

## Observation of Massive Muon Pairs in Hadron Collisions\*

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Muon pairs in the mass range  $1 < m_{\mu\mu} < 6.7 \text{ GeV}/c^2$  have been observed in collisions of high-energy protons with uranium nuclei. At an incident energy of 29 GeV, the cross section varies smoothly as  $d\sigma/dm_{\mu\mu} \approx 10^{-32}/m_{\mu\mu}^5 \text{ cm}^2 (\text{GeV}/c)^{-2}$  and exhibits no resonant structure. The total cross section increases by a factor of 5 as the proton energy rises from 22 to 29.5 GeV.

Various techniques have been used to probe the electromagnetic structure of hadrons. By far the most extensive has been electron-proton scattering which explored the region of large spacelike momentum transfers up to  $q^2 = 25 (\text{GeV}/c)^2$ . We report here on an experiment designed to extend this probe to large timelike momentum transfers via the reaction

$$p + U \rightarrow \mu^+ + \mu^- + \text{anything.}$$

The spectrum of effective masses of the muon pair emerging from high-energy proton-nucleus collisions is observed. Earlier research<sup>1-4</sup> in this domain has been limited to momentum transfers  $\lesssim 1 (\text{GeV}/c)^2$ . The high energy and intensity of the primary proton beam at the alternating-gradient synchrotron (AGS) enabled us to record muon pairs with effective masses squared ( $m^2 = -q^2$ ) up to  $40 (\text{GeV}/c^2)^2$ , where the cross section  $d\sigma/dm \sim 10^{-39} \text{ cm}^2/(\text{GeV}/c)^2$ . This timelike reaction is also sensitive to the possible existence of resonant structures, i.e., massive vector mesons, neutral weak bosons, etc. Data were taken at incident proton energies of 22, 25, 28.5, and 29.5 GeV/c.

Muon pairs produced by totally absorbing the slow extracted proton beam in a thick uranium target were detected by the apparatus shown in Fig. 1. The direction and range of each muon were measured to allow the determination of the mass and vector momentum of the dimuon. An iron and concrete wall following the target suppressed the overwhelming flux of nonmuonic background while eliminating muons with momenta less than 5 GeV/c. The very dense target absorbed most pions and kaons before they decayed. Nevertheless, the high intensity of pions and kaons resulted in a large flux of muons which penetrated the shielding wall. To suppress this

background further, a thick, tapered, iron absorber required the transverse momentum of a detected muon to exceed 0.5 GeV/c. These background muons were thereby strongly reduced without seriously affecting the detection efficiency for muon pairs of effective mass greater than  $\sim 1 \text{ GeV}/c^2$ .

The mass resolution of the lepton pairs was limited by multiple scattering in the shield. Hence, modest precision in measuring the direction and range of each muon was adequate. Minimum angular uncertainty was obtained by assuming the muon originated in the target and measuring its direction by means of a single counter in a 36-element plastic scintillation-counter hodoscope mounted on the face of the tapered absorber. A subsequent plane of liquid scintillators provided crude angular confirmation. Additional planes following 4-, 6-, and 8½-ft-thick steel walls defined the muon range. Monte Carlo studies indicate a mass resolution that varies from  $\pm 15\%$  at a mass of  $2 \text{ GeV}/c^2$  to  $\pm 8\%$  at  $5 \text{ GeV}/c^2$ . Additional counters placed at large angles to the proton direction served to extend the mass range to  $\sim 7 \text{ GeV}/c^2$ . These were used only during the 29.5-GeV run.

Muon-pair candidates were signaled by a coin-

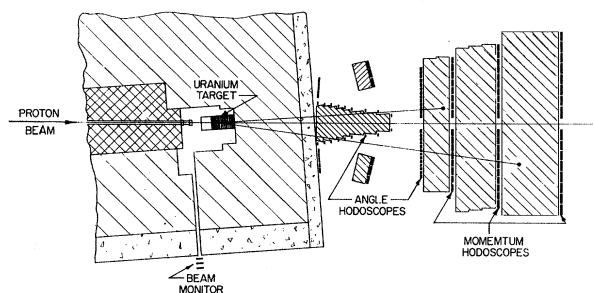


FIG. 1. Plan view of the apparatus.

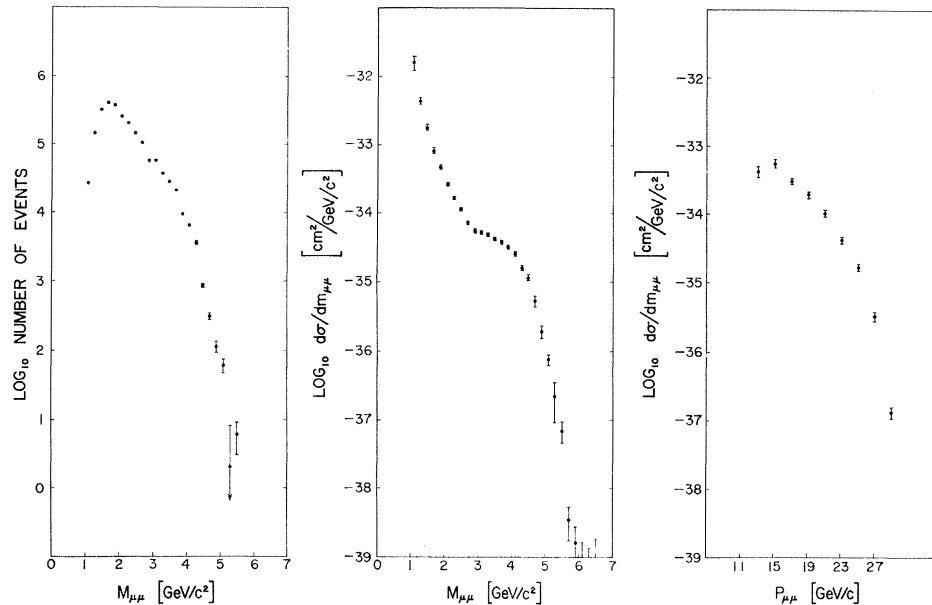


FIG. 2. (a) Observed events as a function of the effective mass of the muon pair. (b) Cross section as a function of the effective mass of the muon pair (these data include the wide-angle counters). (c) Cross section as a function of the laboratory momentum of the muon pair.

cidence between the left and right halves of the first hodoscope. About  $10^6$  muons (from pion and kaon decay) passed through this hodoscope per AGS cycle, resulting in  $\sim 2000$  accidental coincidences per pulse. To facilitate removal of this large background, the following system was devised: Two precisely adjusted coincidence circuits (resolving times  $\sim 2.7$  nsec) triggered the electronics, one sensitive to in-time or simultaneous pairs, the other to muons arriving 5 nsec apart in time. Between AGS pulses, coaxial relays interchanged the roles of these two circuits thereby canceling the error arising from slight differences in their resolving times. A third broad coincidence monitored the accidental rate for each relay position and permitted corrections due to fluctuations in beam intensity and duty cycle. The system was adjusted and tested by means of a set of radioactive sources distributed among the hodoscope counters to provide realistic rates. The numbers of in-time and delayed coincidences recorded in these tests were always the same within 0.03%.

For each muon pair detected, the status of all counters was ascertained and electronic logic performed quality checks on the event, rejecting those containing incomplete muon trajectories or extraneous counter firings. In the course of the experiment, some 300 million events were recorded, most being unwanted accidentals. The

Brookhaven PDP-6 computer received these events on-line and reduced the large bulk of data to a compact form in real time.

Subtraction of the delayed events from those in-time revealed a definite residue of real muon pairs comprising some 4% of the in-time data sample. The effect varied with dimuon mass from  $\sim 2\%$  at 1.5 GeV/c<sup>2</sup> to 40% at 5 GeV/c<sup>2</sup>. As seen in Fig. 2(a), the events appear as a broad continuum in dimuon effective mass, extending over the entire mass aperture of the experiment.

Since the signal-to noise ratio is very small, exhaustive tests were performed to ensure that the real mass spectrum was not distorted by the background subtraction. One check that probed the electronics and computer system in depth was made by inserting 5-nsec relative delays in both coincidence circuits and accumulating data in an otherwise normal fashion. The two mass spectra should be identical within statistics and should yield a null result on subtraction. The result was indeed consistent with zero, yielding a  $\chi^2$  of 18 for 20 degrees of freedom. The total numbers of events in the two categories were the same to 0.3%, contributing an uncertainty in the final absolute cross section of  $\lesssim 10\%$ . Further tests ruled out any mass bias induced by timing correlations. Lack of systematic variation of the real muon-pair cross section with proton intensity further indicates that all accidentals

have been expunged from the data. Muon pairs originating from pions generated far upstream by beam halo were eliminated by appropriate shielding.

Data accumulated with the effective density of the uranium target reduced by a factor of 3 show that the muons were directly produced. Any  $\pi\pi \rightarrow \mu\mu$  background would have increased by a factor of 9, but no rise was observed. A limit of 10% was placed on this contribution to the muon-pair rate. High-frequency time structure in the proton beam (rf structure) was monitored continuously and held to an insignificant level.

The detection efficiency of the apparatus was determined by Monte Carlo techniques. These calculations depend somewhat on the specific empirical model chosen to describe the pair production because of the extreme steepness of the observed mass spectrum and the restricted kinematic aperture of the apparatus. A simple parametrization was found that produced distributions of events in mass, momentum, and angle of the pair that were in good agreement with the experimental data, and the corresponding efficiencies were used to calculate the cross sections. Model-dependent uncertainties in the cross sections were determined from parametrizations that gave poor fits to the data. No correlations between mass, momentum, and angle were needed to fit the data. The distribution in  $\theta_{\mu}^*$ , the muon decay angle in the pair center of mass, was assumed to be isotropic. Poor resolution in  $\theta_{\mu}^*$ , coupled with a limited aperture around  $90^\circ$ , frustrate measurement of this distribution. Other possible distributions, such as  $\sin^2\theta_{\mu}^*$  or  $1 + \cos^2\theta_{\mu}^*$ , do not alter the shape of the observed cross sections as a function of mass but do change the normalization by  $\pm 20\%$ .

An independent test of the Monte Carlo propagation of muons through the apparatus is provided by the normally troublesome accidentals. By using known pion- and kaon-production spectra, the dimuon mass spectrum due to accidental events may be generated, with no adjustable parameters. Good agreement was found between experiment and Monte Carlo, indicating that the treatment of multiple scattering, ionization loss, and range straggling was adequate.

The cross section as a function of mass  $d\sigma/dm$  at a proton energy of 29.5 GeV is plotted in Fig. 2(b). All results are given for dimuon laboratory momenta above 12 GeV/c and for production angles out to 65 mrad. The 29.5-GeV cross sections include data from the wide-angle counters

mentioned above and extend in mass beyond the spectrum shown in Fig. 2(a). Results are given per free target nucleon where a total nucleon-nucleon inelastic cross section of 20 mb has been used.<sup>5</sup> The statistical errors arise both from the data and the Monte Carlo calculation. The systematic errors arise from the production-model uncertainties in the Monte Carlo calculations and are not independent of one another. Rather, they collectively describe a "road" within which  $d\sigma/dm$  may vary in a smooth fashion. Uncertainties due to the subtraction procedure and Monte Carlo systematics are not included in  $d\sigma/dm$  but are accounted for in the total cross sections at each proton energy. Further, an additional overall uncertainty of 60% is assigned to the absolute cross section, reflecting uncertainties in the  $\theta_{\mu}^*$  distribution, a 15% error in the calibration of the secondary emission chamber used to measure the proton flux, and a 20% uncertainty in the appropriate nucleon-nucleon inelastic cross section.

As seen both in the mass spectrum and the resultant cross section  $d\sigma/dm$ , there is no forcing evidence of any resonant structure. To obtain limits on the production probability of a vector meson at a given mass, a narrow resonance was introduced in the Monte Carlo production distribution and increased in amplitude until the resulting bump visibly distorted the output spectrum. This procedure properly introduced the single-particle mass resolution and efficiency into the analysis. The sensitivity to vector-meson production is somewhat impaired by the rapidly falling continuum upon which any structure must reside. Indeed, in the mass region near  $3.5 \text{ GeV}/c^2$ , the observed spectrum may be reproduced by a composite of a resonance and a steeper continuum. These considerations are reflected in the limits obtained. We list below, for the 29.5-GeV data, the inseparable product of the production cross section of the vector particle and its branching ratio into two muons. We note that these limits apply to strong production of  $\rho$ -type particles as well as to weak production of neutral intermediate bosons.

Mass (GeV/c <sup>2</sup> )	Resonance limits $\sigma B$ (cm <sup>2</sup> )
1.5	$2 \times 10^{-32}$
2.5	$3 \times 10^{-34}$
3.5	$3 \times 10^{-34}$
4.5	$3 \times 10^{-35}$
5.5	$4 \times 10^{-35}$

In an attempt to eliminate divergence difficulties in quantum electrodynamics, the possible existence of a "heavy photon" has been suggested.<sup>6</sup> This object would modify the usual photon propagator by a multiplicative Breit-Wigner factor resulting in an integrated enhancement by a factor of  $\sim 100$ . We set a limit of  $\geq 5 \text{ GeV}/c^2$  on the mass of the heavy photon.

The cross section  $d\sigma/dm$  varies approximately as  $1/m^5$ , falling seven orders of magnitude from 1 to  $6 \text{ GeV}/c^2$ . The steep falloff above  $4 \text{ GeV}/c^2$  is attributed to the rapid reduction of available phase space. Fermi motion of the target nucleons provides sufficient center-of-mass energy to create muon pairs above the  $5.7\text{-GeV}/c^2$  kinematic limit. Data at proton energies of 22, 25, and  $28.5 \text{ GeV}$  show a dependence on mass consistent with the  $2.95\text{-GeV}$  data. The total cross section in our mass and momentum aperture rises monotonically by a factor of 5 as the incident-proton energy increases from 22 to  $29.5 \text{ GeV}$ :

$E_p$ (GeV)	$\sigma$ (cm <sup>2</sup> )
22	$(6.0 \pm 0.6) \times 10^{-34}$
25	$(1.2 \pm 0.1) \times 10^{-33}$
28.5	$(2.6 \pm 0.3) \times 10^{-33}$
29.5	$(2.9 \pm 0.3) \times 10^{-33}$

The laboratory momentum distribution of the dimuon is shown in Fig. 2(c). The distribution in transverse momentum of the dimuon is flat out to  $1 \text{ GeV}/c$  and then falls sharply.

A complete theoretical treatment of this experiment should include dimuon production from pions and other secondary particles produced in the thick target. A detailed comparison of the data with various models is thus complicated since the incident particle is not identified experimentally. On the other hand, this variety of initial states provides a more complete survey of muon-pair production in hadron collisions. The contribution to muon-pair production from real photons (from  $\pi^0$  decay) is entirely negligible in our mass and momentum interval. A vector-dominance<sup>7,8</sup> approach to virtual-photon production predicts that  $d\sigma/dm$  varies as  $m^{-5}$  in reasonable agreement with experiment. However, predictions of the absolute cross section and dependence on dimuon momentum and total energy await better data on vector-meson production in high-energy  $p$ - $p$  collisions. Two parton models<sup>9,10</sup> were suggested by the Stanford Linear Accelerator Center (SLAC) data on deeply inelastic scattering. Parton bremsstrahlung<sup>9</sup> pre-

dicts an absolute yield too low by a factor of  $\sim 20$  and falls too steeply with mass. The parton-annihilation model<sup>10</sup> is in rough shape agreement with the data but contains the unknown parton charge  $\lambda$  as a normalization parameter. (We find  $\lambda \sim 2$ .) Another calculation<sup>11</sup> related to deeply inelastic scattering employs light-cone commutators and Regge theory, yielding a relative cross section in good agreement with the shape of the experimental distribution. The SLAC-inspired calculations all predict an increase in cross section with proton energy (in our kinematic aperture) by a factor of 2 to 3 from 22 to  $29 \text{ GeV}$ .

It has been noted<sup>12,13</sup> that the production cross section for virtual photons is related to the probability for production of charged intermediate vector mesons ( $W^\pm$ ) of the same mass via the conserved-vector-current theorem. For example, at  $s = 60 \text{ GeV}^2$  (typical for the AGS) and  $M_W = 2 \text{ GeV}/c^2$ , the results presented here suggest  $\sigma_W \sim 4 \times 10^{-35} \text{ cm}^2$ .<sup>14</sup> Extrapolation of these data in  $s$  and  $q^2$  to a  $500\text{-GeV}$  accelerator (using the model of Ref. 10) yields a cross section for  $W^\pm$  production greater than  $10^{-36} \text{ cm}^2$  for  $M_W \lesssim 28 \text{ GeV}/c^2$ , well within observable limits.

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<sup>1</sup>A. Wehmann *et al.*, Phys. Rev. Lett. **17**, 1113 (1966) ( $12\text{-GeV}/c$  pions on carbon).

<sup>2</sup>B. D. Hyams *et al.*, Phys. Lett. **24B**, 634 (1967) ( $11\text{-GeV}/c$  pions on LiH).

<sup>3</sup>J. E. Augustin *et al.*, Phys. Lett. **28B**, 508 (1969) ( $e^+ + e^- \rightarrow$  hadrons).

<sup>4</sup>D. R. Earles *et al.*, Phys. Rev. Lett. **25**, 129 (1970) (electroproduction of muon pairs).

<sup>5</sup>E. W. Anderson *et al.*, Phys. Rev. Lett. **19**, 198 (1967) [this is estimated from the study of inelasticity in  $p$ - $p$  collisions (the total inelastic  $\sigma$  is  $29 \text{ mb}$ )].

<sup>6</sup>T. D. Lee and G. C. Wick, Nucl. Phys. **B9**, 209 (1969), and Phys. Rev. D **2**, 1033 (1970).

<sup>7</sup>V. A. Matveev, R. M. Muradyan, and A. N. Tavkhelidze, Joint Institute for Nuclear Research Report No. E2-4968, 1970 (unpublished).

<sup>8</sup>J. J. Sakurai, Phys. Rev. Lett. **24**, 968 (1970).

<sup>9</sup>S. M. Berman, D. J. Levy, and T. L. Neff, Phys. Rev. Lett. **23**, 1363 (1969).

<sup>10</sup>S. Drell and T.-M. Yan, Phys. Rev. Lett. **25**, 316 (1970).

<sup>11</sup>G. Altarelli, R. A. Brandt, and G. Preparata, to be published.

<sup>12</sup>Y. Yamaguchi, Nuovo Cimento **43**, 193 (1966).

<sup>13</sup>F. Chilton, A. M. Saperstein, and E. Shrauner, Phys. Rev. **148**, 1380 (1966).

<sup>14</sup>For relevant experiments, see P. J. Wanderer *et al.*, Phys. Rev. Lett. **23**, 729 (1969); R. Burns *et al.*, Phys. Rev. Lett. **15**, 830 (1965).