Constraints on supersymmetric particles from the CERN LEP data on Z^0 decay properties

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We show that the recent measurements of the total Z^0 width and the peak hadronic cross section at CERN LEP lead to, with very mild assumptions, the bounds $m_{\tilde{\nu}} > 36$ GeV, $m_{\tilde{l}_L} > 38$ GeV, and $m_{\tilde{d}_L} > 33$ GeV. For the minimal supersymmetric model, we are able to derive the additional bounds $M_{\tilde{W}_-} > 37$ GeV, $M_{\tilde{Z}_3} > 57$ GeV on the mass of the lighter chargino and third lightest neutralino, respectively, while the bound on $m_{\tilde{d}_L}$ is strengthened to 39 GeV. Finally, some improved strategies for searches of new physics using the peak cross section are commented on.

Ever since the discovery of the intermediate vector bosons $W^{\pm}$ and Z^0 at the CERN $p\bar{p}$ Collider,[1] precision measurements of their properties have been one of the most important issues for high-energy experimental physics, since these provide stringent tests[2] of the standard model (SM). The first precise measurement of the mass M_Z and width Γ_Z of the Z^0 boson was made in the summer of 1989 by the Mark II experiment[3] at the SLAC Linear Collider (SLC) and the Collider Detector at Fermilab (CDF) experiment[4] at the Tevatron. The Mark II experiment, within the SM framework, also obtained a bound[5] $N_\nu < 3.9$ (95% C.L.) on the number of massless neutrino species. Shortly after that, the four experiments at LEP reported on a data sample of almost 10^4 Z^0 events,[6] making it possible to improve significantly the previous measurements of M_Z, Γ_Z, and N_ν. Since then,[7] the size of this data sample has increased by almost an order of magnitude. We have summarized these latest results in Table I where we have also shown the combined result for Γ_Z and N_ν that we use for our analysis. The high-precision measurement of M_Z makes it possible to test the SM radiative corrections, which depend on the mass of the top quark (m_t) and the mass of the Higgs boson (M_H); at present, it can only be inferred[8] that 40 GeV $< m_t <$ 210 GeV (90% C.L.) if 10 GeV $< M_H <$ 1 TeV. In this paper, we concentrate on the implications of the other two measurements (Γ_Z and N_ν) for physics beyond the SM with a focus on supersymmetry (SUSY).[9]

We begin by considering the constraints from the combined total width measurement shown in Table I. This translates to the 90% (95%) C.L. bound $\Gamma_Z < 2.588$ GeV (2.600 GeV). On the other hand, the total width of the Z^0 boson within the SM framework has been recently computed by Bardin *et al.*[10] to be between 2.468 and 2.514 GeV for the allowed range of M_H and m_t. Combining these results, we find that the contribution $\Delta\Gamma$ of nonstandard physics to Γ_Z is bounded by

$$\Delta\Gamma < \begin{cases} 0.120 \text{ GeV} & (90\% \text{ C.L.})\,, \\ 0.132 \text{ GeV} & (95\% \text{ C.L.})\,. \end{cases} \tag{1}$$

We can now use (1) to obtain mass bounds on anything Z^0 couples to, provided only the couplings of the new particle to Z^0 are known. We first consider the SUSY

TABLE I. A tabulation of the LEP results on M_Z, Γ_Z, and N_ν. We have not given the combined result for M_Z as we do not use it in our analysis. In averaging Γ_Z and N_ν, we have combined the systematic and statistical error on N_ν in quadrature for the ALEPH experiment. The numbers marked by an asterisk are from Ref. 6 while the rest are from Ref. 7.

	M_Z (GeV)	Γ_Z (GeV)	N_ν
ALEPH	91.174±0.026±0.03	2.541±0.056	3.01±0.15±0.05
DELPHI	91.1±0.04±0.03	2.42 ±0.21*	2.91±0.7*
L3	91.166±0.024	2.539±0.055	3.32±0.17
OPAL	91.132±0.025±0.03	2.571±0.057	3.41±0.26
Average		2.547±0.032	3.19±0.105

partners of neutrinos ($\tilde{\nu}$) which, of all the sfermions, have the largest coupling to Z^0. Each sneutrino contributes a width

$$\Gamma(Z \to \tilde{\nu}\bar{\tilde{\nu}}) = 0.5 \times \Gamma(Z \to \nu\bar{\nu}) \times (1 - 4m_{\tilde{\nu}}^2/M_Z^2)^{3/2} , \quad (2)$$

where $\Gamma(Z \to \nu\bar{\nu})$, the partial width for Z^0 to decay into a particular $\nu\bar{\nu}$ pair, is[10] 166.5 MeV. Assuming that all the sneutrinos are approximately degenerate, we find[11]

$$m_{\tilde{\nu}} \geq 28.3 \text{ GeV} \quad (90\% \text{ C.L.}) . \quad (3a)$$

Assuming two degenerate flavors, since a few GeV splitting for $\tilde{b}_L$ can be important, we find

$$m_{\tilde{d}_L} \geq 32.8 \text{ GeV} \quad (90\% \text{ C.L.}) , \quad (3b)$$

whereas the corresponding bound on $\tilde{u}_L$ is

$$m_{\tilde{u}_L} \geq 27.7 \text{ GeV} \quad (90\% \text{ C.L.}) . \quad (3c)$$

The bounds on the other sfermions are not at this time significant compared to those available from KEK TRISTAN and DESY PETRA experiments.[12]

Next, we turn our attention to the charginos and neutralinos of SUSY. The situation in this case is not as clean as for sfermions, since the gaugino-Higgsino couplings are determined by model-dependent mixing angles. Within the minimal supersymmetric model[13] all the couplings and masses of the gaugino-Higgsino sector are determined by three parameters which we may take using the notation of Refs. 14 and 15 (where all relevant couplings may be found) to be (i) $2m_1$, the supersymmetric Higgsino mass, (ii) the gluino mass $m_{\tilde{g}}$ which is assumed by a unification condition to determine the other gaugino masses, and (iii) v'/v, the ratio of VEV's of the two Higgs fields h' and h that give masses to the $T_3 = -\frac{1}{2}$ and $T_3 = +\frac{1}{2}$ fermions, respectively. These parameters uniquely determine the gaugino-Higgsino contribution to the Z^0 width.

Shown by the solid (dashed) line in Fig. 1 is the minimum contribution to the Z^0 width[15] as a function of the lighter chargino ($\tilde{W}_-$) mass [the third lightest neutralino ($\tilde{Z}_3$) mass] within the minimal model, assuming[12] $m_{\tilde{W}_-} > 25$ GeV. For example, $\Delta\Gamma$ from all the gaugino-Higgsinos accessible in Z^0 decay is *at least* 120 MeV if values of $2m_1$, v'/v, and $m_{\tilde{g}}$ are chosen such that $m_{\tilde{W}_-} = 37$ GeV. The dashed curve starts at 42 GeV since that is about as light as $\tilde{Z}_3$ can get. If we further require[16] $m_{\tilde{W}_-} > m_{\tilde{Z}_1}$, the only change is to move the starting point of the $\tilde{Z}_3$ curve to about 45 GeV. The reason we have chosen $\tilde{Z}_3$ is that it is possible for $\tilde{Z}_1$ and $\tilde{Z}_2$ to be very light and yet contribute nothing to $\Delta\Gamma$. For example, if $v'/v = 1$, the $Z\tilde{Z}_i\tilde{Z}_i$ couplings all vanish;[15] if we in addition take $m_{\tilde{g}}$ to be small so that one of the light neutralinos is photinolike, the $Z\tilde{Z}_1\tilde{Z}_2$ coupling is very small, while $\tilde{Z}_3, \tilde{Z}_4$ and the charginos can be made too heavy to contribute. We see that Eq. (1) gives the 90% C.L. bounds

$$m_{\tilde{W}_-} \geq 37 \text{ GeV}, \quad m_{\tilde{Z}_3} \geq 57 \text{ GeV} . \quad (4)$$

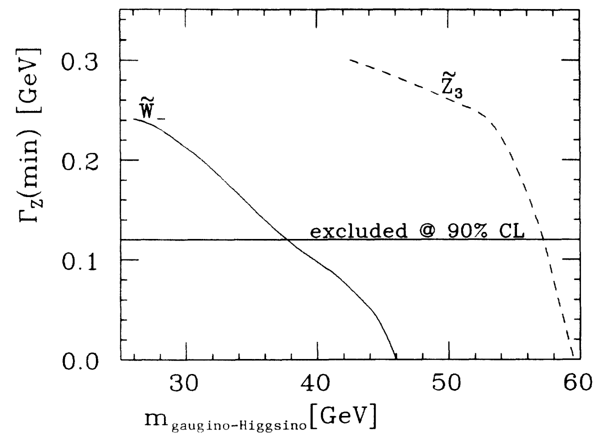

FIG. 1. The minimum contribution to the Z^0 width from the decay of Z^0 into charginos and neutralinos within the framework of the minimal model for a fixed mass of the lighter chargino (solid line) and of the third lightest neutralino (dashed line). The dashed curve starts at 42 GeV since $m_{\tilde{Z}_3} < 42$ GeV is not possible for any set of parameters.

The chargino bound is competitive with the best bounds from other machines whereas the $\tilde{Z}_3$ bound is new. We note also that these bounds are independent of how the gaugino-Higgsinos decay and are applicable in regions of parameter space where the bounds from direct searches may be evaded [e.g., when the lightest SUSY particle (LSP) mass is very close to the parent mass so that the visible decay products become very soft].[17]

Shown in Fig. 2 is the region of the SUSY parameter space excluded at the 90% C.L. by the constraint (1) for

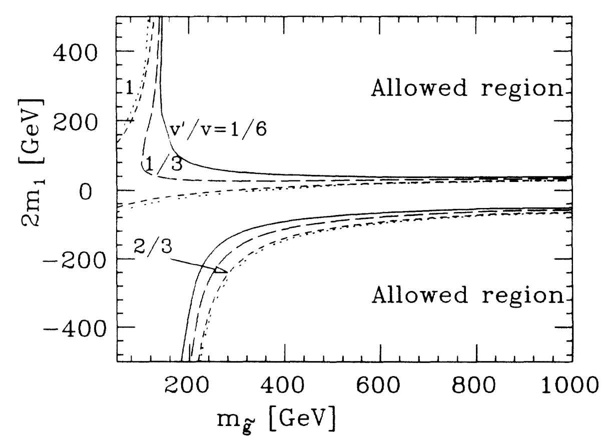

FIG. 2. The region of the SUSY parameter plane excluded at 90% C.L. by the total width constraint (1) assuming that the only NSM contribution to $\Delta\Gamma_Z$ comes from Z^0 decays to charginos and neutralinos. The different curves denote various values of v'/v: dotted, $v'/v = 1$; short-dashed, $v'/v = \frac{2}{3}$; long-dashed, $v'/v = \frac{1}{3}$; solid, $v'/v = \frac{1}{6}$. The area between the lines as well as that enclosed by the dotted and short-dashed curves in the upper left corner is excluded.

several values of v'/v. We begin the curves at $m_{\tilde{g}}=50$ GeV due to existing bounds on $m_{\tilde{g}}$ from $p\bar{p}$ collider data.[18] For negative values of $2m_1$, the region between the two dotted (dashed) lines is excluded for $v'/v=1$ ($\frac{2}{3}$) in addition to the corner in the upper left part of this figure, whereas for smaller values of v'/v the whole region between the corresponding lines is excluded. Note that this analysis substantially expands the excluded region as compared with the analysis of Ref. 19 (which was also based on the decays of $W^{\pm}$ and Z^0 to gaugino-Higgsino) for just the reason discussed above.

We note that the ALEPH bound[20] $m_H>15$ GeV on the Higgs-boson mass requires $v'/v<0.85$ so that the region in the vicinity of the $v'/v=1$ curve in Fig. 2 is already excluded. The preliminary ALEPH bound[7] of $m_H>24$ GeV excludes $v'/v>0.76$ whereas LEP I with its reach of at least 45 GeV for the Higgs-boson mass can potentially probe $v'/v>0.58$. If the charged-Higgs-boson mass is near to M_W, even larger values of v'/v are excluded.[20]

Shown in Fig. 3 are the maximum possible contributions to $\Delta\Gamma$ as a function of the three lightest gaugino-Higgsino masses, again assuming $m_{\tilde{W}_-}>25$ GeV. We have checked that for the heavy gaugino-Higgsino $\tilde{W}_+$, $\tilde{Z}_3$, and $\tilde{Z}_4$, this is almost always larger than 200 MeV. We see from the figure that if $m_{\tilde{Z}_1}>38$ GeV, it is unlikely that the gaugino-Higgsino contribution to $\Delta\Gamma$ will be measurable since a 20 MeV error on the width would be difficult to improve upon. The corresponding numbers for $\tilde{W}_-$ and $\tilde{Z}_2$ can be read off so that this figure indicates the range of gaugino-Higgsino masses for which the constraints on $\Delta\Gamma$ may possibly be of interest.

Before concluding our discussion on the inferences that can be drawn from (1), we note that these may be sensitive to non-SM radiative corrections; however, since at least the leading radiative corrections related to the electroweak ρ parameter[10] increase Γ_Z, our analysis is probably a conservative one.

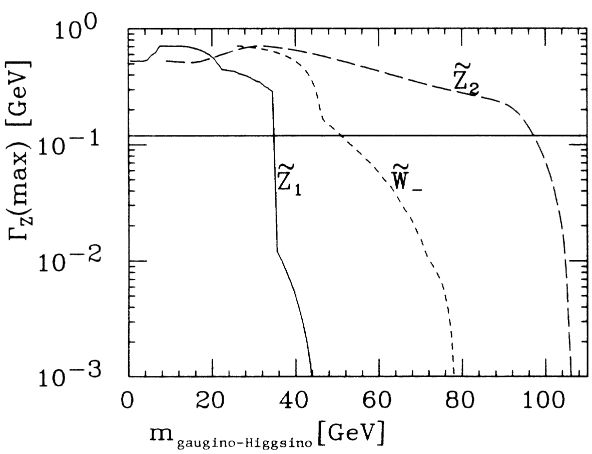

FIG. 3. The maximum possible contribution to the Z^0 width from the decay of Z^0 into charginos and neutralinos within the framework of the minimal model for a fixed mass of $\tilde{Z}_1$ (solid), $\tilde{W}_-$ (short-dashed), and $\tilde{Z}_2$ (long-dashed) subject to the constraint $m_{\tilde{W}_-}>m_{\tilde{Z}_1}$. The sharp drop in the solid line is where only $Z\to\tilde{Z}_1\tilde{Z}_1$ decays are kinematically allowed. For heavy gaugino-Higgsinos, $\Delta\Gamma$(max) is always large.

Next, we turn to the inferences that can be drawn from the measurement of the peak hadronic cross section. The tree-level hadronic cross section which can be extracted from the data after applying SM radiative corrections is

$$\sigma_h^0=(12\pi/M_Z^2)\Gamma_{ee}\Gamma_h/\Gamma_Z^2\ , \tag{5}$$

where Γ_h is the partial width for the hadronic decay of the Z^0 (we count $\tau\bar{\tau}$ decays as leptonic since τ can be easily identified). Assuming there are no non-SM (NSM) sources of hadrons, i.e., $\Gamma_h=\sum\Gamma_{q\bar{q}}$ and Γ_{ee} is known, a measured bound on σ_h^0 can be used to extract a bound on *all NSM nonhadronic decays of* Z^0. Assuming that these can only be new massless neutrinos gives the bound on N_ν quoted in Table I, which gives $N_\nu<3.32$ (3.36) at 90% C.L. (95% C.L.), which translates to the bound on the nonhadronic NSM width

$$\Delta\Gamma_{nh}^{\rm NSM}<53\ \text{MeV}\quad (90\%\ \text{C.L.})\ ,$$
$$<60\ \text{MeV}\quad (95\%\ \text{C.L.})\ . \tag{6}$$

This bound is valid *as long as the* Z^0 *has no NSM hadronic decays* and is much more stringent than (1) precisely because of this additional input. Equation (6) can thus be used to constrain masses of those sparticles that can be produced in Z^0 decay if they have no hadronic decay modes. We note that this bound has the advantage that radiative corrections to σ_h^0 are small.[10,21]

The masses of charged sleptons and sneutrinos can be directly bounded by (6). If they are light, charged sleptons will decay purely leptonically, whereas a light sneutrino will be stable (or at least very long lived) if it is the LSP, or decay invisibly[22] via $\tilde{\nu}\to\nu\tilde{Z}_1$ unless the decay modes $\tilde{\nu}\to\nu\tilde{Z}_2$ or $e\tilde{W}_-$ are kinematically allowed. This, as discussed below, is unlikely.

We begin by considering sneutrinos since they have the largest couplings to Z^0, assuming for the moment that they have no hadronic decays. Using (6) together with (2), we find, for just one light sneutrino,

$$m_{\tilde{\nu}}>23.1\ \text{GeV}\quad (90\%\ \text{C.L.})\ . \tag{7a}$$

If we assume three degenerate sneutrinos, this bound moves to

$$m_{\tilde{\nu}}>36.5\ \text{GeV}\quad (90\%\ \text{C.L.}) \tag{7b}$$

with the 95% C.L. bound being 35.6 GeV.

Our analysis expands the mass range previously excluded for long-lived ($T\geq$ age of the Universe) scalar neutrinos: 3 GeV $<m_{\tilde{\nu}}<$ 25 GeV excluded from a nonobservation[23] of high-energy solar neutrinos in the Kamiokande experiment and 12–20 GeV $<m_{\tilde{\nu}}<$ 1.0 TeV excluded from a nonobservation[24] of $\tilde{\nu}$ in our galactic halo as derived by the germanium detectors set up to search for double β decay. Although, in principle, (6) could also apply to charged sleptons since these decay nonhadronically if their masses are small, we have checked that because of their considerably smaller couplings no significant bound is possible from this constraint.

It is interesting to see that if we assume $v'/v \le 1$, as is the case in all known models (basically because $m_t \gg m_b$), nontrivial constraints can be obtained on the mass of the left-handed charged sleptons. To see this, we note that $m_{\tilde{l}_L}$ and $m_{\tilde{\nu}_l}$ are related by SU(2) invariance by

$$m_{\tilde{l}_L}^2 = m_{\tilde{\nu}_l}^2 + 0.78 r M_Z^2 \quad (8a)$$

with $r = (v^2 - v'^2)/(v^2 + v'^2) > 0$. In writing (8a), the only assumption is that the only scalar fields with substantial VEV's are SU(2) doublets or singlets. Since $m_{\tilde{l}_L} \ge m_{\tilde{\nu}_l}$, we can obtain a bound on the charged slepton from (6) by setting $m_{\tilde{l}_L} = m_{\tilde{\nu}_l}$. For one generation, we find

$$m_{\tilde{l}_L} > 27.9 \text{ GeV} \quad (90\% \text{ C.L.}) . \quad (9a)$$

If we assume three degenerate slepton generations, this bound improves to

$$m_{\tilde{l}_L} > 38.1 \text{ GeV} \quad (90\% \text{ C.L.}) . \quad (9b)$$

In the context of supergravity models, including those related to the superstring, this amounts to the assumptions that all slepton masses are equal at the unification scale and that there are no sizable Yukawa couplings distinguishing between these generations. (The SM Yukawa couplings that give rise to charged-slepton masses are negligible.)

Finally, if we further restrict our attention to "minimal" models, i.e., assume there is no new physics between the unification scale and the electroweak breaking scale, we can expand (8a) to include other sfermions via[25]

$$m_{\tilde{d}_L}^2 = m_{\tilde{\nu}}^2 + 0.93 r M_Z^2 + 0.77 m_{\tilde{g}}^2 , \quad (8b)$$

$$m_{\tilde{u}_L}^2 = m_{\tilde{\nu}}^2 + 0.14 r M_Z^2 + 0.77 m_{\tilde{g}}^2 . \quad (8c)$$

We remark here that ordering $m_{\tilde{\nu}} < m_{\tilde{u}_L}$ or $m_{\tilde{d}_L}$ implied by (8a)–(8c) for $r > 0$ can only be changed by the introduction of new, large Yukawa interactions into the theory so that conclusions drawn on the basis of this may hold even in some nonminimal models.

Since the decay of squarks necessarily leads to NSM hadronic activity, we cannot use (6) to constrain their masses. We can, however, obtain a significant lower bound on the heaviest squark from the total width constraint (1). Again, setting $m_{\tilde{d}_L} = m_{\tilde{u}_L} = m_{\tilde{e}_L} = m_{\tilde{\nu}}$, we find at 90% C.L. that

$$m_{\tilde{d}_L} \ge 39.2 \text{ GeV} . \quad (9c)$$

Here, we have assumed three degenerate slepton families but only two families of squarks, since the splittings between even the $\tilde{b}$ eigenstates (expected to be $\sim m_b$) can be significant for this analysis. Note that if supergravity mass relations (8) hold, the bound (9b) derived from the "nonhadronic" width also applies to $m_{\tilde{d}_L}$.

Before turning to a discussion of gaugino-Higgsinos, we note that the bounds (7) and (9) would not apply if the $\tilde{\nu}$ also decays via $\tilde{\nu} \to \nu \tilde{Z}_2$ or $e\tilde{W}_-$ since the subsequent gaugino-Higgsino decays can lead to NSM hadronic activity. We have searched the space of parameters $(2m_1, m_{\tilde{g}}, v'/v)$ for regions where this can happen for sneutrino masses violating the bound (7b), subject to the constraint that the total gaugino-Higgsino contribution to Γ_Z satisfy $\Delta\Gamma < 67$ MeV (three generations of these light $\tilde{\nu}$ contribute at least 53 MeV) so that (1) is satisfied. We find that NSM hadronic contributions are only possible when $-44 \text{ GeV} < 2m_1 < 68$ GeV and $m_{\tilde{g}} < 225$ GeV. The region is largest for $v'/v = 1$ and shrinks to just one point ($m_{\tilde{g}} = 190$ GeV, $2m_1 = 60$ GeV) at $v'/v = 0.24$, so that if the SUSY parameters are outside this region, our bounds (7) and (9) are applicable.

It is clear that we cannot directly use (6) to bound the gaugino-Higgsino masses since these can lead to hadronic activity. Nevertheless, we know that there are regions in parameter space where the gaugino-Higgsinos contribute significantly to the invisible width of Z^0 without substantial contributions to the visible width. If $|2m_1|$ is large, there can be a light neutralino only for relatively small values of $m_{\tilde{g}}$; in this case, the chargino is light and gauginolike and makes a large contribution to the visible width. For this reason, we have shown in Fig. 4 contours of $\Delta\Gamma_{\tilde{Z}_1\tilde{Z}_1} = 10$ (long-short dashed), 30 (solid), and 50 (long-dashed) MeV in the region of parameter space not excluded by the bound (1) for small values of $|2m_1|$. Also shown by the short-dashed (dotted) lines are contours where the contribution from other gaugino-Higgsino pairs to the Z width (the potential visible con-

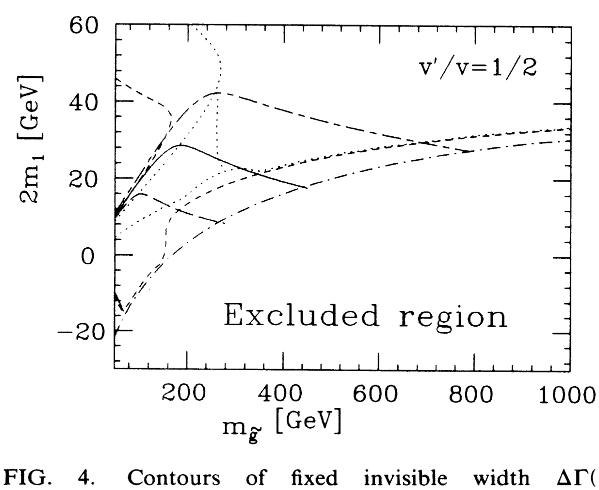

FIG. 4. Contours of fixed invisible width $\Delta\Gamma(Z^0 \to \tilde{Z}_1\tilde{Z}_1) = 50$ MeV (long dashed), 30 MeV (solid), and 10 MeV (long-short dashed) in the $m_{\tilde{g}} - 2m_1$ plane for $v'/v = \frac{1}{2}$. Also shown is the region excluded by the total width constraint (1). Finally, contours of fixed and, in principle, visible width from Z^0 decays into gaugino-Higgsinso pairs where at most one of the gaugino-Higgsinos is $\tilde{Z}_1$ are shown for $\Delta\Gamma = 20$ MeV (short dashed) and 1 MeV (dotted). Thus the region enclosed by the dotted line is where there are essentially only invisible supersymmetric decays of Z^0 provided the sfermions are heavy.

tribution) is 20 MeV (1 MeV). Since this plot is for illustrative purposes only, we have fixed $v'/v=\frac{1}{2}$ and taken $m_{H^+}=0.5$ TeV. For heavy sneutrinos $\Delta\Gamma_{\tilde{Z}_1\tilde{Z}_1}$ is an excellent approximation to the SUSY contribution to the invisible decays of Z^0. It is interesting to see that there is a triangular region near $m_{\tilde{g}}=200$ GeV where the NSM invisible width may be as large as 50 MeV and in which there is negligible contribution to the NSM hadronic width so that the invisible width bounds such as (6) will be directly applicable from the data of the next LEP run. We remark that the size of this region is parameter dependent. As $v'/v\to 1$, it disappears since the $Z\tilde{Z}_1\tilde{Z}_1$ coupling vanishes, whereas for smaller values of v'/v it disappears because the decay $Z^0\to\tilde{W}_-\tilde{W}_-$ becomes kinematically allowed. If, on the other hand, the sneutrino is light compared to the other sfermions and Z^0, it may mediate invisible decays of the other neutralinos so that this region of invisible Z^0 decays is even larger. For the rather extreme case of the common sfermion mass at the weak scale of 50 GeV, the invisible width exceeds 50 MeV over a significant portion of the "allowed" small $|2m_1|$ region. It is amusing to speculate that "the two standard deviation excess" in the combined value of N_ν in Table I (corresponding to an invisible width of 31 MeV) may be due to supersymmetry, with the SUSY parameters in this triangular region.

The reason that the peak hadronic cross section cannot be used to obtain bounds in the presence of NSM hadronic activity is that both Γ_h and Γ_Z in (5) are unknown. If, however, it would be kinematically possible to separate the NSM hadronic contributions from the SM ones, it may be possible to use (5) to bound other NSM hadronic processes also. This is illustrated for the gaugino-Higgsino decays of Z^0 in Fig. 5 for the case of $v'/v=0.5$ and heavy sfermions. We have taken $m_{H^+}=500$ GeV so that the only possible two-body decays of gaugino-Higgsinos are into the light Higgs scalars. The region between the dotted line as well as that enclosed by the dotted line in the top left-hand corner is excluded by the total width constraint (1). The region enclosed by the short-dashed curves (the short-dashed curve coincides with the long-dashed curve along the hyperbola in the bottom half) is where the largest possible visible width from the decays of Z to gaugino-Higgsinos, i.e., the width assuming everything other than $\tilde{Z}_1\tilde{Z}_1$ is visible, exceeds 100 keV. This corresponds to a branching fraction of 4×10^{-5} for Z^0, or ~160 events per 100 pb^{-1} of integrated luminosity expected in about a year of running at LEP. Thus, this is the region where searching for SUSY by looking for events with unusual topology may be possible.[26] The regions inside the long-dashed curve correspond to $\Delta\Gamma\geq 20$ MeV from gaugino-Higgsinos, which is the very best one can ever hope to do from a total width measurement even from the peak cross section. Finally, the solid curves denote the kinematic boundaries where the maximum visible energy from gaugino-Higgsino decays of the Z^0 is $M_Z/2$, i.e., SUSY events from gaugino-Higgsino production and decay at LEP *always have a visible energy smaller than $M_Z/2$ if $m_{\tilde{g}}$ and $2m_1$ are outside the region enclosed by the solid lines.* (This region, in the case of the heavy charged-Higgs-boson mass considered here is completely determined by the gaugino-Higgsino masses, which in turn are determined by $m_{\tilde{g}}$, $2m_1$, and v'/v.) Thus, by defining the peak hadronic cross section in (5) to include only those events satisfying $E_{\text{vis}}>M_Z/2$, all the NSM hadronic contributions can be excluded whereas only a small (and more importantly, calculable) fraction of the SM cross section is excluded so that (6) can be used to bound gaugino-Higgsino parameters in this region. Note that there are small regions of parameter space where this "inclusive method" may be applicable but where the cross section is too small for direct searches, and vice versa. Furthermore, exclusive signals are proportional to some gaugino-Higgsino branching ratio, while inclusive quantities only depend on the $Z\to$gaugino-Higgsino decay width. Inclusive quantities are thus not only less model dependent, but may also allow the extraction of important additional information if a signal is found. Clearly this is only possible in regions of parameter space where *both* inclusive and exclusive searches can be used.

Finally, we discuss another method by which the peak cross section may be used to obtain bounds on new physics, although this requires significantly higher statistics and so may be applicable only after several months of running at LEP. In analogy with the peak hadronic cross section, one may define the corresponding charged-lepton cross section $\sigma_l^0=(12\pi/M_Z^2)\Gamma_{ee}\Gamma_{ll}/\Gamma_Z^2$. If it can be conclusively established that there are no NSM sources of

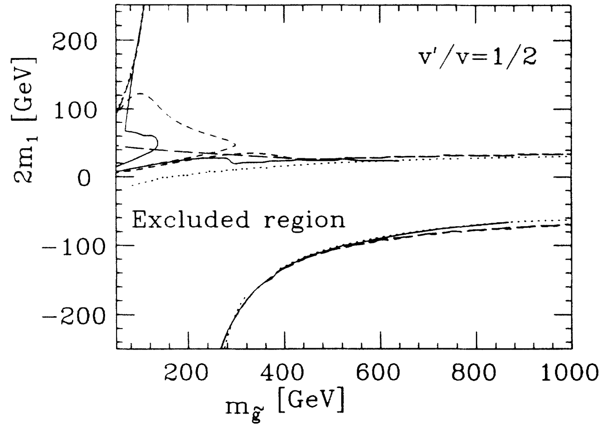

FIG. 5. This figure illustrates the region where hadronic SUSY contributions to the Z^0 width can be separated from the SM contributions so that the peak hadronic cross section can be used to obtain bounds as discussed in the text. The region between the dotted lines as well as that enclosed in the upper left corner by the dotted line is excluded by the total width constraint. In the similar regions bounded by the long-dashed (short-dashed) lines, the total (visible in the definition of Fig. 4) width is larger than 20 MeV (0.1 MeV) which we take to be the limiting values for searches using the total width (exclusive methods). Outside the region enclosed by the solid lines, the maximum possible visible energy (fixed by kinematics) is always smaller than $M_Z/2$. In this figure, we have taken sfermions to be heavy, $v'/v=\frac{1}{2}$ and $m_{H^+}=0.5$ TeV.

purely leptonic events (this would be relatively easy in SUSY since the events would be very characteristic), deviation of σ_l^0/σ_h^0 from SM expectations can only be due to a NSM source of hadrons and so can be cleanly separated from the genuinely invisible contributions to Z^0 decay.

In summary, based on the recent precision measurements of Γ_Z and the peak hadronic cross section σ_h^0 by the four LEP experiments, we have obtained the limits $m_{\tilde{W}_-} \geq 37$ GeV, $m_{\tilde{Z}_3} \geq 57$ GeV, $m_{\tilde{\nu}} \geq 36$ GeV, $m_{\tilde{l}_L} \geq 38$ GeV, and $m_{\tilde{d}_L} \geq 39$ GeV within the framework of the minimal model. We have discussed how these limits are dependent on various assumptions. Although these limits are comparable with or better than those obtained from direct searches at PETRA and TRISTAN (Ref. 12), they are applicable when the direct search limits may fail, e.g., when the LSP mass is close to the parent mass so that visible decay products become too soft to separate from background. Since our limits for charged sparticles are obtained only on the basis of just two measurements, they are somewhat weaker than the recent limits 40–45 GeV on slepton and chargino masses obtained at LEP (Refs. 7 and 27), which have been derived under the assumption that the LSP is a neutralino with mass below about 25–30 GeV. We stress, however, that our bounds are valid independent of the mass (and nature) of the LSP, which in the case of the chargino affects not only the decay kinematics but also the production rate. The chargino lower bound improves very significantly if we assume that the LSP is a photino with $M_{\tilde{\gamma}} < 20$ GeV (corresponding to $m_{\tilde{g}} < 130$ GeV). In this case, the lower bound (4) on $m_{\tilde{W}_-}$ moves to 44 GeV. Our bounds on the neutral sparticles are entirely new; together with astrophysical bounds,[23,24] we rule out the possibility that the sneutrino is the LSP. The rapidity with which the LEP experiments have been able to bound sparticle masses based on the absence of acollinear lepton pair events with $\not{p}_T$ encourages us to believe that the method using the measured peak leptonic cross section as discussed earlier may provide an important tool once a large enough data sample is available. More generally, inclusive methods may prove useful in complementing exclusive searches for new physics signals at the Z^0.

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Since these are generally smaller than the axial-vector couplings, this effect is subdominant. We are not aware of any explicit calculation of radiative corrections to Z^0 decays in the SUSY model but would expect, once again, an overall renormalization of the neutral-current coupling which would cancel in σ_h^0.

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