Test of Scaling in Muon-Pair Production by Hadrons

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We have measured the inclusive production of massive dimuons ($7 \leq M_{\mu\mu} \leq 11$ GeV/c^2) by 200-, 300-, and 400-GeV protons incident on Cu in order to check whether the dimensionless cross section $M_{\mu\mu}^3[d\sigma/dM_{\mu\mu}dy]_{y=0}$ is a function of $M_{\mu\mu}^2/s$ alone, where s is the square of the c.m. energy. The results support the scaling hypothesis.

There is growing confidence that the weak interactions are indeed mediated by heavy vector bosons, charged and neutral, and that their masses may well lie in the range 40–100 GeV/c^2 (as indicated by theories[1] which unify the weak and electromagnetic interactions). If so the intermediate vector boson (W) would, at least energetically, be within the reach of the colliding-beam machines likely to be the accelerators of the next generation. Hence questions bearing on the W production and its detection have received much attention recently.[2-5]

Most of the theoretical estimates for the W-production cross sections rely, among other things, on the scaling hypothesis, i.e., the hypothesis that the dimensionless cross section $m^3 d\sigma/dm$ for electromagnetic production of a lepton pair of mass m in p-p collisions is a function of m^2/s alone, where s is the square of the c.m. energy of the p-p system.[6] Scaling in itself is of course an important theoretical issue; it is a consequence of many models[7] of dilepton production by hadrons—in particular, the well-known Drell-Yan process[8] in which a dilepton is produced by the annihilation of a quark-antiquark pair. It is thus of great theoretical as well as practical interest to investigate the scaling behavior of the dilepton process. This Letter reports the results of such an investigation. It was performed at Fermilab with muon pairs of large mass (7–11 GeV/c^2) produced by 200-, 300-, and 400-GeV protons incident on a Cu target.

At present the data on scaling are rather sparse. (The most recent compilations are given in Refs. 3 and 4.) Although measurements of dilepton production cross sections are now available for a wide range of energies and dilepton masses, they involve *different experimental acceptances*; thus a *direct* check of scaling is not possible. The strength of the present experiment is that it uses the same apparatus at all three c.m. energies (19, 24, and 28 GeV), providing such a direct test; its limitation is the statistical precision attained for the available energy variation.

The apparatus is identical to the one described in a previous publication[9] where our preliminary results on the production of massive dimuons at Fermilab energies have been reported. Briefly stated, the apparatus consists of a highly asymmetric double-arm spectrometer. One arm is a magnetic focusing spectrometer of small solid angle which can be adjusted to select, with high purity, direct single muons produced at $\theta^* \approx 90°$ in the proton-nucleon c.m. system. The other arm, the multihole spectrometer (MHS), consists of ten large liquid scintillator detectors buried in the ground; they detect muons with transverse momentum $p_T \gtrsim 3.2$ GeV/c. The MHS covers in the c.m. system at 400 GeV a polar angle of $60° < \theta^* < 126°$ and an azimuthal angle of $-8° < \varphi^* < 25°$.

Data are taken as a function of p_T^s, the transverse momentum of the muon observed in the magnetic spectrometer. The rate of events for which a second coincident muon is detected in the MHS is recorded. For a given value of p_T^s the dimuon mass acceptance of the system is ~2 GeV/c^2 full width at half-maximum centered[10] about $2p_T^s$. Thus this experiment cannot resolve narrow resonances whose total yield in a 2-GeV/c^2-wide mass band is less than the $\mu\mu$-continuum yield.

To evaluate the efficiency of the apparatus for various dimuon masses we have assumed the parametrization

$$E[d\sigma/d^3p\,dM_{\mu\mu}]_{y=0} \propto \exp(-2p_T/\langle p_T\rangle) \qquad (1)$$

for the p_T dependence of the invariant production cross section in the central region (rapidity $y=0$).

TABLE I. The cross sections per nucleon for the production of muon pairs by 200-, 300-, and 400-GeV protons incident on Cu. Errors are statistical only.

Proton energy (GeV)	p_T^s (GeV/c)	$\langle M_{\mu\mu}\rangle$ (GeV/c^2)	$d^2\sigma/dM_{\mu\mu}dy\|_{y=0}$ (c.m.^{2}/GeV/c^2)
400	3.9	7.7	$(1.2\pm 0.2)\times 10^{-36}$
400	4.6	8.8	$(6.4\pm 0.6)\times 10^{-37}$
400	5.4	10.0	$(2.9\pm 0.5)\times 10^{-37}$
400	6.2	11.3	$(3.8\pm 1.5)\times 10^{-38}$
300	3.9	7.7	$(6.8\pm 1.0)\times 10^{-37}$
300	4.6	8.8	$(3.5\pm 0.5)\times 10^{-37}$
300	5.0	9.3	$(1.9\pm 0.4)\times 10^{-37}$
300	5.8	10.7	$(6.3\pm 1.4)\times 10^{-38}$
200	3.9	7.4	$(4.7\pm 1.2)\times 10^{-37}$
200	4.6	8.3	$(1.2\pm 0.4)\times 10^{-37}$

For $\langle p_T\rangle$, the average p_T of the dimuons, we have used 1.25 GeV/c, a value determined experimentally from the azimuthal angular distribution of the muons detected in the MHS with respect to the plane containing the proton beam and the magnetic spectrometer line. (In the mass range 7–11 GeV/c^2 we measure $\langle p_T\rangle = 1.25\pm 0.30$ GeV/c, in agreement with Hom *et al.*[11] who observe 1.45 ± 0.25 GeV/c for dimuons of mass 6.5–11 GeV/c^2.)

Table I gives for each energy the cross sections *per nucleon*. We have assumed the cross section to be proportional to the atomic number A. The justification for the A^1 dependence comes from our own measurements at $p_T^S = 4.6$ GeV/c ($M_{\mu\mu} \approx 9$ GeV/c^2) of dimuon yields from Cu and Be targets of identical interaction length (40%). We find for the exponent 1.03 ± 0.10. The reason for quoting $d^2\sigma/dM_{\mu\mu}dy|_{y=0}$ is that our apparatus is only sensitive to dimuons produced in the rapidity interval $-0.3 \lesssim y \lesssim 0.2$, i.e., near $y\approx 0$.

Figure 1 shows the cross section $d^2\sigma/dM_{\mu\mu}dy|_{y=0}$ versus $M_{\mu\mu}$ for all three energies. We observe an exponential falloff with $M_{\mu\mu}$ and a strong energy dependence. If, however, the quantity $M_{\mu\mu}^3 \times [d^2\sigma/dM_{\mu\mu}dy]_{y=0}$ is plotted as a function of $M_{\mu\mu}^2/s$, then the energy dependence all but disappears, as seen in Fig. 2. This shows that within the experimental uncertainties the scaling hypothesis does hold in the energy and mass regions under study. A χ^2 fit of all data points by a universal curve (taken here to be an exponential) yields $\chi^2 = 11.5$ for 8 degrees of freedom, an acceptable fit. This curve transforms back into the lines shown in Fig. 1 at each energy.

There are other available data relevant to scaling.[12-15] However, as already mentioned, they were obtained under vastly different experimental conditions (acceptance, target material, etc.) and various assumptions have to be made to extract

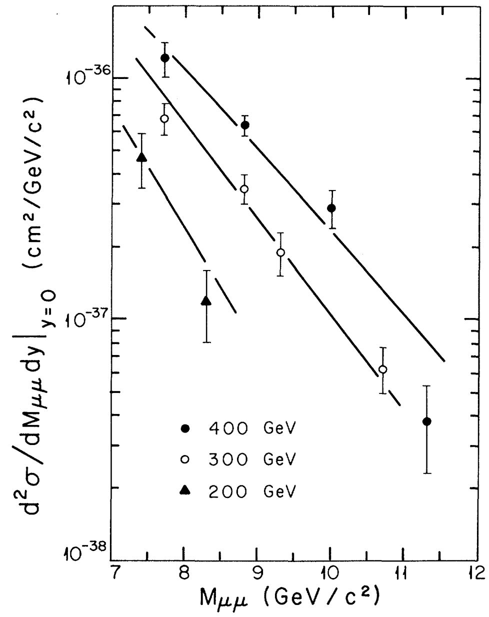

FIG. 1. The cross section per nucleon $d^2\sigma/dM_{\mu\mu}dy|_{y=0}$ for the production of muon pairs at three energies. The lines represent the overall fit of Fig. 2 transformed back for each energy.

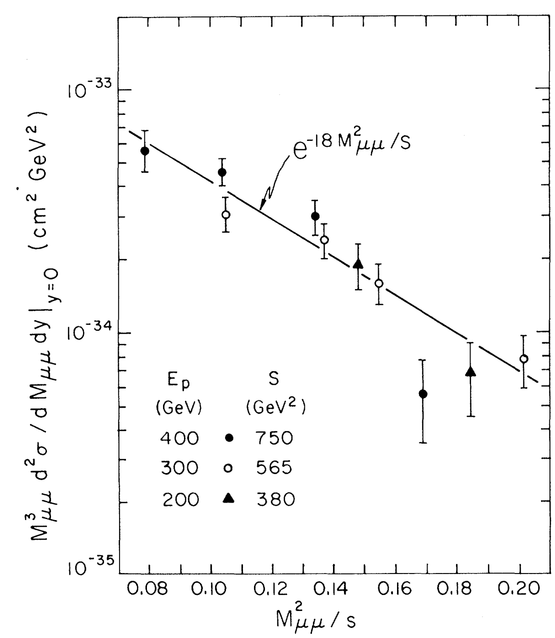

FIG. 2. The scaling behavior of the data. The line is an exponential fit to all points.

the cross section $d\sigma/dm$ per nucleon. Moreover, it is important that all data be treated in the same manner. Such a treatment can be found in Ref. 4.

In conclusion it should be pointed out that the Drell-Yan model, which carries a number of significant implications, in particular scaling, can be easily accommodated to our cross-section data. However, at least in its simplest form, the model provides no appreciable p_T for the dilepton system, in contradiction with the data.

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Note added.—After submission of this paper a resonance structure was reported in the dimuon mass spectrum at $M_{\mu\mu} \sim 9.5$ GeV/c^2.[16] We have investigated the effect of this resonance on the results reported here. While points in the region of the resonance are lowered by ~25%, the conclusion that scaling holds to the precision demonstrated in this paper remains unaltered.

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[1] For example, the unified gauge theory of Weinberg and Salam leads to a $W^{\pm}$ of ~60 GeV/c^2 and a Z^0 of ~75 GeV/c^2 mass.

[2] R. B. Palmer *et al.*, Phys. Rev. D 14, 118 (1976).

[3] C. Quigg, Rev. Mod. Phys. 49, 297 (1977).

[4] R. F. Peierls, T. L. Trueman, and L. L. Wang, BNL Report No. BNL-22628, 1977 (to be published).

[5] J. W. Cronin, in Proceedings of the International School of Subnuclear Physics, "Ettore Majorana," Erice, Italy, July, 1976 (to be published).

[6] The results presented in this paper are for $m^3[d^2\sigma/dmdy]_{y=0}$ and not $m^3 d\sigma/dm$ because the measurements are all made in the central region. In the Drell-Yan model of quark-antiquark annihilation, both $m^3[d^2\sigma/dmdy]_{y=0}$ and $m^3 d\sigma/dm$ are predicted to undergo scaling.

[7] See, for example, Ref. 3 where further references are contained therein.

[8] S. D. Drell and T. M. Yan, Phys. Rev. Lett. 25, 316 (1970).

[9] L. Kluberg *et al.*, Phys. Rev. Lett. 37, 1451 (1976).

[10] Actually the mean of the accepted events is at a mass ~5% lower than $2p_T{}^s$ because of the sharply falling cross section with increasing dimuon mass.

[11] D. C. Hom *et al.*, Phys. Rev. Lett. 37, 1374 (1976).

[12] D. C. Hom *et al.*, Phys. Rev. Lett. 36, 1236 (1976).

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

[14] J. G. Branson *et al.*, Phys. Rev. Lett. 38, 1334 (1977).

[15] L. M. Lederman and B. G. Pope, Phys. Lett. 66B, 486 (1977).

[16] S. W. Herb *et al.*, Phys. Rev. Lett. 39, 252 (1977).

Υ(9.5) as Bound States of New Heavy Quarks

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The cascade-gluon model is used to show that the observed enhancement at 9.5 GeV can be interpreted as due to the production, and subsequent cascade decay into $^3S_1$ states, of at least two and most likely three sets of $C = +$ bound states of quarks Q of mass $m_Q \simeq 5$ GeV and charge $-\frac{1}{3}e$.

The recent controversy concerning the "high-y anomaly"[1] has cast doubt upon what had been the best evidence for the existence of a heavy quark.[2] Indeed, if the newest neutrino data[1] are taken in isolation, it would be natural to accept the most economical SU(2)⊗U(1) Weinberg model[3] for the weak interactions, with only four quark flavors. However, the small upper limits on parity nonconservation in atomic physics[4] and the apparent existence of a heavy lepton[5] obviate the simplest scheme. Both of the preceding experimental observations, taken in conjunction with available theoretical models, suggest that further quarks must exist. Therefore, it is a good time for observations directly indicative of new quark flavors. This we believe is the case for the recent