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High-Momentum Hadrons from e^+e^- Reactions: Spectra, Particle Ratios, and Multiplicities*

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We present results from a study of high-momentum inclusive hadron production in electron-positron interactions at $\sqrt{s}=3.8$ and 4.8 GeV. Comparison of the momentum spectra at these energies shows no scaling violation in the region x $(=E/E_{\text{beam}}) > 0.7$. At $\sqrt{s}=4.8$ GeV the K/π ratio for hadrons with momenta >1.1 GeV/c is 0.27 ± 0.08, and the average number of charged hadrons is 3.6 ± 0.3 for those events which have at least one charged hadron with momentum greater than 1.1 GeV/c.

This paper presents results from an experiment which measured the inclusive cross section for hadron production in e^+e^- interactions. Measurements were made at e^+e^- center-of-mass energies of 3.8, 4.8, 5.0, and 5.1 GeV at the SPEAR facility of Stanford Linear Accelerator Center (SLAC). The experiment occurred prior to the discovery[1] of the ψ (J) particles, so the data do not add direct information about these particles. It has been observed that R, the ratio of the cross section for "$e^+e^-\rightarrow$ hadrons" relative to "$e^+e^-\rightarrow\mu^+\mu^-$," increases[2] from ≈ 2.5 to ≈ 5 around 4 GeV, and we present data below and above this energy. This report will deal with events having a particle with a momentum greater than 1.1 GeV/c, where our particle identification is best and our backgrounds least. Data for lower particle momenta will be presented later. The data samples at $\sqrt{s}=5.0$ and 5.1 GeV together were only about 15% of that at $\sqrt{s}=4.8$ GeV. These have all been combined and will be referred to as $\sqrt{s}=4.8$ GeV.

The main element of the apparatus (Fig. 1) was a single-arm magnetic spectrometer set at 90° to the e^+e^- beams and subtending about 1% of 4π steradians. The magnetic field was vertical and rather uniform at ≈ 4.2 kG; the total $\int B\,dl$ was ≈ 11.8 kG m. Particle positions were measured by proportional wire chambers[3] or scintillation counters. The event trigger required a charged particle passing through the spectrometer in coincidence with the passage of the e^+e^- bunches through the interaction region.

The experiment achieved $e/\mu/\pi/K/p$ identification of the spectrometer particle by a combination of a threshold Cherenkov counter, shower counters, range measurement, and time of flight. The Cherenkov counter was filled with 90 lb/in.^{2} (gauge) of propane. Its pion threshold was 1.05 GeV/c, and it unambiguously separated $e/\mu/\pi$ from K/p above 1.2 GeV/c. This particle identification was aided by time-of-flight (TOF) measurements between 1.1 and 1.2 GeV/c. The Cherenkov pulse height was also helpful in distinguishing electrons from pions above 1.05 GeV/c, but electrons were identified primarily by a five-

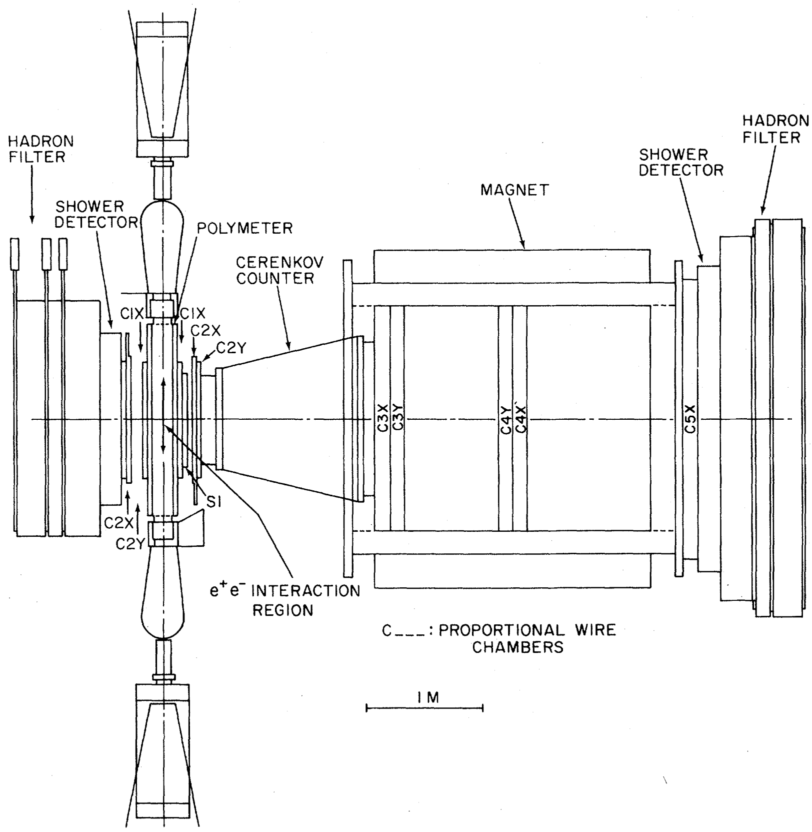

FIG. 1. Plan view of the experimental apparatus.

layer lead-scintillator shower counter. The total thickness of that counter was 7.2 radiation lengths; the average electron pulse was about 6 times that of a minimum-ionizing muon. Muons were identified by their passage through a 26-in.-thick iron "hadron filter." Scintillation counters were located at three depths in this filter to measure particle ranges. Protons were distinguished from kaons by a TOF measurement. A scintillation counter (S1) near the interaction region and the scintillation counters in the first two layers of the shower counter formed the TOF link. The total flight path was ≈ 5 m. During data taking the TOF system was monitored every few hours by pulsing light-emitting diodes mounted on each counter and recording the results on the data tape.

A central detector ("polymeter") surrounded the SPEAR beam pipe and covered 99% of the solid angle. It consisted of four units of three proportional wire chambers each. These sat above, below, and on each side of the interaction region, with wires running parallel to the e^+e^- beams. It measured the charged-particle multiplicity and helped in the reconstruction of the event vertices.

Three proportional wire chambers, a shower counter, and a hadron filter similar to those in the spectrometer were placed on the side of the e^+e^- beams opposite to the spectrometer. This system measured particle directions and identified electrons and muons. It greatly improved our identification of event types $e^+e^- \to e^+e^-$ and $e^+e^- \to \mu^+\mu^-$, the main backgrounds. Studies of these events showed that the cosmic-ray background was negligible and that our vertex reconstruction had a spatial precision of ± 3 mm and collinearity precision of $\pm 0.5°$.

We measured the ratio of hadron events to $e^+e^- \to \mu^+\mu^-$ events, assuming the validity of QED for the muon events. Several experiments[4] have shown that $e^+e^- \to \mu^+\mu^-$ and $e^+e^- \to e^+e^-$ events with small noncollinearity agree with quantum electrodynamics. We therefore imposed a 10° noncollinearity cut upon our $\mu^+\mu^-$ data, although we can identify μ pairs with noncollinearities up to $\approx 40°$. No multiplicity requirement was imposed in the event selection criteria. However, of the 288 $\mu^+\mu^-$ events only nine had a multiplicity other than two. Each of the nine had a multiplicity of three or four, and could be due to the conversion of a radiated γ ray. They give an upper limit of approximately 3% for an accidental particle in the polymeter. We used the computer program of Berends, Gaemers, and Gastmans[5] to calculate the $e^+e^- \rightarrow \mu^+\mu^-$ inclusive cross section (twice the normal cross section) to order α^3 for noncollinearity $\leq 10°$ averaged over our geometrical acceptance. We found $d\sigma/d\Omega = 0.44$ nb/sr at $\sqrt{s} = 4.8$ GeV and $d\sigma/d\Omega = 0.69$ nb/sr at $\sqrt{s} = 3.8$ GeV. The cross sections quoted later in this report have a normalization uncertainty of $\pm 7\%$ at $\sqrt{s} = 4.8$ GeV and $\pm 11\%$ at $\sqrt{s} = 3.8$ GeV due to the $\mu^+\mu^-$ statistics.

Backgrounds in the experiment were determined by two different means. We made separated and single-beam runs during the experiment, scanning these for events containing a high-momentum hadron satisfying our normal selection criteria. Though none was found, the running times involved only limited our background to < 5%. We used e^+e^- and $\mu^+\mu^-$ events to locate the beam interaction region. Comparison of the vertex regions for high-momentum hadron events and for e^+e^- and $\mu^+\mu^-$ events showed that a 2% reduction in cross sections was needed to account for hadronic backgrounds from gas scatters and beam-pipe interactions.

The TOF measurements were used to separate protons from kaons. There were 21 nonpionic events, but no valid measurement could be made on three of them because of shower-counter-system contamination. Of the eighteen events with TOF measurements, fifteen were kaons and three were antiprotons. The three unanalyzable events were weighted as proton or kaon in the same ratio as unambiguous events.

Corrections from our Monte Carlo program were applied to find the original production ratios. This gave K/π ratios of 0.27 ± 0.08 (78 π's and 14 K's observed) and 0.8 ± 0.5 (seven π's and four K's observed) at $\sqrt{s} = 4.8$ and 3.8 GeV, respectively. The p/π ratio is 0.04 ± 0.02 (3 $\bar{p}$'s and 78 π's observed) at $\sqrt{s} = 4.8$ GeV. These ratios are for particles produced at 90° with momenta greater than 1.1 GeV/c. The K/π ratios are larger than those reported at lower momenta[6] in e^+e^- or at similar momenta in pp interactions.[7] No p's or $\bar{p}$'s were found at $\sqrt{s} = 3.8$ GeV.

Figure 2 shows a scatter plot of the charged multiplicity measured by the polymeter versus the momentum of the spectrometer hadron. The

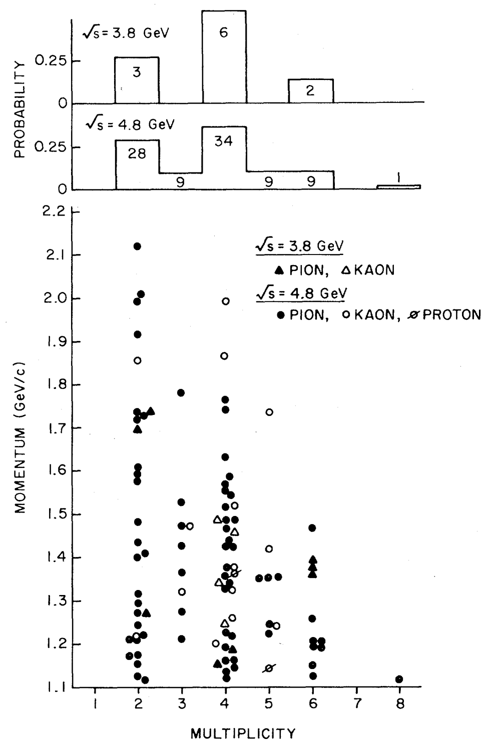

FIG. 2. Charged multiplicity versus spectrometer hadron momentum.

few events which have an odd number are due predominately to γ-ray conversions in the 0.04 radiation lengths of material in the beam pipe and first proportional wire chamber (PWC) and, to a lesser extent, to inefficiencies in the PWC's. The figure shows that the multiplicity does not depend dramatically upon particle type or s, but clearly decreases as the energy of the one particle increases, the tendency one might expect from energy conservation. The average charged multiplicities for all of these events, selected to have at least one charged hadron with momentum greater than 1.1 GeV/c, are 3.6 ± 0.3 and 3.8 ± 0.5 at $\sqrt{s} = 4.8$ and 3.8 GeV, respectively. Note that event types which have two charged hadrons with momentum greater than 1.1 GeV/c contribute to the average with double weighting since they have twice the detection probability, while event types with no high-momentum particles do not contribute at all.

Figure 3 shows the inclusive invariant cross section at 90°, differential in momentum, for π's and K's above 1.1 GeV/c, at $\sqrt{s} = 4.8$ GeV. This figure shows that below 1.6 GeV the π cross sections are distinctly larger than the K cross sec-

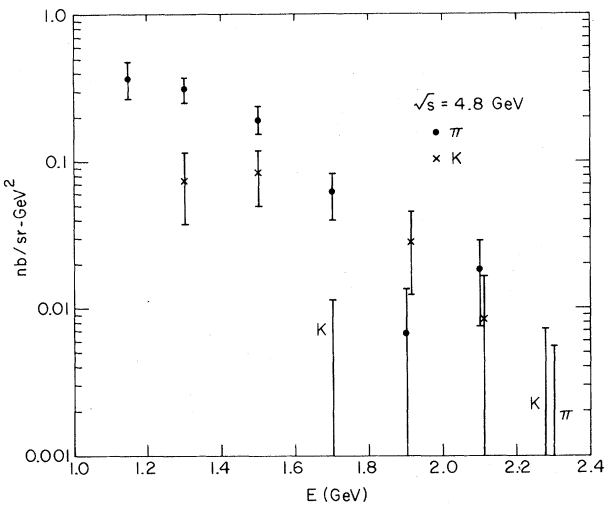

FIG. 3. Inclusive hadron spectrum $(E/p^2)(d\sigma/d\Omega\, dp)|_{90°}$ versus E of particle.

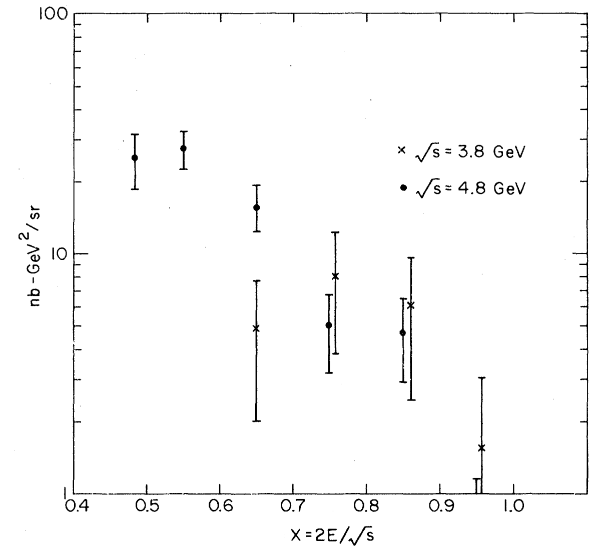

FIG. 4. Inclusive hadron spectrum $s(d\sigma/d\Omega\, dx)|_{90°}$ versus x $(=2E/\sqrt{s})$ of particle.

tions, but may become similar at higher particle energy. It also shows that the statistics are such that the K/π ratio quoted earlier is dominated by the lower energy data. Figure 4 shows the quantity $s\,d\sigma/d\Omega\, dx|_{90°}$ versus x $(\equiv E_{\rm hadron}/E_{\rm beam})$ for all hadrons at $\sqrt{s}=3.8$ GeV and at $\sqrt{s}=4.8$ GeV. No significant scaling violation is observed in the region above $x=0.7$. Below $x=0.7$ there is one point at $x=0.65$ which is suggestive of scaling breakdown, but the data do not permit an extrapolation into this region.

No $e^+e^- \to \pi^+\pi^-$, K^+K^-, $p\bar{p}$ events were seen at either s value. With 95% confidence the normal (not inclusive) differential cross sections for these processes at 90° are below 16, 22, and 15 pb/sr, respectively, at $\sqrt{s}=3.8$ and are below 3.8, 4.9, and 3.7 pb/sr, respectively, at $\sqrt{s}=4.8$ GeV.

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