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PARTICLE SEARCHES IN e^+e^- EXPERIMENTS AT PEP AND PETRA*

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INTRODUCTION

This talk reviews recent results in new particle searches performed by experiments at the high energy e^+e^- storage rings PEP and PETRA. I will concentrate on recent searches for :

a) hadrons with a new quark flavor,

b) spin-1/2 charged heavy leptons,

c) spin-0 charged leptons,

d) spin-0 point-like scalars or pseudoscalars, and

e) neutral heavy leptons.

Earlier results are summarized in review papers in Refs. 1-5.

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SEARCH FOR A NEW QUARK FLAVOR

A search for a new quark production threshold has been made at PETRA up to a center of mass energy (E_{cm}) of 36.7 GeV by measuring the total multihadron production cross section, $\sigma(e^+e^- \rightarrow \text{hadrons})$.[6] In the naive quark-parton model, multihadron production proceeds via primary production of quark antiquark pairs which then fragment to hadrons. The multihadron production cross section, expressed in units of the muon pair production cross section , $\sigma(e^+e^- \rightarrow \mu^+\mu^-)$, is then given by :

$$R = 3 \Sigma e_q^2 (1 + \alpha_s/\pi)$$

where the sum is over accessible quark flavors. The factor of 3 comes from 3 color degrees of freedom for the quarks. The factor $(1 + \alpha_s/\pi)$ includes the QCD corrections due to the final state interactions of the quarks. The strong coupling constant α_s has a value of about 0.16. A new hadronic threshold is therefore indicated by a step increase in R. Naively, R ~ 11/3 for the five known flavors u, d, s, c, and b with 3 colors, and R ~ 5 for an additional quark of charge 2/3, such as the t quark.

The R measurements can also be used to test supersymmetry theories[7], which are attempts to unify particles with integral and half integral spin by 'gauging' the spin of particles. Such theories predict the existence of spin-0 partners for the known leptons and quarks. These particles differ by a quantum number which does not affect the pair production cross section via e^+e^- annihilation. If the supersymmetric partners of the quarks (called the squarks) exist in the present energy range, multihadron production will have an additional contribution to R of

$$\Delta R = 3 \Sigma e_{sq}^2 \, 1/4 \, \beta^3 \quad (1)$$

where the sum is over squarks which can be pair produced. The factor $1/4\ \beta^3$ comes from the fact that squarks are spin-0 particles.

The measurements of R from experiments at PEP and PETRA are summarized in Fig.1. The data are consistent with the constant value of R predicted by the quark-parton model including QCD corrections (solid line), and a new quark threshold for charge 2/3 is ruled out for center of mass energies below 36.7 GeV. The data further exclude production of an additional squark of charge 2/3 with $\beta \sim 1$.

Recently precision measurements of R have been made by the TASSO[8], MAC[9], and JADE[10] collaborations at E_{cm} of 12.0-36.7 and 29 GeV respectively,

R = 4.01 ± 0.03 (stat) ± 0.20 (syst) (TASSO).

R = 3.90 ± 0.04 (stat) ± 0.12 (syst) (MAC).

R = 3.93 ± 0.03 (stat) ± 0.09 (syst) (JADE).

These results are both in excellent agreement with the previous combined measurements and with the quark model prediction for five flavors, 3 colors and including QCD corrections up to order α_s (R = 3.85 for an assumed value of 0.16 for α_s).

Measurements of the fraction of multihadron events accompanied by prompt muons provide another means of detecting new quark flavor production. Mesons with new naked flavor will decay through strong interactions to the lightest meson carrying the same flavor and then will further decay only via the weak interactions. The semimuonic branching ratio (BR) for the weak decays is estimated to be ~10%. The fraction of multihadron events accompanied by a muon with a momentum greater than 2 GeV/c has been measured by the MAC[9], PLUTO[11], MARKJ[12], and JADE[13] collaborations. The results are shown in Fig.2 where the shaded bands are predictions of the quark-parton model. Again, the results clearly exclude production of an additional quark of charge 2/3.

To rule out the existence of an additional quark of charge 1/3 is substantially more difficult. The TASSO, JADE, and CELLO collaborations have studied the topological distributions for their multihadron event samples.[14] Their results are in good agreement with the predictions of the standard quark-parton model with only five flavors and gluon emission. They rule out the existence of an additional quark of charge 1/3 or 2/3 up to a mass of about 16 GeV/c^2. The MARKJ collaboration[15] has performed similar studies using multihadron events accompanied by muons and arrives at the same conclusion. A recent analysis procedure used by the MAC collaboration provides a very sensitive method for detecting heavy particle production.[9] A multihadron event containing a muon is divided into two jets by the plane perpendicular to the thrust axis. The jet mass of the group of particles recoiling against the jet containing the muon is defined by :

$$M_{jet} = E_{beam} (1 - T_{1/2}^2)^{1/2}$$

where $T_{1/2}$ is the thrust of the recoiling particles. This jet mass will correlate with the mass of the parent quark. Fig.3 shows the recoiling jet mass distribution for a sample of 54 multihadron events containing a muon with momentum > 2 GeV/c and transverse momentum > 1 GeV/c relative to the thrust axis. The data are consistent with the predicted Monte Carlo result for c and b quark semimuonic decays assuming a 10% BR and constant fragmentation function, and rule out additional production of a heavy quark of charge 1/3 of a mass less than 13.5 GeV/c^2 at a 95%

lifetime or stable leptons up to a mass of 14 GeV/c^2 is excluded at a 95% CL. The JADE collaboration, using combined momentum and dE/dx measurements, has also looked for charged particles with a mass different from the masses of the known charged particles. Again, there is no evidence for stable charged heavy particles. The lower mass limit from JADE is 12 GeV/c^2.

B) Search for sequential leptons

Charged sequential leptons have their own lepton number and associated neutrinos. The tau lepton τ is a good example. Charged sequential leptons can be pair produced via e^+e^- annihilation with a cross section given by Eqn. 2. Sequential leptons with a mass less than 4 GeV/c^2 would be expected to have decay modes similar to those of the tau lepton and would show up as an excess to the tau pair production events. The good agreement of the tau pair production cross section with the QED prediction has excluded a possible light sequential lepton. The branching ratios of a heavier sequential lepton have been calculated[17]. It agrees quite well with the prediction of the final state counting rule which says the BR's to the possible final states $\nu_L e \nu_e$, $\nu_L \mu \nu_\mu$, $\nu_L \tau \nu_\tau$, $\nu_L u\bar{d}$, and $\nu_L c\bar{s}$ are in the ratio 1:1:1:3:3 where the factor of 3 for the hadronic final states comes from 3 color degrees of freedom. This predicts:

a) ~ 2% BR to $\mu^\pm e^\mp$ + missing momentum,

b) ~ 14% BR to $\mu^\pm$ ($e^\pm$) recoiling against a hadron jet, and

c) ~ 49% BR to two acoplanar jets of hadrons.

Searches based on these final states have been performed extensively at PEP and PETRA. No charged sequential lepton has been found. The methods used and lower mass limits obtained are given in Table I.

confidence level (CL).

SEARCH FOR SPIN-1/2 CHARGED HEAVY LEPTONS

New spin-1/2 charged heavy lepton should fall into the following mutually exclusive categories:[2]

a) stable,

b) sequential,

c) sharing the e, μ, or τ lepton number (paralepton), or

d) an excited e, μ, or τ (ortholepton).

A charged spin-1/2 heavy lepton should be pair produced via e^+e^- annihilation (see Fig.4) with a cross section:

$$\sigma(e^+e^- \to L^+L^-) = \sigma_{\mu\mu}\, \beta(3 - \beta^2)/2 \qquad (2)$$

where $\sigma_{\mu\mu}$ is the point-like cross section for pair producing light spin-1/2 fermions and $\beta(3-\beta^2)/2$ is the threshold factor for heavy spin-1/2 fermions. Experiments at PEP and PETRA have searched for all the above possibilities.

A) Search for long lifetime or stable leptons

The MARKJ[16] and JADE[17] collaborations have looked for heavy leptons which do not decay in their detectors corresponding to a flight-time > 4 ns in the laboratory frame. These events are similar to the QED process $e^+e^- \to \mu^+\mu^-$ except for a slightly different momentum spectrum due to the mass difference. These events would be categorized as muon pair events and would give an additional contribution to the muon pair cross section. No surplus of events has been observed. The existence of long

TABLE I LOWER MASS LIMITS ON SEQUENTIAL LEPTONS

EXPERIMENT	SIGNATURE	LOWER MASS LIMIT (95 % CL) (in GeV/c^2)	REFERENCE
JADE	Two acollinear jets	18.1	4
MARKJ	μ + hadrons	16.0	19
PLUTO	μ + hadrons	14.5	20
TASSO	Isolated charged particle + hadrons	15.5	21
MAC	Acollinear μe and μ + hadrons	14.0	9
MARKII	Acollinear μe	13.8	22

C) Search for paraleptons

A negatively charged paralepton is defined to have the same lepton number as the known positively charged e, μ, or τ.[2] For example, a negatively charged paraelectron (E^-) has the same lepton number as e^+. The radiative decay is forbidden. The weak decays of E^- are very similar to those of sequential leptons. However, due to the identity of the two final state neutrinos in the $\nu_e e \nu_e$ channel, the final state counting rule now predicts the BR's to $\nu_e e \nu_e$, $\nu_e \mu \nu_\mu$, $\nu_e \tau \nu_\tau$, $\nu_e u\bar{d}$, and

$\nu_e c\bar{s}$ to be in the ratio 2: 1 : 1 : 3 : 3. A similar argument applies to the muon and tau-associated paraleptons.

Since the BR's of a paralepton to the leptonic final states are in general larger than those of a sequential lepton of the same mass, the searches for sequential leptons are also sensitive to these paraleptons. Therefore, the mass limits in Table I apply to paraleptons as well.

D) Search for ortholeptons

Ortholeptons are excited states of the known leptons. For example, a negatively charged orthoelectron (e^{*-}) has the same lepton number as e^-. The dominant decay mode is :

$$e^{*\pm} \rightarrow e^{\pm} + \gamma$$

If e* is sufficiently light, they can be pair produced in e^+e^- interactions and detected. There has been no explicit search for $e^{*+}e^{*-}$ pair production at PEP and PETRA. However, a heavy electron can manifest itself by giving an additional contribution to the QED process :

$$e^+e^- \rightarrow \gamma\gamma$$

by a coupling of the e*, e, and γ[23], represented by the following Lagrangian :

$$L = \lambda \Psi_{e^*} \sigma_{\mu\nu} \Psi_e f_{\mu\nu} + h.c. \qquad (3)$$

where λ is a measure of the strength of the ee*γ coupling. The $e^+e^- \rightarrow \gamma\gamma$ cross sections measured by PEP and PETRA experiments[24] are shown in Fig.5, and are in good agreement with the QED prediction. The results of the MAC collaboration used the Bhabha cross section measured with identical cuts to provide a luminosity calibration and are substantially free of systematic errors. If one assumes that e* behaves like a heavy electron in the $e^*e\gamma$ coupling, (i.e., $\lambda = e/M_e^*$ where M_e^* is the mass of the heavy electron), the 95% CL lower mass limits obtained by PEP and PETRA experiments are given in Table II. A typical lower mass limit is 40 GeV/c^2.

TABLE II LOWER MASS LIMIT ON HEAVY ELECTRONS

EXPERIMENT	LOWER MASS LIMIT (95% CL) (in GeV/c^2)	REFERENCE
MAC	55	9
MARKJ	58	16
MARKII	50	22
JADE	47	25
PLUTO	46	26
CELLO	43	27
TASSO	34	28

The search for an orthomuon, or an excited muon, has been performed by the MAC[9], JADE[14], MARKJ[16], and MARKII[22] collaborations. Excited muon pairs can be produced via e^+e^- annihilation which then decay to $\mu\mu\gamma\gamma$ final state. The presence of an excited muon is indicated by events not accountable by higher order QED radiative processes where two muons and two photons are produced. The $\mu\gamma$ invariant mass should also peak at the

μ^* mass. For example, 17 $\mu\mu\gamma\gamma$ events with at least one identified muon and both photons having energy greater than 1 GeV have been observed by the MAC detector in an integrated luminosity of 30 pb^{-1}.[9] The correlation of the two $\mu\gamma$ invariant masses for each event is shown in Fig. 6. (Note that there are two entries for each event.) For $\mu^*\mu^*$ production, the events are expected to populate around a point inside the dotted band which is a 2 standard deviations limit of the mass resolution of the MAC detector. No surplus of events in this region has been found. This excludes an excited muon up to a mass of 14 GeV/c^2. Similar results obtained by other experiments are listed in Table III.

TABLE III LOWER MASS LIMITS ON EXCITED MUONS

EXPERIMENT	LOWER MASS LIMIT (95% CL) (in GeV/c^2)	REFERENCE
MAC	14	9
MARKJ	10	16
MARKII	14	22

The search for a higher mass μ^* can rely on a $\mu\mu^*\gamma$ coupling[19] as given by Eqn. 3 with e^* replaced by μ^*. This allows the production of a single μ^* via

$$e^+e^- \rightarrow \mu\mu^*$$

These events will be mixed with the radiative muon pair production process, $e^+e^- \rightarrow \mu^+\mu^-\gamma$. The MAC[9], MARKJ[16], MARK II[22], and JADE[14] collaborations have studied the $\mu\mu\gamma$ final state and found good agreement with the QED prediction for radiative muon pair production. The limit on the mass of μ^* depends on the value of λ. In most cases, a large region of the λ-M_{μ^*} plane is excluded.

In conclusion, there are no anomalous $\mu\mu\gamma$ or $\mu\mu\gamma\gamma$ events which can be attributed to production of excited muons in the center of mass energies covered by PEP and PETRA.

There has been no explicit search for an excited tau. An analogous search would be to look for anomalous $e\mu\gamma$ and and $e\mu\gamma\gamma$ events.

SEARCH FOR SPIN-0 LEPTONS

As mentioned earlier, supersymmetric theories predict two spin-0 partners for the known charged leptons.[7] If these particles are light, they can be pair produced via e^+e^- annihilations. The production cross section for the supersymmetric partners of the muon and tau, denoted by s_μ and s_τ respectively, is given by Eqn. 1. The production cross section for s_e is slightly more complicated.[7]

These leptons are expected to decay rapidly back to their partners by the emission of a photino which presumably is only weakly interacting. Their signatures therefore are e^+e^-, $\mu^+\mu^-$, $\tau^+\tau^-$ final states with substantial missing momentum. These final states are distinguishable from the QED reactions : $e^+e^- \rightarrow e^+e^-$, $\mu^+\mu^-$, $\tau^+\tau^-$ by having missing momentum transverse to the beam direction. This is indicated by a large angle between the plane containing the leptons and the beam axis (called the acoplanarity angle). Fig.7 is the acoplanarity angle distribution of e^+e^- final state events seen by the TASSO detector.[29] The results are clearly in agreement with Monte Carlo predictions for e^+e^- Bhabha scattering. Expectations of an additional 4 GeV/c^2 and a 12 GeV/c^2 s_e are also indicated in the figure and are clearly ruled out. This analysis excludes a s_e up to a mass of 16.6 GeV/c^2 at a 95% CL. The MAC collaboration has searched for supersymmetric muons by analysing muon pairs with acollinearity angle greater than 10 degrees. To reduce background from the two photon process $e^+e^- \rightarrow e^+e^-\mu^+\mu^-$, at least one muon is required to have greater than 3 GeV/c momentum transverse to the beam. This results in 31 events in an integrated luminosity of 14 pb^{-1}. The acoplanarity angle distribution of these muon pairs is shown in Fig. 8. Plotted along with the data are the Monte Carlo predictions for a 10 GeV/c^2 s_μ. From this analysis, the existence of a heavy supersymmetric muon in the mass range 3-13 GeV/c^2 is ruled out at a 95% CL.

Because of their similarity in final state configurations, the searches for charged sequential leptons are also sensitive to supersymmetric taus. For example, the MAC collaboration has studied events with an isolated muon recoiling against three or more charged particles. If these events arise from s_τ pair production, the muon and the hadron jet are expected to be acoplanar. This can be measured by the momentum of the muon relative to the thrust axis of the hadron jet in a plane perpendicular to the beam. Fig.9 is a plot of this unbalanced transverse momentum for a sample of 60 tau-like events with at least 1 muon. The distribution is clearly in agreement with tau pair production and disagrees with the presence of an additional 10 GeV/c^2 heavy supersymmetric tau. This analysis excludes the existence of heavy supersymmetric taus in the mass range 3-13 GeV/c^2 at a 95% CL.

In conclusion, no spin-0 supersymmetric partners of the e, μ, and τ have been found. The mass limits from PEP and PETRA experiments are given in Table IV.

The MARKII and MAC collaborations have investigated the possibility of a scalar lepton unrelated to supersymmetry which can decay to $e\nu$ and $\mu\nu$ final states.[36] This will result in μe events with missing momentum. The μe events observed by the MAC and MARKII collaborations are totally accounted for by tau pair production.[22] This establishes an upper limit on the product of the $e\nu$ and $\mu\nu$ BR's $(B_e B_\mu)^{1/2}$, which depends moderately on the assumed mass of the spin-0 lepton. The MarkII analysis essentially excludes a spin-0 scalar lepton with $(B_e B_\mu)^{1/2} >$ about 20% in the mass range 2-12 GeV/c^2.

TABLE IV MASS LIMITS ON SUPERSYMMETRIC LEPTONS

EXPERIMENT	PARTICLES	MASS LIMITS (95% CL) (in GeV/c^2)	REFERENCE
MAC	s_{μ}	3-13	
	s_{τ}	3-13	9
TASSO	s_e	< 16.6	
	s_{μ}	< 16.4	29
JADE	s_{τ}	4-13	30
MARKJ	s_{μ}	3-15	31
	s_{τ}	< 14	32
PLUTO	s_e	< 13	33
CELLO	s_e	2-16.8	
	s_{μ}	3.3-16	34
	s_{τ}	1.8-3.8,6-15.3	
MARK II	s_{τ}	1.8-9.9	35

SEARCH FOR SPIN-0 SCALARS AND PSEUDOSCALARS

The standard gauge theory uses a spin-0 neutral Higgs field to break the vacuum symmetry. Current theoretical sentiment regards this as dissatisfying. Technicolor is a simple theoretical attempt to generate the spontaneous symmetry breaking dynamically.[36] In general, these models predict Goldstone bosons called technipions π' which can be as light as a few GeV/c. Light charged Higgs particles ($H^\pm$) are also predicted in some extensions of the standard model.[38] These light particles can be pair produced in e^+e^- annihilation with a cross section typical of spin-0 charged particles (see Eqn. 1).

In these models, the technipions and Higgs particles have a coupling proportional to the mass of the final state particles. Therefore, they are expected to decay leptonically to $\tau\nu_\tau$, and hadronically via the heavier $c\bar{s}$ or $c\bar{b}$ system. A priori, the leptonic BR to τ (B_τ) is unknown. However, the combined searches at PEP and PETRA[39] have exhausted all possibilities : (because of their similarities in production and decay, the following results apply to π' and $H^\pm$,)

a) $B_\tau \sim 50\%$. There is a substantial BR to the final state where one of the π' decays to tau and the other decays hadronically. This will result in events with an isolated muon recoiling against 5 or more charged tracks. The MAC collaboration has searched for these event types and found only two candidates in 30 pb^{-1}.[9] In one of the events, two of the tracks are consistent with photon conversion in the beam pipe. After taking detection efficiency into account, this is far below the expected number from pair production of π'. A large region on the B_τ-$M_{\pi'}$ plane is therefore excluded. (See Fig.10a.) Results of similar analyses from other experiments at PEP and PETRA[39] are also shown in the same figure.

b) $B_T \sim 100\%$. The final state is similar to that of supersymmetric tau pair production with the tau neutrino playing the role of the photino. As explained earlier, there is no evidence for supersymmetric taus. The excluded regions are shown in Fig.10.

c) $B_T \sim 0\%$. The technipions would decay hadronically most of the time. Two characteristics distinguish these events from normal multihadron events : 1) These events are accompanied frequently by a prompt muon from c and b quark decay and the jet mass of the recoiling hadrons should be correlated with the mass of the technipion. Events arising from heavy technipion pair production should populate the high mass region. This signal is especially pronounced if technipions decay preferentially via $c\bar{b}$. 2) Multihadron events from technipion pair production should look like 4-jet events because there are four quarks in the final state. This is more evident if π' decays via the lighter $c\bar{s}$ system.

Searches based on 1 and 2 have been performed by the MAC[9] and TASSO[10] collaborations respectively. The observed jet mass distribution is inconsistent with the existence of a heavy π' in the mass range 7-13 GeV/c^2 decaying 100% to $c\bar{b}$. The method of 4-jet analysis was described in S. Wu's talk in this conference. No evidence for π' has been found. The excluded region is shown in Fig. 10e.

In summary, charged technipions or Higgs particles are excluded up to a mass of about 13 GeV/c^2 at a 95% CL limit independent of their BR's to $\tau\nu_\tau$, $c\bar{s}$, and $c\bar{b}$.

SEARCH FOR NEUTRAL HEAVY LEPTONS

Some models contain neutral heavy leptons. For example, a simple extension of the standard SU(2)XU(1) model proposed by Lee and Weinberg[40] predicts a rich spectrum of charged leptons accompanied by massive neutral partners. In general, it is conceivable to have a neutral heavy lepton which has either its own lepton number or the e, μ, or τ lepton number.

A search for a general neutral heavy lepton can be performed in e^+e^- interactions. Neutral heavy leptons can be pair produced in e^+e^- annihilation via the Z_0

$$e^+e^- \rightarrow Z_0 \rightarrow L_0\bar{L}_0 \ .$$

The production cross section is given by[2]

$$\sigma(e^+e^-\rightarrow L_0\bar{L}_0) = \frac{G^2 \ E_{cm}{}^2(v_e{}^2+a_e{}^2)(v_L{}^2+a_L{}^2)T}{96 \ \pi} \qquad (4)$$

where v_L and a_L are the vector and axial vector coupling constants of L to Z_0, and T is the threshold factor. The coupling constants v_L and a_L are in general model-dependent and of order 1. For rough estimates, I have assumed ($v_L{}^2 + a_L{}^2$) = 1, and T = 1 in the following. The cross section (Eqn. 4) is small, ~ 0.2 pb at 30 GeV center of mass energy, compared with about 100 pb for charged particle pair production. Given typical integrated luminosities of 50-70 pb^{-1} at PETRA and 25-30 pb^{-1} at PEP, there would be only 5-20 events /experiment at best. Furthermore, it is generally difficult to isolate these events.

It is relatively easy to detect events arising from pair production of e or μ-associated neutral heavy leptons because they result in events with 2e's and 2μ's in the final state respectively. These signatures are unlikely to be confused by normal multihadron events or higher order QED reactions. A meaningful search is possible in the near future. The search for e-associated neutral heavy leptons is feasible even at the present luminosity because these E_0's can be produced singly in e^+e^- interaction via W exchange (see Fig.11) which has a cross section about 10 times larger than given by Eqn. 4.[41] For a light E_0, the final state appears as an unbalanced jet containing an electron. The JADE collaboration has searched for these events and found no events satisfying these criteria.[5] The lower mass limit is 18-20 GeV/c^2 depending on details of the assumed model. There has been no explicit search for μ-associated neutral heavy leptons at PEP and PETRA.

CONCLUSIONS

Experiments at PEP and PETRA have searched for production of quarks with new flavors, heavy charged sequential, para and excited leptons, supersymmetric spin-0 charged leptons, spin-0 charged Higgs particles and technipions, and e-associated neutral heavy leptons. None of these particles has been found up to a center of mass energy of 36.7 GeV/c^2. Basically all possible proposed charged states have been searched for and their production is excluded at a 95% CL limit, or better, over most of the accessible range of masses. The lower mass limits are given below:

a) By measuring R and inclusive muon production in multihadrons, the existence of a new quark of charge 2/3 or 1/3 is excluded up to a mass of 18 GeV/c^2 at a 95% CL.

b) All possible decay modes of charged sequential and para leptons have been searched for and such leptons are excluded up to a mass of 18 GeV/c^2 at a 95% CL.

c) Pair production of excited electrons and muons have not been observed up to a center of mass energy of 36.7 GeV. The existence of an excited muon is excluded up to a mass of 14 GeV/c^2 at a 95 % CL. Single production of excited muons is also not observed.

d) Charged spin-0 supersymmetric partners of e, μ, and τ have been searched for and are excluded up to a mass of about 14 GeV/c^2 at a 95% CL.

e) Charged Higgs particles and technipions have been searched for in all possible decay modes. No such particles have been observed and are excluded up to a mass of about 14 GeV/c^2 at a 95% CL.

f) The special class of e-associated neutral heavy leptons have been searched for. No such particle has been found. The lower mass limit assuming standard coupling is 18-20 GeV/c^2 at a 95% CL.

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FIGURE CAPTIONS

Fig.1. Measurements of R from experiments at PEP and PETRA. The solid line is the quark model prediction for 5 flavors, 3 colors, and including QCD corrections. The dotted line is the prediction for an additional top quark of charge 2/3.

Fig.2. Measurements of the rate of production of muons with momentum > 2 GeV/c for multihadron events. The lower shaded band is the quark-parton model prediction with a 10% semimuonic BR and different fragmentation functions for c and b quarks. The upper band includes an additional quark of charge 2/3.

Fig.3. Distribution of mass of hadron jet opposite to a muon with momentum > 2 GeV/c and p_t > 1 GeV/c where p_t is measured relative to the thrust axis.

Fig.4. Feynman diagram for the reaction $e^+e^- \rightarrow L^+L^-$.

Fig.5. Measurements of the reaction $e^+e^- \rightarrow \gamma\gamma$ from experiments at PEP and PETRA. The results are normalized to the QED prediction.

Fig.6. Correlation of the invariant mass of the two $\mu\gamma$ combinations for $\mu\mu\gamma\gamma$ events observed by the MAC detector. Events from $\mu^*\mu^*$ production are expected to populate between the dotted lines. (See text for details.)

Fig.7. The acoplanarity angle distribution of e^+e^- final state events seen by the TASSO detector.

Fig.8. The acoplanarity angle distribution of $\mu^+\mu^-$ final state events seen by the MAC detector.

Fig.9. The muon p_t distribution for tau-like events. p_t is measured relative to the thrust axis on a plane perpendicular to the beam direction.

Fig.10. Regions on the B_T-$M_{\pi'}$ plane excluded by experiments at PEP and PETRA.

Fig.11. Feynman diagram for $e^+e^- \rightarrow \nu E^0$ via W exchange.

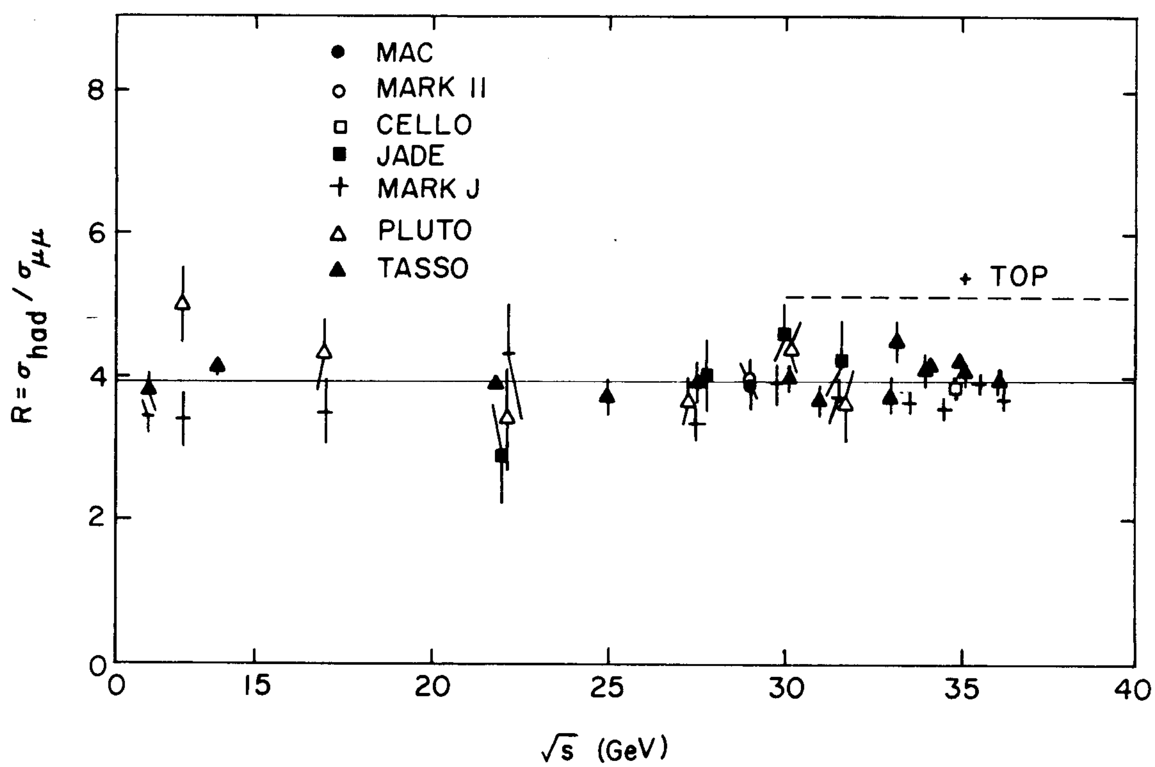
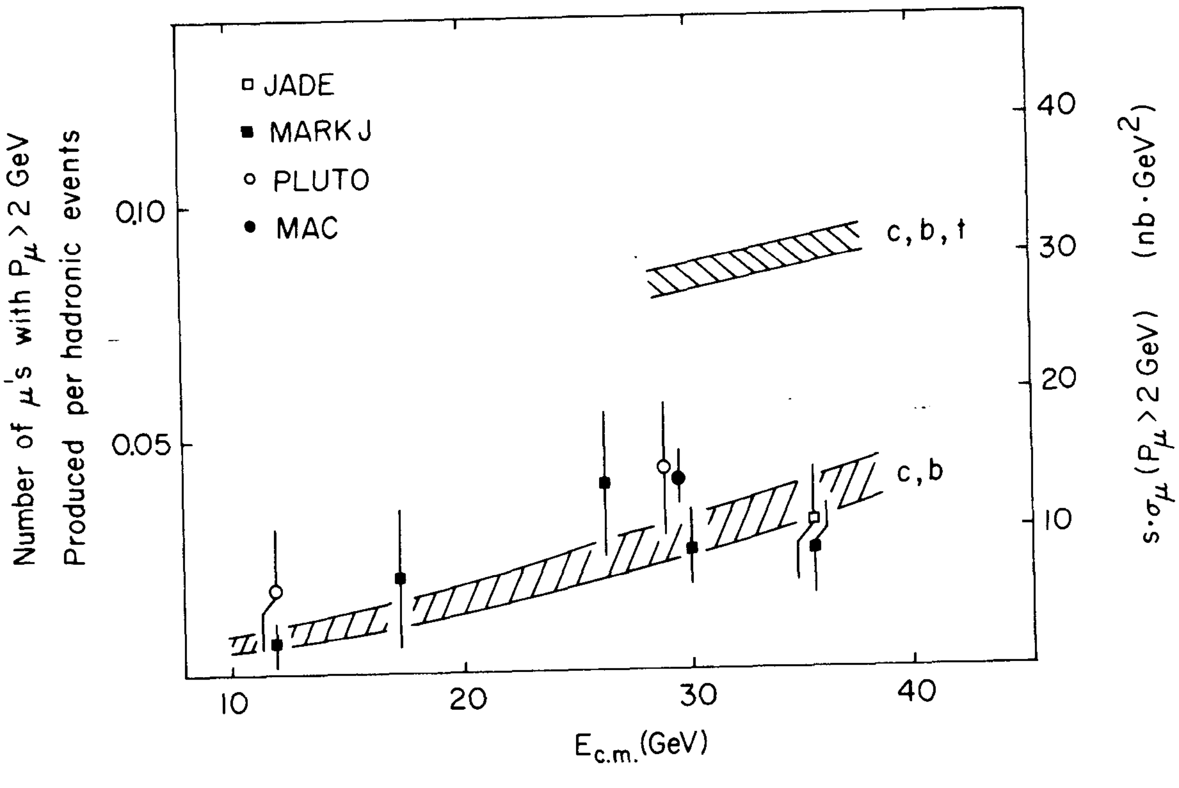

MAC
MARK II
CELLO
JADE
MARK J
PLUTO
TASSO
+ TOP
$R = \sigma_{had} / \sigma_{\mu\mu}$
$\sqrt{s}$ (GeV)
0
2
4
6
8
15
20
25
30
35
40

Fig. 1



JADE
MARK J
PLUTO
MAC
c, b, t
c, b
0.10
0.05
10
20
30
40
$E_{c.m.}$ (GeV)
Number of μ's with $P_\mu > 2$ GeV
Produced per hadronic events
$s \cdot \sigma_\mu (P_\mu > 2\ \text{GeV}) \quad (\text{nb} \cdot \text{GeV}^2)$

Fig. 2

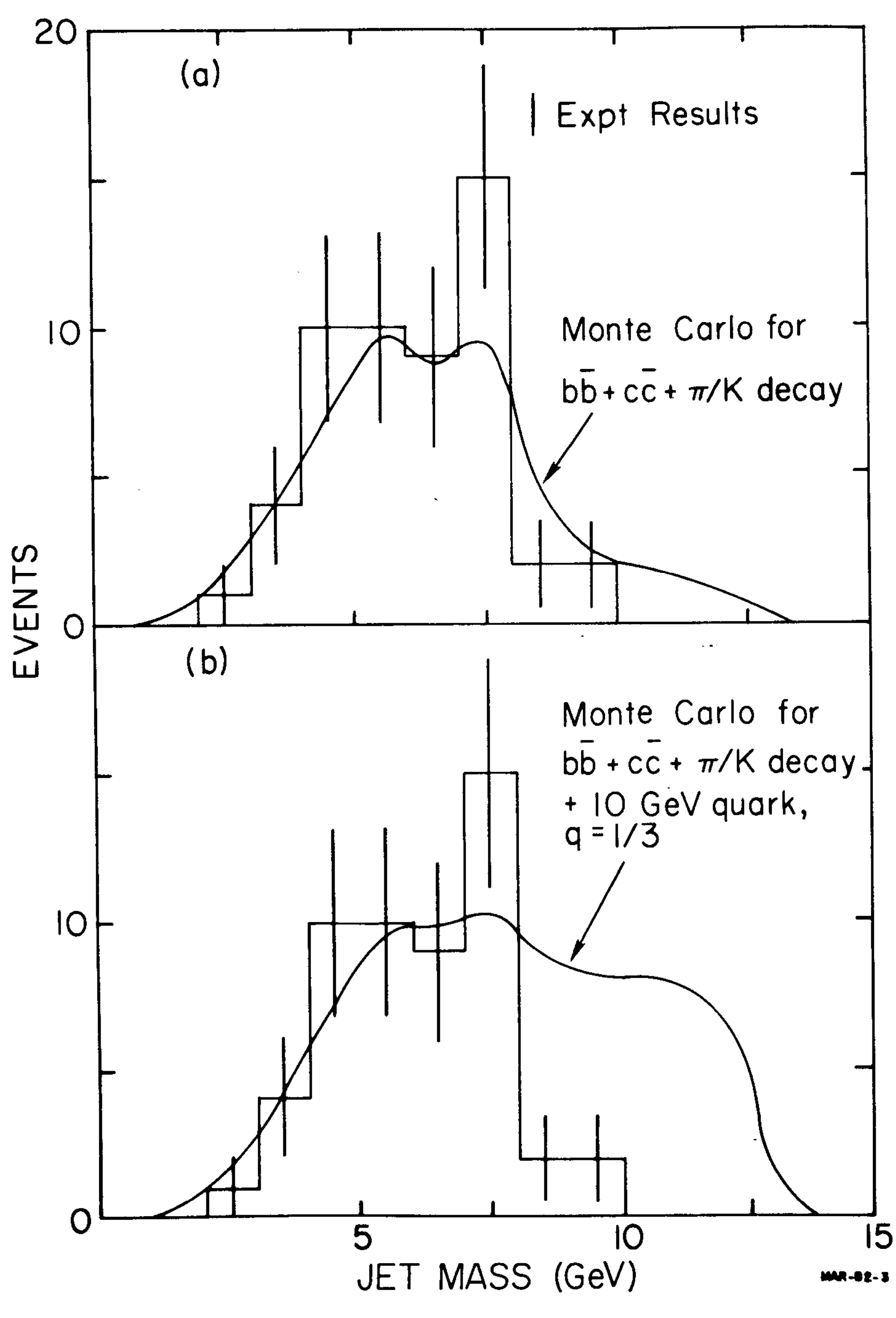

20
(a)
Expt Results
10
Monte Carlo for
$b\bar{b} + c\bar{c} + \pi/K$ decay
0
EVENTS
(b)
Monte Carlo for
$b\bar{b} + c\bar{c} + \pi/K$ decay
+ 10 GeV quark,
q = 1/3
10
0
5
10
15
JET MASS (GeV)
MAR-82-3

Fig. 3

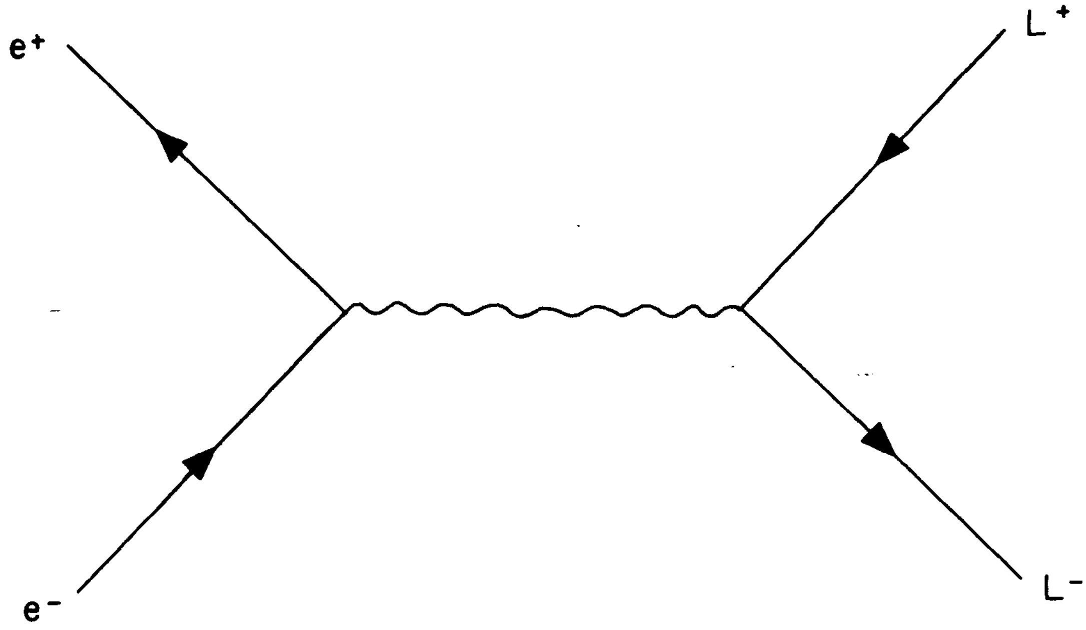


Fig. 4

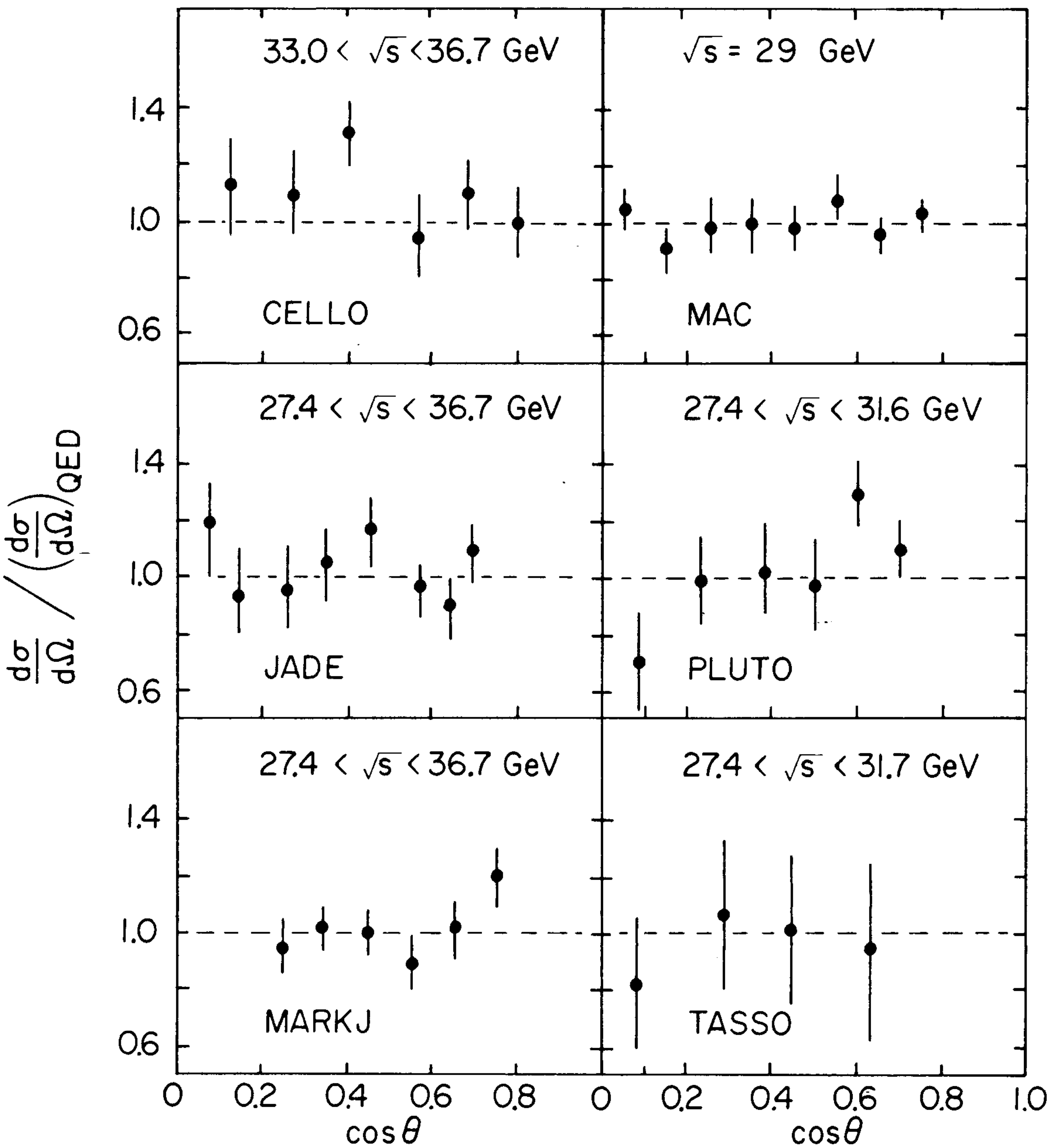
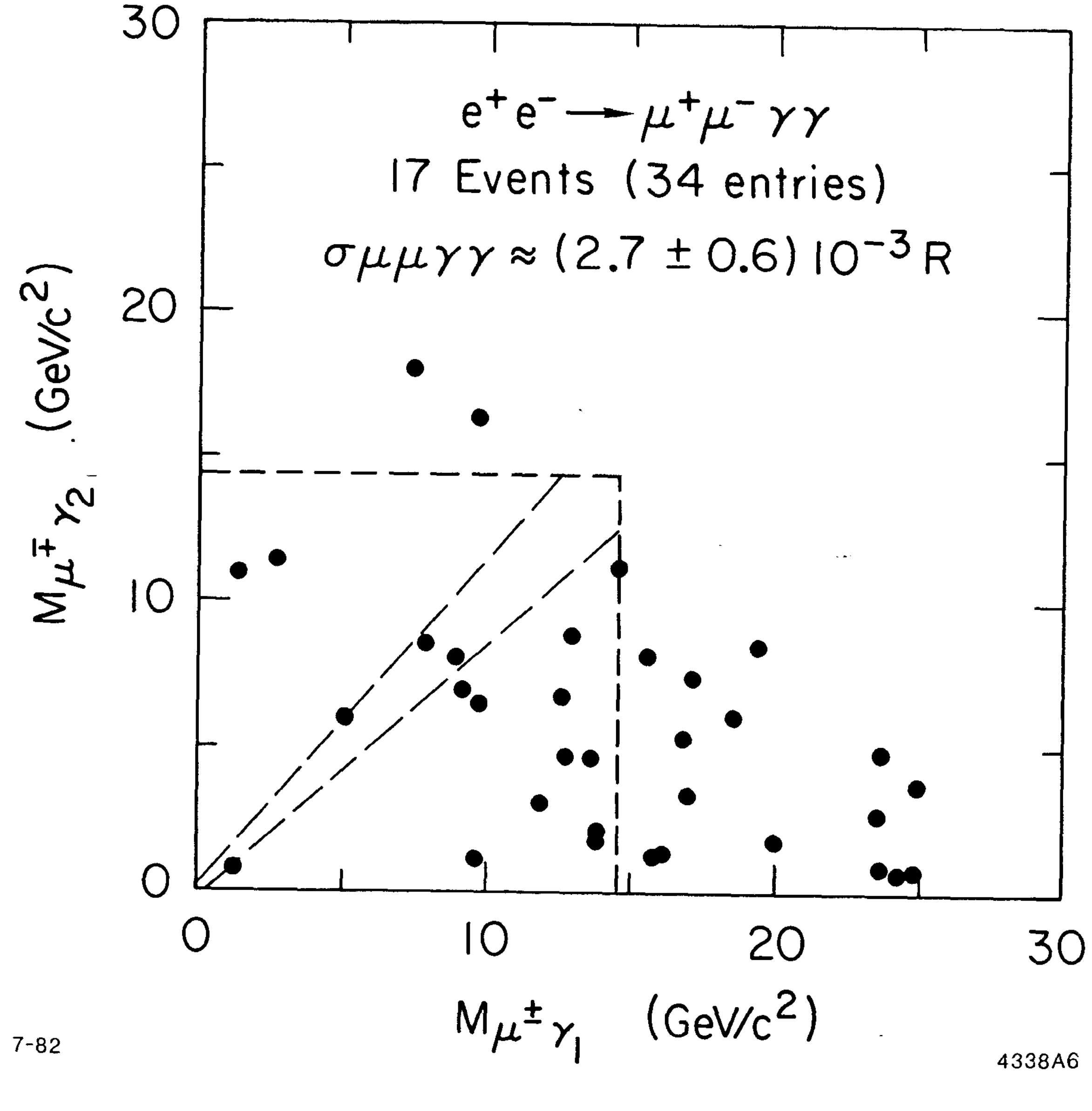
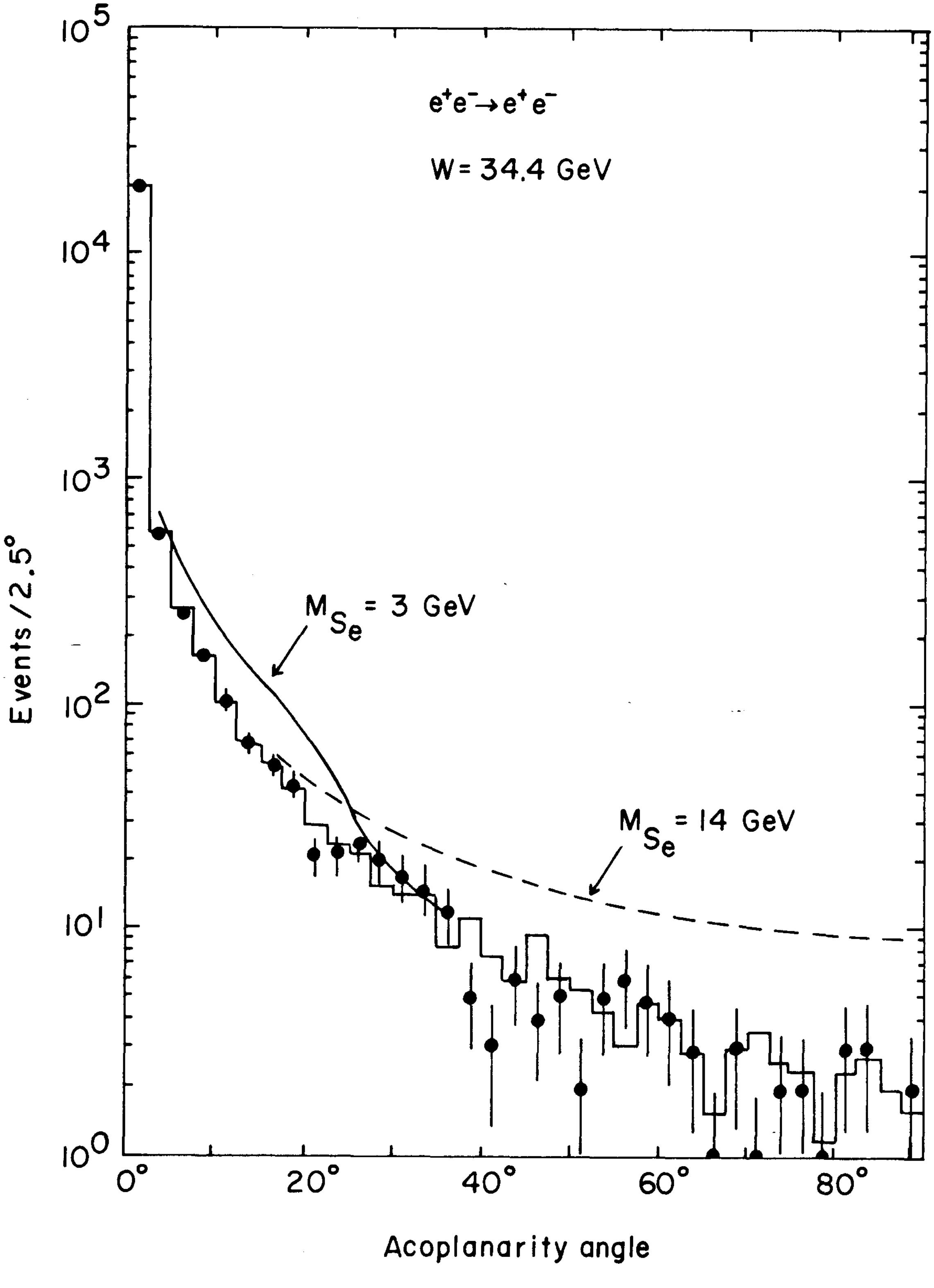

33.0 < $\sqrt{s}$ < 36.7 GeV
CELLO
$\sqrt{s}$ = 29 GeV
MAC
27.4 < $\sqrt{s}$ < 36.7 GeV
JADE
27.4 < $\sqrt{s}$ < 31.6 GeV
PLUTO
27.4 < $\sqrt{s}$ < 36.7 GeV
MARKJ
27.4 < $\sqrt{s}$ < 31.7 GeV
TASSO
$\frac{d\sigma}{d\Omega} \Big/ \left(\frac{d\sigma}{d\Omega}\right)_{QED}$
1.4
1.0
0.6
0
0.2
0.4
0.6
0.8
1.0
cos θ

Fig. 5



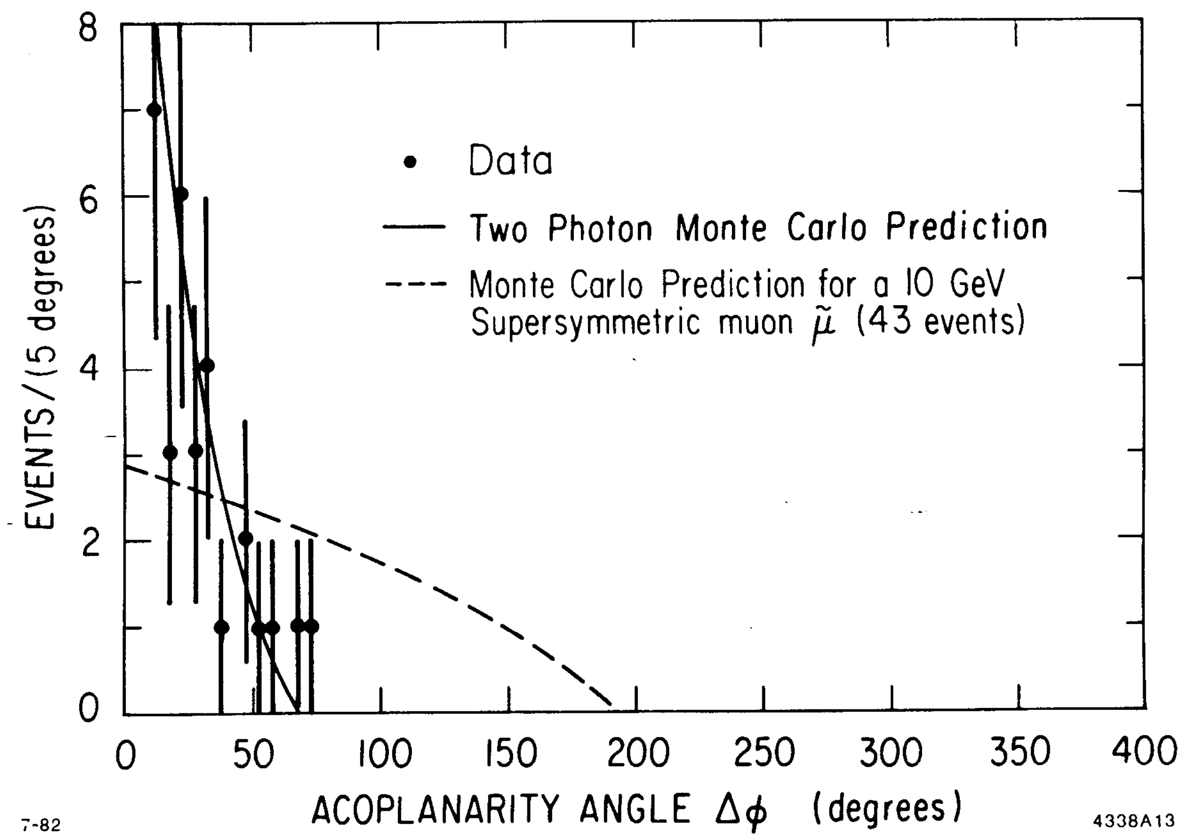
$e^+e^- \rightarrow \mu^+\mu^-\gamma\gamma$
17 Events (34 entries)
$\sigma_{\mu\mu\gamma\gamma} \approx (2.7 \pm 0.6)\, 10^{-3}\, R$
0
10
20
30
$M_{\mu^{\mp}\gamma_2}$ (GeV/c^2)
$M_{\mu^{\pm}\gamma_1}$ (GeV/c^2)
7-82
4338A6

Fig. 6



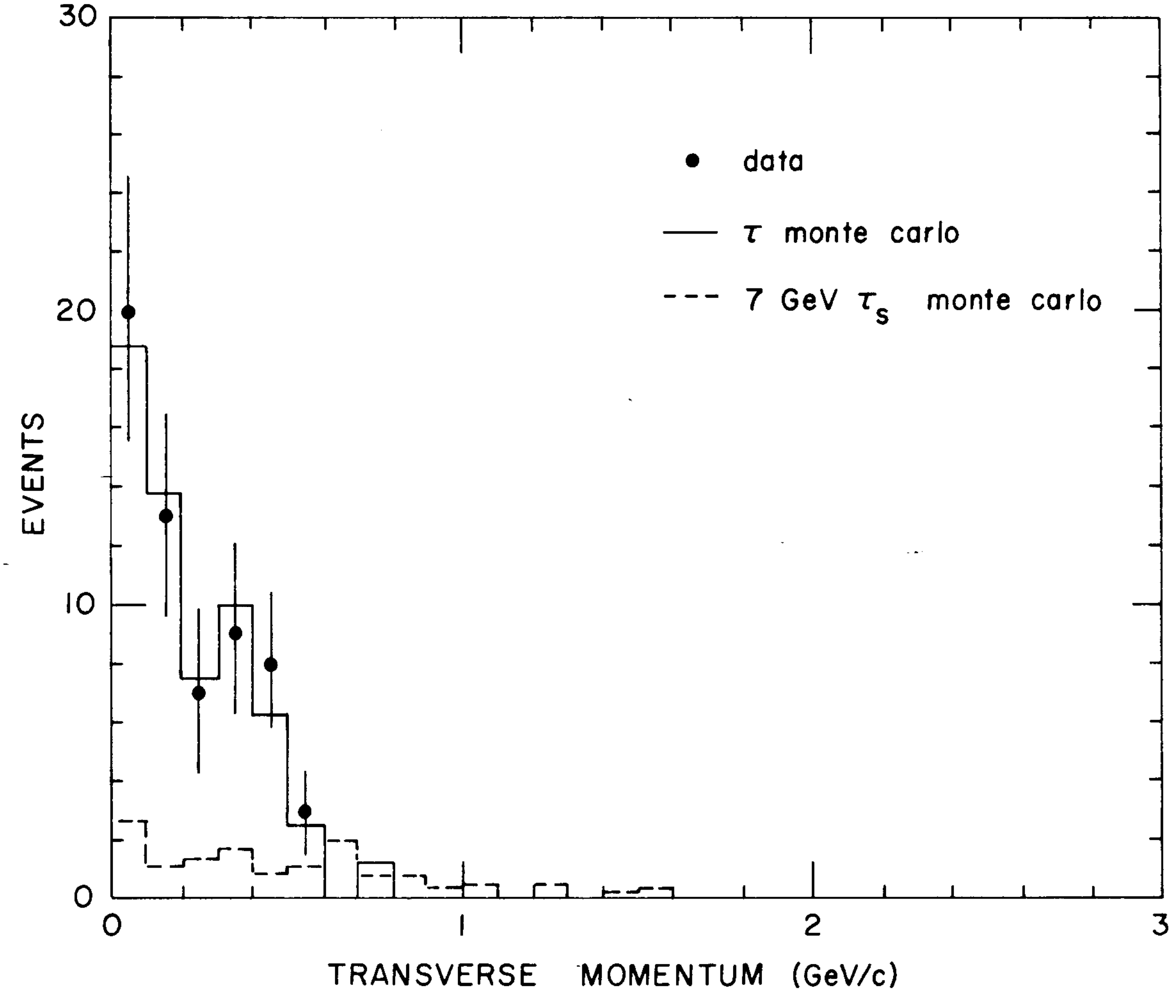
$e^+e^- \to e^+e^-$
W = 34.4 GeV
M_{S_e} = 3 GeV
M_{S_e} = 14 GeV
Events / 2.5°
10^5
10^4
10^3
10^2
10^1
10^0
0°
20°
40°
60°
80°
Acoplanarity angle

Fig. 7



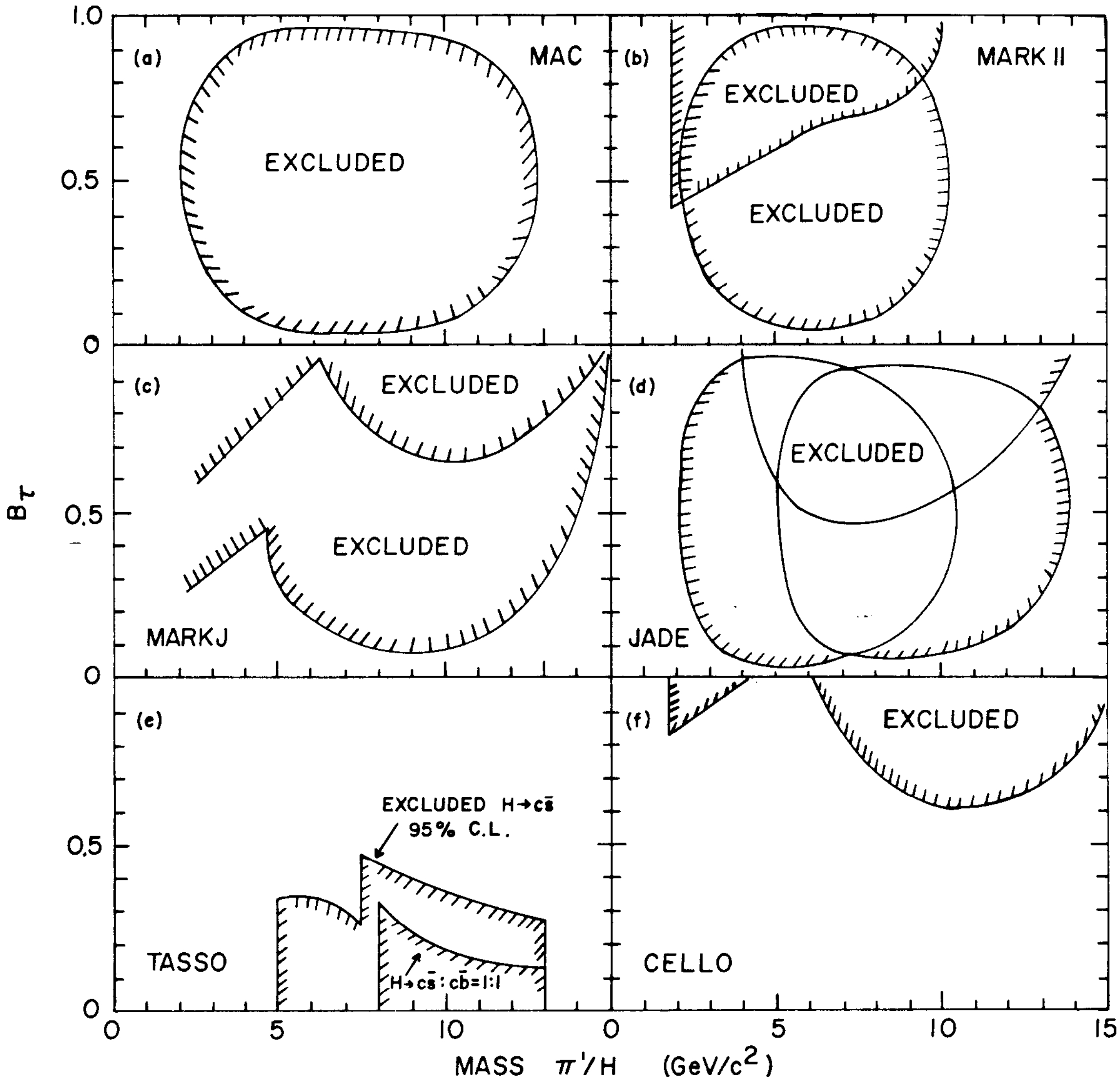
8
6
4
2
0
EVENTS/(5 degrees)
Data
Two Photon Monte Carlo Prediction
Monte Carlo Prediction for a 10 GeV
Supersymmetric muon $\tilde{\mu}$ (43 events)
0
50
100
150
200
250
300
350
400
ACOPLANARITY ANGLE $\Delta\phi$ (degrees)
7-82
4338A13

Fig. 8



data
τ monte carlo
7 GeV τ_s monte carlo
EVENTS
TRANSVERSE MOMENTUM (GeV/c)
0
10
20
30
0
1
2
3

Fig. 9



(a)
MAC
EXCLUDED
(b)
MARK II
EXCLUDED
EXCLUDED
(c)
EXCLUDED
EXCLUDED
MARKJ
(d)
EXCLUDED
JADE
(e)
EXCLUDED H→cs̄
95% C.L.
H→cs̄ : cb̄=1:1
TASSO
(f)
EXCLUDED
CELLO
1.0
0.5
0
B_τ
0
5
10
15
MASS π'/H (GeV/c²)

Fig. 10

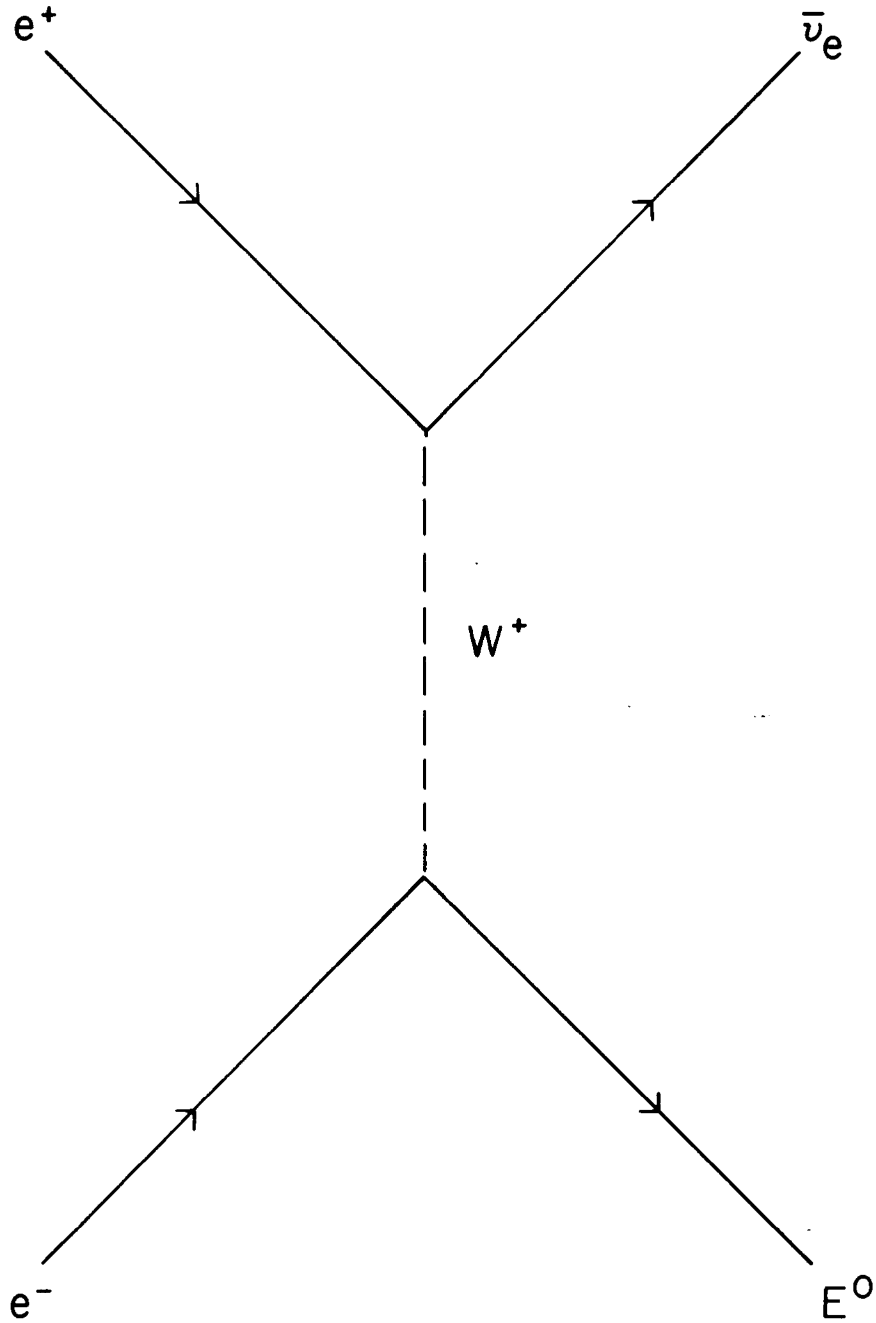


Fig. 11