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Production of High-Mass Muon Pairs in π^-Be Collisions at 150 and 175 GeV/c

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This paper presents production and decay characteristics of 500 high-mass, high-resolution $\mu^+\mu^-$ pairs produced in π^-Be collisions at 150 and 175 GeV/c. The data do not agree with a simple Drell-Yan production mechanism, but indicate that higher-order quantum-chromodynamic corrections must be included.

The production of high-mass $\mu^+\mu^-$ pairs in hadron-hadron collisions is expected to occur by quark-antiquark annihilation into a timelike virtual photon. The simple Drell-Yan model[1] for this process ignores higher-order quantum-chromodynamic (QCD) effects, such as gluon emission from a quark. We have observed 500 muon-pair events in π^-Be interactions at 150 and 175 GeV/c at the CERN Super Proton Synchrotron (SPS). Part of our 150-GeV/c data have already been presented.[2] Our data exhibit many general characteristics of the Drell-Yan model. We show new evidence which strongly suggests that higher-order QCD effects are present in the production process.

Our apparatus consists of a Be target, a large-aperture magnetic spectrometer followed by a multicelled Cherenkov counter, and a 2380-g/cm^2 iron muon filter. Eleven multiwire proportional chambers with a total of 40 000 wires, inside the magnet and upstream and downstream of the Cherenkov counter, measured charged-hadron and -lepton trajectories. Various scintillation counters and hodoscopes were used to trigger on high-mass $\mu^+\mu^-$ pairs. Details of our equipment and trigger scheme have been presented elsewhere.[3] The J/ψ and ψ' mass peaks[3] verify our excellent mass resolution of $\Delta M/M = 0.015$.

Figure 1 shows our $\mu^+\mu^-$ mass spectra, in the form $M^3 d\sigma/dM$ versus $\tau = M^2/s$, for 150 and 175 GeV/c. The data have been corrected for the acceptance of our apparatus. Background can come from uncorrelated (nonprompt) muons, such as when one or both muons originate from a hadron decay and/or from the beam halo. This was studied by triggering our apparatus on like-sign muons. The like-sign muon data were enhanced by taking like-sign muons from different events in this data sample. We found that our lowest-mass data points (the mass interval from 3.8 to 4.3 GeV/c^2) had a background of 17%. For each mass interval the background subtraction was less than the statistical error. The data were normalized by comparing the yield with the ψ yield.[4] We estimate our overall normalization error to be ±20%. Also shown in Fig. 1 are data from other experiments on $\mu^+\mu^-$ production by π^- mesons, at[5] 225 GeV/c and at 200 and 280 GeV/c.[6]

The Drell-Yan mechanism predicts that $M^3 d\sigma/dM$ should scale in the variable M^2/s. This is also true if first-order QCD corrections are included.[7] Figure 1 shows that the 150-, 175-, 200-, and 280-GeV/c data do scale. The 225-GeV/c data do not.[8]

In Fig. 2 we show x_F and p_T distributions and decay angular distributions in the Gottfried-Jackson frame. We have combined our data at 150 GeV/c (60% of sample) and at 175 GeV/c (40% of sample). The smooth curves are fits to the data. For the x_F distribution [Fig. 2(a)] we fit with the form

$$d\sigma/dx_F = A[1 - |x_F - B|]^C.$$

We find $A = 0.43 \pm 0.03$ nb, $B = 0.14 \pm 0.02$, and $C = 2.1 \pm 0.03$; the χ^2 was 4 for eight degrees of freedom. The nonzero value of B suggests that quarks in the pion have greater average momentum than those in the nucleon. When the quarks annihilate, $x_F = x_1 - x_2$, where x_1 and x_2 are the pion and nucleon quark momentum fractions. $\langle x_1\rangle - \langle x_2\rangle$ is expected to be about 0.11 for valence quarks,[9] while we find $\langle x_F\rangle = B = 0.14 \pm 0.02$. The dashed curve is from a Drell-Yan fit to the data, described below. The P_T distribution [Fig. 2(b)] is fitted with

$$\frac{1}{p_T}\frac{d\sigma}{dp_T} = D\left[1 + \left(\frac{p_T}{E}\right)^2\right]^F,$$

with $D = 0.49 \pm 0.05$ nb/GeV/$c)^2$, $E = 1.7 \pm 0.05$ GeV/c, and $F = -3.2 \pm 1.3$. $\chi^2 = 9$ for ten degrees of freedom. We find $\langle p_T\rangle = 1.04$ GeV/c. The simple Drell-Yan model cannot explain[10] this

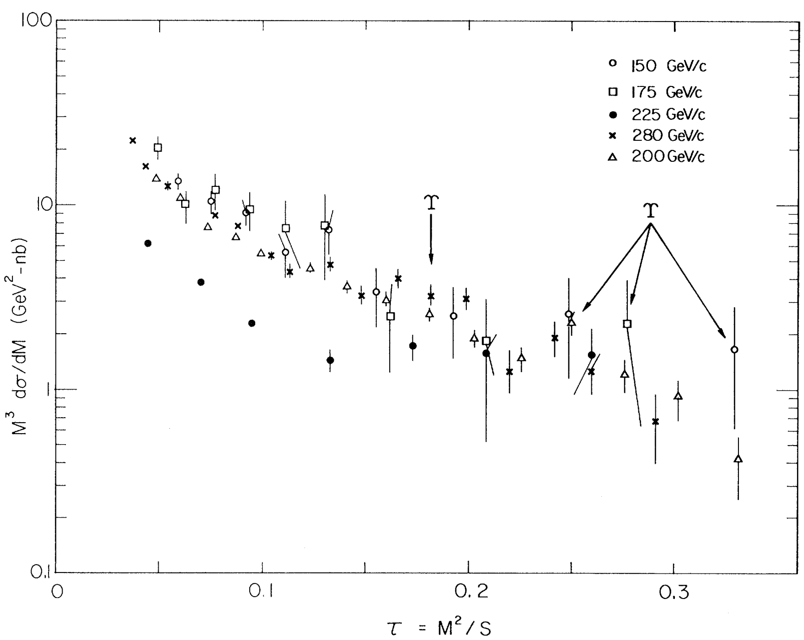

FIG. 1. $M^3 d\sigma/dM$, where σ refers to cross section per nucleon as explained in Ref. 4, is plotted against the scaling variable $\tau = M^2/s$. The 225-GeV/c data are from Ref. 5; the 200- and 280-GeV/c data are from Ref. 6. Data points labeled Υ come from the region of the upsilon.

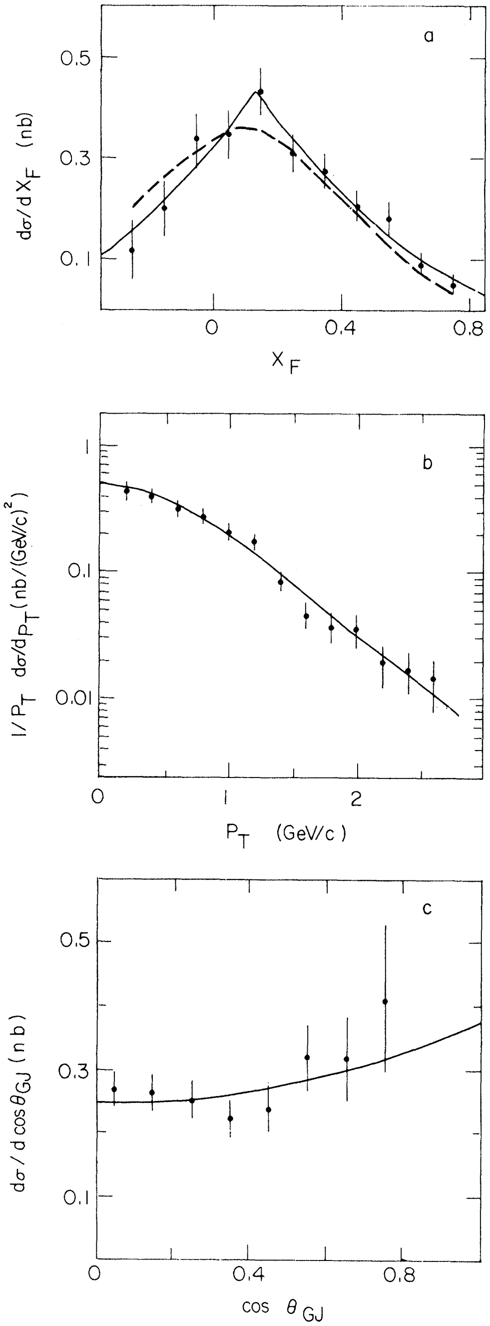

FIG. 2. (a) $d\sigma/dx_F$ vs x_F. (b) $(1/p_T)(d\sigma/dp_T)$ vs p_T. (c) $d\sigma/d\cos\theta_{GJ}$ vs $\cos\theta_{GJ}$; θ_{GJ} is the Gottfried-Jackson angle. For all parts of Fig. 2, the curves are fits to the data and are described in the text.

large $\langle p_T\rangle$. In Fig. 2(c) we show a fit to

$$\frac{d\sigma}{d\cos\theta_{GJ}} = G(1+\lambda\cos^2\theta_{GJ}),$$

where θ_{GJ} is the Gottfried-Jackson angle. We

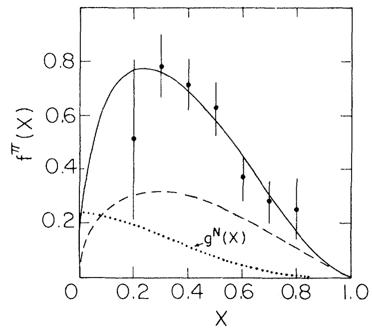

FIG. 3. The smooth curve and data points represent fits to the pion structure function with use of our data. The dashed curve is from a similar analysis at 225 GeV/c (see Ref. 13). The dotted curve is the proton structure function $g^N(x)$.

find $G = 0.25 \pm 0.02$ nb, $\lambda = 0.52 \pm 0.46$, and $\chi^2 = 4$ for six degrees of freedom.[11] The Drell-Yan prediction is $\lambda = 1$, and QCD corrections[10] tend to reduce λ.

The Drell-Yan cross section with colored quarks is

$$\frac{d^2\sigma}{dM\,dx_F} = \frac{8\pi\alpha^2}{9M^3}(x_F{}^2 + 4M^2/s)^{-1/2} f^{\pi}(x_1) g^N(x_2),$$

where $f^{\pi}(x_1) = x_1\bar{u}^{\pi}(x_1)$ and $g^N(x_2) = (\frac{4}{9})x_2 u^N(x_2) + (\frac{1}{9})x_2\bar{d}^N(x_2)$. Here, $\bar{u}^{\pi}(x_1)$ is the distribution function of $\bar{u}$ quarks in the π^- and $u^N(x_2)$ and $\bar{d}^N(x_2)$ are the nucleon u- and $\bar{d}$-quark distribution functions, respectively. The nucleon structure $g^N(x_2)$ can be deduced with lepton probes. We use the nucleon structure function from the analysis of Buras and Gaemers,[12] and derive $f^{\pi}(x_1)$ from our data.

We determine $f^{\pi}(x_1)$ by fitting our data in x_F-M space in the region $-0.1 \le x_F \le 0.8$ and $3.8 \le M \le 7.8$ GeV/c^2. Our mass resolution allows us to fit down to 3.8 GeV/c^2 and still avoid contamination from the ψ'. The results to the fit[13] are shown in Figs. 2(a) (dashed curve) and 3. The smooth curve in Fig. 3 is a fit with the form $f^{\pi}(x_1) = a x_1{}^{1/2}(1-x_1)^b$. We find $a = 2.43 \pm 0.30$ and $b = 1.57 \pm 0.18$, with $\chi^2 = 77$ for 53 degrees of freedom. The data points in Fig. 3 arise from a fit in which $f^{\pi}(x_1)$ is allowed to assume different values in each 0.1 bin in x_1. These data points show that the kinematic domain of our experiment is such that we are not sensitive to the region $x_1 \lesssim 0.2$. Thus, we are not probing the pion sea-quark distribution. Also shown on Fig. 3 (dashed curve) is the result from a similar analysis done on data from $\pi^- N$ interactions at 225 GeV/c.[14]

The dotted line in Fig. 3 is the function $g^N(x_2)$, which we used for x_2 in the range 0.05 to 0.42.

Our pion structure function implies that approximately 40–50% of the π^- momentum comes from the $\bar{u}$ valence quark. Also, $\int_0^1 f^\pi(x_1)x_1^{-1}dx_1 = 2.8$. These values are both about 2.5 times higher than expected.[9] Thus, in contrast with the 225-GeV/c results,[14] our data are in disagreement with the simple Drell-Yan model. The data at 200 and 280 GeV/c also give cross sections[6] which correspond to large values of $f^\pi(x)$. If the quarks were colorless, our $f^\pi(x_1)$ would be reduced by a factor of 3. However, if higher-order effects[15] can increase the cross section by 100%, it seems more natural to attribute our result to QCD corrections to the Drell-Yan mechanism.

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[1]S. D. Drell and T.-M. Yan, Phys. Rev. Lett. 25, 316 (1970), and Ann. Phys. (N. Y.) 66, 578 (1971).

[2]M. A. Abolins *et al.*, Saclay Report No. D. Ph. P. E. 78-05, and a communication at the Nineteenth International Conference on High-Energy Physics, Tokyo, August 1978 (unpublished).

[3]M. Abolins *et al.*, Phys. Lett. 82B, 145 (1979).

[4]We measured the ψ cross section per nucleon to be 95 nb at 150 GeV/c. From this and ψ yields from other experiments, we deduced a total cross section of 110 nb per nucleon for ψ production at 175 GeV/c. Cross sections per nucleon were determined with the assumption that the quarks and gluons in the nucleus act incoherently. Therefore, we divided the ^{9}Be cross sections by 9.

[5]K. J. Anderson *et al.*, Phys. Rev. Lett. 42, 944 (1979); G. E. Hogan *et al.*, Phys. Rev. Lett. 42, 948 (1979).

[6]J. Badier *et al.*, in Proceedings of the European Physical Society International Conference on High-Energy Physics, Geneva, 1979 (to be published) CERN Reports No. CERN/EP 79-67 and No. 79-68.

[7]C. T. Sachrajda, Phys. Lett. 73B, 185 (1978).

[8]The A dependence used by Anderson *et al.*, (Ref. 5) to get cross sections per nucleon was A^α, and with $\alpha = 1.12 \pm 0.05$. This rather large value of α may be partly responsible for the apparent lack of scaling of the 225-GeV/c data.

[9]R. D. Field and R. P. Feynman, Phys. Rev. D 15, 2590 (1977).

[10]E. Berger, SLAC Report No. SLAC-PUB-2314, 1979 (unpublished).

[11]We find that λ is not significantly different if the Collins-Soper angle is used. [See J. Collins and D. Soper, Phys. Rev. D 16, 2219 (1977).]

[12]A. J. Buras and K. J. F. Gaemers, Nucl. Phys. B132, 249 (1978). Averaging over the neutrons and protons in our ^{9}Be target we find

$$g^N(x) = 0.877x^{0.594}(1-x)^{3.08} - 0.455x^{0.706}(1-x)^{3.84} + 0.567x^{0.706}(1-x)^{3.84} + 0.201(1-x)^{14.4}.$$

The first two terms arise from proton valence u quarks, the third term from neutron valence u quarks, and the fourth term from u and $\bar{d}$ sea quarks. We used a fixed Q^2 of (4.65 GeV)^2.

[13]These results have been presented in preliminary form; M. Abolins *et al.*, in Proceedings of the European Physical Society International Conference on High-Energy Physics, Geneva, 1979 (to be published).

[14]C. B. Newman *et al.*, Phys. Rev. Lett. 42, 951 (1979).

[15]G. Altarelli, R. Ellis, and G. Martinelli, Massachusetts Institute of Technology Report No. CTP No. 776, 1979 (to be published); G. Altarelli, G. Parisi, and R. Petronzio, Phys. Lett. 76B, 351, 356 (1978).