SEARCH FOR SCALAR MUONS

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The supersymmetric partner of the muon was searched for in a systematic way. No candidate was found and 95% CL limits on its mass were given for different cases. If it is stable, the limit is 20.9 GeV/c^2. If it decays into a muon and an invisible low-mass particle, the limit is 20.3 GeV/c^2. If it decays into a muon and an unstable neutral particle which decays further into a photon and an invisible massless particle, the limit is 19.2 GeV/c^2.

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Supersymmetry (SUSY) theories [1] [‡1] have been studied extensively. They provide a natural solution to such questions as the hierarchy problem of grand unified theories [4]. In the simplest case the theories assume that every elementary particle has its supersymmetric partner which has a spin differing by 1/2. The SUSY partner of the photon is the photino, $\tilde{\gamma}$, which has spin 1/2. A lepton has two scalar partners corresponding to the right-handed and the left-handed components of the lepton. For the muon they are called smuons and denoted as $\tilde{\mu}_R$ and $\tilde{\mu}_L$ (or simply $\tilde{\mu}$ without distinguishing). Since there is no SUSY multiplet among the known particles, the symmetry is considered to broken with a large mass scale. A theoretical requirement on the mass difference sets an upper limit of O(1) TeV/c^2. Although several schemes are proposed to create the mass splitting, the theories do not predict exact masses for the SUSY particles and the masses must be determined experimentally. A number of searches for the SUSY particles at high energies [5] have not been successful yet and limits on their masses have been obtained. Since there are many different conjectures about the mass spectrum of SUSY particles and experimental searches were based on specific assumptions, one should keep in mind that the limits are valid only under the assumed conditions. We try to investigate systematically different possibilities of smuons assuming that the SUSY quantum number is conserved fairly well if not perfectly. A similar systematic search for a scalar electron is reported in a separate paper [6].

In the e^+e^- reaction, point-like smuons are produced in pairs according to the following formula:

$$(\mathrm{d}\sigma/\mathrm{d}\Omega)(e^+e^- \to \tilde{\mu}\tilde{\mu}) = (\alpha^2/8s)\beta_\mu^3 \sin^2\vartheta_\mu, \qquad (1)$$

where s is the total energy squared and β_μ is the velocity of the $\tilde{\mu}$ normalized by the velocity of light. The masses of the $\tilde{\mu}_R$ and the $\tilde{\mu}_L$ may be degenerate or one of them (e.g. $\tilde{\mu}_R$) may be lighter than the other ($\tilde{\mu}_L$). In the following the second case is assumed and eq. (1) is used without multiplying by a factor 2, which would be necessary in the case of degeneracy.

Experimental searches for the $\tilde{\mu}$ which have been reported so far [7] assume that the $\tilde{\mu}$ decays into a muon and a massless photino. There is, however, a cosmological study [8] which suggests that the photino mass is larger than a few GeV/c^2. In such a case several possibilities about the $\tilde{\mu}$ can be considered. If the $\tilde{\mu}$ is the lightest among the SUSY particles, it may be either stable or extremely longlived. On the contrary, if the $\tilde{\gamma}$ is lighter than the $\tilde{\mu}$, the $\tilde{\mu}$ can decay electromagnetically into a muon and a photino with a short lifetime [9]. For an unstable $\tilde{\mu}$, we assume that the only decay mode [‡2] is $\tilde{\mu} \to \mu\tilde{\gamma}$, where the photino is assumed not to interact in the detector. If the photinos are stable, a signal for $\tilde{\mu}$ pair production is two muons with degraded energies and unbalanced momenta. Since the detection efficiency for the $\tilde{\mu}$ varies with the mass of the $\tilde{\gamma}$, various masses of the $\tilde{\gamma}$ are studied. If the photino decays further into a photon and a light spin 1/2 SUSY particle (goldstino) as has been suggested by some models [10], $\tilde{\mu}$-pair production will result in a $\mu\mu\gamma\gamma$ event with missing energy.

In the following, the three different cases will be discussed: (case 1): stable $\tilde{\mu}$; (case 2): unstable $\tilde{\mu}$ decaying into a muon and a stable $\tilde{\gamma}$; (case 3): unstable $\tilde{\mu}$ decaying into a muon and an unstable $\tilde{\gamma}$. A preliminary result of the work has been reported [11].

Data were accumulated by the JADE detector at PETRA. A detailed description of the detector can be found elsewhere [12]. The essential parts of the detector for this analysis were the central drift chamber ("jet-chamber") which detects charged particles with 48 samplings providing a momentum and dE/dx measurement, the time-of-flight (TOF)/trigger counters surrounding the chamber, the solenoid magnet producing 4.8 kG, the lead glass (LG) shower counter array surrounding the coil and the five layers of muon chambers interspersed between the hadron absorbers. Four types of trigger were effective for this analysis. They were (1) the coplanar charged particle pair trigger; (2) the pure track trigger which requires 2-tracks in the jet-chamber plus 2 TOF counters in coincidence with the LG counters; (3) the track-shower trigger which requires 2-tracks and a LG shower energy deposit ($\geqq$ 1.5 GeV); and (4) the shower trigger (i.e. LG

‡1 For a review, see ref. [2]; for recent developments see ref. [3].

‡2 When the photino is heavier than the $\tilde{\mu}$ and there is a light scalar neutrino, the $\tilde{\mu}$ may decay weakly. Actual branching ratios for various decay modes depend on the masses of the scalar neutrinos and SUSY partners of the weak bosons, the wino and the zino. Since a systematic study for this possibility requires involved assumptions on these masses, such a case is not investigated here.

shower $\geqq 4$ GeV). In the last trigger, tracks were not required. The triggers (3) and (4) were useful only for case 3.

Stable $\tilde{\mu}$'s. A pair of stable $\tilde{\mu}$'s behave like an electron or a muon pair in the detector depending on the mass. If the $\tilde{\mu}$ is as light as the electron, it initiates an electromagnetic shower causing a substantial deviation of the Bhabha scattering cross section from QED. For instance Bhabha scattering cross section at $\cos\vartheta = 0.0$ (0.5) will increase by a factor 1.11 (1.27) compared to QED. Since there is no evidence for such a deviation [13], the very light $\tilde{\mu}$ is excluded. From the muon-pair-production cross section which is well described by the standard electroweak theory at PETRA energies [14,15], one can obtain a limit on the mass of the scalar muons [14,15]. The forward–backward folded muon-pair cross section at 34.2 GeV was fitted to the QED prediction including a possible $\tilde{\mu}$ contribution as given by eq. (1). An estimated error of 5% on the absolute normalisation was taken into account. An upper limit of 0.62 is obtained for β_μ corresponding to a lower limit of 13.4 GeV/c^2 on the mass of the stable $\tilde{\mu}$.

If the $\tilde{\mu}$ is heavier than about 12 GeV/c^2, a more efficient search for $\tilde{\mu}$ pairs can be made by using momentum, time-of-flight and dE/dx measurements. For this purpose a data sample was selected under selection conditions similar to those for collinear $\mu\mu$ pairs [14] except for the TOF cut, which was removed to allow heavy (i.e. slow) particles. The total integrated luminosity of the data used for this analysis was 68.37 pb^{-1} and the highest total energy was 46.78 GeV. The following selection conditions were used to search for heavy particle pairs:

(1) the momenta of the two tracks agree within 3.5 standard deviations, i.e., $|p^+ - p^-| \leqq 0.15\, p_{av}^2$, where p_{av} is the average momentum of the two tracks in GeV/c;

(2) the lead glass energy deposit associated with a track must be less than 1.5 GeV or less than a quarter of the momentum of the track,

(3) the velocities of the tracks as measured by the TOF counters must agree within 3 standard deviations, $|\beta^+ - \beta^-| \leqq 0.4\beta_{av}^2$, where β_{av} is the average of the β^+ and β^-;

(4) both particles are slow, i.e. $\beta^+ \leqq 0.7$ and $\beta^- \leqq 0.7$;

(5) the dE/dx values of the tracks are consistent with cut (4), i.e. $dE/dx \geqq 10$ keV/cm.

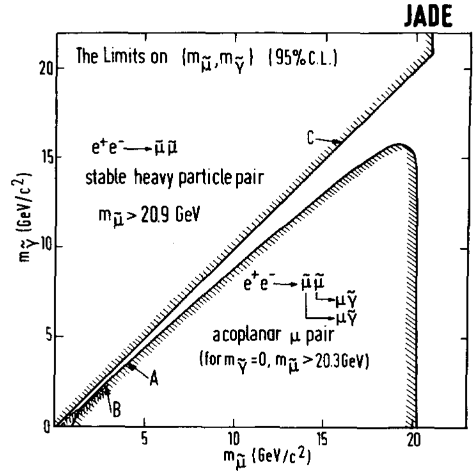

Fig. 1. A limit on the masses for the $\tilde{\mu}$ and $\tilde{\gamma}$ for the stable $\tilde{\gamma}$; curve A, from the acoplanar muon pairs with large $P_{t,miss}$, curve B, from the quasi-acoplanar muon pairs. A limit on the mass of the stable $\tilde{\mu}$ is also shown by curve C.

There are 11 events which satisfy conditions (1)–(4). But none of them satisfies the dE/dx cut. These 11 events with low dE/dx values are consistent with being cosmic ray muons having penetrated the detector a long time after the beam crossing and survived other cuts. The expected number of events for various masses of the $\tilde{\mu}$ was calculated by a Monte Carlo calculation under the above conditions. In the simulation, the luminosity distribution of the data was used and radiative corrections for a scalar particle pair were applied according to Berends and Kleiss [16]. By combining the two analyses a lower limit on the mass of the stable $\tilde{\mu}$ was obtained to be 20.9 GeV/c^2 (curve C in fig. 1) [‡3].

Unstable $\tilde{\mu}$ decaying into a stable $\tilde{\gamma}$. In order to search for $\tilde{\mu}$'s which decay into stable $\tilde{\gamma}$'s, acoplanar muon pairs accompanied by no other visible particles were studied. The distribution of the expected acoplanarity angle, which is defined below, depends on the mass of the $\tilde{\mu}$'s. For a heavy $\tilde{\mu}$, it will be uniformly distributed. The trigger (2) for $\geqq 2$ tracks was effective to record these events. The total integrated luminosity was 52.52 pb^{-1} and the highest total energy of the data was 46.78 GeV. The candidate events were selected under the following conditions:

‡3 If the analysis is applied to a stable fermion, like a stable heavy lepton, a mass limit of 22.3 GeV/c^2 is obtained.

(1) there were only two good tracks produced in the collision volume, which is a cylinder of $r = 40$ mm, $|z| = 200$ mm along the beam at the interaction point, and the calculated vertex point lies in a smaller cylinder of $r = 15$ mm, $|z| = 100$ mm. To be a good track the momentum of the track was required to be $p \geqq 0.06$ GeV/c with the number of hits $\geqq 14$;

(2) it was required that at least one of the charged particles had a momentum of $\geqq 3.5$ GeV/c and the other had a momentum of $\geqq 0.2$ GeV/c;

(3) no photon with $E_\gamma \geqq 0.5$ GeV was allowed;

(4) at least one of the charged tracks was consistent with a muon: i.e. either there were muon chamber hits in $\geqq 2$ layers or the track hitting the fiducial acceptance of the barrel LG array ($|\cos\vartheta| \leqq 0.76$) deposited less than 1.25 GeV equivalent shower energy. For the latter case, the momentum of the track was required to be $\geqq 1.25$ GeV/c. The sum of the shower energies of the charged particles was required to be $\leqq 2.5$ GeV;

(5) the acoplanarity angle defined by

$$\alpha = 180° - \cos^{-1}\left(\frac{(p_1 \times \hat{z})\cdot(p_2 \times \hat{z})}{|p_1 \times \hat{z}|\cdot|p_2 \times \hat{z}|}\right) \tag{2}$$

was required to be greater than 20°, where $\hat{z}$ is the unit vector along the positron beam. In order to have two distinguishable tracks for trigger (2), α was required to be less than 150°;

(6) in order to remove background due to the reaction, $e^+e^- \to \mu^+\mu^-\gamma$, where the photon escapes into the beam pipe or the gap between the barrel and the end cap shower counters, the missing momentum was required to point to the acceptance of the barrel or the end cap shower detectors. In examining this, the uncertainty of the momentum measurement was taken into account (up to 3σ for each track) and if there was a possibility that the missing momentum pointed to a gap, the event was rejected.

The selected events were visually inspected. Most events passing the above cuts were low energy muon pairs which could be due to the 2γ process. A few events were removed because although there was no clear track, there were many hits clustered in the innermost part of the jet-chamber in the missing momentum direction in the azimuthal angle. These hits are caused by a small angle high energy electron/positron showering in the vacuum pipe.

(7) in order to remove background from the two-photon process, $e^+e^- \to ee\mu\mu$, a missing transverse momentum ($P_{t,miss}$) cut was used:

$$P_{t,miss} = [(p_x^+ + p_x^-)^2 + (p_y^+ + p_y^-)^2]^{1/2} \geqq 4.0 \text{ GeV}/c. \tag{3}$$

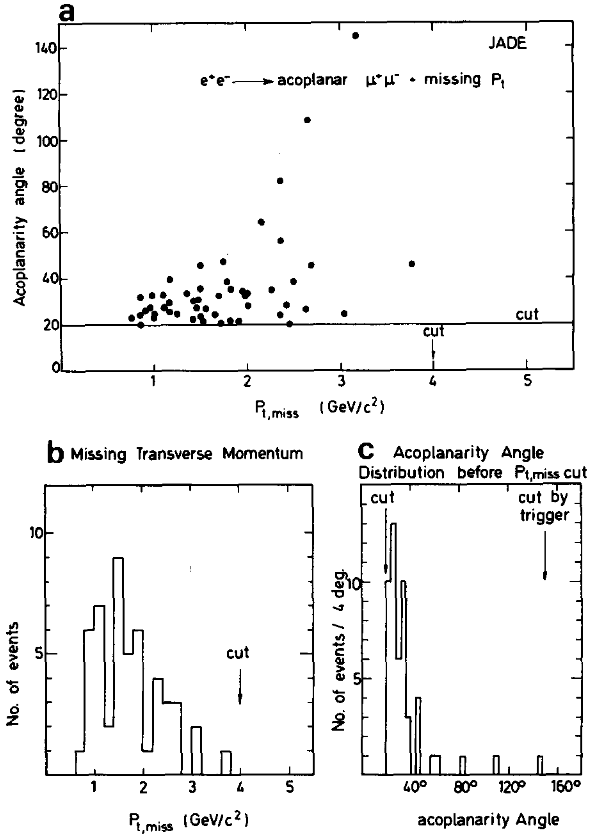

Fig. 2. (a) The scatter diagram of the acoplanarity angle versus the missing transverse momentum for the acoplanar muon pairs. (b) The missing transverse momentum distribution. (c) The acoplanarity angle distribution for muons. Applied cuts are indicated in the figures.

Fig. 2 shows the scatter plot of the acoplanarity angle versus the missing transverse momentum and projections of each variable before the last cut is applied. It is seen that most events have small $P_{t,miss}$. In fig. 3 the distribution of the total visible energy is shown. These distributions indicate that the observed events are consistent with the 2γ process $e^+e^- \to ee\mu\mu$, where the electrons and positrons escape toward the beam directions. After the last cut no event was left.

The expected number of events for different masses of the $\tilde{\mu}$ and $\tilde{\gamma}$ for the above selection conditions was

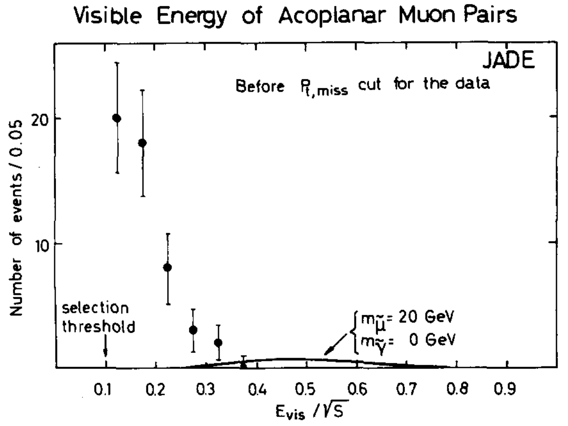

Fig. 3. The visible energy distribution of the acoplanar muon pair before the cut on the missing transverse momentum. The curve is an expected distribution for $M_{\tilde{\mu}}$ = 20.0 GeV/c^2 and $M_{\tilde{\gamma}}$ = 0 GeV/c^2.

calculated by a Monte Carlo simulation, which took the luminosity distribution of the data and radiative corrections according to Berends and Kleiss for a scalar pair into account. The excluded mass range for the $\tilde{\mu}$ and $\tilde{\gamma}$ is shown in fig. 1 by the curve A. The high mass end for the $\tilde{\mu}$ is determined by the production cross section, which decreases as $\beta_{\tilde{\mu}}^3$ and the high mass boundary for the $\tilde{\gamma}$ is determined by the missing transverse momentum cut.

A light $\tilde{\mu}$ was searched for by a separate study, using a muon pair sample with a loose cut on the acoplanarity angle ($\alpha \leqq 0.3$ rad). For details of the muon pair selection criteria, see ref. [15]. From this sample, acoplanar events which had $\alpha \geqq 2°$ were selected. They were scanned in order to remove QED events accompanied by observed hard photons. After the visual scanning 38 events remained. Although they could be background QED events, which had undetected hard photons escaping into the detector holes, they were kept as genuine events in deducing a 95% CL limit on the number of detected events. By means of a similar Monte Carlo calculation modified for light $\tilde{\mu}$ pairs, a limit on the masses of the $\tilde{\mu}$ and the $\tilde{\gamma}$ was obtained as shown by the curve B in fig. 1.

Combining the two results, a lower limit of 20.3 GeV/c^2 (95% CL) has been determined for the mass of the $\tilde{\mu}$, if the mass of the $\tilde{\gamma}$ is lighter than the mass of $\tilde{\mu}$ by several GeV. In the case of degenerage $\tilde{\mu}_R$ and $\tilde{\mu}_L$ the corresponding mass limit is 21.0 GeV/c^2.

Unstable $\tilde{\mu}$ decaying into unstable $\tilde{\gamma}$. If the photino decays into a photon and a massless goldstino (G), the $\tilde{\mu}$ pair will finally decay into $\mu\mu\gamma\gamma$GG. Since the goldstino is considered to be non-interacting like the neutrinos, the visible energy of the final state $\mu\mu\gamma\gamma$ will be degraded. Such events were searched for from all data above 27 GeV taken till Spring 1984. The highest energy is 46.78 GeV and the total integrated luminosity is 94.9 pb^{-1}. Selection criteria were similar to those used for the QED $\mu\mu\gamma\gamma$ study [17]. They were;

(1) there were only two good charged tracks as in the case of the stable $\tilde{\mu}$. The tracks were required to have $\geqq$ 14 hits in the chamber and momenta $\geqq$ 1.0 GeV/c. The energy deposit of the track in the lead glass was required to be $\leqq$ 1.25 GeV shower equivalent;

(2) there were two photons, one of which had $E_\gamma \geqq 1.0$ GeV and the other had $E_\gamma \geqq 0.5$ GeV. No other photons were allowed for $E_\gamma \geqq 0.5$ GeV;

(3) the photon energy clusters were required to be located in the fiducial acceptance of the counter array; i.e., not more than 20% of the energy to be contained in the edge counters;

(4) the $\mu\gamma$ opening angles were required to be $\geqq 15°$ in order to keep a clear separation of the μ and the γ clusters in the LG counters and to remove $\tau\tau$ background;

(5) events due to beam–gas interactions or 2γ-process with an evident imbalance in the longitudinal momentum were removed by requiring at least one particle with an opening angle $\geqq 60°$ w.r.t. the vector sum of the momenta of the observed four particles, $\mu\mu\gamma\gamma$;

(6) the missing transverse momentum with respect to the beam direction was required to be larger than 3.5 GeV/c;

(7) the total visible energy (E_{vis}) should be between 0.25 and 0.8 of the total energy. The cuts (6) and (7) were effective in removing 2γ-process events and QED $\mu\mu\gamma\gamma$ events;

(8) both of the charged tracks were required to have muon chamber hits in $\geqq$ 2 layers.

There were 2 events after the cut (7). These events look consistent with $\tau\tau\gamma$ background where one of the τ's decays into a muon and the other emits a charged track and a photon which makes the second cluster in the LG counter. No events remained after the last cut. Excluded masses of $\tilde{\mu}$ and $\tilde{\gamma}$ are shown in fig. 4.

If the mass of the $\tilde{\mu}$ is light, this method is not effective since the muon track and the decay photon

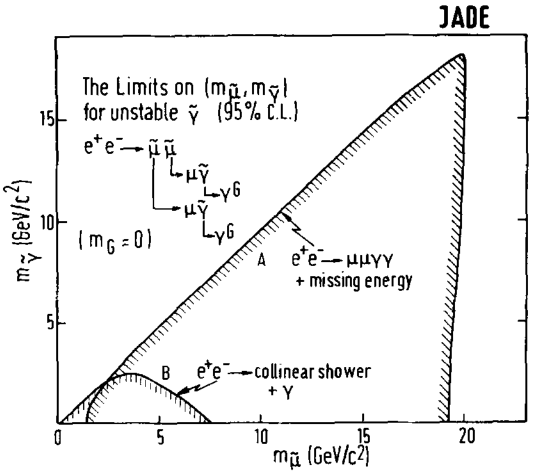

Fig. 4. A limit on the masses for the $\tilde{\mu}$ and $\tilde{\gamma}$ for the unstable $\tilde{\gamma}$, which decays into γ + massless goldstino; curve A, from the $\mu\mu\gamma\gamma$ events, curve B, from the unresolved ($\mu\gamma$)-pairs.

overlap in the LG shower counter. However, this specific feature provides a useful method of searching for a light $\tilde{\mu}$. Such events were sought among a subsample of large angle Bhabha events ($|\cos\vartheta| \leqq 0.76$), which had degraded shower energies $0.3\sqrt{s} \leqq E_{\mathrm{sh}} \leqq 0.9\sqrt{s}$. The acollinearity angle of the two clusters was required to be $\leqq 10°$. Among them, there was no event for which the two tracks were consistent with muons with muon chamber hits in $\geqq 3$ layers. The requirement on the muon hits was tighter for this purpose than the other cases because high energy electromagnetic showers sometimes show muon chamber hits in the inner two layers due to leaking soft gamma rays. An estimation of the expected number of light $\tilde{\mu}$ events was made by a Monte Carlo calculation for the above conditions and requiring that the muon momenta were higher than 2.5 GeV. Taking the muon hit efficiency obtained from collinear muon pairs into account, we obtain a 95% CL limit on the masses of $\tilde{\mu}$ and $\tilde{\gamma}$. They are also shown in fig. 4. Combining the two cases, a limit on the mass of the $\tilde{\mu}$ which decays into an unstable $\tilde{\gamma}$ is 19.2 GeV/c^2, if the mass of the $\tilde{\gamma}$ is not close to the $\tilde{\mu}$ mass.

Conclusions. The supersymmetric partner of the muon was searched for in a systematic way and no indication was found. Lower limits on the mass of the $\tilde{\mu}$ were obtained for different cases. For the stable $\tilde{\mu}$, this limit is 20.9 GeV/c^2. If the $\tilde{\mu}$ decays into the μ and a stable $\tilde{\gamma}$, the limit on the mass of $\tilde{\mu}$ is 20.3 GeV/c^2 if the $\tilde{\gamma}$ mass is not close to the $\tilde{\mu}$ mass. If the $\tilde{\mu}$ decays into a μ and an unstable $\tilde{\gamma}$, which decays into a γ and a massless goldstino, the limit on the mass of $\tilde{\mu}$ is 19.2 GeV/c^2, if the $\tilde{\gamma}$ mass is not close to the mass of $\tilde{\mu}$.

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