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Contents

STUDY OF THE $WW\gamma$ AND WWZ INTERACTIONS AT DØ

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The $WW\gamma$ and WWZ gauge boson couplings have been studied through the direct observation of diboson final states produced in $p\bar{p}$ collisions at $\sqrt{s} = 1.8$ TeV. The total cross section for $W\gamma$ final states, for photons with $p_T^\gamma > 10$ GeV/c and $\mathcal{R}_{\ell\gamma} > 0.7$, times branching ratio of W bosons to leptons, has been measured to be $12.10^{+1.76}_{-1.62} \pm 1.72$ pb, in agreement with the Standard Model expectation. An upper limit of 17 pb on the total WW cross section has been set. The analysis of $W\gamma$ events has allowed us to set 95% confidence level (CL) limits on the anomalous $WW\gamma$ coupling parameters of $-0.96 < \Delta\kappa < 0.98$ and $-0.32 < \lambda < 0.30$. This measurement excludes the $U(1)_{EM}$–only coupling between the photon and the W boson at the 96% CL. Similar measurements of the coupling parameters have been performed using WW final states.

1 Introduction

The study of gauge boson pairs continues to be an important test of the Standard Model (SM) of electroweak interactions. Among the features of the SM that can be directly tested with such events are the gauge boson self–couplings. The self–couplings of the gauge bosons are completely fixed by the $SU(2)_L \otimes U(1)_Y$ symmetry of the SM. Recent limits on the $WW\gamma$ coupling parameters have been derived in measurements by UA2 [1], CDF [2], DØ [3], and CLEO [4]. Recent limits on the $WW\gamma$ and WWZ anomalous couplings have been performed with WW final states at the Tevatron experiments [5,6,7].

The measurement of the trilinear couplings is a search for non–standard interactions between the electroweak gauge bosons. This is done by extending the gauge boson portion of the electroweak Lagrangian density to include anomalous coupling parameters [8] for the WWV ($V = \gamma, Z$) vertices. When electromagnetic gauge invariance and the conservation of CP-parity are assumed, this extended Lagrangian includes the parameters κ_V, λ_V, and g_{WWV}. The overall couplings are set to be $g_{WW\gamma} = e$ and $g_{WWZ} = e \cot\theta_W$. The charge of the electron is e and θ_W is the weak mixing angle. In the SM, the parameters have the values $\kappa_V = 1$ and $\lambda_V = 0$. When describing deviations from the SM couplings, it is common to use $\Delta\kappa_V \equiv \kappa_V - 1$ in place of κ_V. The non-Abelian nature of the SM manifests itself explicitly in the $\kappa_V = 1$ parameter. In the case of the $WW\gamma$ coupling, the fact that $\kappa_\gamma \neq 0$ indicates that the photon couples to more than just the electric charge of the W boson.

With this extended Lagrangian, it is necessary to introduce form factors for each of the coupling parameters to avoid the violation of tree-level unitarity. We assume dipole form factors of the type $\Delta\kappa(\hat{s}) = \Delta\kappa/(1+\hat{s}/\Lambda^2)^2$. The form factor scale Λ is chosen such that the measured limits on the coupling parameters are tighter than the unitarity constraints.

The data presented here were collected with the DØ detector [9] at the Fermilab Tevatron Collider. The results of the $W\gamma$ analysis used data collected during two periods: 1992–1993 (13.8 pb^{-1} of integrated luminosity) and 1993–1995 (73.0 pb^{-1} of integrated luminosity). The WW analyses were restricted to the 1992–1993 data set.

2 $W\gamma$ Analysis

$W\gamma$ events from two decay modes of the W boson were studied: $W \rightarrow e\nu$ and $W \rightarrow \mu\nu$. In each case the photons were required to have a minimum transverse momentum of 10 GeV/c and to be spatially separated from the charged lepton by at least 0.7 units of $\mathcal{R}_{\ell\gamma}$, $\mathcal{R} \equiv \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2}$. We have observed $84.4^{+12.3}_{-11.3} \pm 8.7$ signal events. The asymmetrical error is the 1σ uncertainty due to Poisson statistics, and the second error is due to the uncertainties in the background estimates.

From this observation we calculated the $W\gamma$ cross section times branching ratio of W bosons to leptons, for our photon requirements, to be: $\sigma(p\bar{p} \rightarrow W\gamma + X) \times \mathrm{BR}(W \rightarrow \ell\nu) = 12.10^{+1.76}_{-1.62} \pm 1.59\ (\boldsymbol{syst})\ \pm 0.65\ (\boldsymbol{lum})$ pb. This is in agreement with the SM prediction [10] of 12.5 ± 1.0 pb. Figure 1 shows some of the kinematic distributions of the 127 observed $W\gamma$ candidates from the combined DØ data sets, along with the SM expectations and the background estimates.

We have also used the 1993–1995 $W(e\nu)\gamma$ data to measure the cross section for $W\gamma$ events with a three-body transverse mass $M_T(W\gamma)$ above 90 GeV/c^2. This eliminates $W\gamma$ events originating from radiative decay of the electron and increases the sensitivity to anomalous couplings. The predicted SM cross section times branching ratio [10] for events with $M_T(W\gamma) > 90$ GeV/c^2, and for photons with $p_T^\gamma > 10$ GeV/c and $\mathcal{R}_{\ell\gamma} > 0.7$, is 2.3 ± 0.2 pb. This should be compared with our measured result from the 1993–1995 $W(e\nu)\gamma$ analysis: $\sigma(p\bar{p} \rightarrow W\gamma + X) \times \mathrm{BR}(W \rightarrow e\nu) = 1.84^{+0.75}_{-0.61} \pm 0.23\ (\boldsymbol{syst})\ \pm 0.09\ (\boldsymbol{lum})$ pb.

A combined likelihood analysis of the p_T^γ spectra from the individual $W(e\nu)$ and $W(\mu\nu)$ analyses allowed us to set 95% CL limits on the anomalous $WW\gamma$ coupling parameters of $-0.96 < \Delta\kappa < 0.98$ and $-0.32 < \lambda < 0.30$. These are the 95% CL limits when only one of the couplings is allowed to vary at a time. This measurement excludes the $U(1)_{EM}$-only coupling between the photon and the W boson at the 96% confidence level.

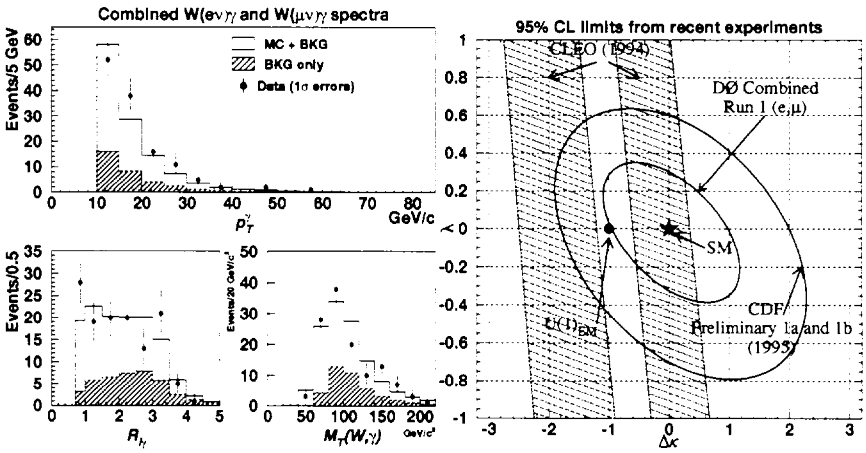

Figure 1: Characteristic distributions of the $W\gamma$ events. Also shown are the limits on the $WW\gamma$ coupling parameters for the $W\gamma$ analysis when compared to recent CLEO and CDF results.

3 *WW* Analysis

The following decay modes of the W-pair events have been studied at DØ: $e\nu\mu\nu$, $e\nu e\nu$, and $\mu\nu\mu\nu$, collectively referred to as the dilepton channels; and $e\nu$+jets, where it is assumed one of the W bosons has decayed hadronically. The hadronic resolution of the DØ detector makes it impossible to distinguish between hadronic W and Z decays, so the $e\nu$+jets study is a simultaneous WW and WZ measurement. The SM prediction for the total $p\bar{p} \to WW$ cross section at the Tevatron has been calculated [11] to be 9.4 ± 0.5 pb, while the SM $p\bar{p} \to WZ$ cross section is estimated [12] to be 2.6 ± 0.3 pb.

In the dilepton decay modes [6], DØ has observed 1 event, with a predicted background of 0.56 ± 0.13 events. The 95% CL upper limit for WW production has been set at 87 pb. If the WWZ and $WW\gamma$ coupling parameters are assumed to be equal, and the form factor scale Λ is set to be 0.9 TeV, the 95% CL limits on the coupling parameters were found to be $|\Delta\kappa_V| < 2.7$ and $|\lambda_V| < 2.1$.

In the $W(e\nu)$+jets search [7], DØ has observed 84 events with a predicted background of 75.5 ± 13.3 events. The upper limit for combined WW and WZ production has been set at 17 pb. If the WWZ and $WW\gamma$ coupling parameters are assumed to be equal, and the form factor scale Λ is set to be 1.5 TeV, the 95% CL limits on the coupling parameters are $|\Delta\kappa_V| < 1.0$ and $|\lambda_V| < 0.7$. If the WWZ parameters are assumed to have their SM values and only the $WW\gamma$ parameters are studied, the 95% CL limits become: $|\Delta\kappa_\gamma| < 3.1$ and $|\lambda_\gamma| < 2.6$. This demonstrates the complementary nature of the $W\gamma$ and WW studies.

Progress is underway at DØ to jointly test the $WW\gamma$ and WWZ couplings from a combined $W\gamma/WW$ analysis. Preliminary studies of the 1992–1993 data set shows that we can expect to set 95% CL limits on the coupling parameters of $|\Delta\kappa_V| \simeq 0.8$ and $|\lambda_V| \simeq 0.5$, for a form factor scale of $\Lambda = 1.5$ TeV, when the WWZ and $WW\gamma$ couplings are assumed to be equal. There are a variety of other assumptions which can also be tested [13].

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RECENT DØ RESULTS ON $Z\gamma$ PRODUCTION

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We report on a new search for anomalous $ZV\gamma$ ($V = Z, \gamma$) couplings in the $Z(ee)\gamma$ mode with 89 pb^{-1} of data. The following limits on anomalous coupling parameters were set at 95% CL: $|h^V_{10,30}| < 1.9$, $|h^V_{20,40}| < 0.4$. We also report on the first measurement of $Z(\nu\nu)\gamma$ production at hadron colliders using 14 pb^{-1} of data. Sensitivity to anomalous couplings in this channel is twice as good as that for the combined electron and muon channel analysis reported earlier [5]. We set the following 95% CL limits on the $ZV\gamma$ couplings: $|h^V_{10,30}| < 0.9$, $|h^V_{20,40}| < 0.2$ which are the tightest available at the present time.

Measurement of $Z\gamma$ production at high energy colliders offers a direct way of probing anomalous $ZZ\gamma$ and $Z\gamma\gamma$ couplings which do not exist within the SM but are suggested by some theoretical models which imply new physics [1]. These couplings can be described [2] by 8 parameters: h^V_i, $i = 1, ..., 4$, $V = Z, \gamma$. Couplings $h^V_{1,2}$ are CP-violating, while $h^V_{3,4}$ preserve CP. In the SM at tree level all $h^V_i = 0$. Since anomalous couplings grow fast with energy they are modified with multipole form-factors in order to preserve partial wave unitarity: $h^V_i = h^V_{i0}/(1 + \hat{s}/\Lambda)^n$, where conventionally $n = 3$ for $i = 1, 3$ and $n = 4$ for $i = 2, 4$ couplings [2]. The form-factor scale Λ is *a priori* unknown and indicates the scale for new physics.

Measurements of $Z\gamma$ production through the $ee\gamma$ and $\mu\mu\gamma$ decay channels at the Fermilab Tevatron were previously reported [3,5]. Here we present a new measurement of the $ee\gamma$ channel based on 89 pb^{-1} of data collected in 1994-1995 Tevatron run with the DØ detector. We also present the first measurement of the $\nu\nu\gamma$ production at hadron colliders (this channel has been studied only in e^+e^--collisions [4]) based on 13.5 pb^{-1} of data collected in the 1992–1993 run. Sensitivity to anomalous couplings in this channel is much higher than that for the dilepton decay modes due to a higher branching ratio and absence of the radiative Z decay background in the neutrino channel. However, this is an experimentally challenging measurement because the background in the $\nu\nu\gamma$ mode at hadron colliders is extremely high.

Event selection for the $ee\gamma$ analysis was similar to the one used in our previous measurement [5]. We required two electrons with $E^e_T > 25$ GeV and a photon with $E^\gamma_T > 10$ GeV. We additionally required that there were no hits

[a] For the DØ Collaboration. See, e.g. [5] for the list of authors.

in the tracking chambers in a road pointing toward the photon, and that the photon was separated from either electron by at least 0.7 units in η-ϕ-space (here η is pseudorapidity related to the polar angle by $\eta = -\log\tan(\theta/2)$, and ϕ is the azimuthal angle). All three electromagnetic (EM) clusters were required to be in the good fiducial volume of the detector, i.e, in central calorimeter (CC) with $|\eta| < 1.0$ or in end calorimeters (EC) with $1.5 < |\eta| < 2.5$. The acceptance as a function of anomalous couplings was determined using the Baur and Berger LO Monte Carlo generator [2] with parametric detector modelling. The detection efficiencies were calculated from data ($Z \to ee$ events in most of the cases). For the SM couplings the geometrical acceptance was 38%, and the overall detection efficiency within the kinematical cuts on the final state particles was $12.5 \pm 0.8\%$.

The above selection criteria yielded 14 candidate events (11 in CC and 3 in EC) with an estimated background of 1.8 ± 0.5 events, dominated by $Z + j$ and multijet production with jets faking the photon or electrons. This background was derived from data. The results agree well with the SM predictions of 12.1 ± 1.2 signal events. The E_T^γ spectrum of the observed candidates together with the background estimate and SM predictions are shown in Fig. 1a. Two high-E_T^γ events are consistent with the background or signal fluctuation within two standard deviations. The following 95% CL limits on anomalous couplings (with assumption of one coupling being non-zero at a time) were obtained by a fit of the E_T^γ spectrum: $|h_{10,30}^V| < 1.9$, $|h_{20,40}^V| < 0.4$ for the form-factor scale of $\Lambda = 500$ GeV (see Fig. 2). The distorted shape of the exclusion contour is due to the events in the tail of the E_T^γ spectrum.

For the $\nu\nu\gamma$ analysis we required a much higher cut on the photon energy: $E_T^\gamma > 40$ GeV which was forced by a dominant background from $W \to e\nu$ decays with the electron being misidentified for a photon due to inefficiency of the central tracker. The photon was required to be in the same fiducial volume as for the $Z(ee)\gamma$ event selection. Analogously to the $ee\gamma$ analysis, we rejected events with central tracker hits in the vicinity of the photon cluster. Missing transverse energy in the event was required to be above 40 GeV. A jet veto was imposed by rejecting events with at least one reconstructed jet with $E_T^j > 15$ GeV. This cut further reduces $W \to e\nu$ background and also improves missing energy resolution. Additional cuts were applied to the shape of the photon EM shower in transverse and longitudinal directions to ensure that it was consistent with a photon originating from the real vertex. This analysis employed several new experimental techniques, e.g. using the finely segmented DØ calorimeter as a tracking device to determine the direction of the photon by measuring the EM shower centroids at different depths. The remaining background was dominated by cosmic and beam halo muons which

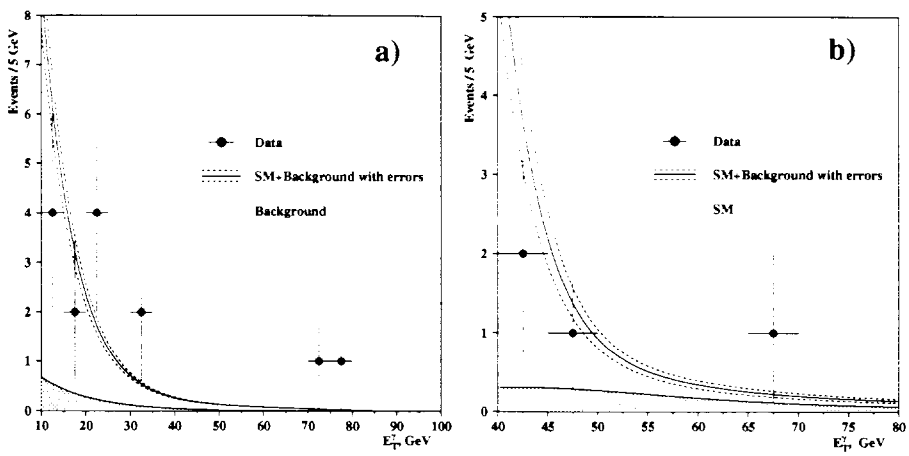

Figure 1: Transverse energy of the photon. a) For $Z(ee)\gamma$ channel. b) For $Z(\nu\nu)\gamma$ channel. Solid and dashed lines show the SM plus background predictions with the errors. Filled area shows a) QCD background; b) SM signal.

radiated photons in the dense calorimeter media and therefore faked the signal signature. This background was suppressed by the requirements of no reconstructed muons in the DØ muon system and additionally no minimum ionizing "tracks" (i.e., chains of hit cells) to be found in the calorimeter close to the photon cluster. The residual background, which had roughly equal contributions from $W \rightarrow e\nu$ decays and muon *bremsstrahlung,* was derived from data. The acceptance and efficiency were estimated in a similar way as for the $ee\gamma$ channel. The jet veto efficiency was calculated using $Z \rightarrow ee$ data and is in excellent agreement with the predictions of NLL calculations for $Z\gamma$ production [6]. The geometrical acceptance was 80% and the overall efficiency within the kinematical cuts was $31 \pm 2\%$.

The above selection criteria enhance the signal-to-background ratio by an impressive factor of $\sim$ 500. We observe 4 candidate events (3 in CC, and 1 in EC) with an expected background of 6.4 ± 1.1 and a SM prediction of 1.8 ± 0.2 events. Although the signal-to-background ratio is less than one, the sensitivity to the anomalous couplings is still high, since the background is concentrated at low E_T^γ while the anomalous coupling contribution is almost flat in E_T^γ up to the kinematic threshold of the reaction. The E_T^γ spectrum of the candidates is shown in Fig. 1b (together with the background and SM predictions) and is consistent with the SM. Limits on anomalous couplings were set at 95% CL by the E_T^γ fit: $|h_{10,30}^V| < 0.9$, $|h_{20,40}^V| < 0.2$. This represents a factor of two improvement compared to the combined $ee\gamma$ and $\mu\mu\gamma$ limits [5] based on the same statistics. The new limits, shown in Fig. 2 together with

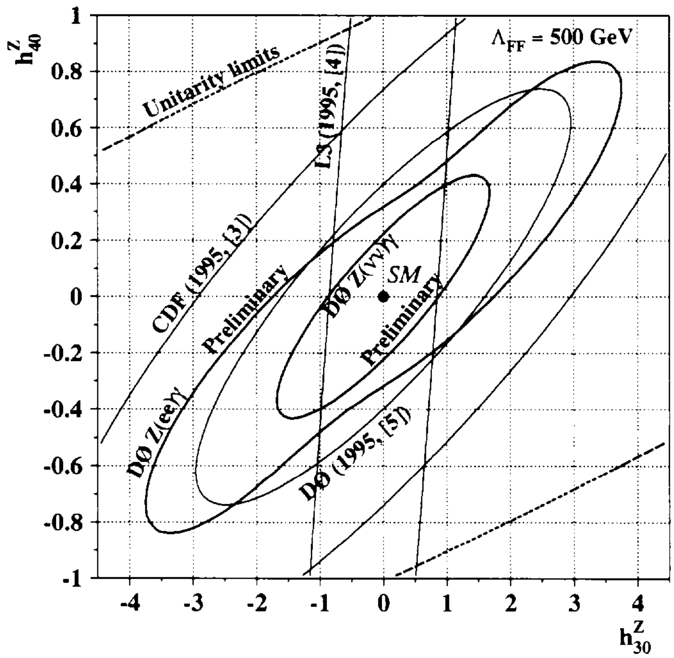

Figure 2: Limits on anomalous CP-conserving $ZZ\gamma$ couplings from $Z(ee)\gamma$, $Z(\nu\nu)\gamma$ production and from previous measurements[3,4,5]. Dashed lines show unitarity contours for the form-factor scale Λ = 500 GeV.

other measurements[3,4,5], are currently the tightest in the world.

Analyses of the $\mu\mu\gamma$ and $\nu\nu\gamma$ channels for 1994–1995 data set are currently under way and we expect to increase sensitivity toward anomalous couplings by another factor of two when they are completed. Any further improvement will be possible only with upgraded Tevatron or at the next generation of hadron colliders.

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W AND Z PRODUCTION CROSS SECTIONS AT DØ

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We present a measurement of the production cross section times branching ratio for W and Z bosons decaying to electrons or muons in $p\bar{p}$ collisions at $\sqrt{s} = 1.8$ TeV using data recorded at the Tevatron during the 1994–95 collider run. Using the ratio of these two measurements, we derive the W leptonic branching fraction and the width of the W boson.

1 Introduction

The measurement of the W and Z production cross sections times leptonic branching fraction $(\sigma \cdot B)$ allows a determination of the width of the W boson and a comparison of W and Z production with QCD predictions. We present here new *preliminary* results from the 1994–95 data run taken with the DØ detector[1] using the electron and muon decay channels. We also measure the ratio $R = \frac{\sigma_W \cdot B(W \rightarrow l\nu)}{\sigma_Z \cdot B(Z \rightarrow \ell\ell)}$ to better precision than either of the individual cross sections since many sources of systematic errors cancel. A measurement of R in conjunction with the theoretical calculation of σ_W/σ_Z and the precise measurement of $B(Z \rightarrow \ell\ell)$ from LEP yields the W boson leptonic branching fraction $B(W \rightarrow l\nu)$. Combining this result with a theoretical calculation of $\Gamma(W \rightarrow l\nu)$ we find the total width of the W, $\Gamma(W)$.

2 Electron Channel Cross Sections

The $W \rightarrow e\nu$ candidates were collected using a trigger that required one electromagnetic (EM) cluster in the calorimeter with transverse energy (E_T) greater than 20 GeV and missing transverse energy $(\not{E}_T)$ greater than 15 GeV. The $Z \rightarrow ee$ candidates were collected using a trigger that required two EM clusters with $E_T > 20$ GeV. Data collected from these two triggers correspond to an integrated luminosity $(\int \mathcal{L}dt) \simeq 76$ pb^{-1} and 89 pb^{-1} respectively.

Two classes of offline electrons are identified: "loose" electrons are isolated highly electromagnetic clusters whose longitudinal and transverse shower profile is consistent with that expected from an electron; "tight" electrons have a

[b]Representing the DØ Collaboration

further requirement of a matching track in the central tracking system. All electrons are restricted to the pseudorapidity regions $|\eta| < 1.1$ or $1.5 < |\eta| < 2.5$.

$W \rightarrow e\nu$ candidates are selected as events with exactly one tight electron with $E_T > 25$ GeV, and missing transverse energy $\not\!\!E_T > 25$ GeV, resulting in a sample of 59579 candidates. $Z \rightarrow ee$ candidates are selected as events with two loose electrons (one of which is required to be tight) with $E_T > 25$ GeV. We apply an additional cut on the dielectron invariant mass (M_{ee}) of $75 < M_{ee} < 105$ GeV/c^2, resulting in a sample of 5705 candidates. Background sources to both samples are estimated separately either from data (QCD multijets) or from Monte Carlo ($W \rightarrow \tau\nu$, $Z \rightarrow \tau\tau$, $Z \rightarrow e\not{e}$ and Drell-Yan). Electron efficiencies are determined from the $Z \rightarrow ee$ sample. The geometric and kinematic acceptance is calculated from a fast Monte Carlo. Table 1 gives the preliminary values of the cross sections.

3 Muon Channel Cross Sections

The $W \rightarrow \mu\nu$ and $Z \rightarrow \mu\mu$ candidates were collected using a common inclusive muon trigger that required a reconstructed track with hits in all the layers of the muon system and with transverse momentum (p_T) greater than 15 GeV/c. A partial data sample was used which corresponds to $\int \mathcal{L}dt \simeq 32$ pb^{-1}.

Two classes of offline muons are identified: "loose" muons have a mininum ionizing particle (MIP) trace in the calorimeter and have passed through enough magnetized iron to ensure a proper momentum determination; "tight" muons must, in addition, be isolated, be consistent with the beam crossing, have a matching track in the central tracking system, and pass a global fit (which incorporates the muon track, central detector track, calorimeter MIP trace and the reconstructed event vertex). All muons are restricted to the pseudorapidity region $|\eta| < 1.0$.

$W \rightarrow \mu\nu$ candidates are selected as events with a tight muon with $p_T > 20$ GeV/c and missing transverse energy $\not\!\!E_T > 20$ GeV. Events with a second loose muon with $p_T > 10$ GeV/c are rejected, resulting in a sample of 4477 candidates. $Z \rightarrow \mu\mu$ candidates are selected as events with one tight muon with $p_T > 20$ GeV/c and a second loose muon with $p_T > 15$ GeV/c, resulting in a sample of 173 candidates. Background sources to both samples are estimated separately either from data (QCD multijets, cosmic and combinatoric muons) or from Monte Carlo ($W \rightarrow \tau\nu$, $Z \rightarrow \tau\tau$, $Z \rightarrow \mu\not{\mu}$ and Drell-Yan). Muon trigger efficiencies are determined from an unbiased sample of muons, the reconstruction efficiency from a scanned sample of "good" muons and the selection efficiency from the $Z \rightarrow \mu\mu$ sample. The geometric and kinematic acceptance is calculated from a Monte Carlo. Table 1 gives the preliminary values of the cross sections.

Table 1: The DØ *preliminary* cross sections for W and Z bosons.

Channel	$W \rightarrow e\nu$	$Z \rightarrow ee$	$W \rightarrow \mu\nu$	$Z \rightarrow \mu\mu$
N_{obs}	59579	5702	4477	173
Background(%)	8.1 ± 0.9	4.8 ± 0.5	18.6 ± 2.1	8.0 ± 2.1
Efficiency(%)	70.0 ± 1.2	75.9 ± 1.2	24.7 ± 1.5	43.2 ± 3.0
Acceptance(%)	43.4 ± 1.5	34.2 ± 0.5	20.1 ± 0.7	5.7 ± 0.5
Luminosity [pb^{-1}]	75.9 ± 6.4	89.1 ± 7.5	32.0 ± 2.7	32.0 ± 2.7
$\sigma \cdot B$ [nb] ($\pm$stat)	2.38 ± 0.01	0.235 ± 0.003	2.28 ± 0.04	0.202 ± 0.016
($\pm$syst) ($\pm$lum)	$\pm 0.09 \pm 0.20$	$\pm 0.005 \pm 0.020$	$\pm 0.16 \pm 0.19$	$\pm 0.020 \pm 0.017$

4 Ratio of Cross Sections and Conclusions

We can now calculate $R = \frac{\sigma \cdot B(W \rightarrow l\nu)}{\sigma \cdot B(Z \rightarrow ll)}$ taking the correlations in the efficiencies and acceptances into account. For the combined electron and muon channels, we obtain the *preliminary* value of

$$R = 10.32 \pm 0.43.$$

Using the LEP measurement[2] of $B(Z \rightarrow ll) = (3.367 \pm 0.006)\%$, and the theoretical calculation[3] of $\sigma_W / \sigma_Z = 3.33 \pm 0.03$, we find

$$B(W \rightarrow l\nu) = (10.43 \pm 0.44)\%$$

Combining this result with a theoretical calculation of the W leptonic partial width[4] $\Gamma(W \rightarrow l\nu) = 225.2 \pm 1.5$ MeV, we obtain a *preliminary* result of the total width:

$$\Gamma(W) = 2.159 \pm 0.092 \text{ GeV}.$$

All these results are in good agreement with previous DØ results[5], and with Standard Model predictions.

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MUON CHARGE ASYMMETRY FROM W DECAYS AT THE DØ DETECTOR

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Preliminary results on the charge asymmetry of muons from W decays, as a function of the muon pseudorapidity, from the 1992-1995 run of the Tevatron, using the DØ detector, are presented.

1 Introduction

At the Tevatron ($\sqrt{s}$ = 1.8 TeV), W bosons are produced in $p\bar{p}$ collisions primarily by quark-antiquark annihilations

$$u + \bar{d} \rightarrow W^+ \rightarrow \mu^+ + \nu_\mu, \qquad \bar{u} + d \rightarrow W^- \rightarrow \mu^- + \bar{\nu_\mu}.$$

On the average, the $u(\bar{u})$ quarks carry a larger fraction of the momentum of the $p(\bar{p})$ than do the $d(\bar{d})$ quarks. Thus upon production, the $W^+(W^-)$ are preferentially boosted in the direction of the $p(\bar{p})$ beam direction. This leads to a production asymmetry in the rapidity of the W, y_W, defined by

$$A(y_W) \equiv \frac{d\sigma_{W^+}(y)/dy_W - d\sigma_{W^-}(y)/dy_W}{d\sigma_{W^+}(y)/dy_W + d\sigma_{W^-}(y)/dy_W} \approx \frac{u_1 d_2 - u_2 d_1}{u_1 d_2 + u_2 d_1} = \frac{d_2/u_2 - d_1/u_1}{d_2/u_2 + d_1/u_1} \quad (1)$$

$A(y_W)$ is thus related to the difference in the d/u ratio between parton 1 in the proton and parton 2 in the anti-proton. The density functions u and d are functions of Bjorken x, given at leading order by $x_{1,2} = (M_W/\sqrt{s})\, e^{\pm y}$. Since the longitudinal momentum of the neutrino from W decays cannot be determined, the asymmetry of the muon from the decay is used. The distribution of muons due to the production asymmetry gets convoluted with their decay distribution due to $V - A$. The overall muon charge asymmetry is defined as a function of the pseudorapidity of the muon, η_μ, as

$$A(|\eta_\mu|) = \frac{N^+(|\eta_\mu|) - N^-(|\eta_\mu|)}{N^+(|\eta_\mu|) + N^-(|\eta_\mu|)}, \qquad \eta_\mu = -\ln\{\tan(\theta_\mu/2)\} \quad (2)$$

where, N^+ = number of μ^+ in the region $\eta > 0$ and μ^- in the region $\eta < 0$
and N^- = number of μ^+ in the region $\eta < 0$ and μ^- in the region $\eta > 0$.
This measurement may be used to constrain knowledge of parton distribution functions of the proton, specifically the d/u ratio.[1]

[c]for the DØ collaboration

2 Data

The data consists of 6.5 pb^{-1} from the 1992-1993 run (run 1a). From the 1994-1995 run (run 1b), there is 55 pb^{-1} for $|\eta_\mu| < 1.0$ and 35 pb^{-1} for $1.0 < |\eta_\mu| < 1.7$ of the DØ detector. The data is obtained with a trigger that requires at least one good muon with $p_T^\mu \geq 15$ GeV/c . Additional track quality cuts and kinematic cuts of $p_T^\mu \geq 20$ GeV/c and $\not{E}_T \geq 20$ GeV are imposed offline. Charge asymmetry measurements at DØ can only be done with muons since there is no central field to distinguish electrons from positrons. The muon charge is determined using the toroidal magnets of the muon detector.

3 Backgrounds and Systematic Errors

The main contaminants in the W sample are cosmic ray muons, combinatorics, muons from QCD processes, $W \to \tau \to \mu$, $Z^0 \to (\mu)\mu$, and $Z^0 \to \tau\tau \to (\mu)\mu$, where only one of the muons is detected. With a kinematic cut of 20 GeV/c on the muon and the neutrino, $W \to \tau \to \mu$ has the same asymmetry as that of $W \to \mu + \nu$ and need not be subtracted. The background fractions for the first three sources are obtained from data by fitting the candidate distribution with a background and a signal distribution. The background for the Z-sources is obtained from Monte Carlo. These fractions are then subtracted out from each eta bin of the candidate sample taking into account the charge asymmetry of the background sources.

The sample is corrected for detector asymmetries. The detection efficiencies for μ^+ and μ^- can be different in regions with cracks in the DØ muon detector coverage where muons of one charge may be bent into a chamber while those with the other charge can go undetected into a crack. This effect is largely compensated for by flipping the polarity of the toroid periodically. The data is corrected in proportion to the unbalanced luminosity.

Misidentification of the muon sign can dilute the charge asymmetry. The charge misidentification probability is obtained by taking a sample of high quality Z events and finding the ratio of the number of same sign pairs to the total number of pairs. The probability per track is 0.088 ± 0.052 for run 1a and 0.027 ± 0.007 for run 1b and have been used to correct the data.

4 Results

The combined charge asymmetry from run 1a and run 1b data, after background subtraction and corrections for various systematic effects, is shown in Figure 1. The theoretical curves in Figure 1 are obtained from a fast Monte

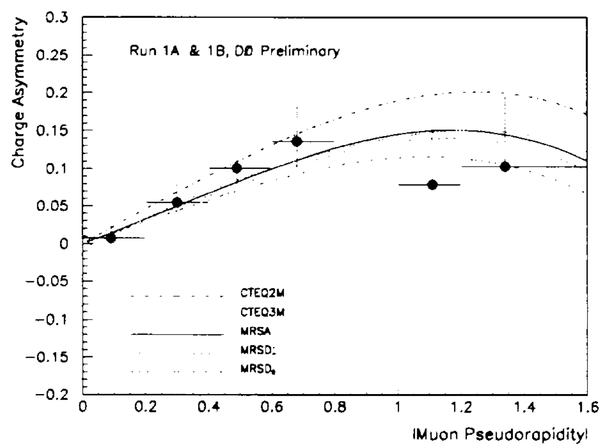

Figure 1: Charge asymmetry from muons from W decays.

Carlo program that does a leading order treatment with input $p_T^W(y)$ obtained from a next-to-leading order resummation calculation.[4] The input parton distribution functions are varied to obtain the different curves which are so labelled. The match between data and theory is quantified by a reduced χ^2 shown in Table 1. The values obtained show that all the parton distribution functions considered are consistent with the data but none of these is particularly favoured.

Table 1: Reduced χ^2 for some recent parton distribution functions.

PDF	χ^2/ 6 $d.o.f$
CTEQ2M	0.6394
CTEQ3M	0.2587
MRSA	0.2927
MRSD'$_-$	0.3211
MRSD'$_0$	0.4061

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MEASUREMENT OF THE W BOSON MASS

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We present a preliminary measurement of the W boson mass using data collected by the DØ experiment at the Fermilab Tevatron during the 1994/95 collider run 1b. We use $W \rightarrow e\nu$ decays to extract the W mass from the observed spectrum of transverse mass of the electron ($|\eta| < 1.2$) and the inferred neutrino. We use $Z^0 \rightarrow ee$ decays to constrain our model of the detector response. We measure $m_W/m_Z = 0.8815 \pm 0.0011(stat) \pm 0.0014(syst)$ and $m_W = 80.38 \pm 0.07(W\ stat) \pm 0.08(Z\ stat) \pm 0.13(syst)$ GeV. Combining this result with our previous measurement from the 1992/93 data [1], we obtain $m_W = 80.37 \pm 0.15$ GeV (errors combined in quadrature).

1 Introduction

The parameters of the electroweak sector of the Standard Model[2] can be taken to be the fine structure constant α_{em}, the Fermi constant G_F, and the mass of the Z^0 boson m_Z, all measured to a precision better than 0.01%. Radiative corrections due to loop diagrams then relate the mass of the W boson m_W and the weak mixing angle θ_W, through these three parameters, the heavy fermion masses, and the Higgs boson mass. Within the Standard Model, a direct measurement of m_W thus constrains the allowed region for the top quark and Higgs masses. In conjunction with a measurement of the top quark mass, it constrains the Higgs mass. Alternatively, a precise measurement of the W mass in combination with measurements of $\sin^2\theta_W$ provides a test of the Standard Model.

2 Data Samples

The DØ detector is described elsewhere [3]. Electrons are identified using the longitudinal and transverse shower shape measurements of clusters in the Uranium-liquid argon calorimeter and matching tracks in the central and forward drift chamber tracking detectors. Electron candidates from $W \rightarrow e\nu$ and $Z^0 \rightarrow ee$ decays are required to be isolated. The transverse momentum of the neutrino in $W \rightarrow e\nu$ decays is inferred by imposing transverse momentum balance.

The electron (two electrons) with highest transverse momentum (p_T) in the event is (are) associated with the W (Z^0) decay. The following kinematic and

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acceptance cuts are made on the W and Z^0 candidate events: $p_T(e) > 25$ GeV, $p_T(\nu) > 25$ GeV and hadronic recoil $p_T(rec) < 30$ GeV (for W only), electron pseudorapidity $|\eta| < 1.2$ (central) or $1.5 < |\eta| < 2.5$ (forward). The final 1994/95 data sample, corresponding to an integrated luminosity of 76 pb^{-1}, consists of 32856 $W \to e\nu$ candidates with central electrons, 1562 $Z^0 \to ee$ candidates with both electrons central, and 1548 $Z^0 \to ee$ candidates with one central and one forward electron.

3 Analysis Technique

Analogous to the invariant mass, we define the transverse mass of the W using the transverse momenta of the decay products only,

$$m_T = \sqrt{2p_T(e)p_T(\nu)\,(1 - \cos{(\phi(e) - \phi(\nu))})}. \tag{1}$$

The transverse mass distribution of $W \to e\nu$ decays has a characteristic Jacobian shape with a mass scale which is set by the W mass. The distribution observed in the data is fitted with templates generated by a Monte Carlo simulation of the W production, decay, detector response and backgrounds. The same procedure is used to extract the W mass from the electron and neutrino p_T spectra as cross-checks, and the Z^0 mass from the ee invariant mass spectrum for calorimeter energy scale calibration purposes.

A fast Monte Carlo simulation is used to generate large numbers of events to obtain statistically precise templates to compare with the data. The W double differential cross section with respect to transverse momentum and rapidity is obtained from the calculation of Ladinsky and Yuan [4]. The mass dependence is parametrized as a relativistic Breit-Wigner line shape, skewed by an exponential parton luminosity factor. The MRSA parton distributions [5] are used for these calculations. The W helicity is chosen according to the probabilities of the various parent quark configurations. Radiative decays ($W \to e\nu\gamma$ and $Z^0 \to ee\gamma$) are generated according to the calculation of Berends and Kleiss [6], and the detector response to radiative decays is simulated. The $W \to \tau\nu \to e\nu\bar{\nu}\nu$ are topologically indistinguishable from $W \to e\nu$ decays, and are included in the W decay model.

The calorimeter energy response to electrons is constrained using test beam data, and calibrated using measurements of the response to π^0 and J/ψ decays, and the Z^0 mass measurement which is calibrated against the value measured at LEP [7]. The calorimeter response to the hard recoil is measured using the $Z^0 \to ee$ decays, in which the p_T of the Z^0 can be measured using the electrons and the recoil separately, and compared. The underlying event is modelled using measurements of minimum bias events. The electron energy and angular resolutions, energy biases due to overlap between electron and recoil, trigger and offline identification efficiencies are measured and incorporated in the detector simulation. The shape and the normalization of backgrounds to the W from QCD and $Z^0 \to ee$ sources are measured and included in the resolution functions. The QCD and Z^0 backgrounds are estimated to be $(1.5 \pm 0.3)\%$ and $(0.55 \pm 0.05)\%$ respectively.

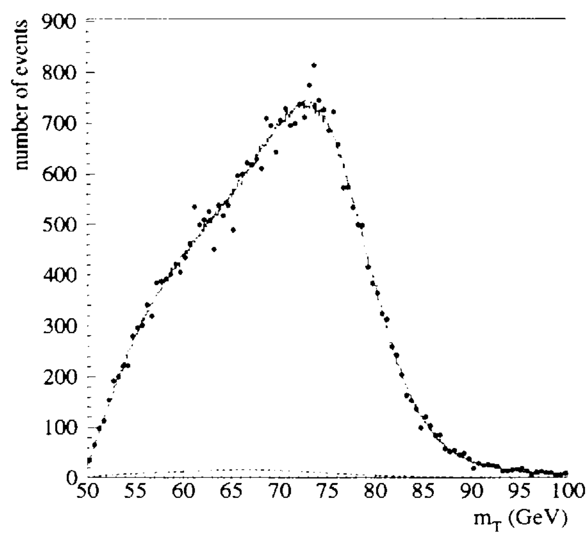

Figure 1: The transverse mass distribution for the Run1b W sample. The points indicate the data, the solid line the simulated m_T lineshape for the maximum likelihood fit, and the dashed line the background contribution.

4 Results

A maximum likelihood fit to the W transverse mass spectrum in the range $60 < m_T < 90$ GeV (figure 1) yields the result $m_W = 80.38 \pm 0.068$ (stat) GeV. We have checked that the result is insensitive to the fitting window. The energy scale uncertainty due to the statistical error in the Z^0 mass measurement is 74 MeV. All other systematic uncertainties combined in quadrature give an uncertainty of 130 MeV. These include uncertainties in calorimeter linearity, electron energy resolution, calibration of the central tracker, hadronic recoil and resolution, lepton removal, efficiencies, backgrounds, W production and decay modelling, and modelling of the detector at high luminosities. The results are preliminary and the systematic uncertainty is expected to reduce as the analysis progresses.

5 Conclusion

A preliminary measurement of the W boson mass from the transverse mass spectrum of central $W \rightarrow e\nu$ decays from the DØ 1994/95 (Run 1b) data is presented. The preliminary result is $m_W = 80.38 \pm 0.07(W\ stat) \pm 0.08(Z\ stat) \pm 0.13(syst)$ GeV (total uncertainty is 170 MeV), in good agreement with previous measurements. Combining this result with our previous measurement from the 1992/93 data [1], we obtain $m_W = 80.37 \pm 0.15$ GeV (errors combined in quadrature).

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MEASUREMENT OF M_W USING THE TRANSVERSE MASS RATIO OF W AND Z

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We report on the measurement of W boson mass from a direct determination of the ratio of the transverse masses of W and Z using the DØ detector at the Fermilab Tevatron $p\bar{p}$ Collider operating at $\sqrt{s}$=1.8 TeV. The analysis is a preliminary result based on a partial data sample of 13 pb^{-1} using $W \to e\nu$ and $Z \to ee$ decays.

1 Introduction

The transverse mass (M_T) constructed for $W \to e\nu$ decays is given by:

$$M_T^W = \sqrt{2E_T^e \not{E}_T \ (1 - cos\Delta\phi_{e\nu})} \tag{1}$$

where E_T^e is the observed transverse energy of the electron, $\not{E}_T$ is the observed missing transverse energy signifying the presence of a neutrino and $\Delta\phi_{e\nu}$ is the opening azimuthal angle between the two.

The conventional technique [1] to measure the W boson mass involves simulating the M_T spectra with M_W as a free parameter and fitting the observed M_T distribution using an unbinned log likelihood technique. Therefore the modelling of W production, decay and detector response are crucial and contribute significantly to the overall systematic uncertainty in this technique.

The transverse mass ratio method discussed here treats the $Z \to ee$ sample similar to the $W \to e\nu$ sample thus cancelling many of the common systematic uncertainties in the process. A Z transverse mass is constructed with the E_T^e of one of the decay electrons, while the $\not{E}_T$ is derived by adding the E_T of the other electron to the residual $\not{E}_T$ in the event. Hence two such combinations can be formed for each $Z \to ee$ event.

The Z transverse mass distribution is scaled down in finite steps and compared with the W transverse mass distribution. The W mass is then determined from the scale factor (M_W/M_Z) that gives the best fit of the M_T distributions using a Kolmogorov test [2]. The differences in the production mechanism, acceptance and resolution effects between the W and the Z sample lead to differences in the shapes of the M_T distributions. The Z sample is corrected to account for these effects. The differences and the corrections applied are discussed in the next section.

2 Detector effects

The observed E_T of the electron in terms of the true $\vec{p}_T$ can be stated as: $\vec{E}_T = \alpha \cdot \vec{p}_T \oplus \sigma_{EM} + \vec{\beta} + \vec{U}_e$. Here α and β refer to the electromagnetic energy scale and offset, σ_{EM} is the resolution term, $\oplus$ represents the smearing of the true p_T and U_e is the underlying event under the electron due to spectator interactions and vector boson recoil after correcting for zero suppression effects of the DØ calorimeter electronics. The observed event recoil can also be expressed in terms of the true recoil (p_T^{rec}): $\vec{E}_T^{rec} = \delta \cdot \vec{p}_T^{rec} \oplus \sigma_{had} + \vec{U}$. Here δ refers to the hadronic scale factor, σ_{had} is the resolution term and $\vec{U}$ is the contribution of the underlying event under the recoil. The presence of additive terms in the smeared (observed) quantities does not cancel out while taking the ratio of the M_T distributions. Hence the effects of scale and offsets are unfolded from E_T^e and $\not{E}_T$ before computing M_T.

For the method to work, the resolution (σ/E) of the electron for the W and Z must be the same. Because the Z electrons on average are more energetic, the resolution for Z is better (smaller) than for W. This effect produces a Z transverse mass that falls sharper than the W. This is corrected by adding additional smearing terms to the electron and missing transverse energy in Z events. The technique has been tested on Monte Carlo samples and has been found to work well.

The effect of requiring the second leg of the Z decay to be in the fiducial volume of the detector causes a bias since an equivalent restriction does not exist for the neutrino from the W. This effect is corrected by reweighting the event with the probability that the electron falls outside the fiducial volume.

3 Systematic Studies

Differences between W and Z production mechanisms and residual acceptance effects are studied using a fast Monte Carlo [1]. The difference leads to an effective correction of 109 MeV. An additional correction of -116 MeV comes from inclusion of radiative effects, leading to a net correction of -7 MeV.

The systematic uncertainties due to various effects are listed in Table 1. Electromagnetic and hadronic resolution effects mostly cancel out in this procedure as expected. The dominant systematic uncertainty arises from the uncertainty in the energy underlying the electron. The error due to efficiency effects include uncertainties in electron finding efficiency and trigger effects.

Table 1: Summary of sources of systematic uncertainties on the W mass.

Parameter	Error (MeV)	Parameter	Error (MeV)
EM Energy Scale/Offset	20	z vertex mean/width	15
EM Resolution effects	5	PDF variation	15
U_e under electron	35	P_T(boson)	15
Efficiency	30	Radiative Effects	15
Hadronic Scale/Resolution	15	MC statistics	20
# Minimum Bias events	30	Backgrounds	25
Total Systematic Uncertainty			**75**

The error due to number of minimum bias events reflects the uncertainty in the underlying event energy. Uncertainties due to parton distribution functions have been estimated using three different sets: MRSD-$'$, MRSA and CTEQ3M.

The total systematic error is estimated to be 75 MeV. Further cross checks are being performed, specifically on the difference between the W and Z production mechanism and its impact on the W mass. However these are not expected to have a large effect on the quoted systematic uncertainty.

4 Data Sample

The DØ detector [3] and particle identification [1] are described elsewhere. Electrons from W and Z decay are identified as in the conventional W mass analysis. Kinematic cuts on the electrons are applied after correcting for offset and scale effects. W candidates are selected by requiring $p_T^e > 30$ GeV and $p_T^\nu > 30$ GeV while electrons from Z decay are required to have $p_T > 34.1$ GeV (since they are eventually scaled down). Electrons from W decay and at least one electron from Z decay are required to be in the central pseudorapidity region ($|\eta| < 1.1$). The Z event is used twice if both electrons fall in the central region. The selection results in 5244 W and 535 Z events. In addition to the selection process, backgrounds are appropriately subtracted and Z events are weighted to remove the acceptance effects. The shape comparison is performed in the fitting window $65 < M_T < 100$ GeV.

The selected Z sample is oversmeared and scaled down in finite steps and the M_T shape compared to the W sample at every step using the Kolmogorov test. Since the oversmearing of Z events introduces a randomness, the fit is performed several times with different starting seeds. For each fit the resulting Kolmogorov probability distribution is fit to a gaussian function and its mean

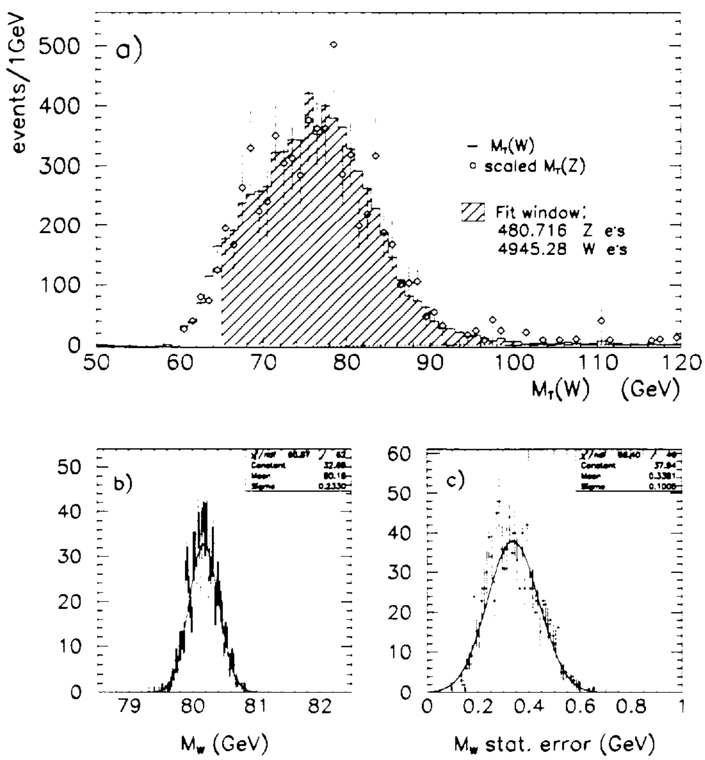

Figure 1: a) Data: M_T^W (solid histogram) with scaled M_T^Z (points) superimposed, b) Mean and c) Error from 1000 Kolmogorov fits.

and error are recorded. Figure 1(b,c) shows the distributions of the means and errors for an ensemble of 1000 fits. Figure 1a shows the M_T^Z distribution superimposed on the M_T^W distribution for one of the fits.

The statistical error from the fit is 338 MeV. The error based on an ensemble test using equivalent numbers of simulated W and Z events is 360 MeV, consistent with that found from data fits. We choose to be conservative and quote the higher of the two numbers. After carrying over the -7 MeV correction discussed earlier, the fit result is $M_W = 80.160 \pm 0.360(\text{stat}) \pm 0.075(\text{syst})$ GeV.

Our analysis on the complete Run I data sample ($\approx 100\ pb^{-1}$) is still ongoing. The quoted result based on the partial data sample is not competitive with the current W mass result. However the limitation in this procedure comes entirely from the limited Z statistics, the error from which is expected to reduce purely as $N^{-\frac{1}{2}}$. Inclusion of W and Z decays with electrons in the forward region will further reduce this error.

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