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Search for Heavy Long-Lived Particles

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Summary

Utilizing the existing apparatus and unique properties of the M6E beam - Single Arm Spectrometer we propose a relatively short experiment which will search for stable and long-lived particles which:

- a) improves sensitivity over previous experiments by a factor of 200 or more;
- b) extends the energy range of such searches at FNAL to 400 GeV;
- c) will be sensitive to masses over a range from 1 GeV to nearly the kinematic limit without exclusion of fractional or multiply-charged particles;
- d) studies the particles (especially in the 2 GeV "antideuteron" peak) as to their hadronic interaction.

We request 50 hours of setup time and 100 hours of running time with standard targeting. Under these conditions we will inspect $\sim 10^{10}$ light particles of both signs. With the usual parametrization of the light particle cross section[†], this total flux corresponds to an upper limit for heavy particle production of $\sim 4 \times 10^{-5}$ $\mu\text{b}/\text{GeV}/\text{c}\text{-ster.}$, per nucleon.

[†]Wang, Phys. Rev. D7 (1973) 2609.

Search for Heavy, Long-Lived Particles

Searches for long-lived particles (mean lifetime $\geq 10^{-8}$ sec) more massive than the proton have been undertaken whenever a new accelerator has been commissioned. These searches, while motivated by the desire to look for new phenomena when a new energy regime becomes accessible, have also been encouraged by specific theoretical speculations. Recent theoretical predictions and experimental discoveries have suggested that new degrees of freedom and new families of particles exist¹. These create a new interest in looking for massive particles, both short- and long-lived with increased sensitivity.

We propose to use the long flight paths and substantial Cerenkov counter power uniquely available in the M6E-Single Arm Spectrometer Facility to study the production of long-lived charged particles in 400 GeV/c p-Be collisions². Studies of this kind have been undertaken at Fermilab³, at the ISR⁴, at Serpukhov⁵, and at lower energies. In these experiments, deuterons, anti-deuterons, and tritons have been observed. At energies greater than 30 GeV/c no other particles of mass greater than the anti-deuteron have been found at a level of $\sim \frac{1}{7} \times 10^{-7}$ of the light particle flux. Our objectives are (1) to improve this sensitivity to $\sim 10^{-10}$ of the light particle flux -- an improvement at least by a factor of 200; (2) to accurately measure the deuteron to anti-deuteron ratio to test models of the production of these particles; (3) to study the properties of the particles in the 2 GeV/c² peak to make sure that they are all conventional hadrons; and (4) to extend the range of mass searches at FERMILAB to 400 GeV.

Experimental Technique:

Since the M6 beam has a narrow momentum acceptance ($\pm 1\%$), the problem of measuring the mass of a particle of known charge reduces to determining its velocity. We will use a combination of time-of-flight and Cerenkov counter techniques to

accomplish this. The detectors of the facility which are relevant to this experiment are shown in Figure 1. Five threshold Cerenkov counters and three differential Cerenkov counters are available.

Light particles of mass less than $1.1 \text{ GeV}/c^2$ are efficiently rejected by two threshold Cerenkov counters, C2 and C3, counting π , K, p, and the differential counter D1, set to count protons. This light particle veto is designated as

$$\ell = C2 + C3 + D1 \quad .$$

Based on our previous experience with these counters in E96 and E118, we expect the inefficiency for counting a light particle will be between 10^{-8} and 10^{-10} .

To measure the velocities of particles surviving this veto, we will use both Cerenkov counter and time-of-flight techniques. The two techniques are complementary in the following sense: the Cerenkov counters perform best at the lower end of the mass range (near where they are conventionally operated) while the time-of-flight differences between heavy and light particles increase as the mass increases.

All accepted events are also monitored by a "muon identifier" located at the end of M6-SAS to check on the hadronic-like nature of all detected particles.

(a) Low Mass Region: 1.1 to 5 GeV/c^2 :

In this mass interval, we rely on Cerenkov counters C1, C4, and C5 to determine the velocity. These counters will be run on nitrogen gas with pressures set to achieve 99.99% (9 photoelectrons) efficiency on the highest mass in the interval. The counters will be sensitive to the following mass regions:

$$C1: \text{ Mass} < 2.4 \text{ GeV}/c^2$$

$$C4: \text{ Mass} < 3.8 \text{ GeV}/c^2$$

$$C5: \text{ Mass} < 5.0 \text{ GeV}/c^2$$

Each Cerenkov counter is flagged and its pulse height is recorded on tape by an on-line computer. The coincidences $C1 \cdot \bar{\ell}$, $C4 \cdot \bar{\ell}$, and $C5 \cdot \bar{\ell}$ give an on-line

indication of massive particles. Note that even without the pulse height information the logic still selects four mass bins. The final off-line identification of the particles' mass is made by coincident requirements on the pulse height from all three threshold counters. Figure 2 shows the expected pulse heights in the counters as a function of mass at the operating pressures for 110 GeV/c. As we discuss below, the light particle flux can be used to continuously calibrate the pulse height scales. An event in a given mass region must satisfy several pulse height conditions simultaneously. With the good resolution available from the ADC's the conditions for certification of a particular mass are very stringent. For example, candidates for mass $3.8 \text{ GeV}/c^2$ must have no count in C1, C2, and C3 as well as pulse height ratios (to threshold particle) of about 1 in C4 and 10 in C5.

The deuteron and anti-deuteron flux will be measured independently with the Disc Cerenkov counter, D2. This signal can be used to cross check the threshold counters C1, C4, and C5 (which will also count deuterons). In this way we can monitor the performance of the threshold counters and establish the calibration between the pulse height measurements and the mass scale.

The differential counter D3 is available to count tritons or to improve the light particle veto should this be necessary. Alternatively, D3 can be used to improve mass discrimination should candidates show up close to an established particle such as a proton or deuteron.

A "muon identifier" is already installed at the end of the single arm spectrometer. It has been used in E96 and an improved version is being implemented and tested now for E118. This new version consists of transmission and calorimeter sections; hadron rejection of 1/500 is expected (rejection of 1/20 was already achieved in the old version). It is our intention to flag each trigger with this "muon" signal. Since in this run we are expecting 10^4 \bar{n} 's (based on

observed^{3a,c} fluxes of 2 GeV, negative particles), a possible "heavy muon-like" component at the 1% level could be seen at that mass. Other mass intervals are of course covered simultaneously, so that any new particle will be identified as hadronic or non-hadronic.

(b) High Mass Region: above 5 GeV/c²:

The velocities of all particles surviving the light particle veto are determined by several independent time-of-flight measurements made over the 1400' flight path from the first focus of M6E to the back of the Single Arm Spectrometer. The time of flight difference ΔT between a proton (mass = M_p) and a particle of mass M in a momentum selected beam is

$$\Delta T = \frac{L}{2cp^2} (M^2 - M_p^2)$$

where L is the length of the flight path and p is the momentum of the particle.

Figure 3 shows the time-of-flight differences between a particle of mass M and a pion from counter T3 to T6. (The curve relative to protons is 0.3 nsec. lower, for 110 GeV/c.)

The small phase space and small spot size of the M6 beam are well suited to time-of-flight measurements. Path length differences of the trajectories accepted by the beam contribute less than 0.2 nsec to the time-of-flight resolution. The momentum spread of $\pm 1\%$ contributes a negligible amount to the resolution. The spot sizes are so small that the direct light paths from the phototubes to the points where a particle cross the scintillators have essentially constant lengths. Veto counters with adjustable apertures are available at several places to suppress beam halo.

Thick scintillators will be installed to reduce amplitude variations due to photon statistics. Several of these timing counters will be located along the beam and spectrometer axis to provide redundant time-of-flight measurements over different path lengths. In addition to timing, these counters will have their

pulse heights recorded, to assist in establishing particle charge and reduce spurious events. We hope to achieve time-of-flight resolutions of between 1/2 and 1 nsec, full width at half-maximum. From previous experience in E96, we know that pulse degradation in these long cable runs will not prevent us from achieving this accuracy. The masses corresponding to these resolving times can be read from Figure 3. If we run at a momentum of 110 GeV/c, time-of-flight becomes viable at $5 \text{ GeV}/c^2$ for 1 nsec resolution and $3.5 \text{ GeV}/c^2$ for 1/2 nsec resolution (FWHM).

The central momentum of the M6 beam is established in the first stage, reconfirmed in the second and third stages, and determined again in the spectrometer. The fact that several confirmations of the momentum and several independent determinations of the velocity will be made will reduce the backgrounds in the time-of-flight spectrum to a very low level.

The use of both time-of-flight and Cerenkov techniques allows us to cover the whole mass interval -- ~ 1.1 to $15 \text{ GeV}/c^2$ -- at once. We should emphasize that the running conditions are static; there is no need to change Cerenkov pressures or parameters of the time-of-flight system to cover different mass ranges.

Choice of Spectrometer Momentum Setting:

The problem of selection of a momentum to run at is essentially one of optimization.

Some of the considerations we have made are designed to achieve:

- a) Simultaneous coverage of all masses up to the kinematic limit;
- b) Minimization of bias due to production mechanisms;
- c) Operating range for time-of-flight and Cerenkov techniques which are complementary, overlapping and are still of high sensitivity.

This is a straightforward choice and is nicely met by 110 GeV/c. How this choice was made can be seen from an example based upon p-p collisions in the production targets. There are three parameters we have taken as fixed constraints: the incident beam on the production target is 400 GeV/c, the production angle for the M-6 line is 2.8 milliradians, and the maximum momentum of the M6-SAS line is 200 GeV/c. Figures 4 and 5 show graphically two simple kinematic regimes and serve to point-up important features. If X is the particle of interest then Figure 4 considers it to be made with its anti-particle, -- for example, $p + p \rightarrow p + p + X + \bar{X}$; whereas Figure 5 makes it singly, as in $p + p \rightarrow p + p + X$. Both mechanisms illustrate the point that low masses (e.g., <5 GeV) are produced with low Feynman x regardless of X's laboratory momentum (p_X); while high mass objects very quickly achieve high negative x values at low momenta. In fact, this effect sets a kinematic upper limit on the mass range even though it is "energetically" possible to produce X masses up to ~ 26 GeV. We would like to keep this upper mass limit high and to keep both x and p_{\perp} low. As is known from the work of Sanford and Wang^{9,10}, the inclusive cross sections for most known particles are well parametrized by

$$\frac{d\sigma}{dpd\Omega} \propto A e^{-Bx - Dp_{\perp}}$$

where x and p_{\perp} are the usual variables and the constants are of the order $B \approx 4-6$, $D \approx 5-4$ and $A(\pi) \approx 70-60$; hence our desire for low x and p_{\perp} . Choice of a very high momentum gives too high p_{\perp} for all masses and makes too high a low mass limit on the time-of-flight technique. As is mentioned elsewhere the low mass region covered by the Cerenkov identification method is quite comfortable up to 5 GeV. We therefore choose to have this mass overlap our lower limit from the time-of-flight method (see Figure 3).

Insertion of the numbers mentioned above leads to the conclusion that the range from 100 to 125 GeV/c is appropriate. We choose 110 GeV/c to put us about

in the center of the mass range $1-15 \text{ GeV}/c^2$; $|x|$ and p_{\perp} are less than ~ 0.3 for most of it.

Charge and Mass Acceptance:

Trigger counters will be biased to be efficient for particles of charge $1/3e$ and greater. Charge $1/3e$ ($2/3e$) particles transported by the beamline have momenta of $1/3$ ($2/3$) of the nominal momentum setting. Time-of-flight techniques will work well down to masses* of $3.3 \text{ GeV}/c^2$ ($2/3e$) and $1.7 \text{ GeV}/c^2$ ($1/3e$) for 1 nsec time-of-flight resolution. Additionally, fractionally charged particles will be detected by the coincidence of anomalously low pulse heights in the time-of-flight counters.

Particles of charge $2e$ have twice the nominal momentum. Two problems arise: first, particles with masses* up to $2.2 \text{ GeV}/c^2$ will be suppressed by the light particle veto; second, time-of-flight differences are reduced. To enable us to see these particles, we will install a parallel trigger which bypasses the light particle veto and is instead sensitive to anomalously large pulse heights in two or more time-of-flight scintillators. R-F buckets containing two particles produce a pulse which is, on the average, only half as large as a pulse from a charge two particle. In addition, the requirement of only one hit in the beam hodoscope eliminates $\sim 95\%$ of the doubly-populated buckets.

By these means we expect to develop a system which can detect particles of charge $1/3e$ and greater over a mass interval extending from $1.1 \text{ GeV}/c^2$ to very high masses ($>15 \text{ GeV}/c^2$).

Equipment Requirements:

We require only a subset of the standard equipment already in place for this experiment. No movement of standard equipment is necessary. All Cerenkov

* These values are for a beamline momentum of $110 \text{ GeV}/c$.

counters, the trigger counters, the beam hodoscopes, the fast electronics, and the on-line computing system are needed. No hydrogen target is involved. MWPC's in the spectrometer will be used only for initial setup of the system and will be turned off during data taking. Some small, new counters for the time-of-flight measurements will be added in locations already containing counters or breaks in the vacuum pipe. Minor re-wiring of the fast electronics will also be necessary.

Calibration and Monitoring of the Apparatus:

The hardware and software of the facility are capable of handling several triggers. Sampling and countdown circuitry exists so that trigger rates can be adjusted. The Cerenkov counter efficiencies and pulse height scales, as well as the time-of-flight scale, can be continuously calibrated and monitored by triggering on a small fraction of the light particle flux. In addition, the threshold counters used in the velocity measurement can be cross checked against the deuteron signal from the Disc.

Run Time Estimates and Schedule:

We assume conservatively that we can run at rates of 5×10^5 particles/pulse. -- a factor of 10 below the rates produced by 2×10^{12} 400 GeV/c protons striking the 8" Be target. Assuming 6 pulses per minute, we can inspect 1.8×10^{10} particles in 100 hours. We would spend half the time at +110 GeV/c and half at -110 GeV/c. During this time we expect to see $\sim 10^6$ deuterons^{3a}, and $\sim 2 \times 10^4$ ^(3b) anti-deuterons^{2b}. If antitritons are produced at $\sim 10^{-9}$ of the light particle flux³, we expect to see ~ 10 .

To set limits, we normalize our heavy particle production cross section measurement with the total number of light particles in the beam counted during our run. For obtaining a best upper limit for this cross section it is helpful to be in a kinematic region where the light particle cross section is small (but

where we are still rate limited). The settings for our beam ($p = 110 \text{ GeV}/c$, $\theta = 2.8 \text{ mrad}$) correspond to an $x = 0.28$ for light particles; their production cross section¹⁰ is down a factor ~ 5 from $x = 0$, and our sensitivity is accordingly enhanced. The observation of one event with the fluxes requested would give a cross section per nucleon of $4 \times 10^{-5} \text{ } \mu\text{b}/\text{GeV}/c\text{-ster}$. (Although the kinematic regions are not identical this limit compares favorably with previous FNAL measurements at $300 \text{ GeV}/c$ of $\sim 1.0 \text{ } \mu\text{b}/\text{GeV}/c\text{-ster}$.^(3b) and $\sim 0.1 \text{ } \mu\text{b}/\text{GeV}/c\text{-ster}$.^(3a).)

Our running time estimates correspond to an improvement of better than 200 in the upper limit¹¹ for heavy stable particle production. Figure 6 illustrates the varying sensitivity of the experiment for particles with lifetimes in the neighborhood of 10^{-8} seconds. For example, 1% of $10 \text{ GeV}/c^2$ mass particles with lifetime 4×10^{-8} sec survive to the end of our beamline.

The overhead for setting up the experiment can be very small if it is scheduled to follow a run of M6E. We would hope under these conditions to get everything working in 50 hours of beam.

Conclusions

A significant improvement of the limits on long-lived heavy particle production can be achieved with a relatively small investment of beam time. Only minor additions and alterations to existing equipment are required. The Cerenkov counters, which are the key to the experiment, have been operating for two years and their properties are well understood. With standard time-of-flight techniques we will achieve acceptable resolution; any improvements will allow us to extend the overlap of the mass range. The high quality of the beam, the sophistication of the apparatus and the large number of cross checks lead us to believe that our backgrounds will be very small.

References:

1. See for example:
 - EXPT: Augustin et al., Phys. Rev. Lett. 33 (1974) 1406
 - Abrams et al., Phys. Rev. Lett. 33 (1974) 1453
 - Aubert et al., Phys. Rev. Lett. 33 (1974) 1404
 - Perl et al., Phys. Rev. Lett. 35 (1975) 1489
 - Benvenuti et al., Phys. Rev. Lett. 34 (1975) 419
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 - THEORY: De Rujula, Georgi, Glashow, Phys. Rev. Lett. 35 (1975) 628
 - Gaillard, Lee, Rosner, Rev. Mod. Phys. 47 (1975) 77
 - M. Suzuki, Phys. Rev. Lett. 35 (1975) 1553
 - Fritzsch, Gell-Mann, Minkowski, Phys. Lett. 59B (1975) 256
2. Use of targets other than beryllium is also feasible and may have intrinsic interest.
3. FNAL EXPERIMENTS: a) Appel et al., Phys. Rev. Lett. 32 (1974) 428
b) Leipuner et al., Phys. Rev. Lett. 31 (1973) 1226
c) SAS Group, FERMILAB Report - NAL 73/83 EXP 7100.096
4. ISR EXPERIMENTS: a) Bott-Bodenhausen et al., Phys. Lett. 40B (1972) 693
b) Alper et al., Phys. Lett. 46B (1973) 265
5. SERPUKHOV EXPERIMENTS: a) Bushnin et al., Phys. Lett. 29B (1969) 48
b) Binon et al., Phys. Lett. 30B (1969) 506
c) Binon et al., Phys. Lett. 30B (1969) 510
d) Antipov et al., Phys. Lett. 29B (1969) 245
e) Antipov et al., Nucl. Phys. B27 (1971) 374
6. LOWER ENERGY EXPERIMENTS: a) Dorfan et al., Phys. Rev. Lett. 14 (1965) 995
b) Dorfan et al., Phys. Rev. Lett. 14 (1965) 999
c) Dorfan et al., Phys. Rev. Lett. 14 (1965) 1003
d) Allaby et al., Nuovo Cim. LXIV (1969) 75
7. Binon et al., Phys. Lett. 31B (1970) 230.
8. Binon et al., Phys. Lett. 30B (1970) 510.
9. Sanford and Wang, BNL Report Nos. BNL 11299, 1967; BNL 11479, 1967 (unpublished).
10. Wang, Phys. Rev. D7 (1973) 2609.
11. The factor of 200 is the ratio of the total number of light particles we sample to the flux sampled by other experiments. For all masses covered we have one kinematic setting, while the total flux from previous experiments is spread over a number of points. Correspondingly, when comparing production cross section upper limits -- at specific kinematic settings -- we obtain the larger factors of 2×10^3 to 2×10^4 , as indicated above, using a specific model (Ref. 10) for light particle production. To make a more conservative and model independent comparison with other experiments we simply ratio the total flux, giving the factor of 200.

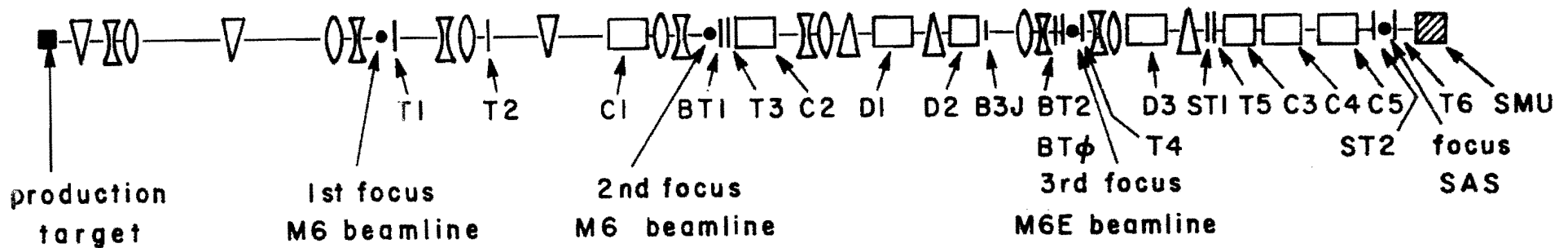


Figure 1. Beamline M6E and Single Arm Spectrometer, showing detectors to be used in this experiment (not to scale; the total length is 1945 feet). These detectors include the following existing counters:

Trigger counters: BT1, BT2, ST1, ST2
 Halo suppression counters: B3J, BT ϕ
 Threshold Cerenkov counters: C1, C2, C3, C4, C5
 Differential Cerenkov counters: D1, D2, D3
 Muon Identifier: SMU

To be added for this experiment are:

Counters for time-of-flight (and $\frac{dE}{dx}$) measurements: T1, T2, T3, T4, T5, T6

CERENKOV PULSE HEIGHTS
vs. MASS

for 110 $\frac{\text{GeV}}{c}$ when set

as per $C_j (\leq m_j)$
counter # \uparrow mass for which $N_e = 9.0$

(Note: Number of photoelectrons in each counter is 9 times the left-hand scale)

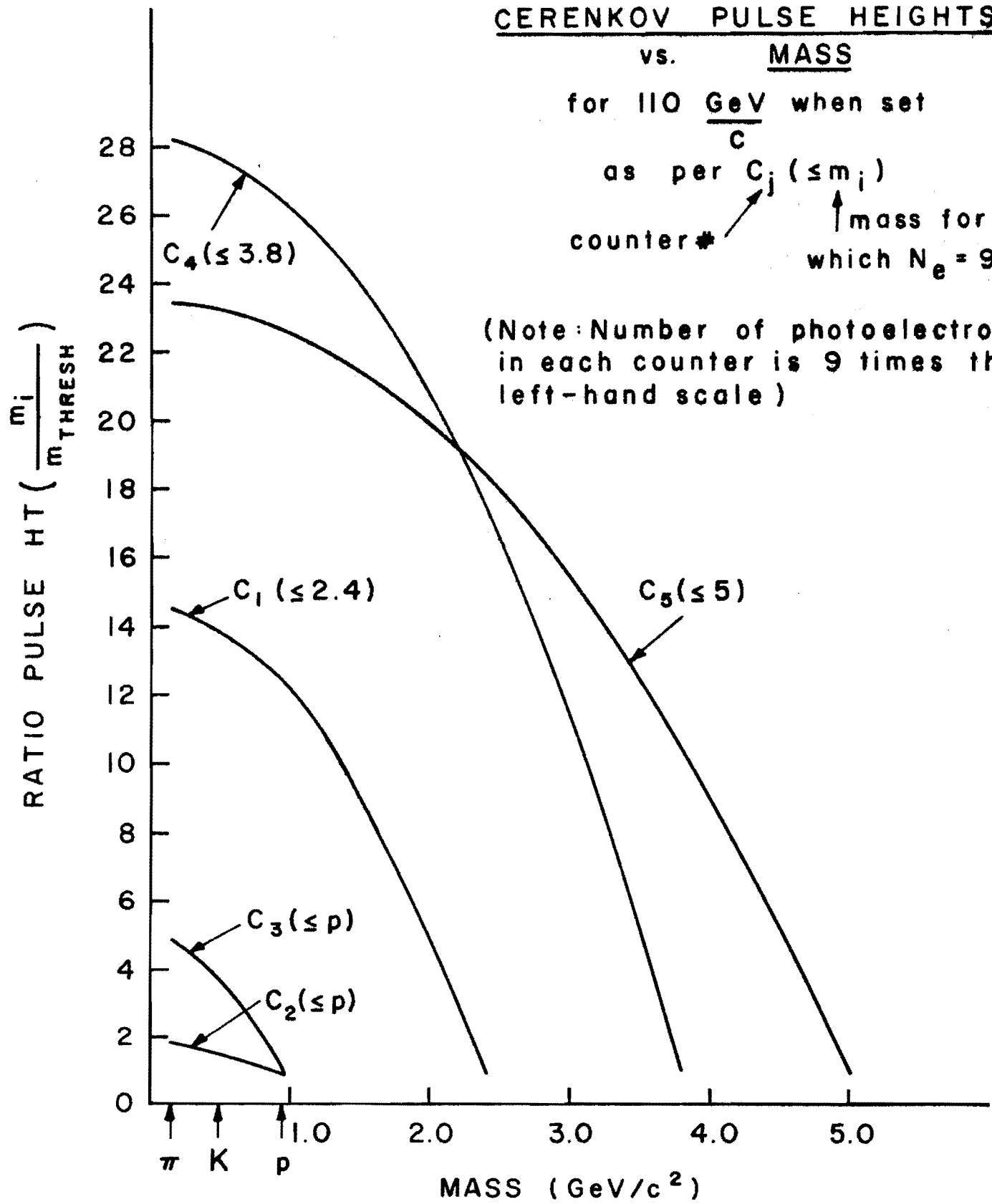


Figure 2

Δ (Time-of-Flight) vs. MASS
for flight path T3 \rightarrow T6

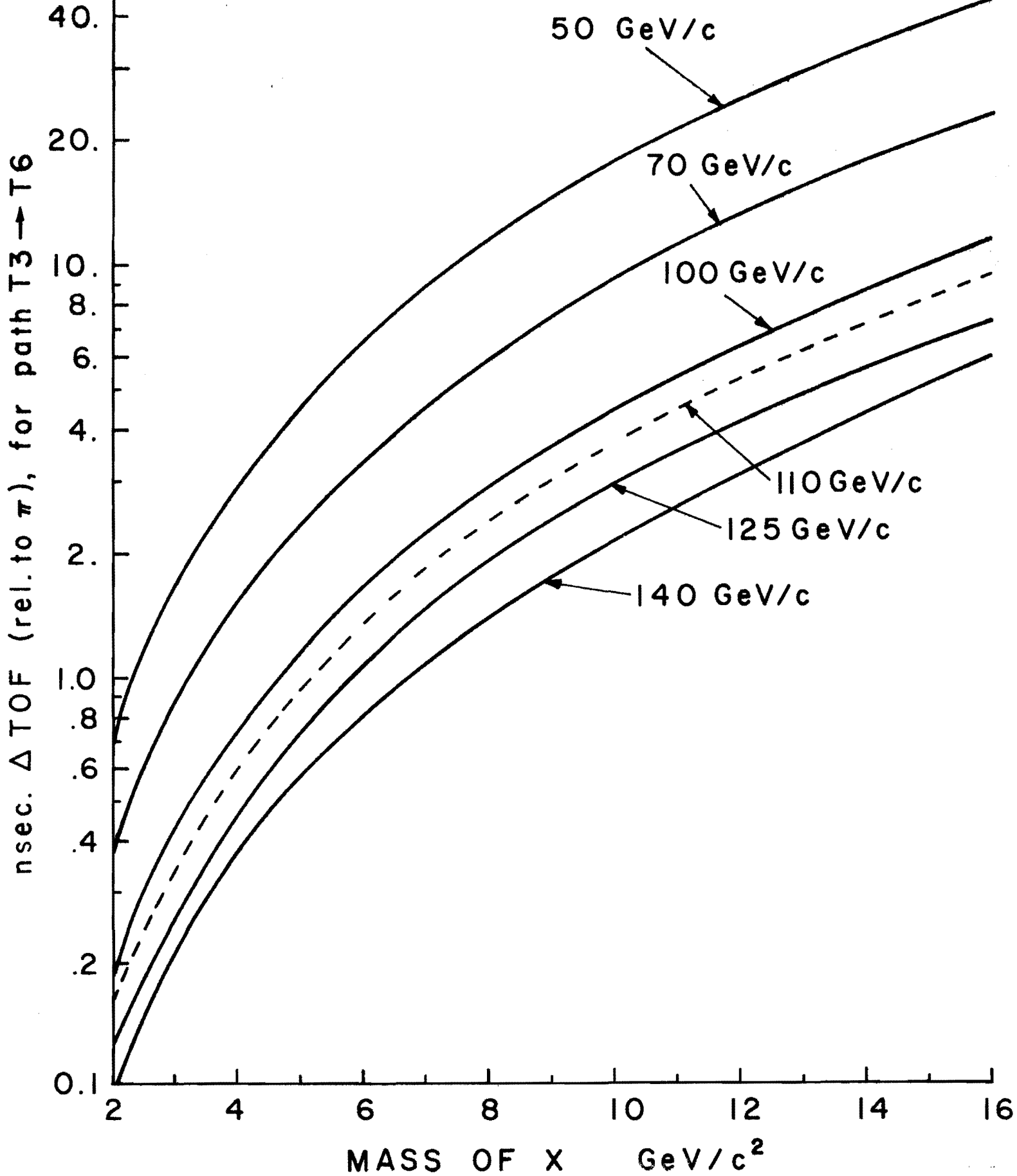


Figure 3

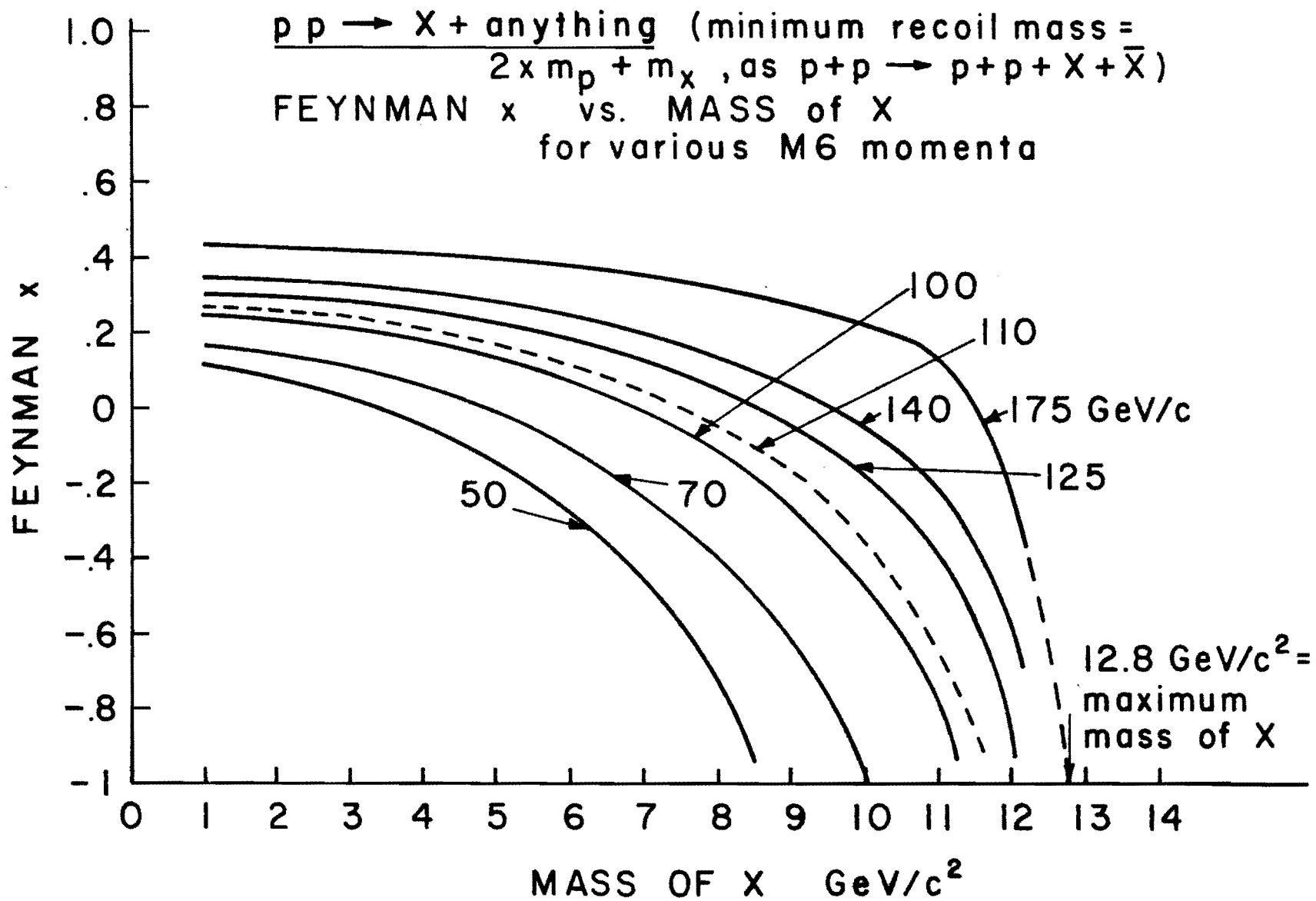


Figure 4

$p p \rightarrow X + \text{anything}$

(minimum recoil mass = $2x m_p$, as $p+p \rightarrow p+p+X$)

FEYNMAN x vs. MASS of X, for various M6 momenta

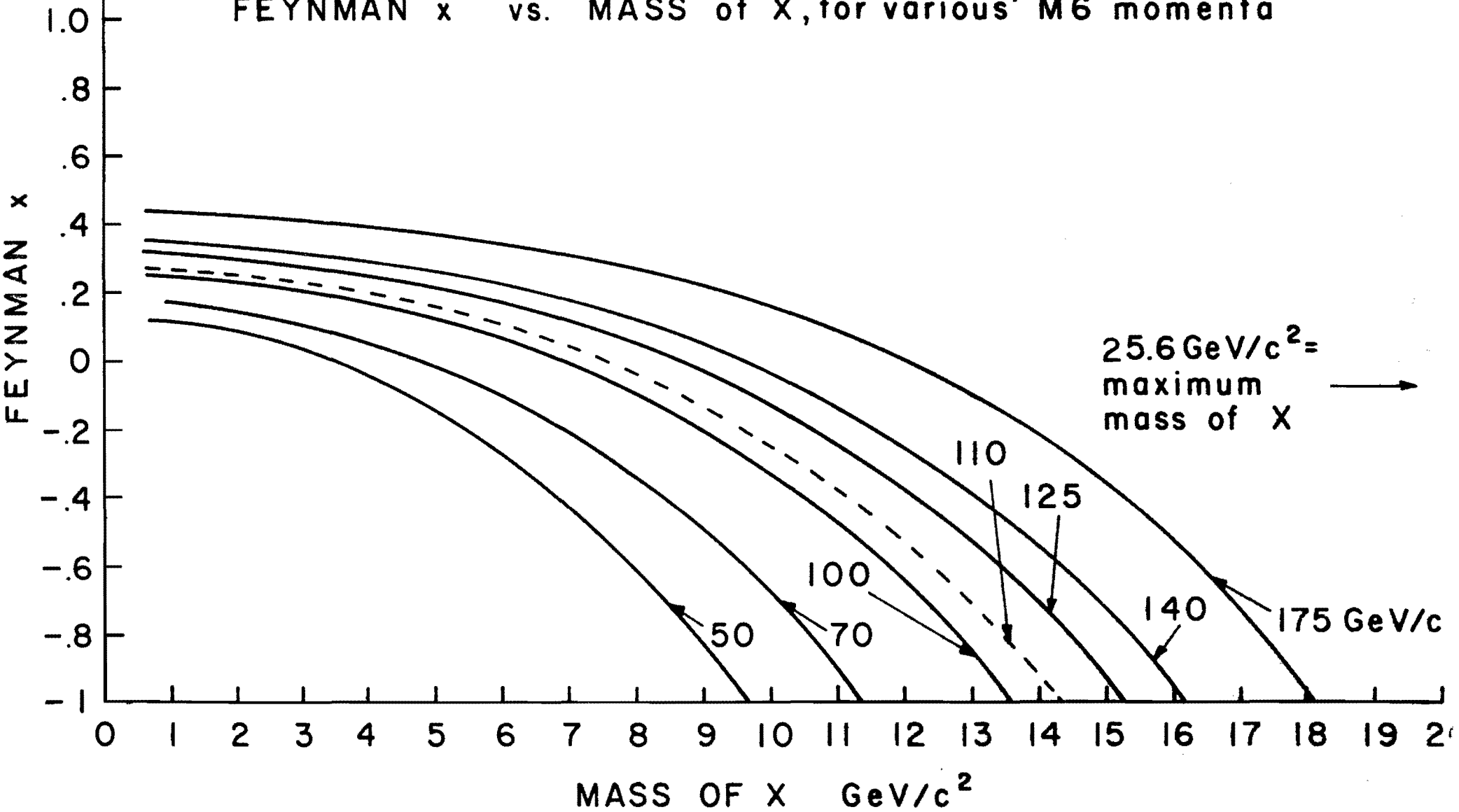


Figure 5

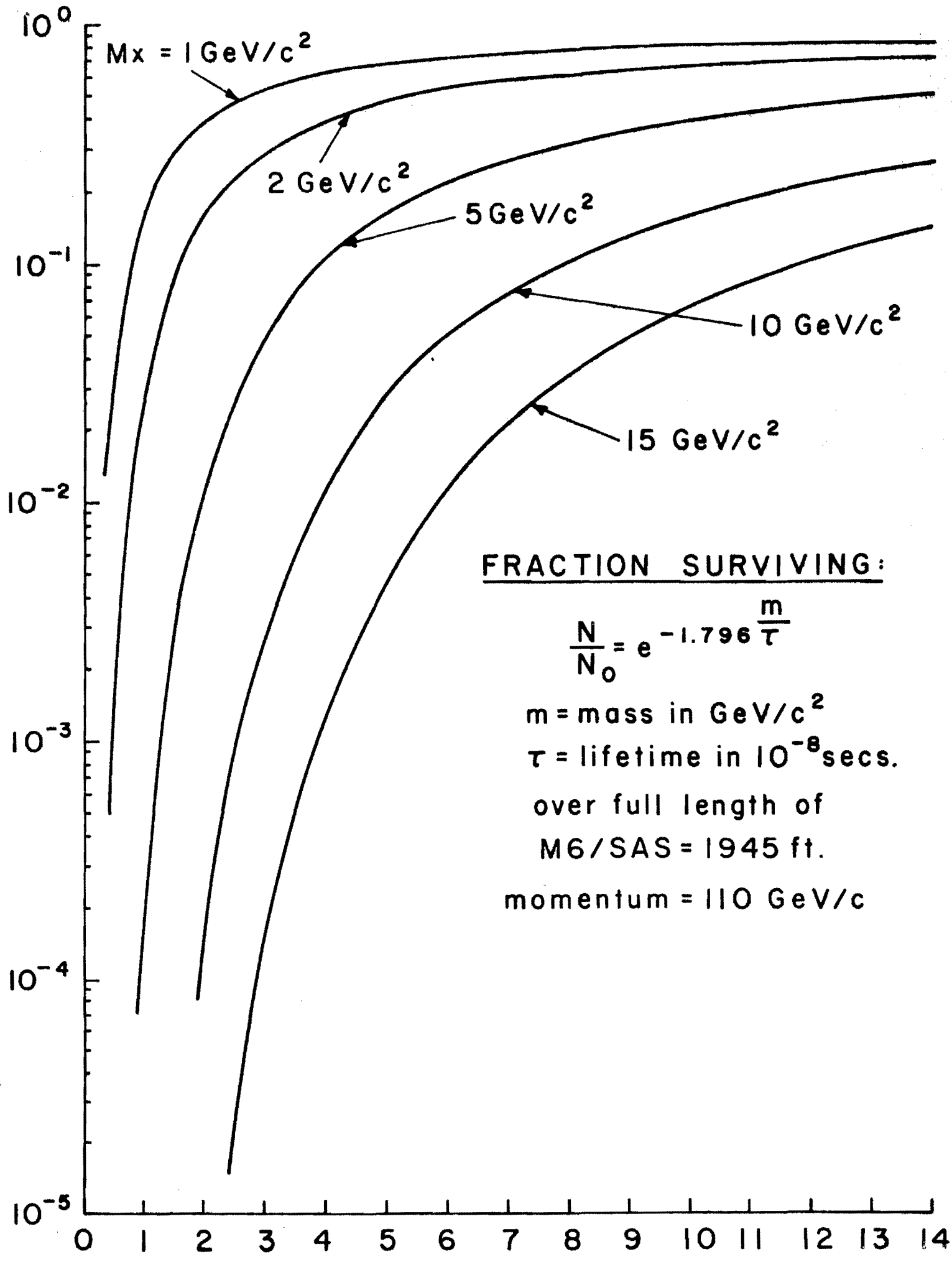


Figure 6