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STUDY OF NEUTRINO INDUCED DIMUON EVENTS IN GARGAMELLE AT CERN SPS

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ABSTRACT

This letter reports a study of 117 opposite-sign and 41 like-sign dimuons, in a wide-band neutrino exposure of Gargamelle at CERN SPS. No signal is found in the $\mu^-\mu^-$ channel. The $\mu^-\mu^+$ channel is found to be dominated by D-meson production and decay. There is evidence in these events for missing energy which may be interpreted as an unseen neutrino. The V^0 multiplicities, K^0/event = $0.53^{+0.25}_{-0.20}$ and Λ/event = $0.03^{+0.06}_{-0.04}$ show only evidence for charmed meson production. Information on the D-meson fragmentation-function is presented. In a specific model, a rate $\frac{\sigma(\mu^-\mu^+)}{\sigma(\mu^-)} = (0.72 \pm 0.14)\ 10^{-2}$ is found, independent of the energy. An investigation of these events for visible D-decays sets a limit on the life-time $\tau_D < 0.8\ 10^{-12}$ sec. at 90% C.L.

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Since the discovery of the $\mu^-\mu^+$ [1] and μ^-e^+ events [2], neutrino-induced dilepton events have been studied by two different and complementary approaches: a few hundred dimuon events have been analysed in counter experiments [3], allowing the comparison of semi-inclusive properties with charm production models [4], but without showing the details of hadronic showers. Heavy liquid bubble-chambers have permitted a study of the detailed properties of the μ-e events [5] showing the correlation with strange particles. However statistics are limited and scanning biases have not been demonstrated to be negligible for high energy events.

This experiment, performed by means of a hybrid technique, offers the advantages both of an efficient selection of dimuon events and of the details available in a bubble chamber.

The heavy liquid bubble chamber Gargamelle was operated with a set of counters [6], allowing timing of the events, muon identification and scanning of selected topologies. The chamber was filled with a propane-freon mixture (90.5/9.5 in moles) the radiation length of which is 61 cm, interaction length for pions is of the order of 2.0 m, and density is 0.51 g/cm^3. Two multi-wire proportional chambers (MWPC) were placed just upstream (veto-counter) and downstream (picket-fence counter) of the chamber body, perpendicular to the beam. The spatial resolution of these chambers is ±3 cm (±1 cm) in the vertical (horizontal) direction (the magnetic field is horizontal). Two planes of 8 MWPC, separated by iron shielding (80 to 160 cm thick), constitute the external muon identifier (EMI). The resolution of these chambers is 0.4 cm in the central part and 1.6 cm in the external part of the EMI planes. The time resolution of this set of chambers is ±250 ns. The system is auto-triggered with a 500 ns gate (referred to as a time-slot). The shielding before the first plane consists of the coils of the magnet and the plates of a hadron calorimeter (used in other experiments) equivalent to 80 cm of copper. The geometrical acceptance of the apparatus is shown in fig. 1a.

The experiment was performed in the CERN SPS wide-band neutrino beam, using a total of 2.3×10^{18} 350 GeV protons on target. The shape of the neutrino fluxes is given in ref. [7]. The mean energy of normal charged current events is around 44 GeV.

Dimuon candidates were selected off-line if they had the following topology: no particle recorded in the veto-counter, at least one particle in the "picket-fence", and two possible muons coming from Gargamelle and reaching the two planes of the EMI in the same time-slot. One candidate was thus selected in approximately 30 pictures and the corresponding frames were examined. Events inside a fiducial volume of 3.1 m^3 having at least two leaving particles were measured and processed through the track-following programme, which extrapolates tracks to the EMI planes, propagating measuring and multiple scattering errors. The tracks are described in terms of a χ^2 of association with the nearest hit in each plane. All events were retained as dimuon candidates for which at least two tracks had a χ^2 less than 40 in both planes. A total of 117 $\mu^-\mu^+$ and 41 $\mu^-\mu^-$ candidates were found in a sample of 419,500 pictures corresponding to (39,000 ± 3,000) charged current events.

There are three sources of background:

B1: Decay in flight of charged hadrons from the primary interaction producing muons. This occurs mainly inside the chamber itself, and was computed by a Monte-Carlo method, using neutrino and antineutrino data for semi-inclusive π and K production [8]. This input was checked by the measurement of ordinary charged current events in this experiment. The pion interaction-length was calibrated by measuring 19 GeV proton interactions in the same mixture.

B2: Punch-through of a hadron which generates a shower of secondaries inside the shielding, one of which reaches the EMI, and is associated with any of the primary leaving tracks.

B3: Association of a hadron with random hits in the EMI.

B1 gives a χ^2 distribution similar to, and only slightly broader than, that expected from the signal, whereas B2 and B3 lead to a flat distribution. The χ^2 distribution for the μ^- of $\mu^-\mu^+$ events is in good agreement with that expected from measurement and multiple scattering errors (fig. 1b). However, μ^+ of $\mu^-\mu^+$ and μ^- of $\mu^-\mu^-$ show a long tail which is consistent with these last two sources (fig. 1c). To reduce this background a cut at χ^2 greater than 10 was applied to these muons. A summary of background calculations is given in Table 1.

No significant signal of $\mu^-\mu^-$ events is observed, but a signal in $\mu^-\mu^+$ is clearly present. Dimuon events are currently interpreted as being due to the production of charmed particles and their semileptonic decay. There follows an analysis of the $\mu^-\mu^+$ events to check this hypothesis and obtain more detailed information.

In the 94 $\mu^-\mu^+$ events there are 9 K^o_s and 3 Λ, after kinematical fit. Efficiencies for detecting kaons and lambdas have been computed to be 0.25 ± 0.02 and 0.48 ± 0.03. Background was subtracted using the V^o multiplicities as a function of the total hadronic mass as measured in several experiments [9]. These multiplicities were increased by 0.5 for K^+-induced background events. After corrections for efficiencies and background, $0.53\,^{+0.25}_{-0.20}$ K^o and $0.03\,^{+0.06}_{-0.04}$ Λ per dimuon event are found, showing no evidence for Λ production. The $K^o\mu^+$ masses are all compatible with the decay of the lightest known charmed meson, D. The $\Lambda\mu^+$ masses, (3.71 ± 0.16), (2.89 ± 0.10), (1.9 ± 0.06) GeV/c^2 however, are compatible with background, the mass of the lightest charmed baryon being currently assumed between 2 and 2.5 GeV/c^2. This favours the dominance at these energies of charmed meson over charmed baryon production given the acceptance conditions of this experiment.

A correction was made for the missing energy of undetected neutral particles, in order to obtain a good estimate of the total energy and of the kinematical variables of the events. For this purpose the ratio:

$$f = p_\perp^m \text{ (measured hadrons)}/P_\perp(\mu^-)$$

of the transverse momentum of hadrons projected on the μ-ν plane to that of the negative muon was calculated for each event. This is an unbiased estimation of the fraction of the total hadronic energy actually measured.

The values of f for all samples was fitted with a theoretical distribution of mean f_o [10]. The f distribution for the $\mu^-\mu^+$ events with $\chi^2 < 10$ was compared to a sample consisting of all $\mu^-\mu^-$ and those $\mu^-\mu^+$ having $\chi^2 > 10$, (64 events) which are essentially background. The energies, multiplicities and spatial distribution of the two samples are very similar. The fitted values of f_o are (0.66 ± 0.04) for the $\mu^-\mu^+$ sample and (0.83 ± 0.04) for the background sample. Carmer's test on the f distribution function [11] shows that there is a definite excess of missing energy in the $\mu^-\mu^+$ sample at a confidence level lower than $2.3\ \ 10^{-3}$.

It is tempting to interpret this result as evidence for a missing neutrino, no other trivial explanation being satisfactory. Under this assumption, the mean fraction of the hadronic energy carried by the neutrino is, after background subtraction:

$$< Z_{\nu} > = 0.24 \pm 0.09.$$

The inclusive properties on $\mu^- \mu^+$ events were interpreted in the frame of a model of D production and subsequent semi-leptonic decay. For the production of charm a standard quark-parton model was used assuming slow rescaling "à la Barnett" with a charmed quark mass $M_C = 1.5$ GeV, and a threshold $W_t = M_N + M_D$ [12]. The branching-ratios for the decay modes $D \rightarrow K\mu\nu$ and $D \rightarrow K\pi\mu\nu$ were taken to be 0.4 and 0.6 respectively, as measured by D production in e^+e^- collisions,[13] and form factors have been taken as constant.

The model is most sensitive to the assumed longitudinal D momentum distribution, usually parametrized as a parton fragmentation-function $D\ (Z_D)$ (where Z_D is the fraction of the hadronic energy carried by the D-meson). The shape is so far unknown and a Z_D dependence of the type e^{+bZ_D} was assumed. Usual hadron production falls off rapidly as e^{-3Z_D}, while a bremsstrahlung analogy for multiparticle production favours a flat distribution $(b = 0)$ [4]. The detection efficiencies and other quantities such as y (fraction of the total energy carried by the hadrons), Z_{μ^+}, and Z_{ν} (fraction of the hadronic energy carried by the μ^+ or the missing neutrino) depend on the b value. The comparison of some semi-inclusive properties with the model is shown in fig. 2. Fitting the experimental distributions, the best estimate for b is $+1.25^{+1.1}_{-0.75}$, most of the information being in the Z_{μ^+} variable. For this value of b the agreement with the experimental distributions is excellent.

In order to compute the production rate as a function of neutrino energy, the data were corrected for the limited geometrical and kinematical acceptance of the EMI. For the process

$$\nu_{\mu} + N \rightarrow \mu^- + \underbrace{D}_{\hookrightarrow\ \mu^+ + \nu + \text{hadrons}} + \ldots$$

with the assumptions stated above, the probability that both muons reach the EMI is well described by $P = 0.45 \times Z_D$ averaged over all neutrino energies. The result is shown is table 2. No variation of the production rate as a function of the incident neutrino energy is observed.

Thus, the data are compatible with the hypothesis of single D production and its semi-leptonic decay. The D particles detected in the apparatus have a mean momentum of 27 GeV/c. This corresponds to a decay path of a few millimetres which should be observable, at least in some events, if the lifetime is about 10^{-12} s. The $\mu^-\mu^+$ candidates have been scrutinized for possible multiprong decays of charmed mesons.

As no decay-vertex was seen, a limit can be set to the D mean life-time. For each event, a maximum length ℓ_{max} was defined visually, after which none of the considered decays could have occured. A likelihood function was written as

$$V(\tau) = \prod_{\text{events}} \left\{ P_B + (1-P_B)\ \{P_u + \sum_j P_j\ (1-\exp \frac{-\ell^j_{max}}{(\frac{P_D}{P_\mu})\ \frac{P_\mu}{M_D}\ c\tau})\} \right\}$$

where an event has a probability P_B to be due to the background, $P_u = (D^+ \rightarrow \mu^+ + \text{neutrals}/(D^+ + D^o)\ )$ is the fraction of invisible decay modes and P_j are the fractions of visible decay modes. This formula makes no distinction between the D^+ and D^o lifetimes.

The limit at 90% confidence level depends essentially on P_μ/P_D and P_u. The value of P_μ/P_D quoted in this formula is unknown for each individual event and was replaced by the average value given by the Monte Carlo calculation $<P_\mu/P_D> = .36$. The effect of this is to overestimate the limit. Recent results[9,14] on the D^+/D^o rate in neutrino-production and the high $K^*\mu\nu/K\mu\nu$ decay fraction of the D-mesons indicate P_u values smaller than 0.4.

With these values the upper limit is $\tau_D < 0.8\ 10^{-12}$ sec. at 90% confidence level which is obviously model-dependent. Figure 3 illustrates the dependence of the limit upon these variables and shows that one could not envisage much longer lifetimes, within reasonable assumptions.

CONCLUSION

These results are consistent with the hypothesis that dimuon events are dominated by D meson production and decay. The information given on the D fragmentation functions supports bremsstrahlung-like production models and the limit on the D lifetime is crucial for the interpretation of recent beam dump neutrino experiments [15]. These results complement, with reasonable statistics the conclusions of studies on the μe channel, at higher energies and with different experimental biases.

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FIGURE CAPTIONS

Fig. 1a Detection efficiency of the EMI (two-plane) for i) the μ^- and ii) the μ^+ of the $\mu^-\mu^+$ events, as a function of their momentum. Fig. 1b and 1c show the experimental χ^2 distributions for the μ^- and the μ^+ respectively, in $\mu^-\mu^+$ events. χ^2 is understood as the biggest of the χ^2 in the two planes and therefore does not follow the normal shape for two degrees of freedom. The dots show the Monte Carlo simulation for a pure muon sample.

Fig. 2 Comparison of semi-inclusive properties of the $\mu^-\mu^+$ events with the predictions of the charm production model for various values of the parameter b defined in the text. (The dotted line holds for $b = -3$, the solid one for $b = 1.25$, the dashed one for $b = + 3$).
a) $Z_{\mu^+} = P_{\mu^+}/E_H$, b) total incident neutrino energy E_ν ,
c) $y = E_H/E_\nu$, d) $\langle Z_{\mu^+}\rangle$ - $\langle Z_\nu\rangle$ plane

Fig. 3 Variation of the limit at 90% confidence level of the D lifetime as a function of $P_u = (D^+ \rightarrow \mu^+ + \text{neutrals})/(D^0 + D^+)$, and $\langle P_{\mu^+}/P_D\rangle$.

	$\mu^-\mu^+$	$\mu^-\mu^-$
events $\chi^2 < 40$	117	41
after cut at $\chi^2 < 10$	94	25
Background		
π decay in flight	24.2 ± 2	14.5 ± 1
K decay in flight	3.9 ± 1	2.5 ± 1
Punch through + random association	4 ± 2	3 ± 2
Total background	32.1 ± 3	20 ± 2.5
SIGNAL	62 ± 10	5 ± 6

TABLE 1: Summary of background calculations

Neutrino energy (GeV)	15 - 35	35 - 75	75 - 300	> 15
charged current events ($\nu_\mu + N \rightarrow \mu^- + X$)	18 600	10 000	6 500	35 100
$\mu^-\mu^+$ candidates	22	32	40	94
background	6.6 ± 1	13.3 ± 2	12.2 ± 2	32 ± 3
signal	15.4 ± 5.3	18.7 ± 6.5	27.8 ± 7.2	62 ± 10
geometrical efficiency	0.14 ± 0.02	0.31 ± 0.03	0.55 ± 0.04	0.28 ± 0.04
corrected rate	$(6.5\pm2.6)10^{-3}$	$(6.9\pm2.2)10^{-3}$	$(8.9\pm2.3)10^{-3}$	$(7.2\pm1.4)10^{-}$

TABLE II: Computation of $\frac{\sigma(\mu^-\mu^+)}{\sigma(\mu^-)}$ as a function of the incident ν energy. The quoted errors are only statistical. An overall 15% systematic uncertainty should be added for the flux and acceptance calculations.

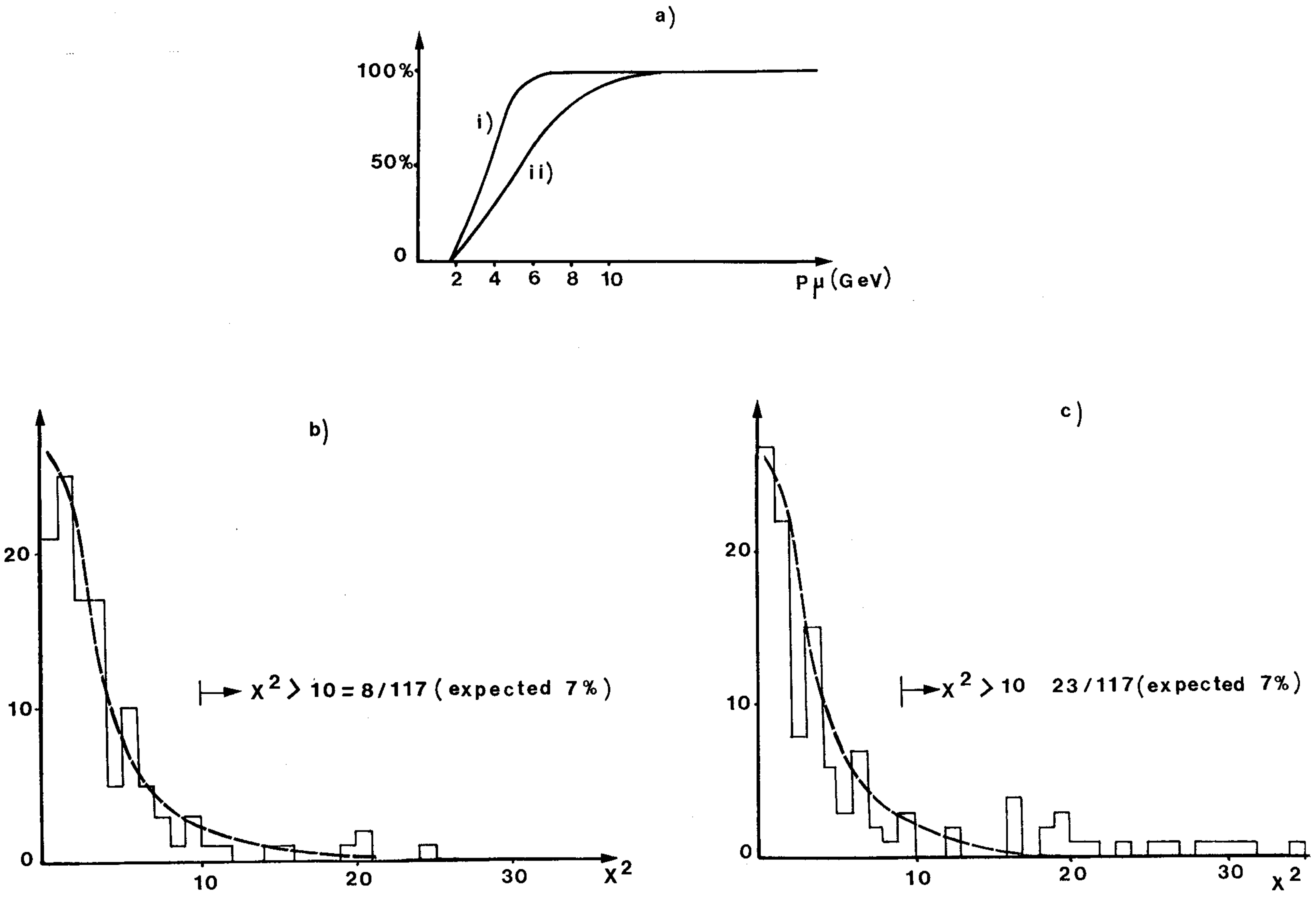
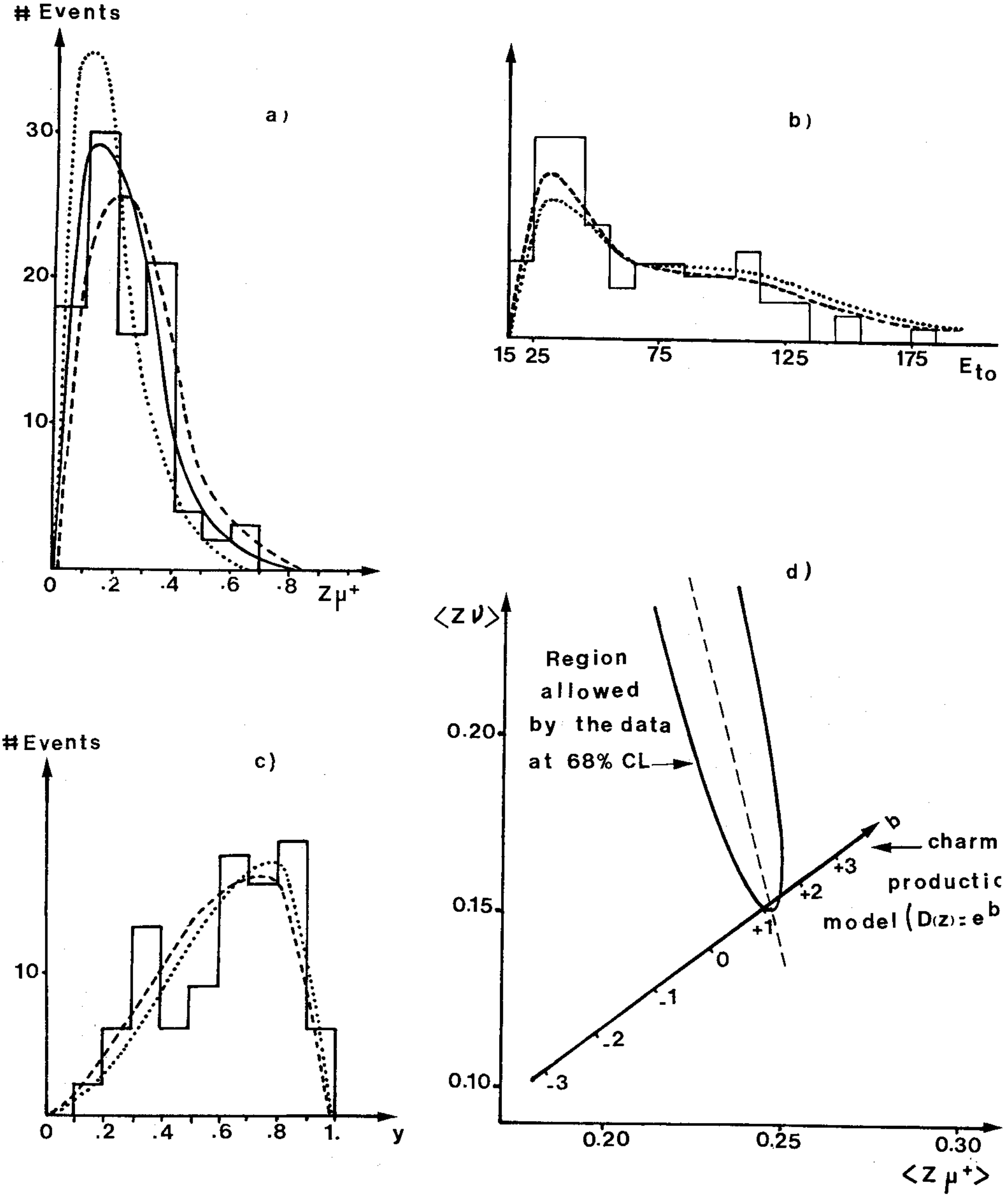
a)
100%
50%
0
i)
ii)
2
4
6
8
10
Pμ (GeV)
b)
20
10
0
10
20
30
X²
|→ X² > 10 = 8/117 (expected 7%)
c)
20
10
0
10
20
30
X²
|→ X² > 10 23/117 (expected 7%)

Fig. 1



Events
a)
30
20
10
0
.2
.4
.6
.8
Zμ+
b)
15
25
75
125
175
Eto
Events
c)
10
0
.2
.4
.6
.8
1.
y
d)
⟨Zν⟩
0.20
0.15
0.10
Region allowed by the data at 68% CL
b
charm productic model (D(z) = e^b
+3
+2
+1
0
-1
-2
-3
0.20
0.25
0.30
⟨Zμ+⟩

Fig. 2

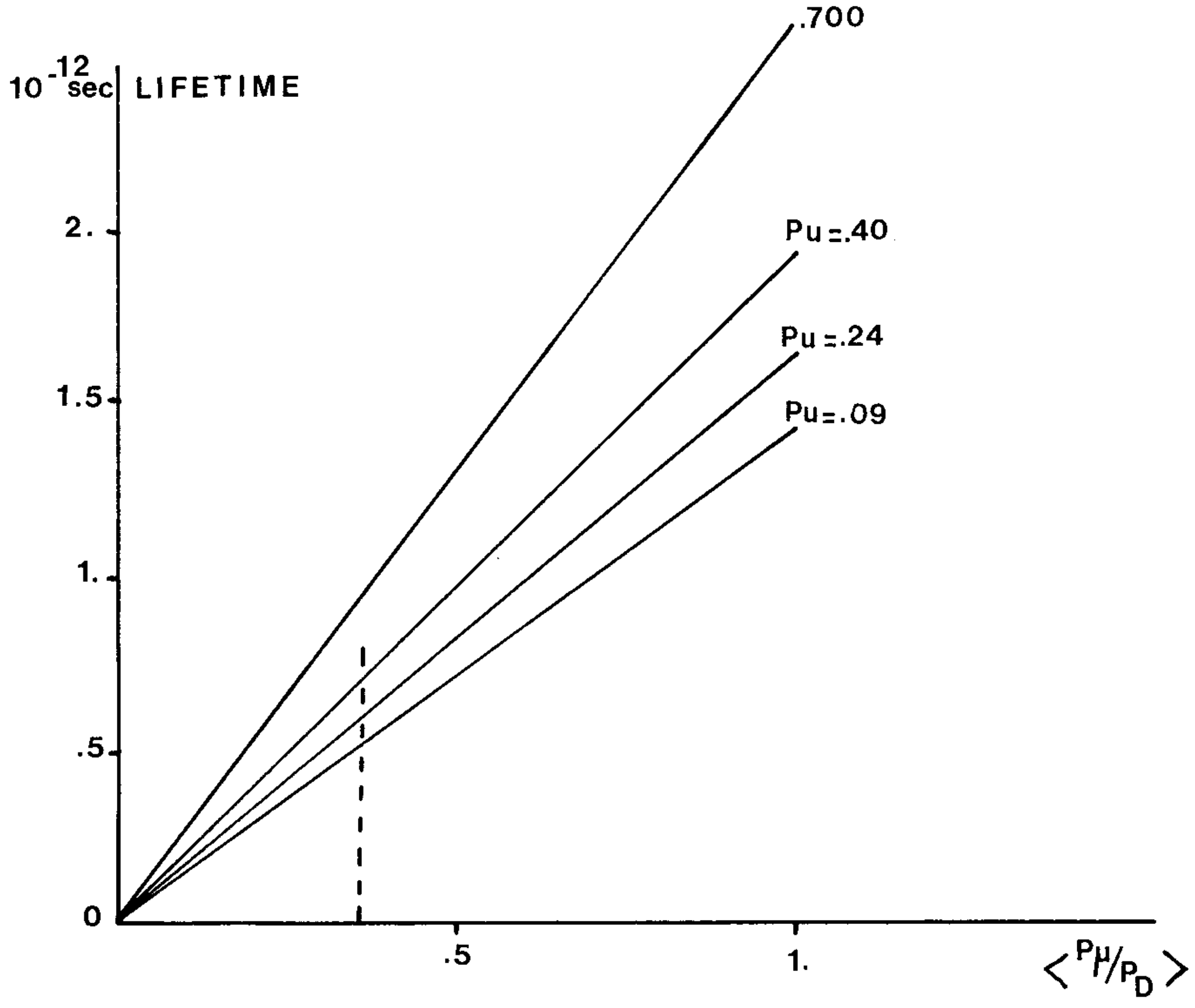

10^{-12} sec
LIFETIME
2.
1.5
1.
.5
0
.5
1.
$\langle P_{\mu}/P_D \rangle$
.700
Pu=.40
Pu=.24
Pu=.09

Fig. 3