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Anomalous Production of High-Energy Muons in e^+e^- Collisions at 4.8 GeV*

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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 $n_{\rm ch} \geq 3$ has an upper limit of 96 pb (assuming isotropy). For $n_{\rm ch} = 2$ and noncoplanarity $> 20°$, an excess of muonic events is observed, corresponding to $(d\sigma/d\Omega)|_{90°} = 23^{+12}_{-9}$ pb/sr; the probability that known processes produce the observed events is 2×10^{-4}.

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 quantum-electrodynamic (QED) predictions. We then discuss anomalous muons in two categories of events: (i) events where more than two charged particles were detected ($n_{ch} \geqslant 3$), 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 Cherenkov counter, produce minimum-ionizing pulses in a five-layer shower counter, and traverse a hadron filter consisting of 69 cm of iron and three planes of five scintillation counters each, placed side by side. 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 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 ± 0.3°. In addition, a large-solid-angle central detector (≈ 99% of 4π with an average efficiency of 98% for track detection) composed of three proportional planes surrounded the interaction region. This central detector measured only the azimuthal angle of charged tracks, to a precision of ± 3°.

Muons are produced predominantly by the reaction $e^+e^- \rightarrow \mu^+\mu^-$. 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, Gaemers, and Gastman,[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°. The observed distribution at angles greater than 3° is seen to agree with QED ($\chi^2 = 7.7$ for 9 degrees of freedom). Based on this normalization, the integrated luminosity for our data sample is 3.84 ± 0.31 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

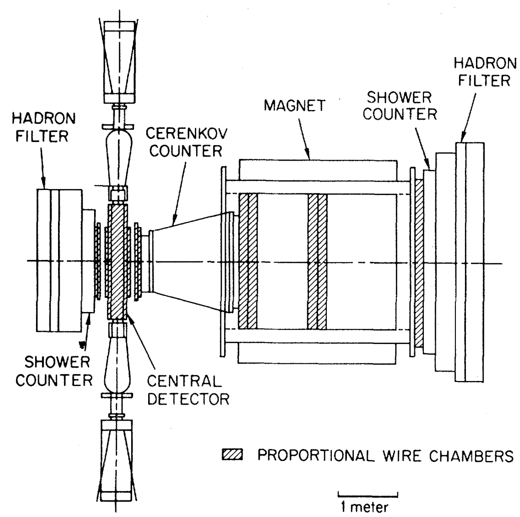

Fig. 1. Plan view of the experimental apparatus.

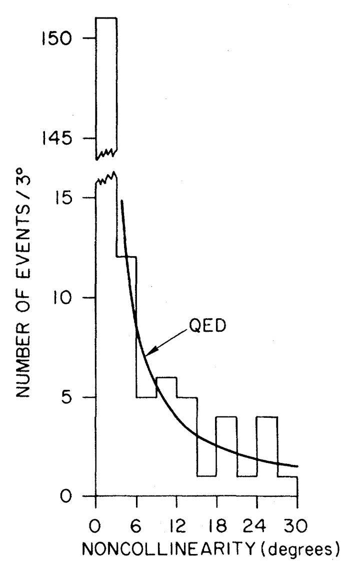

Fig. 2. Noncollinearity distribution out to 30° for $e^+e^- \rightarrow \mu^+\mu^-\gamma$ at $\sqrt{s} = 4.8$ GeV (angular resolution ± 0.3°). Both muons required to penetrate ≳69 cm Fe. QED curve from Ref. 9 ($\chi^2 = 7.7$ for 9 degrees of freedom).

processes. The expected hadron penetration of the Fe absorber was obtained from the experimentally determined 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 $e^+e^- \to \mu^+\mu^-e^+e^-$, 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 with a resultant contribution of 2.0 events for $n_{ch} = 3$ or 4.[14] The process $e^+e^- \to \psi' \to \pi^+\pi^-\mu^+\mu^-$ yields 0.2 events. The total expected background is therefore 5.3 events, consistent with the two events observed. Based on these two events, the predicted upper limit for μ production is 6.3 events with 95% confidence. 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 $(d\sigma/d\Omega)|_{90°} = 2.5$ 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. 3(a). The second particle in the events marked "×" in the figure could not be identified. The eleven "×" events with noncoplanarity less than 30° have a nonpenetrating particle in the conjugate apparatus. Seven of these have angles such that they do not pass through the hadron filter. All are consistent with minimum ionizing particles in the shower counters. They could be muons or hadrons or even electrons with energy $\lesssim 400$ MeV. The QED curve was calculated using a second program of Berends, Gaemers, and Gastman[9] with total energy thresholds for muons of 1000 and 115 MeV (the minimum energy for a muon to be detected) and using the previously determined integrated luminosity. The distribution for φ

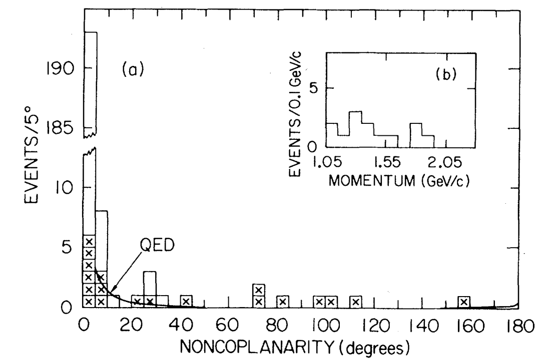

FIG. 3. (a) Noncoplanarity distribution for two-prong events having at least one muon penetrating $\gtrsim 69$ cm Fe (average angular resolution ±1°). The second prong is not identified for events marked with an "×". QED curve from Ref. 9. (b) Muon momentum distribution for events with $\varphi > 20°$.

$< 20°$ is in fair agreement with QED, whereas at larger angles an excess of events is evident. The total number of events with $\varphi > 20°$ is thirteen. The spectrometer muon momentum distribution for the thirteen events is shown in Fig. 3(b). (Only one of these events appears in the noncollinearity distribution, Fig. 2.)

The thirteen events with $\varphi > 20°$ are not accounted for by QED processes or hadronic background. Integration of the QED differential noncoplanarity cross section over angles $\varphi > 20°$ gives a total of 3.0 events.[15] The number of events with $p_\mu > 1.05$ GeV/c from the process $ee \to ee\mu\mu$ with only two particles in the central dectector was found to be negligible. Based on a total of eighteen hadronic events[4,16] with $n_{ch} = 2$ and $\varphi > 20°$, the number of background events due to π and K decay was found to be 0.5 and the number of hadrons expected to penetrate the Fe absorber was 0.4.[7,11] We also investigated the probability that random tracks simulate noncoplanar μx events and found it to be negligible. Thus 3.9 events out of the thirteen can be accounted for. The probability that the extra nine events observed are a result of statistical fluctuation is 2×10^{-4}. The inclusive cross section corresponding to the nine events is $(d\sigma/d\Omega)|_{90°} = 23^{+12}_{-9}$ pb/sr. The assumption of isotropy gives a total muon inclusive cross section of 285^{+151}_{-113} pb.

In order to see if these results are compatible with the μ-e cross section reported by the SLAC-LBL collaboration,[3] we can make two comparisons. One is for the total cross sections; the other is for those events in our experiment that could be tagged specifically as μ-e. (The shower counter opposite to the spectrometer would have identified these μ-e events, if the particles had noncollinearity $\lesssim 40°$ and energy $\gtrsim 400$ MeV.) The first comparison shows our total cross sections to be considerably larger than their observed μ-e cross section (~ 20 pb), but the strong effects of having different final states and different angular and momentum cuts make a comparison of these results somewhat model dependent. The second comparison, still crude, suggests that we could only expect ~ 0.3 events as identified μ-e's, which is consistent with our observation of none. Our limit on the cross section for μ-e events, given our noncollinearity and momentum cuts, is $(d\sigma/d\Omega)|_{90°} < 7.5$ pb/sr with 95% confidence. Thus these comparisons indicate that while our equipment is not sensitive to the specific μ-e signature at its published value, we are sensitive to the more general μ-x process and have detected a significant signal of this type.

In summary, we find that inclusive muon production above 1.05 GeV/c in multiparticle ($n_{\rm ch} \geq 3$) 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 $n_{\rm ch} = 2$ events that is not explained by background or known QED processes.

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[10]The event with $n_{\rm ch} = 3$ has two identified muons on opposite sides of the interaction region and an unidentified particle penetrating only the shower counter.

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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. Mostly $n_{\rm ch} = 3$ events should be seen from this reaction in our apparatus. This results from the noncoplanarity restriction ($\varphi > 20°$) where the net transverse momentum of the muons is balanced by the electrons. Characteristically, one of the electrons would be deflected into our central detector (but not into the shower counters). We note that no event with both an identified μ and e on the conjugate side was seen.

[15]This number does not include contributions from higher-order QED processes, e.g., $ee \rightarrow \mu\mu\gamma\gamma$. The amplitude for this process should be negative and small, such that its inclusion would reduce the QED $ee \rightarrow \mu\mu\gamma$ cross section by 5%–10% (private communication from K. J. F. Gaemers).

[16]Each of these events had one hadron traversing the spectrometer with $p > 1.05$ GeV/c. (The number of hadronic events with $n_{\rm ch} = 2$, $p > 1.05$ GeV/c, and $\varphi < 20°$ was twelve pions and zero kaons.)

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