PHYSICAL REVIEW LETTERS

VOLUME 37 | 29 NOVEMBER 1976 | NUMBER 22

Production of Massive Muon Pairs by 300- and 400-GeV Protons*

L. Kluberg,† P. A. Piroué, and R. L. Sumner
Department of Physics, Joseph Henry Laboratories, Princeton University, Princeton, New Jersey 08540

and

D. Antreasyan, J. W. Cronin, H. J. Frisch, and M. J. Shochet
The Enrico Fermi Institute, University of Chicago, Chicago, Illinois 60637
(Received 5 August 1976)

We have observed muon pairs with effective masses in the range $7 \le M_{\mu\mu} \le 11$ GeV/c^2 produced by 300- and 400-GeV protons incident on a Cu target at Fermilab. The production cross section per nucleon, $d\sigma/dM_{\mu\mu}$, for 400-GeV incident protons is found to fall from 1×10^{-36} cm^2/(GeV/c^2) at $M_{\mu\mu}=7.7$ GeV/c^2 to 2.7×10^{-38} cm^2/(GeV/c^2) at $M_{\mu\mu}=11.2$ GeV/c^2. We find that a significant fraction of the observed direct single muons come from high-mass dimuons.

We report here preliminary results of an experiment which has a bearing on two related problems. The first concerns the nature of the source of directly produced single leptons observed at high transverse momentum ($p_\perp$) at Fermilab,[1-3] CERN intersecting storage rings (ISR),[4] and Serpukhov[5]; the second is the magnitude of production of lepton pairs whose mass represents a substantial fraction of the available energy in a hadron-hadron interaction. The observation of a continuum of lepton pairs would not only shed light on the nature and distribution of pointlike constituents in the proton,[6] but would also be of practical value in the estimation of the production cross section of charged and neutral heavy vector bosons.[7]

Experiments on dilepton production in proton-nucleon collisions have been performed at Brookhaven National Laboratory,[8,9] and more recently at Fermilab,[10-15] ISR,[16] and Serpukhov.[17] In the present experiment, our original motivation was to investigate further the production, at large $p_\perp$, of direct single muons measured in our previous experiment.[1] We ask the simple question: What fraction of the single muons is accompanied by a high-$p_\perp$ muon on opposite side of the beam?

Figure 1 shows a schematic view of the apparatus. A magnetic spectrometer,[18] which selects particles produced at ~90° in the proton-nucleon c.m. system, was used to obtain a nearly pure sample of direct muons (~70% pure) in a manner identical to that described in a previous Letter.[1] The Fermilab incident proton beam and the magnetic spectrometer are located in tunnels and pits approximatively 3.5 m below the nominal surface of the ground. A second arm, called the multihole spectrometer (MHS), consisted of ten 3.6 $\times1.1\times0.1$ m^3 liquid scintillation counters inserted

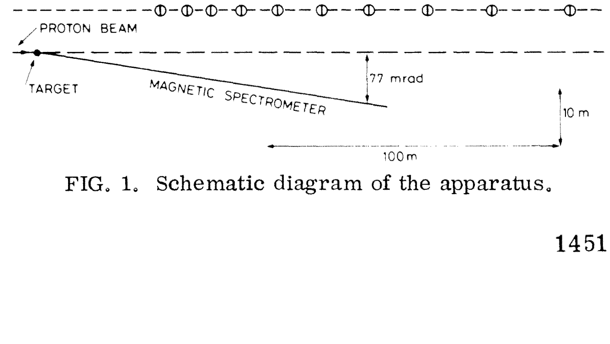

FIG. 1. Schematic diagram of the apparatus.

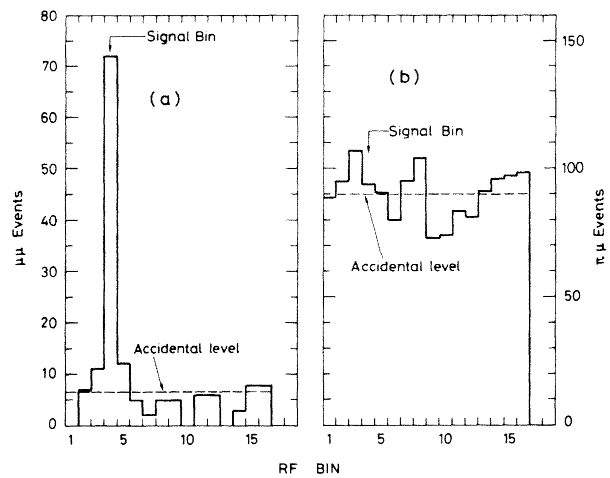

FIG. 2. Time distributions of MHS counts with respect to (a) a muon trigger and (b) a pion trigger in the magnetic spectrometer (set at $p_\perp^s = 4.5$ GeV/c). Time intervals are plotted in units of an rf period of the Fermilab accelerator (18.9 nsec).

into holes in the ground. The counters, shielded from the target by steel and earth, are placed along a line parallel to the incident proton beam and displaced by ~6 m so that only muons with $p_\perp \gtrsim 3.2$ GeV/c are detected.[19] A steel absorber could be inserted close to the target to modulate backgrounds in the MHS from pion and kaon decays. For 400-GeV incident protons, the MHS covers in the c.m. system a polar angle of $60° < \theta < 126°$ and an azimuthal angle of $-8° < \varphi < 25°$.

Runs were taken as a function of $p_\perp^s$, the transverse momentum selected by the magnetic spectrometer. The MHS counters were interrogated each time a particle was detected in the magnetic spectrometer. Pulses were recorded within a time gate extending from −70 to +250 nsec with respect to the trigger particle in the magnetic spectrometer. Both the time with respect to the trigger and the magnitude of each pulse were recorded.

The beam spill had an rf structure which contained bunches of ~2 nsec wide, 18.9 nsec apart. The time resolution of a given MHS counter was 5 nsec [full width at half-maximum (FWHM)]. The time of arrival of a muon at the MHS could be associated unambiguously with a given rf bunch of the incident beam which produced the trigger particle.

Figure 2 shows the result of a run with 400-GeV incident protons with the magnetic spectrometer set at $p_\perp^s = 4.5$ GeV/c. A time distribution of counts in the MHS is plotted in units of the rf period of the Fermilab accelerator. The rf bin labeled 4 was independently established to be the rf bin coincident with the trigger particle. In Fig. 2(a), $\mu\mu$ events are plotted; these are events for which a muon is identified in the magnetic spectrometer. A clear coincidence signal is observed in the fourth rf bin. The level of counts in the other bins gives a measure of the accidental background. Figure 2(b) shows the time distribution of MHS counts associated with a pion trigger in the magnetic spectrometer. There is no evidence here of an excess in the coincidence bin. These data, taken *simultaneously* with the data of Fig. 2(a), demonstrate in a most conclusive manner that the signal of $\mu\mu$ coincidences is real.

In Table I we present a summary of the raw results obtained in each of the seven runs. The steel absorber was periodically inserted and removed during each run. In no case was any effect of the shutter observed within statistics. The sixth column of Table I gives the fraction of single direct muon which are accompanied by a count

TABLE I. Raw data obtained in the experiment. The event yields have been corrected for accidental coincidences. The missing entries in the last column were not measured.

Proton energy (GeV)	$p_\perp^s$ (GeV/c)	Charge of trigger muon	Dimuon yield (events)	Dimuon yield per 10^{17} protons	Dimuons per direct single muon (%)
400	3.75	−	51 ± 10	109 ± 18	1.1 ± 0.2
400	4.50	−	64 ± 10	77 ± 10	6.0 ± 1.0
400	4.50	+	45 ± 8	75 ± 12	
400	5.25	−	36 ± 6	37 ± 7	12.7 ± 2.1
400	6.00	−	8 ± 2.8	8.4 ± 3	19 ± 7
300	3.75	−	30 ± 7	35 ± 8	
300	4.50	−	53 ± 8	39 ± 6	

TABLE II. Results of cross-section evaluation for the two models discussed in the text. The results are given in units per Cu nucleus.

	Model I		Model II	
Proton energy (GeV)	$\langle M_{\mu\mu}\rangle$ (GeV/c^2)	$d\sigma/dM_{\mu\mu}$ $[\mathrm{cm}^2/(\mathrm{GeV}/c^2)]$	$\langle M_{\mu\mu}\rangle$ (GeV/c^2)	$d\sigma/dM_{\mu\mu}$ $[\mathrm{cm}^2/(\mathrm{GeV}/c^2)]$
400	7.7	$(6.4\pm1.1)\times10^{-35}$	7.7	$(1.4\pm0.2)\times10^{-34}$
400	8.8	$(2.7\pm0.3)\times10^{-35}$	8.6	$(7.0\pm0.7)\times10^{-35}$
400	10.0	$(8.9\pm1.5)\times10^{-36}$	9.4	$(2.7\pm0.5)\times10^{-35}$
400	11.2	$(1.7\pm0.6)\times10^{-36}$	10.2	$(5.8\pm2.0)\times10^{-36}$
300	7.6	$(1.8\pm0.4)\times10^{-35}$	7.6	$(3.8\pm0.9)\times10^{-35}$
300	8.6	$(1.2\pm0.2)\times10^{-35}$	8.4	$(3.2\pm0.5)\times10^{-35}$

in the MHS detector. At $p_\perp{}^s = 5.25$ GeV/c, ~13% of the single muons also have a count in the MHS. Using only up-down symmetry with respect to the production plane and a conservative extrapolation of the observed distribution beyond the solid angle subtended, one can estimate that at least 30% of the single μ's have their origin as one member of a high-mass muon pair. One should also note that the production of dimuons is the same, within statistics, when either positive or negative muons are selected at $p_\perp{}^s = 4.5$ GeV/c in the magnetic spectrometer. This fact strengthens our implicit assumption that the two muons are of opposite sign.

We have evaluated the production cross section for the dimuons as a function of their mass. If the transverse momentum of the dimuon parent is limited ($\lesssim 300$ MeV/c), its mass would be approximately twice the transverse momentum setting of the magnetic spectrometer ($p_\perp{}^s$). If the transverse momentum of the parent is significantly larger, the mass acceptance of the apparatus would be broadened but still centered about $2p_\perp{}^s$. Typically, the mass acceptance (FWHM) is ~2 at 10 GeV/c^2 for a mean $p_\perp$ of the dimuon of 1.25 GeV/c. Two effects alter this simple conclusion. First, the minimum mass that can be accepted by the system is effectively set by the sum of $p_\perp{}^s$ and the MHS cutoff of 3.2 GeV/c. Secondly, the sharply falling cross section with increasing mass means that the average mass observed for $p_\perp{}^s > 3.2$ GeV/c is lower than the peak of the acceptance curve.

To evaluate the cross section $d\sigma/dM_{\mu\mu}$, we must assume a model for the $p_\perp$ and x dependences of the cross section ($x = p_\perp/p_\perp{}^{\max}$). The efficiency of the detector for various $M_{\mu\mu}$ can then be evaluated. We have used two models of dimuon production. The first model (I), which has x and $p_\perp$ dependences derived from J/ψ production,[13] viz.,

$$E\, d\sigma/d^3p\, dM_{\mu\mu} \propto (1-|x|)^{4.3}\exp(-1.6p_\perp),$$

corresponds to a mean transverse momentum of 1.25 GeV/c. The second model (II),

$$E\, d\sigma/d^3p\, dM_{\mu\mu} \propto (1-|x|)^{4.3}\exp(-bp_\perp),$$

where $b = 6/M_{\mu\mu}$, is characterized by $\langle p_\perp\rangle = M_{\mu\mu}/3$. Table II gives the results of the cross section *per Cu nucleus* for each model.

Inspection of these results shows that the cross-section dependence on mass is the same for the two models [i.e., $d\sigma/M_{\mu\mu} \sim \exp(-1.1M_{\mu\mu})$] and that the cross sections differ by a factor ~2. We have computed $d\sigma/dM_{\mu\mu}$ for x dependences $(1-|x|)^1$ and $(1-|x|)^{10}$ and find changes of less than a factor of 2. A variation of ± 300 MeV/c in the transverse momentum cutoff for the MHS causes changes of less than 20%.

To make a comparison with the recent work of Hom *et al.*[13] on dielectron production at Fermilab, we show in Fig. 3 the cross section per nucleon, $(d^2\sigma/dM_{\mu\mu}dy)_{y=0}$, evaluated for Model I over the rapidity interval $-0.3 < y < 0.2$. (An A^1 dependence of the cross section has been assumed.) Model I is identical to the model used by Hom *et al.*[13] to evaluate their own apparatus efficiency.

Our data at the two energies are statistically consistent with the scaling relation

$$M_{\mu\mu}{}^3\, d\sigma/dM_{\mu\mu} = f(M_{\mu\mu}{}^2/s),$$

where $f(M_{\mu\mu}{}^2/s)$ is a universal function of $M_{\mu\mu}{}^2/s$, and s is the square of the c.m. energy. We plan to carry out further measurements on the scaling properties of dimuon production.

We wish to thank the staff of the Proton Laboratory of Fermilab for their support, and R. Ev-

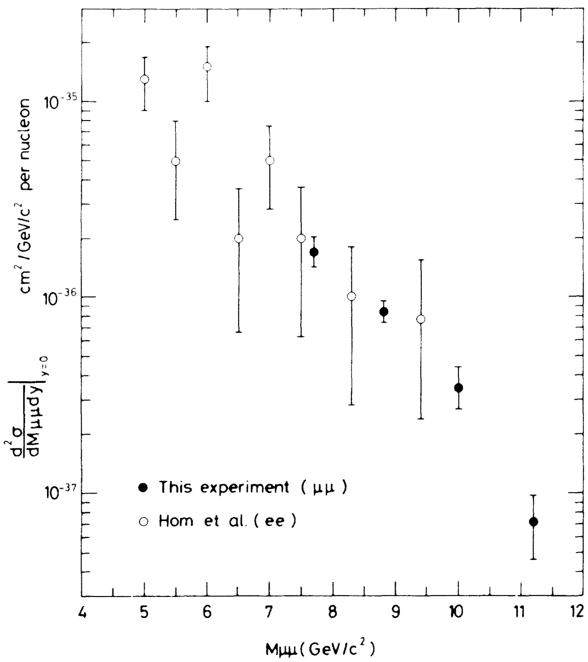

FIG. 3. Comparison of this experiment with results of Hom *et al.* (Ref. 13).

ans for his assistance in the construction of the apparatus and the taking of the data.

*Work supported by the National Science Foundation and the U. S. Energy Research and Development Administration.

†On leave from Ecole Polytechnique, Paris, France.

[1] J. P. Boymond *et al.*, Phys. Rev. Lett. 33, 112 (1974).
[2] J. A. Appel *et al.*, Phys. Rev. Lett. 33, 722 (1974).
[3] D. Bintinger *et al.*, Phys. Rev. Lett. 35, 72 (1975).
[4] F. W. Büsser *et al.*, Phys. Lett. 53B, 212 (1974).
[5] V. V. Abramov *et al.*, in *Proceedings of the Seventeenth International Conference on High Energy Physics, London, England, 1974*, edited by J. R. Smith (Rutherford High Energy Laboratory, Didcot, Berkshire, England, 1975).
[6] S. D. Drell and T.-M. Yan, Phys. Rev. Lett. 25, 316 (1970).
[7] Y. Yamaguchi, Nuovo Cimento 43, 193 (1966); L. M. Lederman and B. G. Pope, Phys. Rev. Lett. 27, 765 (1971).
[8] J. H. Christenson *et al.*, Phys. Rev. D 8, 2016 (1973).
[9] J. J. Aubert *et al.*, Phys. Rev. Lett. 33, 1404 (1974).
[10] B. Knapp *et al.*, Phys. Rev. Lett. 34, 1044 (1975).
[11] G. J. Blanar *et al.*, Phys. Rev. Lett. 35, 346 (1975).
[12] K. J. Anderson *et al.*, Phys. Rev. Lett. 36, 237 (1976).
[13] D. C. Hom *et al.*, Phys. Rev. Lett. 36, 1236 (1976).
[14] H. D. Snyder *et al.*, Phys. Rev. Lett. 36, 1415 (1976).
[15] D. Eartly *et al.*, Phys. Rev. Lett. 36, 1355 (1976).
[16] F. M. Büsser *et al.*, Phys. Lett. 56B, 482 (1975).
[17] Y. M. Antipov *et al.*, Phys. Lett. 60B, 309 (1976).
[18] A detailed description of the magnetic spectrometer is given in J. W. Cronin *et al.*, Phys. Rev. D 11, 1811 (1975).
[19] The μ detection efficiency rises linearly from zero at $p_\perp = 2.6$ GeV/c to unity at $p_\perp = 3.8$ GeV/c.

When is the Deuteron Six Quarks?—Possible Evidence Against Dimensional Scaling*

Geoffrey B. West
Theoretical Division, Los Alamos Scientific Laboratory, University of California, Los Alamos, New Mexico 87545
(Received 11 August 1976)

Recent data on high-energy elastic and threshold inelastic electron scattering are shown to provide a sensitive test of the constituent nature of the target. Present evidence seems to support a quark description at these energies but mitigates against a naive dimensional-scaling argument.

Recently, a series of experiments exploring both the elastic and threshold inelastic behavior of electron scattering from deuterium at large momentum transfers (Q) have been reported.[1] One of the aims of this Letter is to exploit the theoretical connection between them[2-4] in an attempt to determine whether the deuteron is behaving more quarklike than nucleonlike at these values of Q^2. Below I shall propose a quantitative test that is independent of the detailed underlying dynamics and requires only measured data as input.

The elastic data have been analyzed[1] both in terms of conventional nuclear physics, using essentially nonrelativistic potential models,[5] and in terms of the quark-parton model using dimensional-scaling arguments.[6] Both have been found to give an adequate description, although each is subject to serious criticism. A somewhat different analysis which de-emphasizes the detailed in-