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NEW RESULTS FROM ASP ON SINGLE-PHOTON PRODUCTION AT $\sqrt{s} = 29$ GeV*

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Abstract

This Letter reports results of a search for radiative production by e^+e^- annihilation of particles that interact only weakly in matter. The search has been made in the total data set of 115 pb^{-1} acquired with the ASP detector at the SLAC storage ring PEP ($\sqrt{s} = 29$ GeV). No anomalous signal was observed. The number of generations of light neutrinos has been limited to $N_\nu < 7.5$ (90% CL). Limits are also placed on the masses of particles predicted to exist by models of supersymmetry.

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This Letter reports a search in the total data sample taken with the ASP detector at the e^+e^- storage ring PEP for events in which only a single photon is observed in the final state. Such events signal the radiative production of particles that interact only weakly in matter,

$$e^+e^- \to \gamma + \textit{weakly interacting particles.} \tag{1}$$

The ASP detector is designed specifically to search for events of this type. The known process that contributes to (1) is the radiative production of neutrino pairs. For N_ν generations of light neutrinos and to lowest order in QED, the cross section for $e^+e^- \to \gamma\nu\bar{\nu}$ is[1]

$$\frac{d^2\sigma}{dp_T^\gamma dcos\theta_\gamma} = \frac{G_F^2\alpha}{6\pi^2} \cdot \frac{s(1-x_\gamma)}{p_T^\gamma sin^2\theta_\gamma} \cdot \left[(1-\frac{1}{2}x_\gamma)^2 + \frac{1}{4}x_\gamma^2 cos^2\theta_\gamma\right] \cdot$$
$$\cdot \left\{\frac{M_Z^4\{N_\nu(g_V^2+g_A^2)+2(g_V+g_A)[1-s(1-x_\gamma)/M_Z^2]\}}{[s(1-x_\gamma)-M_Z^2]^2+M_Z^2\Gamma_Z^2}+2\right\}, \tag{2}$$

where p_T^γ is the momentum transverse to the beam line of the detected photon, θ_γ is the polar angle of the detected photon, and $x_\gamma = 2E_\gamma/\sqrt{s}$. The term proportional to N_ν arises from the s-channel neutral current, while the remaining terms result from charged and neutral-current production of electron-neutrino pairs. A measurement of the cross section for (1) will[2] determine (or place limits on) the value of N_ν. In most theories of supersymmetry (SUSY), the lightest supersymmetric particle is stable and interacts only weakly in matter. Radiative production of pairs of such particles would[3] also contribute to reaction (1). Regardless of its source, the observation of a single-photon rate significantly in excess of that predicted by (2) for $N_\nu = 3$ would signal the production of new particles.

Potential backgrounds to (1) can arise from other e^+e^- radiative processes (especially $e^+e^- \rightarrow e^+e^-\gamma$), cosmic rays, and beam-gas interactions. The ASP detector provides charged-particle tracking and electromagnetic calorimetry over the complete solid angle above $\theta_{\rm veto} = 21$ mrad, so only those events with photons that have $p_T^\gamma < 2 \cdot \theta_{\rm veto} \cdot E_{\rm beam}$ (0.6 GeV/c for this experiment) could possibly be mistaken for reaction (1). We therefore search for photons with p_T^γ >0.8 GeV/c. Cosmic rays and beam-gas events are distinguished from photons by timing, tracking and shower shape. The residual background photons that pass our selection criteria arise almost entirely from π^0s that are produced by beam-gas collisions at all points along the beam line. Single photons are produced at the interaction point (IP) only, so we perform a likelihood analysis that exploits this difference in production point and the difference in p_T distributions to distinguish the single-photon signal from this background.

The ASP detector, shown in Fig. 1, has been described in a previous Letter.[4] Photon recognition is achieved for $20° < \theta_\gamma < 160°$ by five layers of lead-glass bars that surround the interaction point. These layers are interleaved with proportional wire chambers (PWC) to provide full reconstruction of electromagnetic showers. The region between the lead glass and the beam pipe is filled by wire chambers and scintillator planes that are used to detect charged particles. Above the lead glass is an array of time-of-flight scintillation counters (not shown in Fig. 1) that is used to reject cosmic rays. The detector is triggered if the energy in the calorimeter is greater than 1.5 GeV, or if it is greater than 0.6 GeV and is observed in two or more layers in one quadrant or two adjacent quadrants. Other triggers record Bhabha and radiative Bhabha ($ee\gamma$) events, random beam crossings and other diagnostic processes. Particularly useful is a sample of 40000 fully-reconstructed and kinematically-fitted $ee\gamma$ events. The trigger for this sample requires only a very low energy in the lead glass (0.2 GeV), so these events provide an unbiased measurement of single-photon trigger and analysis efficiencies and performance characteristics of the detector. The integrated luminosity of the experiment is measured to be 115 pb^{-1} using the recorded low-angle Bhabha events. This includes the luminosity reported in Ref. 4.

The energy resolution of the lead-glass calorimeter, averaged over all angles, is $\sigma_E/E = 14\%$ at $E_\gamma = 1$ GeV, and the angular resolutions are $\sigma_\theta = 4.4°$ and $\sigma_\phi = 3.2°$. The extrapolated origin of an electromagnetic shower is characterized by R, the signed distance-of-closest-approach to the interaction point in the XZ or YZ planes. The measured distribution function for this quantity is a Gaussian with $\sigma_R = 2.8$ cm and a small exponential tail. The distance-of-closest-approach to the beam line, R_{xy}, is determined by the PWC signals with a resolution of $\sigma_{xy} = 5.5$ cm. The timing resolution is $\sigma_T = 1.2$ ns at $E_\gamma = 1$ GeV, and decreases to 1.0 ns above 2.5 GeV.

Single-photon candidates must pass two major sets of selection criteria. These differ somewhat from those used in our earlier analysis because of improved tracking and timing, and better understanding of the beam-gas background. We first look for a photon candidate in the lead-glass calorimeter. We require that there be a well-measured shower in the fiducial region $20° < \theta_\gamma < 160°$, $|R| < 30$ cm, $p_T^\gamma > 0.8$ GeV/c, and $E_\gamma < 10$ GeV. If any of these quantities is poorly measured, the event is rejected. The requirement $E_\gamma < 10$ GeV eliminates a background that arises when a photon in an $e^+e^- \rightarrow \gamma\gamma$ event fails to convert in the lead glass. We expect three such events in our sample and find four. For further rejection against cosmic rays, we require $|R_{xy}| < 18$ cm, the time of the lead-glass shower to be within $\pm 3\sigma_{\mathrm{T}}$ of the beam-crossing time, and the time from the time-of-flight counters, if available, to be consistent with a shower propagating away from the IP rather than towards it. Pattern recognition tests that use the moments of the energy deposition in the lead glass and PWC's are applied to distinguish single-photon showers from those produced by π^0s or other hadrons. The efficiency with which photons pass all selection criteria is measured with the $e^+e^-\gamma$ sample as a function of the photon energy and production angles. When folded with distribution (2) for neutrino-pair production we obtain an efficiency of 75% for photons in our fiducial region.

The second part of the analysis demands that there be no evidence of any other particle in the detector. No significant signal is allowed in any component of the detector away from the photon candidate shower and no charged track anywhere. The efficiency of this isolation cut is established to be 89% by applying it to random beam crossings. There is a further 6.8% loss of signal due to backsplash from the photon shower or conversion of the photon in the beam pipe and central tracker (measured with $e^+e^-\gamma$ events), a 1.4% loss due to photons that do not convert early enough in the lead glass to be well-tracked, and a 0.3% trigger inefficiency. The overall efficiency for detecting events with single photons in our signal region is then 61%.

The R-p_T distribution of single-photon candidate events is displayed in Fig. 2. We perform a fit to this distribution using the known shapes of the signal and background to extract the number of signal events from the $N_{\mathrm{ev}} = 24$ events with $p_T^\gamma > 0.8$ GeV/c. The most probable signal, $\hat{S}$, and corresponding background, $\hat{B}$, are those values of S and B that maximize the generalized logarithmic likelihood function:

$$\ln\left(\frac{e^{-(S+B)}(S+B)^{N_{\rm ev}}}{N_{\rm ev}!}\right)+\sum_{i=1}^{N_{\rm ev}}\ln\left(\frac{SP_S(R_i)P_S(p_{Ti})+BP_B(R_i)P_B(p_{Ti})}{S+B}\right).$$

The distribution of the signal in R, $P_S(R)$, is measured with the kinematically fitted $ee\gamma$ events, and $P_S(p_T)$ is computed from (2) folded with the efficiency and resolution of the detector. The background distribution $P_B(R)$ is measured with events that fail the pattern recognition tests, and $P_B(p_T)$ is determined from single-photon candidates with $|R| > 3\sigma_R$ and $0.5 < p_T < 0.8$ GeV/c to be an exponential with decay constant ≈ 0.12 GeV/c. The signal and background distributions are markedly different, so the fit is extremely robust; the limits on physical parameters given below depend very little on the region of p_T and R used in the fit, and are not sensitive to the estimated uncertainties in the $P(R)$ and $P(p_T)$ distributions that are used.

The likelihood maximization gives $\hat{S} = 1.6$ events, corresponding to a cross section for single-photon production of 0.023 pb in the fiducial region $E_\gamma <$ 10 GeV, $p_T^\gamma > 0.8$ GeV/c and $20^\circ < \theta_\gamma < 160^\circ$. The probability of observing ≤ 1.6 events is obtained from an ensemble of Monte Carlo generated experiments equivalent to the one we have performed, and is plotted as a function of the radiative neutrino cross section (2) in Fig. 3. We take the 90% confidence level (CL) for the cross section as the value at which this probability is reduced to 10%. From Fig. 3 we obtain $\sigma(e^+e^- \to \gamma\nu\bar{\nu}) < 0.069$ pb. The 95% CL is $\sigma < 0.084$ pb. These limits are equivalent to $N_\nu < 7.5$ (90% CL) and $N_\nu < 9.7$ (95% CL). The 90% CL limit on N_ν is a factor of two lower than those set by previously published e^+e^- searches.[4, 5] Our limits on N_ν are comparable to those from $\bar{p}p$ collider experiments,[6] but depend only on radiative corrections to expression

(2),[7] whereas the $\bar{p}p$ limits depend on the unknown mass of the top quark and on theoretical QCD calculations.

We may hypothesize that single-photon events are also due to the radiative production of the lightest SUSY particle. Radiative neutrino production (2) then becomes a source of background which is expected to produce 2.7 events in our fiducial region (if $N_\nu = 3$). To obtain upper limits on the SUSY contribution we perform two different statistical procedures to handle this background.[8] Following a classical statistical procedure, we have performed a MC simulation to find the probability of observing ≤ 1.6 single-photon events from radiative production of the lightest SUSY particle in addition to three light neutrino species. If the $\tilde{\gamma}$ is the lightest SUSY particle,[9] then this probability is 10% for a selectron mass $m_{\tilde{e}} = 67$ GeV/c^2 (with $m_{\tilde{\gamma}} = 0$ and degenerate $\tilde{e}$ mass states), and 5% for $m_{\tilde{e}} = 59$ GeV/c^2. Under the alternative hypothesis[10] that the $\tilde{\nu}$ is the lightest SUSY particle (and that there are three massless $\tilde{\nu}$ generations), we find this probability to be 10% for $m_{\widetilde{W}} = 69$ GeV/c^2, and 5% for $m_{\widetilde{W}} = 60$ GeV/c^2. We have also performed a Bayesian analysis with the *a priori* assumption that all values of the expected number of SUSY events (N_{SUSY}) are equally likely. This analysis yields the 90% CL limit $N_{SUSY} < 3.2$ events. The corresponding limits on the $\tilde{e}$ and $\tilde{\gamma}$ masses are shown in Fig. 4. For three massless $\tilde{\nu}$ generations, our 90% CL on the mass of the $\widetilde{W}$ is $m_{\widetilde{W}} > 61$ GeV/c^2, and our 95% CL limit is $m_{\widetilde{W}} > 57$ GeV/c^2.

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FIGURE CAPTIONS

1. (a) Cross-section of the ASP central calorimeter and tracking system. Only a section of the central tracker is shown; it completely surrounds the IP. (b) Elevation view of one quarter of the ASP detector. Only the horizontal lead-glass bars are shown in this view. There are 632 bars in the detector. X_0 denotes 1 radiation length.
2. R and p_T distribution of single-photon candidates with $p_T^\gamma > 0.5$ GeV/c.
3. Probability of observing ≤ 1.6 single-photon events in our fiducial region as a function of the radiative neutrino cross section. The dashed line marks the cross section expected for $N_\nu = 3$.
4. Limits (90% C.L.) placed on $\tilde{e}$ and $\tilde{\gamma}$ masses by this experiment. The solid line is the limit for degenerate $\tilde{e}$ masses and the dash-dotted line is the limit if only one mass eigenstate contributes to the cross section. The dashed line is $m_{\tilde{e}} = m_{\tilde{\gamma}}$. For degenerate mass states and $m_{\tilde{\gamma}} = 0$, the 90% CL is $m_{\tilde{e}} > 58$ GeV/c^2 and the 95% CL is $m_{\tilde{e}} > 55$ GeV/c^2.

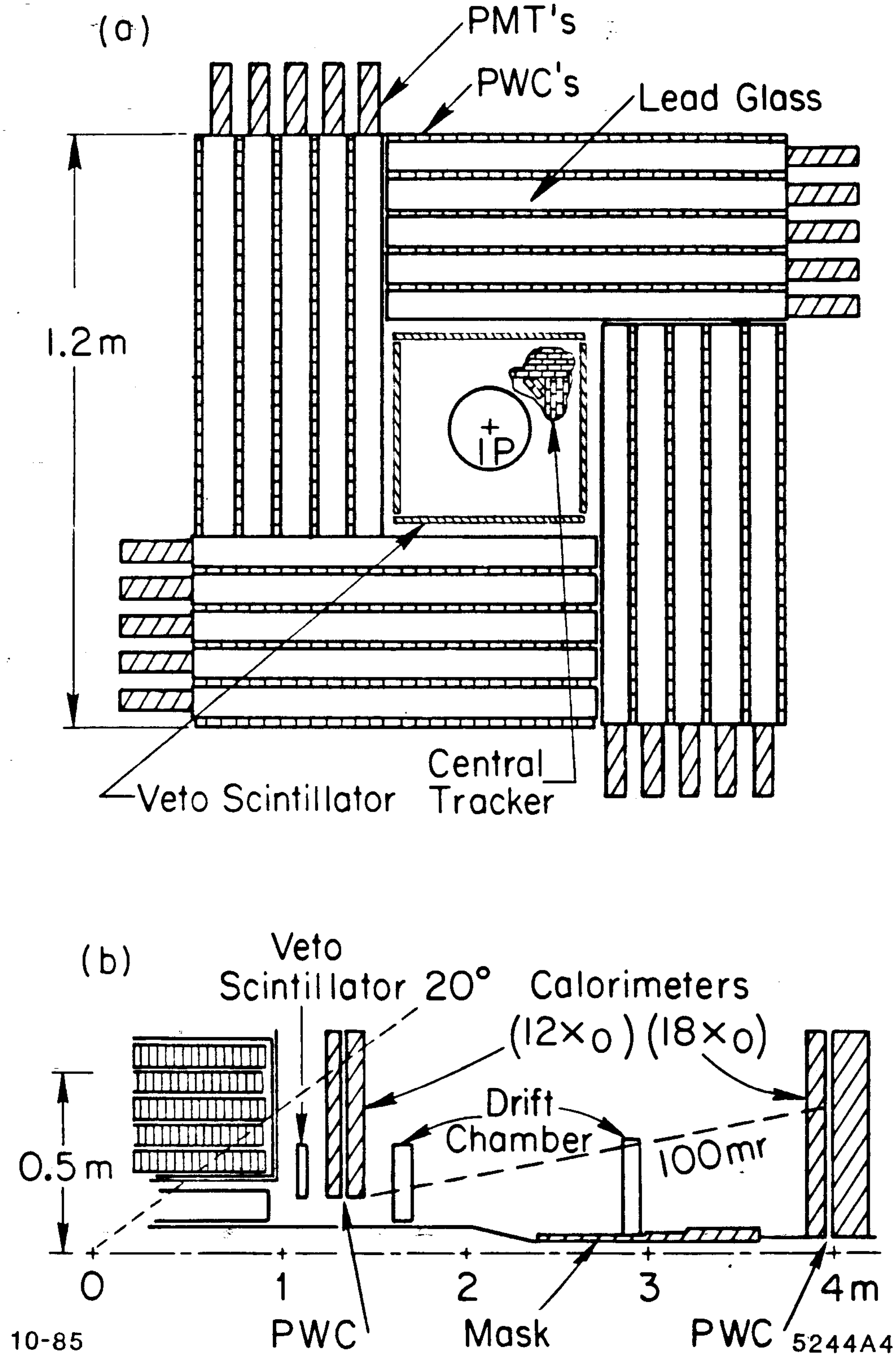

(a)
PMT's
PWC's
Lead Glass
1.2m
IP
Veto Scintillator
Central Tracker
(b)
Veto Scintillator
20°
Calorimeters
(12X0) (18X0)
Drift Chamber
100mr
0.5m
0
1
2
3
4m
PWC
Mask
PWC
10-85
5244A4

Fig. 1

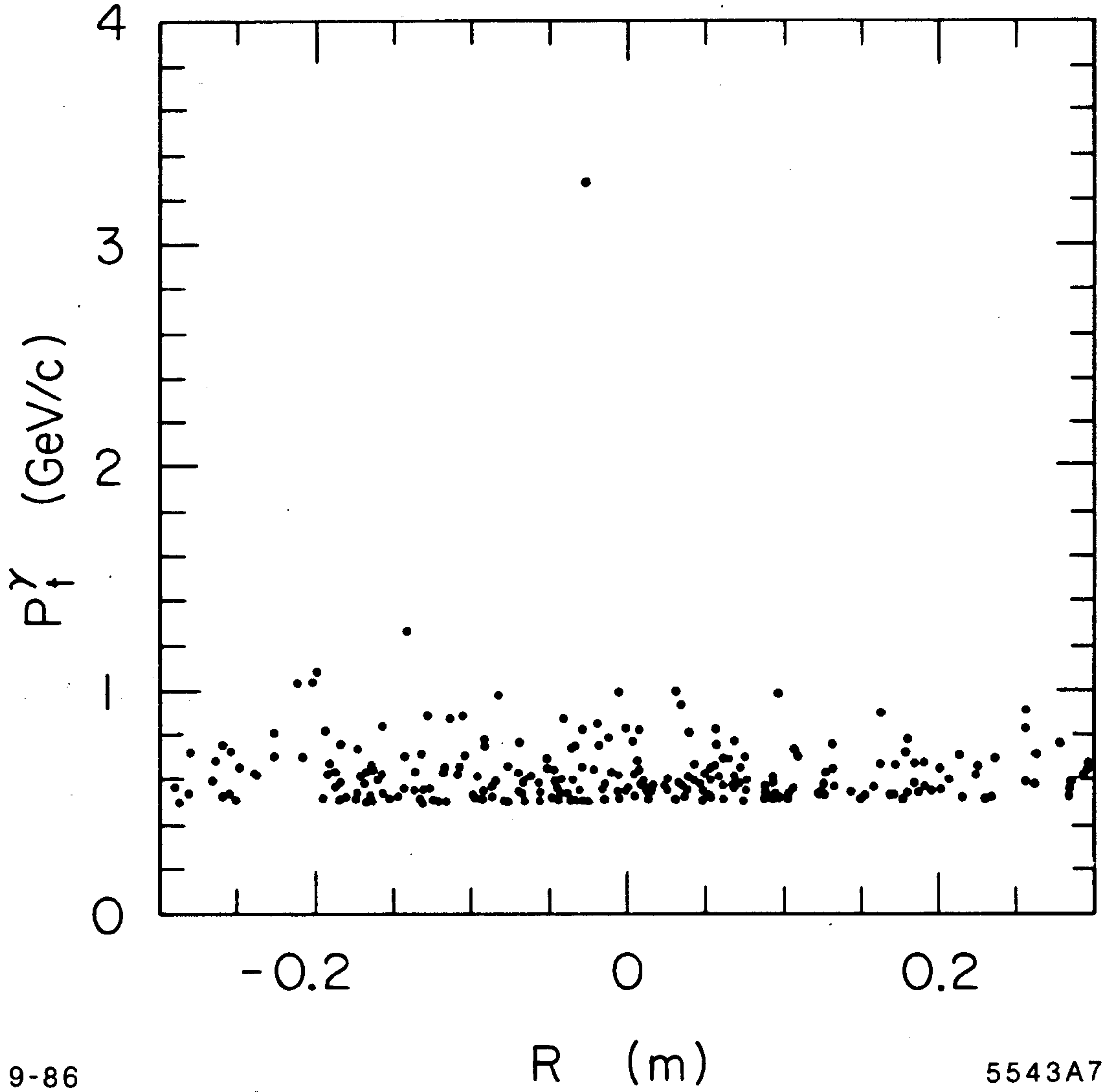
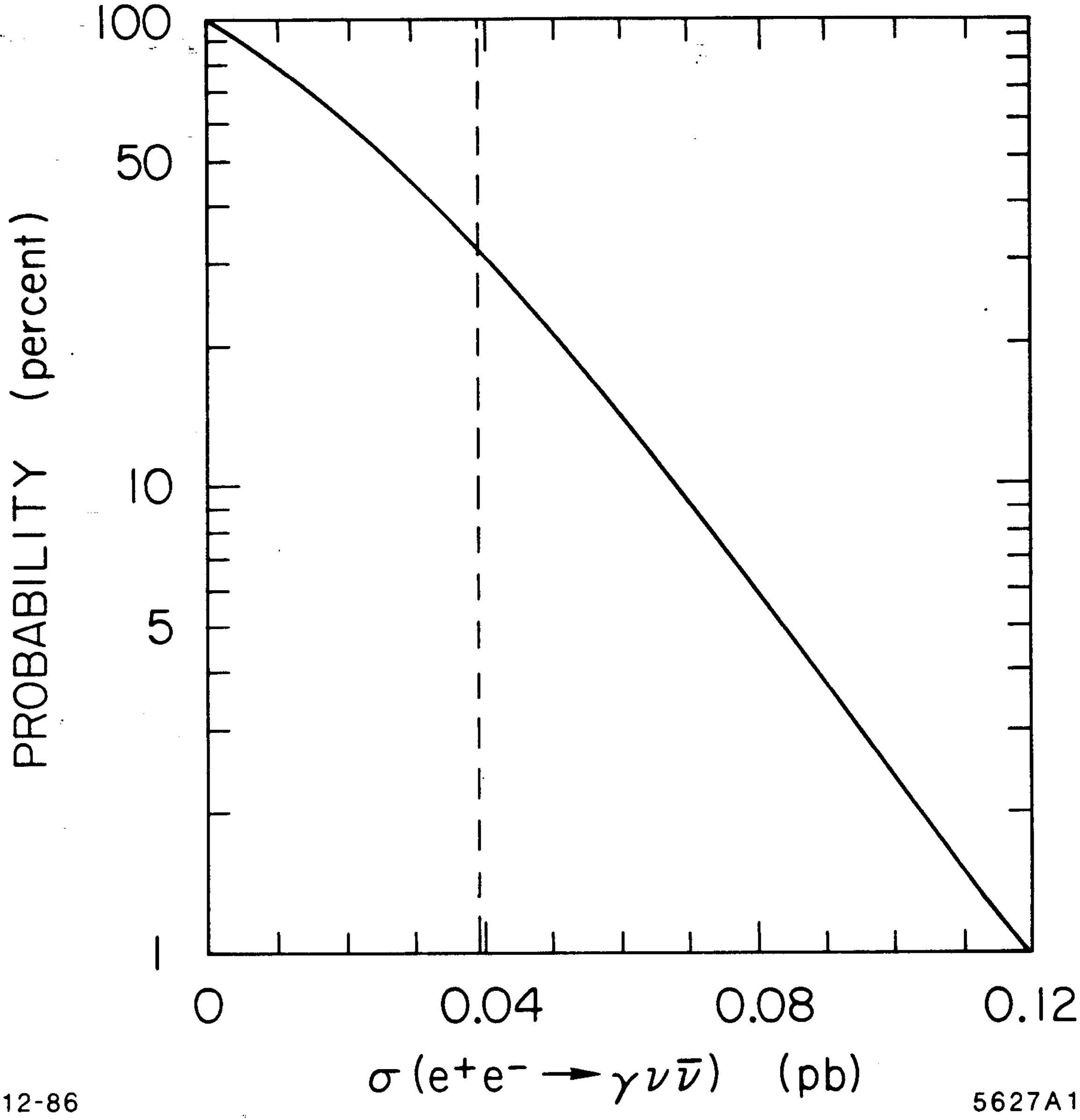
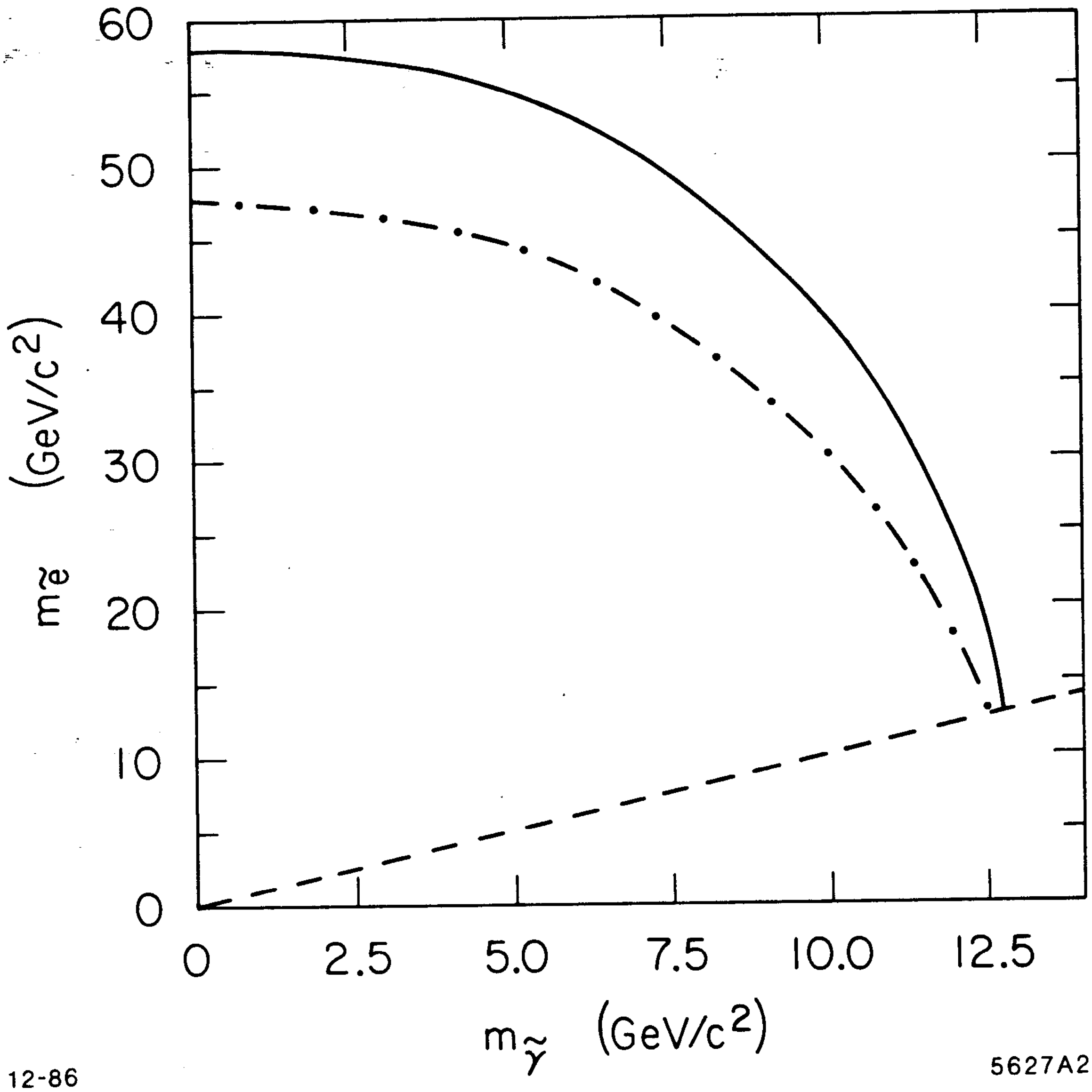


Fig. 2



100
50
10
5
1
PROBABILITY (percent)
0
0.04
0.08
0.12
σ (e⁺e⁻ → γνν̄) (pb)
12-86
5627A1

Fig. 3



60
50
40
30
20
10
0
0
2.5
5.0
7.5
10.0
12.5
$m_{\tilde{e}}$ (GeV/c²)
$m_{\tilde{\gamma}}$ (GeV/c²)
12-86
5627A2

Fig. 4