SLAC–PUB–5141
November 1989
(T/E)

A Measurement of the Z Boson Resonance Parameters at the SLC*·

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We have measured the resonance parameters of the Z boson using 480 Hadronic and Leptonic Z decays collected by the Mark II Detector at the Stanford Linear Collider. We find the Mass to be 91.14±0.12 GeV/c^2, and the width to be $2.42^{+0.45}_{-0.35}$ GeV.If we constrain the visible width to its Standard Model value, we find a partial width to invisible decay modes corresponding to 2.8±0.6 neutrino species with a 95% confidence level limit of 3.9.

1. Introduction

Precision measurements of the resonance parameters of the Z boson provide several missing details of the Standard Model. By measuring the mass of the Z, one determines a fundamental input parameter of the Standard Model. By measuring the cross section and width one discovers the spectrum of particles which couple to the Z. In particular, the number of light neutrino generations is determined.

This talk is a report on the measurement of the resonance parameters by the Mark II collaboration. The results presented here include data collected through the most recent Mark II publication[1]. The numbers presented at Madrid were for data collected through September 1, 1989[2].The results shown were M_Z=91.17±0.18 GeV/c^2, $\Gamma = 1.9^{+0.4}_{-0.3}$ GeV, invisible width = 2.7±0.7 neutrino generations ($N_\nu < 3.9$ at 95% C.L.).

2. Detector

The measurement of a resonances' parameters requires measuring the cross section for the production at a variety of different energies. The accuracy which one can determine the mass of the resonance is determined primarily by how accurately the *absolute* energy is measured. The peak cross section measurement requires a precise *absolute* luminosity measurement, while measuring the width of the resonance is limited by the accuracy of the *relative* energy and luminosity measurements.

2.1.Energy Spectrometers

The Mark II has built precision devices in the extraction lines of the SLC for measuring the absolute energy of the electron and positron beams[3]. The measurement is made when the beams travel through a string of 3 dipole magnets on their way to their respective dumps.

The first dipole creates a swath of synchrotron light which is imaged on a phosphorescent screen. The second dipole is a very accurately mapped spectrometer[4] which produces a large deflection transverse to the first bend. The third bend is parallel to the first bend, and creates a second swath of synchrotron light. The positions of the two swaths are measured to determine the deflection produced by the spectrometer[5]. This deflection along with measuring the field strength of the spectrometer, and the distance from the spectrometer to the phosphor screens allows a precise determination of the energy.

Table 1 summarizes the estimates of the systematic error contributed by each component of the spectrometer system in determining the energy of each beam. Combining the measurements of both beams in quadrature, and allowing for a possible error due to an offset of beams with finite dispersion, we estimate the systematic error on the center-of-mass energy to be 35 MeV.

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* Work supported by the Department of Energy contract DE-AC03-76SF00515.
· Presented at the European Physical Society Meeting HEP'89, Madrid, September 6-13, 1989.
§ Presented on behalf of the Mark II collaboration.

Presented at the International Europhysics Conference High-Energy Physics, Madrid, Spain, September 6–13, 1989

Mapping of the spectrometer field	5 MeV
Rotational misalignments between dipoles	16 MeV
Determination of synchrotron stripe position	10 MeV
Survey of distance from spectrometer to phosphor screen	5 MeV
Totals	20 MeV

Table 1: Systematic errors in determining energy

2.2.Small Angle Monitor

The Small Angle Monitor (SAM) is a device for accurately measuring the luminosity of the SLC by measuring small angle Bhabha production. The SAM covers the angular region in θ from 50 to 165 mrad. This device contains both tracking and calorimetry for determining the position and energy of Bhabha electrons.

In order to determine the luminosity, one must accurately reconstruct the position of the electrons. Since reconstruction near the edges of the device can be slewed by energy leaking out the side of the detector, only events which are well contained in the SAM are used for the absolute luminosity calculation. In the region from 65 to 165 mrad, the cross section for Bhabha events is calculated to be 25.2 nb at 91.1 GeV[6]. Events in this *precise* region are used to calculate the absolute luminosity.

The systematic error on this measurement is estimated as 2% for uncertainty in the position of the electron shower, and 2% uncertainty in calculating higher order radiative corrections to the cross section. This gives a total systematic error of 2.8%

2.3.Mini-Small Angle Monitor

The Mini-Small Angle Monitor (Mini-SAM) covers the angular region between 15.2 and 25 mrad. This device does not allow an accurate measurement of the absolute luminosity, but its much higher statistics make it useful for measuring the relative luminosity between scan points.

The Mini-SAM is very close to the SLC beampipe, hence it is subject to backgrounds from the machine. For this reason, it is necessary to correct the Mini-SAM counts for backgrounds and inefficiencies. Backgrounds are determined by looking for events which pass all cuts, but have non back to back geometries. 17 events (0.4%) of this type are found, and this background is subtracted on a scan point to scan point basis. The uncertainty in this background subtraction contributes a point to point error on the cross section measurement. Efficiencies are calculated by overlaying monte Carlo Bhabha events on top of data taken on random beam crossings. The ability of the analysis to find the events with the added background determines the efficiency. This is done on a run by run basis. Runs with efficiencies below 50% are dropped from the analysis.

The ratio between Mini-SAM and SAM *precise* events is calculated in order to determine the luminosity scale for the Mini-SAM. Events in the non-Precise region of the SAM are also used for relative luminosity measurements. The accuracy of this scale factor is limited by the statistics of *precise* events which are measured. This error on the scale factor is included in the fits.

2.4.Mark II

The Mark II detector has been described in detail elsewhere[7]. The components which are used in this analysis are the Central Drift Chamber for finding charged particles, and the Endcap and Barrel Calorimeters for finding neutral particles.

The trigger for charged particles requires at least two charged particles with $|\cos\theta| < 0.75$ and transverse momentum of at least 150 MeV/c. This trigger is estimated to be 97% efficient for Hadronic Z decays. The neutral trigger requires that at least 2.2 GeV/c be deposited in the Endcap, or that 3.3 GeV/c be deposited in the Barrel. This trigger is determined to be 95% efficient for Hadronic decays. The overall trigger is a logical OR of the two triggers giving a trigger efficiency for Hadrons of 99.98%.

3. Event Selection

3.1. Hadrons

Each event analyzed by the Mark II has the following cuts applied to tracks. Charged tracks must come from within a cylinder of radius 1mm surrounding the interaction point, and be within 3 mm in Z of the interaction point (where Z is defined to be the axis along the beam direction). In addition these tracks must have a minimum transverse momentum of 110 MeV/c, and be produced at an angle of $|\cos\theta| < 0.92$. Any neutral track must deposit at least 1 GeV/c in one of the calorimeters.

Given the above track cuts, an Hadronic event is defined by demanding that there be at least 3 charged tracks. In addition, the sum of charged and neutral energy in both the forward and backwards hemispheres of the detector must be greater than 5% of the center-of-mass energy.

We look for beam gas events by applying the above cuts to events where the vertex of the event is displaced in Z from the interaction point. We observe no events of this type which pass our cuts. A Monte Carlo simulation of two photon events predicts that we should see 0.04 events in our present sample.

The efficiency for Hadronic events is 0.953±0.006. The contributions to the error come from varying Hadronic Monte Carlo generators, varying the energy scale of the Calorimeters in the detector simulation, and uncertainty in the tracking efficiencies used in the detector simulation.

3.2. Leptons

We also use leptons in our event sample. We accept Muons and Taus which have a thrust axis with $|\cos\theta| < 0.65$. In this region, our trigger is highly efficient, and the events are easily identified. We estimate our efficiency for identifying Muons in this region as 99±1%, and for Taus as 96±1%. Electrons are not used in this analysis.

4. Data

4.1. Luminosity Data

Table 2 presents the data from the luminosity monitors. Shown in the table are the average energy of each scan point, the number of SAM events (including events outside the Precise region), the number of Mini-SAM events, and the efficiency of the Mini-SAM. Of the 815 total SAM events, 485 were in the Precise region used for calculating the absolute luminosity.

Scan Point	<E> (GeV)	N_S	N_M	ε_M	Lum. (nb^{-1})
3	89.24	24	166	0.99	0.68±0.05
5	89.98	36	174	0.99	0.76±0.05
10	90.35	116	617	1.00	2.61±0.10
2	90.74	54	266	0.96	1.21±0.07
7	91.06	170	923	0.99	4.08±0.12
8	91.43	164	879	0.91	4.12±0.13
4	91.50	53	275	0.99	1.23±0.07
1	92.16	31	105	0.97	0.54±0.05
9	92.22	128	680	0.98	3.05±0.11
6	92.96	39	214	0.98	1.00±0.07
Totals		815	4299		19.3±0.9

Table 2: Data from the Luminosity Monitors.

4.2. Hadronic and Leptonic Data

Table 3 shows the number of of Hadrons, Taus, and Muons which are measured at each scan point, and the calculated cross section for Hadrons, and Muons and Taus in our fiducial region.

Scan Point	<E> (GeV)	N_{Had}	N_τ	N_μ	σ_Z (nb)
3	89.24	3	0	0	$4.5^{+4.5}_{-2.5}$
5	89.98	8	1	1	$13.5^{+6.0}_{-4.3}$
10	90.35	60	1	1	$24.8^{+3.8}_{-3.3}$
2	90.74	33	1	2	$31.7^{+6.8}_{-5.5}$
7	91.06	114	3	3	$31.6^{+3.4}_{-3.1}$
8	91.43	108	3	3	$29.8^{+3.3}_{-2.9}$
4	91.50	33	5	1	$34.3^{+7.0}_{-5.7}$
1	92.16	11	0	0	$21.5^{+9.2}_{-6.6}$
9	92.22	67	2	2	$24.3^{+3.4}_{-3.0}$
6	92.96	13	1	0	$14.6^{+5.4}_{-4.0}$
Totals		450	17	13	

Table 3: Detected Z decays at each Scan Point.

5. Fits

5.1. Details about the fits

We fit the data to a relativistic Breit-Wigner resonance as given in formula 1.

$$\sigma_Z(E) = \frac{12\pi}{m_Z^2} \frac{s\Gamma_e\Gamma_f}{\left(s - m_Z^2\right)^2 + s^2\Gamma^2 / m_Z^2} (1 + \delta(E)) \tag{1}$$

In this formula, Γ_e is the partial width for Z decays into electrons, and Γ_f is the width of Z decays into events satisfying our fiducial cuts. This includes all Hadronic events, and Muons and Taus with $|\cos\theta| <0.65$. $\delta(E)$ contains radiative corrections to the line shape due primarily to initial state QED radiation. We use an analytic form for these corrections given by Cahn [8].

We construct a likelihood function as given in formula 2. In this formula, ε represents the efficiency for detecting Z decays, σ_L is the total luminosity cross section given by $\sigma_L = \sigma_{Sam} + \varepsilon_{MSam}\sigma_{MSam}$, n_Z and n_L are the number of Z and luminosity (Sam + MiniSAM) events respectively.

$$L = \prod \frac{(\varepsilon\sigma_Z)^{n_Z}}{(\varepsilon\sigma_Z + \sigma_L)^{n_Z+n_L}} \tag{2}$$

We perform 3 fits to the data. In the first fit, we constrain the total width to be that given by the Standard Model for 5 quarks, 3 charged leptons, and 3 neutrino generations. The Z mass is a free parameter in this fit. In the second fit, the visible cross section is constrained to be due to the Standard Model with 5 quarks, 3 charged leptons, the number of neutrino generations and the mass are free parameters. In the final fit, we remove the constraints of the Standard Model, and fit to a line shape given by formula 3. In this fit the mass, total width (Γ) and peak cross section (σ_0) are free parameters.

$$\sigma_Z(E) = \sigma_0 \frac{s\Gamma^2}{\left(s - m_Z^2\right)^2 + s^2\Gamma^2 / m_Z^2}(1 + \delta(E)) \tag{3}$$

5.2. Results for Mass

The mass is a free parameter in all three fits. Each gives the same results $M_Z = 91.14 \pm 0.12$ GeV/c^2. The largest systematic error in the determination of the mass is the 35 MeV uncertainty in the absolute energy scale.

5.3. Results for Invisible Width

The invisible width is a free parameter only in the second fit. In this fit, the value found for the invisible width is 0.46±0.10 GeV. If we assume that this width comes from massless neutrinos, we get for the invisible width 2.8±0.6 neutrino generations. This gives a 95% confidence Limit on the number of massless neutrino generations of 3.9. This rules out a fourth neutrino generation within the framework of the Standard Model. The systematic error on this measurement is equivalent to 0.45 neutrino generations, and comes from the uncertainty in the measurement of the absolute luminosity.

Mass	91.14±0.12 GeV/c^2.
Invisible Width	2.8±0.6 neutrino generations
Total Width	$2.42^{+0.45}_{-0.35}$ GeV.
Peak Cross Section	45±4 nb

Table 4: Results of the Fits

5.4. Results for Total Width

In the third fit, the total width is found to be $2.42^{+0.45}_{-0.35}$ GeV. This is consistent with the Standard Model value of 2.45 GeV[9]. The uncertainty in the MiniSAM background subtraction contributes 50 MeV to the error on the width. In addition, the peak cross section is found to be 45±4 nb which agrees with the Standard Model prediction of 43.6 nb.

Figure 1 displays the data, the lower curve is the first fit. The second and third fits which produce indistinguishable line shapes are shown on the upper curve..

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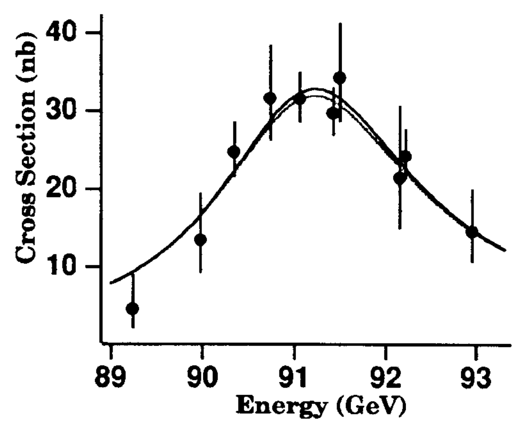

Figure 1: Fits to the Data