

**Determination of γ/Z interference
in e^+e^- annihilation at LEP**

L3 Collaboration

Abstract

An S-Matrix ansatz is used to determine the mass and width of the Z boson, as well as the contributions of γ/Z interference and Z boson exchange to fermion-pair production. For this purpose we use hadron and lepton-pair production cross sections and lepton forward-backward asymmetries that have been measured with the L3 detector at centre-of-mass energies between 87 GeV and 189 GeV.

Submitted to *Phys. Lett. B*

Introduction

The successful operation of LEP has allowed a precise measurement of fermion–pair production, $e^+e^- \rightarrow f\bar{f}$, at centre-of-mass energies near the Z resonance. The mass and the total and partial widths of the Z boson have been determined with excellent accuracy. The Standard Model [1, 2] is confirmed with high precision by the experimental results of L3 [3] and other experiments [4–7]. In these analyses, the contribution of the interference between the photon and the Z boson exchange amplitudes is fixed to the Standard Model expectation.

In this paper, we use an S–Matrix [8] approach to determine the contributions of γ/Z interference and Z boson exchange, thus reducing the number of theoretical assumptions. At centre-of-mass energies well above the Z resonance, the reduced importance of Z boson exchange allows the determination, in particular, of γ/Z interference with enhanced precision. The running of LEP in 1997 and 1998 at energies of 182.7 GeV and 188.7 GeV, together with a tenfold increase of integrated luminosity at high energy compared to our previous S–Matrix analysis [9], improves substantially the sensitivity to the S–Matrix parameters. Similar analyses have been performed by the DELPHI and OPAL collaborations [10, 11].

Measurements of Fermion–Pair Production

Measurements of cross sections and forward–backward asymmetries for the reactions $e^+e^- \rightarrow f\bar{f}$, have been performed with the L3 detector [12] at centre-of-mass energies, \sqrt{s} , in the vicinity of the Z resonance [3] and at 130.0, 136.1, 161.3, 172.3, 182.7 and 188.7 GeV [9, 13, 14].

At energies greater than 130 GeV both leptons of the e^+e^- final state are required to be in the range $44^\circ < \theta < 136^\circ$, where θ is the angle between the incoming electron and the outgoing lepton. Muon- and tau-pair candidates are selected by the cuts $|\cos\theta| < 0.9$ and $|\cos\theta| < 0.92$, respectively, for both final-state leptons. Hadron events are selected in the full solid angle. In total, 27470 hadron events and 9417 lepton-pair events are selected. These correspond to an integrated luminosity of 258.7 pb^{-1} .

For centre-of-mass energies in the vicinity of the Z resonance, the sensitivity to photon exchange and γ/Z interference is suppressed due to the large Z exchange cross section. Therefore, a minimum effective centre-of-mass energy, $\sqrt{s'}$, or a maximum acollinearity angle in the Bhabha channel, are required to select events without substantial energy loss due to initial state radiation. The remaining event samples at $\sqrt{s} \geq 130$ GeV contain, in total, 7785 hadron and 7704 lepton-pair events. The details of the analyses such as selection procedures, efficiencies, background contributions, measured cross sections and forward–backward asymmetries, together with the statistical and systematic uncertainties, are discussed in References 9, 13, and 14.

Standard Model expectations are calculated using the ZFITTER [15] and TOPAZ0 [16] programs with the following values [3, 17–20] for the Z boson mass, m_Z , the top quark mass, m_t , the Higgs boson mass, m_H , the electromagnetic coupling constant, α , and the strong coupling constant α_s :

$$\begin{aligned} m_Z &= 91\,189.8 \pm 3.1 \text{ MeV}, & 1/\alpha(m_Z^2) &= 128.887 \pm 0.089, \\ m_t &= 173.8 \pm 5.2 \text{ GeV}, & \alpha_s(m_Z^2) &= 0.119 \pm 0.002, \\ 95.3 \text{ GeV} &\leq m_H \leq 1 \text{ TeV}. \end{aligned} \tag{1}$$

The results of our analysis are not sensitive to the uncertainties on these parameters. At energies above the Z resonance, the theoretical uncertainties on the predicted cross sections are estimated to be 0.5% [21] except for the predictions for large-angle Bhabha scattering which

have a larger uncertainty of 2% [22]. Uncertainties on the forward–backward asymmetries are smaller and negligible compared to the statistical uncertainties of the measurements. The theoretical uncertainties are propagated into the systematic uncertainty on our results.

Determination of γ/Z interference

The measurements of cross sections and forward–backward asymmetries are analysed in the framework of the S–Matrix ansatz. The programs SMATASY [23], together with ZFITTER and TOPAZ0, are used for the calculation of the theoretical predictions and QED radiative corrections to the cross sections and forward–backward asymmetries.

The lowest–order total cross section, σ_{tot}^0 , and forward–backward asymmetry, A_{fb}^0 , for $e^+e^- \rightarrow f\bar{f}$ [8] are:

$$\begin{aligned}\sigma_a^0(s) &= \frac{4}{3}\pi\alpha^2 \left[\frac{g_f^a}{s} + \frac{j_f^a(s - \bar{m}_Z^2) + r_f^a s}{(s - \bar{m}_Z^2)^2 + \bar{m}_Z^2 \bar{\Gamma}_Z^2} \right], \quad \text{where } a = \text{tot, fb}, \\ A_{\text{fb}}^0(s) &= \frac{3}{4} \frac{\sigma_{\text{fb}}^0(s)}{\sigma_{\text{tot}}^0(s)}, \quad \text{with } \sigma_{\text{fb}}^0 = \frac{4}{3} (\sigma_f - \sigma_b).\end{aligned}\tag{2}$$

The S–Matrix ansatz defines the Z resonance using a Breit–Wigner denominator with an s –independent width. In other approaches, a Breit–Wigner denominator with an s –dependent width is used, which implies the following transformation of the values of the Z boson mass and width [8]: $m_Z = \bar{m}_Z + 34.1$ MeV and $\Gamma_Z = \bar{\Gamma}_Z + 0.9$ MeV. In the following, the fit results are quoted after applying these transformations. The S–Matrix parameters r_f , j_f and g_f give the Z exchange, γ/Z interference and photon exchange contributions for fermions of type f , respectively. For hadronic final states the parameters $r_{\text{had}}^{\text{tot}}$, $j_{\text{had}}^{\text{tot}}$ and $g_{\text{had}}^{\text{tot}}$ are sums over all produced quark flavours.

In Figure 1 the measured hadronic cross sections are compared to the theory predictions for different values of $j_{\text{had}}^{\text{tot}}$. The S–Matrix parameters are determined in a χ^2 fit to our published measurements [14] at centre–of–mass energies of 130 to 189 GeV, using our results of S–Matrix fits to the Z–peak data [3] as constraints. As a cross–check, a fit to all cross–section and asymmetry measurements is performed, which gives identical results. Correlations between measurements taken close to the Z resonance and measurements at high centre–of–mass energies are estimated and their influence on the fit results is found to be negligible. Correlations between different measurements at high centre–of–mass energy are taken into account in the fits. The photon exchange contributions, g_f , are fixed in the fits to their QED predictions. The fit results do not depend on the uncertainty on $\alpha(m_Z^2)$.

The fitted S–Matrix parameters for electrons, muons, taus and hadrons, and their correlations, are listed in Tables 1, 3 and 2. The fits are performed with and without the assumption of lepton universality. The parameters obtained for the individual lepton types are compatible with each other and support this assumption.

A large correlation is observed between the mass of the Z boson and the hadronic γ/Z interference term, $j_{\text{had}}^{\text{tot}}$. This correlation causes an increase in the uncertainty on m_Z with respect to fits where the hadronic γ/Z interference term is fixed to its Standard Model prediction. The value of this correlation is reduced from -0.95 when using Z peak data alone [3] to -0.57. Under the assumption of lepton universality the fitted hadronic γ/Z interference term is:

$$j_{\text{had}}^{\text{tot}} = 0.31 \pm 0.13(\text{exp}) \pm 0.04(\text{th}).$$

This value agrees with the Standard Model prediction of 0.21 and improves significantly the precision of our previous S–Matrix analyses [3, 9]. The theoretical uncertainty is due to the uncertainty of 0.5% on the calculation of cross sections for $\sqrt{s} > 130$ GeV of the ZFITTER program. For the leptonic γ/Z interference terms we obtain similar improvements. The fitted value for m_Z is:

$$m_Z = 91\,187.5 \pm 3.1(\text{exp}) \pm 2.3(\Delta j_{\text{had}}^{\text{tot}}) \pm 0.6(\text{th}) \text{ MeV}.$$

The contribution to the uncertainty due to the γ/Z interference is separated from the rest of the experimental uncertainty. It is reduced significantly with respect to our previous results [3, 9]. Again, the theoretical uncertainty is due to the limited precision of the cross section calculations with the ZFITTER program. Figure 2 shows the 68% confidence level contours in the $(m_Z, j_{\text{had}}^{\text{tot}})$ plane for the data taken at the Z–pole and after including the 130–189 GeV measurements. The improvement resulting from the inclusion of the high energy measurements is clearly visible.

Our measurement of the hadronic interference term agrees with results from data taken at energies below the Z resonance [24]. Adding these low energy measurements to the fits, we obtain:

$$\begin{aligned} j_{\text{had}}^{\text{tot}} &= 0.159 \pm 0.082(\text{exp}) \pm 0.015(\text{th}), \\ m_Z &= 91\,190.4 \pm 3.1(\text{exp}) \pm 1.5(\Delta j_{\text{had}}^{\text{tot}}) \pm 0.3(\text{th}) \text{ MeV}, \end{aligned}$$

with a correlation coefficient of -0.40 between these quantities.

In summary, we use the S–Matrix framework to analyse data taken at the Z resonance and at higher centre–of–mass energies. Our measurements provide an improved determination of the γ/Z interference terms and the Z boson mass. All parameters show good agreement with the Standard Model predictions.

Acknowledgements

We wish to express our gratitude to the CERN accelerator divisions for the excellent performance of the LEP machine. We acknowledge the contributions of the engineers and technicians who have participated in the construction and maintenance of this experiment.

References

- [1] S.L. Glashow, Nucl. Phys. **22** (1961) 579; S. Weinberg, Phys. Rev. Lett. **19** (1967) 1264; A. Salam, “Elementary Particle Theory”, Ed. N. Svartholm, (Almqvist and Wiksell, Stockholm, 1968), 367.
- [2] M. Veltman, Nucl. Phys. **B 7** (1968) 637; G.M. 't Hooft, Nucl. Phys. **B 35** (1971) 167; G.M. 't Hooft and M. Veltman, Nucl. Phys. **B 44** (1972) 189; Nucl. Phys. **B 50** (1972) 318.
- [3] L3 Collab., M. Acciarri *et al.*, Measurements of Cross Sections and Forward-Backward Asymmetries at the Z Resonance and Determination of Electroweak Parameters, Preprint CERN-EP/2000-022, CERN, 2000, accepted by E. Phys. J. C.
- [4] ALEPH Collab., R. Barate *et al.*, E. Phys. J. **C 14** (2000) 1.
- [5] DELPHI Collab., P. Abreu *et al.*, Cross-Sections and Leptonic Forward-Backward Asymmetries from the Z⁰ Running of LEP, Preprint CERN-EP-2000-037, CERN, 2000, accepted by E. Phys. J. C.
- [6] OPAL Collab., R. Akers *et al.*, Z. Phys. **C 61** (1994) 19.
- [7] SLD Collab., K. Abe *et al.*, Phys. Rev. Lett. **73** (1994) 25; SLD Collab., K. Abe *et al.*, Phys. Rev. Lett. **78** (1997) 2075; SLD Collab., K. Abe *et al.*, Phys. Rev. Lett. **79** (1997) 804.
- [8] A. Leike, T. Riemann and J. Rose, Phys. Lett. **B 273** (1991) 513; T. Riemann, Phys. Lett. **B 293** (1992) 451.
- [9] L3 Collab., M. Acciarri *et al.*, Phys. Lett. **B 407** (1997) 361.
- [10] DELPHI Collab., P. Abreu *et al.*, E. Phys. J. **C 11** (1999) 383.
- [11] OPAL Collab., K. Ackerstaff *et al.*, E. Phys. J. **C 2** (1998) 441.
- [12] L3 Collab., B. Adeva *et al.*, Nucl. Inst. Meth. **A 289** (1990) 35; M. Acciarri *et al.*, Nucl. Inst. Meth. **A 351** (1994) 300; M. Chemarin *et al.*, Nucl. Inst. Meth. **A 349** (1994) 345; A. Adam *et al.*, Nucl. Inst. Meth. **A 383** (1996) 342; G. Basti *et al.*, Nucl. Inst. Meth. **A 374** (1996) 293; I.C. Brock *et al.*, Nucl. Inst. Meth. **A 381** (1996) 236.
- [13] L3 Collab., M. Acciarri *et al.*, Phys. Lett. **B 370** (1996) 195.
- [14] L3 Collab., M. Acciarri *et al.*, Phys. Lett. **B 479** (2000) 101.
- [15] ZFITTER version 6.21 is used.
D. Bardin *et al.*, Preprint hep-ph/9908433; Z. Phys. **C 44** (1989) 493; Nucl. Phys. **B 351** (1991) 1; Phys. Lett. **B 255** (1991) 290. For the comparison with our measurements, the following ZFITTER flags have been changed from their default values: FINR = 0, INTF = 0, and BOXD = 2.
- [16] TOPAZ0 version 4.4 is used.
G. Montagna *et al.*, Nucl. Phys. **B401** (1993) 3; Comp. Phys. Comm. **76** (1993) 328.

- [17] L3 Collab., M. Acciarri *et al.*, Phys. Lett. **B 461** (1999) 376.
- [18] Particle Data Group, C. Caso *et al.*, E. Phys. J. **C 3** (1998) 1.
- [19] S. Eidelman and F. Jegerlehner, Z. Phys. **C 67** (1995) 585.
- [20] CDF Collab., F. Abe *et al.*, Phys. Rev. Lett. **74** (1995) 2626; CDF Collab., F. Abe *et al.*, Phys. Rev. Lett. **82** (1999) 2808; DØ Collab., S. Abachi *et al.*, Phys. Rev. Lett. **74** (1995) 2632; we use the average top quark mass as given in Reference [18].
- [21] D. Bardin *et al.*, in Proceedings to the LEP2 MC workshop 1999, ed. S. Jadach G. Passarino and R. Pittau, (to be published as CERN Yellow Report).
- [22] H. Anlauf *et al.*, in Physics at LEP2, Vol. 2, ed. T. Sjöstrand G. Altarelli and F. Zwirner, (Yellow Report: CERN 96-01, 1996), p. 229.
- [23] SMATASY version 6.21 is used.
S. Kirsch and T. Riemann, Comp. Phys. Comm. **88** (1995) 89.
- [24] TOPAZ Collab., K. Miyabayashi *et al.*, Phys. Lett. **B 347** (1995) 171; VENUS Collab., K. Yusa *et al.*, Phys. Lett. **B 447** (1999) 167.

The L3 Collaboration:

M.Acciarri,²⁶ P.Achard,¹⁹ O.Adriani,¹⁶ M.Aguilar-Benitez,²⁵ J.Alcaraz,²⁵ G.Alemanni,²² J.Allaby,¹⁷ A.Aloisio,²⁸ M.G.Alvigi,²⁸ G.Ambrosi,¹⁹ H.Anderhub,⁴⁸ V.P.Andreev,^{6,36} T.Angelico,¹² F.Anselmo,⁹ A.Arefiev,²⁷ T.Azemoon,³ T.Aziz,¹⁰ P.Bagnaia,³⁵ A.Bajo,²⁵ L.Baksay,⁴³ A.Balandras,⁴ S.V.Baldew,² S.Banerjee,¹⁰ Sw.Banerjee,¹⁰ A.Barczyk,^{48,46} R.Barillère,¹⁷ P.Bartalini,²² M.Basile,⁹ R.Battiston,³² A.Bay,²² F.Becattini,¹⁶ U.Becker,¹⁴ F.Behner,⁴⁸ L.Bellucci,¹⁶ R.Berbeco,³ J.Berdugo,²⁵ P.Berges,¹⁴ B.Bertucci,³² B.L.Betev,⁴⁸ S.Bhattacharya,¹⁰ M.Biasini,³² A.Biland,⁴⁸ J.J.Blaising,⁴ S.C.Blyth,³³ G.J.Bobbink,² A.Böhm,¹ L.Boldizar,¹³ B.Borgia,³⁵ D.Bourilkov,⁴⁸ M.Bourquin,¹⁹ S.Braccini,¹⁹ J.G.Branson,³⁹ F.Brochu,⁴ A.Buffini,¹⁶ A.Buijs,⁴⁴ J.D.Burger,¹⁴ W.J.Burger,³² X.D.Cai,¹⁴ M.Campanelli,⁴⁸ M.Capell,¹⁴ G.Cara Romeo,⁹ G.Carlino,²⁸ A.M.Cartacci,¹⁶ J.Casaus,²⁵ G.Castellini,¹⁶ F.Cavallari,³⁵ N.Cavallo,³⁷ C.Cecchi,³² M.Cerrada,²⁵ F.Cesaroni,²³ M.Chamizo,¹⁹ Y.H.Chang,⁵⁰ U.K.Chaturvedi,¹⁸ M.Chemarin,²⁴ A.Chen,⁵⁰ G.Chen,⁷ G.M.Chen,⁷ H.F.Chen,²⁰ H.S.Chen,⁷ G.Chiefari,²⁸ L.Cifarelli,³⁸ F.Cindolo,⁹ C.Civinini,¹⁶ I.Clare,¹⁴ R.Clare,¹⁴ G.Coignet,⁴ N.Colino,²⁵ S.Costantini,⁵ F.Cotorobai,¹² B.de la Cruz,²⁵ A.Csilling,¹³ S.Cucciarelli,³² T.S.Dai,¹⁴ J.A.van Dalen,³⁰ R.D'Alessandro,¹⁶ R.de Asmundis,²⁸ P.Dégion,¹⁹ A.Degré,⁴ K.Deiters,⁴⁶ D.della Volpe,²⁸ E.Delmeire,¹⁹ P.Denes,³⁴ F.DeNotaristefani,³⁵ A.De Salvo,⁴⁸ M.Diemoz,³⁵ M.Dierckxsens,² D.van Dierendonck,² C.Dionisi,³⁵ M.Dittmar,⁴⁸ A.Dominguez,³⁹ A.Doria,²⁸ M.T.Dova,^{18,4} D.Duchesneau,⁴ D.Dufournaud,⁴ P.Duinker,² I.Duran,⁴⁰ H.El Mamouni,²⁴ A.Engler,³³ F.J.Eppling,¹⁴ F.C.Erne,² P.Extermann,¹⁹ M.Fabre,⁴⁶ M.A.Falagan,²⁵ S.Falciano,^{35,17} A.Favara,¹⁷ J.Fay,²⁴ O.Fedin,³⁶ M.Felcini,⁴⁸ T.Ferguson,³³ H.Fesefeldt,¹ E.Fiandrin,³² J.H.Field,¹⁹ F.Filthaut,¹⁷ P.H.Fisher,¹⁴ I.Fisk,³⁹ G.Forconi,¹⁴ K.Freudenreich,⁴⁸ C.Furetta,²⁶ Yu.Galaktionov,^{27,14} S.N.Ganguli,¹⁰ P.Garcia-Abia,⁵ M.Gataullin,³¹ S.S.Gau,¹¹ S.Gentile,^{35,17} N.Gheordanescu,¹² S.Giagu,³⁵ Z.F.Gong,²⁰ G.Grenier,²⁴ O.Grimm,⁴⁸ M.W.Gruenewald,⁸ M.Guida,³⁸ R.van Gulik,² V.K.Gupta,³⁴ A.Gurtu,¹⁰ L.J.Gutay,⁴⁵ D.Haas,⁵ A.Hasan,²⁹ D.Hatzifotiadou,⁹ T.Hebbeker,⁸ A.Hervé,¹⁷ P.Hidas,¹³ J.Hirschfelder,³³ H.Hofer,⁴⁸ G.Holzner,⁴⁸ H.Hoorani,³³ S.R.Hou,⁵⁰ Y.Hu,³⁰ I.Iashvili,⁴⁷ B.N.Jin,⁷ L.W.Jones,³ P.de Jong,² I.Josa-Mutuberría,²⁵ R.A.Khan,¹⁸ M.Kaur,^{18,48} M.N.Kienzle-Focacci,¹⁹ D.Kim,³⁵ J.K.Kim,⁴² J.Kirkby,¹⁷ D.Kiss,¹³ W.Kittel,³⁰ A.Klimentov,^{14,27} A.C.König,³⁰ A.Kopp,⁴⁷ V.Koutsenko,^{14,27} M.Kräber,⁴⁸ R.W.Kraemer,³³ W.Krenz,¹ A.Krüger,⁴⁷ A.Kunin,^{14,27} P.Ladron de Guevara,²⁵ I.Laktineh,²⁴ G.Landi,¹⁶ M.Lebeau,¹⁷ A.Lebedev,¹⁴ P.Lebun,²⁴ P.Lecomte,⁴⁸ P.Lecoq,¹⁷ P.Le Coultre,⁴⁸ H.J.Lee,⁸ J.M.Le Goff,¹⁷ R.Leiste,⁴⁷ P.Levtchenko,³⁶ C.Li,²⁰ S.Likhoded,⁴⁷ C.H.Lin,⁵⁰ W.T.Lin,⁵⁰ F.L.Linde,² L.Lista,²⁸ Z.A.Liu,⁷ W.Lohmann,⁴⁷ E.Longo,³⁵ Y.S.Lu,⁷ K.Lübelsmeyer,¹ C.Luci,^{17,35} D.Luckey,¹⁴ L.Lugnier,²⁴ L.Luminari,³⁵ W.Lustermann,⁴⁸ W.G.Ma,²⁰ M.Maity,¹⁰ L.Malgeri,¹⁷ A.Malinin,¹⁷ C.Mañá,²⁵ D.Mangeol,³⁰ J.Mans,³⁴ G.Marian,¹⁵ J.P.Martin,²⁴ F.Marzano,³⁵ K.Mazumdar,¹⁰ R.R.McNeil,⁶ S.Mele,¹⁷ L.Merola,²⁸ M.Meschini,¹⁶ W.J.Metzger,³⁰ M.von der Mey,¹ A.Mihul,¹² H.Milcent,¹⁷ G.Mirabelli,³⁵ J.Mnich,¹⁷ G.B.Mohanty,¹⁰ T.Moulik,¹⁰ G.S.Muanza,²⁴ A.J.M.Muijs,² B.Musicar,³⁹ M.Musy,³⁵ M.Napolitano,²⁸ F.Nessi-Tedaldi,⁴⁸ H.Newman,³¹ T.Niessen,¹⁴ A.Nisati,³⁵ H.Nowak,⁴⁷ R.Ofierzynski,⁴⁸ G.Organtini,³⁵ A.Oulianov,²⁷ C.Palomares,²⁵ D.Pandoulas,¹ S.Paoletti,^{35,17} P.Paolucci,²⁸ R.Paramatti,³⁵ H.K.Park,³³ I.H.Park,⁴² G.Passaleva,¹⁷ S.Patricelli,²⁸ T.Paul,¹¹ M.Pauluzzi,³² C.Paus,¹⁷ F.Pauss,⁴⁸ M.Pedace,³⁵ S.Pensotti,²⁶ D.Perret-Gallix,⁴ B.Petersen,³⁰ D.Piccolo,²⁸ F.Pierella,⁹ M.Pieri,¹⁶ P.A.Piroué,³⁴ E.Pistoiesi,²⁶ V.Plyaskin,²⁷ M.Pohl,¹⁹ V.Pojidaev,^{27,16} H.Postema,¹⁴ J.Pothier,¹⁷ D.O.Prokofiev,⁴⁵ D.Prokofiev,³⁶ J.Quartieri,³⁸ G.Rahal-Callot,^{48,17} M.A.Rahaman,¹⁰ P.Raics,¹⁵ N.Raja,¹⁰ R.Ramelli,⁴⁸ P.G.Rancoita,²⁶ A.Raspereza,⁴⁷ G.Raven,³⁹ P.Razis,²⁹ D.Ren,⁴⁸ M.Rescigno,³⁵ S.Reucroft,¹¹ S.Riemann,⁴⁷ K.Riles,³ J.Rodin,⁴³ B.P.Roe,³ L.Romero,²⁵ A.Rosca,⁸ S.Rosier-Lees,⁴ J.A.Rubio,¹⁷ G.Ruggiero,¹⁶ H.Rykaczewski,⁴⁸ S.Saremi,⁶ S.Sarkar,³⁵ J.Salicio,¹⁷ E.Sanchez,¹⁷ M.P.Sanders,³⁰ M.E.Sarakinos,²¹ C.Schäfer,¹⁷ V.Schegelsky,³⁶ S.Schmidt-Kaerst,¹ D.Schmitz,¹ H.Schopper,⁴⁹ D.J.Schotanus,³⁰ G.Schwering,¹ C.Sciacca,²⁸ A.Seganti,⁹ L.Servoli,³² S.Shevchenko,³¹ N.Shivarov,⁴¹ V.Shoutko,²⁷ E.Shumilov,²⁷ A.Shvorob,³¹ T.Siedenburger,¹ D.Son,⁴² B.Smith,³³ P.Spillantini,¹⁶ M.Steuer,¹⁴ D.P.Stickland,³⁴ A.Stone,⁶ B.Stoyanov,⁴¹ A.Straessner,¹ K.Sudhakar,¹⁰ G.Sultanov,¹⁸ L.Z.Sun,²⁰ H.Suter,⁴⁸ J.D.Swain,¹⁸ Z.Szillasi,^{43,4} T.Sztaricskai,^{43,4} X.W.Tang,⁷ L.Tauscher,⁵ L.Taylor,¹¹ B.Tellili,²⁴ C.Timmermans,³⁰ Samuel C.C.Ting,¹⁴ S.M.Ting,¹⁴ S.C.Tonwar,¹⁰ J.Tóth,¹³ C.Tully,¹⁷ K.L.Tung,⁷ Y.Uchida,¹⁴ J.Ulbricht,⁴⁸ E.Valente,³⁵ G.Vesztegombi,¹³ I.Vetlitsky,²⁷ D.Vicinanza,³⁸ G.Viertel,⁴⁸ S.Villa,¹¹ M.Vivargent,⁴ S.Vlachos,⁵ I.Vodopianov,³⁶ H.Vogel,³³ H.Vogt,⁴⁷ I.Vorobiev,²⁷ A.A.Vorobyov,³⁶ A.Vorvolakos,²⁹ M.Wadhwa,⁵ W.Wallraff,¹ M.Wang,¹⁴ X.L.Wang,²⁰ Z.M.Wang,²⁰ A.Weber,¹ M.Weber,¹ P.Wienemann,¹ H.Wilkens,³⁰ S.X.Wu,¹⁴ S.Wynhoff,¹⁷ L.Xia,³¹ Z.Z.Xu,²⁰ J.Yamamoto,³ B.Z.Yang,²⁰ C.G.Yang,⁷ H.J.Yang,⁷ M.Yang,⁷ J.B.Ye,²⁰ S.C.Yeh,⁵¹ An.Zalite,³⁶ Yu.Zalite,³⁶ Z.P.Zhang,²⁰ G.Y.Zhu,⁷ R.Y.Zhu,³¹ A.Zichichi,^{9,17,18} G.Zilizi,^{43,4} B.Zimmermann,⁴⁸ M.Zöller,¹

- 1 I. Physikalisches Institut, RWTH, D-52056 Aachen, FRG[§]
 - III. Physikalisches Institut, RWTH, D-52056 Aachen, FRG[§]
 - 2 National Institute for High Energy Physics, NIKHEF, and University of Amsterdam, NL-1009 DB Amsterdam, The Netherlands
 - 3 University of Michigan, Ann Arbor, MI 48109, USA
 - 4 Laboratoire d'Annecy-le-Vieux de Physique des Particules, LAPP,IN2P3-CNRS, BP 110, F-74941 Annecy-le-Vieux CEDEX, France
 - 5 Institute of Physics, University of Basel, CH-4056 Basel, Switzerland
 - 6 Louisiana State University, Baton Rouge, LA 70803, USA
 - 7 Institute of High Energy Physics, IHEP, 100039 Beijing, China[△]
 - 8 Humboldt University, D-10099 Berlin, FRG[§]
 - 9 University of Bologna and INFN-Sezione di Bologna, I-40126 Bologna, Italy
 - 10 Tata Institute of Fundamental Research, Bombay 400 005, India
 - 11 Northeastern University, Boston, MA 02115, USA
 - 12 Institute of Atomic Physics and University of Bucharest, R-76900 Bucharest, Romania
 - 13 Central Research Institute for Physics of the Hungarian Academy of Sciences, H-1525 Budapest 114, Hungary[‡]
 - 14 Massachusetts Institute of Technology, Cambridge, MA 02139, USA
 - 15 KLTE-ATOMKI, H-4010 Debrecen, Hungary[¶]
 - 16 INFN Sezione di Firenze and University of Florence, I-50125 Florence, Italy
 - 17 European Laboratory for Particle Physics, CERN, CH-1211 Geneva 23, Switzerland
 - 18 World Laboratory, FBLJA Project, CH-1211 Geneva 23, Switzerland
 - 19 University of Geneva, CH-1211 Geneva 4, Switzerland
 - 20 Chinese University of Science and Technology, USTC, Hefei, Anhui 230 029, China[△]
 - 21 SEFT, Research Institute for High Energy Physics, P.O. Box 9, SF-00014 Helsinki, Finland
 - 22 University of Lausanne, CH-1015 Lausanne, Switzerland
 - 23 INFN-Sezione di Lecce and Università Degli Studi di Lecce, I-73100 Lecce, Italy
 - 24 Institut de Physique Nucléaire de Lyon, IN2P3-CNRS, Université Claude Bernard, F-69622 Villeurbanne, France
 - 25 Centro de Investigaciones Energéticas, Medioambientales y Tecnológicas, CIEMAT, E-28040 Madrid, Spain^b
 - 26 INFN-Sezione di Milano, I-20133 Milan, Italy
 - 27 Institute of Theoretical and Experimental Physics, ITEP, Moscow, Russia
 - 28 INFN-Sezione di Napoli and University of Naples, I-80125 Naples, Italy
 - 29 Department of Natural Sciences, University of Cyprus, Nicosia, Cyprus
 - 30 University of Nijmegen and NIKHEF, NL-6525 ED Nijmegen, The Netherlands
 - 31 California Institute of Technology, Pasadena, CA 91125, USA
 - 32 INFN-Sezione di Perugia and Università Degli Studi di Perugia, I-06100 Perugia, Italy
 - 33 Carnegie Mellon University, Pittsburgh, PA 15213, USA
 - 34 Princeton University, Princeton, NJ 08544, USA
 - 35 INFN-Sezione di Roma and University of Rome, "La Sapienza", I-00185 Rome, Italy
 - 36 Nuclear Physics Institute, St. Petersburg, Russia
 - 37 INFN-Sezione di Napoli and University of Potenza, I-85100 Potenza, Italy
 - 38 University and INFN, Salerno, I-84100 Salerno, Italy
 - 39 University of California, San Diego, CA 92093, USA
 - 40 Dept. de Física de Partículas Elementales, Univ. de Santiago, E-15706 Santiago de Compostela, Spain
 - 41 Bulgarian Academy of Sciences, Central Lab. of Mechatronics and Instrumentation, BU-1113 Sofia, Bulgaria
 - 42 Laboratory of High Energy Physics, Kyungpook National University, 702-701 Taegu, Republic of Korea
 - 43 University of Alabama, Tuscaloosa, AL 35486, USA
 - 44 Utrecht University and NIKHEF, NL-3584 CB Utrecht, The Netherlands
 - 45 Purdue University, West Lafayette, IN 47907, USA
 - 46 Paul Scherrer Institut, PSI, CH-5232 Villigen, Switzerland
 - 47 DESY, D-15738 Zeuthen, FRG
 - 48 Eidgenössische Technische Hochschule, ETH Zürich, CH-8093 Zürich, Switzerland
 - 49 University of Hamburg, D-22761 Hamburg, FRG
 - 50 National Central University, Chung-Li, Taiwan, China
 - 51 Department of Physics, National Tsing Hua University, Taiwan, China
- [§] Supported by the German Bundesministerium für Bildung, Wissenschaft, Forschung und Technologie
[‡] Supported by the Hungarian OTKA fund under contract numbers T019181, F023259 and T024011.
[¶] Also supported by the Hungarian OTKA fund under contract numbers T22238 and T026178.
^b Supported also by the Comisión Interministerial de Ciencia y Tecnología.
[‡] Also supported by CONICET and Universidad Nacional de La Plata, CC 67, 1900 La Plata, Argentina.
[◇] Also supported by Panjab University, Chandigarh-160014, India.
[△] Supported by the National Natural Science Foundation of China.

Parameter	Treatment of Charged Leptons		Theory uncertainty	Standard Model
	Non-Universality	Universality		
m_Z [MeV]	91188.3 ± 3.9	91187.5 ± 3.9	0.6	—
Γ_Z [MeV]	2502.8 ± 4.1	2502.5 ± 4.1	0.1	$2492.7^{+3.8}_{-5.2}$
$r_{\text{had}}^{\text{tot}}$	2.9856 ± 0.0092	2.9848 ± 0.0092	0.0003	$2.9584^{+0.0088}_{-0.0119}$
r_e^{tot}	0.14317 ± 0.00075	—	0.00002	
r_μ^{tot}	0.14287 ± 0.00079	—	0.00002	
r_τ^{tot}	0.14375 ± 0.00102	—	0.00002	
r_ℓ^{tot}	—	0.14318 ± 0.00059	0.00002	$0.14242^{+0.00035}_{-0.00049}$
$j_{\text{had}}^{\text{tot}}$	0.30 ± 0.13	0.31 ± 0.13	0.04	0.21 ± 0.01
j_e^{tot}	-0.030 ± 0.045	—	0.002	
j_μ^{tot}	-0.001 ± 0.027	—	0.002	
j_τ^{tot}	0.061 ± 0.031	—	0.002	
j_ℓ^{tot}	—	0.017 ± 0.019	0.002	0.0041 ± 0.0003
r_e^{fb}	0.00177 ± 0.00111	—	0.000002	
r_μ^{fb}	0.00333 ± 0.00064	—	0.000002	
r_τ^{fb}	0.00448 ± 0.00092	—	0.000002	
r_ℓ^{fb}	—	0.00332 ± 0.00047	0.000002	0.00255 ± 0.00023
j_e^{fb}	0.700 ± 0.075	—	0.001	
j_μ^{fb}	0.807 ± 0.034	—	0.001	
j_τ^{fb}	0.732 ± 0.044	—	0.001	
j_ℓ^{fb}	—	0.770 ± 0.026	0.001	0.799 ± 0.001
χ^2 /d.o.f.	30.4/28	33.0/36		—

Table 1: Results of the fits in the S–Matrix framework without and with the assumption of lepton universality. The theory uncertainties on the S–Matrix parameters are determined from the 0.5% uncertainty on the ZFITTER predictions for cross sections. The Standard Model expectations are calculated using the parameters listed in Equation 1.

	m_Z	Γ_Z	$r_{\text{had}}^{\text{tot}}$	r_e^{tot}	r_μ^{tot}	r_τ^{tot}	$j_{\text{had}}^{\text{tot}}$	j_e^{tot}	j_μ^{tot}	j_τ^{tot}	r_e^{fb}	r_μ^{fb}	r_τ^{fb}	j_e^{fb}	j_μ^{fb}	j_τ^{fb}
m_Z	1.00	0.38	0.07	-0.08	0.01	0.01	-0.58	-0.14	-0.15	-0.14	-0.05	0.08	0.03	-0.01	-0.06	-0.02
Γ_Z		1.00	0.91	0.54	0.52	0.40	0.01	-0.02	0.02	0.02	0.00	0.02	0.02	-0.01	0.04	0.04
$r_{\text{had}}^{\text{tot}}$			1.00	0.56	0.53	0.41	0.01	-0.03	0.01	0.01	0.00	0.02	0.02	-0.01	0.04	0.04
r_e^{tot}				1.00	0.33	0.25	0.08	0.05	0.04	0.03	0.13	-0.01	0.00	-0.02	0.04	0.02
r_μ^{tot}					1.00	0.23	0.00	-0.02	0.10	0.02	0.00	0.03	0.01	-0.01	0.11	0.02
r_τ^{tot}						1.00	0.00	-0.01	0.02	0.09	0.00	0.01	0.03	-0.01	0.02	0.10
$j_{\text{had}}^{\text{tot}}$							1.00	0.13	0.13	0.13	0.04	-0.04	-0.03	0.01	0.05	0.02
j_e^{tot}								1.00	0.03	0.03	0.00	-0.01	-0.01	0.30	0.01	0.01
j_μ^{tot}									1.00	0.03	0.01	0.07	-0.01	0.00	0.31	0.01
j_τ^{tot}										1.00	0.01	-0.01	0.04	0.00	0.01	0.15
r_e^{fb}											1.00	-0.01	0.00	0.03	0.00	0.00
r_μ^{fb}												1.00	0.01	0.00	0.13	0.00
r_τ^{fb}													1.00	0.00	0.00	0.11
j_e^{fb}														1.00	0.00	0.00
j_μ^{fb}															1.00	0.00
j_τ^{fb}																1.00

Table 2: Correlation coefficients of the S-Matrix parameters listed in Table 1 not assuming lepton universality.

	m_Z	Γ_Z	$r_{\text{had}}^{\text{tot}}$	r_ℓ^{tot}	$j_{\text{had}}^{\text{tot}}$	j_ℓ^{tot}	r_ℓ^{fb}	j_ℓ^{fb}
m_Z	1.00	0.05	0.06	-0.02	-0.57	-0.24	0.05	-0.06
Γ_Z		1.00	0.92	0.69	0.01	0.01	0.02	0.05
$r_{\text{had}}^{\text{tot}}$			1.00	0.71	0.01	0.00	0.03	0.05
r_ℓ^{tot}				1.00	0.04	0.08	0.05	0.08
$j_{\text{had}}^{\text{tot}}$					1.00	0.21	-0.03	0.06
j_ℓ^{tot}						1.00	0.04	0.25
r_ℓ^{fb}							1.00	0.11
j_ℓ^{fb}								1.00

Table 3: Correlation coefficients of the S-Matrix parameters listed in Table 1 assuming lepton universality.

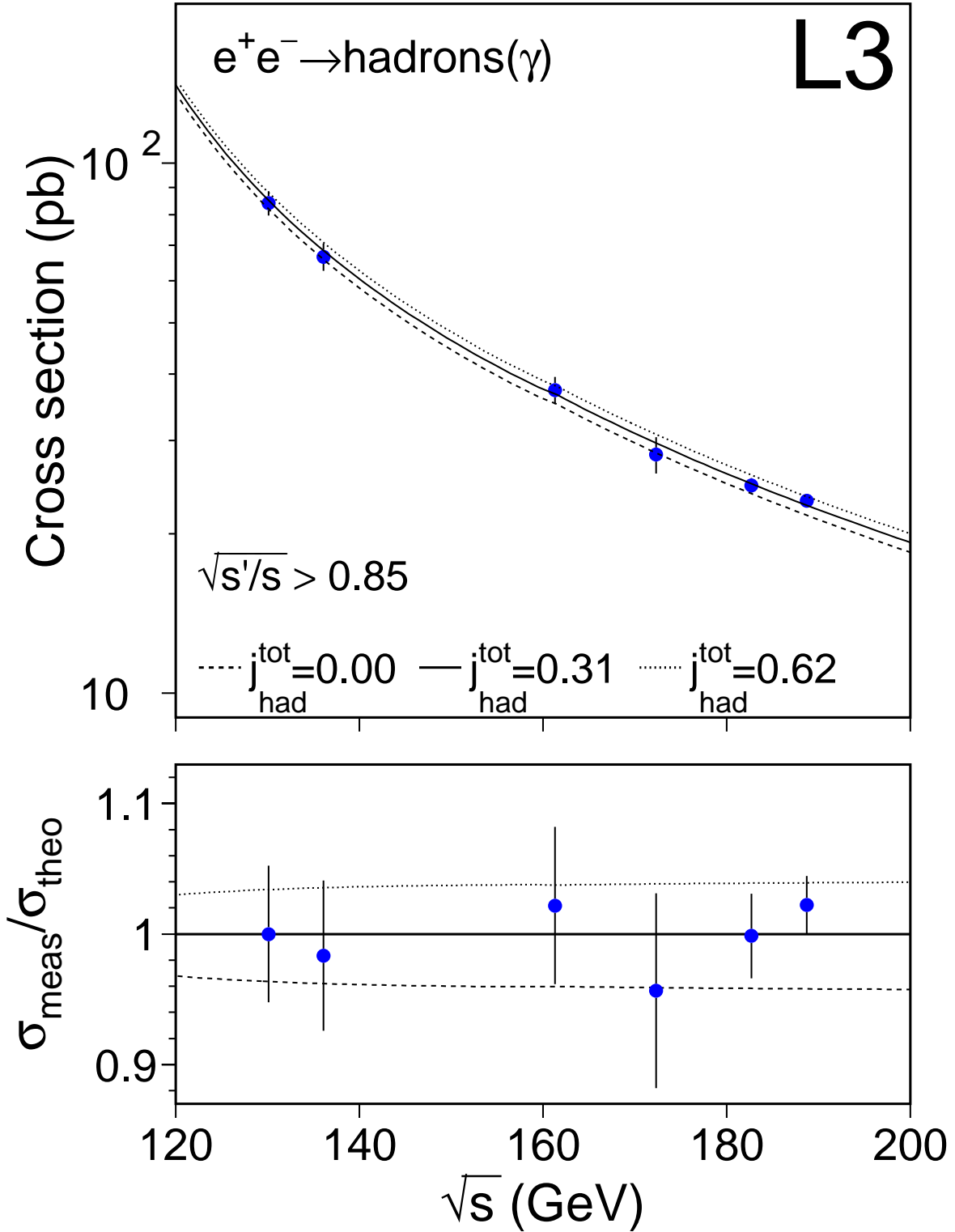


Figure 1: Cross sections for the process $e^+e^- \rightarrow \text{hadrons}(\gamma)$, for $\sqrt{s'/s} > 0.85$. The lines represent the theory predictions for different values of $j_{\text{had}}^{\text{tot}}$. The lower plot normalises the measurements and predictions to that of $j_{\text{had}}^{\text{tot}} = 0.31$.

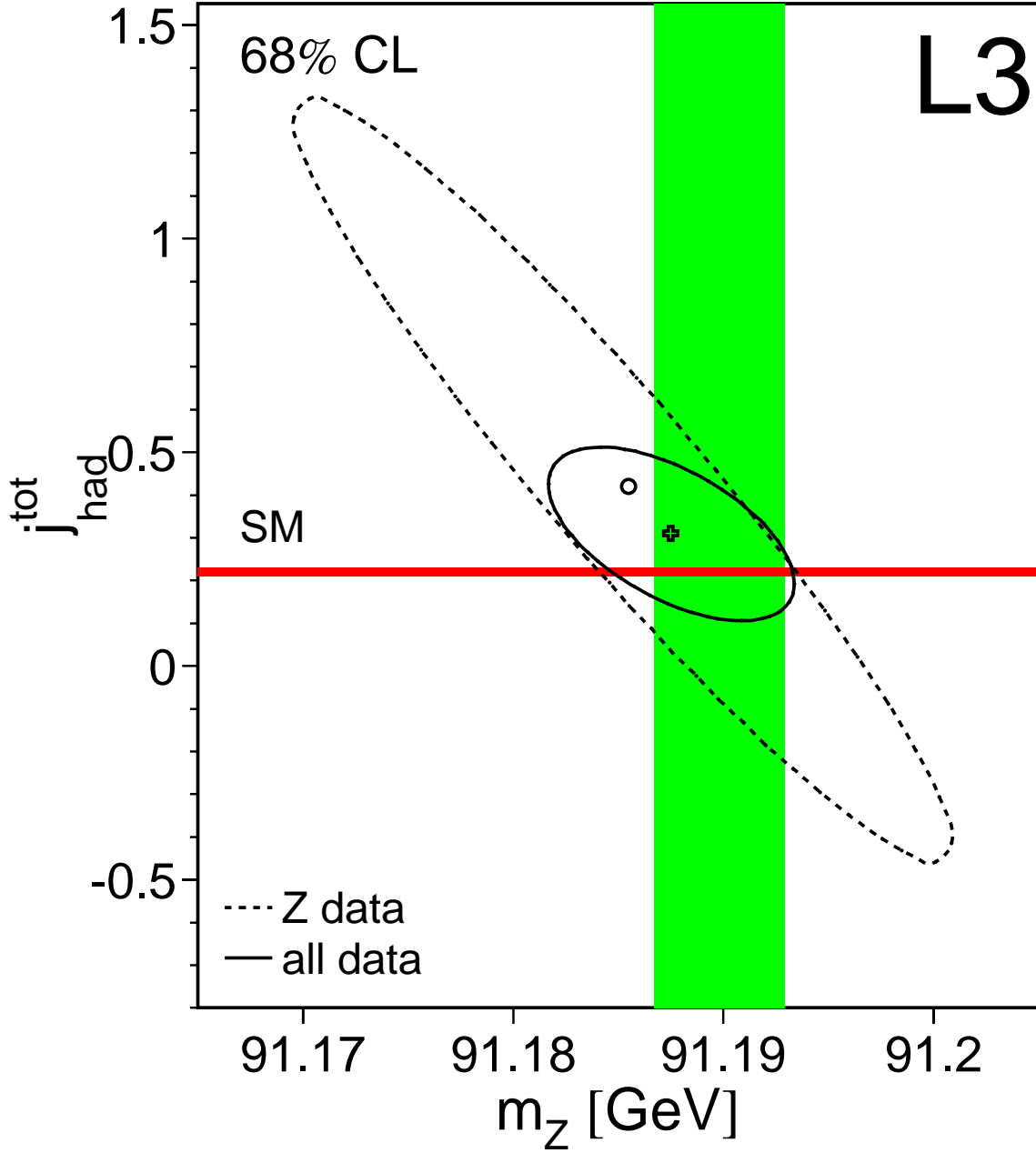


Figure 2: Contours in the $(m_Z, j_{\text{had}}^{\text{tot}})$ plane at 68% confidence level under the assumption of lepton universality. The dashed line is obtained from Z data only; the inclusion of 130 GeV to 189 GeV data gives the solid line. The circle (Z data) and the cross (all data) indicate the central values of the fits. The Standard Model prediction for $j_{\text{had}}^{\text{tot}}$ is shown as the horizontal band. The vertical band corresponds to the 68% confidence level interval on m_Z in a fit assuming the Standard Model value for γ/Z interference.