VOLUME 37 | 27 SEPTEMBER 1976 | NUMBER 13

PHYSICAL REVIEW LETTERS

Inclusive μ-Pair Production at 150 GeV by π^+ Mesons and Protons*

K. J. Anderson, G. G. Henry, K. T. McDonald,† J. E. Pilcher,‡ and E. I. Rosenberg
Enrico Fermi Institute, University of Chicago, Chicago, Illinois 60637

and

J.G. Branson, G. H. Sanders, A. J. S. Smith, and J. J. Thaler
Joseph Henry Laboratories, Princeton University, Princeton, New Jersey 08540
(Received 14 July 1976)

We report the measurements of the inclusive μ-pair production by 150-GeV protons and π^+ mesons on beryllium. Absolute cross sections as well as the Feynman-x and P_T dependence are presented in the mass region between 0.211 and 3.5 GeV/c^2. Upper limits are also given for the inclusive production of η and $\rho'(1600)$ mesons.

We have recently completed a measurement at Fermilab of the inclusive μ-pair production by 150-GeV protons and π^+-mesons on beryllium. Results for the J production have already been reported.[1] In this paper we report on some of the lower-mass resonances and the μ-pair continuum.

The measurements were carried out with the University of Chicago cyclotron spectrometer in the muon laboratory at Fermilab. The beam, spectrometer, and trigger logic have already been described.[1] For most of the results presented here, eight additional planes of multiwire proportional chambers were used. A module of four planes ($XYUV$) was placed at the upstream face of the hadron shield, centered on the beam 100 cm downstream from the target. A second module of four planes was placed with similar orientation halfway through the shield. The (X, Y) and (U, V) wire planes each formed an orthogonal coordinate system and were oriented at 45° relative to each other. These detectors improved the effective mass resolution by a factor of 2.5 and provided a strong discrimination against the μ pairs arising from secondary interactions in the shield. Using the methods discussed below, we determined that the rejection power against such background is 17 at a mass of 300 MeV/c^2 and that it rises sharply with increasing μ-pair mass to over 100 at a mass of 1 GeV/c^2.

To study the effectiveness of the event reconstruction in the presence of the extra hadron tracks in the upstream detectors, μ pairs generated by Monte Carlo calculations were superimposed on the actual data recorded in these chambers. The standard reconstruction program was used and the reconstruction efficiency was determined as a function of Feynman-x (x_F), P_T, and the mass of the pair. At a typical x_F of 0.3, the reconstruction efficiency was approximately 70% and independent of the μ-pair mass above 500 MeV/c^2; it was lower by a factor of 2 at 325 MeV/c^2. The kinematic minimum is $2M_\mu = 211$ MeV/c^2. The reduction in efficiency is associated with pairs of small opening angle, where there is a reduced probability of unambiguously linking the tracks seen in the spectrometer with those seen in the upstream detectors.

A similar method was used to determine the rejection power against the background from the shield. μ-pairs generated by Monte Carlo calculations and originating within the first absorption length of the shield were added to the data of nor-

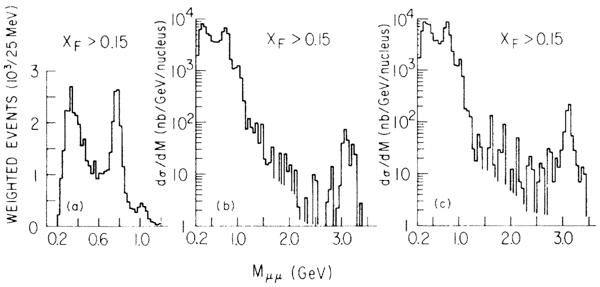

FIG. 1. (a) Muon-pair effective mass. Pion- and proton-induced data are combined to show more clearly the the resonance line shapes and the proportion of the continuum signal. Events are weighted to correct for acceptance and reconstruction efficiency. (b) Effective mass spectrum for proton-induced muon pairs. (c) Effective mass spectrum for pion-induced muon pairs.

mal events. The reconstruction efficiency for such events was determined to give the rejection power described above.

Figure 1 shows the $\mu^+\mu^-$ mass spectrum for the data with x_F greater than 0.15 after the correction for detector acceptance has been made.[2] The measured linewidth for the ρ-ω signal is 100 MeV. Both the pion- and proton-induced data have a strong continuum signal at low masses which falls steeply with increasing mass.

In considering possible background sources for the continuum signal, there are several important points. First, the muons of the observed low-mass pairs are overwhelmingly of the opposite charge. Like-sign pairs occur at the level of 1% so that any background source must produce correlated muons. Second, the requirement $x_F > 0.15$ provides a suppression against the low-energy background. Third, since the event trigger and data analysis require an interaction in the target, the only background from the shield is through some secondary interactions rather than the primary beam interactions. Finally, because of our upstream analysis, we have an additional rejection power against shield-produced background which is greater than 15.

A number of background sources for the continuum spectrum have been considered. Photons produced in the target or in secondary interactions can convert to μ pairs. Let the cross section associated with this source be written as $\sigma_{\rm bkgd} = \sigma_{\rm inel}\langle n_\gamma\rangle FSC/R$, where $\sigma_{\rm inel}$ is the inelastic proton-beryllium cross section (200 mb), $\langle n_\gamma\rangle$ is the mean photon multiplicity (which is 5.6), F is the fraction of photons with $x_F > 0.15$ (2.7%), S is a scale factor to take into account the production of secondary photons with $x_F > 0.15$ (2, as determined by a Monte Carlo simulation of the hadronic cascade), C is the probability of a photon conversion in iron to $\mu^+\mu^-$ rather than e^+e^- (1.3×10^{-5}, obtained from integrating the Bethe-Heitler cross section given by Tsai[3]), and R is the rejection power of our analysis against pairs originating in the shield (17, at a mass of 300 MeV and rising strongly with higher mass). Thus the Bethe-Heitler background from this estimate is 51 nb or 2.2% of the observed cross section seen for $M_{\mu\mu} < 0.65$ GeV/c^2. A similar analysis of the K^+K^- associated production and leptonic decay leads to an even smaller background contribution. We conclude that the signal is real and we shall discuss below some possible sources for the continuum.

To study the dependence of the μ-pair production on the longitudinal and transverse momenta of the pair (x_F and P_T), the data were divided into six mass intervals as specified in Table I. Figure 2 compares $E\,d\sigma/dx_F$ for the μ-pair production by protons and positive pions. In all mass intervals, the pions are more effective than the protons in producing μ pairs of large x_F. The x_F dependence is substantially steeper at low masses than at high masses. This dependence has been fitted by the form $(1 - x_F)^c$; the resulting fits are shown in Fig. 2 and recorded in Table I. For the mass regions III and IV, which contain the ρ-ω and φ signals, fits have also been made after the continuum component has been subtracted. Within statistical errors, the shapes are independent of the subtraction process. The results for the shapes, specified in Table I and Fig. 2, are those without subtraction.

It should be noted that in order to gain statistics in the mass interval VI, which corresponds to the J production, the proportional chambers upstream of the shield were not used in the analysis. These detectors were available only for the latter portion of the data-taking run.

The P_T dependence of μ-pair production has been studied in a similar way as the x_F dependence. Figure 3 shows the data for proton and π^+ production. The data are fitted by the form $(d\sigma/dP_T)/P_T \propto \exp(-bP_T)$. Because this function is a poor representation of the data at very low P_T, we eliminate the first bin from the fit. Within statistical errors, there are no significant differences between the proton- and pion-induced P_T spectra. There is, however, a definite trend for the mean transverse momentum of the pairs to increase with increasing mass. This is just as true for the continuum regions, as for the vector

TABLE I. Results of fitting the Lorentz-invariant cross section with the form $E\,d^3\sigma/d^3p = A(1-x_F)^c \exp(-bP_T)$ for different mass regions. The x_F and P_T projections of the data were fitted independently. The calculation of the integrated cross sections is described in the text.

Region	Mass GeV	Source	A nb/GeV^2/c^3	b (GeV/c)$^{-1}$	c	Cross Section /Nucleus $x_F > 0.15$ nb	Cross Section/Nucleon $x_F > 0.15$ nb	Cross Section/Nucleon $x_F > 0$ nb
				Proton Production				
I	0.21 - 0.45	Continuum	2.67±.53 x 10^4	4.63±.15	6.03±.22	1470±300	340±70	1550±620
II	0.45 - 0.65	Continuum	9.03±1.8 x 10^3	4.58±.14	4.34±.21	800±160	185±37	620±220
III	0.65 - 0.93	ρ-ω	4.69±.95 x 10^3	3.79±.09	2.79±.12	960±190	220±44	510±150
		Continuum	1.83±.40 x 10^3			372±75	86±17	200±60
IV	0.93 - 1.13	φ	1.06±.21 x 10^3	3.93±.28	4.06±.40	127±38	29±9	83±25
		Continuum	.55±.11 x 10^3			66±20	15±5	43±13
V	1.13 - 2.0	Continuum	250±100	3.41±.85	3.78±.80	39±16	6.0±2.5	16±7
VI	2.7 - 3.5	J	36±12	2.08±.26	2.94±.32	14±5	1.6±.6	3.3±1.1
				Pion Production				
I	0.21 - 0.45	Continuum	2.20±.44 x 10^4	5.07±.25	4.30±.33	1660±330	383±76	1250±500
II	0.45 - 0.65	Continuum	4.02±.80 x 10^3	4.64±.24	1.92±.25	780±160	180±37	370±130
III	0.65 - 0.93	ρ-ω	3.41±.70 x 10^3	4.31±.16	1.34±.14	960±190	220±44	370±110
		Continuum	1.46±.30 x 10^3			410±82	94±20	160±50
IV	0.93 - 1.13	φ	4.90±1.5 x 10^2	3.61±.40	1.73±.44	160±48	37±11	70±21
		Continuum	1.47±.44 x 10^2			48±14	11±3	21±6.4
V	1.13 - 2.0	Continuum	89±53	3.2±2.4	1.33±1.0	40±24	6.2±3.7	10±6
VI	2.7 - 3.5	J	81±27	2.57±.36	1.72±.38	35±12	3.9±1.3	6.5±2.2

mesons.

If the Lorentz-invariant cross section is parametrized as $E\,d^3\sigma/d^3p = A(1-x_F)^c \exp(-bP_T)$, we obtained the normalization parameter A, given in Table I for each of the mass regions. Because a clear signal for ρ-ω production is seen even without the use of the upstream detectors, it is

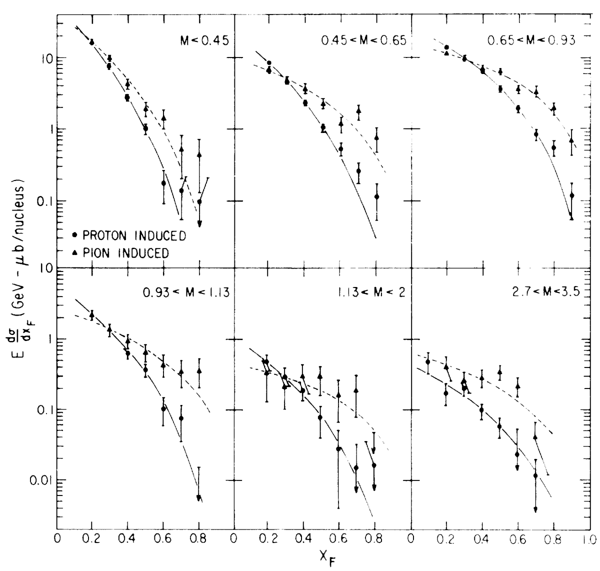

FIG. 2. Dependence of muon-pair production on Feynman-x. The lines represent fits of the form $(1-x_F)^c$. The best-fit parameters are given in Table I.

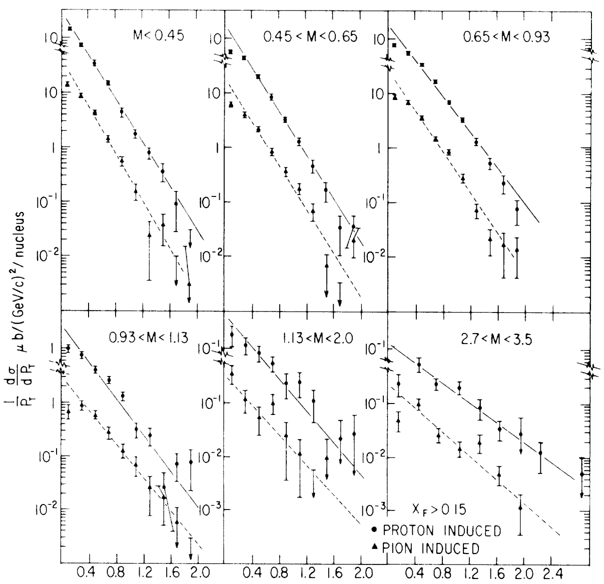

FIG. 3. Dependence of muon-pair production on transverse momentum. The lines represent fits of the form $(d\sigma/dP_T)/P_T \propto \exp(-bP_T)$. The lowest P_T bin is excluded from the fit. Best-fit parameters are given in Table I.

possible to check the normalization with only the detectors downstream from the shield. The normalizations from the two analyses agree to better than 10%.

Table I gives the integrated cross sections for $x_F > 0.15$. To obtain the total cross section for the whole forward hemisphere, three different methods have been used: (1) to extrapolate the fit of $E\,d\sigma/dx_F$ to $x_F = 0$; (2) to extrapolate the fit of $d\sigma/dx_F$ to $x_F = 0$; or (3) to assume that $E\,d\sigma/dx_F$ is constant for $x_F < 0.15$. Methods (2) and (3) give total-cross-section estimates which agree to 10% for mass intervals. The estimate of method (1) is within this tolerance in the high mass interval but becomes systematically larger as the μ-pair mass decreases, reaching a 60% excess in the lowest mass interval. The results of method (2) are presented in Table I; and the error associated with the extrapolation is seen to increase in the lower mass intervals.

Production cross sections from a free-nucleon target are determined from our measurements with beryllium, using the A dependence obtained by Binkley *et al.*[4] We use an $A^{0.67}$ variation for $M_{\mu\mu} < 1.13$ $A^{0.85}$ for $1.13 < M_{\mu\mu} < 2.0$, and A for $M_{\mu\mu} > 2$ GeV/c^2.

The data of Table I, together with known branching ratios,[5] can be used to deduce the total inclusive production cross sections for the vector mesons. If we take $\sigma_\rho = \sigma_\omega$, as is consistent with the observed linewidth, we obtain 8.6 ± 2.5 mb for the ρ or ω production by protons, 660 ± 200 μb for the φ production, and 94 ± 31 nb for the J production. These cross sections are in good agreement with other similar measurements.[6]

For the observed continuum signal, there are a number of simple sources which must exist at some level. The branching ratio $\Gamma(\eta \to \mu^+\mu^-\gamma)/\Gamma(\eta \to \gamma\gamma)$ is calculated[7] to be 7.5×10^{-4}. If all the data with $M_{\mu\mu} < 450$ MeV/c^2 are attributed to this source, we obtain an upper limit for the inclusive η production by protons of 11 mb/nucleon. This is to be compared with the 8.6 mb/nucleon for ρ production.

The process $\omega \to \pi^0\mu^+\mu^-$ is calculated to have a branching ratio[8] $\Gamma(\omega \to \pi^0\mu^+\mu^-)/\Gamma(\omega \to \pi^0\gamma)$ of 5.5×10^{-4}. Thus the expected μ-pair signal from this source is approximately 60% of that from $\omega \to \mu^+\mu^-$ or 13% of the low-mass continuum using the assumption that $\sigma_\rho = \sigma_\omega$.

An upper limit on the production of the $\rho'(1600)$ and decay to μ pairs can be extracted from the data in the mass interval V. We obtain an upper limit of $B\sigma < 6$ nb/nucleon from the proton-induced data.

We would like to acknowledge the support received from Fermilab and in particular R. Lundy and his staff in the neutrino laboratory. We are indebted to the technical support groups at both the University of Chicago and Princeton University. One of us (J.E.P.) would like to acknowledge valuable discussions with C. Rubbia during the formative stage of the experiment. The Chicago-Harvard-Illinois-Oxford muon-scattering collaboration is responsible for providing much of the apparatus.

---

*Research supported by the National Science Foundation and the U. S. Energy Research and Development Administration, and performed at the Fermi National Accelerator Laboratory.

†Enrico Fermi Postdoctoral Fellow.

‡Alfred P. Sloan Foundation Fellow.

[1]K. J. Anderson *et al.*, Phys. Rev. Lett. 36, 237 (1976).

[2]The acceptance calculation uses a flat decay angular distribution for the μ pair. Our analysis of ρ-ω decays gives a distribution of $1-(0.07 \pm 0.24)\cos^2\theta$. A decay asymmetry at the 1 standard deviation level would produce a 5% change in the overall acceptance.

[3]Y. S. Tsai, Rev. Mod. Phys. 46, 815 (1974).

[4]M. Binkley *et al.*, Phys. Rev. Lett. 37, 571 (1976).

[5]For ρ and ω decays we assume μ-e universality and we use the e^+e^- storage-ring data. Thus, $\Gamma(\rho \to \mu^+\mu^-)/\Gamma(\rho \to \mathrm{all}) = 4.3 \times 10^{-5}$ and $\Gamma(\omega \to \mu^+\mu^-)/\Gamma(\omega \to \mathrm{all}) = 7.6 \times 10^{-5}$. We also use $\Gamma(\varphi \to \mu^+\mu^-)/\Gamma(\varphi \to \mathrm{all}) = 2.5 \times 10^{-4}$ and $\Gamma(J \to \mu^+\mu^-)/\Gamma(J \to \mathrm{all}) = 0.07$.

[6]M. Binkley *et al.*, "Dynamics of Inclusive Dimuon Production" (to be published).

[7]C. Jarlskog and H. Pilkuhn, Nucl. Phys. B1, 264 (1967); C. Quigg and J. D. Jackson, Lawrence Berkeley Laboratory Report No. UCRL-18487 (to be published).

[8]C. H. Lai and C. Quigg, private communication.