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DØ & CDF

W Mass from the Tevatron

Michael Rijssenbeek
For the DØ and CDF Collaborations
SUNY at Stony Brook
Stony Brook, New York 11794-3800

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

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W MASS FROM THE TEVATRON

Michael Rijssenbeek
(for the DØ and CDF Collaborations[1])

State University of New York at Stony Brook Stony Brook, NY 11794-3800, USA

We report the preliminary W mass measurement at the Tevatron by the DØ collaboration using central electrons from the 1992–1995 data set: $M_W = 80.37 \pm 0.15\,\mathrm{GeV/c^2}$. This value is combined with the previously reported measurement of M_W by the CDF collaboration from their 1992-1993 data set of central electrons and muons, to obtain a new world average: $M_W = 80.35 \pm 0.13\,\mathrm{GeV/c^2}$. We discuss the measurement procedure and its systematical uncertainties, and indicate prospects for the full 1992–1995 result from the Tevatron.

I. INTRODUCTION

The parameters of the electroweak sector of the Standard Model (SM) can be chosen as the fine structure constant, the Fermi constant, and the Z boson mass, all measured to better than 0.01%. Higher order radiative corrections then relate the W boson mass, M_W, and the weak mixing angle through these three parameters, the heavy fermion masses, and the Higgs boson mass. Within the SM, a precision measurement of M_W thus constrains the allowed region for the top quark and Higgs masses. Alternatively, it provides a consistency test of the SM.

The W mass has been determined recently by the UA2 collaboration at CERN (2), and the CDF and DØ collaborations in Fermilab (1,3). We discuss in some depth the new preliminary measurement from DØ from data collected during the 1992–1995 run at the Tevatron collider (4). The world average for M_W is updated.

The mass of the W is determined from its decays into $e\nu$ (CDF, DØ) or $\mu\nu$ (CDF). Since the longitudinal momentum of the neutrino is not measured, M_W must be extracted from a correlated kinematical quantity, such as the electron energy or transverse energy, the neutrino transverse momentum, or the transverse mass M_T (5), via a model-based fit. The M_T fit was used as it is least sensitive to certain systematics, notably the production model.

Electrons from W and Z bosons tend to be isolated and have high transverse momentum, and trigger and off-line selections made use of these properties (3). Calorimeter fiducial criteria ensured that the electron candidates were well measured. In W decays the neutrino transverse energy is equated to the missing transverse energy $\not{E}_T$, and required to exceed 25 GeV.

The run was subdivided into two periods: Run 1a(b) from 1992–1993 (1993–1995), with collected sample size for DØ of 12.8(76)pb^{-1}. The DØ Run 1b sample contains 32856 central $W \to e\nu$ candidates and 1562(1548) central-central(forward) $Z \to ee$ candidates.

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II. ELECTRON ENERGY SCALE

CDF used its magnetic field to measure muon momenta directly, and to calibrate the electron energy scale with W electrons, correcting for radiative losses upstream of the tracker. The CDF momentum scale is accurately calibrated with $J/\psi \rightarrow \mu\mu$ decays ($\simeq$ 60k events in Run 1a), and checked with the Υ and Z resonances.

In calibrating the electron energy response, DØ used the relationship between the measured calorimeter energy and the true energy $E_{\rm meas} = \alpha E_{\rm true} + \delta$, derived from its test beam data.

The first approach exploited the variation in energy of the electrons from Z decays. The measured and true mass values are, to first order, related as $M_{\rm meas} = \alpha\, M_{\rm true} + \delta\, f$, where f depends only on the decay topology. A fit to the Z mass as function of f determined both α and δ.

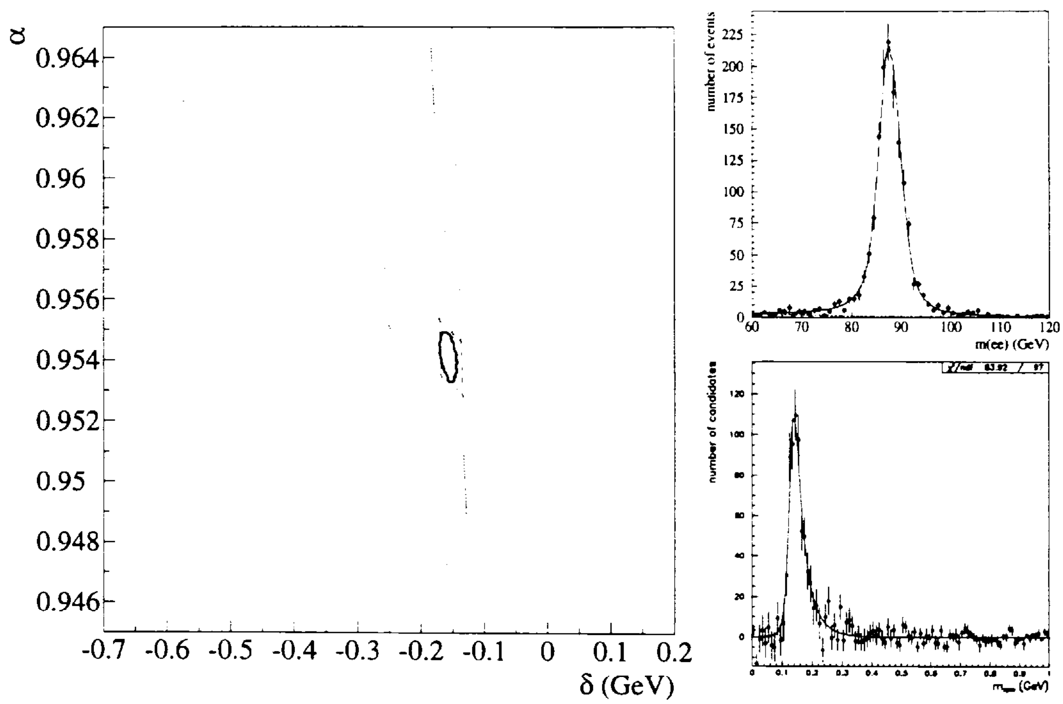

FIG. 1. Constraints on α and δ from $J/\psi \rightarrow e^+e^-$ (dashed lines), $\pi^0 \rightarrow \gamma_c\gamma_c$ (steep solid lines, mass plot right bottom), and $Z \rightarrow ee$ decays (inclined ellipse, mass plot right top). The inner contour shows the combined result.

In the second approach, the Z resonance was used in conjunction with $\pi^0 \rightarrow \gamma\gamma$ and $J/\psi \rightarrow e^+e^-$ decays, and the precisely known masses (6,7). Both π^0 decay photons were required to convert before the tracking in order to measure the opening angle. Because the clusters from the decay are not resolved in the calorimeter, equal sharing of the cluster energy was assumed. The energy scale and offset were extracted by comparing the observed mass spectrum to a simulation of the lineshape.

Figure 1 shows the independent constraints on α and δ obtained from the π^0 data, the J/ψ data, and the complementary approach using just the Z events. When combined, α and δ are limited to the small elliptical region.

The electron polar angle is computed from the center of gravity of the calorimeter cluster and of the matched track in the central drift chamber. Its resolution was determined from $Z \to ee$ data.

The uncertainty on the energy scale results in an uncertainty on M_W of 160(77) MeV/c^2 for the Run 1a(b) data. The uncertainty is dominated by the limited statistics of the Z mass measurement. Test beam measurements accomodate a small nonlinearity in the energy response, which alters the ratio M_W/M_Z largely through its effect on δ. This 21 Mev/c^2 effect is included.

The energy underlying the electron was obtained from W events as the energy deposited in a calorimeter region the size of the electron cluster, rotated away in azimuth. The underlying event adds an average energy of 16.7 ± 1.5 MeV per tower ($\Delta\eta \times \Delta\varphi = 0.1 \times 0.1$) to a central electron, resulting in a 28 MeV/c^2 uncertainty on M_W.

III. FAST EVENT GENERATOR

A fast event generator was used to predict M_T spectra as a function of M_W and provide the template functions for a maximum likelihood fit. The generator began with a theoretical calculation of W or Z production and decay at the 4–vector level. Relevant detector effects were simulated. These included the electron energy resolution, scale and resolution of the hadronic recoil system which balances the p_T of the W or Z, kinematic and fiducial acceptances, trigger and selection efficiencies and underlying event effects.

W or Z bosons were generated according to a theoretical calculation (8) of $d^2\sigma/dp_T dy$ which includes a resummation of the leading divergences in $1/p_T^2$ as $p_T \to 0$. The calculation depends on parton distribution functions (pdf) and on a parametrization of non-perturbative physics at very small momenta (8). MRSA pdf (9) were used.

The mass of the W or Z was generated as a relativistic Breit-Wigner lineshape with a skewing from the decrease of parton luminosity with mass. The W width was fixed to its measured value (10). The decay products were generated with angular distributions respecting the boson polarization.

In addition, radiative decays were generated (11). In $W \to e\nu\gamma$ decays the $e\nu$ mass does not reconstruct to the W mass if the radiated photon falls outside the electron cluster. If the photon falls near, but not fully within, the electron cluster is distorted and may fail the shower shape cuts. The same applies to radiative Z decays but the effects do not cancel completely in the mass ratio.

The irreducible background due to $W \to \tau\nu \to e\nu\nu\nu$ was included in the event generator. Functions describing other backgrounds were included in the M_T spectra. The QCD jet background in the W sample was determined from an independent jet data sample to be $1.6 \pm 0.8 (1.5 \pm 0.3)\%$ for the selected Run 1a(b) sample. Its inclusion shifted the W mass by +33 MeV/c^2. The background from $Z \to ee$ events in which one electron was not identified, was estimated using ISAJET (12) to be $\approx 0.5\%$. Its effect on M_W was negligible.

The width of the Run 1b $Z \to ee$ invariant mass distribution constrains the constant term in the electron energy resolution.

The relative response of the hadronic calorimeter with respect to the electromagnetic (EM) calorimeter, α_{rec}, was established with Z events. Figure 2 shows the imbalance

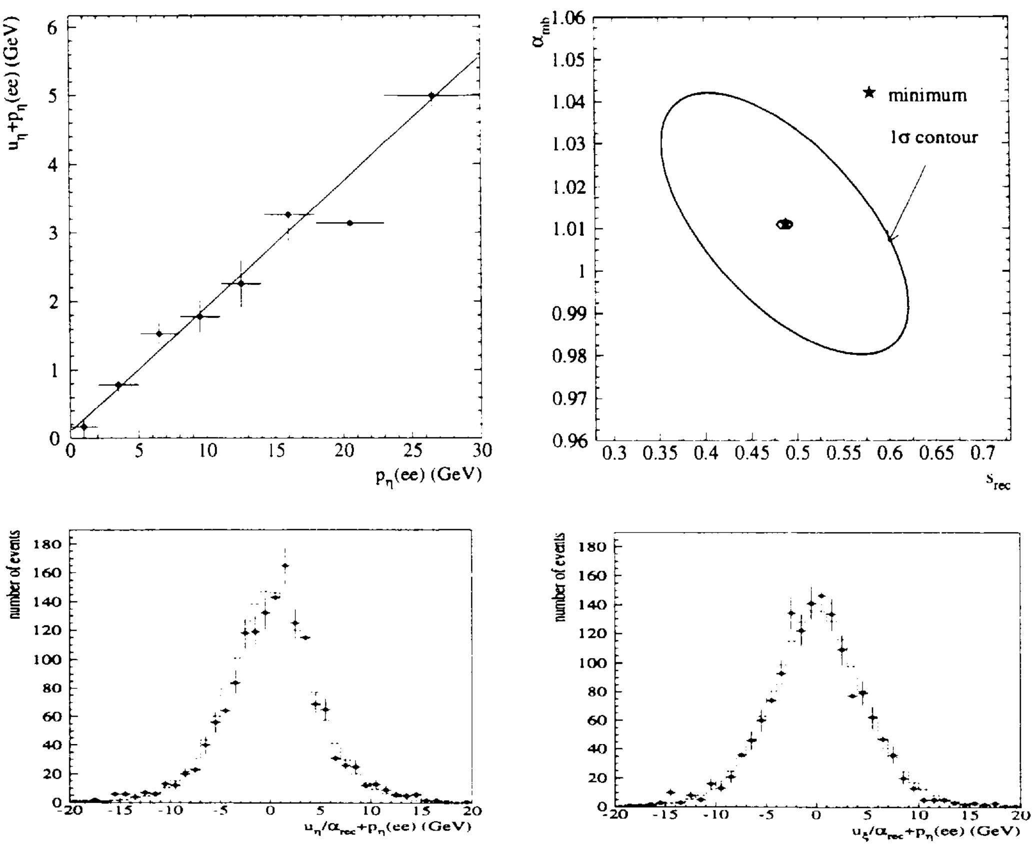

FIG. 2. Top: balance of EM and hadronic transverse energy vs. p_T^{ee} in Z events along the η-axis (left), 1σ contour of α_{mb} vs. the recoil sampling term S_{rec} (right, see text). Bottom: the η-balance (left), and ξ-balance (right) distributions after the fit of the simulation (⊓) to the data (•).

between the p_T of the Z measured with the electrons, $\vec{p}_T^{ee}$, and the p_T measured with the hadronic system, $\vec{u}_T$. Both are projected onto the η axis, the bisector of the transverse momentum vectors of the electrons (the other axis is denoted as ξ). This minimizes the effect of the electron resolution. A linear dependence is observed, with $\alpha_{rec} = 0.83 \pm 0.04 (0.81 \pm 0.015)$ for Run 1a(b).

The recoil vector was modelled from two components, one parallel to the true boson p_T, and the second symmetrically distributed with respect to the boson p_T direction. Intuitively, the first component corresponds to a recoil jet and the second to a resolution vector which combines the effects of the underlying event debris from spectator partons in the boson production interaction, particles from multiple interactions and pileup effects from previous interactions.

The asymmetric component is modelled by scaling the true p_T by the scale α_{rec} and applying a resolution with a 4% constant term and a sampling term S_{rec}. The symmetric component is modelled with minimum bias events with a luminosity distributed so that the mean number of interactions is the same as that in the W sample. The $\vec{\not{E}}_T$ vector from the minimum bias events is allowed to vary by a factor α_{mb}. The correlated parameters S_{rec} and α_{mb} are constrained by comparing the p_T balance in $Z \rightarrow ee$ events along the η and ξ directions, after correcting for the relative hadronic response, see Figure 2. α_{mb} was consistent with unity for both Run 1a and Run 1b.

Significant detector and reconstruction biases were modelled in the simulation. The recoil system may affect the electron identification, especially if close to the electron. A measure of the event selection biases, through electron shape and isolation cuts, is obtained by studying the projection of the momentum recoiling against the W along the electron p_T direction $(\hat{p}_T^e)$: $u_{\parallel} \equiv \vec{p}_T^{\,rec} \cdot \hat{p}_T^e$. An inefficiency in $u_{\parallel}$ causes a kinematic bias for the W decay products. In the Run 1b analysis, fully simulated electrons were superimposed on W events, taking into account the appropriate kinematic correlations. The efficiency as a function of $u_{\parallel}$ was determined directly from this hybrid sample. The transverse mass fit is largely insensitive to this inefficiency.

IV. FIT RESULTS

The Run 1 M_T^W distribution and the simulated lineshape corresponding to the best fit are shown in Fig. 3. The fitted W mass is $M_W = 80.38 \pm 0.07$(stat.) $\pm$ 0.13(syst.) $\pm$ 0.08(scale) GeV/c^2.

Table 1 lists the uncertainties and sources. The χ^2 for the M_T fit is 87 for 59 degrees of freedom. A Kolmogorov-Smirnov test yields a 95% probability that the fit and the data came from the same parent distribution. The fit was insensitive to the choice of fitting window over a large range of the upper and lower M_T limits.

V. SYSTEMATIC ERRORS

Systematic errors were estimated by varying the assumptions of the Monte Carlo model and determining the sensitivity of the W mass fit to each of the input parameters to the model. The systematic uncertainties in M_W due to the parameters in the MC model are listed in Table 1.

A 70 MeV/c^2 mass shift is observed when Run 1b events at luminosities greater than 9×10^{30}cm^{-2}s^{-1} are excluded from the sample. Although possibly statistical in origin, a conservative systematic error of 70 MeV/c^2 was included to account for possible inadequacies in modelling events at very high luminosity. Extensive analysis is in progress, and this uncertainty is anticipated to disappear in the final result.

A large systematic uncertainty is due to the model for the p_T^W spectrum and the pdf's. The correlation between the pdf's and the p_T^W distribution has been addressed. The pdf's are constrained by the measured HERA data (13) and W charge asymmetry ($\mathcal{A}_W$) (14). New pdf's were obtained from the CTEQ group (15) incorporating all available data with the $\mathcal{A}_W$ data points moved coherently by $\pm 1\sigma$. The parameters governing the non-perturbative part of the p_T^W spectrum (16) were varied simultaneously, as constrained by the Run 1a p_T^Z spectrum. The resulting variation in the W mass leads to an uncertainty of 65 MeV/c^2. Work is in progress to further constrain the production model using Run 1b data.

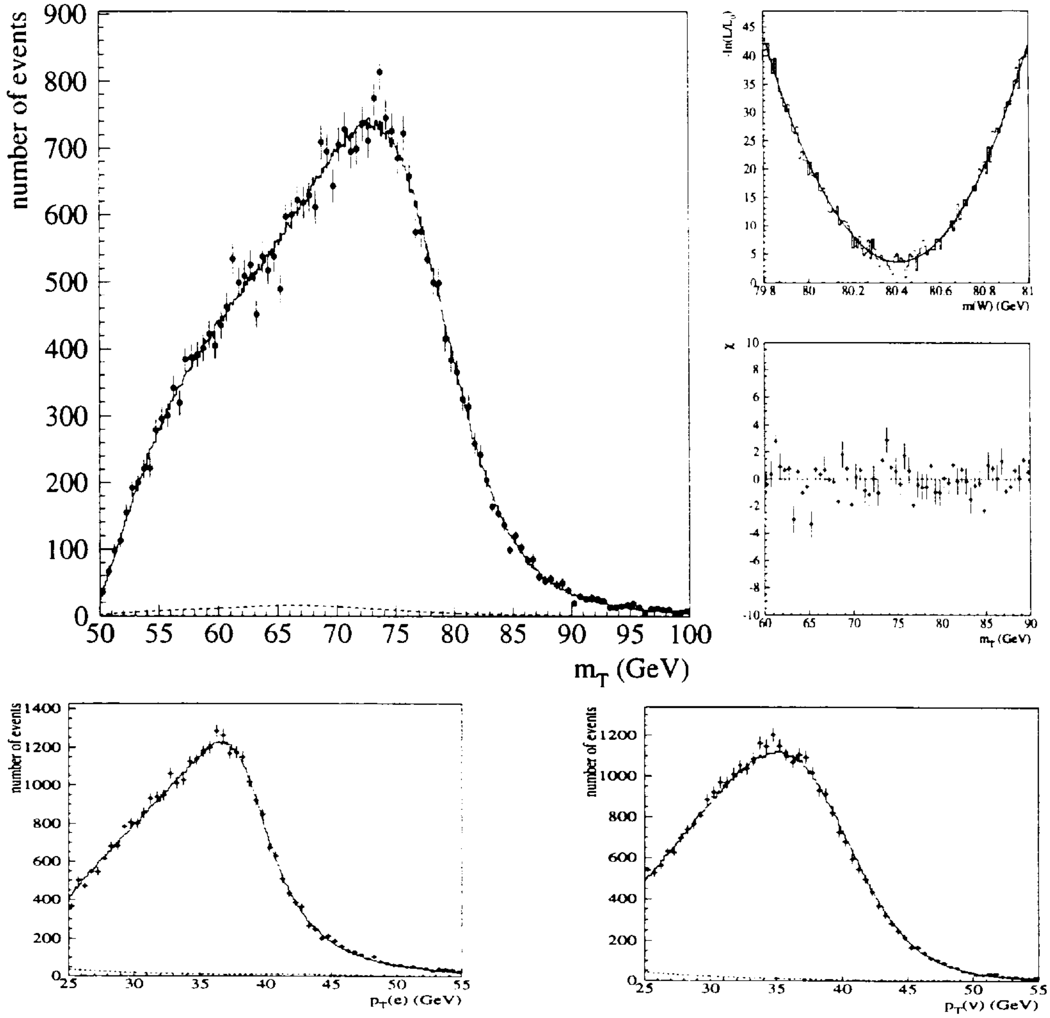

FIG. 3. Top: The transverse mass distribution for the Run 1b W sample (left), the relative likelihood profile vs M_W (right), and the χ distribution over the fit region (right middle). Bottom: the p_T^e (left) and p_T^ν distributions at the fitted M_W. The points indicate the data, the solid line the simulated lineshape at the best M_W fit, and the dashed line the background contribution.

VI. CONCLUSION

Combining the DØ Run 1a and the preliminary 1b results together, accounting for common systematics, one finds $M_W = 80.37 \pm 0.15\,\mathrm{GeV/c^2}$. This new result is combined with CDF (1) and UA2 (2) measurements into a new world average $M_W = 80.35 \pm 0.13\,\mathrm{GeV/c^2}$. Future CDF and DØ results from present data will further reduce the W mass error to well below $100\,\mathrm{MeV/c^2}$.

Uncertainty (MeV/c^2)	Run 1a	Run 1b	common
Statistical	140	70	
Energy scale	160	80	
p_T^W, pdf	65	*65*	65
W Natural Width	20	10	10
Radiative Decays	20	20	20
Backgrounds	35	15	
EM Energy resolution	70	30	10
Angle Calibration	50	40	40
Underlying Event	35	30	
Hadronic Energy Scale	50	30	
Hadronic Resolution	65	20	
# of Min Bias events	60	40	
Efficiencies	30	20	
Cal. non-uniformity	10	10	10
Fit Error	5	5	
Luminosity effects		*70*	
Total Systematic	165	130	85
Total	270	170	

TABLE 1. Uncertainties in the W boson mass measurement

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