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Neutrino Experiment - Analysis from HLBC since the Sienna Conference

Preliminary results from the bubble chamber have been reported at Brookhaven(1) and Sienna(2). The present aim of the analysis is to achieve a more detailed understanding of the neutrino events, and to deduce cross-sections. In the statistics quoted here some 33 extra events have been added to the 142 used for Sienna.

This report is for very limited circulation among those involved in the neutrino experiment, to inform them of the progress of the analysis since Sienna, and particularly of some of the problems which are appearing.

1. Non-Pionic Events.

As previously reported, the non-pionic events are predominately of the type

$$\nu + n \longrightarrow \mu^- + p$$

A visible energy histogram of 87 non-pionic events, and 20 events, with a track which is indistinguishable between p, π^+ or sometimes μ^+, and plotted with half weight, is shown in Fig. 1. The curve shows the calculated neutrino spectrum(3) and the neutrino elastic cross-section(4) normalized to 97 events. It appears that there is an excess of events below 0.6 GeV, with 25 found and 11 expected.

For a target nucleon of mass m at rest and an elastic event of the above type

$$E_\nu = \frac{mE_\mu - \frac{m_\mu^2}{2}}{m - E_\mu + p_\mu \cos\theta}$$

where θ is the angle between the muon and neutrino direction. Thus E_ν may be calculated from the muon to test for gross errors due to unseen neutrons, which could make E_{vis} a low estimate of the neutrino energy.

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Thus the histogram of Fig. 2 has been calculated for the preceding 107 events, and it is seen that the general features are the same as in Fig. 1. $E_\nu - E_{vis}$ as a function of E_ν are shown in Fig. 3, but only those values near zero are susceptible to a simple interpretation, which is that for those particular events there was no unseen neutron.

In Fig. 4 the histogram of C.M. energy E^* calculated from the muon is shown, and obviously it retains the same general features as Fig. 1 and 2. Expected distribution from the most recent(3) and previously estimated(5) spectra are shown. Neither may be regarded as a fit of the experimental data, the χ^2's being 73 and 57 respectively for 19 intervals, which corresponds to a probability of $< 10^{-6}$.

Thus it must be concluded that either the calculated neutrino spectrum, or the predicted elastic cross-section (or perhaps both) are inconsistent with the energy distribution of the non-pionic events. It is believed that most elastic events are correctly classified.

1.1 The (μ-p) invariant mass.

In those events which have not been disturbed by scattering of the recoil proton the invariant (μ-p) mass gives a precise indication of E^*, independently of Fermi motion. The p_T , p_x distribution(6) for 51 single proton events is shown in Fig. 5. Only 28 satisfy the criterion that the momentum is < 300 MeV/c.

Fig. 6 shows the invariant mass distribution, together with that expected. It seems that the distribution from events with momentum unbalance < 300 MeV/c is different from those with unbalance > 300 MeV/c. The former seems grouped in two peaks, 7 events are found where 1·5 might be expected at 1·2 GeV and 12 instead of 5 at 1·85 GeV.

No significant peaking of the (μ-p) mass has been found in pionic events. The immediate problem then is to assess to what extent there may be physical significance in this observation.

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1.2 Invariant masses from unbalanced and multiproton events.

There is no apparent peaking in the $(\mu\text{-}p)$ mass of unbalanced or multiproton events. However, since these events may be interpreted as those in which the nucleon interacted with the nucleus after the primary neutrino-neutron interaction, it is obvious that the $(\mu\text{-}p)$ mass calculated is not correlated with the μ-p mass in the primary interaction. The C.M. energy of the event may be calculated from the direction and energy of the muon assuming that the muon leaves the nucleus without scattering. This energy is shown in Fig. 7 which is derived from Fig. 4 by removing the balanced events. The distribution is similar to that of Fig. 4.

1.3 Possible origins of the $(\mu\text{-}p)$ mass clusters.

a) Reflection of the neutrino spectrum.

For a stationary nucleus the mass peak at 1·2 GeV corresponds to an E_ν of $\sim$0·3 GeV. In that region of the neutrino spectrum the estimate of the flux is difficult because of uncertainties in the direct pion spectrum, and secondary pion production, so that an important error cannot be excluded. Whether it could reach to almost an order of magnitude, which is needed to account for the peak, is difficult to assess, but it is not expected.

For stationary nucleons the thresholds for elastic, single and double pion reactions are for neutrino energies of $\sim$0·1, 0·3 and 0·45 GeV respectively. Thus an enhancement of the neutrino spectrum deduced from the non-pionic event rate should also manifest itself to some extent in the pionic events if the enhancement occurred at 0·3 GeV, and clearly, if the enhancement occurred at 1·3 GeV. At least for the 1·85 GeV mass cluster ($E_\nu \sim$ 1·3 GeV) this is not obviously the case, but the 1·2 GeV cluster ($E_\nu \sim$ 0·3 GeV) could have such an origin.

b) Nuclear transparency.

A nuclear transparency for recoil protons of certain energies might be postulated as the cause of the balanced events. Fig. 8 shows the proton momentum distribution in the laboratory system compared with that expected(7). There is no evidence for nuclear transparency as a significant

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factor. The disagreement at $E^* \sim 1{\cdot}5$ GeV is what would be expected for unbalanced events, where the proton has been scattered in the nucleus.

c) Structure in the elastic cross-section.

From the preceding discussion it cannot be excluded that there is structure in the elastic cross-section.

1.4 Angular distribution of μ in (μ-p) CS.

The angular distribution of the muon with respect to the line of flight of the (μ-p) CS for the single proton events is shown in Fig. 9 as a function of E^*. Projections of three sections of the diagram on the ordinate are shown in Fig. 10 together with the expected distribution(7) for the elastic neutrino interaction.

The distribution of the muon direction in CS relative to the neutrino direction is shown for all non-pionic events in Fig. 11, this being the only corresponding analysis which can be made for multiproton events. As for the single proton events the same three projections have been made, and are shown in Fig. 12.

2. Pionic Events.

A histogram of the visible energy of 88 events is shown in Fig. 13, and by comparison with Fig. 1, extends to higher energy.

For Sienna the analysis proceeded as if the neutrino energy (E_ν) was the visible energy (E_{vis}) of an event, excluding the rest mass of baryons. This was known to be an approximation, but the choice of a more satisfactory approach leads to many difficulties. In the events

$$\nu + n \longrightarrow \mu^- + n + \pi^+ \qquad (1)$$

$$\nu + p \longrightarrow \mu^- + p + \pi^+ \qquad (2)$$

$$\nu + p \longrightarrow \mu^- + n + \pi^+ + \pi^+ \qquad (3)$$

the assumption $E_\nu = E_{vis}$ is least erroneous in (2).

Attempts have been made to estimate the magnitude of the corrections to E_{vis} for "unseen neutrons". For events type (2) the correction should account for Fermi motion and neutrons produced by interactions in the nucleus

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by products of the neutrino interaction. In types (1) and (3), additionally, a neutron is a direct product of the neutrino interaction and may have an appreciable fraction of the available energy, thus it is important to attempt a correction.

Suppose a neutron of energy E_n and mass m compensates the momentum unbalance, then its momentum component perpendicular to the neutrino direction must balance p_T. If its longitudinal component is p_x,

$$p_x = E_n + E_{vis} - \sum p_x - m$$

where $\sum p_x$ is the longitudinal component of visible momentum in the event. Define

$$\alpha = m + \sum p_x - E_{vis}$$

then $$E_n = \frac{1}{2\alpha}(p_T^2 + \alpha^2 + m^2).$$

Clearly an event can accept a single "missing neutron" only if α is positive, which is in fact so for almost all events. For those few for which the postulate of a single missing neutron is excluded, there is either some doubt about track identification, or two neutrons must be postulated.

The result of the addition of the kinetic energy of the "missing neutron" to the visible energy (E_c) is shown in the histogram of Fig. 14, and the distribution of the corrections as a function of E_c is shown in Fig. 15. As already explained the calculation for Fig. 3 is not basically the same, but nevertheless comparison with Fig. 15 shows that for the pionic events there are often much larger corrections. This together with occasional evidence of neutron stars near neutrino events(2) gives confirmation of neutrons in some pionic events.

2.1 Missing neutrinos.

In a few pionic events $\sum p_x > E_{vis}$, thus compensation by a missing neutrino is possible. Of those events so far examined, only one has a μ^+ candidate together with the μ^- and the invariant $(\nu-\mu^+)$ mass is 0·4 GeV.

Clearly a neutrino in the longitudinal direction can be added to any event without changing the components of the momentum unbalance, so that the kinematics involved with a missing neutrino is difficult to interpret.

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3. Cross-sections.

From the distributions of events according to the various estimates of the neutrino energy and the calculated spectrum, approximate cross-sections may be deduced. These are not necessarily strictly comparable, as already explained.

3.1 Cross-sections from the E_{vis}, without neutron correction.

The form of $\sigma(E_{vis})$ for non-pionic events is shown in Fig. 16, it is seen to be generally higher than that predicted by Lee and Yang(4). The departures reflect, of course, the discussion of 1.1.

The pionic cross-section rises steadily from a low value with evidence for fluctuations with some statistical weight.

3.2 Cross-sections from E_c, (i.e. with neutron corrections).

From Fig. 17 it is seen that the non-pionic cross-section is little modified by the calculation of E_ν from section 1.

However the pionic cross-section is smoothed due to the displacement of events by correction for missing neutrons.

4. Further Remarks on Fluctuations in the Histograms of E_{vis}, and the Cross-sections.

Some possible sources of fluctuations of the cross-sections, other than those which might find their origin in the neutrino interactions have been discussed already. The origins of all fluctuations must be among :

a) statistical fluctuations, including experimental errors,
b) unexpected fluctuations in the neutrino spectrum,
c) fluctuations in partial neutrino cross-sections.

Except for very low energy neutrinos ($E_\nu < 1{\cdot}5$ GeV) it can be deduced(8) that even for perfect parent focusing, a particular neutrino energy over the area of the HLBC is contributed from such a wide band of parents, that it is improbable that a fluctuation in their energy spectrum could have passed previously unnoticed.

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In the absence of an experimental determination of the neutrino spectrum there is no means to exclude the possibility of an underestimation of the pion spectrum at low energy in the decay tunnel, or that the kaon production for the particular mode of operation of the copper target is not as estimated. Either could account for some but not all of the features of the cross-sections.

Similarly it can be seen that there is some broad resemblance of the cross-sections to the reciprocal of the multiplying function for the horn (Fig. 8 of Ref. 3). This might occur if the multiplication factor was not as expected, but otherwise the function retained its general form with neutrino energy, a form which in fact was its origins to the two classes of parents, pions and kaons.

It is implicit in the monotonic nature of the data for the input pion and kaon spectra, and the smoothness in the resultant computed neutrino spectra, that the focusing properties of the horn introduce no fine structure in the neutrino intensity.

Speculation that the absence of events in a particular band of E_{vis} may be due to an unusually high neutrino cross-section in the shielding may be excluded. A 10 % absorption in the shielding involves $\sigma \sim 10^{-29}$ cm^2. It is difficult to imagine a transition to $\sigma \sim 10^{-38}$ cm^2 so rapid that it does not create a noticeable event rate in the chamber, with a neutrino flux $\sim 10^{14}/\mathrm{m}^2$ integrated from a band of some 10 GeV.

Finally, Fig. 18 shows the result of deducing a neutrino spectrum from the observed non-pionic event rate, assuming the Lee and Yang cross-section. At $E_\nu < 1$ GeV it could be interpreted as an unexpectedly enhanced flux, and > 3 GeV as demanding that the kaon to pion ratio was almost an order of magnitude greater than that used in the flux calculation.

5. Conclusions.

It is manifestly evident that the statistical limitations of the available data make the physical significance of the present observations very difficult to assess. It is equally evident that to arrive at reliable cross-sections an experimental determination of the neutrino spectrum is essential.

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There are no other conclusions, but the following brief remarks summarize this report.

a) We have as yet no explanation for the structure of the (μ-p) mass distribution in terms of an obvious bias in the experimental techniques.

b) Only by postulating that the low energy neutrinos, and the neutrinos coming from kaons, have been underestimated by almost an order of magnitude is it possible to reach the conclusion that the elastic cross-section up to 4 GeV has the general form predicted by Lee and Yang.

Such a postulate would of course imply an even more rapid rise for the pionic events than that now observed between 1 and 3 GeV.

These problems are still being studied.

D. Cundy, R. Mollerud, G. Myatt, M. Paty, C.A. Ramm, R. Stump, H. Yoshiki.

HLBC Neutrino Group.

<u>Circulation closed.</u>

Prof. V.F. Weisskopf	(1)
Prof. G. Bernardini	(1)
Neutrino Group	(12)
Prof. L. van Hove + Colleagues	(5)

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3) M. Giesch, S. van der Meer, G. Pluym and K.M. Vahlbruch - Magnetic Horn and Flux Calculations.

4) T.D. Lee and C.N. Yang - Phys. Rev. Letters 4, 307, 1960.

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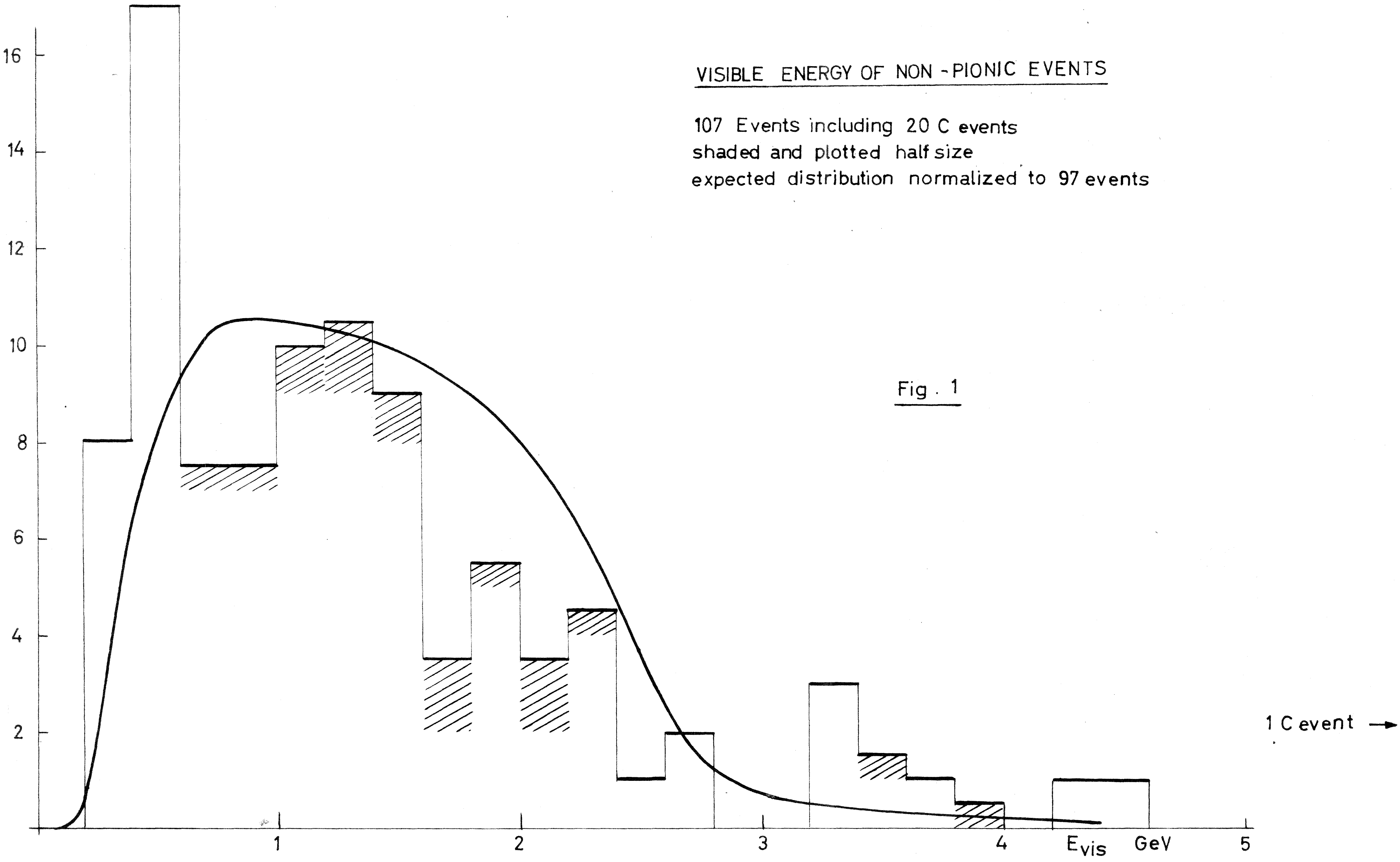
6) H. Yoshiki - CERN NPA/Int. 63-30.

7) J. Løvseth - Private Communication.

8) C.A. Ramm - CERN NPA/Int. 63-2.

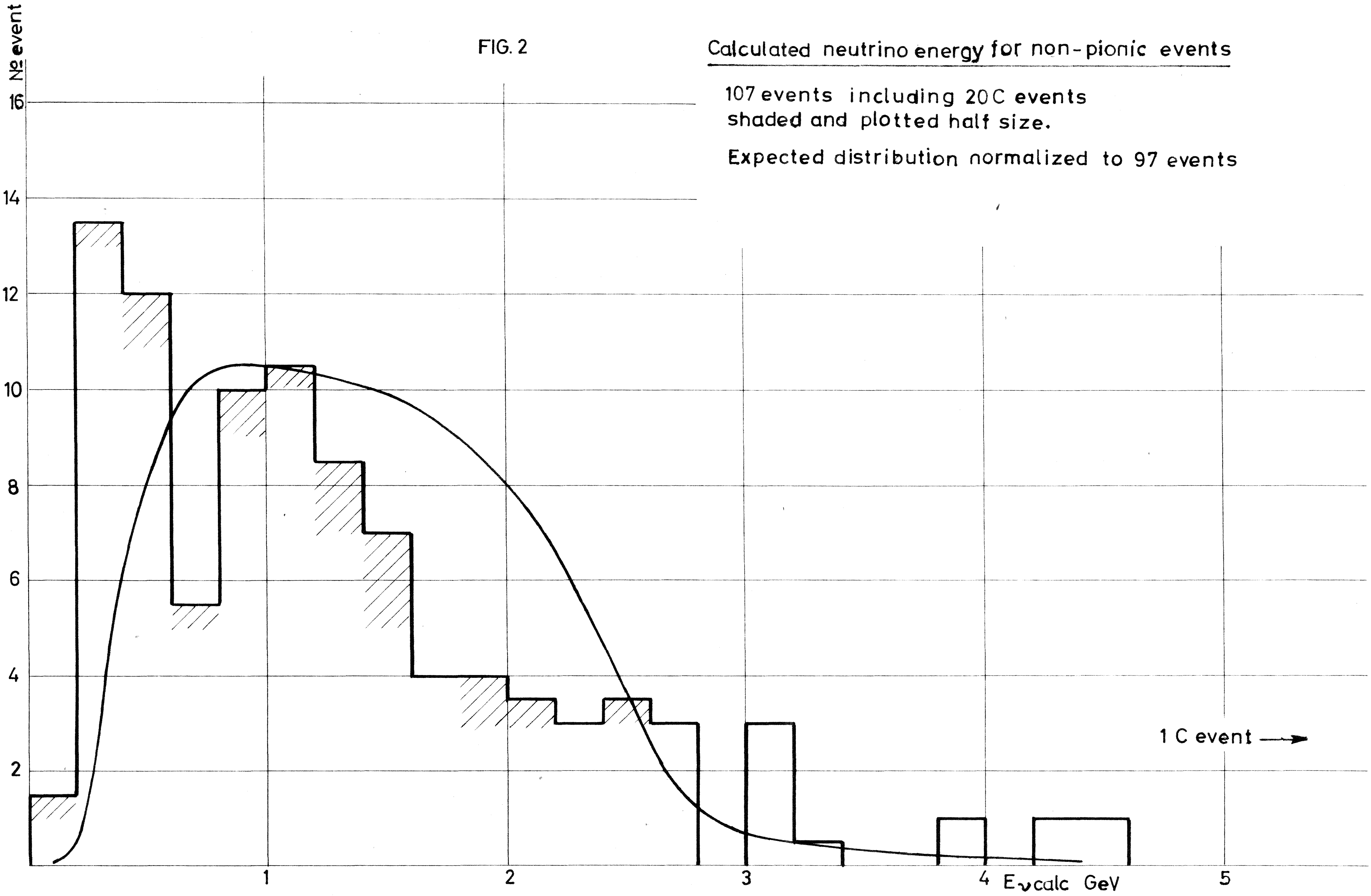


VISIBLE ENERGY OF NON - PIONIC EVENTS

107 Events including 20 C events
shaded and plotted half size
expected distribution normalized to 97 events

Fig. 1

FIG. 2



Calculated neutrino energy for non-pionic events

107 events including 20C events
shaded and plotted half size.

Expected distribution normalized to 97 events

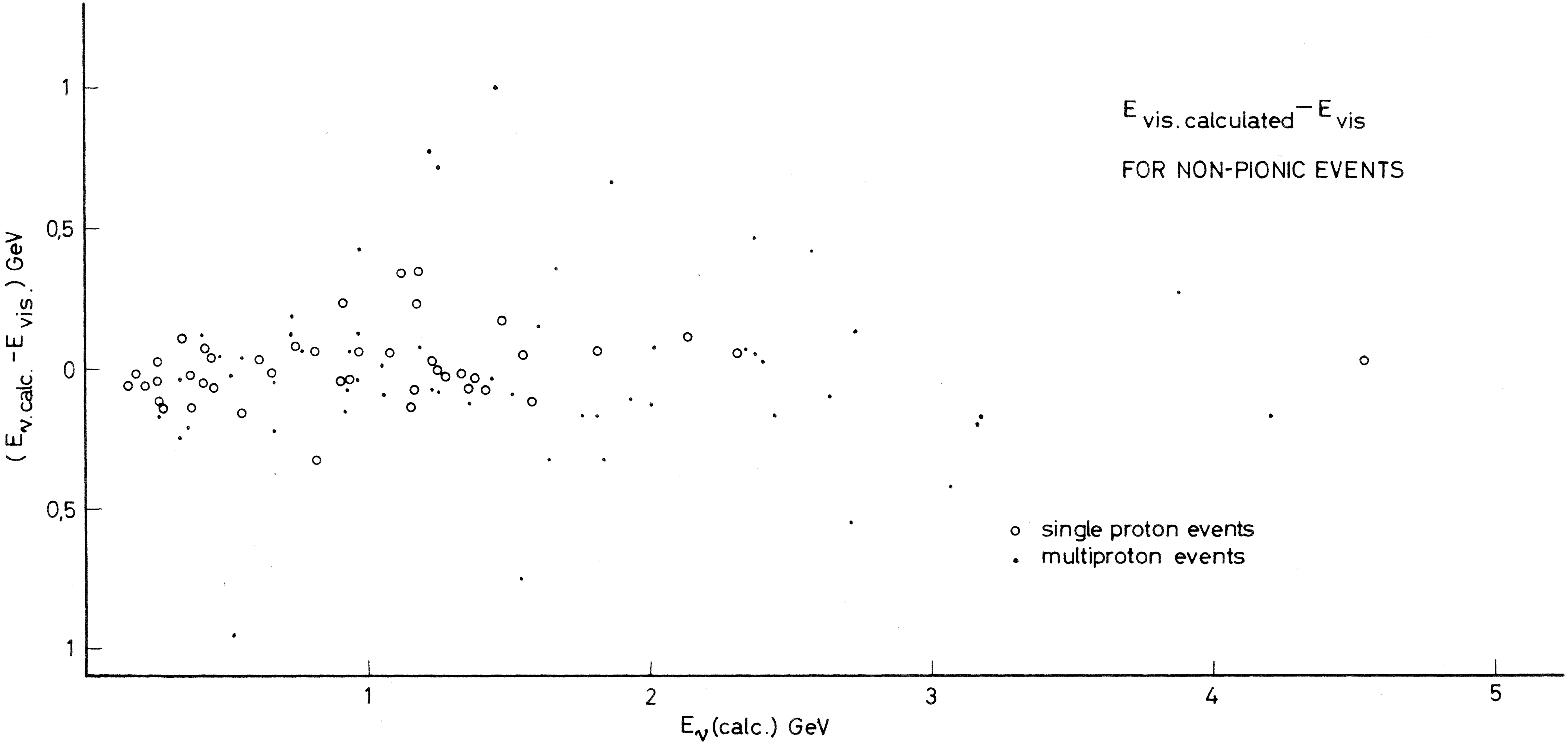

$E_{\text{vis.calculated}} - E_{\text{vis}}$
FOR NON-PIONIC EVENTS
○ single proton events
• multiproton events
$(E_{\nu\text{.calc.}} - E_{\text{vis.}})$ GeV
1
0,5
0
0,5
1
1
2
3
4
5
E_ν(calc.) GeV

Fig. 3

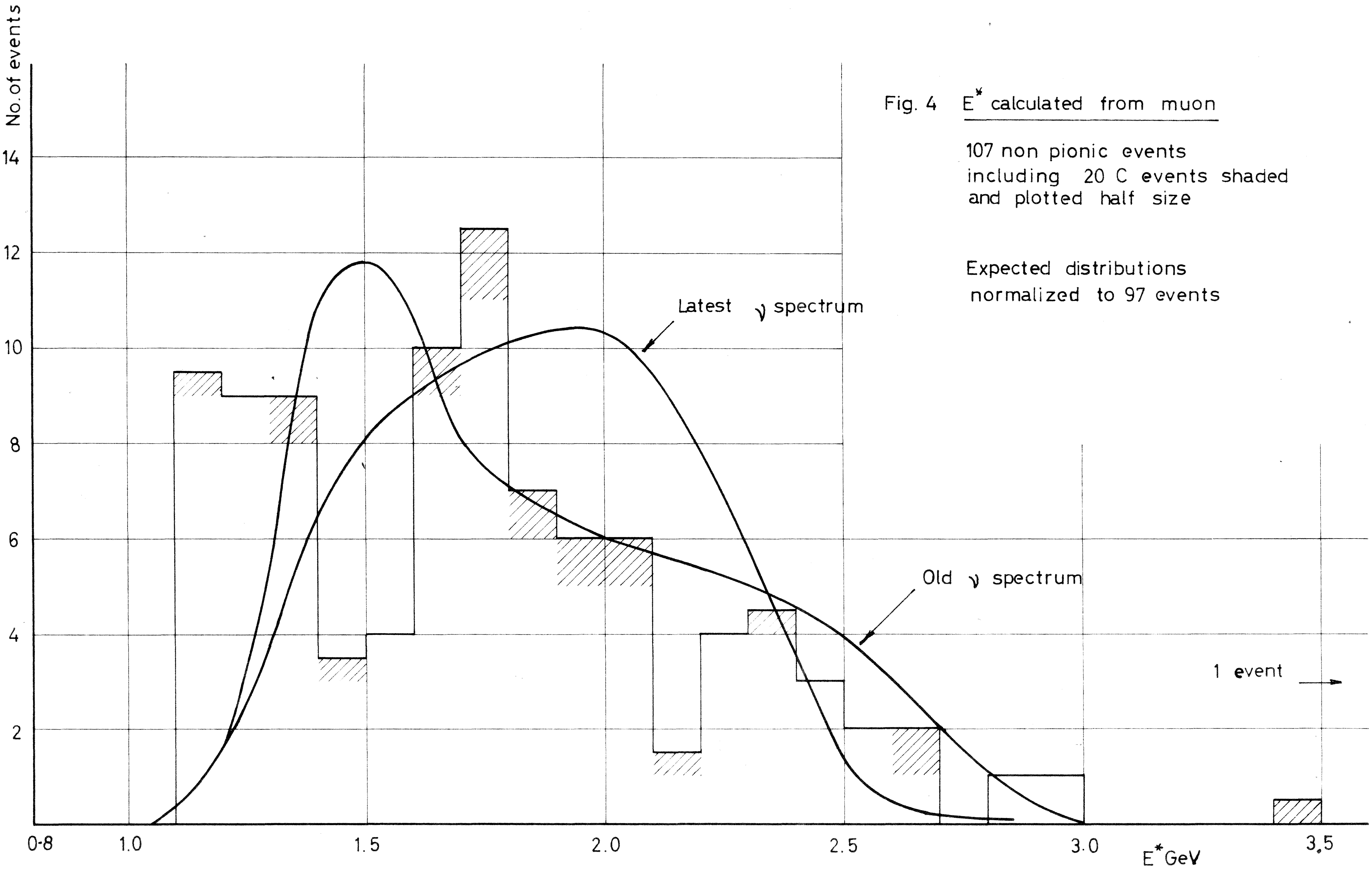

No. of events
14
12
10
8
6
4
2
0-8
1.0
1.5
2.0
2.5
3.0
3,5
E* GeV
Fig. 4 E* calculated from muon
107 non pionic events including 20 C events shaded and plotted half size
Expected distributions normalized to 97 events
Latest γ spectrum
Old γ spectrum
1 event →

Fig. 5 Momentum unbalance for 1 proton non-pionic events

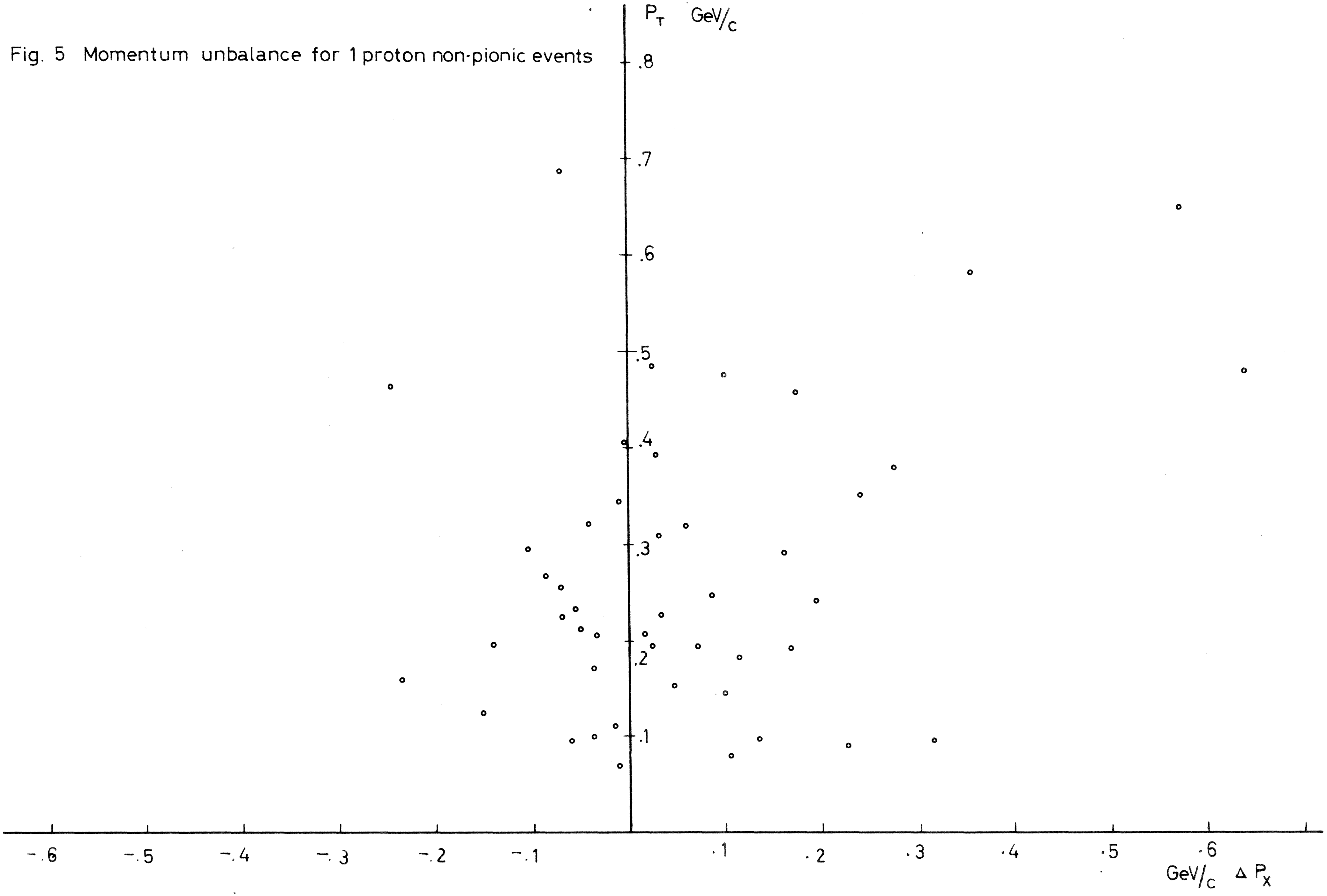


Fig. 6

(μp) - INVARIANT MASS 43 events

1p elastic events + 6 C events

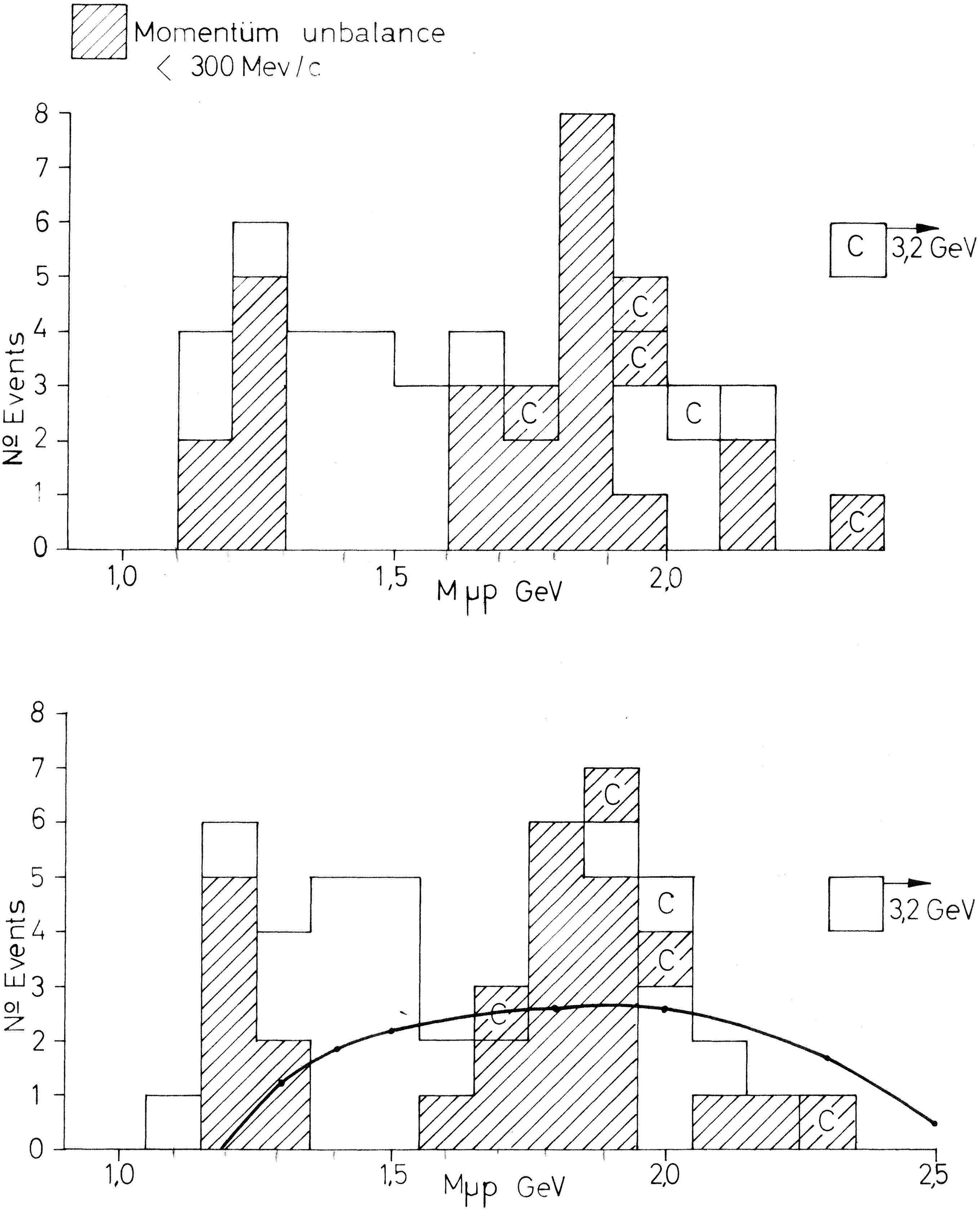
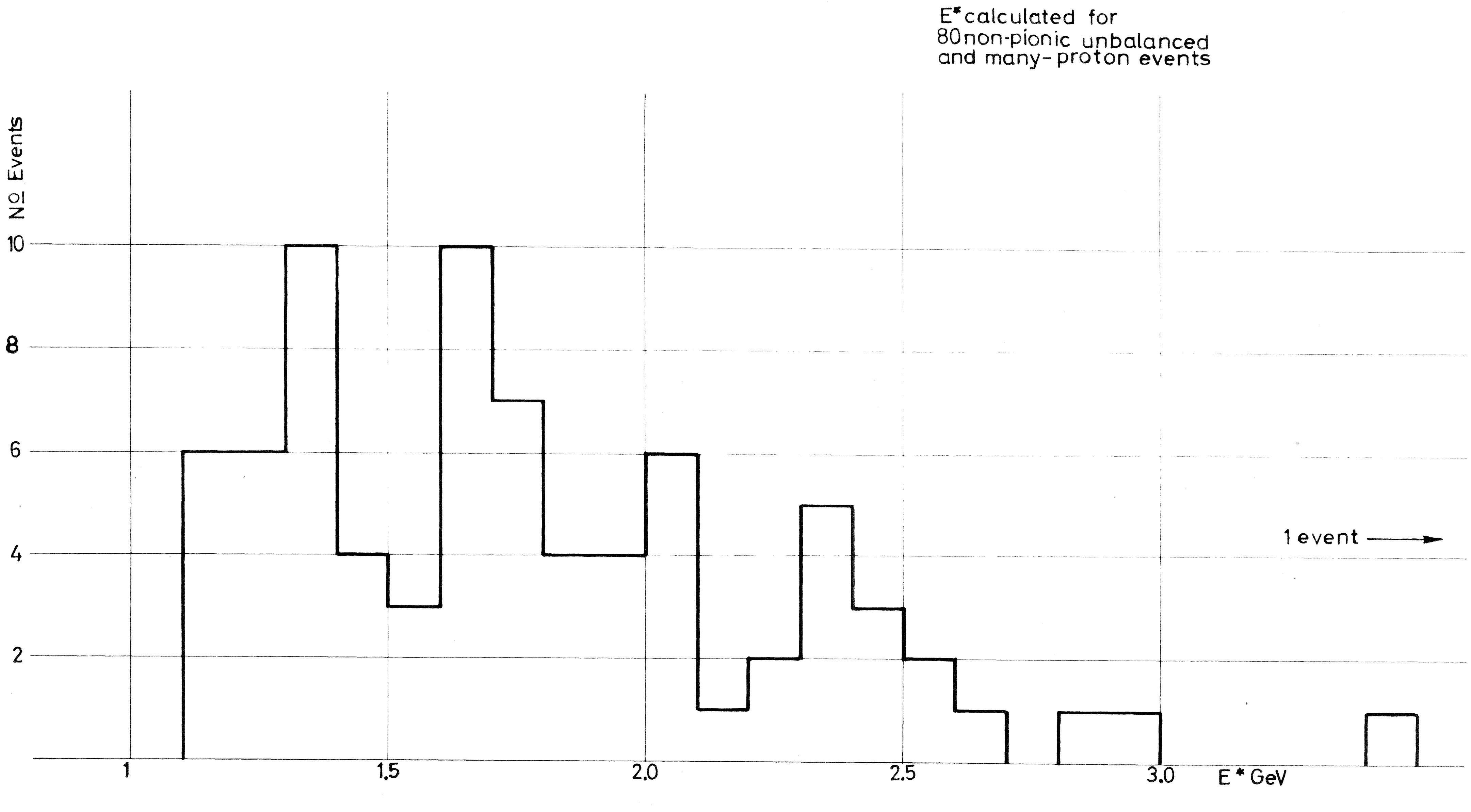


FIG. 7


E* calculated for
80 non-pionic unbalanced
and many-proton events
No Events
10
8
6
4
2
1 event ⟶
1
1.5
2.0
2.5
3.0
E* GeV

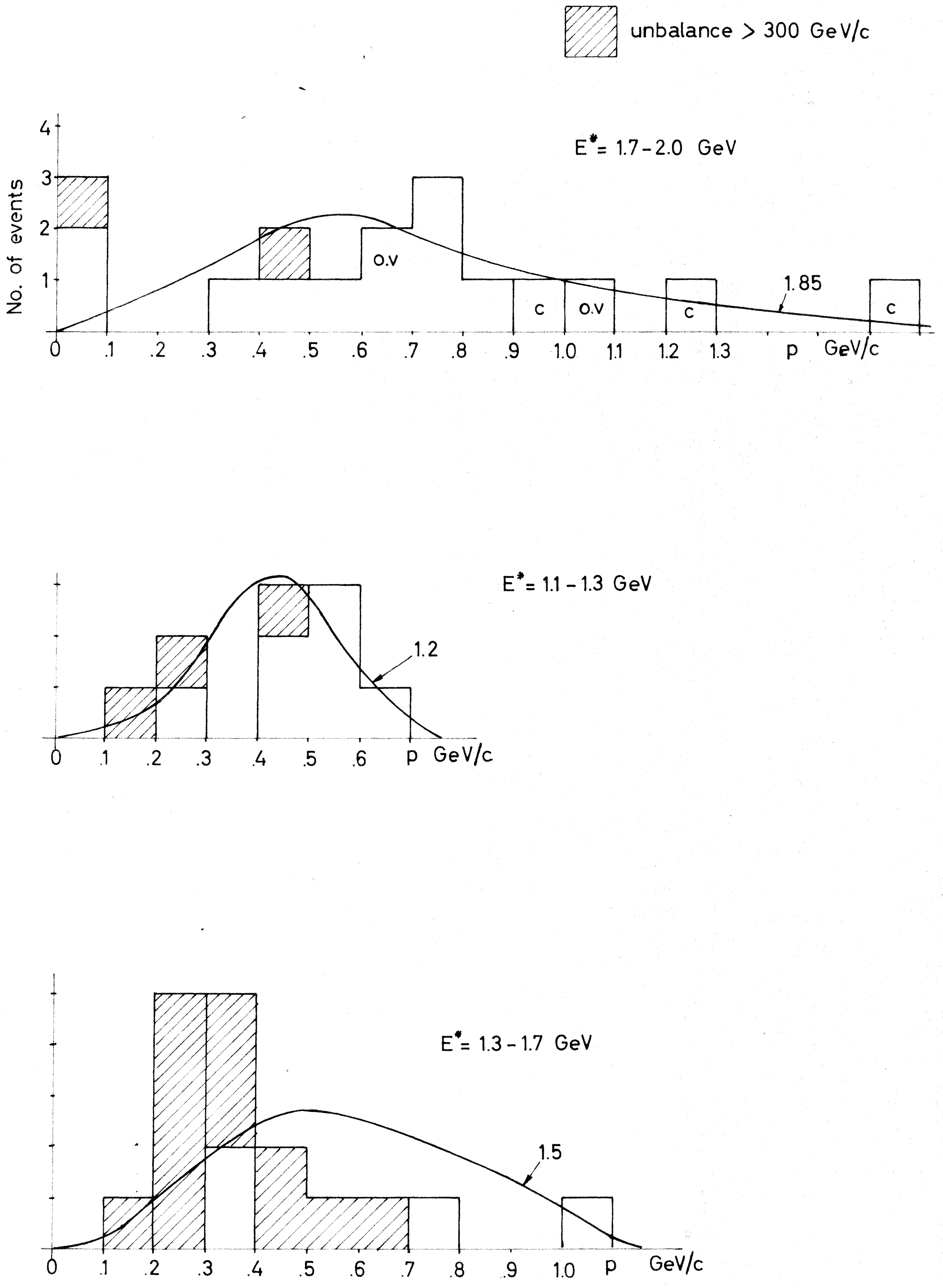


Fig. 8 Proton momentum spectrum from 1p non-pionic events

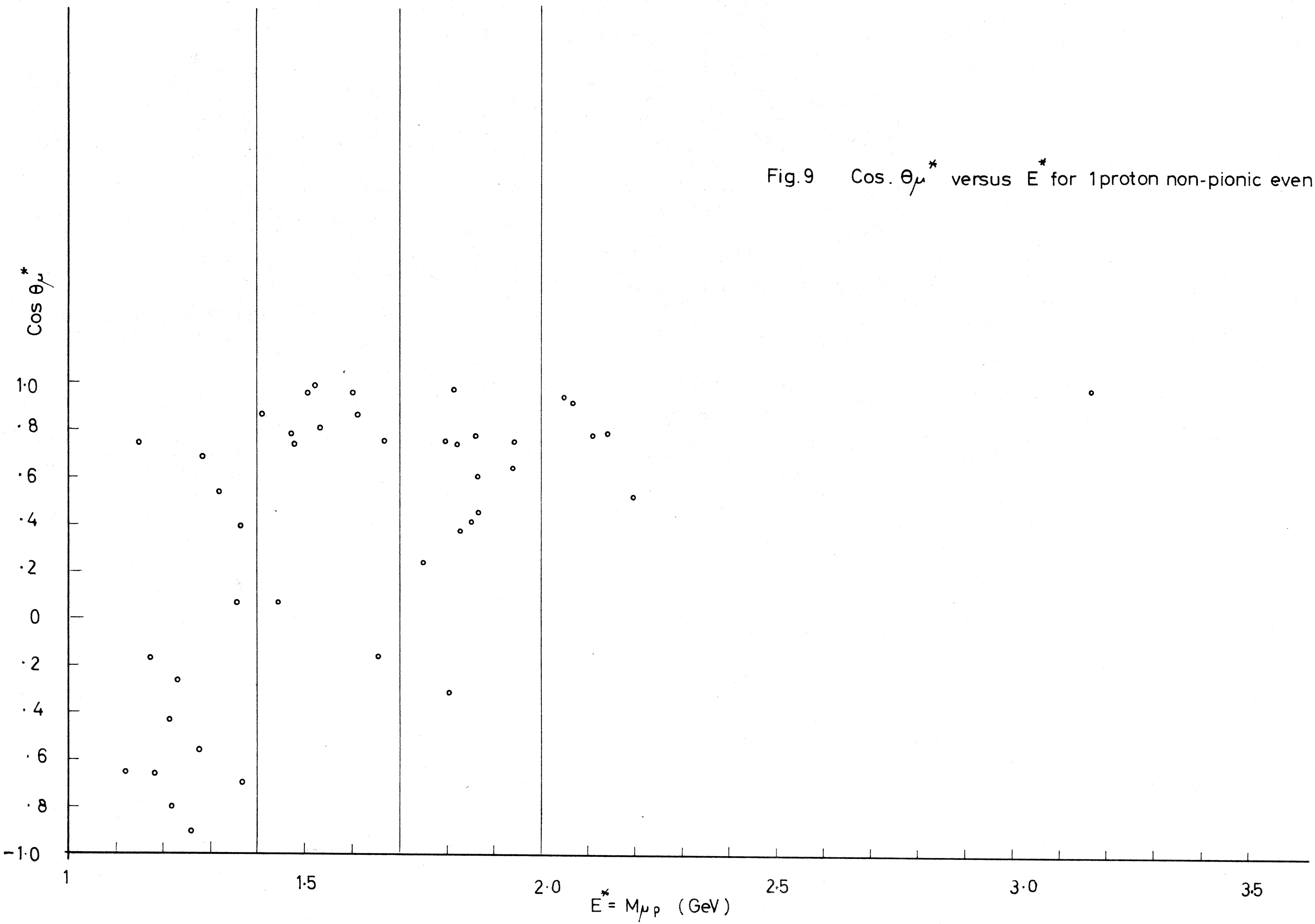


Fig. 9 Cos. θ_{μ}^{*} versus E^{*} for 1 proton non-pionic events

Fig.10 μ^- angular distribution in CM system of νP for 1 proton elastic events

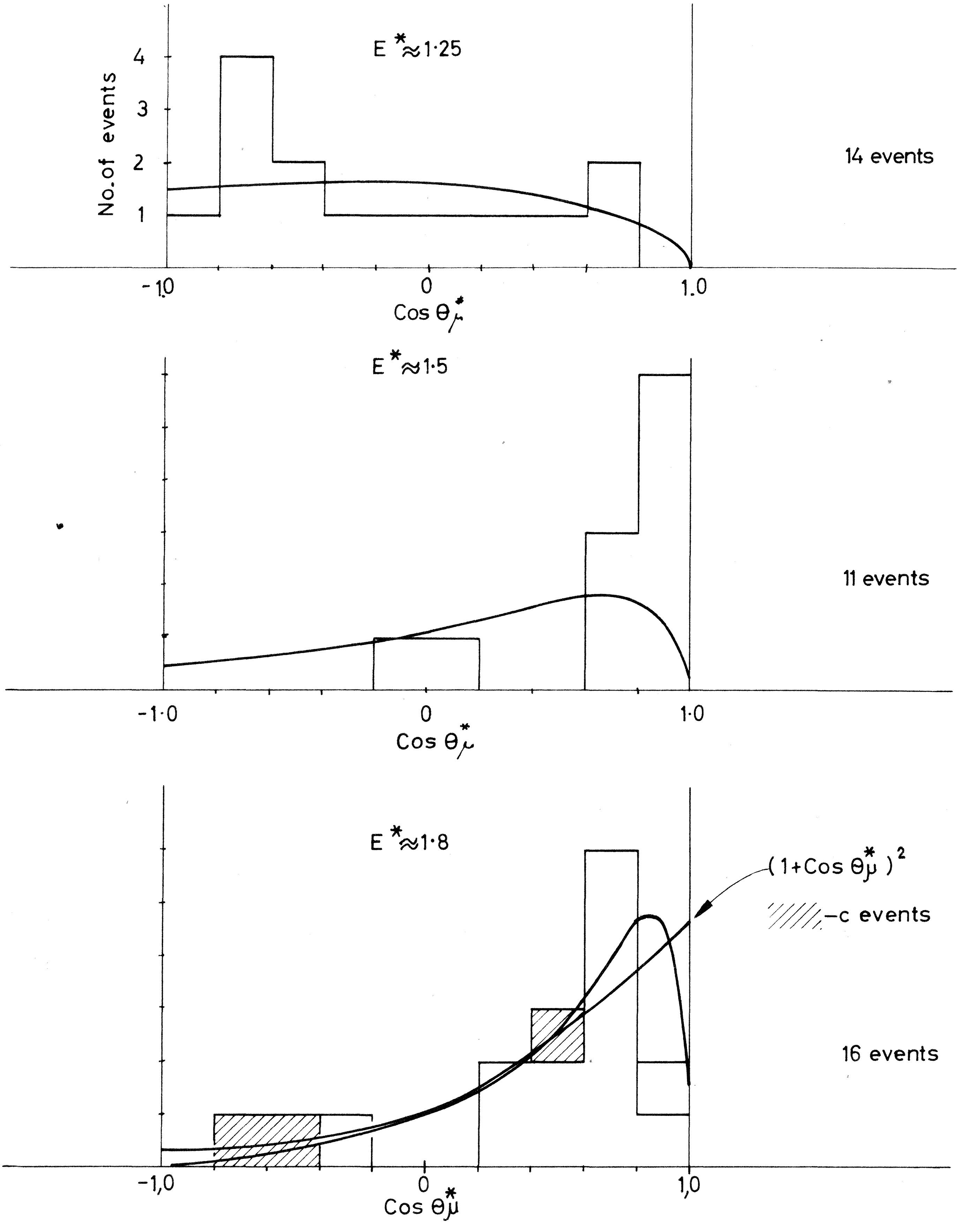


Fig. 11 $\cos \Theta_{\mu}^{*}$ for all Non-pionic events

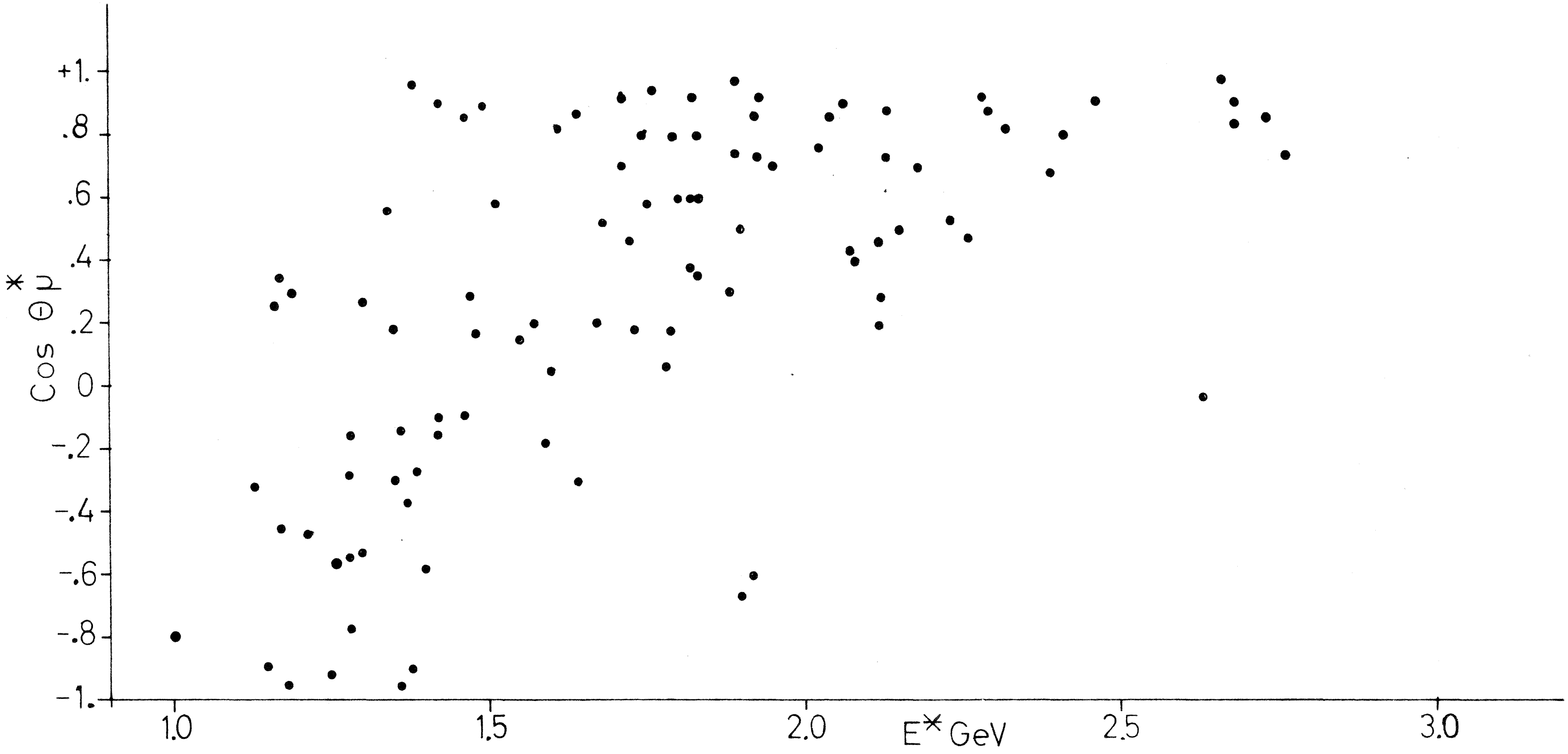
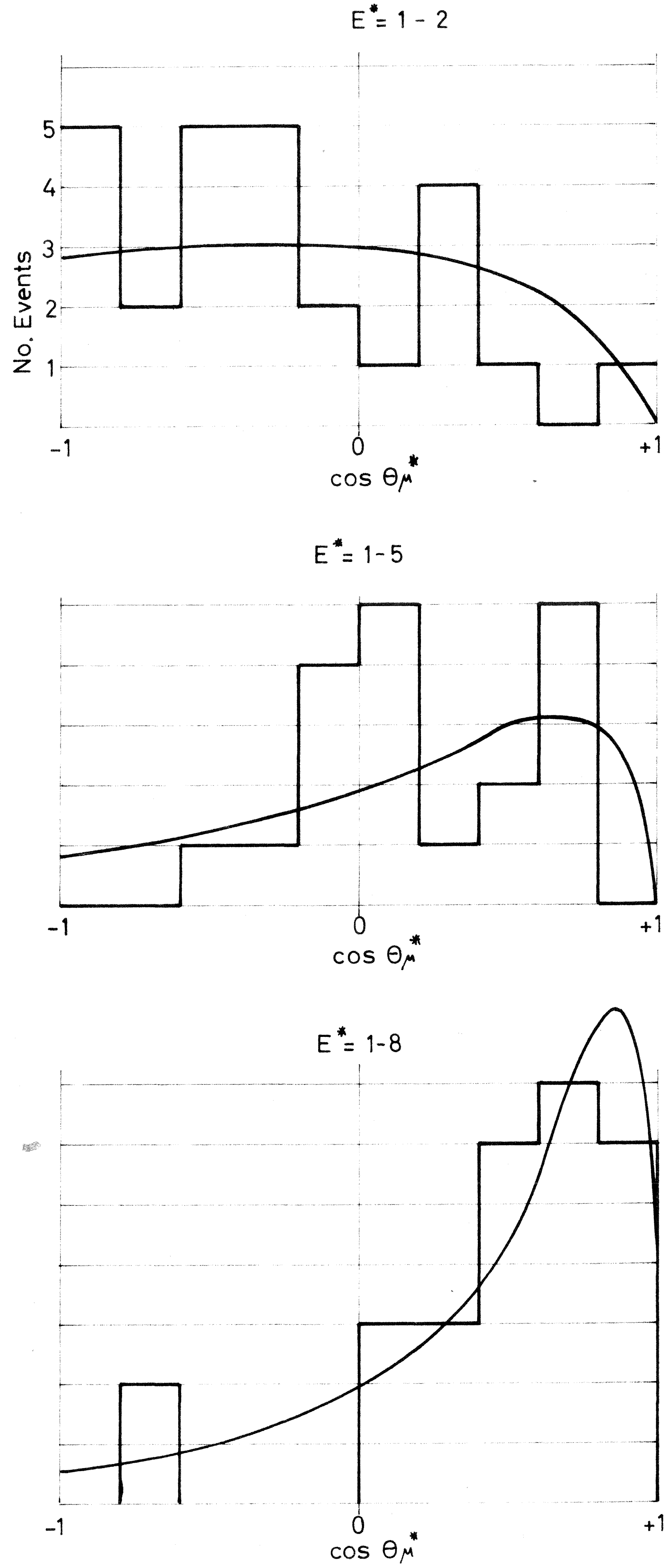


Fig. 12 μ^- Angular distribution in CM system for all non-pionic events



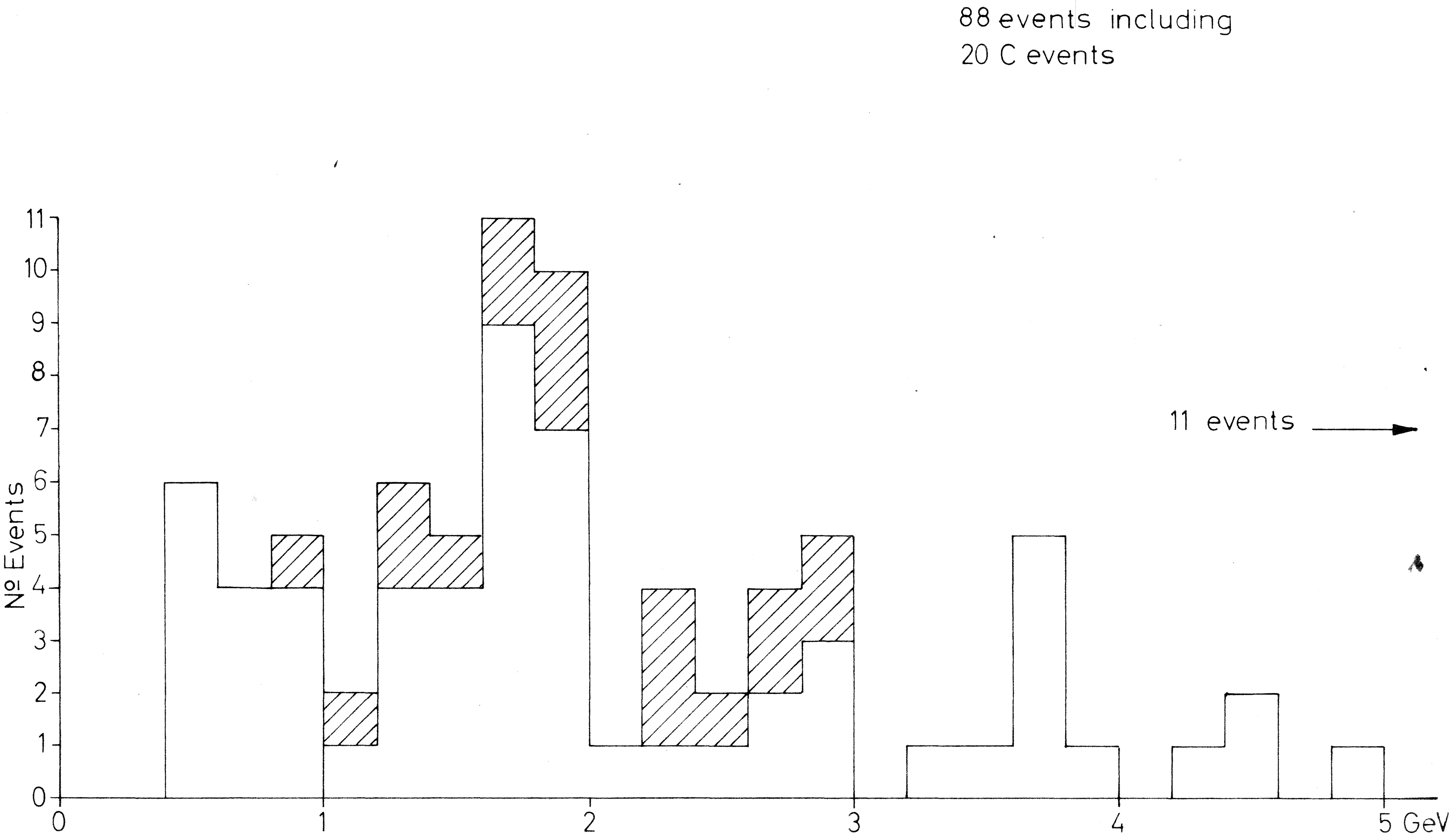


Fig. 13

$E_{vis.}$ pionic events

Fig. 14 E_{vis} calculated for PIONIC EVENTS

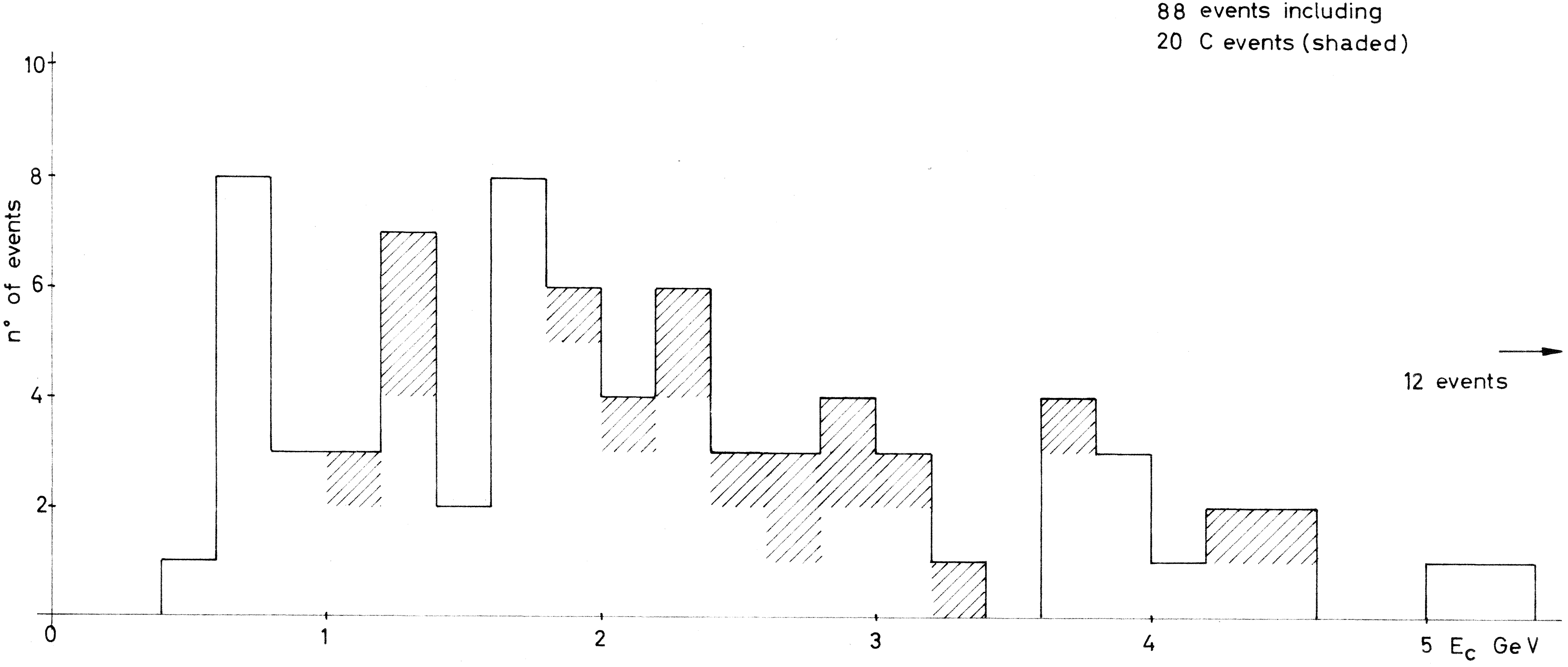
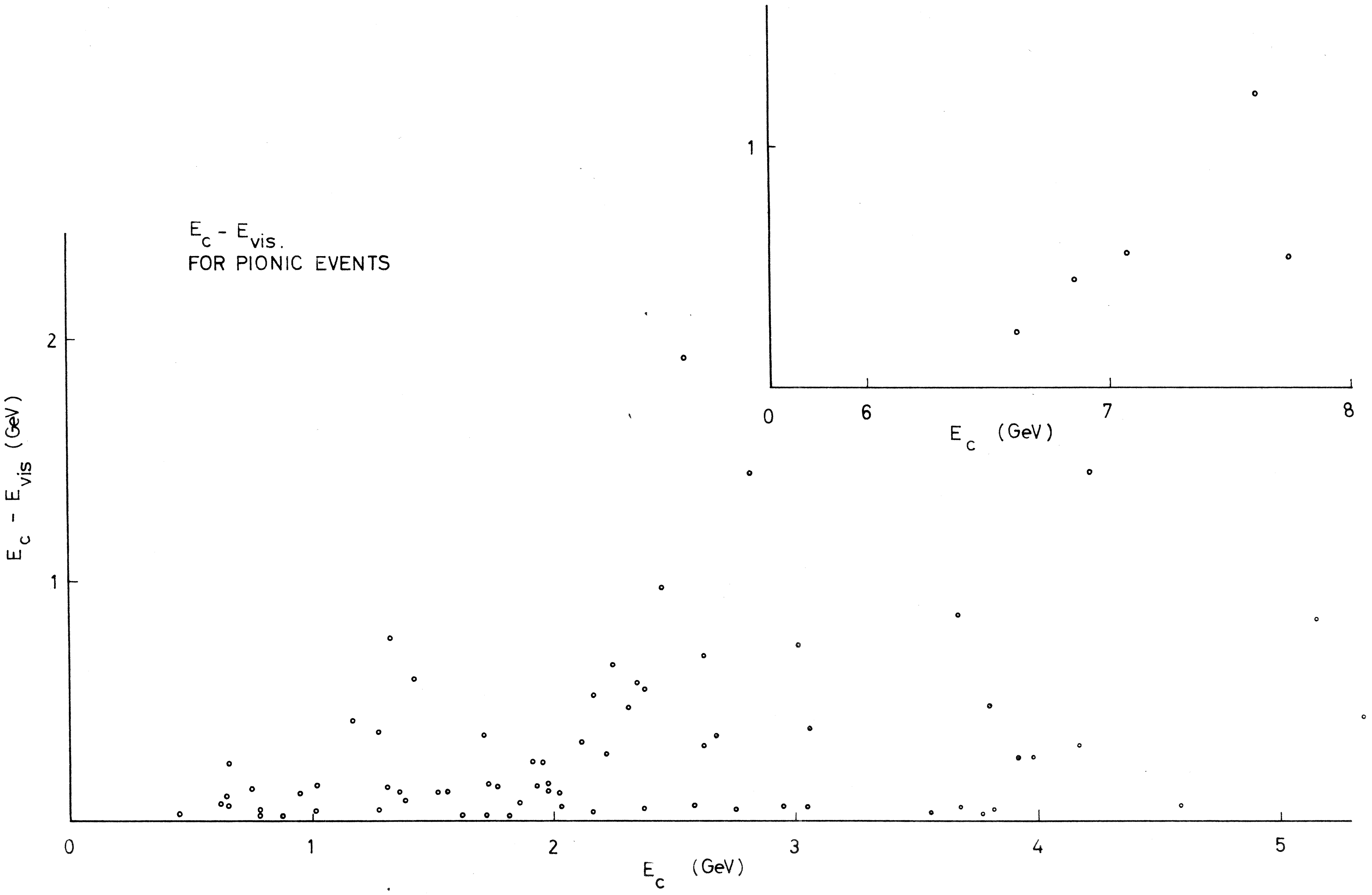
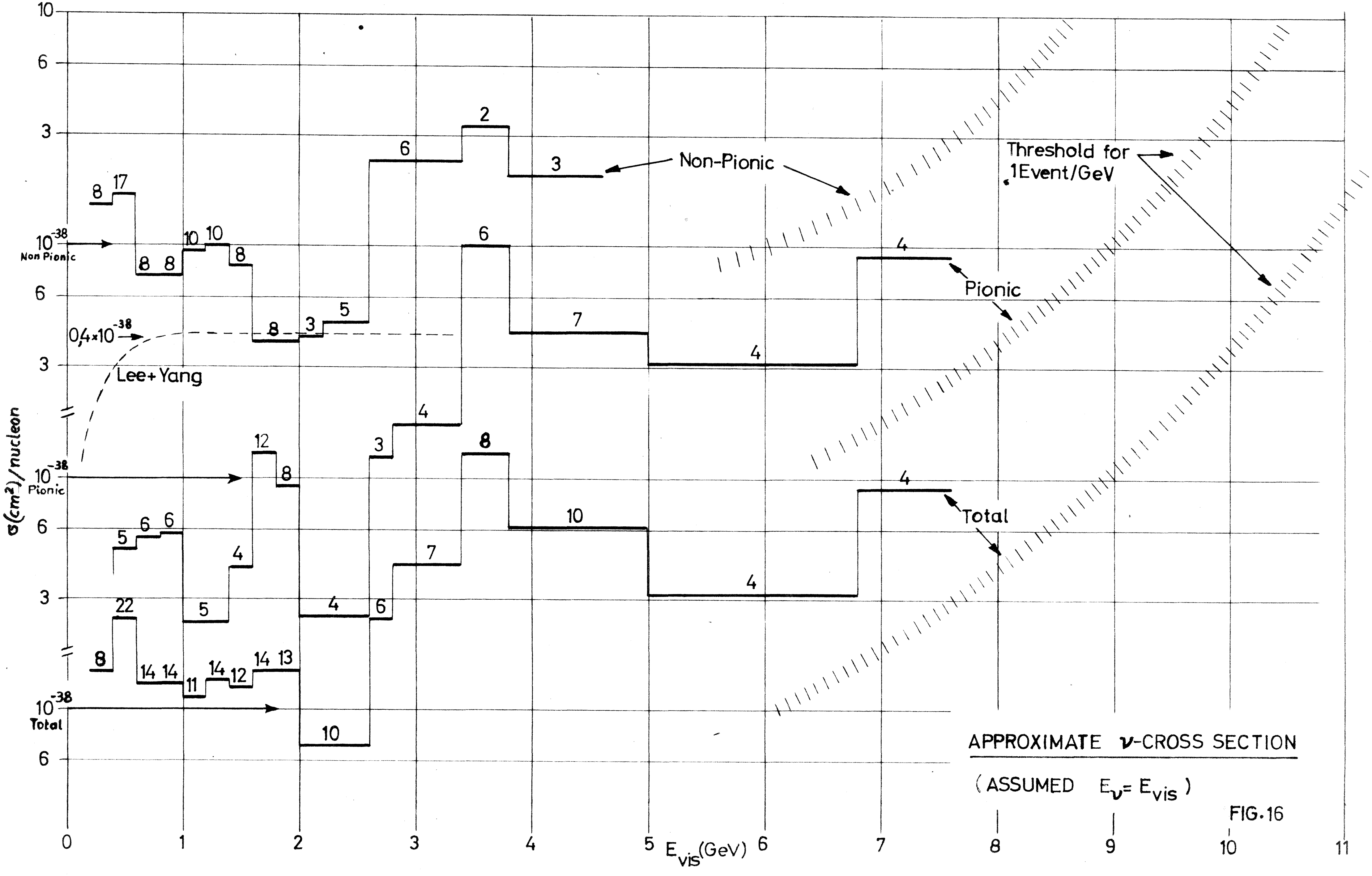


Fig. 15

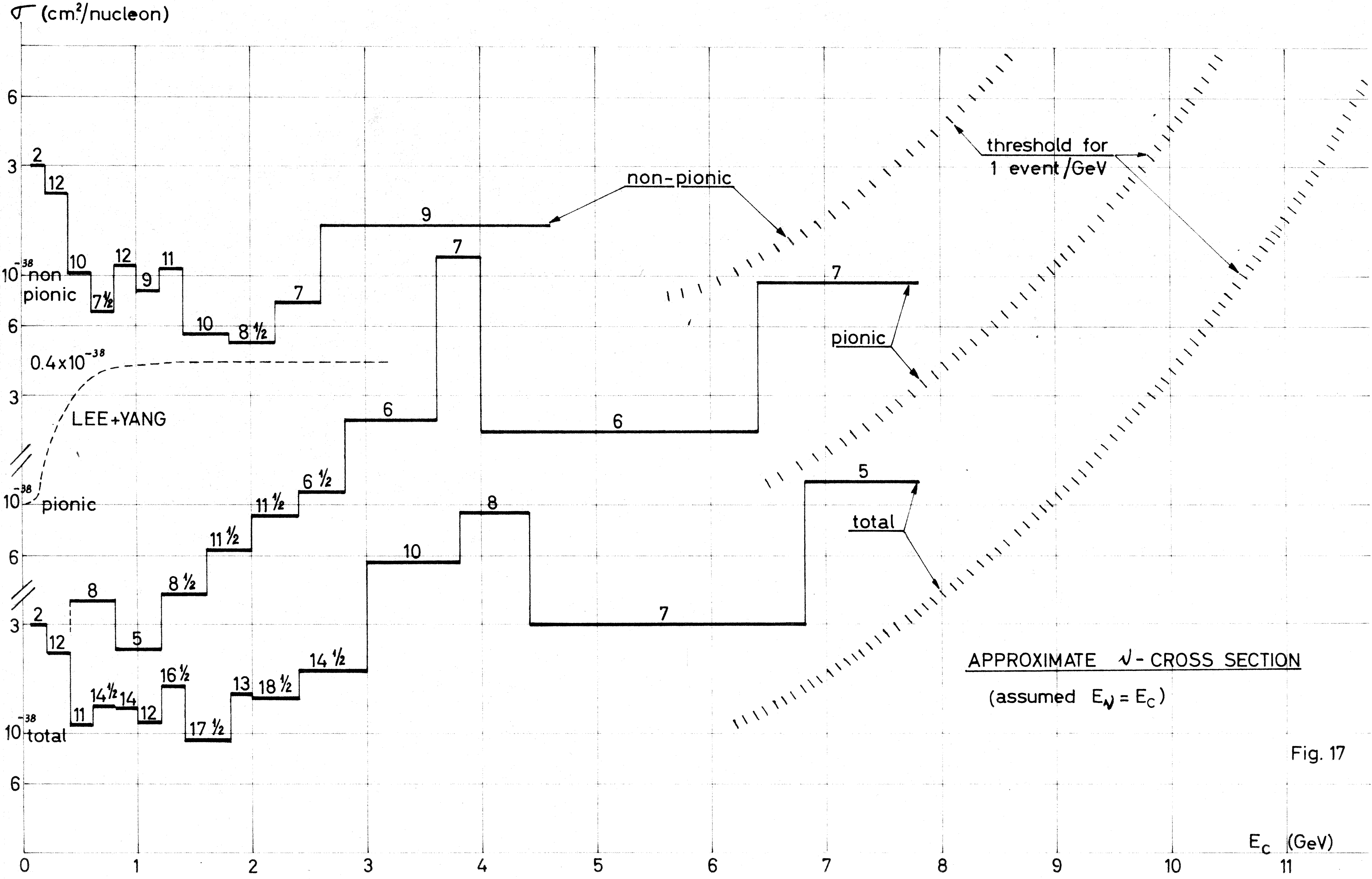

$E_c - E_{vis.}$
FOR PIONIC EVENTS
$E_c - E_{vis}$ (GeV)
2
1
0
1
2
3
4
5
E_c (GeV)
1
0
6
7
8
E_c (GeV)



APPROXIMATE ν-CROSS SECTION

(ASSUMED $E_{\nu} = E_{vis}$)

FIG.16



APPROXIMATE ν - CROSS SECTION

(assumed $E_\nu = E_C$)

Fig. 17

Fig.18 PREDICTED AND CALCULATED NEUTRINO SPECTRUM