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NEUTRINO INTERACTIONS IN THE CERN HEAVY LIQUID BUBBLE CHAMBER

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Preliminary results of the analysis of neutrino interactions in the CERN 500 litre freon chamber have been reported at the Sienna Conference [1]. This paper presents results of a more detailed analysis of a total of 459 events. The new data were obtained in experimental conditions similar to those described previously, apart from modifications to the inner conductor of the magnetic horn, which increased the high energy flux.

Of the 459 events, 454 contain a negative muon candidate, and 5 a negative electron of energy exceeding 400 MeV. We expect 3.3 electron events from the ν_e flux resulting from Ke_3 decay, thus our data confirm the earlier findings of the Brookhaven - Columbia group regarding the two-neutrino hypothesis [2]. Of the muon events 236 contain no pions (non-pionic); 209 contain pions ; and 9 contain pions and strange particles. Fig. 1 shows the visible energy distributions of the different classes of events. It must be emphasized that all events occur in complex nuclei, and that the characteristics of the elementary neutrino-nucleon interaction are modified both by Fermi motion and by secondary nuclear processes.

Elastic Process

From the 236 non-pionic events containing a muon and one or more protons, we have attempted to extract those due to the elastic process :

$$\nu + n \longrightarrow \mu^- + p \tag{1}$$

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The events observed will contain background. By selecting those of visible energy $E_{vis} > 1$ GeV, contamination from interactions due to neutrons or incoming charged particles can be shown to be negligible. The most serious remaining source of contamination is from neutrino events in which a pion is produced in the primary collision, and subsequently re-absorbed in its passage through the parent nucleus. For example, if $N^* (\frac{3}{2}, \frac{3}{2})$ production is assumed to dominate in the observed one-pion events, the absorption probability can be estimated. For $E_{vis} > 1$ GeV, the expected contamination of elastic events would be ~ 25 o/o. The corresponding loss of elastic events, in the case where the outgoing proton creates a pion in a secondary collision, is known to be negligible.

The nucleon form factors for the weak interactions in elastic processes can be computed from the distribution of the squared four-momentum transfer $q^2 = (P_\nu - P_\mu)^2$. P_ν and P_μ are the four-momenta of the incoming neutrino and the outgoing muon. For each event, q^2 can be determined experimentally from the momentum and direction of the muon, assuming the event to be elastic and the target nucleon at rest. The background from inelastic events was subtracted on the basis of a comparison of the q^2 distribution of both pionic and non-pionic events. For $E_{vis} > 1$ GeV, 120 selected non-pionic events were analysed.

Assuming the CVC hypothesis [(3)], G - symmetry and time reversal invariance, and neglecting pseudoscalar terms and possible effects due to the intermediate boson, $d\sigma(E_\nu) / dq^2$ can be expressed in terms of the electromagnetic isovector form factors F_1 and F_2, and the axial form factor F_A. Electron scattering experiments are consistent with $F_1 = F_2 = F_V = (1 + q^2 / M_V^2)^{-2}$ with $M_V = 0.84$ GeV. Therefore $d\sigma(E_\nu) / dq^2$ is determined except for F_A. If the parametric form $F_A = (1 + q^2 / M_A^2)^{-2}$ is assumed, M_A can be determined from the experimental data.

To avoid errors due to the uncertainty in the neutrino spectrum, the expected q^2 distribution summed over all energies :

$$\frac{dN}{dq^2}\, dq^2 = dq^2 \int \phi\,(E_\nu)\ \frac{d\,\sigma(E_\nu \mid M_A)}{dq^2}\, dE_\nu \qquad (2)$$

was then calculated by taking the neutrino spectrum as :

$$\phi\,(E_\nu)dE_\nu \approx \frac{1}{\sigma(E_\nu \mid M_A)}\ \frac{dN}{dE_\nu}\ \Delta E_\nu$$

where $\frac{dN}{dE_\nu}\ \Delta E_\nu$ is the number of observed events in the energy interval E_ν to $E_\nu + \Delta E_\nu$, and $\sigma(E_\nu \mid M_A)$ is the theoretical total cross section for the elastic process. . The relation (2) was compared with the observed q^2 distribution and M_A determined by likelihood methods. The analysis then does not depend on assumptions about the absolute ν flux. Appropriate corrections were applied to the calculated distributions for the effects of Fermi motion and exclusion principle. This analysis yields $M_A = 1.0 {+0.35 \atop -0.20}$ GeV, where the errors are purely statistical, the observed and expected q^2 distributions for this value of M_A are shown in Fig. 2. If the background subtraction is doubled, the best value of M_A is 1.4 ± 0.4 GeV, it is clear that the systematic error due to uncertainty in the background contribution may be comparable with the statistical errors. We conclude that $M_A = 1.0 {+0.5 \atop -0.3}$ GeV, showing that $F_A \approx F_V$.

It is also possible to extract F_A directly from the data. The absolute neutrino flux can be estimated from the events in the range $0 < q^2 < 0.2$ $(\mathrm{GeV/c})^2$ where the approximation $F_A = F_V$ can be used. From this flux and the overall q^2 distribution the relationship between F_A / F_V and q^2 can be deduced. The result is shown in Fig. 3.

Single Pion Production

Single pion production has been predicted [4] to take place mainly through excitation of the $(\frac{3}{2}, \frac{3}{2})$ nucleon isobar :

$$\nu + N \longrightarrow \mu^- + N^* \qquad (3)$$
$$\hookrightarrow \pi + N$$

Other processes such as peripheral π or ω exchange have cross sections which, at the neutrino energies considered, are calculated to be one or two orders of magnitude smaller [5].

$N^* (\frac{3}{2},\frac{3}{2})$ production, together with the $\Delta I = 1$ rule, implies a ratio of final states $p\,\pi^+ : p\,\pi^0 : n\,\pi^+ = 9 : 2 : 1$, or an overall ratio $\pi^+/\pi^0 = 5/1$. For the observed one-pion events, the ratio is 1.9 ± 0.4 . The observed ratio could be compatible with a large contribution of N^* production since the charge distribution will be severely distorted by charge-exchange interactions of the N^* decay products in the parent nucleus.

In the two-body reaction (3) the mass M^* of the isobar can be deduced from the relation $M^{*2} = M^2 - q^2 + 2\,M\,(E_\nu - E_\mu)$, where M is the nucleon mass, and the neutrino energy E_ν is taken equal to the visible energy in the event. In practice, even if M^* were unique, the observed distribution would be broadened by $\sim$ 15 o/o by measurement errors and Fermi motion and distorted to slightly lower values by energy losses of the pion and nucleon in the parent nucleus. At low energy, a " phase space" distribution of M^* of the final products is grouped around the value of the isobar mass, for kinematical reasons. We have therefore considered only those events with $E_{vis} > 1.5$ GeV; their M^* distribution is shown in Fig. 4. The curve shows the estimated phase space distribution for the final products (μ, π, p). The peak between $M^* = 1.0$ and $M^* = 1.4$ GeV is consistent with the assumption that single pion production proceeds through excitation of the $(\frac{3}{2},\frac{3}{2})$ isobar in more than half the events. However, $\sim$ 30 o/o of events have $M^* > 1.4$ GeV, and most of these are associated with high-energy protons. It is difficult therefore to attribute them to peripheral processes.

A cut-off at $M^* = 1.4$ GeV will contain most of the N^* events. Figure 5 shows the one-pion event rate and cross section for $M^* < 1.4$ GeV, the data have been corrected for pion absorption in both the one and two pion events. As can be seen, the theoretical cross section calculated using the form factors $F_A = F_V = (1 + (q/0.9)^2)^{-2}$ is too high by a factor of two. The cross section for one-pion events in the range $0 < q^2 < 0.2$ $(GeV/c)^2$ and $1.0 < E_{vis} < 3.0$ GeV, after correction for absorbed pions, is observed to be :

$$\frac{d\sigma}{dq^2} = (0.5 \pm 0.2) \times 10^{-38} \text{ cm}^2 \text{ (GeV/c)}^{-2} \text{ per nucleon}$$

in agreement with the predicted value [4] of $\sim 0.7 \times 10^{-38}$ cm^2 (GeV/c)$^{-2}$ per nucleon. The experimental cross sections are evaluated from the calculated neutrino spectrum, the effect of the exclusion principle (estimated < 30 o/o) has been neglected. A choice of a smaller value of M_A could improve the agreement between experiment and theory in the whole q^2 range.

Neutrino Flux and Total Inelastic Cross Section

Fig. 6 shows the energy distribution of the neutrino flux up to 4 GeV, derived from the elastic event rate, the cross section computed for $M_A = 1.0$ GeV [6]. Except at low energy, it is consistent with the flux calculated by van der Meer on the basis of measured pion and kaon production spectra [7]. Assumptions of target efficiencies in this calculation have been cross checked by measuring the muon range spectrum in the shielding. At high energies the neutrino spectrum cannot be considered to be known to better than a factor of two. The calculated variation of neutrino flux with energy may be used to estimate the inelastic neutrino cross sections, σ_{inel} at high energy. (Fig. 7). It indicates a marked increase of the inelastic cross section with neutrino energy.

Intermediate Vector Boson

The intermediate vector boson [8] is predicted to have a lifetime of $\lesssim 10^{-17}$ sec and to decay in the modes :

$$
\begin{aligned}
W^+ \longrightarrow\ & e^+ + \nu \\
& \mu^+ + \nu \\
& \pi\pi\text{'s, etc.}
\end{aligned}
$$

The two leptonic modes are assumed to have equal decay probability ; the e^+ decay mode should be easily observable in a bubble chamber and the μ^+ decay in the spark chamber [6]. To increase the weight of the data, half of the 450 events originating outside the fiducial volume of the chamber have been taken together with all the 459 events inside. From ~ 700 events only one possible " candidate" for the e^+ decay has been observed. We expect about 1 event from $\bar{\nu}_e$ background. If the boson mass $M_W = 1.8$ GeV, and the branching ratio for e^+ decay is 50 o/o, we expect to observe 2.5 such events [9], thus $M_W > 1.8$ GeV unless the pionic decay mode is predominant.

To discuss evidence for the pionic mode of decay of W^+, we restrict ourselves to events of $E_\nu > 6$ GeV, where W production is more likely to dominate over other processes. Of the 23 events observed, 14 have mesonic charge + 1, as required for " elastic" W production. There is no clear peak in the spectrum of invariant mass of these pions, 8 events occur in the interval 1 to 2 GeV, to be compared with 11 expected if $M_W = 1.5$ GeV and the branching ratio for decay into pions is > 90 o/o.

To summarize, we have no evidence for the existence of the W boson in agreement with our previous conclusion [1]. If the boson does exist, $M_W > 1.5$ GeV irrespective of branching ratios; and $M_W > 1.8$ GeV unless leptonic decay is rare.

Strange Particle Production

As shown in Fig. 1 the events with strange particles occur mostly at high neutrino energy. A pair of strange particles is seen in four cases, which is consistent with associated production in the total of 9 events. In the elastic and single pion events with $E_{vis} < 4$ GeV, where associated production is unlikely, only one hyperon is found. Since single hyperon production would violate the $\Delta Q/\Delta S$ rule, this observation can be used to set a limit to the violation of < 20 o/o.

Secondary production of these hyperons by collision of pions in the parent nucleus seems unlikely considering the observed pion spectrum. We conclude that the strange particles could not be produced by associated production in secondary processes. Thus the strange particles may come from the primary neutrino interaction.

Other Conclusions

A number of other fundamental questions were discussed in our previous report (1), their present status is :

Violation of muon number conservation $(\nu_e \neq \nu_\mu)$ < 1 o/o

Violation of lepton conservation < 6 o/o

$(\Delta S = 0$, neutral current coupling $/\Delta S = 0$, charged current coupling$)$ < 3 o/o

Neutrino flip intensity / no neutrino flip intensity

$$= \frac{K \longrightarrow \mu + \nu_e}{K \longrightarrow \mu + \nu_\mu} < 10 \text{ o/o}$$

A boson has been postulated which produces a resonance of the type $\nu_\mu + n \longrightarrow W'_\mu \longrightarrow \mu^- + p$. If its properties are as predicted (10,11) its mass is > 5.5 GeV.

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Finally our best thanks to " our scanning girls"

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Figure Captions

Fig. 1 Visible energy distribution of various event types.

Fig. 2 Corrected four momentum distribution for elastic events with $E_{vis} > 1$ GeV.

Fig. 3 $\frac{F_A}{F_V}$ as a function of q^2.

Fig. 4 M^* distribution for single pion events with $E_{vis} > 1.5$ GeV.

Fig. 5 Energy distribution and cross section for single pion events with $M^* < 1.4$ GeV. Event rate corrected for pion absorption.

Fig. 6 Neutrino flux calculated from event rate and cross section, compared with predicted flux.

Fig. 7 Energy distribution and cross section of all inelastic events. Event rate corrected for pion absorption.

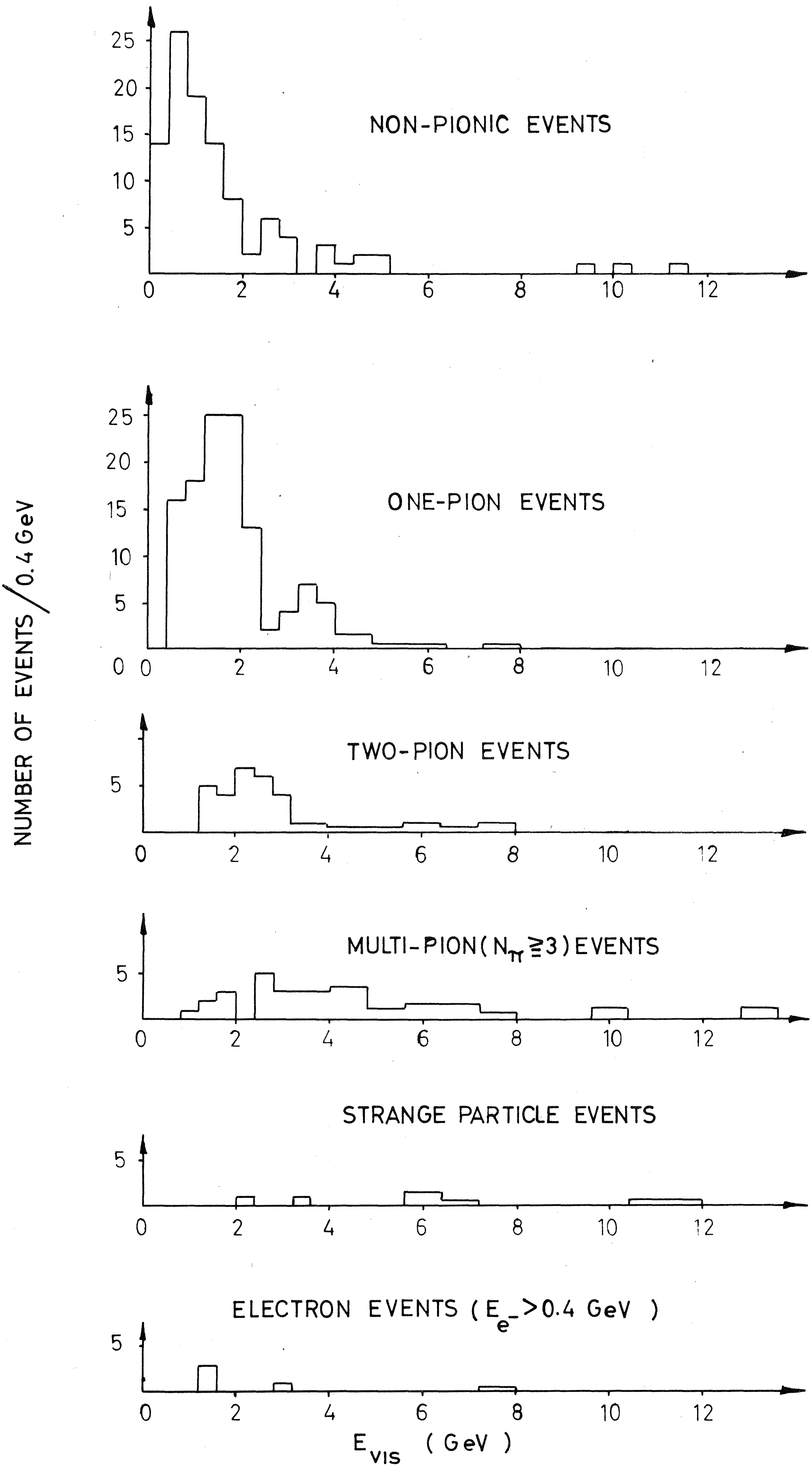


FIG 1

SIS/R/9389

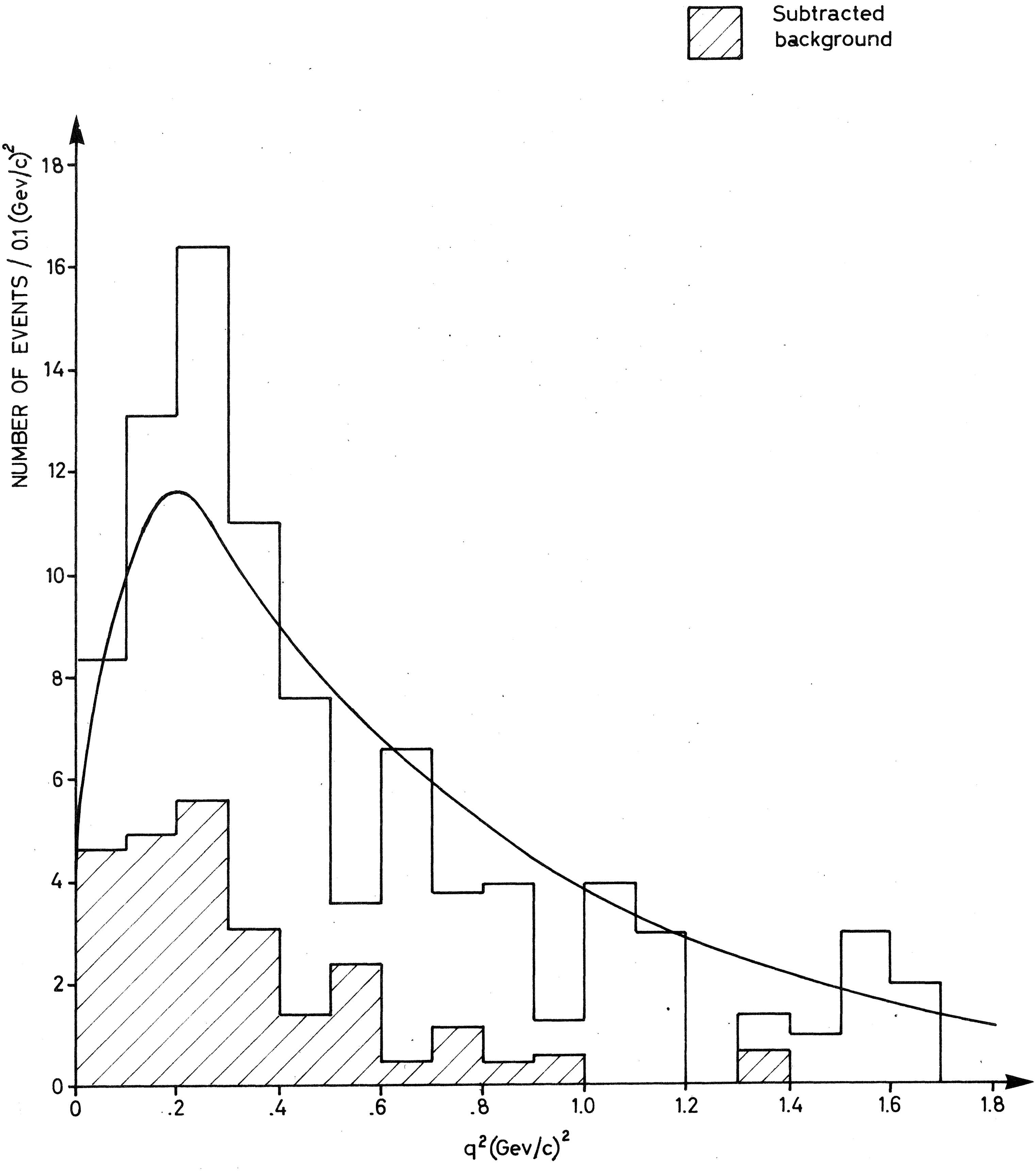


FIG. 2

SIS/R/9388

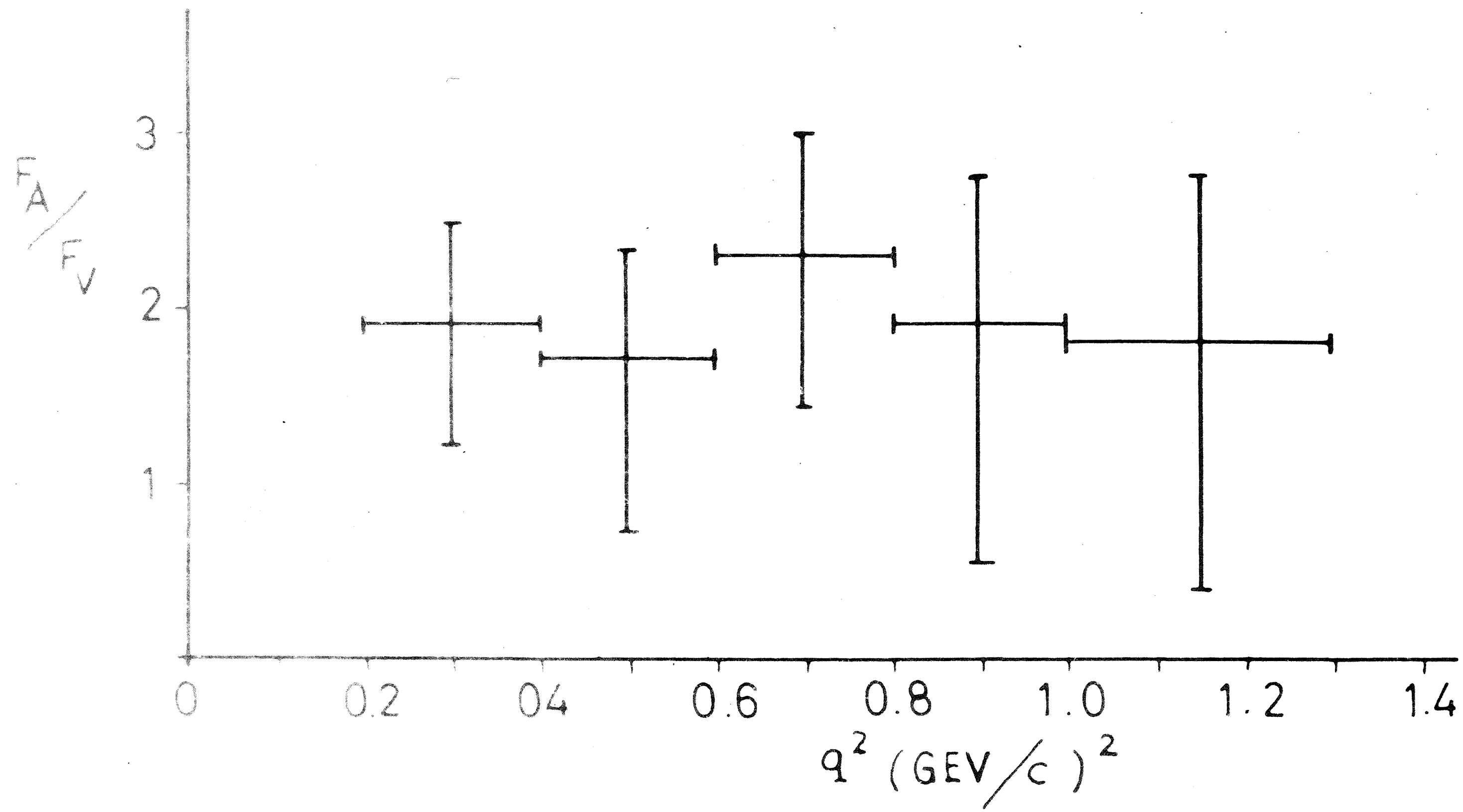


FIG. 3

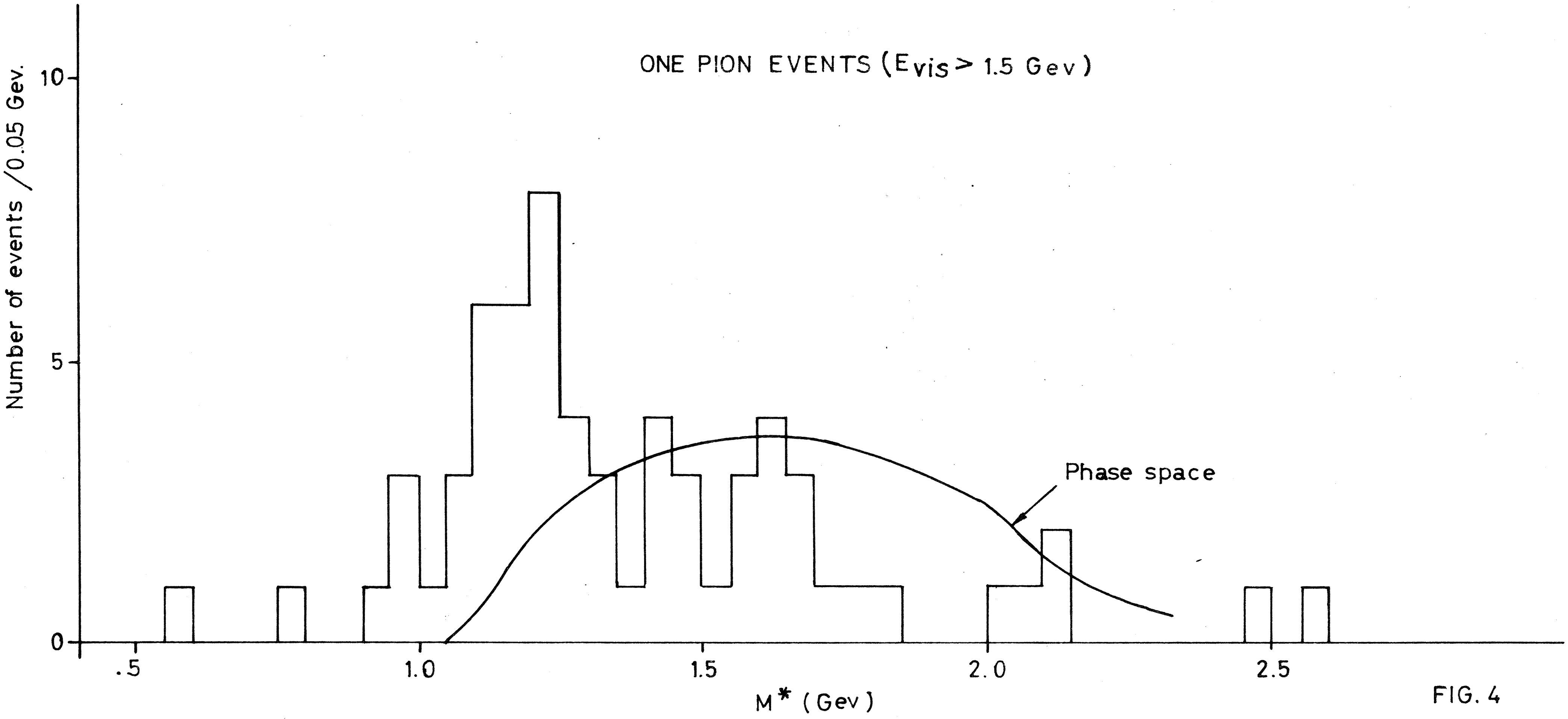
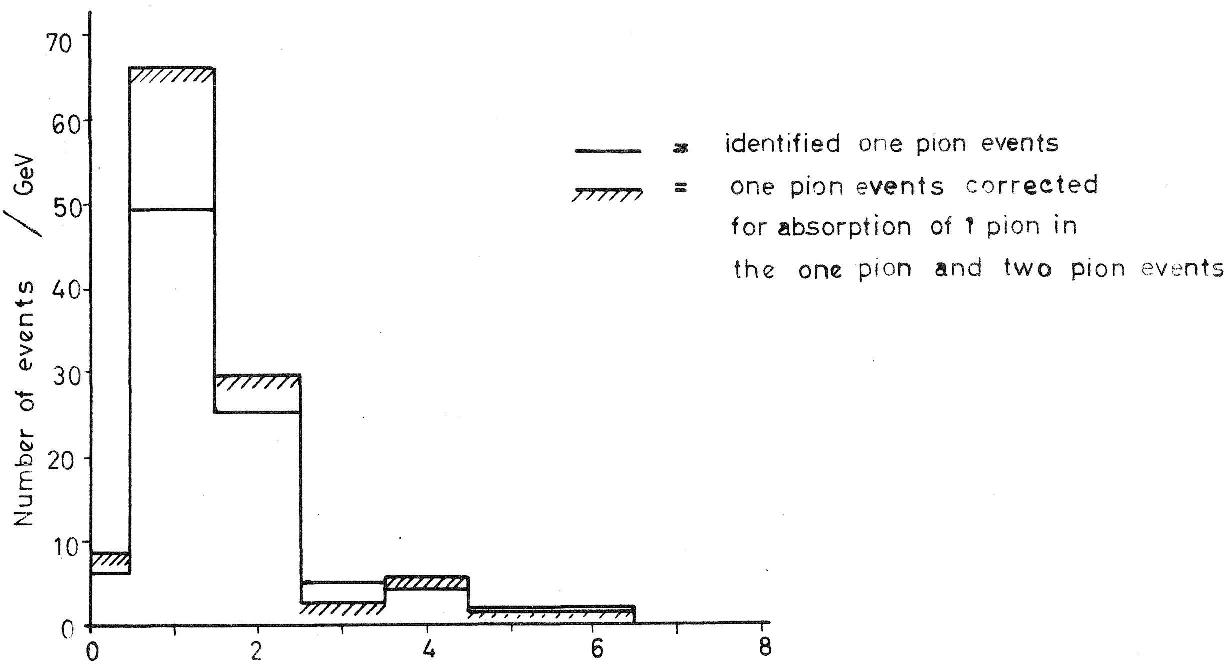

ONE PION EVENTS (E_{vis} > 1.5 Gev)
Number of events /0.05 Gev.
10
5
0
.5
1.0
1.5
2.0
2.5
M* (Gev)
Phase space

FIG. 4



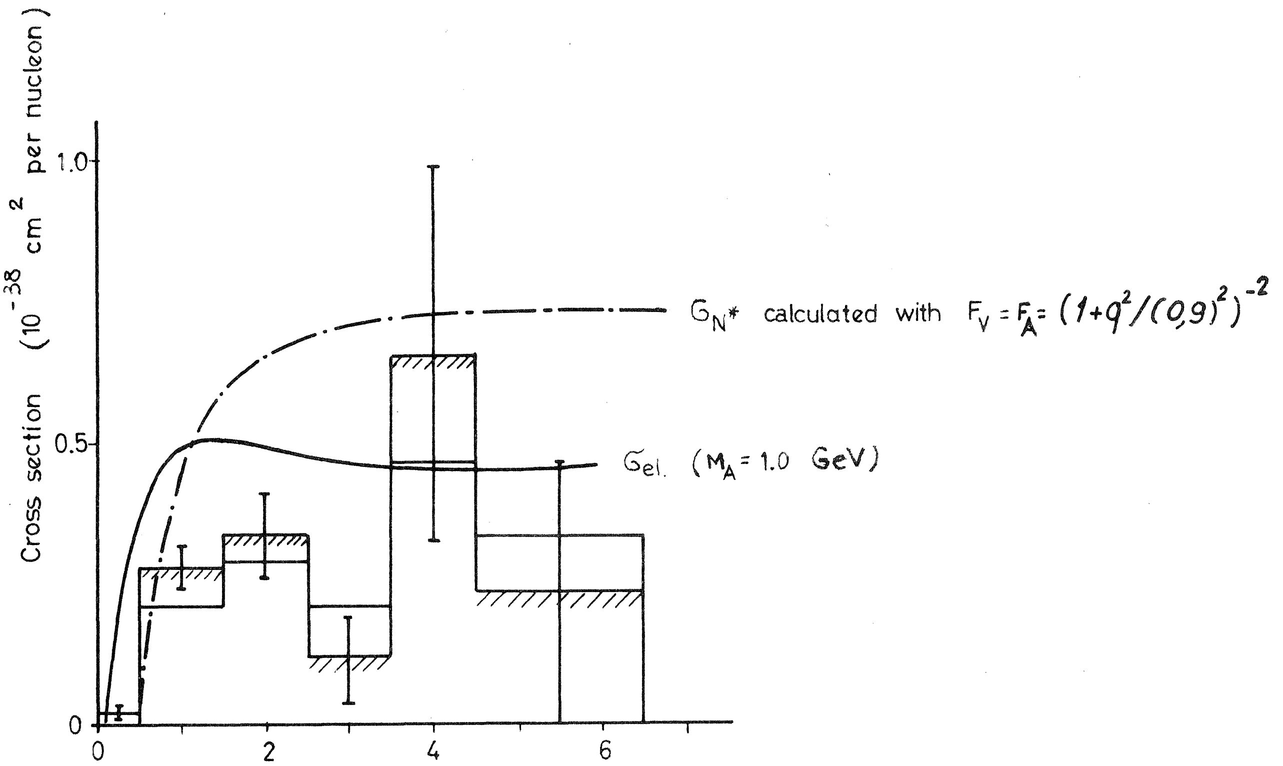


Fig. 5

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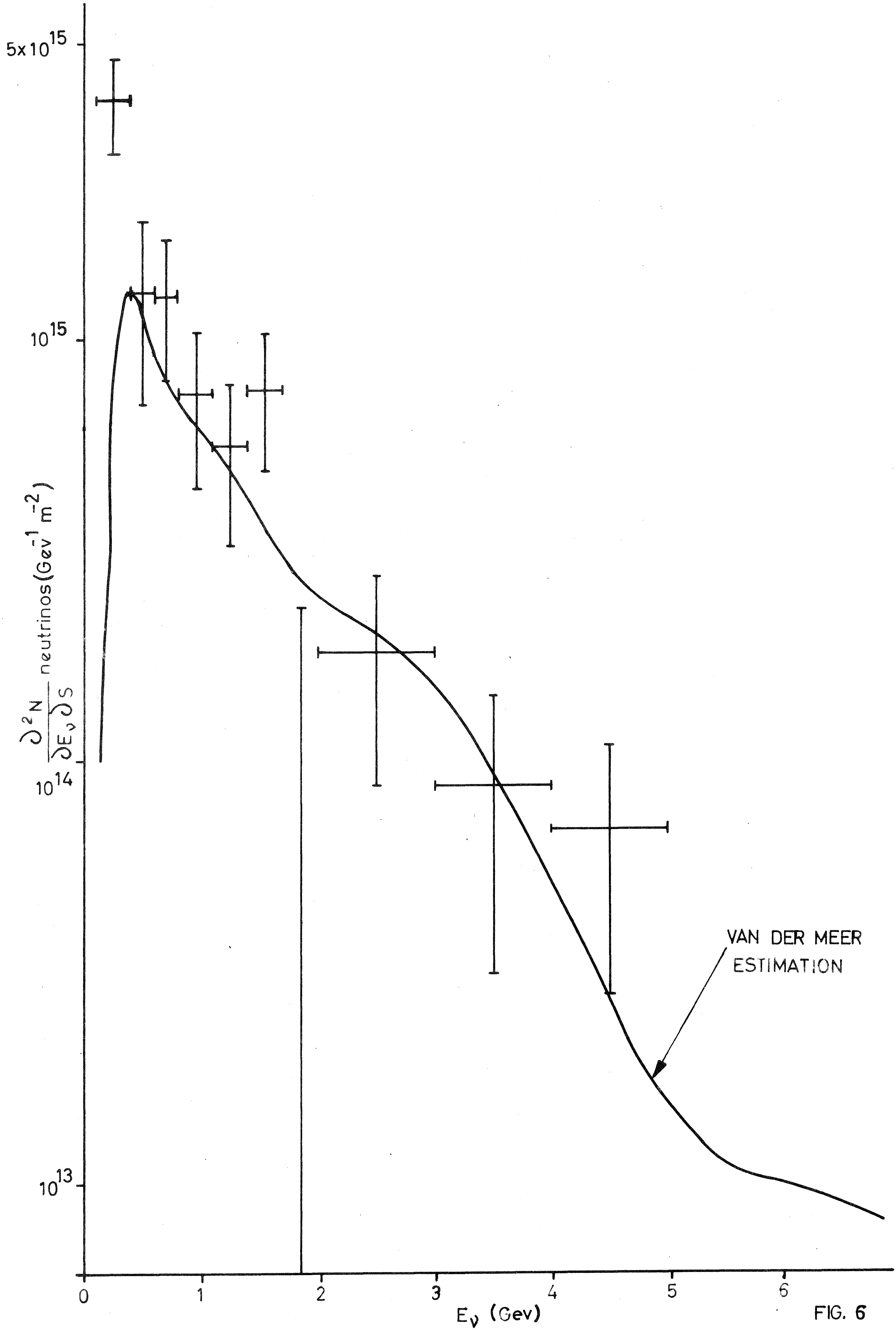

FIG. 6

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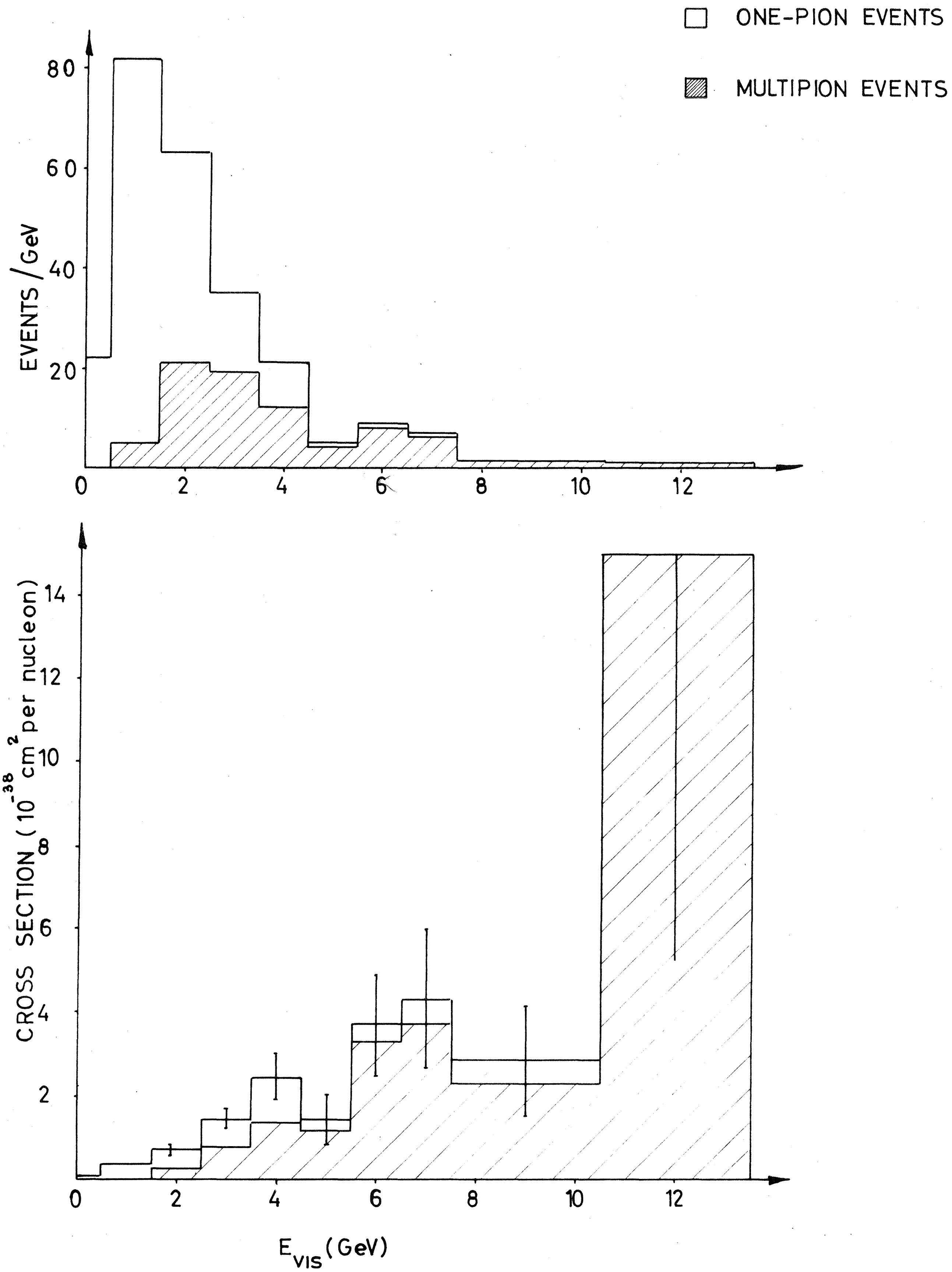

FIG 7

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