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Test of supersymmetry in single-scalar-fermion decays of the Z^0 boson

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Searching for the supersymmetric (scalar) partners of charged leptons and quarks at Z^0 factories will only be relatively easy in the favorable case of pair decay, when $m_{\tilde{f}} < M_Z/2$. Using the scalar electron as an illustration, we calculate the rate for the decays $Z^0 \rightarrow e^{\pm}\tilde{e}^{\mp}_{1,2}\tilde{\gamma}$, relevant to the *a priori* equally likely case of larger scalar-lepton masses $M_Z/2 \lesssim m_{\tilde{l}} < M_Z - m_{\tilde{\gamma}}$. We conclude that for photino masses under 10 GeV, scalar electrons (or other scalar leptons) of mass up to 55 GeV may be detected in such Z^0 decays. We also comment on single-scalar-quark decays of the Z^0, with the emission of either a photino or a gluino.

One of the more pressing issues in high-energy physics is whether some experimental evidence for broken supersymmetry (SUSY) will eventually turn up. The past few years have witnessed a great deal of activity devoted to working out the consequences of SUSY for phenomenology, in a wide variety of processes and decays.[1] Relevant experimental results are scant: all that is currently available consists of bounds on the masses of gluinos ($\tilde{g}$) produced in hadron-hadron scattering,[2] $m_{\tilde{g}} > 3$–5 GeV, and on those of the scalar partners ($\tilde{l}^{\pm}$) of charged leptons, presumed to be pair produced in e^+e^- collisions,[3] $m_{\tilde{e},\tilde{\mu}} > 16$ GeV and $m_{\tilde{\tau}} > 15.3$ GeV (Ref. 4).

It has also been suggested[5,6] that even if the scalar-electron mass exceeds the beam energy, one might look for it produced *singly* in e^+e^- collisions, provided the photino is light enough, e.g., through the reaction $e^+e^- \rightarrow e^-\tilde{e}^+\tilde{\gamma}$. This has led to the slightly improved bound,[7] $m_{\tilde{e}} > 22$ GeV. There are no direct experimental bounds on the mass of the photino, presumed to be the lightest stable supersymmetric particle: indirect evidence comes from cosmology. Goldberg[8] has studied the evolution of the photino number density in the early Universe (taking into account the Majorana character of the photino) and obtained upper and lower bounds on the photino mass, respectively: $m_{\tilde{\gamma}} < 1$ keV *or* $m_{\tilde{\gamma}} > 1.8$ GeV. The lower bound in fact depends on the scalar-electron mass, and holds only in the range $m_{\tilde{e}} < 50$ GeV: for higher $m_{\tilde{e}}$, the lower bound is pushed up, and becomes $m_{\tilde{\gamma}} \gtrsim 10$ GeV for $m_{\tilde{e}} \sim M_W$. The last word has in fact probably not been said on this, as the bounds are derived by requiring that photinos do not represent more than the critical density of the Universe, which is probably too much when one thinks of multi-GeV masses and their effect on scenarios of galaxy formation. More can be said concerning gaugino masses in models where $SU(3) \times SU(2) \times U(1)$ is eventually embedded in a grand unifying group.[9] A remarkable feature of supersymmetric gauge theories is that in leading order the renormalization-group equations for gaugino masses are identical with those for the gauge couplings $\alpha_i(Q^2)$, $i = 3, 2, 1$. If there is an underlying grand unification group, the α_i all become equal at some scale $M_{\rm GU}$, as do the effective gaugino masses: It follows that at lower energies, $m_{\tilde{i}}/\alpha_i$ is independent of i. This leads to[9] $m_{\tilde{g}}/m_{\tilde{\gamma}} \simeq 50\alpha_s(m_{\tilde{g}})$, and the experimental lower limit of 3–5 GeV on the gluino mass serves to exclude the lower branch of cosmologically allowed masses for the photino: this of course is somewhat speculative.

With the coming advent of Z^0 factories, a most promising way of looking for scalar electrons (or indeed any scalar lepton or scalar quark) is in the decay $Z^0 \rightarrow \tilde{e}^+\tilde{e}^-$, with an expected rate

$$\frac{\Gamma(Z^0 \rightarrow \tilde{e}^+_{1,2}\tilde{e}^-_{1,2})}{\Gamma(Z^0 \rightarrow e^+e^-)} = \frac{1}{2}\left[1 - \frac{4m_{\tilde{e}}^2}{M_Z^2}\right]^{3/2} , \quad (1)$$

summed over both types of scalar partners, corresponding to left- and right-handed electrons, presumed here and in what follows to be degenerate. The subscripts 1 and 2 refer to mass eigenstates. If scalar electrons exist, with a mass $m_{\tilde{e}} < 47$ GeV, they should be found at the Z^0.

The purpose of this note is to consider single-scalar-electron decay of the Z^0 (for definiteness), to show that a scalar-electron search at the Z^0 is still possible even if $m_{\tilde{e}} > M_Z/2$. Such a situation can easily obtain in recent models based on spontaneously broken supergravity (see, e.g., Ref. 10 for a nice review), where scalar-lepton masses are typically given by

$$m_{\tilde{l}_{1,2}} = |m_{3/2} \pm O(m_l)| , \quad (2)$$

where $m_{3/2}$ is the gravitino mass resulting from the supersymmetry Higgs effect. For consistency of this approach, and to achieve $SU(2) \times U(1)$ breaking, this must satisfy the bounds $m_{\tilde{l}} < m_{3/2} \lesssim 1$ TeV. The $O(m_l)$ term in Eq. (2) is the splitting induced by $SU(2) \times U(1)$ breaking between the mass eigenstates $\tilde{l}_1$ and $\tilde{l}_2$: this we accordingly neglect. For scalar quarks, the corresponding typical mass is

$$m_{\tilde{q}_{1,2}} = |m_{3/2} + O(m_{\tilde{g}}) \pm O(m_q)| . \quad (3)$$

The $O(m_{\tilde{g}})$ term arises from radiative corrections. Scalar quarks, though expected to be heavier than scalar leptons, may also be presumed to be degenerate, with the obvious exception of the partners of the top quark[9] and perhaps of the bottom quark.

In general, the mass eigenstates $\tilde{l}_{1,2}$ are given in terms of the interaction eigenstates $\tilde{l}_{L,R}$ (partners of the chiral lepton components) via a mixing angle ϕ, which is model dependent:

$$\tilde{l}_L = \tilde{l}_1\cos\phi + \tilde{l}_2\sin\phi ,$$
$$\tilde{l}_R = -\tilde{l}_1\sin\phi + \tilde{l}_2\cos\phi . \quad (4)$$

The appropriate pieces of the Lagrangian relevant to the calculation of $Z^0 \to e^{\pm}\tilde e^{\mp}_{1,2}\tilde\gamma$ are, in terms of interaction eigenstates,

$$\bar g Z^\mu (a_L \bar e_L \gamma_\mu e_L + a_R \bar e_R \gamma_\mu e_R) + i\bar g Z^\mu (a_L \tilde e_L^\dagger \overleftrightarrow{\partial}_\mu \tilde e_L + a_R \tilde e_R^\dagger \overleftrightarrow{\partial}_\mu \tilde e_R) + \sqrt{2}e[(\bar e_L \tilde e_L + \bar e_R \tilde e_R)\tilde\gamma + \text{H.c.}] \ . \tag{5}$$

Here, $\bar g = g/\cos\theta_W$, $a_L = -\frac{1}{2} + \sin^2\theta_W$, and $a_R = \sin^2\theta_W$. With this, the amplitude for, say, $Z^0 \to e^- \tilde e_1^+ \tilde\gamma$ follows from the diagrams shown in Fig. 1 and is of the form (with momenta labeled as in the figure, and with $m_e = 0$)

$$\mathcal{M}_1 = -\sqrt{2}e\bar g \bar u(p_1)\left[\frac{\gamma^\mu \not{Q}_1}{s_1} + \frac{(Q_3 - p_3)^\mu}{s_3 - m_{\tilde e}^2}\right](a_L \cos\phi\, P_R - a_R \sin\phi\, P_L) v(p_2) \epsilon_\mu(K,\lambda) \ . \tag{6}$$

Recall that we take $m_{\tilde e_1} = m_{\tilde e_2} = m_{\tilde e}$; we also define, with i,j,k running from 1 to 3,

$$Q_i = p_j + p_k, \quad Q_i^2 = s_i, \quad i \neq j \neq k \ . \tag{7}$$

The amplitude for $Z^0 \to e^- \tilde e_2^+ \tilde\gamma$ is simply obtained from Eq. (6) by the substitution

$$(a_L \cos\phi\, P_R - a_R \sin\phi\, P_L) \to (a_L \sin\phi\, P_R + a_R \cos\phi\, P_L) \ ;$$

P_L and P_R are the usual left- and right-handed projection operators. A straightforward calculation then gives the differential rate for the decay $Z^0 \to e\tilde e\tilde\gamma$ relative to $Z^0 \to e^+e^-$, summed over charges and the $\tilde e_{1,2}$ modes. When $m_{\tilde\gamma} = 0$, the result has the fairly simple form

$$\frac{1}{\Gamma(Z^0 \to e^+e^-)}\frac{d\Gamma(Z^0 \to e^{\pm}\tilde e^{\mp}\tilde\gamma)}{dX} = \frac{\alpha}{2\pi}\left[\frac{(1-3X-2X^2)}{X^3}(1-X)(X-\eta)^2 + (1-8\eta+4\eta^2/X)\ln(1/X - 1/\eta + X/\eta) + (4\eta-1)\left[1 + \frac{\eta X}{(1-X)(X-\eta)-\eta X}\right]\right] \tag{8}$$

where $X = s_1/M_Z^2$ and $\eta = m_{\tilde e}^2/M_Z^2$. As expected, all dependence upon the mixing of interaction eigenstates has disappeared from this expression, as a result of the summation over the degenerate states $\tilde e_1$ and $\tilde e_2$.

Integration over X gives the total relative rate as a function of $m_{\tilde e}$ displayed in Fig. 2, along with the rate for $Z^0 \to \tilde e^+ \tilde e^-$ [Eq. (1)] for $\eta < \frac{1}{4}$. The singularity at $\eta = \frac{1}{4}$ is easily dealt with[6] by modifying the scalar-electron propagator to include the width

$$\Gamma(\tilde e \to e\tilde\gamma) = \frac{\alpha}{2} m_{\tilde e}(1 - m_{\tilde\gamma}^2/m_{\tilde e}^2)^2 \ .$$

When $m_{\tilde\gamma} \neq 0$, the corresponding expressions are a good deal more complicated, and it would not be too useful to quote them here. It will suffice to show results for the same relative rate, when $m_{\tilde\gamma} = 5$, 10, and 20 GeV, as seen in Fig. 3. From the figures, we see that as long as $m_{\tilde\gamma} \lesssim 10$ GeV, the branching ratios for scalar-electron (or other

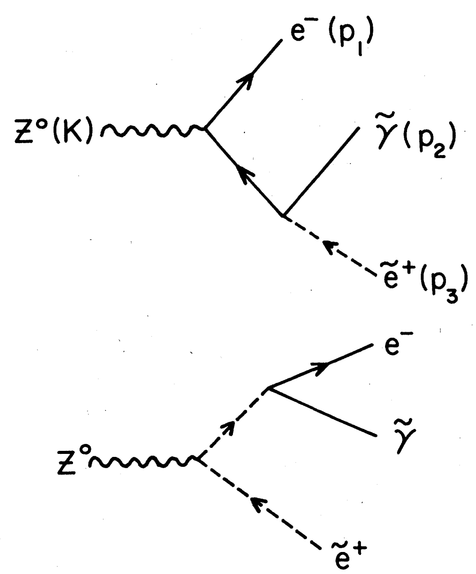

FIG. 1. Diagrams contributing to the amplitude for the decay $Z^0 \to e^- \tilde e^+ \tilde\gamma$.

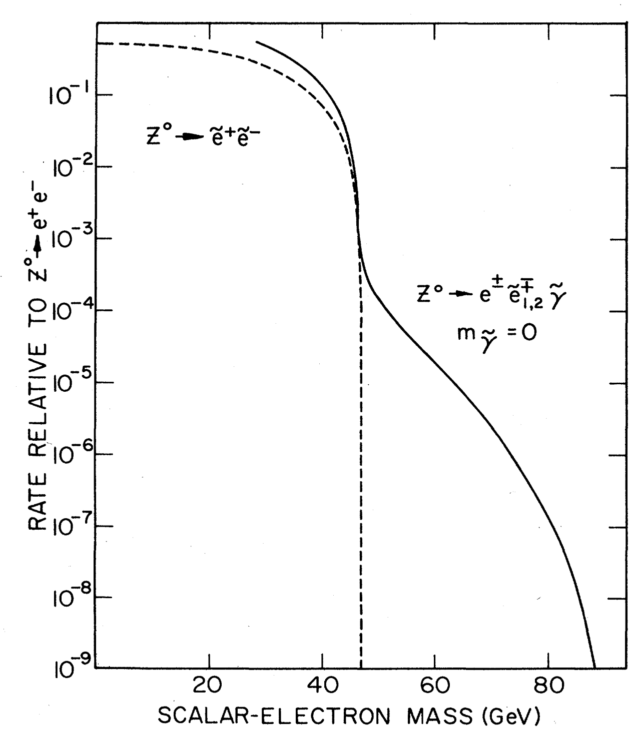

FIG. 2. Rate for the decays $Z^0 \to e^{\pm}\tilde e^{\mp}\tilde\gamma$ (summed over charges and scalar-electron mass eigenstates, and with $m_{\tilde\gamma} = 0$) relative to $Z^0 \to e^+e^-$, as a function of scalar-electron mass. Also shown, the relative rate for $Z^0 \to \tilde e^+ \tilde e^-$.

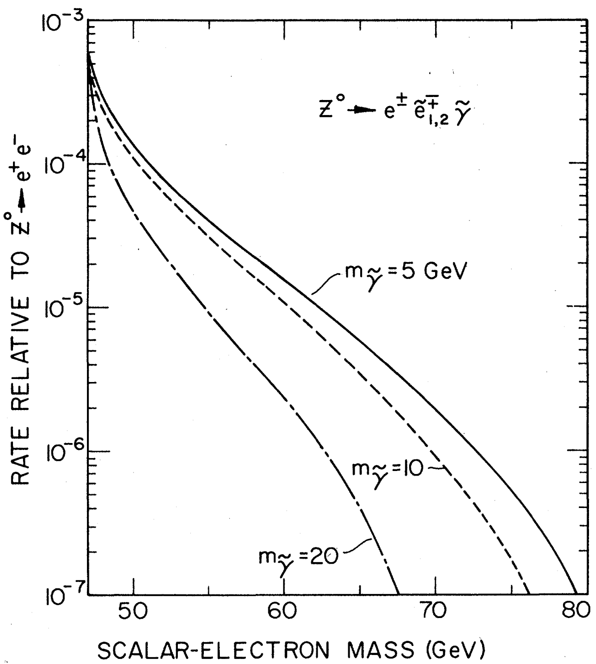

Fig. 3. Rates for the decays $Z^0 \rightarrow e^{\pm}\tilde{e}^{\mp}\tilde{\gamma}$ (summed over charges and scalar-electron mass eigenstates) relative to $Z^0 \rightarrow e^+e^-$, for nonvanishing photino masses: $m_{\tilde{\gamma}} = 5$ GeV (solid curve), 10 GeV (dashed curve), and 20 GeV (bottom curve).

scalar-lepton) decays of the Z^0 will exceed the 10^{-6} level for $m_{\tilde{e}} \lesssim 55$ GeV, so that scalar electrons might be seen in a Z^0-factory experiment with, say, 10^7 Z's on hand.

One sees from the figures that the number of $Z^0 \rightarrow l^{\pm}\tilde{l}^{\mp}\tilde{\gamma}$ events drops off very rapidly with scalar-lepton mass above $M_Z/2$: as a result, careful examination of the expected standard-model backgrounds to this process is required to assess the feasibility of a scalar lepton search by this method. The backgrounds to scalar-lepton decays of the Z^0 are well understood:[1] as $\tilde{l}$ undergoes rapid decay into $l\tilde{\gamma}$, and photino-matter interactions are very weak, one looks for a final state of an acollinear, acoplanar, identical lepton and antilepton pair l^+l^- + missing energy (typically a third of the total or more). Apparently similar signatures can be expected from a variety of processes, which we enumerate in turn.

(1) An important source of background will be the decay $Z^0 \rightarrow \tau^+\tau^-$, followed by the leptonic decays $\tau^{\pm} \rightarrow l^{\pm}$ + neutrinos; here, the signal-to-noise ratio will amount to a few tenths of a percent for $m_{\tilde{l}} \lesssim 50$ GeV and $m_{\tilde{\gamma}} \lesssim 10$ GeV (more if the photino is nearly massless), which does not seem encouraging. Nevertheless, event topologies are totally different. Most importantly, at these energies, the leptons from τ decay will be almost back-to-back, while one expects considerable acollinearity in the single-scalar-lepton decay final state. A collinearity cut should be very efficient in enhancing the signal-to-noise ratio up to a value of probably 10–20%. There is a further handle on this background by comparing the *unlike-dilepton* signal, say $\tau^+\tau^- \rightarrow e^+\mu^-$ + missing energy, with the l^+l^- one.

(2) There is the possibility that the radiative decay $Z^0 \rightarrow l^+l^-\gamma$ with the photon undetected could fake the signal. In principle, this process should be nothing more than a QED radiative correction to the leptonic decay of the Z^0 and its features completely understood. The resulting sample contamination can be efficiently reduced by a missing-energy cut and by requiring that the missing-momentum vector lie in the acceptance of the detector.

(3) Another possible QED background is the two-photon process $e^+e^- \rightarrow e^+e^- + l^+l^-$, with the scattered electrons lost down the beam pipe. As in the previous case, this can be considerably reduced by requiring that the missing-momentum vector lie in the acceptance of the detector, and a further reduction can be achieved by requiring a minimum angle between the observed leptons l^+ and l^-. In the last two cases, the detector should clearly have large solid-angle acceptance for electromagnetic energy.

In view of all this, the observation of single-scalar-lepton decay of the Z^0 appears marginally possible, at a high-luminosity Z^0 factory, and for scalar-lepton masses not too far in excess of $M_Z/2$. One should also compare the relative merits of this and the related proposal[5] to look for the process $e^+e^- \rightarrow e^{\pm}\tilde{e}^{\mp}\tilde{\gamma}$ in the continuum: both should in any event only be seriously considered in the last resort and if one is forced to, as the search for the on-shell production of scalar-lepton pairs will always be immensely easier. Nevertheless, consider sitting on the Z peak: most of the cross section for continuum single-scalar-electron production corresponds to the scattered electron going in the forward direction, where there is a sharp peak. Given a cut of $|\cos\theta_e| < 0.8$, by extrapolation of the results of Ref. 6 (corresponding to lower c.m. energy), one expects a ratio

$$\sigma(e^+e^- \rightarrow e^{\pm}\tilde{e}^{\mp}\tilde{\gamma})/\sigma_{pt}$$

on the order of a tenth of a percent or so for scalar-electron mass under 50 GeV. This would appear more favorable than the corresponding Z^0 decay, which, however, will have a more central angular distribution. One can guess that this difference, and an only slightly more rigorous cut on the scattered-electron angle (given a specific detector say, and the need for background subtraction) would in all likelihood put both proposals on the same footing. This last point, however, is a delicate one, and can only be resolved by detailed calculations done at $s = M_Z^2$ and taking unknown detector characteristics into account.

Finally, one can clearly extend the above results to single-scalar-quark decays of the Z^0: restricting our attention to the lighter quark species u, d, s, and c and their scalar partners, the kinematics are the same as for the scalar-lepton decays just considered. The rate for $Z^0 \rightarrow \bar{q}\tilde{q}\tilde{\gamma}$ relative to $Z^0 \rightarrow \bar{q}q$ is then easily obtained from the figures by a rescaling by a factor of e_q^2, where e_q is the quark electric charge in units of e (a suppression which is however compensated in the absolute rate by the fact that the branching ratio for Z^0 decay into an up-type quark species is about 11% and that into a down-type species about 14%, as compared to the 3% into electrons). If the gluino is heavy, and the decay $\tilde{q} \rightarrow q\tilde{\gamma}$ is dominant, the final state will be two acollinear, acoplanar jets, with half of the energy missing on the average. To cut down backgrounds, the best strategy is to search for events with no observable leptons and significant energy loss. It is not necessary to go into details to appreciate that, like the single-scalar-lepton search, this will be a difficult enterprise.

One might also consider the case of a relatively light gluino, and ask for the rate for $Z^0 \rightarrow \bar{q}\tilde{q}\tilde{g}$ relative to $Z^0 \rightarrow \bar{q}q$. This in turn is obtained from the figures by multiplying by a factor $4\alpha_s/3\alpha \sim 27$. Reasoning as before, we deduce that there should be a statistically significant sample of such events, given a total of 10^7 Z's or so, provided $m_{\tilde{q}} \lesssim 65$ GeV and $m_{\tilde{g}} \lesssim 20$ GeV. Both the scalar quark and the gluino will promptly decay, respectively, into $\tilde{q} \rightarrow q\tilde{g}$ (consistent with our assumption of a fairly light gluino) and $\tilde{g} \rightarrow q\bar{q}\tilde{\gamma}$: the sought-for final state will therefore be $Z^0 \rightarrow \bar{q}q(\bar{q}q\tilde{\gamma})(\bar{q}q\tilde{\gamma})$, not an outstanding signature as the missing photino energy will be fairly small. Differentiating these events from standard Z^0 decay into heavy quarks followed by nonleptonic decay will be a challenging task.

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