CM-P00064017

SEARCH FOR SINGLE POSITIVE MUON PRODUCTION IN NEUTRINO INTERACTIONS

M. Holder, J. Knobloch, J. May, H.P. Paar, P. Palazzi, F. Ranjard,
D. Schlatter, J. Steinberger, H. Suter, H. Wahl, S. Whitaker
and E.G.H. Williams,
CERN, Geneva, Switzerland

F. Eisele, C. Geweniger, K. Kleinknecht, G. Spahn and H.-J. Willutzki,
Institut für Physik^{*)} der Universität, Dortmund, Germany

W. Dorth, F. Dydak, V. Hepp, K. Tittel and J. Wotschack,
Institut für Hochenergiephysik^{*)} der Universität, Heidelberg, Germany

P. Bloch, B. Devaux, M. Grimm, J. Maillard, B. Peyaud,
J. Rander, A. Savoy-Navarro and R. Turley,
D.Ph.P.E., CEN-Saclay, France

F.L. Navarria,
Istituto di Fisica dell'Università, Bologna, Italy

ABSTRACT

A search has been made for neutrino interactions with a positive (wrong-sign) muon in the final state. All the events found can be attributed to known sources. A cut at a visible energy of 100 GeV leaves one event, giving an upper limit for μ^+ production relative to μ^- of 1.6×10^{-4} at the 90% confidence level. Upper limits are given for (a) charm-changing neutral currents, (b) positive heavy lepton production, and (c) neutrino-antineutrino oscillations.

Geneva - 20 January 1978

(Submitted to Physics Letters)

^{*)} Supported by Bundesministerium für Forschung und Technologie.

In addition to the study of the charged-current neutrino interaction on iron [1],

$$\nu_{\mu} + N \rightarrow \mu^{-} + \text{anything} , \quad (1)$$

a search was made for events with a single muon of the opposite charge in the final state,

$$\nu_{\mu} + N \rightarrow \mu^{+} + \text{anything} . \quad (2)$$

The observation of reaction (2) can be related to different processes. Interesting ones are:

a) Charm-changing neutral currents (NC):

$$\nu_{\mu} + N \rightarrow \nu_{\mu} + C + \text{hadrons} , \quad (3)$$

where C is a charmed particle which decays promptly,

$$C \rightarrow \mu^{+} + \nu_{\mu} + \text{anything} .$$

This reaction corresponds to charm production by the interaction of the weak neutral current with valence u-quarks [2].

b) Production of heavy leptons postulated by some gauge theories [3]:

$$\nu_{\mu} + N \rightarrow M^{+} + \text{anything} , \quad (4)$$

followed by the leptonic decay of the heavy lepton:

$$M^{+} \rightarrow \mu^{+} + \nu_{\mu} + \nu_{\mu} .$$

c) Neutrino-antineutrino oscillations [4]: If it is assumed that ν_{μ} and $\bar{\nu}_{\mu L}$ can be described by

$$\begin{aligned} \nu_{\mu} &= \nu_1 \cos \alpha + \nu_2 \sin \alpha \\ \bar{\nu}_{\mu L} &= -\nu_1 \sin \alpha + \nu_2 \cos \alpha , \end{aligned}$$

where ν_1, ν_2 are Majorana neutrinos with non-zero masses m_1 and m_2 , and α is a mixing angle, an initially pure neutrino beam will contain at some distance from its origin a fraction of left-handed antineutrinos $\bar{\nu}_{\mu L}$, which could interact in the normal way:

$$\bar{\nu}_{\mu L} + N \rightarrow \mu^+ + \text{hadrons} .$$

The experiment was performed at the CERN Super Proton Synchrotron (SPS), using the narrow-band beam of the West Area Neutrino Facility. In this beam, neutrinos of known energy are produced by selecting (200 ± 9) GeV/c positive pions and kaons generated by 400 GeV protons interacting in a beryllium target. This beam also contains a small admixture of antineutrinos due to π 's and K's decaying prior to the momentum selection. This so-called wide-band (WB) background is concentrated at low energy, with a steeply falling spectrum, approximately $\exp(-E_{\nu}/20 \text{ GeV})$, and is calculated to yield 0.1% of all charged-current events with energy above 50 GeV *).

The apparatus [5] which integrates the functions of target and detector for both hadrons and muons, consists of 19 magnetized iron toroids, 3.75 m in diameter, with inserted plastic scintillator layers, each toroid being followed by a three-gap drift chamber. The muon momentum p_{μ} is determined either by magnetic deflection or by range, and the hadron energy E_h is measured through total absorption calorimetry. The magnetic field polarity is chosen such that negative muons are focused, and a correction for the difference in acceptance of positive and negative muons was applied: each μ^+ event was given a weight equal to the ratio of the acceptances for positive muons and negative muons. These weights are calculated by Monte Carlo for each radial position, momentum, and polar angle, and integrated over all azimuthal angles.

To avoid the need for dealing with muons which go through the centre of the toroids where the field changes sign, the event vertex was required to be at a distance more than 25 cm from the axis of the apparatus. The interaction was also required to take place in the first 13 toroids. Muons are required to cross at least five drift chambers (corresponding to $p_{\mu} \gtrsim 5.5 \text{ GeV/c}$), and in order to reduce the WB background, a further cut was made on the visible energy, asking

*) This contamination is expected to be about ten times bigger for the antineutrino narrow-band beam, which makes the antineutrino data unfit for a wrong-sign muon search.

$E_{\text{vis}} = E_h + E_\mu > 50 \text{ GeV}$. These cuts were also applied to the charged-current and neutral-current reference samples.

A total of 19 wrong-sign muon events survived these cuts. Several known sources can be considered to explain these events (a summary of the number of observed events and expected background events is given in Table 1 for two different cuts: $E_{\text{vis}} > 50 \text{ GeV}$ and $E_{\text{vis}} > 100 \text{ GeV}$):

a) Wide-band (WB) background of antineutrinos which interact via normal charged-current interaction:

$$\bar{\nu}_\mu + N \rightarrow \mu^+ + \text{hadrons} .$$

Figure 1 shows the visible energy distribution of the μ^+ events superimposed with the shape expected from WB background. This source of background is calculated to yield 22 wrong-sign events with visible energy above 50 GeV.

b) Dilepton production by electron neutrinos:

$$\nu_e + N \rightarrow e^- + \mu^+ + \text{anything} ,$$

as the electron shower is indistinguishable from the hadron cascade in our detector. Electron-neutrinos are mainly due to K_{e3} decays and represent about 3% of all neutrinos. Assuming μ -e universality and using our experimental result [6] for the production of opposite-sign dimuons relative to single muons (0.4% with the present cuts), which is in agreement with the rate of μe production in bubble chambers [7], we expect 2 wrong-sign events with a visible energy above 50 GeV.

c) Dimuon events with an undetected μ^- .

In addition to the 19 wrong-sign muon events, three more μ^+ events were found which show an additional soft negative muon, with momentum lower than the threshold of 4.5 GeV/c defined for dimuon events [6]. On the basis of the observed dimuon sample and extrapolating to small μ^- energies with a charm production model [6], we expect 3 events of this type. Using the same calculation, we expect about 3 dimuon events where the negative muon is masked by the hadron shower.

d) Neutral current with a subsequent π or K decay:

$$\begin{array}{l} \nu_{\mu} + N \rightarrow \nu_{\mu} + \pi^{+} \text{ (or } K^{+}) + \text{hadrons} \\ \quad \quad \quad \downarrow \\ \quad \quad \quad \mu^{+} + \nu_{\mu} \end{array}$$

The probability for a π or K decay in the hadron shower was calculated [8] to be 4×10^{-4} , giving 2 events with $E_{\text{vis}} > 50$ GeV.

e) Associated charm-anticharm production by neutral current:

$$\begin{array}{l} \nu_{\mu} + N \rightarrow \nu_{\mu} + C + \bar{C} + \text{hadrons} \\ \quad \quad \quad \downarrow \quad \quad \downarrow \\ \quad \quad \quad \mu^{+} + \text{anything} \quad \text{hadrons} \end{array}$$

In an experiment where our detector was exposed to a wide-band beam, we found a ratio of trimuon events [9] to normal charged-current events of about 3×10^{-5} , for $E_{\text{vis}} > 50$ GeV. Assuming that all these trimuon events are due to charm-anticharm production and that the same rate holds for neutral currents, and taking the branching ratio for the decay $C(\bar{C}) \rightarrow \mu^{+}(\mu^{-}) + \text{anything}$ to be 15% [6], we expect from this source at most 1 wrong-sign event with visible energy above 50 GeV.

Figure 2 displays the $y_{\text{vis}} = E_h/E_{\text{vis}}$ distribution of the μ^{+} events, which is compatible with a $(1-y_{\text{vis}})^2$ distribution as expected for WB background antineutrinos, with in addition a few events at high y_{vis} which can be attributed to the other sources of background described above. Summing all background contributions, we obtain 30 ± 15 events, which accounts for the observed μ^{+} events with visible energy above 50 GeV.

In order to further reduce the background level, we now consider only events with a visible energy greater than 100 GeV. Thus we are left with a single event, whereas we expect 5.5 from background calculation (see Table 1). Taking this background into account, we can set an upper limit for a possible signal of 2.5 events at the 90% confidence level, that is, compared to 15,600 charged-current events surviving the same cuts, an upper limit for wrong-sign muon production of 1.6×10^{-4} .

A limit on charm-changing NC [reaction (3)] relative to all NC can also be calculated. We obtain

$$\frac{\sigma(\text{charm-changing NC})}{\sigma(\text{NC})} < \frac{2.5}{N \times B_{\mu} \times \epsilon_{\mu}} = 2.6\% \quad (90\% \text{ confidence}) .$$

Here N is the observed number of NC events with $E_{\text{vis}} > 100 \text{ GeV}$, B_{μ} is the branching ratio for $C \rightarrow \mu + \text{anything}$, and ϵ_{μ} is the calculated detection efficiency using a charm production model [6], with $B_{\mu} \times \epsilon_{\mu} \sim 0.075$.

The absence of charm-changing NC agrees with the Salam-Weinberg model [10] where this type of event appears only as a second-order effect.

Let us now consider the production of a positive heavy muon in reaction (4). In the scaling limit, assuming also the Callan-Gross relation [11] and neglecting possible antiquark contributions, the differential cross-section is calculated to be [12]:

$$\frac{d^2\sigma}{dx dy} = \frac{G^2 s}{2\pi} F_2(x) \left(1 - \frac{m^2}{sx}\right) ,$$

where s is the square of the centre-of-mass energy, and m the mass of the heavy lepton M^+ . In the following, the coupling constant G is taken to be identical for muon and heavy-lepton production.

The acceptance of our detector for reaction (4) was calculated using the above cross-section and taking also into account the M^+ polarization and its decay angular distribution [13]. It has been shown [12,13] that the branching ratio

$$B(m) = \frac{\Gamma(M^+ \rightarrow \mu^+ + \nu_{\mu} + \bar{\nu}_{\mu})}{\Gamma(M^+ \rightarrow \text{all})}$$

can be related to electron-positron annihilation data. Using recent results [14], we find, for example, $B \approx 0.2$ for $m = 12 \text{ GeV}/c^2$.

Figure 3 shows the expected number of μ^+ events with visible energy above 100 GeV as a function of the heavy-lepton mass. The one event found corresponds to a lower limit of $m = 12 \text{ GeV}/c^2$ at the 90% confidence level. Previous experimental

searches for the production of positive heavy muons by neutrinos [15,16] have set lower limits on m between 8 and 9 GeV/c².

Let us now turn to neutrino-antineutrino oscillations. The fraction of left-handed antineutrinos in a neutrino beam, at a distance ℓ from the decay point, is expected to be

$$R \equiv \frac{I_{\bar{\nu}}}{I_{\nu}} = \frac{1}{2} \left(1 - \cos 2\pi \frac{\ell}{L} \right) \sin^2 2\alpha .$$

Here the oscillation length L is given by

$$L = \frac{4\pi \bar{E} \hbar c}{\Delta m^2} ,$$

$\bar{E}$ denotes the average neutrino energy and $\Delta m^2 = |m_1^2 - m_2^2|$.

Assuming $\ell \ll L$, we get

$$\sin 2\alpha \times \Delta m^2 = R^{\frac{1}{2}} \times \frac{4 \bar{E} \hbar c}{\ell} .$$

In our experiment, $\ell = 610$ m on the average, and the mean neutrino energy for events with $E > 100$ GeV is $\bar{E} = 148$ GeV. We thus obtain, at the 90% confidence level,

$$\sin 2\alpha \times \Delta m^2 \lesssim 2.5 \text{ eV}^2 .$$

A similar calculation yields for $\nu_e, \bar{\nu}_{\mu L}$ oscillations, with 2% ν_e above 100 GeV in our beam, $\sin 2\alpha \times \Delta m^2 \lesssim 18 \text{ eV}^2$ at the 90% confidence level.

In conclusion, no evidence is found for μ^+ production by either charm-changing neutral current or μ^+ decay of a heavy lepton. The gross features of the wrong-sign events found in this experiment agree with the expected background, mainly wide-band background.

We thank the SPS staff and our many technical collaborators.

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Table 1

Summary of wrong-sign rates

	$E_{\text{vis}} > 50 \text{ GeV}$	$E_{\text{vis}} > 100 \text{ GeV}$
<u>Observed events</u>		
CC	24,200	15,600
NC	4,000	1,300
Dimuons with short μ^- (calculated)	3 (3)	2 (1.3)
Single μ^+	19	1
Single μ^+ weighted ^{a)}	22.3	1
<u>Expected number of μ^+ events from known sources^{b)}</u>		
i) Wide-band $\bar{\nu}$	21.6	2.4
ii) $\nu_e + N \rightarrow e^- + \mu^+ + \text{anything}$	2.5	0.9
iii) Dimuons with undetected μ^-	3.0	1.3
iv) NC plus (π^+/K^+) decay	1.6	0.5
v) NC plus $(C\bar{C})$ production	0.8	0.4
<u>TOTAL (i)-(v)</u>	29.5	5.5

a) μ^+ corrected for acceptance relative to μ^- .

b) The uncertainty on the background calculation is estimated to be $\pm 50\%$.

Figure captions

- Fig. 1 : Visible energy distribution of the μ^+ events. The solid line represents the shape expected from wide-band background, normalized to the first bin.
- Fig. 2 : y_{vis} distribution of the μ^+ events.
- Fig. 3 : Number of expected μ^+ events versus heavy lepton mass. The dotted line corresponds to the 90% confidence level limit.

Fig. 1

Fig. 2

Fig. 3