Production Dynamics of High-Mass Muon Pairs

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We report the results of a study of the mechanism of inclusive dimuon production from the reaction $p+p\to\mu^+\mu^- +X$ at the CERN intersecting storage rings. The present experiment was done at the center-of-mass energies $\sqrt{s}=62$ and 44 GeV and in the dimuon pair invariant-mass region $m=3$–25 GeV. The dependence on the Feynman variable x has been measured. The average transverse momentum is found to increase with $\sqrt{s}$ and with mass and reaches $\langle p_T\rangle\simeq 1.9$ GeV, compatible with predictions from quantum-chromodynamic gluon processes.

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We present results on a high-statistics measurement of the reaction

$$pp\to\mu^+\mu^- + \text{anything} \qquad (1)$$

carried out at the CERN intersecting storage rings (ISR). The physics interest of Reaction (1) comes from the possibility of probing the internal proton structure with timelike photons. In particular, the model of Drell and Yan[1] views the μ pairs as originating from quark-antiquark annihilation; hence the production dynamics is related to quark distributions in the proton. Quantum chromodynamics (QCD) modifies this mechanism by invoking quark-gluon interaction terms.[2] The production of muon pairs with P_T larger than the confinement momenta of quarks is thus possible from hard-gluon emission.

Integrated luminosities $L=1.12\times10^{38}$ cm^{-2} at $\sqrt{s}=62$ GeV and $L=0.42\times10^{38}$ cm^{-2} at $\sqrt{s}=44$ GeV were accumulated above the energy range of previous dimuon measurements[3] with use of nuclear targets.

The detector, which consists of magnetized iron toroids interleaved with scintillation counters and drift chambers, has been described elsewhere.[4] Details on the event selection, fitting procedures, and results on the dimuon mass spectrum[4] have also been reported. In this paper we report the results of our study of the production mechanism of a clean sample of muon pairs. Beam-associated backgrounds and hadron track contaminations were suppressed by (a) eliminating muon tracks parallel to the plane containing the ISR beams, (b) requiring the fitted χ^2 of each muon track to be consistent with multiple scattering, which eliminates hadron showers, and (c) requring each muon to traverse at least 22 kG m of magnetized iron. Studying the J width, we find $\Delta m/m=11\%$. Comparing the difference in cosmic-ray momenta obtained from the upper and lower halves of the detector confirms $\Delta m/m=11\%$ and measures the rms resolutions $\Delta x=0.03$ and $\Delta P_T=0.5$ GeV averaged over our acceptance. This agrees with calculations by the Monte Carlo method. To obtain acceptances, the Monte Carlo program generated events with variables m', x', p_T', $\cos\theta'$ (θ' is the Collins-Soper[5] angle). Each event is weighted by the production mechanism so that

$$\frac{d^4N}{dm'\,dp_T'^2\,dx'\,d\cos\theta'}=A\frac{(1-m'/\sqrt{s}\,)^{10}}{m'^4/\sqrt{s}}(1-|x'|)^a\exp(-bp_T')(1+c\cos^2\theta'). \qquad (2)$$

Each Monte Carlo event is traced through the detector taking into account multiple scattering and energy loss, and is analyzed by the same program used to treat the data. The reconstructed variables for the Monte Carlo events are m, x, p_T, and $\cos\theta$. Comparing event distributions in these variables with the measured events ensures accurate treatment of the resolution. The parameters A, a, b, and c are determined by fitting Monte Carlo event distribution to the data by minimizing the χ^2. The fitted values of a, b, and c were used to calculate acceptances. The acceptance covers the x range from -0.1 to 0.8. The acceptance in p_T is roughly flat up to $p_T \simeq 8$ GeV for $m > 8$ GeV, and slowly drops as a function of p_T for lower pair masses. The acceptance in $\cos\theta$ is peaked at 0°.

We have subdivided the $\sqrt{s} = 62$ GeV data into mass intervals of 2–4, 5–8, 8–11, and 11–25 GeV with 4389, 1457, 536, and 143 events, respectively, and with relative background rates of 13%, 19%, 4%, and 1% as computed from the rate of like-sign pairs. For the 44-GeV data, the mass intervals were 2–4, 5–8, and 8–17 GeV, with 897, 259, and 77 events with 14%, 10%, and 1% background, respectively.

The distributions in m, x, and p_T for like-sign pairs were found to reproduce exactly when tracks from different pairs were interchanged. This is expected for punchthrough and decay muons. Opposite-sign pairs were constructed from the measured $\mu^+\mu^+$ and $\mu^-\mu^-$ pairs and were used to make a bin-by-bin background subtraction. The background distribution is slightly broader in p_T and narrower in x than for $\mu^+\mu^-$ pairs. For both data sets the J dominates the 2–4 GeV mass region, and the Υ resonances contribute about 50% to the mass interval which contains 10 GeV.

For the resonance-free region $5 < m < 8$ GeV at $\sqrt{s} = 62$ GeV, the angular distribution of the muons relative to the Collins-Soper axis[5] was fitted with $(1 + c\cos^2\theta)$. We find $c = 1.0 \pm 0.5$, consistent with expectations from the Drell-Yan mechanism and with measurements at lower energies.[3] Similar results are obtained for mass intervals above 8 GeV (with indications of smaller polarization in the Υ region[6] and at $\sqrt{s} = 44$ GeV.

Figure 1 gives the measured distributions in x

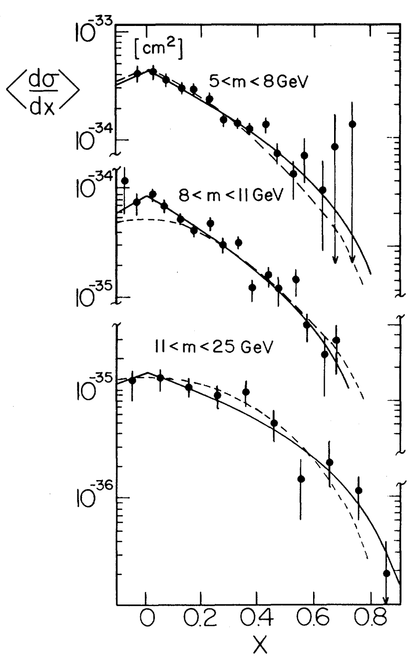

FIG. 1. Distribution of dimuons in x for three mass intervals. The solid line is the fit given in the text. The dashed line is a Drell-Yan calculation (Ref. 7) scaled up by a factor of 1.6.

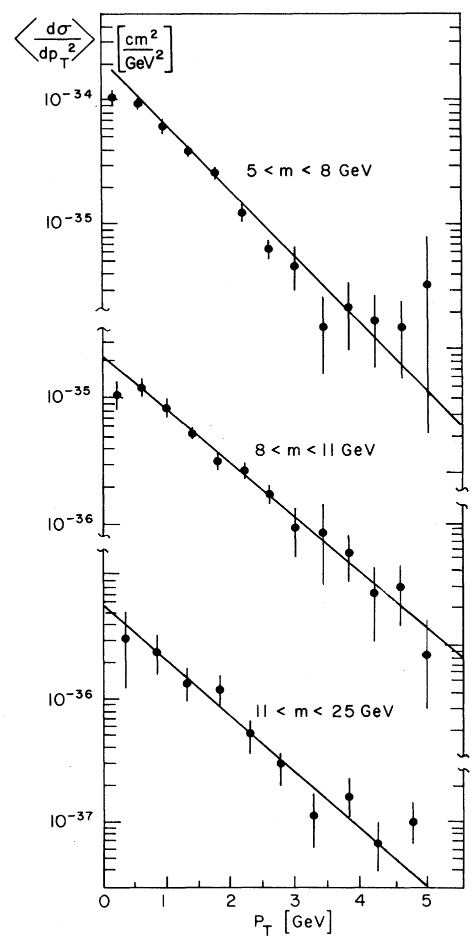

FIG. 2. Distribution in the transverse momentum of the dimuon. The lines are simple exponential fits, omitting the first point.

TABLE I. Fits to $A\exp(-bp_T)$ and average transverse momenta. The errors include estimates of systematic uncertainties. (DF is the degrees of freedom.)

$\sqrt{s}$	Mass range (GeV)	A (10^{-35} cm^2/GeV^2)	χ^2/DF	$2/b \simeq \langle p_T \rangle$ (GeV)	$\langle p_T \rangle$ from events (GeV)
62 GeV	2 – 4	3300 ± 1000	7.9/10	1.4 ± 0.2	1.40 ± 0.20
	5 – 8	22 ± 2	8.2/10	1.5 ± 0.1	1.60 ± 0.10
	8 – 11	2.3 ± 0.3	2.9/10	1.9 ± 0.2	2.05 ± 0.15
	11 – 25	0.54 ± 0.23	6.5/7	1.9 ± 0.4	1.95 ± 0.25
44 GeV	2 – 4	2500 ± 1000	5.1/8	1.1 ± 0.2	1.10 ± 0.20
	5 – 8	9.3 ± 2.3	4.3/7	1.5 ± 0.2	1.50 ± 0.15
	8 – 17	0.9 ± 0.4	0.9/7	1.9 ± 0.4	1.50 ± 0.15

for the 62-GeV data, which are fitted by $(1-|x|)^a$, with $a = 2.7 \pm 0.3$, 3.3 ± 0.3, and 2.1 ± 0.3 for the 5–8, 8–11, and 11–25 GeV mass intervals, respectively. In particular, we notice a higher a value in the 8–11-GeV region (50% contribution from Υ resonances), and a slightly flatter behavior at $11 < m < 25$ GeV. As noted with the dashed line, the distributions are in good agreement with a calculation[7] of the Drell-Yan model, scaled up by an empirical factor of 1.6.

The cross section $d\sigma/dp_T^2$ is presented in Fig. 2 for the 62-GeV data for different mass intervals. As observed at lower energies,[3] the distribution appears exponential except in the very-low-p_T region. Omitting the first bin, we obtain good fits to a simple exponential $A\exp(-bp_T)$ as stated in Table I. We observe large average transverse momenta $\langle p_T \rangle \simeq 1.8$–$2.0$ GeV. In addition, the $\langle p_T \rangle$ values were independently calculated by summing individual events and weighting with the detector acceptance. We have summed events with p_T up to 4 GeV, and estimated the small contribution from higher-p_T events from the fitted exponentials. Results for the 62- and 44-GeV measurements are also summarized in Table I. We see good agreement in the values of $\langle p_T \rangle$ from the two different methods. The error in the J region is twice the statistical error due to the very limited range of acceptance. In the overlap mass region $2 < m < 11$ GeV our values are in agreement with electron pair measurements.[8]

Figure 3 summarizes our values of dimuon $\langle p_T \rangle$ obtained from the event counting methods together with the data of Ref. 3 over a range of dimuon masses with $\sqrt{s}$ extending from 19 to 62 GeV. The large value of $\langle p_T \rangle$ and the increase of $\langle p_T \rangle$ with $\sqrt{s}$ cannot be understood in the Drell-Yan model but are in agreement with QCD predictions based on gluon-quark interaction.[9]

We conclude that most dimuon production characteristics can be described by the quark-antiquark annihilation picture when it is expanded to include hard-gluon processes of QCD to account for the measured large $\langle p_T \rangle$ values.

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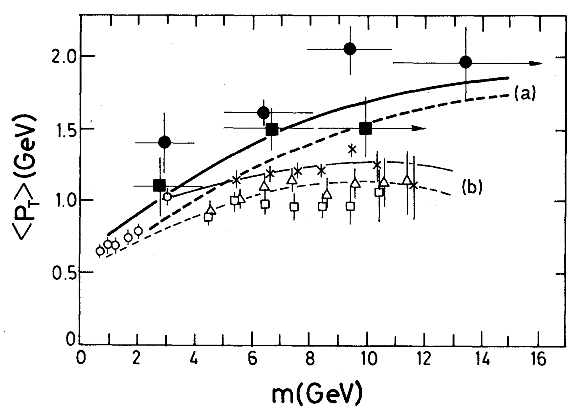

FIG. 3. Average transverse momentum as a function of the pair mass. The solid circles are 62-GeV data, the solid squares denote 44-GeV data. Also shown are points from Ref. 3 with $\sqrt{s}$ ranging from 19.4 to 27.4 GeV. The open circles are from Branson *et al.* and Anderson *et al.* at $\sqrt{s} = 20.5$ GeV. The open squares, open triangles, and crosses are from Yoh *et al.* at $\sqrt{s} = 19.4$, 23.7, and 27.4 GeV, respectively. The ISR and the lower-energy results are compared to QCD predictions for $\sqrt{s} = 58$ GeV (curves *a*), and $\sqrt{s} = 27.4$ GeV (curves *b*), respectively. In each case two hypotheses of quark momentum spread have been made: 500 MeV (solid line) and 300 MeV (dotted line).

[1]S. D. Drell and T.-M. Yan, Phys. Rev. Lett. 25, 316, 920(E) (1970). For recent reviews concerning the Drell-Yan mechanism, see J. LeFrancois, in *High Energy Physics—1980,* edited by L. Durand and L. Pondrom, AIP Conference Proceedings No. 68 (American Institute of Physics, New York, 1981), and Proceedings of the Sixteenth Recontre de Moriond Workshop on Lepton Pair Production, 1981, edited by Tran Thanh Van (to be published).

[2]These were studied in the inverse reaction of lepton pair annihilation, see D. P. Barber *et al.*, Phys. Rep. 63, 337–391 (1980). For details on p_T, see G. Altarelli, G. Parisi, and R. Petronzio, Phys. Lett. 76B, 351, 356 (1978); Yu. L. Dokshitzer, K. I. Dyakonov, and S. I. Trovan, Phys. Rep. 58, 269–395 (1980), and references therein.

[3]J. Branson *et al.*, Phys. Rev. Lett. 38, 1344 (1977); J. K. Yoh *et al.*, Phys. Rev. Lett. 41, 684 (1978); K. Ueno *et al.*, Phys. Rev. Lett. 42, 486 (1979); K. J. Anderson *et al.*, Phys. Rev. Lett. 42, 944 (1979); G. E. Hogan *et al.*, Phys. Rev. Lett. 42, 948 (1979).

[4]D. Antreasyan *et al.*, Phys. Rev. Lett. 45, 863 (1980).

[5]J. C. Collins and D. E. Soper, Phys. Rev. D 16, 2219 (1977). θ is the angle between μ^+ and the average direction of the incident protons in the dimuon c.m. energies.

[6]J. A. Paradiso, thesis, Massachusetts Institute of Technology, 1981 (unpublished).

[7]J. G. H. de Groot *et al.*, Z. Phys. C 1, 143 (1979); J. Badier *et al.*, Phys. Lett. 89B, 145 (1979). The structure functions used are $u_v(x) = 2.13x^{0.5}(1-x)^{2.8}$, $d_v(x) = 1.26x^{0.5}(1-x)^{3.8}$, $u_s = \bar{u} = d_s = \bar{d} = 2s = 2\bar{s} = 0.27(1-x)^{8.1}$.

[8]A. L. S. Angelis *et al.*, Phys. Lett. 87B, 398 (1979); C. Kourkoumelis *et al.*, Phys. Lett. 91B, 475, 481 (1980).

[9]H. Fritzsch and P. Minkowski, Phys. Lett. 73B, 80 (1978).