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Observation of Scale Breaking in Inclusive Hadron Production by e^+e^- Annihilation

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Measurements are presented of the inclusive charged-particle cross sections $s\,d\sigma/dx$ for e^+e^- annihilation at center-of-mass energies of 5.2, 6.5, and 29.0 GeV. Significant scale breaking is observed in these cross sections.

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The naive quark-parton model provides a good qualitative description of the process $e^+e^- \rightarrow$ hadrons. At sufficiently high energies, where quark and hadron masses may be neglected, this model predicts that quark fragmentation depends only on the quark flavor and the dimensionless variable x, the ratio of the hadron energy to the beam energy. Thus the cross section $s\,d\sigma/dx$ should be independent of the center-of-mass energy $\sqrt{s}$.[1] In quantum chromodynamics (QCD), emission of gluons by the primary quarks leads to a depletion of particle production at large x by an amount which is s dependent.[2] Since these effects are small and vary only logarithmically with s, a sensitive test of these predictions requires a large energy range and good understanding of systematic errors. Previous measurements showed that scaling is approximately valid in the region 3 GeV $<\sqrt{s}<$ 8 GeV.[3] However, as a result of large systematic uncertainties early measurements at higher energies were not sufficiently sensitive to observe deviations from scaling behavior.[4]

In this Letter, we present measurements of the cross section $s\,d\sigma/dx$ for charged particles at center-of-mass energies of 5.2, 6.5, and 29.0 GeV. Since in this experiment particles were not identified, x was approximated by the ratio of the particle momentum rather than energy to the beam energy.[5] The data were acquired with the Mark II detector at the SPEAR (for $\sqrt{s}=5.2$ and 6.5 GeV) and PEP (for $\sqrt{s}=29$ GeV) storage rings located at the Stanford Linear Accelerator Center. The corresponding integrated luminosities were 4.16, 1.63, and 13.6 events/pb at the three energies. The use of the same detector over this wide range in energy helps to reduce the systematic errors to a level where deviations from the simple quark-parton model can be observed.

The Mark II detector[6] was essentially the same at SPEAR and PEP. Charged particles were tracked by an array of cylindrical drift chambers in an axial magnetic field of 4.1 kG at SPEAR and 4.65 kG at PEP, with a momentum resolution of $(0.01^2p^2+0.015^2)^{1/2}$ (p in gigaelectronvolts). Tracks which passed within 1.5 cm in radius and 15 cm in z from the beam interaction point were constrained to this point, improving the momentum resolution to $(0.007^2p^2+0.015^2)^{1/2}$. The tracking efficiency estimated from Monte Carlo studies and a visual scan of a subset of the data was $>99\%$ for the data taken at SPEAR, and 95% for the PEP data as a result of the much larger track density. In both cases, the efficiency was approximately independent of x. The detector trigger required at least two charged tracks to be found by a hardware processor. At 6.5 and 29.0 GeV both tracks were required to be within the central 65% of the detector solid angle, whereas at 5.2 GeV the second track was only required to be within the central 85%. At 29 GeV an independent total-energy trigger was added which was satisfied if more than 1 GeV of energy was deposited in the front half of each of at least two liquid-argon modules. From the redundancy provided by this requirement, the trigger efficiency for hadronic events was found to be > 99%.

For the 5.2- and 6.5-GeV data sets, hadronic events were required to have at least three charged tracks with transverse momentum > 100 MeV/c and $|\cos\theta| < 0.79$, both with respect to the beam direction. The tracks were also required to pass within 6 cm in radius from the beam interaction point, and satisfy an x-dependent requirement on the distance of closest approach along the beam (z) direction varying from < 30 cm at small x to < 5 cm for $x > 0.5$. To reduce contamination from interactions of the beam with the walls of the vacuum chamber or with the residual gas, the fitted event vertex was required to lie within 4 cm in radius and 10 cm in z of the beam interaction point. The remaining contamination was estimated by studying the distribution of vertices along the z direction with $|z_v| \geq 10$ cm, and was found to be $(6.5 \pm 0.6)\%$ of the events at $\sqrt{s} = 5.2$ GeV and $(15.8 \pm 1.6)\%$ at $\sqrt{s} = 6.5$ GeV. This contamination, which contributed only to $x \leq 0.4$, was subtracted from the observed distributions. An estimated $(3 \pm 1)\%$ of genuine annihilation events were lost by the vertex-radius cut. This loss was due to displacements of the reconstructed vertex by tracks scattered in the material preceding the drift chambers, or by tracks from K_s or Λ decay. To suppress background from QED processes, three-prong events were rejected if they contained a track with momentum > 900 MeV/c identified as an electron from its energy deposition in the liquid-argon shower counters. Four-prong events with two such tracks were also rejected. A visual scan of a subset of the data showed that background from radiative Bhabha scattering was negligible. Cosmic-ray events were eliminated on the basis of time-of-flight information. The contribution from τ-lepton production and decay was statistically subtracted by use of a Monte Carlo–generated sample incorporating measured branching ratios. This correction amounted to $(8.6 \pm 1.3)\%$ of the events at 5.2 GeV and $(6.8 \pm 1.2)\%$ at 6.5 GeV, the uncertainty due mainly to uncertainties in the branching ratios. The τ contamination in the inclusive distributions prior to subtraction varied as a function of x from 4.5% at small x to 20% at $x = 0.8$. After subtraction of the estimated beam-gas and τ backgrounds, there were 44 180 events remaining at 5.2 GeV and 11 900 events at 6.5 GeV.

For the data at $\sqrt{s} = 29.0$ GeV, hadronic events were required to contain at least five charged tracks as defined above. In addition, to suppress background from two-photon processes, as well as from beam-gas interactions, the sum of the magnitudes of the particle momenta was required to exceed 7.25 GeV, or 3.75 GeV if there was at least 4 GeV of energy in photons deposited in the liquid-argon shower counters. After these cuts, background from beam-gas interactions was negligible, and background from τ production was estimated to comprise $(2.5 \pm 0.5)\%$ of the remaining events (varying from less than 2% at small x to 6% above $x = 0.4$ for the inclusive distributions). Background from hadron production via the two-photon process was estimated to be $(1.5 \pm 0.8)\%$, concentrated at low momentum, from Monte Carlo simulations and from events in which an electron was detected in a small-angle tagging system covering the range 22–80 mrad from the beam direction. There were 4750 events remaining after statistical removal of these backgrounds.

Detection efficiencies were computed with a Monte Carlo simulation based on the quark fragmentation model of Field and Feynman,[7] with extensions by Ali *et al.*[8] for gluon emission at high energies. With appropriate fragmentation parameters, these models provided a good description of the observed charged-particle multiplicity and momentum distributions. The charged-particle detection efficiency as a function of x (in the absence of initial-state radiation) is displayed in Fig. 1. To determine the sensitivity of these efficiencies and background subtractions to the production model, the cuts on multiplicity, momentum, $|\cos\theta|$, and charged energy were varied. Different fragmentation parameters and production models were used. From the corresponding variations in the computed cross sections, the uncertainties in these efficiencies are estimated to be 4% independent of x at 29 GeV, and to vary from 4% at small x to 7% for $x \geq 0.4$ at the two low energies. This uncertainty is larger for the SPEAR energies at large x because of the re-

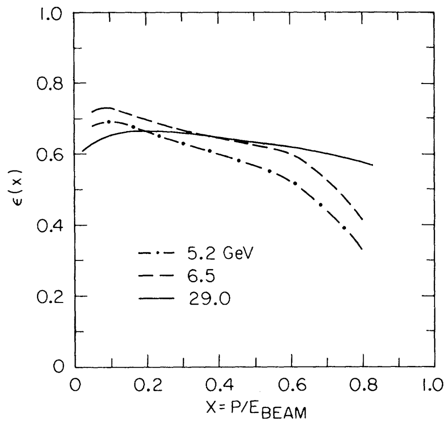

FIG. 1. The charged-particle detection efficiency as a function of $x = p/E_{\text{beam}}$ at $\sqrt{s} = 5.2$, 6.5, and 29.0 GeV.

quirement that three tracks be observed; events containing a high-momentum track tend to have lower than average multiplicity.

The inclusive particle spectra include long-lived charged particles produced either at the primary vertex or from the decay of short-lived particles, such as K_s and Λ. A correction was made for electrons from photons which converted in the 0.065 radiation length (0.09 at PEP) of material preceding the drift chambers. This correction was about 5% at $x = 0.1$ and about 1% above $x = 0.25$.

Corrections for initial-state radiation were computed with the method of Berends and Kleiss.[9] As a function of x this correction varied from $(10 \pm 2)\%$ at small x [$(15 \pm 2.5)\%$ at 29.0 GeV] to less than $(5 \pm 1)\%$ at large x. The quoted errors are due to uncertainties in the cross section and detection efficiency at lower energies, and from the possible contribution of higher-order effects.

The normalization was obtained from Bhabha scattering events observed in the central detector. The uncertainty in this measurement is estimated to be $\pm 3\%$ at each of the three energies considered, due mainly to uncertainties in the α^3 and higher-order radiative corrections. Bhabha events detected in a monitor located at small angles to the beam line provided a cross check, with a systematic uncertainty of 6% at 5.2 and 6.5 GeV and 3% at 29.0 GeV. Both measurements agree well within the estimated errors.

The total systematic error in the inclusive cross sections is estimated to be $\pm 6\%$ at small x, rising to $\pm 10\%$ for the largest x considered. This rise is due to the model dependence and τ subtraction at the two low energies, and to uncertainties in the tracking efficiency and momentum resolution effects at 29 GeV.

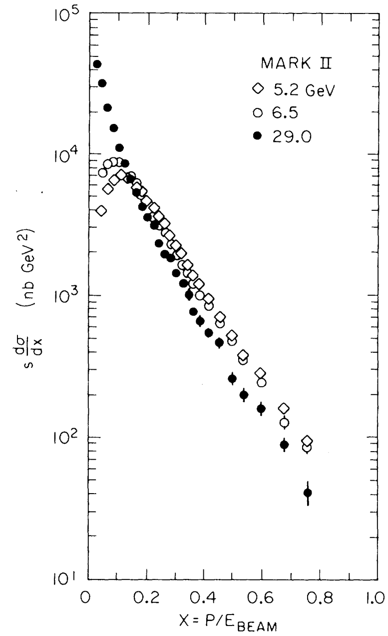

FIG. 2. The cross section $s\,d\sigma/dx$ vs x for charged particles measured at $\sqrt{s} = 5.2$, 6.5, and 29.0 GeV. Only statistical errors are plotted.

The inclusive cross sections $s\,d\sigma/dx$ are shown in Fig. 2. The 29-GeV data lie above the low-energy data for $x < 0.2$, and significantly below for $x > 0.2$, the difference being well outside the

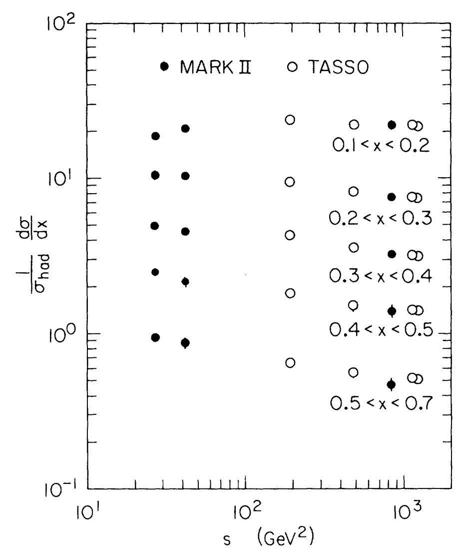

FIG. 3. $(1/\sigma)\,d\sigma/dx$ vs center-of-mass energy. Both statistical and systematic errors are included. Also plotted are data from Ref. 10 at $\sqrt{s} = 14$, 22, 34, and 35 GeV.

estimated relative systematic errors. In Fig. 3, the same data are compared with results from the TASSO experiment of Brandelik *et al.*,[10] which cover the energy range 11 GeV $\leq \sqrt{s} \leq$ 36 GeV. The data for each experiment have been normalized to the corresponding measured total hadronic cross section[11] σ_{had} to compensate for differences in normalization and changes in total hadron production due to the b-quark threshold. Above $x = 0.2$, the cross sections decrease with increasing s as qualitatively predicted by QCD. A quantitative comparison with the predictions of QCD requires a knowledge of the c- and b-quark fragmentation functions and decay modes, since only the decay products of particles containing these quarks are detected. Furthermore, nonperturbative effects that lead to a substantial rise in multiplicity in this energy range may significantly contribute to the observed scale breaking.

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