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PHOTON PAIR PRODUCTION BY e^+e^- ANNIHILATION AND SEARCH FOR SUPERSYMMETRIC PHOTINOS AT ENERGIES GREATER THAN 40 GeV

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Photon Pair Production by e^+e^- Annihilation and Search for Supersymmetric Photinos at Energies greater than 40 GeV

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ABSTRACT. The cross section for the process $e^+e^- \to \gamma\gamma$ has been measured for c.m. energies $39.5 < W < 46.8$ *GeV*. Good agreement with the predictions of QED was found and lower limits for the cut-off parameters of $\Lambda_+ > 61$ *GeV* and $\Lambda_- > 56$ *GeV* (95% confidence level) have been determined. A search for two photon final states with missing energy provided lower limits on the masses of the photino and selectron.

The process $e^+e^- \to \gamma\gamma$ provides a particularly clean test of QED since the hadronic vacuum polarisation as well as electroweak effects can only contribute in higher order. Two photon final states allow also a sensitive test for the production of photinos. Pair production of photinos is exspected to proceed via the exchange of a supersymmetric electron, the selectron, leading to two photons in the final state provided the photino is unstable. We present in this letter a study of two photon production by e^+e^- collisions at c.m. energies near 43 GeV.

The detector. The experiment was performed at the e^+e^- storage ring PETRA using the TASSO detector. The analysis is based on charged particle information from the inner-detector (proportional-chamber, drift-chamber, time-of-flight counters) [1] and on photon detection from the Liquid Argon Barrel Calorimeter (LABC), which is mounted outside of the coil. The LABC, which has been described in detail in Ref. [2] , is segmented in 8 submodules, each consisting of 672 front towers (FT) of dimension $7 \times 7cm^2$ and 160 back towers (BT) of dimension $14 \times 14cm^2$. The front- and back-towers have a thickness of 6.1, 7.6 radiation lengths respectively. The minimum distance between the first sensitive layer and the beamline is 178 cm. The total energy of a shower is measured with a resolution of $\sigma_E/E = 0.136/\sqrt{E} + 0.03$ (E in GeV). Precise shower localisation is provided by four layers of 2 cm wide z-strips (perpendicular to the beam axis), the first two of which are also used for dE/dx measurements, and by three ganged layers of φ-strips (parallel to the beam-axis). The spatial resolution of the LABC for electron (and photon) showers of beam energy is 2 mrad in the azimuthal and 4 mrad in the polar angle. The LABC covers polar angles $|\cos\Theta| < 0.73$ and azimuthal angles $34° < \varphi < 146°$ and $214° < \varphi < 326°$, with a total solid angle of ≈ 40 % of 4π.

Trigger. For the neutral trigger the energy of all front- and back-towers was summed up individually in 160 'local' elements (each corresponding to $\sim \frac{1}{20}$ submodule) and 8 'global' elements (corresponding to the 8 submodules). The pulse height from each element was fed into a discriminator with 4 different energy-thresholds. The neutral trigger used in this analysis demanded either two global elements with $E_{FT} > 2.0\ GeV$ each or two local elements, each with $E_{FT} > 2.0\ GeV$ and $E_{BT} > 0.6\ GeV$ in coincidence. The threshold values varied within ±25% during the data taking period. The threshold conditions lead to a threshold energy of ~ 2 GeV for each photon. Note, however, that due to longitudinal fluctuations in the shower development the fraction of the energy registered in the front- and in the back-towers varies. As a result, the trigger efficiency will only rise gradually above the threshold. In addition to the neutral trigger a 1-track trigger was formed, demanding two local elements each with $E_{FT} > 0.4\ GeV$ in coincidence with at least one charged track.

Data. The data were taken during an energy scan covering c.m. energies W between 39.5 GeV and 46.8 GeV in steps of 30 MeV. At each point about 60 nb^{-1} were accumulated, leading to a total luminosity of 13.6 pb^{-1}.

$\mathbf{e^+e^- \to \gamma\gamma}$. We first discuss the reaction $e^+e^- \to \gamma\gamma$. To distinguish events of this reaction from those of Bhabha-scattering, $e^+e^- \to e^+e^-$, which are roughly 8 times more frequent in our acceptance, only those events were considered where no or only one of the photons converted in the material in front of the tracking chambers. The selection criteria were as follows:

1. At least 2 shower clusters, each with

a) $\frac{1}{3}E_{beam} < E_{cluster} < 1.2E_{beam}$,

b) at least one z- and one φ-strip and

c) the energy seen in the back-towers was required to be at least 10 % of that detected in the front towers.

2. The two most energetic clusters had to be collinear to within 0.2 rad.

3. Events with charged tracks in both the upper ($0° < \varphi < 180°$) and the lower ($180° < \varphi < 360°$) hemisphere were rejected.

In the case of a photon conversion the energies of all clusters belonging to the photon were combined in evaluating condition 1a. Conditions 1b, c served to suppress spurious clusters.

All events selected were inspected visually to reject background from Bhabha-scattering (10%) and cosmic-ray showers (3.5%). The background from Bhabha-scattering arose mainly from two different event topologies:

a) Collinear e^+e^- pairs, where one of the tracks was not reconstructed or one of the tracks had a transverse momentum relative to the beam $p_T < 0.1\ GeV$ due to hard photon emission.

b) e^+e^- pairs with hard bremsstrahlung in the initial or final state with either one electron (positron) going in the forward direction ($|cos\Theta| > 0.87$) or e^+e^- going into the same hemisphere.

After the visual inspection a total of 282 events were found for the reaction $e^+e^- \to \gamma\gamma$, of these 215 events had no photon conversion, for 67 events one of the photons was converted. The background from cosmic ray induced showers could be supressed by timing and cluster shape requirements to a negligible fraction. The remaining background from Bhabha-scattering was estimated by a Monte-Carlo calculation [3] to be less than 0.5%.

For the determination of the cross section the acceptance and the correction factors for trigger inefficiencies, detector losses, selection cuts and QED effects to order α^3 were evaluated.

The efficiency of the LABC triggers ε_{trig} was determined by selecting Bhabha scattering events, that satisfied conditions 1, 2, and comparing the number of events detected with that trigger with those detected independently by the inner detector trigger for two collinear charged tracks (see Ref. [1]). Averaged over the angular acceptance the neutral trigger efficiency was found to be: $\varepsilon^0_{trig} = 73.2 \pm 0.8\%$. The efficiency of the 1-track trigger, which contributes in the case of a photon conversion, was found to be $\varepsilon^1_{trig} = 97.5 \pm 0.3\%$.

The loss of photon pair events due to hardware problems of the LABC was determined using Bhabha scattering events with two back to back tracks and momenta $p > 0.75E_{beam}$, with correct timing and within the LABC acceptance. The efficiency of the LABC, ε_{LABC}, was obtained by comparing the events which satisfied the conditions 1, 2 to the total number of Bhabha events. After correcting for the contamination of events from μ pair and τ pair production (6.7%) the efficiency averaged over the LABC acceptance was found to be: $\varepsilon_{LABC} = 86.2 \pm 0.7\%$. The efficiencies ε_{trig} and ε_{LABC} were determined as a function of running period, polar angle Θ and azimuthal angle φ.

With the help of Monte-Carlo generated events of the type $e^+e^- \to \gamma\gamma$, which were tracked through the detector, we determined a) the azimuthal acceptance of the LABC for this reaction including the loss of events due to shower leakage for photons at the edge of the LABC to be 52.6 %, b) the fraction of doubly converted $\gamma\gamma$ events rejected by condition 3 to be 0.8 % and c) the loss of events due to higher order (α^3) QED radiation [4] to be 6.7 % . In determining the correction factors the effect of the shower development in the LABC was simulated with the computer code EGS [5]. The observed fraction of events with one converted photon was found to be consistent with the Monte Carlo result.

The corrected differential cross-section for $e^+e^- \rightarrow \gamma\gamma$ is presented in Fig. 1a. The errors shown include the statistical error of the data as well as that of the efficiencies. The curve shown in Fig. 1a gives the QED prediction. It agrees well with the data. The total systematic error for the cross section normalisation is estimated to be 5 %; it includes 3.2 % uncertainty due to the luminosity measurement. The cross section integrated over $|\cos\Theta| < 0.7$ was found to be $s\,\sigma = 21.5 \pm 2.0 \pm 1.0\ nb\ GeV^2$, which is in agreement with the QED prediction of 21.4 $nb\ GeV^2$. This is consistent with our previous results obtained at lower energies [6].

Possible deviations from QED via the exchange of a heavy electron, e^*, can be expressed in terms of cut-off parameters Λ_+, Λ_- [7] :

$$s\frac{d\sigma}{d\Omega} = \alpha^2\,\frac{1+\cos^2\Theta}{1-\cos^2\Theta}\,\left(1 \pm \frac{s^2}{2\Lambda_\pm^4}(1-\cos^2\Theta)\right) \qquad (1)$$

The Λ_+ can be interpreted as $\Lambda_+ = m_{e^*}/\lambda$, where λ represents the ratio of the couplings between e, e^*, γ and e, e, γ. A fit of this expression to the data including the systematic uncertainties yielded lower limits of

$$\Lambda_+ = 61\ GeV \quad \text{and} \quad \Lambda_- = 56\ GeV$$

with 95 % confidence. The ratio of the measured differential cross section to the lowest order QED is shown in Fig. 1b together with the prediction using the lower limits of the cut-off parameters $\Lambda_\pm$. Our results may be compared with those of JADE ($\Lambda_+ > 61\ GeV$, $\Lambda_- > 57\ GeV$) [8], CELLO ($\Lambda_+ > 59\ GeV$, $\Lambda_- > 44\ GeV$) [9] and MARK J ($\Lambda > 70\ GeV$) [10].

Search for photinos. The supersymmetric partner of the photon is the photino $\tilde{\gamma}$ [11] with spin-$\frac{1}{2}$. The photino can be pair produced in e^+e^- collisions by the exchange of a scalar electron, $\tilde{e}$ (selectron). The selectrons are the

spin-0 partners of the right- and left-handed electrons. This experiment is only sensitive to photinos which decay inside the detector. In supergravity theories [12] the gravitino absorbs the goldstino $\tilde{G}$ and as a result the photino may or may not decay. In most global supersymmetries [13] the goldstino is the lightest supersymmetric particle (mass of order eV) and the photino decays predominantly via $\tilde{\gamma} \rightarrow \tilde{G} + \gamma$ into a photon and a non-interacting goldstino with a lifetime given by [14,15]:

$$\tau_{\tilde{\gamma}} = \frac{8\pi d^2}{m_{\tilde{\gamma}}^5} \qquad (2)$$

The parameter d represents the scale of the supersymmetry breaking and is exspected to be of the order of $10^4\ GeV^2$; $m_{\tilde{\gamma}}$ is the photino mass. The experimental signature for $e^+e^- \rightarrow \tilde{\gamma}\tilde{\gamma} \rightarrow \gamma\gamma$ + *non-interacting particles* is a pair of photons with average energies $E_\gamma = \frac{1}{2}E_{beam}$. The photons will be almost back to back for small photino masses and will appear less collinear, as the photino mass increases. or acollinear for high masses.

Fig. 2b shows the results of a Monte-Carlo simulation for photino production with $m_{\tilde{\gamma}} = 2$ GeV and for the major background reaction $e^+e^- \rightarrow \gamma\gamma\ ,\gamma\gamma\gamma$. The simulation includes the acceptance and resolution of the LABC. The shape of the energy-sum distribution for the two photons, $E = E_{\gamma_1} + E_{\gamma_2}$, is nearly independent of the photino mass, whereas the acollinearity angle ξ varies strongly with $m_{\tilde{\gamma}}$. This suggests that the supersymmetric process is best discriminated against $\gamma\gamma$ production from QED by a cut in the energy-sum varying with ξ. Candidates for photino production were selected with the following criteria:

1. Exactly two clusters with $2\ GeV < E_{cluster} < 1.3\ E_{beam}$ and at least one z- and one φ-strip per cluster.
2. Both clusters lay in the fiducial volume of the LABC, which in polar angle is defined by $|\cos\Theta| < 0.65$ and in azimuth being $\geq 16\ mrad$ inside of a submodule.
3. The numbers of towers and strips associated with each cluster were restricted. (≤ 20 FT, ≤ 10 BT, ≤ 10 strips for each dE/dx-layer, ≤ 12 φ-strips and ≤ 12 z-strips)
4. Clusters which enclosed a dead tower or where the energy measured in the strips was inconsistent with the front tower energy were rejected.

5. The shower direction was determined from the strip information with an r.m.s. resolution of 70 mrad. Clusters were rejected if their shower direction did not point back to the nominal interaction point within 50 cm measured along the beam.

6. No charged tracks in the inner detector.

A series of additional cuts was imposed to further reduce background from cosmic rays. They differ slightly for $W < 43\ GeV$ ($W \geq 43\ GeV$) because of different beam conditions.

7. The number of hits seen in the drift chamber had to be < 90 (< 110). For comparison the average number of hits produced by synchrotron radiation was 37 (65).

8. The total number of hits seen by all muon chambers had to be less than 20 (45) and less than 8 (10) for the muon yoke chambers alone.

9. The number of drift chamber hits lying in a band stretched between the two clusters had to be less than 29 (35).

Only the following cuts (besides criterion 6 in case of a conversion) should reduce events from the QED reaction $e^+e^- \to \gamma\gamma$.

10. For events with two almost collinear clusters ($\xi < 1°$), the energy of one cluster had to be > 9 (10) GeV, that of the other < 16 (18) GeV.

11. The sum of the cluster energies had to be $E_1 + E_2 < 1.33 E_{beam} - 8\xi$ (energies in GeV, ξ in radian).

A total of 162 events satisfied cuts 1 - 10, they were inspected visually and found to be mostly events of the type $e^+e^- \to \gamma\gamma$. None of the events survived the energy-sum criterion 11. Since no candidate was found for photino production, limits on the masses of photino and selectron were determined.

The cross section for photino pair production, assuming equal contributions from the two types of selectrons (corresponding to the right- and left-handed electrons), can be written as [16]

$$s\frac{d\sigma}{d\Omega} = \frac{\alpha^2\pi\beta^3 s^2}{2}\frac{K^2(1+\cos^2\Theta) - s(2K - m_{\tilde{\gamma}}^2 - \frac{s}{4})\cos^2\Theta + \frac{1}{4}s^2\beta^2\cos^4\Theta}{(K^2 - \frac{1}{4}s^2\beta^2\cos^2\Theta)^2} \quad (3)$$

where $K = m_{\tilde{e}}^2 - m_{\tilde{\gamma}}^2 + \frac{1}{2}s$ and $\beta^2 = 1 - 4m_{\tilde{\gamma}}^2/s$. Monte-Carlo events of the type $e^+e^- \to \tilde{\gamma}\tilde{\gamma}$ were generated for different photino and selectron masses according to equ. 3 and using expression 2 for the photino lifetime. The events were passed through the detector and the conditions 1 - 11 were imposed. Trigger and detector efficiencies were taken into account; QED radiative corrections were not included. The trigger efficiency and its energy dependence were determined using the same procedure as for ε_{trig} but taking the wide energy spectrum of photons resulting from photino decay into account. In order to measure the efficiency of the neutral LABC trigger at low cluster energies, events with two clusters from $e^+e^- \to e^+e^-\gamma$ and from two photon collisions leading to $e^+e^- \to e^+e^-e^+e^-$ were used. This efficiency as a function of the lower cluster energy is shown in Fig. 2a. The rapid drop of the trigger efficiency below 9 GeV is due to the fact that the trigger thresholds were imposed separately on the front tower energies and on the back tower energies.

Fig. 3 shows the range of photino and selectron masses which are excluded with 95 % confidence provided $d = 10^4\ GeV^2$. The lower limit on $m_{\tilde{\gamma}}$ is dominated by the requirement, that the photino decays inside the detector and hence depends on the value of d. The upper limit on $m_{\tilde{\gamma}}$ is basically given by the kinematical constraint $m_{\tilde{\gamma}} < \frac{W}{2}$. For photino masses between 0.1 and 1 GeV the selectron mass has to be > 58 GeV (see insert in Fig. 3). For selectron masses $m_{\tilde{e}} < 30\ GeV$ photino masses in the range $0.06 < m_{\tilde{\gamma}} < 12$ GeV are excluded. Results from the other experiments [8,9,17] are also included in this figure.

Summary. We have measured the reaction $e^+e^- \to \gamma\gamma$ up to c.m. energies of 46.8 GeV. Good agreement with QED was found and cut-off parameters of $\Lambda_+ > 61$ GeV and $\Lambda_- > 56$ GeV were determined. A search for photinos in two photon final states excluded their existence in a mass range given in Fig. 3, provided the photinos are unstable.

FIGURE CAPTIONS

Fig. 1 a The measured differential cross section for $e^+e^- \to \gamma\gamma$ and the lowest order QED prediction.

b The ratio of the measured differential cross section for $e^+e^- \to \gamma\gamma$ to the QED prediction. The solid line shows the deviation from QED characterized by $\Lambda_+ = 61\ GeV$ and $\Lambda_- = 56\ GeV$.

Fig. 2 a The efficiency of the LABC neutral trigger for two clusters with energies $E_1 > E_2$ as a function of E_2. The line represents the function used in the photino simulation.

b The Monte-Carlo simulation of the QED reaction $e^+e^- \to \gamma\gamma, \gamma\gamma\gamma$ and the process $e^+e^- \to \tilde{\gamma}\tilde{\gamma} \to \gamma\gamma$ + *non-interacting particles* assuming a photino mass of 2 GeV and a selectron mass of 55 GeV. The c.m. energy for both cases is 43 GeV; the photinos were generated with a relative luminosity 10 times higher than that of the QED reaction. Shown is the correlation between the energy sum of the two detected photons, $E_1 + E_2$, versus their acollinearity angle ξ. The curve indicates the cut $E_1 + E_2 < 1.33E_{beam} - 8\xi$ (energies in GeV, ξ in radian).

Fig. 3 A plot of the photino mass versus the selectron mass region excluded with 95 % confidence by this experiment; d is assumed as $10^4\ GeV^2$. The insert shows the behaviour at low photino masses. Also shown are the limits obtained by CELLO for $m_{\tilde{\gamma}} = 2$, 12 GeV [**9**] and those of JADE [**17**] and MARK-J [**10**].

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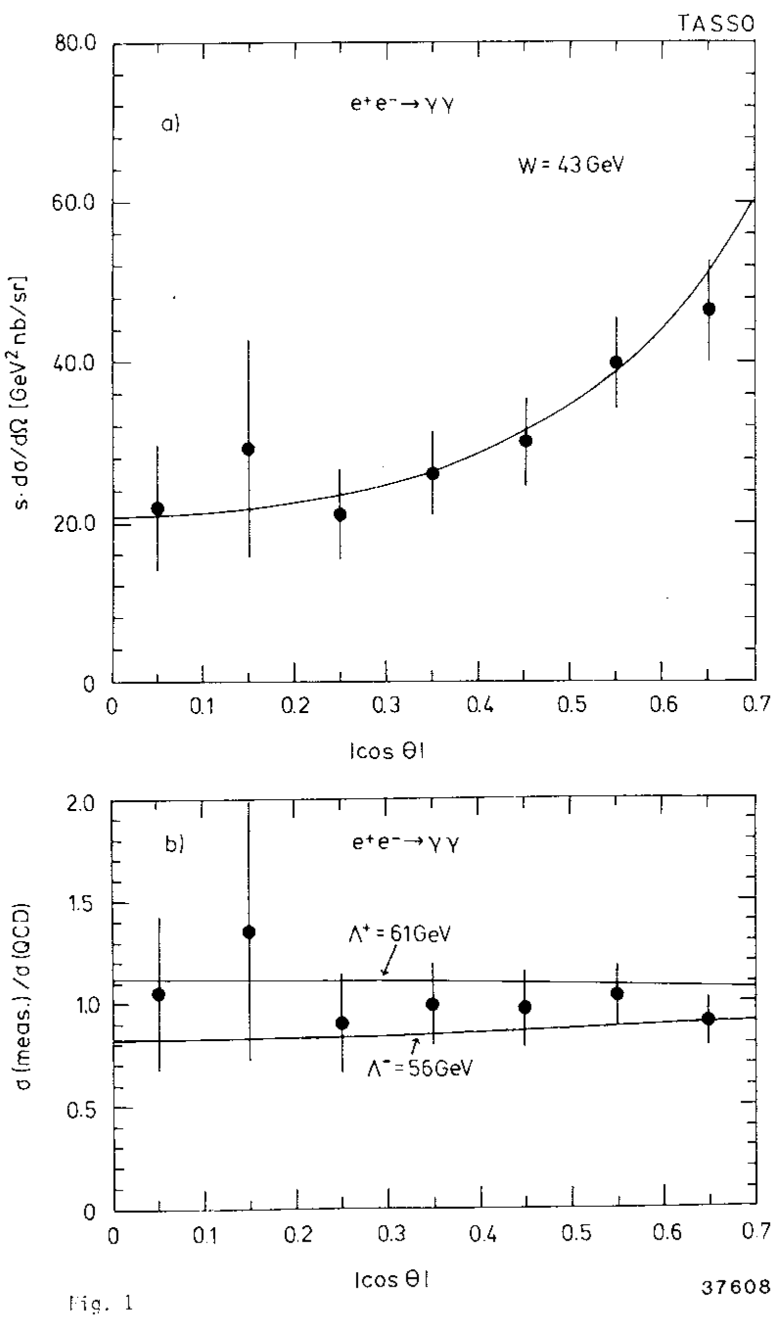

TASSO
a)
$e^+e^- \to \gamma\gamma$
W = 43 GeV
$s \cdot d\sigma/d\Omega$ [GeV^2 nb/sr]
b)
Λ^+ = 61GeV
Λ^- = 56GeV
σ(meas.) / σ(QCD)
|cos θ|
37608

Fig. 1

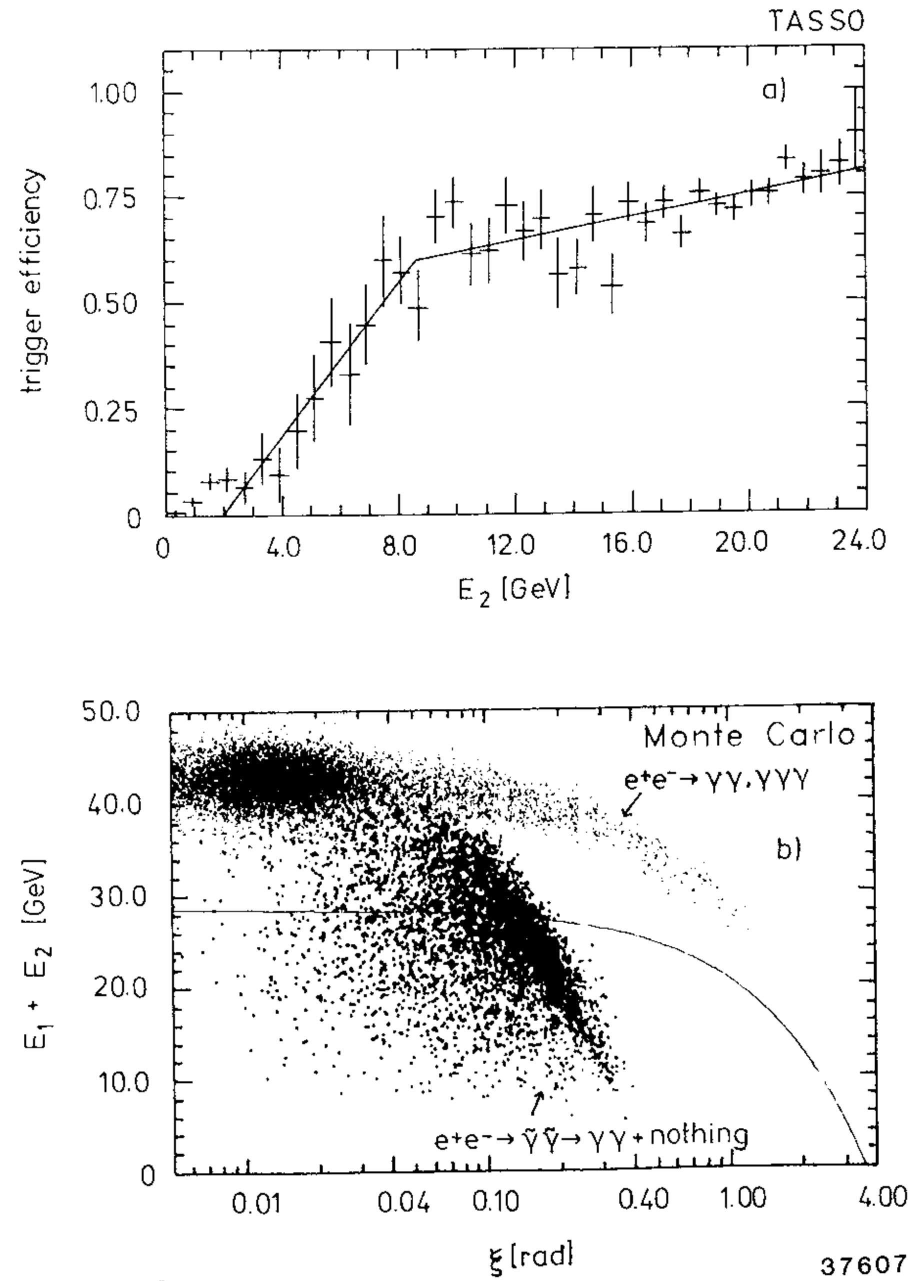
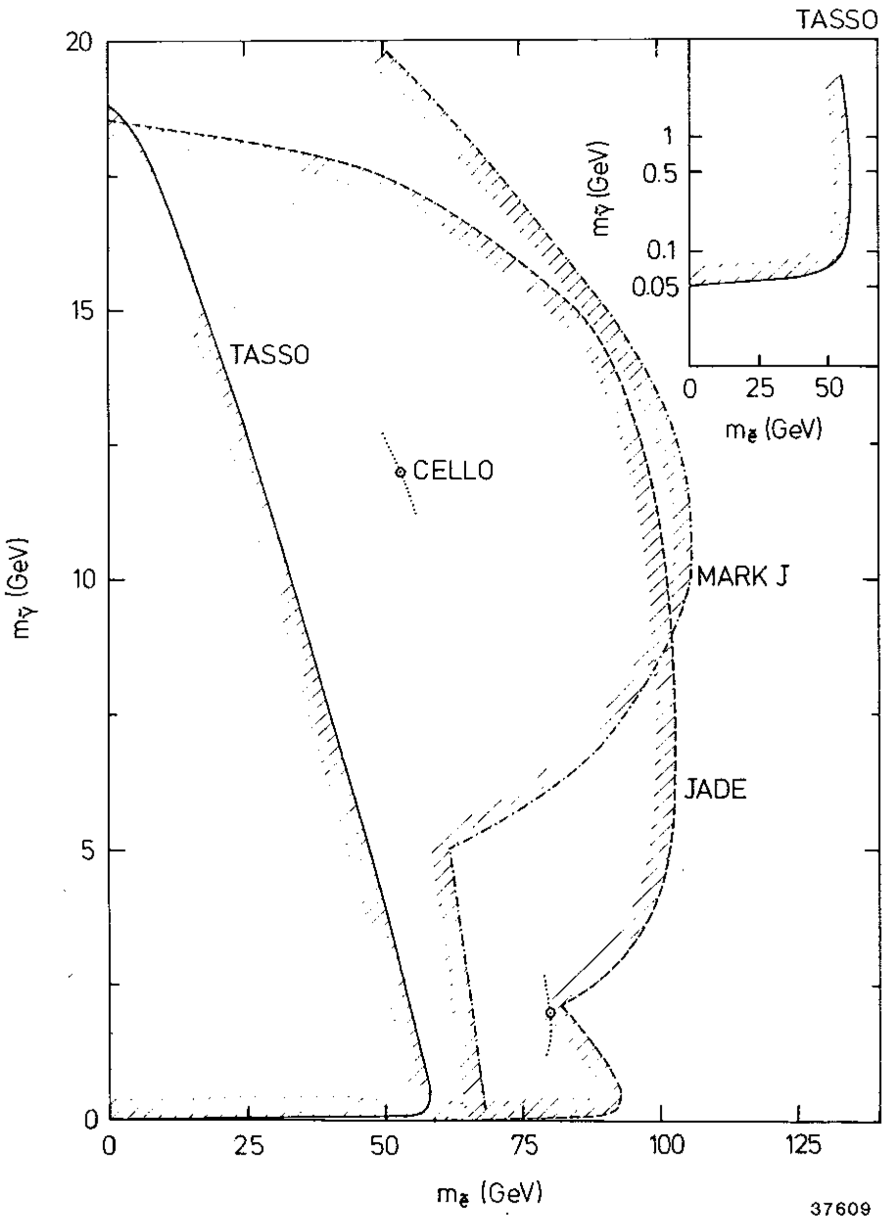

TASSO
a)
trigger efficiency
E_2 [GeV]
Monte Carlo
$e^+e^- \to \gamma\gamma, \gamma\gamma\gamma$
b)
$e^+e^- \to \tilde{\gamma}\tilde{\gamma} \to \gamma\gamma$ + nothing
$E_1 + E_2$ [GeV]
ξ [rad]
37607

Fig. 2



TASSO
CELLO
MARK J
JADE
TASSO
$m_{\tilde{\gamma}}$ (GeV)
$m_{\tilde{e}}$ (GeV)
0
5
10
15
20
25
50
75
100
125
1
0.5
0.1
0.05
37609

Fig. 3