A MODEL INDEPENDENT ANALYSIS OF THE Z LINESHAPE

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Talk held at the XXIX Rencontres de Moriond,
March 12th to 19th 1994 in Meribel

ABSTRACT

The S-matrix, effective coupling and partial width ansatzes are used to describe total cross sections and asymmetries in the vicinity of the Z pole. Fit results using the 1990-1992 data taken with the L3 detector are presented. The partial width ansatz, with fixed γZ interference term, neglects the correlation between the interference term and the Z mass. This leads to an underestimation of the error on the Z mass, δm_{Z}. A possibility to improve the measurements of the γZ interference and therefore δm_{Z} is discussed.

1 Introduction

After four years of running LEP at CERN the determination of the properties of the Z boson has reached an impressive level of precision. In the light of these precision measurements, the model independent ansatzes used to describe the total cross section σ_{tot}, the forward-backward asymmetry $\mathcal{A}_{\rm fb}$, the τ polarization $\mathcal{A}_{\rm pol}$ and the forward-backward τ polarization $\mathcal{A}_{\rm fb-pol}$ have to be checked carefully for possible Standard Model biases. The L3 collaboration uses the S-matrix, effective coupling and partial width ansatzes for the determination of the electroweak parameters of the neutral current [1, 2]. Results derived from data taken with the L3 detector in 1990-1992 are presented. It is shown that fixing the γZ interference term, j_{tot}, in the partial width approach leads to an underestimated error on the Z mass, $\delta m_{\rm Z}$. In a truly model independent approach the γZ interference is not fixed. Possibilities to measure j_{tot} and reduce $\delta m_{\rm Z}$ are discussed.

2 The Model Independent Approaches

2.1 The S-matrix approach

In reference [3] a rigorously model independent approach is proposed to describe cross section and asymmetries in e^+e^-annihilation. It relies only on basic quantum mechanical assumptions. No assumptions are made on the dynamics of the scattering process. The matrix element for the exchange of a photon and Z boson between a massless $e^+e^-$and $f\bar{f}$pair is written as:

$$\mathcal{M}^{fi}(s) = \frac{\rm R_\gamma}{s} + \frac{{\rm R}_{\rm Z}^{fi}}{s - s_Z}; \quad i = 0, 3, \tag{1}$$

with $s_Z = \overline{m}_Z^2 + i\overline{m}_Z\overline{\Gamma}_Z$. $\rm R_\gamma$ and ${\rm R}_{\rm Z}^{fi}$ represent the residuals of the photon and the Z boson, respectively. ${\rm R}_{\rm Z}^{fi}$ denotes the four helicity amplitudes assuming helicity conservation. Non resonant contributions in $\mathcal{M}^{fi}$ are neglected in this paper. The four cross sections σ^{fi} derived from $\mathcal{M}^{fi}$ can be combined to total, forward-backward, polarization and forward-backward polarization cross sections, which can all be measured at LEP. These cross sections σ_A are parameterized as follows:

$$\sigma_A(s) = \frac{4}{3}\pi\alpha^2\left[\frac{r_A^\gamma}{s} + \frac{s r_A + (s - \overline{m}_Z^2) j_A}{(s - \overline{m}_Z^2)^2 + \overline{m}_Z^2\overline{\Gamma}_Z^2}\right]; \quad A = tot, fb, pol, fb - pol. \tag{2}$$

r_A^γ denotes the photon exchange term, which is zero for $A \neq tot$. The asymmetries ($A \neq tot$) are defined by $\mathcal{A}_A(s) = \sigma_A(s)/\sigma_{tot}(s)$. Assuming that the pure QED contributions are known (r_A^γ), the free parameters of this ansatz are the mass of Z, $\overline{m}_Z$, its total width $\overline{\Gamma}_Z$ and the four helicity amplitudes, ${\rm R}_{\rm Z}^{fi}$. Instead of ${\rm R}_{\rm Z}^{fi}$ the Z exchange terms r_A and γZ interference terms j_A can be used. $\overline{m}_Z$ and $\overline{\Gamma}_Z$ are related to $m_{\rm Z}$ and $\Gamma_{\rm Z}$ in the formalism using an s-dependent total Z width in the propagator by [4]:

$$\begin{array}{rclcccl} \overline{m}_{\mathrm{Z}} & = & [1+(\Gamma_{\mathrm{Z}}/m_{\mathrm{Z}})^2]^{-\frac{1}{2}} m_{\mathrm{Z}} & \approx & m_{\mathrm{Z}} & - & 34 \ \mathrm{MeV}, \\ \overline{\Gamma}_{\mathrm{Z}} & = & [1+(\Gamma_{\mathrm{Z}}/m_{\mathrm{Z}})^2]^{-\frac{1}{2}} \Gamma_{\mathrm{Z}} & \approx & \Gamma_{\mathrm{Z}} & - & 1 \ \mathrm{MeV}. \end{array} \tag{3}$$

2.2 The effective coupling approach

In the effective coupling approach [5] the Standard Model vector and axial vector couplings are replaced by effective couplings $\hat{v}_f$ and $\hat{a}_f$, which absorb all higher order weak corrections. The relationship between r_A and j_A and the couplings is given by:

$$\begin{array}{llllll} r_{tot} & \propto & (\hat{a}_{\mathrm{e}}^2+\hat{v}_{\mathrm{e}}^2)(\hat{a}_f^2+\hat{v}_f^2); & j_{tot} & \propto & \hat{v}_{\mathrm{e}}\hat{v}_f; \\ r_{fb} & \propto & \hat{a}_{\mathrm{e}}\hat{v}_{\mathrm{e}}\hat{a}_f\hat{v}_f; & j_{fb} & \propto & \hat{a}_{\mathrm{e}}\hat{a}_f; \\ r_{pol} & \propto & (\hat{a}_{\mathrm{e}}^2+\hat{v}_{\mathrm{e}}^2)\hat{a}_f\hat{v}_f; & j_{pol} & \propto & \hat{v}_{\mathrm{e}}\hat{a}_f; \\ r_{fb-pol} & \propto & \hat{a}_{\mathrm{e}}\hat{v}_{\mathrm{e}}(\hat{a}_f^2+\hat{v}_f^2); & j_{fb-pol} & \propto & \hat{a}_{\mathrm{e}}\hat{v}_f. \end{array} \tag{4}$$

The free parameters of this approach are the mass and width of the Z and its effective couplings for the electron and the final state fermion, $\hat{v}_{\mathrm{e}}$, $\hat{a}_{\mathrm{e}}$, $\hat{v}_f$ and $\hat{a}_f$, respectively. As before, the photon exchange term r_A^{γ} is given by QED. This ansatz allows a description of all four cross sections defined before.

2.3 The partial width approach

The partial width approach [6] describes the total cross section $\mathrm{e}^+\mathrm{e}^-\to f\bar{f}$ as the formation and decay of a resonance. The Z exchange of the total cross section is proportional to

$$r_{tot} \propto \Gamma_e \Gamma_f. \tag{5}$$

Γ_f denotes the partial decay width of the Z in a fermion pair $f\bar{f}$. The γZ interference term is usually not treated as a free parameter and is fixed to the Standard Model expectation value [1]. Therefore the partial width approach has as free parameters m_{Z}, Γ_{Z} and the partial decay widths, Γ_e and Γ_f.

3 L3 Results

The results presented in this section are based on the measurements of σ_{tot} for hadrons and leptons and of $\mathcal{A}_{\mathrm{fb}}$ for leptons using the 1990-1992 data [2]. In addition, the measurement of $\mathcal{A}_{\mathrm{pol}}$ using the 1990-1991 data is included [9].

To determine the model independent parameters introduced in Section 2 we use the analytical programs ZFITTER and SMATASY [10]. All fits are performed assuming lepton universality.

For the S-matrix approach we determine $\overline{m}_Z$, $\overline{\Gamma}_Z$, the helicity amplitudes for leptons, $\mathrm{R}_{\mathrm{Z}}^{li}$ as well as the Z exchange and γZ interference term for hadrons, $r_{\mathrm{tot}}^{\mathrm{had}}$ and $j_{\mathrm{tot}}^{\mathrm{had}}$. An independent determination of $\mathrm{R}_{\mathrm{Z}}^{li}$ requires the measurement of σ_{tot} and all three asymmetries. Because L3 has not published a measurement of $\mathcal{A}_{\mathrm{fb-pol}}$, CP invariance

[1]This is adopted in the analytical programs ZFITTER [7] and MIZA [8], which are used by the LEP experiments to determine electroweak parameters.

is assumed, which reduces the number of independent helicity amplitudes to three.
In Table 1 the results for fits are presented with different treatments of $j_{\rm tot}^{\rm had}$. The only parameter which is affected significantly by the fixing of $j_{\rm tot}^{\rm had}$ is $\overline{m}_Z$. The mean value shifts by +4 MeVand the error decreases by 9 MeV(subtracted in quadrature).

In Table 2 the results are shown for a fit using the effective coupling approach for

Parameter	$j_{\rm tot}^{\rm had}$ free	$j_{\rm tot}^{\rm had}$ fixed to SM
$\overline{m}_Z$ [GeV]	91.157±0.013	91.161±0.009
$\overline{\Gamma}_Z$ [GeV]	2.496±0.011	2.495±0.011
R_Z^{l0}	0.427±0.012	0.427±0.012
R_Z^{l1}	−0.372±0.002	−0.372±0.002
R_Z^{l2}	0.326±0.015	0.326±0.015
$r_{\rm tot}^{\rm had}$	2.862±0.030	2.860±0.029
$j_{\rm tot}^{\rm had}$	0.467±0.628	fixed to 0.219

Table 1: The fit results of the S-matrix approach.

the lepton data and partial width approach for the hadron cross sections, because the experimental information is not sufficient to allow the determination of the Z couplings to hadrons. Thus $j_{\rm tot}^{\rm had}$ is fixed. Comparing the mean values of the Z mass in Tables 1

Parameter	Eff. Coupling, Partial Width
$m_{\rm Z}$ [GeV]	91.195±0.009
$\Gamma_{\rm Z}$ [GeV]	2.495±0.011
$\hat{v}_\ell$	−0.0378±0.0045
$\hat{a}_\ell$	−0.4999±0.0014
$\Gamma_{\rm had}$	1.748±0.010

Table 2: The fit results of effective coupling and partial width approach.

and 2, one finds the expected 34 MeV shift between $\overline{m}_Z$ and $m_{\rm Z}$ only in the case where $j_{\rm tot}^{\rm had}$ is fixed to the Standard Model. In this case also the error on the Z mass is the same. Thus the partial width approach with fixed interference term in the case of the hadron cross section neglects the uncertainty in $j_{\rm tot}^{\rm had}$ and leads to an underestimated error of $m_{\rm Z}$. The leptonic parameters are not affected. These results are reproduced by a fit using a modified ZFITTER version in which a free interference term in the partial width approach has been introduced [11].
A more realistic number for $\delta m_{\rm Z}$ therefore includes the uncertainty in $j_{\rm tot}^{\rm had}$:

$$\begin{aligned} \delta m_{\rm Z} &= \pm 6\ \text{MeV(Exp.)} \pm 7\ \text{MeV(LEP)} \pm 9\ \text{MeV}(j_{tot}^{had})(90-92) \\ \delta m_{\rm Z} &= \pm 3\ \text{MeV(Exp.)} \pm 3\ \text{MeV(LEP)} \pm 8\ \text{MeV}(j_{tot}^{had})(90-93). \end{aligned} \tag{6}$$

The first contribution to $\delta m_{\rm Z}$ in Equation 6 arises from statistical and systematic uncertainties of the experimental measurement excluding the contribution from $j_{\rm tot}^{\rm had}$. The second error is given by the precision of the LEP beam energy. Note that the dominant contribution now arises from the poor measurement of $j_{\rm tot}^{\rm had}$, which is only marginally improved by the inclusion of the 1993 data into the analysis.

4 Improvements in the Measurement of $j_{\rm tot}^{\rm had}$

To improve the measurement of the γZ interference term at LEP one has to run further away from the Z pole, since the relative contribution of $j_{\rm tot}^{\rm had}$ to the total cross section increases with distance from the pole. A study of the optimal energy region was performed in reference [12]. This investigation uses the L3 hadron cross section of 1990-1993 extrapolated for a further LEP run, assuming an integrated luminosity of $\mathcal{L} = 40\mathrm{pb}^{-1}$. Spending 10% of this luminosity at an energy point $E_{\rm add} = 80$ GeV and the remaining luminosity at the Z pole would reduce the error on the Z mass in the hadron channels, $\delta m_{\rm Z}^{had}$, from 14 MeV to 6.5 MeV. Running exclusively on the pole will give no improvement. Above the peak the sensitivity to $j_{\rm tot}^{\rm had}$ is reduced due to initial state radiation. Even a run with $20\mathrm{pb}^{-1}$ at 140 GeV would only reduce $\delta m_{\rm Z}^{had}$ to 8 MeV. The different scenarios are illustrated in Figure 1. The evolution of $\delta m_{\rm Z}^{\rm had}$ with the integrated luminosity, $\mathcal{L}_{\rm add}$ spent at an additional energy point $E_{\rm add}$ is shown. The total integrated luminosity is always $40\mathrm{pb}^{-1}$. The point $\mathcal{L}_{\rm add} = 0$ reflects the case where LEP runs only on the Z pole. The arrow shows the result for running only on the peak and fixing $j_{\rm tot}^{\rm had}$ in the analysis.

Another possibility to improve the precision in the measurement of $j_{\rm tot}^{\rm had}$ is to use results

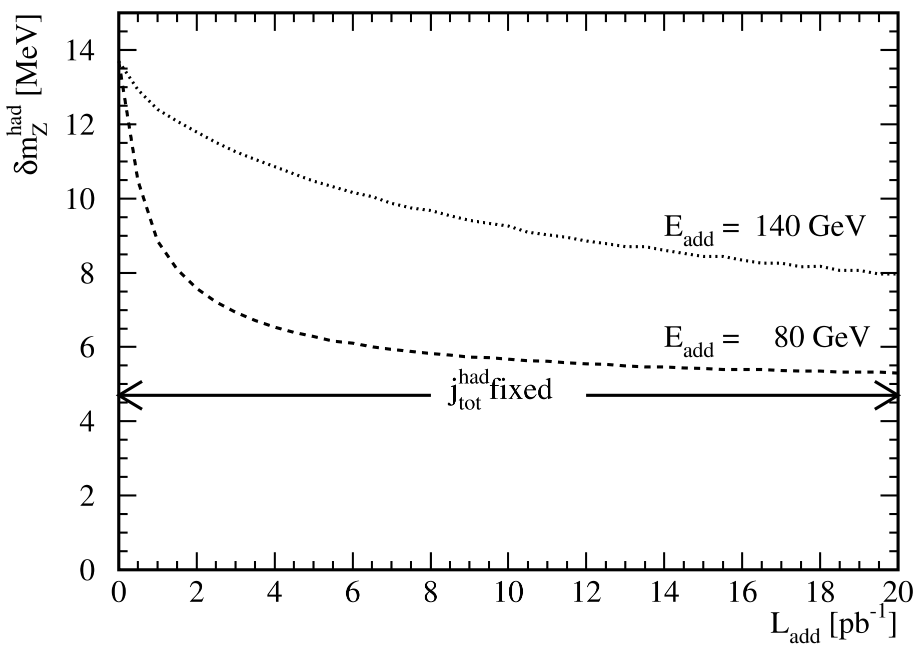

Figure 1: The evolution of $\delta m_{\rm Z}^{\rm had}$ with the integrated luminosity, $\mathcal{L}_{\rm add}$, spend at an additional energy point $E_{\rm add}$, using hadrons only.

from other experiments, e.g. cross sections measured at TRISTAN at 58 GeV[13], which also reduces $\delta m_{\rm Z}^{\rm had}$. However, a higher accuracy can be achieved at LEP [12].

5 Conclusions

It is shown that S-matrix, effective coupling and partial width approaches yield equivalent results for $m_{\rm Z}$, if the γZ interference term is treated identically. Fixing $j_{\rm tot}^{\rm had}$ in the partial width approach neglects its correlation with the Z mass and leads to an underestimated error on m_Z. The leptonic parameters are not affected. The uncertainty from $j_{\rm tot}^{\rm had}$ represents the largest contribution to δm_Z of 8 MeV. The precision of $j_{\rm tot}^{\rm had}$ and therefore also of m_Z can be improved by measuring at energies around 80 GeV.

6 Acknowledgments

I would like to thank Tran Than Van and the organizers of the Moriond meeting for their hospitality. Furthermore I thank Sabine Riemann and Martin Grünewald for stimulating discussions in the preparation of the talk and the writeup and Ian Brock and Marcel Merk for the careful reading of the manuscript.

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