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An Investigation of the Interference Between Photon and Z Boson Exchange

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Abstract

Preliminary results on the parameters m_{Z} and $j_{\mathrm{had}}^{\mathrm{tot}}$ of the S-Matrix ansatz for $\mathrm{e^+e^-} \rightarrow \mathrm{f\bar{f}}$ are presented, based on the full LEP I and LEP II data sets, combining data for the 4 LEP Experiments.

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1 Introduction

The S-Matrix ansatz provides a coherent way of describing LEP measurements of the cross-section and forward-backward asymmetries in s-channel $e^+e^- \to f\bar{f}$ processes at centre-of-mass energies around the Z resonance, from the LEP-I program, and the measurements at centre-of-mass energies from 130 – 207 GeV from the LEP-II program.

Compared with the standard 5 and 9 parameter descriptions of the measurements at the Z [1], the S-Matrix formalism includes an extra 3 parameters (assuming lepton universality) or 7 parameters (without lepton universality) which explicitly determine the contributions to the cross-sections and forward-backward asymmetries of the interference between the exchange of a Z and a photon. The LEP-I data alone cannot tightly constrain these interference terms, in particular the interference term for hadronic cross-sections, since their contributions are small around the Z resonance and change sign at the pole. Due to strong correlations between the size of the hadronic interference term and the mass of the Z, this leads to a larger error on the fitted mass of the Z compared to the standard 5 and 9 parameter fits, where the hadronic interference term is fixed to the value predicted in the Standard Model. Including the LEP-II data leads to a significant improvement in the constraints on the interference terms and a corresponding reduction in the uncertainty on the mass of the Z. This results in a measurement of m_{Z} which is almost as sensitive as the standard results, but without constraining the interference to the Standard Model prediction.

This chapter describes the first, preliminary, combination of data from the full data sets of the 4 LEP experiments, to obtain a LEP combined results on the parameters of the S-Matrix ansatz. These results update those of a previous combination [2] which was based on preliminary LEP-I data and only partial statistics from the full LEP-II data set.

Different strategies are used to combined the LEP-I and LEP-II data. For LEP-I data, an average of the individual experiment's results on the S-Matrix parameters is made. This approach is rather similar to the method used to combine the results of the 5 and 9 parameter fits. To include LEP-II data, a fit is made to LEP combined measurements of cross-sections and asymmetries above the Z, taking into account the results of the LEP-I combination of S-Matrix parameters.

In Section 2 the parameters of the S-Matrix ansatz are explained. In Sections 3.1 and 3.2 the average of the LEP-I data and the inclusion of the LEP-II data are described. The results are discussed in Section 3.3 and conclusions are drawn in Section 4.

2 The S-Matrix Ansatz

The S-matrix ansatz [3] is a rigorous approach to describe the cross-sections and forward-backward asymmetries in the s-channel e^+e^- annihilations under the assumption that the processes can be parameterised as the exchange of a massless and a massive vector boson, in which the couplings of the bosons and their interference are treated as free parameters.

In this model, the cross-sections can be parametrised as follows:

$$\sigma^0_{tot,f}(s) = \frac{4}{3}\pi\alpha^2 \left[\frac{g_{\mathrm{f}}^{tot}}{s} + \frac{j_{\mathrm{f}}^{tot}(s-\overline{m}_{\mathrm{Z}}^2) + r_{\mathrm{f}}^{tot}\, s}{(s-\overline{m}_{\mathrm{Z}}^2)^2 + \overline{m}_{\mathrm{Z}}^2\overline{\Gamma}_{\mathrm{Z}}^2} \right] \quad \text{with } \mathrm{f} = \mathrm{had}, \mathrm{e}, \mu, \tau\,, \tag{1}$$

while the forward-backward asymmetries are given by:

$$A^0_{\mathrm{fb,f}}(s) = \pi\alpha^2 \left[\frac{g_{\mathrm{f}}^{fb}}{s} + \frac{j_{\mathrm{f}}^{fb}(s-\overline{m}_{\mathrm{Z}}^2) + r_{\mathrm{f}}^{fb}\, s}{(s-\overline{m}_{\mathrm{Z}}^2)^2 + \overline{m}_{\mathrm{Z}}^2\overline{\Gamma}_{\mathrm{Z}}^2} \right] / \sigma^0_{\mathrm{tot,f}}(s)\,, \tag{2}$$

where $\sqrt{s}$ is the centre-of-mass energy. The parameters r_{f} and j_{f} scale the Z exchange and the $\mathrm{Z}-\gamma$ interference contributions to the total cross-section and forward-backward asymmetries. The contribution g_{f} of the pure γ exchange was fixed to the value predicted by QED in all fits. Neither the hadronic charge asymmetry, nor the flavour tagged quark forward-backward asymmetries are considered in the LEP implementation of the S-Matrix ansatz, which leaves 16 free parameters to described the LEP data: 14 r_{f} and j_{f} parameters and the mass and width of the massive Z resonance. Applying the constraint of lepton universality reduces this to 8 parameters.

In the Standard Model the Z exchange term, the $\mathrm{Z}-\gamma$ interference term and the photon exchange term are given in terms of the fermion charges and their effective vector and axial couplings to the Z by:

$$
\begin{aligned}
r_{\mathrm{f}}^{\mathrm{tot}} &= \kappa^2 \left[g_{\mathrm{Ae}}^2 + g_{\mathrm{Ve}}^2\right] \left[g_{\mathrm{Af}}^2 + g_{\mathrm{Vf}}^2\right] - 2\kappa\, g_{\mathrm{Ve}}\, g_{\mathrm{Vf}} C_{Im} \\
j_{\mathrm{f}}^{\mathrm{tot}} &= 2\kappa\, g_{\mathrm{Ve}}\, g_{\mathrm{Vf}}\, (C_{Re} + C_{Im}) \\
g_{\mathrm{f}}^{\mathrm{tot}} &= Q_{\mathrm{e}}^2 Q_{\mathrm{f}}^2\, |F_A(m_{\mathrm{Z}})|^2 \\
r_{\mathrm{f}}^{\mathrm{fb}} &= 4\kappa^2 g_{\mathrm{Ae}}\, g_{\mathrm{Ve}}\, g_{\mathrm{Af}}\, g_{\mathrm{Vf}} - 2\kappa\, g_{\mathrm{Ae}}\, g_{\mathrm{Af}} C_{Im} \\
j_{\mathrm{f}}^{\mathrm{fb}} &= 2\kappa\, g_{\mathrm{Ae}}\, g_{\mathrm{Af}}\, (C_{Re} + C_{Im}) \\
g_{\mathrm{f}}^{\mathrm{fb}} &= 0\,,
\end{aligned}
\tag{3}
$$

with the following definitions:

$$
\begin{aligned}
\kappa &= \frac{G_F m_{\mathrm{Z}}^2}{2\sqrt{2}\,\pi\alpha} \approx 1.50 \\
C_{Im} &= \frac{\Gamma_{\mathrm{Z}}}{m_{\mathrm{Z}}}\, Q_{\mathrm{e}} Q_{\mathrm{f}}\, \mathrm{Im}\,\{F_A(m_{\mathrm{Z}})\} \\
C_{Re} &= Q_{\mathrm{e}} Q_{\mathrm{f}}\, \mathrm{Re}\,\{F_A(m_{\mathrm{Z}})\} \\
F_A(m_{\mathrm{Z}}) &= \frac{\alpha(m_{\mathrm{Z}})}{\alpha}\,,
\end{aligned}
\tag{4}
$$

where $\alpha(m_{\mathrm{Z}})$ is the complex fine-structure constant, and $\alpha \equiv \alpha(0)$. The photonic virtual and bremsstrahlung corrections are included through the convolution of Equations 1 and 2 with radiator functions as in the 5 and 9 parameter fits. The expressions of the S-Matrix parameters in terms of the effective vector and axial-vector couplings neglect the imaginary parts of the effective couplings.

The usual definitions of the mass m_{Z} and width Γ_{Z} of a Breit-Wigner resonance are used, the width being s-dependent, such that:

$$
\begin{aligned}
m_{\mathrm{Z}} &\equiv \overline{m}_{\mathrm{Z}}\sqrt{1+\overline{\Gamma}_{\mathrm{Z}}^2/\overline{m}_{\mathrm{Z}}^2} \approx \overline{m}_{\mathrm{Z}} + 34.20\ \mathrm{MeV}/c^2 \\
\Gamma_{\mathrm{Z}} &\equiv \overline{\Gamma}_{\mathrm{Z}}\sqrt{1+\overline{\Gamma}_{\mathrm{Z}}^2/\overline{m}_{\mathrm{Z}}^2} \approx \overline{\Gamma}_{\mathrm{Z}} + \ 0.94\ \mathrm{MeV}\,.
\end{aligned}
\tag{5}
$$

In the following fits, the predictions from the S-Matrix ansatz and the QED convolution for cross-sections and asymmetries are made using SMATASY [4].

	m_Z [GeV]	$j_{\mathrm{had}}^{\mathrm{tot}}$	correlation
LEP-I only	91.1925±0.0059	-0.084±0.324	-0.935
LEP-I & LEP-II	91.1869±0.0023	0.277±0.065	-0.461

Table 1: Averaged LEP-I and LEP-II S-Matrix results for m_Z and $j_{\mathrm{had}}^{\mathrm{tot}}$.

3 LEP combination

In the following sections the combinations of the results from the individual LEP experiments are described: firstly the LEP-I combination, then the combination of both LEP-I and LEP-II data. The results from these combinations are compared in Section 3.3.

3.1 LEP-I combination

Individual LEP experiments have their own determinations of the 16 S-Matrix parameters [5–8] from LEP-I data alone, using the full LEP-I data sets.

These results are averaged using a multi-parameter BLUE technique based on an extension of 9. Sources of systematic uncertainty correlated between the experiments have been investigated, using techniques described in [1] and are accounted for in the averaging procedure and benefiting from the experience gained in those combinations.

In this paper only results for the parameters m_Z and $j_{\mathrm{had}}^{\mathrm{tot}}$, from the fits without lepton universality, are reported. These are the parameters which are most sensitive to the inclusion of the LEP-II data which is discussed in the following section. For these parameters the most significant source of systematic error which is correlated between experiments comes from the uncertainty on the e^+e^- collision energy as determined by models of the LEP RF system and calibrations using the resonant depolarisation technique. These errors amount to ±3 MeV on m_Z and ±0.16 on $j_{\mathrm{had}}^{\mathrm{tot}}$ with a correlation coefficient of −0.86. The LEP averaged values of m_Z and $j_{\mathrm{had}}^{\mathrm{tot}}$ are given in Table 1, together with the correlation matrix. The χ^2/D.O.F. for the average of all 16 parameters is 62.0/48, which is acceptable.

3.2 LEP-I and LEP-II combination

Some experiments have determined S-Matrix parameters using combinations of their LEP-I and LEP-II measured cross-sections and forward-backward asymmetries [5, 6, 10, 11]. To do a full LEP combination would require each experiment to provide S-Matrix results and would require an analysis of the correlated systematic errors on each measured parameter.

However, preliminary combinations of the measurements of forward-backward asymmetries and cross-sections from all 4 LEP experiments, for the full LEP-II period, have already been made [12] and correlations between these measurements have been estimated. The combination procedure averages measurements of cross-sections and asymmetry for those events with reduced centre-of-mass energies, $\sqrt{s'}$, close to the actual center of mass energy of the e^+e^- beams, $\sqrt{s}$, removing those events which are less sensitive to the $Z-\gamma$ interference where, predominantly, initial state radiation reduces the centre-of-mass energy to close to the mass of the Z. The only significant correlations are those between hadronic cross-section measurements at different energies, which are around 20–40%, depending on energies.

The predictions from SMATASY are fitted to the combined LEP-II cross-section and forward-backward asymmetry measurements. Theoretical uncertainties on the QED corrected S-Matrix predictions for LEP-II cross-sections and asymmetries are taken to be the same as for the Standard Model predictions of ZFITTER [12] which are dominated by uncertainties in the QED convolution. These amount to a relative uncertainty of 0.26% on the hadronic cross-sections, fully correlated between all LEP-II energies.

The fit also uses as inputs the averaged LEP-I S-Matrix parameters and covariance matrix. These inputs effectively constrain those parameters, such as m_Z, which are not accurately determined by LEP-II data. There are no significant correlations between the LEP-I and LEP-II inputs.

The LEP averaged values of m_Z and $j_{\rm had}^{\rm tot}$ for both LEP-I and LEP-II data are given in Table 1, together with the correlation matrix. The χ^2/D.O.F. for the average of all 16 parameters is 64.4/60, which is good.

3.3 Discussion

In the LEP-I combination the measured values of the Z boson mass $m_Z = 91.1925 \pm 0.0059$ GeV agrees well with the results of the standard 9 parameter fit (91.1876 ± 0.0021 GeV) albeit with a significantly larger error, resulting from the correlation with the large uncertainty on $j_{\rm had}^{\rm tot}$ which is then the dominant source of uncertainty on m_Z in the S-Matrix fits. The measured value of $j_{\rm had}^{\rm tot} = -0.084 \pm 0.324$, also agrees with the prediction of the Standard Model ($0.2201^{+0.0032}_{-0.0137}$).

Including the LEP-II data brings a significant improvement in the uncertainty on the size of the interference between Z and photon exchange compared to LEP-I data alone. The measured value $j_{\rm had}^{\rm tot} = 0.277 \pm 0.065$, agrees well with the values predicted from the Standard Model. Correspondingly, the uncertainty on the the mass of the Z in this ansatz, 2.3 MeV, is close to the precision obtained from LEP-I data alone using the standard 9 parameter fit, 2.1 MeV. The slightly larger error is due to the uncertainty on $j_{\rm had}^{\rm tot}$ which amounts to 0.9 MeV. The measured value, $m_Z = 91.1869 \pm 0.0023$ GeV, agrees with that obtained from the standard 9 parameter fits. The results are summarised in Figure 1.

The good agreement found between the values of m_Z and $j_{\rm had}^{\rm tot}$ and their expectations provide a validation of the approach taken in the standard 5 and 9 parameter fits, in which the size of the interference between Z boson and photon exchange in the hadronic cross-sections was fixed to the Standard Model expectation.

The precision on $j_{\rm had}^{\rm tot}$ is slightly better than that obtained by the VENUS collaboration [13] of ± 0.08, which was obtained using preliminary results from LEP-I and their own measurements of the hadronic cross-section below the Z resonance. The measurement of the hadronic cross-sections from VENUS [13] and TOPAZ [14] could be included in the future to give a further reduction in the uncertainty on $j_{\rm had}^{\rm tot}$.

Work is in progress to understand those sources of systematic errror, correlated between experiments, which are significant for the remaining S-Matrix parameter that have not been presented here. In particular, for $j_{\rm e}^{\rm tot}$ and $j_{\rm e}^{\rm fb}$, it is important to understand the errors resulting from t-channel contributions to the $\rm e^+e^- \to e^+e^-$ process. These errors have only limited impact on the standard 5 and 9 parameter fits.

4 Conclusion

Results for the S-Matrix parameter m_Z and $j_{\rm had}^{\rm tot}$ have been presented for LEP-I data alone and for a fit using the full data sets for LEP-I and LEP-II from all 4 LEP experiments. Inclusion of LEP-II data brings a significant improvement in the determination of $j_{\rm had}^{\rm tot}$, the fitted value

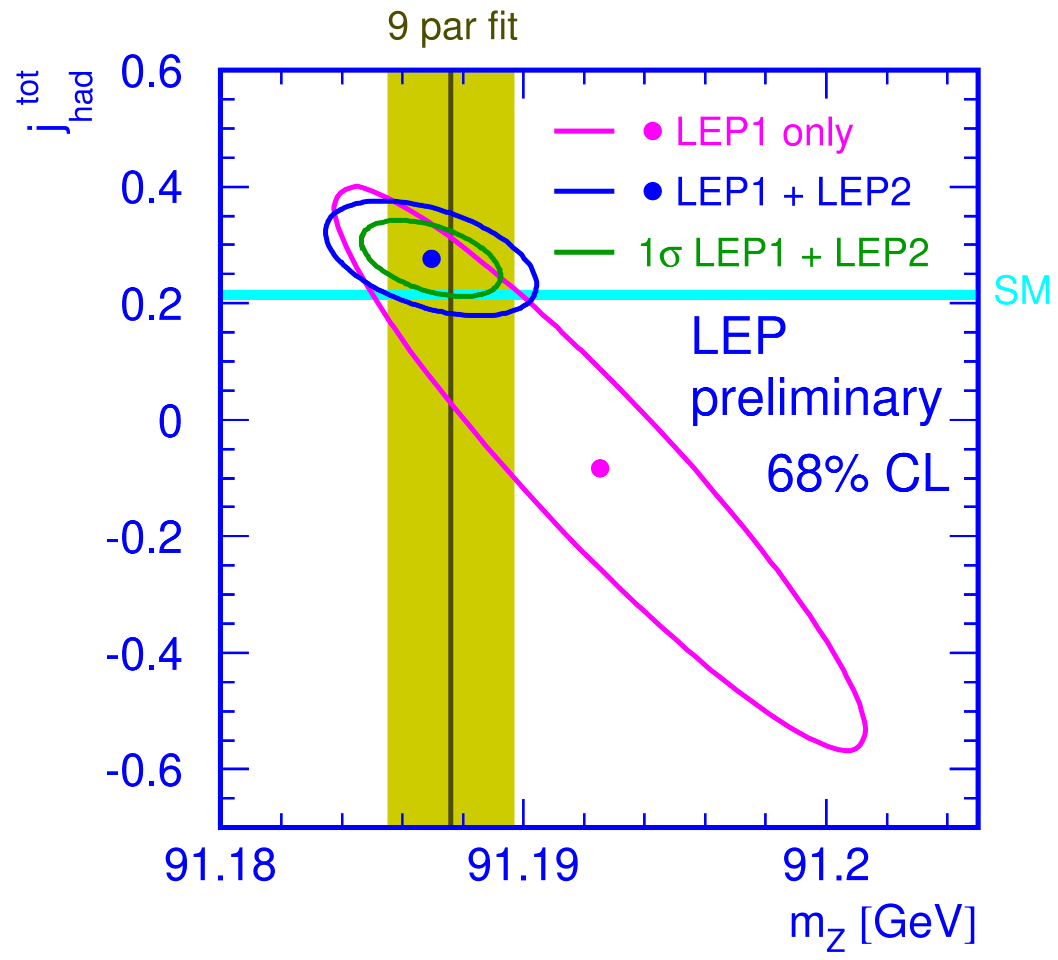

Figure 1: Error ellipses for m_Z and $j_{\rm had}^{\rm tot}$ for LEP-I and the combination of LEP-I and LEP-II S-Matrix fits.

0.277 ± 0.065, agrees well with the values predicted from the Standard Model. As a result in the improvement of the uncertainty in $j_{\mathrm{had}}^{\mathrm{tot}}$, the uncertainty on the fitted value of m_{Z} approaches that of the standard 5 and 9 parameter fits and the measured value $m_{\mathrm{Z}} = 91.1869 \pm 0.0023$ GeV is compatible with that from the standard fits.

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