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A PROPOSAL TO STUDY THE ORIGINS OF "EXTRA" PROMPT MUONS PRODUCED IN DEEP INELASTIC MUON-NUCLEON SCATTERING

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I. Introduction

Several questions of fundamental importance to our understanding of nature continue to be discussed with much intensity in the literature. These are the questions of the origin of prompt muons in high energy collisions and the related question of the production of particles with new quantum numbers.[1] The answer to these questions are seen as paramount to our understanding of the quark-parton structure of hadrons. An experiment capable of studying "extra" muon production in muon-nucleon interactions, that also can study the associated hadronic matter, may well permit an understanding of nature that has eluded us so far. We are proposing such an experiment.

Using the apparatus proposed for E-398 we propose to construct an experiment which is very sensitive to multimuon events. It seems straightforward to increase the acceptance and luminosity of the system for dimuon pairs of either sign, $\mu^+\mu^+$ or $\mu^+\mu^-$, to the point where they <u>must</u> be seen if current ideas about quark structure,[1] and their use in explaining the neutrino dimuon results,[2] are valid. These ideas involve the pair production of charmed particles, and their subsequent semileptonic decay, in the reaction

$$\mu + N \rightarrow \mu^+ c \bar{c} + \text{"X"}$$

One detects the scattered muon and one, or both, of the decay muons whose parents are c or $\bar{c}$. The predicted ratio of dimuons to single muon events

is calculated to be[1]

$$\frac{\mu^+ N \to \mu^+ \mu X}{\mu^+ N \to \mu^+ X} \gtrsim 10^{-3},$$

since the branching ratio $c(\bar{c}) \to \mu^+(\mu^-)$ is taken from neutrino data[2,1] to be about 10%, and charm pair production as 1% of all interactions where it is energetically possible.

Trimuons are then predicted to occur in the ratio

$$\frac{\mu^+ N \to \mu^+ \mu^+ \mu^- X}{\mu^+ N \to \mu^+ X} \gtrsim 10^{-4}.$$

Note that this is the <u>only</u> type of trimuon admissible in the charm picture. Trimuons of the type

$$\mu^+ N \to \mu^+ \mu^+ \mu^+ X$$

are not admitted by any charmed mechanism and, if seen in reasonable numbers (i. e., equal to "right signed" trimuons), would discredit charm as the explanation of multimuon events.

Given that sufficient numbers of multimuon events are recorded it will be possible to look for threshold effects as a function of the

$$s = 2M\nu + M^2 - Q^2,$$

the center of mass energy squared and Q^2, the 4 momentum transfer. This is a unique feature of muon beams. In order to scan in s with hadrons one must run at several energies. With muons one has an a priori s scan. The data from neutrino experiments looking for new forms of matter,[2] indicates that a study of threshold phenomena may be the only straightforward way of isolating the mass of any new objects being produced. This is because the final states often contain neutrinos or other neutral particles which make mass reconstruction extremely difficult.

We will also study, via calorimetry, whether events with multiple muons have anomalous amounts of "missing" energy, i. e., energy not in hadrons or "seen" muons. This could be the result of semileptonic decay of a new type of particle, or the fact that some muons escape detection.

The recent results of the Yale-Brookhaven-Fermilab collaboration[3] indicates that prompt muons produced in proton-nucleon collisions originate primarily from electromagnetic sources. It is claimed that, within 10%, all prompt muons are produced in pairs and the polarization of these muons is zero, within 10%.

If this is also true of prompt muons produced in muon-nucleon scattering the signs will be clear almost immediately. For example, the dimuon events will be similar to the "normal" muon events, i. e., there will be no anomalous "missing energy". Also, governed only by acceptance, the number of dimuons and trimuons will be the same, since the "extra" muons are always produced in pairs. The momentum distribution of these secondary muons is calculable, and has been carried out for the case of proton-proton scattering by Farrar and Frautschi.[4] This experiment should provide definitive statements on the

origin of the extra muons. Either type will be recognized and if both occur the events will be distinguishable.

II. Proposal

We propose a definitive experiment to search for multimuon events and the missing energy effect expected from leptonic decays of charmed particles. We feel this experiment is a use of the muon beam competitive with all other muon proposals presently known. The experiment can be done immediately following E-398. The arrangement is shown in Figure 1. Beginning upstream the apparatus consists of the present E-398 beam chambers and beam hodoscopes, the present Halo veto hodoscope and the concrete wall. These are followed by a "target calorimeter". Beyond this is the CCM magnet instrumented to determine momentum with 1 m × 1 m proportional chambers on entry and 2 m × 4 m and 2 m × 6 m spark chambers on exit. There follow hodoscopes, a 2.5 m steel muon filter and more hodoscopes which now cover the full 6 m aperture of the largest spark chamber. The acceptance of this apparatus as a function of Q^2 and ν has been calculated via Monte Carlo. The results are presented in Figure 2.

The heart of the experiment is the calorimeter. The device is in two sections; the first is the target section, the second the calorimeter section. The target section is proposed to be the first approximately 240 gm/cm^2 of the device. We use this target just as an example to allow us to calculate event rates. It is of the same construction as the calorimeter section and is used as an "active" target in the standard way.

The calorimeter section is of major importance. We demand very good energy resolution for reasons shown in the table below. A good calorimeter coupled with the CCM spectrometer is unsurpassed in determining if there is significant "missing" energy. This is the crucial point since the energy that goes into neutrinos from the decays of charmed particles will not be large. Simple calculation suggests that 10-15% of the energy may be absorbed by this mechanism. Several calorimeters are under discussion. One that will be ready this fall is now being made at the Enrico Fermi Institute for another experiment with the E-398 spectrometer. It has been offered to us for our use. Investigations into liquid argon type calorimeters are presently being pursued at Harvard and at the University of Illinois. These devices appear at this time to be extremely attractive.

We have two outstanding advantages over the similar proposal P-474. We have better calorimetry and moreover, we have far better measurement of the muon energies. These advantages are illustrated by the following example. Suppose that the incident muon has an energy of 224 GeV, and that the ν of the interaction is 174 GeV. The scattered muon carries off 50 GeV. Of the 174 GeV left, assume that half goes into a particle that decays into $K\mu\nu$ and the rest goes to hadrons. For a liquid argon calorimeter we assume

$$\frac{\Delta E}{E} = \frac{20\%}{\sqrt{E\ (\mathrm{GeV})}} .$$

We believe this to be an achievable resolution.[5] The results are given in the following table.

TABLE

Particle	Energy	Energy Resolution: This Proposal	Energy Resolution: P-474
Scattered Muon	50 GeV	50 ± 1.5	50 ± 8
87 GeV Kμν	87 GeV		
μ	30 GeV	30 ± 1.5	30 ± 8
ν	27 GeV	-	-
K (seen as a Hadron)	30 GeV		
"Hadrons"	87 GeV	117 ± 2	117 ± 12
Total Seen	197 GeV	197 ± 3	197 ± 16
Missing	27 GeV	27 ± 3	27 ± 16

For $E_{\mu_{inc}} = 224$ GeV

$$\mu^+ N \rightarrow \mu^+ c \bar{c} X$$

$c \rightarrow K\mu\nu$, $\bar{c} X \rightarrow$ Hadrons

It is to be noted that the calorimeter can be well calibrated over its full range by looking at "normal" μ-p inelastic scattering events.

It is clear that the present proposal is more likely to see missing energy than is P-474, even if our calorimeter has a resolution a factor of 2 worse than we think is achievable.

III. Trigger

We would demand at least two "muons" in the counters surrounding the 6 meter chambers and an interaction in the target. For rates we scale from E-98 experience and make the following comparison.

	E-98	Proposal
Target	20 g/cm^2 LD_2	240 gm/cm^2 LAr + Fe
Integrated Beam	1.5×10^{10} muons	3.6×10^{11} muons (800 hours at 10^6 μ's/pulse)
Nuclear Scatters	18.2 K	5240 K
Rate	1.2×10^{-6}/incident muon	1.44×10^{-5}/incident muon

We expect about (10^{-3} × acceptance) to give dimuon triggers.

The acceptance for a muon from the decay of a charmed particle of mass 2 GeV has been calculated via Monte Carlo (see sppendix). It is about 25%. So we expect the genuine dimuon rate for both $\mu^+\mu^-$ and $\mu^+\mu^+$ to be

$$10^{-3} \times 0.25 \times 2 = 0.5 \times 10^{-3}$$

of the nuclear scatters. This works out to be 2600 dimuon events or

$$7 \times 10^{-9} \text{ dimuons/incident muon.}$$

IV. Background Trigger Rate

1) Single, large ν, scatter with associated hadrons penetrating the iron and giving an additional trigger in the rear hodoscopes. From E-98 data[6] this is measured to be less than

$$3 \times 10^{-3} \times \text{pion punch thru} \times \text{energy cut off.}$$

Pion punch thru × energy cut off is about 10^{-4}. This gives this background as less than

$$3 \times 10^{-3} \times 10^{-4} \times 1.44 \times 10^{-5} = 4.3 \times 10^{-12}/\text{inc. } \mu$$

2) Dimuons from Halo in coincidence with a scattered muon. Probably $3 \times 10^{-3} \times 1.44 \times 10^{-5} = 4.3 \times 10^{-8}/\text{inc. } \mu$.

These events can be identified in the later analysis and should cause no confusion.

3) Others, like electromagnetic showers do not appear to be important as a source of triggers. None the less they can all be identified in the analysis and subtracted from the final data sample.

We thus estimate that the background dimuon trigger rate will be of the order

4×10^{-8}/inc. muon compared to 7×10^{-9} dimuon events/incident muon.

While this total trigger rate is some 6 times the real dimuon rate the background can be easily separated from the signal in the off line analysis. The number of real events expected as a function of ν and Q^2 is given in Figure 3.

V. Comparison with Other Experiments

Experiment 382, is looking for particles of lifetime 10^{-13} seconds, and therefore investigating the physics discussed in this proposal. This experiment, using very different techniques, is complimentary and should give diffferent views of similar phenomena.

Experiment 203, which will not occur until winter 1977 has a somewhat different approach and is expected to study charm production, in detail, among other things.

VI. Run Plan

We propose a run of 3.6×10^{11} muons on target at 225 GeV/c with 10^6 muons per pulse and 7.5 pulses per minute. This can run immediately after Experiment E-398. We choose this energy because it is unlikely that 10^6 muons per pulse can be achieved at 300 GeV with anything like reasonable (10 cm × 10 cm) spot size.

It should be noted that prototype liquid argon calorimeters are being built at Harvard and Illinois. This development is of the sort that has been carried out by other groups working at Fermilab.

APPENDIX

We have scanned approximately 20K D_2 events taken during E-98 for dimuons. This data sample is from an exposure of 1.48×10^{10} muons on a 20 gm/cm^2 D_2 target. We have found 38 $\mu^+\mu^-$ events. We compare these events to the predictions from pion decay.

Analysis

For purposes of realistic estimate of pion decay and charm meson production we set $S > 50$. (This must be true for the slower muon in $\mu^+\mu^+$ event).

For $\mu^+\mu^-$ events $q^2 > .3$ is demanded as otherwise too many μ-e scatters creep into the pion decay calculation.

The scanning criteria for dimuons demand that:

1) both muons hit M and M' within a fiducial cut;
2) both muons link back to the beam track in the target region ($-2900 < z < -2000$).
3) both muons are class (1) in the hadron counters (i.e., all counters along the path of the particle upstream of the muon chambers were hit)
4) both muons must have distinct tracks in the muon chambers (largest source of false dimuons).

Results:

out of 11062 ($S > 50.$ GeV/c) μ's find 38 $\mu^+\mu^+$

out of 5341 $\begin{matrix} S > 50. \text{ GeV/c} \\ q^2 > .3 \end{matrix}$ μ's find 5 $\mu^+\mu^-$.

The single muon events have the same fiducial cuts as the dimuons.

Pion Decays

To estimate the dimuons from pion decay we take the events in the samples defined above and allow the visible hadrons to decay to muons at 10 times the normal rate for pions. Both the real muon and the fake muon are tested for passing through the M and M' fiducial cut. These counters define the muon downstream of the hadron shield. We define pions as decaying upstream and downstream of the Chicago Cyclotron Magnet. The trajectories of the upstream pions are changed according to the visible energy of the decay muon (chosen randomly). Following this procedure we find:

out of 11062 ($S > 50$ GeV/c) μ's predict 57 $\mu^+\mu^+$

out of 5341 $S > 50$ GeV/c, $q^2 > .3$ μ's predict 6.2 $\mu^+\mu^-$

# μ's	Prediction $\mu^+\mu$	Seen	R/P
11062	57^{++}	38^{++}	.66 ± .11
5341	6.2^{+-}	5^{+-}	.80 ± .35

Reals are somewhat lower than prediction. Two factors improve this. The first is the fact that there is some inefficiency unaccounted for in the real dimuon scan. The second is that we have made no correction for the loss of muons due to ranging out in the hadron absorber. Note that $E_\mu < E_\pi$ in a decay. Also the μ-linking criteria may fail for such soft muons.

We feel there is reasonable agreement between our expectations and the data.

Acceptance for "Charmed" Muons

For each of the real muon events we have produced a Monte-Carlo charmed meson according to the hadron distributions already measured.[7] If p_c is the charmed hadron momentum:

$$\frac{1}{\sigma} E_c \frac{d^3\sigma}{dp_c^3} \simeq e^{-3.2|X|} \cdot e^{-6P_T^2} \quad \text{(this is symmetric for } x > 0 \text{ and } x < 0\text{)}$$

We take the mass of the charmed particle to be $M_c = 2.0$ GeV/c^2.

Each charmed meson decays to a positive and negative muon according to a three body decay:

$c(\bar{c}) \rightarrow h^{-(+)}\mu^{+(-)}\nu$ Setting $m_\mu = m_h = 0$ for simplicity we find

$$\langle M \rangle \sim \psi_\mu \gamma^u (1 + \gamma_5)\psi_\nu \cdot (p_c + p_h) f^+(q^2)$$

We then approximate $f^+(q^2)$ by letting it equal 1. For c and $\bar{c}$ produced in the $\mu + N$ collision we find the following acceptances:

$c \rightarrow \mu^+ h^- \nu$	15% acceptance for μ^+
$\bar{c} \rightarrow \mu^- h^+ \nu$	7.5% acceptance for μ^-

This reflects the asymmetry of muon identification. If muon identification was available for the whole 6-m chamber aperture the acceptance rises to 25% in both cases.

Kinematic Comparisons

In Figure 4 we show $\frac{d\sigma}{dp_\perp^*}$ for real and fake $\mu^+\mu^+$ events; $p_\perp^*$ is the perpendicular component of one muon momentum with respect to the scattering plane of the other. For $\mu^+\mu^-$ we show $\frac{d^2\sigma}{dp_\perp^2}$. Here $p_\perp$ is the transverse momentum of the negative muon with respect to the virtual photon defined by the positive muon. There is reasonable agreement.

References

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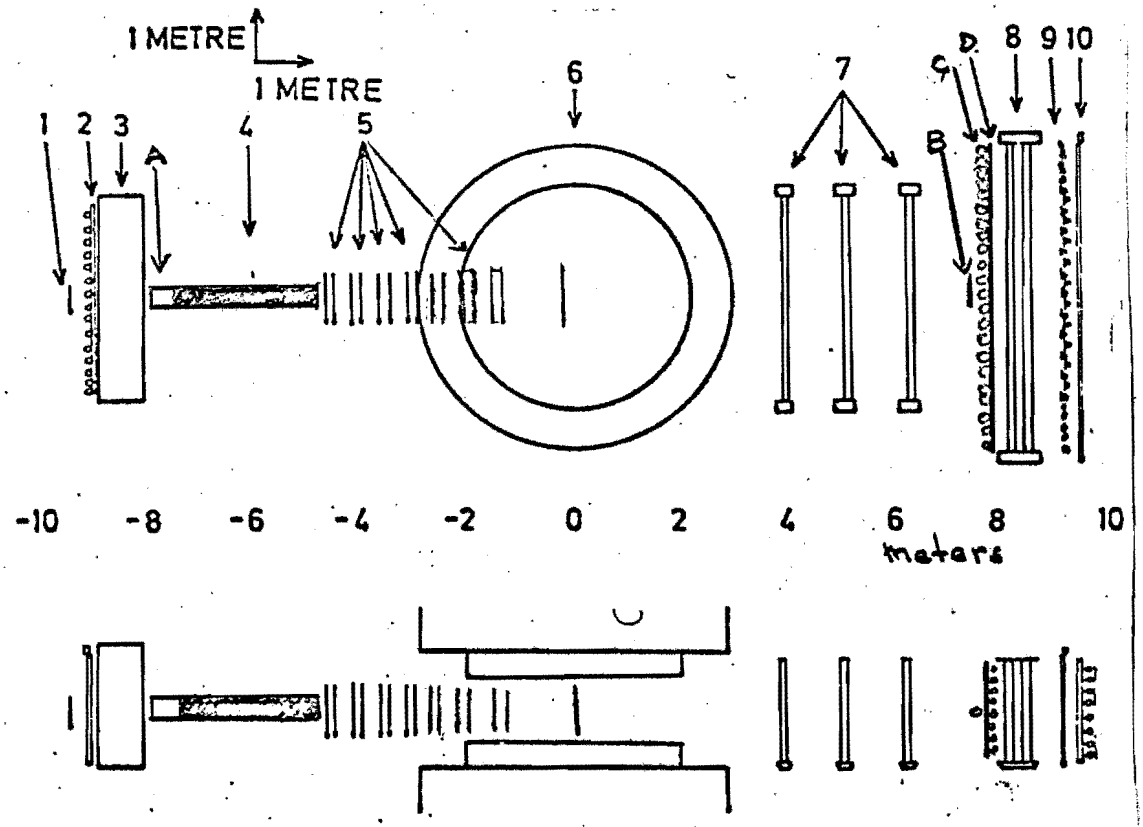
5. Willis and Radeka, "Liquid Argon Ionization Chambers As Total Absorption Detectors", BNL Report 18813.

6. See appendix. This allows all the dimuon candidates to have pions as their source.

7. H. L. Anderson, et al., submitted to Physics Review Letters.



1. Final beam chamber and hodoscope
2. Halo veto hodoscope
3. Concrete wall
A. Target section of calorimeter
4. Hadron calorimeter
5. 8, 1 m^2 MWPC's; 6, 80 cm x 80 cm MWPC's
6. CCM
7. 2 x 4 m chambers
B. "N" counter - horizontal elements
C. "M" Hodoscope = horizontal elements
D. "M" Hodoscope - vertical elements
8. 2 x 6 m chambers
9. H hodoscope
10. G hodoscope

FIGURE 1

ACCEPTANCE

Q^2/ν	25	50	75	100	125	150	175	200
>100	--	--	0.93	0.93	0.46	0.53	0.36	0.06
100	1.0	1.0	1.0	1.0	0.96	0.78	0.71	0.32
31	0.83	0.89	0.90	0.93	0.94	0.90	0.91	0.49
10	0.08	0.17	0.26	0.50	0.67	0.77	0.90	0.70
3.2	--	--	0.01	0.08	0.31	0.60	0.95	0.76
1.0	--	--	--	0.02	0.20	0.66	0.99	0.89
0.3	--	--	--	--	0.11	0.72	1.0	1.0
0.1	--	--	--	--	0.09	0.71	1.0	--

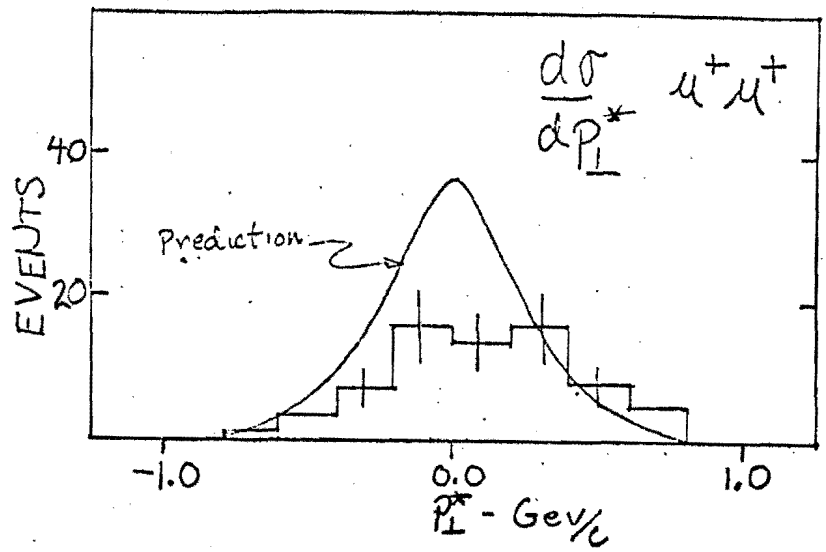
Figure 2

EXPECTED NUMBER OF DIMUON EVENTS

Q^2/ν	25	50	75	100	125	150	175	200
>100	-	-	-	-	-	-	-	-
100	4	5	8	5	4	3	2	1
31	53	37	27	18	14	10	9	3
10	21	23	23	34	32	28	27	15
3.1	1	-	4	17	47	68	85	51
1.0	-	-	-	8	68	172	216	117
0.3	-	-	-	2	58	280	306	108
0.1	-	-	-	-	47	278	182	6

Figure 3

These numbers are calculated by taking the expected number of single muon scatters and multiplying by the probability for the production of dimuons.


$\frac{d\sigma}{dP_\perp^*}$ $\mu^+\mu^+$
40
20
EVENTS
Prediction
-1.0
0.0
1.0
$P_\perp^*$ - Gev/c

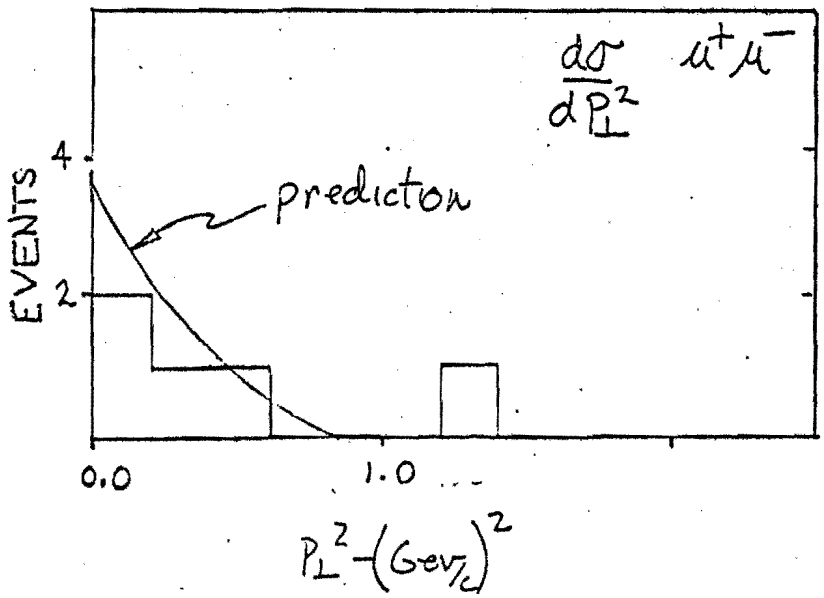

$\frac{d\sigma}{dP_\perp^2}$ $\mu^+\mu^-$
4
2
EVENTS
prediction
0.0
1.0
$P_\perp^2$-(Gev/c)^2

FIGURE 4