ELECTROWEAK PHYSICS FROM DØ

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ABSTRACT

Preliminary electoweak results from the DØ Experiment at the Tevatron $\overline{p}p$ collider are presented. The branching ratio $B(W \rightarrow \ell\nu) = (10.43 \pm 0.44)\%$ $(\ell = e, \mu)$ is determined from the measured production cross section times branching ratio for W and Z bosons. This also gives an indirect measurement of the total width of the W boson: $\Gamma_W = 2.16 \pm 0.09$ GeV. The W cross section times branching ratio into the tau is measured to be $\sigma(p\bar{p} \rightarrow W+X)B(W \rightarrow \tau\nu) = 2.38 \pm 0.13$nb, from which the ratio of coupling constants is determined: $g_\tau^W / g_e^W = 1.00 \pm 0.02 \pm 0.03$. Limits on trilinear gauge couplings are obtained from the following diboson final states: $W\gamma$, WW, WZ, and $Z\gamma$. Finally a measurement of the W boson mass of $M_W = 80.44 \pm 0.11$ GeV is determined from the transverse mass in $W \rightarrow e\nu$ events.

Table 1: Preliminary measurements of cross section time branching ratio for inclusive W and Z production in Run 1B

Mode	value (nb)	δ(stat) (nb)	δ(syst) (nb)	δ(lum) (nb)
$\sigma \cdot B(W \to e\nu)$	2.38	± 0.01	± 0.09	± 0.20
$\sigma \cdot B(W \to \mu\nu)$	2.32	± 0.04	± 0.16	± 0.19
$\sigma \cdot B(W \to \tau\nu)$	2.38	± 0.09	± 0.10	± 0.20
$\sigma \cdot B(Z \to ee)$	0.235	± 0.003	± 0.005	± 0.020
$\sigma \cdot B(Z \to \mu\mu)$	0.202	± 0.016	± 0.020	± 0.017

1 Introduction

In high energy $\overline{p}p$ collisions, it is possible to study electroweak physics by direct observation of the carriers of the weak force, W and Z bosons. W bosons, in particular, have been produced and detected in large numbers at the Fermilab Tevatron collider. More recently, the LEP II e^+e^- collider has attained a high enough energy to produce pairs of W bosons. The large samples of W bosons produced in hadron colliders complement the detailed studies of the Z boson at LEP and SLC, and also the new W studies from LEP II.

All of the results presented here come from the recent runs of the DØ experiment[1] at the Tevatron collider. The run which took place in 1992-93 is referred to as "Run 1A", and it resulted in an integrated luminosity of about 13 pb^{-1}. The run which took place in 1994-96 is called "Run 1B" and yielded ≈ 80 pb^{-1}. In both runs, the $\overline{p}p$ collisions have a center of mass energy of $\sqrt{s} = 1.8$ TeV. Final results are available for most of the Run 1A analyses and some of the 1B analyses, while preliminary results are reported for most of the 1B analyses.

Since their hadronic decay modes are difficult to distinguish from the large background from QCD multijet production, we usually study these gauge bosons through their leptonic decay modes: $W \to \ell\nu$ and $Z \to \ell^+\ell^-$. The cuts used to select W and Z candidates vary slightly among the different analyses presented, but the general requirements are: isolated lepton(s) detected; $p_T(\ell) > 20(\mu), 25(e)$ GeV; missing $E_T > 20(\mu), 25(e)$ GeV (W only); and invariant mass $M(ee) = 91 \pm 10$ GeV ($Z \to ee$ only).

2 Single W and Z production

2.1 The W width and branching ratios

The rate of W and Z bosons observed by the experiment is proportional to the product of production cross section and leptonic branching fraction. The cross sections from Run 1A are published[2], and the preliminary measurements for Run 1B are given in Table 1. The uncertainties are statistical, systematic, and luminosity, respectively. The largest uncertainty on the experimental measurements comes from the uncertainty on the luminosity, and the largest uncertainty on the theoretical predictions is due to the parton distribution functions (pdf's).

Electroweak effects can be studied by examining the ratio of $\sigma \cdot B$ for W and Z production:

$$R_\ell = \frac{\sigma(\overline{p}p \to W \to \ell\nu)}{\sigma(\overline{p}p \to Z \to \ell\ell)} = \frac{\sigma(\overline{p}p \to W)}{\sigma(\overline{p}p \to Z)} \cdot \frac{\Gamma(W \to \ell\nu)}{B(Z \to \ell\ell)} \cdot \frac{1}{\Gamma_W} \tag{1}$$

R_ℓ is predicted more precisely than the individual cross sections because many of the QCD and parton distribution effects partially cancel. Experimentally, it has the advantage that the luminosity errors cancel completely and the efficiency errors cancel partially. The preliminary measurement from DØ for Run 1B is $R_\ell = 10.32 \pm 0.43$. With $\sigma(W)/\sigma(Z)$ from theory[3] and $B(Z)$ from LEP/SLC[4], R_ℓ can be turned into a measurement of the leptonic branching ratio of the W boson: $B(W \to \ell\nu) = (10.43 \pm 0.44)\%$. If the SM prediction for $\Gamma(W \to \ell\nu)$ is assumed as well, then this provides an indirect measurement of the total width of the W boson: $\Gamma(W) = 2.159 \pm 0.092$ GeV. The SM prediction is $\Gamma(W) = 2.077 \pm 0.014$ GeV[5].

2.2 $W \to \tau\nu$

We study the decay $W \to \tau\nu$ as a test of lepton universality. We use the hadronic decays of the τ, which are identified by the presence of an isolated, narrow jet well within the central calorimeter ($|\eta| < 0.9$) with E_T(jet)> 25 GeV. To select τ's from W decays, we require $\not{E}_T > 25$ GeV. We use the Profile variable to help separate τ jets from ordinary QCD jets, where the definition is Profile=(sum of highest two tower E_T)/(cluster E_T). Narrow jets, such as those coming from hadronic τ decays, have most of their energy concentrated in one or two towers of the calorimeter, so they will tend to have a value of Profile near unity. The profile distributions for the τ candidate sample (before the Profile cut) and for a QCD background sample (selected with low $\not{E}_T$) are shown in Fig. 1. We use the shaded low-Profile region to estimate the remaining QCD background.

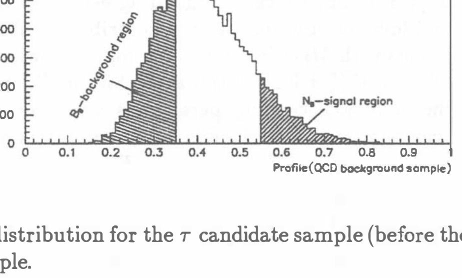


Figure 1: The profile distribution for the τ candidate sample (before the profile cut) and for the QCD background sample.

We select the τ candidates from a special trigger which was active for only a portion of Run 1B. The total luminosity for the sample is $16.8 \pm 0.9\text{pb}^{-1}$. The final data sample contains 1202 events, with estimated backgrounds of $106 \pm 7 \pm 5$ events from QCD, 81 ± 14 events from noisy calorimeter cells, 32 ± 5 events from $Z \to \tau\tau$, and 3 ± 1 events from $W \to e\nu$. The preliminary cross section times branching ratio is $\sigma \cdot B(W \to \tau\nu) = 2.38 \pm 0.09(\text{stat}) \pm 0.10(\text{syst}) \pm 0.20(\text{lum})$nb. When we compare this with the published DØ value for $\sigma \cdot B(W \to$

$e\nu$)[2], we obtain a measurement of the ratio of couplings: $g_\tau^W/g_e^W = 1.00 \pm 0.02 \pm 0.03$. This shows good agreement with e-τ universality at high energy.

3 Diboson Production

An interesting consequence of the non-abelian gauge symmetry $SU(2)_L \times U(1)_Y$ is that the electroweak gauge bosons should be self-coupling. In particular, the SM predicts non-zero trilinear couplings for $WW\gamma$ and WWZ. It is possible to test these couplings by studying final states involving two bosons: $W\gamma$,$Z\gamma$,WW,WZ, etc. For SM couplings, the amplitudes from the s-channel trilinear diagrams interfere destructively with amplitudes from other u- and t-channel diagrams, and the total diboson production rate is near its minimum for the trilinear coupling strengths dictated by the SM. For models with non-SM coupling values, this cancellation is spoiled, and the coupling constants must be regulated by form factors characterized by a scale Λ in order to preserve unitarity.

A formalism has been developed to describe the $WW\gamma$ and WWZ interactions beyond the SM[6]. If Lorentz invariance, C, P, CP invariance and $U(1)_{EM}$ gauge invariance are assumed, the most general Lagrangian describing the three boson vertex can be written in terms of the couplings g_1^Z, κ_V and λ_V, where $V = \gamma$ or Z. In the SM, $g_1^Z = 1$, $\kappa_\gamma = \kappa_Z = 1$ and $\lambda_\gamma = \lambda_Z = 0$.

A similar formalism is used for $ZZ\gamma$ and $Z\gamma\gamma$ couplings[7]. The parameters h_{i0}^V, $V = Z, \gamma$, $i = 1, 2, 3, 4$ represent the anomalous $Z\gamma$ couplings, and all of them are zero in the SM. As for the W couplings, the couplings h_i are regulated with form factors, $h_i(\hat{s}) = h_{i0}/(1 + \hat{s}/\Lambda^2)^n$.

3.1 $W\gamma$

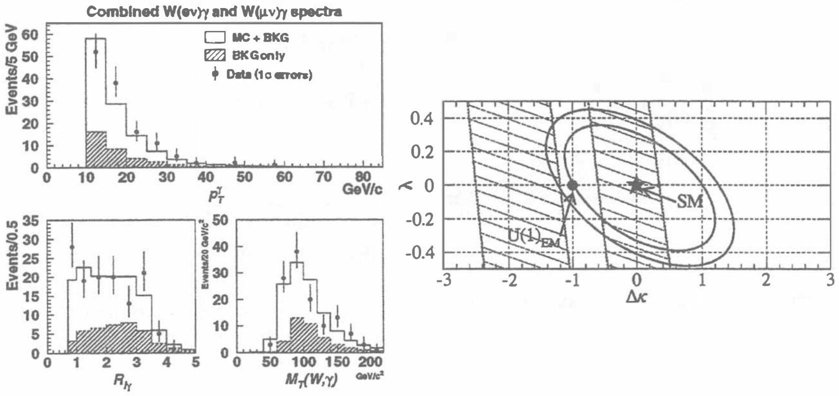
The most abundant diboson final state is $W\gamma$. We study it in both the $e\nu\gamma$ and $\mu\nu\gamma$ channels. In addition to the usual W selection, we require a minimum photon $E_T > 10$ GeV and a minimum separation between the photon and the lepton, $\Delta R(\ell\gamma) = \sqrt{\Delta\phi(\ell\gamma)^2 + \Delta\eta(\ell\gamma)^2} > 0.7$. Such requirements are necessary even in the theoretical predictions in order to avoid infrared and collinear divergences from photon radiation from the final state leptons. Figure 2a shows the kinematic distributions from the complete run 1 sample of the $W\gamma$ candidate events[8, 9]

The estimated signal in this sample is $84^{+12}_{-11} \pm 9$ events. This yields a cross section of $\sigma(p\bar{p} \to W\gamma + X) = 11.3^{+1.7}_{-1.5} \pm 1.5$pb, which is in good agreement with the SM prediction of $\sigma(p\bar{p} \to W\gamma + X) = 12.5 \pm 1.0$pb. In order to suppress contributions from radiative W decays, we may consider only the events with $M_T(W\gamma) > 90$ GeV, for which we obtain a measured cross section of $\sigma(p\bar{p} \to W\gamma + X) = 1.8^{+0.8}_{-0.6} \pm 0.2 \pm 0.1$pb and a SM prediction of $\sigma = 2.3 \pm 0.2$pb.

We obtain Limits on the anomalous coupling parameters λ and $\Delta\kappa$ from a fit to the photon E_T spectrum. The limit contours are shown in Fig. 2b. The limits on the axes are $-0.93 < \Delta\kappa < 0.94$ ($\lambda = 0$) and $-0.31 < \lambda < 0.29$ ($\Delta\kappa = 0$). These parameters are related to the magnetic dipole and electric quadrupole moments of the W boson as follows: $\mu_W = \frac{(\kappa+\lambda+1)e}{2M_W}$ and $Q_W = \frac{-(\kappa-\lambda)e}{M_W^2}$. The point labeled "$U(1)_{\rm EM}$" shows what would be expected for a particle of unit charge and unit spin without any SU(2) couplings. Also shown are limits from CLEO[10] $b \to s\gamma$ measurements.

3.2 $WW/WZ \to e\nu jj$

We select WW and WZ candidate events by requiring a high-p_T isolated electron, missing E_T, and at least two jets. We enhance the signal by requiring $50 < M(jj) < 110$ GeV and $|p_T(jj) - p_T(e\nu)| < 40$ GeV. The jet-jet mass window is designed to accept hadronic decays of



(a) (b)

Figure 2: (a) The kinematic distributions for the total Run 1 DØ $W\gamma$ sample. The points are data, the shaded histograms are background estimates, and the open histograms are the sum of background and the SM prediction. (b) 95% CL limits on λ and $\Delta\kappa$ from the $W\gamma$ sample. The inner ellipse corresponds to one degree of freedom (d.o.f) while the out ellipse corresponds to two d.o.f. The bands show the limits obtained by CLEO from $b \to s\gamma$ studies.

W or Z bosons, but the mass resolution is inadequate to distinguish the two. The results from Run 1a are published[11]. The preliminary sample from Run 1b contains 399 events, with total estimated background of 388 ± 38 events: 280 ± 36 from QCD $W+\geq 2j$, 104 ± 12 from QCD multijets and 3.7 ± 1.3 from $t\bar{t} \to e\nu jjX$. The Standard Model predicts 17.5 ± 3.0 $WW+WZ$ events in the sample, which is quite consistent with the small excess above background. With these statistics we set an upper limit on the production of W pairs: $\sigma(p\bar{p} \to W^+W^-X) < 76$ pb, 95% CL. The measured p_T spectrum of the leptonically decaying W is shown in Fig. 3. A fit to this spectrum gives the following limits at the 95% CL with $\Lambda = 2$ TeV: $-0.43 < \Delta\kappa < 0.59$ ($\lambda = 0$), and $-0.33 < \lambda < 0.36$ ($\Delta\kappa = 0$) under the assumption of $\kappa_\gamma = \kappa_Z$ and $\lambda_\gamma = \lambda_Z$.

3.3 $WW \to \ell\nu\ell'\nu'$

The purely leptonic mode for W pair decays has the advantage of much lower background and no ambiguity between WW and WZ final states. It has the disadvantage that the rate is much lower than the semi-leptonic mode. One event is observed the leptonic mode in Run 1a[12], while in Run 1b we observe 4 events (1 ee, 1 $\mu\mu$, 2 $e\mu$) with an estimated background of 2.6 ± 0.4 events. The excess agrees well with the SM prediction of 1.6 ± 0.2 events. Based on the number of events observed, we obtain preliminary 95% CL limits ($\Lambda = 1000$ GeV) of $|\Delta\kappa| < 1.2$ ($\lambda = 0$) and $|\lambda| < 1.0$ ($\Delta\kappa = 0$) and $\sigma(p\bar{p} \to W^+W^-X) < 41.3$ pb.

3.4 $Z\gamma$ Production

At tree level, the SM coupling between the Z boson and the photon vanishes. Therefore, observed $Z\gamma$ events should result from either initial state radiation or anomalous $Z\gamma$ couplings.

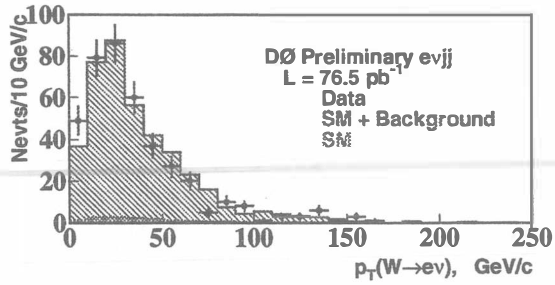


Figure 3: The $p_T(e\nu)$ spectrum in the $WW/WZ \to e\nu jj$ sample. The points are the data, the solid histogram is the SM prediction, and the hatched histogram is the sum of the SM prediction and the background estimate.

Events of the type $\ell^+\ell^-\gamma$ can also result from radiative decays of Z bosons. The production of $Z\gamma$ events is studied with the final states $ee\gamma$, $\mu\mu\gamma$ and $\nu\nu\gamma$. The results from Run 1a are published[13, 14]. Preliminary results for Run 1b are available in the $ee\gamma$ channel. With a minimum photon E_T of 10 GeV, 14 events are observed, with an estimated background of 1.8 ± 0.5 events. The background is dominated by eej and jjj events with jets faking photons and electrons. The SM prediction of 12 ± 1 events is in good agreement with the number observed. We use a fit to the E_T spectrum of the photons to obtain limits on the anomalous parameters h_{i0}.

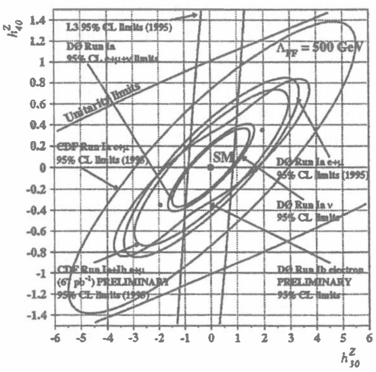


Figure 4: 95% CL limit contours on $Z\gamma$ anomalous coupling parameters.

The most sensitive limits come from the $Z\gamma \to \nu\nu\gamma$ channel[14]. In this channel, we require a single photon with an E_T of at least 40 GeV and 40 GeV of missing E_T. Additional cuts on the calorimeter shower projection help to suppress background from muon bremsstrahlung. A total of four events survive the cuts, with an estimated background of 5.8 ± 1.0 events. The SM predicts 1.8 ± 0.3 events in this sample. We obtain the anomalous coupling limits from a fit to that measured from the recoiling hadrons. The remaining uncertainty in the hadronic scale contributes an uncertainty of 20 MeV to M_W.

The transverse momentum spectrum with which the W bosons are produced influences the p_T^e spectrum and also (at second order) the M_T spectrum. We model the p_T^W distribution according to the calculation of Ladinsky and Yuan[18] after we tune it to reproduce the observed p_T^Z spectrum. We allow the phenomenological parameter g_2 (common to the p_T^W and p_T^Z calculations) to vary over the range allowed by the Z data, and this gives small variations in the measured value of M_W: ± 5 MeV (± 28 MeV) for the M_T (p_T^e) fit.

The preliminary result from the fit to M_T in the Run 1B data is $M_W = 80.45 \pm 0.07$(Wstat) ± 0.065(Zstat) $\pm$ 0.07(syst) GeV. The fit to p_T^e gives good agreement: $M_W = 80.49 \pm 0.09$(Wstat) ± 0.065(Zstat) $\pm$ 0.08(syst) GeV. We use the M_T fit as the result since it has the smaller uncertainty. The breakdown of the contributions to the uncertainties are given in Table 4.

Table 2: The uncertainties in the preliminary Run 1b W boson mass measurement.

Source	δM_W (MeV)	
	M_T fit	p_T^e fit
W statistics	69	86
Z statistics	65	65
total stat	95	108
Systematic	70	79
Calorimeter Linearity	20	20
Calorimeter Uniformity	10	10
z calibration	28	28
Electron Resolution	23	14
Lepton Removal	16	16
Selection Bias	-	9
Recoil Resolution	33	9
Recoil Response	20	16
QCD background	11	16
Z Background	5	8
W Width	9	7
Parton Luminosity	10	10
PDF	21	48
W p_T	5	28
Radiative Decays	20	20
Total	118	134

We also explore a technique of measuring the W mass from the ratio of transverse masses of the W and Z events. For this study, we remove one of the leptons from each Z event, thus simulating a neutrino. We scale the resulting M_T^Z distributions until it matches the M_T^W distribution (after correcting for differences introduced by acceptance and resolution). The preliminary result of this transverse mass ratio measurement is $M_W = 80.16 \pm 0.36 \pm 0.075$ GeV for the Run 1a data. The large statistical error results from the small statistics of the Z sample, and this technique does not presently compete with the more traditional fitting methods. The systematic uncertainty is small, however, and this technique will be an important tool in future high-luminosity runs.

We combine the two DØ measurements, $M_W(\text{Run1A}) = 80.35 \pm 0.21(stat) \pm 0.17(syst)$ GeV and $M_W(\text{Run1B}) = 80.45 \pm 0.10(stat) \pm 0.70(syst)$ GeV (preliminary) with careful attention to common systematic errors. The result is

$$M_W = 80.44 \pm 0.11 \text{ GeV (preliminary)}$$

These values are compared with other measurements of M_W[19, 20, 21, 22, 23, 24] in Fig. 6a.

DØ also measures the mass of the top quark[25], and together with the W mass measurement this can be compared to the predictions of the Standard Model. Figure 6b shows the DØ mass measurements compared to the SM predictions[26] for different values of the Higgs boson mass. The measurements are in excellent agreement with the model for relatively light Higgs masses, but the uncertainties are not yet small enough to exclude large Higgs masses.

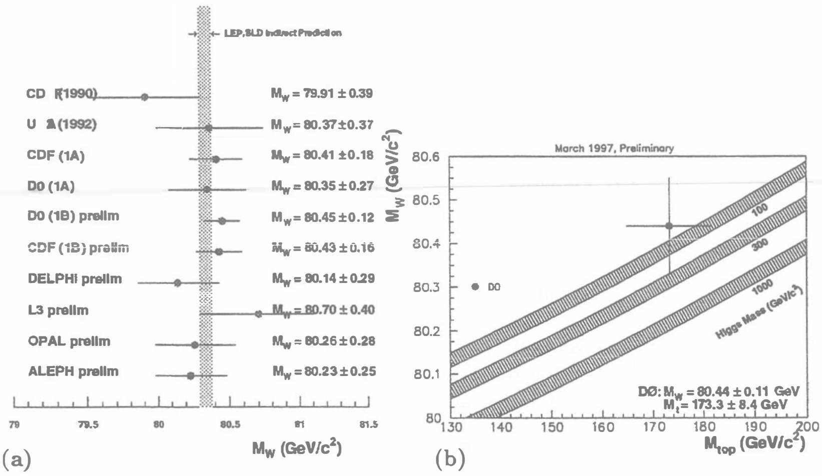


Figure 6: (a) Comparison of current measurements of the W boson mass. (b) Comparison of DØ M_W and M_{top} measurements with predictions of the minimal Standard Model. The width of the bands indicate the uncertainties in the predictions which arise primarily from uncertainties in α_{EM}.

5 Conclusions

With a sample of approximately 10^5 W events and 10^4 Z events from Run 1 of the Tevatron, DØ makes precise measurements of couplings and masses which test the Standard Model. No significant deviations from the Standard Model are seen at this time. The next run of the Tevatron is expected to provide a factor of 20 in integrated luminosity, and even more precise tests will be possible.

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the photon E_T spectrum. The limit contours from DØ and other experiments[15, 16] are shown in Fig. 4. The $\nu\nu\gamma$ limits only use the 1a data at present, but they give the strongest limits now available. The combined limits ($ee\gamma$,$\mu\mu\gamma$,$\nu\nu\gamma$) from Run 1a only are $|h_{30}^{Z,\gamma}| < 0.44, 0.45$ and $|h_{40}^{Z,\gamma}| < 0.06$, where a value of $\Lambda = 750$ GeV is used and the couplings are varied one at a time. These are tighter than those shown in Fig. 4 because of the different value of Λ used.

4 The W Mass

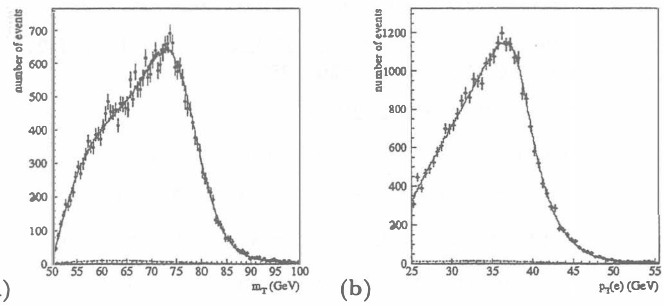

Figure 5: The fit to the (a) transverse mass spectrum and (b) electron transverse momentum spectrum for the Run 1b W mass sample. The points are the data and the histogram shows the fit. The fit is performed over the range 60 GeV $< M_T <$ 90 GeV and 30 GeV $< p_T^e <$ 50 GeV. The dashed curves show the estimated background.

The W mass measurement is the most precise electroweak measurement from the hadron colliders. We fit the M_T and the p_T^e spectra of the W bosons to simulated spectra generated with different W masses, where $M_T^2 = 2p_T^e p_T^\nu(1 - \cos\Delta\phi_{e\nu})$. We study the systematic effects with data and Monte Carlo, with the $Z \to ee$ sample playing an essential role in constraining the systematic uncertainties.

The DØ data from Run 1a yield a mass measurement of $M_W = 80.35 \pm 0.14(\text{stat}) \pm 0.165(\text{syst})$ $\pm 0.16(\text{scale})$ GeV [17] from the M_T fit. A new preliminary measurement is made from the Run 1b $W \to e\nu$ sample. (The W mass results described here are an update with respect to what was presented at this meeting.) We select a total of 28323 $W \to e\nu$ candidates from the Run 1b data. In addition to the E_T^e and $\not{E}_T$ cuts, we require that $p_T^W < 15$ GeV. The primary result comes from a fit to the Run 1b transverse mass spectrum, shown in Fig. 5a. A fit to the p_T^e spectrum (Fig. 5b) gives a similar results with somewhat larger uncertainties.

The energy calibration of the calorimeter is critical for this measurement. We use a combination of $Z \to ee$, $J/\psi \to ee$ and $\pi^0 \to \gamma\gamma$ events to constraint the electromagnetic response of the calorimeter. The calorimeter response is modeled as $E_{meas} = \alpha E_{true} + \delta$, and the parameters are determined to be $\alpha = 0.95372 \pm 0.00091$ and $\delta = -0.16\ ^{+0.03}_{-0.21}$ GeV. The Z decays, with very similar kinematics to the W decays, give the most important contribution to the calibration, and the uncertainty on the W mass due to Z statistics is 65 MeV.

Since the transverse mass calculation requires the missing E_T, which in turn relies on the measurement of the momentum of the hadrons recoiling against the W boson, the calibration of the hadronic calorimeter response is also important. We calibrate the hadronic response of the calorimeter with $Z \to ee$ events by comparing the p_T measured from the electrons to

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