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First Observation of Neutrino Trident Production

The CHARM II Collaboration

D. Geiregat[1], G. Wilquet[2]
Inter-University Institute for High Energies (ULB-VUB), Brussels, Belgium

U. Binder, H. Burkard, U. Dore[3], W. Flegel, H. Grote, T. Mouthuy, H. Øverås, J. Panman, R. Santacesaria[4], P. Vilain[2,5], K. Winter, G. Zacek, V. Zacek
CERN, Geneva, Switzerland

R. Beyer, F. W. Büsser, C. Foos, L. Gerland, T. Layda, F. Niebergall, G. Rädel, P. Stähelin, T. Voss
II. Institut für Experimentalphysik[6], Universität Hamburg, Hamburg, FRG

D. Favart, G. Grégoire, E. Knoops[1]
Université Catholique de Louvain, Louvain-la-Neuve, Belgium

P. Gorbunov, E. Grigoriev, V. Khovansky, A. Maslennikov, A. Rozanov[7]
Institute for Theoretical and Experimental Physics, Moscow, USSR

W. Lippich, A. Nathaniel, A. Staude
Sektion Physik der Universität[6] München, Munich, FRG

M. Caria[8], B. Eckart, A. Ereditato, R. Iasevoli, V. Palladino, P. Strolin
Università e Istituto Nazionale di Fisica Nucleare (INFN), Naples, Italy

A. Capone[9], D. De Pedis, E. Di Capua[0], A. Frenkel-Rambaldi, P. F. Loverre, G. Piredda, D. Zanello
Università 'La Sapienza' e Istituto Nazionale di Fisica Nucleare (INFN), Rome, Italy

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[1] Inter-University Institute for Nuclear Science, Brussels, Belgium.
[2] National Foundation for Scientific Research, Belgium.
[3] On leave of absence from Università 'La Sapienza', Rome ,Italy.
[4] On leave of absence from INFN, Rome, Italy.
[5] On leave of absence from Inter-University Institute for High Energies (ULB-VUB), Brussels, Belgium.
[6] Funded by the Ministry for Research and Technology (BMFT), FRG.
[7] Presently at CERN, Geneva, Switzerland.
[8] Dipartimento di Scienze Fisiche, Università di Cagliari, Cagliari, Italy.
[9] Facoltà di Scienze, Università della Basilicata, Potenza, Italy.
[0] Dipartimento di Fisica, Università di Ferrara, Ferrara, Italy.

Abstract

We report on the first observation of neutrino induced production of muon pairs in the electromagnetic field of a nucleus. The data has been obtained using the CHARM II detector exposed to the CERN wideband neutrino and antineutrino beams. A clear signal of 55 ± 16 events is seen in a sample of dimuons of opposite charge without visible recoil at the vertex. The cross section is determined and found to be in agreement with the Standard Model prediction.

1. Introduction

Neutrino induced creation of lepton pairs in the electromagnetic field of a nucleus, usually called neutrino trident production, offers a further possibility to study neutrino lepton interactions. The reactions

$$\overset{(-)}{\nu}_\mu + A \rightarrow \overset{(-)}{\nu}_\mu + \mu^+ + \mu^- + A \tag{1}$$

are of particular interest as both charged and neutral weak currents contribute (see fig. 1). A cross section measurement of these processes therefore provides a direct test of the interference between the amplitudes of W and Z exchange as predicted by the Standard Model [1].

The cross sections for trident production by neutrinos and antineutrinos are equal and can be calculated precisely using the electromagnetic form factor of the nucleus. Such calculations have been carried out by several authors for charged current exchange alone [2] − [6]. Because of the destructive W-Z-interference in the coupling with left-handed leptons the cross section is lowered by 40% as compared to the contribution from charged currents [1].

The main experimental difficulty for an investigation of trident production is the smallness of the cross section which is five orders of magnitude lower than the inclusive neutrino nucleon cross section. Searches for this process have been performed in several experiments [7] − [10], but no clear evidence was observed. In this paper we are reporting on the first clear observation of neutrino trident production and a measurement of the cross section.

2. Experimental set-up

The experiment was performed using the CHARM II detector. This detector consists of a fine-grain target calorimeter and a muon spectrometer behind it. Details of the arrangement are given in ref. [11]. The calorimeter is composed of 420 modules each made-up of a 48 mm thick glass plate and a plane of 352 plastic streamer tubes as sensitive elements. The active area of the modules is 3.7x3.7 m^2. The total mass of the target amounts to 796 tonnes. The present analysis uses the signals from the digital wire readout. The measurent of the hadronic energy based on the number of hit wires has a resolution of $\sigma/E = 46\%/\sqrt{E/GeV}$. The spectrometer consists of six magnetized iron toroids interleaved with drift chambers. A momentum resolution of 14% is achieved for 20 GeV/c muons.

The CHARM II detector was exposed to the CERN wideband neutrino and antineutrino beams. The mean energy of the muon neutrinos and antineutrinos was measured to be 23.8 GeV and 19.3 GeV respectively [12].

3. Trigger and data taking

The experimental signature for process (1) is a muon pair of opposite charge with a small invariant mass [13]. No hadronic activity should be observed at the interaction vertex as the momentum transfer to the nucleus is limited by the photon propagator and the nuclear form factor.

A specific dimuon trigger has been designed to select events with a two track topology. It requires two tracks at a distance of at least 10 cm over a length of at least 30 planes in the calorimeter. The length criterion corresponds to a minimal energy of the tracks of 0.75 GeV. The trigger also selected inclusive neutrino nucleon interactions with a threshold of 3 GeV which were used to determine the neutrino and antineutrino fluxes.

The data for the present study have been obtained during the years 1987, 1988, and 1989 together with data for neutrino electron scattering [12]. The total exposure of 1.5×10^{19} protons yielded 4×10^{7} neutrino induced and 2×10^{7} antineutrino induced events. Neutrino and antineutrino data were combined for this analysis.

4. Data analysis

A large fraction of the total number of 2.7×10^{6} dimuon triggers is due to accidental coincidences of beam induced and cosmic tracks. The first step of the analysis therefore consisted in selecting events having two tracks with a common origin in the calorimeter. The longitudinal fiducial volume extended from module 5 to module 390. The first 4 planes served to veto against incoming tracks and the last 30 planes are required for the two track trigger condition. Laterally the vertex position was limited to $3.2\times3.2\ m^2$. The fiducial mass amounts to 547 tonnes. Both tracks were required to penetrate the muon spectrometer in order to measure the sign of the charges and the momenta of the two muons. After the selection of muon pairs of opposite charge with momenta above 4 GeV/c 10^4 reconstructed events remained.

Oppositely charged dimuon events have been studied previously in several experiments [14]. They are dominantly due to charm production in charged current neutrino and antineutrino nucleon interactions:

$$\nu_\mu + d,s \rightarrow \mu^- + c, \qquad \bar{\nu}_\mu + \bar{d},\bar{s} \rightarrow \mu^+ + \bar{c}. \tag{2}$$

The second muon originates from the semileptonic decay of the charm quark. In contrast to trident production process (2) is associated with a hadronic shower at the vertex.

In order to distinguish trident production (1) from charm production (2) the hadronic activity within the first 10 planes following the event vertex was analysed. We measured the activity by counting streamer tube hits which cannot unambiguously be assigned to one of the muon tracks. Fig. 2 shows the distribution of these additional hits for events having an invariant mass of the two muon system below 2.5 GeV/c² (full line histogram). A clear peak is seen at low vertex activity. An example of an event from the peak region is shown in fig. 3a. The width of the peak is due to activity generated by the muons themselves, mainly by δ-ray production. It agrees with the expectation derived from a study of muon tracks far from the vertex. The broad continuum with high vertex activity is mainly due to charm production. This continuum extends into the peak region and contributes to the background for the trident signal. We evaluated this background by studying the corresponding distribution for events with $m_{\mu\mu} > 2.5\ GeV/c^2$ where trident production does not contribute. This distribution has been scaled to the continuum of events with $m_{\mu\mu} < 2.5\ GeV/c^2$ for more than 20 additional hits and is shown as crosses in fig. 2. The shape of the continuum for both distributions is found to be compatible. We therefore used the distribution of events with $m_{\mu\mu} > 2.5\ GeV/c^2$ to extrapolate the charm production background to the signal region. The implied assumption that the compatibility of the two distributions extends into the peak region is justified by the observed approximate independence of hadronic activity and dimuon invariant mass in charm production. The influence of small differences between the two shapes was studied experimentally by varying the normalisation region from 20 − 120 to 20 − 60 additional hits. In the peak region defined as less than 8 additional hits the best estimate of the background is 35±11 events. An excess of 63±15 events is observed.

Coherent single charged pion production in charged current interactions may result in a final state similar to that of trident production if the pion decays before interacting in the target.

$$\overset{\leftrightarrow}{\nu}_\mu + A \rightarrow \mu^{\mp} + \pi^{\pm} + A \tag{3}$$

The pion decay angle is of the order of the mean Coulomb scattering angle and can therefore not be detected. Pions are produced in process (3) at small angles with respect to the outgoing muon [15]. This process may therefore contribute a background of events with low vertex activity and small invariant masses.

We have determined this background experimentally. Candidates for reaction (3) have been selected from the dimuon trigger sample for which the pion interacts only after traversing at least 40 planes (see fig. 3b). The condition of 40 traversed planes contains safely the trigger condition of two tracks in 30 planes. An invariant mass was calculated for these events under the assumption that the pion decayed. An excess of events at low vertex activity with $m_{\mu\mu} < 2.5\ GeV/c^2$ as compared to those with $m_{\mu\mu} > 2.5\ GeV/c^2$ was found; it was scaled with the probability for a pion to traverse 40 planes without showering and the probability to decay before interacting. Before subtracting this background we have corrected it for the difference in acceptance for single pion production relative to trident production using Monte Carlo methods. A contribution of 8±4 (sys.) events of reaction (3) to the signal was thus obtained.

After background subtraction a signal of trident production of 55±16 events is observed over a background of 43±12 events. The possibility that the signal is due to a fluctuation of the background is ruled out by more than four standard deviations.

5. Cross section calculation

The cross section for trident production was calculated from the number of observed events, the neutrino flux and the efficiencies of the trigger and event selection criteria. The efficiencies were determined by a Monte Carlo simulation. Events were simulated for charged current exchange alone [13]. However, the kinematical distributions for the process under study are not significantly modified by including neutral currents [6]. The simulated events were subjected to the same selection chain as the data. The overall efficiency of the selection is 8.2±1.3 % (sys.) and is mainly given by the geometrical acceptance of the muon spectrometer and by the requirement that the muon momenta are larger than 4 GeV/c.

The absolute neutrino flux was determined by counting inclusive neutrino nucleon scattering events with a visible hadronic energy deposition in the calorimeter of more than 3 GeV. The number of events was corrected for detection efficiency and the measured mean neutrino energies and the known cross sections for inclusive charged current and neutral current neutrino and antineutrino interactions [16] were used. The total time integrated flux is $1.31 \pm 0.07(sys.) \times 10^{12} cm^{-2}$

Combining these numbers we find for the trident production cross section averaged over the neutrino and antineutrino wideband beam spectra

$$\sigma_{exp.} = [3.0 \pm 0.9\,(stat.) \pm 0.5\,(sys.)] \times 10^{-41}\, cm^2 \quad per \quad nucleus.$$

Systematic errors were combined quadratically. Splitting the data in neutrino in antineutrino exposures we found the corresponding cross sections compatible with the expected equality.

To confront the present measurement with the Standard Model prediction the cross section for neutrino trident production off nuclei has been computed for the energy spectrum of the CERN wideband neutrino and antineutrino beams and the nuclear composition of the CHARM II calorimeter. A phenomenological form factor based on a Fermi distribution of the charge density was used to describe the electromagnetic coupling to the nucleus. With this form factor a satisfactory description of experimental data from elastic electron nucleus scattering has been obtained [5]. In addition to coherent trident production off nuclei, production off single nucleons contributes to the experimental sample as also in this case the momentum transfer to the nucleon is too small for the nucleon to be detected. We estimated the diffractive contribution to the cross section for trident production following ref. [6]. The reduction of the diffractive cross section for small momentum transfer due to Pauli suppression was included in the calculation. The diffractive component amounts to 32% of the total cross section. The result for the total cross section including the destructive W-Z-interference as predicted by the Standard Model for $\sin^2\theta_W = 0.23$ is

$$\sigma_{theor.} = [1.9 \pm 0.4] \times 10^{-41}\, cm^2 \quad per \quad nucleus.$$

The error is due to the uncertainty in the form factor and in the estimation of the diffractive contribution to the cross section.

6. Conclusions

Neutrino trident production has been clearly identified for the first time. The backgrounds from charm production and single pion production have been determined experimentally. Within its errors the cross section agrees with the Standard Model. However the destructive interference of the charged and neutral weak boson amplitudes cannot be demonstrated from this measurement. A sizeable part of the uncertainty is due to the theoretical prediction.

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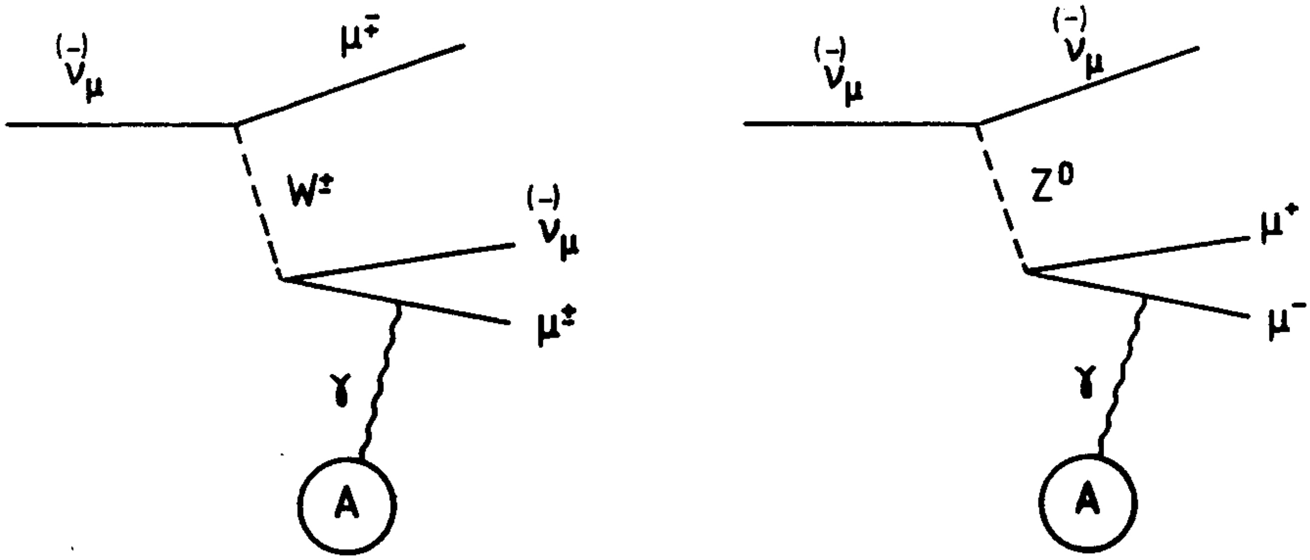

Figure 1: Feynman diagrams for trident production by neutrinos and antineutrinos.

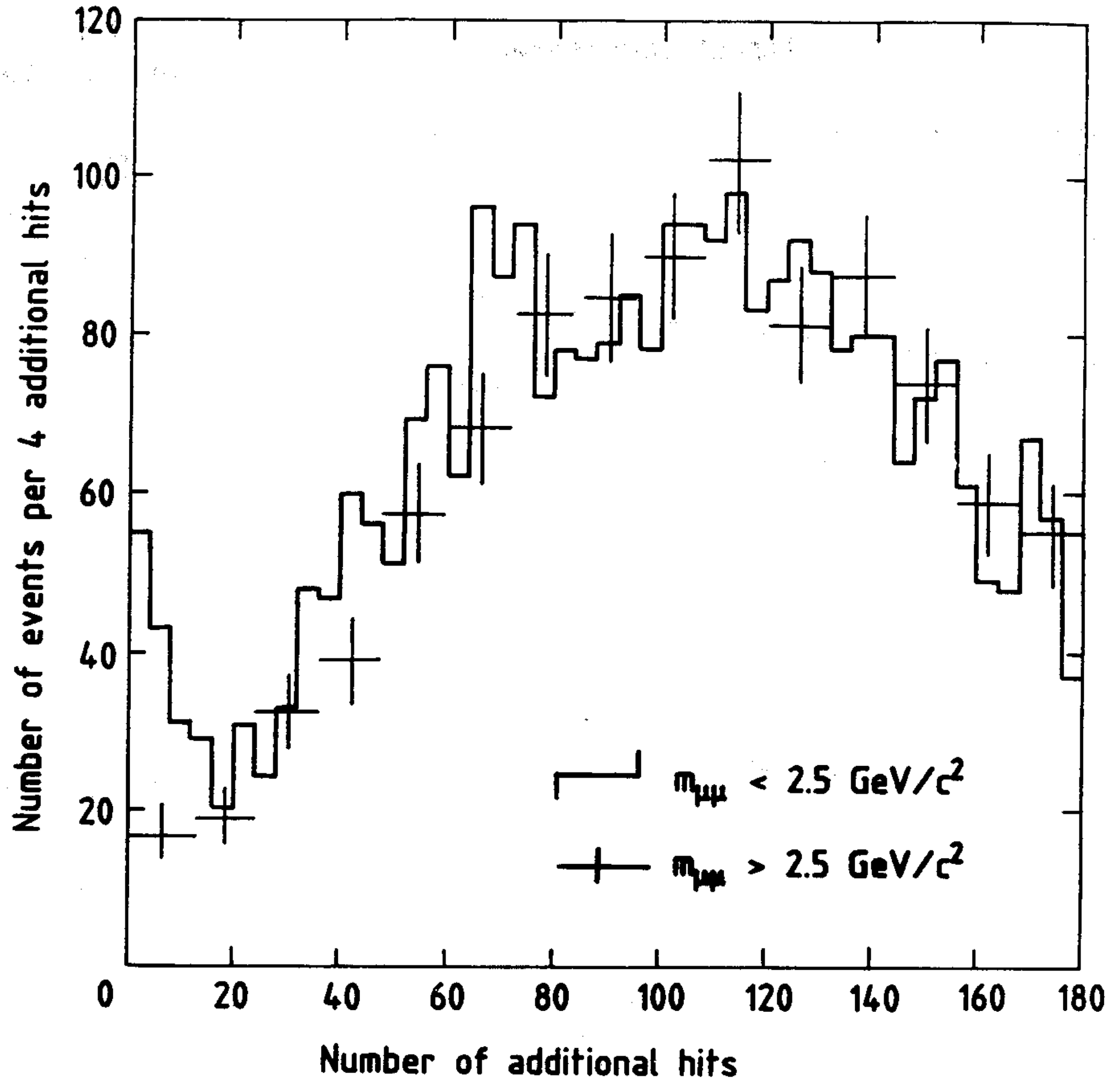

Figure 2: Vertex activity determined by the number of additional hits in 10 planes following the vertex for dimuon events of opposite charge.

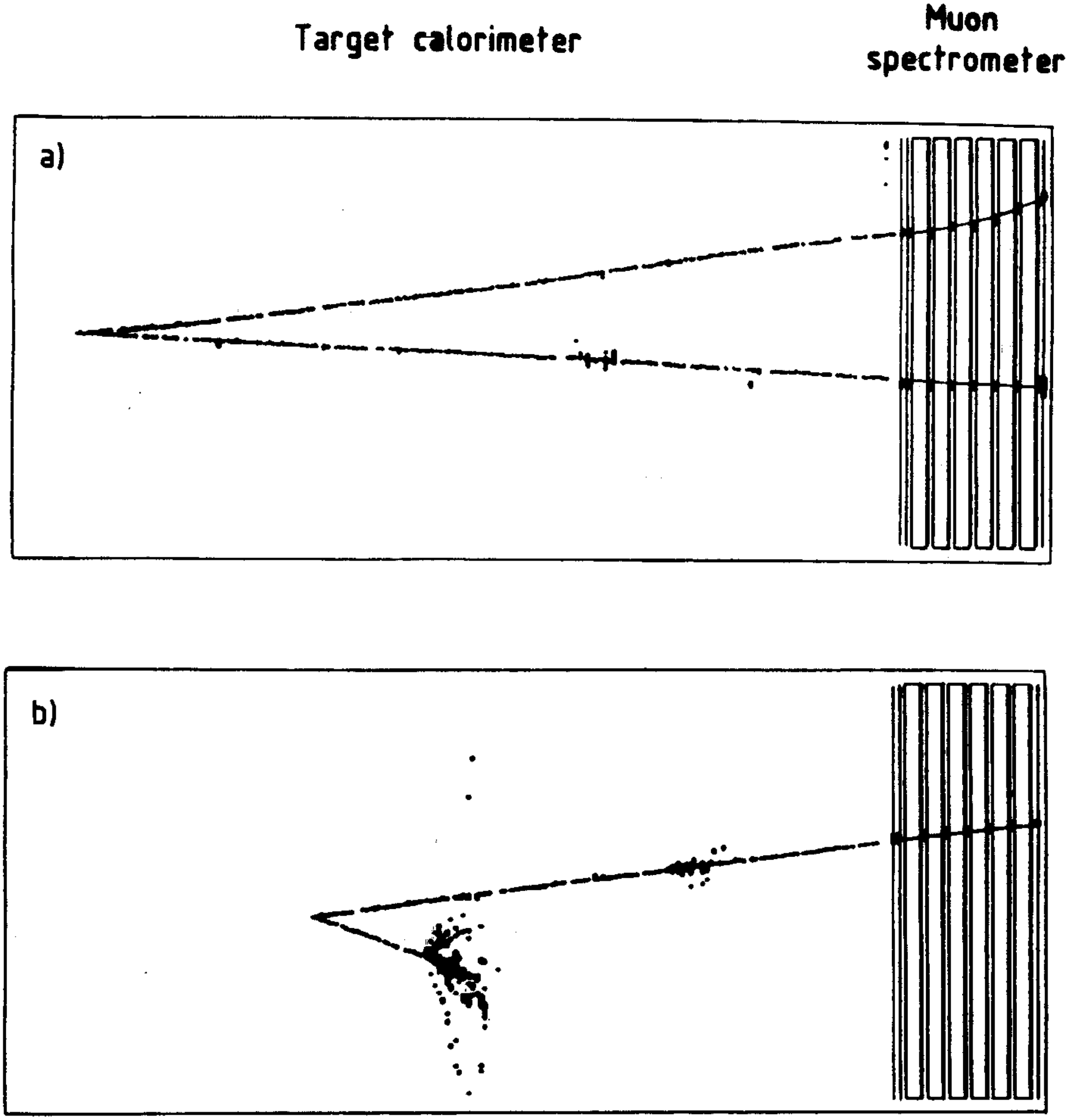

Figure 3: Example of trident production candidate event (a) and single pion production candidate event (b) in the CHARM II detector. The neutrino beam enters from the left. Each point in the calorimeter represents a hit wire. In the muon spectrometer the drift chamber hits are shown together with the reconstructed muon tracks.