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A SEARCH FOR NEW PARTICLES PRODUCED IN ASSOCIATION WITH THE HADRONIC PRODUCTION OF ψ (3.1) MESONS

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ABSTRACT

We propose to study the reaction $P + Be \rightarrow \ell^+\ell^- + Y_f + X$. The forward going hadrons, Y_f, and the lepton pair will be detected. The range of dilepton mass will extend from .5 GeV/c^2 to 6 GeV/c^2. Particular emphasis will be placed on searching for new particles when the dilepton pair is due to the decay of a ψ (3.1). The detector will be the E-87/358 apparatus with small additions. The feasibility of the technique of detecting the ψ (3.1) has been established in E-87 and E-358.

I. INTRODUCTION

The discoveries of the ψ (3.1) and the ψ (3.7) have yet to be followed by a satisfactory explanation of the narrow width of these particles. The fact that the ψ (3.1) is photoproduced and the fact that its production in nucleon-nucleon collisions, once an allowance is made for its large mass, is characterized by $P_{\perp}^{2}$ and P_{11} distributions which are similar to the other vector mesons, are part of the evidence that established the ψ (3.1) as a hadron. These observations were made in two experiments[1,2] which were done by the members of this proposal in a detector with which we propose to undertake a further investigation of these new particles.

Since the ψ (3.1) is a hadron it is natural to ask the question, is it made up of a new kind of quark and anti-quark? If it is, there is a reasonable chance that other particles containing the new kind of quark would accompany the production of the ψ (3.1) in nucleon-nucleon collisions. The fact that the production of the ψ (3.1) increases by a factor of 100 between BNL and Fermilab suggests that a new production mechanism becomes important in this energy range.[3]

If the production of the new ψ (3.1) obeys Zweig's rule then two additional particles, one which contains a new quark and the other which contains the corresponding anti-quark, would be produced whenever a ψ (3.1) is produced. If these particles have masses between 2.5 and 3.5 GeV/c^2, then the threshold for the process is above 50 GeV. Since the energy of the BNL AGS is 28.5 GeV, the production of the ψ (3.1) at the AGS could proceed only by a mechanism which did not obey Zweig's rule. A production process which obeys this rule was possible in E-358, since it was carried out with mean neutron energies of 240 and 350 GeV. Because the allowed process should be much more copious, the large increase in the cross section has a natural explanation.

We propose to look at the forward going particles which are produced in association with the production of a ψ (3.1) in the central region. The reaction which we wish to measure is;

$$P + Be \rightarrow \underbrace{\psi}_{\hookrightarrow \ell^+\ell^-} + Y_f\ (A, \cdots\cdot) + X \tag{1}$$

Y_f are the detected particles which are produced in the forward hemisphere of the center of mass system, while X are the undetected particles. The ψ (3.1), which will be detected by its decay into two leptons, will be produced near $x = 0$.* The production cross section is a maximum at this x value. The new particles, A, contained in the group of particles Y_f, will be detected by searching for narrow baryon and meson resonances among the detected particles. Narrow is taken to correspond to a width of 150 MeV or less. If the new particles have significant leptonic decay modes they will be detected by the presence of a third lepton.

A diagram which illustrates the aforementioned production process is shown in Figure 1.

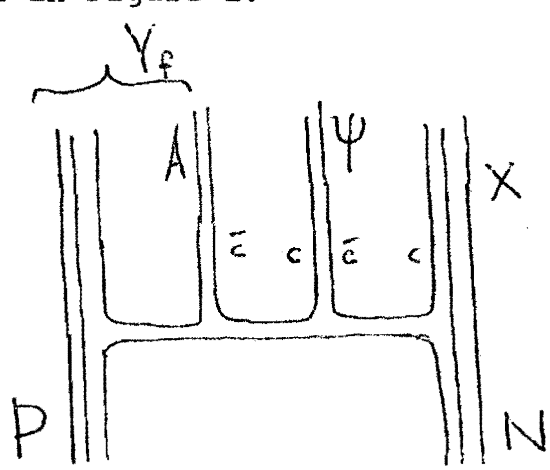


Figure 1 - A possible production mechanism for the ψ (3.1) in nucleon-nucleon collisions

*x is the ratio of the parallel momentum in the c.m. frame to the maximum value of the parallel momentum.

Independent of a particular model, it seems to us that one of the best places to look for new particles at the Fermi Lab is in collisions which produce ψ (3.1) or other massive dileptons. For example, another possible source of dileptons is the simultaneous leptonic decay of pairs of short lived hadrons. In this case, it is important to search for an excess of strange particles which accompany the dilepton. Moreover, when the two muons have the same sign, the probability that new particles accompany the dilepton is increased.

The first physics objective of this proposal is to make a thorough study of the multiparticle final states produced in conjunction with a dilepton. We expect this to be an especially sensitive search for new particles when the dilepton is a ψ (3.1). The dilepton continuum may also be an important signature. Moreover, as a test of the applicability of Zweig's rule, we will look for an increase in K^o production when a ϕ^o (1020) is produced.

The second physics objective is to measure the yield and production dynamics of the ρ^o (770), ϕ^o (1020), ψ^o (3.1), ψ^o (3.7) and the continuum of masses between 0.5 - 6.0 GeV/c^2. A unique feature of these measurements is that they would provide $P_\perp{}^2$ and x dependence of lepton pairs. With the exception of the ψ^o (3.7), all these features were observed in E-358. The interpretation of the results is difficult because the neutrons were not monochromatic.

II. EXPERIMENTAL TECHNIQUE

The detector which we will use is essentially the same as we used for E-87 and E-358. In those experiments we demonstrated the ability to detect lepton pairs and to reconstruct complicated multi-body final states. These capabilities are required to carry out the experiment. The improvements to the detector which we plan to make will both increase the acceptance of the detector substantially and reduce the number of triggers due to unwanted events.

The detector which we used to observe the ψ (3.1) is shown in Figure 2. We will briefly summarize its features here. The details of the apparatus can be found in reference 1. It consists of a multiwire proportional chamber spectrometer. There are five chambers labeled P_0, P_1, P_2, P_3 and P_4. Each chamber has three planes of wires. Downstream of the spectrometer there is a particle identifier. It consists of an electron calorimeter, which has a resolution of $\pm 4\cdot\sqrt{100/E}$ %, a hadron calorimeter which has a resolution of $\pm 14\sqrt{100/E}$ %, and a muon identifier. The properties of the electron calorimeter are described in more detail in our measurement of the decay of the ψ (3.1) into e^+e^- pairs, reference 5.

The features of our apparatus which we find so powerful are: It can take up to 200 very complex events per spill, while the average number of interactions in the target is 3×10^6 per spill. It can distinguish leptons from hadrons in the trigger at the same interaction intensity. We have been able to reconstruct tracks from this type of data efficiently and rapidly. The first results for the ψ (3.1) photoproduction from 300 GeV protons were submitted for publication well before the E-87A data runs were finished. These features make our detector unique among the multiparticle detectors at Fermilab.

We have routinely reconstructed 4, 6, and 8 prong events in the photoproduction of hadrons. A paper[7] is in preparation on the production of $\rho' \to \pi^+\pi^-\pi^+\pi^-$ and $\rho' \to \pi^+\pi^-$ by 50 to 200 GeV photons.

This paper will also present evidence for diffractive photoproduction of six and eight body charged final states.

We have been able to routinely identify K^o_S and Λ^o decays which occur before the second multiwire proportional chamber. A paper is in preparation on the production of the Q_A by K^o_L and the photoproduction of $\Lambda^o\overline{\Lambda}^o$ + pions and $K^o_S K^o_S$ + pions.[8]

We propose the following changes:

1) To use a beam of 400 GeV protons;

2) To increase the acceptance by a factor of four;

3) To improve the momentum resolution of the detected secondaries;

4) To improve the electron and muon identification.

We choose to use the protons because they will provide the highest possible energy thereby making it more likely to detect both the leptons and the forward going hadrons. In addition the definition of x is clear since the energy of the protons is known. Finally the small spot size of the proton beam compared to the neutron beam is an advantage.

The arrangement of the new detector is shown in Figure 3. The increase in acceptance was obtained by decreasing the length of the detector. The target will be located 180" in front of the 24" x 16" x 72" analysis magnet, rather than 300" in our previous experiments. In this arrangement a ψ (3.1) produced at $x = 0$ by a 400 GeV proton will be detected. A plot of both the yield of the ψ (3.1) and the efficiency as a function of x is shown in Figure 4.

The momentum resolution will be $\frac{\delta p}{p} = .02 \left(\frac{p}{100}\right)$ for a field of 18 kG in the magnet. The mass resolution for the ψ (3.1) when averaged over the full range of momenta will be $\pm$ 60 MeV/c^2.[4] We have used the data of Reference 2 to estimate the expected $P_\perp^2$ and P_{11} distributions for the ψ (3.1) production. The mass resolution of the new particles, A, would be similar if they were produced with the same dependence on $P_\perp^2$ and P_{11}.

The improvement in the electron detector consists of adding two horizontal scintillation counter hodoscopes e_H and γ_H. The γ_H hodoscope is preceded by two radiation lengths of lead. Electrons will be identified as a coincidence between an e_H and a γ_H counter, while photons, if they convert, will be identified by a count only in a γ_H counter. Pulse height analysis will be done on all counters. This technique has provided satisfactory identification of electrons in other Fermilab experiments.[6]

In addition, a fifth proportional chamber, P_5, will be placed downstream of γ_H. A measurement of the conversion point of a photon in P_5 leads in turn to a measurement of its direction. The energy of the γ's and e's will be measured in the electron calorimeter. With this improvement it will be possible to both detect γ rays from a π^o or η^o with reasonable efficiency and to measure their momentum with an accuracy comparable to our measurement of charged particles. We have in a similar, but poorer, arrangement detected the photoproduction of the ω $(\pi^+\pi^-\pi^o)$.

The muon identification is improved relative to E-87 by the reduction in the overall length of the spectrometer by nearly a factor of two, thereby reducing the probability of pion decay. In order to eliminate the false triggers due to the punch through of energetic hadrons additional steel will be added in the hole in HC_1 and between HC_1 and the muon identifier. Finally we plan to exclude low mass pairs from the trigger, by improvements to the muon identifier electronics.

We believe, on the basis of our experience, that we can routinely identify a baryonic or a mesonic state which decays according to the reactions

$$B_A \rightarrow \underset{\hookrightarrow p\pi^-}{\Lambda^o} + n\pi^+ \; m\pi^- + q\pi^o \qquad n,m = 1,2,3 \tag{2}$$

$$M_A \rightarrow \underset{\hookrightarrow \pi^+\pi^-}{K^o_S} + n\pi^+ + m\pi^- + q\pi^o \qquad q = 0 \text{ or } 1 \tag{3}$$

The experiment will also be very sensitive to decays which include the semileptonic decays of hadrons. Thus process (4) can be observed

$$A \rightarrow \begin{pmatrix} \mu & & \nu_M \\ & + & \\ e & & \nu_e \end{pmatrix} + \text{hadrons} \tag{4}$$

by the presence of a third energetic lepton.

In order to establish the level of the three muon signal, part of the data will be taken with steel placed between the target and P_1. By adding the steel the decay length can be reduced from 280 inches to 70 inches or less. This arrangement of equipment, which is shown in Figure 2, was used successfully in E-358. In that experiment as in this proposal the added steel was a calorimeter. The "steel in" data would serve two purposes: First, it would allow us to determine the background levels due to pi decay in the same charge two muon events, the opposite charge two muon events, and the three or more muon events. Second it would allow us to look at the single muon events.

Because of the large data collection capability we can look for new baryons and new mesons simultaneously. Moreover we can look for these particles without a prior prejudice about their decay modes.

In other experiments it has been necessary to focus on a single simple decay mode, such as $K\pi$.

III. RATE CALCULATIONS AND EVENT COLLECTION

We have used a flux of 10^7 protons per pulse incident on a 2" Be target in order to calculate the number of interactions per spill. We have used the "White Book" parameters for a 400 GeV spill, which are a 2 second flattop with an 8 second repetition rate in order to arrive at the total number of interactions for a 750 hour experiment. Finally we have used a value of 2×10^{-32} cm^2/Be nucleus for the product of the branching ratio of the ψ (3.1) into muon pairs times its production cross section for $x > 0$, in order to estimate the yield of events per proton interaction.[2]

The geometric acceptance of the apparatus as a function of x has been calculated. The results of that calculation are shown in Figure 4. In addition the relative yield of events as a function of x is shown in the same figure. The dependence of the production cross section on x was approximated by $(1-x)^7$ for these calculations. The average detection efficiency for positive x was calculated to be 14%. The average x of the accepted ψ (3.1) was .2 . On the basis of these assumptions the yield of ψ (3.1) for 600 hours of steel out running is 4000 events. The total number of dimuon triggers for the same period will exceed 2×10^7 events. We estimate that such a sample will contain 4×10^5 ρ^o (770) $\rightarrow \mu^+\mu^-$ events, 4×10^4 ϕ^o (1020) $\rightarrow \mu^+\mu^-$ events, and 2×10^4 events in the continuum between the ϕ^o (1020) and the ψ (3.1).

The instantaneous flux of particles through the chambers corresponds to a flux which has actually been sustained. If the flattop is only one second long the number of spills which will be needed to accumulate 4000 events of ψ (3.1) $\rightarrow \mu^+\mu^-$ will increase by nearly a factor of 2.

The efficiency to detect a three body final state with x = .25 which is produced in association with a dilepton varies from 35% at 4 GeV mass to 70% at 2 GeV mass. As the momentum of the final state increases the efficiency for detection increases. If new particles were produced in association with the ψ (3.1) half of the time, there would be a sample of more than 1000 events which would contain new particles.

The only contribution of unwanted triggers will arise from the decay of uncorrelated low momentum pions. Since the decay length for hadrons is 280", the decay probability of a 14 GeV pion is 1.2%. 14 GeV is the minimum momentum pion that can be contained in the spectrometer if it is produced with a $P_\perp$ of 0. Since the average number of charged pions with this momenta or greater is between 2 and 3, the probability that two pions decay is 4 x 10^{-4} per 400 GeV proton interation. This trigger rate without further improvements would be 400 events/pulse.

By imposing additional requirements such as a minimum opening angle, the separation of the muons at the μ_V plane, and the correlation of the opening angle and the momenta, correlations among the e_H and μ_H counters, another factor of 10 to 20 can be achieved. As long as the trigger rate is less than or equal to 100 events per pulse, data can be taken with less than 5% dead time. While our goal would be to reduce the 2μ trigger to a minimum, we would plan to take 100 to 150 events per pulse by simultaneously recording ee and μe events.

A similar yield of high mass dileptons without the associated hadrons can be obtained with the "steel in" data for 100 hours of running. The "steel in" data would be taken with a 6" target and a 3" target. The beam intensity would be 10^6 protons/spill when the pulse height information from the upstream calorimeter was used. This would be used for only a small part of the data, during most of the steel in running the beam intensity would be 10^8 protons/spill. The trigger rate with the "steel in" will be reduced since the contribution due to π decay will be reduced by a factor of sixteen or more. The acceptance for the "steel in" is less since the target needs to be placed further upstream. The reduction is more than compensated by the fact that the interaction rate is increased by a factor of thirty.

IV. BACKGROUND IN RECONSTRUCTED EVENTS

On the basis of the results of E-358, we can estimate the ratio of the pi decay background to the direct dimuon signal after reconstruction. When the dilepton momentum exceeded 20 GeV/c the ratio of the sum of $\mu^+\mu^+$ and $\mu^-\mu^-$ events to $\mu^+\mu^-$ events was 5% 0.5% in the mass range of .65 GeV/c^2 to .9 GeV/c^2 (the ρ region). When the dilepton mass was greater than 2 GeV/c^2, no events with the same charge were observed, while 120 events were observed with opposite charge. Fifty of the latter were ψ (3.1) decays. Since the effective decay length in that experiment was 80", we would expect that the signal-to-noise ratio would deteriorate by a factor of ten. For a dimuon mass of .77 GeV/c^2, and a dimuon momenta of 45 GeV/c, we expect background at the level of 10%. In the region of the ψ (3.1) we expect less than 1% background due to π decay. The steel in data will provide an experimental evaluation of these backgrounds.

V. BEAM AND EQUIPMENT

We propose to bring a proton beam with an intensity of 10^6 to 10^8 protons/spill through the present 0 mr neutral beam line. It would not be necessary to remove the D_2 filter as this beam will fit through the cryostat tubes without difficulty. The magnets which are in the beam line can be used for steering. The method of getting a low intensity proton beam to our B3 target in EE4 is as follows:

The beam will be collimated to a spot size of 12 mm x 12 mm in enclosure H as has been done in P-Center. It would be desirable to have this collimation ahead of MH323 so that the 8 mr bend of MH323 can sweep away off momentum particles. After MH323 the beam drifts a distance of 2000 feet to the P-East target hall.

We propose to collimate the beam a second time to a spot of 3 mm x 3 mm with a fixed collimator placed in the space between QV400 and QH401. These quadrupoles form the doublet which is used to focus the beam on the target in the P-East target box 140 feet further downstream. We propose instead to focus the beam on our target in EE4, 600 feet downstream of the quadrupoles. This will produce a beam, which is slightly convergent, with a spot size which is roughly 1.5 mm x 1.5 mm at the target. Following the quadrupoles there is a 6 mr horizontal bend, BH403, which will sweep the off momentum particles away. The E-87 target drawers form a channel which is 12 mm x 12 mm, eighty feet downstream of the magnet bend point. It would remove most of the secondary halo and make the beam plus halo smaller than the bore of the D_2 filter.

The collimator in P-East will reduce the beam intensity by a factor of fifty, while the collimation in enclosure H will provide another factor of five. Consequently a beam of 3×10^9 can be reduced to 10^7. The method presented here is one of several possible schemes. Since the "steel in" data requires a greater beam intensity the collimators would be changed.

We propose to add two additional coils to the present 24" x 16" x 72" magnet in order to raise the field to 18 kG. The present 500 kW power supply will be adequate, although the water supply in EE4 will need to be improved.

The additions to the γ ray detector will require additional PREP equipment. We estimate that an additional fifty discriminators and a number of matrix coincidence units are needed besides the PREP equipment now being used by E-87/E-358.

We proposed to fill the hole of HC_1 with a steel and tungsten dump. By doing this, HC_1 would become a well shielded reentrant beam dump for the protons. We propose to add a steel shield between HC_1 and the muon identifier which is 5' x 5' x 4' (25 tons). We also propose to add an additional 50 tons of steel behind the muon identifier to further increase the minimum range required of the muons. The steel does not need to be machined.

VI. RUNNING TIME REQUESTS

We propose a test of fifty hours in order to identify technical problems which affect the beam quality, to assess some of the methods of collimation, and to obtain a preliminary measurement of the trigger rates and the background after reconstruction. This could be done by turning the target box magnets off at the conclusion of Experiment 358.

We propose that a 5 mm x 5 mm channel be incorporated into the beam dump of E-300, so that the option of transmitting protons to

EE4 exists when that experiment runs. This would permit two things; first, parasitic operation during the low intensity phase of E-300 would allow our detector to be fully tested before the data taking began and second, it would not be necessary to change target box components or move the E-300 spectrometer when a transition is made from E-300 to this experiment.

If the experiment is not interleaved with E-300 it can readily be interleaved with E-87 or its successor; since the E-87 target system is compatible with this proposal. If the first test were done by September we would be ready to start by November 1975 or whenever the two additional coils are installed in the magnet.

We will need 100 hours of test time to establish the beam and check out our detector. In addition we will need 600 hours of beam time to take data with the steel out and an additional 120 hours with the "steel in". In more precise terms we need 300,000 beam spills of 2 seconds duration of an average intensity of 10^9 to 5×10^9 protons/spill for the data taking phase of the experiment. Six days are a more appropriate measure for the test time.

References

1. "Photoproduction of Narrow Resonances", B. Knapp et al. Phys. Rev. Letters 34, 1040 (1975). Experiment 87.
2. "Dimuon Production by Neutrons", B. Knapp et al. Phys. Rev. Letters 34, 1044 (1975). A preliminary report on the 340 GeV data was presented by J. Peoples at the Washington APS Meeting. A final article is in preparation.
3. "The Production of J-ψ in pp scattering", R. Michael Barnett and D. Silverman, to be published. Harvard University Preprint. "Possible Production of Charmed Hadrons in Conjunction with the ψ (3100). D. Sivers SLAC-PUB-1558.
4. The momentum resolution can be improved considerably by using drift chambers at the present location of P3 and P4. If a quadrupole doublet located in EE-1 were used to focus the proton beam on the target in EE-4 a spot size which is less than .3 mm vertical can be obtained. We are exploring these possibilities.
5. A preliminary report on the detection of the ψ (3.1) into e^+e^- pairs was presented at the Washington APS Meeting. Paper J03, "Production of Large Invariant Mass e^+e^- pairs by High Energy Photons", L. Cormell et al. A final report is in preparation.
6. "Performance of a Lead Glass Electromagnetic Shower Detector at Fermilab", J.A. Appel, et al. to be published in Nuclear Instruments and Methods.
7. A preliminary report on 2, 4, 6, and 8 body diffractively photo-produced states was presented at the Washington APS Meeting. Paper J05, "Photoproduction of Hadrons at Fermilab", S.D. Smith et al. Bulletin of the American Physical Society, Washington APS Meeting, April 1975. A final article is in preparation.

8. A preliminary report on the photoproduction of K^{o}_{S}, Λ^{o}, and $\overline{\Lambda}^{o}$ has been presented at the Washington APS Meeting. Paper J07, "Strange Particle Photoproduction at FNAL Energies", P. Leung et al. Bulletin of the American Physics Society, Washington APS Meeting, April 1975. A final article is in preparation.

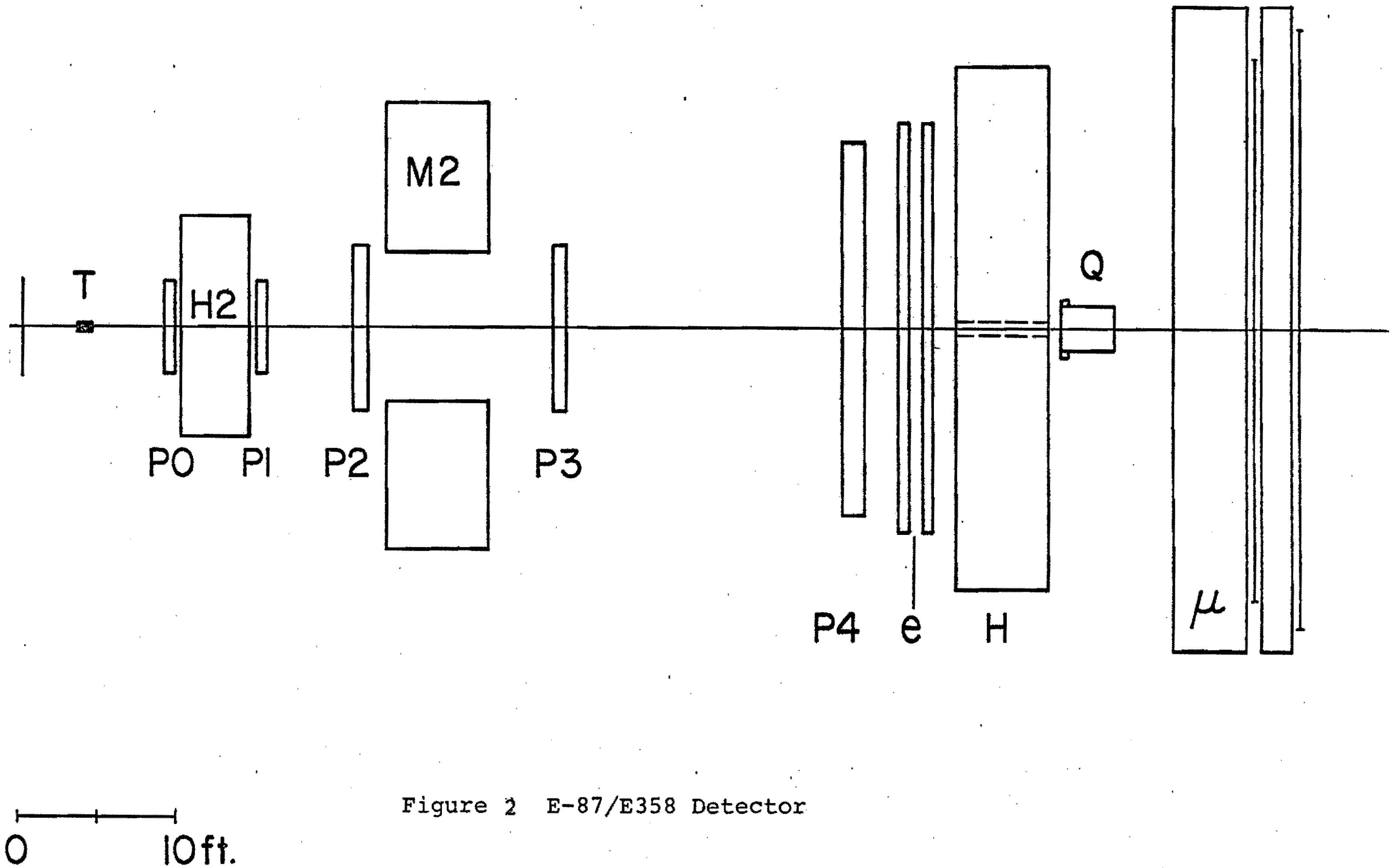


Figure 2 E-87/E358 Detector

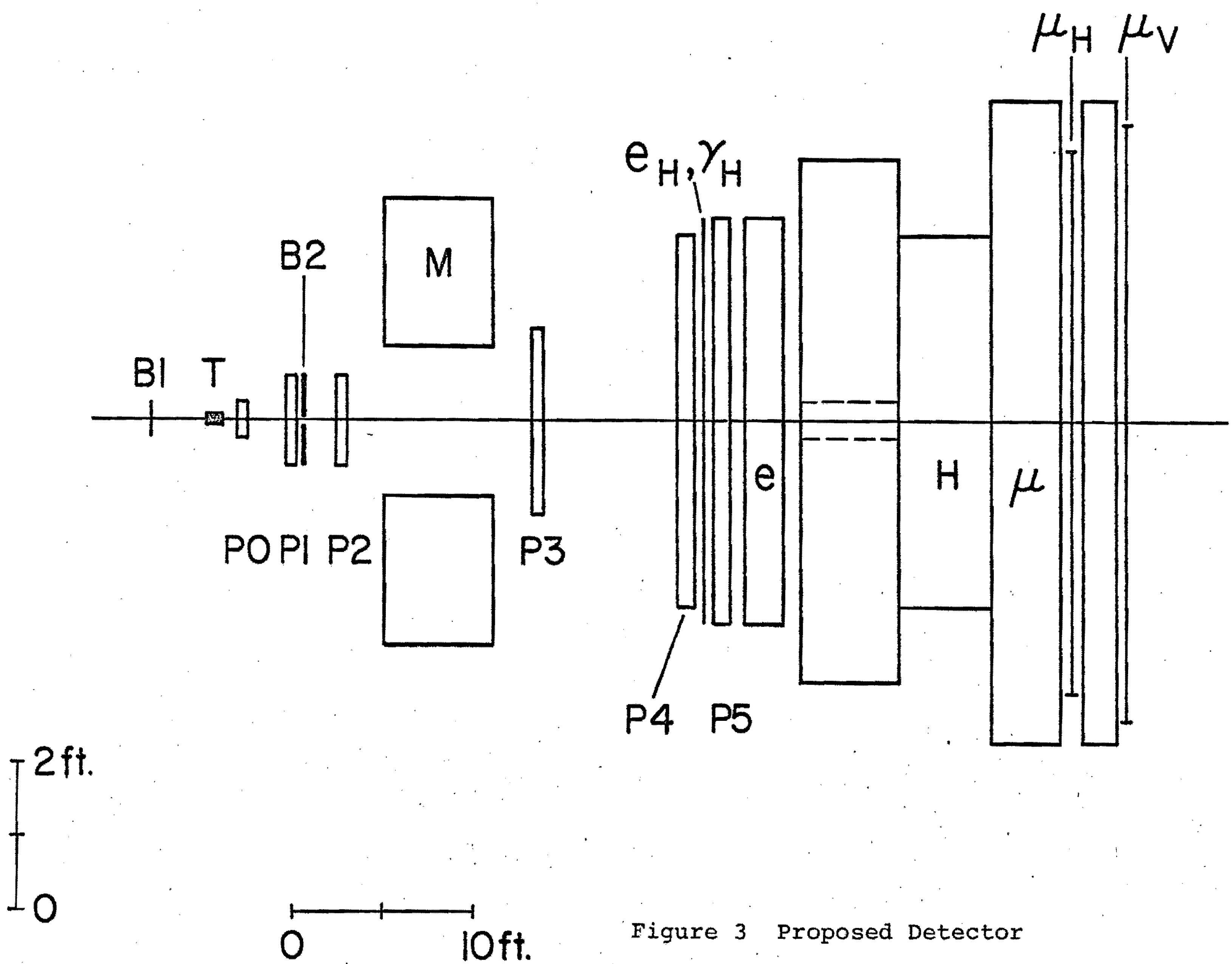
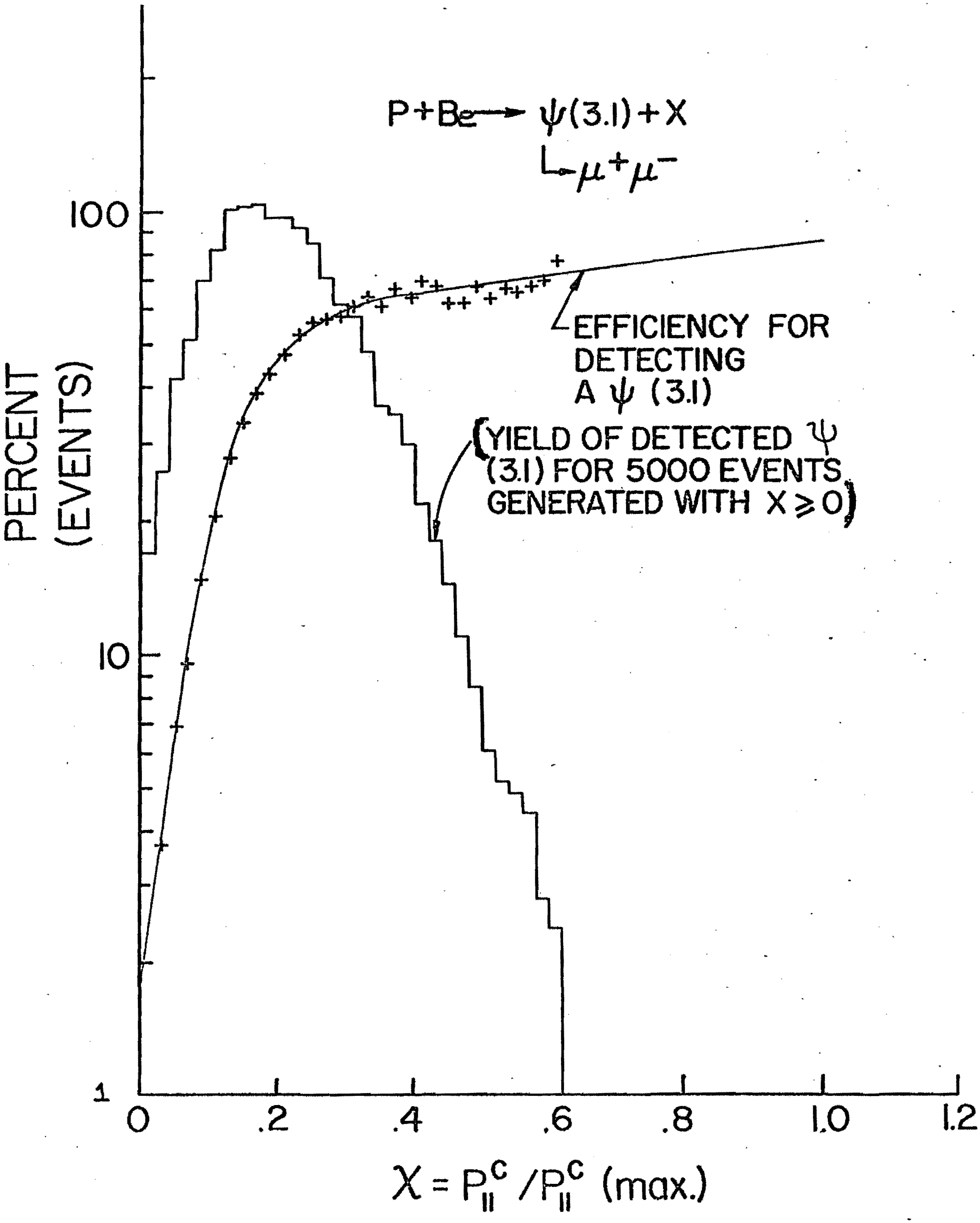


Figure 3 Proposed Detector

Figure 4


P+Be → ψ(3.1) + X
→ μ+μ−
100
10
1
PERCENT (EVENTS)
EFFICIENCY FOR DETECTING A ψ (3.1)
YIELD OF DETECTED ψ (3.1) FOR 5000 EVENTS GENERATED WITH X ≥ 0
0
.2
.4
.6
.8
1.0
1.2
X = P∥c / P∥c (max.)

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E-400 REVISED OBJECTIVES

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E-400 REVISED OBJECTIVES

E-400 was approved in 1975 to search for new particles which accompany the production of the J/ψ in hadron collisions. The dimuon decay of the J/ψ should be a powerful tool to search for beauty. As we will show, the unique features of our detector will provide a sensitive search for beauty which is different from the other Fermilab experiments which are planning such a search.

Five years ago we proposed E-400 as a way of searching for charm particles. Since the lightest charmed mesons and baryons have now been identified, we believe that merely observing a handful of charm particles is not a sufficient justification to carry out an experiment. Encouraged by our success in observing charmed particles in the E-4XX detector , we have expanded our original goals to include a measurement of the production dynamics of the D^+ , $(D^*)^+$ and C_o^+ , to search for the charmed baryons with one unit of strangeness, A^+ and A^o , and to obtain a large very pure sample of D^+ and D^-, which will be a tool to search for beauty in a way which is complimentary to the use of the J/ψ .

It is worth recalling some of the discoveries of the past five years that led us to reconsider the goals of E-400.

1. The Υ family was discovered at Fermilab by E-288 establishing that a new quark, the b quark, exists with a mass of about 5 GeV/c^2. This allows the possibility that a meson or baryon which contains a b quark will have decay modes which contain the J/ψ [1].

2. The lowest lying charmed baryon, C_0^+ and the charmed mesons, D^0 & D^+, with the strangeness 0 have been observed in e^+e^- annihilations at SPEAR[2] and in photo-production at Fermilab, by our collaboration E(87)[3].
3. Several experiments at Fermilab, the first of which, E-358, was done by our collaboration, convincingly showed that D^+ and D^- do not accompany the production of the J/ψ in hadron collisions at the level of one D^+ for every thirty J/ψ[4]. This limit has subsequently been improved by the Stanford-Fermilab-Cal Tech-Rochester collaboration (E-379)[5].
4. The lifetime of the charged D^+ has been measured and found to be about 8×10^{-13} seconds by the neutrino emulsion experiment E-531 at Fermilab[6]. The same experiment showed that the C_0^+ (2285) lifetime is about 2×10^{-13} seconds, while the D^0 lifetime is much shorter[7].
5. A single prompt muon signal has been observed in p-p collisions by E-379 and E-595. This result can be explained by a charm cross section of about 22 μ barns[8]. The interpretation of the yield of prompt ν's from a beam dump is consistent with this cross section for charm[9].

These discoveries did not go unnoticed in the experimental community. Shortly after E-400 was approved the Goliath group at CERN redirected its efforts away from a π^--p backward scattering experiment to an experiment with the same goals as E-400. A brief summary of the efforts at Fermilab which are relevant to the goals of E-400 is as follows:

1. E-610 has been approved to look for the hadronic production of χ states which decay into a $\psi + \gamma$. This experiment expects to obtain a sample of about 20,000 dimuon decays of the J/ψ, which should allow a beauty search of comparable sensitivity to the Goliath experiment. Other experiments such as E-537 have also proposed to look for χ's.
2. E-515 has been approved to look for charm particles which are produced in association with prompt muons. It has the sensitivity to see a few hundred reconstructed charmed particle decays for several decay modes.
3. P-630/E-490 has developed a superb streamer chamber capable of measuring tracks to an accuracy of better than 50 μ, with the intention of looking for a small sample of charm and beauty decays. While the final state cannot be reconstructed in this experiment, it is sensitive to observing beauty if the lifetime is between 5×10^{-14} seconds and 5×10^{-12} seconds.
4. E-595 will run again to measure the properties of the single prompt muon signal. Since the experiment cannot connect the source of the prompt leptons to specific charm mesons or baryons it can only provide limited information on the hadronic cross sections of charmed particles.
5. E-516, an elegant spectrometer which is being built in the tagged photon laboratory, possesses all of the features of our present detector without the K_L^0 back-

ground which plagued our experiment. This experiment should provide details of the mechanism of charm photo-production with a small but very well measured set of final states.

After having been a pioneer in the field of hadronic production of the J/ψ and the photoproduction of both the J/ψ and charm we found ourselves in the position of being just another experiment trying to explain prompt lepton production. Because we believe that the new experiments will succeed in measuring what they proposed to measure, we plan to redirect our efforts at measurements which these experiments cannot do. Our redirected goals are as follows:

1. To obtain an unbiased measurement of inclusive D^+ and C_0^+ as a means of establishing the Feynman X and $P_\perp$ dependence of charmed meson and baryon production. We expect to obtain a combined D^+ and D^- sample of about 50,000 events in the $K^\mp \pi^\pm \pi^\pm$ decay mode.
2. To search for charmed baryons which have one unit of strangeness. The sensitivity of this experiment will be 150 events per nanobarn of cross section times branching ratio. By comparison we expect to observe 2,500 events of C_0^+ decaying into $K_s^0(\pi^+ + \pi^-)P$ if its cross section times branching ratio is 15 nanobarns.
3. To obtain a background free sample of at least 30,000 $K^\pm \pi^\mp \pi^\pm$ decays of D^+ and D^-. This will be accomplished by using a small high resolution ($\sim 60\ \mu$) multiplane multiwire proportional chamber. This chamber,

when supplemented with the powerful pattern recognition of the E-4XX spectrometer will provide a resolution of .5 mm on the separation of the decay and production vertices. Because we will be able to distinguish the decay vertex of D^+ or D^- from the production vertex when the two are separated by more than 3 mm, the ratio of signal to background will be better than 100 to 1. Since beauty is expected to decay most of the time into charm particles this sample can be used to search for evidence of beauty production in hadron collisions. The sample is so large that it should provide unique information on the underlying production mechanisms.

4. To search for the fully reconstructed decays of beauty. The power of our detector will permit the reconstruction beauty decays into final states such as $J/\psi + K^- + p$ and $J/\psi + K^- + \pi^+$. There is some evidence that such decays have been seen at CERN by the Goliath experiment[6].

5. To obtain a large sample of J/ψ decaying into $\mu^+ \mu^-$ pairs ($\sim$ 35,000 events) and e^+e^- pairs ($\sim$ 23,000 events). This sample can be used to look for inclusive decays of beauty into J/ψ plus other particles. The method is particularly sensitive if the lifetime of one of the beautiful particles is greater than 2×10^{-13} seconds, since it will then be possible to observe the dimuon decay vertex of the J/ψ a few millimeters downstream of the production vertex of beauty particle.

The remainder of this report describes how we can achieve our five objectives and why we think it is worth it to make these measurements. The report is divided into the following sections:

1. Beam requirements
2. A description of the E-4XX detector
3. A high resolution track chamber and charm enrichment
4. The Cerenkov counter system and particle identification
5. The neutral particle identification and prompt electron identification
6. Prompt muon identification
7. Trigger and trigger processing
8. Rate calculations and background estimates

1. Beam Requirement

We have chosen to use neutrons, instead of protons, because the neutrons which do not interact in our target will not leave tracks in either the high resolution chamber or the downstream proportional chamber spectrometer. We require 6×10^6 neutrons/pulse in a beam spot which is 4 mm high and 40 mm wide. We require a 1 second flat top or longer and we prefer an energy of 400 GeV or more. Based on our past experience with the broad band beam, a very modest intensity of 5×10^{11} protons/pulse should be sufficient to provide us with the desired flux of neutrons. It is worth noting that our proton intensity requirement is less than 2.5% of the normal machine intensity.

We plan to use a segmented target which consists of three 2.5 mm sheets of Be separated from each other by 12.5 mm. The segmentation will reduce the confusion between downstream decays and interactions of secondary particles in the target.

2. A description of the E-4XX detector

The detector as used in the 1979 runs for E-401 is shown in Figure 1. The essential features were two magnets, one which can provide a deflection of 500 Mev/c, M1, and one which can provide a deflection of 800 Mev/c, M2. The direction of the field was in the horizontal plane perpendicular to the beam. There were 5 sets of proportional chambers. Each chamber had three planes, x , u , v . Wires were spaced by 1 mm in PO and by 2 mm in all other planes except the P4X plane, which had a 3 mm spacing. The MWPC system provided exceptional pattern recognition and good momentum resolution. For example, Ξ^- , Λ^o , K_s^o were all easily reconstructed in events with charged multiplicities between 4 and 12 tracks in the E-87 experiments. The Λ^o and K_s^o invariant mass spectra are shown in Figure 2. We define the part of the spectrometer which is subtended by the second magnet, M2, the inner detector. The remainder is called the outer detector. The measured RMS mass resolution of a D^o decaying to $K^-\pi^+$ which was detected in the inner detector was 10 Mev and the measured mass resolution of a C_o^+ (2285) decaying to $K_s^o p$ in the inner detector was 7 Mev. The quality of the mass resolution is shown in Figure 3 which shows both the D^o and the C_o^+ invariant mass distributions.

The position resolution of the MPWC system was approximately 250 μ . This resolution was achieved by measuring the time of arrival of the individual MWPC hits relative to a reference time. The time of arrival was then used to interpolate the position of the hit relative to the wire with a hit. This is the Columbia mini drift which was developed for E-87. Further details on chamber sizes and magnet apertures are given in Table I.

Table I - Properties of the E-4XX Magnetic Spectrometer

Device	Aperture or Useful Area	Comment
AN423B	14 " x 30"	$e\int B\cdot dl$ = 500 Mev/c
PO	11 1/2" x 15 1/2"	1 mm wire spacing
P1	20" x 28"	2 mm wire spacing + mini-drift
P2	32" x 40"	2 mm wire spacing + mini drift
AN422B	20" x 24"	$e\int B\cdot dl$ = 800 Mev/c
P3	32" x 40"	2 mm wire spacing + mini drift
P4	40" x 60"	2 mm or 3 mm (P4X) wire spacing + mini drift

The spectrometer had two threshold Cerenkov Counters C_1 and C_2 . C_1 had 12 cells and C_2 had 16 cells. Modifications will be made to C_1 and C_2 for E-400. It also had an inner electron-photon identifier e_i which consisted of lead glass blocks and an outer electron/photon identifier e_o which consisted of lead and scintillator sandwiches. The trigger, trigger processor and analog electronics are described in Section 7.

The reconfigured E-400 detector is shown in Figure 4. The basic magnetic spectrometer is changed by adding a high resolution chamber described in the next section, and a third Cerenkov Counter, C3. We also plan to rewind the x signal planes of P_2, P_3 and P_4 with a 20% greater wire spacing in order to reduce the failures caused by wire breakage. It has been known to us for some time that those chambers were at the edge of mechanical stability. During the last E-401 run one or two wires broke in P_2, P_3 and P_4. Wires have never broken in the other chambers in nearly seven years of operation.

3. A high resolution track chamber and charm enrichment

The improvement which will allow us to make the measurements described earlier, is a very small high resolution MWPC chamber. It will consist of eighteen planes of wires each with 1/2 mm spacing. The active area of the chamber will be 40 mm (vertical) by 80 mm (horizontal). It will have 6 x planes (vertical wires) and 6 u planes and 6 v planes (45° wires). The planes will be arranged in pairs separated by 3 mm. The wires of each pair of planes will be displaced by 1/2 wire spacing relative to one another thereby providing an effective 250 μ wire spacing. It will have an overall length of 100 mm and its upstream end will be located 100 mm downstream of the center of the Be target. The argon ethane gas will be at four atmospheres. The Yale group has built and operated chambers which are similar to the chambers we are proposing[11].

Since the typical minimum projected angle between tracks which will be detected in the inner detector is greater than 10 mr, tracks will be usually separated by more than two wires when they reach the first plane of the high resolution detector. Since chambers P_0 , P_1 , and P_2 can resolve projected angles as small as 2 mr the degradation of resolution which occurs when tracks share hits in the high resolution chamber can be improved significantly. Because of P0, P1, and P2 we believe that it will be possible to resolve tracks with projected angles as small as 5 mr in the high resolution chamber.

The transverse location of the primary production vertex or a decay vertex will be measured to an accuracy of 60 μ without making use of the minidrift. Our preliminary calculations indicate that the separation between the primary vertex and the decay vertex can be measured to about 0.5 mm when the mini drift is used. Such a separation is adequate to separate D^+ decays from the production vertex, since a typical D^+ detected in our detector will have a momentum of 40 GeV/c, corresponding to a mean decay length of 5 mm. As an example of how the high resolution chamber can improve the purity of the charm signal consider its effect on the $K^+ \pi^- \pi^-$ final state. We expect a signal of 25,000 events over a background of 1,000,000 combinations. Although the signal to background is adequate to definitively observe the D^+ , the poor signal to background will not allow a detailed study of the particles which accompany the D^+ . By requiring that the decay vertex and the production vertex be separated by 3 mm, the signal is reduced to 18,000 events and the background to 30 events. The chamber should be very useful in searching for the A^+ which is expected to have a lifetime which is about 4 x 10^{-13} seconds, since with such a lifetime it will travel about 2.5 mm before it decays.

The high resolution chamber will also be useful in isolating the decays of the C_0^+ (2285) and the A^0 since it will improve our mass resolution. Tracks which traverse the outer detector were poorly measured in E-87 and E-401. By defining a point on the tracks to better than .05 mm in front of the Magnet M1 the momentum measurement will be improved. If these particles have a lifetime of 2×10^{-13} seconds we may be able to observe them in the same way as the D^+.

4. <u>Cerenkov Counter System and Particle Identifier</u>

The Cerenkov counter system used successfully in E-87 to observe charmed mesons and baryons will need greater segmentation to cope with the higher average multiplicities expected in E400. We have studied neutron-induced events collected in E-87 to learn the best way to segment these counters. We plan to modify C1 by removing all but 2' of the radiator from the magnetic field and by increasing the number of cells from 12 to 28. The counter C2 will be shortened from 15' to 11' by dropping off one four-foot long section. The mirror plane and part of the photo-multiplier port assembly will be rebuilt to accommodate a total of 30 cells. In both counters, the cells will be smaller toward the center of the system where the average particle density is highest. The cell sizes are chosen so that no cell sees more than 1/3 track per event on the average.

As in E-87, C1 will have a π-threshold of 6 GeV and C2 will have a π-threshold of 12 GeV. These thresholds permit the separation of protons and anti-protons from pions and kaons from 20 to 80 GeV/c. Below 20 GeV, the existing two counter system cannot distinguish protons from kaons. Since our Monte-Carlo calculations show that a factor of two increase in acceptance can be obtained if the K identification is extended down to 10 GeV, we plan on building a third counter, C3, which will be able to distinguish K's from P's between 10 and 20 GeV. This counter, when filled with isobutane at 1 atm, will have a π -threshold of 2.6 GeV, a K-threshold of 9.4 GeV, and a p-threshold of 18 GeV. This will be an excellent match to the other two counters. Since the length of the radiator can be as short as 10", the counter will not require a major reconfiguration of our detector. A segmentation of 12-16 cells will be adequate.

This 3-counter system will provide better particle identification than any of the currently approved hadronic charm searches. We believe that it is essential to a successful measurement of the inclusive charm cross sections.

5. Neutral Particle Identification and Prompt Electrons

The neutral particle and electron identifier will consist of blocks of lead glass. The inner detector will consist of an array of 2 1/2" x 2 1/2" x 24" blocks and 6" x 6" x 18" blocks. Between the two layers of blocks there will be an array of proportional tubes. The position of gamma rays which convert in the 3.5 radiation length upstream of the proportional tubes will be measured to an accuracy of $\pm$ 5 mm.

The outer electron identifier will consist of an array of 6" x 6" x 18" blocks and 2 1/2" x 2 1/2" x 24" blocks . Proportional tubes will be used to measure the location of the rays as in the inner detectors.

6. Prompt muon identification

Candidates for muon pairs will be identified by first requiring each muon to penetrate either the inner muon detector or the outer muon detector. An inner muon will be defined as a coincidence among the master gate, to be defined in the next section, and the two muon counter hodoscopes. An inner muon must penetrate a minimum of 2100 grams of iron and lead glass in order to reach the most downstream counter bank. An outer muon must penetrate the 1400 grams of iron in the return yoke of the magnet M2. Since the bulk of the particles which satisfy these requirements will be low energy pion decays, a measure of the muon momentum must be made with the M7 before the event is written on tape. An inner muon will be further identified by the position of its hits in the muon drift chambers in the steel. The M7 will process this information in order to select a sample of muons with a minimum transverse momentum of 1 GeV/c.

7. Trigger and Data Acquisition

Our triggering system relies on a multi-stage trigger which takes advantage of a large buffer memory and of the computing power available in our M7 hardware processor to produce a selective yet relatively unbiased set of events on tape to study hadronic production of charm. The trigger is applied in 3 stages: first, more or less conventional fast logic (together with our standard DC-logic system) is used to select events for real-time processing by the M7; second, the M7, using information from the muon drift chambers and from fast ors of bands of MWPC wires, selects events to be written into our buffer memory; and third, between spills the M7 can examine events in more detail (up to 10 msec/event) to make a selection of the events to be written on tape.

The M7 trigger processor (see TM 747 for more details) is actually a fast pipelined computer with a special purpose instruction set especially designed for dealing with track-finding and related problems. Its basic instruction, which it executes in about 100 nsec, is $E = A \cdot B - C \cdot D.$, which is ideal for predicting a hit position in a third chamber based on observing positions in the two other chambers. It also has instructions which allow it to scan through a list of data (e.g., hits in a chamber) looking for a match.

Two special purpose interfaces have already been constructed to rapidly transmit certain blocks of the experimental data to the M7 and thus allow it to make real-time trigger decisions in 5 to 100 μ sec. The first of these read the data from the bi-dimensional muon drift chambers in the back of our detector. Using this data the M7 can calculate the mass of a dimuon or the transverse momentum of a single muon in 5-10 μ sec for use in prompt lepton triggers. The second interface gives the M7 chamber coordinates from our spectrometer MWPC's based on fast ors of groups of 8, 16, and 32 wires. Using this data the M7 can do crude resolution track-finding for use in the Cerenkov and $P_\perp$ triggers described below in 50-100 μ sec. Such track-finding was already done on-line in E-401, and the performance of the M7 allowed us to run at higher intensities and lower dead times than previously possible.

Using these features of the M7, we will set up triggers for the two separate, but simultaneously running, parts of the experiment as follows:

a) Inclusive charm trigger. This part of the experiment runs at an effective interaction rate of 5×10^4/pulse by pre-scaling the actual interaction rate of 5×10^5 . The higher rate will be used for the second part of the experiment.

The first stage trigger requires a large energy deposit outside the central hole in our hadron calorimeter, a multiplicity of at least 3 tracks in the inner detector and a loose requirement of a heavy particle in Cerenkov counters C_1 and C_2. A heavy particle will be defined as an anticoincidence between a scintillation counter matched to a Cerenkov mirror and the absence of count on that corresponding mirror. All of these triggers have already been used in our fast triggers in E-87 and E-401. Studies of background data taken during E-87 suggest that these requirements can reduce the raw interaction rate by a factor of 15 , i.e., from 5×10^4/pulse to 3300/pulse.

The second stage (real-time M7) trigger will reduce this rate by a factor of 5 by requiring the presence of a track of sufficient momentum and $P_\perp$ to be pointing at the Cerenkov mirror that was off. The momentum calculation will be done using the fast OR's of groups of eight wires. This will eliminate below threshold pions and uninteresting low $P_\perp$ heavy particles from the trigger. Note that this does not require finding all tracks or reconstructing low momentum tracks, but rather it merely requires finding a single track of sufficient stiffness pointing at the proper mirror. This is very similar to the M7 programs which were already used in E-401. The calculation will require 50-100 μsec/event, causing at the most a 20% dead time. It will cause 400 events/pulse to be read into our buffer memory. We plan to expand the buffer memory from its present 64k to 256k 16 bit words.

Finally, even though we could write all of these events onto tape using a 6250 BPI drive, we plan to make an additional reduction of a factor of 5-10 by doing a full track reconstruction of these events in the M7 between spills. The events will be read out of the buffer memory by the PDP-11 and the MWPC wire addresses will be block transferred to the M7's transfer memory via a DMA Camac link, overlapped with the M7 computation of previous events. This hardware already exists and has been used, although not for this purpose. The M7 will have more than 10 msec available for each event. For comparison, complete reconstruction on the CYBER system, with an instruction set less well suited for the problem takes 3 msec/event. We feel confident that the M7 can reconstruct events, in 10 msec corresponding to 100,000 M7 instruction cycles if a few enhancements to handle detailed high precision fits are included in the repetoire of M7 instruction. This will allow the PDP-11 in conjunction with the M7 to put quite sophisticated mass and $P_\perp$ cuts on the data to reduce the number of events written to tape below our canonical 150 events/pulse.

b) ψ and prompt leptons trigger. This part of the experiment will take advantage of an interaction rate of 5×10^5. While the interaction rate will be higher, the trigger rate will be quite a bit lower because of the scarcity of leptons. The first stage trigger, which will start the M7, will demand a target interaction together with counts in the muon hodoscope, and will only count at 10^2/pulse. The second stage real-time M7 trigger will easily reduce this to a few tens of events/pulse by imposing a dimuon mass cut at 1.5 GeV and a single muon $P_\perp$ cut of 1 GeV in 5-10 μ sec/event. This calculation will cause a dead time of $\sim$ 1%. Third stage M7 processing should not be necessary for the prompt lepton triggers but will be available.

8. Rates

In this section we present the results of acceptance calculations for the final states which we plan to detect. We have also made estimates of the background which we expect to encounter in each final state.

a. Inclusive D^+ production

On the basis of the E-379 result we have assumed that the inclusive D^+ production cross section is 11 μ barns/nucleon or 100 μ barns/Be nucleus.[8] For the purpose of efficiency calculation we assumed that the D^+ is produced from the decay of a 4 GeV object which decays into a D^+ and D^-. The parent object has a Feynman X distribution of $(1-X_f)^\alpha$, where $\alpha = 3.4$ and an exponential $P_\perp$ distribution, for which the average $P_\perp$ is 500 Mev/c. This model predicts a geometric acceptance of 19% for the D^+ decaying into $K^- \pi^+ \pi^+$. If we require the K^- to be unambiguously separated from pions and protons the efficiency drops to 14%. The acceptance and yields for other particles and other decay modes are presented in Table II.

The background which we expect in the $K^- \pi^+ \pi^+$ channel at a mass of 1.87 Gev/c^2 is 1,000,000 events per 10 Mev bin. The D^- peak is expected to be entirely within one 10 Mev bin. The background was obtained by scaling the number of $K^- \pi^+ \pi^+$ combinations in the mass interval $1.87 \pm .01$ Gev/c^2 which were from events with more than 250 Gev of visible energy up by a factor of 500. We estimated that there were 100 neutron interactions per pulse in the photon running of E-87. This figure was arrived at by using the measurement of neutron flux which was obtained when the cryostat was empty and then using a calculation of the neutron attenuation by the cryostat when filled with D_2. Relative normalization was made using the total flux of incident protons as measured by the SEM in P-East. The expected backgrounds are also given in Table II.

Table II - Detection efficiency of some representation charm particle decays

Particle	Decay Mode	Detection Efficiency	Yield/7.5×10^9 Neutron Interactions	Estimated Background
D^+	$K^- \pi^+ \pi^+$	14%	29K	10^3K
$(D^*)^+$	$(K^- \pi^+) \pi^+$	11%	7.5K	10K
C_o^+	$K_s^o P$	10%	1.4K	4K
	$K^- p \pi^+$	11%	4.4K	1.5×10^3K
A^+	$\Lambda^o K^- \pi^+ \pi^+$	6%	300*	10^3K
A^o	$\Lambda^o K^- \pi^+$	8%	300*	10^3K

*Assumes a ratio of $\sigma \cdot B$ for charmed-strange baryon production to charmed baryon production of 1:10. The background will be tremendously reduced in such states as $A^+ \to \Xi^- \pi^+ \pi^+$ for which the acceptance is comparable.

If we assume that the basic mechanism for producing the C_o^+, D^+, and D^o in hadron collisions is by gluon fusion and if we assume that the basic mechanism for producing these particles in photoproduction is by photon-gluon collisions, then we can use the E-87 results to estimate the C_o^+ cross section. In E-87 we observed the K^op decay of the C_o^+ and $K^-\pi^+$ decay of the D^o.

$$\frac{(B_{K^op}\cdot\sigma_{C_o^+})_\gamma}{(B_{K^-\pi^+}\cdot\sigma_{D^o})_\gamma} = \frac{3\pm1\ nb}{7\pm3\ nb} = .4\pm.2$$ [13]

If the preceeding assumption is valid we expect that this ratio will be the same for hadron collisions. Moreover it is reasonable to assume that the D^+ and D^o cross sections are the same. On this basis we can estimate the yield of C_o^+ which decay to K_s^op.

$$Y_{C_o^+\to K_s^op} = N_n\cdot\frac{\sigma_{D^o}}{\sigma_T}\cdot B_{K^-\pi^+}\left(\frac{B_{K^op}\cdot\sigma_{C_o^+}}{B_{K^-\pi^+}\cdot\sigma_{D^o}}\right)_\gamma \epsilon_{K_s^op}$$

The efficiency of K_s^op detection for $X_f > 0$ as calculated for a model for which α = 3.4 and the parent mass is 5 is 10%. The yield for this state is 1.4 x10^3 events in one 10 mev/bin. A study of the neutron background in E-87 leads us to expect 4,000 events per 10 mev/bin.

A similar calculation was carried out for the $K^-p\pi^+$ decay mode. If we assume $\Gamma_{K^-\pi^+p} = 2\Gamma_{K^op}$ then we expect 4.4 x 10^3 events. Again the study of the neutron background in E-87 leads us to expect a background of 1,500,000 events.

b. ψ rates and estimates of beauty.

We have used our result from E-358 which measured the product of the ψ production cross section times its branching ratio into $\mu^+ \mu^-$ in neutron nucleon collisions, weighted over the energy spectrum of the P-east neutron beam. That result was

$$B_{\mu\mu} \int_{.24}^{1} \frac{d\sigma}{dx} dx = 3.5 \text{ nb}$$[12]

In order to extrapolate to X_f less than .24 we have assumed an X_f dependence of $(1 - X_f)^{3.4}$. The efficiency for detecting ψ decay into $\mu^+ \mu^-$ is 39%.

Assuming that the average interaction rate of neutrons on the Be target, corrected for dead time, is 5×10^5 neutron interactions/pulse. The yield of ψ events is as follows: Y(inner-inner) 8,100 events, Y(inner-outer) 18,000 events, and Y (outer-outer) 9,000 events. The total detected decays of to $\mu^+ \mu^-$ will be about 35,000 events.

We also expect to trigger on the inner-inner and inner-outer electrons. The acceptance of the electron events is about 2/3 of the muon events. The combined sample which is approximately 58,000 events is more than respectable. Respectable is one Goliath.

The value which we see in this large sample is that we can look for a ψ which emanates from a vertex which is 1.5 mm or more downstream of the primary vertex. If the B (baryon or meson) decays into a ψ plus other particles with a branching ratio of 3%, and if the production cross section of B's (one state) is 100 nanobarn[1] ($B^{\psi}_{\mu\mu} B^{B}_{\psi} \sigma_B$ = .21 nb) then we expect 200 $\psi \rightarrow \mu^+ \mu^-$ could come from B decay.

If the lifetime of the B is 2×10^{-13} seconds then 10 events from the B would appear more than 3 mm downstream of the primary vertex. The background, ψ's produced at the production vertex, would be reduced below 1 event by this requirement if the errors remain gaussian. Thus we conclude that if $\tau_B > 2 \times 10^{-13}$ seconds we will obtain direct evidence for B's .

The large sample of ψ's can also be used to reconstruct specific final states of beauty such as $K^- \pi^+ \psi$ (seen by Goliath) and $K^- p \psi$. Our estimated yield of these states per nanobarn of cross section times the branching ratio are given in Table III.

Table III - Detection efficiency of some representative beauty particle decays

Particle	Decay Mode	Detection Efficiency	Yield/nanobarn
b(ud)	$D^+ p \pi^- \pi^-$, $D^+ \to K^- \pi^+ \pi^+$	2.0%	.04
b(ud)	$\psi K^- p$, $\psi \to \mu^+ \mu^-$	5.0%	13
b d	$\psi K^- \pi^+$, $\psi \to \mu^+ \mu^-$	6.0%	15
b d	$D^+ \pi^- \pi^-$, $D^+ \to K^- \pi^+ \pi^+$	5.0%	.09

Summary:

We believe that the combination of a high rate multi-particle spectrometer, a high resolution vertex detector, and excellent particle identification makes our detector unique at Fermilab. A pure sample of 36,000 D^+ and D^- will not only make it possible to learn about the details of heavy quark production, but it opens the possibility of studying the weak decays of the D^+ and D^-.

The high resolution chamber should open the possibility of directly observing new particles such as the charmed baryons with strangeness one. It also opens up the possibility to look for τ lepton production through its decay into the $A_1 + \nu_\tau$ when the A_1 decays into $\pi^+ \pi^- \pi^-$. The number of possibilities are quite large.

Several Fermilab experiments such as E-610 and E-515 will try to search for beauty by the traditional method of reconstructing complete final states. We believe our approach which relies on searching over all decay modes which involve the J/ψ will be more sensitive.

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List of Figures

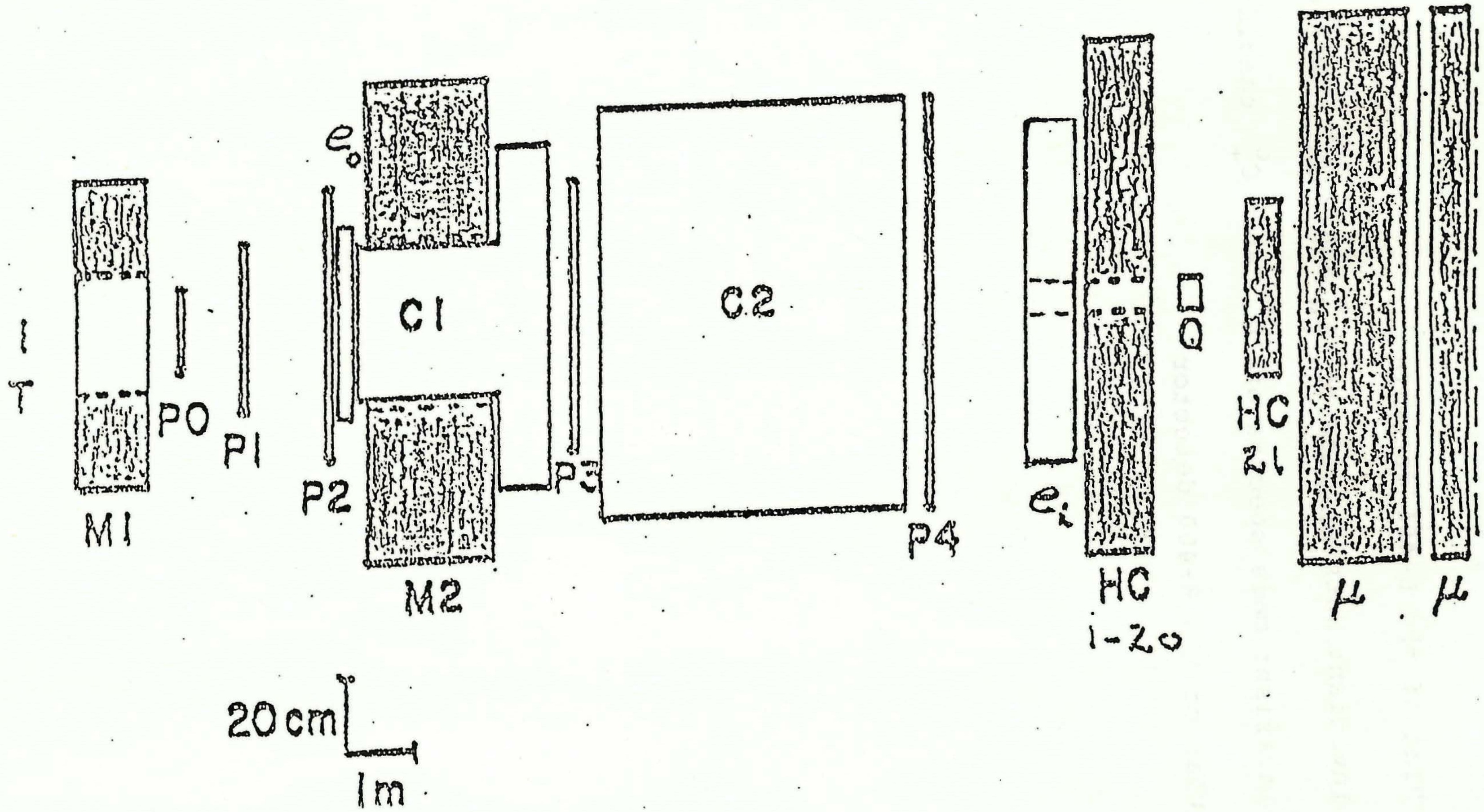
1. Plan of the E-401 detector

2. Invariant mass spectra of K_s^o and Λ^o candidates

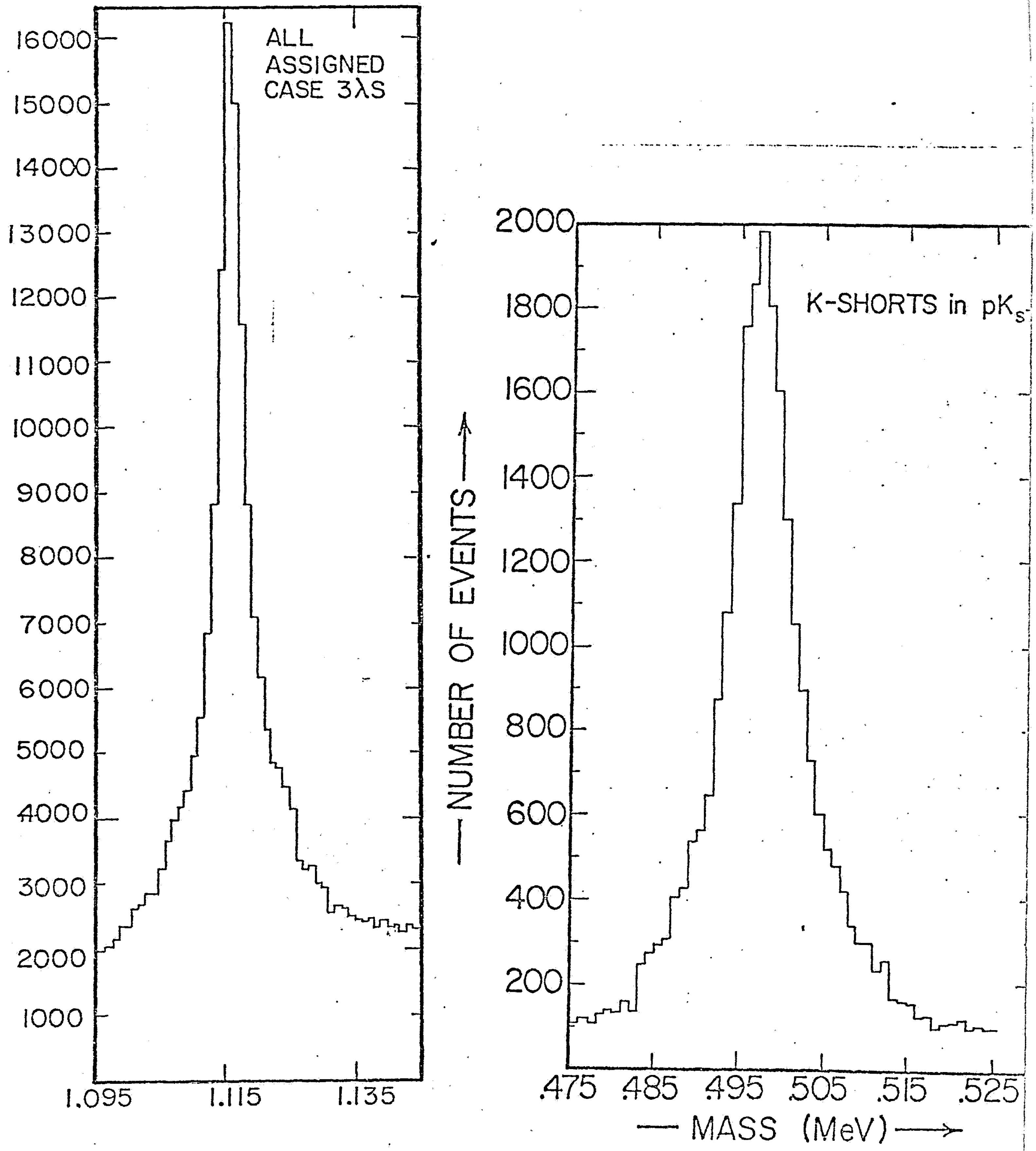
3. Invariant mass spectra of D^o and C_+^o candidates

4. Plan of the E-400 detector

FIG. 1.

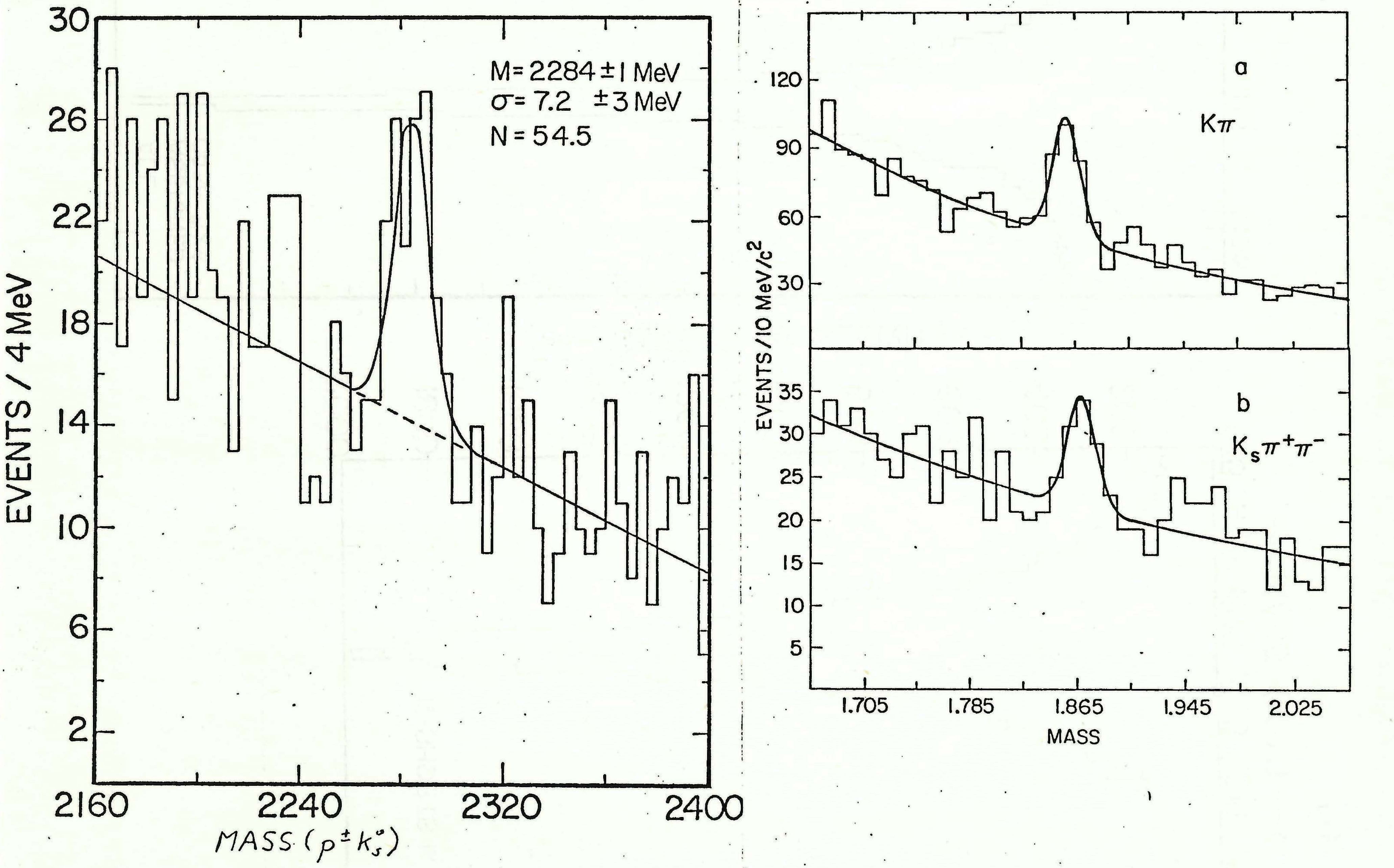


E-401



ALL
ASSIGNED
CASE 3λS
16000
15000
14000
13000
12000
11000
10000
9000
8000
7000
6000
5000
4000
3000
2000
1000
1.095
1.115
1.135
— NUMBER OF EVENTS —→
K-SHORTS in pK_s
2000
1800
1600
1400
1200
1000
800
600
400
200
.475
.485
.495
.505
.515
.525
— MASS (MeV) —→

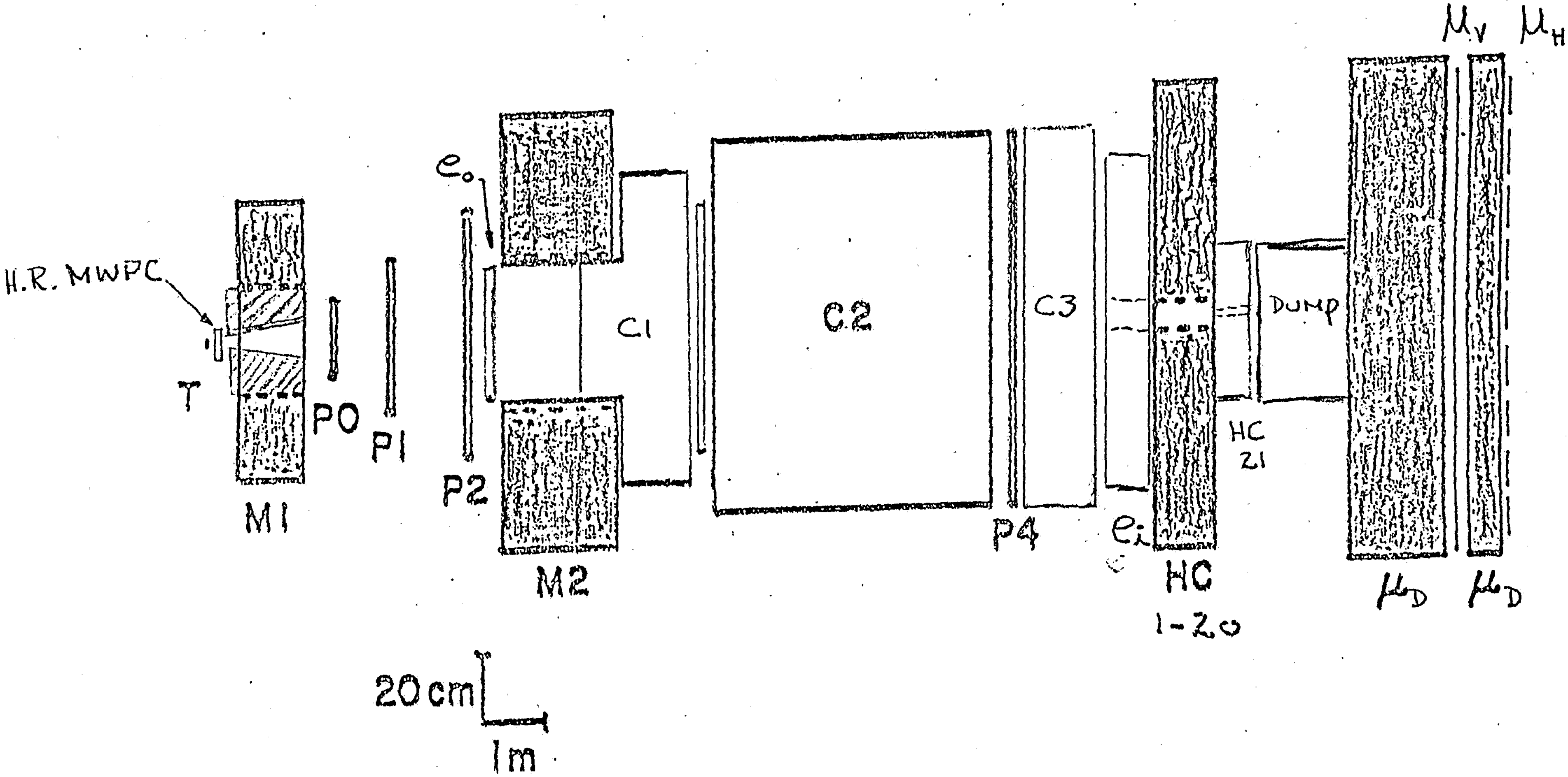
Fig. 2



M= 2284 ±1 MeV
σ= 7.2 ±3 MeV
N = 54.5
EVENTS / 4 MeV
30
26
22
18
14
10
6
2
2160
2240
2320
2400
MASS (p± k°s)
EVENTS / 10 MeV/c²
a
Kπ
120
90
60
30
b
Ksπ+π−
35
30
25
20
15
10
5
1.705
1.785
1.865
1.945
2.025
MASS

Fig 3

FIG 4


H.R. MWPC
T
M1
P0
P1
e_0
P2
M2
C1
C2
C3
P4
e_i
HC
1-20
HC
21
DUMP
μ_V
μ_H
μ_D
μ_D
20 cm
1m

E-400

APPENDIX A

The high resolution chamber, its electronics, the Cerenkov counter C_3 and the proportional tubes are the only items which are not in our present detector system. The remainder of the items are upgraded versions of detectors which are already in the detector. The new equipment and modified pieces of equipment comprise a list of nine items which is given below:

1. High resolution chamber package (Fermilab Physics)
2. High resolution chamber electronics (Fermilab Physics)
3. Upgrade of the M-7 and the data acquisition system Fermilab Physics)
4. Rebuilding of PØ (Fermilab Physics)
5. Upgrade of the Cerenkov counters C_1 and C_2 (Illinois)
6. Construction of a new Cerenkov counter C_3 (Illinois)
7. Upgrade of the neutral particle identifier through the addition of proportional tubes (Illinois)
8. A common mounting stand for chambers PØ and P1 (Proton)
9. Modified collimators and Magnet Shims (Proton)

Some work is needed to refurbish the MWPC planes which have been used over the past seven years, in order to improve the detector reliability. The problem is well understood and can be corrected by rewinding the x plane in each of the three plane packages P_2, P_3, and P_4. The aforementioned requires the support of the Proton Department and the Physics Departments of the University of Illinois and Fermilab.

Columbia University has agreed in writing to loan us the parts of the detector which it built for E-87, all of the 6" x 6" lead glass blocks, and the ADC system. The latter items were used in E-401.

The Fermilab participants will request funds from the Physics Department to build items 1, 2, 3, and 4. They will also request the support of three technicians between the period April 15, 1980 and January 15, 1981. Thereafter the support of one technician will be needed when the detector is being debugged. The University of Illinois will be responsible for items 5, 6, and 7 together with Joel Butler. The University of Illinois will provide funds and labor for these items.

We will also require the full complement of PREP used during E-401. The value of this equipment is about $150,000. We will also require technical support from Research Services to modify M7. We will also request technical support from Research Services in the design of the high resolution chamber MWPC electronics.

From the Proton Department we will require the modification of the collimators CF408B and CF410B. If the D_2 cryostat is removed we will need two vacuum pipes in its place. Except for the collimators the beam requires no changes. We will need the magnet AN423B (Cornell magnet) repaired. Since this is a magnet borrowed from Cornell the Laboratory has an obligation to repair it in any case. We will require a new set of shims and fringe plates to be put on the AN422B magnet (wide gap BM109) and a set of shims and fringe plates is needed for the AN423B magnet (Cornell magnet).

In order to be ready to test this detector by January 1, 1981 on muons (which are abundant in the pit when the tagged photon beam runs) we will have to begin the engineering of the high resolution chamber package and the upgrade of the M-7 in early April. The former should be started early since it may require considerable testing and modification. The latter should be started early because of the long lead time required for even the simplest of electronic parts. Construction of the high resolution chamber would begin in June. The modification of bulky detectors such as the Cerenkov counters would be done during the three month shutdown.

The construction of the remainder of the detector could be done during the fall. Installation could be done in the early part of the winter. This schedule would allow us to operate the full system on single track muons, thereby testing both the new components and old components. By March 1981 we would be ready to do beam tests. On the basis of our past experience a ten week run which includes all of the trigger studies will be adequate to complete the experiment. If the experiment is successful we will undoubtedly request additional running in 1982.

Our requirements for computing will be the same as for E-401. In that experiment we required about 400 hours to do the reconstruction. The remainder of the analysis takes about 100 hours. The software changes to the program to incorporate the new detectors are nearly complete. We plan to use neutron events from E-87 to simulate the properties of the expected background events. From these events artificial data will be generated for analysis by the revised software routines.

The estimated costs for the detector improvements and repairs are as follows:

High Resolution Chamber (materials)	\$ 20,000
High Resolution Chamber electronics (3,000 wires)	\$ 75,000
Cables and miscellaneous equipment related to the High Resolution Chamber	\$ 20,000
Upgrade of the M-7 and the data acquisition system	\$ 25,000
Construction of the new Cerenkov Counter and modification of the present counters	\$ 25,000
Repair of the MWPC	\$ 10,000
Upgrade of the Neutral Particle Detector	\$ 25,000
Total Cost for Upgrading the Detecr	\$200,000

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High Energy Photoproduction of the D^{*+}

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ABSTRACT

We have observed the photoproduction of the D^{*+} where the D^{*+} decays via $D^{*+} \to \pi^+ D^o$ and the D^o decays via $K^- \pi^+$ and $K_s \pi^+\pi^-$. The D^{*+}, D^o mass difference and the D^o mass observed here are in excellent agreement with previous measurements of charmed mesons produced in e^+e^- annihilations. The photoproduced D^{*+} and D^{*-} signals are produced nearly equally at the level of about 100 nb/nucleon.

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PACS INDEX: 13.60.Kd

We report on the observation of the D^{*+} (D^{*-}) produced in the wideband neutral beam at Fermilab. Both this beam and our detector have been described in a previous Letter.[1] Our exposure consisted of approximately 6×10^{11} photons with an energy greater than 50 GeV incident on a 2 cm long scintillator target. The particles emerging from these interactions were analyzed by a large acceptance magnetic spectrometer system (multiwire proportional chambers) which includes two multicell Cerenkov counters with pion thresholds of 6 and 12 GeV, a large lead glass array for neutral detection, and a hadron calorimeter. The data described here were recorded under a trigger requiring at least 3 tracks in the spectrometer and a minimum energy deposition of 75 GeV in the hadron calorimeter. A non-negligible number of events collected under this trigger are K_ℓ or neutron induced rather than photon induced; approximately 25% of the data were taken with six radiation lengths of lead inserted into the neutral beam in order to measure the contribution of this hadronic background.

Within a range of momentum from 6 to 22 GeV/c, charged kaons and protons are separable from pions, while kaons are separable from protons and pions if in the momentum range from 22 to 44 GeV/c. For the purposes of this Letter, charged kaon candidates are only required to be unambiguous with pions and thus can lie in the full momentum range from 6 to 44 GeV/c. K_s candidates are selected from two track V^o candidates which verticize downstream of the target but have a momentum vector which intersects the overall interaction vertex. In order to reduce the Λ^o contamination we require the reconstructed V^o mass to lie within 15 MeV/c^2 of the K_s mass, and require that the track with the larger momentum is inconsistent with being a proton or antiproton. Our absolute mass scale is determined by calibrating the J/ψ, K_s, and Λ^o to their known masses.

In a previous Letter[1] we reported on the observation of $D^o(\bar{D}^o)$ mesons decaying into $K\pi$, observed among 520,000 events which contain both a K^+ and K^-

candidate. In an effort to study the photoproduction of charmed mesons in a more inclusive and model independent way, we have analyzed 9.8 million events containing at least one charged kaon or K_s candidate. In order to avoid unwieldly notation in the discussion which follows, reference to a given state will always imply a reference to its charged conjugate.

The advantages in searching for the D^{*+} pionic cascade using the D^{*+}, D^o mass difference variable rather than the D^{*+} mass are illustrated in Ref. 2. Fig. 1 shows the $M_{K^-\pi^+\pi^+} - M_{K^-\pi^+}$ mass difference distribution obtained in our data for all $K^-\pi^+\pi^+$ combinations with (1a) $1.800 < M_{K^-\pi^+} < 1.825$ GeV/c^2, (1b) $1.850 < M_{K^-\pi^+} < 1.875$ GeV/c^2, and (1c) $1.900 < M_{K^-\pi^+} < 1.925$ GeV/c^2. The only requirement for a combination's entry into Fig. 1 is that the kaon must be identified by the Cerenkov system. A clear enhancement is observed at a mass difference of about .1455 GeV for events with $1.850 < M_{K^-\pi^+} < 1.875$ GeV/c^2. We attribute this enhancement to the process $D^{*+} \to \pi^+ D^o \to \pi^+K^-\pi^+$, where the $K^-\pi^+$ invariant mass is consistent with the known D^o mass of 1.863 GeV/c^2. The position of the mass difference peak is found to be in excellent agreement with the observed $M_{D^{*+}} - M_{D^o}$ of 0.1453 ± 0.0005 GeV/c^2 measured at SPEAR[2], while the width of the peak is consistent with our experimental resolution.

The shaded portions of Fig. 1 show the appropriately normalized mass difference distributions obtained in the K_ℓ – neutron background runs. The absence of any enhancement in the shaded portion of Fig. 1b demonstrates that the D^{*+} signal is predominately photoproduced.

Figure 2 repeats this exercise for the decay sequence $D^{*+} \to \pi^+ D^o \to \pi^+ K_s\pi^+\pi^-$. Owing to the larger combinatoric background for this signal we only include events with less than 8 visible tracks. Again, there appears to be a narrow enhancement at a mass difference of 0.1455 GeV/c^2 for those events with $M_{K_s\pi^+\pi^-}$ consistent with the mass of the D^o. Figure 3 shows the $K^-\pi^+$ (3a) and $K_s\pi^+\pi^-$ (3b) invariant mass distributions for combinations within the $D^{*+} - D^o$ mass difference peak. The curves drawn on Fig. 3 are fits to these mass spectra consisting of a Gaussian signal peak over a smooth exponentially falling background. The fit finds 143 ± 20 signal events at a mass of 1.860 ± .002 GeV/c^2 and a width of σ = .010 ± .002 GeV/c^2 for the $K^-\pi^+$ signal of Fig. 3a, and 35 ± 13 signal events at a mass of 1.869 ± .004 GeV/c^2 and a width of σ = .012 ± .003 GeV/c^2 for the $K_s\pi^+\pi^-$ signal of Fig. 3b. Both signals have a width comparable to our experimental mass resolutions. The mass centroids are in good agreement with the previously measured D^o mass of 1.8633 ± .0009 GeV[3]. We estimate that systematic mass scale shifts for the D^o signal should be less than 5 MeV/c^2.

In addition to studying the $(K^-\pi^+)\ \pi^+$ channel as discussed above, we have looked for enhancements in the non-exotic $(K^+\pi^-)\pi^+$. An enhancement in the $M_{K^+\pi^-\pi^+} - M_{K^+\pi^-}$ mass difference distribution near 0.1455 GeV/c^2 could arise from the conjectured D^0 -- $\bar{D}^o$ mixing process[2], or the presence of $\Delta C = -\Delta S$ double Cabibbo suppressed decays. No enhancement was observed in the non-exotic channel, thus allowing us to conclude that the fraction of times that a D^o decays into a K via $K^+\pi^-$ rather than $K^-\pi^+$ is less than 11% (90% c.l), which can be compared to the 16% upper limit quoted in Reference 2.

We find that the ratio of photoproduced D^{*+} to D^{*-} signal events is 1.4 ± .4. From this observation we conclude that D mesons are predominantly produced in pairs in our data. Figure 4 shows some measured inclusive properties of our D^{*+} signal which bear on its production mechanism. The data points and error bars of Fig. 4 are obtained by fitting the $K\pi$ invariant mass spectrum (subject to cuts on the D^{*+}, D^o mass difference) for every bin in the given inclusive plot. The plots have <u>not</u> been corrected for variations in the D^{*+} detection efficiency.

Figure 4a shows that the bulk of the D^{*+} signal appears in events with a total visible (charged and neutral) energy of 75 to 100 GeV. The fall off of this distribution at low energies can be explained by acceptance considerations while the high energy fall off partially reflects our steeply falling photon spectrum[1]. Figure 4b showing the fraction of total visible energy carried by the D^{*+} shows that the majority of D^{*+} events are consistent with having ≈ 1/2 of the visible beam energy, while Fig. 4c shows that the bulk of the signal is observed to have a P_t^2 of less than 1 GeV^2/c^2.

We see that the data appear consistent with models where the D^{*+} is produced in association with another D or D^* via the decay of a diffractively photoproduced, low mass (4 to 5 GeV/c^2) parent. We have used such a model to estimate the spectrum averaged total D^{*+} inclusive photoproduced cross section for photons over 50 GeV. We assume that the cross section is independent of energy above 50 GeV. Based on the 6% average detection and trigger efficiency obtained in this model, we find that:

$$\sigma_{\gamma p \to D^{*+}X} \times \frac{\Gamma(D^{*+} \to \pi^+ D^o)}{\Gamma(D^{*+} \to \text{all})} \times \frac{\Gamma(D^o \to K^- \pi^+)}{\Gamma(D^o \to \text{all})} = 1.8 \pm .6 \text{ nb/nucleon}$$

where we have assumed a linear A dependence for the nuclear correction. Using the measured values[3,4] of .60 ± .15 and .026 ± .004 for the $D^{*+} \to \pi^+ D^o$ and $D^o \to K^- \pi^+$ branching ratio we conclude that $\sigma_{\gamma p \to D^{*+} X}$ = 118 ± 49 nb/nucleon. The ratio of the $D^o \to \bar{K}_o \pi^+ \pi^-$ to the $D^o \to K^- \pi^+$ branching ratio is found to be 1.7 ± .8 in our data compared to 1.15 ± .3, the value presented in Ref. 5.

Finally we estimate the fraction of D^o events arising from D^{*+} pionic cascades. A fit to the completely inclusive $K^- \pi^+$ invariant mass spectrum (not shown) reveals an ≃ 3σ excess of 660 ± 230 events over a background of ≃ 33000 events at the D^o mass. This would represent an inclusive D^o cross section of 492 ± 267 nb/nucleon, in good agreement with Ref. 1, and indicates that $.24^{+.13}_{-.06}$ of photoproduced D^o's come from $D^{*+} \to \pi^+ D^o$.

We wish to thank the staffs of Nevis Laboratories, the University of Illinois, and Fermilab for their support in the preparation and completion of this experiment. This work was supported in part by the National Science Foundation and the U. S. Department of Energy.

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FIGURE CAPTIONS

Fig. 1 Mass difference distributions ($\Delta \equiv M_{K^\mp\pi^\pm\pi^\pm} - M_{K^\mp\pi^\pm}$) for combinations satisfying:

(a) $1.800 < M_{K^\mp\pi^\pm} < 1.825$ GeV/c^2

(b) $1.850 < M_{K^\mp\pi^\pm} < 1.875$ GeV/c^2

(c) $1.900 < M_{K^\mp\pi^\pm} < 1.925$ GeV/c^2

The shaded distribution shows the Δ distribution obtained for K_ℓ - neutron background runs. We have multiplied the background by 2.35 to normalize the flux to the photon runs.

Fig. 2 Mass difference distribution ($\Delta \equiv M_{K_s\pi^+\pi^-\pi^\mp} - M_{K_s\pi^+\pi^-}$) for combinations satisfying:

(a) $1.800 < M_{K_s\pi^+\pi^-} < 1.825$ GeV/c^2

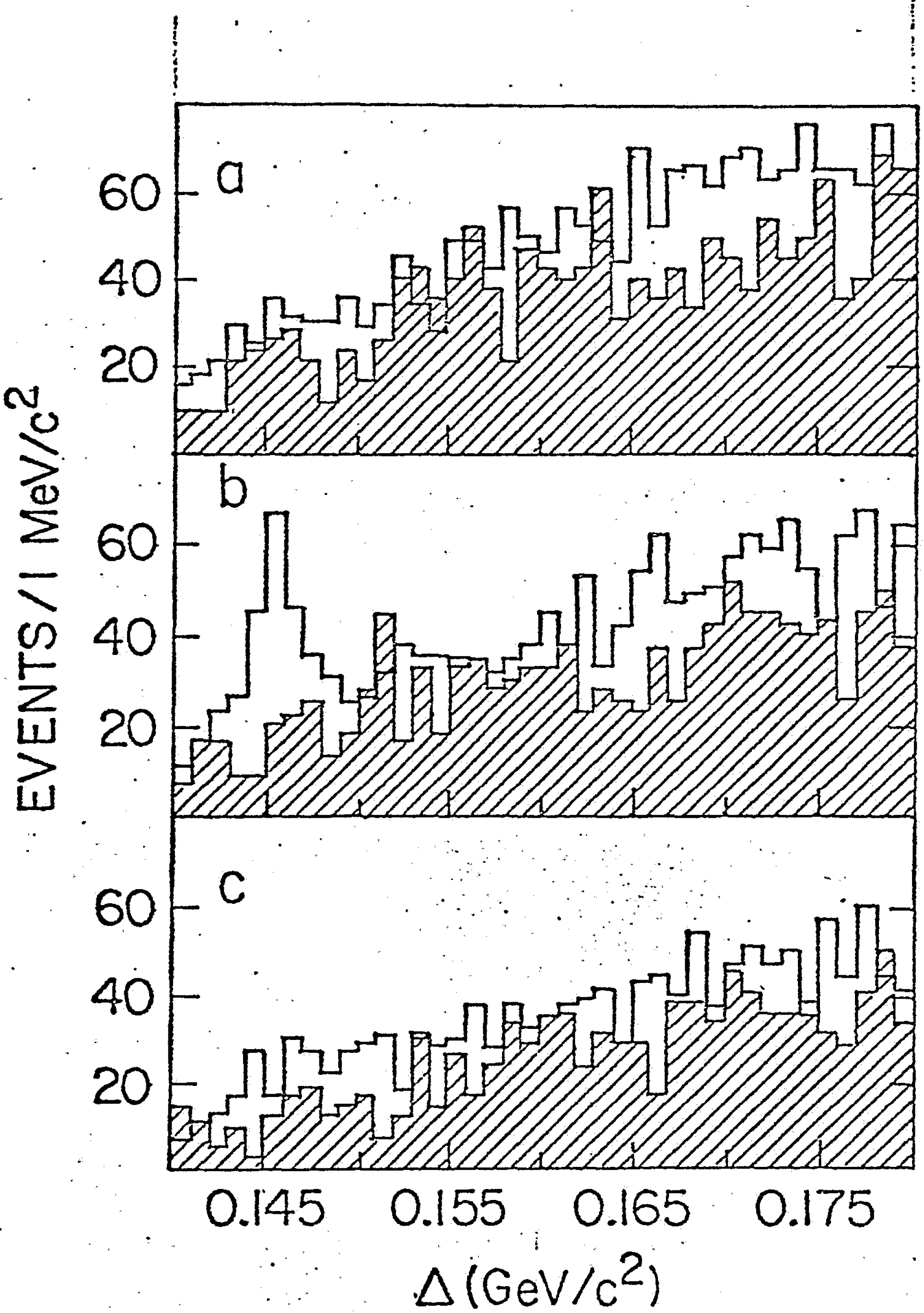
(b) $1.850 < M_{K_s\pi^+\pi^-} < 1.875$ GeV/c^2

(c) $1.900 < M_{K_s\pi^+\pi^-} < 1.925$ GeV/c^2

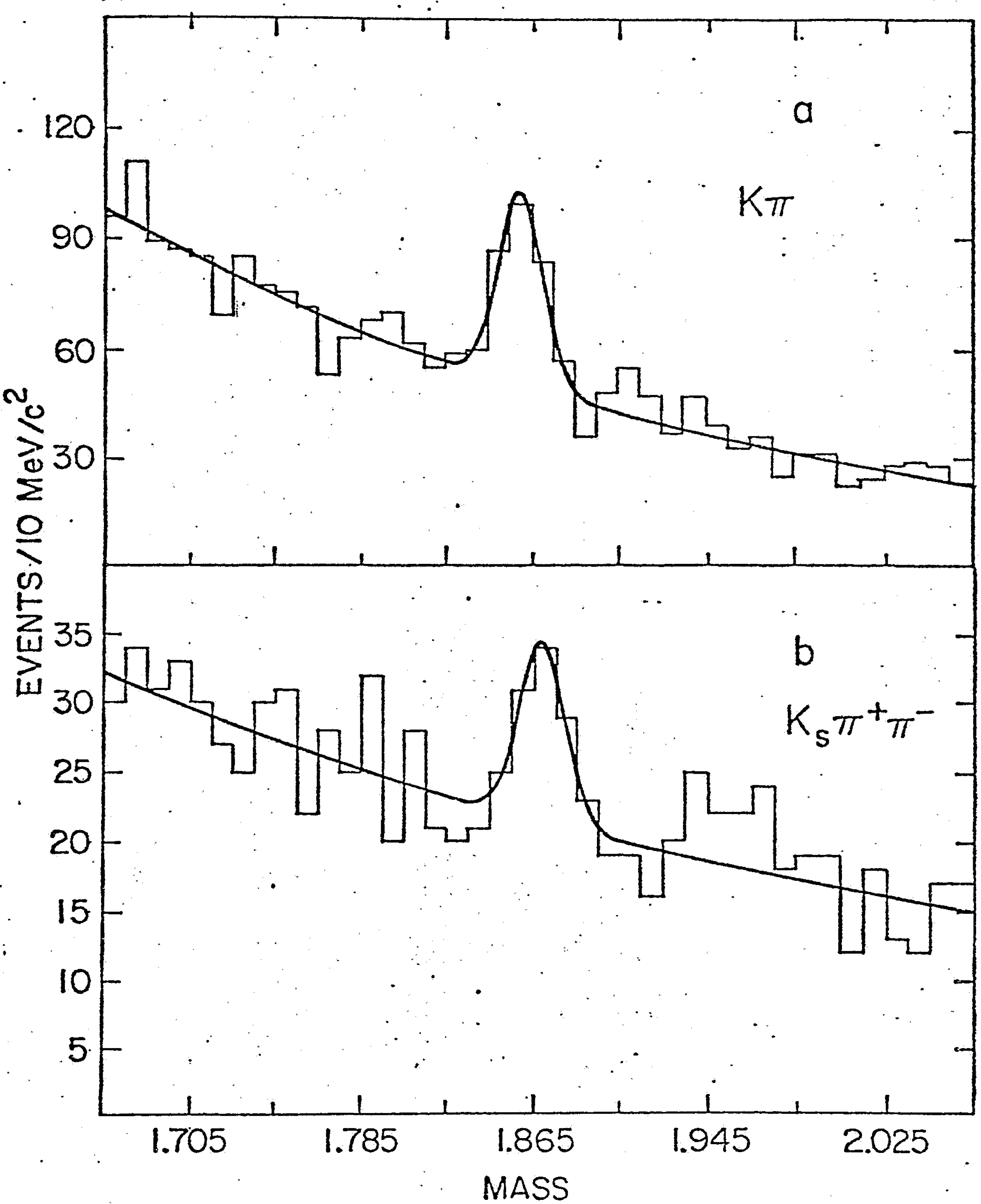
Fig. 3 (a) $K^\mp\pi^\pm$ invariant mass distribution for combinations satisfying $0.1425 < \Delta < 0.148$ GeV/c^2.

(b) $K_s\pi^+\pi^-$ invariant mass distribution for combinations satisfying $0.1445 < \Delta < 0.1465$ GeV/c^2.

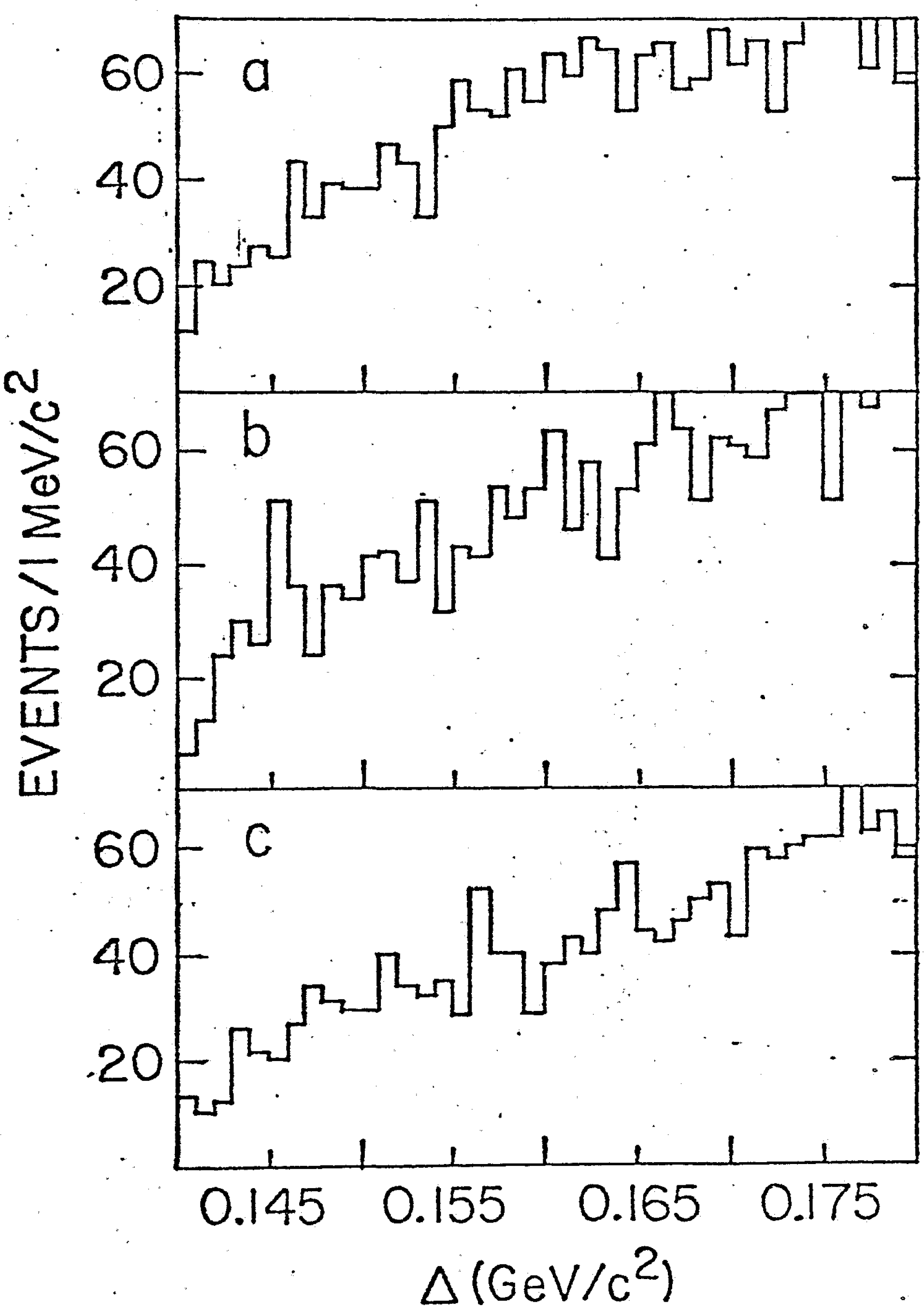
Fig. 4 Inclusive properties of the photoproduced $D^{*\pm}$ signal. These distributions are uncorrected for variations in acceptance. E_{vis} is the sum of the visible charged and neutral energy seen in our apparatus.



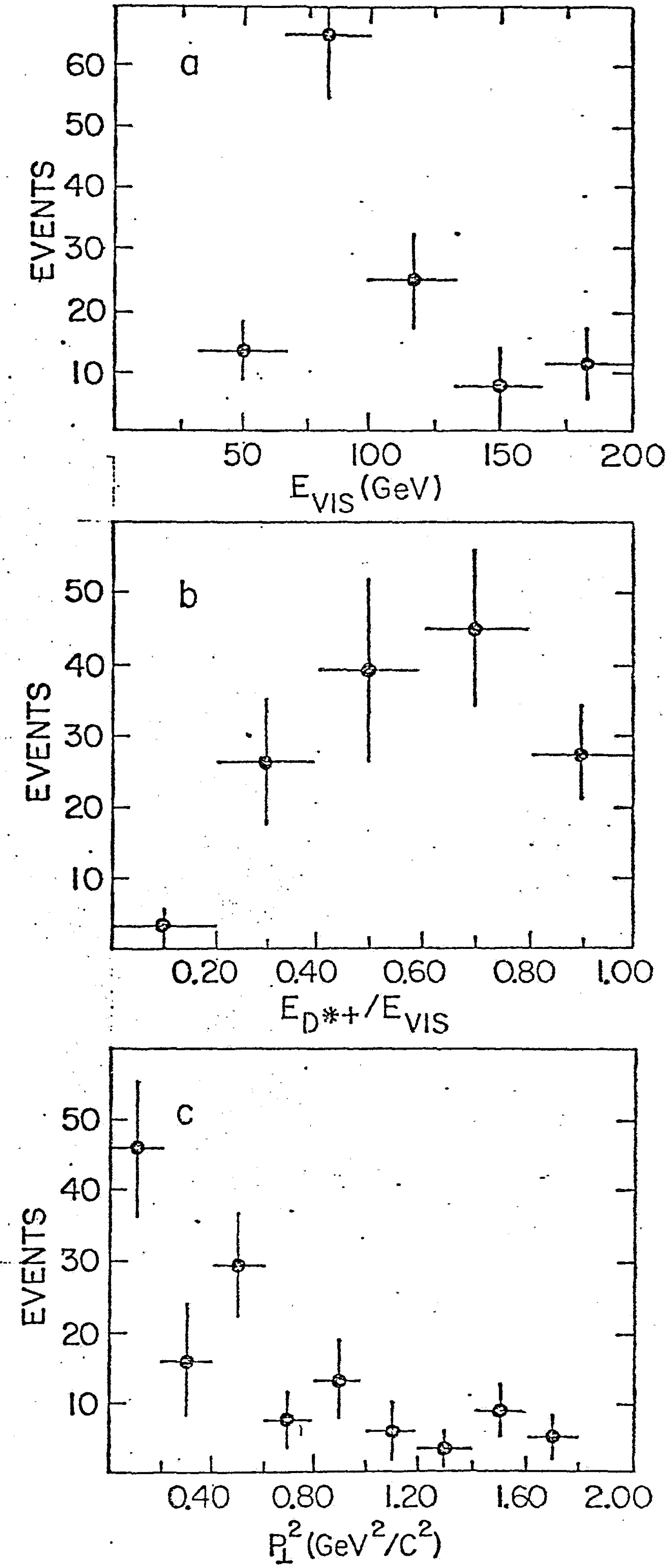
a
b
c
60
40
20
EVENTS/1 MeV/c²
0.145
0.155
0.165
0.175
Δ (GeV/c²)



a
Kπ
b
$K_s\pi^+\pi^-$
EVENTS/10 MeV/c^2
120
90
60
30
35
30
25
20
15
10
5
1.705
1.785
1.865
1.945
2.025
MASS



EVENTS/1 MeV/c^2
a
b
c
60
40
20
0.145
0.155
0.165
0.175
Δ (GeV/c^2)


a
b
c
EVENTS
E_{VIS} (GeV)
$E_{D^{*+}}/E_{VIS}$
$P_\perp^2$ (GeV^2/C^2)

TM-747
2500.000
Oct. 1977

"THE M7 - A HIGH SPEED DIGITAL PROCESSOR FOR SECOND LEVEL TRIGGER SELECTIONS"

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Summary

A digital processor is described which reconstructs mass and momentum as a second level trigger selection. The processor is a five-address, microprogrammed, pipelined, ECL machine with simultaneous memory access to four operands which load two parallel multipliers and an ALU. Source data modules are extensions of the processor.

Introduction

As High Energy Physics experiments become larger and more complex, the amount of data collected per experiment has become so large that central computer facilities can no longer process the data as it is collected. Larger computer centers do not appear to be the whole answer since even higher data rate experiments are foreseen. Often preliminary screening by a relatively simple program will greatly reduce the quantity of data to be analyzed, since some experiments have only a very small fraction of interesting events. Every effort is made through the use of fast trigger electronics in the experimental design to select only good events for storage (on tape usually) and later analysis. Often the fast trigger electronics is too complex to be physically realizable and there has been no alternative but to write tapes which are mostly full of junk for later selection at the central computing facility.

Experiment #400 at Fermilab (Figure 1) is a particle search experiment using a dimuon trigger. Based on previous experiments, it is known that the dimuon spectrum is dominated by low mass dimuons of no particular interest. E-400 will trigger on only high mass and high transverse momentum muon pairs so that the experiment can be run at high enough intensity to search down to theoretically interesting cross sections. The M7 processor has been designed to quickly analyze the tracks from a pair of x-y muon drift chambers of the delay line type[1] and to provide fast determination of mass and transverse momentum prior to writing the event on tape.

Engineering Considerations

While a general goal has been the application of special purpose digital processors to the enrichment of recorded experimental data and their possible use as off-line track processors, the specific goal of this project was the improvement of the fraction of good events taken by E-400 at Fermilab.

To meet the goal of two orders of magnitude trigger reduction with reasonable dead time it is necessary to scan the input detectors and compute the dimuon mass and momentum in the order of ten microseconds.

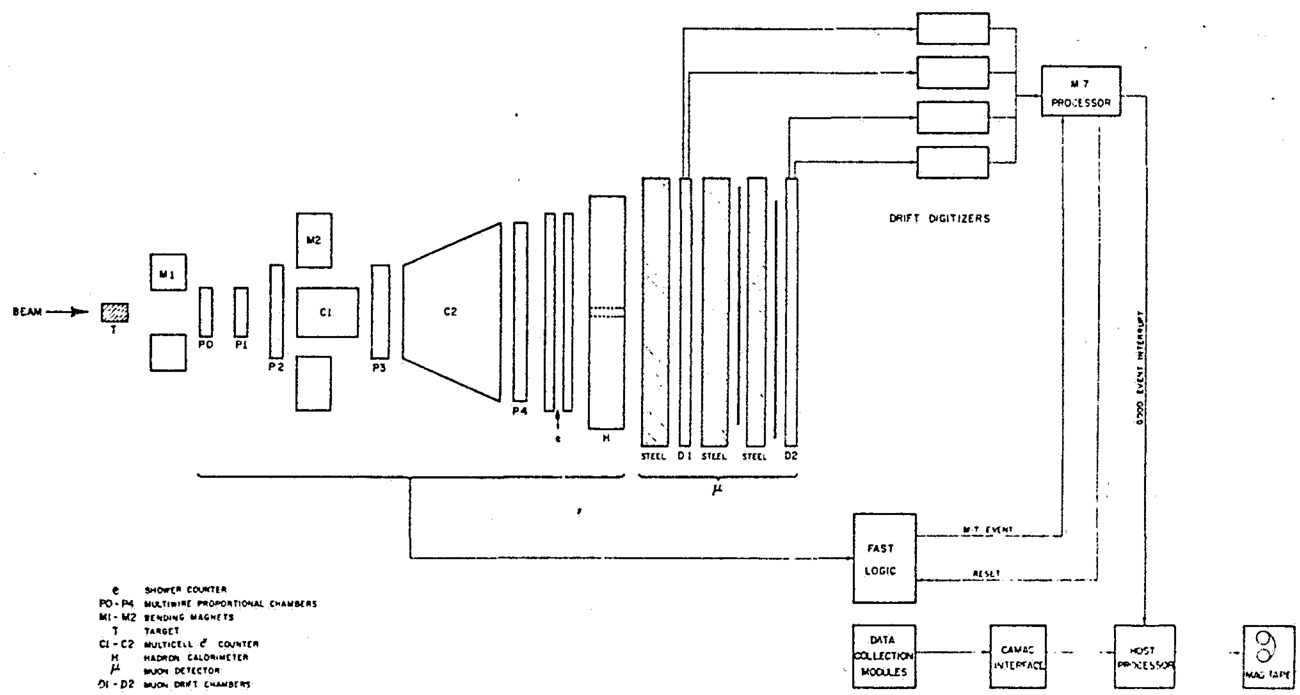


Fig. 1. Configuration of Experiment 400 at Fermilab with the M7 Processor used for Second Level Trigger Selection

This requires fast computation as well as fast digitization of the chamber drift time and fast scan of the drift digitization modules. An arbitrary time budget goal of 5 microseconds was set for the entire operation.

It is immediately apparent that the most common present technique of High Energy Physics Digital Data Collection[2] (CAMAC) is completely inadequate for trigger processors. For CAMAC to scan the 80 time digitizer modules for the expected four hits would exceed the total time budget by an order of magnitude. It was therefore necessary to design a high speed bus for this application. The physics community has recognized this limitation of CAMAC and work is underway to develop a standard bus for high speed data collection.[3] To reduce engineering time it was decided to modify standard CAMAC crates to incorporate a token passing scheme similar to the DEC UNIBUS[4] which allows data to be located in a CAMAC crate in under a microsecond.

The drift chamber digitizers were further divided into four quadrants, each of which would expect one hit in a normal event and these were arranged to be scanned in parallel. To measure delay line times to a resolution of 1ns while avoiding problems of 1 GHz clocks and scalers or long run down times, vernier type digitizers[5] were designed which run down in less than 1μs. This time is overlapped with the read out scan time.

Analysis of the mass and momentum equations (Figure 2) indicated that they could be efficiently solved by a processor which could perform ax ± by → c. In fact, 14 of 18 program steps (Figure 3) make full use of this operation. Meeting the goal of a 5 microsecond trigger requires that this operation be performed in about 200ns. Since error analysis indicated the need for 9 bit precision, parallel combinatorial multipliers were selected as the only available devices which could match this speed.

$$P_\perp^2 = \frac{K^2\left[\left(A_1 X_2 - B_1 X_1\right)^2 + \left(A_2 Y_2 - B_2 Y_1\right)^2\right]}{\left(A_3 Y_2 - B_3 Y_1\right)^2}$$

$$M^2 = \frac{K^2\left[\left(A_1\, \Delta X_2 - B_1\, \Delta X_1\right)^2 + \left(A_2\, \Delta Y_2 - B_2\, \Delta Y_1\right)^2\right]}{\left(A_3 Y_2 - B_3 Y_1\right)\left(A_3 \bar{Y}_2 - B_3 \bar{Y}_1\right)}$$

Fig. 2. Equations Solved by the M7 Processor for Fermilab Experiment 400

At first it was planned to build a fast very special processor which could efficiently perform successive operations of the form ax ± by → c. From the beginning it was planned to fetch the four operands simultaneously from memory and have two parallel multipliers. The initial plan was to make the processor a very simple microcoded processor which solved the specific equations with a second hardware processor which would scan the input data for track candidates. Later it was realized that the addition of a few instructions would allow the same processor to efficiently search for tracks.

1. $\bar{X}_1 - X_1 \rightarrow \Delta X_1$
2. $\bar{X}_2 - X_2 \rightarrow \Delta X_2$
3. $\bar{Y}_1 - Y_1 \rightarrow \Delta Y_1$
4. $\bar{Y}_2 - Y_2 \rightarrow \Delta Y_2$
5. $a_1 X_2 - b_1 X_1 \rightarrow A$
6. $A_2 Y_2 - b_2 Y_1 \rightarrow B$
7. $(A^2 + B^2)/256 \rightarrow C1$
8. $a_1 \bar{X}_2 - b_1 \bar{X}_1 \rightarrow A$
9. $a_2 \bar{Y}_2 - b_2 \bar{Y}_1 \rightarrow B$
10. $(A^2 + B^2)/256 \rightarrow C2$
11. $a_1 \Delta X_2 - b_1 \Delta X_1 \rightarrow A$
12. $a_2 \Delta Y_2 - b_2 \Delta Y_1 \rightarrow B$
13. $(A^2 + B^2)/256 \rightarrow C3$
14. $a_3 Y_2 - b_3 Y_1 \rightarrow D1$
15. $a_3 \bar{Y}_2 - b_3 \bar{Y}_1 \rightarrow D2$
16. $K_1 C_1 - D1^2 \geq 0?$
17. $K_1 C_2 - D2^2 \geq 0?$
18. $K_2 C_3 - D1D2 \geq 0?$

Fig. 3. An 18 Instruction Program Implementing the Equations from Figure 2, where the Particle Coordinates are $X_1 X_2\ Y_1 Y_2$ for the First Track and $\bar{X}_1 \bar{X}_2\ \bar{Y}_1 \bar{Y}_2$ for the Second Track. K1 and K2 Determine $P_\perp^2$Min. and M^2Min.

Many of the design decisions were made to reduce the amount of time required to build this processor since to a great extent real costs to the Laboratory (i.e., what fraction of total laboratory effort went into this project x total budget = real cost) are proportional to calendar time and in any case were an order of magnitude higher than the identifiable parts cost.

ECL logic was chosen over Schottky TTL even though TTL would have been fast enough because it is believed that noise problems are easier to solve with ECL.

While the design was in progress the 2 x 4 bit ECL multiplier chips[6] became available increasing the processor speed by a factor of two and eliminating the need for level translation in and out of TTL multipliers.

Standard ECL wire wrap panels were selected for packaging the electronics with several panels mounted together on a single ground plane. This plane was then mounted vertically in a relay rack. Interconnections were wire wrapped single ended with only moderate care taken to push all wiring close to the ground plane. All connections were terminated in 100 ohms. While this is not the optimum interconnection technique for ECL, the result is only a small increase in rise time and overshoot, particularly if care is taken in locating major units so that most critical wiring runs are short.

An interesting feature of High Energy Physics (HEP), is the statistical nature of the data. Compared to payroll processing computers, for example, it is not necessary to get the right answer all the time. Since all the data taken will be later completely re-analyzed the worst result of an occasional error is to sometimes throw out a good event. Since good experimental practice requires taking samples of rejected events there is a continous operational check on the health of the processor. Note that an error rate of 1 in 1000 would be quite tolerable (if random) and error rates this high without complete failure are difficult to achieve in digital systems so that the deletion of error detection schemes, particularly those such as parity which slow down computation, is justified.

Again the nature of HEP is that it is event oriented. There is little chance of events occuring in an unexpected sequence and those that do can be serviced slowly by the host processor. Thus, there is no necessity for interrupts, eliminating a decision process that both complicates and slows down every instruction in conventional computers.

The announced approach to software was to design a processor for which it was not possible to write a complicated program. Thus the announced design did not include any kind of jump instruction or index registers. This kept thinking along lines of how to solve a specific problem (i.e., E-400 trigger) rather than solving general problems of computation. Later features were added where they were easy or where they would solve problems elsewhere - i.e., index registers and jumps allow doing the track finding in software rather than the original plan of having hardware present all possible track pairs to the processor for selection.

It was recognized that this is a one of a kind digital processor with no real expectation of additional copies. Since it promises at least an order of magnitude improvement in data rate in an experiment that costs on the order of $5 million to equip, (if we include the cost of building the accelerator and consider the total number of experiments which might be run), it is believed that this effort is justified. Still the one of a kind nature and thus the high ratio of burdened labor cost to material cost

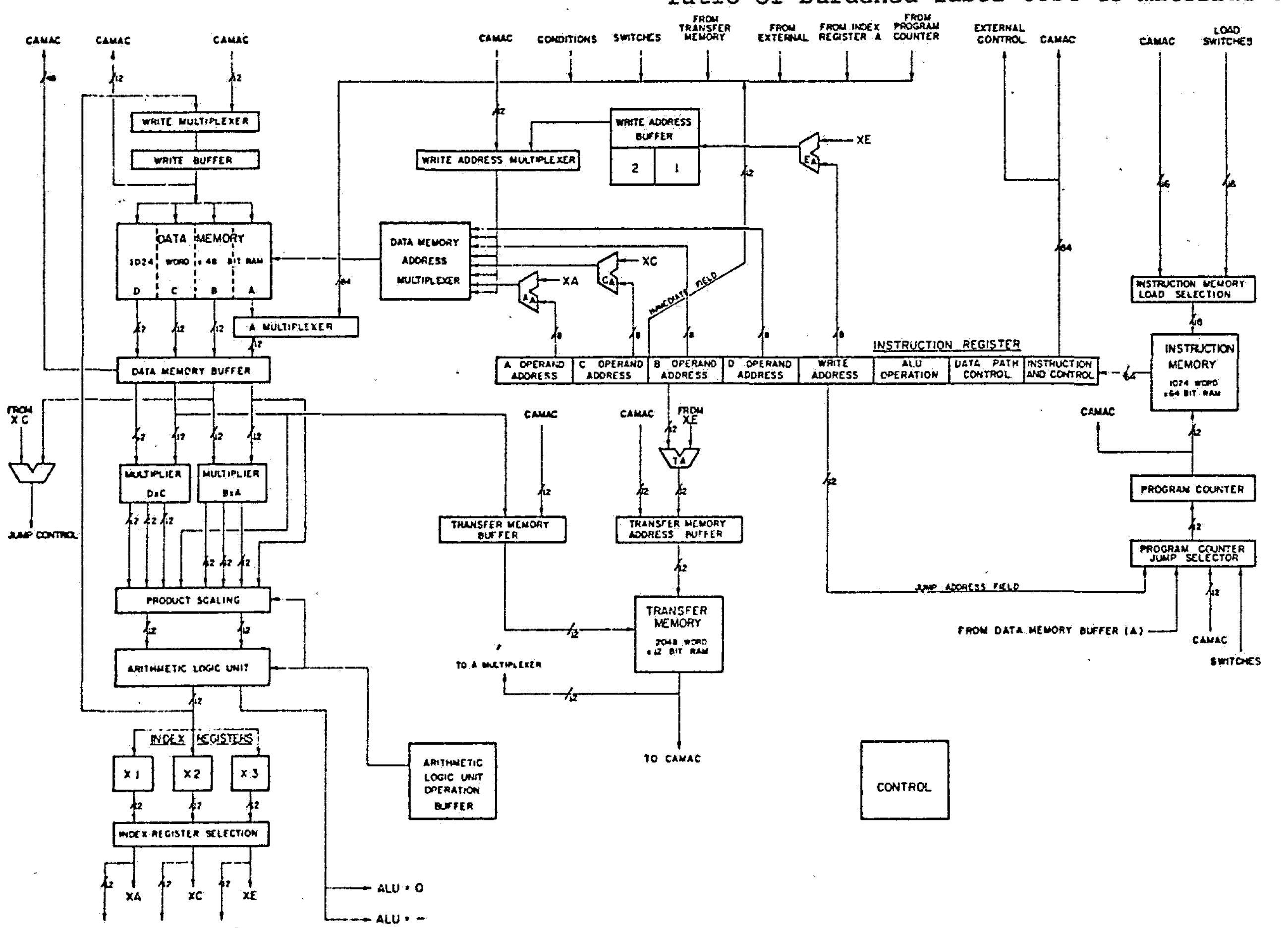
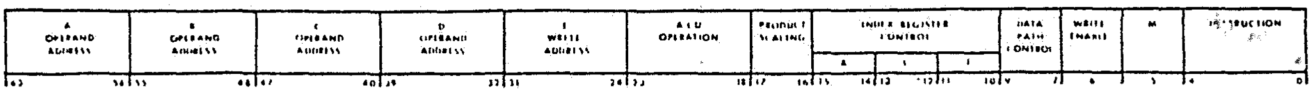
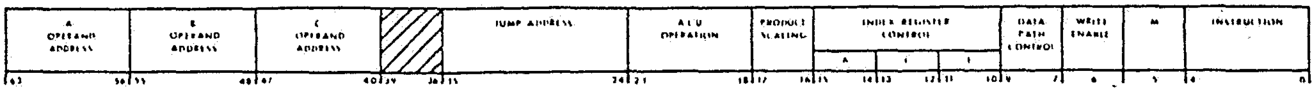


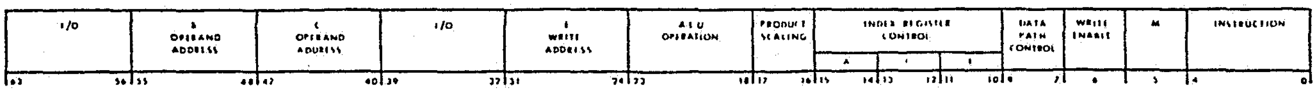
Fig. 4. M7 Processor Block Diagram



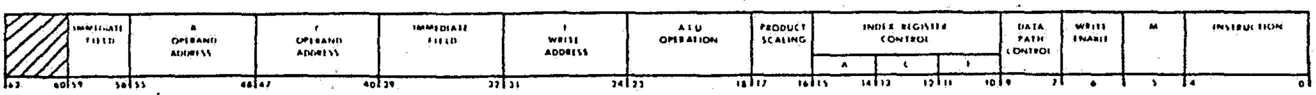
Basic Instruction Configuration



Instruction Configuration For Jump Instructions



Instruction Configuration For I-O Instructions



Instruction Configuration For Immediate Instructions

Fig. 5. Instruction Microcode Format

(at least 10/1) considerably affected the design approach. Indicators were put on all important registers, and all were interfaced to CAMAC. In general hardware was added wherever it would reduce checkout and test time and the tempation to be clever was resisted at the expense of more parts if the result was easier to understand and thus check out.

The design is very conservative for the parts used. By using extra parts and by keeping well back from the state of the art, long check out and debugging time was avoided. Again to avoid problems the package design is very conservative with respect to power distribution, cooling, and packaging density.

The M7 Processor

The M7 Processor is a 12 bit parallel machine (Figure 4) constructed from 10,000 series ECL. Major components are a 1024 word by 12 bit 4 port Data Memory, two 12 bit parallel multipliers, an arithmetic Logic Unit, three hardware Index Registers, a 1024 word by 64 bit microprogram Instruction Memory and a 2048 word by 12 bit Transfer Memory. The memory read access time for all three memories is 29ns, and the settling time for the 12 bit multipliers is typically 55ns.

The 64 bit microcoded instruction contains 5 eight bit address fields (Figure 5). Other fields include 6 bits for control of the ALU, 7 bits for control of various data paths, 5 bits for the instruction, and 6 bits to specify index registers for use with two of the source addresses and the destination.

Each instruction can access up to four words simultaneously from memory so that two multiplys with an ALU operation on the two products can be started every major clock cycle (approximately every 100ns). Instruction fetch and execute cycles are completely overlapped so that the primary limit on speed is the settling time for the 12 bit ECL multipliers.

The four port memory is implemented by the brute force technique of having four separate memories, one for each operand address. The memories are addressed separately for the read operation but are always addressed in common during write operations.

Since the processor program for this application is mostly computation with few decision operations no special effort is made on the jump instructions, or computations which require the results of the previous step -the processor simply stops and waits on these instructions. Since the primary program requires only one jump and one wait for a previous result this is not a problem.

The instruction cycle for the M7 varies from 4 to 8 micro cycles with the normal instruction (i.e., ax ± by + c) being 4 micro cycles long. Figure 6 shows the pipe line operation for three successive instructions. Data Memory write operations always take place during the first two micro cycles and read operations during the third and fourth micro cycle. If cycles 5 and 6 are used they are a memory write cycle.

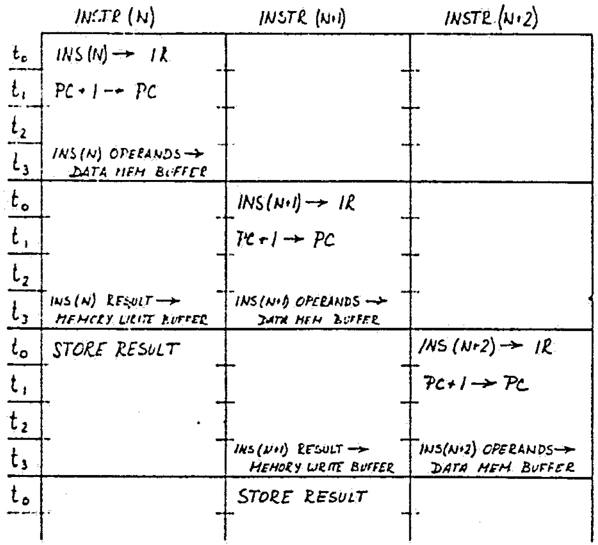


Fig. 6. Instruction Pipeline Timing

At the leading edge of the first micro cycle, the Instruction Register (IR) is loaded with the instruction from the Instruction Memory (IM) which has been settling since t_1 time of the previous instruction. If the previous instruction is a jump instruction, then the previous instruction length is extended into t_4, t_5, t_6, t_7 time as necessary to allow sufficient IM access time. At the trailing edge of t_3 time, the operand addresses have settled and the Data Memory (DM) contents are loaded into the Data Memory Buffer.

The next instruction (n + 1) is now started by performing another instruction fetch. At the end of t_3 time of the n + 1 instruction, the output of the ALU is loaded into the Write Buffer (WB). Thus each instruction can use the entire instruction time for the multipliers and ALU to stabilize.

At t_{01} time of the n + 2 instruction the result is written into memory.

The relatively large microprogram word allows fairly complex instructions to be designed if fields are assigned different meanings than that required for the primary instruction, ax±by→c. One instruction, for example, was designed for efficient track searching. This instruction will search a list until an entry is found larger than one operand. If such an entry is found it exits with a jump, otherwise the next inetruction is taken when the list is exhausted. The simple register structure of the M7 allows this instruction to be implemented with only 5 gates (Figure 7).

Check Out

The M7 was checked out and placed into operation with minimum programming effort. About 4 total man months were spent in debugging the system. We consider this a modest effort and attribute the short time to several design factors:

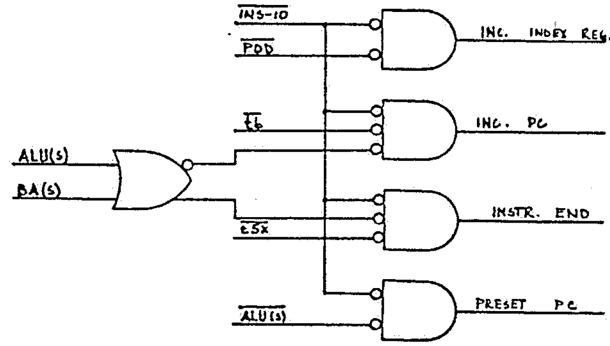


Fig. 7. Gates Required to Add List Search Instructions

1) Elimination of design complications which are difficult to debug and test-such as interrupt logic.

2) Very simple register structure, with most operations simple register to register transfers. The result is that a typical instruction requires only 4 gates, and even the list search instruction required only 5 gates.

3) Use of a relatively long microprogram instruction word.

4) Use of ECL 10,000 logic which is much quieter even though faster than TTL.

5) Use of an extensive CAMAC interface which allows all major registers to be examined and loaded from CAMAC.

6) Use of a Time-Sharing Computer CAMAC Controller.

The experimental configuration of the M7, Figure 1, will transfer data to the host computer (at first a Sigma 3 - later a PDP-11) through a CAMAC interface. While it would have been possible to acquire a CAMAC interfaced PDP-11 for check-out and test purposes, this was rejected for several reasons:

1) PDP-11 systems are a scarce resource at Fermilab and the system that would have been available to us was limited in operating features.

2) It would have been necessary to train a programmer and maintain programming skills. This is estimated to be at a half-time effort whether useful work is done or not.

3) A computer would require space, air-conditioning and maintenance effort-even when done by others, this is a considerable load.

4) A computer would require software and file structure maintenance to assure that test programs would be available

when needed.

The scheme adopted (Figure 8), was to build a CAMAC Crate Controller, the FBB, which is able to perform most CAMAC operations (except interrupts), by interpreting character strings received from a remote time-sharing computer. Operation of the FBB as well as its design is relatively simple. The RS232 cable between the terminal and its audio coupler is disconnected and plugged into the FBB. A cable from the FBB completes the circuit. Character strings generated in the central computer is a high level language (in this case, BASIC) perform all necessary CAMAC functions. One control character is used to suppress printing to save paper.

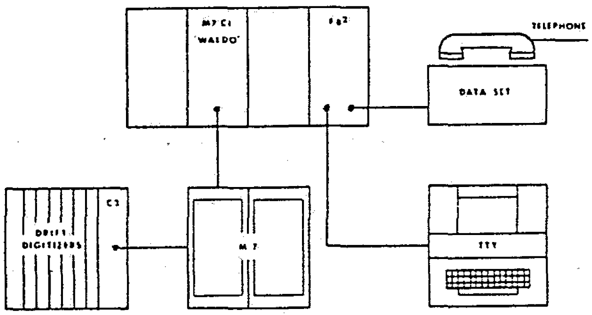


Fig. 8. M7 Check-Out Configuration

While the result is very slow, several CAMAC operations per second, it is still quite adequate for test and debugging and the editing features of BASIC allow very fast program modification. High speed tests are performed by downloading programs to the M7 which then tests itself. Note we consider this solution superior to a microprocessor crate controller in that while it is much slower, we have available to us the features of a large central facility with its extensive software and file maintenance.

With 10,000 series ECL a variable speed clock is a very useful debugging tool. One of the more common design errors is to forget to terminate a signal line. When this is the problem, operations will be performed correctly at clock speeds which allow about 1 microsecond between operations but not faster. In this case, if correct operation is achieved by slowing the system clock from 40 MHz to 1MHz it is a certain indication that a terminator is missing. Oscilloscope tracing in the indicated area typically revealed a "ski slope" signal.

Current Status

The M7 processor is now executing the program of Figure 3 in 2.1 microseconds. The present speed limitation is due to control logic, not arithmetic speed. The clock can presently be varied from zero to a 38MHz micro cycle rate. A variable speed clock is a convenient debugging feature and it is planned to limit operation to this speed until pressed. The M7 can be run at a clock speed of 53MHz by timing critical parts and operating at a fixed clock frequency. This corresponds to a program execution time of 1.5 microseconds at which time arithmetic errors begin to be made.

In order to evaluate the effectiveness of the M7 in the final experimental environment a Monte Carlo program is presently being run on the laboratory time-sharing computer. This program simulates an event and transmits the coordinates of the drift chamber hits over the telephone link to the M7. The time-sharing computer starts the M7 and then examines the result. In this way, it is possible to study how well the M7 will perform, though at seven orders of magnitude slower data rate. Figure 9 is the result of this simulation which was performed by the real M7 and which indicates that the M7 will improve the trigger efficiency by nearly two orders of magnitude.

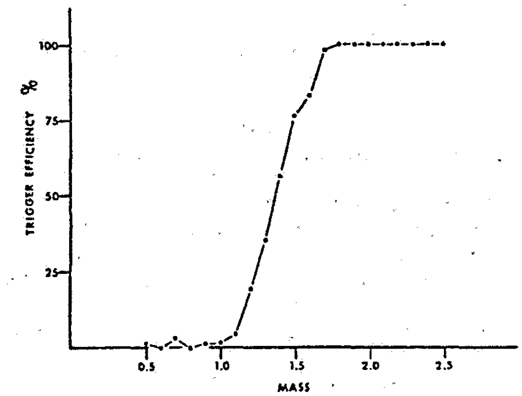


Fig. 9. Trigger Efficiency for 100Gev Dimuon Events after Processing by the M7 with a Mass Cut at 1.41 GeV/c^2

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