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COHERENT PRODUCTION OF π^+ AND π^- MESONS BY CHARGED CURRENT INTERACTIONS OF NEUTRINOS AND ANTINEUTRINOS ON NEON NUCLEI AT THE TEVATRON

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Abstract

First results are presented on π^+ and π^- coherent production by ν and $\bar{\nu}$ interactions on neon nuclei, in the 15′ bubble chamber exposed to the Tevatron neutrino beam. The mean charged current event energies are 150 and 110 GeV for neutrinos and antineutrinos respectively. Coherent events are selected with an energy $E > 40$ GeV. Within the statistics available in this first part of the data, the absolute value of the cross section and the kinematical distributions are in agreement with predictions based on PCAC.

In this paper, we present a first report on the coherent production of π^+ and π^- mesons by charged current neutrino and antineutrino interactions on neon nuclei at the Tevatron.

Over the last few years, a consistent picture has been emerging from a series of experimental studies on single pion coherent production. The data are well described by the process illustrated in Fig. 1, which is based on the Partial Conservation of Axial-vector Current (PCAC) hypothesis: the pion in the final state is produced by the coherent scattering off the nucleus of the longitudinal component of the axial-vector field, dominated by the $J^{PC} = 1^{++}$ a_1 resonance; at $Q^2 = 0$, the latter couples to the W field with the pion decay constant f_π [1,2].

The energy domain studied so far ranges from 2 to 100 GeV. At the lower end, π^0 coherent production was studied in experiments at the CERN PS [3,4]. At Serpukhov, between 5 and 20 GeV, results on π^+, π^- and π^0 production were obtained using the bubble chamber SKAT [5]. Several experiments have reported results at higher energy: at the CERN SPS, π^- production by $\bar{\nu}$ [6] and π^+ production by ν [7] were studied using the bubble chamber BEBC, whereas π^0 production by ν and $\bar{\nu}$ was studied by the counter experiment CHARM [8]; data were also obtained on π^0 production by neutrinos [9] and on π^- production by antineutrinos [10] in the 15′ bubble chamber exposed to the Fermilab wide-band beams.

The specific feature of the data presented here is that the bulk of our events have energies larger than those reached in experiments reported before. These data were obtained in a 4-month exposure, in 1985, of the 15′ bubble chamber to the Fermilab neutrino beam, during the first neutrino run at the Tevatron. The beam was a Quadrupole Triplet beam, composed of roughly 2/3 neutrinos and 1/3 antineutrinos; the ν and $\bar{\nu}$ beams have, respectively, average energies of 90 and 75 GeV, and extend beyond 300 GeV; the average energies of the charged current events are, respectively, 150 and 110 GeV. For this exposure the chamber was filled with a heavy (72 to 76 mole %) $Ne - H_2$ mixture.

In the 1985 run, some 140000 pictures were taken. The data used here comes from about 105000 frames, corresponding to 1.80×10^{17} protons on target; this in turn corresponds to (10800 $\pm$ 10%) charged current ν and (2600 $\pm$ 10%) charged current $\bar{\nu}$ interactions.

For the 1985 run, the events with 2 or 4 charged secondaries (2 or 4 prongs) have been measured, as well as a complete sample of $\sim$ 10% of the total number of events, used for normalization: the measuring process is nearly completed.

In 1987-88, a new run took place, where about 300000 pictures were taken, corresponding to $\sim 4.5 \times 10^{17}$ protons on target; the chamber was filled with a lighter mix (64 mole % $Ne - H_2$). Thus, when all the data are available, the statistics presented here will be more than tripled.

For the present analysis, we select 2-prong $\mu\pi$ events with energy greater than 40 GeV, where the specific contribution of this experiment is most significant. Events with associated γ or V^0, fitting a K^0 or Λ^0, or with no particle leaving the chamber without interacting, were rejected, as were events where the projections of the particle momenta on the plane transverse to the (anti)neutrino direction made an angle $< 90^0$. For these runs, the bubble chamber was equipped with a new external muon identifier (EMI), and an Internal Picket Fence (IPF). However, for the present work, they are not used, and instead, among the selected 2-prong events, a particle is called a muon if it leaves the bubble chamber without interacting; if both particles do so, the one with the higher momentum is taken as the muon.

A total of 51 $\mu^-\pi^+$ and 9 $\mu^+\pi^-$ events with $E > 40$ GeV and $p_\mu > 20$ GeV was thus selected (any charged particle not selected as a muon or identified as a proton stopping in the bubble chamber, is classified as a pion). An additional 14 $\mu^-\pi^+$ and 1 $\mu^+\pi^-$ events contained, at the vertex, nuclear fragments or protons with momentum below 250 to 400 MeV (the momentum cut, evaluated at the scan table, varies with the depth of the event in the chamber); these protons, called "stubs", are not used to compute the kinematical quantities of the event.

Using a method defined in [11], the coherent signal is obtained by comparing the $|t|$-distributions of the events with and with no stubs (Fig. 2), t being the square of the 4-momentum transferred to the nucleus. As the latter recoils as a whole, without being detected, t cannot be measured directly, and must be evaluated using the final state particles; to an excellent approximation, $|t|$ is given by

$$|t| = [\sum_{\mu,\pi}(E_i - p_i^{\|})]^2 + [\sum_{\mu,\pi}\vec{p}_i^T]^2 \qquad (1)$$

where E_i, $p_i^{\|}$ and $\vec{p}_i^T$ are, respectively, the energy and the longitudinal and transverse momenta of the muon and the pion, relative to the neutrino direction.

As observed in Fig. 2, the $|t|$-distribution of the events with no stub is characterized by a large peak at small $|t|$-values , whereas the $|t|$-distribution of the events with stubs is flatter: for $|t| < 0.1\ GeV^2$, the numbers are, respectively, 20 and 2 events, whereas they are 40 and 13 for $|t| > 0.1\ GeV^2$. Among the 20 events with no stub, 16 are $\mu^-\pi^+$ events and 4 are $\mu^+\pi^-$ events. The excess of events with no stub at $|t| < 0.1\ GeV^2$ over the background given by the events with stubs is attributed to coherent interactions. For $E > 40\ GeV$, the coherent signal is thus evaluated to be (14 ± 5) events. It will be compared hereafter to predictions based on PCAC [1,2], in a similar way as was done in [6,7]; Monte-Carlo studies have been performed, taking into account the specific smearing conditions of the present experiment.

To evaluate the absolute cross section, the signal of (14 ± 5) events has to be corrected for several factors:
- the scanning efficiency for $\mu\pi$ events is provisionally estimated to be (0.7 ± 0.1). A special scan will be started soon, using the EMI and the IPF, in order to evaluate this efficiency better; this will also improve the conservative estimate of 10% uncertainty on the total number of charged current interactions quoted above;
- events where the pion charge and momentum are poorly evaluated ($\Delta p/p > 0.7$) are discarded, giving a correction factor of 1.11;
- the correction factor for the cut at $|t| < 0.1\ GeV^2$ is estimated, using the Monte-Carlo simulation, to be 1.24. This rather large correction is mainly due to the smearing on the muon momentum ($<\Delta p/p>= 0.10$ for $p_\mu > 20$ GeV);
- the loss of events due to the cut on the muon momentum at $p_\mu > 20$ GeV is negligible for the coherent events with $E > 40$ GeV: about 1%;
- the loss of events due to the use of the kinematical method is also negligible: at low $|t|$-values and high energy, the projections of the momenta of the muon and the pion in the plane transverse

to the neutrino direction are constrained to be in opposition; indeed, if this were not the case. the second term in (1), which is the square of the total momentum imbalance of the event, would exceed the $|t|$-cut, given the observed distributions of the muon and the pion transverse momenta;

- the contamination of charged current events at $|t| < 0.10\ GeV^2$ by neutron stars or neutral current events is also negligible for a similar reason: the total p_T of such events exceeds the low value allowed by the $|t|$-cut;
- finally, the wrong identification of the muon in the case where both particles leave the chamber without interacting is also small: the Monte-Carlo studies show that 94% of all coherent events have $p_\mu > p_\pi$, and the pion interacts in two thirds of the events.

The cross section for coherent interactions in the Tevatron Quadrupole Triplet beam, with $E > 40$ GeV, is thus finally evaluated to be $(350 \pm 140) \times 10^{-40} cm^2/$ neon nucleus. This is obtained using the total number of charged current events, the beam composition and spectra, the known cross sections for ν and $\bar{\nu}$ charged current interactions (respectively 0.70 and $0.35 \times 10^{-38} \times E\ cm^2/GeV$), and the composition of the mix. This value is compared in Fig. 3 to data points from the BEBC experiments [6,7], and to the model predictions for 2 values of the axial mass: 1.05 GeV, as published by τ lepton decay experiments [12] , and 1.35 GeV, as obtained in [6] from the study of the Q^2-distribution in π^- coherent production; the Particle Data Group gives a mass of $\sim$ 1.28 GeV for the a_1 meson, obtained from hadronic production experiments.

The distributions for the kinematical variables E_ν, $\nu = E_\nu - p_\mu$, Q^2 (the square of the 4-momentum transfer from the leptons to the hadrons), $x = Q^2/2M_p\nu$ (M_p is the nucleon mass), $y = \nu/E_\nu$ and $|t|$ are shown in Fig. 4, and compared to the model predictions (for $m_A = 1.05$ GeV); the positions of the 2 events with stubs are shown by the arrows on the figure. Given the small statistics, one observes a general agreement between the data and the predictions; the Q^2-, x- and $|t|$- distributions appear flatter than expected, but are still compatible with the predictions within statistics. In addition, these distributions contain about one third of background, which has not been subtracted: this will require detailed studies, which will be made easier by the measurement of the 3-prong events in the film taken during the 1987 run.

In conclusion, a study has been performed of the coherent production of π^+ and π^- mesons by charged current interactions of ν and $\bar{\nu}$ on neon nuclei, in the 15′ bubble chamber exposed to the Tevatron neutrino beam. Within the limited statistics available for the moment, the absolute value of the cross section and the distributions of the kinematical variables are in agreement with the predictions based on PCAC. This extends, in the highest energy domain, the consistent picture of this process emerging from several experiments, scattered in the energy range 2 to 200 GeV. More detailed studies will be possible soon, when further data are available and the statistics are more than tripled.

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[12] see e.g. H. Albrecht et al. : Z. Phys. C33, 7, (1986); note however the reanalysis of those data by N.A.Törnqvist : Z. Phys. C36, 695 (1987), giving a mass $m_A \sim 1.25$ GeV.

Figure Captions

Fig. 1 Coherent π production by charged current neutrino interaction on nucleus.

Fig. 2 Distributions of the square of the 4-momentum transfer $|t|$ for 60 events with no stub (solid histogram) and for 15 events with stubs (dashed histogram), normalized to the former for $|t| > 0.10\ GeV^2$.

Fig. 3 Cross section for coherent π production by ν and $\bar{\nu}$ interactions on neon, as a function of the energy E_ν; the curves are the predictions of the PCAC-based model for two choices of the axial-vector mass m_A.

Fig. 4 Distributions of kinematical variables for the 20 $\mu\pi$ events with no stub with $|t| < 0.10\ GeV^2$; the positions of 2 events with stubs are shown by arrows. The curves, normalized to the events with no stub, are the predictions of the model for $m_A = 1.05$ GeV.

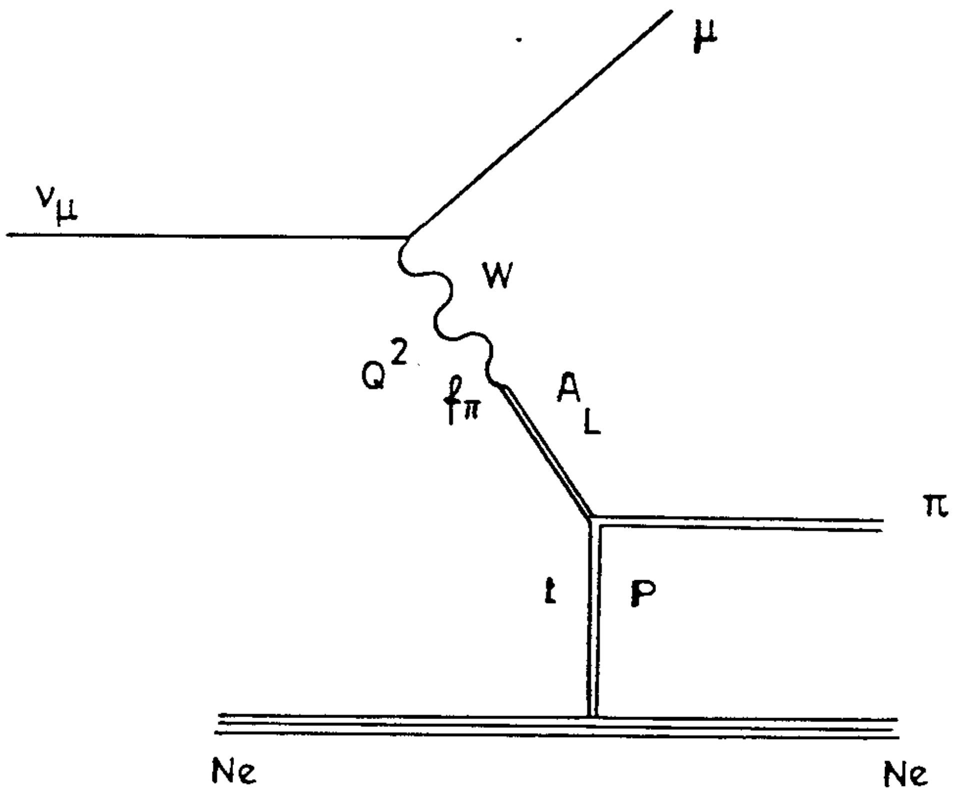


Fig.1

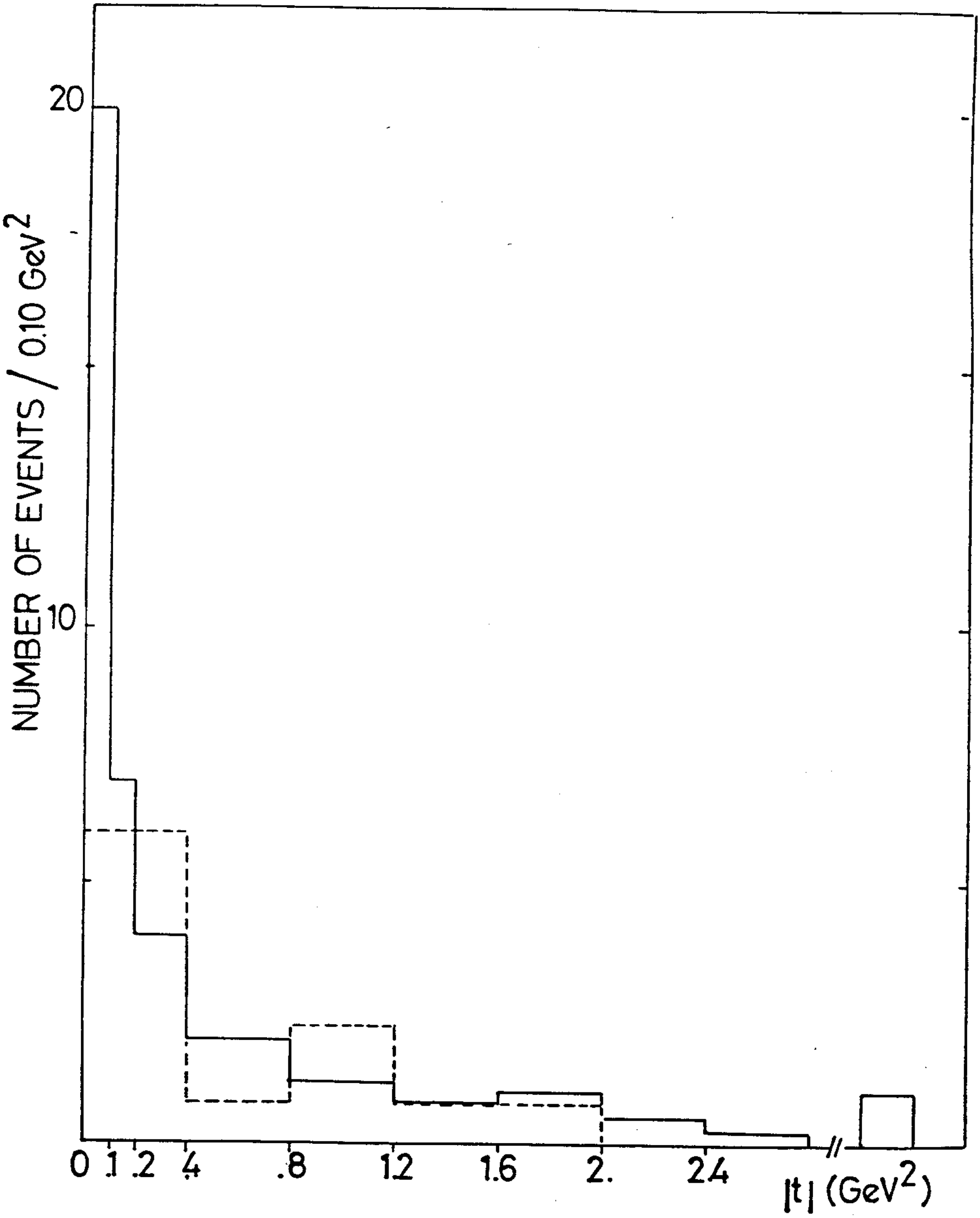


Fig. 2

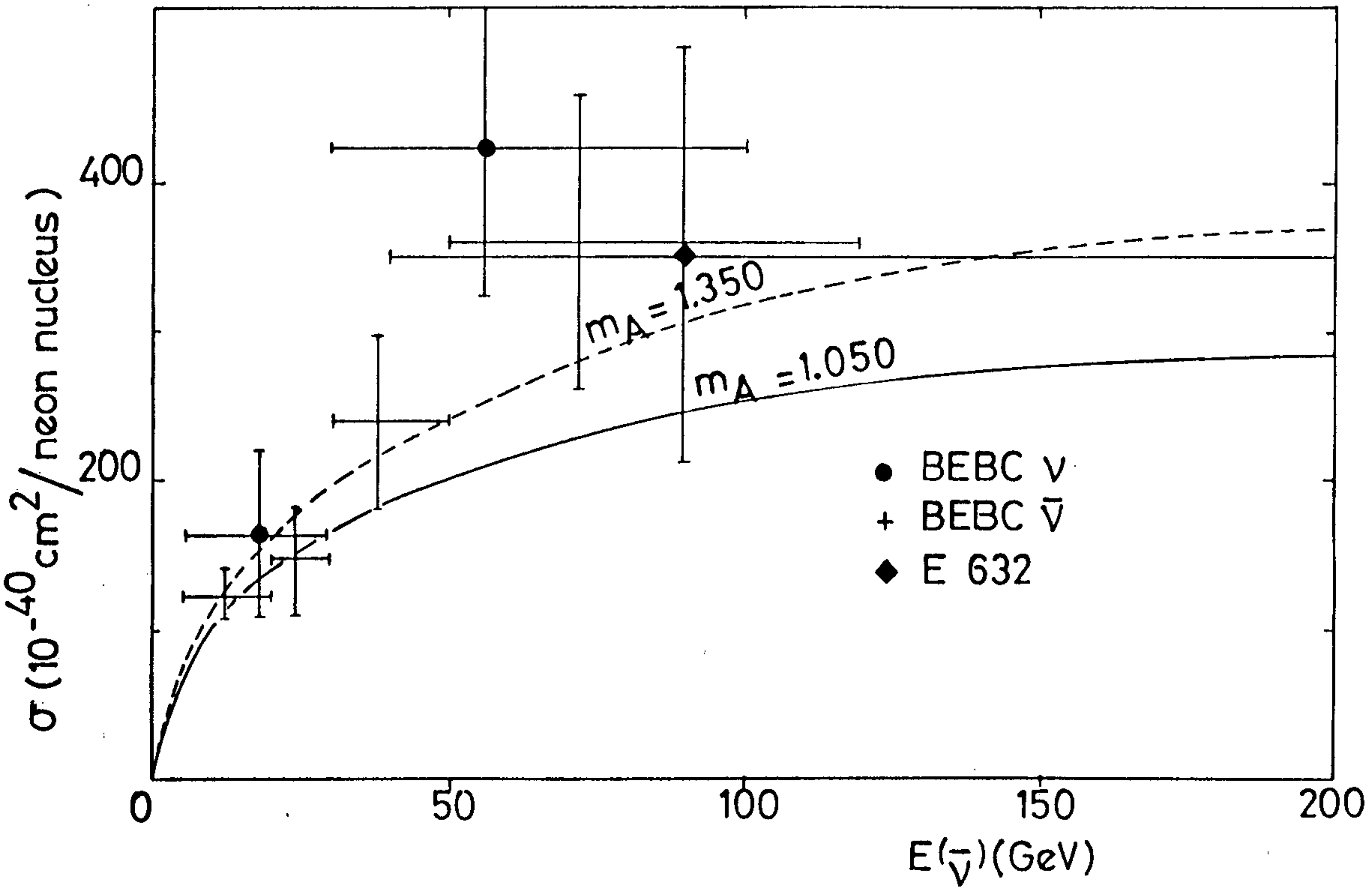
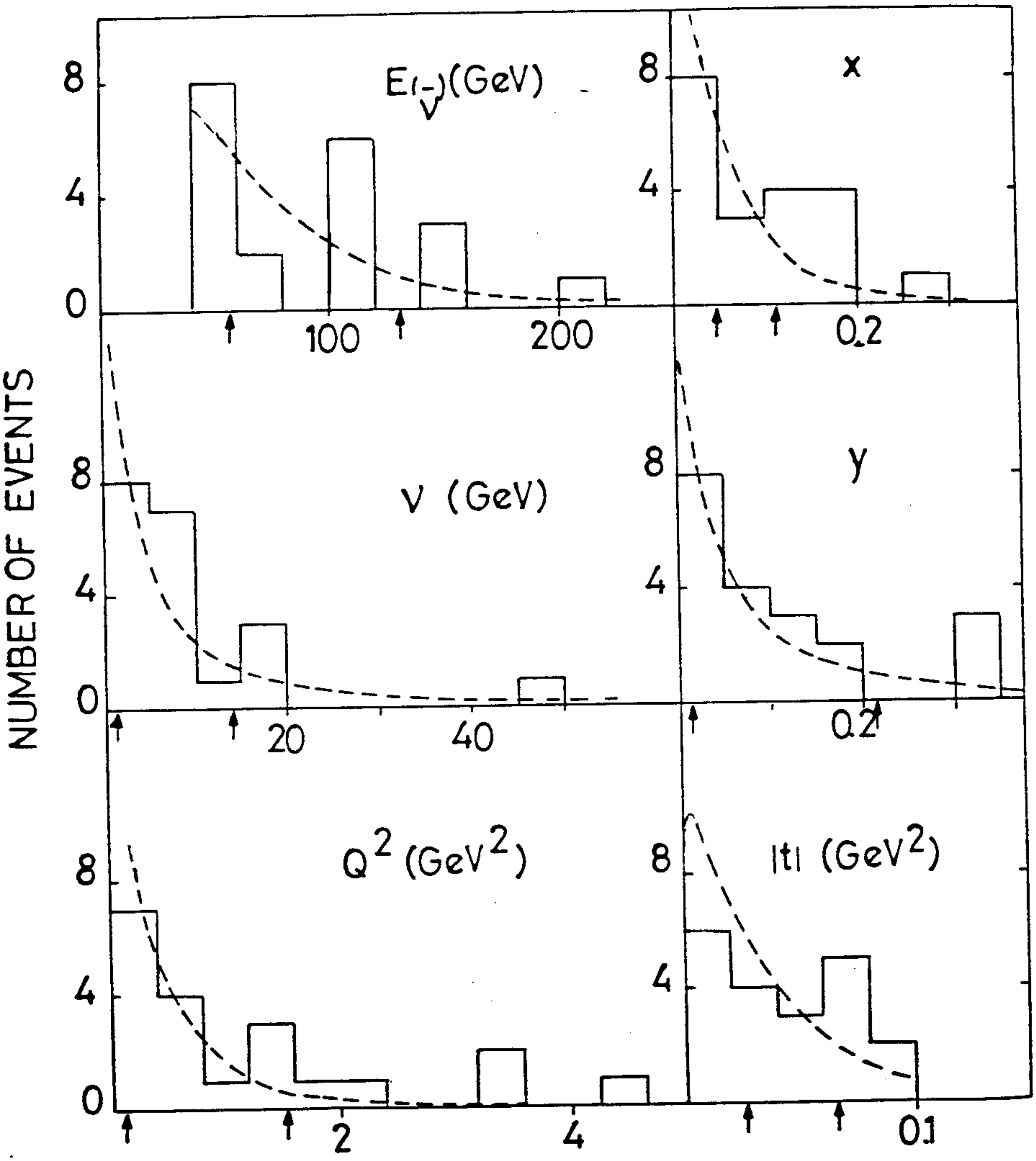

σ (10^-40 cm^2/neon nucleus)
400
200
0
50
100
150
200
E(ν̄)(GeV)
m_A = 1.350
m_A = 1.050
BEBC ν
BEBC ν̄
E 632

Fig. 3


NUMBER OF EVENTS
$E_{\overset{(-)}{\nu}}$ (GeV)
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4
0
100
200
x
8
4
0.2
ν (GeV)
8
4
0
20
40
y
8
4
0.2
Q^2 (GeV^2)
8
4
0
2
4
|t| (GeV^2)
8
4
0.1

Fig. 4