NAL PROPOSAL NO. 365

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# A PROPOSAL TO SEARCH FOR THE PRODUCTION OF CHARMED MESONS IN $\pi^-$P INTERACTIONS

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## ABSTRACT

An experiment is proposed which searches for the production of charmed mesons, D, produced in the reactions

$$\pi^- p \rightarrow X^- p \rightarrow D\bar{D}p \qquad (1)$$

$$\pi^- p \rightarrow X^- p \rightarrow D\bar{D}(n\pi)p \qquad (2)$$

Reaction (2) differs from reaction (1) in that n additional pions are produced. For each event the final state proton as well as one or more of the muons from the D or $\bar{D}$ decays will be measured. The experiment looks for D's in the mass range $1.0 \leq M_D \leq 4.5$ GeV. A total production cross section for reaction (1) plus reaction (2), $\sigma_{1,2}$, of 5 $\mu$b for $2M_D \leq M_X \leq (2M_D + 1\text{ GeV})$ and a branching ratio for $D \rightarrow (\mu\nu$ hadrons) of 0.1 is expected to give in one day of running more than a 7 standard deviation effect in the observed mass, $M_x$, spectrum from $\mu$ p coincidence events.

The experiment uses the existing apparatus of Experiment 51a in addition to a $\mu$ detector yet to be installed in the M2 beam line. The experiment can be carried out in a three week running period with 200 hours of beam. (40 testing, 160 hours of data taking)

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## 1. Introduction

The recent discovery of a narrow, $\Gamma \leq 2$ MeV, neutral meson $\psi^{o}(3105)$ at SPEAR and at BNL strongly suggests there exists at least one additional quantum number which like strangeness is conserved by the strong and electromagnetic interactions but is not conserved by the weak interactions. We, like others[(1)], call this new quantum number charm. The simplest interpretation[(1)] of the $\psi^{o}(3105)$ is that it is a bound state of a charmed quark anti-quark pair $c\bar{c}$ in a $J^{P} = 1^{-}$ state which decays electromagnetically. If there are charmed quarks, they will combine with the normal quarks to produce new families of mesons with non-zero charm quantum numbers. For example in this picture the charmed meson $D^{-}$ is a $0^{-}$ $\bar{c}d$ quark state[(1)] which is produced along with another charmed meson or a charmed baryon via the strong interactions but can decay only through the weak interactions. The D mesons are expected[(1)] to have widths of less than one MeV and masses of approximately 2 GeV. The D particles will have charm quantum number, $C = \pm 1$ whereas the $\psi^{o}$ has $C = 0$. This means that the D cannot be produced singly as is the $\psi^{o}$. It must be produced in pairs analogous to the associated production of strange particles. Thus it will be produced in the reactions:

$$\pi^{-} p \rightarrow D\bar{D}\, p \qquad (1)$$

$$\pi^{-} p \rightarrow D\bar{D}(n\pi)p \qquad n = 1,2,\ldots \qquad (2)$$

The proposed experiment will measure the cross section for the reaction

$$\pi^{-} p \rightarrow X^{-}p \rightarrow \mu\, Xp' \qquad (3)$$

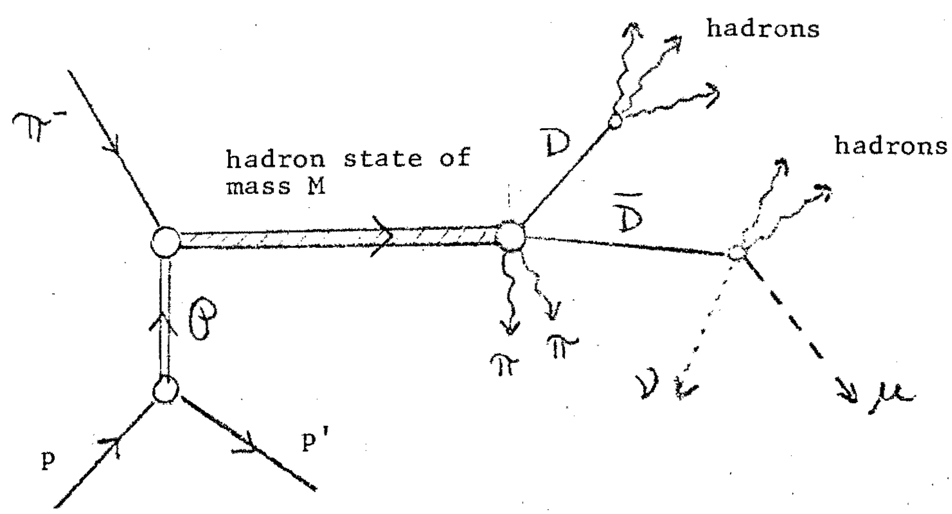
using the high resolution ($\delta M$(fwhm) $\sim$ 0.1 GeV at M $\sim$ 5 GeV) missing mass spectrometer system currently installed in the M2 beam line for Exp. 51A, along with a forward muon detector. Thus the missing mass arm will determine the invariant mass of the $X^-$ system for events in which either the D or $\bar{D}$ (or both) have decayed under $\mu$ emission.

If, for example, the total cross section for reactions (1) plus (2), $\sigma_{1,2}$, is 5$\mu$b for $2M_D \leq M_X \leq 2M_D + 1$ GeV and the branching ratio $D \rightarrow (\mu\nu$ hadrons) is $\sim$ 10%, the missing mass spectrum will exhibit a 7 standard deviation increase in the vicinity of $M_X \sim 2M_D$. Clearly, the measured size of the effect determines the product of production cross section for reactions (1) and (2) times the $D \rightarrow (\mu\nu h)$ branching ratio. The experiment will at a minimum provide essential data required for design of future experiments[2] which could measure the masses, widths, spins, parities, etc, of the charmed meson.

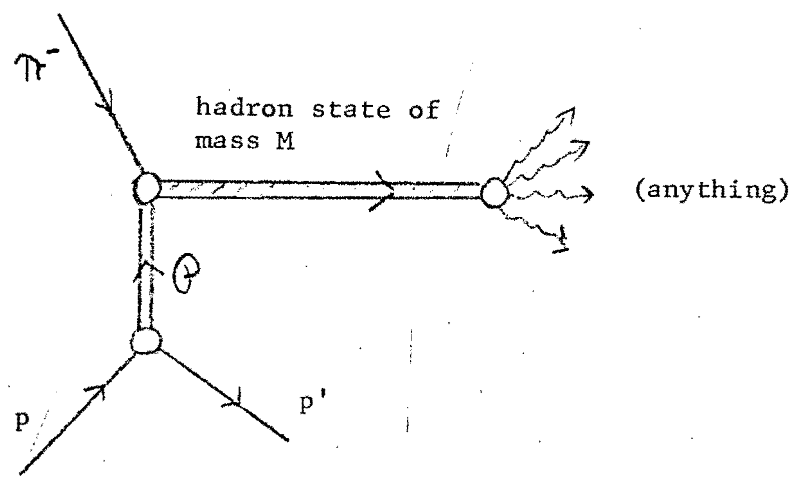
Conventionally the missing mass technique has been used to search for new particles produced in a two body final state with resulting peaks in the mass spectrum. However, we stress that this technique can also be used for detecting pair production processes such as reactions 1 and 2 above. The missing mass spectrum from these reactions will not contain narrow peaks at the mass of the D, but there will be a sizeable step function discontinuity at the missing mass value of $\sim 2M_D$. The discontinuity arises simply from the fact that these reactions produce no protons below the mass threshold of $2M_D$ and at threshold the proton yield rises abruptly.

In actuality this step function will sit on top of a smooth missing mass spectrum produced by protons from all other processes. For a production cross section of 5$\mu$b for reactions 1 and 2 we expect the step to be .3% of the smooth total background. The purpose of the muon detector is to greatly enhance the signal to noise ratio. The muon detector has been especially designed to detect direct muon production and minimize muons from $\pi$ and K decays in flight. If the only source of direct muon production were the charm particle decays, then a mass spectrum taken with a direct muon in coincidence with the recoil proton would be extremely clean, i.e., no events at all below charm - anticharm meson threshold and a dramatic rise above threshold. However, we do expect some $\mu$ p coincidence backgrounds under the expected threshold discontinuity. They are direct muons from meson decays ( $\rho$ and $\phi$, etc. ) and muon decay of $\pi$'s and K's simulating direct muon production. We have reason to believe (see Section 4) that these backgrounds will result in a 1:1 signal/background ratio for the 5$\mu$b charm production cross section discussed above.

Another way of interpreting the proposed experiment is that it is a measurement of the total cross section for charmed meson production vs center of mass energy, M, in the reaction $\pi^- \wp \rightarrow$ (charmed meson) + (anything) where $\wp$ is the virtual hadron field of the proton. This can be represented graphically as:




where $\pi^-$ is the incident beam $\pi^-$, p the target proton, p' the recoil proton and D and $\bar{D}$ the charmed mesons. The apparatus looks at channels in which either the D or $\bar{D}$ (or both) decay under the emission of a muon, i.e., in the experiment the detected $\mu$ is used to indicate when charmed meson production has taken place. For $M_D \sim 2.5$ GeV, the meaning of the statement that the cross section $\sigma_{1,2} \sim 5 \mu b$ for $2M_D \leq M \leq 2M_D + 1$ GeV (or for $M_D \sim 2.5$ GeV, $5.0 \leq M \leq 6.0$ GeV) becomes clear when one takes into account that the total inclusive cross section for $\pi^- p \rightarrow X\bar{p}$ at 100 GeV is $\sim 1700 \mu b$ for $5.0 \leq M \leq 6.0$ GeV[5]. The reaction $\pi^- p \rightarrow X\bar{p}$ can be represented graphically as:




Thus, the proposed experiment will observe a 7 standard deviation effect if charmed meson production is $\sim 0.3\%$ of the total $\pi \rho$ cross section in the region from charmed meson threshold, $M = 2M_D$, to 1 GeV above threshold, $M = 2M_D + 1$ GeV. Because the detected $\mu$ provides a signal that charmed meson production had taken place the onset of charmed meson production is expected to appear as a 100% effect above background for $\sigma_{1,2} \sim 5 \mu b$ (see Fig. 3).

2. <u>Cross section estimates, threshold effects and decay branching ratios.</u>

This experiment is designed to detect charmed mesons, D's, and assumes

(1) $M_D \sim 1$ to 4.5 GeV

(2) In reaction (3) there is a $D\bar{D}$ or $D\bar{D} + \pi$'s enhancement or rise in the $M_{D\bar{D}}$ or $M_{D\bar{D}+\pi\text{'s}}$ effective mass spectrum near $2M_D$ in a region $2M_D \leq M_X \leq 2M_D + 1$ GeV ($X = D\bar{D}$ or $D\bar{D} + \pi$'s).

(3) The total cross section for this enhancement in the region 1 GeV above $2M_D$ is $\sim 5\,\mu b$.

(4) The branching ratio for $D \to (\mu\nu$ hadrons) decays is $\sim 10\%$.

Let us now attempt to examine the basis for these assumptions. First, theory[1] suggests that the mass of the D should be in the region 2.0 to 2.5 GeV given that the $\psi^c(3105)$ is indeed the expected $J^P = 1^-$ $c\bar{c}$ quark state. Thus, an experiment that searches in the $1.0 \leq M_D \leq 4.5$ GeV region is called for. Second, in reactions that we are familar with such as $\pi p \to \pi\rho\, p$, $\pi p \to \pi f p$, $\pi^- p \to K^- K^+ n$, $\pi^- p \to \bar{p}pn$ and others there are low mass enhancements in the $\pi\rho$, $\pi f$, $K^-K^+$ and $\bar{p}p$ systems[3]. (Deck and other such effects and resonances.) We expect that the reactions $\pi p \to D\bar{D}p$ and $\pi p \to D\bar{D}(n\pi\text{'s})p$ will have a mass threshold behavior and/or enhancements similar to the known $\pi\rho$, $\pi f$, $K^-K^+$ and $\bar{p}p$ enhancements and mass threshold effects. Third, present analyses[1] of the observed ratios of the yields of leptons and $\pi$'s from high energy pp interactions strongly suggest that charmed mesons are produced with cross sections similar to those for the production of K mesons. Thus the cross section for D production in $\pi p$ interactions is expected to be at least 5% of the total $\pi p$ cross section providing the incident beam momentum is significantly above the threshold for producing D's. If the mass spectrum for the reaction $\pi p \to D\bar{D}(n\pi\text{'s})p$ is flat vs $M_X^2(D\bar{D}\ (n\pi\text{'s}))$ then at 100 GeV for a region $\Delta M_X^2 \sim 2M_X \Gamma_X \sim 10\ GeV^2$ one expects for $(2M_D)^2 \leq M_X^2 \leq (2M_D)^2 + 10\ GeV^2$:

$\sigma \sim (5 \times 10^{-2})\ (\sigma_{TOT\ \pi p}) \left( \Delta M^2 / M^2_{max} \right) \sim 50\ \mu b$. If the $M^2(D\bar{D}(n\pi's))$ cross section falls approximately linearly from $(2M_D)^2$ to the kinematic limit, $M^2_{max} = 2P_{Beam} m_p$, and approaches zero near the limit then $\sigma(D\bar{D}(n\pi's)$ $\sim 100\ \mu b$ for $(2M_D) \leq M^2 \leq (2M_D)^2 + 10\ GeV^2$. This suggests that the cross section sensitivity of the proposed experiment, $\sigma \sim 5\ \mu b$ will be more than sufficient to detect the existence of charmed particles.

Finally, the present theoretical understanding(1) of the weak interactions and charm suggest a branching ratio for $D \rightarrow (\mu \nu h) \sim 10\%$.

3. Apparatus

A layout of the proposed proton and $\mu$ detectors is shown in Fig. 1. The apparatus, with the exception of the absorber, toroids and three spark chambers SC5, SC6, SC7, is already installed in the M2 beam line and is completely working from both a hardware and software point of view. Three beam threshold Cerenkov counters, not shown, separate the incident particles into three groups, $g_i$, $g_1 = \pi + e + \mu$'s, $g_2$ = K's, $g_3 = \bar{p}$'s such that the contamination of K's and $\bar{p}$'s in the $g_1$ sample is less than $\sim 2\%$. Beam hodoscopes, not shown, measure the incident beam particle's momentum, $P_B$, to $\delta P_B / P_B \sim 0.2\%$, and its incident vertical and horizontal angles, $\theta_V$, $\theta_H$, to $\delta\theta \sim 0.2$ m rad. The X and Y coordinates of the beam particle are measured to an accuracy of $\delta X \sim 1/16''$ and $\delta Y = 1/8''$. When the beam is set to 100⁻ the flux is approximately $10^6\ \pi$'s, $10^4$K's and $10^4\ \bar{p}$ per pulse for $\sim 10^{12}$ p's targeted in the Meson Area and at 200⁻ about 10% of this $\pi$ flux is obtained per incident proton. The beam spot at 100⁻ GeV is $\delta X_B \sim 1/4''$, $\delta Y_B \sim 1/8''$ and varies as $(P_{Beam})^{-1}$. The present beam quality is more than adquate for the proposed experiment.

The recoil proton spectrometer has been described in detail elsewhere[4]. It detects recoil protons in the $|t|$ range 0.1 to 0.4 $GeV^2$ and measures the proton production angle to better than 10 mrad (fwhm). The t resolution is $\delta t/t \sim 7\%$ (fwhm) at $|t| = 0.1$ and $\delta t/t \propto t^{-\frac{1}{2}}$. This gives a missing mass resolution of $\delta M^2(\text{fwhm}) \sim P_{Beam} \times 10^{-2}\ GeV^2$. The solid angle subtended by this detector, $\Delta\Omega_p$, is approximately $\Delta\Omega_p \sim 70$ msr.

The beam particle's coordinates and the proton recoil track determine the production point in the $H_2$ target to an fwhm accuracy of $\delta X \sim \delta Y \sim \delta Z \sim 1/10''$.

The absorber immediately downstream of the $H_2$ target consists of 12" of tungsten, W, followed by either W, U or Fe depending on which materials are available. Obviously W is preferred. For example if W is used the absorber need be only 5' long, whereas if the absorber is made out of 12" of W or U followed by Fe it would have to be $\sim 8'$ long to have the same effectiveness.

The hadron absorber is followed by a proportional chamber, 7" x 14", which has a measurement accuracy, fwhm, of ($\delta X \sim \delta y \sim 1/25''$), a trigger counter, 15' of magnetized Fe(B $\sim$ 12 kilogauss, toroids), three spark chambers, a small absorber, and additional trigger counters.

Since the production point of the $\mu$ is well determined by the beam and recoil spectrometers both the $\mu$'s production angle and its momentum can be determined from just its origin in the $H_2$ target and its direction after the magnetized Fe. The proportional chamber provides additional accuracy in determining the $\mu$ production angles and momentum. The calculated resolution of the $\mu$ detector is shown in Fig. 2.

The entire apparatus is connected on line to a PDP9 computer which performs on-line checks on the performance of the apparatus. The system can record more than 100 events per second. Since the trigger rate is expected to be $<$ 10 events per pulse the high data recording ability of the apparatus will be exploited by recording other types of events needed for determining backgrounds in the experiments. For example events of the type $\pi^- p \rightarrow$ "$\pi$"$\mu$ and $\pi^- p \rightarrow$ "$\pi$"$\mu\mu$ will be recorded where the "$\pi$" is detected in the recoil spectrometer. These events will be used to determine other physical backgrounds, which can give rise to the $p\mu$ coincidences other than charmed particle production.

4. Backgrounds

The backgrounds in this experiment will probably determine the ultimate sensitivity of the apparatus for detecting charmed particles. The backgrounds are of two types. First, instrumental backgrounds such as a recoil proton in random electronic coincidence with a muon in the beam or in the beam halo. We know from existing measurements with the apparatus that this type of background is small. Second, other physical processes such as (A): secondary $\pi$'s and K's decaying before the absorber (background type A); (B): direct $\mu$ production by processes other than charmed particle production such as $\rho^0 \rightarrow 2\mu$ decays from the reaction $\pi\, p \rightarrow \rho^0\, x\, p$ (background type B); and (C): secondary $\pi$'s and K's making $\mu$'s in the absorber (background type C). Backgrounds from the decays of $\pi$'s and K's made by secondary hadrons interacting in the absorber can be made negligibly small compared to the $\pi$ decay background from the secondaries themselves by selecting on $\mu$ momentum in the final analysis of the data. This is true since the tertiary $\pi$'s have, on the average, much lower momentum than do the secondaries produced along with the proton recoil.

We now discuss backgrounds A, B and C.

Type A

This type of background can in principle be calculated from the known bubble chamber results on inclusive $\pi$ and K production at $100^-$ and $200^-$

GeV. Fortunately, we have a measured upper limit for this background. We have measured the probability $P'_{\mu}(M^2)$ that a recoil proton gives rise to a $\mu$ into an aperture of $1^o \times 2^o$ when the absorber is placed 35' from the target. The absorber used was $\sim$ 20' of Fe (the E8 magnet). We find that to within $\pm$ 30% for $0 \leq M^2 \leq 40$ GeV$^2$, $P'_{\mu}(M^2) \sim 4 \times 10^{-3}$ and is independent of $M^2$. In the proposed experiment the average flight path for the secondaries before they interact will be $\sim$ 2'. Thus an upper limit on $P_{\mu}(M^2)$ in the experiment is: $P_{\mu}(M^2) \sim (2'/35')(4 \times 10^{-3}) \sim 2 \times 10^{-4}$. Since in this experiment we will also be able to select on $\mu$ production angle and momentum we expect to reduce this background to better than $P_{\mu}(M^2) \sim 7 \times 10^{-5}$. In addition, since for our data we will know the event origin in the $H_2$ target the effect of $\pi$ and K decays before the absorber can be studied in the final analysis of the data to determine the best cuts to make on $\theta_{\mu}$ and $P_{\mu}$. This is true since the $\pi$ and K decay backgrounds vary by a factor of 3 from one end of the $H_2$ target to the other.

Type B

While taking data on the $\mu$xp final state we will also record data on the final states $\mu\chi$ "$\pi$" and $\mu\mu\chi$ "$\pi$" where the "$\pi$" is detected in the recoil spectrometer. This will allow us to estimate the contamination in our data from processes other than charmed particle production as well as their $M^2$ dependences. In addition, the $\mu\chi$ "$\pi$" and $\mu\mu\chi$ "$\pi$" data themselves are of considerable physics interest (see Appendix A).

Type C

Even though though this type of background will probably be negligible, as a check, some measurements with the apparatus will be made. To insure a pure beam of $\pi$'s incident in the absorber (i.e. no $\mu$ contamination) we will set the recoil spectrometer to detect elastic $\pi$p scattering. Since contamination of the $\pi$ beam with $\mu$'s is less than 1% and the $\mu p$ elastic cross section is $\sim 10^{-4}$ of the $\pi p$ elastic cross section the $\mu$ contamination in this sample will be $\sim 10^{-6}$. We will do these measurements at several beam momenta below 200 GeV to study the effects of the production of $\mu$'s by secondaries in the $\mu$ detector. Because the energies of the secondaries are much lower, on the average, than the energy of the incident beam, we believe this background will be negligibly small compared to the direct production of $\mu$'s in the target itself.

5. Calibrations

The calibrations of the beam and recoil spectrometer are straightforward and have been described in great detail elsewhere[(4)]. The $\mu$ detector will be calibrated with a high quality $\mu$ beam made by closing the collimator at the first focus of the M2 beam.

6. Sensitivity and Counting Rates

Assuming a cross section for $\pi^- p \to D\bar{D}(n\pi)p$ of the form $d\sigma/_{dt} = Ae^{Bt}$, $B \sim 8\ \text{GeV}^2$, $\sigma_{TOT} = A/B$, the number of events $N_{obs}$ observed per 20 hours is:

$$N_{obs} \simeq (\#\ p's/cm^2)\ (\tfrac{1}{2}\sigma_{TOT})\ \left(\frac{\Delta\varphi_p}{2\pi}\right)\ (2BR(D\to\mu))\ (\text{Det. Eff}\ (D\to\mu))(\#\pi's/_{20\ \text{hours}})$$

where $BR(D\to\mu)$ is the branching ratio for D decay into a $\mu$ and Det. Eff$(D\to\mu)$ is the detection efficiency for detecting the $\mu$ from D decay. For a 2' $H_2$ target: $\#p's/cm^2 \sim 2.5 \times 10^{24}\ cm^{-2}$.

Also, $\dfrac{\Delta\varphi_p}{2\pi} \sim \left(\dfrac{20''}{72''}\right)\left(\dfrac{1}{2\pi}\right) \sim 4.4 \times 10^{-2}$.

In evaluating $N_{obs}$ at 100 GeV we assume: (1) A branching ratio for $(D\to\mu\nu h)$ of 10% and that on the average the $\mu$ in the D rest frame has a momentum of $P^*_\mu \sim M_D/3$. (2) $M_D \sim 2.5$ GeV. (3) The D decays isotropically in its own rest frame.

(4) The D's are produced at small $P_\perp$ and therefore travel along the beam direction. (5) The average D energy in the lab is 50 GeV. (6) Cuts will be made to make the $\mu$ detector effectively subtend a $1^\circ \times 2^\circ$ aperture which is the same aperture for which the $\pi$ and K decays have already been measured 35' from the $H_2$ target. The $\mu$ detector that will actually be used will subtend a $4^\circ \times 4^\circ$ aperture so our estimate of the $\mu$ detection efficiency is conservative. The detection efficiency under the above assumptions is $\sim$ 15%. We assume 600 pulses per hour and $10^6$ $\pi$'s per pulse.

Thus, for $\sigma_{TOT} \sim 5\,\mu b$ we get:

$$N_{obs} = (2.5 \times 10^{24})\ (\tfrac{1}{2} \times 5 \times 10^{-30})\ (4.4 \times 10^{-2})\ (2 \times 10^{-1})\ (1.5 \times 10^{-1})$$

$$\times\ (1.2 \times 10^{10}) = 95 \text{ events/20 hours}$$

or for a $D\bar{D}(n\pi)$ enhancement near 2 $M_D$ of $\Gamma_{DD} \sim$ 1 GeV, $M_D \sim$ 2.5 GeV, $d\,N_{obs}/dM^2 \sim 9.5$ events/GeV$^2$.

The most serious background will be in decays of $\pi$ and K secondaries for which we have measured an upper limit of $F = 2 \times 10^{-4}$ independent of $M^2$ or equivalently independent of proton angles and energy in the t range $0.1 \leq |t| \leq .4$ GeV$^2$ (see Section 4). Thus the upper limit on the background is determined by $\frac{d\sigma}{dM^2}$ $(.1 \leq |t| \leq .4\ \text{GeV}^2)$ for the reaction $\pi^- p \rightarrow X\bar{p}$ at 100 GeV times F. Very accurate estimates of $d\sigma/dtdM^2$ are possible[4,5]. For $M^2 \sim 25$ GeV$^2$, $0.1 \leq |t| \leq 0.4$ GeV$^2$ we get $d\sigma/dM^2 \sim 85\,\mu b/\text{GeV}^2$.

This gives: $d\sigma/dM^2(\pi p \rightarrow p + \text{decay}\,\mu) \leq 1.7 \times 10^{-2}\,\mu b/\text{GeV}^2$.

Our best estimate is $d\sigma/dM^2(\pi p \rightarrow p + \text{decay}\,\mu) \sim 0.5 \times 10^{-2}\,\mu b/\text{GeV}^2$.

Therefore:

$$N_{obs}\ (\text{backgrd}\ \pi p \rightarrow p + \text{decay}\ \mu)\Big|_{\text{upper limit}} < 190/20\ \text{hours},$$

or

$$N_{obs}\ (\text{backgrd}\ \pi p \rightarrow p + \text{decay}\ \mu)\Big|_{\text{best estimate}} \simeq 70/20\ \text{hours}$$

Results expected from a 20 hour run under the above assumptions are shown in Fig. 3.

7. Run plan and scheduling of the experiment

Our plan is to scan the $M^2$ region $0 \leq M^2 \leq 40\ \text{GeV}^2$ at 100 GeV in three angle settings of the recoil spectrometer. This will require 80 hours of data taking. Likewise, the $M^2$ region $0 \leq M^2 \leq 80\ \text{GeV}^2$ will be measured at 200 GeV in 80 hours of data taking. We require an additional 40 hours of beam to perform calibrations, checks, etc. We thus request a total of 200 hours of beam at $10^6$ $\pi$'s per pulse, 600 pulses per hour.

If this proposal is approved before December 2, 1974 we expect we could set up the apparatus in the period December 2 through December 19 and carry out the experiment in the three week running period starting December 19, 1974.

8. Requirements of FNAL

(1) 200 hours of beam, $10^6$ $\pi$'s/pulse at 100 GeV and 200 GeV.

(2) Work with us to obtain and install the hadron absorber and toroids.

(3) 20 hours of CDC 6600 high priority-fast turn around computer time (bicycle on-line service).

(4) Other equipment and $H_2$ target currently in use by Experiment 51a.

## Appendix A: Dimuons

### I Introduction

The recent observation at FNAL of anomalously high $\mu/\pi$ ratios at large values of $p_\perp$ increases interest in experiments on di-muons. A large number of such experiments were recently proposed to FNAL and reviewed. To date we know of no actual data on di-muon production by $\pi$ mesons. An initial measurement of this process will be a byproduct of this experiment. We believe it is of considerable interest to compare the di-muon production in pp collisions in which anti-quarks are rare, to the production in $\pi$ p collisions which are rich in quark-anti-quark interactions.

As a natural byproduct of measurements of the background, in the search for $\bar{D}D$ meson pair production, some data on di-muons will be obtained which we believe will be interesting. The purpose of this appendix is to briefly discuss this di-muon aspect of the experiment.

### II Momentum Measurement

The momentum will be measured by the curvature of the muon trajectory in magnetized iron. The length of the field region will be 15' and the field value will be 12 kg (See Fig. 1.)

The resolution in momentum is dominated by the multiple scattering of the muon in the iron. There is also a non-negligible contribution to momentum resolution due to spatial resolution of the MWPC and WSC's.

Fig. 2(a) shows the momentum resolution, hwhm, vs $p_\mu$. For $p_\mu \lesssim$ 70 GeV/c, the momentum resolution is determined almost entirely by multiple scattering. The resulting resolution is momentum independent, and for thin targets it is given by

$$\frac{Y_{rms}}{Y_B} = \frac{10\sqrt{T}\;LB}{T^{1/2}} \qquad \frac{T^{1/2}}{2LB} \qquad \text{A-1}$$

where L is the magnet length in meters, B the field in $Wb/m^2$, and T is the number of radiation lengths in the magnet "gap". Above $p_{\mu}$ = 70 GeV the chamber resolution becomes significant rising from a 12% effect at 70 GeV to a 40% effect at 140 GeV/c.

For the proposed magnet geometry, which was chosen primarily to allow an early and reliable measurement of $D\bar{D}$ production, $Y_{rms}/Y_B \approx 16.9\%$. This is the dominant contribution to the di-muon mass resolution (Fig. 4). We will attempt to improve the resolution beyond this value to the extent that it is consistent with an early run on $D\bar{D}$; the values given here represent numbers we feel confident of achieving within the time scales outlined in the main proposal.

III <u>Angle Measurement</u>

The muon production angle is measured by the target vertex and the MWPC. Angles in the interval $\pm 2^o$ are accepted by the magnet. The target interaction vertex is known to $(2.5 \text{ mm})^3$ due to a pion track in the proton spectrometer and a beam particle in the beam hodoscopes. The MWPC defines the $\mu$ track to 1 mm x 1 mm., and the WSC's to 0.75 mm x 0.75 mm. This overdetermines the muon trajectory by 1 measurement and provides a consistency check.

The dominant term in the angular resolution is the multiple scattering in the absorber preceeding the MWPC. Figure 2b shows the resulting $\delta\theta$ vs $p_{\mu}$. Since $\delta\theta$ is dominated by multiple scattering, $\delta\theta \propto 1/p_{\mu}$.

The angular resolution may be able to be improved by reducing the amount of absorber between the hydrogen target and the MWPC.

IV Mass Resolution

In the case of symmetric muon pairs, $M_{\mu\mu} = 2p_{\mu}\theta_{\frac{1}{2}}$ where $\theta_{\frac{1}{2}}$ is the angle made with the Z axis by a single muon, and $2\theta_{\frac{1}{2}}$ is the di-muon opening angle. At large angles $\delta\theta/\theta \ll \delta p_{\mu}/p_{\mu}$, and hence $\delta M_{\mu\mu}/M_{\mu\mu}$ is dominated by the momentum resolution. At small angles $\delta\theta/\theta \gg \delta p_{\mu}/p_{\mu}$ and hence the mass resolution is dominated by the angular resolution. The mass resolution is shown in Fig. 4.

This mass resolution is not inspiring. Nevertheless we believe that useful data on the di muon mass spectrum can be obtained for $M_{\mu\mu} >$ .5 GeV The acceptances of the apparatus permit useful data up to $M_{\mu\mu} \sim 7$ GeV.

It may be possible for us to significantly improve the mass resolution by using a longer magnet, less absorber in front of the MWPC, and also larger separation of the WSC's, to approach the resolution proposed in E359.

V Yields

The observations of muon to pion ratios of $\sim 10^{-4}$, made at FNAL, may imply a di-muon production cross section of about 8 $\mu$b. We assume a beam with $10^{6}\pi$ /pulse, and a 2' hydrogen target. Recall that in the $D\bar{D}$ measurement we use the proton spectrometer to define the position of origin in the target. In order to study the di-muon mass spectrum however, we need not require a proton in the spectrometer, a clean $\pi$ track will do. The requirement of such $\pi$ tracks in the spectrometer introduces a factor of $.5 \times 10^{-2}$ for spectrometer solid angle. The resulting yield, if all $\mu$'s are due to $M_{\mu\mu}$ such that $M_{\mu\mu} < 5$ GeV, is $\sim 300$ pairs/20 hours of running.

Approximately 1/20 of these events will be accompanied by a proton recoil in the spectrometer. i.e. 15 of the di-muon events per day are expected to appear in the proton data described in the body of the report.

The di-muon events are also expected to contain μ pairs due to, eg,

$$\pi + p \rightarrow p + D + \bar{D} + \ldots$$

$\quad D \rightarrow \mu + \cdots$

$\quad \bar{D} \rightarrow \mu + \cdots$

Using the cross sections outlined in the main part of the proposal, the yields of these are expected to be ~ 12/day. It is expected that we will not be able to resolve these from the more numerous di-muons mentioned above.

VI Backgrounds

We note, finally, that the background for the di-muon spectrum due to decays of π and K mesons is greatly reduced by the simple fact that two uncorrelated decays are required, each having probability of $\sim 10^{-4}$.

10. References


1. M. K. Gaillard, B. W. Lee, and J. L. Rosner, FERMILAB-Pub-74/86 THY and references cited therein (to be published).

2. For example, the effective mass measurements proposed in FNAL proposal #51 using as a trigger a forward high energy $\mu$.

3. See "Review of Particle Properties" Particle Data Group, Phys. Lett. 50B, No. 1, (1971), for $\pi\rho$, $\pi f$ and $K^-K^+$ enhancements and for $\bar{p}p$ Grayer, et al., Phys. Lett. 29B, 563 (1972).

4. D. Bowen, et al., in "Experimental Meson Spectroscopy - 1972, AIP Conference Proceedings No. 8, edited by K.-W Lai and A. H. Rosenfeld (American Institute of Physics, New York, 1972), p. 215, and references cited therein.

5. The cross section for $\pi p \rightarrow xp$ at 100 GeV can be deduced from Ref. 4 if one takes into account the fact that the data of Bowen et al., Ref 4, are consistent with a cross section behavior of the form $P_\pi \, d^2\sigma/dtdM^2 = f(\theta_p, T_p)$ where $P_\pi$ is the laboratory incident $\pi$ energy and $\theta_p$ and $T_p$ the recoil proton laboratory angle and kinetic energy. In addition to the data of Ref. 4 one must realize that $A(M^2)$ of Ref. 4 has the behavior $A(M^2) \propto M^{-1}$ for $M^2 \geq 4$ GeV$^2$ and that $P_\pi/M^2$ and $P_\perp^2$ are just functions of $\theta_p$ and $T_p$.

## 11. Figure Captions

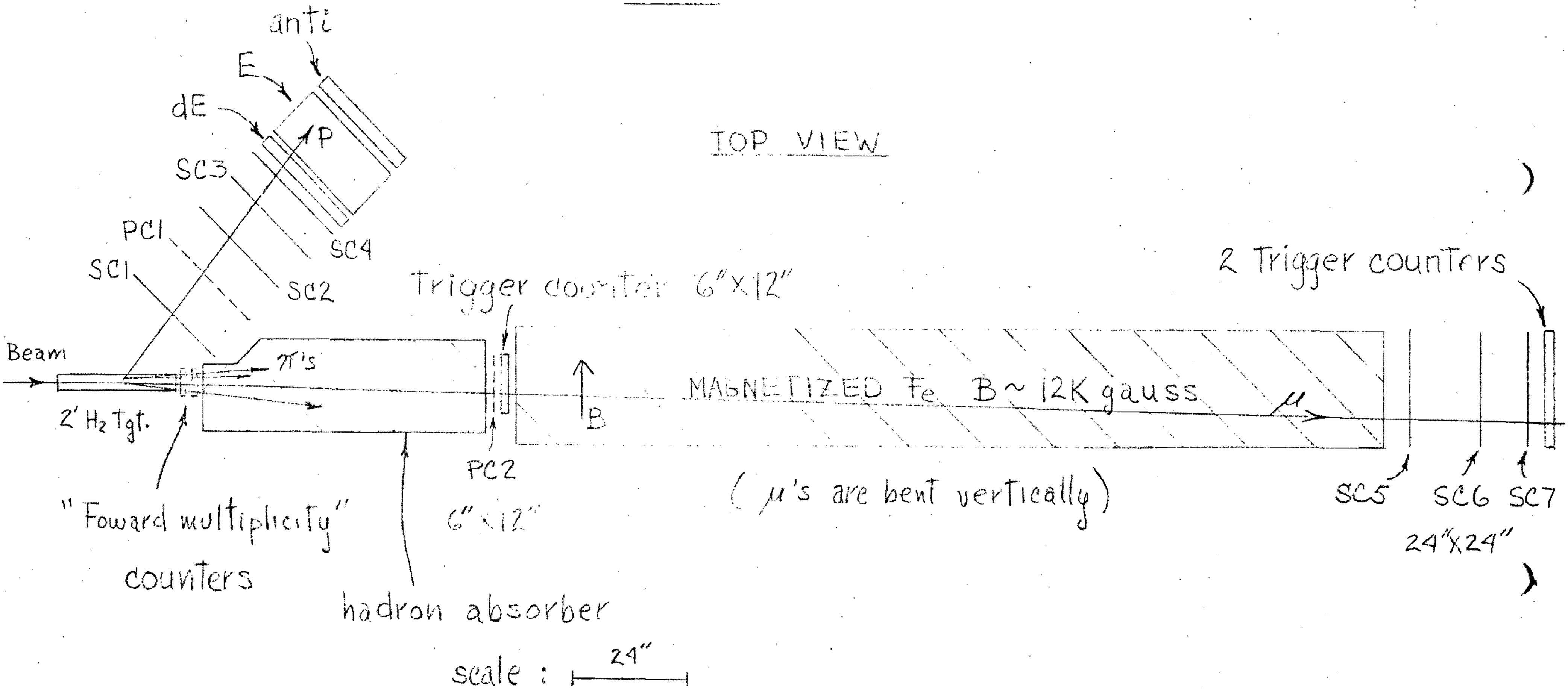
Fig. 1. Layout of the proton and $\mu$ detectors. SC1, SC2, ..., and SC7 are spark chambers and PC1 and PC2 are proportional chambers.

Fig. 2. Resolutions in $\mu$ production angle and momentum, $P_{\mu}$, vs. P .

Fig. 3. Expected results for $\sigma_{1,2} \sim 5\,\mu b$. For details, see text.

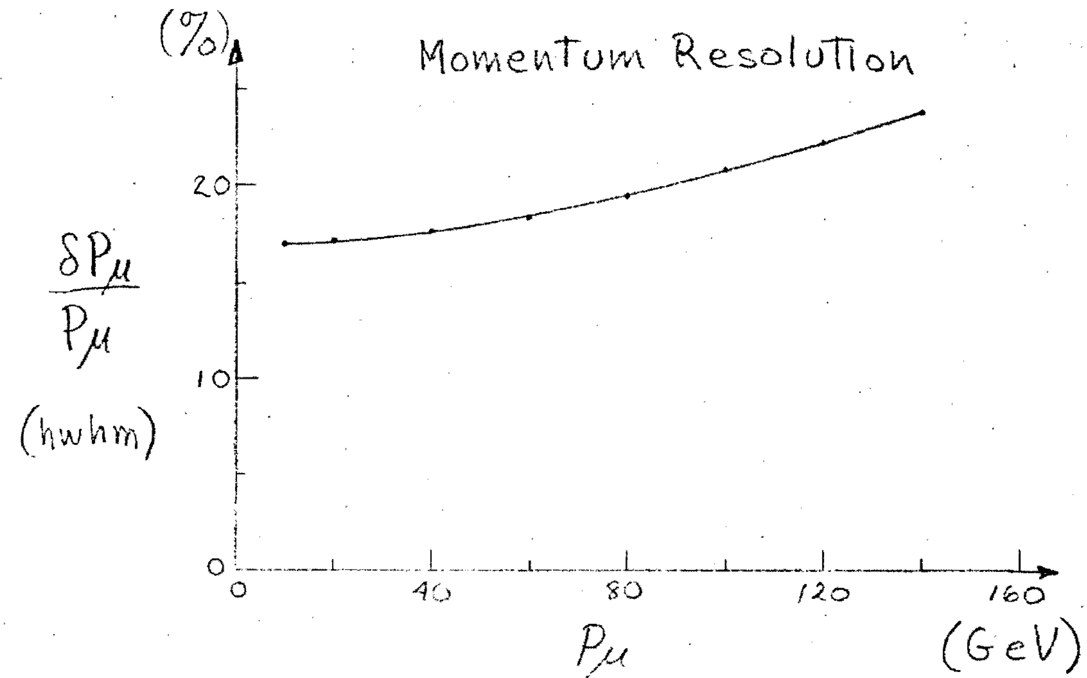
Fig. 4. Di-muon mass resolution $\delta M_{\mu\mu}/M_{\mu\mu}$ vs. di-muon mass, $M_{\mu\mu}$.

Fig. 1



TOP VIEW
anti
E
dE
P
SC3
SC4
PC1
SC1
SC2
Beam
π's
2' $H_2$ Tgt.
"Foward multiplicity" counters
hadron absorber
Trigger counter 6"x12"
PC2 6"x12"
B
MAGNETIZED Fe B ~ 12K gauss
μ
(μ's are bent vertically)
2 Trigger counters
SC5
SC6
SC7
24"x24"
scale : 24"

Fig. 2a


(%)
Momentum Resolution
20
10
0
$\frac{\delta P_\mu}{P_\mu}$
(hwhm)
0
40
80
120
160
$P_\mu$
(GeV)

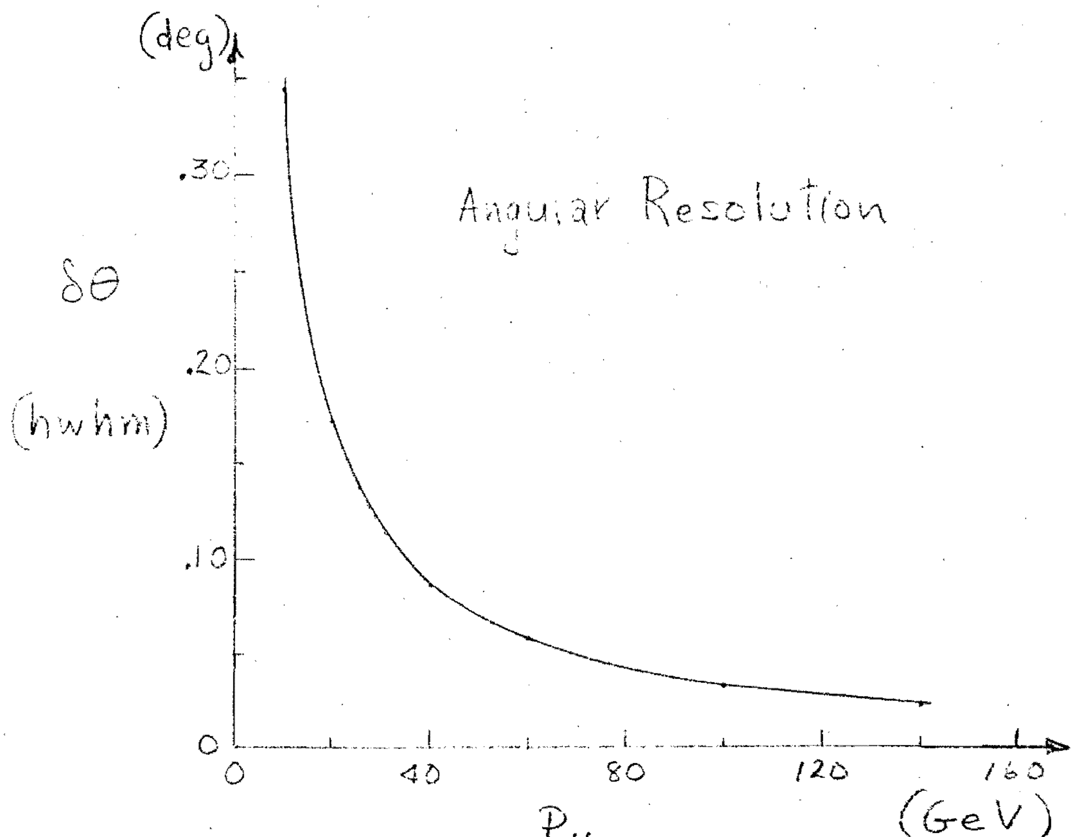

(deg)
.30
.20
.10
0
Angular Resolution
$\delta\theta$
(hwhm)
0
40
80
120
160
$P_\mu$
(GeV)

Fig. 2b

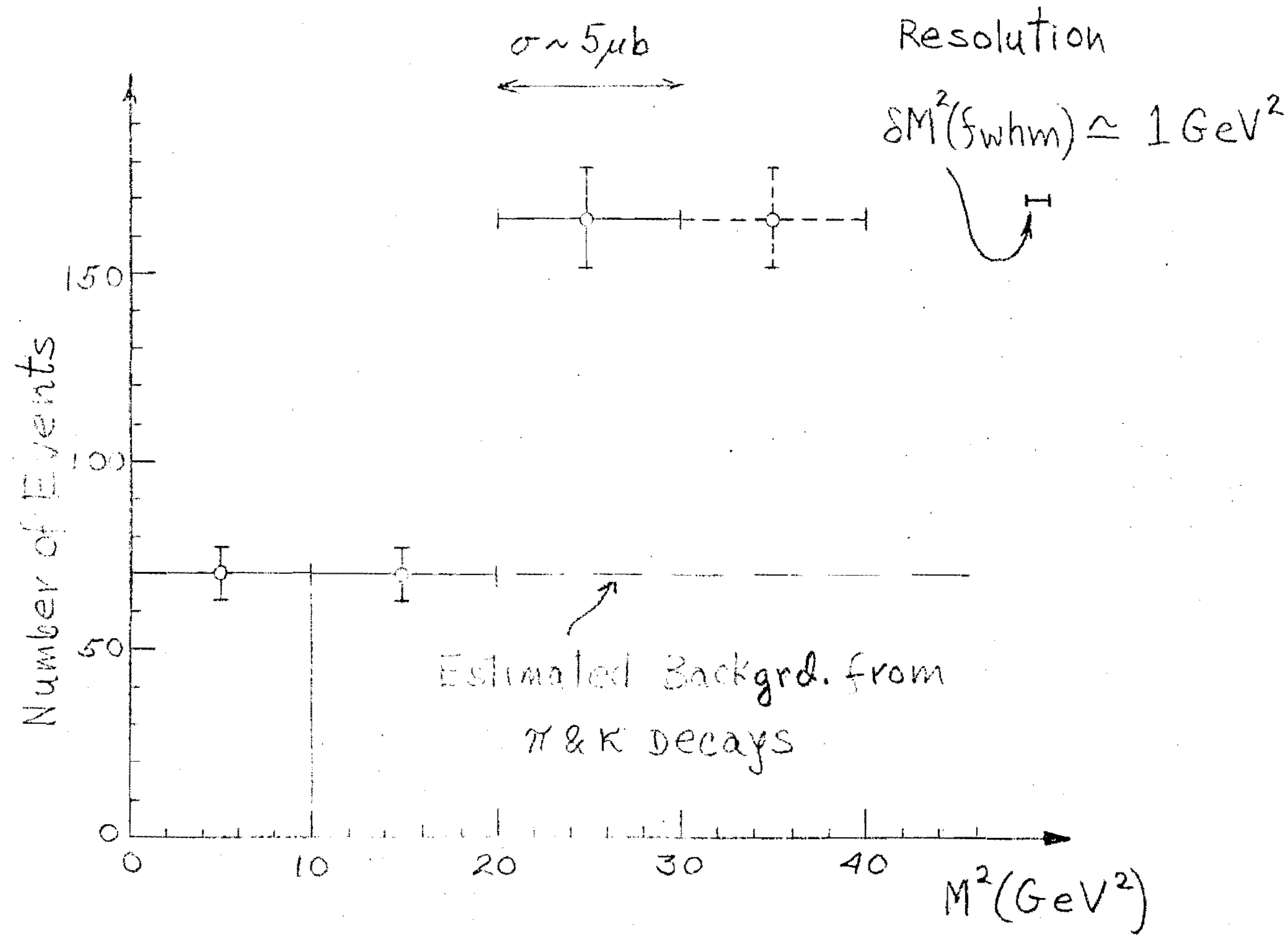
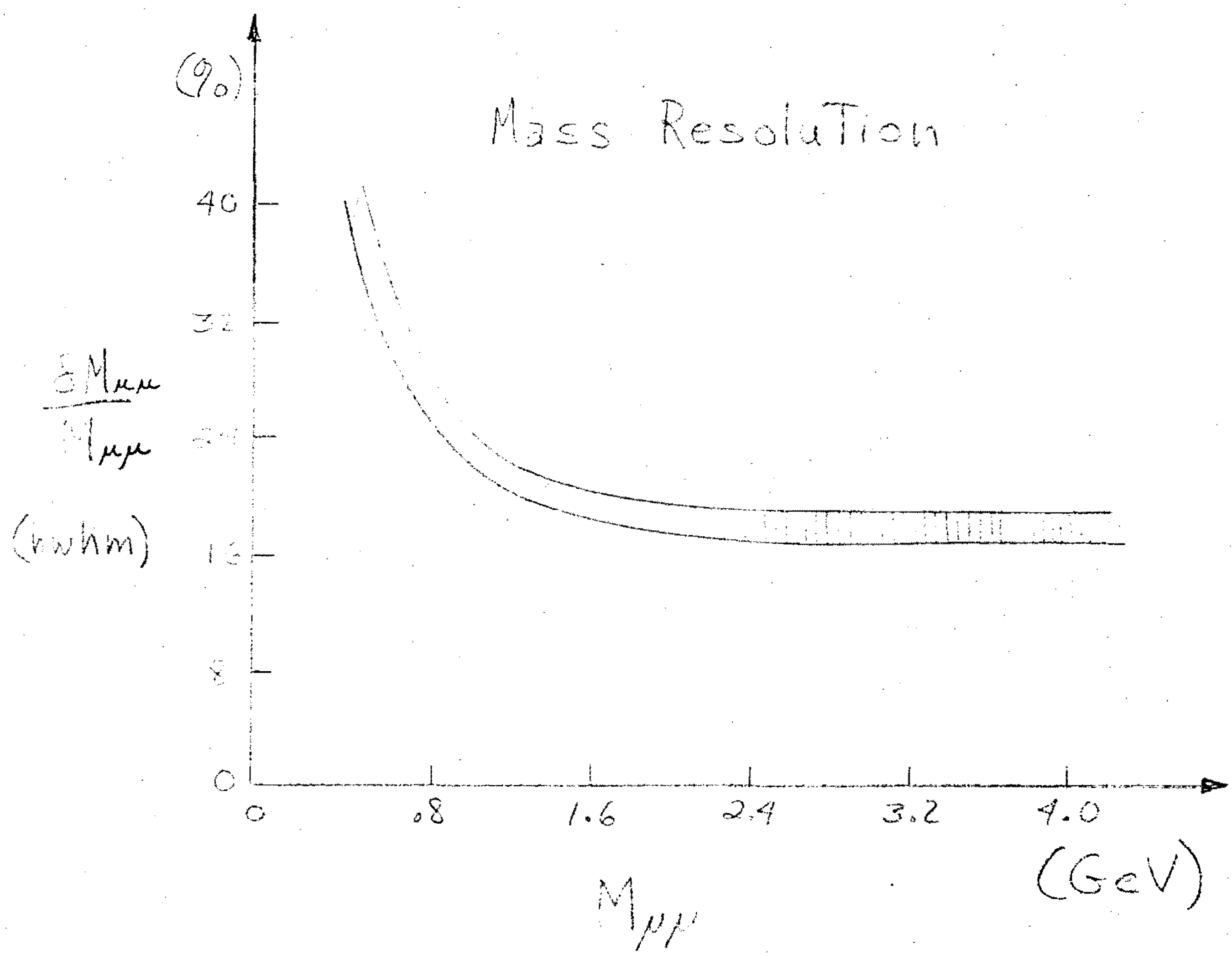



Fig. 3: Expected Results for $\sigma \sim 5 \mu b$

Fig. 4


(%)
Mass Resolution
40
32
24
16
8
0
$\frac{\delta M_{\mu\mu}}{M_{\mu\mu}}$
(fwhm)
0
.8
1.6
2.4
3.2
4.0
(GeV)
$M_{\mu\mu}$

Addendum to FNAL Proposal #365

Additional Physics Justification and Improvements (12/20/74)

(1) It appears evident to us that observation of the semi leptonic decays of charmed mesons is the most definitive way to show that there is a new quantum number. In this sense the other FNAL "approved" experiments are not definitive. For example, a narrow $K\pi$ or $K\pi\pi$ resonance if found could also be accommodated into $SU_3$ as a higher radial excitation of already known quark states. Also, the $K\pi$ decay may be suppressed[(1)] whereas we have good reason to believe the $\mu$ decay is not suppressed. (See Section 6.)

(2) A strong mass threshold effect has been recently seen in $\pi^- p \rightarrow x^- p$

$$x^- \downarrow (K_s + \text{anything})$$

proving that the production of strangeness takes place mainly through a diffractive mechanism at high energies. (See Fig. 1'.) This gives strong support to the idea that charmed mesons will be produced in a narrow diffractive peak. In $\pi^- p \rightarrow x^- p$ at 200 GeV and at lower energies $\sim$ 20 GeV the diffractive $x^-$ mass peak is consistent with it arising entirely from the final state $\rho\pi p$. There is also an established diffractive peak observed in the reaction $K^{\pm} p \rightarrow (K^*\pi)^{\pm} p$. This plus the observation of a diffractive peak in $\pi^- p \rightarrow x^- p$, mentioned above, substantiates the

$$x^- \downarrow (K_s^o + \text{anything})$$

hypothesis that there will always be diffractive peaks whenever a reaction of the type $0^- + \text{Nucleon} \rightarrow (1^- + 0^-) + \text{Nucleon}$ takes place.

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(1) There are theroretical reasons to believe that the decay of the charged D's into hadrons will, in some cases, be supressed. (J. Rosner, FNAL seminar, Dec. '74.) Thus the branching ratio $D^{\pm} \rightarrow \mu^{\pm}\nu$ + hadrons may be much larger than the 10% assumed in our proposal.

Therefore: $\pi^- p \rightarrow D^{*} \bar{D} p$ "will" have a large diffractive peak.

In our presentation at NAL we considered diffractive production as a possibility which would be very favorable to our experiment, but in giving our final sensitivity we did not assume this favorable case. The new bubble chamber results on $K_s^o$ argue strongly for the assumption of a diffractive production mechanism for charmed mesons. This alone results in a factor of 20 greater sensitivity compared to our conservative estimates. Our sensitivity, assuming diffractive production of charmed mesons, and factors enumerated in Item 3, below, is better than BR x $\sigma_{TOT}$ = 50 nb.

(3) We believe that the apparatus can work reliably with an incident flux of $\sim 10^7$ $\pi$'s/pulse thus increasing the data rate by a factor of 10. We have already operated with fluxes of $3 \times 10^6$ (3 x greater than discussed in our proposal) with no trouble, and $10^7$ appears to be achievable.

(4) The background cross section for $\pi p \rightarrow$ anything + p, used in the proposal, was overestimated. The correct value is $d\sigma/dm_x^2 \simeq 29\ \mu b/GeV^2$ (for $.1 \leq t \leq .4\ GeV^2$) for $\pi^- p \rightarrow x^- p$ at 100 GeV. Thus the expected background at 100 Ge from $\pi$ and K decays was overestimated by a factor of 3 in the proposal. (This is shown in Fig. 3 of the proposal). In addition, for a 200 GeV run, which we expect to be the major run, the background in Figure 3 of the proposal is 3 x 2 x 2 = 12 times too high![†] The expected results for 200 GeV are shown in Figure 2', attached.

To summarize: In our original proposal, our sensitivity was BR x $\sigma_{TOT}$ = 10 $\mu$b. (It was expressed for many different levels of statistical significance,

† A factor of 3 due to the cross section error; a factor of 2 since $d\sigma/dm^2(100\ GeV) \simeq 2\ d\sigma/dm^2\ (200\ GeV)$; and another factor of 2 since the average secondary $\pi$ or K energy is a factor of 2 higher at 200 GeV than at 100 GeV giving half as many $\mu$'s from $\pi$ and K decay.

and for different mass bins, but it is equivalent to 10 $\mu$b for the six standard deviation experiment being discussed here.) We believe we are justified in assuming diffractive production. This increases our sensitivity by a factor of 20. We know that we can run at a higher beam intensity. This, coupled with the lower noise, gives us another factor of 10 in sensitivity in our 200 GeV run. The total factor is 200, and results in a sensitivity of BR x $\sigma$ = 50 nb.

(5) For BR $\simeq$ .1 we expect to detect 1/3 as many events in which both D's decay into $\mu$'s as in the case where a single $\mu$ is detected. This is true since the full detector size is used in the 2$\mu$ observation but only $\sim$ 1/3 is used in the single $\mu$ observation. The noise due to $\pi$ and K decay contamination in the 2$\mu$ sample is expected to be negligible. We believe that this data will provide very important flexibility in interpreting the results of the single muon experiment. The/ detailed value of this data depends on the production mechanism.

The $\rho^o \to 2\mu$ contamination in the 2$\mu$ signal is also expected to be negligible since nearly all $\rho^o$'s seem to be produced at low $M^2$. (F. Winkelman, private communication.) (Also, see Sec. 2.)

(6) Much attention has been drawn to the observation of profuse production of muons at large $p_\perp$.

Additionally, Pilcher et al[(1)] have done a rough measurement of $\mu$ pairs produced by $\pi$'s in preparation for E331.

We have performed preliminary calculations on the consistency of the above observations, and conclude that <u>the observed $\mu$ pair rate appears to be insufficient to account for the observed $\mu$ singles rate</u>. We are led

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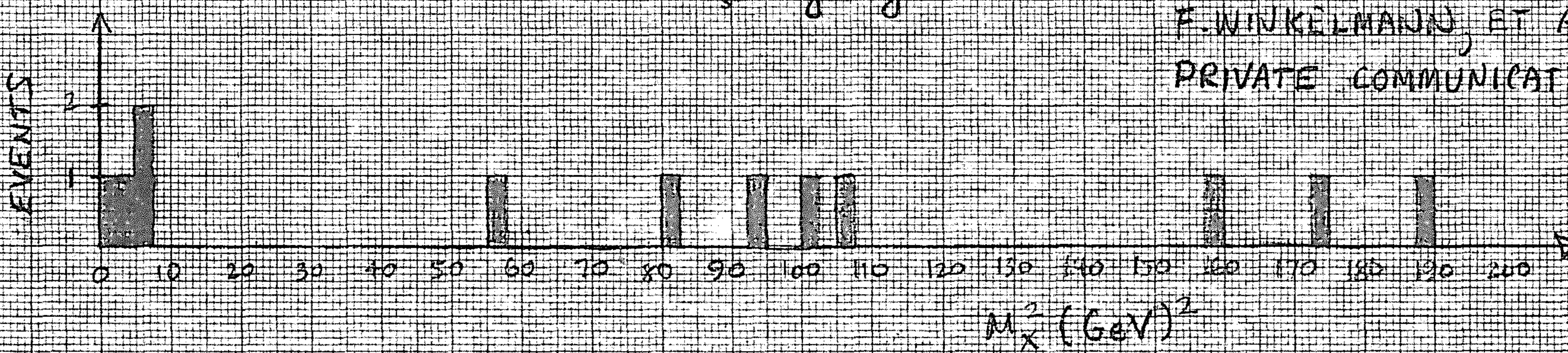
(1) E331 proposal, Appendix 1

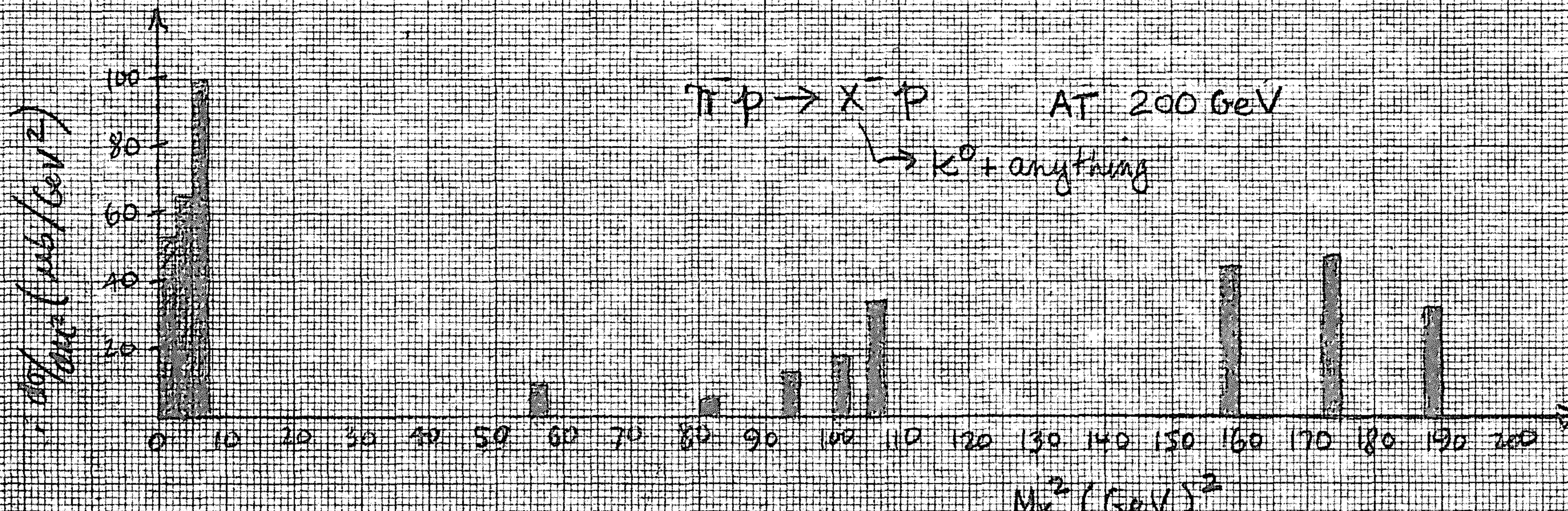
to the conclusion that a large fraction of the single μ's observed at large $p_\perp$ originate not as μ pairs, but as μ singles. This in turn implies the existence of a particle which β decays, (weak interaction) with a life time much shorter than that of the K's. Assuming associated production of such particles we find BR $\sigma_{TOT} \sim 20$ μb.

We believe that comparison of the preliminary results of E331 to the results of wide angle μ experiments constitutes strong grounds for pursuing a muon experiment in searching for the D meson. The sensitivity of our proposed experiment is more than 400 times as much as is needed to observe the above cross section.

FIG. 1' CROSS SECTION FOR $\pi^- p \to X^- p$ AT 200 GeV (DATA FROM LBL-FNAL 30" BC COLLABORATION F. WINKELMANN, ET AL., PRIVATE COMMUNICATION)

$\hookrightarrow K_s^0$ + anything




$\sigma(M^2 < 7.5\,GeV^2) = (550 \pm 280)\,\mu b$

$\sigma(M^2 > 50.\,GeV^2) = (230 \pm 130)\,\mu b$

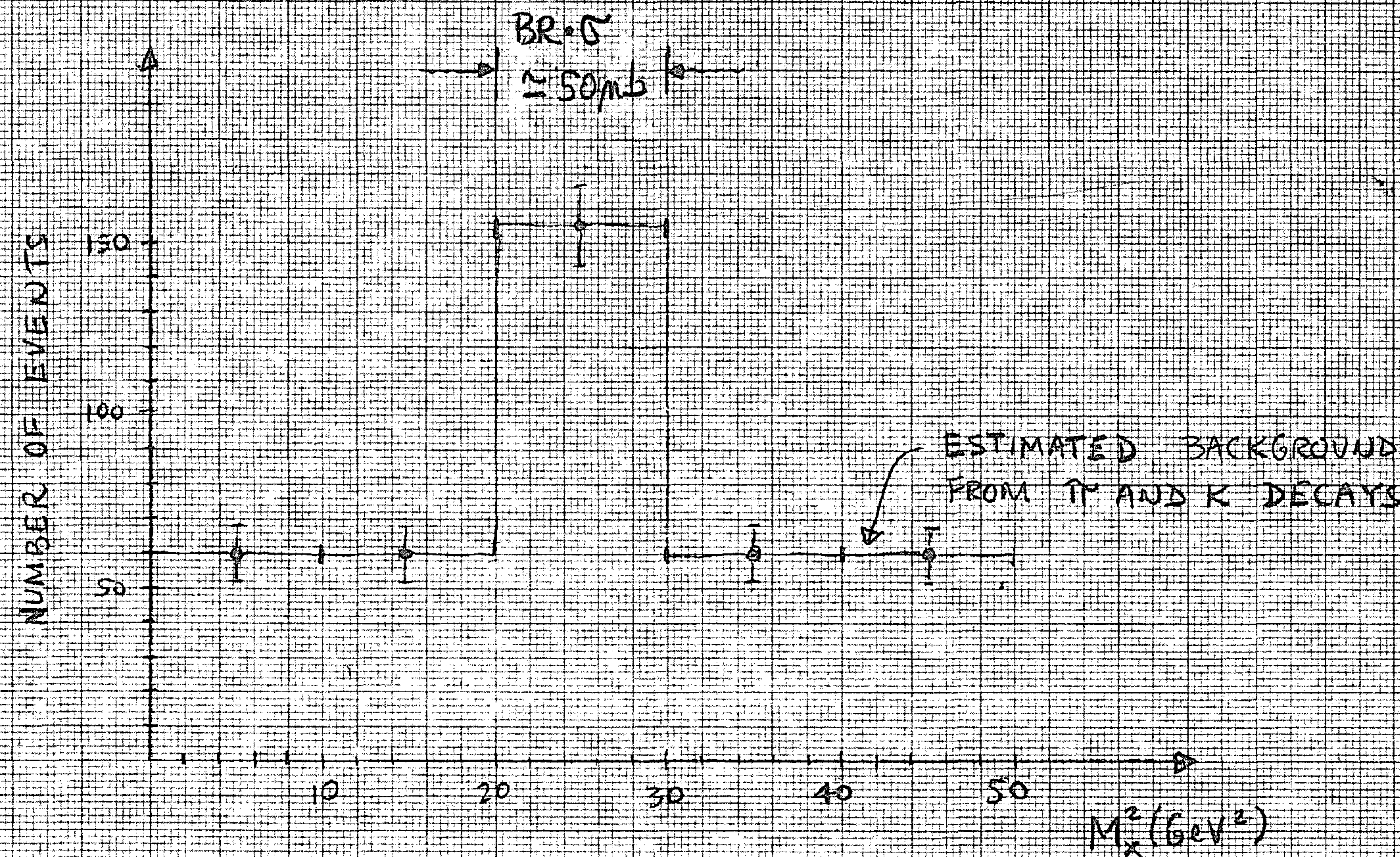



FIG. 2' EXPECTED RESULTS FOR $\pi^- p \to X^- p \to D^* \bar{D} p$ AT 200 GeV.
($\bar{D} \to \mu$)

( $10^7$ π's / PULSE ; ~20 HOURS OF DATA ; BR $\sigma(\pi p \to D^* \bar{D} \cdots) \simeq 50$ nano barns)

( BR ≡ branching ratio $D \to \mu \nu h$ )