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Radiative τ Pair Production and Search for New Particles Decaying Into τ

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Abstract. A study of radiative τ pair production, $e^+e^-\to\tau^+\tau^-\gamma$ and $e^+e^-\to\tau^+\tau^-\gamma\gamma$, is presented. The observed events agree with QED predictions of order α^3 and α^4. Excited τ's have been searched for and lower limits on single and pair production are obtained. For QED-like coupling the τ^* mass is limited to values greater than 40 GeV (95% CL). A search for unstable charged scalars ($S^\pm$) decaying into τ, e.g. charged Higgs, technipions or the supersymmetric partners of τ's, yields no evidence for such particles. Assuming a branching fraction of $B(S\to\tau\nu)=1$, S masses up to 18.7 GeV are excluded with 95% CL.

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Introduction

The reactions $e^+e^-\to l^+l^-\gamma$ and $e^+e^-\to l^+l^-\gamma\gamma$ ($l=e,\mu,\tau$), which represent lepton pair production with additional bremsstrahlung photons, are QED processes of order α^3 and α^4. A study of these reactions therefore allows tests of QED to higher orders. One important aspect is a test of whether radiative corrections, which are applied in order to extract the lowest order cross section for $e^+e^- \to l^+l^-$, have been correctly calculated.

Another motivation for studying radiative lepton pair production is to search for excited leptons l^* decaying into $l+\gamma$, which are predicted, for example, by composite models [1]. The experimental signature of excited leptons, assuming a prompt decay, is a lepton pair accompanied by one or two photons.

Investigations on radiative e and μ pair production and limits on the existence of e^* and μ^* have been previously presented by the JADE collaboration and other experiments [2, 3]. In this paper we report on the first study of radiative τ pair production, using the JADE detector [4] at the e^+e^- storage ring PETRA. We also present an update with higher statistics on our previous search for charged scalar particles [5]. Data were collected at centre-of-mass energies in the range $30.0 \leqq \sqrt{s} \leqq 46.78$ GeV, with an integrated luminosity of 89.0 pb^{-1}. The average centre-of-mass energy is 36.6 GeV.

A clean sample of $e^+e^- \to \tau^+\tau^-$ events was selected including all decay modes of the τ except those where both τ's decayed into electrons or both into muons. 2,919 events were found. The background was estimated to be $(5.7 \pm 0.8)\%$, and resulted mainly from $e^+e^- \to e^+e^-\tau^+\tau^-$ and multihadronic events. A detailed description of the selection criteria is given in [6]. In this selection no cuts were applied to suppress accompanying photons. For the present analysis, a subsample was selected which contained either one or two well separated photons, detected in the lead-glass shower counters. The geometrical acceptance for the lead-glass hodoscope is $|\cos\theta| \leqq 0.82$ (barrel) and $0.89 \leqq |\cos\theta| \leqq 0.97$ (endcaps), where θ is the polar angle. The energy resolution for photons and electrons in the barrel part is $\sigma_E/E = 0.04/\sqrt{E} + 0.015$ (E in GeV) [7].

$\tau^+\tau^-\gamma$ Events

In the final state of τ pair events there is a high probability of observing photons which originate from semileptonic τ decays, mainly from decays containing π^0's. Because of the small Q-value of the τ decay, the decay products including photons are emitted in a narrow cone around the original τ direction. Radiative τ pair events are selected by demanding at least one isolated photon well separated from the τ decay products. Contributions from τ events of higher order than α^3 and background from other reactions are reduced by the requirement that there be no additional isolated photons with energy $E_\gamma > 1$ GeV and by demanding that the events be planar.

The following selection criteria are applied to the τ data sample of [6] in order to select $\tau^+\tau^-\gamma$ events.

1) There is at least one *isolated* photon with $E_\gamma > 0.5$ GeV, which is separated by more than 30° from the directions of both τ's. The directions of both τ's were reconstructed from the vector sum of the track momenta and the energy weighted direction of all lead glass clusters in a cone of 30° half opening angle with respect to the sum of the track momenta.

2) The energy clusters in the lead glass lie in the fiducial acceptance of the counter array; i.e. not more than 20% of the cluster energy is contained in edge counters of the barrel and end caps.

3) The energy sum of additional isolated photons is less than 1 GeV.

4) The sum of the three opening angles $\sphericalangle(\tau^+,\gamma)$, $\sphericalangle(\tau^-,\gamma)$, $\sphericalangle(\tau^+,\tau^-)$ is greater than 350°, i.e. the event is planar. (The τ direction was defined as described above.)

5) The scalar momentum sum of charged tracks of each τ is required to be larger than 1 GeV.

6) At least one τ is required to decay into exactly one charged particle.

Criterion 5) rejects background from lowest order τ pairs with semileptonic decays into π^0 and one or three low momentum charged pions. The last requirement was used to reduce further background due to multihadronic events and to ensure a good charge determination in order to measure the differential cross section. 123 events passed these selection criteria.

The background from other known reactions was estimated by Monte-Carlo methods to be 11 ± 3 events corresponding to $(9.0 \pm 2.5)\%$ of the final data sample. The main contributions come from multihadronic events (3.7 events) and radiative μ pairs (3.5 events) and to a smaller extent from $e^+e^-\tau^+\tau^-$ (2.5 events) and $e^+e^-q\bar{q}$ (1.4 events) events. After subtracting the background, 112 ± 3 events remain, where the error is due to the uncertainty in the background estimation. A Monte-Carlo simulation of lowest order τ pair events shows that the background from non-radiative events, where the photon originated from a τ decay, is very small, namely 0.5% of the final data sample.

In order to compare the observed events with QED predictions, $\tau^+\tau^-\gamma$ Monte-Carlo events [8] were generated. The τ decay was then simulated according to the measured branching fractions [9] and all decay products were subjected to a full com-

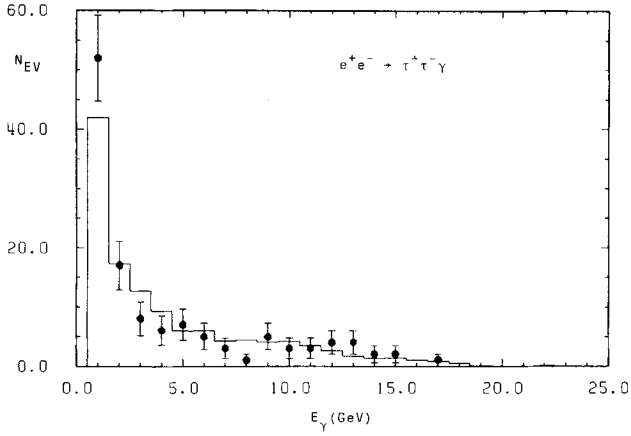

Fig. 1. The photon energy distribution of $\tau^+\tau^-\gamma$ events. The histogram is the QED prediction to order α^3

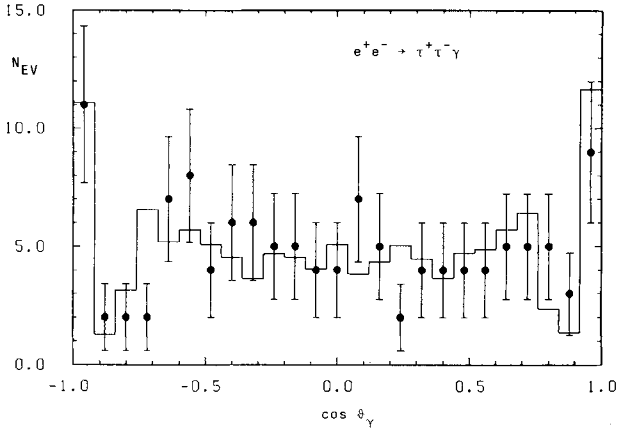

Fig. 2. The photon polar angle distribution for the reaction $e^+e^- \to \tau^+\tau^-\gamma$. The histogram is the QED prediction to order α^3

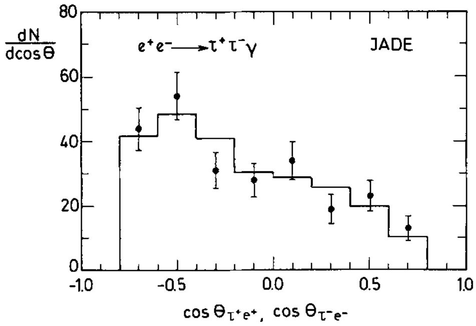

Fig. 3. The τ polar angle distribution for the reaction $e^+e^- \to \tau^+\tau^-\gamma$. The angle of the $\tau^+(\tau^-)$ is measured with respect to the direction of the $e^+(e^-)$ beam. The histogram is a prediction from QED to order α^3

puter simulation of the detector. The simulation took into account the time-integrated luminosities at different centre-of-mass energies, photon conversion in the detector material and inefficiencies of the detector such as the gaps between the lead glass counters (2% for photons) as well as dead counters (0.5%). The Monte-Carlo generated events were then analysed with the same programs as the data. Event losses not included in the acceptance calculation, such as nuclear interaction of particles in the material before the drift chamber and scanning losses, were corrected for separately [10]. The expected number of events from QED diagrams of order α^3 was 100 ± 4, which agrees with the observation within the statistical fluctuation of 11 events. The error of the QED prediction takes into account the uncertainty in the efficiency calculation (2.5%), the luminosity error (2%) and the statistical error of the Monte-Carlo simulation (2%).

The agreement with theory can be further tested by comparing various experimental distributions with QED predictions. The photon energy spectrum (Fig. 1), photon polar angle distribution (Fig. 2) and various other distributions are well reproduced by the QED simulation. The observed distribution of the τ polar angle θ is shown in Fig. 3, where θ is measured with respect to the direction of the e^+ beam for τ^+ and with respect to the e^- beam for τ^-. For events with τ decays into more than one charged particle, the charge of the single track (criterion 6.) was used to determine the τ charge. The simulated distributions are always normalized to the number of observed events without any subtraction of background contributions.

The angular distribution (Fig. 3) shows a negative asymmetry of $A_{\tau\tau\gamma} = (-27.6 \pm 8.7)\%$, comparing the number of events in the forward ($\cos\theta > 0$ for a positive track) and the backward ($\cos\theta < 0$) direction. This asymmetry is due to the interference of the diagrams with initial and final state radiation and is well reproduced by the QED prediction. The expected asymmetry from QED is $A = -(31.4 \pm 2.2)\%$, and from the standard model taking into account Z^0 exchange in addition $A = -(36.2 \pm 4.0)\%$, where the two latter errors are due to limited Monte Carlo statistics. The error of the measured asymmetry does not allow us to distinguish between QED and Standard Model predictions.

For the selection cuts used, both initial and final state radiation are important. The average value of the squared moduli of the amplitudes for initial and final state photon production are in the ratio $|M_i|^2 : |M_f|^2 = 64:36$, which was calculated using the Monte-Carlo program by Berends et al. [8]. Since photons radiated in the initial state are predominantly emitted at small angles with respect to the beams, we used cuts on the photon polar angle to enhance the effects of final or initial state radiation. Events where the photon is observed in the barrel part of the shower counter ($|\cos\theta_\gamma| < 0.82$) show a

Table 1. Measured and expected asymmetries (A). $|M_i|^2:|M_f|^2$ is the ratio of the squared moduli of the amplitudes for initial and final state bremsstrahlung

	A (%)		$\|M_i\|^2:\|M_f\|^2$
	measured	QED prediction	
All events	-27.6 ± 8.7	-31.4 ± 2.2	64:36
$0.89<\|\cos\theta_\gamma\|<0.97$	-8.0 ± 19.9	-0.5 ± 7.1	91:9
$\|\cos\theta_\gamma\|<0.82$	-32.7 ± 9.5	-39.1 ± 3.4	47:53

large asymmetry of $(-32.7\pm 9.5)\%$; for these, the squared moduli of the amplitudes are in the ratio 47:53. In the endcap region ($0.89<|\cos\theta_\gamma|<0.97$) the ratio is 91:9, and the interference effect is smaller ($A=-8.0\pm 19.9\%$). This behaviour of the asymmetry agrees with the prediction from QED (see Table 1).

$\tau^+\tau^-\gamma\gamma$ Events

The study of $\tau^+\tau^-\gamma\gamma$ events is broadly similar to the $\tau^+\tau^-\gamma$ analysis. We again use the τ data set and impose the following selection criteria:

1) There are at least two isolated photons with $E_\gamma>0.5$ GeV, which are separated by more than 30° from the direction of both τ's.

2) The angle between the two highest energy photons is greater than 10°, and the $\gamma\gamma$ invariant mass larger than 0.5 GeV.

3) The sum of the energy of any additional isolated photons is required to be less than 0.5 GeV.

4) At least one τ is required to decay into exactly one charged particle.

After these criteria are applied, 11 events are selected. Three events are also contained in the $\tau^+\tau^-\gamma$ data sample. All the events have exactly two isolated photons with $E_\gamma>0.5$ GeV. The background from τ pair production of order α^2 and α^3, estimated using Monte-Carlo simulation, is 1.6 ± 0.4 events. Contributions from other processes are calculated to be negligible.

The number of events expected from the α^4 QED prediction was calculated by a Monte-Carlo method according to the formula for the reaction $e^+e^-\to\mu^+\mu^-\gamma\gamma$ given by Berends et al. [11]. The Monte-Carlo program for muons, modified to include τ production and decay, predicts 9.7 ± 1.2 events. The number of observed events corrected for background, 9.4 ± 0.4, is in good agreement with the expectation within the statistical fluctuation of 3.3 events. The experimental distributions of photon energy (Fig. 4) and photon polar angle (Fig. 5) were found to be consistent with the expectations from QED of order α^4.

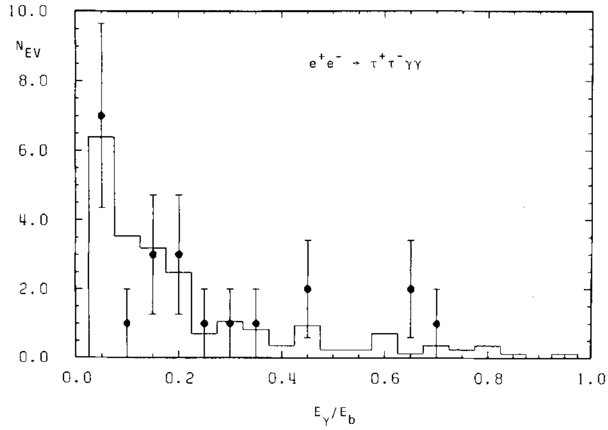

Fig. 4. The normalized photon energy distribution of $\tau^+\tau^-\gamma\gamma$ events. The histogram is the QED prediction to order α^4

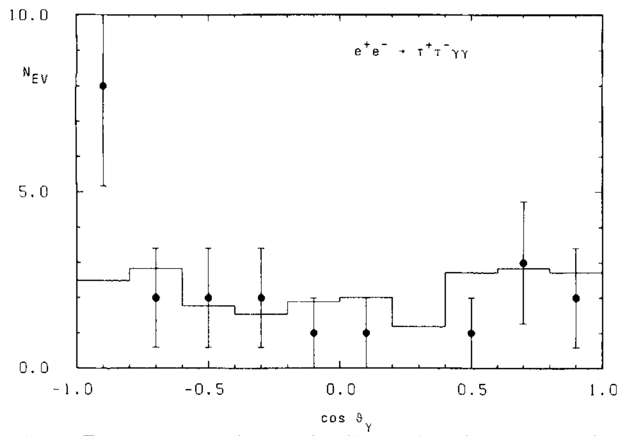

Fig. 5. The photon polar angle distribution for the reaction $e^+e^-\to\tau^+\tau^-\gamma\gamma$. The histogram is the QED prediction to order α^4

Search for τ^* Production

An excited spin $\frac{1}{2}$ lepton may couple to the corresponding ground state lepton and the photon by the following interaction [12–14]:

$$L_{\text{int}}=\frac{\lambda e}{2M_{\tau^*}}\bar{\Psi}_\tau\sigma_{\alpha\beta}\Psi_{\tau^*}F^{\alpha\beta}+\text{h.c.},$$

where λ is a dimensionless parameter relating the $\tau^*\tau\gamma$ coupling to the ordinary electromagnetic coupling e, M_{τ^*} is the τ^* mass and $F^{\alpha\beta}$ the electromagnetic field tensor. The differential cross section for the reaction $e^+e^-\to\tau^{*+}\tau^-$ or $\tau^+\tau^{*-}$ is given by [13, 14]:

$$\frac{d\sigma}{d\Omega}=\frac{\alpha^2\lambda^2}{2M_{\tau^*}^2}\left(1-\frac{M_{\tau^*}^2}{s}\right)^2\left[\left(1-\frac{M_{\tau^*}^2}{s}\right)\sin^2\theta+\frac{2M_{\tau^*}^2}{s}\right],$$

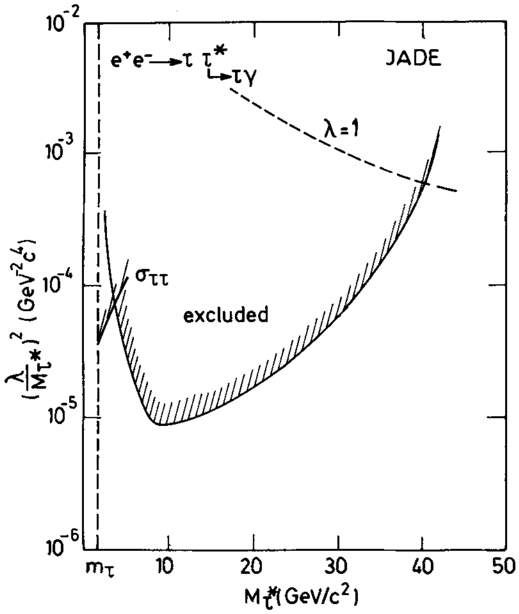

Fig. 6. The 95% CL upper limit of $(\lambda/M_\tau^*)^2$ as a function of M_{τ^*} for the reaction $e^+e^- \to \tau\tau^* \to \tau^+\tau^-\gamma$. The low mass region is excluded from the measurement of the total cross section of $e^+e^- \to \tau^+\tau^-$

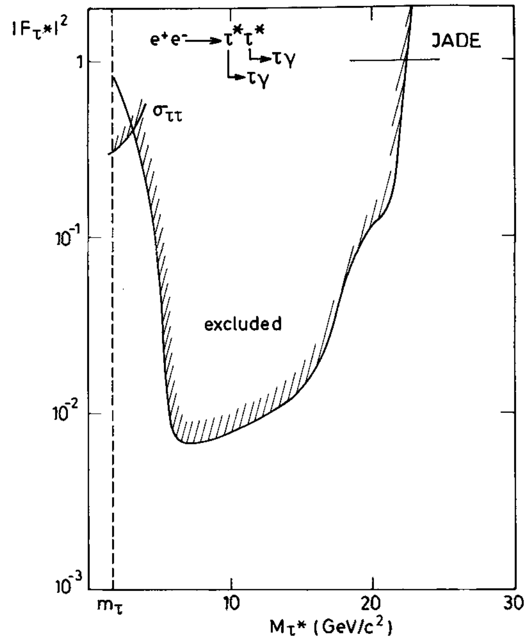

Fig. 7. The 95% CL upper limit on the τ^* pair production form factor F_{τ^*} as a function of M_{τ^*}. The low mass region is excluded from the measurement of the total cross section of $e^+e^- \to \tau^+\tau^-$

where form factor effects are absorbed in the coupling λ neglecting the q^2 dependence.

The differential cross section for $\tau^*\tau^*$ production is:

$$\frac{d\sigma}{d\Omega} = \frac{\alpha^2}{4s}\beta[1+\cos^2\theta + (1-\beta^2)\sin^2\theta]|F_{\tau^*}|^2,$$

where β is the velocity of the τ^* and F_{τ^*} is a form factor, which has a value of 1 for a point-like particle.

A study of $\tau^+\tau^-\gamma$ events allows one to search for τ^* in the process $e^+e^- \to \tau\tau^*$ with τ^* masses nearly up to the centre-of-mass energy, the final result depending on the coupling parameter λ. Pair production of the τ^* is only possible for τ^* masses less than half that centre-of-mass energy.

Because of undetected neutrinos, the original τ momentum cannot be precisely reconstructed. We therefore do not use the invariant mass distribution to distinguish between τ^* and bremsstrahlung events. A better separation is obtained by using the photon energy, which in the τ^* rest frame is equal to half the τ^* mass. In addition the sensitivity for τ^* events is enhanced by looking for events where the photon is observed in the barrel part of the detector. In the search for excited leptons produced in the processes $e^+e^- \to \tau^*\tau$ or $\tau^*\tau^*$ we applied the following additional cuts to the observed $\tau^+\tau^-\gamma[\tau^+\tau^-\gamma\gamma]$ events:

1) The photon is [both photons are] detected in the barrel part of the shower counter array ($|\cos\theta| < 0.82$) and

3) the photon energy [energy of each photon] is larger than $M_{\tau^*}/3$.

An upper limit on $(\lambda/M_{\tau^*})^2$ is determined from the total number of observed $\tau^+\tau^-\gamma$ events, taking into account the known QED contribution and the number of expected $\tau\tau^*$ events. The number of expected events was calculated using Monte-Carlo events generated according to the cross section given above. It is difficult to distinguish between $\tau\tau^*$ and QED events if the τ^* mass is small ($M_{\tau^*} < 3$ GeV). We therefore used the measured total cross section of the process $e^+e^- \to \tau^+\tau^-$ [6] to determine a limit on τ^* production in the low mass region. The result for the upper limit at 95% CL on $(\lambda/M_{\tau^*})^2$ is shown in Fig. 6. Assuming $\lambda = 1$, i.e. the τ^* couples like an ordinary lepton, we derive a lower limit on the τ^* mass of 40 GeV (95% CL). Similar results have recently been obtained by the CELLO collaboration [16].

We observe no indication for τ^* pair production. In order to obtain a limit on the form factor, the efficiency to observe $\tau^*\tau^*$ events was calculated by a Monte-Carlo method according to the cross section. The upper limit on the form factor was determined from the number of observed $\tau^+\tau^-\gamma\gamma$ events, that passed the additional cuts, the QED α^4 prediction and the expected number of $\tau^*\tau^*$ events. The result for the 95% CL upper limit is shown in Fig. 7 as a function of the τ^* mass. If the form factor is equal to one, the τ^* mass is limited to values greater than 22.5 GeV (95% CL).

Search for Charged Scalar Particles

In this section, we present an update of our previous search for charged scalar particles [5], which was based on a smaller data sample. The existence of charged scalar particles $S^\pm$ is predicted in a number of models, e.g. supersymmetry, hyper (techni)-color models or electroweak models with a non-minimal Higgs sector. Charged Higgs particles or technipions are assumed to decay predominantly into heavy particles, i.e. decays into τ are favoured among leptonic decays, $(S^\pm \to \tau^\pm \nu_\tau)$. Hadronic decays could proceed via $(c\bar{s})$ or $(c\bar{b})$ quark pairs. Characteristic features of the process $e^+e^- \to S^+S^- \to (\tau^+\nu)(\tau^-\nu)$ or $(\tau\nu)$(hadrons) are missing energy and large acoplanarity between the observed $S^\pm$ decay products. Independent analyses were performed for the $(\tau\nu)(\tau\nu)$ and the $(\tau\nu)$(hadrons) modes.

Events where both scalar particles decayed into $(\tau\nu)$ were searched for in the τ data sample [6]. In order to suppress $e^+e^- \to \tau^+\tau^-$ events the following criteria were applied:

1) There is no isolated photon with $E_\gamma > 0.5$ GeV, which is separated by more than 30° from the directions of both τ's.

2) The scalar momentum sum of charged particles of each τ is greater than 2 GeV.

3) The acoplanarity angle of both τ's with respect to the beam axis has to be greater than 30°.

The momentum cut 2) was applied to reject τ events with one τ decaying asymmetrically into a very low momentum charged particle. One event, produced at $\sqrt{s} = 35$ GeV, with a low energy photon ($E_\gamma < 0.5$ GeV) detected at the edge of the lead glass endcap survived all cuts, and is consistent with the background expected from QED τ pair production of 0.8 events.

The significance of this result was assessed using Monte-Carlo simulation of the process $e^+e^- \to S^+S^- \to (\tau^+\nu)(\tau^-\nu)$. In the simulation, an S pair was created according to the point-like differential cross section:

$$\frac{d\sigma}{d\Omega} = \frac{\alpha^2}{8s}\beta^3 \cdot \sin^2\theta,$$

where β is the velocity of S. The result for the upper limit on the branching fraction $B(S \to \tau\nu)$ as a function of the S mass (m_S) is shown in Fig. 8. As this method is not sensitive to low m_S a region at low masses can be excluded using our measurement of the $e^+e^- \to \tau^+\tau^-$ total cross section [6], which is in good agreement with the QED prediction. This result is also indicated in Fig. 8.

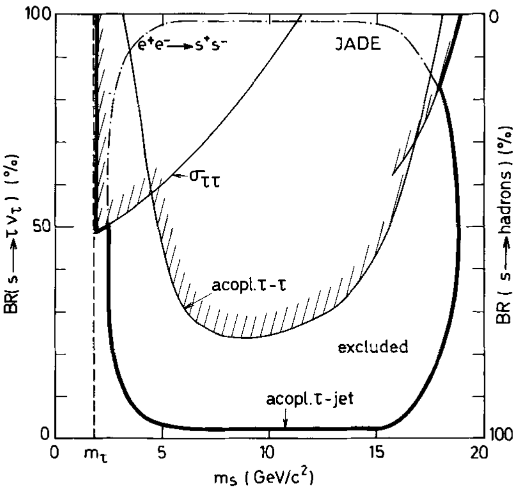

Fig. 8. Upper limits on the branching fraction $B(S \to \tau\nu_\tau)$ as a function of m_S for a charged scalar particle S. The different curves represent the limits obtained from acoplanar τ pair and multihadronic events and the measurement of the total cross section for the reaction $e^+e^- \to \tau^+\tau^-$. Combining these results, the dashed area is excluded with 95% confidence

Candidates for the $(\tau\nu)$(hadrons) mode were sought among a high multiplicity data sample, which consists of ordinary multihadrons and hadronic two-photon events, by looking for acoplanar events. The detailed criteria to search for S events are given in [5]. In the Monte-Carlo simulation the S^+ and S^- were allowed to decay into $(\tau\nu)$ and $(c\bar{s})$. The quark pair was then fragmented into hadrons according to the Lund scheme [15]. Using the constraint: $B(S \to \tau\nu) + B(S \to (c\bar{s})) = 1$, we derive a limit on the branching ratio versus m_S as shown in Fig. 8. The decay into $(c\bar{b})$ quarks was also investigated and resulted in very similar limits on the branching fraction. The limit for example at $m_S = 18$ GeV changed from $B(S \to \tau\nu) = 18\%$ to 20% using the decay mode $(c\bar{b})$ instead of $(c\bar{s})$. The production of S^+S^- is excluded with 95% CL for 3 GeV $< m_S <$ 18 GeV if the branching fraction into τ is greater than 10%. Similar results have been obtained by other experiments [15].

For $B(S \to \tau\nu) = 1$, e.g. a supersymmetric partner to the τ lepton, we can exclude the existence of charged scalar particles decaying into τ up to masses of 18.7 GeV with 95% CL, assuming that the photino $(\tilde{\tau} \to \tau\tilde{\gamma})$ or goldstino $(\tilde{\tau} \to \tau\tilde{G})$ mass is zero.

Summary

The production of radiative τ pair events has been studied and has been compared with QED predictions. The corrected number of observed $\tau^+\tau^-\gamma$ events ($112 \pm 11 \pm 3$ events) and various experimental distributions are well described by QED of order α^3, where 100 ± 4 events are expected. A forward-backward asymmetry of $(-27.6 \pm 8.7)\%$ is observed, which is due to the interference of the diagrams with initial and final state radiation. Order α^4 processes have been studied using $\tau^+\tau^-\gamma\gamma$ events. The result of 9.4 ± 3.3 events is in good agreement with the QED α^4 prediction of 9.7 ± 1.2 events.

The observed $\tau^+\tau^-\gamma$ and $\tau^+\tau^-\gamma\gamma$ data samples were further used to search for the existence of an excited τ that decays into $\tau\gamma$. For single τ^* production, limits on the coupling constant have been obtained. Assuming ordinary electromagnetic coupling, τ^* production is excluded up to τ^* masses of 40 GeV with 95% CL. From the $\tau^+\tau^-\gamma\gamma$ final states, an upper limit on the τ^* form factor was derived. If the τ^* pair production is point-like, the mass is larger than 22.5 GeV (95% CL).

A search for unstable charged scalar particles $S^{\pm}$ has been performed using τ pair and multihadronic data sets. No evidence for such particles was observed in the decay modes $e^+e^- \to S^+S^- \to (\tau\nu)(\tau\nu)$ and $(\tau\nu)$(hadrons). A large region of the plot of branching fraction $B(S \to \tau\nu)$ versus the S mass is excluded. For $B(S \to \tau\nu) = 1$, e.g. a supersymmetric partner to the τ lepton, we determined a lower limit of 18.7 GeV with 95% CL assuming that the photino (goldstino) is massless.

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