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Inclusive Muon Production in e^+e^- Annihilation with $\langle s^{1/2}\rangle = 7.3$ GeV

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We present results on charged multiplicity $n_{ch} = 2$ and $n_{ch} > 2$ muon events produced in e^+e^- collisions with $\langle s^{1/2}\rangle = 7.3$ GeV at 90° to the beams. The background-subtracted inclusive cross section for the $n_{ch} = 2$ events is 10.2 ± 5.4 pb/sr, in agreement with the expected contribution from the heavy lepton τ. The cross section for the $n_{ch} > 2$ events is 19.0 ± 6.5 pb/sr whereas we expect only 2.9 pb/sr from the τ, indicating that we may be seeing the weak decays of charmed mesons.

The first evidence for heavy-lepton production in e^+e^- annihilation was obtained at SPEAR by Perl *et al.*[1] They observed an anomalously high cross section for the process $e^+e^- \to \mu^\pm e^\mp$ + missing energy in the 4-GeV center-of-mass energy region. Subsequently Cavalli-Sforza *et al.*[2] measured an inclusive anomalous muon signal at SPEAR at a center-of-mass energy of $\sqrt{s} = 4.8$ GeV for two-prong charged multiplicity ($n_{ch} = 2$) events with an acoplanarity angle $\varphi > 20°$ and with a muon momentum $p_\mu > 1.05$ GeV/c.[2] No signal above background was observed for events with charged multiplicity $n_{ch} > 2$ at $\sqrt{s} = 4.8$ or 3.8 GeV. In the 7-GeV center-of-mass energy region an $n_{ch} = 2$ anomalous muon signal has been reported by Feldman *et al.*[3] and, in contrast to their results (Ref. 2) at lower energies, they found a significant anomalous muon signal in the $n_{ch} > 2$ channel. Recently, Burmester *et al.* have reported anomalous muon production for $n_{ch} = 2$ events at DORIS in the center-of-mass energy region from 4 to 5 GeV.[4]

In this Letter we report on new measurements at SPEAR II in the higher-energy range with $\langle s^{1/2}\rangle = 7.3$ GeV in which an anomalous muon signal is seen in $e^+e^- \to \mu^\pm X$ both for $n_{ch} = 2$ and $n_{ch} > 2$ final-state charged multiplicities.

The apparatus used in this experiment is quite similar to that used in a previous experiment.[5] Several modifications were made to improve the measurements of charged-particle multiplicities, particle trajectories, and time of flight. The trigger required traversal of the single-arm spectrometer ($\Delta\Omega \cong 0.084$ sr) by a charged particle at $90° \pm 13°$ relative to the e^+e^- beams; the minimum momentum for traversal of the spectrometer was ~ 350 MeV/c.

Spectrometer muon candidates were selected using the following criteria. The threshold Cherenkov counter, filled with 90 lb/in.^{2} (gauge) of propane, was required to be on, thus selecting muons with $p_\mu \gtrsim 0.8$ GeV/c. The particle was also required to traverse at least two layers (the equivalent of 77 cm of Fe) of the hadron filter. Range-straggling calculations determined that 95% of the muons with $p_\mu = 1.15$ GeV/c would penetrate this amount of material. In a similar way the hadron filter opposite the spectrometer (conjugate side) was used to identify muons within its solid angle of ~ 0.5 sr by requiring penetration out to the second plane of scintillation counters (also 77 cm of Fe).

The charged-particle multiplicity, $n_{\rm ch}$, for each event was measured with the cylindrical central detector, shown in detail in Aschman *et al.*,[6] consisting of four layers of proportional tubes (219 total) which subtended $0.9\times(4\pi$ sr) for events coming from the beam interaction region. A charged-particle track was defined by at least two tubes aligned with the interaction region. A charged particle with momentum $\gtrsim 65$ MeV/c and within the central detector acceptance had a 98% detection probability.

Back-to-back muons with acollinearity angles $\theta < 3°$ were used together with the quantum-electrodynamics (QED) calculations of Berends, Gaemers, and Gastman[7] to determine the luminosity. The 119 $e^+e^- \to \mu^+\mu^-(\gamma)$ events observed (the γ was not detected) correspond to a time-integrated luminosity of 8.47 ± 0.78 pb^{-1}, obtained by integrating over the apparatus acceptance. Since the QED calculations were made with high precision to order α^3, only the statistical error is given.

Multiplicity $n_{ch} = 2$ Events.—Multiplicity $n_{\rm ch} = 2$ events were defined by a spectrometer muon candidate and a second particle track in the central detector that was not required to be detected in the conjugate side. The acoplanarity angular distribution of these events is shown in Fig. 1; an "×" indicates that the conjugate particle was not identified as a muon. The $\mu\mu\gamma$ curve was calculated using a program of Berends, Gaemers, and Gastman[7,8] with the requirement that the muon momenta be greater than 1.15 GeV/c for one and 65 MeV/c for the other. The curve was normalized to the integrated luminosity. Whereas we observe fourteen events with acoplanarity $20° \leq \varphi \leq 180°$, the calculated number of $\mu\mu\gamma$ events is 5.5 ± 0.5.

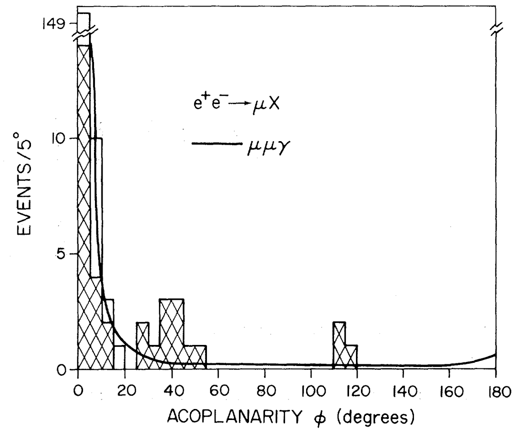

FIG. 1. Acoplanarity distribution of the multiplicity $n_{\rm ch} = 2$ muon events with $p_\mu > 1.15$ GeV/c. Events with an "×" indicate that the conjugate particle was not identified. The solid line is the calculated $\mu\mu\gamma$ contribution.

Other backgrounds to this anomalous muon signal in addition to $\mu\mu\gamma$ must also be considered. Hadron misidentification due to π and K punchthroughs and decays was calculated to be 0.8 ± 0.2 events using our observed $n_{\rm ch} = 2$ hadrons with $\varphi > 20°$ and the experimental results of Sander[9] and Abe *et al.*[10] which are in agreement with the punchthroughs seen in our hadron data at the ψ and ψ' energies.[11] The contamination due to the two-photon process, $e^+e^- \to e^+e^-\mu^+\mu^-$, was calculated to be 0.5 ± 0.1 $n_{\rm ch} = 2$ muon events using the program of Grammer and Kinoshita.[12] The sum of all $n_{\rm ch} = 2$ backgrounds, including $\mu\mu\gamma$, is 6.8 ± 0.6 events.

Subtracting this background from the total of fourteen $n_{\rm ch} = 2$ muon events with $20° < \varphi < 180°$ gives a signal of 7.2 ± 3.8 events. This corresponds to a cross section of $d\sigma/d\Omega = 10.1 \pm 5.4$ pb/sr. We previously reported[2] at $\sqrt{s} = 4.8$ GeV and 90° a cross section of $d\sigma/d\Omega = 26^{+11}_{-8}$ pb/sr.

The momentum distribution of the fourteen observed $n_{\rm ch} = 2$ muon events with $20° < \varphi < 180°$ is shown in Fig. 2. Also shown is the distribution expected from background.

While the measured spectrum peaks toward

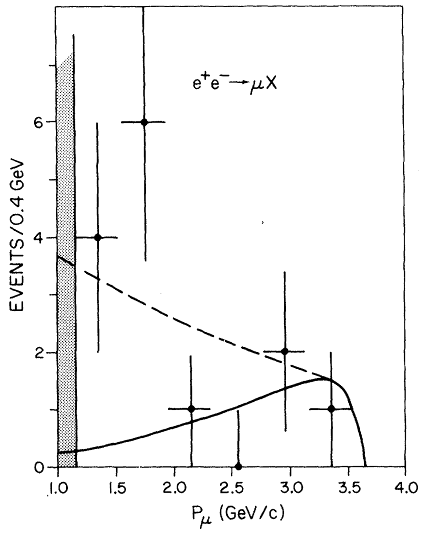

FIG. 2. Momentum distribution of the multiplicity $n_{ch} = 2$ muon events with acoplanarity $\varphi > 20°$. The solid line is the expected $\mu\mu\gamma$ plus background contribution; the dashed line is the expected $\mu\mu\gamma$ plus background plus τ contribution. The momentum cut $p > 1.15$ GeV/c is indicated by the stippled region.

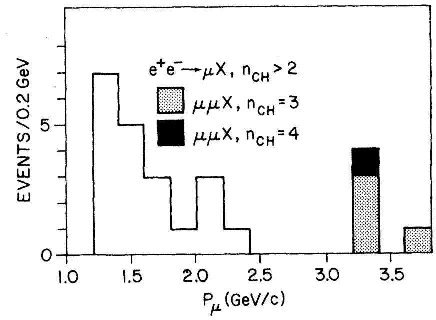

FIG. 3. Momentum distribution of the multiplicity $n_{ch} > 2$ events. The shaded portion of the histogram indicates the five events that have an identified muon in both the spectrometer and conjugate detectors.

low momentum, the background, which derives predominantly from $\mu\mu\gamma$, does not: Below 2.2 GeV/c, one QED event is predicted whereas the observed number is eleven events. Background and $\mu\mu\gamma$ predictions alone do not explain the experimental observations. The addition of other sources is suggested,[1,2] one possibility being the production of a pair of sequential heavy leptons, $\tau^\pm$. The dashed line in Fig. 1 shows the expected muon momentum distribution from background and the process $e^+e^- \to \tau^+\tau^-$. The τ is assumed to have a mass of 1.9 GeV/c^2, spin $\frac{1}{2}$, $V-A$ coupling, a massless neutrino, and decay branching ratios as calculated by Tsai.[13] The expected μX, $n_{ch}=2$ cross section is, under these assunptions, 10.2 pb/sr for $p_\mu > 1.15$ GeV/c, in agreement with the observed 10.1 ± 5.4 pb/sr. The momentum distribution, as well, is in reasonable agreement with the theory (χ^2 per degree of freedom is 1.4). Assuming that the background-subtracted signal is due to τ decay, the branching ratio into muons is 0.17 ± 0.09, which agrees with our previous results[2] at $\sqrt{s} = 4.8$ GeV of $0.22^{+0.10}_{-0.07}$. This result is also in agreement with the experimental determinations by Perl *et al.*[1] of $B_\mu = 0.175 \pm 0.04$, and by Burmester *et al.*[4] at 4 GeV $< \sqrt{s} < 5$ GeV of $B_\mu = 0.15 \pm 0.03$.

Multiplicity $n_{ch} > 2$.—The momentum distribution of the 25 muon events with $n_{ch} > 2$ and momentum $p_\mu > 1.15$ GeV/c is shown in Fig. 3. The shaded portion of the histogram indicates the five events that contain a muon on the conjugate side. These events have acoplanarity $\varphi < 10°$ and acollinearities between 1° and 10°, and they peak at high momentum. Four of these events have $n_{ch} = 3$ and the fifth has $n_{ch} = 4$. Our calculations support the hypothesis that these events derive from $\mu^+\mu^-\gamma$ in which there is γ conversion in either the beam pipe or central detector.[14] In order to reduce this background, we consider $n_{ch} = 3$ and $n_{ch} = 4$ μX events only if the smallest acoplanarity angle, defined with respect to the spectrometer muon, is greater than 10°. The effect of this cut is to eliminate the five shaded events in Fig. 3, leaving twenty events.

An upper bound to the number of expected $\mu\mu\gamma$ events with $n_{ch} = 3$ and $\varphi > 10°$ was determined to be one event, based on the calculated $\mu\mu\gamma$ momentum and acoplanarity distributions and the hard photon conversion probability in the beam pipe and central detector. The other backgrounds for $n_{ch} > 2$ events, calculated in a manner analogous to that described for the $n_{ch} = 2$ events, are 5.5 ± 0.5 events from π and K punchthrough and decays and a negligible contribution from the two-photon process. The total background to the multiplicity $n_{ch} > 2$ events is 6.5 ± 0.7 giving a background-subtracted signal of 13.5 ± 4.5 events.

The background-subtracted cross section for $n_{ch} > 2$ muon events with $\langle s^{1/2} \rangle = 7.3$ GeV is 19.0 ± 6.3 pb/sr. Using Tsai's calculated branching ratios[10] for decays of the τ, we expect 2.9 pb/sr. Our previous data[2] at $\sqrt{s} = 4.8$ GeV were consistent with background and placed an upper limit on the $n_{ch} > 2$ signal of 14 pb/sr (95% confidence level). We are seeing, therefore, a substantial inclusive cross section for $n_{ch} > 2$ muon events with $p_\mu > 1.15$ GeV/c and $\langle s^{1/2}\rangle = 7.3$ GeV that we did not see at a lower center-of-mass energy. A possible source of these muons is the weak decays of charmed particles. Figure 4 shows the background-subtracted cross sections plotted as a function of multiplicity for both $n_{ch}=2$ and $n_{ch} > 2$ events. Though our geometrical and momentum acceptance is different from those of Refs. 1 and 3, the relative $n_{ch}=2$ and $n_{ch}>2$ signals are in reasonable agreement with the results reported by Feldman *et al.*[3] for the total cross sections $\sigma_{\mu X}$ in the energy region 5.8 GeV $< \sqrt{s} <$ 7.8 GeV.

In conclusion, the multiplicity $n_{ch}=2$ muon data with acoplanarity $\varphi > 20°$ can be explained by the decay of the τ. The multiplicity $n_{ch}>2$ events, however, cannot derive solely from this source and may indicate that we are seeing the semileptonic decays of charmed particles.

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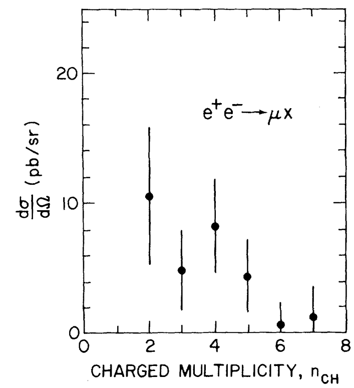

FIG. 4. Inclusive cross sections at 90° relative to the e^+e^- beams as a function of charged multiplicity.

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[8]These calculations do not include higher-order QED calculations, e.g., $ee \rightarrow \mu\mu\gamma\gamma$. The amplitude for this process would reduce the $ee \rightarrow \mu\mu\gamma$ cross section by (5–10)% (private communication from K. S. F. Gaemers).

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[14]The photon acoplanarity angle in the central detector was calculated for each of the four $n_{ch}=3$ events and was found to be kinematically consistent with the $\mu\mu\gamma$ hypothesis given the momentum resolution ($\Delta p \sim 140$ MeV/c) and acollinearity resolution ($\Delta\theta \sim 0.5°$) of the apparatus. While the $n_{ch}=4$ event is kinematically consistent with the $\mu\mu\gamma$ final state with a spurious track, it may derive from $\mu\mu\gamma\gamma$ or some other background source.