Z Decay Confronts Nonstandard Scenarios

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We show that recent data from the CERN e^+e^- collider LEP on the Z line shape and decays give stringent new constraints on mixing of e and τ with exotics and Z-Z' mixing. Even in nonstandard models, where both the visible and the invisible part of the Z width are modified, a fourth light neutrino is unlikely unless substantial mixings between neutrinos and exotics are allowed. If the gluino is detectable at the Fermilab Tevatron then the lighter-chargino mass is tightly constrained (>42 GeV).

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The recent results from the CERN e^+e^- collider LEP[1] and the SLAC Linear Collider[2] on the mass (M_Z) and the width (Γ_Z) of the Z are now sufficiently precise to put new constraints on extensions of the minimal standard model (MSM). For example, the measured invisible width Γ_{inv} constrains the number of light neutrinos to (see below for details) $n_\nu = 3.18 \pm 0.20$. Thus a scenario with four sequential fermion families is now allowed only with the somewhat unconventional choice $M_{\nu_4} \geq M_Z/2$.

Here we focus on Γ_Z in the several nonstandard scenarios and the possibility of evading the above bound. We have analyzed (a) models which may reduce the visible Z width, creating superficially room for additional light neutrinos, and (b) models with additional light particles contributing to the Z width. Models with mixings between sequential fermions and exotic fermions[3] [i.e., with noncanonical $SU(2)_L \times U(1)$ quantum numbers] and models with Z-Z' mixing,[4] where Z' arises from an additional U(1) symmetry, are in category a. Supersymmetric (SUSY) models[5] belong to category b, since Z can decay, e.g., into electroweak gauginos. The Z-line-shape data set new, more restrictive constraints on these models. In spite of the flexibility in these scenarios, we show that it is not enough to accomodate a fourth light neutrino unless there is significant mixing with exotics in the neutrino sector.

The well-known expression for the Z line shape is

$$\sigma^Z_{\text{had}}(s) = [(\Gamma_{ee}\Gamma_{\text{had}})/\Gamma_Z^2] F(M_Z, \Gamma_Z, s) , \qquad (1)$$

where $\Gamma_{ff'}$ and Γ_{had} are, respectively, the partial widths $\Gamma(Z \to f\bar{f})$ and $\Gamma(Z \to \text{hadrons})$. F is a function containing the standard Breit-Wigner form folded with initial-state radiation.[6] Using the above formula, the 28 data points of the four LEP experiments[1] have already been fitted in several ways.[7] Systematic errors of the experiments have been taken care of by introducing scale factors which multiply the theoretical prediction [Eq. (1)]. These scale factors treated as free parameters were found (by minimizing the appropriately modified κ^2) to be 0.991, 1.054, 0.976, and 1.032 for ALEPH, DELPHI, L3, and OPAL Collaborations, respectively. The model-independent fit using the above scale factors and treating $\Gamma_{ee}\Gamma_{\text{had}}$, Γ_Z, and M_Z as free parameters yields (in GeV)

$$M_Z = 91.10 \pm 0.03, \quad \Gamma_Z = 2.580 \pm 0.074 . \qquad (2)$$

Using Eq. (2) one can calculate n_ν in an $SU(2)_L \times U(1)$ gauge model assuming that the t quark and charged fermions belonging to the higher generations do not contribute to the Z width. Using the well-known MSM values $\Gamma^{\text{SM}}_{uu} = \Gamma^{\text{SM}}_{cc} = 0.296$, $\Gamma^{\text{SM}}_{dd} = \Gamma^{\text{SM}}_{ss} = \Gamma^{\text{SM}}_{bb} = 0.381$, $\Gamma^{\text{SM}}_{ee} = \Gamma^{\text{SM}}_{\mu\mu} = \Gamma^{\text{SM}}_{\tau\tau} = 0.083$, and $\Gamma^{\text{SM}}_{\nu\bar{\nu}} = 0.165$ (all in GeV),[8] one finds from Eq. (2) $n_\nu = 3.66 \pm 0.45$. These are QCD- and QED-corrected values with $M_Z = 91.1$ GeV and $1 - c_W^2 = s_W^2 \equiv \sin^2\theta_W = 0.233$, where θ_W is the Weinberg angle.

A tighter bound on n_ν may be obtained by fixing $\Gamma_{ee}\Gamma_{\text{had}}$ in Eq. (1) from a given theory while M_Z and Γ_Z are still treated as free parameters. Using such a more restricted fit for the standard model one gets the stronger limit given before. In general, we write $\Gamma_{ee}\Gamma_{\text{had}} = \Gamma^{\text{SM}}_{ee}\Gamma^{\text{SM}}_{\text{had}}(1+\alpha)$, where α parametrizes the effect of nonstandard physics on the Z line shape. Accounting for systematic errors as above, one now obtains the best-fit values of M_Z and Γ_Z as functions of α. Since M_Z turns out to be insensitive to α while Γ_Z varies to some extent, we set $M_Z = 91.1$ GeV. In the resulting one-parameter fit, the range of α is conservatively constrained by requiring that the confidence level of the fit be 10% or more. For 27 degrees of freedom this corresponds to $\chi^2 < 37$ and we find from the fit the model-independent result $-0.08 \leq \alpha \leq 0.26$.

For a comparison of specific models we parametrize

Γ_{ll} $(l=e,\mu,\tau)$ and $\Gamma_{\rm had}$ as follows:

$$\Gamma_{ll}/\Gamma_{ll}^{\rm SM}=1+\alpha_l,\quad \Gamma_{\rm had}/\Gamma_{\rm had}^{\rm SM}=1+\alpha_h\,. \tag{3}$$

α is then given by $\alpha=\alpha_e+\alpha_h+O(\alpha^2)$. For $\Gamma_{ll}^{\rm SM}$ and $\Gamma_{\rm had}^{\rm SM}$ we use the values quoted after Eq. (2). The effect of a possible small change in the numerical value of G_F due to the mixing of the first two generations of leptons with exotics is negligible.[3] The same holds for a possible small change in s_W.[3] $\Gamma_{\rm inv}$ in any nonstandard scenario is therefore given by

$$\Gamma_{\rm inv}=\Gamma_Z-\Gamma_{ee}^{\rm SM}(3+\alpha_e+\alpha_\mu+\alpha_\tau)-\Gamma_{\rm had}^{\rm SM}(1+\alpha-\alpha_e)\,, \tag{4}$$

where for any α the corresponding Γ_Z is obtained from the fit.

In nonstandard models the α_f's (f represents leptons, u, and d quarks) are given by

$$\alpha_f=(1+\delta\rho)(a_L^2+a_R^2)/[(a_L^{\rm SM})^2+(a_R^{\rm SM})^2]-1\,, \tag{5}$$

where $\rho\equiv M_W^2/M_Z^2c_W^2\equiv 1+\delta\rho$. In models with fermion-exotics mixing, $\delta\rho=0$ and

$$a_L=T_{3L}^f(c_{\theta_L^f})^2-(s_W)^2q^f,$$
$$a_R=T_{3R}^f(s_{\theta_R^f})^2-(s_W)^2q^f\,, \tag{6}$$

where $s_\theta=\sin\theta$ and $c_\theta=\cos\theta$. $T_{3L,R}^f$ and q^f are, respectively, the weak isospin and the electric charge of the relevant fermions, and $\theta_{L,R}^f$ are fermion-exotic fermion mixing angles defined in Ref. 3. $a_{L,R}^{\rm SM}$ are obtained by setting $\theta_L^f=\theta_R^f=0$.

For leptons the Z-decay branching ratios set new bounds on the mixing in the e and τ sectors which are stronger than those in Ref. 3. (The bounds on $\theta_{L,R}^\mu$ in Ref. 3 imply $\alpha_\mu\simeq 0$.) In obtaining these constraints we use the high-statistics data with 20000 events from ALEPH:[9]

$$\Gamma_{e\bar e}=82.1\pm 3.4,\quad \Gamma_{\mu\bar\mu}=87.9\pm 6.0,\quad \Gamma_{\tau\bar\tau}=86.1\pm 5.6 \tag{7}$$

(all in MeV). Using these results and Eqs. (3) and (5), $\theta_{L,R}^{e,\tau}$ can be constrained as shown in Fig. 1. Note that in the τ case these data rule out a large region of the parameter space allowed in Ref. 3.

We now plot in Fig. 2 $\Gamma_{\rm inv}$ vs α for three values of α_e consistent with Fig. 1. It is then clear that irrespective of the details of α_h, $\Gamma_{\rm inv}$ is sufficiently restricted and a fourth light neutrino is rather unlikely. For negative α_e, α_τ, and α_h the visible width would decrease. However, it follows from the fit that Γ_Z is also reduced in such cases and there is no dramatic change in $\Gamma_{\rm inv}$. In plotting Fig. 2 we have set $\alpha_\tau=0$. For the allowed region of Fig. 1 the mixing of the τ lepton with exotics can at most increase $\Gamma_{\rm inv}$ by 7 MeV. The contributions to α due to the mixings in the quark sector (as obtained from Ref. 3) are also indicated in Fig. 2. The mixing of ordinary charged fermions with their exotic partners therefore cannot by itself create in $\Gamma_{\rm inv}$ the room required for an additional light neutrino. However, as discussed in Ref. 3, the physical neutrinos could themselves be mixtures of sequential and exotic weak eigenstates. To have a feeling for the effects of neutrino mixings, we consider the following simplified scenario with four light neutrinos. Each of these is assumed to be dominantly a mixture of a sequential neutrino and an exotic (mirror, vector doublet, or singlet) one. In this case the mixing angles $\theta_L^{\nu_l}$ $(l=e,\mu,\tau,4)$ in the neutral-current sector are identical to the angles constrained in Ref. 3 and we find that $\Gamma_{\nu_l\bar\nu_l}$

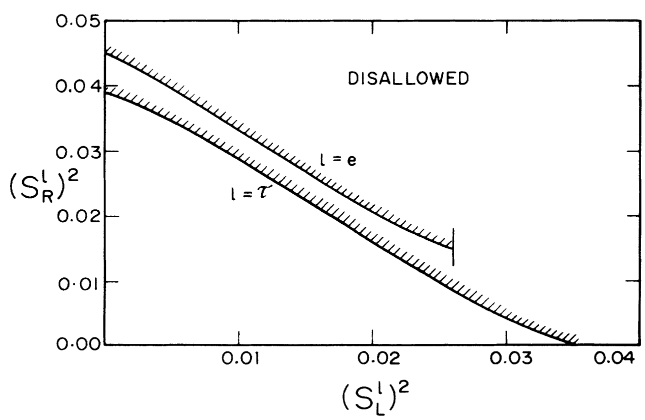

FIG. 1. The allowed regions in the $(s_L^l)^2$-$(s_R^l)^2$ plane for the e and the τ. The bounds from Ref. 3 are $(s_L^e)^2<0.0260$, $(s_R^e)^2<0.050$, $(s_L^\tau)^2<0.10$, and $(s_R^\tau)^2<0.20$.

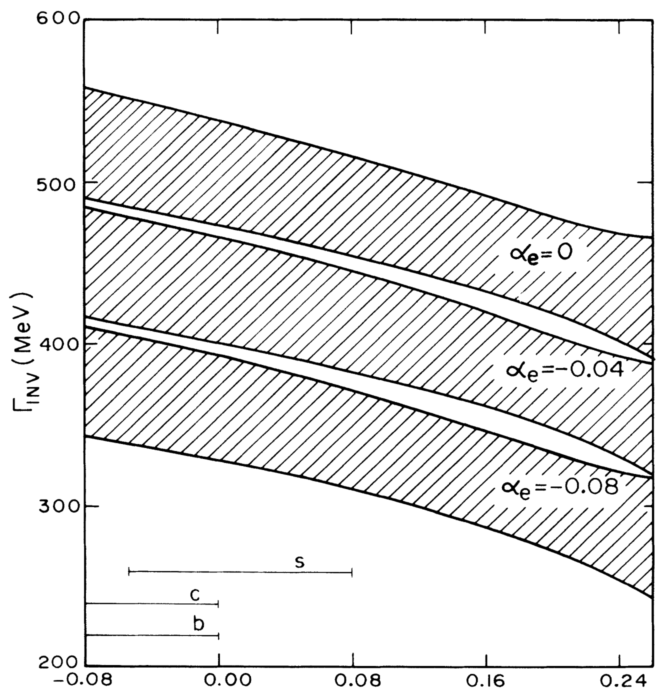

FIG. 2. $\Gamma_{\rm inv}$ vs α [see Eq. (4)]. The hatched region, which incorporates the uncertainty in Γ_Z from the fit, indicates the allowed range.

will be multiplied by $(1-b\sin^2\theta_L^{\nu_l})^2$, where $b=2$ if the exotic neutrino is a member of a vector doublet or a mirror multiplet and $b=1$ for a singlet. Since[3] $\sin^2\theta_L^{\nu_e}<0.03$ and $\sin^2\theta_L^{\nu_\mu}<0.002$, the effects of such mixings are ignored. The invisible Z width in this model is therefore given by

$$\Gamma_{\rm inv}=[2+(1-b\sin^2\theta_L^{\nu_\tau})^2+(1-b\sin^2\theta_L^{\nu_4})^2]\Gamma_{\nu_l\bar\nu_l}\cdots \quad (8)$$

Now[3] $\sin^2\theta_L^{\nu_\tau}<0.1$, while $\theta_L^{\nu_4}$ cannot be constrained from the available phenomenology. Thus unless $\theta_L^{\nu_4}$ is large, four light neutrinos may not be accomodated with $b=1$ (see Fig. 2). For $b=2$, however, four light neutrinos are still consistent with the data even if $\sin^2\theta_L^{\nu_4}\sim\sin^2\theta_L^{\nu_\tau}\sim0.1$.

In models with Z-Z' mixing there are two neutral-vector-boson mass eigenstates (Z_1,Z_2). The lighter of the two (Z_1) is identified with the state with mass ≈ 91.1 GeV. Of the two weak eigenstates, Z is the usual standard-model neutral gauge boson. The other, Z' (Z_2^0 in Ref. 4), originates from an additional U(1) gauge symmetry. Three models are of particular interest—the so-called Z_χ, Z_ψ, and Z_η models—which arise due to different symmetry-breaking chains of an E(6) grand unified model. The fermion couplings to Z' (g_2, Q_f', $Q_{\bar f}'$) in these cases are given in Ref. 4, using whichever one obtains the analogs of Eq. (6) in this model,

$$a_{L(R)}=a_{L(R)}^{\rm SM}c_\phi\pm(g_2/g_1)Q'_{f(\bar f)}s_\phi\,, \quad (9)$$

where ϕ is the Z-Z' mixing angle and $g_1=g/4c_W$ [g being the $SU(2)_L$ coupling constant]. In these models α_l and α_h [Eq. (3)] are related. In using Eqs. (5) and (9) we let $\delta\rho$ vary in the range -0.01 to $+0.01$. (This is motivated by the currently accepted values of M_W, M_Z, and s_W^2. For our purpose the numerical change in s_W^2 for $\delta\rho$ in the above range is negligible.) We constrain the mixing angle ϕ, and hence α_l and α_h, by using Eq. (7). We obtain the average leptonic partial width by combining $\Gamma_{e\bar e}$, $\Gamma_{\mu\bar\mu}$, and $\Gamma_{\tau\bar\tau}$ (for the last two cases appropriate modifications are made since in Ref. 9 universality, which holds in this case, was not assumed) and get $\Gamma_{l\bar l}=83.8\pm1.9$ MeV. For $\delta\rho=0.01$ (-0.01) the new bounds on ϕ are Z_χ, $-2^0\to2^0$ $(-3^0\to1^0)$; Z_ψ, $-1^0\to2^0$ $(-3^0\to1^0)$; and Z_η, $-6^0\to5^0$ $(-4^0\to5^0)$. For the Z_η case this is tighter than the bounds in Ref. 4. Using Eq. (4) and the result of our fit it is now a simple matter to obtain $\Gamma_{\rm inv}$ in such models. Employing an appropriately reduced $\Gamma_{\nu\bar\nu}$ we obtain for n_ν at 90% C.L. Z_χ, 3.53 ± 0.19; Z_ψ, 3.55 ± 0.20; and Z_η, 3.24 ± 0.20, which suggests that a fourth light neutrino is unlikely in these scenarios.

In the minimal SUSY model with a universal gaugino mass (M), the masses of the electroweak gauginos and their couplings with the Z are determined by three independent parameters M, μ (the Higgsino mass parameter), and v_2/v_1 (the ratio of the vacuum expectation values of the two neutral Higgs bosons present in such models).[5] The parameters M and μ can be traded in favor of the directly measurable quantities $M_{\tilde g}$ (the gluino mass) and $\tilde M$ (the mass of the lighter chargino). However, for given v_2/v_1 and $M_{\tilde g}$, there are two allowed values of μ for each choice of $\tilde M$.

It can readily be deduced from Eq. (2) (and the partial widths given after it) that in any model with three generations of quarks and leptons, the total contributions due to nonstandard physics are bounded (at 90% C.L.) by $\Gamma_Z^{\rm NS}<231$ MeV. In Fig. 3 we show the regions in the $M_{\tilde g}$-$\tilde M$ parameter space allowed by the above bound for $v_2/v_1\approx1$. For the sake of completeness, we also exhibit the regions excluded by (i) the cosmological bound on the lightest neutralino[10] ($M_{\tilde N}<5$ GeV) and (ii) the requirement that μ be real.

We have considered relatively light gluinos[11] ($73\le M_{\tilde g}\le200$ GeV) within the striking range of the Fermilab Tevatron.[12] It follows from Fig. 3 that in such scenarios $\tilde M>42$ GeV. This is stronger than the bound $\tilde M>25.5$ GeV (from the KEK storage ring TRISTAN)[13] and is comparable to the bound $\tilde M>42$ GeV from LEP.[14] But unlike the latter, this bound derived from Γ_Z does not depend on the details of the chargino decay patterns. In the region of parameter space con-

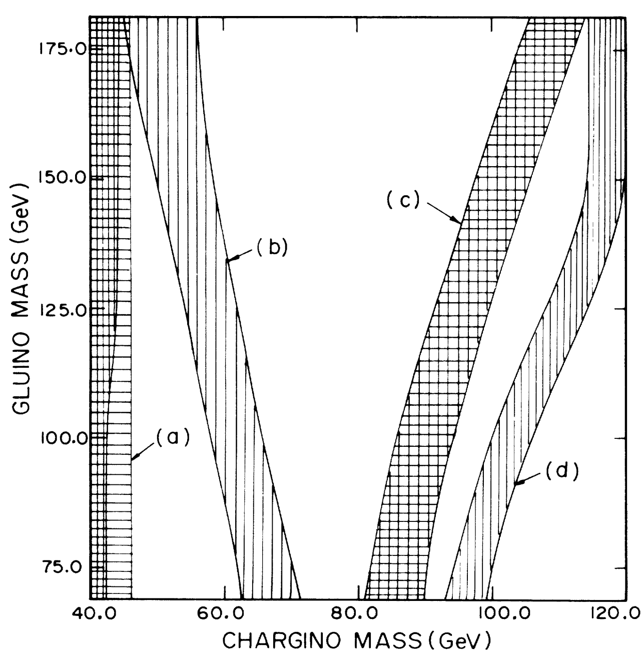

FIG. 3. Disallowed regions (hatched) in the gluino-mass–chargino-mass plane. Vertical and horizontal hatchings distinguish the two possible roots of μ (see text). Region a violates $\Gamma_Z^{\rm NS}<231$ MeV and rules out all scenarios with $0<\tilde M<42$ GeV, region c gives complex roots for μ while regions b and d are ruled out by the cosmological constraint on the lightest-neutralino mass.

sidered by us, the neutralino contributions are not large enough so that additional constraints on their properties cannot be derived. Other choices of v_2/v_1 for relatively light gluionos lead to results which are similar. From an examination of the chargino mass matrix and the coupling of the lighter chargino with the Z one finds that, for much heavier gluinos ($M_{\tilde{g}} \sim 1$ TeV), the latter is much reduced. As a result the lower bound on $\tilde{M}$ becomes $\cong 30$ GeV.

In the above we have not used the constraints from Γ_{inv} (Fig. 2) since the hadronic decays of gauginos may mimic $Z \rightarrow$ hadrons. This modification is model dependent. $\Gamma(Z \rightarrow e^+e^-)$ remains unaffected ($a_e = 0$). It is readily seen from Fig. 2 that in this case Γ_{inv} is smaller since α ($=a_h$) is now positive and the room for SUSY contributions to Γ_{inv} will be further squeezed. More stringent limits on $\Gamma(Z \rightarrow$ neutralinos) are therefore expected.

In models with a universal scalar mass, the contribution of scalar superpartners of ordinary fermions (sleptons, squarks, and sneutrinos) to the Z width does not yield any useful new constraints in view of the current Tevatron bound[11] on the squark mass.

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