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Single Pion Production by Neutrinos on Free Protons

I. Budagov,[a] D. C. Cundy, C. Franzinetti, W. B. Fretter,[b] H.W.K. Hopkins, C. Manfredotti, G. Myatt, F. A. Nezrick,[c] M. Nikolić,[d] T. B. Novey,[e] R. B. Palmer,[f] J.B.M. Pattison, D. H. Perkins, C. A. Ramm, B. Roe,[g] R. Stump,[h] W. Venus, H. W. Wachsmuth, H. Yoshiki

CERN, Geneva, Switzerland

Using a propane bubble chamber the average cross-section for single pion production by neutrinos on free protons has been determined to be $(1.13 \pm 0.28) \times 10^{-38}$ cm^2 for neutrinos of energy between 1 and 4 GeV. The invariant mass distribution of the (πp) system indicates that $N^*(1236)$ production is the dominant process. Angular distributions of the pion in the (πp) rest frame are also presented. The results of the experiment are compared with theoretical predictions.

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[a] Visitor from Laboratory for Nuclear Problems, Joint Institute for Nuclear Research, Dubna, U.S.S.R.

[b] Visitor from University of California, Berkeley, California, U.S.A.

[c] Now at National Accelerator Laboratory, Batavia, Illinois, U.S.A.

[d] Now at Institute of Nuclear Science, Beograd-Vinča, Yugoslavia.

[e] Visitor from Argonne National Laboratory, Argonne, Illinois, U.S.A.

[f] Visitor from Brookhaven National Laboratory, Upton, New York, U.S.A.

[g] Visitor from University of Michigan, Ann Arbor, Michigan, U.S.A.

[h] Visitor from University of Kansas, Lawrence, Kansas, U.S.A.

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The CERN Heavy Liquid Bubble Chamber[1] with a propane filling was exposed at the CERN PS for 1.08×10^6 pulses, corresponding to 6.8×10^{17} protons of momentum 20.6 GeV/c on the target of the improved neutrino beam.[2]

The neutrino spectrum is shown in Fig. 1a. It is based on measurements[3] of the muon flux in the neutrino filter, and is estimated to be accurate within ± 15%. This error includes an estimate of systematic effects. The spectrum calculated by using the available pion and kaon production data is consistent with that of Fig. 1a, although subject to greater uncertainties.

The film was scanned for all interactions in the propane, whether due to incident neutral or charged particles. The scanning efficiency determined 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 85% of the total data.

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

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

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 121 accepted events. Among the 121 events were 17 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 17 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 much smaller because the incoming track will be assumed "outgoing" for this calculation. A cut was therefore made requiring $\Sigma P_X > 300$ MeV/c. Nineteen events were rejected by this cut.

For the remaining 85 events the longitudinal momentum unbalance $\Delta P_X = E_{VIS} - \Sigma P_X$, and P_T, the resultant momentum of all particles transverse to the neutrino beam direction, were calculated, where E_{VIS} is the sum of the energies of the mesons and the kinetic energy of the proton.

For events of type (1) on free protons ΔP_X 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. The distribution of ΔP_X and P_T for the 85 events is shown in Fig. 2. There is a clear concentration of events with ΔP_X and P_T near zero. Events were retained as candidates for reaction (1) on free protons if $|\Delta P_X| < 120$ MeV/c and $P_T <$ 240 MeV/c. A study of the measurement errors indicated that $(5 \pm 2)\%$ of genuine events would be rejected by these cuts. Fifty-two events passed all selection criteria and are used for the cross-section determination.

The selected events may contain the following types of background:

1. Incoming neutron interactions which simulate neutrino events,

2. Events caused by incoming pions which are not removed by the various criteria,
3. Events containing unidentified tracks,
4. Events of the type $(\mu^-\pi^+\pi^o p)$ where the π^o is undetected,
5. Events in carbon.

1. Neutron interactions

In neutron-induced events with the same topology as reaction (1) the negative track must be a pion, which would have a probability of about 0.4 to interact in the chamber. Since no such event with an interacting negative pion passed all the cuts, we estimate the neutron background to be less than 1.5 events.

2. Incoming pion interactions

Among a randomly chosen set of 38 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 which passed the selection criteria and 37 had $\Sigma P_X < 300$ MeV/c. The cut on ΣP_X removed 19 events from our original sample. On this basis we estimate a background of less than 0.5 events from this source.

3. Unidentified tracks

Of the 52 selected events, 23 contained one positive track which was too energetic ($\gtrsim 1$ GeV/c) to be identified by ionization and which did not have a delta-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 statistical analysis based on those positive pions identified by a delta-ray leads to an estimated background of less than 1.3 events of the types $(\mu^-\pi^+\pi^+)$ or (μ^-pp) among the 23 ambiguous events.

4. Background from $(\mu^-\pi^+\pi^o p)$ events

Twelve events of the types $(\mu^-\pi^+\gamma p)$ or $(\mu^-\pi^+2\gamma p)$ were observed. If the γ-rays had not been converted, three of these events would have been included in the hydrogen sample. Using the calculated average γ-ray conversion probability of 0.23, we estimate a background of (4.3 ± 2.5) events among the 52 selected events.

5. Background from carbon

In order to estimate this background we have studied two types of interactions which are known to occur on bound nucleons:

a. events of the type ($\mu^- \pi^+ p$) observed in the previous neutrino experiments in freon CF_3Br,[5]

b. the quasi-elastic process $\nu n \rightarrow \mu^- p$ in propane.

a. Using a sample of 51 ($\mu^- \pi^+ p$) events observed in freon and normalizing to the propane data on the basis of those events with $|\Delta P_X| > 120$ MeV/c or $P_T > 240$ MeV/c, we obtain a background estimate of (3.2 ± 1.2) events from bound nucleons in the region used to define the hydrogen sample. However it is likely that the background would be higher when the events occur in carbon rather than in freon since the pion and proton have a lower probability to destroy the momentum balance by interaction in the nucleus. Calculations based on nuclear sizes and pion-nucleon and proton-nucleon cross-sections indicate that the background caused by carbon would be 50% higher than that caused by freon. The background estimate thus becomes (4.8 ± 1.8) events.

b. With a sample of 81 ($\mu^- p$) events observed in the present experiment we have made a background estimation using those events with $120 < |\Delta P_X| < 220$ MeV/c and $P_T < 240$ MeV/c to normalize between the ($\mu^- p$) and ($\mu^- \pi^+ p$) events. In this region Fermi motion should be the major cause of unbalance and this should be the same in the two event types. We thus obtain a background estimate of (4.0 ± 2.8) events from bound nucleons.

Since estimates a. and b. are compatible we combine them to obtain an estimated carbon background of (4.6 ± 1.5) events.

The total background estimate becomes (8.9 ± 2.9) events, i.e. (17 ± 6)%.

In order to calculate the cross-section for process (1) on free protons we make the following corrections to the 52 observed events: background subtraction (- 17 ± 6)%, unmeasurable events (+ 16 ± 4)%, scanning efficiency (+ 11 ± 11)%, good events failing selection criteria (+ 5 ± 2)%. The energy distribution of the 52 events and the resulting cross-sections are shown in Figs. 1b and 1c respectively. In calculating the cross-section the non-uniformity of the neutrino flux over the chamber was taken into account.

We compare our data with theoretical predictions by Adler,[6] Altarelli et al.,[7] and Salin.[8] These authors have calculated the cross-section for process (1) with the nucleon axial-vector form factor F_A parametrized as $F_A = (1 + q^2/M_A{}^2)^{-2}$, where q is the four-momentum transfer between the leptons. The values of M_A used by the various authors are indicated in Fig. 1c. It may be seen that the data are in good agreement with the calculations of Altarelli et al., and of Salin with a value of M_A close to that suggested by studies[5,9] of the quasi-elastic process, $\nu n \to \mu^- p$, while the calculation by Adler with a similar M_A gives a lower cross-section.

For a more quantitative comparison we have computed the observed cross-section in the region 1 to 4 GeV where the neutrino flux can be determined with greater accuracy and the predicted cross-sections are approximately constant. We find, $\sigma(\nu p \to \mu^- \pi^+ p) = (1.13 \pm 0.28) \times 10^{-38}\ \mathrm{cm}^2$, where the error quoted is partly statistical and partly the result of the estimated errors in the neutrino flux, scanning efficiency, and corrections. The various predictions for this cross-section are:

$$\sigma(\nu p \to \mu^- \pi^+ p) = 0.42 \times 10^{-38}\ \mathrm{cm}^2,\quad M_A = 0.84\ \mathrm{GeV}/c^2 \qquad \text{(Adler)}$$
$$= 0.85 \times 10^{-38}\ \mathrm{cm}^2,\quad M_A = 0.84\ \mathrm{GeV}/c^2 \qquad \text{(Altarelli et al)}$$
$$= 0.77 \times 10^{-38}\ \mathrm{cm}^2,\quad M_A = 0.88\ \mathrm{GeV}/c^2 \qquad \text{(Salin)}$$

In Fig. 3 are shown the distributions in q^2 and in the square of the invariant mass of the pion-proton system ($M^2(\pi p)$) for the 46 selected events with $E_{VIS} > 1$ GeV. The $M^2(\pi p)$ histogram 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]

We have also studied the angular distribution of the pion in the (πp) rest frame. To do this we have taken events from a larger fiducial volume than that used for the cross-section determination. We have used two coordinate systems: those proposed by Adler[6] and by Berman and Veltman.[10] The definitions of these systems are given in Fig. 4a and Fig. 4b respectively. The distributions in Adler's angles φ and δ for events with $M(\pi p) < 1.39$ GeV/c^2, the region covered by his calculation, are shown in Fig. 4a. The distributions in the angles θ' and φ' defined by Berman and Veltman, for those events with $1.3 < M^2(\pi p) < 1.9$ (GeV/c^2)^2 and $\sin^2\alpha/2 < 0.1$, are shown in Fig. 4b. For N_{33}^* production Berman and Veltman calculate that as $\sin^2\alpha/2 \to 0$ the angular distribution of the pion should become

$$D(\theta', \varphi') \propto 1 + 3\cos^2\theta' \qquad (2)$$

The observed distribution in $\cos\theta'$ is consistent with (2). However the distribution in φ' shows a 2.9 standard deviation asymmetry with respect to the ($\mu\nu$) plane. Conservation of parity would require that this distribution be symmetric. Adler[6] has suggested that interference between the N_{33}^* and the non-resonant background could give rise to an effect of this nature.

In conclusion we may remark that at present the discrepancies between the various theoretical predictions prevent the determination of M_A from our measured cross-section. The calculations of Altarelli et al. and of Salin suggest that $M_A \sim 1$ GeV/c^2 whereas that of Adler would indicate that $M_A > 2$ GeV/c^2. The distribution in $M^2(\pi p)$ and the angular distribution of the pion indicate that $N_{33}^*(1236)$ production is the dominant process, but that interference with the non-resonant background can give significant effects.

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Distribution : (open)
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Figure Captions

1a. Neutrino flux averaged over 40 cm radius detector.

1b. Energy distribution of 52 events accepted as $\nu p \rightarrow \mu^- \pi^+ p$.

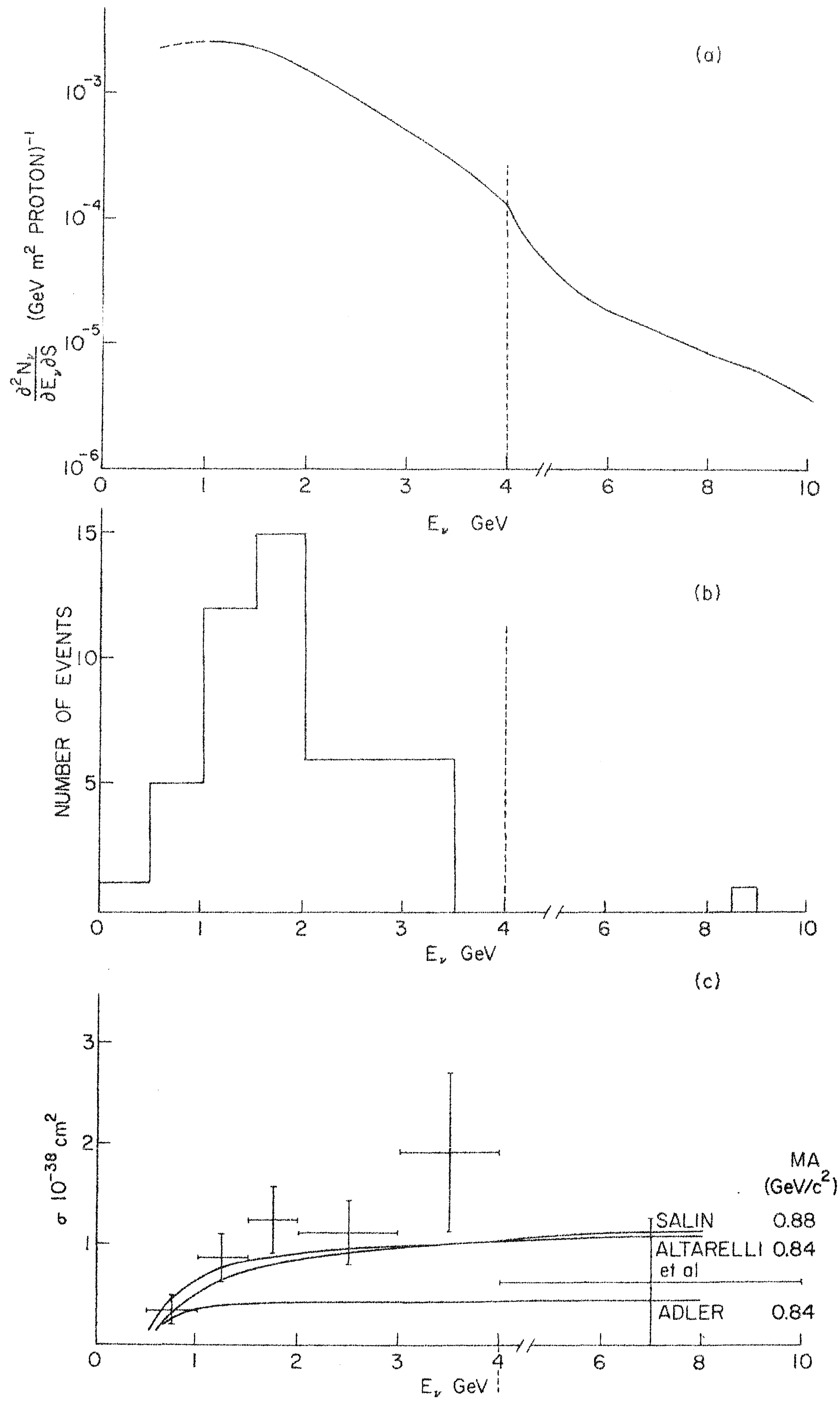
1c. Cross-section for $\nu p \rightarrow \mu^- \pi^+ p$. The errors shown are purely statistical; the systematic errors are ± 20%.

2. ΔP_X vs. P_T for $(\mu^- \pi^+ p)$ candidates.

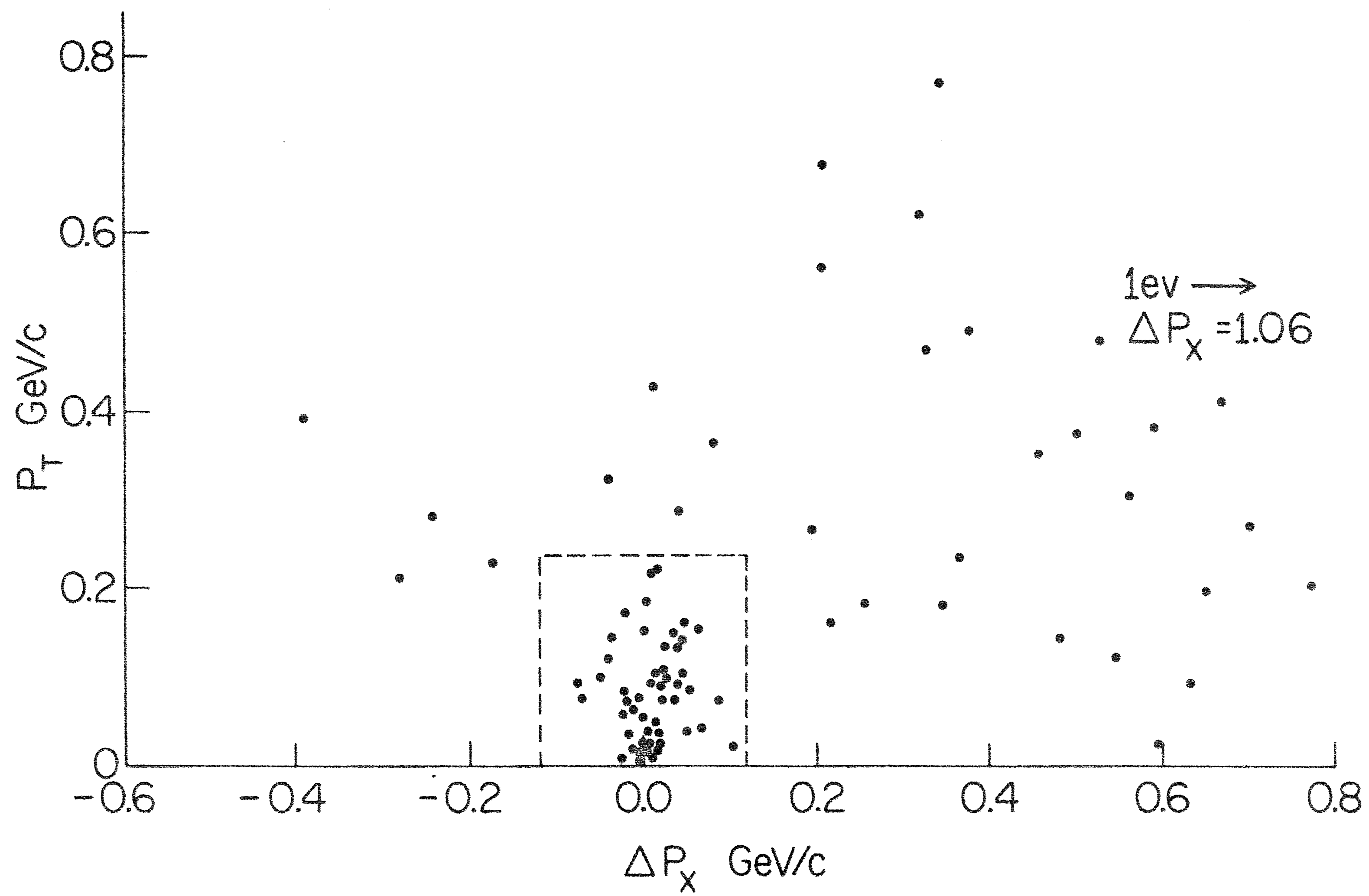
3. q^2 and $M^2(\pi p)$ distributions for $(\mu^- \pi^+ p)$ events with $E_{VIS} > 1$ GeV.

4a. Definition of pion angles used by Adler and distributions in $\cos\varphi$ and δ for events with $M(\pi p) < 1.39$ GeV/c^2.

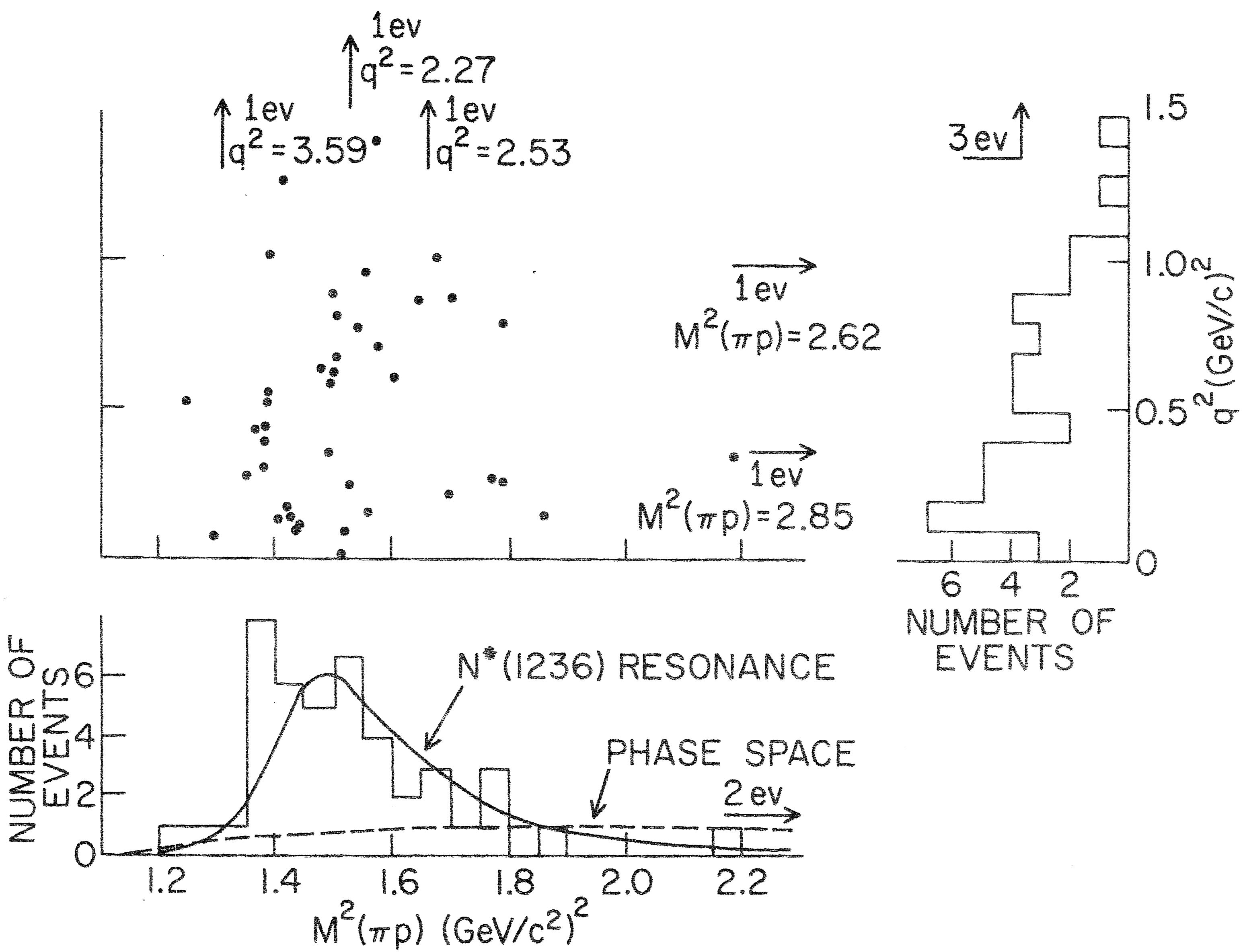
4b. Definition of pion angles used by Berman and Veltman and distributions in $\cos\theta'$ and φ' for events with $1.3 < M^2(\pi p) < 1.9$ $(\mathrm{GeV}/c^2)^2$ and $\sin^2\alpha/2 < 0.1$.



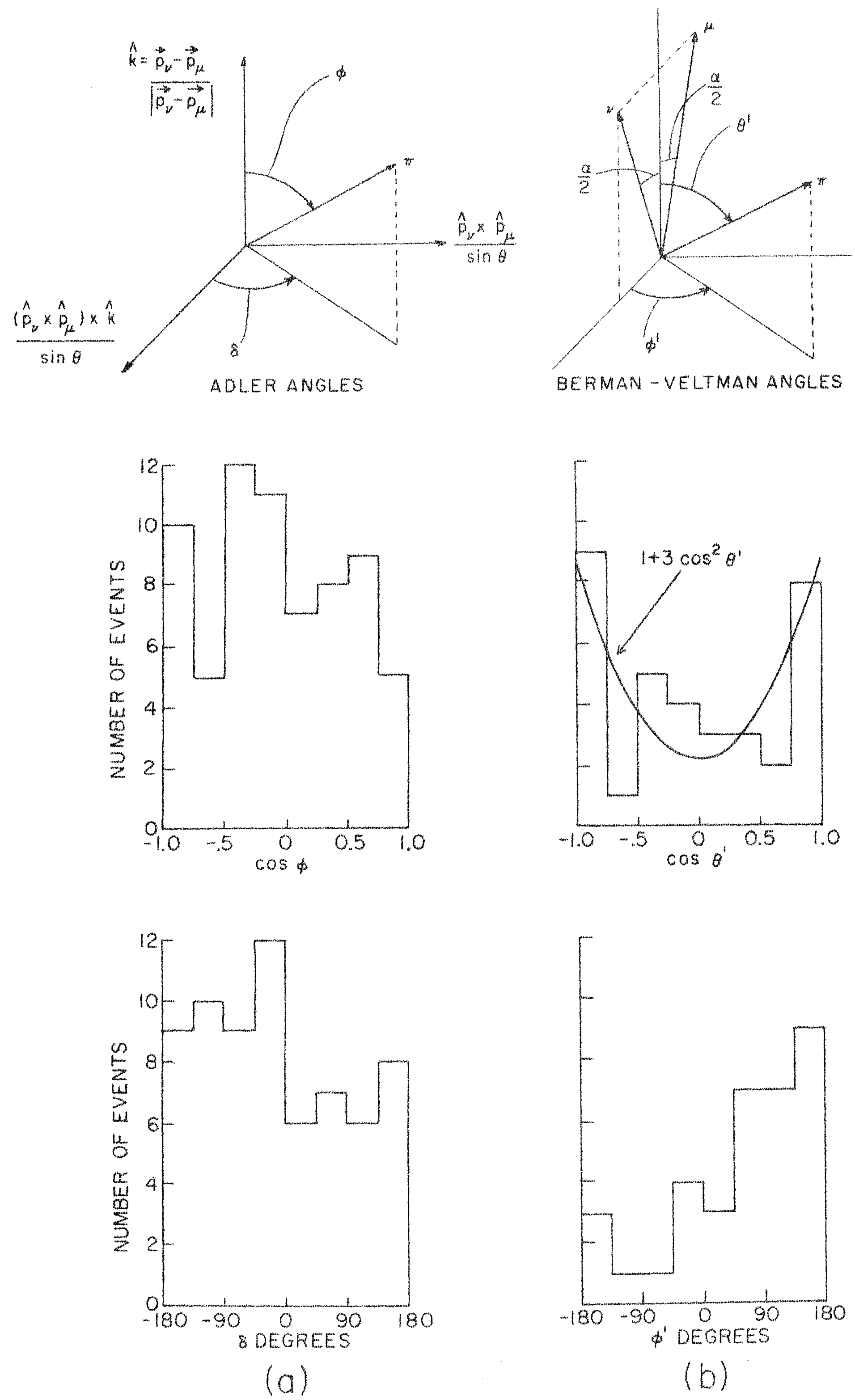
(a)
$\frac{\partial^2 N_\nu}{\partial E_\nu \partial S}$ (GeV m^2 PROTON)$^{-1}$
10^{-3}
10^{-4}
10^{-5}
10^{-6}
0 1 2 3 4 6 8 10
E_ν GeV
(b)
NUMBER OF EVENTS
15
10
5
0 1 2 3 4 6 8 10
E_ν GeV
(c)
σ 10^{-38} cm^2
3
2
1
MA
(GeV/c^2)
SALIN 0.88
ALTARELLI 0.84
et al
ADLER 0.84
0 1 2 3 4 6 8 10
E_ν GeV



0.8
0.6
0.4
0.2
0
P_T GeV/c
1ev →
ΔP_X =1.06
−0.6
−0.4
−0.2
0.0
0.2
0.4
0.6
0.8
ΔP_X GeV/c



1ev
q² = 2.27
1ev
q² = 3.59
1ev
q² = 2.53
1ev
M²(πp) = 2.62
1ev
M²(πp) = 2.85
3ev
1.5
1.0
0.5
0
q²(GeV/c)²
6 4 2
NUMBER OF EVENTS
N*(1236) RESONANCE
PHASE SPACE
2ev
NUMBER OF EVENTS
0
2
4
6
1.2
1.4
1.6
1.8
2.0
2.2
M²(πp) (GeV/c²)²



ADLER ANGLES
BERMAN - VELTMAN ANGLES
NUMBER OF EVENTS
cos φ
1+3 cos² θ'
cos θ'
NUMBER OF EVENTS
δ DEGREES
φ' DEGREES
(a)
(b)