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Scientific Spokesman:
P. H. Garbincius
Fermilab
840-3693

SEARCH FOR MASSIVE LONG-LIVED CHARGED PARTICLES

A. E. Brenner, D. C. Carey, J. E. Elias, P. H. Garbincius
and V. A. Polychronakos
Fermi National Accelerator Laboratory, Batavia, IL
and
J. Butler
University of Illinois, Urbana, IL

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A. E. Brenner, D. C. Carey, J. E. Elias, P. H. Garbincius, V. A. Polychronakos (Fermilab); J. Butler (University of Illinois)

A further search for new long-lived charged particles in the mass range $4<M<12$ GeV/c^2 in the M6E-SAS beam line is proposed. The sensitivity of this search will be between one and two orders of magnitude greater than previous experiments for integrally charged particles of $M<8$ GeV/c^2 and approaching 4 to 5 orders of magnitude greater for the highest masses $M \gtrsim 10$ GeV/c^2.

A number of models predict the existence of new long-lived particles. Typical cross sections are expected to be those characteristic of weak interactions. Furthermore, pessimistic predictions indicate that the production of $b\bar{u}$ mesons is two orders of magnitude less than Υ production—a level of sensitivity not yet reached.

The experiment uses extensions of the time-of-flight and Cerenkov counter techniques employed successfully in the earlier measurement by this group. The improved sensitivity comes about in part by higher level of segmentation of the timing counters and improvements in the associated PM, discriminator and timing electronics, and also in the installation of additional small atmospheric pressure Cerenkov counters.

By choosing an operational point in x and p_t, the yield at a given mass and the signal (heavy mass particle) to noise ("light" particle) ratio can be optimized. The choice of secondary beam with P=110 GeV/c^2 for 400 GeV/c incident protons on target at a viewing angle of 6 mrad sets the mass range of 4 to 12 GeV/c^2 and allows for an improved signal to noise ratio.

A primary flux on the M6 target of 6×10^{12} protons per pulse is requested and the experiment will require 350 hours of data taking. In addition, 100 hours will be required for setup.

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INTRODUCTION

We propose an experiment to search for new long-lived particles in the mass range $4<M<12$ GeV/c^2 and with charge $|q|\geq 2/3$. The sensitivity of this search will be between one and two orders of magnitude greater than previous efforts for integrally charged particles of $M\lesssim 8$ GeV/c^2 and approaching four to five orders of magnitude greater for the highest masses $M\gtrsim 10$ GeV/c^2. We propose to use the M6E-SAS beam line with its full complement of Cerenkov counters.

This effort should be viewed as a continuation of E469.[1] In that experiment, we established a limit on the invariant cross section for the production of long-lived particles of $M\sim 5$ GeV/c^2 and charge $|q|\geq 2/3$ of

$$E\frac{d^3\sigma}{dp^3}\leq 1.1\times 10^{-37}\text{cm}^2/(\text{GeV/c})^2.$$

Under reasonable assumptions about the transverse and longitudinal momentum dependences[2], the limit on the total cross section, σ_t, for the production of new heavy long-lived particles is:

$$\sigma_t \lesssim 4\times 10^{-37}\text{cm}^2.$$

The running conditions in E469 were chosen to optimize the sensitivity for $M\approx 5$ GeV/c^2. Under those conditions the sensitivity was seriously degraded for $M>8$ GeV/c^2. The connection of this result to the physics associated with the Υ(9.4) is discussed below (Section II).

The basic technique of the proposed experiment will be similar to that of E469, which used Cerenkov counters to reject all known particles and time-of-flight to measure the mass of all particles surviving the Cerenkov veto. The increased sensitivity will be obtained by:

1) Rate hardening the detector so as to be able to handle at least 2×10^7 particles/pulse.
2) Running 3½ times longer (350 hours).
3) Viewing the target at larger transverse momentum to improve the signal to background (π^-, K^-, $\bar{p}$, $\bar{d}$) ratio.

With these improvements, we will be able to operate the time-of-flight spectrometer with larger acceptance in solid angle and momentum and will be able to greatly increase the incident proton intensity.

The remainder of this proposal is organized as follows: Section I is a review of the physics motivation for this experiment; Section II summarizes the experimental technique, emphasizing the improvements to E469 that will produce the increase in sensitivity; Section III sets forth the running conditions and explains the advantages of utilizing a higher transverse momentum; Section IV states the requirements this experiment makes on the Meson Lab and the accelerator.

I. PHYSICS JUSTIFICATION

There are many models which predict the existence of new, long-lived particles.[3] These particles typically are associated with gauge theoretic models of the weak and electromagnetic interactions. Their production in interactions purely between hadrons is suppressed due to their large masses and to the fact that they may be produced by complicated subprocesses. Meaningful searches for this class of particles must therefore achieve cross section sensitivities which are more characteristic of weak processes (i.e., $\sim 10^{-37}-10^{-40} cm^2$) than of strong processes ($\sim 10^{-27}-10^{-30} cm^2$). Until E469 and E596,[4] a similar experiment, this sensitivity had been approached only in the search for fractionally charged quarks. We feel that the moderate increase of sensitivity for $M \lesssim 8$ GeV/c^2 and the substantial increase for $M \gtrsim 8$ GeV/c^2 provide ample justification for this experiment.

The recent discovery[5] of $\Upsilon(9.4)$ and its interpretation as a bound state of a new quark, b, and its antiquark, $\bar{b}$, imply the existence of new particles with masses between 5 and 7 GeV/c^2. The weak decay of the lightest of these particles into normal hadrons requires new mixing angles, analogous to the Cabibbo angle, whose size is not at present known. If the mixing angles are zero, or very small, ~1 milliradian, these particles will be quite long-lived and can be detected by our time-of-flight technique.

In Experiment 469, we showed that no long-lived particle whose production cross section is comparable to $\Upsilon(9.4)$ exists. We, therefore, concluded that these particles are not stable and that new, non-zero mixing angles must exist. In reaching this conclusion, we were careful to point out that it depended critically on the expectation that the production of states with bare flavor ought to be comparable to the production of the corresponding quarkonium states. This situation is known to be true for the strange quark. There is indirect evidence that it is true for the charmed quark but charmed particles have not yet been clearly observed in purely hadronic interactions. Because of this, we feel that we should attempt to improve our sensitivity beyond the level of the more pessimistic predictions for bare flavor production. As a guideline, we use the thermodynamic model to estimate the relative size, R, of the Υ and bare beauty (B^+B^-) production:

$$R\left[\frac{M(B^+B^-)}{M(\Upsilon)}\right] = e^{-\left\{M(B^+B^-)-M(\Upsilon)\right\}/To} \approx 0.2$$

for $M(B^{\pm}) = 5\,GeV/c^2$, $To = 0.16\ GeV/c^2$.

Since the present best limits are at the level of 0.1 of the total Υ production, another order of magnitude increase in sensitivity is desirable.

II. EXPERIMENTAL METHOD

The basic technique will be similar to the one employed successfully in E469:

1) Light particles will be vetoed by several threshold Cerenkov counters.
2) The mass of each surviving candidate particle will be obtained from time-of-flight measurements made at several locations along a 1500' flight path.

The good rejection of light particles at the trigger level, combined with the good time-of-flight resolution, produced an experiment with virtually no background and high detection efficiency. The technical challenge of the new experiment will be to maintain these properties with approximately five times higher fluxes passing through the detector. The proposed improvements are outlined below.

Time-of-flight System

The time-of-flight resolution was observed to deteriorate at rates higher than 3×10^6 particles/pulse. To operate at five times higher rate, we propose:

1) to optimize the timing counters, phototubes, and bases for operation at high average anode currents.
2) to use multi-element hodoscopes at each location to cover the aperture rather than two elements, as used in E469. The beam can be configured to provide nearly uniform illumination of the counters at each station so that each counter will bear an approximately equal burden in sustaining the higher rates.

The choice of two element segmentation in E469 was based on our concern about whether we would be able to keep all the counters properly calibrated. However, our technique of using a prescaled sample of light particles to continuously monitor photo-tube gains and time-of-flight distributions was extremely successful. The on-line computer was able to provide adequate diagnostic information to maintain the performance of the system and increasing the number of timing counters does not present a serious problem.

While the RMS time resolution of 220 psec realized in E469 is perfectly adequate for this experiment, we expect to achieve some improvement in resolution by using photomultipliers with lower single-photo-electron transit-time jitter and using better electronics. In test beam situations, we have already achieved time resolutions as good as 150 psec.

Cerenkov System

In E469, the veto efficiency ε *for light particles,* π, K, p, was given by: $1-\varepsilon = 1\times10^{-7}$.

This is two orders of magnitude worse than what would be predicted based on the efficiencies of the individual counters measured at low rates. This is due to i) pulse shape problems which cause pileup, and consequent loss of efficiency, at the higher operating rates of the actual experiment, and ii) correlated inefficiencies in two of the counters which were located in close proximity to each other.

We expect to solve the first problem by slightly modifying the divider chains in the PMT bases. The second problem will be solved by adding several small gas Cerenkov counters, operating at or near atmospheric pressure. Each counter will yield 4 photoelectrons for $\beta=1$ particles. The counters will be distributed over the length of the detector in such a way to overcome the correlated inefficiencies encountered in E469.

In E469, we vetoed all particles of mass below 1.3 GeV/c^2. The remaining triggers were primarily anti-deuterons. Since ~300k anti-deuterons were recorded during that experiment, these formed a substantial background in the high mass distribution as determined from the time-of-flight information. Most anti-deuterons, however, were positively tagged by a differential counter, and could therefore be eliminated. Of the half percent that were not eliminated in this manner, it was estimated that only one would have an apparent mass >4 GeV/c^2. While anti-deuteron leakage was therefore not a problem in E469, it could become one for the new experiment. Towards the end of the running period, we were able to reduce the anti-deuteron leakage by tagging with threshold counters sensitive to masses <3.5 GeV/c^2. We are considering setting all the threshold counters in this manner so that anti-deuterons (and anti-tritons) will, in effect, be considered as "light particles" on an equal footing with π^-, K^-, and $\bar{p}$ and will be rejected accordingly.

Considerations Relating to RF Structure at High Rates

In E469, our light particle veto made it impossible to detect a massive particle produced in the same rf bucket as a light particle. Thus, that experiment was "live" or sensitive only to singly occupied rf buckets. At the higher rates of the new experiment, the fraction of singly occupied buckets could be as low at 50% when the spill duty factor is less than optimum. Thus, we must plan to utilize doubly occupied buckets.

We plan to attack this problem from two directions:

1) It is quite easy to detect the presence of doubly occupied buckets at the trigger level using our hodoscopes. We can then apply a veto to any bucket based on whether the pulse heights in the threshold counters are consistent with light particles. With the large number of threshold counters available (five long ones and up to six short ones), it should be possible to reject buckets with two light particles with ε given by $1-\varepsilon = 1\times10^{-6}$, while maintaining >90% efficiency for buckets with one light particle and one heavy particle candidate.

2) We will attempt to develop a Cerenkov counter that detects light from massive particles but not from lighter particles. Such a counter would provide a positive trigger for massive particle candidates and would nicely solve the complications of multiply occupied buckets. However, we cannot know in advance of testing a prototype whether such a counter can achieve adequate rejection against light particles.

When there is a heavy particle candidate in the same bucket as a light particle, the two will generally pass through different timing counters. Still, the pattern of times will be difficult to disentangle. Here we are aided by certain beam optics correlations between the counters at the different locations and we will be further helped by the highest possible rf bunching of the extracted beam.

III. RUNNING CONDITIONS

A. CHOICE OF MOMENTUM

In the original E469 proposal, a detailed discussion was given for making the choice of operating momentum for M6/SAS. Briefly, to maximize the yields for particles in the mass range of interest, those particles should be produced with as low a Feynman $|x|$ as possible. Furthermore, the operating point chosen must also be compatible with the sensitive range for the time-of-flight and Cerenkov counter techniques used for measurement. Figures 1 and 2 illustrate the kinematics for production by incident 400 GeV/c protons of a particle of mass X on the assumption that such a particle is produced in pairs or singly, respectively. The secondary momentum choice of 110 GeV/c translates into the production of an $\sim$8 GeV/c^2 mass particle at rest in the center-of-mass. Assuming such particles are produced in pairs, Fig. 1 shows that we will be sensitive to up to 12-14 GeV/c^2 masses, depending on the actual production mechanism. Also, the mass range 4<mass<10 GeV/c^2 will be contained within $|x| < 0.2$, assuring maximum yields of the heavy particle. This will allow good threshold Cerenkov rejection of particles up to 3.5 GeV/c^2 mass while permitting the use of TOF techniques for masses above 3 GeV/c^2.

B. CHOICE OF TARGET ANGLE AND TARGET MATERIAL

Our general philosophy will be to optimize the ratio of the heavy particle signal to light particle background. This will be accomplished by increasing the M6 production angle and possibly by using a Tungsten production target. After the Mesopause, M6 will have a production target independent of M1-M4 with a system of angle varying bends similar to the system presently in use for the common target.

The present Meson Lab horizontal angle targeting system and the variation of M6 yields with angle are described in Ref. 6. The yields were verified during a production angle scan during E451 and agree with the E118 measured spectra.[7] During the scan from $\theta(M6)\doteq 0$ mrad to $\theta(M6)=6.0$ mrad, the negative yield at 100 GeV/c drops by a factor of 2.5 while the $\bar{p}/\pi^-$ ratio increases by a factor of 1.35. We compare the expected rates for ψ/J, Υ, and continuum $\mu^+\mu^-$ production as a function of P_t in Table I. Note that in the high mass region, Υ and $\mu\mu(m>4$ GeV) have a much shallower P_t dependence than light particles. If the heavy particles being sought have similar P_t dependencies by virtue of their mass, we would expect our signal to noise ratio to increase by a factor of 2 at $\theta = 6.0$ mrad relative to the E469 sensitivity at $\theta = 2.5$ mrad.

We may further increase our signal/noise ratio by using a Tungsten production target to replace the normal Beryllium target. We define the relative yields of particle X and to π^- for Tungsten versus Beryllium as:

$$R_X = \left\{\frac{Y(X)}{Y(\pi^-)}\right\}_W \Big/ \left\{\frac{Y(X)}{Y(\pi^-)}\right\}_{Be} = \left\{\frac{A^{\alpha(X)}}{A^{\alpha(\pi^-)}}\right\}_W \Big/ \left\{\frac{A^{\alpha(X)}}{A^{\alpha(\pi^-)}}\right\}_{Be}$$

where:

$Y(X)$ is the yield of particle X for the listed target

$A^{\alpha(X)}$ is the atomic mass number power law dependence for production of the particle X.

The atomic mass number dependencies of the particle yields in Table II indicate an increase in signal if the heavy particle production is similar to the production of high mass muon pairs. Being a little less optimistic, we may hope for a 15% increase by using a Tungsten target. Coupled with the factor of 2 increase due to the larger production angle, we have a total increase in signal to noise ratio of 2.3 - 4.0.

The measured rate[8] for pion production using an 8" Be target at 110 GeV for θ=6 mrad is 2.4×10^{-6} π^-/proton at our maximum aperture of 1.5 μster.%. Note, also that E469 ran with a typical acceptance of 0.5 μster.% to optimize system performance. This would require targeting 4×10^{12} protons per pulse to attain a secondary beam of 10^7 pions/pulse. If we are able to operate the experiment at 2×10^7 pions/pulse, this would require close to 10^{13} protons/pulse on the Be target. Independent of the target material finally used, the number of interaction length could also be increased in the interest of proton economy, so that we would keep our request for protons in the neighborhood of 6×10^{12}/pulse.

IV. EQUIPMENT AND RUNNING TIME

The bulk of the equipment needed for this experiment is the same as in E469 and is already in place. Since the whole Meson Lab configuration will significantly change during the Mesopause, we request that the Single Arm Spectrometer be kept compatible with the upgraded M6 line. The four SAS quadrupoles (4Q120) which already have been reassigned can be replaced with 3Q120's for which the power supplies, the power leads and cooling circuits already exist. The SAS fast electronics and on-line computer will be used in addition to a small amount of additional of PREP electrc specifically constant fraction (low slew rate) discriminators, TDCs, etc., for the time-of-flight system.

The beam requirements for this experiment will be somewhat different from those for E469 to allow us better high rate handling and higher signal to noise ratio. To the extent that our demands do not interfere with the Meson and the Laboratory's overall program, we request the following:

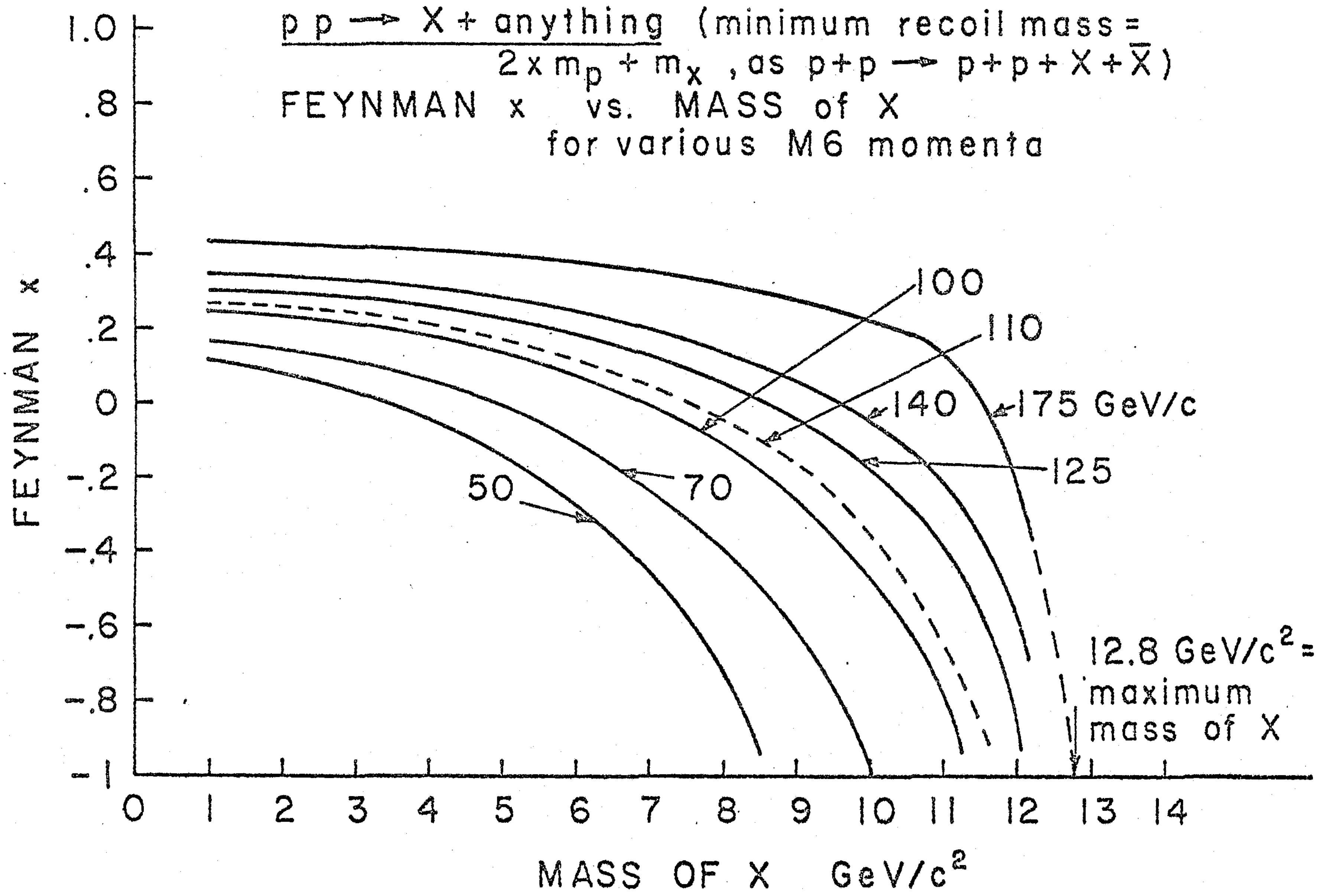
a) A beam intensity to the M6 target station of $6\text{x}10^{12}$ ppp.

b) As tight rf bunching of the primary beam as possible.

c) Four 3Q120 quadrupoles.

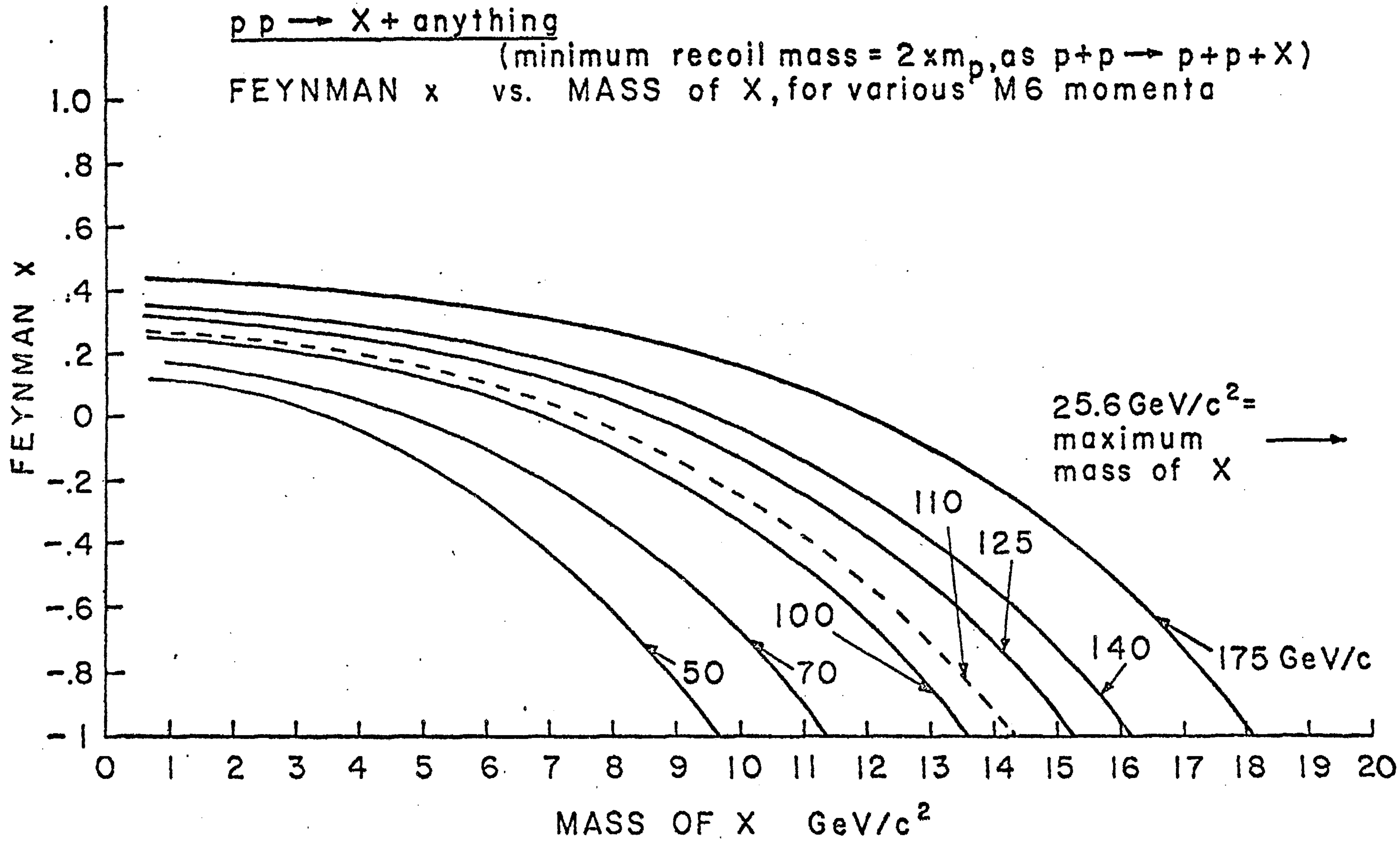
If it is possible, the replacement of the present Be target with a W target (See Section III) would be desirable. The design of this target should be such as to withstand the increased thermal load and be remotely adjustable.

Finally, we request a total of 350 hours of data-taking time plus an additional 100 hours for set-up. We can be ready by the time of the post-Mesopause recommission of the Meson Lab, or three months after approval.



pp → X + anything (minimum recoil mass = 2 x m_p + m_X , as p+p → p+p+X+X̄)
FEYNMAN x vs. MASS of X
for various M6 momenta
FEYNMAN x
1.0
.8
.6
.4
.2
0
-.2
-.4
-.6
-.8
-1
0
1
2
3
4
5
6
7
8
9
10
11
12
13
14
MASS OF X GeV/c²
50
70
100
110
125
140
175 GeV/c
12.8 GeV/c² = maximum mass of X

Figure 1



pp → X + anything
(minimum recoil mass = 2 x m_p, as p+p → p+p+X)
FEYNMAN x vs. MASS of X, for various M6 momenta
FEYNMAN X
1.0
.8
.6
.4
.2
0
-.2
-.4
-.6
-.8
-1
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20
MASS OF X GeV/c²
25.6 GeV/c² = maximum mass of X
50
70
100
110
125
140
175 GeV/c

Figure 2

TABLE I PRODUCTION RATIOS AT 110 GeV, ASSUMING (x, P_t) FACTORIZATION

PARTICLE	MASS	Production Ratio to π^- for $(\theta = 6.0)/(\theta = 2.5)$	DEPENDENCE	REFERENCE
$\bar{p}$	.94 GeV/c^2	1.4	Measured	A.Wehmann, TM-775
ψ	3.1	1.4	$e^{-1.5P_t}$	B.C.Brown, et al, Fermilab 77/54-EXP.
$\mu^+\mu^-$	>4.0	1.9	$\left\{1+(P_t/2.73)^2\right\}^{-6}$	J.K. Yoh, et al, PRL 41, 684(1978)
Υ	9.4	2.1	$\left\{1+(P_t/3.35)^2\right\}^{-6}$	D.M.Kaplan, E288, Private Comm.

TABLE II. NUCLEAR TARGET YIELDS NEAR $P_t = 0.7$ GeV/c

PARTICLE	α	R_x	REFERENCE
π^-	0.86	1	J.W. Cronin, et al., Phys.Rev. 11, 3105(1975)
$\bar{p}$	0.92	1.16	
ψ	0.90	1.12	K.Anderson, et al., EFI-78-38 Submitted to Tokyo Conf.
$\mu^+\mu^-(m \geq 4)$	1.10	2.06	

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