EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

CERN/EP/79-27
16 March 1979

EXPERIMENTAL STUDY OF THE REACTION $\nu_\mu + e^- \rightarrow \mu^- + \nu_e$

N. Armenise, O. Erriquez, M.T. Fogli-Muciaccia, S. Natali, S. Nuzzo, F. Romano.
Istituto di Fisica dell'Università and INFN, Bari (Italy)

G. Bonneaud, H. Burmeister, G. Carnesecchi, M. Haguenauer, C. Matteuzzi,
P. Musset, G. Poulard, M. Price, H. Sletten, J.P. Vialle, M. Willutzky.
CERN, Geneva (Switzerland)

P. Alibran, A. Blondel, J. Bourotte, B. Degrange,
J. Gillespie, F. Jacquet, U. Nguyen-Khac.
LPNHE, Ecole Polytechnique, Palaiseau (France)

S. Bonetti, D. Cavalli, E. Fiorini, A. Pullia, S. Ragazzi,
M. Rollier, L. Zanotti
Istituto di Fisica dell'Università and INFN, Milano (Italy)

C. Arnault, D. Blum, P. Heusse, C. Longuemare, A.M. Lutz, C. Pascaud, J. Sleeman.
Laboratoire de l'Accélérateur Linéaire, Orsay (France)

ABSTRACT

The first observation of the reaction $\nu_\mu + e^- \rightarrow \mu^- + \nu_e$ has been made in the bubble chamber Gargamelle exposed to the CERN SPS Wide-Band neutrino beam. A signal of 26 ± 6 events has been found. This is 0.90 ± 0.20 times the prediction of the V-A theory.

(Submitted to Physics Letters)

This paper presents the first observation of the inverse μ-decay reaction $\nu_\mu + e^- \rightarrow \mu^- + \nu_e$ (1) which is predicted by the V-A theory [1]. This reaction had never been observed before owing both to its high threshold, 10.9 GeV incident neutrino energy, and to an exceedingly low cross section [2]. Since only leptons are involved, this reaction is a direct test of the weak leptonic charged current.

During 1977-78 the heavy liquid bubble chamber Gargamelle was exposed to the CERN-SPS wide band neutrino beam in order to study neutrino interactions in the energy range 10-200 GeV (fig.1). In this experiment the bubble chamber was filled with a light mixture of propane (90.5% in moles) and freon CF_3Br (9.5%) of mean density .51. Two MWPC were placed upstream (the "Veto" chamber) and downstream (the "Picket Fence"), these were close to the chamber body. This assembly was followed by an External Muon Identifier composed of two planes of 8 MWPC (3 x 1m) each, which were separated by iron shielding for the identification of muons above 2.5 GeV (fig.2). The Picket Fence in such a configuration was used to determine the time at which interactions occured in the chamber within a 2 ms spill time, and thus to reduce to a negligible level random associations between a charged track leaving the chamber and hits in the EMI produced by sky-shine muons.

377000 pictures were analysed, corresponding to $2.0\ 10^{18}$ protons on target. These were scanned for events consisting of a single negative track leaving the chamber and making an angle to the beam smaller than 100 mrad, with possibly one proton attached to the vertex and stopping in the liquid. No γ-ray was allowed to point to the vertex. The events were retained only if they occurred in a fiducial volume of 4.01 m^3 inside a visible volume of 7.2 m^3. The overall efficiency of the scanning was found to be only 67 ± 9% (including 60% of films scanned twice), owing to the difficulty in finding an isolated track created in the liquid, and thus additional information from the MWPC was used to select candidates. This information was registered in time slots of 0.5 μs duration. A program selected all time slots in which there were simultaneous hits in the two planes of the EMI and one single hit in the picket fence which could be produced by a muon originating from the liquid. In order to reduce the number of candidates, a conservative angular cut has been applied. Furthermore, no hit was allowed in the same time slot in the "Veto" in order to reduce the background of through-going muons accompanying the beam. This procedure reduced by a factor of 10 the number of pictures to be scanned, and predicted the approximate position of the muon track inside the chamber. All the pictures selected were scanned using this information and the total detection efficiency combining the two methods was found to be equal to (94 ± 3)%. The difference between this and the 99% efficiency of the EMI was due to the selection criteria.

Candidates were classified as "isolated μ^-" if there was only one negative track at the vertex leaving the chamber and identified as a muon in the EMI, and no other track of length greater than 2 mm projected on the scanning table (about 8 mm in space). All other events were classified as candidates for the reaction $\nu n \to \mu^- p$, referred to as $\mu^- p$ candidates hereafter. This criterion left a small background of $\mu^- p$ events in the sample of isolated μ^-, but avoided the loss of signal events with a small δ-ray or parasitic bubbles near the vertex. This was taken into account in the calculations of the background. 84 isolated μ^- and 456 $\mu^- p$ candidates were found with muon energy $E_\mu > 10$ GeV and with an angle θ to the beam smaller than 100 mrad.

The isolated μ^-'s can be generated by three different reactions:

i) the inverse muon-decay (1)

ii) the reaction on nucleons, $\nu_\mu + N \to \mu^- +$ unseen hadrons, (2)

which comes mainly from the elastic reaction $\nu_\mu n \to \mu^- p$ with the proton escaping detection;

iii) the reaction on nuclei, by excitation of the giant dipole resonance[3]

i.e. $\nu_\mu + {}^{12}C \to \mu^- + {}^{12}N$ (3)

and similar reactions on fluorine and bromine.

The background due to single π^- events in which the π^- decays in flight or punches through simulating a muon was found to be negligible since no isolated track interacting in the chamber and satisfying the kinematical cut was found. The background processes (2) and (3) and reaction (1) have indeed different kinematical properties. First, in reactions (2) and (3) the muon carries almost all the energy of the neutrino whereas for reaction (1) the muon takes about half this energy on average. Secondly, for reaction (1) the angle θ of the muon with respect to the beam is severely limited to about 5 mrad and must satisfy the constraint $\rho = E_\mu \theta^2/2m_e < 1$. On the contrary the values of q^2 near 0 are strongly suppressed for reactions (2) and (3). Background subtraction thus necessitates a good angular resolution. The precision obtained in this experiment is 1.6 mrad on azimuth and 1.2 mrad on the dip angle. The average uncertainty on the muon momentum is $\langle \Delta p/p \rangle \simeq 5\%$.

Fig. 3 shows the quantity ρ for the isolated μ^- sample compared to the theoretical predictions. A clean peak at $\rho < 1$ is expected for reaction (1) whereas the background has rather large ρ values. Furthermore, in the sample, an excess of μ^- events is observed near the threshold at 11 GeV as expected from the kinematics of the reaction $\nu_\mu e^- \rightarrow \mu^- \nu_e$.

The background from reactions (2) and (3) has been computed in two different ways. First, data taken with Gargamelle exposed to the CERN-PS neutrino beam were used (neutrino energy range 1-10 GeV) [4]. The chamber liquid was identical in composition to the present one. Reactions (2) and (3) created isolated μ^-'s exactly as in the present experiment, but there was no contribution from reaction (1) to this topology since the neutrino energy was below the threshold. Pictures taken in the PS conditions were scanned twice for all topologies and 27 isolated μ^- were found. The global scanning efficiency for isolated μ^- was estimated to be $(73 \pm 5)\%$ from this double scan. These events were extrapolated to SPS neutrino energies by considering that for neutrino energies greater than 1 GeV the cross sections and the q^2 distribution of reactions (2) and (3) are independent of the energy, so that for each event only the energy has to be scaled without changing the transverse momentum. The advantage of this method is that all physical phenomena including re-interaction in the final state, are taken into account automatically. These background events are at rather large P_T, and only 2 out of 27 lie at $P_T < 160$ MeV/c, where most of the signal is concentrated. From a Monte-Carlo calculation including the effect of measurement errors, only 11% of the genuine signal has $P_T > 160$ MeV/c. After normalization to the neutrino flux in the SPS experiment, the number of background events predicted below $P_T = 160$ MeV/c is 4.8 ± 3.4 to be compared with the 27 SPS-events obverved within the same cuts. Therefore after correction for losses the signal from the $\nu_\mu + e^- \rightarrow \mu^- + \nu_e$ reaction is 26 ± 6 events. The probability that these 27 events come from background reactions (2) and (3) is thus definitely negligible.

In the second method, a likelihood function in the plane (E_μ, θ^2) was used in order to determine the relative contribution of the 3 reactions. The likelihood function was written

$$\log \mathcal{L} = \sum_i \log \{N_S P_1 (E_i, \theta_i^2) + N_B (\beta P_2 (E_i, \theta_i^2) + (1-\beta) P_3 (E_i, \theta_i^2))\} - (N_S + N_B)$$

where N_S and N_B represent respectively the number of events from the signal and from the background, and where the index i ranges through the experimental sample. The P_J J = 1,2,3, are the theoretical densities of probability in the plane (E_μ, θ^2) for reactions (1) (2) and (3) respectively, integrated over the neutrino flux and smeared by experimental errors. P_1 was computed with the V-A cross section of the inverse μ-decay. The differential cross section for reaction $\nu_\mu n \rightarrow \mu^- p$ was used to compute P_2 with an axial mass $M_A = .95$ GeV/c^2 [5] and taking into account the Pauli principle [6], the Fermi motion of the nucleon target and the nuclear interactions in the final state. The differential cross section for reaction (3) was taken from a calculation of O'Connel et al. [7] and parameterized as $d\sigma/dq^2 \propto (q^2)^2 e^{-b\sqrt{q^2}}$ with b = 28 GeV^{-1}. It must be remarked that in this method only the shape of the differential cross sections are used, these are rather independent of the theoretical assumptions but are fixed by the form factor of the nucleon or, for reaction (3), by the shape of the giant dipole resonance.

The final result is $N_S = 24 \pm 5.5$ (68% C.L.). After correction for scanning efficiency, a signal of 26 ± 6 events is obtained in good agreement with the previous determination.

The theoretical cross-section for the inverse μ-decay process [8] assuming that there are only V and A components is written as:

$$\frac{d\sigma}{d(\cos\theta^*)} = \frac{G^2}{\pi} \frac{(S - m_\mu^2)^2}{32\,S} \{(1+p)(1-\lambda)(1-\cos\theta^*)(a-b\cos\theta^*) + 4(1-p)(1+\lambda)\} \quad (4)$$

$$a = 1 + m_\mu^2/S \,;\, b = 1 - m_\mu^2/S \,;\, \lambda = \frac{2g_A g_V}{|g_A|^2+|g_V|^2} \,;\, p = \text{beam polarization} = \frac{N_R - N_L}{N_R + N_L}$$

Integration of the expression (4) over the neutrino spectrum gives the following relation in the plane p, λ.

$$N = \frac{No}{32} \{(1+p)\ (1-\lambda) * 3 + 8\ (1-p)\ (1+\lambda)\}$$

where No = 29 is the number of events expected for left-handed neutrino p = -1 and pure V-A coupling (λ = 1)

The result of this experiment, illustrated in fig. 5, is in agreement with the V-A hypothesis. It rules out exotic possibilities like V + A coupling or right-handed neutrinos.

In conclusion, we have observed for the first time the reaction $\nu_\mu + e^- \to \mu^- + \nu_e$, the so-called inverse μ-decay.

ACKNOWLEDGEMENT

It is a pleasure to thank M.K. Gaillard for many useful discussions. We would like also to express our gratitude to the SPS, beam, chamber and scanning teams.

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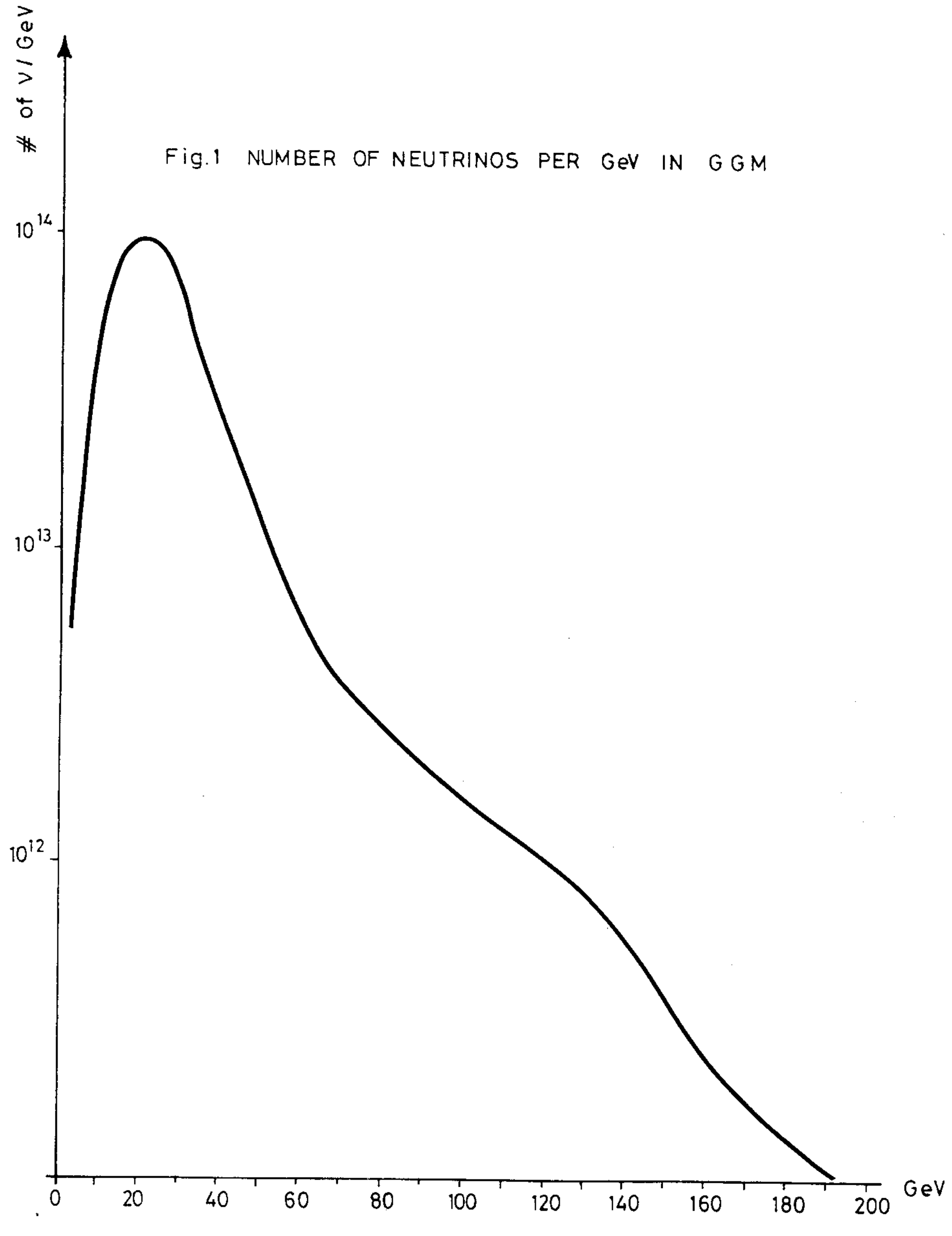

Fig.1 NUMBER OF NEUTRINOS PER GeV IN GGM

225_820_4

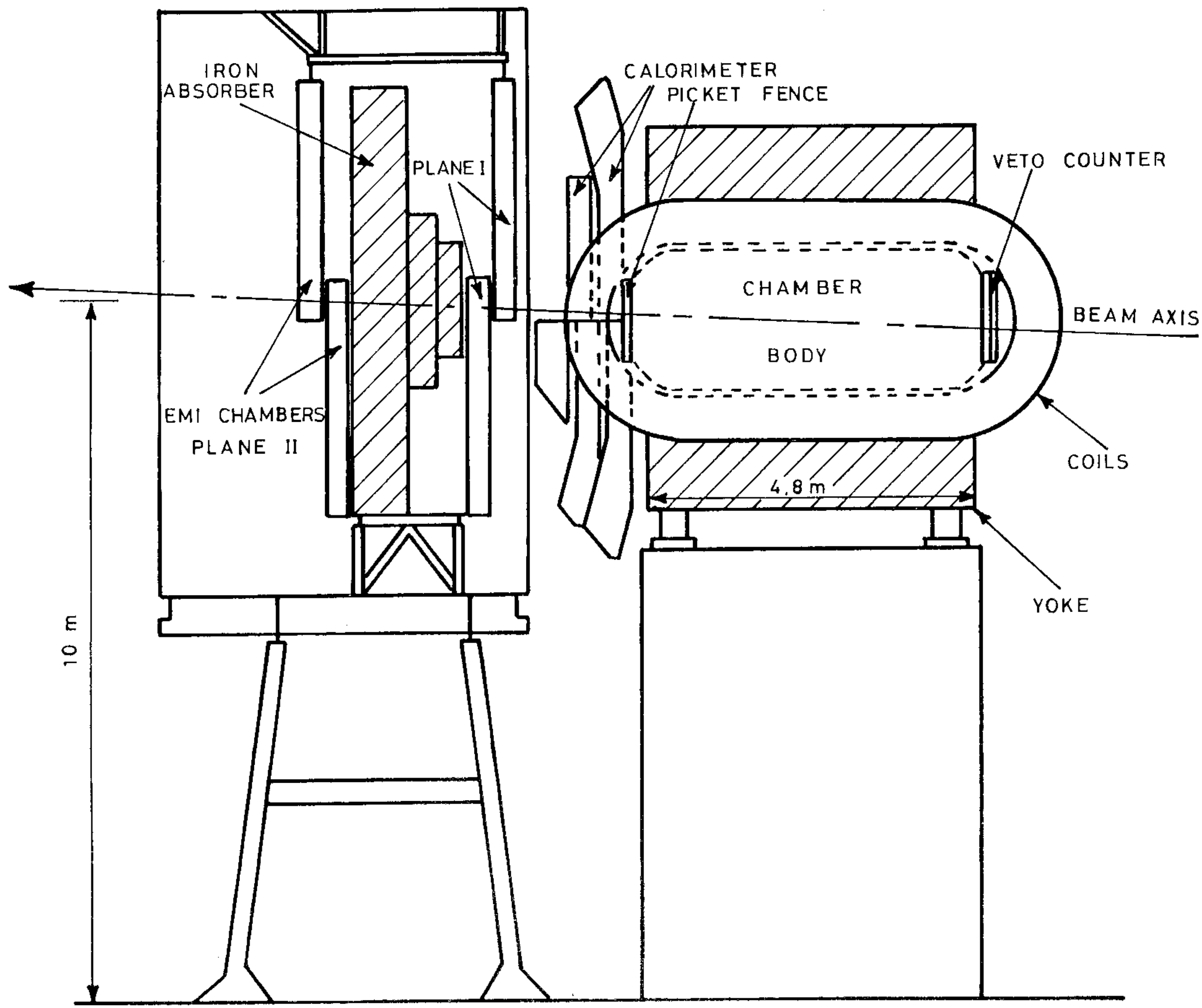

Fig. 2

225 _ 819 _ 4

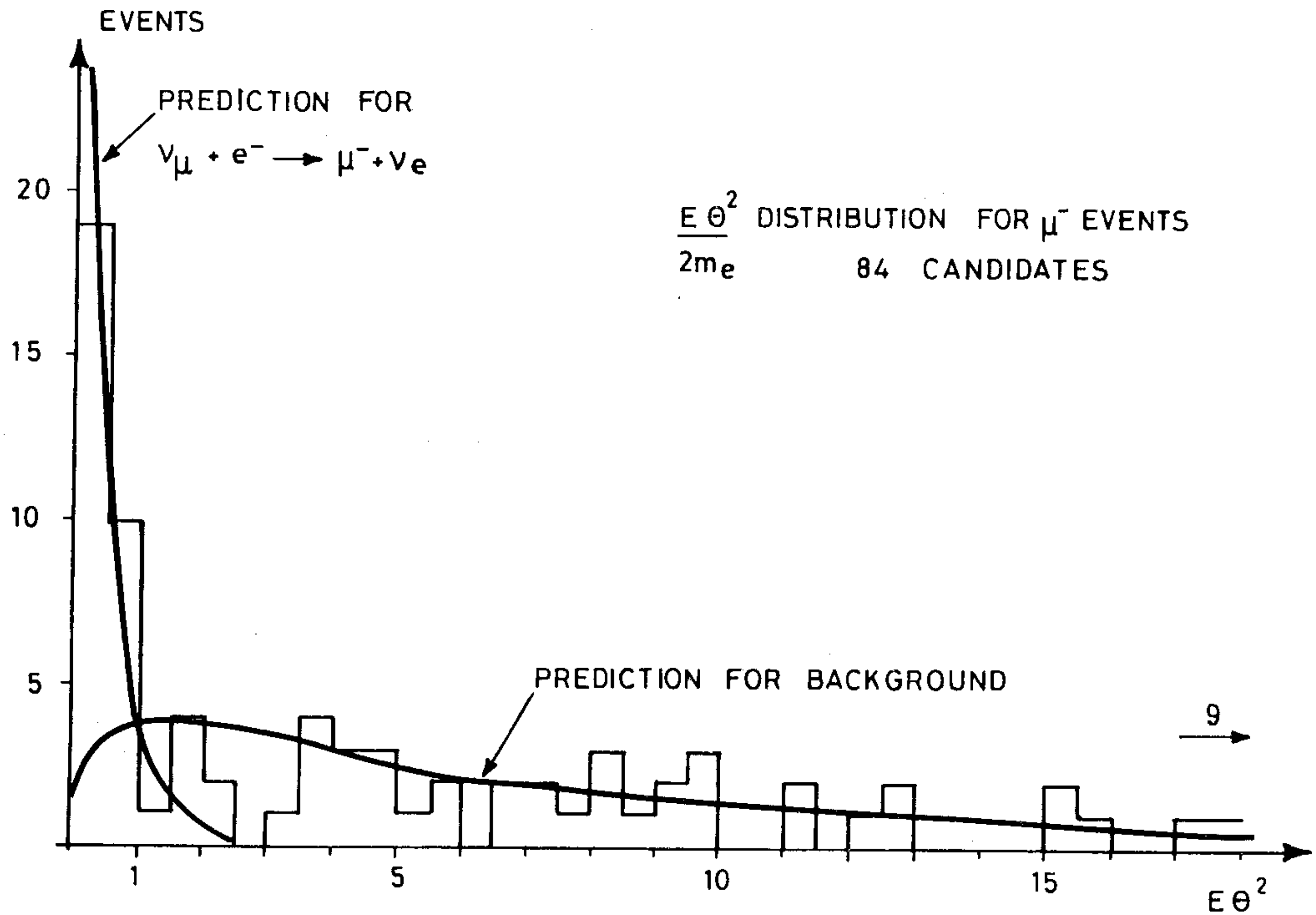

Fig. 3

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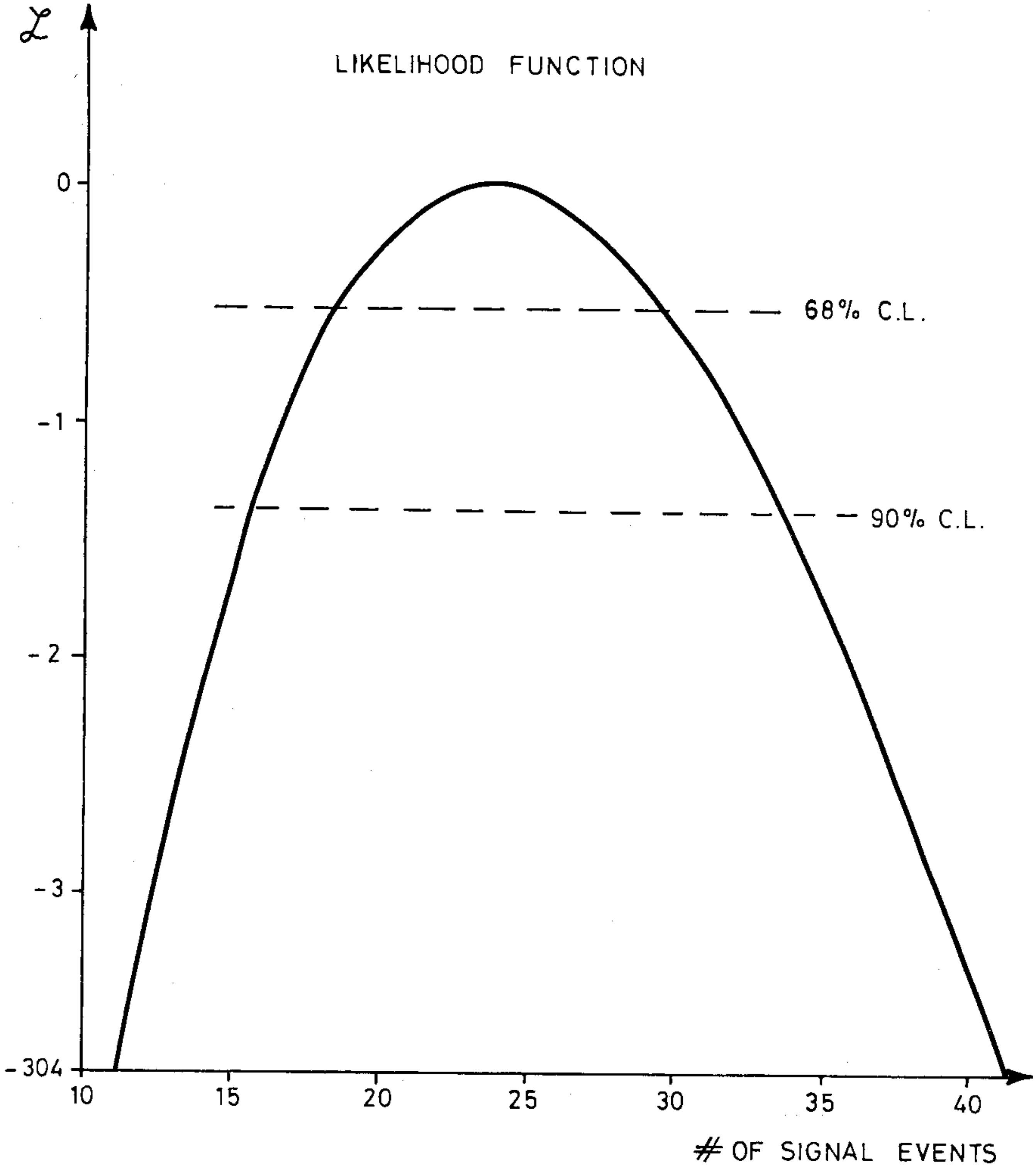
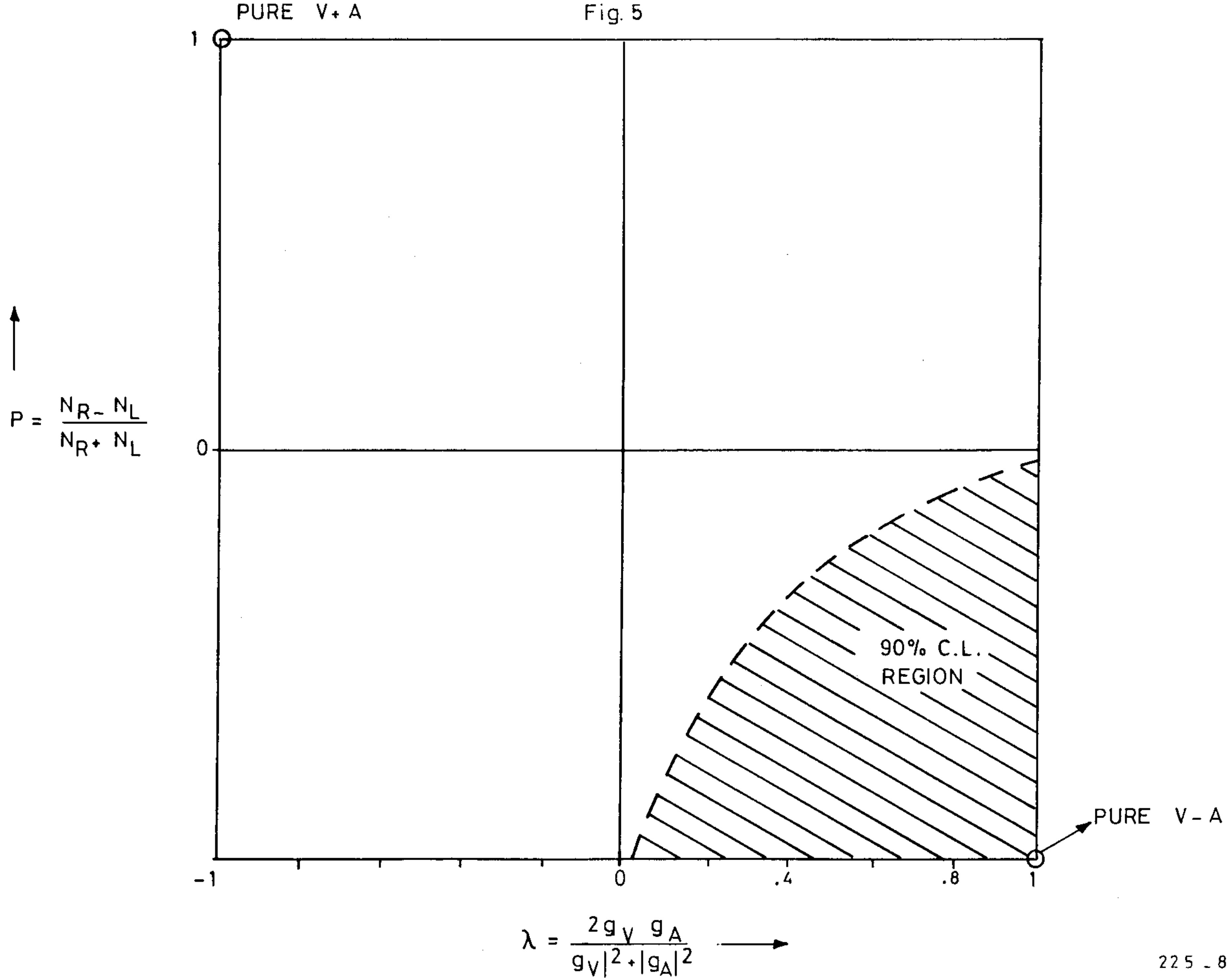


$\mathcal{L}$
LIKELIHOOD FUNCTION
0
-1
-2
-3
-304
68% C.L.
90% C.L.
10
15
20
25
30
35
40
OF SIGNAL EVENTS

Fig. 4

Fig. 5



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