charmed-particle production in association with the J/ψ events[4,17] also supports the gluon fusion picture.

We are pleased to note our continuing indebtedness to the staff of the Fermilab Neutrino Division, and to the members of the Chicago-Harvard-Illinois-Oxford collaboration. We have been greatly assisted in the data analysis by F. E. Hogan and C. Newman.

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Hadronic Production of Massive Muon Pairs: Dependence on Incident-Particle Type and on Target Nucleus*

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Data from a study of muon pairs produced in hadron-nucleus collisions are compared with the Drell-Yan model. Comparison of dimuon production by π^+ and π^- mesons on an isoscalar target shows evidence for a charge asymmetry characteristic of an isospin-nonconserving electromagentic process. The average transverse momentum of the pairs increases smoothly with pair mass. Data taken on carbon and tin targets are used to extract the dependence on target atomic weight.

As part of our study at Fermilab of muon pairs produced in hadron-nucleus collisions, we present results for nonresonant and resonant dimuons which illustrate the dependence of the production on incident-particle type and on target nucleus. We compare several features of this data with predictions of the Drell-Yan model.[1] In the preceding Letter[2] we discuss other aspects of this data sample, obtained with 225-GeV/c beams of π^+, π^-, and protons incident on carbon and tin targets.

Many authors[1,3-5] predict the formation of nonresonant muon pairs by the electromagnetic annihilation of fractionally charged quarks and antiquarks in the target and projectile. Recent experiments with proton beams[6,7] at 300 and 400 GeV have measured cross sections $(d^2\sigma/dMdy)_{y=0}$ which are in reasonable agreement with some of the predictions, and also are approximately consistent with scaling of the form

$$M^3 d\sigma/dM = f(M^2/s). \qquad (1)$$

A neutron experiment[8] at 300 GeV, on the other hand, finds the model unable to account for the yield of pairs with $x_F \gtrsim 0.25$ and masses ≤ 2.5 GeV/c^2. None of the previous studies, however, has shown whether the production process is via an electromagnetic or strong interaction.

This paper describes the first experiment to use both π^+ and π^- beams. Using an isoscalar target (carbon), one has a particularly attractive experimental situation, in which a charge asymmetry in the cross sections should appear if the pairs are produced by electromagnetic annihilations of valence antiquarks in the pion beam with valence quarks in the target. Such a picture also results in pions being much more effective than protons in producing high-mass pairs. These features are then crucial tests of the Drell-Yan hypothesis. It is also interesting to examine the π^+/π^- ratio and $p/\pi^\pm$ ratios for resonance production, which is thought to proceed via isospin-symmetric strong interactions.

Figure 1(a) shows the mass spectra for π^-, π^+, and p beams on a carbon target. The spectra are similar to our previous results[9] at 150 GeV/c. Also shown in Fig. 1(a) is the range of predictions of three calculations[3-5] of the cross section for proton-induced muon pairs as a function of mass, based on the Drell-Yan model with color. As can be seen, the predictions of the model fall well below the data. In Fig. 1(b) we have plotted our last two data points and the higher-mass data of Refs. 6 and 7, scaled to our kinematic region using Eq. (1), linear dependence on atomic weight, and our measured x_F dependence. In this range of M^2/s, the calculations of the cross section overlap the data. Thus, we conclude that at lower masses the quark-annihilation picture fails to account for the observed signal, but does succeed at higher masses, as shown by previous experiments.[6,7]

The remaining features of the data have been studied by dividing the data into eight mass intervals chosen to isolate the regions containing the resonances ρ^0-ω, φ, and J/ψ from the nonresonant regions, and to have reasonable statistics in each interval.

We have previously reported[9] a comparison of the production of muon pairs by π^+ and protons as a function of x_F, at 150 GeV/c. In our earlier data and in the sample presented here, we observe that at all masses the π^+- (and π^--) induced data have a broader distribution in x_F than the proton-induced data. Using a parametrization of the invariant differential cross section $E\,d\sigma/dx_F$ of the form $(1-x_F)^N$, we plot in Fig. 2(a) the exponent N in seven mass intervals. The pion-induced data fall more slowly with x_F at all masses, and there is no significant difference between π^+ and π^- beams. This feature of the data is consistent with the annihilation model. In Fig. 2(b) the data for the nonresonant mass region 1.9 to 2.3 GeV/c^2 are compared to a calculation using the results of Ref. 3. The calculation falls below the data, but agrees qualitatively in shape and in the relative dependence on the incident hadron. Data taken on a tin target show no significant difference in the slope parameter, except at the lowest masses where the distributions peak more strongly near $x_F = 0$ as shown in Table I of the preceding Letter.[2]

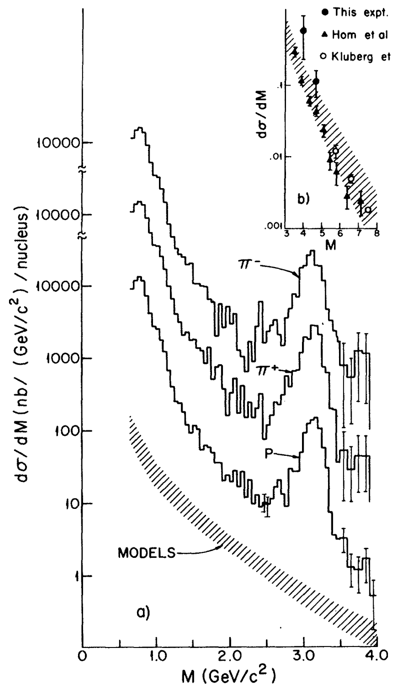

FIG. 1. (a) Mass spectra $d\sigma/dm$ for π^-, π^+, and proton-induced production of dimuons on carbon. Also shown is the range of yields for proton-induced data using calculations of Refs. 3-5. Data and calculated yield are for the region $x_F \geq 0.1$. Statistical errors are indicated in the highest mass bins. (b) Proton-induced yields at higher dimuon masses. Two high-mass points from this experiment, and appropriately scaled data of Refs. 6 and 7 are plotted. The calculated-yield range is also shown.

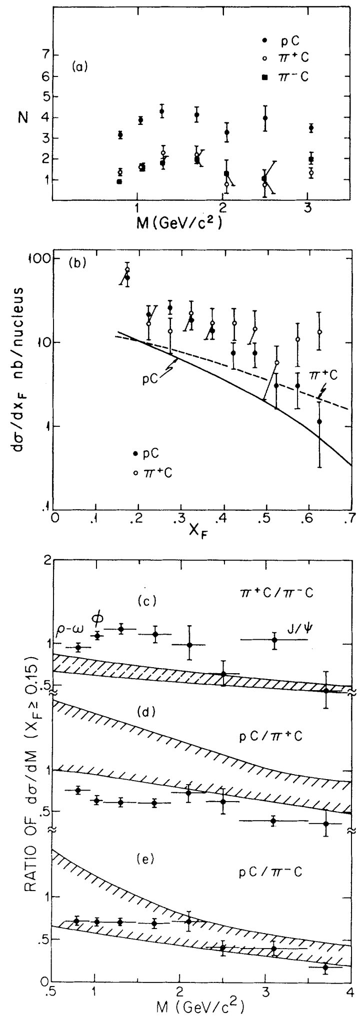

FIG. 2. (a) The variation with muon-pair mass of the invariant cross section $Ed\sigma/dx_{\rm F}$ parametrized as $(1-x_{\rm F})^N$ for π^-, π^+, and proton beams on a carbon target. (b) Comparison of the differential cross section $d\sigma/dx_{\rm F}$ for π^+ and proton beams on a carbon target in the pair-mass range 1.9 to 2.3 GeV/c^2. Reference 3 has been used to calculate the cross sections for pairs of mass 2 GeV/c^2 shown as solid and dashed curves. All data are in the region $x_{\rm F} \geq 0.15$. (c) The ratio of π^+- to π^--induced data for $x_{\rm F} > 0.15$ as a function of dimuon mass. No separation of resonant and nonresonant data has been made in the indicated resonance regions. The range of predictions of Refs. 3-5 are shown as the shaded band. (d), (e) The ratios of proton-induced yields to π^+- and π^--induced yields in the same mass intervals, and in the same region of $x_{\rm F}$. The calculated yields are indicated.

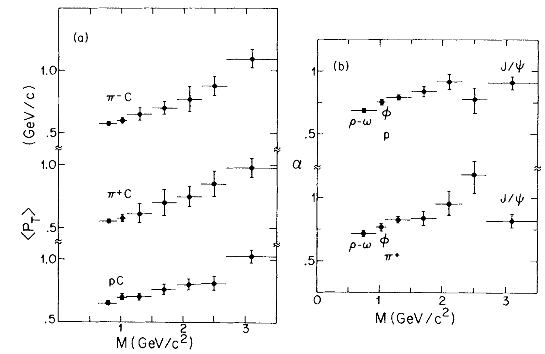

FIG. 3. (a) The mean transverse momentum of dimuons produced by π^-, π^+, and protons, respectively, on a carbon target in the selected mass intervals for $x_{\rm F} \geq 0.15$. (b) The dependence on target atomic weight of proton- and π^+-induced events. The result is expressed as the exponent of α of a power-law dependence on the atomic weight A.

We present the first search for the predicted charge asymmetry in the π^+ and π^- production of nonresonant dimuons. The valence quarks of the incident π^+ or π^- provide a single $\bar{d}$ or $\bar{u}$ antiquark, respectively, which may annihilate with one of the symmetric set of u and d quarks in the carbon target. From valence-quark annihilations, one would expect the dimuon production cross-section ratio to reflect only the ratio of the squares of the annihilating-quark-pair charges so that $\sigma(\pi^+{\rm C})/\sigma(\pi^-{\rm C})$ would be $\frac{1}{4}$. This large asymmetry is diluted by the presence of the isospin-symmetric quark pairs in the sea. Using recent measurements, several authors[3-5] have constructed quark distribution functions which we have used to estimate the effect of the sea. These calculations predict the charge ratio to be close to 1 at low pair masses, and then to decrease slowly to the value 0.25 as M^2/s increases.

In Fig. 2(c) we compare the production of dimuons by π^+ and π^- on carbon. Three of the mass bins contain the resonances ρ^0-ω, φ, and J/ψ and as expected, the ratio of π^+ to π^- production is close to unity, consistent with no charge asymmetry. In the nonresonant data, the π^+/π^- ratio appears to change from approximate unity at low mass to about 0.5 at highest masses.[10] A comparison of these ratios with the Drell-Yan model is independent of our knowledge of our absolute normalization. The behavior in the mass range 1.1 to 2.0 GeV/c^2 is further evidence that these pairs are produced by other than Drell-Yan mechanisms. Above 2.3 GeV/c, within the limited statistics, there is qualitative agreement with the predictions of the annihilation model. Superimposed on the figure is the range of predictions of Refs. 3–5. When $\pi^\pm$ and proton-induced pairs are compared, [Figs. 2(d) and 2(e)] one sees that, as the mass increases, pions become more effective than protons in producing pairs. The range of predictions of the model[3-5] is also shown in Figs. 2(d) and 2(e).

Figure 3(a) shows the average transverse momentum $\langle p_T\rangle$ for each mass interval with sufficient statistics for π^--, π^+-, and p-induced events.[11] No discontinuity is apparent between the $\langle p_T\rangle$ of resonant and nonresonant dimuons. Instead, one sees a slow, smooth increase of $\langle p_T\rangle$ with increasing dimuon mass. There is some evidence[6] that this smooth increase continues out to dimuon masses of 11 GeV/c^2. We have observed no significant difference in the $\langle p_T\rangle$ at any mass between carbon and tin data.

We have studied the dependence of dimuon production on the target atomic weight by comparing exposures of π^+ and proton beams on carbon and tin targets. Parametrizing the cross section per nucleus in different mass regions as a power of the atomic weight A^α, we find the behavior shown in Fig. 3(b). The exponent of A is an increasing function of pair mass rising from approximate $A^{2/3}$ behavior in the ρ-ω region to just below linear A dependence at the J/ψ mass. This is consistent with the results of a study done with a neutron beam on Be, Al, Cu, and Pb targets.[8] The effect seems independent of the beam-particle type. The hadronic nature of the J/ψ might affect the A dependence. Using a recent determination[12] of $\sigma_{\psi N}$, we estimate that the absorption of J/ψ within the nucleus should alter α by no more than a few percent. We have also studied the dependence on atomic weight for data in selected kinematic regions. The parameter α is slightly higher for low-mass, high-p_T data, and slightly lower for low-mass, high-x_F data, perhaps indicating that a small fraction of the data may include secondary interactions within the tin nucleus itself.

We have presented evidence for several features of muon pair production by hadrons. Pairs in the nonresonant mass range 2.3–2.7 GeV/c^2 are produced by an isospin-nonconserving electromagnetic interaction. The interaction may not be the Drell-Yan mechanism as evaluated in several current parametrizations. Pions are more effective than protons in producing dimuons at all masses, by a factor $\sim(1-x_F)^2$. The average transverse momentum of the pairs rises linearly with the mass. The dependence of muon pair production on target atomic weight increases smoothly from $A^{2/3}$ at low masses to $\sim A^{0.9}$ at 3 GeV/c^2.

We conclude that further study of the features of higher-mass dimuons with pion beams should provide a stringent test of the quark-annihilation hypothesis.

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[10]Data in the mass bin 3.5–3.9 GeV/c^2 of Fig. 2(c) includes the $\psi'(3.7)$ signal. A charge ratio of unity, characteristic of resonance production, does not appear here. As we have noted in the preceding Letter (Ref. 2), the π^--induced data is dominated by μ-pair continuum in this region, resulting in the charge ratio shown.

[11]The mean transverse momenta plotted here are computed from cross sections in each mass interval. At the lower masses our low-x_F efficiency is very small, leading to possible large uncertainty in the $\langle p_T\rangle$ in this region. An alternate procedure is to calculate $\langle p_T\rangle$ in each mass interval from fits of $(E/p_T)d\sigma/dp_T \propto \exp(-Bp_T)$ so that $\langle p_T\rangle = 2/B$. This reduces the values of $\langle p_T\rangle$ in the lower few mass bins by less than 10%.

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