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ANOMALOUS PRODUCTION OF HIGH ENERGY MUONS IN e^+e^- COLLISIONS AT 4.8 GeV *

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ABSTRACT

In view of the possible production of heavy leptons or charmed states in e^+e^- collisions we searched for anomalous muons with momenta $p_\mu \gtrsim 1$ GeV/c. The inclusive cross section for $n_{ch} \geq 3$ has an upper limit of 96 pb (assuming isotropy). For $n_{ch} = 2$ and noncoplanarity $> 20^\circ$, an excess of muonic events is observed, corresponding to $\left.\frac{d\sigma}{d\Omega}\right|_{90^\circ} = 23^{+12}_{-9}$ pb/sr; the probability that known processes produce the observed events is 2×10^{-4}.

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Single or double lepton production has been observed in hadron-hadron,[1] lepton-hadron[2] and e^+e^- collisions[3] with rates significantly higher than expected from known physical processes. We have examined our data[4] on e^+e^- collisions for the occurrence of anomalous high energy muons. This search addresses in particular the questions of production of heavy leptons[5] and charmed states[6] since both, if produced, would give rise to decay muons.

In this letter we report on muons with $p_\mu \gtrsim 1.05$ GeV/c from e^+e^- collisions at $\sqrt{s} = 4.8$ GeV. Following a description of the apparatus, centering on its muon detection characteristics, we discuss the $\mu\mu$ events and compare them with QED predictions. We then discuss anomalous muons in two categories of events: (i) events where more than two charged particles were detected ($n_{ch} \geq 3$) and (ii) events with only two charged particles ($n_{ch} = 2$).

A plan view of the experimental apparatus is shown in Fig. 1. The apparatus was designed to study the inclusive particle spectra in e^+e^- collisions and is described in detail elsewhere.[4] Muon events were selected by the single-arm magnetic spectrometer covering 0.1 sr. The muon signature required that a particle trigger a threshold Cerenkov counter, produce minimum-ionizing pulses in a 5-layer shower counter, and traverse a hadron filter consisting of 69 cm of iron. The momentum needed by the muon to penetrate the iron was ~1.05 GeV/c, the exact value depending on angle of incidence, scattering, and straggling.[7] A similar shower counter and hadron filter, covering respectively 2.5 sr and 1.7 sr on the opposite side of the interaction region, identified back-to-back electrons and muons. Multiwire-proportional chambers were used for particle detection. The spectrometer momentum resolution was ±1% at 2.4 GeV, and the angular resolution for particles going toward the hadron filters was $\pm 0.3^\circ$. In addition, a large solid angle central detector (≈ 99% of 4π with an average efficiency of 98%

for track detection) composed of 3 proportional planes surrounded the interaction region. This central detector measured only the azimuthal angle of charged tracks, to a precision of $\pm 3^{\circ}$.

Muons are produced predominantly by the reaction $e^+e^- \to \mu^+\mu^-$. The cross section is known to agree with QED for small noncollinearities.[8] We defined $\mu\mu$ events by requiring that both back-to-back muons penetrate a hadron filter and compared our sample of 190 events with QED. The acceptance of our hadron filters imposed a noncollinearity limit of 30°, within which all $\mu\mu$ events could be identified. The $\mu\mu$ noncollinearity angle distribution is shown in Fig. 2. The QED curve in the figure was calculated using the program of Berends et al.[9] with the requirement that each muon have total energy $E_{\mu} > 1.0$ GeV, and was normalized to the number of events having noncollinearity $< 3^{\circ}$. The observed distribution at angles greater than 3° is seen to agree with QED ($\chi^2 = 7.7$ for 9 d.f.). Based on this normalization, the integrated luminosity for our data sample is $3.84 \pm .31$ pb^{-1}.

The first category of events we discuss is defined by one particle with $p > 1.05$ GeV/c traversing the spectrometer and at least two additional particles in the central detector. This sample contains 73 events; 71 have a hadron identified in the spectrometer and two have a muon ($n_{ch} = 3,8$).[10] These muon events could come from hadron misidentification because of iron penetration or decay, or from direct muon production processes. The expected hadron penetration of the Fe absorber was obtained by calculating the momentum-dependent attenuation probability[11] for each of the 71 observed hadron events,[4] including range, scattering, and straggling; the result is 1.3 events. The background from π-μ decays was obtained by calculating the probability for each observed pion[4] to decay to a muon with $p_{\mu} > 1.05$ GeV/c; this source yields 1.8 events. The number of K-μ

decays passing our event selection criteria was found by Monte Carlo studies to be negligible. The direct muon production processes we have considered are the virtual $\gamma\gamma$ process $e^+e^- \rightarrow \mu^+\mu^-e^+e^-$, and the radiative tails of the ψ and ψ' particles.[12] The first reaction has been studied by Grammer and Kinoshita.[13] The effective cross section was calculated for our geometry and conditions[14] with a resultant contribution of 2.0 events with $n_{ch} = 3$ or 4. The process $e^+e^- \rightarrow \psi' \rightarrow \pi^+\pi^-\mu^+\mu^-$ yields 0.2 events. The total expected background is therefore 5.3 events, consistent with the two events observed. With 95% confidence, the upper limit for the number of events (background plus direct muons) is 6.3. This is one event above expected background, corresponding to a direct muon production cross section in multiparticle events with $p_\mu \gtrsim 1.05$ GeV/c of $\left.\frac{d\sigma}{d\Omega}\right|_{90^\circ} = 2.5$ pb/sr. Assuming instead that the two observed events are background, the upper limit to the same direct muon cross section is 7.5 pb/sr with 95% confidence; assuming isotropy, this yields a total inclusive cross section of 96 pb.

The second category of events to be discussed consists of events with only two charged particles, one of which traversed the spectrometer with momentum $p_\mu \gtrsim 1.05$ GeV/c and was tagged as a muon. The distribution of noncoplanarity angle ϕ for these events is presented in Fig. 3a. The QED curve was calculated using a second program of Berends et al.[9] with total energy thresholds for muons of 1000 MeV and 115 MeV (the minimum energy for a muon to be detected). The distribution for $\phi < 20^\circ$ is in fair agreement with QED, whereas at larger angles an excess of events is evident. The total number of events with $\phi > 20^\circ$ is 13. A few of these are tagged as $\mu\mu$, but for most events (indicated by an "x" in the figure), the charged particle associated with the muon either did not enter the hadron filter or did not penetrate; so it was not tagged as a high momentum muon. The spectrometer muon momentum distribution for the 13 events is shown in Fig. 3b. (Only one of these events appears in the noncollinearity distribution, Fig. 2.)

The 13 events with $\phi > 20^{\circ}$ are not accounted for by QED processes or hadronic background. Integration of the QED differential noncoplanarity cross section over angles $\phi > 20^{\circ}$ gives a total of 3.0 events.[15] The number of events with $p_{\mu} > 1.05$ GeV/c from the process ee $\rightarrow$ ee$\mu\mu$ with only two particles in the central detector was found to be negligible. Based on a total of 18 hadronic events[16] with $n_{ch} = 2$ and $\phi > 20^{\circ}$, the number of background events due to π and k decay was found to be 0.5 and the number of hadrons that penetrated the Fe absorber was 0.4. We also investigated the probability that random tracks simulate non-coplanar μx events and found it to be negligible. Thus 3.9 events out of the 13 can be accounted for. The probability that the extra 9 events observed are due to a statistical fluctuation is 2×10^{-4}. The inclusive cross section corresponding to the 9 events is $\left.\frac{d\sigma}{d\Omega}\right|_{90^{\circ}} = 23^{+12}_{-9}$ pb/sr.

No events with a μe signature were observed in this experiment. The shower counter opposite to the spectrometer would have identified these events if the particles had noncollinearity $\leq 40^{\circ}$. The cross section for this type of events, given our noncollinearity and momentum cuts, is $\left.\frac{d\sigma}{d\Omega}\right|_{90^{\circ}} < 7.5$ pb/sr, with 95% confidence. No model-independent comparison could be made with the results on μe events of the SLAC-LBL collaboration[3] due to the different angular and momentum cuts of the two experiments.

In summary, we find that inclusive muon production above 1.05 GeV/c in multiparticle ($n_{ch} \geq 3$) events is small; we set a new upper limit for the total inclusive cross section assuming isotropy.[17] We detect small but significant production of muons within the same momentum cut in $n_{ch} = 2$ events that is not explained by background or known QED processes.

We gratefully acknowledge the large contributions of the staffs at SLAC, Pavia, Princeton and Maryland without whom this experiment would not have been possible. We would especially like to thank G. A. Snow for many helpful discussions and K.J.F. Gaemers, G. Grammer, Jr., and P. Lepage for their cooperation and QED calculations.

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14. This calculation was performed by G. Grammer, Jr. and P. Lepage and was an extension of the exact calculation of Ref. 13 to include all t-channel amplitudes to fourth order.

15. This number does not include contributions from higher order QED processes, e.g., ee $\rightarrow \mu\mu\gamma\gamma$. This amplitude should be negative and small, such that its inclusion would reduce the QED prediction by $\sim 5 \rightarrow 10\%$ (private communication from K.J.F. Gaemers).

16. Each of these events has one hadron traversing the spectrometer with $p > 1.05$ GeV/c.

17. We are indebted to G. Feldman for critical comments on this result.

FIGURE CAPTIONS

1. Plan view of the experimental apparatus.

2. Noncollinearity distribution out to 30° for $e^+e^- \rightarrow \mu^+\mu^-\gamma$ at $\sqrt{s} = 4.8$ GeV. (Angular resolution $\pm 0.3^{\circ}$.) Both muons required to penetrate $\gtrsim 69$ cm Fe. QED curve from Berends et al.[9] ($\chi^2 = 7.7$ for 9 d.f.).

3. (a) Noncoplanarity distribution for 2-prong events having at least one muon penetrating $\gtrsim 69$ cm Fe. (Average angular resolution $\pm 1^{\circ}$.) The second prong is not identified for events marked with an "x". QED curve from Berends et al.[9] (b) Muon momentum distribution for events with $\phi > 20^{\circ}$.

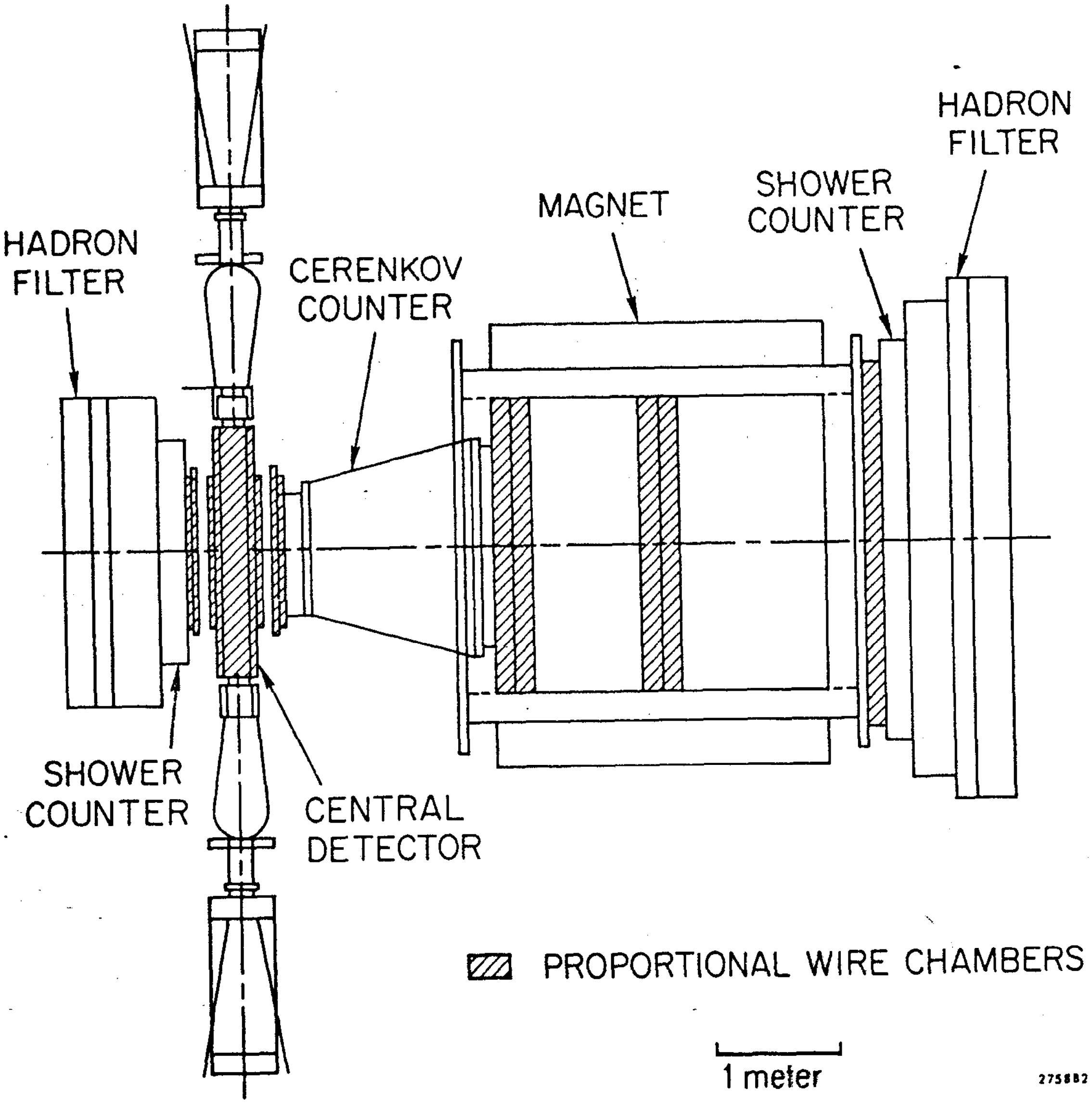

HADRON
FILTER
SHOWER
COUNTER
MAGNET
HADRON
FILTER
CERENKOV
COUNTER
SHOWER
COUNTER
CENTRAL
DETECTOR
PROPORTIONAL WIRE CHAMBERS
1 meter
275882

Fig. 1

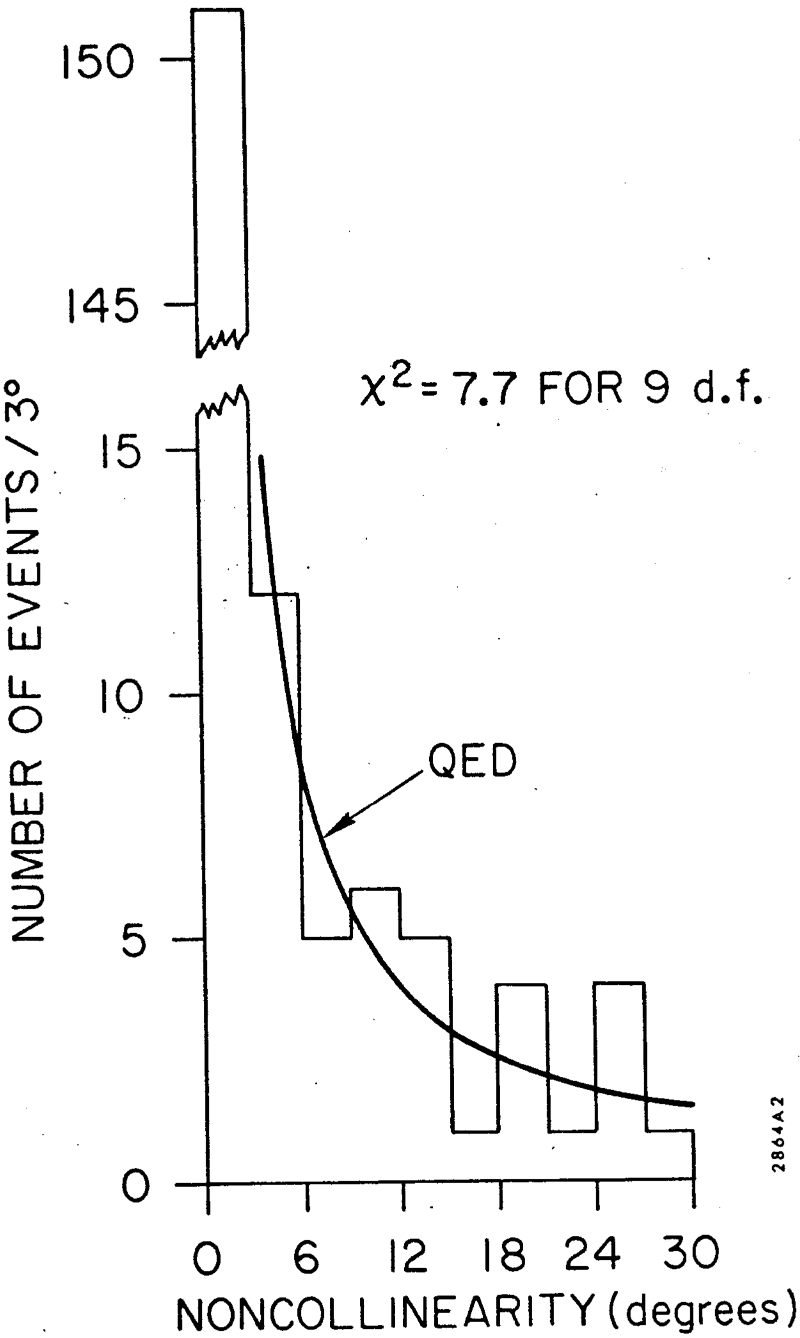
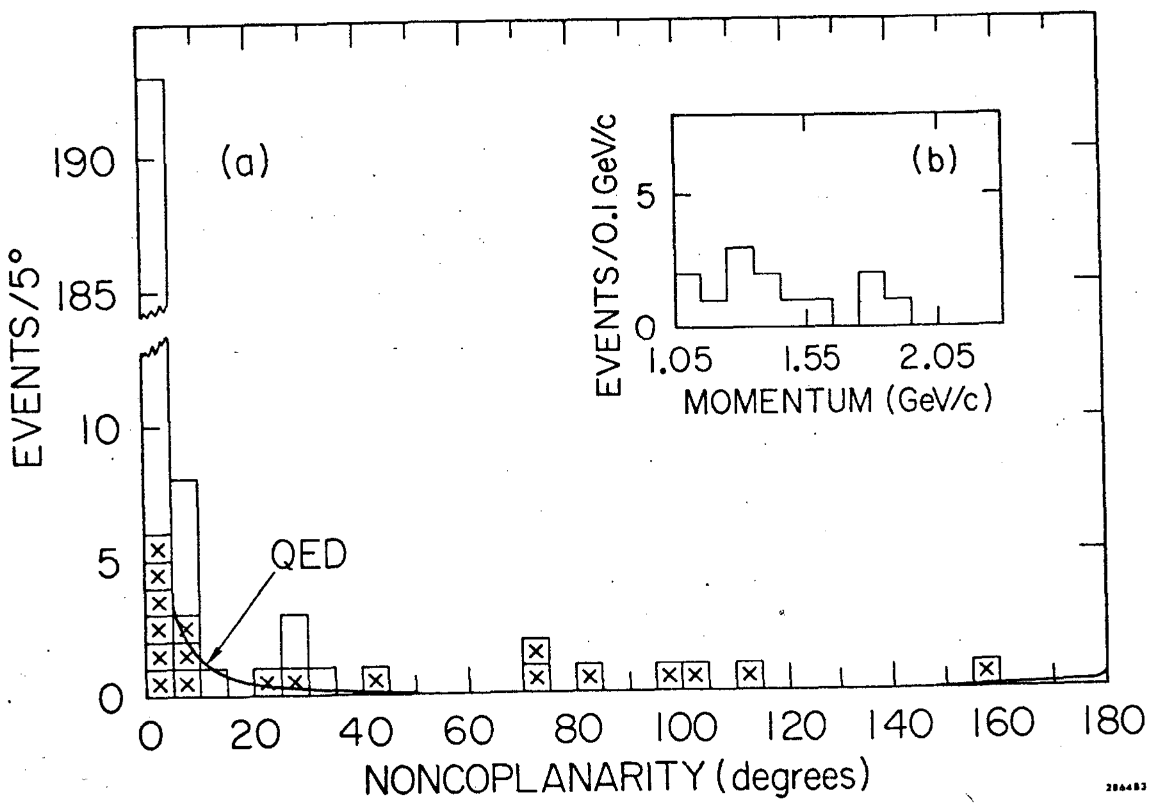

150
145
$\chi^2 = 7.7$ FOR 9 d.f.
15
10
5
0
NUMBER OF EVENTS / 3°
QED
0
6
12
18
24
30
NONCOLLINEARITY (degrees)
2864A2

Fig. 2



(a)
(b)
EVENTS/5°
190
185
10
5
0
QED
0
20
40
60
80
100
120
140
160
180
NONCOPLANARITY (degrees)
EVENTS/0.1 GeV/c
MOMENTUM (GeV/c)
1.05
1.55
2.05

Fig. 3