

STUDY OF RARE MUON INDUCED PROCESSES\*

A.R. Clark, K.J. Johnson, L.T. Kerth, S.C. Loken, T.W. Markiewicz,  
P.D. Meyers, W.H. Smith, M. Strovink, and W.A. Wenzel

Physics Department and Lawrence Berkeley Laboratory,  
University of California, Berkeley, California 94720

and

R.P. Johnson, C. Moore, M. Mugge, and R.E. Shafer

Fermi National Accelerator Laboratory  
Batavia, Illinois 60510

and

G.D. Gollin, F.C. Shoemaker, and P. Surko

Joseph Henry Laboratories, Princeton University  
Princeton, New Jersey 08544

Invited Paper Presented by S.C. Loken at the  
European Physical Society  
International Conference on High Energy Physics  
Geneva, Switzerland  
June 27 - July 4, 1979

ABSTRACT

Interactions of the type  $\mu N + (\mu\mu)X$  ( $n=1,2,3,4,5$ ) are being studied with high sensitivity in the Multimoon Spectrometer in the Fermilab muon beam. Results are reported on inelastic structure functions, production of  $\psi(3100)$  and exotic multimoon final states.

NOTICE

This report was prepared as an account of work sponsored by the United States Government. Neither the United States nor the United States Department of Energy, nor any of their employees, nor any of their contractors, subcontractors, or their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness or usefulness of any information, apparatus, product or process disclosed, or represents that its use would not infringe privately owned rights.

\*Work supported by the High Energy Physics Division of the U.S. Department of Energy under contract Nos. W-7405-Eng-48, EY-76-C-02-3072, and EY-76-C-02-3000.

fcg

## STUDY OF RARE MUON INDUCED PROCESSES

A.R. Clark, K.J. Johnson, L.T. Kerth, S.C. Loken, T.W. Markiewicz,  
P.D. Meyers, W.H. Smith, M. Strovink, W.A. Wenzel

Lawrence Berkeley Laboratory, Berkeley, California, USA

R.P. Johnson, C. Moore, M. Mugge, R.E. Shafer  
Fermi National Accelerator Laboratory, Batavia, Illinois, USA

G.D. Gollin, F.C. Shoemaker, P. Surko  
Princeton University, Princeton, New Jersey, USA

### ABSTRACT

Interactions of the type  $\mu N \rightarrow (\nu) X$  ( $n=1,2,3,4,5$ ) are being studied with high sensitivity in the Multimoon Spectrometer in the Fermilab muon beam. Results are reported on inelastic structure functions, production of  $\psi(3100)$  and exotic multimoon final states.

### INTRODUCTION

Data have been collected using the Multimoon Spectrometer recently constructed in the Fermilab muon beam. To achieve the desired luminosity ( $>10^{33}$  cm<sup>-2</sup>/experiment) the experiment uses a massive target (5 kg/cm<sup>2</sup>). An integrated spectrometer magnet provides high acceptance along the length of the target even for tracks along the beam direction.

The apparatus shown in Fig. 1, consists of 18 modules of 5 10-cm thick steel plates each followed by a calorimeter scintillator (SC). A 25 cm gap between modules contains a drift chamber (DC) for precise determination of track position in the bend plane and a proportional chamber which reads out 3 coordinates to resolve multi-hit ambiguities.

Signals from banks of trigger scintillators S<sub>1</sub>-S<sub>12</sub> are used to form parallel triggers for  $>1$ ,  $>2$ ,  $>3$  muons in the final state. The single muon trigger incorporated a veto on a hit in the beam area; the two muon trigger required deposition of approximately 20 GeV in the hadron calorimeter. Three muons triggered only on multiplicity.

Beam tracks were momentum-analyzed by 2 separate upstream bends. Accepted outgoing tracks, registering  $>4$  proportional chamber hits in 2 views and  $>3$  hits in the third, were required to intersect a common vertex optimized by iteration. Extra hits due mainly to small showers induced by direct electron pairs, were identified and rejected using a complex momentum-fitting algorithm which solves for the Coulomb-scattering in each module.

The acceptance and resolution of the spectrometer were modeled for each final state by Monte Carlo simulation. Coordinates of randomly sampled beam muons are used as input and all energy loss and scattering processes are included for each iron plate. Trajectories were deflected in each plate using measured field maps. Simulated interactions occurred between muons and nucleons in Fermi motion or coherently between muons and iron nuclei. These simulated events were output in the same format as raw data and were reconstructed and momentum-fit exactly as the data.

**MULTI-MUON SPECTROMETER**  
**BERKELEY-FERMILAB-PRINCETON**

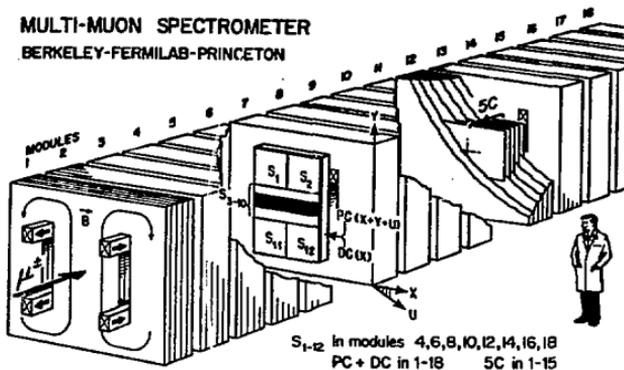


Figure 1. Schematic view of the apparatus.  $S_1$ - $S_{12}$  are trigger scintillators. PC and DC are proportional and drift chambers. The scintillators labelled SC form a hadron calorimeter.

EXOTIC MULTIMUON FINAL STATES

Identification of exotic events begins in the reconstruction and fitting programs. Events satisfying normal analysis criteria which possess unusual characteristics are saved on microfilm containing tabulated data and computer-generated track pictures. Events are double scanned by physicists and are refit using hand-selected information as a consistency test.

Table 1 presents the properties of four rare events found in an initial scan of 20% of the data. The three muon event with two missing  $\mu^+$  or  $\nu_\mu$  is similar to events seen in the CDHS neutrino experiment<sup>1)</sup>. In this case also, the small pair masses and transverse momenta favor interpretation as  $\pi/K$  decay contamination of dimuon events.

Two events with 5 muon final states have been observed. Event 1208-3386 possesses characteristics similar to those of the more abundant (by  $\sim \alpha^{-2}$ ) muon tridents. Event 851-11418, however, does not seem consistent with any plausible QED process.

The four muon event, 1191-5809, has properties which differ significantly from those of the three reported events in neutrino experiments<sup>2,3,4)</sup>. The softest lepton has at least 4 times the energy and the lightest  $\mu^+\mu^-$  daughter has at least 4 times the mass of any neutrino-induced counterpart. The most obvious potential background, single muon production due to any process in random association with  $\mu^+\mu^-$  pair production due to any process within the same diagram, has been estimated using measured properties of 2 and 3 muon final states in this experiment to be less than  $7 \times 10^{-4}$ .

**TABLE 1**  
Properties of Exotic Events

Event	Scattered Muon	Energies (GeV)	Masses (GeV/c <sup>2</sup> )	Unseen p to $\gamma\gamma$ (GeV/c)
851-5726 $\mu^+\mu^-\mu^+\mu^-$ 1 2 3 4	2 $Q^2=0.1\pm 0.1$ $v=160\pm 6$	$E_3=19\pm 2$ $E_4=11\pm 2$ $E_{had}=103\pm 15$ $E_{miss}=27\pm 17$	$M_{34}=0.5\pm 0.1$	$0.3\pm 0.1$
1191-5809 $\mu^+\mu^-\mu^+\mu^-$ 1 2 3 4 5	2 $Q^2=0.3\pm 0.2$ $v=158\pm 7$	$E_3=26\pm 3$ $E_4=18\pm 2$ $E_5=25\pm 4$ $E_{had}>57\pm 11$ $E_{miss}<31\pm 14$	$M_{34}=3.0\pm 0.3$ $M_{35}=3.2\pm 0.3$ $M_{345}=4.6\pm 0.3$	$2.0\pm 0.2$
1208-3386 $\mu^+\mu^-\mu^+\mu^-\mu^+$ 1 2 3 4 5 6	2 $Q^2=0.2\pm 0.2$ $v=149\pm 9$	$E_3=50\pm 5$ $E_4=27\pm 3$ $E_5=61\pm 6$ $E_6=10\pm 2$ $E_{had}=6\pm 3$ $E_{miss}=-4\pm 13$	$M_{35}=1.3\pm 0.2$ $M_{36}=0.3\pm 0.1$ $M_{45}=0.4\pm 0.1$ $M_{46}=0.5\pm 0.1$ $M_{3456}=2.0\pm 0.2$	$0.1\pm 0.3$
851-11418 $\mu^+\mu^-\mu^+\mu^-\mu^+$ 1 2 3 4 5 6	2 $Q^2=3.5\pm 0.6$ $v=61\pm 12$	$E_3=13\pm 2$ $E_4=19\pm 2$ $E_5=15\pm 2$ $E_6=10\pm 2$ $E_{had}=5\pm 3$ $E_{miss}=-1\pm 13$	$M_{34}=2.3\pm 0.2$ $M_{35}=2.0\pm 0.2$ $M_{46}=0.5\pm 0.1$ $M_{56}=0.3\pm 0.2$ $M_{3456}=3.5\pm 0.3$	$1.8\pm 0.4$

### INELASTIC STRUCTURE FUNCTIONS

The values of the inelastic structure function  $F_2(x, Q^2)$  are extracted using a Monte Carlo simulation to correct for acceptance and resolution. The simulation uses fits to  $F_2$  and  $R(x, Q^2)=\sigma_L/\sigma_T$  determined from earlier experiments<sup>5)</sup> with the neutron-proton ratio a parameterization of electron data<sup>6)</sup>.

The values of  $F_2$ /nucleon averaged for iron are presented in Figure 2b. This represents 17% of the data on tape. Systematic uncertainties in the energy calibration and resolution, and in trigger efficiency are folded in quadrature with the statistical. There is an overall normalization uncertainty of  $\pm 14\%$ .

The data indicate less dependence on  $Q^2$  than measured in earlier experiments<sup>5)</sup> although the result is not inconsistent with those. The values of  $F_2$  fall approximately 20% below the extrapolation of fits to those lower  $Q^2$  data at all values of  $x$ . Changing the value of  $R$  from the form  $R=1.2(1-x)/Q^2$  to a large value would increase the measured  $F_2$  particularly at larger values of  $Q^2$ . The data presented here are in good agreement with values measured in neutrino scattering from iron<sup>7)</sup>.

### $\psi(3100)$ PRODUCTION BY MUONS

Previous experiments at Fermilab, SLAC, and Cornell have measured  $\psi$  photoproduction. We report here  $1000\pm 80 \mu^+\mu^-$  pairs from  $\psi$  decay drawn from 16834 muon interactions producing 3 fully-reconstructed muon tracks in the final state. These represent 12% of the data on tape.

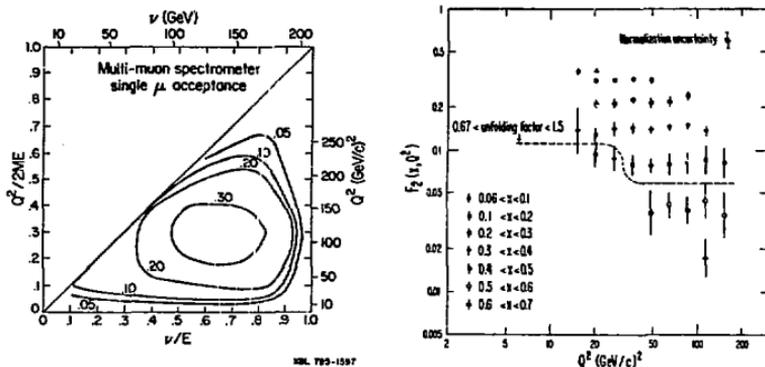


Figure 2. (a) Calculated efficiency for inelastic muon scattering vs.  $Q^2$  and  $\nu$ , averaged over full target length. (b) Measurements of  $F_2(x, Q^2)$  for bins of  $x$ . Points above the dashed line have been corrected by a factor less than 1.5 for smearing. Errors shown include statistical and systematic uncertainty.

Only one choice of  $\mu^+\mu^-$  pairing is plotted in the mass spectrum of Figure 3(a). The centroid of 3(b) is consistent with 3.1 GeV and the width of 9# agrees with Monte Carlo predictions and with direct calculations. The  $\psi(3685)$  is not resolved.

Data taken at low intensity with interactions restricted to the upstream 8 spectrometer modules were used for determination of the total cross-section

$$\sigma(\mu N + \mu \psi X) = 0.76 \pm 0.22 \text{ nb}$$

allowing for the 7%  $\psi \rightarrow \mu^+\mu^-$  branching fraction. (Monte Carlo corrections for nuclear coherence, shadowing and  $|t|_{\min}$  effects yield

$$\sigma(\mu N + \mu \psi X) = 0.67 \pm 0.20 \text{ nb}$$

where the error is due to normalization uncertainty. A calculation using a photon-gluon-fusion model is consistent with this result<sup>4)</sup>.

To make contact with other data at small  $\nu$ , the  $t$ -dependence of the cross section was assumed in the Monte Carlo simulation using parameters based on other experiments. The  $E_\nu$  dependence of Figure 3(c) is insensitive to reasonable variations of the parameters.

Above 30 GeV, the cross sections vary less steeply than is predicted by a photon-gluon-fusion calculation (shaded band). The broken line is the shape of the kinematic factor  $(p_{c.m.}^\psi / p_{c.m.}^Y)^2$ . In the simplest VMD interpretation the ratio of solid to broken lines in Fig. 3(b) gives the energy dependence of the square of the  $\psi$ -nucleon total cross section.

The shallow  $Q^2$ -dependence in Fig. 3(c) is fit by  $(1+Q^2/M^2)^{-2}$  with  $M=2.7 \pm 0.5$  consistent with a  $\psi$  propagator; the choice  $M=m_p$  is ruled out.

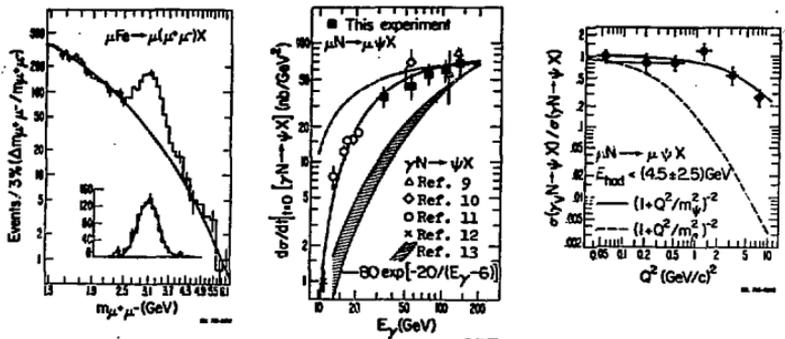


Figure 3.  $\mu^+\mu^-$  mass spectrum before (a) and after subtraction (b). Cross sections for  $\psi$  production by equivalent virtual photon flux as a function of  $E_\gamma$  (c) and  $Q^2$  (d).

If the charmed quark mass is approximately half of the  $\psi$  mass, the kinematics of the photon-gluon-fusion produce a  $Q^2$ -dependence similar to that in VMD. Data like that of Fig. 3 may provide a critical test of a more exact QCD calculations.

\* \* \*

#### REFERENCES

- 1) T. Hansl et al., Phys. Lett. **77B**, 114 (1978).
- 2) M. Holder et al., Phys. Lett. **73B**, 105 (1978).
- 3) R.J. Loveless et al., Phys. Lett. **78B**, 505 (1978).
- 4) A. Benvenuti et al., Phys. Rev. Lett. **42**, 1024 (1979).
- 5) H.L. Anderson et al., Fermilab Pub. 70/30EXP, submitted to Physical Review.
- 6) S. Stein et al., SLAC PUB. 1585 (1975).
- 7) J.G.H. deGroot et al., Z. Physik C. Particles and Fields **1**, 143 (1979).
- 8) V. Barger, W.Y. Keung, and R.J.N. Phillips, Univ. of Wisconsin preprint C00-881-83 (1979).
- 9) B. Knapp et al., Phys. Rev. Lett. **34**, 1040 (1975); W.Y. Lee, in Proc. Int. Symp. on Lepton and Photon Interactions at High Energies (DESY, Hamburg, 1977); M. Binkley, private communication.
- 10) T. Nash et al., Phys. Rev. Lett. **36**, 1233 (1976).
- 11) U. Camerini et al., Phys. Rev. Lett. **35**, 483 (1975).
- 12) B. Gittelmann et al., Phys. Rev. Lett. **36**, 1616 (1975).
- 13) M. Glück and E. Reya, Phys. Lett. **79B**, 453 (1978); M. Glück and E. Reya, DESY preprint 79/05 (1979). In Fig. 3(c) we have multiplied their result for  $\sigma$  by 2.4 to obtain  $d\sigma/dt(t=0)$ .