Determination of the Parameter of the Z Line-Shapes at LEP

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Abstract

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DETERMINATION of the PARAMETERS of the Z LINE-SHAPES at LEP

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ABSTRACT

The measurement of the cross-section for the processes $e^+e^- \rightarrow \text{hadrons}$ and $e^+e^- \rightarrow \text{lepton pairs}$ at several collision energies near the Z resonance peak as performed by the 4 LEP experiments from 1989 to 1991 is presented. A 5 parameter fit applied to the measured line-shapes and lepton asymmetries provides the following *preliminary* values for the line-shape parameters: $M_Z = 91.187 \pm 0.007$ GeV, $\Gamma_Z = 2.492 \pm 0.007$ GeV, $\Gamma_l = 83.33 \pm 0.30$ MeV and $R_l = 20.85 \pm 0.07$. From these values the Born level hadronic peak cross-section was found to be $\sigma_0^h = 41.16 \pm 0.18$ nb. The invisible width was found to be $\Gamma_{inv} = 505 \pm 7$ MeV, leading to $N_\nu = 3.047 \pm 0.033$ light neutrino species. All these values are in agreement with the Minimal Standard Model expectations. From a 3 parameter fit constrained by the Minimal Standard Model prescriptions the strong coupling constant was found to be $\alpha_s(M_Z^2) = 0.135 \pm 0.009$, in agreement with the values derived from global event shape variables. Finally the measured values of Γ_Z and Γ_{inv} were used to derive lower mass bounds for new particles predicted by several extensions and alternatives of the Minimal Standard Model.

1. Introduction

LEP experiments have the unique ability to measure the Z line-shapes with extreme precision. This allows a determination of parameters which are not predicted by the Minimal Standard Model (MSM), to compare experimental measurements to the MSM predictions with the possibility to detect new features beyond it, and to set lower mass bounds on particles predicted by its alternatives or extensions.

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Line-shape parameters should be determined with the highest possible precision at LEP, since comparable accuracy may never be achieved elsewhere, and because the possible departure of the data from the *MSM* predictions are expected to be rather small.

This paper reports on a *preliminary* measurement of the line-shape parameters performed by the 4 LEP collaborations with the combined 1989, 1990 and 1991 data samples. It is based on a total amount of about $1.7 \cdot 10^6$ hadronic and $1.8 \cdot 10^5$ leptonic decays of the Z measured in the vicinity of the resonance peak from August 1989 through November 1991. This selected sample corresponds to a total integrated luminosity of $(16 - 20) \text{ pb}^{-1}$ per interaction point (IP). Since the total integrated luminosity achievable at LEP-I until 1994 should be larger than 100 pb^{-1} per experiment, the present paper is essentially a progress report.

Compared to the combined 1989 and 1990 measurements published in [2], those from 1991 benefit from about twice larger statistics, still better running conditions (with sometimes upgraded detectors), reduced systematic uncertainties (in particular those affecting the luminosity determination) and a well improved knowledge of the beam energy. Furthermore, the 1990 data were reanalysed, taking into account the improvements from the analysis of the 1991 data.

The paper is organised as follows. After a brief review of the basic motivations for measuring the line-shape parameters (Section 2), the method to determine them is recalled (Section 3) with its present major sources of uncertainty or improvement with respect to the published analyses of the 1990 data. The results of the fits are given in Section 4. The paper is summarised in Section 5, with an outlook towards the final accuracy achievable at LEP-I.

2. Physics Motivation

The Z mass (M_Z) and the number of light neutrino species (N_ν) are the parameters not predicted by the *MSM* which are best determined from the Z line-shape measurements. These measurements allow also to determine the strong coupling constant (α_s) and mass ranges where the top quark (m_t) and the standard Higgs boson (M_H) are likely to be found.

M_Z needs to be measured with high accuracy not only since it characterises the Z boson itself, but also because it is a fundamental constant entering the calculus of *MSM* predictions, making it essential for tests of the latter. Excellent knowledge of the beam energy is required in order to make use of the high statistical precision (i.e. a few 10^{-5}) achievable on M_Z .

Already the data collected at LEP in 1989 [3] demonstrated that there are 3 light neutrino species in Nature, the alternative hypotheses of 2 or 4 light Dirac neutrino generations being irrefutably ruled out. At present LEP experiments aim to measure N_ν as accurately as possible in order to seek for features beyond the MSM. For instance, a fourth massive Dirac neutrino would give an effective number of light neutrinos slightly larger than 3 whereas this number would be slightly below 3 if the fourth generation neutrino would be right-handed [4]. The existence of other new particles, such as weakly interacting massive particles (WIMP) or additional gauge bosons (Z') can also manifest itself in a departure of N_ν from 3 [5].

The determination of α_s based on the hadronic and leptonic line-shapes is a very powerful method. Since it relies on inclusive cross-sections its theoretical treatment is under much better control than methods based on event shape variables [6]. An other benefit of inclusive cross-sections is analyticity, which allows in principle to derive the scale Q at which α_s is determined. At LEP Q would be equal to M_Z within a few %. This is however still controversial.

Allowed mass ranges for the top quark and - to a lesser extent - of the Higgs boson can be derived from the combination of the observed electroweak (EW) radiative corrections to the hadronic, leptonic and total widths of the Z with its mass. Although this approach is indirect and biased by MSM assumptions made on the origin of the observed EW corrections, it will remain, combined with the quark and lepton asymmetries and the tau polarisation measured at LEP, the most accurate way of estimating the mass of these particles until they are directly observed. The determination of m_t could be as precise as ± 15 GeV to combine with another ± 20 GeV uncertainty due to the lack of knowledge on M_H [7]. The precision achievable on M_H is only about 0.3 TeV for a rather light Higgs (i.e. M_H close to 100 GeV) and reaches 0.5 TeV if it is rather heavy (i.e. M_H close to 1 TeV). A more accurate knowledge of m_t would however allow to determine M_H more precisely.

Lepton universality can be tested at LEP with a precision better than 1 % by comparing the measured values of the charged leptonic partial widths ($\Gamma_e, \Gamma_\mu, \Gamma_\tau$) with each other. This has major outcomes in the understanding of the baryogenesis of the Universe and provides also upper limits of the neutrino masses [8].

The total and invisible widths are most sensitive to the production of new particles predicted by extensions of or alternatives to the MSM. Conversely, in the absence of a direct observation of any new particle, their measured values can be used to derive lower mass bounds for these particles.

Physics beyond the MSM hidden in radiative corrections can be revealed

by observables chosen because of their weak sensitivity to the MSM unknowns, especially to m_t and M_H . Some observables combine line-shape parameters with forward-backward asymmetries and tau polarisation [9]. Only observables derived from the line-shapes alone will be considered here.

3. Determination of the Line-Shape Parameters

Multihadronic final states represent the bulk (i.e. about 70 %) of the Z decays, whereas only about 3.5 % of the Z 's decay in each of the 3 charged lepton final states.

The determination of the corresponding line-shape parameters is a two step procedure, where first, the cross-section of the process $e^+e^- \rightarrow \gamma, Z \rightarrow \text{hadrons}$, e^+e^- , $\mu^+\mu^-$ or $\tau^+\tau^-$ is measured at several collision energies near the Z resonance peak, and second, the 4 line-shapes are fitted with a theoretical expression of the cross-sections where the resonance parameters are left free to vary. The results presented in this paper were obtained from a simultaneous fit to the 4 line-shapes and to the 3 leptonic forward-backward asymmetries. The line-shape parameters are not affected significantly by the inclusion of the asymmetries in the fit.

3.1. Cross-Section Computation

The experimental cross-sections (σ) are computed at each center-of-mass energy ($\sqrt{s}$) from the following expression:

$$\sigma(s) = \frac{N_f - N_{bg}}{\epsilon_Z \cdot L} \cdot (1 + f_{\delta s}) \quad (1)$$

N_f stands for the number of selected events in a specific final state. N_{bg} is the number of background events (typically a few 10^{-3} times N_f). ϵ_Z stands for the overall trigger, reconstruction and selection efficiency (at least 95 % for hadrons and about 70 – 95 % for leptons)². L is the integrated luminosity at each collision energy, and $f_{\delta s}$ is an unfolding function accounting for the energy spread of the beams.

The main features of the improvements achieved on each component of the aforementioned cross-section expression since the published 1990 analyses are summarised hereafter.

² The ALEPH and DELPHI collaborations also perform a flavour independent selection of the leptonic final states which leads to very similar results.

3.1.1. LEP energy knowledge [10]

A major improvement has been achieved by measuring the beam energy with the resonant depolarisation method [11], which is typically an order of magnitude more precise than any of the methods used for absolute energy measurements in 1990.

Significant progress has also been made in the understanding of the variations of the beam calibration measurements with time, temperature, humidity, RF alignment errors, moon tides, etc.. Some of its main features are given below.

The ageing of the 3280 dipole magnets of the LEP collider is understood to originate mainly from the dehydration of the mortar slices filling the space between the steel laminations of the core of the dipoles. This results in stresses on the steel laminations which change the dipoles magnetic properties. The shrinkage of the dipoles core with dehydration is also the major cause for the ageing of the flux loops which are embedded in the cores and are used to monitor the beam energy.

Laboratory tests proved that the magnetic characteristics of the dipoles change with temperature, due to variations of their central field and length. The latter result also in a change of the flux loop measurements as a function of temperature as large as 10^{-4} per $^{\circ}$ C.

The temperature of the dipole magnets was monitored and shown to depend mainly on the current applied to each of them. Therefore the cooling system of the magnets was modified in order to keep their temperature more constant. At the time of this improvement (mid-August 1991) a drift of the flux loop measurements was observed, which is not yet well understood. Since no depolarisation measurement was performed before this drift was observed, energy points of the line-shape scan measured before and after 14 August 1991 had to be considered separately.

A simulation showed that misalignments with respect to the highest of the two frequencies at which the RF cavities of the machine are operated produce a local increase of the collision energy of about 13 – 16 MeV. Since the RF cavities are located on both sides of only two (i.e. IP2 and IP6) out of the 4 interaction points, the collision energy at these interaction points is higher than at the two interaction points not surrounded by RF cavities (i.e. IP4 and IP8). The effect of cavity trips was also simulated and found to change the c.m. energy at all interaction points by a few MeV. These studies of the effect of the RF cavities on the local value of the beam energies allowed to reduce the initial dispersion of very preliminary values of M_Z found by the 4 experiments (i.e. about 4 standard deviations between the lowest and the highest values of M_Z) to a level well compatible with statistical

fluctuations (about 2 standard deviations). This feature may indicate the benefit of having 4 different experiments making high precision measurements of the same fundamental quantities.

Moon tides, and to a lesser extent sun tides, can induce variations of the machine radius as large as 0.15 mm (i.e. $3.5 \cdot 10^{-8}$ of the machine radius), which translate in a 12.5 Hz change of the effective frequency of the machine. This results in a 8 MeV change of the collision energy from low to high tide. It was checked that the depolarisation measurements sample the phase of tidal forces as a function of time, thus explaining most of their observed spread (about ± 3 MeV).

The 5 depolarisation measurements could only be performed starting from 16 September 1991 and at a single nominal collision energy setting, 93 GeV. The total uncertainty on this energy scale is approximately ± 5 MeV, i.e. four times less than the 0.02 GeV uncertainty previously assigned to the 1990 energy scale. Point-to-point uncertainties arise when calibrating the six other energy points of the scan. They are largest at the nominal energy setting of 88.5 GeV where they amount to ± 7 MeV. For the 1991 period preceding the drift in the flux loop measurements, where no depolarisation measurements are available, the point-to-point errors remain unchanged but the uncertainty on the absolute energy scale is estimated to be about ± 18 MeV. It was decided to take the energy scale of the 1990 data taking period from the value of M_Z obtained in 1991, whereas the point-to-point uncertainties could be considered as equal to those in 1991 although the energy settings were slightly different.

The net effect of the aforementioned uncertainties on the line-shape parameters determined from the combined 1990 and 1991 data is essentially a systematic uncertainty of about ± 6.3 MeV on M_Z and ± 4.5 MeV on Γ_Z .

The beam energy spread is equal to 33 ± 3 MeV. Taking into account the correlation between the energy and the position of the colliding particles, the spread in the collision energy is about 1.55 times as much, viz. 51 ± 5 MeV. It is taken into account by the function $f_{\delta s}$. Its effect is a broadening of Γ_Z by almost 4 MeV.

3.1.2. Luminosity measurement

The integrated luminosity (L) at each energy is computed from the number (N_{BB}) of Bhabha events measured at small polar angles (typically from 30 to 130 mrad) and selected with an efficiency, ϵ_{BB} , close to 100 %:

$$L = \frac{N_{BB}}{\epsilon_{BB} \cdot \sigma_{BB}^{vis}} \quad (2)$$

Depending on the precise polar angles intercepted by the luminometers of each experiment, the visible cross-section (σ_{BB}^{vis}) varies from about 26 to 88 nb at the peak energy. High precision measurements of the luminosity depend strongly on the knowledge of the geometrical acceptance of the luminometers. Since the Bhabha cross-section increases rapidly with decreasing scattering angle of the electron, much effort is devoted in understanding the inner border of the acceptance.

Significant progress was achieved in the luminosity measurement since the published 1989 and 1990 results. The theoretical error was decreased from $\pm 0.5\%$ to $\pm 0.3\%$ for DELPHI, L3 and OPAL³. This is due to a more complete calculation of the QED corrections to the Bhabha cross-section [12]. The uncertainty of $\pm 0.5\%$ published previously was therefore reduced to $\pm 0.25\%$. The total theoretical error is however estimated to $\pm 0.3\%$. This is due to the uncertainty in the magnitude of the interference of the resonant elementary process, where the electron and the positron annihilate in a Z boson, with the non-resonant process where they exchange a photon in the t-channel. The effect of this interference on the Bhabha cross-section is shown in figure 1 as a function of the collision energy, computed with the programs BHLUMI [12], which contains only the Born term of the interference, and BABAMC [13], which contains also its $O(\alpha)$ correction due to photon radiation. The main differences between both results are located around the peak energy. Depending on the angular range covered by the luminometers, the difference ranges from about 0.1% to 0.4%. The corresponding variation of σ_0^h is slightly larger and Γ_Z varies by (2–8) MeV. Whether missing higher order corrections would bring the end result closer to the BHLUMI or to the BABAMC values was subject to controversy. A recent calculation [14] shows that the inclusion of the dominant higher order QED corrections to the EW interference reduces the result of BABAMC by at most 0.05%. The collaborations which have computed σ_{BB}^{vis} with the interference term of the BHLUMI program need therefore to correct their results accordingly. The fit results presented in this paper were not updated for this correction.

The statistical precision on the luminosity measurement relies on the magnitude of σ_{BB}^{vis} . For experiments where σ_{BB}^{vis} is not significantly larger than the cross-section of the hadronic line-shape (i.e. ALEPH, DELPHI and OPAL), the statistical uncertainty of the latter contains a substantial contribution from the Bhabha statistics; the net effect is an increase of the statistical uncertainties of M_Z and Γ_Z which can reach 20 %, an effect similar to 40 % less beam time. The DELPHI collaboration computed therefore the 1991 off peak cross-sections with the

³ The results of the ALEPH collaboration were already published with $\pm 0.3\%$ uncertainty.

luminosity provided by their *Very Small Angle Luminometer*, which measures the rate of Bhabha events at polar angles between 5 and 7 mrad and has therefore a much larger visible cross-section (about 500 nb instead of 27 nb). Furthermore, these measurements are not affected by the energy dependence of the EW interference mentioned above since it is negligible at very small angles. They can however not be used for the absolute luminosity since the theoretical cross-section is not known in this angular range as accurately as between 30 and 130 mrad.

Fig. 1: The EW correction to the Bhabha cross-section in the angular range $56 < \theta < 128$ mrad of the DELPHI Small Angle Tagger as a function of the collision energy, computed with the programs BABAMC (▲) and BHLUMI (○) [15]. Errors are statistical.

The experimental precision on the absolute integrated luminosity obtained by each collaboration for the 1990 and for the 1991 data is given in Table 1.

	ALEPH	DELPHI	L3	OPAL
1990	0.6	0.6	0.9	0.9
1991	0.46	0.55	0.9	no value yet

Table 1: Experimental systematic uncertainty (in %) achieved in each experiment on the integrated luminosity for the data taking of 1990 and 1991. 1991 values are *preliminary* (the 1991 cross-sections of the OPAL collaboration were normalised to the 1990 values).

3.1.3. Selection efficiency

The precision on the selection efficiencies for each final state is given in Table 2 for each experiment. The comparison between the values obtained in 1990 and those obtained in 1991 shows a significant improvement. These uncertainties are likely to be still reduced by a factor of two in the coming years. One should notice that the $(0.2 - 0.3)\%$ precision for hadrons is well below the uncertainty on the absolute luminosity.

	hadrons		e^+e^-		$\mu^+\mu^-$		$\tau^+\tau^-$	
	1990	1991	1990	1991	1990	1991	1990	1991
ALEPH	0.2	0.2	0.5	0.4	0.5	0.5	0.9	0.5
DELPHI	0.4	0.3	0.7	0.4	0.8	0.5	1.2	0.9
L3	0.4	0.3	1.0	0.6	0.8	1.0	2.1	1.0
OPAL	0.4	0.20	0.7	0.45	0.5	0.25	1.3	0.78

Table 2: Precision (in %) achieved by each experiment on the selection efficiencies for each final state of the Z decays. 1991 values are *preliminary*.

3.1.4. Number of events

The number of events obtained by each collaboration in 1990 and in 1991 is given in Table 3 for each final state. Overall, about $1.7 \cdot 10^6$ hadronic and $1.8 \cdot 10^5$ leptonic events were selected since the start of LEP, corresponding to a total integrated luminosity of about $(16 - 20) \text{ pb}^{-1}$ per experiment.

	hadrons (10^3)		lepton pairs (10^3)	
	1990	1991	1990	1991
ALEPH	169	286	25	38
DELPHI	125	243	10	25
L3	115	310	10	26
OPAL	166	273	18	33
total/year	585	1112	63	122
total 1990 + 1991	1697		185	

Table 3: Number of hadronic and leptonic events selected by each experiment in 1990 and in 1991. 1991 values are *preliminary*.

The observed number of e^+e^- final states contains a substantial fraction of events due to the EW interference mentioned in section 3.1.2. This contamination is estimated with the ALIBABA [16] and MIBA [17] programs. Its subtraction introduces a small uncertainty on Γ_e which amounts to 0.5 % of the contamination and is common to all 4 experiments.

3.2. Fit to Line-Shapes

In each collaboration the theoretical expression of the cross-section was fitted simultaneously to the hadronic and to the three leptonic line-shapes, as well as to the three leptonic forward-backward asymmetries.

Two fits were performed. A 9 parameter fit was first applied, where the Z mass (M_Z) and total width (Γ_Z), the Born level hadronic peak cross-section (σ_0^h), the ratios (R_e, R_μ, R_τ) of the hadronic partial width (Γ_h) to the charged leptonic partial widths ($\Gamma_e, \Gamma_\mu, \Gamma_\tau$) and the 3 leptonic forward-backward asymmetries were left free to vary. If the data were consistent with lepton universality a second (5 parameter) fit was performed, where the ratios and the asymmetries were replaced by their “universal” average (R_l, A_{FB}^l), thus leading to more precise fit results.

The DELPHI, L3 and OPAL collaborations performed the fits with the theoretical cross-section computed with the program ZFITTER [18] whereas the ALEPH collaboration used the program MIZA [19]. Both programs include the most recent calculations of pure QED, EW and QCD corrections to the Born cross-section. Details on the calculation of radiative corrections can be found in [18], [19] and references therein.

Initial state photon radiation is responsible for the dominant radiative correction. It decreases the peak cross-section by about 25 % and increases the total width by approximately 9 %. It also moves the peak energy by more than 100 MeV. Electroweak corrections modify essentially the Z propagator. The net effect is a shift of the peak energy by about -35 MeV and a change of Γ_Z by only 2 MeV. QCD corrections originate mainly from final state gluon radiation. They essentially reduce the peak cross-section by about 1.6 % and increase Γ_h and Γ_Z by about 70 MeV, i.e. by about 4 % and 3 % respectively.

With respect to the published analysis of the 1990 data, the major improvement in the theoretical cross-section calculation is the addition of the initial state radiation of low mass fermion pairs [20]. This correction reduces σ_0^h by 0.25 % and increases Γ_Z and M_Z by 2.1 and 1.3 MeV respectively.

Missing higher order QED and EW corrections introduce an uncertainty on the present cross-sections estimated to $\pm(0.2 - 0.3)$ %. The corresponding un-

certainty on σ_0^h is of the order of $\pm(0.1 - 0.2)\%$ and that on the partial widths is about twice less. The uncertainty on M_Z and Γ_Z are estimated to about ± 2 MeV.

The fit parameters should in principle be determined in a way as independent as possible from the MSM prescriptions, i.e. the cross-section formula should only follow from Quantum Mechanics and Field Theory. Since the EW radiative corrections are sizeable, this requirement is not completely fulfilled.

Because the knowledge of the absolute energy scale is much better in 1991, M_Z was only fitted to the data taken in 1991, the energy scale being a free parameter in the fit to the data of the previous years.

Hadronic and leptonic line-shapes measured in each final state are shown in figure 2, together with the results of the 5 parameter fit.

Fig. 2: Line-shapes measured in 1990 ($\square$) and 1991 ($\bullet$). Errors are statistical. The full lines stand for the result of the 5 parameter fit.

4. Fit Results

This section contains the main line-shape results obtained from the 5 and 9 parameter fits mentioned in Section 3.2. The fact that the lepton asymmetries are fitted together with the line-shapes does not influence significantly the values and uncertainties of the line-shape parameters.

4.1. Line-Shape Parameters

The results of the 5 parameter fit obtained by each of the 4 collaborations are shown in figure 3.

Fig. 3: Preliminary values of M_Z , Γ_Z , R_l , σ_0^h obtained by the 4 LEP collaborations; the uncertainties of the individual measurements do not include the systematic uncertainties which are common to all 4 experiments; the computation of the average values and of the MSM predictions are described in the text.

The combined values (i.e. the weighted averages) of the parameters are also shown without and with the systematic uncertainties common to all 4 experiments. Their computation follows the recommendations given in [21], assuming the uncertainties below as common to all 4 experiments:

- ± 6.3 MeV on M_Z due to the limited knowledge of the absolute energy scale;
- ± 4.5 MeV on Γ_Z due to the relative point-to-point uncertainty on the collision energy;
- $\pm 0.3\%$ on σ_0^h due to the $\pm 0.3\%$ theoretical uncertainty on the Bhabha cross-section;
- an uncertainty smaller than 0.1% on Γ_e due to the subtraction of the t-channel contamination;

The theoretical values of the parameters given in figure 3 were computed with $M_Z = 91.187 \pm 0.007$ GeV, $m_t = 130 \pm 30$ GeV, $M_H = 300$ GeV and $\alpha_s = 0.120 \pm 0.007$. All uncertainties were treated as gaussian errors. Since the uncertainty on M_H is essentially not gaussian, the corresponding uncertainties of the line-shape parameters were taken as half of the difference between their value obtained with $M_H = 300$ GeV and their value taken for $M_H = 60$ or 1000 GeV.

The LEP averages for Γ_e , Γ_μ , Γ_τ obtained from the 9 parameter fit are shown in Table 4 together with the value of Γ_l obtained from the 5 parameter fit.

Γ_e	Γ_μ	Γ_τ	Γ_l
83.19 ± 0.36	83.69 ± 0.53	83.49 ± 0.63	83.33 ± 0.30

Table 4: LEP average of the 3 leptonic partial widths and of their average value (in MeV).

4.2. Interpretation of the Results

All 4 experiments give compatible results. The agreement of the measured value of each individual parameter with its MSM prediction is good, and lepton universality is verified with a precision better than 1%.

More severe tests of the MSM predictions can be performed by combining several parameters and comparing them to the MSM prediction. This is done in figure 4 which shows the correlations σ_0^h versus R_l and Γ_Z versus σ_0^h . The MSM prediction for the former correlation is the most accurate since σ_0^h and R_l are both made from ratios of widths and are therefore only weakly sensitive to the MSM unknowns m_t and M_H . The second correlation, however, acts in a complementary way since it involves also the line-shape total width rather than only quantities proportional to the peak height of the line-shapes.

Fig. 4 Preliminary average values of R_l versus σ_0^h and of σ_0^h versus Γ_Z measured by the 4 LEP collaborations, compared to the MSM predictions with their uncertainties. The 3 different MSM contours were computed with $M_Z = 91.187 \pm 0.007$ GeV, $m_t = 130 \pm 30$ GeV and $\alpha_s = 0.120 \pm 0.007$. They correspond to 3 different values of M_H : 60 GeV (horizontally hatched area), 300 GeV (black area), 1000 GeV (vertically hatched area).

A good agreement with the MSM expectations is observed. Another test of the latter is provided by the variable T [22] defined as:

$$T = \frac{3}{59} \cdot R_l - \frac{270}{59} \cdot \frac{\Gamma_l}{M_Z \alpha(M_Z)} \quad (3)$$

The definition of T makes it rather weakly sensitive to M_H and the bulk of its m_t dependence originates from the (relatively small) $Zb\bar{b}$ vertex correction. For a top quark heavier than 90 GeV, the MSM predicts T to be less than 0.530. The LEP average for this variable is 0.522 ± 0.004 , consistent with the MSM prediction.

4.2.1. Effective number of light neutrino species (N_ν^{eff})

The value of N_ν^{eff} was derived from the measured value of the invisible width (Γ_{inv}) defined as the difference between the total and the visible (i.e. the sum of the hadronic and charged leptonic) widths: $\Gamma_{inv} = \Gamma_Z - \Gamma_h - 3 \cdot \Gamma_l$. A more accurate value of Γ_{inv} is obtained by expressing Γ_Z with respect to σ_0^h (since $\sigma_0^h = \frac{12\pi\Gamma_e\Gamma_h}{M_Z^2\Gamma_Z^2}$), leading to the following expression:

$$\Gamma_{inv} = \Gamma_l \left(\sqrt{\frac{12\pi R_l}{M_Z^2 \sigma_0^h}} - R_l - 3 \right) \quad (4)$$

The value found is $505 \pm 7 \text{ MeV}$.

N_ν^{eff} being equal to the ratio $\Gamma_{inv} / \Gamma_\nu$, it reads:

$$N_\nu^{eff} = \frac{\Gamma_l}{\Gamma_\nu} \left(\sqrt{\frac{12\pi R_l}{M_Z^2 \sigma_0^h}} - R_l - 3 \right) \quad (5)$$

Since the theoretical ratio of the charged leptonic to neutrino partial widths, Γ_l/Γ_ν , has only a weak dependence on m_t and M_H , its value (0.5013 ± 0.0003) can be used instead of the experimental one, which is less accurate. The value of N_ν^{eff} is then 3.04 ± 0.04 . Using the theoretical value of R_l (i.e. 20.76 ± 0.05) instead of its measured value, gives a still more precise estimate of N_ν^{eff} . One obtains in this case 3.047 ± 0.033 .

Both values of N_ν^{eff} are compatible with 3, viz. no evidence for physics beyond the MSM is found.

4.2.2. Strong coupling constant ($\alpha_s(M_Z^2)$)

The value of α_s is derived from a MSM constrained fit to the line-shapes with α_s , M_Z and m_t as free parameters (the uncertainty on M_H being of minor importance). This is a practical way to extract α_s simultaneously from all line-shape parameters sensitive to QCD corrections, Γ_h , R_l , Γ_Z and σ_0^h being the most sensitive ones. In fact, R_l and Γ_Z determine almost entirely α_s because they have the smallest combined experimental and theoretical uncertainty in comparison with the magnitude of their QCD correction and because their correlation factor is only about 5 %. The additional information contained in Γ_h and σ_0^h is negligible because the former has a significant theoretical uncertainty coming from the lack of knowledge of m_t and M_H and suffers from the absolute luminosity uncertainty whereas the latter has a too large experimental uncertainty in comparison with the size of its rather limited QCD correction (i.e. about -1.6%).

The result of the 3 parameter fit is :

$$\alpha_s(Q^2 = M_Z^2) = 0.135 \pm 0.009.$$

The values of α_s derived from R_l and Γ_Z alone are 0.132 ± 0.0105 and 0.134 ± 0.0175 respectively. Their weighted average is thus 0.133 ± 0.009 , a value very close to the fit result.

With the increase in statistics foreseen at LEP-I, R_l should allow to determine α_s with about 4 % accuracy whereas the accuracy expected from Γ_Z will depend on the knowledge of m_t : it will be only about $(8 - 9) \%$ if m_t is known

within ± 25 GeV but it would be about $(5 - 6)\%$ if m_t is known within ± 10 GeV. The ultimate precision on $\alpha_s(M_Z^2)$ is thus likely to become as good as ± 0.005 , an accuracy similar to the one achieved with the analyses of global event shape variables. A still better precision will be obtained if σ_0^h will be determined with an accuracy better than 0.15% .

4.2.3. Limits on physics beyond the MSM

The absence of any significant departure of the data from the MSM predictions can be converted into lower bounds on the mass of new visible or invisible particles predicted by extensions of or alternatives to the MSM.

The method used to derive the mass limits is described in [23]. Being based on extra partial widths, the method is complementary to searches based on event topologies and has the advantages of being sensitive to light, even massless, particles and of being less model dependent. It consists of first deriving 95 % confidence level upper limits of Γ_Z and Γ_{inv} from their measured value. The comparison of these limits with the MSM predictions results in 95 % confidence level upper limits on the allowed extra total and invisible widths, called Γ_Z^{new} and Γ_{inv}^{new} , related to new particles. The values of Γ_Z^{new} and Γ_{inv}^{new} can then be interpreted in terms of lower bounds on the mass of new particles.

The relationship between the limit on the extra total width and its measured and predicted values reads:

$$\Gamma^{true} = \Gamma_Z^{new} + \Gamma_Z^{MSM} = \Gamma_Z^{exp} + 1.65 \cdot \Delta(\Gamma_Z^{exp} - \Gamma_Z^{true}) \quad (6)$$

where $\Delta(\Gamma_Z^{exp} - \Gamma_Z^{true})$ is the uncertainty on the difference between the experimental and the theoretical values of Γ_Z . A similar relationship holds for Γ_{inv} . The widths predicted by the MSM and their uncertainties were computed with the same inputs as in Section 4.1, except for M_H which was fixed to 1000 GeV in the present case. This minimises the theoretical values of the widths and leads therefore to safer limits. The confidence level of the limits computed is thus larger than 95 %. The numerical result coming out from the combined LEP data is:

$$\Gamma_Z^{new} < 28 \text{ MeV} \quad \text{and} \quad \Gamma_{inv}^{new} < 18 \text{ MeV}. \quad (7)$$

Lower mass bounds corresponding to these two partial widths are given in Table 5 in case of a fourth generation of MSM like fermions, of Minimal Supersymmetry and of Grand Unification Theories which lead to excited quarks and leptons.

Particle type	Lower bound (GeV/c ²)
b'	45.
$L^\pm$	33.
L_{Dirac}^0	44.
L_{Dirac}^0 (from Γ_{inv})	45.
$L_{Majorana}^0$	38.
$L_{Majorana}^0$ (from Γ_{inv})	42.
squark u (L+R)	39.
squark d (L+R)	40.
squarks (L+R) (5 sflavours)	44.
sleptons (L+R)	22.
sneutrino	32.
LSP sneutrino (from Γ_{inv})	39.
chargino	44.
u^*	45.
d^*	45.
$L^{\pm*}$	33.

Table 5: Lower mass bounds on new particles in GeV; the values correspond to a confidence level larger than 95 %. Except when indicated from Γ_{inv} , they are derived from Γ_Z .

The value of Γ_Z^{new} also excludes a top quark lighter than 43 GeV.

5. Summary - Prospects

Based on approximately $(16 - 20) \text{ pb}^{-1}$ integrated luminosity accumulated in each LEP experiment, a total sample of $1.7 \cdot 10^6$ hadronic and $1.8 \cdot 10^5$ charged leptonic decays of the Z boson have been selected from August 1989 to November 1991.

A fit to line-shape cross-sections and forward-backward lepton asymmetries measured at several energies near the resonance peak gave the following results: $M_Z = 91.187 \pm 0.007 \text{ GeV}$, $\Gamma_Z = 2.492 \pm 0.007 \text{ GeV}$, $\Gamma_l = 83.33 \pm 0.30 \text{ MeV}$ and $R_l = 20.85 \pm 0.07$. From these values the Born level hadronic peak cross-section was found to be $\sigma_0^h = 41.16 \pm 0.18 \text{ nb}$, and the invisible width was found to be $\Gamma_{inv} = 505 \pm 7 \text{ MeV}$. These values are all in agreement with the MSM expectations.

The effective number of light neutrino species was found to be 3.047 ± 0.033 , i.e. consistent with the value of 3.

The strong coupling constant was found to be 0.135 ± 0.009 at the energy scale of the Z mass, consistent with the values based on event shape variables measured at LEP.

Limits on the production of new particles due to extensions of or alternatives to the MSM were set, most of them being close to the kinematical limit.

Until the end of the LEP-I data taking campaign the integrated luminosity should increase by an order of magnitude and the uncertainties on the line-shape parameters are likely to decrease by a factor 2 – 3. The gain in statistics, combined with the excellent knowledge of the beam energy based on the depolarisation method, may allow to measure M_Z and Γ_Z with an accuracy of $\pm 3 \text{ MeV}$. An ultimate precision of about ± 0.005 on α_s (an accuracy similar to that obtained from event shape variables) seems achievable. The reduction of the uncertainty on σ_0^h , and therefore on N_ν^{eff} , is less straightforward since it requires an improvement on the precision of the absolute luminosity. In order to reduce significantly the experimental error on the luminosity, all 4 experiments will modify or replace their actual luminometer before the 1993 or 1994 data taking campaigns. The goal of each collaboration is an experimental precision of $(0.1 - 0.2) \%$. Progress is also expected on the theoretical accuracy. The ultimate precision on σ_0^h should therefore be $(0.1 - 0.2) \%$, leading to an accuracy better than 0.02 on N_ν^{eff} , which makes N_ν^{eff} a very sensitive tool to physics beyond the MSM.

6. Acknowledgements

I am indebted to the 4 LEP collaborations for providing their data. This report benefits from enlightening discussions with several LEP collaborators. Special thanks go to my DELPHI colleagues G.Myatt, A.Olchevski and A.Read for their criticism and careful reading of the manuscript as well as for their help in making the figures. I also want to thank A.Tissier for her efficient collaboration in editing the text and C.Cornus for the figure drawing.

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