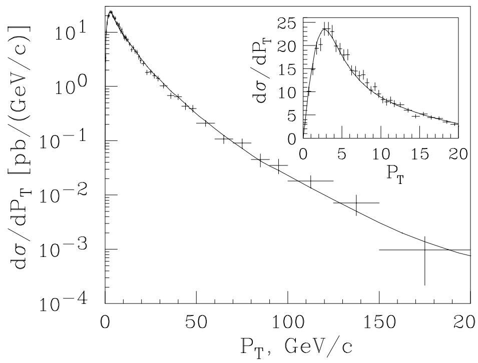

**Figure 2.** The $Z$ boson transverse momentum spectrum, showing the CDF result (solid points) with total uncertainty (other than an overall normalization uncertainty due to the luminosity uncertainty of 3.9%). The data have been unfolded for detector resolutions and are compared to the theoretical calculation by Balazs and Yuan [3], scaled up by 6.4% to match the measured inclusive $Z$ production cross section.

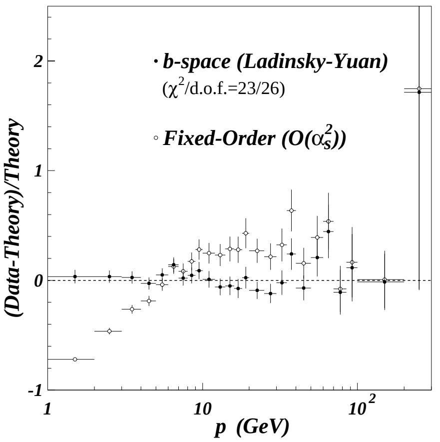

**Figure 3.** Fractional difference between DØ $Z$ $p_T$ data and the resummed [3] and fixed-order calculations [1].

distribution. The resulting value of $g_2 = 0.59 \pm 0.06$ GeV$^2$, is considerably more precise than previous determinations.

## 2. Angular Decay Distribution of $W$ boson

The angular decay distribution of leptons from $W$ bosons produced in high-energy $p\overline{p}$ collisions is determined at tree-level by the (V-A) character of electroweak interactions which leads to the well-known angular dependence of the cross section $\frac{d\sigma}{d(\cos\theta^*)} \propto (1 \pm \cos\theta^*)^2$.

In the case of high-$p_T$ $W$ production the additional produced partons alter the helicity state of the $W$ boson and thus its angular decay distribution. An $\mathcal{O}(\alpha_s^2)$ calculation [7] of the cross section can be written in terms of the lepton polar angle $\theta^*$ in the Collins-Soper rest frame of the $W$ boson (integrating over the azimuthal angle) as: $\frac{d^3\sigma}{dq_T^2\,dy\,d\cos\theta^*} = C(1 + P(W)\alpha_1\cos\theta^* + \alpha_2\cos^2\theta^*)$; where $P(W)$ is the polarization of the $W$ boson. The angular parameters $\alpha_1$ and $\alpha_2$ are functions of the transverse momentum of the $W$ boson.

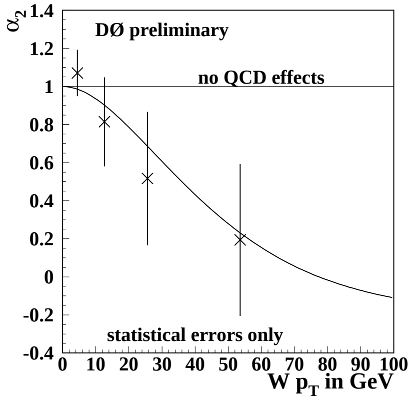

**Figure 4.** Measured $\alpha_2$ as a function of $p_T$ and its statistical errors compared to $\mathcal{O}(\alpha_s^2)$ QCD calculation [7] (curve) and calculation in the absence of QCD (horizontal line).

DØ measures the parameter $\alpha_2$ as a function of $W$ boson $p_T$ [8]. To directly measure the decay angle $\theta^*$ of the electron in the Collins-Soper frame, all momenta in the lab frame have to be known to perform the boost to this particular rest frame of the $W$ boson. This is not possible, however, since the longitudinal momentum of the neutrino cannot be measured. Instead the correlation between $\cos\theta^*$ and the transverse $W$ mass was used to infer $\cos\theta^*$ on a statistical basis. This was done using Monte Carlo (MC) events processed through a parametrized detector simulation.

DØ used a log-likelihood method to extract the angular parameter $\alpha_2$ from the angular distribution obtained by inverting the transverse mass distribution. Figure 4 shows the extracted values of $\alpha_2$ as a function of $W$ boson $p_T$. The dominant source of uncertainty is statistical. The DØ data prefer the $\mathcal{O}(\alpha_s^2)$ QCD calculation by $\approx 2\sigma$ over a calculation where no QCD effects are taken into account.

## 3. Color Coherence Effects in $W$+jets Events

In perturbative QCD, color coherence effects arise from interference of soft gluon radiation emitted from color connected partons [9]. Color coherence, which results in a suppression of soft gluon radiation in the partonic cascade in certain regions of phase space, can be approximated by *Angular Ordering* (AO). In this approximation the successive emission angles of soft gluons decrease as the cascade evolves away from the hard process. For incoming partons the emission angles increase as the process evolves from the initial hadrons to the hard subprocess.

Color coherence effects in $W$+jets events were studied in DØ by comparing the distributions of soft particles around the $W$ boson and opposing leading-$E_T$ jet [10]. Since the $W$ boson is a colorless object, it should not contribute to the production of secondary particles, thereby providing a template against which the pattern around the jet may be compared. Initial-to-final state color coherence effects are expected to manifest themselves as an enhancement of soft particle production around the tagged jet in the event plane relative to the transverse plane when compared with the particle production around the $W$ boson. This is the first observation of color coherence effects in $p\overline{p}$ events containing $W$ bosons and jets.

Once the $W \rightarrow e + \nu$ boson direction has been determined, the opposing jet was identified by selecting the leading-$E_T$ jet in the azimuthal hemisphere opposite to the $W$ boson. Annular regions are defined around both the $W$ boson and the tagged jet in $(\eta, \phi)$ space. The angular distributions of calorimeter towers with $E_T >$ 250 MeV are measured in these annular regions using the polar variables $R = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2}$ and $\beta_X = \tan^{-1}(\frac{sign(\eta_X)\cdot\Delta\phi_X}{\Delta\eta_X})$; where $X = W$ or jet, $\Delta\eta_W = \eta_{\mathrm{tower}} - y_W$, $\Delta\eta_{\mathrm{jet}} = \eta_{\mathrm{tower}} - \eta_{\mathrm{jet}}$, and $\Delta\phi_X = \phi_{\mathrm{tower}} - \phi_X$, in a search disk of $0.7 < R < 1.5$. DØ defines $\beta_{W(\mathrm{jet})} = 0$ to point along the beam direction nearest to the $W$ boson (jet). The interference effects were studied in regions $|\eta_{\mathrm{jet}}| < 0.7$ and $|y_W| < 0.7$, requiring the tagged jet to have $E_T > 10$ GeV and the $W$ boson $p_T > 10$ GeV/c.

To measure the color coherence signal, DØ defines the variable $R_{\mathrm{sig}}$ as the jet/$W$ boson tower multiplicity ratio of the event plane ($\beta = 0, \pi$) to the transverse plane ($\beta = \pi/2$). $R_{\mathrm{sig}}$ is expected to be near unity in the absence of color coherence effects. Figure 5 compares the $R_{\mathrm{sig}}$ variable for the data to various PYTHIA 5.7 predictions and to a Modified Leading-Log Approximation (MLLA) perturbative calculation of Khoze and Stirling [11] based on the local parton–hadron duality hypothesis (LPHD). Clearly the value of $R_{\mathrm{sig}}$ for the data deviates from unity in agreement with PYTHIA with AO on and string fragmentation (SF), and in disagreement with AO off and SF or AO off and independent fragmentation (IF). These comparisons imply that for the process under study, string fragmentation alone cannot describe the effects seen in the data. The AO approximation is an element of parton-shower event generators that needs to be included if color coherence effects are to be modeled successfully. Finally, the analytic prediction by Khoze and Stirling is consistent with the data, thus giving additional evidence supporting the validity of the LPHD hypothesis.

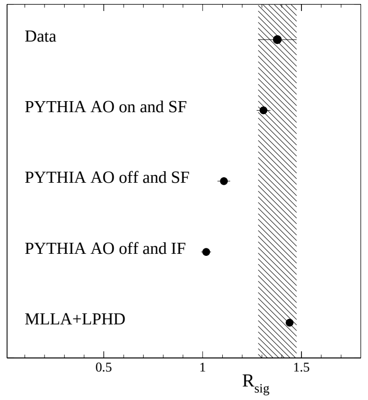

**Figure 5.** $R_{\mathrm{sig}}$ for DØ data, PYTHIA with various coherence implementations, and a MLLA+LPHD QCD calculation. The shaded band shows the statistical uncertainty on the $R_{\mathrm{sig}}$ variable for the data.

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