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SEARCH FOR HEAVY PARTICLES PRODUCED IN ASSOCIATION WITH PROMPT MUONS

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Summary

A little over one year ago FNAL approved P-357, the original proposal to search for the hadronic decays of charmed particles. During this year our group has built a powerful double-arm spectrometer which includes 32 drift chambers, 6 Cherenkov counters, and 54 scintillation counters. We had our first and to date only data run in November and December of 1975. We have seen a very clean J/ψ signal in the $\mu^+\mu^-$ decay mode and the run yielded two-body hadron data whose general experimental and statistical quality compares very favorably with the hadron data of the MIT/BNL[(1)] effort.

Since this investigation concerns processes with extremely small cross sections and large physical backgrounds, we believe it to be imperative to improve the sensitivity of this particle search. Data from hadron interactions, neutrino interactions, and e^+e^- annihilations with prompt leptons in the final state give rather compelling evidence for the production of new particles. Therefore, we propose to search for narrow resonances in two-body hadron mass spectra for events containing a prompt muon.

Muons will be identified with a 15½ foot long hadron absorber built in two parts and covering more than 50% of the c.m. solid angle. An 8 foot long steel absorber with a hole for passage of the beam and channels leading to each spectrometer arm will replace the first two Cherenkov counters in our present apparatus. The second part of the absorber will utilize the iron in the BM-109 magnet yokes. The function of the two displaced Cherenkov counters will be taken over by two similar counters to be positioned behind the BM-109 magnets.

Introduction

Prior to November 1974, the excess of leptons produced at large $p_\perp$ values suggested the possible existence of some new important phenomena.[2] The confirmed existence of weak neutral currents which, however, do not change strangeness, suggested that SU(4) and "charm" were ideas worth pursuing. On these bases we proposed E-357, a search for charm in the two-body hadron decay modes which had been predicted to be relatively large.[3] Later, the indications of the existence of some new phenomena were confirmed by the announcement of the J/ψ discovery.[4] Following the many new discoveries in e^+e^- annihilations, in particular the structure at 4.1 GeV, there was a feeling of great anticipation and some felt that charm would be discovered in a matter of weeks. This did not happen. Since that early exhilarating time, only a little over a year ago, much new information has become available.

Of particular interest is the discovery of prompt single muons and electrons in neutrino interactions and e^+e^- annihilations. The most reasonable explanation of these results is that new particles are produced which decay via the weak interaction. The presence of a prompt lepton could then be taken as a powerful signature for events containing new particle production. It is, of course, not yet clear what the correct interpretation of these phenomena will be. However, the possibility that some new heavy particle is produced and is associated in some way with direct lepton production should be thoroughly investigated at Fermilab.

Therefore, in this proposal we outline a modification of the existing operational double-arm spectrometer in use for E-357 which will allow us to search for the two-body hadron decays of massive new states produced in association with a direct muon.

In the next section we review our technique and give a brief status report on E-357. Subsequent sections discuss new apparatus needed, the expected counting rates and backgrounds, and essential supplemental FNAL support.

E-357 Review and Status Report

In December 1974, FNAL approved our proposal to search for the two-body hadronic decay modes of charmed particles in the mass range from 1.5 to 4.0 GeV. The experimental apparatus presently resides in the 400 GeV/c diffracted proton beam (M2) in the Meson laboratory. The apparatus in its present configuration is pictured schematically in Figure 1. Each arm of the pair spectrometer is capable of identifying $\pi^{\pm}$, $K^{\pm}$, and $p^{\pm}$ by utilizing three threshold Cherenkov counters operating in the momentum interval from 7.0 to 20.0 GeV/c. A six (6) foot steel absorber is placed after each spectrometer for muon identification. Spatial coordinates are measured by 32 drift chambers and the trigger is provided by 54 scintillation counters.

This apparatus was installed in late spring 1975 and debugged during the following summer and early fall. In our first data run during November and December 1975 we accumulated $\sim$ 8 million triggers integrated over all hadron pair combinations of particle type and charge species.

For this first run no Cherenkov requirements were included in the trigger, which simply required a charged particle in each arm of the spectrometer. This trigger results in a trigger rate of $\sim$ 500 per 10^8 protons on a 10% target. At this rate, $\sim$ 55% of the events have at least one track which reconstructs in a given arm and approximately 30% of the events have a reconstructable track in both arms. Hence, the trigger is very clean and is dominated by real physics. For the November-December run we normally ran at $\sim 0.5 \times 10^8$ ppp. At present our data-taking rate is limited by the computer data acquisition rate to ~ 110 events per pulse. At this rate our capability is ~ 0.6 million events per day of uninterrupted beam. The analysis of these data is presently in progress. Some preliminary results will be presented which will indicate what the final quality of the data will be.

We begin with a discussion of some of the techniques used to guarantee the clean identification of pair events. The target, which is placed on a movable platform, is ~ 10% of an interaction length of polyethylene divided into seven (7) equal pieces spaced 4" apart along the beam (Z-axis). Figure 2(a) shows the results of a horizontal target scan; here we plot the normalized double-arm trigger rate as a function of target position. One observes that 80% of the trigger rate is target-associated. Figure 2(b) shows the calculated distance of closest approach for left and right arm tracks. The half width in this vertex determination is ~ 0.060 in. (1.5 mm). Figure 2(c) shows the vertex location in Z for events satisfying a 0.3 in. cut on distance of closest approach; the seven pieces of the target are clearly resolved. Left and right spectrometer tracks for real events must of course originate from the same target piece, while left and right tracks associated with random triggers may or may not originate in the same target piece. Thus, it is possible to reduce the random contribution in the data sample by a factor of 7 by requiring a vertex in one of the target pieces. Figure 2(c) shows that our final data sample contains little background from randoms and secondary interactions. These data were accumulated at $\sim 0.5 \times 10^8$ ppp, the same intensity at which the bulk of the data were taken. Figure 2(d) shows a direct measure of the accidental coincidence rate as given by the left to right arm timing distribution.

Events which satisfy the tracking and target criteria are then classified with respect to particle type using the Cherenkov counters and the scintillators (μ-counters) located behind the steel absorber in each spectrometer arm. Because the steel absorbers are located at a large distance from the target, the single-arm μ data are dominated by pion decay (the decay probability is $\approx$ 1.5% for 15 GeV/c pions). However, the double-arm rejection against pion pairs is the single-arm rejection squared; therefore, the rejection against π pairs at the J/ψ mass is $\approx 2 \times 10^{-4}$.

$\mu\mu$ data were accumulated simultaneously with the hadron pair data in order to calibrate the mass scale, mass resolution, and sensitivity of the experiment with the J/ψ particle. Our J/ψ statistics are limited since the beam rate was optimized for hadron running. The hadron trigger rate saturated the data recording capability at $\sim 0.5 \times 10^8$ ppp. No special attempt was made to improve J/ψ statistics at the expense of the hadron data by running with only a μ-pair trigger. The μ-pair effective mass spectrum representing $\sim$ 2/3 of the data taken in November and December is presented in Figure 3. The J/ψ signal is very clean with most of the events lying in a single 20 MeV bin. This resolution ($\sigma \sim$ 10 MeV) is consistent with the Monte Carlo resolution calculated in the E-357 proposal. The J/ψ cross section times branching ratio at 400 GeV/c is 3×10^{-33} cm^2.(5) On the basis of these numbers the sensitivity of the entire November-December run is approximately 10 events/nb.

Convinced by our J/ψ signal that we understand our apparatus well, we are presently investigating the hadron pair effective mass spectra. As an example we present in Figure 4 the $\pi^+\pi^-$ spectrum from one-half of our present data sample. At a mass of $\sim$ 2.0 GeV this spectrum contains $\sim$ 4000 events per 20 MeV bin. The following table indicates the total number of events expected from the complete analysis of the November-December run for some of the possible particle combinations. Also shown are the cross sections that would give five standard deviation peaks in a 20 MeV bin at masses of 2 and 3 GeV.

TABLE I

	Total # of Events	σ_5 st. dev. at 2.0 GeV	σ_5 st. dev. at 3.0 GeV
$\pi^+\pi^-$	420,000	65 nb	20 nb
$K^+\pi^-$	65,000	18 nb	7 nb
$K^-\pi^+$	26,000	13 nb	6 nb
K^+K^-	8,000	5 nb	4 nb
$\bar{p}p$	6,600	---	5 nb

E-357 is scheduled for one more run in the spring of 1976. During this run we will proceed to accumulate more data in the rarer modes. For this purpose our present apparatus can be used unchanged merely by vetoing any event containing a pion. We have checked the trigger rate in this mode and find it to be reduced by a factor of 6 over the unrestricted mode. We should be able to increase our data sample for events not containing a pion by at least a factor of 4 during the next run. These new data will allow us to search for states decaying into K^+K^-, Kp, and $\bar{p}p$ with a sensitivity of $\sigma B \approx 2$ nb. The pseudoscaler bound state of two charmed quarks, η_c, is one good candidate for this search.

Proposal to Extend the Particle Search to Events with Prompt Muons

After our spring run the data acquisition phase of E-357 will be completed. We will have accumulated approximately 16 million events and will have reached a natural limit on sensitivity in the 2 to 4 GeV mass range imposed by the physics of two-body hadron production and the logistical problem of analyzing the accumulated tapes. In order to improve on this sensitivity, an additional idea regarding the production mechanism of the particles we seek must be incorporated into the trigger.

The anamolous lepton production observed in several diverse experiments suggests a possible signature for events containing new particles. We have, at present, a unique capability at Fermilab to study two-body hadronic decay modes. With a minor modification to our apparatus we can select events with a direct muon and thereby reduce the hadron pair "background" not associated with prompt muons by at least two orders of magnitude (see later section, Expected Rates and Backgrounds). Due to this reduction in the trigger rate we will have smaller dead times and will be able to run a more intense beam ($\sim 2 \times 10^8$ ppp) with a net gain of a factor of ~ 10 in live protons. We can reasonably expect to reach a sensitivity of $\sigma B \approx 0.2$ nb at a mass of 3.0 GeV in $K^-\pi^+$ for a 5 standard deviation signal during a run whose length is similar to our November-December run. This represents a gain of a factor of ~ 30 in sensitivity. This gain will be partially offset to the extent that the particles we seek are not always accompanied by a prompt muon.

Let us assume that the new particles are produced in pairs with a cross section, $\sigma_{c\bar{c}}$, and a branching ratio, B_{hh}, into two hadrons. Our present sensitivity, S_{hh}, for $\sigma_{c\bar{c}} B_{hh}$ is given in Table I. The sensitivity for the proposed search requiring a prompt muon is given by

$$\sigma_{c\bar{c}}\, B_{hh}\, B_{\mu x}\, A_{\mu} = \frac{S_{hh}}{\sqrt{10^3}} .$$

$B_{\mu x}$ is the branching ratio into a muon plus anything, A_{μ} is the detection probability for the decay muon ($\sim$ 50%), and $\sim 10^3$ is the improvement gained from suppression of the normal hadron background and the higher possible beam flux. The sensitivity improves only as the square-root of this factor. The relative improvement in sensitivity over the data of our November-December run, given a similar length run with the proposed absorber, is a factor of

$$\sqrt{10^3}\; B_{\mu x}\, A_{\mu} .$$

It should also be noted that the proposed hadron absorber will improve the signal to background ratio by about one order of magnitude.

These calculations are based on a specific idea for the excess of prompt leptons and should be taken only as a guide. The final understanding of these new phenomena may be as yet unanticipated. Viewed this way, the proposed experiment is simply a high sensitivity search for particles in events containing prompt muons.

We note also the fact that approximately 2% of the time a second track is found in one arm of the spectrometer. Hence, we may search for charged particles in three-body spectra such as $K^+\pi^+\pi^-$, $K^-\pi^+\pi^-$ in E-357 and in the proposed experiment with sensitivities only one order of magnitude down from the two-body searches.

The segmentation of the proposed muon detectors will also allow us to look at two-hadron mass spectra in association with di-muons.

The Absorber

In order to accomplish this we propose to build a hadron absorber of steel composed of two parts:

1) The first set of Cherenkov counters in our experiment will be removed. In their place immediately downstream from the target will be placed a steel hadron absorber with an overall length of 8 feet with three open channels, one to pass the beam and one leading to each spectrometer arm. One hodoscope will be placed at a distance of 7 feet into the steel and a second will follow the final 12" of absorber. Each hodoscope layer will be composed of two counters of dimension 1' x 3' x ½" to cover an area 2' x 3'. These hodoscopes will also have holes for the beam and spectrometer acceptances.

2) A second section of absorber will utilize the iron of the BM-109 spectrometer magnet yokes. The small volume between the two magnets will be filled with steel except for a small hole for the beam. A third shielded hodoscope (to cover an area 5' x 5') will be positioned after this second section of steel absorber. In this way, an additional 7½ feet of steel hadron absorber is provided.

Overall, the muons must traverse 15½ feet of steel. The three hodoscopes will provide prompt muon detection over ~ 50% of the c.m. solid angle. Finally, the function of the two Cherenkov counters displaced by the front absorber will be taken over by two similar counters to be positioned behind the BM-109 magnets, one in each spectrometer arm.

Figure 5 indicates the location of the absorber components and the two new Cherenkov counters relative to the existing E-357 apparatus.

In addition to a charged particle in each spectrometer, our new trigger will require a threefold coincidence between the three absorber hodoscopes. In this way we will select hadron-pair events associated with a direct muon.

Expected Rates and Backgrounds

The μ/π ratio has been measured to be $\sim 10^{-4}$ (6) and the average multiplicity of hadrons, $\langle n \rangle$, produced in 400 GeV/c interactions is $\langle n \rangle \sim 10$. The absorber hodoscopes described above have been determined from Monte Carlo calculation to subtend $\sim 50\%$ of the solid angle in the center of mass system. From these numbers one calculates that 1 event in ~ 2000 will have a prompt μ which enters the absorber and triggers the hodoscopes. Hence, under ideal circumstances one could expect a suppression of $\sim \frac{1}{2} \times 10^{-3}$ in the trigger rate and a similar rejection of the normal hadron pair background relative to events with an associated prompt μ.

Of course, we will not do as well as this because of muons from π and K decay, muons in the beam halo, and punch-through of the hadronic shower. We now present what are believed to be realistic estimates of the size of these effects.

A. Decay Muons

We have simulated the production and decay of pions produced in the target using a Monte Carlo technique.

i) Pions were generated in accord with measured $p_\perp$ and rapidity distributions. They were then allowed to decay with a time distribution characteristic of $\pi \to \mu\nu$.

ii) If the decay occurred in the steel of the front absorber, the event was retained only with the probability that the pion would have survived absorption in the steel.

iii) Finally, the resulting μ's were required to have sufficient energy to survive the range requirement in the steel of the front absorber.

Thus we find that the probability per interaction that a decay muon hits the front absorber hodoscopes is $< 0.5\%$. The effect of the second absorber will be to further reduce this number by absorption of decay muons. Pions which pass through the channels of the front absorber and then decay downstream will not contribute to the overall rate as they will not count in the front absorber hodoscopes.

B. Muons in the Beam Halo

We have made measurements of the muon halo in the M2 beam line tuned for diffracted protons at 400 GeV/c. We expect $\sim 5 \times 10^4$ muons each accelerator pulse in an area 2' x 3' with 3×10^{12} on the Meson target. With the M2 intensity at $\sim 2 \times 10^8$/pulse we calculate ~ 1 event in our trigger per pulse due to random coincidences between a halo muon (counting in the absorber hodoscopes) and the hadron pair trigger from the spectrometers. This should not be a serious source of background.

C. Hadron Shower Punch-Through

We estimate that hadrons from 400 GeV/c incident protons will punch through the 15½ feet of steel absorber with a probability of $\sim 5 \times 10^{-4}$ per interaction. This estimate is based on a measurement of hadron penetration in our present experiment and then scaling this measurement to the beam energy and the proposed absorber thickness. The absorbers presently in use in E-357 consist of six feet of steel, a scintillator, 18" of concrete, then another scintillator at the end of each spectrometer arm. Using the spectrometer Cherenkov counters it is possible (for each type of particle) to examine what fraction of particles incident on the absorber creates a shower which has some fragment to reach and count in the scintillators. For π and K the number obtained is consistent with the decay probability. For protons, since no decay is possible, the result is a good measure of the actual hadron shower punch-through. We find the punch-through probability to be $\sim \frac{1}{2}\%$ at 20 GeV/c. This result is consistent with that quoted by Citron et al. at 20 GeV/c.[7]

We then scale this measurement to 400 GeV incident particles and 15½ feet of steel using the calculations of Van Ginneken and Awschalom[8] and the measurements of Anderson et al.[9] We obtain an overall probability for hadron punch-through of 5×10^{-4} per interaction. We estimate this number to be accurate to within a factor of five.

Thus, taking into account decay muons, random muons from the beam halo, and hadron punch-through, we obtain an overall suppression of hadronic events without prompt muons by a factor of $\geqslant 100$ by requiring a muon that penetrates the proposed absorber.

New Apparatus, Time Scale, Request of FNAL

The only new pieces of apparatus to be built are the two Cherenkov counters and the hadron absorber plus its associated scintillation counters. The front absorber is presently under construction. The Cherenkov counters will be ready by late spring, 1976. We would be ready to run the proposed experiment at that time.

We request 100 hours for final debugging of the new components and 500 hours in which to take data. Some of the debugging time may not be necessary if parasitic time can be obtained.

Conclusion

We propose to increase our sensitivity in searching for heavy states which decay into two hadrons by a factor of up to 30 over our present data sample. This will be accomplished by triggering on prompt muons. The proposed absorber will reduce our trigger rate by at least 10^{-2} and thereby allow us to tolerate a higher beam flux. We can be ready to run this experiment late in the spring. We feel that this represents a unique opportunity at Fermilab with a small additional investment to search for charmed particles or other heavy particles whose production is correlated with direct lepton production with sensitivities at the 10^{-33} to 10^{-34} cm^2 level.

References

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Figure Captions

1. Plan view of present E-357 apparatus in M2.

2. a) Trigger rate as a function of horizontal target position.

   b) Distance of closest approach of left and right tracks.

   c) Distribution of vertex locations along beam axis.

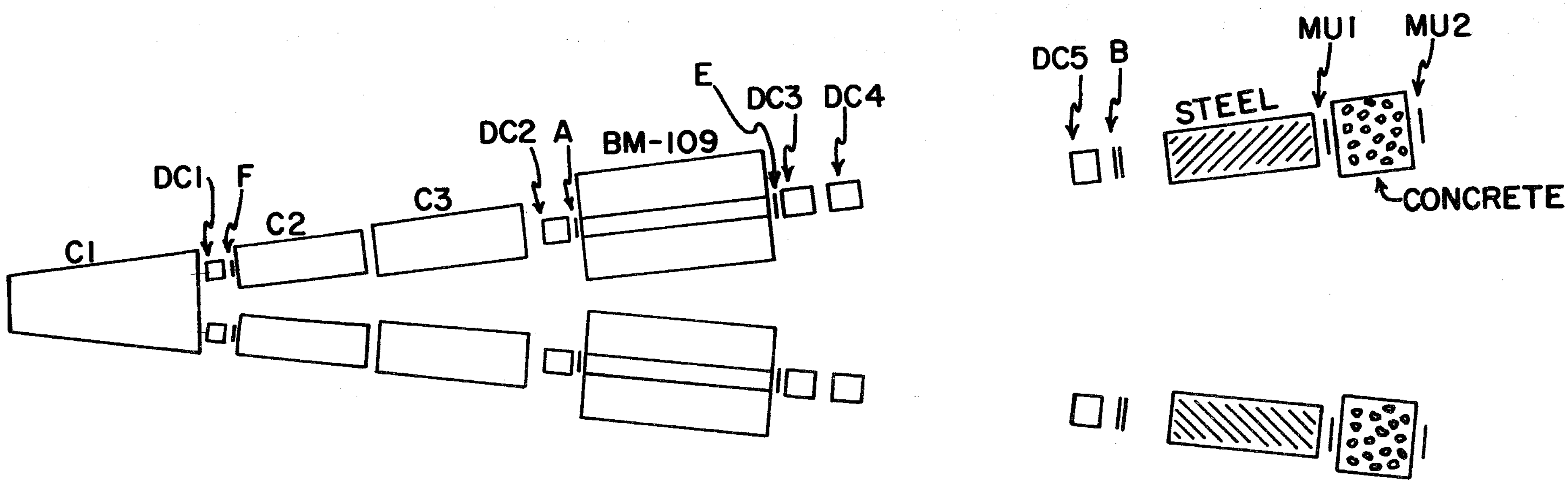
   d) TOF spectrum between left and right arm triggers.

3. Muon pair effective mass spectrum from approximately 2/3 of Nov-Dec run.

4. $\pi^+\pi^-$ spectrum representing $\sim 1/2$ of present data sample.

5. Plan view of proposed apparatus.

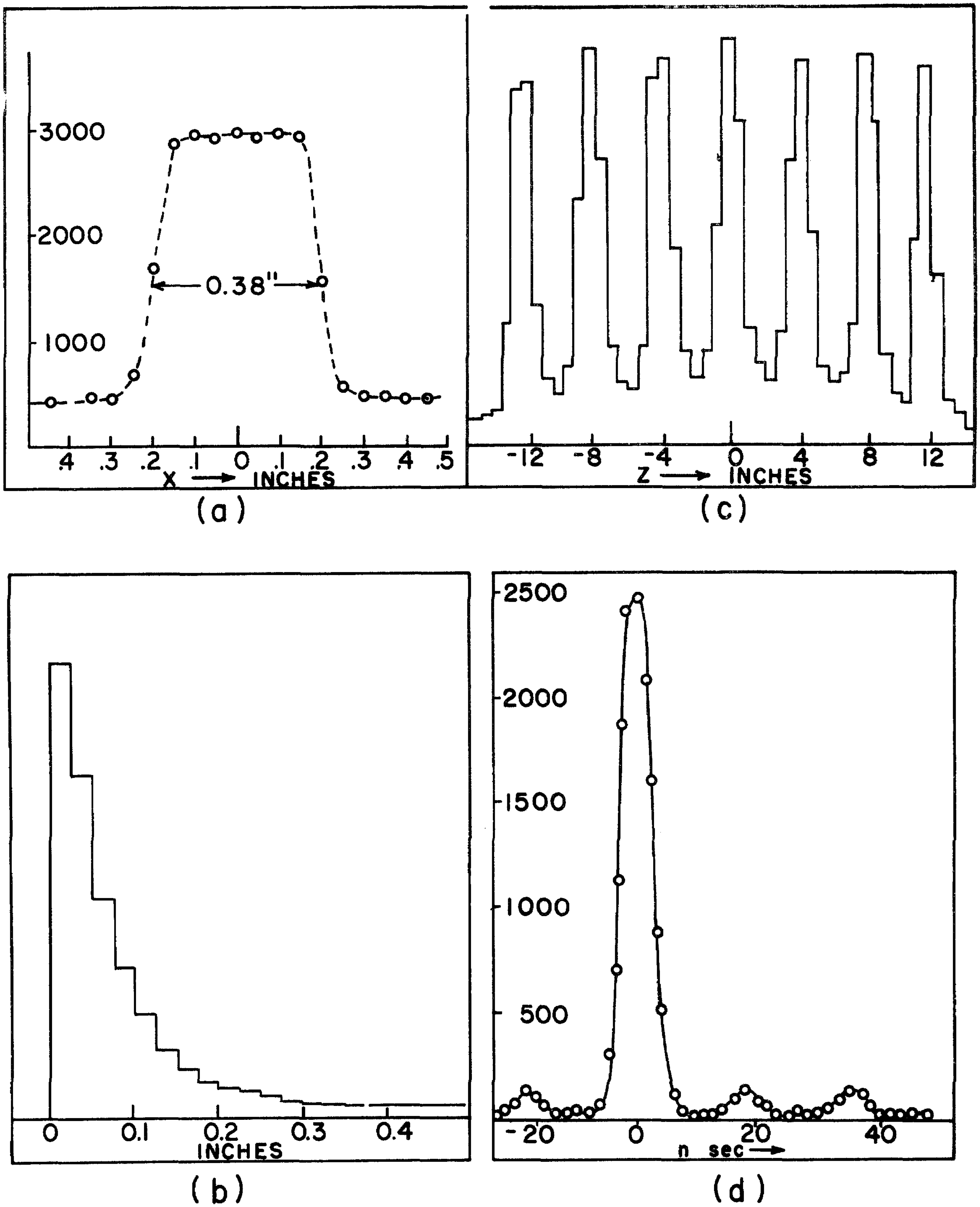
PRESENT E-357 LAYOUT
FNAL/MICHIGAN/PURDUE



C : Cherenkov
DC: Drift Chamber Module

Fig. 1

472-15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(a)
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Z → INCHES
(c)
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INCHES
(b)
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2000
1500
1000
500
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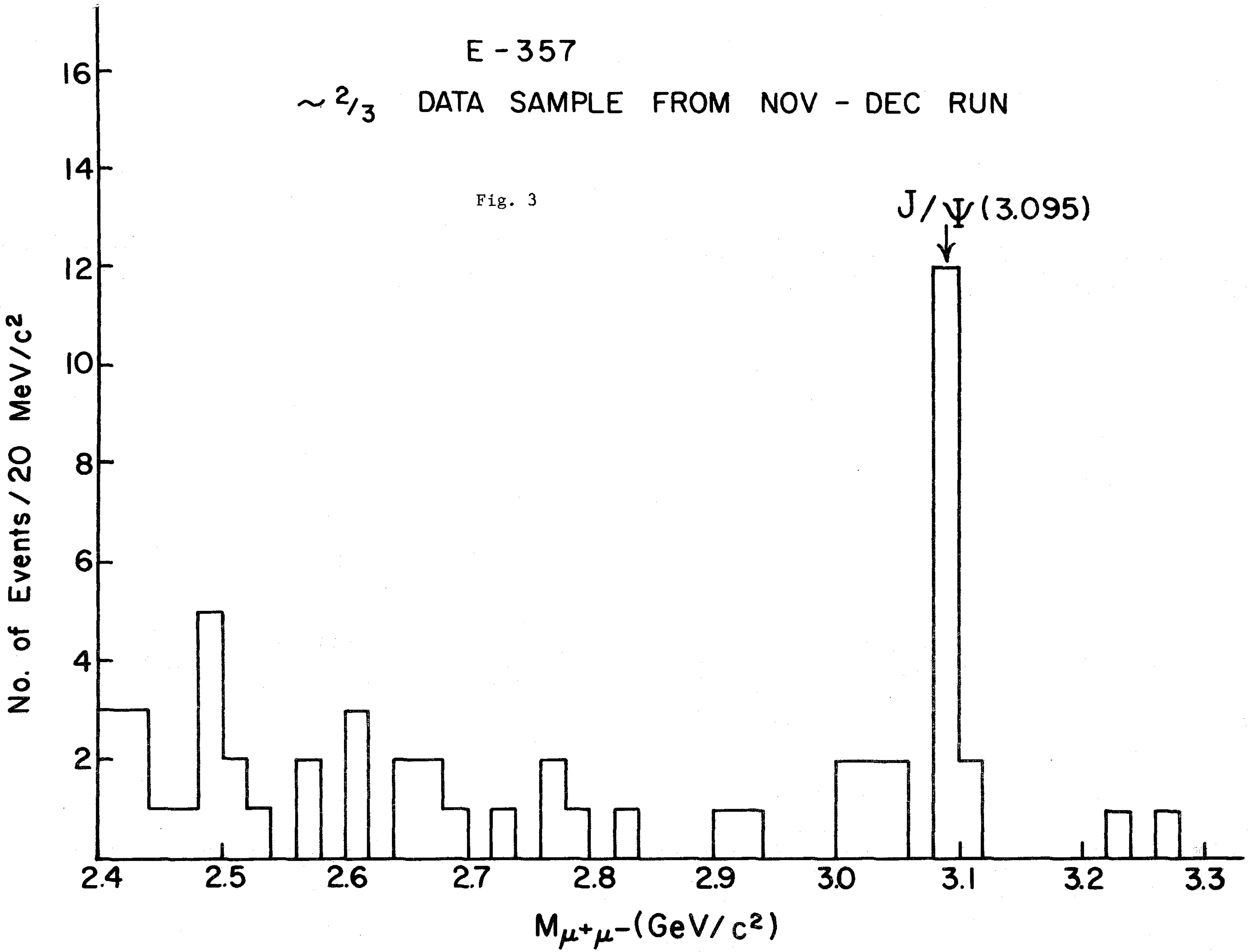
n sec →
(d)

Fig. 2


E - 357
~ 2/3 DATA SAMPLE FROM NOV - DEC RUN
J/Ψ (3.095)
No. of Events / 20 MeV/c²
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14
12
10
8
6
4
2
2.4
2.5
2.6
2.7
2.8
2.9
3.0
3.1
3.2
3.3
Mμ+μ- (GeV/c²)

Fig. 3

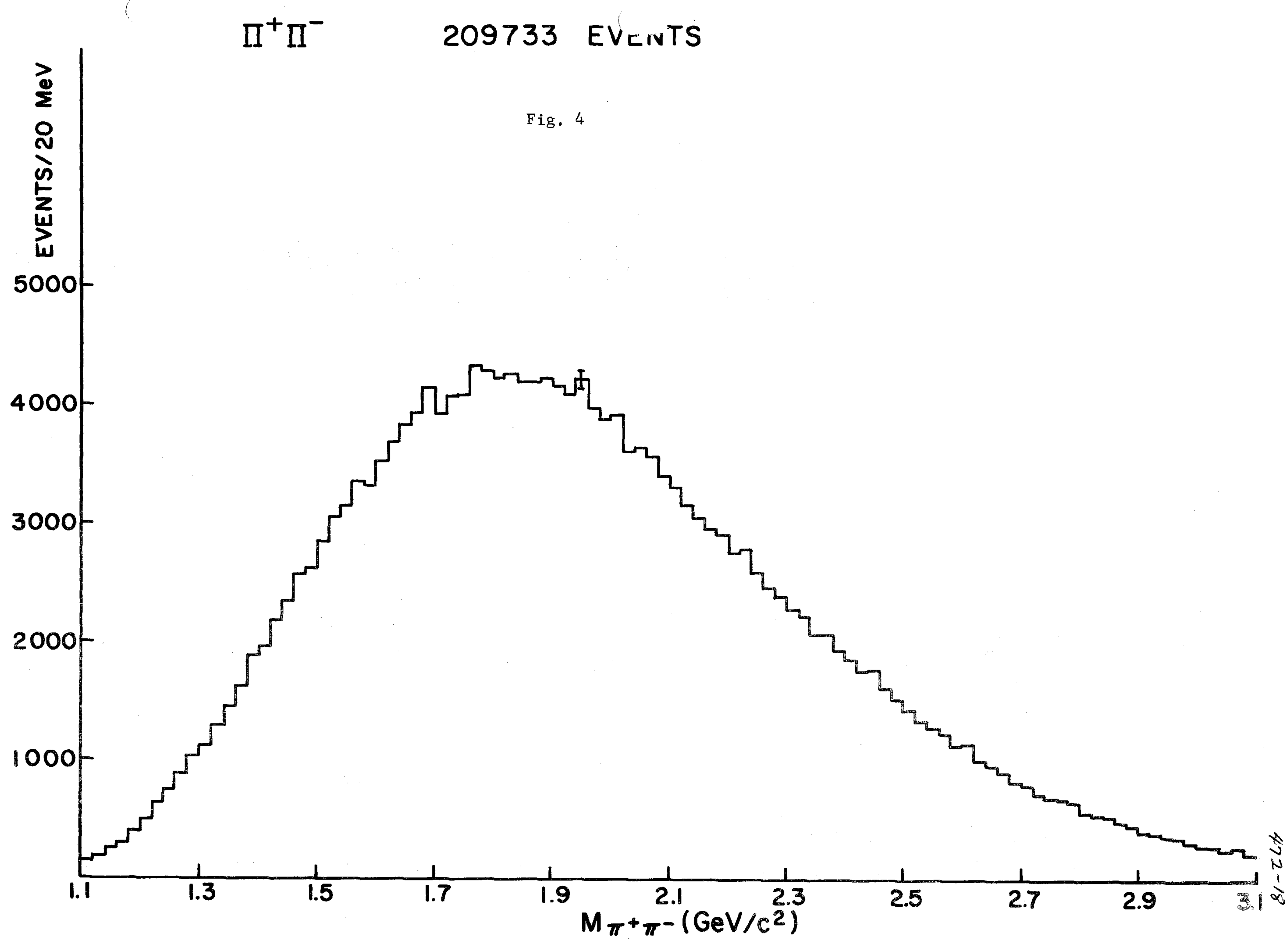
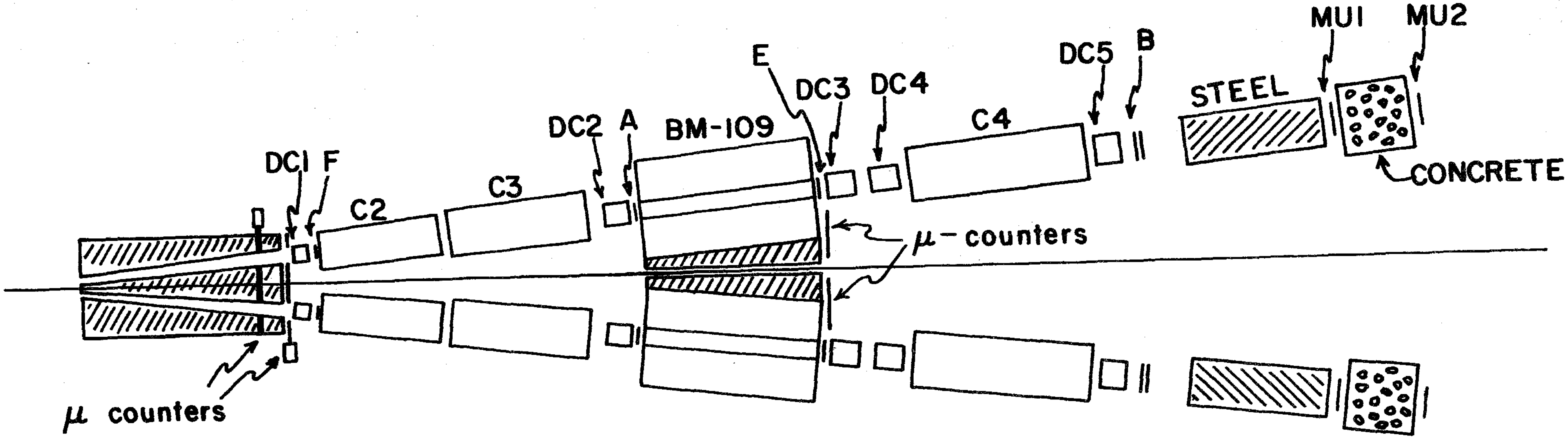

$\Pi^+\Pi^-$ 209733 EVENTS
EVENTS/20 MeV
5000
4000
3000
2000
1000
1.1
1.3
1.5
1.7
1.9
2.1
2.3
2.5
2.7
2.9
3.1
$M_{\pi^+\pi^-}$ (GeV/c^2)
472-18

Fig. 4

PROPOSED SET-UP



C : Cherenkov

DC : Drift Chamber Module

Fig. 5