Measurement of the Mass and Width of the Z^0 Boson at the Fermilab Tevatron

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An analysis of $Z^0 \to e^+e^-$ and $Z^0 \to \mu^+\mu^-$ data from the Collider Detector at Fermilab in $\bar{p}p$ collisions at $\sqrt{s}=1.8$ TeV yields a mass of the Z^0 boson of $M_Z = 90.9 \pm 0.3$ (stat + syst) ± 0.2 (scale) GeV/c^2 and a width of $\Gamma_Z = 3.8 \pm 0.8 \pm 1.0$ GeV.

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In the standard model of electroweak interactions the mass of the Z^0 gauge boson is directly related to the $SU(2)_L$ and U(1) coupling constants g' and g,[1] and to the vacuum expectation value of the Higgs field.[2] The width of the Z^0 is also predicted in the theory from its couplings to the quark and lepton generations. In this Letter we present a measurement of the Z^0 mass and width based on an integrated luminosity of 4.7 pb^{-1} of $p\bar{p}$ collisions at $\sqrt{s}=1.8$ TeV collected with the Collider Detector at Fermilab (CDF).

The CDF is described in detail in Ref. 3; here we provide a brief description of components used in this analysis. A vertex time-projection chamber (VTPC) close to the beam pipe is used to measure the event z-vertex position. A drift chamber (CTC) surrounding the VTPC allows reconstruction of tracks in three dimensions. A superconducting solenoid encloses these tracking chambers.

External to the solenoid, an electromagnetic (EM) calorimeter covers the central region $|\eta| < 1.1$, where $\eta = -\ln(\tan\theta/2)$. Behind this is a hadronic calorimeter. Both calorimeters are organized into projective towers of size $\delta\eta = 0.1$ by $\delta\phi = 15°$. Gas proportional chambers ("strip chambers") are embedded in the EM calorimeter near shower maximum to provide accurate shower position determination. Drift chambers located behind the ~ 5 absorption lengths of the central calorimeter are used to identify muons.

The triggers used to collect this data set were (1) an "electron" trigger requiring an EM transverse energy deposition of $E_T > 12$ GeV within a "trigger tower" ($\delta\eta = 0.2$, $\delta\phi = 15°$) associated with a track of $P_T > 6$ GeV/c found by the on-line track processor; (2) a "diphoton" trigger requiring two or more EM clusters each with $E_T > 10$ GeV and with no requirement on tracks; and (3) a "muon" trigger requiring a muon track segment in the central muon chambers matching an on-line track with P_T greater than 9 GeV/c.

The Z^0 mass is measured using the $Z^0 \to \mu^+\mu^-$ tracking data and using the $Z^0 \to e^+e^-$ calorimeter data. A tracking analysis of $Z^0 \to e^+e^-$ is also presented for comparison. The analyses are restricted to the central region to exploit the optimum track momentum and calorimeter energy resolutions. We first describe the muon analysis.

Dimuon events were selected by requiring the following: (1) two tracks with $P_T > 20$ GeV/c; (2) at least one match in ϕ between a muon-chamber track segment and a CTC track; (3) nonzero hadronic and electromagnetic energy deposition, but less than 6.0 and 2.0 GeV, respectively, in the single calorimeter tower associated with each track; and (4) no jets with $E_T > 15$ GeV within 10° of these tracks.

Events with two muons back to back within 0.1 unit in η and 1.5° in ϕ were rejected as cosmic rays. Events having muon pairs with invariant masses between 50 and 150 GeV/c^2 were selected. This sample consists of 132 events. There are no like-sign muon pairs in this mass range.

Transverse momenta are calculated from track curvature using 1.4116 T for the axial component of the magnetic field. The uncertainty in the field is $\pm 0.05\%$, where the dominant contribution stems from the fact that the solenoid was operated at a current of 4650 A, whereas it was mapped at 5000 A.[4]

The CTC alignment was adjusted using electrons from W decay so that the ratio of track momentum to calorimeter energy was charge independent. This alignment was checked using cosmic-ray muon tracks passing through the CTC close to the beam axis. These were reconstructed as two tracks, each emanating from a point of closest approach to the beam axis. On average, the two tracks passed through the same space point with the same curvature. Constraining the W-decay tracks to come from the beam axis gives a measured final CTC resolution of $\delta P_T / P_T^2 = 0.11\%\,(\text{GeV}/c)^{-1}$. This constraint is applied to the tracks in the Z^0 samples.

The CTC alignment and the magnitude of the magnetic field were verified by studying $K_S^0 \to \pi^+\pi^-$, J/ψ, and $\Upsilon(1S) \to \mu^+\mu^-$ decays. Beam constraints were applied to the tracks in the latter two data samples. The reconstructed masses of 0.498 ± 0.002, 3.097 ± 0.001, and 9.469 ± 0.010 GeV/c^2 agree well with the world-average values. Based on these measurements, we estimate a mass-scale error $< 0.2\%$ due to systematic momentum-scale uncertainties.

To study the effects of radiative corrections, $Z^0 \to e^+e^-$ and $Z^0 \to \mu^+\mu^-$ events were simulated with a Monte Carlo event generator which uses the exact matrix elements to order α^2.[5] To study external radiation (bremsstrahlung), the generated events were passed through a detailed simulation of the CDF.

The mass distribution for $Z^0 \to \mu^+\mu^-$ [Fig. 1(a)] was fitted in the range 75 to 105 GeV/c^2 using a maximum-likelihood fit with a signal modeled by a relativistic Breit-Wigner form convoluted with a Gaussian resolution in $1/P_T$. Of the 132 events in the sample, 123 events are in this mass range. The fitted mass and width are 90.7 ± 0.4 (stat) ± 0.2 (scale) GeV/c^2 and 4.0 ± 1.2 (stat) ± 1.0 (syst) GeV. The fit is insensitive to the

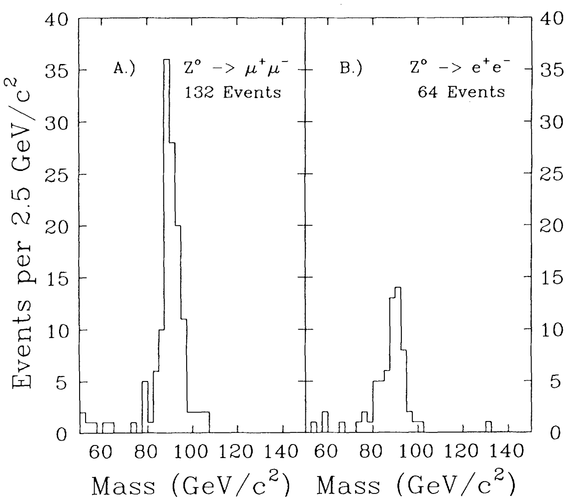

FIG. 1. The invariant-mass distribution for (a) $Z^0 \rightarrow \mu^+\mu^-$ candidates and (b) $Z^0 \rightarrow e^+e^-$ candidates using the track information.

nonresonant Drell-Yan contribution. The effects of radiative corrections, different structure functions, and the mass window used are included in the estimate of the uncertainties (see Table I).

An inclusive electron sample was obtained by requiring at least one electron candidate satisfying the following: (1) the electron is several cm away from calorimeter edges so as to have its shower fully contained; (2) a ratio of hadronic to electromagnetic calorimeter energy of < 0.10; (3) a ratio of electromagnetic energy to track momentum $E/P < 1.4$; (4) a transverse shower profile in the strip chambers consistent with an electron shower, using a χ^2 test in both projections; and (5) a match between the strip-chamber shower position and the extrapolated track position of < 3.0 cm in the z direction and < 1.5 cm in the ϕ direction.

From the inclusive sample, 73 events have electron pairs with both particles satisfying the above criteria and with invariant mass between 50 and 150 GeV/c^2. These criteria are very stringent in order to obtain a sample of the best measured events. There are no like-sign pairs in this mass range.

The same mass-fitting technique using tracking information was applied to the $Z^0 \rightarrow e^+e^-$ event sample as for $Z^0 \rightarrow \mu^+\mu^-$ [Fig. 1(b)]. Of the 73 events, 64 have both tracks of the quality to pass the beam-constrained tracking fits and 58 are in the mass range of the fit. The radiative effects on the observed mass are appreciably larger in the muon mode (see Table I); consequently, the best measurement of the Z^0 mass in this mode is obtained using calorimeter information.

To determine the Z^0 mass from the calorimeter, the EM calorimeter was calibrated on a tower-by-tower basis using the fitted means of the E/P distributions from a sample of $\sim$17000 inclusive electrons. The measured energy resolution of the calorimeter for electromagnetic showers is

$$\left(\frac{\sigma_E}{E}\right)^2 = \left(\frac{13.5\%}{(E\sin\theta)^{1/2}}\right)^2 + (1.7\%)^2 ,$$

where the constant term is the average uncertainty in the individual tower calibrations.

The overall energy scale was established from the momentum scale using the mean E/P from $\sim$1000 W-decay electrons. The expected shape and mean of the E/P distribution for these W electrons was simulated including external and small-angle internal bremsstrahlung (Fig. 2). For $E/P < 1.4$, the mean E/P is 1.026. The systematic uncertainty in E/P is estimated to be $\pm 0.4\%$ (0.3% from the determination of the mean E/P, and 0.3% from the bremsstrahlung calculation). We have checked that the E/P distribution for Z^0 decay electrons is consistent with bremsstrahlung predictions and with that for W-decay electrons. A small correction was also applied to the Z^0 mass for internal wide-angle photon emission (see Table I).

The mass and width of the Z^0 peak (Fig. 3) were fitted in the mass range of 80 to 100 GeV/c^2 using the maximum-likelihood method and the calorimeter resolution. For the 65 events in this mass range, the corrected fitted values for the Z^0 mass and width are $91.1 \pm 0.3 \pm 0.4$ GeV/c^2 and $3.6 \pm 1.1 \pm 1.0$ GeV, respectively. The quoted systematic uncertainties reflect reasonable

TABLE I. Corrections and uncertainties in the Z^0 mass. All units are in GeV/c^2. The first uncertainty is statistical and the second is systematic.

	$Z^0 \rightarrow \mu^+\mu^-$ (Tracking)		$Z^0 \rightarrow e^+e^-$ (Tracking)		$Z^0 \rightarrow e^+e^-$ (Calorimeter)	
Number of events used in fit	123		58		65	
Observed fitted mass	90.41 ± 0.40		89.27 ± 0.80		90.93 ± 0.34	
Radiative corrections	$+0.22$	± 0.03	$+2.19$	± 0.30	$+0.11$	± 0.03
Structure functions	$+0.08$	± 0.03	$+0.08$	± 0.03	$+0.08$	± 0.03
E/P calibration	...	...	...	...		± 0.38
Mass scale		± 0.20		± 0.20		± 0.20
Corrected mass	$90.7 \pm 0.4 \pm 0.2$		$91.5 \pm 0.8 \pm 0.4$		$91.1 \pm 0.3 \pm 0.4$	

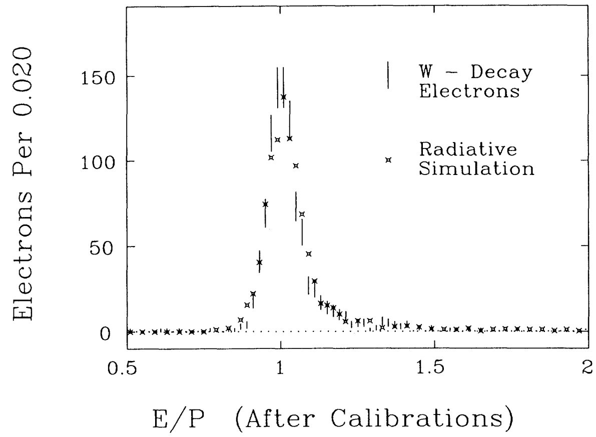

FIG. 2. The ratio of electromagnetic energy (E) to track momentum (P) for electrons in the W sample compared to Monte Carlo radiative simulation using a CTC P_T resolution of $\delta P_T/P_T^2 = 0.11\%\,(\mathrm{GeV}/c)^{-1}$.

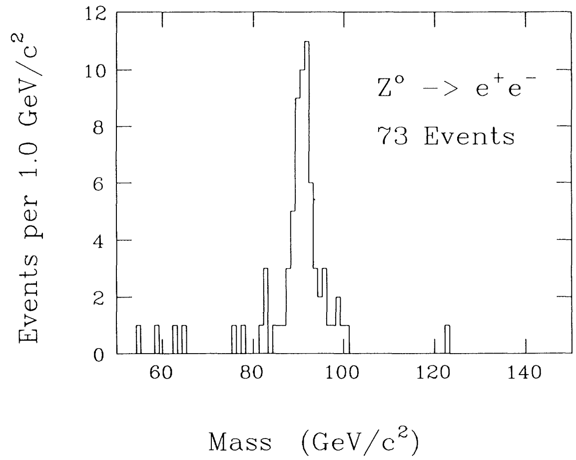

FIG. 3. The invariant-mass distribution for $Z^0 \to e^+e^-$ candidates using the information from the calorimeter.

variations in the energy resolution, the mass window, the choice of structure functions, and the fitting procedure. Determination of the Z^0 width is sensitive to non-Gaussian tails of the resolution, but not to the fitted value of the Z^0 mass.

The corrections and uncertainties in each of the mass measurements are summarized in Table I. Our best value for the Z^0 mass is a weighted mean of the tracking measurement of the $\mu^+\mu^-$ sample and the calorimeter measurement of the e^+e^- sample. For each of these measurements an overall uncertainty is formed by combining in quadrature the statistical and systematic uncertainties, excluding the common mass-scale uncertainty.

In conclusion, we have determined the Z^0 boson mass to be 90.9 ± 0.3 (stat+syst) ± 0.2 (scale) GeV/c^2 and the width of the Z^0 boson to be $3.8 \pm 0.8 \pm 1.0$ GeV. Our measured value for the Z^0 mass is consistent with previous measurements by UA1 of $93.1 \pm 1.0 \pm 3.1$ GeV/c^2 and UA2 of $91.5 \pm 1.2 \pm 1.7$ GeV/c^2.[6] The Z^0 width is consistent with standard-model expectations.

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