Study of the High-Mass Dimuon Continuum in 400-GeV Proton-Nucleus Collisions

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The mass spectrum of muon pairs in the range 5 to 15 GeV is studied in the inclusive reaction p + nucleus $\rightarrow \mu^+ + \mu^-$ + anything. The Υ and continuum distribution are presented as is the A dependence of the continuum. Comparison with a parton-annihilation model yields a sea-quark distribution.

We have recently[1,2] presented data on resonances observed in dimuon production near 9.5 GeV. In this Letter, we discuss the dimuon continuum in the mass range 5 to 15 GeV: $p+N \rightarrow \mu^+ + \mu^-$ +anything. Results are based upon 26 000 events observed in the collision of 400-GeV protons with Be, Cu, and Pt nuclei.

The experimental apparatus has been described elsewhere.[1,3] Each arm of the double-arm spectrometer accepts particles of either sign emitted from 50 to 95 mrad horizontally and within ±12 mrad vertically of the incident proton beam. Limited acceptance in $p_{\parallel}$ (or proton-nucleon center-of-mass rapidity, y) is handled by expressing cross sections at the central value $y=0$; we are sensitive in the region $-0.3<y<0.3$. The residual model dependence arises from limited acceptance in the polar decay angle θ^*. In the Gottfried-Jackson frame, we have assumed the form $1+\beta\cos^2\theta^*$ and calculated acceptances for $\beta=0$ and $\beta=1$. We present data below using $\beta=1.0$. For the hypothesis $\beta=0$, there is a 27% increase in acceptance (21% decrease in cross section) which is independent of p_T and mass.[4]

Table I presents the data, the background (obtained from the like-sign muon pairs), the mass acceptance, the differential cross section (with background subtracted) per Pt nucleus, and the cross section per nucleon. Our subtraction of like-sign muon pairs corrects for accidentals and muons from the decays of correlated hadrons. We have already[1] demonstrated that resolution tails do not contaminate these data with spillover from lower mass dimuons.

The reduction of data to "per nucleon" cross sections requires a knowledge of the A dependence and a study of Fermi motion. We have compared yields in Pt and Be as a function of dilepton mass. Assuming $\sigma \sim A^{\alpha}$, we find that $\alpha = 0.97 \pm 0.05$ averaged over the mass range 5–12 GeV, in agreement with earlier measurements.[5] However, in the following we continue to reduce the data using $\alpha=1.0$ until a more precise determination is made. The distributions in p_T follow the same fits for the Be target as for the Pt target, indicating that α is not a sensitive function of dilepton p_T for values of p_T less than 3 GeV.[6] We note that the "nucleon" in platinum is 60% n + 40% p.

Fermi motion increases the effective c.m. energy due to the approximately exponential increase of cross section with energy.[7] We estimated this effect using both a simple Fermi-gas model with a maximum momentum of 260 MeV and an experimentally determined Fermi momentum distribution.[8] Using an energy dependence based upon m^2/s scaling, both calculations predict a slope parameter b [Eq. (1)] which is 0.03 GeV^{-1} steeper for the per nucleon cross section compared to that of a heavy nucleus. We have divided by A and corrected for Fermi motion to obtain the last column of Table I, Fig. 1, and Table II.

We have fitted the resulting data, excluding the 9.0–10.8-GeV region, with the form

$$d^2\sigma/dm\,dy\,|_{y=0} = C\,e^{-bm} \quad (5.2 < m_{\mu^+\mu^-} < 15), \tag{1}$$

TABLE I. Derivation of the cross section.

$M_{\mu^+\mu^-}$ GeV/c^2	Events (+ -) + (- +)	Events (+ +) + (- -)	Acceptance %	$d^2\sigma/dm\,dy\vert_{y=0}$ (cm^2/GeV) per Pt Nucleus	$d^2\sigma/dm\,dy\vert_{y=0}$ (cm^2/GeV) per Nucleon
5.0 - 5.5	6768	346	0.165	307.0 ± (4.0) x 10^{-35}	159.0 ± (2.1) x 10^{-37}
5.5 - 6.0	5198	104	0.220	183.0 (2.6)	92.8 (1.3)
6.0 - 6.5	3953	23	0.275	113.0 (1.8)	56.4 (0.9)
6.5 - 7.0	2770	8	0.328	66.4 (1.3)	32.8 (0.6)
7.0 - 7.5	2013	2	0.378	41.9 (0.9)	20.4 (0.45)
7.5 - 8.0	1466	0	0.424	27.2 (0.7)	13.0 (0.34)
8.0 - 8.5	986	1	0.467	16.6 (0.5)	7.84 (0.25)
8.5 - 9.0	708	0	0.505	11.0 (0.4)	5.13 (0.19)
Upsilon Region	2106	0	0.570		
10.5 - 11.0	141	0	0.624	1.78 (0.15)	0.78 (0.07)
11.0 - 12.0	125	0	0.657	0.75 (0.07)	0.320 (0.028)
12.0 - 13.0	59	0	0.693	0.33 (0.04)	0.139 (0.018)
13.0 - 14.0	27	0	0.723	0.147 (0.028)	0.059 (0.011)
14.0 - 15.0	10	0	0.753	0.052 (0.016)	0.020 (0.006)
> 15.0	1	0	0.8	< 0.014	< 0.005

and find

$$C=(2.60\pm 0.02)\times 10^{-33}\ \mathrm{cm}^2\ \mathrm{GeV}^{-1}\ \mathrm{nucleon}^{-1},$$

$$b=0.986\pm 0.006\ \mathrm{GeV}^{-1},$$

$$\chi^2=76 \text{ for 78 degrees of freedom.}$$

The errors shown are statistical. The dominant systematic uncertainties in C are ±15% due to $\Delta\alpha$ and $^{+0\%}_{-21\%}$ due to $\Delta\beta$. In addition to these eventually measurable factors, there is an overall normalization uncertainty of ±25%. The systematic error in b is ±0.02 due to the Fermi-motion correction and acceptance uncertainties.

The dominant mechanism for producing the continuum of massive lepton pairs in hadron collisions is expected to be the annihilation of quark-antiquark pairs.[9] At $y=0$, the annihilating antiquark from the quark-antiquark sea of one nucle-

TABLE II. Invariant cross section ($E\,d^3\sigma/dp^3$) evaluated at $y=0$ vs p_T for several mass bins in units of 10^{-39} cm^2 GeV^{-2}.

p_T (GeV) \ Mass (GeV)	5 - 6	6 - 7	7 - 8	8 - 9	9 - 10.5	> 10.5
0.0 - 0.2	2110±(74)	762 ± (40)	292 ± (23)	127 ± (15)	101 ± (14)	9.0 ± (2.6)
0.2 - 0.4	2090 (49)	703 (24)	264 (13)	97 (8)	107 (8)	8.3 (1.4)
0.4 - 0.6	1756 (42)	662 (20)	240 (11)	95 (6)	86 (6)	6.9 (1.1)
0.6 - 0.8	1584 (42)	537 (17)	196 (9)	80 (5)	72 (5)	5.4 (0.8)
0.8 - 1.0	1174 (37)	439 (17)	166 (8)	59 (4)	59 (4)	6.0 (0.9)
1.0 - 1.2	944 (35)	333 (15)	124 (7)	54 (4)	54 (4)	3.6 (0.6)
1.2 - 1.4	693 (30)	264 (13)	95 (6)	33.2 (3.4)	40 (4)	3.2 (0.6)
1.4 - 1.6	444 (25)	179 (11)	68 (5)	29.0 (3.1)	26.1 (2.8)	2.1 (0.5)
1.6 - 1.8	326 (22)	123 (9)	43 (4)	16.3 (2.3)	20.8 (2.6)	0.89 (0.27)
1.8 - 2.0	228 (19)	81 (8)	26.8 (3.3)	14.2 (2.3)	15.5 (2.2)	1.03 (0.34)
2.0 - 2.2	151 (17)	40 (5)	22.1 (3.2)	8.9 (1.7)	11.6 (1.9)	0.82 (0.31)
2.2 - 2.4	91 (15)	25 (4)	15.7 (2.7)	5.0 (1.2)	7.3 (1.3)	0.32 (0.20)
2.4 - 2.6	66 (13)	25 (4)	6.4 (1.7)	2.5 (0.9)	5.0 (1.3)	0.40 (0.20)
2.6 - 2.8	28 (9)	12.8 (3.2)	5.0 (1.5)	2.1 (0.9)	2.8 (0.9)	0.06 (0.06)
2.8 - 3.0	32 (9)	9.6 (3.0)	4.7 (1.5)	1.1 (0.6)	2.4 (0.9)	0.0 (0.07)
3.0 - 3.2	14 (9)	8.6 (2.6)	3.1 (1.2)	0.6 (0.4)	1.5 (0.6)	0.07 (0.08)
3.2 - 3.4	-3 (7)	7.6 (2.6)	3.3 (1.4)	1.0 (0.6)	2.0 (1.0)	0.09 (0.07)
3.4 - 3.6	34 (16)	1.3 (1.3)	1.4 (0.8)	0.0 (0.4)	0.4 (0.3)	--
3.6 - 3.8	6 (4)	2.2 (1.7)	0.4 (0.4)	0.4 (0.4)	0.9 (0.7)	--
3.8 - 4.0	--	0.8 (0.9)	--	0.3 (0.3)	0.9 (0.6)	--

on and the quark from the other nucleon will have $x_1 = x_2 = m/\sqrt{s} \equiv x$. For protons incident on platinum, assuming color and neglecting p_T, the model predicts

$$(d^2\sigma/dm\,dy)|_{y=0} = (8\pi\alpha^2/9m^3) \sum_{k=u,d,s} e_k^2 x^2 [q_k^{\,p} q_{\bar{k}}^{\,N}(x) + q_{\bar{k}}^{\,p}(x) q_k^{\,N}(x)]. \quad (2)$$

The functions $q_k(x)$ $[q_{\bar{k}}(x)]$ are the fractional momentum distributions for quarks (antiquarks) of flavor k and charge e_k (the superscripts p and N label the beam proton and target nucleon, respectively). Using the quark momentum distributions defined by Feynman and Field[10] yields the prediction shown in Fig. 1.

The further assumption that the sea of quark-antiquark pairs is SU(3) symmetric, $q_{\bar{u}}(x) = q_{\bar{d}}(x) = q_s(x) = q_{\bar{s}}(x) \equiv S(x)$, results in a further simplification of Eq. (2),

$$(d^2\sigma/dm\,dy)|_{y=0} = (8\pi\alpha^2/9m^3) x S(x) [\nu W_2^{\,p}(x) + \nu W_2^{\,N}(x) - \tfrac{4}{3} x S(x)].$$

$\nu W_2^{\,p}(x)$ and $\nu W_2^{\,N}(x)$ are the inelastic structure functions measured directly in μ-p and e-N inelastic scattering.[11] We find an excellent fit to the data using

$$x S(x) = 0.6(1-x)^{10}, \quad 0.2 < x < 0.5. \quad (3)$$

Figure 1 shows several curves displaying the sensitivity to $S(x)$.

The statistical precision of the dimuon data require that the effects of scale breaking and quark transverse momenta on Eq. (2) be fully understood before taking Eq. (3) seriously. Recently reported high-statistics, high-energy lepton scattering data,[11,12] combined with the dimuon data presented here, will pose a tight constraint on the quark-parton model.

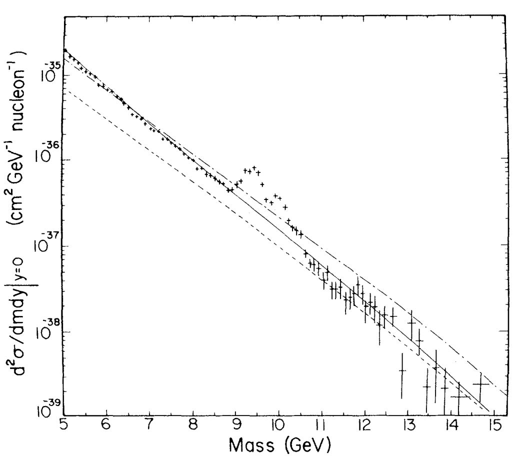

FIG. 1. Cross section for $p + N \to \mu^+ + \mu^- + X$ vs the effective mass of the muon pair. The curves are quark-antiquark annihilation-model predictions with the following assumptions: solid curve, measured νW_2 (Ref. 11) and $xS(x) = 0.6(1-x)^{10}$; dash-dotted curve, measured νW_2 (Ref. 11) and $xS(x) = 0.5(1-x)^8$; dashed curve, Feynman-Field (Ref. 10) structure functions.

Table II presents the p_T distributions. The large statistical power now clearly determines a shape which can no longer be fitted by a simple exponential.[5] All the spectra, excluding the Υ region (9.0–10.5 GeV) can be fitted by

$$E(d^3\sigma/dp^3)|_{y=0} = A(m)[1 + p_T^{\,2}/(2.8)^2]^{-6}.$$

The mean and mean square p_T's are plotted in Fig. 2 together with data[13] at lower mass. There are several conclusions: (i) The mean p_T of the dilepton continuum is independent of mass above 5 GeV. (ii) The Υ region has a significantly higher $\langle p_T \rangle$ than the neighboring continuum (if the continuum background is unfolded, the Υ $\langle p_T \rangle = 1.44 \pm 0.11$ implying a production mechanism which differs from that of the continuum). (iii) $m_\perp$ scaling does not hold here. (iv) To the extent that the annihilation model holds, the mean p_T measures directly the mean transverse momen-

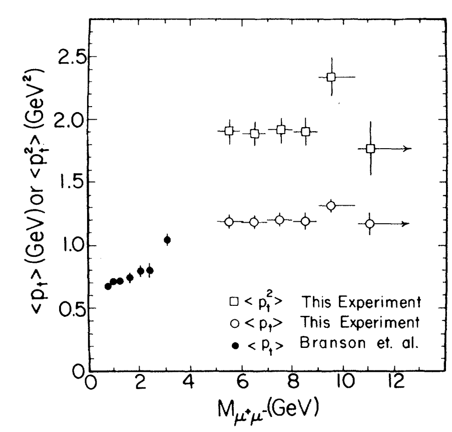

FIG. 2. Mean p_T and mean square p_T of the muon pairs vs effective mass. The data of Branson *et al.* are from Ref. 13.

tum, k_T, of the annihilating quarks[14]; in fact,

$$\langle k_T^2 \rangle = \tfrac{1}{2} \langle p_T^2 \rangle$$

so that the rms k_T of the quarks is of the order of ~1.0 GeV/c.

In summary, we find in the mass range 5–15 GeV a remarkable consistency between the quark-parton model interpretation of the dilepton data and deep inelastic scattering results. In the context of this model we measure the sea-quark distribution and the initial-state quark transverse momenta. Finally we note that the last row of Table I sets a significant upper limit to the cross section for dilepton production from 15 to 27 GeV.

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[4]$B[d\sigma/dy]_{y=0}$ for Υ depends upon the Υ decay distribution. We now find that for $\beta = 1$, $B[d\sigma/dy]_{y=0} = 0.27$ pb/nucleon; for $\beta = 0$, $B[d\sigma/dy]_{y=0} = 0.21$ pb/nucleon.

[5]D. C. Hom *et al.*, Phys. Rev. Lett. 37, 1374 (1976). Note that the high values of $\langle p_T \rangle$ derived in this reference reflect the choice of the fitting function, $\exp(-bp_T)$.

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[11]W. Francis, in Proceedings of the APS Division of Particles and Fields Meeting, Argonne, Illinois, September 1977 (to be published); T. Kirk, private communication. We have taken the values of $\nu W_2(x, Q^2)$ for $Q^2 = 9$. If we had taken $Q^2 = m^2$ then Eq. (3) would have been $xS(x) = 0.5(1-x)^9$.

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[14]See, for example, C. S. Lam and T-M. Yan, Cornell University Laboratory for Nuclear Studies Report No. CLNS-365, 1977 (unpublished), and references therein. For an alternative viewpoint see M. Duong-Van *et al.*, SLAC Report No. SLAC-PUB-1882, 1977 (unpublished). These authors predicted the results of Fig. 2 using the constituent-interchange model. However, T. Kinoshita *et al.*, Phys. Lett. 63B, 355 (1977), did the same via annihilation of high-k_T quarks. Still another viewpoint attributes $\langle k_T \rangle$ to gluon effects treated within quantum chromodynamics as corrections to the basic Drell-Yan process: See H. Fritzch and P. Minkowski, CERN Report No. CERN Th-2400, 1977 (unpublished); K. Kajantie and R. Raitio, Helsinki University Report No. HU-TFT-77-21, 1977 (unpublished).

Three-Body Calculation of πd Elastic Scattering at 142 MeV

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We calculate the pion-deuteron elastic scattering at $E_\pi = 142$ MeV using nonrelativistic three-body equations in which relativistic kinematics are retained only for the pion. The NN tensor force is taken into account, and, for the first time, all S and P πN partial waves are included in an exact way. The coupling between $l = J \pm 1$ πd channels is found to be not negligible, and we establish the large interference effects of all other than P_{33} πN channels leading to a rather good description of the experimental data at $E_\pi = 142$ MeV.

The elastic scattering of medium energy pions off deuterium has recently been given a considerable attention. The properties of the pion nucleon interaction and its richness with interesting physical phenomena (such as absorption, production, resonance structure, etc.) make the pion-deuteron system the most interesting three-body entity. With the advent of mesons factories on the one hand, and complete three-body calculations on the other hand, the pion-deuteron system probably will receive even more attention.

Let us briefly discuss the most relevant calculations performed up till now, together with the motivation for the present work. Two types of