# Measurement of the Shape of the Transverse Momentum Distribution of $W$ Bosons Produced in $p\bar{p}$ Collisions at $\sqrt{s} = 1.8$ TeV

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The shape of the transverse momentum distribution of $W$ bosons ($p_T^W$) produced in $p\bar{p}$ collisions at $\sqrt{s} = 1.8$ TeV is measured with the D0 detector at Fermilab. The result is compared with QCD perturbative and resummation calculations over the $p_T^W$ range from 0 to 200 GeV/$c$. The shape of the distribution is consistent with the theoretical prediction. [S0031-9007(98)06465-5]

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The transverse momentum ($p_T^W$) of $W$ intermediate vector bosons produced in proton-antiproton collisions is due to the production of one or more gluons or quarks along with the boson. At low transverse momentum

($p_T^W < 10$ GeV/$c$), multiple soft gluon emission is expected to dominate the cross section. A soft gluon resummation technique [1–6] is therefore used to make QCD predictions. At high transverse momentum ($p_T^W > 20$ GeV/$c$), the cross section is dominated by the radiation of a single parton with large transverse momentum. Perturbative QCD [6] is therefore expected to be reliable in this regime. A prescription [4] has been proposed for matching the low and high $p_T^W$ regions to provide a continuous prediction for all $p_T^W$. Thus, a measurement of the transverse momentum distribution may be used to check the soft gluon resummation calculations in the low $p_T^W$ range, and to test the perturbative QCD calculations at high $p_T^W$.

The transverse momentum spectrum of $W$ bosons has been measured previously by the UA1 [7], UA2 [8], and CDF [9] Collaborations, but with smaller data samples than the one used here. This paper presents a measurement of the shape of the $p_T$ spectrum of $W$ bosons produced in $p\bar{p}$ collisions at $\sqrt{s} = 1.8$ TeV with the D0 detector [10] at Fermilab, and extends the $p_T^W$ range of the previous measurements. The data come from a sample of $12.4 \pm 0.7$ pb$^{-1}$ collected during the 1992–1993 run. A measurement of the inclusive cross section for $W$ and $Z$ boson production based on the same data set has been reported [11] and agrees with QCD predictions.

This measurement uses the decay mode $W \to e\nu$. Electrons were detected in a hermetic uranium–liquid-argon calorimeter with an energy resolution of about $15\%/\sqrt{E(\mathrm{GeV})}$. The calorimeter has a transverse granularity of $\Delta\eta \times \Delta\phi = 0.1 \times 0.1$, where $\eta$ is the pseudorapidity and $\phi$ is the azimuthal angle. Electrons were accepted in the central pseudorapidity region only, $|\eta| < 1.1$, to keep the background contamination from multijet events at a reasonably low level for high values of $p_T^W$. The transverse momentum of the neutrino was calculated using the calorimetric measurement of the missing transverse energy ($\not\!\!E_T$) in the event. We take the $p_T^W$ to be the sum of the electron and neutrino transverse momenta, measuring it only from the recoiling hadrons. The analysis used a single electron trigger, which required one electron with transverse energy ($E_T$) greater than 20 GeV.

The offline electron identification requirements consisted of four criteria: (i) the electron had to deposit at least 95% of its energy in the electromagnetic calorimeter (21 radiation lengths deep); (ii) the transverse and longitudinal shower shapes had to be consistent with those expected for an electron [12]; (iii) a good match had to exist between a reconstructed track in the drift chamber system and the shower position in the calorimeter; and (iv) the electron had to be isolated from other energy deposits in the calorimeter, with $I < 0.1$. This isolation variable is defined as $I = [E_{\mathrm{TOT}}(0.4) - E_{\mathrm{EM}}(0.2)]/E_{\mathrm{EM}}(0.2)$, where $E_{\mathrm{TOT}}(0.4)$ is the total calorimeter energy inside a cone of radius $\sqrt{\Delta\eta^2 + \Delta\phi^2} = 0.4$ and $E_{\mathrm{EM}}(0.2)$ is the electromagnetic energy inside a cone of radius 0.2. To select the $W$ boson candidate sample, we required one electron with $E_T > 25$ GeV and $\not\!\!E_T > 25$ GeV. Events having a second electron with $E_T > 20$ GeV that satisfies criteria (i), (ii), and (iv) were excluded from the candidate sample as possible $Z \to e^+e^-$ events. Criterion (iii) was not applied to this second electron in order to allow for possible tracking inefficiencies. These selection criteria yielded 7132 $W \to e\nu$ candidates.

The trigger and selection efficiencies were determined using $Z \to e^+e^-$ events in which one of the electrons satisfied the trigger and selection criteria. The second electron then provided an unbiased sample with which to measure the efficiencies. No dependence of the trigger or selection efficiency on $p_T^W$ was found, to an accuracy of 5%.

A Monte Carlo program [13] was used to simulate the D0 detector response and calculate the kinematic and geometric acceptance as a function of $p_T^W$. The detector resolutions used in the Monte Carlo program were determined from data, and were parametrized as a function of energy and angle. The relative response of the hadronic and EM calorimeters was studied using the transverse momentum of the $Z$ boson as measured by the $p_T$ of the two electrons compared to the hadronic recoil system in the $Z$ event. This parametrized representation of the D0 detector was used to smear the theoretical prediction by detector effects and compare it to our measured $p_T^W$. We prefer this method of comparison to a standard unfolding procedure [14] that proved to be sensitive to the choice of the prior distribution function. This sensitivity is caused by the Jacobian zero in $dN/dp_T^W$ at the origin, which induces a peak that appears near $p_T^W \approx 4$ GeV/$c$ after it is broadened by our $p_T^W$ resolution. Only below 4 GeV/$c$ do the true $p_T^W$ distributions predicted by the two available models [4,5] exhibit a difference, which is masked in the data by these same resolution effects.

The dominant source of background in the $W$ boson sample was multijet events where one or more of the jets fluctuated to fake an electron. Some multijet events also have significant $\not\!\!E_T$ due to fluctuations and mismeasurements of the jet energies. This could fake a neutrino from $W$ boson decay. The amount of multijet background in the $W \to e\nu$ candidate sample was determined by first defining a "loose" event sample which had the same selection criteria as the candidate sample except that electron identification criteria (i) and (ii) were not applied. This loose sample consisted of $N_{\mathrm{s}}$ signal events and $N_{\mathrm{b}}$ multijet background events. The $W \to e\nu$ candidate sample (described above) consisted of $\varepsilon_{\mathrm{s}}N_{\mathrm{s}}$ signal events and $\varepsilon_{\mathrm{b}}N_{\mathrm{b}}$ multijet background events, where $\varepsilon_{\mathrm{s}}$ and $\varepsilon_{\mathrm{b}}$ are the electron selection efficiencies for the candidate relative to the loose samples, for signal and background, respectively. We obtained $\varepsilon_{\mathrm{s}}$ from the $Z \to e^+e^-$ sample, and $\varepsilon_{\mathrm{b}}$ from events with $\not\!\!E_T < 15$ GeV. The total multijet background was determined to be $(4.2 \pm 2.3)\%$. The shape of the multijet background as a function of $p_T^W$ was determined by repeating the procedure in different $p_T^W$ bins.

To cross–check the multijet background estimate, the transverse mass and the $\not\!\!E_T$ distributions of the final data sample were compared to a model of the expected distributions obtained from a combination of $W \to e\nu$ Monte Carlo events plus the estimated multijet background. The comparison was performed in three $p_T^W$ bins: 0–30 GeV/$c$, 30–60 GeV/$c$, and >60 GeV/$c$; the number of $W \to e\nu$ candidates in each bin was 6726, 282, and 124. The amount of multijet background in each $p_T^W$ bin was estimated as (2.9 ± 1.6)%, (20.9 ± 11.7)%, and (38.3 ± 21.5)%, respectively. Figure 1 shows the results of the comparisons. The distinctive shape of the transverse mass distribution for multijet background arises from applying the kinematic cuts and the minimum $p_T^W$ requirement to a sample predominantly composed of dijet events that lie back–to–back in the transverse plane. The goodness of the fit between the data and the model is evaluated by performing a $\chi^2_\lambda$ test [15]. The numerical results for $\chi^2_\lambda$/d.o.f. for each fit in Fig. 1 are (a)20.2/25, (b) 26.4/19, (c) 4.7/7, (d) 5.4/9, (e) 3.0/13, and (f) 2.1/7. They correspond to fit probabilities of (a) 74%, (b) 12%, (c) 69%, (d) 80%, (e) 99%, and (f) 95%, respectively. We therefore conclude that the tests show good agreement between the data and the expectation.

The normalized multijet background was subtracted bin by bin from the $W$ boson candidate sample transverse momentum spectrum. Additional corrections (all less than 5%) were made to account for top quark background events and for $Z \to e^+e^-$ events where one of the electrons was lost or not identified. Since $p_T^W$ was measured from the recoiling hadrons, the events originating from $W \to \tau\nu$ (where $\tau \to e\nu\nu$) contributed properly to the differential distribution; this source of background therefore was included in the Monte Carlo simulation of the $p_T^W$ distribution.

The normalized distribution of the $W$ boson transverse momentum ($\frac{1}{N}\frac{dN}{dp_T^W}$) is shown in Fig. 2 and given in Table I. The largest contributions to the systematic error in the $p_T^W$ measurement are the uncertainty in the magnitude of the multijet background, the uncertainty in the hadronic recoil energy scale factor and resolution used in the detector simulation, and the uncertainty in the selection efficiency. These are all added in quadrature since they are independent. We compare our experimental result to the theoretical prediction [4] computed using the MRSA′ [16] parton distribution function and smeared for detector resolutions. The variation of the theoretical prediction for various parton distribution functions is negligible. The measurement and the prediction are independently area normalized to unity. These points are used to perform a more detailed comparison between data and theory by plotting the ratio (data-theory)/theory, which is shown in Fig. 3. At low $p_T^W$ (< 60 GeV/$c$), where the statistical errors are small but the detector resolution

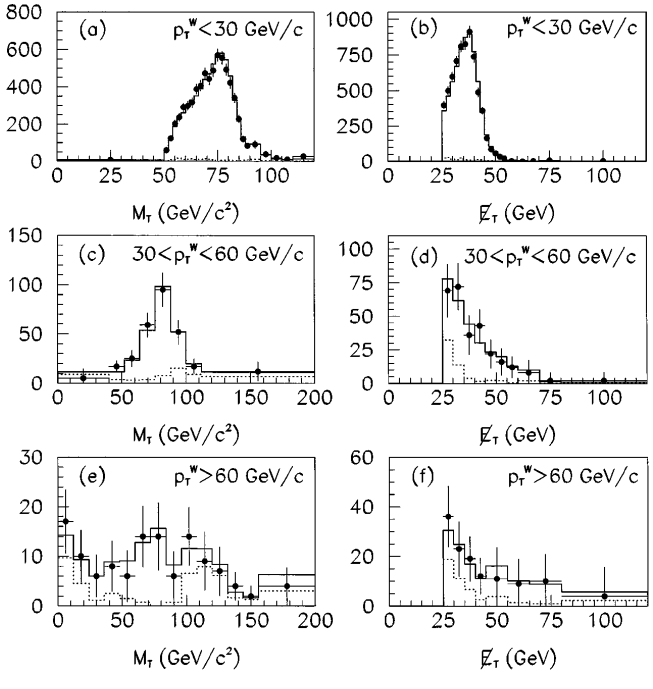


FIG. 1. The transverse mass (left) and $\not\!\!E_T$ (right) distributions for three $p_T^W$ bins. The points are the D0 data. The solid histogram is the sum of the Monte Carlo signal and the estimated background. The dotted histogram is the estimated background alone.

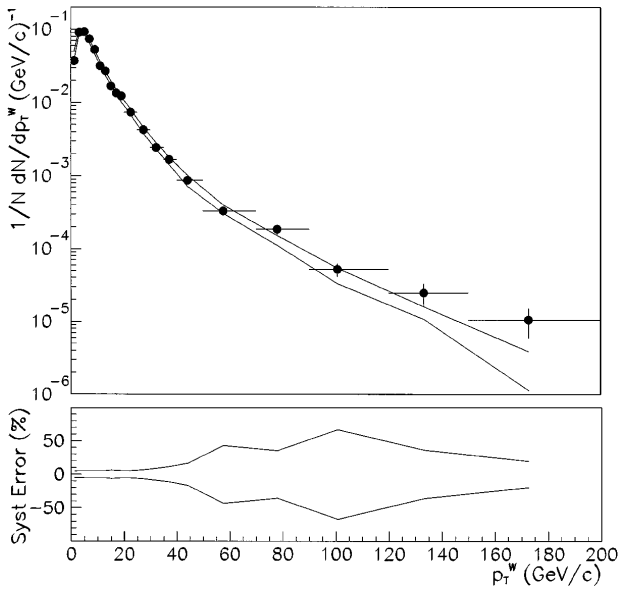


FIG. 2. The $W$ boson transverse momentum spectrum, showing the D0 result (solid points) with statistical uncertainty. The theoretical calculation by Arnold and Kauffman 4], smeared for detector resolutions, is shown as two lines corresponding to the $\pm 1\sigma$ variations of the uncertainties in the detector modeling. Within each bin, the values are plotted at the mean $p_T^W$. The fractional systematic uncertainty on the data is shown as a band in the lower portion of the plot. The values of the uncertainties for different $p_T^W$ bins are 100% correlated with each other. Upward fluctuations in the magnitude of the multijet background cause the widening observed in the band at about 60 and 100 GeV/$c$ in $p_T^W$.

TABLE I. The $W$ boson transverse momentum distribution corresponding to Fig. 2. The column labeled "Stat. error" shows the statistical uncertainty; "Syst. error" shows the systematic uncertainty in background and efficiency; "Detector error" shows the systematic uncertainty in the detector modeling; "Total error" is the sum in quadrature of the previous three columns.

| Bin width (GeV/$c$) | $\langle p_T^W \rangle$ (GeV/$c$) | $N_{\text{signal}}$ | $(1/N)(dN/dp_T^W)$ ($c$/TeV) | Stat. error ($c$/TeV) | Syst. error ($c$/TeV) | Detector error ($c$/TeV) | Total error ($c$/TeV) |
|---|---|---|---|---|---|---|---|
| 2 | 1.2 | 506.8 | 37.4 | 1.6 | 1.9 | 6.1 | 6.6 |
| 2 | 3.0 | 1232.0 | 90.8 | 2.6 | 4.6 | 7.9 | 9.5 |
| 2 | 5.0 | 1253.0 | 92.4 | 2.6 | 4.8 | 4.4 | 7.0 |
| 2 | 7.0 | 1006.6 | 74.2 | 2.3 | 3.9 | 3.7 | 5.8 |
| 2 | 9.0 | 718.4 | 53.0 | 1.9 | 2.8 | 2.6 | 4.2 |
| 2 | 11.0 | 431.2 | 31.8 | 1.5 | 1.7 | 2.0 | 3.0 |
| 2 | 13.0 | 368.4 | 27.2 | 1.4 | 1.4 | 1.6 | 2.6 |
| 2 | 15.1 | 228.0 | 16.8 | 1.1 | 1.1 | 1.2 | 1.9 |
| 2 | 17.1 | 184.4 | 13.6 | 1.0 | 0.8 | 0.8 | 1.5 |
| 2 | 19.0 | 167.9 | 12.4 | 0.9 | 0.7 | 0.9 | 1.5 |
| 5 | 22.6 | 252.0 | 7.43 | 0.46 | 0.42 | 0.65 | 0.89 |
| 5 | 27.3 | 145.4 | 4.29 | 0.34 | 0.30 | 0.43 | 0.61 |
| 5 | 32.3 | 83.0 | 2.45 | 0.25 | 0.22 | 0.26 | 0.42 |
| 5 | 37.2 | 56.7 | 1.67 | 0.20 | 0.19 | 0.18 | 0.33 |
| 10 | 44.2 | 59.4 | 0.875 | 0.099 | 0.147 | 0.150 | 0.232 |
| 20 | 57.7 | 45.2 | 0.333 | 0.037 | 0.144 | 0.045 | 0.155 |
| 20 | 78.0 | 25.2 | 0.186 | 0.028 | 0.066 | 0.020 | 0.075 |
| 30 | 100.7 | 10.7 | 0.052 | 0.011 | 0.035 | 0.010 | 0.038 |
| 30 | 133.2 | 5.1 | 0.025 | 0.008 | 0.009 | 0.002 | 0.013 |
| 50 | 172.7 | 3.6 | 0.011 | 0.005 | 0.002 | 0.001 | 0.005 |

effects dominate the result, the data are encompassed by the systematic error band. This agreement persists at high $p_T^W$ ($> 60$ GeV/$c$) but with larger statistical errors. A quantitative comparison of data and theory in the high $p_T^W$ region shows that the two agree when the correlations in the systematic errors are properly taken into account. We therefore conclude that the shape of the distribution is consistent with the theoretical prediction.

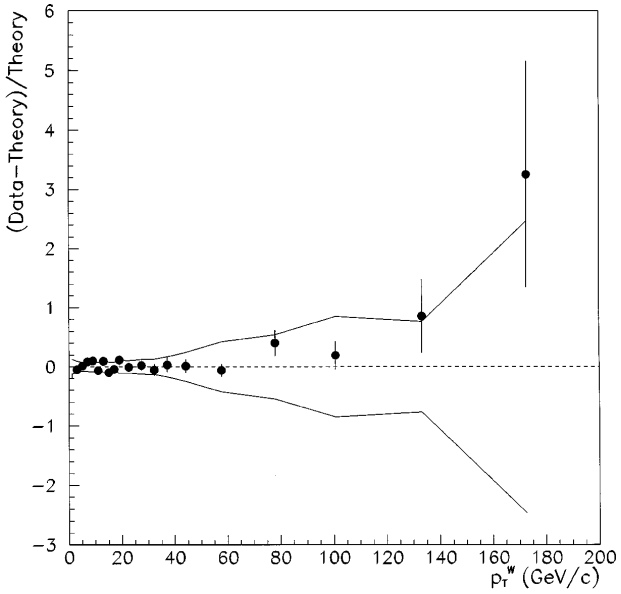


FIG. 3. The ratio (data–theory)/theory shown as a function of $p_T^W$ with its statistical uncertainty as error bars. Within each bin, the values are plotted at the mean $p_T^W$. The theory corresponds to Ref. [4], smeared for detector resolutions. The systematic uncertainties from data (background and efficiency) and from the detector modelling are added in quadrature and shown as a band.

In summary, we have measured the shape of the transverse momentum distribution of $W$ bosons produced in $p\bar{p}$ collisions at $\sqrt{s} = 1.8$ TeV, and have found that it is consistent with the combined QCD perturbative and resummation calculations.

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