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A SEARCH FOR ELASTIC NONDIAGONAL LEPTON PAIR PRODUCTION IN e^+e^- ANNIHILATION AT $\sqrt{s} = 29$ GeV*

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ABSTRACT

We have searched for the annihilation of e^+e^- into the exclusive channels $e^\pm\tau^\mp$ and $\mu^\pm\tau^\mp$ at $\sqrt{s}$ = 29 GeV, using 226 pb^{-1} and 133 pb^{-1}, respectively, of data taken with the MARK II detector at PEP. The resulting candidate sample is compatible with the expected background from τ pair production. Our analysis yields a 95% C.L. cross section limits of $\sigma_{e\tau}/\sigma_{\mu\mu} < 1.2 \cdot 10^{-3}$ and $\sigma_{\mu\tau}/\sigma_{\mu\mu} < 4.1 \cdot 10^{-3}$, where $\sigma_{\mu\mu}$ is the QED cross section for production of a lepton pair. This is the first high-Q^2 test of lepton flavor conservation involving τ leptons.

1. INTRODUCTION

It has long been understood that the appearance of lepton-flavor-violating terms in lepton-lepton or lepton-nucleon interactions is likely to be a telling feature of physics beyond the Standard Model, just as the observation of flavor-changing currents in the quark sector has profoundly affected our understanding of hadronic interactions. Lepton flavor, like quark flavor, is not a conserved quantity protected by an established gauge principle. Although a number of low-energy and low-momentum-transfer studies have established impressive limits on a possible nonconservation of lepton flavor involving electrons and muons, it has been repeatedly pointed out[1] that no such studies exist at high Q^2 or high energy, and that the inclusion of heavy flavors may well be more sensitive.[2] A number of models would find lepton flavor mixing involving the (heavy) τ lepton a natural place to look for new information on the family structure phenomenon.[3–5]

Consequently, we have searched for the processes[6]

$$e^+e^- \rightarrow e^-\tau^+ \quad , \tag{1}$$

$$e^+e^- \rightarrow \mu^-\tau^+ \quad . \tag{2}$$

We used a total of 226 pb^{-1} for the analysis (1) and a total of 133 pb^{-1} for the analysis (2).[7] The data were taken with the MARK II detector at the PEP storage ring at a center-of-mass energy of $\sqrt{s}$ = 29 GeV. The MARK II detector has been described elsewhere.[8,9] The momenta of charged tracks are measured with a cylindrical drift chamber (DC) in a 4.75 kG solenoidal magnetic field. Photons are detected in electromagnetic calorimeters that cover the region $|\cos\theta| < 0.92$, where θ is the angle of the track with respect to the incident beam. The calorimeters in the central region ($\cos\theta < 0.72$) are lead-liquid-argon sampling calorimeters (LA) with an energy resolution $\sigma_e/E = 0.14/\sqrt{E}$ (E in GeV). The calorimeters in the forward and backward directions are lead-proportional-tube sandwiches. The muon detectors consist of four layers of chambers separated by iron hadron absorbers. A particle traveling through this system must traverse at least 7.2 interaction-lengths in order to reach the fourth layer. The muon system covers about 45% of the solid angle.

2. EVENT SELECTION AND BACKGROUND SUPPRESSION

The event signature for the processes $e^+e^- \rightarrow e^-(\mu^-)\tau^+$ is very distinctive: An energetic electron (muon) of beam energy recoils against a τ. The τ provides a well-defined signature: One or three charged prongs, plus missing energy and momentum that are carried off by undetected neutrinos. Consequently, the initial event sample was subjected to the following selection procedure:

We demand either two or four charged prongs in a back-to-back, one-versus-one or one-versus-three topology. The tracks are required to project into a cylindrical volume of radius 1 cm and half-length 3 cm around the nominal collision point parallel to the beam axis, to be within the angular region $|\cos\theta| < 0.68$ in order to guarantee a good measurement of the charged tracks' energies and momenta, to have transverse momenta with respect to the beam axis of at least 150 MeV/c, and add up to zero net charge. In addition, there must be significant missing energy, $E_{miss} > 2$ GeV, and transverse momentum, $P_{\perp miss} > 1$ GeV, to account for the unobserved neutrinos.

Next, we demand that the track of highest energy be identified as an electron or as a muon, respectively, with energy close to the beam energy. In the case of the l.vs.3 topology, the highest energy track and the three-prong system must be recoiling against each other. Since at $\sqrt{s} = 29$ GeV the LA calorimeter has a much better resolution than the DC, we use the former to measure the energy of the electron in the $e^+e^- \rightarrow e^-\tau^+$ analysis, while only the momentum of the muon in the $e^+e^- \rightarrow \mu^-\tau^+$ analysis is measured with the DC. The energetic electron of the process $e^+e^- \rightarrow e^-\tau^+$ is identified by imposing the criteria $E_e > E_{min}$ and $(E/P)_e \geq 0.7$, where E_e, P_e are the electron candidate energy (measured by LA) and momentum (measured by DC), and E_{min} is a cut energy close to that of the beam, e.g., E_{min} = 10 GeV. The energetic muon of the process $e^+e^- \rightarrow \mu^-\tau^+$ is identified by requiring that the candidate track hits be found within 2 rms standard deviations of the trajectory expected of a muon with beam momentum, in all four layers of the muon system, and that the track energy (which is taken to be equal to its momentum, since the μ mass is negligible at this energy) be larger than E_{min}.

Finally, we demand that the remaining one or three charged prongs (which we denote by the index "tag") be consistent with a τ hypothesis. Here, the decay mode $\tau^- \rightarrow e^- \bar{\nu}_e \nu_\tau$ is not accepted in the $e^+e^- \rightarrow e^-\tau^+$ analysis, since it leads to a configuration (two electrons in the final state, one of them with full beam energy) that can easily be confused with radiative Bhabha events, one of the major backgrounds to this process. Similarly, for the analysis $e^+e^- \rightarrow \mu^-\tau^+$, we do not accept the decay mode $\tau^- \rightarrow \mu^-\bar{\nu}_\mu\nu_\tau$, in order to avoid the radiative muon pair production background. Therefore, in the $e^+e^- \rightarrow e^-\tau^+$ analysis, the tag tracks must be consistent with a non-electron hypothesis. This is realized by our requiring that any energy deposition in the calorimeter be small, $E_{tag} < 2$ GeV; by limiting the maximum track momentum to $P_{tag} < 10$ GeV; and by imposing a low E/P ratio, $(E/P)_{tag} < 0.5$. In the $e^+e^- \rightarrow \mu^-\tau^+$ analysis, the 1.vs.1 topology has to verify that the tag track must be consistent with a non-muon hypothesis. A track is defined as not a muon if it does not hit the number of muon layers expected from its momentum. In the cases of the 1.vs.3 topology we also demand that the invariant mass of the three-prong system be smaller than the τ mass, and use a pair finding algorithm to reject events that appear to be produced by photon conversion. With these selection criteria, our

Monte Carlo study shows a global efficiency for detecting an $e^+e^- \to e^-\tau^+$ event of $F_{e\tau}$ = 16%, and a global efficiency for detecting an $e^+e^- \to \mu^-\tau^+$ event of $F_{\mu\tau}$ = 8.5%. The geometrical acceptances and the strict criteria for accepting a tag are the main limitations of our efficiency.

Next, we estimate the impact of different backgrounds. The two major backgrounds to the $e^+e^- \to e^-(\mu^-)\tau^+$ process are, first, τ pair production, where one τ subsequently decays via $\tau^- \to e^-\bar{\nu}_e\nu_\tau$ ($\tau^- \to \mu^-\bar{\nu}_\mu\nu_\tau$) and the electron (muon) is at the endpoint of its energy distribution; and second, radiative QED pair production. By this we mean radiative Bhabha scattering and radiative muon pair production events that simulate a τ topology (i.e., where the radiative electron or muon is not recognized as such, and where the detected topology, including neutral energy, passes the cuts). Lastly, there is a small background due to events of the type $e^+e^- \to e^+e^-\gamma\gamma$ ($\gamma\gamma \to \mu^+\mu^-$ or $\tau^+\tau^-$). We have also examined the influence of multihadronic events and found it to be negligible.

The radiative pair production events are a potentially serious background, especially in the $e^+e^- \to e^-\tau^+$ analysis, since radiative Bhabha events, due to the t channel production, have a very large cross section ($\sigma_{bhabha} \sim$ 1700 pb for $|\cos\theta| < 0.68$). To reduce it to a negligible level, we take advantage of the fact that $e^+e^- \to e^-\tau^+$ events, as-opposed to radiative Bhabha events, are characterized by missing energy and momentum. Since we do not select events in which the τ decays via $\tau^- \to e^-\bar{\nu}_e\nu_\tau$, $e^+e^- \to e^-\tau^+$ events will have *one and* only *one* identified electron. According to our Monte Carlo calculations, the cuts in missing energy and missing transverse momentum suppress the radiative Bhabha background by a factor of 10^4. Remaining events of this type are suppressed by another factor >50 by our permitting only one electron in the event, as explained above. Thus, this background is reduced by a total factor of at least $5 \cdot 10^5$. The effectiveness of the cuts is illustrated in Fig. 1. The level of suppression of radiative muon pairs for the $e^+e^- \rightarrow \mu^-\tau^+$ analysis is at least as good as that achieved for the radiative Bhabha events. Also, this is a much less severe background: only the s channel contributes to muon pair production with a cross section that is more than an order of magnitude smaller than that for radiative Bhabha events, in the angular range considered.

The other possible QED background, "photon-photon scattering" into the $e^+e^-\mu^+\mu^-$ and $e^+e^-\tau^+\tau^-$ channels, contains a small probability that one electron and one τ (or μ) be emitted into the detector, while the conjugate pair escapes in the respective forward directions. The cross-section for these processes is very small ($\sigma_{ee\mu\mu} \sim 1$ pb for the high electron/muon invariant masses needed to pass our cuts). Their suppression is achieved through the cut on the energy of the electron candidate, along with the requirements of zero net charge, and the cut on missing transverse momentum. We estimate that at most one such event makes it into our final data sample.

Backgrounds due to multihadronic events are very strongly suppressed, since their probability for exhibiting a topology with one very energetic electron recoiling against one or three charged tracks is practically zero. Our Monte Carlo calculations show that our rejection factor for this background is 10^6 at least.

The most important background to the processes $e^+e^- \rightarrow e^-\tau^+$ and $e^+e^- \rightarrow \mu^-\tau^+$ is τ pair production. To suppress it, we impose a cut as high as possible on the energy of the electron (muon) candidate. The efficiency of this cut is limited by the detector resolution. The final-state electron energy distribution, for the $e^+e^- \rightarrow e^-\tau^+$ process, can be crudely approximated by a Gaussian (with a radiative tail) with mean value $< E > = E_{beam}$ and dispersion σ_{LA}, where σ_{LA} is the LA calorimeter resolution; for $E_{beam} = 14.5$ GeV, $\sigma_{LA} \sim 0.75$ GeV. Likewise, the muon energy distribution in the case of the $e^+e^- \rightarrow \mu^-\tau^+$ process can be approximated by a Gaussian of dispersion σ_{DC}, where σ_{DC}—the DC resolution-is $\sim$2.50 GeV for E_{beam} = 14.5 GeV. On the other hand, the energy distribution of the electrons (muons) produced in the decays $\tau^- \to e^- \bar{\nu}_e \nu_\tau$ ($\tau^- \to \mu^- \bar{\nu}_\mu \nu_\tau$) is linear near the endpoint. Thus, we impose a cut $E_{cut} = E_{beam} - r\sigma$, where r is selected to maximize the τ background rejection while keeping a reasonable efficiency for the signal. The optimum value of r turns out to be $r = 2$, leading to a cut $E^e_{cut} \sim 13$ GeV and $E^\mu_{cut} \sim 10$ GeV. Since the shapes of the energy distributions for both the signal and the τ background are well understood, we expect our results to be stable when E_{cut} is varied around the beam energy; This is illustrated below.

3. MAXIMUM-LIKELIHOOD FIT

Subsequent to the application of all cuts, we perform a maximum-likelihood fit to the electron (muon) energy distribution. Since the only relevant background passing the cuts is the τ pair background, we can obtain further rejection from our knowledge.,. of the exact shape of the final-state electron and muon energy distributions for both the signal ($e\tau$, $\mu\tau$) and the background ($\tau\tau$). We obtain a roughly Gaussian distribution for the signal by fitting Bhabha scattering and muon-pair distributions from our data sample. For the decays $\tau^- \to e^- \bar{\nu}_e \nu_\tau$ ($\tau^- \to \mu^- \bar{\nu}_\mu \nu_\tau$), we fit Monte Carlo -data that incorporate the detector resolution and radiative corrections. The shape of the signal and the background is illustrated in Fig. 2.

Assuming that our data sample has n events of energies X_i, with $i = 1, \ldots n$, we define the likelihood function L_e in terms of a parameter α_e which describes the admixture of $\tau^+\tau^-$ ($\tau^- \to e^- \bar{\nu}_e \nu_\tau$) events to a putative $\tau^+ e^-$ sample in our data:

$$L_e(\alpha_e) = \prod_{i=1}^{n} f(x_i, \alpha_e) = \prod_{i=1}^{n} (1 - \alpha_e)\, U^e_b(x_i) + \alpha_e\, U^e_s(x_i)$$

Here, U_s^e and U_b^e are normalized functions describing the $(e\tau)$ signal and the $(\tau\tau)$ background, respectively. In exactly the same way, we define the likelihood function L_μ in terms of a parameter α_μ which describes the admixture of $\tau^+\tau^-(\tau^- \rightarrow \mu^-\bar{\nu}_\mu\nu_\tau)$ events to a possible $\tau^+\mu^-$ signal. A detailed description of the application of the likelihood method to this problem is given in Ref. 10.

From the determination of α_e and α_μ, we obtain upper limits to the lepton-flavor nondiagonal cross sections $\sigma_{e\tau}$, $\sigma_{\mu\tau}$ via the ratios

$$\sigma_{e\tau}/\sigma_{\mu\mu} = \frac{\sigma_{e\tau}}{\sigma_{\tau\tau}} = \alpha_e\frac{F_{\tau\tau}}{F_{e\tau}} \quad ,$$

$$\sigma_{\mu\tau}/\sigma_{\mu\mu} = \frac{\sigma_{\mu\tau}}{\sigma_{\tau\tau}} = \alpha_\mu\frac{F_{\tau\tau}}{F_{\mu\tau}} \quad .$$

Here, $F_{\tau\tau}$ and $F_{e\tau}$, $F_{\mu\tau}$ are the efficiencies for τ pair backgrounds and for the two types of signal events.

Minimizing the quantities $\{-\log(L_e(\alpha_e))\}$ and $\{-\log(L_\mu(\alpha_\mu))\}$, we obtain our best estimates for the parameters α_e and α_μ. The limits thus obtained depend only very slightly on the cutoff energy. This is illustrated in Table 1, where we show the results of the $\{-\log(L_e(\alpha_e))\}$ minimization for different values of E^e_{cut}.

4. RESULTS AND CONCLUSIONS

In Fig. 3, we show the electron (muon) energy distribution for the events passing all the cuts in our data and in a Monte-Carlo-generated τ pair event set that is equivalent to our total integrated luminosity. The distributions are seen to be fully compatible. Our analysis yields the limits

$$\sigma_{e\tau}/\sigma_{\mu\mu} < 1.2 \cdot 10^{-3} \qquad \text{at 95\% C.L.,} \qquad (i)$$

$$\sigma_{\mu\tau}/\sigma_{\mu\mu} < 4.1 \cdot 10^{-3} \qquad \text{at 95\% C.L.,} \qquad (ii)$$

where the reduced stringency of the second limit is due entirely to limitations of the MARK II detector.

In summary, we report on the first quantitative investigation of a high-Q^2 lepton-flavor-changing process involving only leptons, and including the third-generation τ. It leads to the observation of signal candidate events that are fully compatible with the rate expected from τ pair production. Our limits (i, ii) on the cross sections for the processes $e^+e^- \rightarrow e^-\tau^+$, $e^+e^- \rightarrow \mu^-\tau^+$, can be interpreted in a standard theoretical framework[1,2] in terms of new (beyond the Standard Model) interaction energy scales $\Lambda_{e\tau} > 1.75$ TeV, and A,, > 1.30 TeV, respectively. These implications have been explored elsewhere.[1,10] By comparison, the best limit available from rare decay data, $BR(\tau^- \rightarrow e^-e^+e^-) < 4 \times 10^{-5}$, translates” into $\Lambda_{e\tau} > 0.66$ TeV. It should be noted that studies comparable to ours but performed at the Z^0 pole need a greatly enhanced data sample in order to reach a sensitivity comparable to that reported here.[1,10]

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7. This is because the energies of the muons in analysis (2) are measured using the DC, while the energies of the electrons in the analysis (1) are measured using the LA. While the quality of the data was good for the LA for the 226 pb^{-1} used in the analysis (1), only 133 pb^{-1} of data had the high-quality DC information needed for analysis (2).

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11. The convention we follow here is a comparison of the interaction scales A for the process $e^+e^- \to e^-\tau^+$, and m_W for the process $\tau^- \to e^-\bar{\nu}_e\nu_\tau$.

TABLE CAPTION

1. Limits of $\sigma_{e\tau}/\sigma_{\mu\mu}$ (at 95% C.L.).

Table 1

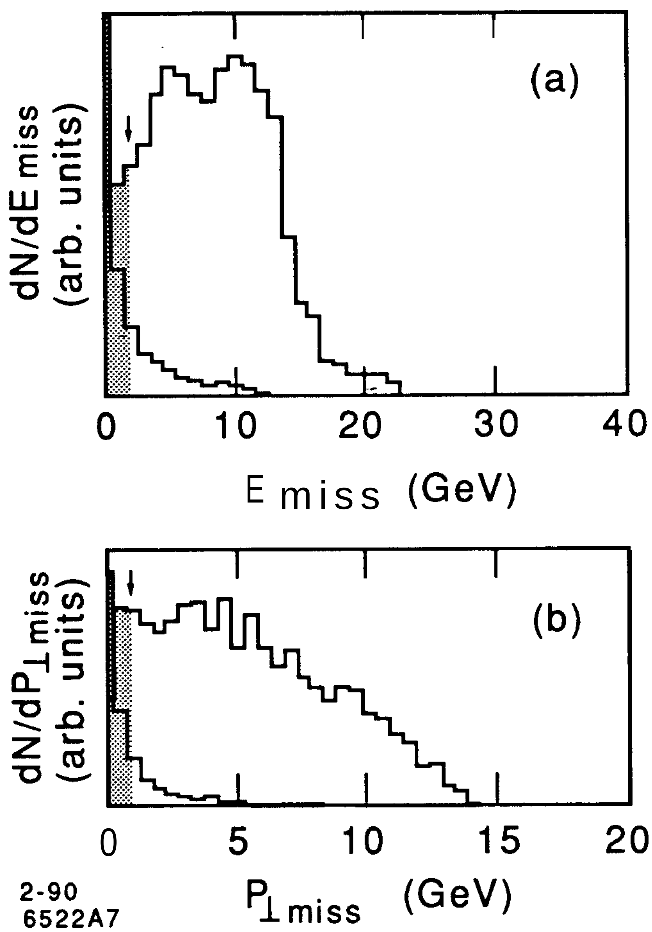
E_{cut}^e	$\alpha_e \pm \Delta\alpha_e$	$F_{\tau\tau}/F_{e\tau}$	$\sigma_{e\tau}/\sigma_{\mu\mu}$
10	0.02 ± 0.02	$3.5 \cdot 10^{-2}$	$1.4 \cdot 10^{-3}$
12	0.07 ± 0.07	10^{-2}	$1.4 \cdot 10^{-3}$
13	0.12 ± 0.12	$5 \cdot 10^{-3}$	$1.2 \cdot 10^{-3}$

FIGURE CAPTIONS

1. Missing energy and momentum for the signal $(e^+e^- \rightarrow e^-\tau^+)$ and the radiative Bhabha background (Monte Carlo generated distributions): (a) E_{miss}; and (b) $P_{\perp miss}$: The arrows mark the cuts; the shaded regions correspond to events rejected by the cuts.

2. Energy spectrum of the signal and the background (a) for the process $e^+e^- \rightarrow e^-\tau^+$, and (b) for the process $e^+e^- \rightarrow \mu^-\tau^+$. Notice that the electron energy in distribution (a) is measured with the LA, while the muon energy in distribution (b) is measured with the DC. The normalization of the distributions is arbitrary.

3. Energy distributions for the events passing all cuts: (a) electron energy; (b) muon energy.



(a)
dN/dE miss
(arb. units)
0
10
20
30
40
E miss (GeV)
(b)
dN/dP⊥miss
(arb. units)
0
5
10
15
20
P⊥miss (GeV)
2-90
6522A7

Fig. 1

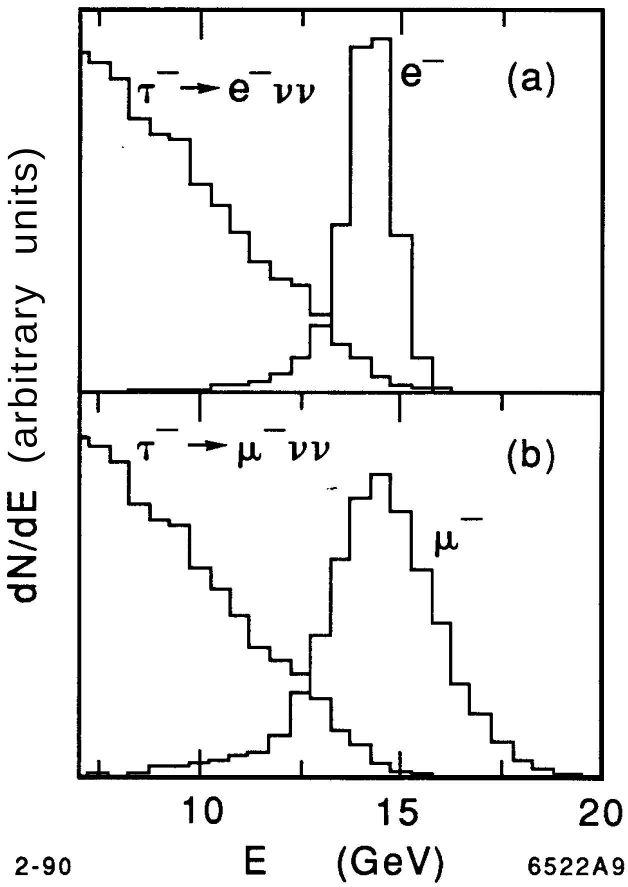


Fig. 2

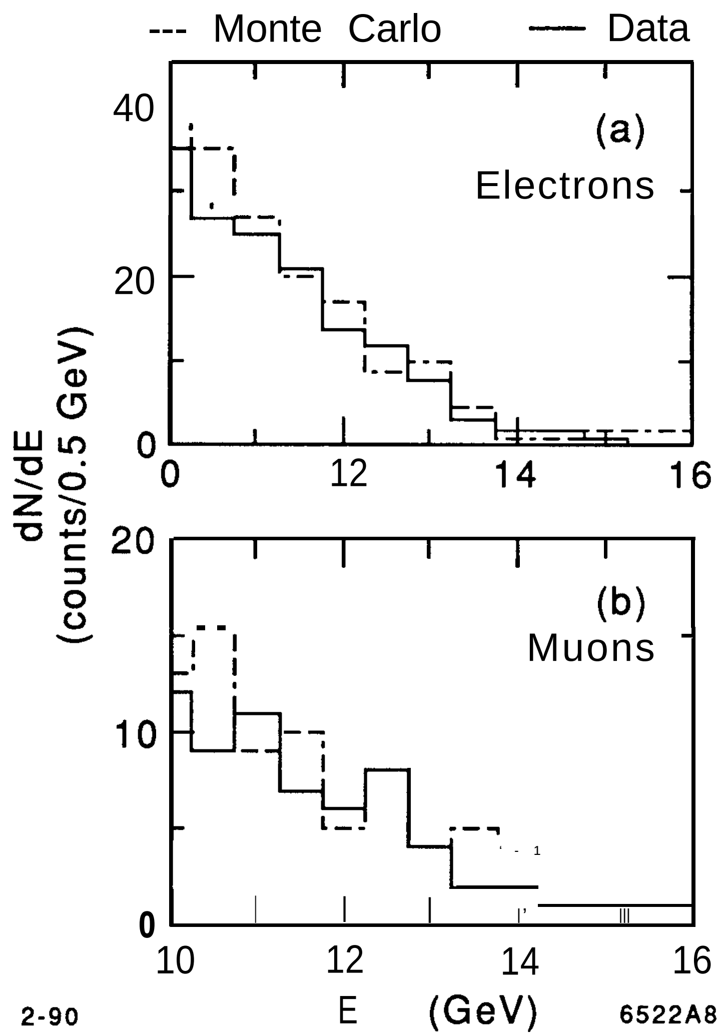

--- Monte Carlo
— Data
(a)
Electrons
40
20
0
0
12
14
16
dN/dE
(counts/0.5 GeV)
(b)
Muons
20
10
0
10
12
14
16
2-90
E (GeV)
6522A8

Fig. 3