Nonsupersymmetric interpretation of the $e^+e^-\gamma\gamma +$ missing energy event observed by the Collider Detector at Fermilab

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The $e^+e^-\gamma\gamma + \not{E}_T$ event reported recently by the CDF Collaboration has been interpreted as a signal of supersymmetry in several recent papers. In this Rapid Communication, we report on an alternative nonsupersymmetric interpretation of the event using an extension of the standard model that contains new physics at the electroweak scale that does not effect the existing precision electroweak data. We extend the standard model by including an extra sequential generation of fermions, heavy right-handed neutrinos for all generations, and an extra singly charged SU(2)-singlet Higgs boson. We discuss possible ways to discriminate this from the standard supersymememtric interpretations. [S0556-2821(96)50319-X]

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The Collider Detector at Fermilab (CDF) Collaboration [1] has recently reported an event that contains a hard electron-positron pair with two hard photons and missing transverse energy. The standard model (SM) background for this event is negligible [1]; therefore, if more events such as this are obtained further, it will indeed signal the existence of new physics beyond the SM. In two recent papers [2,3], it has been proposed that this single event is consistent with a supersymmetric interpretation, when e.g., $q\overline{q}\rightarrow\widetilde{e}_R\overline{\widetilde{e}}_R$ with either (i) $\widetilde{e}_R\rightarrow e+\widetilde{\gamma}$ followed by $\widetilde{\gamma}\rightarrow\gamma+\widetilde{G}$ or (ii) $\widetilde{e}_R\rightarrow e+\chi_2$ followed by $\chi_2\rightarrow\chi_1+\gamma$ ($\widetilde{G}$ denotes a massless goldstino in the gauge mediated low-energy supersymmetry-breaking scenario and $\chi_{1,2}$ denote the lightest and the second-lightest neutralino, respectively). Clearly, this has given further boost to the activities in the area of supersymmetry (SUSY), which already enjoys a number of theoretical advantages in terms of understanding the puzzles of the SM. While this type of $e^+e^-\gamma\gamma+\not{E}_T$ events (or for that matter $\mu^+\mu^-\gamma\gamma+\not{E}_T$ events, if they appear) receives a natural interpretation in terms of SUSY, before one can be completely sure about this, one must rule out any other reasonable nonsupersymmetric interpretation. The purpose of this Rapid Communication is to point out that the reported experimental features of the single $e^+e^-\gamma\gamma+\not{E}_T$ can be obtained in a simple weak scale extension of the SM without invoking SUSY. While the model we present is completely consistent with all known low-energy data and could easily be a viable model of particle physics at the electroweak scale, our goal is more to present it as a possible alternative to SUSY that can fake the CDF signal. If more such ''zoo'' events accumulate, an experimental discrimination is necessary before one can accept *prima facie* that SUSY itself is manifesting.

The model we propose is based on the SM gauge group $SU(2)_L\times U(1)_Y$. In addition to the particles of the SM, it contains (i) an extra sequential generation denoted by $Q_4\equiv(t',b')_L$, t'_R,b'_R $L_4\equiv(N,E)_L$, N_R, E_R, (ii) right-handed SU(2)-singlet neutrinos (ν_{iR}) corresponding to the first three generations, and (iii) a singly charged SU(2)-singlet scalar denoted by $\eta(\equiv\eta^{\pm})$ that can only couple to L_4 and not to Q_4. An absolutely model-independent bound on any of the fourth-generation masses is $M_Z/2$, which comes from its nonobservation at the CERN e^+e^- collider LEP 1. The CDF Collaboration has put an experimental lower limit on the b' mass as 85 GeV from an analysis of two-lepton final states [4]. The nondegeneracy among the multiplet members is restricted to be within $\sim$100 GeV from the near consistency of the oblique electroweak ρ parameter with unity [4]. Another important constraint is that a heavy sequential generation of degenerate fermions contributes $+2/3\pi$ to the oblique electroweak parameter S and with the present precision of electroweak data one complete sequential generation can still be accommodated [5]. The fermions of the fourth generation are kept heavy enough so that they do not effect any other consequence of the SM. It may also be noted that the t'-induced triangle loop at the Zbb vertex adds correction in the same direction as the t-induced loop; however, the $t'-b$ charged-current mixing angle can be kept small enough not to worsen the situation further as far as R_b is concerned. The relevant part of the new Yukawa Lagrangian of the model looks like

$$L_Y^{\rm new}=f_i\eta^+l_{iR}\nu_{iR}+f'_i\eta^+l_{iR}N_R+f_{4i}\eta^+E_R\nu_{iR}+f_{Ei}\eta^+L_4L_i + f_{ij}\eta^+L_iL_j+hL_iH\nu_{iR}+\text{H.c.}, \quad (1)$$

where $l_i=e,\mu,\tau$; the subscript i,j also go over e,μ,τ; L_4 and L_i in the above equation denote the $SU(2)_L$-doublet part of the fourth and the first three generations, respectively, and H is the Higgs field. In the first term in the Lagrangian, we have kept only the diagonal terms for simplicity. To start with, let us assume that $i=e$, i.e., new physics couples only to the first generation, except for f_{ij} where antisymmetry in the indices imply $j=\mu$ or τ. ν_{iR} have large Majorana masses

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in the ~ 65 GeV region. The smallness of the left-handed SM neutrino masses can be explained by adjusting the off-diagonal Dirac masses invoking the usual seesaw mechanism. We will show below that if $M_{E,N} > M_\eta > M_{\nu_{eR}}$ are satisfied and if f_{ij} is vanishingly small, then in a hadron collider, one can pair produce η by gauge interactions with $\eta \to e_R \nu_{eR}$ followed by $\nu_{eR} \to \nu_e + \gamma$. To explain the kinematics of the $e^+e^-\gamma\gamma + \not{E}_T$ event, we will assume that $M_\eta \simeq 100$ GeV and $M_{\nu_{eR}} \simeq 65$ GeV. We will show that for our choice of the parameters, both the above decays constitute almost 100% branching ratios and the emerging final states (electrons and γ's) are hard as required. It is a necessity to assume the existence of the fourth-generation leptons, which in conjunction with $f_{ij} = 0$ guarantees a virtually 100% branching ratio to the $\nu_{eR} \to \nu_e \gamma$ decay mode and prevents other channels (such as $\nu_\mu \overline{\nu}_\mu e^+ e^-$ etc.) from appearing as final states in ν_{eR} decay. Moreover, the coupling h has to be smaller than ~ 0.1 to suppress decay modes like $\nu_{eR} \to \nu_e b \overline{b}$. This nonsupersymmetric scenario can provide as good an explanation of the CDF $e^+e^-\gamma\gamma + \not{E}_T$ event.

In the simplest version of the model with $f_e, f_{4e}, f_{Ee} \neq 0$, $f_{ij} = 0$ and all other couplings involving the second- and third-generation leptons switched off, the mass hierarchy mentioned in the previous paragraph implies that all the new heavy particles except the ν_{eR} have tree-level decays to lighter particles by virtue of the interactions in Eq. 1. In fact it is required that all heavy paricles must decay into lighter ones before ~ 1 s or so since injecting extra energy at the nucleosynthesis era is cosmologically troublesome. Guarded by all these requirements we are now set to see how this model can explain the $e^+e^-\gamma\gamma + \not{E}_T$ event.

The first step is the pair production of η's by gauge interactions. Since the η has the same gauge quantum number as the $\tilde{e}_R$, its production cross section is at the 10 fb level for mass of order 100 GeV or so (see, e.g., [2,3,6] for numerical details). Being lighter than E or N, η will decay to $\nu_{eR} + e$ with a strength proportional to f_e^2; we assume that the $M_\eta - M_{\nu_{eR}} \simeq 35$ GeV or so to understand the observed electron energy. Let us now look for the decay of ν_{eR}; since we set $f_{ij} = 0$ and $M_\eta > M_{\nu_{eR}}$, the only tree-level decays for the ν_{eR} are through its mixings with the light neutrino via the seesaw mechanism and these decays can be either Z mediated or $W^\pm$ mediated leading to $\nu_{eR} \to 3\nu$ or $\nu_{eR} \to \nu l^+ l'^-$. The decay widths for these processes are given by $\Gamma_{3\nu \text{ or } \nu e^+ e^-} \simeq (G_F^2 M_{\nu_{eR}}^5 / 192\pi^3)(m_{\nu_L}/M_{\nu_{eR}})$; note that they are suppressed by the small neutrino masses. However, at the one-loop level, one gets the penguin decay $\nu_{eR} \to \nu_e + \gamma$. The amplitude for this decay arises from the E and η flowing as virtual particles in the loop. This decay is controlled by the heavy fourth-generation masses and its amplitude is estimated to be

$$A(\nu_{eR} \to \nu_e \gamma) \simeq \frac{f_{4E} f_{Ee} e}{16\pi^2 M_E}. \quad (2)$$

Although this is a loop decay, it can dominate the tree-level decay that is suppressed by light neutrino masses, mentioned earlier. The one-loop decay width for the ν_{eR} is about $\Gamma_{\nu_{eR}} \simeq 1.8 \times 10^{-10}$ GeV for $f_{4e} \simeq f_{Ee} \simeq 10^{-1}$ for $M_{\nu_{eR}} \simeq 65$ GeV and $M_E \simeq 150$ GeV or so. Note that the presence of the fourth-generation lepton is crucial for this purpose. The purely W- and Z-mediated decay widths mentioned above are much smaller than the photonic decay mode if $m_{\nu_L} < 4.5$ KeV for $M_{\nu_{eR}} = 65$ GeV, leading to $\nu_{eR} \to \nu_e + \gamma$ as the dominant decay mode of the ν_{eR}. The kinematics is similar to the gravitino mode discussed in Refs. [2,3]. We also expect the ν_{eR} to travel about $\sim 10^{-3}(10^{-2}/f_{4e} f_{Ee})^2$ mm before decay. For lower values of the f parameters, one should observe a displaced vertex for the photons from the e^+e^-.

An interesting set of predictions follow if we switch on the muon couplings in the model (i.e., $f_\mu, f_{4\mu}, f_{E\mu} \neq 0$). If we assume analogously that $M_{\nu_{\mu R}} < M_\eta$, we would expect the branching ratio for the electron to muon modes to be proportional to f_e^2/f_μ^2 as a result, one would get also $\mu^+\mu^-\gamma\gamma + \not{E}_T$-type events in $p\overline{p}$ collider experiments if the muon-neutrino mass is assumed to be less than 4.5 keV.

However, the presence of both f_{Ee} and $f_{E\mu}$ will lead to the rare process such as $\mu \to e\gamma$ or $\mu \to 3e$. This in turn will put constraints on the simultaneous production of both ee- and $\mu\mu$-type events. To see these constraints in detail, we calculate the $B(\mu \to e + \gamma)$ and find that the present upper limit of 4.9×10^{-11} on it implies that $f_{Ee} f_{E\mu} < 6 \times 10^{-5}$ and $f_{Ee} f'_e < 6 \times 10^{-8}$. Once $\mu \to e\gamma$ bound is satisfied, $\mu \to 3e$ is also seen to be satisfied. Requiring the ν_{eR} and the $\nu_{\mu R}$ to decay inside the detector puts the following constraints on the couplings: $f_{4e} f_{Ee} > 8 \times 10^{-6}$ and $f_{4\mu} f_{E\mu} > 8 \times 10^{-6}$. It is possible to satisfy all these constraints simultaneously by appropriately choosing the Yukawa coupling parameters.

In this scenario, one should expect the number of events of ee-, $\mu\mu$-, and $e\mu$-types to satisfy the relation $N_{e\mu}^2 = N_{ee} N_{\mu\mu}$, which is different from the prediction of the SUSY model [2,3] where any mixed $e\mu$-type event will arise only from the $\tau\tau$-type events. In our case the number of $\tau\tau$-type events will be proportional to another parameter f_τ and is therefore arbitrary. The relative number of $ee\gamma\gamma$- and $\mu\mu\gamma\gamma$-type events can therefore be used to distinguish this model from its SUSY counterpart.

A few additional comments regarding the model are in order.

(i) The new Yukawa interaction will induce corrections to $Z \to ee, \mu\mu$ and also to $Z \to \text{inv}$ at the one-loop level via η- and L_4- mediated triangles. For example, the tree level coupling $a_L^e = t_3^e - Q_e \sin^2\theta_W$ of Z to the left-handed electron is modified by $\sim f_{Ee}^2/16\pi^2 = 6.3 \times 10^{-5}$ for $f_{Ee} \sim 10^{-1}$. It is perfectly compatible with the precision of leptonic branching ratio of Z at LEP, which is presently at the per mille level. Flavor-violating $Z \to e\mu$ will also be induced for simultaneous presence of e- and μ-related new Yukawa couplings generating an effect of order $\sim (f_{Ee} f_{E\mu}/16\pi^2)^2$ and the condition of satisfying $\mu \to e\gamma$ automatically takes care of its consistency with experiment. The new Yukawa couplings also add corrections to $g-2$ of the electron of order $\simeq (f_e^2 m_e^2 / 16\pi^2 M_\eta^2)$, which is at the level of 10^{-15} for our choice of parameters safisfying present measurements.

(ii) The standard neutrinos are massive in this model. However, their masses are arbitrary since they depend on the values of the corresponding Dirac masses from the seesaw formula and hence can be tuned to the desired values.

(iii) A recent publication by the L3 Collaboration of LEP [7] gives experimental lower limits on the masses of the sequential leptons E and N from their nonobservation. They exclude the range $M_E < 61$ GeV and $M_N < 48.6$ GeV on the basis of nearly 6 pb^{-1} data collected at $\sqrt{s} = 130 - 136$ GeV run at LEP last year. Since we assume these masses in the 100 GeV range, our model is consistent with these bounds. The possibility of observing the sequential leptons in the oncoming phases of LEP 2 run have been investigated [8] with the conclusion that their mass reach could go very close to their kinematic limits under favorable conditions. (iv) It may be noted that the masses of the fourth-generation leptons are bounded by the electroweak symmetry-breaking scale. As far as the neutrino states of the fourth generation are concerned, the masses of the two Majorana eigenstates are $M_{N_1} \simeq v_{\mathrm{wk}}^2/M$ [where $v_{\mathrm{wk}} \simeq 246$ GeV, the SM vacuum expectation value (VEV)] and $M_{N_2} \simeq M$, induced by the see-saw mechanism. The experimental lower limit of $M_Z/2$ on the lighter one (from the Z-invisible width constraint at LEP) implies an upper bound $M_{N_2} < 2 v_{\mathrm{wk}}^2 / M_Z \simeq 1.3$ TeV on the heavier eigenstate [9]. Therefore future colliders, e.g., the Next Linear Collider (NLC), have chances to see them under favorable conditions.

In conclusion, we have presented a nonsupersymmetric interpretation of the CDF $e^+e^-\gamma\gamma + \not{E}_T$ event by invoking new physics at the electroweak scale in the context of an extended particle content for the SM that has a fourth sequential fermion generation and massive Majorana right-handed neutrinos and a singly charged scalar. The kinematics of our model can be set exactly analogous to the SUSY scenario while fitting the CDF event —the singly charged scalar playing the role of selectron and the right-handed neutrino acting as a counterpart of the next-to-lightest supersymmetric particle. We admit that our scenario is quite *ad hoc* and tailored to fit the CDF $e^+e^-\gamma\gamma + \not{E}_T$ event. However, it has some features quite distinct from SUSY and, if this type of ''zoo'' event shows up in large number, it may be possible to distinguish between the two scenarios.

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