SLAC – PUB – 4003
June 1986
(T/E)

Search for Single Photons from Radiative Neutrino or Supersymmetric Particle Production*

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Contributed to the XXIII International Conference on High Energy Physics,
Berkeley, California, July 16–23, 1986

* This work was supported in part by the U. S. Department of Energy under contract numbers DE-AC02-81ER40025 (CU), DE-AC03-76SF00515 (SLAC), and DE-AC02-76ER00881 (UW); by the National Science Foundation under grant numbers NSF-PHY82-15133 (UH), NSF-PHY82-15413 and NSF-PHY82-15414 (NU), and NSF-PHY83-08135 (UU); and by the Istituto Nazionale di Fisica Nucleare.

ABSTRACT

Final results are presented from a search for single-photons produced in association with neutrinos or other weakly interacting neutral particles in e^+e^- annihilations at $\sqrt{s} = 29\,\mathrm{GeV}$. The search was performed with the MAC detector at PEP in a total integrated luminosity of $177\,\mathrm{pb}^{-1}$. The search limits the number of light-neutrino families to $N_\nu < 16$. The mass of the selectron is limited to $m_{\tilde{e}} > 50\,\mathrm{GeV}/c^2$ if $m_{\tilde{e}_L} = m_{\tilde{e}_R}$ and $m_{\tilde{\gamma}} = 0$. The mass of the wino is limited to $m_{\widetilde{W}} > 51\,\mathrm{GeV}/c^2$ if $m_{\tilde{\nu}} = 0$. These limits are at the 90% confidence level.

Searches for photons from the reaction $e^+e^- \to \tilde{\gamma}\tilde{\gamma}\gamma$ currently provide the most restrictive limits on the masses of possible supersymmetric partners to the electron ($\tilde{e}$) and photon ($\tilde{\gamma}$) in models where the the $\tilde{\gamma}$ is light and stable.[1,2] A dominant background to these searches, the reaction $e^+e^- \to \nu\bar{\nu}\gamma$, is also of considerable interest since part of the cross section is sensitive to N_ν, the number of light-neutrino families.[3] Present limits on N_ν from e^+e^-, although not quite as restrictive as recent $\bar{p}p$ collider results,[4] provide an independent measurement of this fundamental quantity. This paper reports final results from a search for single-photons accompanied by weakly interacting particles in three data samples totalling $177\,\mathrm{pb}^{-1}$ of e^+e^- interactions accumulated by the MAC detector on the PEP storage ring at SLAC. An improved understanding of beam-related backgrounds is incorporated in a maximum likelihood analysis allowing an improvement in the limits on radiative neutrino and photino production compared with previous publications of this search.[1] New limits on radiative sneutrino production from the calculation of Grifols, Martínez, and Solà[5] are presented.

Although supersymmetric (SUSY) theories[6] continue to generate much theoretical activity, none of the predicted partners to ordinary particles has yet been found. In many SUSY models the lightest SUSY particle is neutral, stable, interacts only weakly with matter, and thus cannot be directly detected. Two candidates for this lightest SUSY particle which can be produced in e^+e^- interactions are the $\tilde{\gamma}$ produced via virtual $\tilde{e}$ exchange and the sneutrino ($\tilde{\nu}$) produced via Z or supersymmetric W ($\widetilde{W}$) exchange. The cross section for radiative production of $\tilde{\gamma}$ or $\tilde{\nu}$ pairs is a function of both the $\tilde{\gamma}$ or $\tilde{\nu}$ masses and the masses of the exchanged particles.[7] At PEP, the $\tilde{\gamma}\tilde{\gamma}\gamma$ and $\nu\bar{\nu}\gamma$ cross sections are comparable for $m_{\tilde{e}_L} = m_{\tilde{e}_R} = 50\,\mathrm{GeV}/c^2$, $m_{\tilde{\gamma}} = 0$, and $N_\nu = 3$. The $\tilde{\nu}\tilde{\bar{\nu}}\gamma$ cross section for $m_{\widetilde{W}} = 50\,\mathrm{GeV}/c^2$ and $m_{\tilde{\nu}} = 0$ is twice as large.

Photons from $e^+e^- \to \nu\bar{\nu}\gamma$, $\tilde{\gamma}\tilde{\gamma}\gamma$, and $\tilde{\nu}\tilde{\bar{\nu}}\gamma$ have similar energy and angular distributions, peaked sharply at low energy and at small polar angles. Other radiative processes, $e^+e^- \to e^+e^-\gamma$, $\gamma\gamma\gamma$, $\mu^+\mu^-\gamma$, and $\tau^+\tau^-\gamma$, can also produce single-photon events if the other particles in the event are lost into uninstrumented or inefficient regions of the detector. For a detector completely efficient above some polar angle relative to the beam axis, the background from $e^+e^-\gamma$, $\gamma\gamma\gamma$, and $\mu^+\mu^-\gamma$ is kinematically limited to $E_{\perp\gamma} \leq (\sqrt{s} - E_\gamma)\sin\theta_{\mathrm{veto}}$ where $E_{\perp\gamma}$ is the transverse energy of the detected photon and θ_{veto} is the maximum polar angle of undetected particles. This restriction does not apply to $e^+e^- \to \tau^+\tau^-\gamma$ where decay neutrinos may carry significant momentum. However, given the photon energy resolution, the luminosity, and θ_{veto}, the background from all of these processes is easily calculated. The data in this report were collected in three running periods of differing θ_{veto}. The single-photon search region for each period was chosen accordingly.

The MAC detector, composed of calorimetric and tracking chambers covering $> 98\%$ of 4π sr, has been described in previous reports.[8] Of particular importance to this experiment are the electromagnetic shower calorimeters (SC) in which photon energies and directions are measured, and the endcap calorimeters (EC) and small angle detectors which define θ_{veto}. The other MAC detector elements (inner and outer drift chambers, hadron calorimeters, and scintillation counters) provide rejection of cosmic ray, single-electron, and beam-related backgrounds. The 14 radiation length (r.l.) SC, constructed from alternating planes of lead and proportional wire chambers (PWC) covering $35° < \theta < 145°$, is segmented radially into three layers. Position information is derived from 1.9° azimuthal segments digitized at both ends. The angular resolution has been determined from radiative Bhabha scattering events to be 1.3° in azimuth (ϕ) and 1.7° in the polar angle (θ). The energy resolution is $\sigma_E/E = 20\%/\sqrt{E\,(\mathrm{GeV})}$.

The first data sample of $36\,\mathrm{pb}^{-1}$ was collected with the original detector configuration. Endcap calorimeters covered polar angles greater than 10° with at least 20 r.l. of steel and PWC planes. A single plane of scintillators provided redundant coverage to about 12° from the beam axis. Fully efficient small angle veto calorimeters (SAV) covering $3.8° < \theta < 17.5°$ were installed for the second data sample of $80\,\mathrm{pb}^{-1}$. Downstream of the SAV detectors, small angle tagging counters (SAT) cover 85% of the azimuth between $2.5° < \theta < 6.2°$. Each SAV was constructed from alternating discs of lead and PWC planes totalling 8.5 r.l. Each SAT was made from 6-8 r.l. of lead backed by 2 cm of plastic scintillator. Mechanical supports for the beam pipe precluded complete azimuthal coverage for the SAT. A vertex chamber (VC) was installed for the last data sample of $61\,\mathrm{pb}^{-1}$. The additional shielding necessary for the VC obstructed the SAV and SAT below 6.8°. Rings of 24 bismuth germanate (BGO) crystals with photodiode readout were added between the VC and shielding, recovering part of the lost veto coverage. These BGO rings cover $4.8° < \theta < 7.2°$ with 10 r.l. of active material.

Data for this experiment were collected with a single-photon trigger requiring energy deposition in at least two of the SC layers and a minimum of 1 GeV of energy in good time coincidence (±75nsec) with the beam crossing. Subsequent data analysis required that candidate events have a photon well inside the SC, $40^\circ < \theta_\gamma < 140^\circ$, and that no evidence of other particles appear in any of the other parts of the detector. Cuts applied on the energy deposition pattern were designed to reject cosmic ray, beam-related, and noise backgrounds. A detailed description of the event selection follows.

Photon showers were recognized by a clustering algorithm that combined calorimeter hits above 100 MeV from the SC, EC, and hadron calorimeters with neighboring hits in ϕ and θ. The minimum cluster contains two hits. Clusters were allowed to span calorimeter boundaries and were allowed to extend into the hadron calorimeter. Each shower was assigned energy E and angles θ and ϕ from the scalar and vector sum of its individual hits. Only events with a single cluster greater than 40° from the beam axis were kept. Events initiated by showering charged particles were reduced by rejecting events with more than four central drift chamber hits. Events with an outer drift chamber track or with greater than 30% of the cluster energy in the hadron calorimeter were identified as cosmic rays and rejected. Cuts on small angle detectors installed after the first data period were made to reduce θ_{veto} to angles below the endcaps. Events were vetoed if the energy in the SAV was greater than 250 MeV. For the second data sample, events were also rejected if the SAT was hit. The SAT was not used in the third data sample. Instead, events with greater than 100 MeV in the BGO rings were rejected.

Events surviving the above cuts included $e^+e^- \to e^+e^-\gamma$ and $\gamma\gamma\gamma$, background beam-gas and beam halo scatterings, and fake showers caused by detector noise. To further reduce the backgrounds, cuts were made on the shower profile.

Every shower was required to have hits in all three layers of the SC. Showers were required to have narrow width δ_ϕ in azimuthal angle. A straight line trajectory not constrained to the beam vertex was fit to the hits in each shower. The point of intersection z_0 with the beam axis in the plane containing the beam axis and the shower centroid, and its distance of closest approach r_{min} to the interaction point in the plane transverse to the beam axis, were calculated with a resolution $\sigma_{z_0} = 12\,\mathrm{cm}$ and $\sigma_{r_{min}} = 3.3\,\mathrm{cm}$. Showers were required to have $r_{min} < 15\,\mathrm{cm}$. Events passing these cuts are identified as single-photon candidates.

In previous analyses of this search,[1] candidates with $|z_0| < 30\,\mathrm{cm}$ and narrow shower width δ_θ in polar angle were assumed to be a background-free selection of single-photons since showers with these properties are consistent with photons produced at the e^+e^- interaction point. The $E_{\perp\gamma}$ distributions of these single-photons are shown in Fig. 1 for the three data samples. In this analysis, the candidates selected without cuts on z_0 and δ_θ are expected to include events from beam-gas and beam halo backgrounds. A maximum likelihood analysis is employed to estimate the size of the true single-photon signal in the presence of beam-related backgrounds. First, a search region with limited contamination from QED backgrounds is determined.

The efficiency of the cuts and trigger were determined with showers from radiative Bhabha scattering events. Losses due to background noise in the SAV, SAT, BGO, drift, calorimeter and scintillator detectors were studied with beam crossings selected at random. The photon conversion probability in the beam pipe was 2–5% depending on the running period. The overall efficiency for each data sample, calculated from the product of the above efficiencies, typically rises

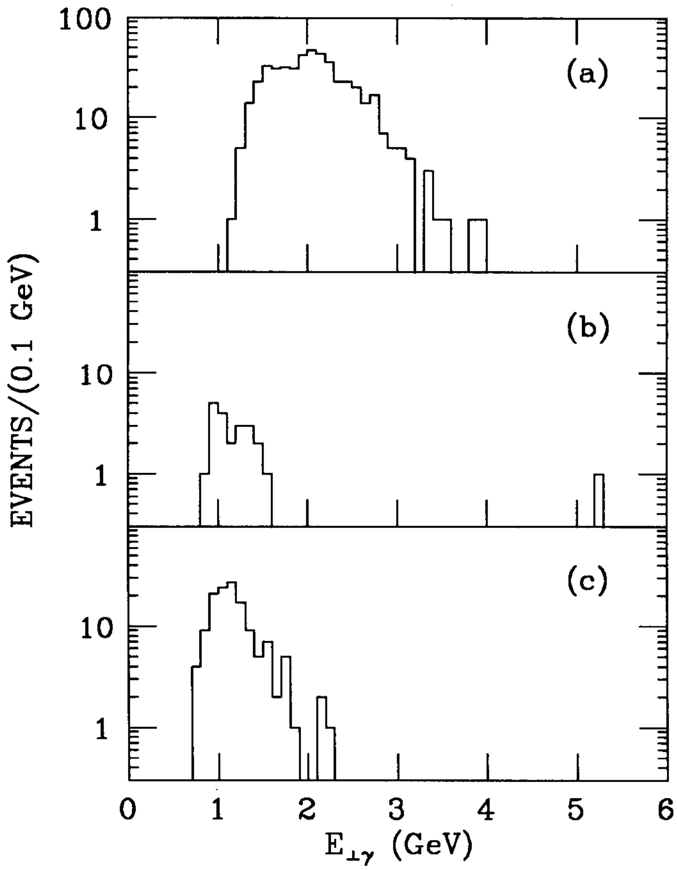

FIGURE 1. $E_{\perp\gamma}$ spectrum of single-photons in (a) the first data sample of $36\,\mathrm{pb}^{-1}$ with $\theta_{\mathrm{veto}} = 10°$ and search region $E_{\perp\gamma} > 4.5\,\mathrm{GeV}$, (b) the second data sample of $80\,\mathrm{pb}^{-1}$ with $\theta_{\mathrm{veto}} = 2.5°$ and search region $E_{\perp\gamma} > 2.0\,\mathrm{GeV}$, and (c) the third data sample of $61\,\mathrm{pb}^{-1}$ with $\theta_{\mathrm{veto}} = 4.5°$ and search region $E_{\perp\gamma} > 2.6\,\mathrm{GeV}$.

from 53% at $E_{\perp\gamma} = 2.0\,\mathrm{GeV}$ to 69% at $E_{\perp\gamma} = 4.5\,\mathrm{GeV}$.

The QED background was calculated by Monte Carlo simulation. The single-photon $E_{\perp\gamma}$ spectra of simulated $e^+e^-\gamma$, $\gamma\gamma\gamma$, $\mu^+\mu^-\gamma$, and $\tau^+\tau^-\gamma$ events[9] corrected for resolution, acceptance, efficiency, and luminosity was determined for different θ_{veto}. The best θ_{veto} fit to each data sample agreed with the angles expected from the geometry of the small angle detectors. A separate analysis of single-electron events from $e^+e^-\gamma$ verified the θ_{veto} determined by this procedure. A search region for each of the three running periods was defined such that the combined background from $e^+e^-\gamma$, $\gamma\gamma\gamma$, $\mu^+\mu^-\gamma$, and $\tau^+\tau^-\gamma$ events was expected to be less than 0.1 event in each search region. The search regions are (a) $E_{\perp\gamma} > 4.5\,\text{GeV}$, (b) $E_{\perp\gamma} > 2.0\,\text{GeV}$, and (c) $E_{\perp\gamma} > 2.6\,\text{GeV}$. The expected yield of photons from $e^+e^- \to \nu\bar{\nu}\gamma$ ($N_\nu = 3$) is 0.1 in (a), 0.6 in (b) and 0.4 in (c). There are 10 single-photon candidates in the search region, all from the second running period.

Unlike the above QED processes, it is difficult to make an accurate estimate of the size of possible backgrounds from beam-gas and beam halo interactions. Since the general characteristics of showers produced by beam-related backgrounds differ from showers initiated by photons produced at the e^+e^- collision point, a maximum likelihood analysis can be used to estimate the true size of the single-photon signal in the presence of this type of background. The broad distribution of beam-related backgrounds along the beam axis and the shallow trajectories at which background particles enter the detector give background showers a broader distribution of reconstructed axial vertex positions z_0 and shower widths δ_θ than showers from photons which originate from the e^+e^- collision point. The measured $E_\perp$ spectrum of these backgrounds falls off more steeply than for signal.

Distributions of measured z_0, δ_θ, and $E_\perp$ for the beam-related background are determined with a background sample containing 67 events that have measured $E_\perp$ in the single-photon search region but fail the cut on the maximum allowed number of central drift chamber hits. The drift chamber hits in the events in the background sample were caused predominantly by charged particles that entered the detector from one end and traversed several layers of drift cells before showering in the SC. Distributions of z_0 and δ_θ for signal events are measured with showers from radiative Bhabha scattering events. The distribution of $E_{\perp\gamma}$ for signal is chosen to be the differential cross section for $e^+e^- \to \gamma\nu\bar{\nu}$, which is similar to $e^+e^- \to \gamma\tilde{\gamma}\tilde{\gamma}$ for $m_{\tilde{e}} = 50\,\mathrm{GeV}/c^2$ and $m_{\tilde{\gamma}} = 0$.

The probability of finding n events, s from signal and b from beam-related backgrounds, with measurements z_{0i}, $\delta_{\theta i}$, and $E_{\perp i}$ for $i = 1, \ldots, n$, is the generalized likelihood function[10]

$$\mathcal{L}(s, b) = \frac{e^{-(s+b)}(s+b)^n}{n!} \prod_{i=1}^{n} \frac{sp_s(z_{0i}, \delta_{\theta i}, E_{\perp i}) + bp_s(z_{0i}, \delta_{\theta i}, E_{\perp i})}{s+b} \qquad (1)$$

where $p_s(z_{0i}, \delta_{\theta i}, E_{\perp i})$ and $p_b(z_{0i}, \delta_{\theta i}, E_{\perp i})$ are the probabilities for making the observed measurements on signal and background events, respectively. The maximum likelihood estimate of the number of signal events in the search region is the value $s = \hat{s}$ which maximizes $\mathcal{L}$ for the $n = 10$ single-photon candidates. The maximum likelihood estimate of signal from equation (1) is $s = 0.99$ events, which agrees with the previous analysis of this search in which cuts on z_0 and δ_θ retained one event in the search regions.[1] The confidence level of an upper limit S on s is computed by a Monte Carlo method as the fraction of equivalent experiments that, when exposed to a true number of signal events S, would estimate a number of signal events larger than the $\hat{s}$ estimated in this experiment. The 90% confidence level upper limit on signal is $S = 3.7$ events. Estimates of the systematic error in S due to determining the background distributions from the 67 event background sample lead to upper limits no more than 0.05 events larger than the above $S = 3.7$. The results of the maximum likelihood analysis are insensitive to whether or not the small QED background in the search regions, calculated to be less than 0.1 event per data period, is included as a third parameter in the likelihood function.

The 3.7 event upper limit on signal in the search regions corresponds to a limit of $N_\nu < 16$ at the 90% confidence level with no SUSY or background production assumed or subtracted. Limits on anomalous single-photon production were calculated after subtracting the expected $\nu\bar{\nu}\gamma$ background of 1.1 events. Using the differential cross section for $\tilde{\gamma}\tilde{\gamma}\gamma$ production as calculated by Ware and Machacek,[11] the regions of excluded $\tilde{e}$ and $\tilde{\gamma}$ masses are shown in Fig. 2 for (a) $m_{\tilde{e}_L} = m_{\tilde{e}_R}$, and (b) $m_{\tilde{e}_L} \gg m_{\tilde{e}_R}$. For $m_{\tilde{\gamma}} = 0$ the 90% confidence level limits on the $\tilde{e}$ mass are (a) $m_{\tilde{e}} > 50\,\mathrm{GeV}/c^2$ and (b) $m_{\tilde{e}_R} > 41\,\mathrm{GeV}/c^2$. Limits on $\tilde{\nu}$ and $\widetilde{W}$ masses depend on the specific SUSY model selected. Using the differential cross section for $\tilde{\nu}\tilde{\bar{\nu}}\gamma$ production as calculated by Grifols, Martínez, and Solà,[5] the regions of excluded $\widetilde{W}$ and $\tilde{\nu}$ masses are shown in Fig. 3. For $m_{\tilde{\nu}} = 0$ the 90% confidence level limit on the $\widetilde{W}$ mass is $m_{\widetilde{W}} > 51\,\mathrm{GeV}/c^2$. These limits are higher than those obtained in previous publications of this search[1] and greater than or comparable to results from other searches.[2]

We thank J. D. Ware and M. Martínez for providing calculations of the $\tilde{\gamma}\tilde{\gamma}\gamma$ and $\tilde{\nu}\tilde{\bar{\nu}}\gamma$ cross sections for the MAC detector acceptance. We also thank N. Erickson, J. Escalera, M. J. Frankowski, and J. Schroeder for technical assistance, and the SLAC staff for continued reliable operation of the PEP storage ring. We acknowledge the technical assistance and regret the passing of C. T. Pulliam.

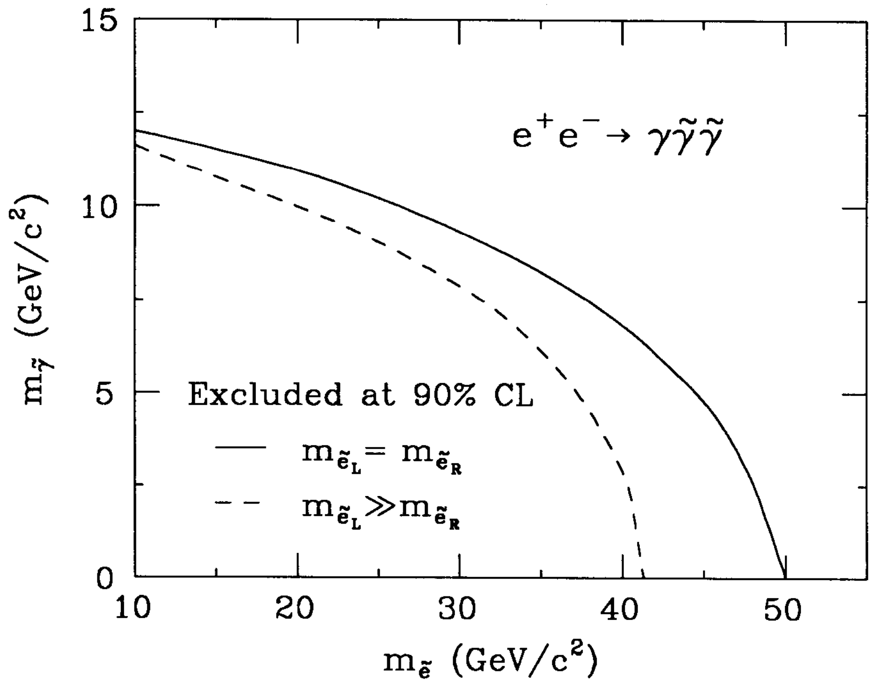

FIGURE 2. Lower limits on the $\tilde{e}$ and $\tilde{\gamma}$ masses determined by this experiment.

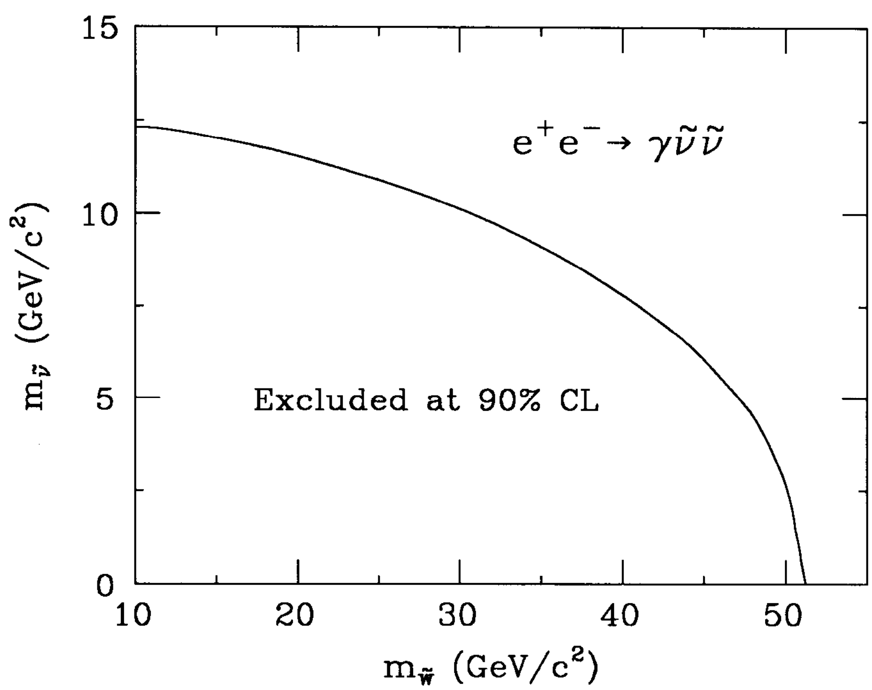

FIGURE 3. Lower limits on the $\widetilde{W}$ and $\tilde{\nu}$ masses determined by this experiment.

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