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Model Independent Limit of the Z-Decay-Width into Unknown Particles

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Abstract

Using the LEP lineshape data combined by the LEP electroweak working group and the left-right asymmetry measured at SLD an almost model independent limit on the decay width of the Z into unpredicted modes is derived. Assuming only that the $Z \to e^+e^-$ and $Z \to \mu^+\mu^-$ decays can be selected cleanly a limit of $\Gamma_{\rm new} < 6.3\,{\rm MeV}$ at 95% confidence level is derived.

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1 Introduction

The LEP collaborations measure the total width of the Z boson ($\Gamma_{\rm Z}$) with a precision of about 2.5 MeV [1]. An interesting question in the search for new physics is the partial decay width left for Z-decays into up to now unknown particles once the partial widths for the known decays are subtracted.

For Z decays into invisible particles this is a relatively easy task. The partial decay widths into hadrons and charged leptons are known from experiment and the ratio of the neutrino to the charged lepton partial width is known from the Standard Model with good accuracy.

The situation is much more complicated if the new decays also involve visible particles. Since the new decays can enter into the event selections of the different Z decay modes with an unknown efficiency, the measured partial widths are not reliable anymore. On the other hand radiative corrections to the known decays from top and Higgs loops are larger than the experimental uncertainty on $\Gamma_{\rm Z}$, so that also virtual effect from new physics could produce effects of the same size as the new Z-decays searched for.

For Z-decays into $\rm e^+e^-$ and $\mu^+\mu^-$ pairs only two particle each having the beam energy are visible in the detector so that a new decay mode that fakes these signatures is hard to imagine. In the following a model independent limit on Z-decays into unknown particles ($\Gamma_{\rm new}$) will be derived under the assumption that the cross section and asymmetry measurements of $\rm e^+e^- \to Z \to e^+e^-, \mu^+\mu^-$ events are reliable.

2 Fit Method

As mentioned in the introduction the aim of this analysis is to be as model independent as possible. The only assumptions made are that the $\rm e^+e^-$ and $\mu^+\mu^-$ final state are not polluted by unknown Z decays and that new physics does not give rise to large flavour dependent vertex corrections.

Within the improved Born approximation the Z partial widths can be expressed in a model independent way using effective couplings by:

$$\Gamma_{\rm ff} = \frac{G_{\rm F} m_{\rm Z}^3}{6\pi\sqrt{2}} (g_{V\rm f}^2 + g_{A\rm f}^2)(1+\delta_f^{QED})(1+\delta_f^{QCD})$$

and all asymmetries with the coupling parameters

$$\mathcal{A}_f = \frac{2 g_{V\rm f} g_{A\rm f}}{g_{V\rm f}^2 + g_{A\rm f}^2}$$

with

$$|g_{A\rm f}| = \frac{1}{2}\sqrt{1+\Delta\rho_f} \qquad \text{and}$$

$$\frac{g_{V\rm f}}{g_{A\rm f}} = 1 - 4 q_f \sin^2\theta_{\rm eff}^f$$

The parameters $\Delta\rho_f$ and $\sin^2\theta_{\rm eff}^f$ receive large contributions from loops in the Z propagator which are independent of the fermion species. The vertex corrections are small and in most models not depending on new physics so that the radiative corrections can be described in a model independent way using the two leptonic parameters $\Delta\rho_\ell$ and $\sin^2\theta^\ell_{\rm eff}$ which can be fixed by measuring one partial width and one asymmetry.

An alternative, however equivalent, parameter set are the so called ε parameters [2], defined as [1]

$$
\begin{aligned}
\Gamma_\ell &= (\Gamma_\ell)_{\rm Born}\,(1+1.20\varepsilon_1-0.26\varepsilon_3)\\
A^{0,\,\ell}_{\rm FB} &= \left(A^{0,\,\ell}_{\rm FB}\right)_{\rm Born}(1+34.72\varepsilon_1-45.15\varepsilon_3)
\end{aligned}
$$

where QCD corrections and the running of α are already included in the Born terms. They can also be expressed in terms of $\Delta\rho$ and $\sin^2\theta_{\rm eff}$:

$$
\begin{aligned}
\Delta\rho_\ell &= \varepsilon_1\\
\sin^2\theta^\ell_{\rm eff} &= \frac{1}{2}\left(1-\sqrt{1-\frac{4\pi\alpha(m_{\rm Z}^2)}{\sqrt{2}G_{\rm F}m_{\rm Z}^2}}\right)(1-1.43\varepsilon_1+1.86\varepsilon_3)\,.
\end{aligned}
$$

Since this parameter set is more prominent in the literature it will also be used here.

The left-right asymmetry measured at SLD is sensitive only to the initial state coupling parameter $\mathcal{A}_e$ practically independent of the final state. It can therefore be used safely in this analysis.

The partial width of the Z decaying into $\rm b\overline{b}$ receives sizable contributions from vertex corrections involving the top quark. In the fit the top quark mass has thus to be constrained to its value measured at the TEVATRON.

The knowledge of the running of α is needed for the extraction of the ε-parameters and has thus to be included in the fit. Since, however, the $\sin^2\theta_{\rm eff}$ extracted from the asymmetries enters directly in the prediction of the partial width it completely cancels out in the limit on $\Gamma_{\rm new}$.

On the contrary the strong coupling constant $\alpha_s(m_{\rm Z}^2)$ enters in the prediction of $\Gamma_{\rm had}$ and turns out to be one of the larger uncertainties in $\Gamma_{\rm new}$.

If the the hypothetical new particles decay partly into hadronic final states, $\Gamma_{\rm had}$ measured by the experiments is not identical to the sum of the quark partial widths but larger by some unknown fraction of $\Gamma_{\rm new}$. For that reason $\Gamma_{\rm had}$ is described in the fit as $\Gamma_{\rm had}=\Gamma^{(SM)}_{\rm had}+\delta\Gamma_{\rm had}$. For numerical reasons $\delta\Gamma_{\rm had}$ is treated as independent of $\Gamma_{\rm new}$, however it has to be statistically compatible with being smaller than $\Gamma_{\rm new}$.

The fit has therefore eight free parameters: $m_{\rm Z}$, ε_1, $\varepsilon_3, m_{\rm t}$, $\alpha(m_{\rm Z}^2)$, $\alpha_s(m_{\rm Z}^2)$, $\delta\Gamma_{\rm had}$ and the parameter of interest $\Gamma_{\rm new}$.

3 Results

For this analysis the data prepared for the summer conferences in 1997 which are presented in [1] are used. All data that enter into the fit are summarised in table 1 and the correlation matrix for the LEP data in table 2. The value of $\sin^2\theta^\ell_{\rm eff}$ from $A_{\rm LR}$ is taken from [3] and $m_{\rm t}$ from [4]. To avoid any circularity in the argumentation $\alpha_s(m_{\rm Z}^2)$ is taken from [5] which excludes its determination from the Z hadronic width.

[1] ε_2 is defined using the W-mass which is not discussed here

Parameter	Value
m_Z(GeV)	91.1867±0.0020
Γ_Z(GeV)	2.4948±0.0025
σ_h^0(nb)	41.486±0.053
R_e	20.757±0.056
R_μ	20.783±0.037
$A_{FB}^{0,e}$	0.0160±0.0024
$A_{FB}^{0,\mu}$	0.0163±0.0014
$\sin^2\theta_{eff}^{\ell}(A_{LR})$	0.23055±0.00041
m_t(GeV)	175.6±5.5
$\alpha_s(m_Z^2)$	0.118±0.003
$\alpha(m_Z^2)^{-1}$	128.896±0.090

Table 1: Data used in the determination of the Γ_{new} limit. For the definition of the parameters see [1].

	m_Z	Γ_Z	σ_h^0	R_e	R_μ	$A_{FB}^{0,e}$	$A_{FB}^{0,\mu}$
m_Z	1.00	0.05	−0.01	0.00	−0.03	0.02	0.05
Γ_Z	0.05	1.00	−0.16	0.00	−0.01	0.00	0.00
σ_h^0	−0.01	−0.16	1.00	0.06	0.11	0.00	0.00
R_e	0.00	0.00	0.06	1.00	0.05	−0.02	0.01
R_μ	−0.03	−0.01	0.11	0.05	1.00	0.00	0.01
$A_{FB}^{0,e}$	0.02	0.00	0.00	−0.02	0.00	1.00	0.01
$A_{FB}^{0,\mu}$	0.05	0.00	0.00	0.01	0.01	0.01	1.00

Table 2: Correlation matrix for the LEP data used in the Γ_{new} fit.

Fitting with the precudure described above the following results are obtained:

$$\begin{aligned}
m_Z &= (91.1867 \pm 0.0020)\,\text{GeV} \\
\varepsilon_1 &= (3.9 \pm 1.3) \cdot 10^{-3} \\
\varepsilon_3 &= (2.3 \pm 1.5) \cdot 10^{-3} \\
m_t &= (175.6 \pm 5.5)\,\text{GeV} \\
\alpha_s(m_Z^2) &= 0.118 \pm 0.003 \\
\alpha(m_Z^2)^{-1} &= 128.896 \pm 0.090 \\
\Gamma_{\text{new}} &= (0.9 \pm 2.9)\,\text{MeV} \\
\delta\Gamma_{\text{had}} &= (1.7 \pm 3.2)\,\text{MeV}
\end{aligned}$$

The correlation matrix for the fit result is shown in table 3.

The ε parameters are consistent with the Standard Model prediction $3.47 \cdot 10^{-3} < \varepsilon_1 < 6.43 \cdot 10^{-3}$ and $4.63 \cdot 10^{-3} < \varepsilon_3 < 6.67 \cdot 10^{-3}$ for $m_t = (175 \pm 5)$ GeV and 65 GeV $< m_H < 1$ TeV [2].

Normalising only over the physical region $\Gamma_{\text{new}} > 0$ a limit of $\Gamma_{\text{new}} < 6.3$ MeV at 95% confidence level can be derived.

To understand better the stability of the result against the selection of the $\sin^2\theta^{\ell}_{\text{eff}}$ values used in the analysis two cross checks have been made. In a first fit A_{LR} has been omitted from the used data sample yielding

$$\begin{aligned}
\varepsilon_1 &= (4.3 \pm 1.4) \cdot 10^{-3} \\
\varepsilon_3 &= (4.3 \pm 2.2) \cdot 10^{-3} \\
\Gamma_{\text{new}} &= (1.7 \pm 3.0)\,\text{MeV}
\end{aligned}$$

completely consistent with the results quotes above.

If, in a second fit, all LEP and SLD measurements of $\sin^2\theta^{\ell}_{\text{eff}}$ are used the ε parameters and Γ_{new} become

$$\begin{aligned}
\varepsilon_1 &= (4.3 \pm 1.3) \cdot 10^{-3} \\
\varepsilon_3 &= (4.1 \pm 1.3) \cdot 10^{-3} \\
\Gamma_{\text{new}} &= (1.7 \pm 2.9)\,\text{MeV}
\end{aligned}$$

where the change in ε_3 reflects the marginal agreement between the $\sin^2\theta^{\ell}_{\text{eff}}$ determinations from A_{LR} and A^b_{FB}. The value for Γ_{new} corresponds to a limit of $\Gamma_{\text{new}} < 6.9$ MeV at 95% confidence level.

4 Conclusions

Assuming only that the $e^+e^- \to Z \to e^+e^-$ and $e^+e^- \to Z \to \mu^+\mu^-$ decays can be selected cleanly an almost model independent limit for the Z decaying into unpredicted decay-modes of $\Gamma_{\text{new}} < 6.3$ MeV at 95% confidence level has been derived. The only model assumption needed is that not strong flavour dependent vertex corrections due to new physics are present. This limit is valid independent of the efficiency with which the new decays are selected into the $Z \to$ hadrons and the $Z \to \tau^+\tau^-$ event samples. However, if the new Z-decays are not selected by any of the analyses a much harder limit of $\Gamma^{(inv)}_{\text{new}} < 2.8$ MeV [1] applies.

	$m_{\rm Z}$	ε_1	ε_3	$m_{\rm t}$	$\alpha_s(m_{\rm Z}^2)$	$\alpha(m_{\rm Z}^2)^{-1}$	$\Gamma_{\rm new}$	$\delta\Gamma_{\rm had}$
$m_{\rm Z}$	1.00	0.00	−0.01	0.00	0.00	0.00	−0.03	−0.02
ε_1	0.00	1.00	0.76	0.00	0.00	0.00	−0.48	−0.41
ε_3	−0.01	0.76	1.00	0.00	0.00	−0.38	−0.25	−0.19
$m_{\rm t}$	0.00	0.00	0.00	1.00	0.00	0.00	0.14	0.13
$\alpha_s(m_{\rm Z}^2)$	0.00	0.00	0.00	0.00	1.00	0.00	−0.58	−0.53
$\alpha(m_{\rm Z}^2)^{-1}$	0.00	0.00	0.38	0.00	0.00	1.00	0.00	0.00
$\Gamma_{\rm new}$	−0.03	−0.48	−0.25	0.14	−0.58	0.00	1.00	0.82
$\delta\Gamma_{\rm had}$	−0.02	−0.41	−0.19	0.13	−0.53	0.00	0.82	1.00

Table 3: Correlation matrix for the fit results.

References

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