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# DILEPTON PRODUCTION IN HADRON-HADRON COLLISIONS AND THE "FACTOR OF THREE" FROM COLOR

C. Quigg*
Fermi National Accelerator Laboratory†
P. O. Box 500, Batavia, Illinois 60510

Abstract: Recent data on inclusive dilepton production are compared with the Drell-Yan model with colored quarks.

Résumé: Les résultats expérimentaux récents concernant la production inclusive de dileptons sont comparés avec les prédictions du modèle de Drell-Yan contenant des quarks de couleur.

*Alfred P. Sloan Foundation Fellow; also at Enrico Fermi Institute, University of Chicago, Chicago, Illinois 60637.

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The organizers of this session have asked me to comment upon the current state of the data on inclusive dilepton production in hadron-hadron collisions. The question to be investigated is whether there is any evidence for or against color as a degree of freedom of the quark constituents of hadrons.

Let us recall the quark-parton model description of inclusive hadronic decays of a virtual photon. We assume the virtual photon to decay into a quark-antiquark pair which is dressed by the confinement mechanism, whatever that may be, into hadrons. Thus the inclusive rate is

$$\Gamma(\gamma_V \to \text{hadrons}) = \sum_{\text{flavors } i} \Gamma(\gamma_V \to q_i \bar{q}_i). \tag{1}$$

The back-to-back quark and antiquark in the semifinal state define a jet axis for the final-state hadrons. Evidence for well-collimated hadron jets has been obtained[1] in studies of event structure in

$$e^+e^- \to \gamma_V \to \text{hadrons}, \tag{2}$$

at CM emergies exceeding about 4 GeV. Since quarks are assumed to be pointlike entities, we may relate the decay rate into each quark-antiquark pair to the decay rate into muon pairs:

$$\Gamma(\gamma_V \to q_i \bar{q}_i) = 3 \times e_i^2 \times \Gamma(\gamma_V \to \mu^+\mu^-), \tag{3}$$

where $e_i$ is the charge of the quark flavor "i". The factor of three arises because there are three colors of quark -- hence three distinct decay processes -- for each flavor. Applying (1) and (3) to reaction (2) we recover the celebrated result

$$R = \frac{\sigma(e^+e^- \to \text{hadrons})}{\sigma(e^+e^- \to \mu^+\mu^-)} = 3 \sum_{\substack{\text{flavors} \\ i}} e_i^2 . \tag{4}$$

Below charm threshold the u, d, and s quarks with charges 2/3, -1/3, and -1/3 can be excited, so we expect $R \approx 2$, in good agreement with the data.[2] Above charm threshold the c quark with charge 2/3 is expected to increase the total to $R \approx 10/3$. It is not yet known how much of the new physics at 4 GeV is to be attributed to charm,[3] so we lack a definitive test of this prediction. The same manner of counting has implications for inclusive dilepton production in hadron-hadron collisions.

In the quark-parton model, the cross section for the hadronic reaction

$$a + b \rightarrow c + \text{anything}, \tag{5}$$

is given by

$$\sigma(a + b \rightarrow c + \text{anything}) = \sum_{\{q\}} P_a(q_1)P_b(q_2)\,\sigma(q_1 + q_2 \rightarrow c + \text{anything}), \tag{6}$$

where $P_i(q_j)$ is the probability of finding quark $q_j$ in hadron i and $\sigma(q_1 + q_2 \rightarrow c + \text{anything})$ is the cross section for the elementary process leading to the desired final state. The summation runs over all contributing quark configurations. Drell and Yan treated the reaction illustrated in Fig. 1,

$$a + b \rightarrow \ell^+\ell^- + \text{anything}, \tag{7}$$

in which a lepton pair of invariant mass $\mathcal{M}$ is produced with CM momentum fraction x in collisions at CM energy $s^{1/2}$. The differential cross section is given by

$$\frac{d\sigma}{d\mathcal{M}^2 dx} = \left(\frac{4\pi\alpha^2}{3\mathcal{M}^4}\right) F(\tau, x), \tag{8}$$

where the function F contains information about the quark distributions within the colliding hadrons and depends upon the scaled variable

$$\tau = \mathcal{M}^2/s. \tag{9}$$

The Drell-Yan picture carries a number of significant implications. The most general of these is the scaling prediction that $\mathcal{M}^4 d\sigma/d\mathcal{M}^2$ should be a function of $\tau$ alone. At the present time there are insufficient data outside the region of known resonances (which are apparently not produced by the Drell-Yan process) to test scaling.[5] Preliminary data of the Chicago-Princeton Collaboration, presented at this meeting by Shochet[6] indicate that in pp collisions from 200 to 400 GeV/c, and at invariant masses above 5 GeV/$c^2$, scaling holds within about 20%.

The Drell-Yan model carries a second implication of experimental interest. Consider the production of lepton pairs in $\pi^{\pm}$ collisions on an isoscalar target such as Carbon. Since the Drell-Yan process is intrinsically electromagnetic, it implies[7] a specific violation of isospin invariance. Define the ratio

$$\rho = \frac{d\sigma}{d\mathcal{M}^2}(\pi^+ C \to \ell^+\ell^- + X) \Big/ \frac{d\sigma}{d\mathcal{M}^2}(\pi^- C \to \ell^+\ell^- + X). \tag{10}$$

If the pairs are produced through noninterfering resonances in

$$\begin{array}{l} \pi^{\pm} C \to \text{hadron} + X \\ \qquad\quad \hookrightarrow \ell^+\ell^- \end{array}, \tag{11}$$

$\rho = 1$, but if they are produced through

$$\begin{array}{l} \pi^{\pm} C \to \gamma_V + X \\ \qquad\quad \hookrightarrow \ell^+\ell^- . \end{array} \tag{12}$$

$\rho \neq 1$ in general. An extreme example of the latter is Drell-Yan production by valence quark annihilation. For incident $\pi^+$, the elementary process is $d\bar{d} \to \gamma_V$; for incident $\pi^-$ it is $u\bar{u} \to \gamma_V$. The cross section is proportional to the square of the quark charge, so we find

$$\rho = \frac{1}{4} . \tag{13}$$

In a less schematic Drell-Yan model, with valence and sea quarks, the value $\rho = 1/4$ is attained only for rather large lepton pair masses. At very small masses, for which sea quark-sea quark annihilations are dominant, $\rho \to 1$. The ratio $\rho$ has now been measured, and exhibits the trend anticipated by the Drell-Yan model,[8] as shown in Fig. 2.

The third consequence of the Drell-Yan picture is the one which in principle tests the color hypothesis. If the quark distributions within hadrons are known, specific predictions can be made on the basis of (6) and (8) for dilepton cross sections. In the case of nucleons, data on deep-inelastic lepton scattering provide substantial information on the parton distributions, and many parametrizations have appeared in the literature. Two of these represent, in my view, reasonable extremes of parton parametrizations: the Pakvasa-Parashar-Tuan (PPT) parametrization,[9] with a sea quark distribution $\propto x^{-1}(1-x)^{7/2}$, and the Field-Feynman (FF) parametrization,[10] with a sea quark distribution $\propto x^{-1}(1-x)^{7}$. The existence of color reduces by a factor of 3 the magnitude of the Drell-Yan prediction because quarks of the same color and flavor must annihilate to create the virtual photon. Recent measurements of dilepton production in p-nucleus collisions at 400 GeV/c by the Columbia-Fermilab-Stony Brook[11] and Chicago-Princeton[12] Collaborations do permit a test of the Drell-Yan prediction. These are compared in Fig. 3 with predictions based upon the PPT and FF parton distributions. Roughly speaking, the data lie within the swath bounded by the two theoretical curves, a necessary but not sufficient condition for accepting the Drell-Yan formula. Even assuming that the agreement is not coincidental, the data do not select one parton distribution over the other, as they are confined to the small-$\tau$ region in which the two predictions differ by no more than one order of magnitude. The accumulation of data at other energies and at higher values of $\tau$ is of prime importance.

What conclusions may we draw at this time?

(1) The Drell-Yan mechanism makes predictions which are in excellent agreement with the high-energy data. However the consequences of scale breaking in deep-inelastic lepton scattering have not yet been understood, and the nonzero mean transverse momentum of dileptons remains to be incorporated into the picture.

(2) The factor of three due to color gives good agreement with the data, but its presence is not yet proved by this process.

(3) New data are on the way in the high-mass region. The Chicago-Princeton[6] and the Columbia-Fermilab-Stony Brook groups have in hand extensive new measurements of $\mu^+\mu^-$ and $e^+e^-$ pairs, respectively. In the near future, the Columbia-Fermilab-Stony Brook group will measure dimuons in an improved apparatus.[13] We also await the first results on the post-$J/\psi$ region from the ISR.

## REFERENCES


[1] G. Hanson, et al., Phys. Rev. Lett. 35, 1609 (1975).

[2] J. E. Augustin, et al., Phys. Rev. Lett. 34, 764 (1975).

[3] See the talks by V. Lüth, Nguyen Khanh, M. Perl, W. Bartel, V. Blobel, and W. Wallraff at the Leptonic Interactions Session for an up to date survey.

[4] S. D. Drell and T.-M. Yan, Phys. Rev. Lett. 25, 316 (1970); Ann. Phys. (NY) 66, 578 (1971). A relatively recent critical review is provided by J. D. Sullivan, in Particle Searches and Discoveries - 1976, edited by R. S. Panvini (AIP, New York), p. 142.

[5] See, however, the reanalysis of data from the original BNL experiment by L. M. Lederman and B. G. Pope, Phys. Lett. 66B, 486 (1977).

[6] M. Shochet, these proceedings.

[7] P. Mockett, et al., Fermilab proposal P-332.

[8] K. J. Anderson, et al., "Production of Continuum Muon Pairs at 225 GeV by Pions and Protons," contribution to the XVIII International Conference on High Energy Physics, Tbilisi.

[9] S. Pakvasa, D. Parashar, and S.-F. Tuan, Phys. Rev. D10, 2124 (1974).

[10] R. D. Field and R. P. Feynman, Caltech report CALT-68-565 (1976, unpublished).

[11] D. C. Hom, et al., Phys. Rev. Lett. 36, 1236 (1976); ibid. 37, 1374 (1976).

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

[13] CERN *Courier* 17, 25 (1977).

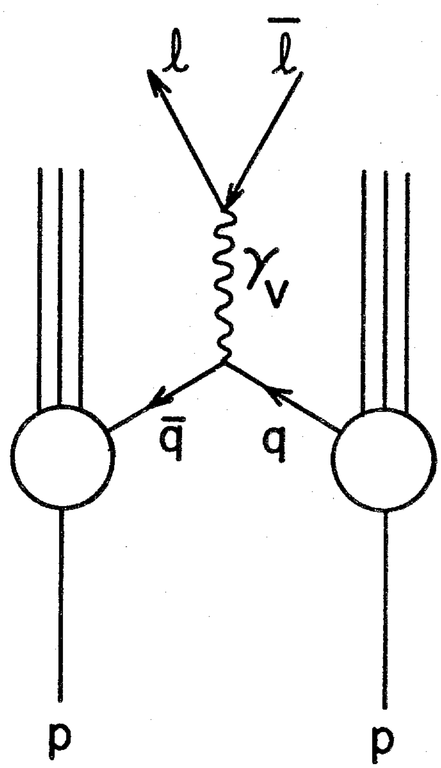


Fig. 1: The Drell-Yan mechanism for massive lepton-pair production in pp collisions.

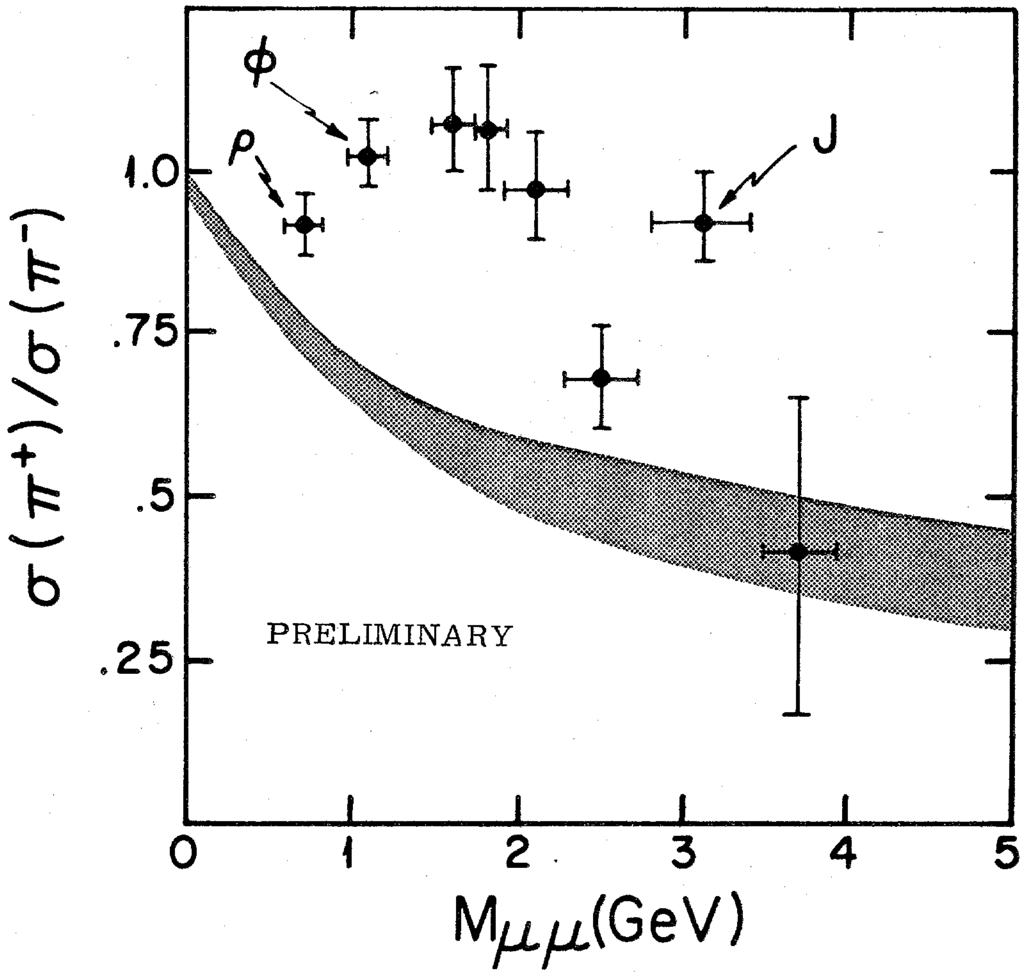


Fig. 2: Ratio of μ-pair production in $\pi^{\pm}C$ collisions at 225 GeV/c. Data are from Ref. 8. The shaded band is the expectation of the Drell-Yan model, computed over the kinematical region accepted by the experiment. The two points away from $(\rho, \omega, \phi, \rho', J)$ resonances agree with the theoretical trend.

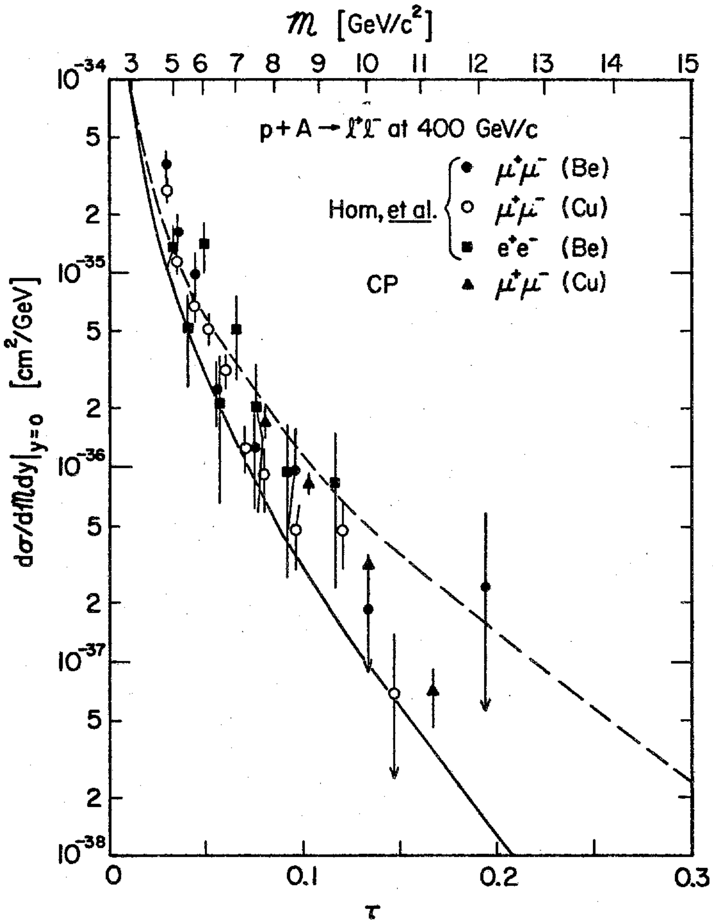


Fig. 3: Comparison of the Drell-Yan model with data on dilepton production at CM rapidity $y = 0$ by 400 GeV/c protons on nuclear targets. The cross sections per nucleon are displayed, assuming linear A-dependence. Computations were performed for Beryllium; the neutron to proton ratio of Copper is nearly identical. The solid curve is calculated using the FF parton distributions. The dashed curve is for the PPT parametrization. Data are from Refs. 11 and 12. The abscissa is $\tau = \mathcal{M}^2/s$.