Measurement of M_W Using the Transverse Mass Ratio of W and Z

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ABSTRACT

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 $\mathrm{p\overline{p}}$ 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 $W \rightarrow e\nu$ and $Z \rightarrow ee$ decays.

I. INTRODUCTION

The transverse mass (M_T) constructed for $W \rightarrow e\nu$ 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. The simulation consists of building a physics model for W production and its subsequent decay into an electron and a neutrino and incorporating detector response effects such as resolution, underlying event energy and hadronic recoil effects. Therefore the modelling of W production and detector response play a crucial role and contribute significantly to the overall systematic uncertainty in this technique.

The transverse mass ratio method [2] discussed here treats the $Z \rightarrow ee$ sample similar to the $W \rightarrow e\nu$ sample thus cancelling many of the common systematic uncertainties in the process. A Z transverse mass is constructed with the E_T 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:

$$\vec{\not{E}}_T^{fake} = \vec{\not{E}}_T^Z + (\vec{E}_T^{e_2} - \vec{U}_{e_2}) \tag{2}$$

Here, $\vec{\not{E}}_T^Z$ refers to the observed missing E_T and $\vec{\not{E}}_T^{fake}$ is the reconstructed $\not{E}_T$ for the fake neutrino in the Z event using the second electron (e_2). The term U_{e_2} is needed because discarding the second electron creates an energy "hole" which otherwise would see some underlying event activity in the case of a real neutrino. Two transverse mass combinations can be formed for each $Z \rightarrow ee$ event. We have verified that the two entries are very loosely correlated.

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 [3]. 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.

The mass ratio can also be extracted by comparing the shapes of the electron E_T and $\not{E}_T$ distribution from W and Z decays. The comparison of electron E_T distributions is thought to be the most viable solution for fitting the W mass in the high luminosity regime since the procedure is independent of many resolution effects. However, the shapes of the electron E_T distributions are very sensitive to the differences in W and Z production, which need to be better understood. This method is still under investigation and will not be reported in this paper.

II. DETECTOR EFFECTS

The observed E_T of the electron in terms of the true $\vec{p}_T$ can be stated as:

$$\vec{E}_T = \alpha \cdot \vec{p}_T \oplus \sigma_{EM} + \vec{\beta} + \vec{U}_e \tag{3}$$

Here α and β refer to the electromagnetic energy scale and offset (transverse component), 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}):

$$\vec{E}_T^{rec} = \delta \cdot \vec{p}_T^{rec} \oplus \sigma_{had} + \vec{U} \tag{4}$$

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. The electron resolution has been determined from testbeam measurements with the form:

$$\frac{\sigma}{E} = \sqrt{\sigma_C^2 + \frac{\sigma_S^2}{E_T} + \left(\frac{\sigma_N}{E}\right)^2} \tag{5}$$

with the noise term, σ_N = 0.4 GeV; the sampling term, σ_S = 13.5% $\mathrm{GeV}^{\frac{1}{2}}$. The constant term, σ_C = 1.5%, is determined from fits to the Z data. 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 over smearing (σ_{ov}) is determined from the condition:

$$\left(\frac{\sigma}{\langle E\rangle}\right)^2_Z + \left(\frac{\sigma_{ov}}{\langle E\rangle}\right)^2_Z \equiv \left(\frac{\sigma}{\langle E\rangle}\right)^2_W \quad (6)$$

where $\langle E_T\rangle_W = \frac{M_W}{M_Z}\langle E_T\rangle_Z$. Solving the above, the over smearing is determined to be:

$$\sigma^2_{ov} = \left[\left(\frac{M_Z}{M_W}\right)^2 - 1\right]\sigma^2_N + \left(\frac{M_Z}{M_W} - 1\right)\frac{E^Z_T}{sin\theta}\sigma^2_S \quad (7)$$

The technique has been tested on Monte Carlo samples and has been found to work well.

The additional smearing introduced to the hadronic part is simpler since we assume that the hadronic recoil tranverse momentum does not scale with the vector boson mass ($\langle P^W_T\rangle = \langle P^Z_T\rangle$). The over smearing of the hadronic resolution term simplifies to:

$$\sigma^{recoil}_{ov} = \left[\left(\frac{M_Z}{M_W}\right)^2 - 1\right]^{\frac{1}{2}}\sigma_{recoil} \quad (8)$$

Here we have further assumed that $\sigma_{recoil}(W) = \sigma_{recoil}(Z)$. Using a similar procedure, additional smearing is added to the underlying event contribution under the recoil which is modelled using a minimum bias sample picked from the same luminosity distribution.

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. The effect is corrected by reweighting the event with the inverse probability that both the electrons fall in the fiducial volume. The probability is measured using the known z vertex distribution and varying the projected vertex position of the electron along z. The reweighting procedure has been extensively tested on Monte Carlo samples. A shift in the measured W mass of approximately -200 MeV is noted without reweighting the events. The reweighting procedure removes the above bias and in addition results in an improved match between the M_T spectra from W and Z decays leading to a higher Kolmogorov probability. It is worthy to note that the usage of the z vertex distribution from the data to remove the effects of the rapidity restrictions is completely independent of the model assumptions in the fast Monte Carlo including the choice of the parton distribution functions.

In the central calorimeter, electrons which fall near the module boundaries (in azimuth) have lower identification efficiencies and hence are removed from the analysis. This introduces a bias in the Z sample similar to that caused by rapidity restrictions. We again correct for this acceptance loss to remove the bias.

III. SYSTEMATIC STUDIES

Differences between W and Z production mechanisms and residual acceptance effects are studied using a fast Monte Carlo [1]. Large statistical samples of W and Z decays are generated and smeared using the parameterized fast Monte Carlo. The Z decays are then over smeared as explained in the previous section and its transverse mass distribution compared to W decays using a binned Kolmogorov test procedure, since an unbinned procedure presents a computational problem. We have checked that for fine bins (5 MeV), the unbinned and binned procedure yield the same result. The difference leads to a shift in the fitted W mass of 109 MeV using MRSD-$'$ parton distribution functions. Usage of other pdf's and $P_T(boson)$ combinations lead to different shifts which are accounted for in the systematic uncertainty for the production model. We have performed extensive studies to verify that this difference is primarily due to the differences in W and Z production mechanism. The mass shift is completely removed if Z events are used to simulate W events thereby removing any dependence on the parton distribution functions. An additional shift of -116 MeV comes from inclusion of radiative effects, leading to a net shift due to the two effects of -7 MeV. This shift is carried over as a correction to the fitted mass value from the data.

The systematic uncertainties due to various effects are listed in Table I. Electromagnetic and hadronic resolution effects mostly cancel out in this procedure as expected. The error due to efficiency effects include uncertainties in electron finding efficiency and trigger and $U_{||}$ effects. The effects of trigger are negligible because the E_T cuts on the electron and neutrino are high compared to the trigger threshold. The electron signature is spoiled due to the overlap of hadronic recoil and the EM object leading to a loss of efficiency. Termed as the $U_{||}$ effect, its systematic effect on the ratio measurement is determined to be small.

The uncertainty in the acceptance reweighting mechanism are determined from variation of the width and mean of the z vertex distribution. The dominant systematic uncertainty arises from the uncertainty in the energy underlying the electron. The error due to number of minimum bias events reflects the uncertainty in the underlying event energy. In the standard technique, the error in the number of minimum bias events is known to within 5%. We have taken conservative estimates to take into account uncertainties arising from our assumptions in the modelling of the underlying event energy of Z relative to W events.

Various sources of backgrounds that effect the W and Z transverse mass distribution have been extensively studied. For $W \rightarrow e\nu$ decays, QCD multijet and $W \rightarrow \tau\nu \rightarrow e\nu$ form the dominant backgrounds accounting for 1.6% and 0.9% respectively, whereas $Z \rightarrow ee$ backgrounds where one of the legs is lost accounts for approximately 0.4%. For $Z \rightarrow ee$ decays, Drell Yan backgrounds have been determined from Monte Carlo and parameterized as a function of M_T. The overall background normalization for $Z \rightarrow ee$ decays comes from fitting the sidebands in the corresponding invariant mass distribution and measuring the fractional area under the Z peak. The backgrounds are subtracted from the data before comparing the M_T distributions. Variation of the magnitude of the backgrounds by their estimated errors lead to a systematic uncertainty of 25 MeV.

Uncertainties due to parton distribution functions have been estimated using three different sets: MRSD-$'$, MRSA and CTEQ3M. The error due to the uncertainty in the input P_T spec-

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

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

trum [5] of the boson has been estimated by varying the $g2$ parameter [5] describing the non-perturbative region. This effect is expected to be reduced by constraining the $g2$ parameter using the p_T^Z spectrum.

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 an effect on the quoted systematic uncertainty. The systematics derived with Monte Carlo are consistent with analytical estimates that can be made for a number of parameters. The total systematic uncertainty is expected to reduce further for the full data sample ($\approx$ 100 pb^{-1}) as many of the model errors are limited by Z statistics.

IV. DATA SAMPLE

The DØ detector [4] and particle identification [1] are described elsewhere. During the first phase of the run at the Tevatron collider (1992-93), the DØ experiment accumulated approximately 13 pb^{-1} of data to tape. The second phase of the run (1994-95) has accumulated an additional 90 pb^{-1}. The analysis reported here is based on the data sample collected during the first phase. However, due to a limited range in luminosity covered during this period, we have used a fraction of the data sample from the second running phase to study luminosity dependent effects.

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 based on a total data sample of approximately 13 pb^{-1}. 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.

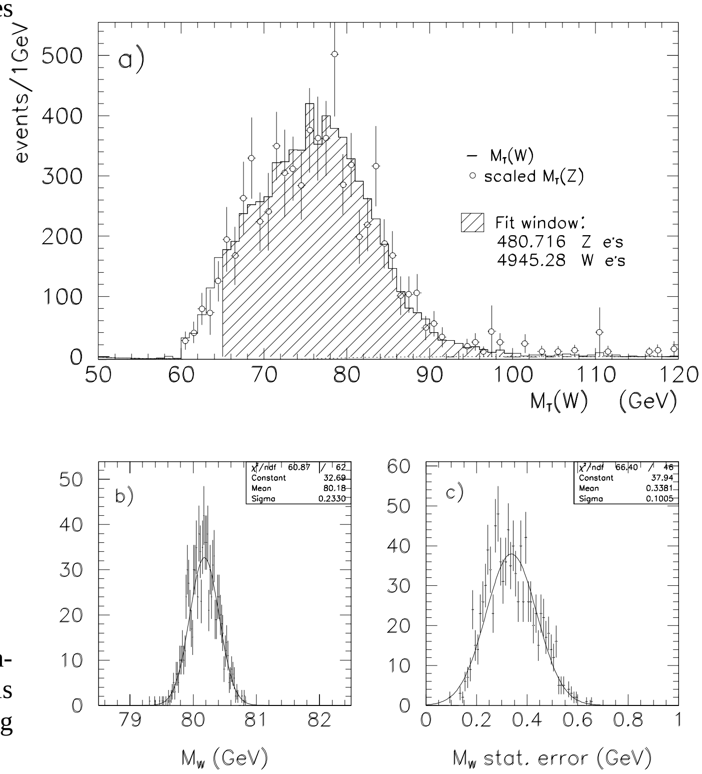

Figure 1: a) Data: M_T^W (solid line) with scaled M_T^Z (open circles) superimposed, The hatched area represents the fit window. b) Mean and c) Error from 1000 Kolmogorov fits.

The selected Z sample is over smeared and scaled down in finite steps and the M_T shape compared to the W sample at every step using an unbinned Kolmogorov test procedure. Since the over smearing 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 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. The ensemble test utilizes 1000 independent simulated event samples and hence better reflects the true statistical uncertainty. We choose to be conservative and quote the larger of the two numbers as our best estimate. After carrying over the -7 MeV correction discussed earlier, the preliminary fit result is $\mathrm{M_W} = 80.160 \pm 0.360(\mathrm{stat}) \pm 0.075(\mathrm{syst})\ \mathrm{GeV}$. The lower and upper limits of the standard fit window have been varied to check

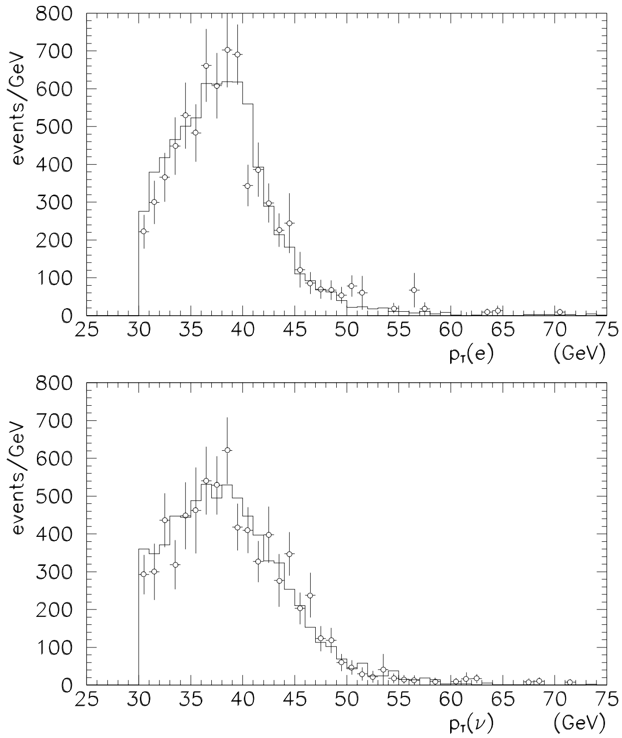

Figure 2: p_T^e (top plot) and p_T^ν (bottom plot) distributions from W and Z decays. In each plot, the solid line represents $W \to e\nu$ sample and open circles represents the scaled $Z \to ee$ sample.

for any bias. The variation in the fitted W mass is taken to be a part of the fit statistics.

Similar results obtained from p_T^e and p_T^ν fits are consistent with those from M_T fits. Figure 2 shows the p_T^e and p_T^ν distributions for the W and the scaled Z sample. The statistical error obtained from the p_T^e fits are comparable with those for the M_T fit. However, systematic uncertainty studies for these fits are currently under progress.

Using a large fraction of our full data sample, we have studied for possible luminosity dependence in this method. The luminosity range explored at the Tevatron during the second running phase was $\mathcal{L} < 2 \times 10^{31}\ cm^{-2} sec^{-1}$. The W and Z data sample were binned into four luminosity bins, each with equal number of entries. In each bin, the fit was carried out using the ratio method and compared to the fit result averaged over all bins. Figure 3 shows the deviation from the average for the M_T and the p_T^e fits. The errors on each point represents the statistical error for each of the four independent data samples. The dashed line represents the statistical error for the combined sample from all four luminosity bins. This preliminary result indicates that the scatter in the points are consistent with statistical fluctuations and no mass dependence is seen with increasing luminosity. Systematic checks of these trends are currently being performed.

Our analysis on the complete 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

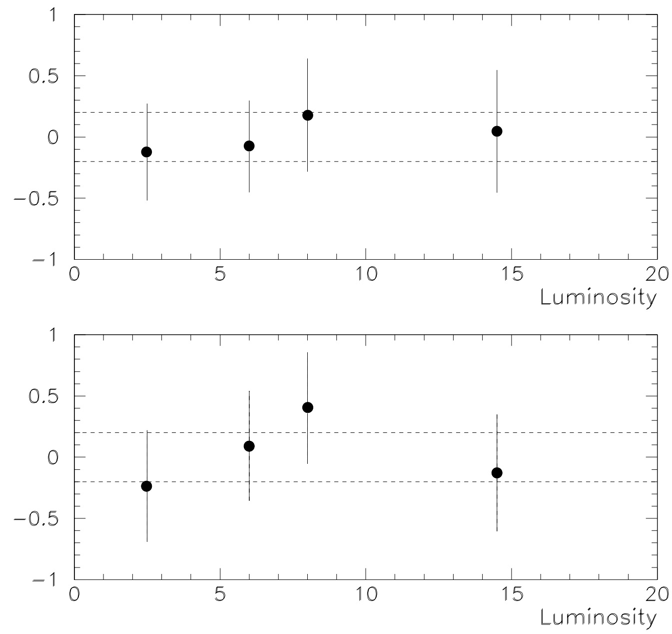

Figure 3: Luminosity (units of $\times 10^{30}\ cm^{-2} sec^{-1}$) dependence for M_T (top plot) and p_T^e (bottom plot) fits. The ordinate represents the deviation from average in units of GeV.

limitation in this procedure comes entirely from the limited Z statistics, the error from which is expected to reduce purely as $N^{-\frac{1}{2}}$. Based on this assumption, the expected statistical error from the ratio method using $1\ fb^{-1}$ of data would be about 40 MeV. Inclusion of W and Z decays with electrons in the forward region will further reduce the error.

V. REFERENCES

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