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PRODUCTION OF MUON PAIRS IN THE CONTINUUM REGION BY 39.5 GeV/c $\pi^\pm$, $K^\pm$,
p AND $\bar{p}$ BEAMS INCIDENT ON A COPPER TARGET

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Abstract

General features of the inclusive hadroproduction of muon pairs of mass greater than 1.5 GeV/c² are shown. For incident π^- , the data extend up to $M = 5.7$ GeV/c² (i.e. $M^2/s \approx 0.4$). The scaling cross section $M^3 d\sigma/dM$ for π^-N reactions is much flatter than that for pN reactions and exceeds the latter by two to three orders of magnitude at large M^2/s .

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We report further results of an experiment designed to measure muon pair production by 39.5 GeV/c $\pi^\pm$, $K^\pm$, p and $\bar{p}$ beam particles incident on a copper target using the CERN Omega Spectrometer⁽¹⁾. The apparatus detected muon pairs of invariant mass $M > 1.5 \text{ GeV}/c^2$ with good efficiency for x_F -values above 0.0 (where $x_F = 2p_{||}^* / \sqrt{s}$). The results of a study of the cross sections for ψ production based on a total of about 1000 ψ 's have been published earlier ((2), called hereafter I). Other experiments using proton⁽³⁾, neutron⁽⁴⁾ and pion⁽⁵⁾ beams have measured the production of continuum dimuons over more limited x_F ranges.

The high mass dimuon continuum is normally assumed to be produced via the Drell-Yan mechanism: a quark from one of the interacting particles and an anti-quark from the other one produce a lepton pair via a virtual photon. Thus, for pN and $\bar{p}$ N interactions, the process can be computed entirely from the valence and sea quark distributions measured in lepton nucleon interactions, making allowance for the quark colours. In principle, valence quark distributions of the mesons could then be derived from π N and KN data. In practice, however, there are large uncertainties about the nucleon sea quark distributions, and our $\bar{p}$ N data - which are sensitive mainly to the valence quark distributions - are not precise enough to check the theory. Also the scaling behaviour which is expected in the simplest form of the theory is not fully supported by experiment. We shall therefore discuss only the qualitative predictions of the Drell-Yan mechanism. (Quantitative predictions have been calculated⁽⁶⁾ using a recent model by Donnachie and Landshoff⁽⁷⁾).

The apparatus, beam, trigger logic and event reconstruction are described in some detail in I. Three threshold Cerenkov counters were used to identify incident beam particles. The target, 1.3 absorption lengths long, consisted of five 4cm thick copper slabs interleaved with scintillation counters to localise the interaction point. A 1.46m copper absorber, placed immediately after the target, was followed by 40 gaps of spark chambers - all in a magnetic field of 1.8T. The magnet return yoke (1.25m of iron) followed by a 60-element hodoscope completed the muon identification.

Two event selection criteria, described in I, reduced the background from halo and beam muons: only muons of momenta below 30 GeV/c were retained; and the distance of each extrapolated muon track from the beam axis, measured in the plane through the centre of the target element in which the interaction occurred, was required to be compatible with multiple scattering. A third requirement was added for the present work: both muons were required to be in time with the triggering beam particle. For each trigger, the arrival time of the muons at the hodoscope downstream of the magnet yoke was measured to an accuracy of ± 2 nsec. These cuts did not decrease the ψ signal. Their effectiveness can be measured by the like sign muon pairs, which were reduced to a small fraction of the $\mu^+\mu^-$ pairs, namely 3% around $M = 1.7$ GeV/c², and less than 1% above $M = 2.7$ GeV/c². As the acceptance of the apparatus and the production cross section for the parent pions are comparable for like and unlike sign muon pairs, the contribution from accidental coincidences of decay and/or beam muons has been neglected.

Finally, only events with $x_F \geq 0$ are retained. The geometric acceptance for these varies from 3% to 50%, and is computed assuming unpolarised dimuons. For fully spin aligned dimuons, with a $1 + \cos^2\theta_{GJ}$ dependence on the Gottfried-Jackson angle θ_{GJ} , the weights and hence the cross sections would have to be increased by $\sim 20\%$, the slope parameters, B , of the p_T^2 distributions by ~ 0.1 , and the $\langle p_T \rangle$ values would decrease by ~ 0.03 . We therefore estimate an overall normalisation error of (+40, - 20)%.

The sample of $\mu^+\mu^-$ continuum events thus obtained is somewhat reduced with respect to Fig. 2 of I, and comprises 877 (191) events generated by π^- (π^+) in the interval $1.5 \leq M \leq 2.7$ GeV/c², where there are also 27 $\bar{p}$, 28 p , 33 K^- and 8 K^+ events. The ψ region, from 2.7 to 3.5 GeV/c², has been discussed in I. Above $M = 3.5$ GeV/c², there are 70 π^- , 8 π^+ , 2 $\bar{p}$ and 2 K^- events. The highest mass π^- induced event is at $M = 5.7$ GeV/c².

The production of dimuons from secondary interactions in the target and in the beginning of the absorber has been estimated by Monte Carlo methods and subtracted from the data. For dimuon masses below the ψ region, the effect, which is concentrated at small x_F , varies between 8% and 15% for the different primary particles; it is assigned a $\pm 50\%$ relative error. It is negligible for masses above the ψ .

In addition, the mass interval which starts at $3.5 \text{ GeV}/c^2$ contains 1.5% of the ψ signal, as well as the (unresolved) ψ' signal, which is estimated at $(1 \pm 0.5)\%$ of the full ψ signal. Both contributions were subtracted, allowing again for a $\pm 50\%$ relative error.

Figure 1 shows, for each type of beam particle, the differential cross-sections $d\sigma/dM$ per copper nucleus for $x_F \geq 0$. The overall normalisation error is not included in the errors. The cross sections fall very rapidly with increasing mass. For π^- , an exponential fit gives $d\sigma/dM = (3000 \pm 850) \exp((-1.7 \pm 0.1)M) \text{ nb/GeV}/c^2/\text{Cu nucleus}$. The errors cover the solutions obtained when the first or the last data point is excluded from the fit.

Figure 2 shows the more significant ratios of cross sections for muon pair production for different incoming particles. Also shown is the interval from 2.7 to $3.5 \text{ GeV}/c^2$, which involves mainly ψ production. Fig. 2a shows the π^+/π^- ratio, which displays the trend already noted by Branson et al. (5d): while it is close to unity for ψ production, for the continuum it decreases with increasing dimuon mass towards the asymptotically expected value of $1/4$, which is the ratio of the squares of the annihilating valence quark charges. Fig. 2b shows the $\bar{p}/\pi^-$ ratio, which is compatible with unity both for the continuum and for ψ production. In terms of the Drell-Yan mechanism this implies that the single valence antiquark of the π^- is as effective as the three antiquarks of the $\bar{p}$ because of its flatter x distribution (x is the fractional momentum carried by the quark in the hadron). The K^- cross sections seem to be below those for π^- . (The ratio $\sigma(K^-) / \sigma(\pi^-)$ is 0.7 ± 0.2 for $1.5 \leq M \leq 1.9 \text{ GeV}/c^2$ and 0.45 ± 0.2 for $1.9 \leq M \leq 2.7 \text{ GeV}/c^2$). Equality of the cross sections is expected in the Drell-Yan mechanism at high M^2/s since K^- and π^- contain the same valence antiquark. Fig. 2b also shows the p/π^- ratio, which is low and decreases with increasing mass. This reflects the fact that in p-nucleus interactions the antiquarks have to come from the "sea"; they therefore have low x and can produce only dimuons of low M^2/s . A similar trend would be expected for K^+ -nucleus interactions, whereas the 8 observed K^+ events give the somewhat high cross section ratios $\sigma(K^+) / \sigma(\pi^-) = 0.7 \pm 0.25$ for $1.5 \leq M \leq 2.7 \text{ GeV}/c^2$, and 0.75 ± 0.35 for the ψ bin ($2.7 \leq M \leq 3.5 \text{ GeV}/c^2$).

Figure 3 combines the pion and proton data for $x_F \geq 0$, expressed in the scaling variables $M^3 d\sigma/dM$ vs. M^2/s . Representative results from other experiments are also shown. All data have been converted to cross sections

per target nucleon assuming proportionality to the mass number A . We have converted the data of refs. (3e) and (3f) from $d^2\sigma/dMdy$ ($y = 0$) to $d\sigma/dM$ using the parton model and the quoted parametrization $(1-x)^{10}$ of ref. 3e for the sea quark distribution, assuming this to be valid at all x . The systematic error involved in this procedure is $\leq 20\%$.

The proton induced cross section decreases much faster with M^2/s than the π^- induced cross section. At $M^2/s \simeq 0.3$, the π^- cross section is two orders of magnitude greater than the reanalysed BNL data (3a) and three orders of magnitude greater than the recent FNAL data (3e).

Figure 4a shows the x_F distribution for continuum $\mu^+\mu^-$ pairs in the mass range $1.9-2.7 \text{ GeV}/c^2$ for π^- and π^+ beams. The cross section induced by π^- is larger than that induced by π^+ mainly at small x_F . The high-mass π^- data are shown in Fig. 4b. A peaking around $x_F \simeq 0.3$ was observed for ψ production (Fig. 3 of I).

The p_T^2 distributions are well fitted by the form $Ae^{-Bp_T^2}$. For $1.9 \leq M \leq 2.7 \text{ GeV}/c^2$, B is 1.6 ± 0.1 and $1.25 \pm 0.15 (\text{GeV}/c)^{-2}$ for incident π^- and π^+ respectively, to be compared with the corresponding values in the ψ region of 1.3 ± 0.1 and $1.5 \pm 0.2 (\text{GeV}/c)^{-2}$ (see I). Fig. 2c, for π induced events, shows the familiar increase of $\langle p_T \rangle$ with M (cf. Fig. 3 of ref. 5d). Within statistics, similar values are observed for p , $\bar{p}$ and K^- , and possibly lower values for the K^+ ($\langle p_T \rangle = 0.56 \pm 0.1$ for $1.9 \leq M \leq 2.7 \text{ GeV}/c^2$ and 0.62 ± 0.1 in the ψ region, $2.7 \leq M \leq 3.5 \text{ GeV}/c^2$). We observe no correlation between $\langle p_T \rangle$ and x_F : as an example, for π^- and $1.9 \leq M \leq 2.7 \text{ GeV}/c^2$, $\langle p_T \rangle = 0.74 \pm 0.04$ (0.72 ± 0.03) GeV/c for $0 \leq x_F \leq 0.25$ ($0.5 \leq x_F \leq 1$).

In conclusion we have observed that the ratio of the π^- to the proton induced cross section changes from about unity at small M^2/s to $10^2 - 10^3$ at $M^2/s \simeq 0.3$. Secondly the ratios of the $\bar{p}$ to π^- and K^- to π^- induced cross sections are not far from unity. Thirdly the π^+/π^- ratio at high M^2/s is consistent with the value 0.25. These three observations, the first two of which are new, are in agreement with the expectations of the Drell-Yan mechanism.

References

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Figure Captions

Fig. 1: $d\sigma/dM$ per Cu nucleus for $x_F \geq 0$ and (a) $\pi^\pm$, (b) $K^\pm$ and (c) $\bar{p}$ and p beams. The exponential fit to the π^- data described in the text is also shown.

Fig. 2: a) Ratios of π^+ induced to π^- induced dimuon cross sections versus dimuon mass.
 b) id. for $\bar{p}/\pi^-$ and for p/π^- .
 c) $\langle p_T \rangle$ for π^- and π^+ induced events (weighted).
 The dashed symbols refer to the mass bin which contains mainly ψ events.

Fig. 3: In the Drell-Yan model, the product $M^3 d\sigma/dM$ scales and depends on M^2/s only. We display our data for π^- -Cu and p-Cu, together with the 225 GeV/c π^- -C and p-C data of ref. 3c, the 22-29 GeV p-U data of ref. 3a, the last two points of the 400 GeV/c p-Pt data of ref. 3e, together with their fit, and the 420-2000 GeV/c p-p points of ref. 3f. Proportionality of the cross sections with A has been assumed to extract cross sections per nucleon. Cross sections integrated over $x_F \geq 0$ were obtained for ref. 3e and 3f as described in the text, and for ref. 3c, by integrating their parametrized cross section from $x_F = (x_F)_{\max}$ down to $x_F = 0.15$, and assuming flat x_F dependence for the (unmeasured) interval $0 \leq x_F \leq 0.15$. Overall normalisation errors are not shown; they are typically ± 20 -40%, including the uncertainty of the described procedures.

Fig. 4: $d^2\sigma/dM dx_F$ vs. x_F for (a) π^- and π^+ induced events for $1.9 \leq M \leq 2.7$ GeV/c², and (b) π^- events for $3.5 \leq M \leq 5.7$ GeV/c².

Fig.1

Fig. 2

Fig. 3

Fig.4