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NEUTRINO INTERACTIONS IN A PROPANE BUBBLE CHAMBER

Single Pion Production on Free Protons

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Exposure

The CERN Heavy Liquid Bubble Chamber [1] with a propane filling was exposed for 1.08×10^6 pulses, corresponding to 6.8×10^{17} protons on the target of the improved neutrino beam [2].

The neutrino spectrum is shown in Fig. 1a. It is based [3] on measured pion and kaon production spectra and measurements of the muon flux in the neutrino filter, and is estimated to be accurate within ± 30 %. This error includes an estimate of systematic effects, the analysis of which is still in progress.

Scanning and Measurement

The film was scanned for all interactions in the propane, whether due to incident neutral or charged particles. The scanning efficiency derived from a rescan of 14 % of the film was (90 ± 10) %. The error allows for the possibility of a variation in the scanning efficiency as a function of position in the chamber, for which some evidence was found. The events were measured on image-plane digitizers and the measurements passed through the DRAT-GRIND [4] chain of programmes. This report is based on 75 % of the total data available.

Selection of Events

We have determined the total and differential cross-sections for the process

$$\nu_\mu + p \longrightarrow \mu^- + \pi^+ + p \qquad (1)$$

occurring on the free protons in the propane. A fiducial volume of 509 litres was chosen to ensure good measurability. All events which were compatible with this three-prong topology were retained.

Use was made of bubble density and delta-ray information to decide, where possible, between pion and proton hypotheses for fast positive tracks. If a delta-ray indicated that one of the tracks was incoming the event was rejected. There were 113 accepted events of which 51 contained a positive track ambiguous between pion and proton. Among the 113 events were 12 in which either the pion or proton interacted after such a short distance that its momentum could only be measured with an uncertainty exceeding 30 %. In order to minimize backgrounds these 12 events were removed from the sample and corrected for statistically.

For each event the total momentum of all tracks resolved along the neutrino direction (ΣP_x) was calculated. In reaction (1) this quantity will equal the neutrino energy and in general be of the order of 1 GeV or more. In contrast ΣP_x for an event caused by an incoming pion will in general be zero or small because the incoming track will be assumed " outgoing" for this calculation. A cut was therefore made that required $\Sigma P_x \geqslant 300$ MeV/c. 20 events were rejected by this cut.

For the remaining 81 events the quantities P_{xun} and P_T were calculated, where

$$P_{xun} = E_{vis} - \Sigma P_x \quad ,$$

E_{vis} is the sum of the energies of the mesons and the kinetic energy of the proton, and P_T is the resultant momentum of all particles transverse to the neutrino beam direction.

For events of type (1) on free protons P_{xun} and P_T should differ from zero only by measurement errors, whereas for events in carbon, Fermi motion and scattering in the nucleus can give large values of these quantities. Fig. 2 shows a plot of P_{xun} vs P_T for the 81 remaining candidates. There is a clear concentration of events with P_{xun} and P_T near zero. Events were retained as candidates for reaction (1) on free protons if $|P_{xun}| < 120$ MeV/c and $P_T < 240$ MeV/c.

A study of the measurement errors suggested that (5 ± 2) % of genuine events would be expected to be rejected by these cuts. 49 events passed all selection criteria and are the basis of the cross-section determination. An investigation of the P_{xun} and P_T distributions as functions of E_{vis} and the square of the four-momentum transfer (q^2) indicated that the selection criteria did not introduce any significant bias in these variables.

Backgrounds

The selected events may contain background from the following sources :

1) Neutron interactions which simulate neutrino events
2) Events caused by incoming pions which are not removed by the various criteria
3) Events containing mis-identified tracks
4) Events in carbon

1) Neutron background

In neutron-induced events with the same topology as reaction (1) the negative track must be a negative pion. About 40 % of these would be identified by an interaction in the chamber volume, but 60 % would remain in our sample. In fact there was one well-measured event of this type in which the π^- interacted, and thus we would estimate 1.5 similar events where the π^- had not interacted. However the neutron event was unbalanced and failed the P_{xun} and P_T cuts. Thus the estimated background due to neutrons is less than 1 event.

2) Incoming pion background

Among a randomly chosen set of 14 events which would have been candidates for reaction (1) had the direction of the incoming pion not been indicated by a delta-ray, there was no event with $\Sigma P_x > 300$ MeV/c, in fact all had $\Sigma P_x < 100$ MeV/c. The cut on $\Sigma P_x > 300$ MeV/c removed 20 events from our original sample. Thus on the basis of these 20 events we estimate less than 1 event of background from this source to remain after the ΣP_x cut.

3) Mis-Identification of tracks

Of the 49 selected events, 21 contained one positive track which was too energetic ($>$ 1 GeV/c) to be identified by ionization, and which did not have a δ-ray of sufficient energy to distinguish between the pion and proton hypotheses. The nature of the particle was taken such as to satisfy the topology ($\mu^-\pi^+p$). A mis-identification would therefore give rise to a background. However a statistical analysis based on those positive pions identified by a δ-ray leads to an estimated background of less than one event of the types ($\mu^-\pi^+\pi^+$) or μ^-pp) among the 21 ambiguous events.

4) Carbon background

Reactions of type (1) which occur on bound nucleons and which yield only one visible proton can be distinguished from events on free protons only by the P_{xun} and P_T cuts. In order to estimate what fraction of bound nucleon events would be expected to pass these cuts we have studied :

the (μ^-p) events, mainly examples of the elastic process in carbon,

and the ($\mu^-\pi^+p$) events observed in the previous neutrino experiments in freon [5].

a) (μ^-p) events

A plot of P_{xun} vs P_T for 82 events of the type (μ^-p) is shown in Fig. 3. Since the overall distributions are not the same for the (μ^-p) and ($\mu^-\pi^+p$) categories we have based the estimate on those events with small P_{xun}. Here Fermi motion might be expected to be the principal cause of unbalance, and this should be similar for the two event types. Of the (μ^-p) events 32 have $|P_{xun}| < 120$ MeV/c and $P_T < 240$ MeV/c; 24 events have $120 < |P_{xun}| < 220$ MeV/c. Among the ($\mu^-\pi^+p$) candidates 5 have $120 < |P_{xun}| < 220$ MeV/c. Using these 5 events to normalize we can estimate a carbon background of (7 $\pm$ 3) events among the 49 accepted events.

b) $(\mu^- \pi^+ p)$ events in freon

The plot of P_{xun} vs P_T for 51 events $(\mu^- \pi^+ p)$ observed during the neutrino experiments in freon CF_3Br is shown in Fig. 4. 7 events have $|P_{xun}| < 120$ MeV/c and $P_T < 240$ MeV/c. Since the distributions in P_{xun} and P_T for the freon and propane events are similar in the region outside the free proton peak, we have used all events failing the P_{xun} and P_T cuts for normalization, thus improving the statistical accuracy of the estimates. This leads to an estimated background of (5 ± 2) events. However one would expect the background to be more serious when all events occur in carbon, because of the somewhat lower probability for the pion or proton to destroy the momentum balance by interaction, when leaving a carbon nucleus as compared to a bromine nucleus. Simple calculations of this effect based on nuclear size and free pion and proton cross-sections suggest that the background caused by carbon would be 50 % higher than that caused by freon. The background estimate thus becomes (7.5 ± 3) events.

The two independent estimates obtained above are compatible. Taking the mean of the two we get a background estimate of 7.2 events among 49, i.e. (15 ± 5) %.

Results and Discussion

In order to calculate the cross-section for process (1) on free protons we make the following corrections to the 49 observed events :

a)	Carbon background subtraction	(- 15 ± 5) %
b)	Unmeasurable events	(+ 12 ± 3) %
c)	Scanning efficiency	(+ 11 ± 10)%
d)	Good events failing selection criteria	(+ 5 ± 2) %

The energy distribution of the 49 events and the resulting cross-section are shown in Figs. 1b and 1c respectively. In calculating the cross-sections the non-uniformity of the neutrino flux over the chamber was taken into account. The errors shown on this plot are statistical only.

Various authors [6] have made theoretical predictions for the cross-section for reaction (1). We compare our data with the most recent computation by Adler [7]. In Fig. 1c are shown Adler's predictions for values of $M_A^2 = 0.71$ and $3.0\ (\mathrm{GeV}/c^2)^2$ in the nucleon axial-vector form factor F_A :

$$F_A = (1 + q^2/M_A^2)^{-2}$$

For a more quantitative comparison we have computed the observed cross-section in the region 1 to 4 GeV where the neutrino flux is expected to be reliable and the predicted cross-sections are approximately constant. We find :

$$\sigma_{exp} = (1.3 \pm 0.5) \times 10^{-38}\ \mathrm{cm}^2$$

where the uncertainty here is due to statistics and uncertainties in the neutrino flux, scanning efficiency and corrections. This may be compared with Adler's predictions

$$\sigma_{Th} = 0.42 \times 10^{-38}\ \mathrm{cm}^2 \quad \text{if} \quad M_A^2 = 0.71\ (\mathrm{GeV}/c^2)^2$$

$$\sigma_{Th} = 0.77 \times 10^{-38}\ \mathrm{cm}^2 \quad \text{if} \quad M_A^2 = 3.0\ (\mathrm{GeV}/c^2)^2$$

However it is appropriate to note that the theoretical predictions are not unique. Both Adler [7] and Salin [8] quote cross-sections for single pion production averaged over the neutrons and protons in freon. Using essentially equivalent form factors they obtain at 2 GeV neutrino energy

$$\sigma = 0.37 \times 10^{-38}\ \mathrm{cm}^2/\text{nucleon} \qquad \text{(Adler)}$$

$$\sigma = 0.61 \times 10^{-38}\ \mathrm{cm}^2/\text{nucleon} \qquad \text{(Salin)}$$

The results of previous experiments in freon [5] are not immediately comparable with the present result, since they concern the cross-section averaged over neutrons and protons. Furthermore there are serious experimental problems associated with studying the single-pion process in complex nuclei, and also the neutrino fluxes were less well-known. However if it is assumed that only $T = 3/2$ final states of the pion and nucleon are important and with reasonable estimates of the numbers of events and neutrino fluxes, a cross-section per proton of approximately 0.8×10^{-38} cm^2 is obtained for comparison with the present result.

In Fig. 5 are shown the distributions in q^2 and in the invariant mass squared of the pion-proton system (M^2 (πp)) for the 43 selected events with $E_{vis} > 1$ GeV. The M^2 (πp) plot shows a marked accumulation at low values compared with the phase space distribution. The expected distribution for entirely N^*_{33} (1236) excitation is also shown. It is clear that reaction (1) results largely in the formation of this isobar, as was suggested by the previous experiments in freon [5].

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References

1) C.A. Ramm and L. Resegotti - Proc. Int. Conf. on Instr., Berkeley 127, 1960.

2) A. Asner and Ch. Iselin - CERN 65-17
D.H. Perkins and W. Venus, unpublished.

3) W. Venus - Private communication.
The measurements of muon flux were made by
D. Bloess, J.B.M. Pattison, G. Plass, D. Rusch,
K.M. Vahlbruch and H.W. Wachsmuth - To be published.

4) K. Soop - Prog. Nucl. Techn. Instr. II, 216 (1967).
R. Böck - Nucl. Instr. and Meth., 20, 435 (1963).

5) M.M. Block et al. - Phys. Letters, 12, 281 (1964).

6) For bibliography see E.M.C. Young - CERN 67-12.

7) S.L. Adler - To be published in Annals of Physics.

8) Ph. Salin - Nuovo Cimento 48, 506 (1967).

Figure Captions

Fig. 1a Neutrino flux.

1b Energy distribution of $(\mu^-\pi^+p)$ events.

1c Cross-section for $\nu + p \rightarrow \mu^- + \pi^+ + p$.

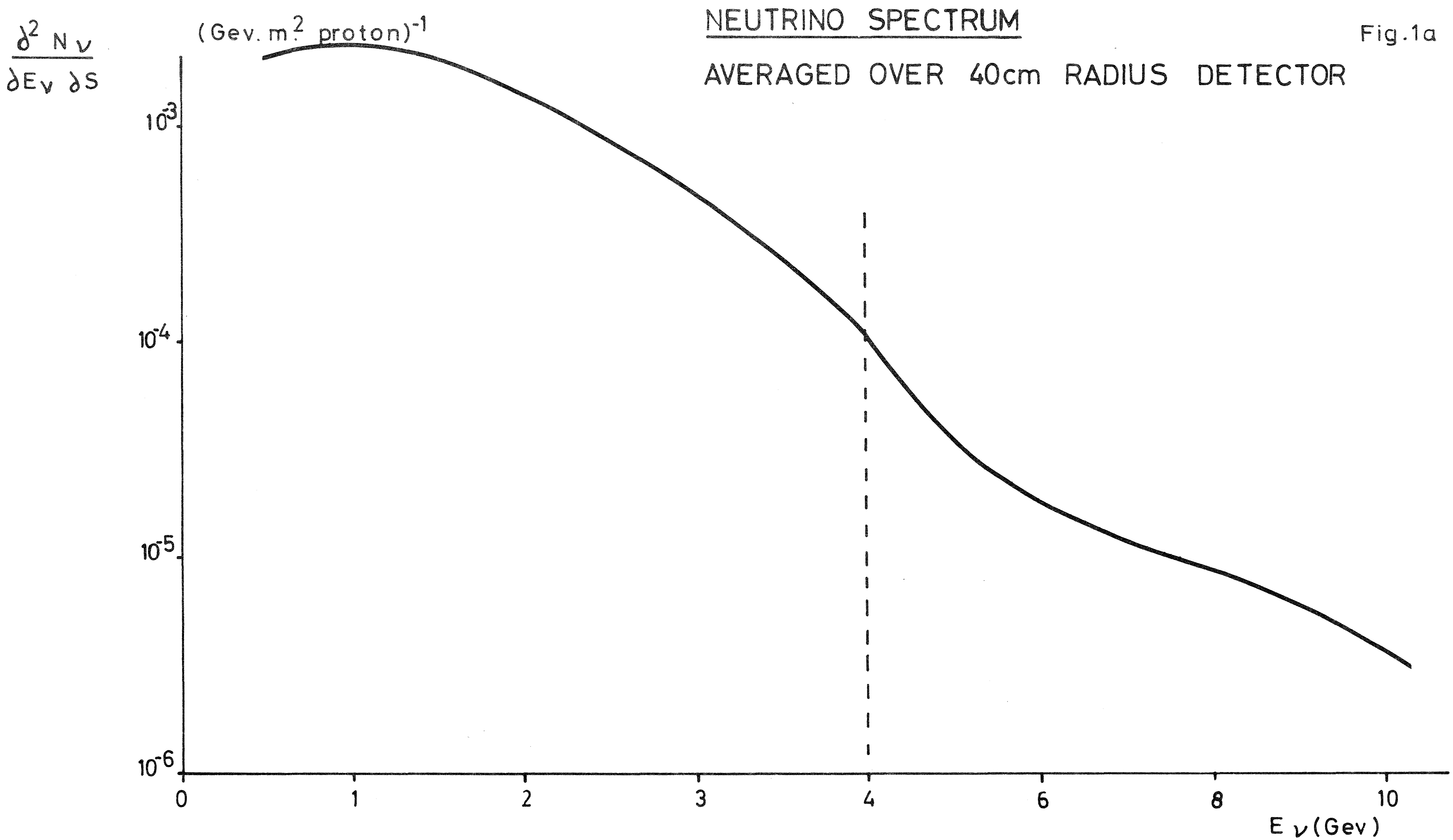
Fig. 2 P_{xun} vs P_T for $(\mu^-\pi^+p)$ candidates.

Fig. 3 P_{xun} vs P_T for (μ^-p) events.

Fig. 4 P_{xun} vs P_T for $(\mu^-\pi^+p)$ events in freon.

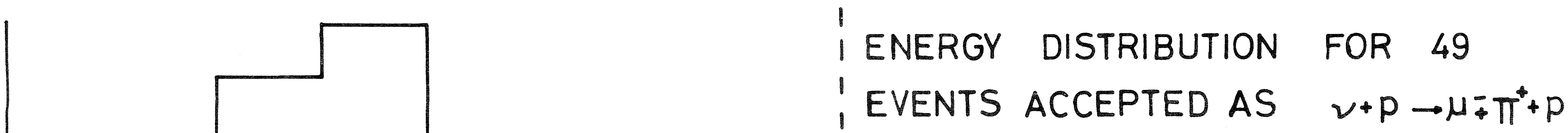
Fig. 5 q^2 and M^2 (πp) distributions for $\mu^-\pi^+p$ events with $E_{vis} > 1$ GeV.

Fig. 1a



NEUTRINO SPECTRUM
AVERAGED OVER 40cm RADIUS DETECTOR
$\frac{\partial^2 N_\nu}{\partial E_\nu \partial S}$ (Gev. m^2 proton)$^{-1}$
10^{-3}
10^{-4}
10^{-5}
10^{-6}
0
1
2
3
4
6
8
10
E_ν (Gev)

Fig. 1b



ENERGY DISTRIBUTION FOR 49
EVENTS ACCEPTED AS $\nu + p \to \mu^- + \pi^+ + p$

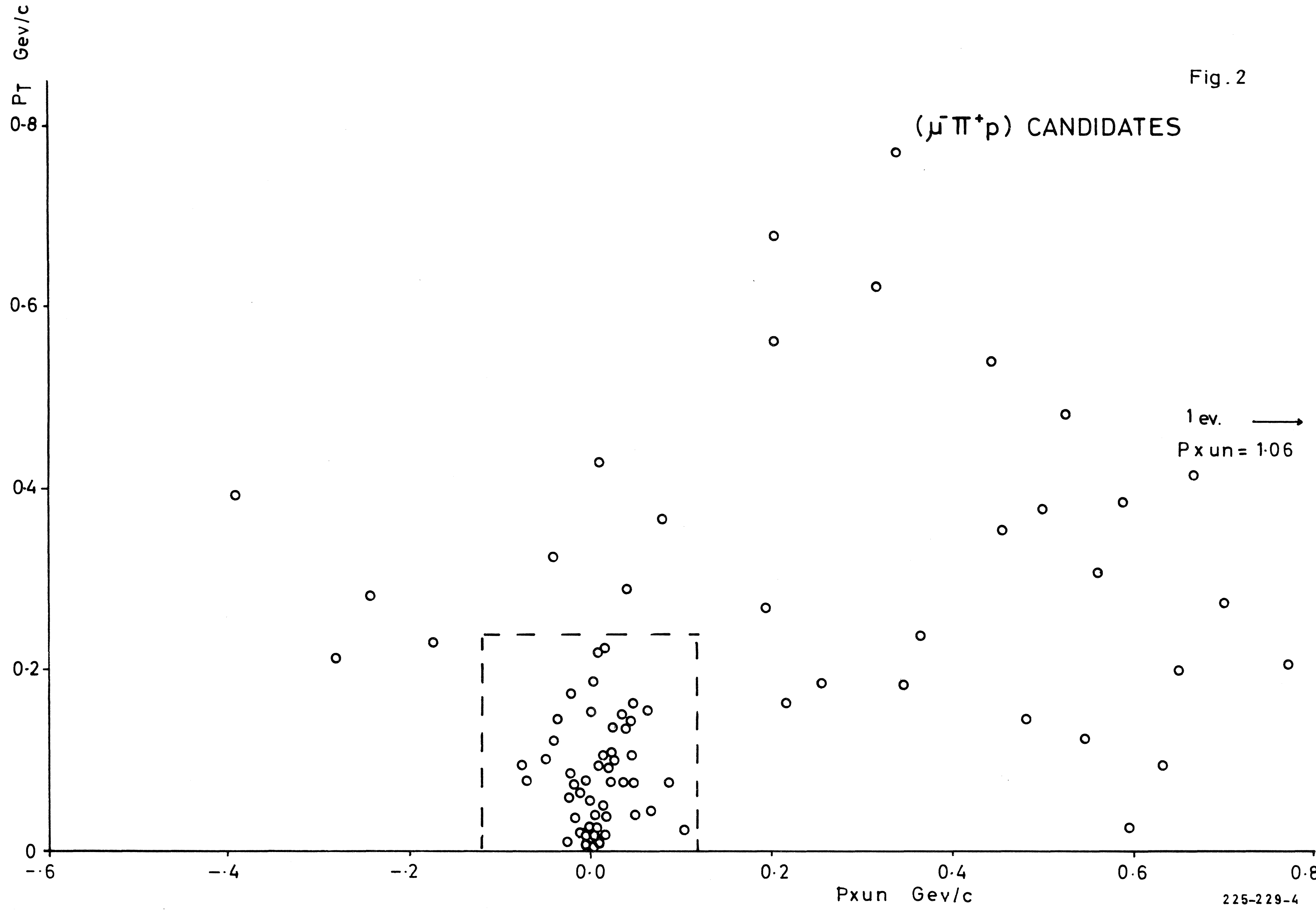


Fig. 2
($\mu^- \pi^+ p$) CANDIDATES
P_T Gev/c
0·8
0·6
0·4
0·2
0
−·6
−·4
−·2
0·0
0·2
0·4
0·6
0·8
Pxun Gev/c
1 ev.
P x un = 1·06
225-229-4

Fig. 3

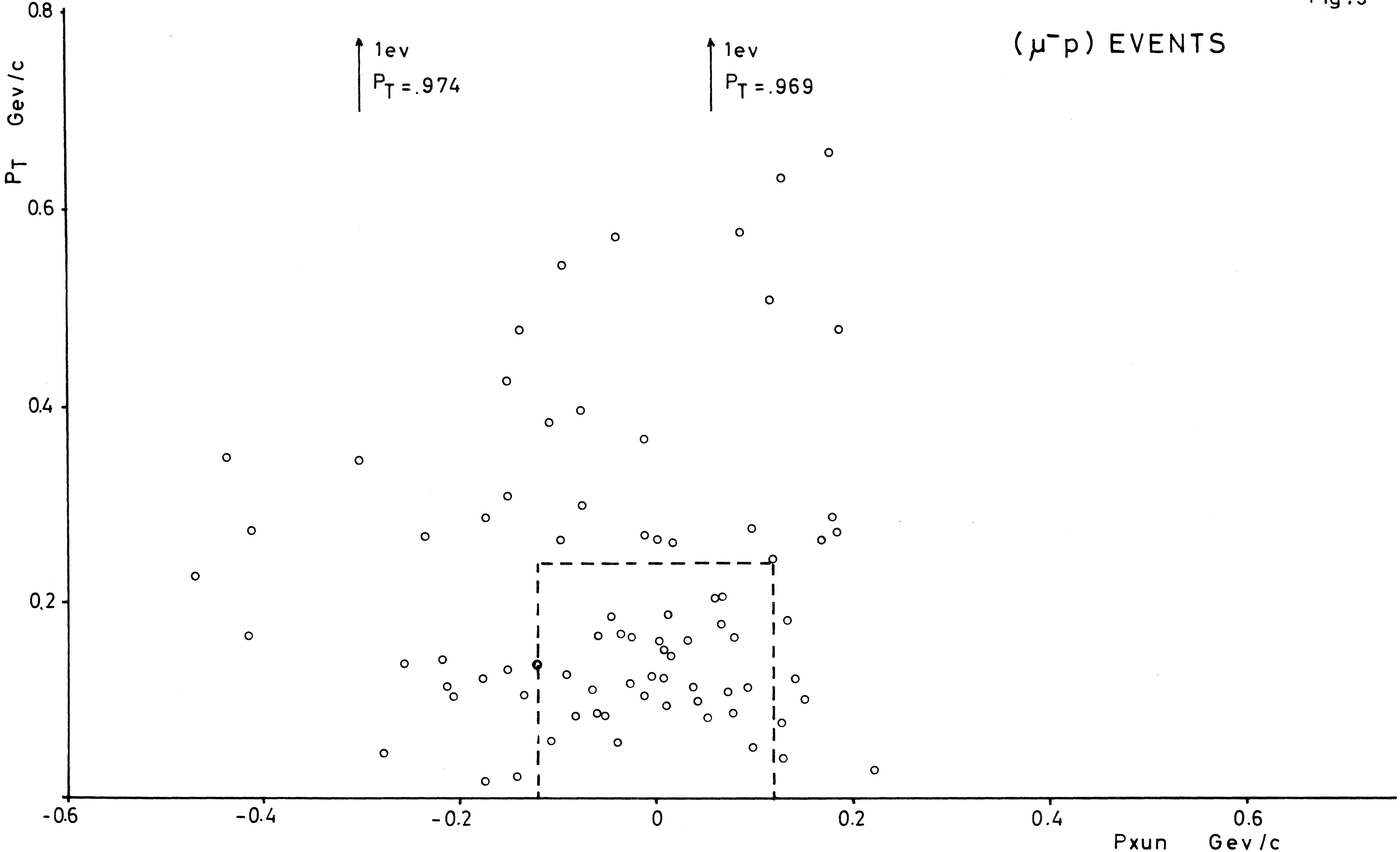


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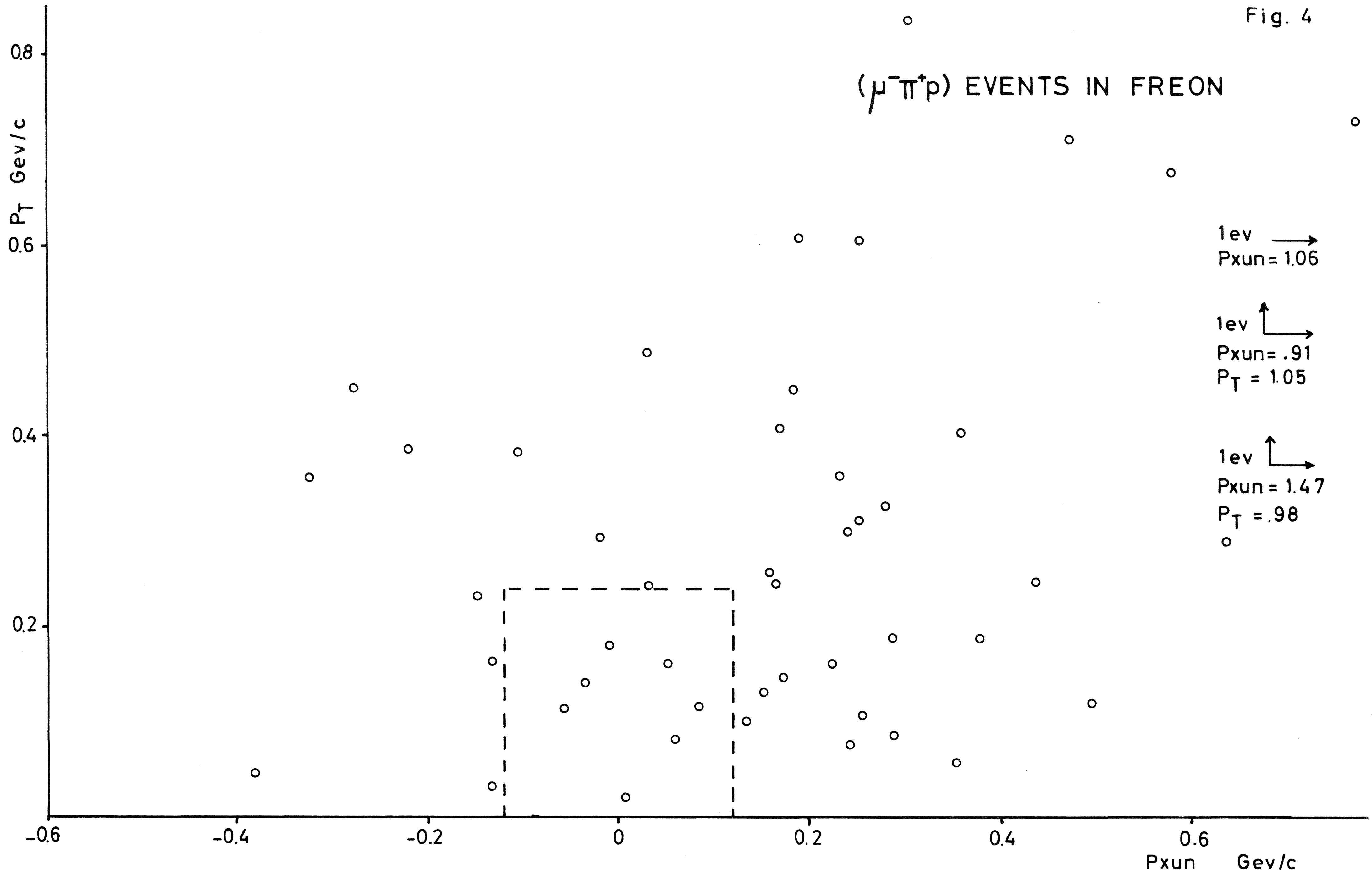
Fig. 4



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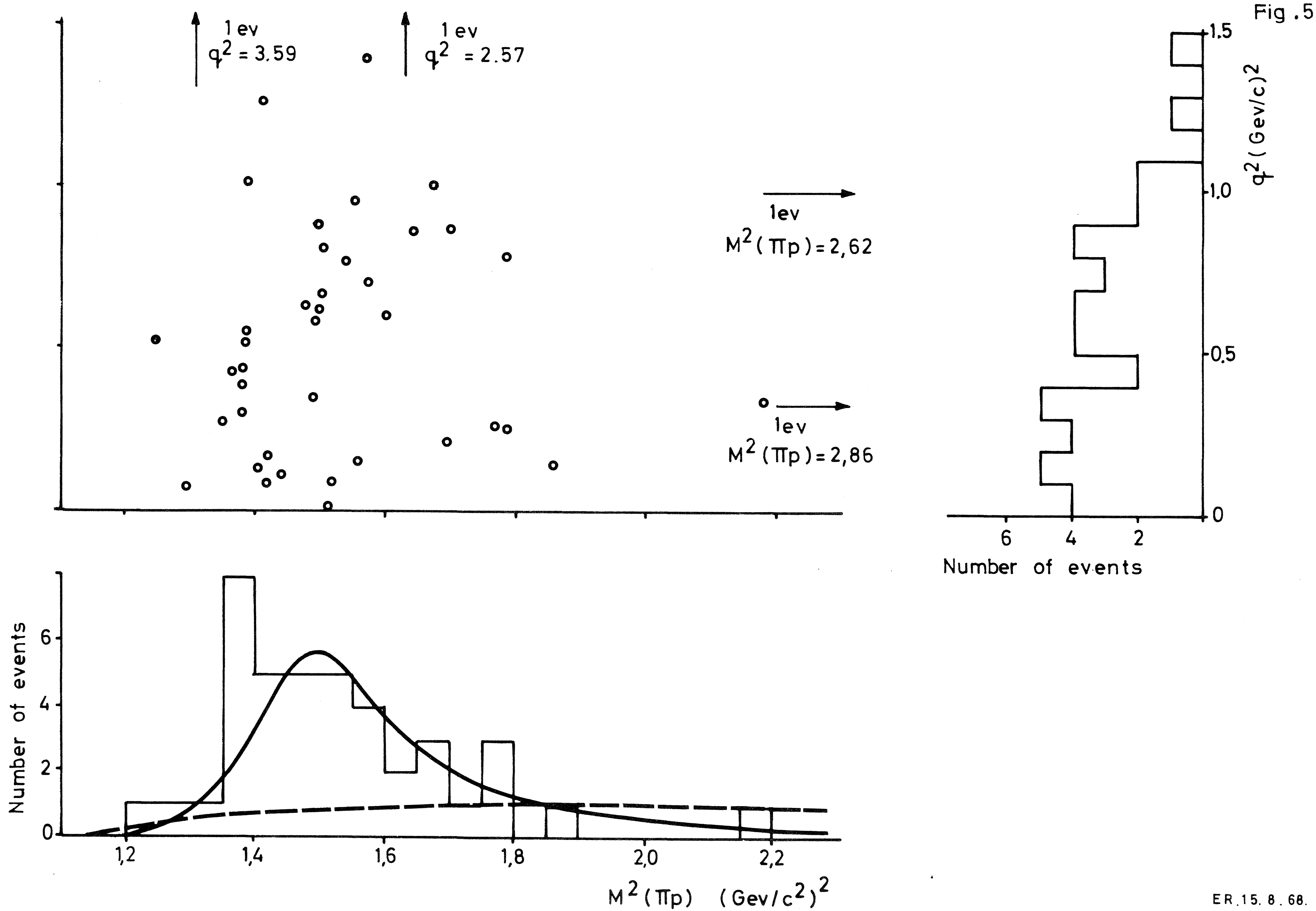

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