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A search for neutral penetrating particles has been made using an 800 GeV proton beam incident on the magnetized beam dump of the E605 spectrometer. Limits on the mass and couplings of such particles are presented. A 1.8 MeV axion coupled only to e^+e^- is ruled out.

Attempts to extend the SU(3)xSU(2)xU(1) model of lepton and quark interactions by including specific dynamical mechanisms for spontaneous symmetry breakdown lead to the appearance of nearly massless, spinless Nambu-Goldstone bosons. The Peccei-Quinn[2] mechanism for preventing CP violation in QCD is an example of such a model which predicts a light pseudoscalar boson, the axion. The various experimental limits restricting the mass, lifetime and couplings of an as yet unseen light boson have been noted by many authors[3]. Nevertheless, one can still construct models containing such bosons which would have escaped attention[4,5]. The apparent observation of a 1.8 MeV state decaying into an electron-positron pair in heavy ion collisions[6] has added impetus to the search for these bosons.

The Experiment 605 spectrometer[1] at Fermilab was constructed to study the production of leptons and hadrons at high transverse momentum. A 5.5-meter-long copper beam dump, located within the first analyzing magnet of the spectrometer, absorbed the 800 GeV proton beam. New particles could be produced in the resulting hadronic and electromagnetic shower. If these particles interact weakly with matter, like the axion, they could traverse the beam dump without being absorbed. A subsequent decay to e^+e^- in the 7. meter-long decay volume before the end of the first spectrometer magnet would be detected in the spectrometer with high efficiency.

The main set of data for the axion search was recorded by triggering on a summed energy deposition greater than 150 GeV in the electromagnetic calorimeter. The electromagnetic calorimeter covered the full acceptance of the spectrometer. It consisted of a 19 radiation length lead-scintillator sandwich with a fractional energy resolution of $43\%/\sqrt{E}$. The data sample was scanned for events with isolated clusters of energy in the electromagnetic calorimeter with coincident tracks which pointed to the downstream face of the dump. Events containing high energy muons dominated the sample.

A large flux of muons exited the back of the dump, having been created in the initial hadron shower. Since the dump was embedded in a horizontal 19 kG. field (3.1 GeV transverse kick over the length of the dump), these muons typically exited the dump at a large vertical angle with respect to the initial beam direction. Even so, high energy muons can radiate energetic photons in the last radiation length of the dump or in the calorimeter itself, thus satisfying the trigger. Occasionally muon pair production yielded a muon-e^+e^- trident in the last radiation length of the dump. Such events, especially when the muon had lost so much energy that it was not detected by the apparatus, were the dominant background in the search for axion-like decays. A prescaled sample of the high energy muons from the initial hadron shower in the dump was recorded to establish the angular distribution of the muon flux at the downstream face of the dump.

Analysis of data corresponding to $4x10^{13}$ protons incident on the dump yielded 74 e^+e^- pairs having a total energy greater than 150 GeV, all of which reconstructed to a vertex near the downstream face of the dump. The mass, less than 50 MeV, and the Z position of these vertices were consistent with a zero mass e^+e^- pair produced in the last radiation length of the dump. Figure 1 shows the vertical and horizontal angular distributions of these pairs at the dump downstream face. The angular distributions of the muons produced by meson decay in the initial hadronic shower were similar to the e^+e^- pair distributions shown in Figure 1. In contrast, high energy neutral particles would not have shown the characteristic lobes at $\theta_y=\pm10$ mrad due to the magnetic deflection of charged particles while traversing the dump. Thus the e^+e^- angular distribution was consistent with muon pair production in the last radiation length of the beam dump. The one pair (with θ_y=2.0mrad., θ_x=1.8mrad., and E_{tot}=218 GeV.) is consistent with either the decay of a neutral particle produced at the upstream end of the dump or with the tail of the muon distribution due to production of pions at finite transverse momentum in the initial hadron shower.

In order to calculate a limit on the production of an axion-like particle, we explicitly consider a pseudoscalar particle ($1.022\text{MeV} < m_A < 20\text{MeV}$) which couples only to e^+e^- (other assumptions are discussed below). Further, we assume that the particle has an interaction cross section in the dump less than 1 mbarn per nucleon. The bremsstrahlung production of this particle in the initial hadron shower,

$$e + Z \rightarrow e + \text{axion} + Z, \qquad (1)$$

is a function of only one coupling constant. The subsequent decay of the particle to e^+e^- downstream of the dump is a function of the same coupling. Limits can then be calculated as a function of the particle's mass and this single coupling constant.

The flux of π^0's in the initial hadron shower was calculated using a phenomenological fit to thick target production spectra[7]. The resultant total flux of π^0's, photons and electrons is shown in Figure 2. Axion production per radiation length according to Eq.1. was modeled using a bremsstrahlung formula due to Y. S. Tsai[8]:

$$\frac{dn_A}{dx} = \frac{\alpha_A}{2\alpha} \cdot M_e^2 \cdot \frac{\frac{2}{3} M_A^2\, x(1-x) + x^3 M_e^2}{\left(M_A^2 \frac{(1-x)}{x} + x M_e^2\right)^2} \qquad (2)$$

where $x = E_A/E_e$ is the ratio of axion to lepton energy and α_A is the coupling constant of axions to e^+e^-. The lifetime for decay into e^+e^- then follows (Ref. 3):

$$\tau_A = \frac{2}{\alpha_A} \left(M_A^2 - 4M_e^2\right)^{-\frac{1}{2}} \qquad (3)$$

For given values of the axion mass, M_A, and coupling, the number of e^+e^- pairs which should be detected in our apparatus was calculated by standard Monte Carlo techniques. The area in Figure 3 labeled 'excluded by this experiment' includes all combinations of the mass and coupling constant which would yield at least 4 e^+e^- pairs, with total energy above 150 GeV, detected in our apparatus. This is a 90% confidence level limit for a process in which one event (possibly background) is observed.

If the coupling of the assumed particle to e^+e^- is too strong, the contribution of one loop diagrams to the anomalous magnetic moment of the electron will be large. Such contributions would exceed present limits on the agreement of QED calculations and the experimental measurements of the anomalous magnetic moment of the electron and the positron. We have calculated lower limits on the lifetime of the assumed pseudoscalar (indicated in Figure 3) using recent experimental and theoretical work on the anomalous moment[9]. Also shown in Figure 3 are the results of previous experiments[10] which have ruled out longer lifetimes. Thus, from Figure 3, a pseudoscalar lighter than 2.4 MeV coupling only to e^+e^- is ruled out independent of coupling strength. In particular, for a mass of 1.8 MeV, the axion couplings postulated in reference 4 would have yielded more than 500 e^+e^- pairs produced at zero degrees in our experiment.

The bremsstrahlung production mechanism can also be modeled for scalar, vector and pseudovector particles. The resultant rates and hence limits differ only slightly from the pseudoscalar case[8]. It is also possible that a weakly interacting boson is either lighter than twice the electron mass or is coupled more strongly to photons than to e^+e^- and hence decays to a pair of photons. In either case we would detect a decay to photons by the subsequent conversion to e^+e^- of one of the photons in the last radiation length of the dump. Although the limits on such a photon mode depend in detail on the assumed couplings, the increased production by photons via the Primakoff mechanism in the initial shower compensates for the decreased length of the decay space. Since the expected event rate is exponential in lifetime, the limits for photon coupling are similar to the limits shown for e^+e^- coupling in Figure 3. Exact limits can be calculated for any assumed coupling by using the flux curves in Figure 2.

In conclusion, the 1.8 MeV state reported in heavy ion collisions cannot be a simple pseudoscalar boson coupled only to e^+e^-. Other proposed light, weakly interacting particles[4] are also excluded by the absence of zero degree energetic e^+e^- pairs in our data.

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References

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Figure 1: Observed angular distributions in the bend (y) and non-bend (x) planes of the collinear e^+e^- pairs at the downstream face of the dump.

Figure 2: Number of π^0's, γ's and $e^\pm$ per 50 GeV bin in the hadronic showers of $4\text{x}10^{13}$ 800 GeV protons. The $e^\pm$ curve is the sum of the bremsstrahlung degraded spectra of electrons and positrons normalized for a track length of one radiation length in the thick Copper target.

Figure 3: Limits on mass and lifetime of an axion-like particle from a) this experiment, and previously measured limits[10] from b) KEK, Konaka et al., c) FNAL E-613, and d) SLAC E-56. Also shown is the limit from g-2 measurements.

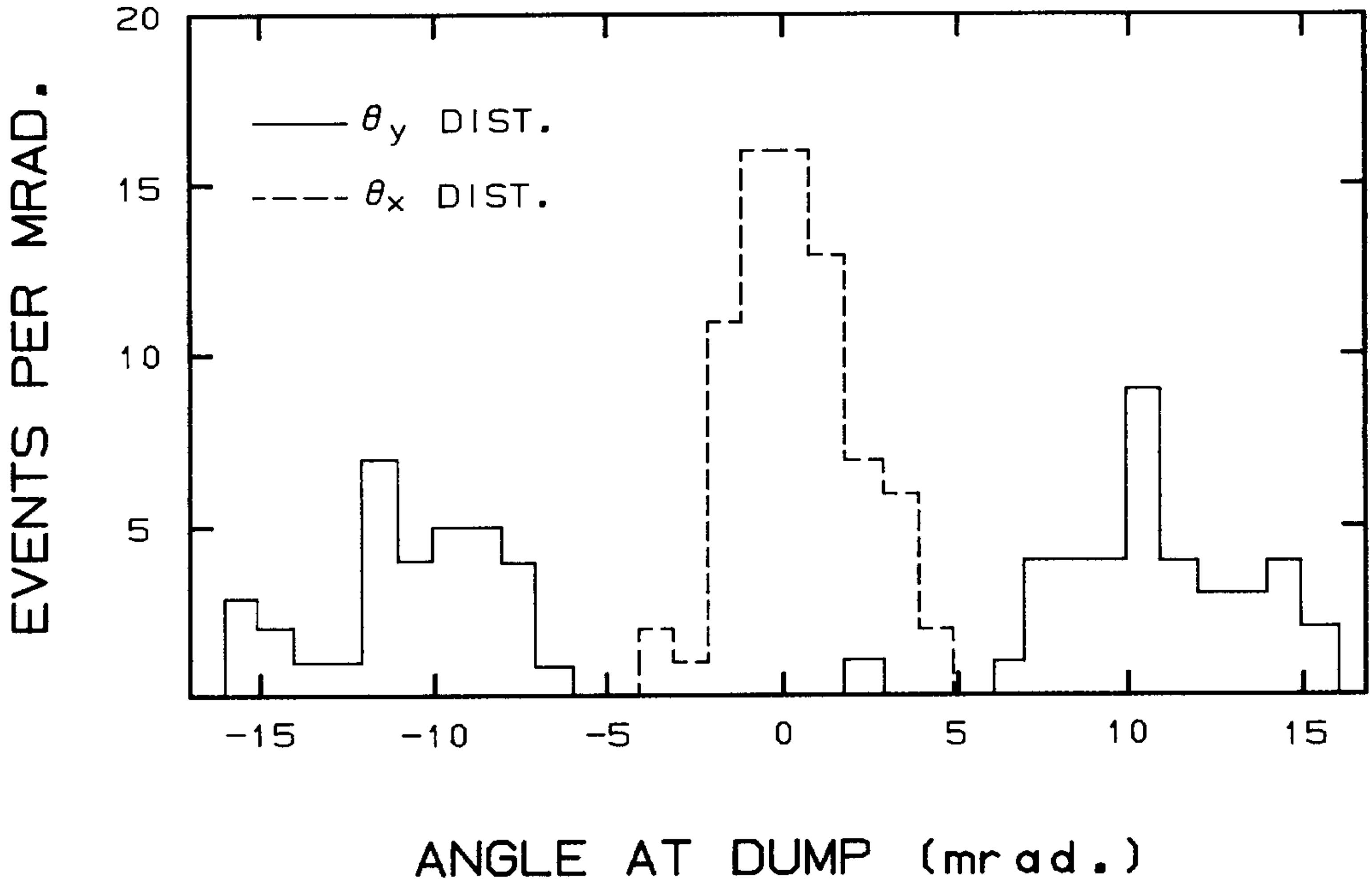

20
15
10
5
EVENTS PER MRAD.
θy DIST.
θx DIST.
-15
-10
-5
0
5
10
15
ANGLE AT DUMP (mrad.)

Fig. 1

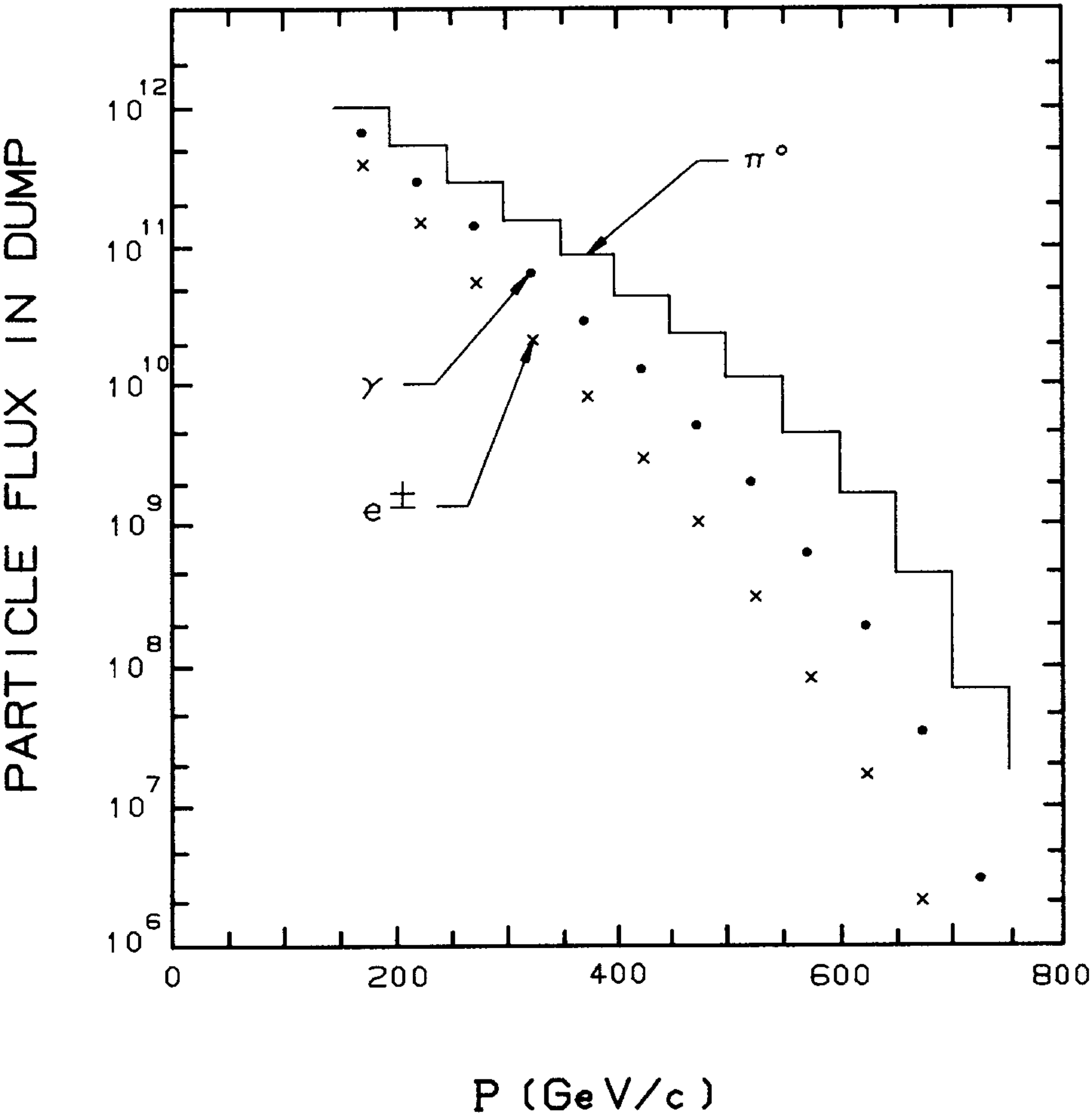
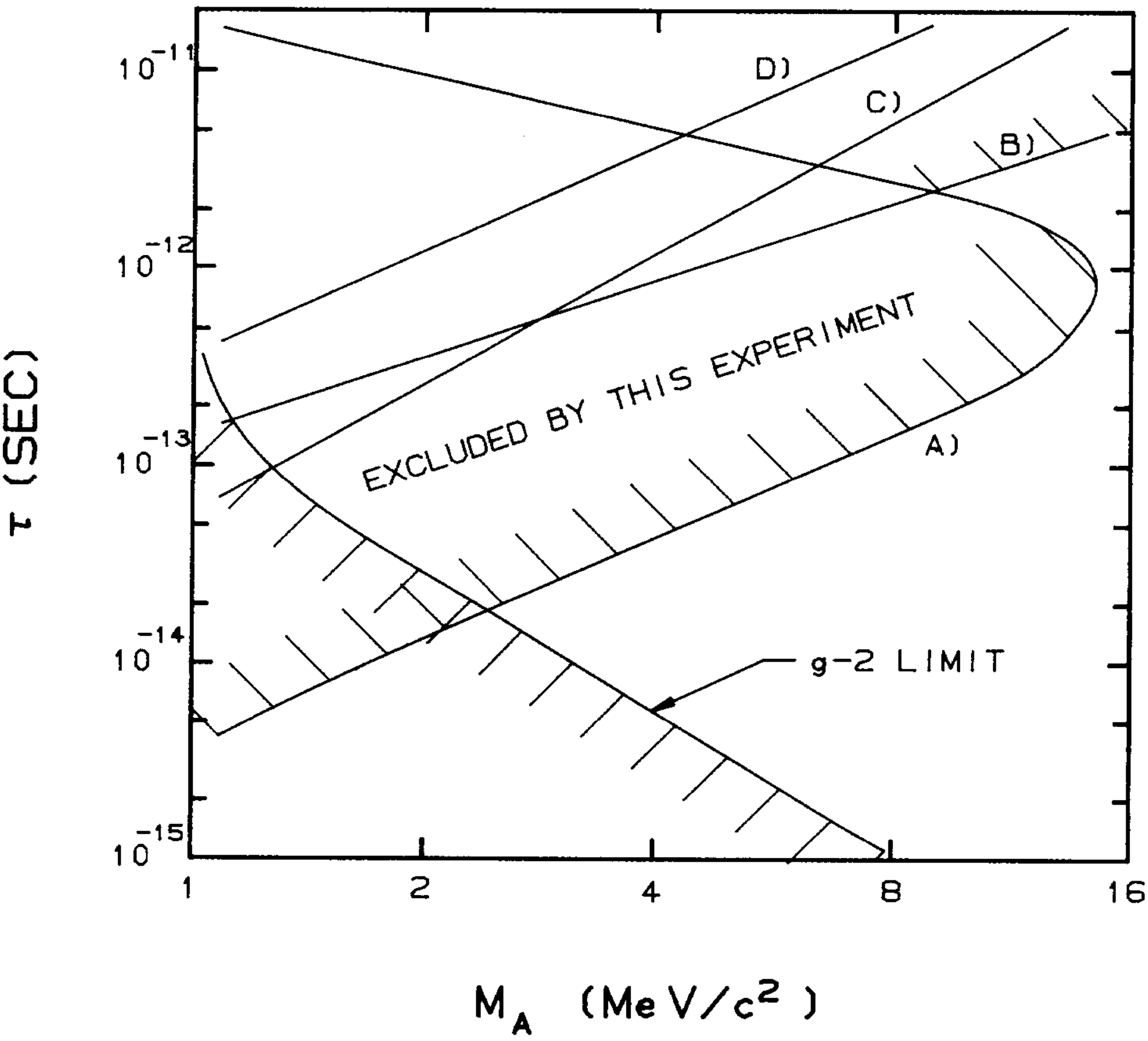

PARTICLE FLUX IN DUMP
10^{12}
10^{11}
10^{10}
10^{9}
10^{8}
10^{7}
10^{6}
π°
γ
$e^{\pm}$
0
200
400
600
800
P (GeV/c)

Fig. 2



τ (SEC)
10^{-11}
10^{-12}
10^{-13}
10^{-14}
10^{-15}
D)
C)
B)
A)
EXCLUDED BY THIS EXPERIMENT
g-2 LIMIT
1
2
4
8
16
M_A (MeV/c^2)

Fig. 3