Available online at www.sciencedirect.com
SCIENCE DIRECT®

Physics Letters B 596 (2004) 44–53

PHYSICS LETTERS B

www.elsevier.com/locate/physletb

Experimental study of trimuon events in neutrino charged-current interactions

CHORUS Collaboration

A. Kayis-Topaksu[1], G. Onengüt

Çukurova University, Adana, Turkey

R. van Dantzig, M. de Jong, J. Konijn, O. Melzer, R.G.C. Oldeman[2], E. Pesen, C.A.F.J. van der Poel, J.L. Visschers

NIKHEF, Amsterdam, The Netherlands

M. Güler, U. Köse, M. Serin-Zeyrek, S. Kama, R. Sever, P. Tolun, M.T. Zeyrek

METU, Ankara, Turkey

M.G. Catanesi, M. De Serio, M. Ieva, M.T. Muciaccia, E. Radicioni, S. Simone

Università di Bari and INFN, Bari, Italy

A. Bülte, K. Winter

Humboldt Universität, Berlin, Germany[3]

B. Van de Vyver[1,4], P. Vilain[5], G. Wilquet[5]

Inter-University Institute for High Energies (ULB-VUB) Brussels, Belgium

B. Saitta

Università di Cagliari and INFN, Cagliari, Italy

E. Di Capua

Università di Ferrara and INFN, Ferrara, Italy

doi:10.1016/j.physletb.2004.06.081

S. Ogawa, H. Shibuya

Toho University, Funabashi, Japan

A. Artamonov[6], J. Brunner[7], M. Chizhov[8], D. Cussans[9], M. Doucet[10], J.P. Fabre, I.R. Hristova[8,11], T. Kawamura, D. Kolev[8], M. Litmaath, H. Meinhard, J. Panman, I.M. Papadopoulos, S. Ricciardi[12], A. Rozanov[7], D. Saltzberg[13], R. Tsenov[8], J.W.E. Uiterwijk, P. Zucchelli[14]

CERN, Geneva, Switzerland

J. Goldberg

Technion, Haifa, Israel

M. Chikawa

Kinki University, Higashiosaka, Japan

E. Arik

Bogazici University, Istanbul, Turkey

J.S. Song, C.S. Yoon

Gyeongsang National University, Jinju, South Korea

K. Kodama, N. Ushida

Aichi University of Education, Kariya, Japan

S. Aoki, T. Hara

Kobe University, Kobe, Japan

T. Delbar, D. Favart, G. Grégoire, S. Kalinin, I. Makhlyoueva

Université Catholique de Louvain, Louvain-la-Neuve, Belgium

P. Gorbunov, V. Khovansky, V. Shamanov, I. Tsukerman

Institute for Theoretical and Experimental Physics, Moscow, Russian Federation

N. Bruski, D. Frekers, D. Rondeshagen, T. Wolff

Westfälische Wilhelms-Universität, Münster, Germany[3]

K. Hoshino, J. Kawada, M. Komatsu, M. Miyanishi, M. Nakamura, T. Nakano,

K. Narita, K. Niu, K. Niwa, N. Nonaka, O. Sato, T. Toshito

Nagoya University, Nagoya, Japan

S. Buontempo, A.G. Cocco, N. D'Ambrosio, G. De Lellis, G. De Rosa, F. Di Capua,
A. Ereditato, G. Fiorillo, A. Marotta, M. Messina, P. Migliozzi, C. Pistillo,
R. Santorelli, L. Scotto Lavina, P. Strolin, V. Tioukov

Università "Federico II" and INFN, Naples, Italy

K. Nakamura, T. Okusawa

Osaka City University, Osaka, Japan

U. Dore, P.F. Loverre, L. Ludovici, A. Maslennikov[15], P. Righini, G. Rosa,
R. Santacesaria, A. Satta, F.R. Spada

Università La Sapienza and INFN, Rome, Italy

E. Barbuto, C. Bozza, G. Grella, G. Romano, C. Sirignano, S. Sorrentino

Università di Salerno and INFN, Salerno, Italy

Y. Sato, I. Tezuka

Utsunomiya University, Utsunomiya, Japan

Received 18 March 2004; received in revised form 9 June 2004; accepted 23 June 2004

Editor: L. Rolandi

E-mail address: biagio.saitta@cern.ch (B. Saitta).

[1] Now at CERN, 1211 Geneva 23, Switzerland.

[2] Now at INFN, Rome, Italy.

[3] Supported by the German Bundesministerium für Bildung und Forschung under contract numbers 05 6BU11P and 05 7MS12P.

[4] Fonds voor Wetenschappelijk Onderzoek, Belgium.

[5] Fonds National de la Recherche Scientifique, Belgium.

[6] On leave of absence from ITEP, Moscow.

[7] Now at CPPM CNRS-IN2P3, Marseille, France.

[8] St. Kliment Ohridski University of Sofia, Bulgaria.

[9] Now at University of Bristol, Bristol, UK.

[10] Now at University of Maryland, MD, USA.

[11] Now at DESY, D-15738, Zeuthen, Germany.

[12] Now at Royal Holloway College, University of London, Egham, UK.

[13] Now at U.C.L.A., Los Angeles, USA.

[14] On leave of absence from INFN, Ferrara, Italy.

[15] CASPUR, Rome, Italy.

Abstract

This Letter reports on a study of trimuon events induced by neutrino interactions in the CHORUS calorimeter exposed to the CERN SPS wide-band ν_μ beam. Among the multimuon events produced in the calorimeter, 42 $\mu^-\mu^-\mu^+$ events were selected and their kinematical properties investigated. In the past, several groups collected a sample of about one hundred events of this type but their source was largely unknown. Taking advantage of experimental data presently available on the production and muonic branching ratios of light neutral mesons and resonances, we make absolute predictions for the expected rates in our experiment. Detailed Monte Carlo simulations described in this article show that more than half of the trimuon events can be attributed to this source. Muons from π^- and K^- decays in charm dimuon events are responsible for an additional $\approx 25\%$ contribution to the total $\mu^-\mu^-\mu^+$ rate. The remaining 25% of events are likely to come from the internal bremsstrahlung of virtual photons into a muon pair. Associated-charm production with subsequent decays of both charmed particles into muons is a negligible source of trimuon events.

1. Introduction

Trimuon production in neutrino interactions was first observed at FNAL [1] and at CERN [2] more than 25 years ago. Detailed studies were later performed by the CDHS [3] and the HPWF [4] groups, that in total collected about one hundred events with three muons, mostly $\mu^-\mu^-\mu^+$ in the final state with an observed rate of $\sim 10^{-5}$ of charged-current (CC) ν_μ interactions. It was established that trimuons were mostly of a hadronic origin, with a contribution from internal bremsstrahlung, a process well understood theoretically [5], in which a muon or a quark from a CC interaction emits a $\mu^-\mu^+$ pair. This process has a characteristic kinematical property (see Section 5), which separates it quite effectively from events of a non-electromagnetic nature.

The CHORUS experiment [6] aimed to search for $\nu_\mu \to \nu_\tau$ oscillations and study charm physics in the CERN SPS wide-band ν_μ beam using an emulsion target. In addition, a large sample of neutrino events originating from its massive calorimeter was recorded. In this Letter properties of trimuon events found in this sample are investigated with the aim of identifying their sources. Detailed Monte Carlo (MC) simulations, including rare decays of light neutral mesons and resonances (η, η', ρ, ω and ϕ) are used, since we believe that they constitute a substantial fraction of the observed event rate. It is possible to make absolute predictions for the expected rates with the experimental data now available on the production rates and muonic branching ratios of these light neutral mesons.

2. The experimental set-up

We have studied trimuon (3μ) production in the CHORUS detector [6] exposed to the wide-band neutrino beam produced by 450 GeV protons from the CERN SPS. The average ν_μ beam energy is 27 GeV, the contamination of $\bar{\nu}_\mu$ is 6%. The 112-ton lead-scintillator calorimeter [7] is used as an active target for multimuon events. It provides the reconstruction of the event vertex, as well as the measurement of hadronic shower energy. The calorimeter consists of three sections with decreasing granularity along the beam direction: electromagnetic (4 planes), the first hadronic (5 planes) and the second hadronic (5 planes). The depths of these sections are 16 cm, 40 cm and 50 cm, respectively, giving a total of 5.2 interaction lengths.

The muon spectrometer located further downstream from the calorimeter identifies muons and determines their trajectory, momentum, and charge.

It consists of six magnetised iron toroids, instrumented with scintillators, and tracking detectors composed of drift chambers and limited streamer tubes. Muon momenta are determined from their curvature in the toroidal magnetic field. The momentum resolution varies from $\approx 15\%$ [8] in the 12–28 GeV$/c$ interval to 19% [6] at about 70 GeV$/c$, as measured with test-beam muons.

The trigger system [9] of the CHORUS experiment has different types of triggers for events originating from the emulsion, the calorimeter, and the muon spectrometer. For our purpose we use the dimuon trigger, which requires a double-hit pattern in the calorimeter or a multiple-hit pattern in the muon spectrometer. In addition, a downscaled one-muon trigger requiring only a muon in the spectrometer allowed us to check the efficiency of the dimuon trigger and to check the normalisation with respect to inclusive CC events.

3. Event selection

In total, 5.6 million events from 1995–1998 exposures recorded with the dimuon trigger [9], were processed with the CHORUS reconstruction program. The sample corresponds to $\approx 4.9 \times 10^{19}$ protons on the neutrino target. Most of these events contain one muon track and an energetic hadronic shower. Some 4.6×10^5 events have two or more reconstructed tracks crossing at least two spectrometer magnets ($\geqslant 1$ m of iron). Events were accepted with their interaction vertex inside a fiducial volume with a lateral size of 240×240 cm^2 and within the calorimeter planes from 5 to 11 to ensure a high dimuon trigger efficiency. The fiducial target mass thus defined is 32 tons.

A detailed description of the event selection is given in Ref. [10] and therefore we mention here only the essential information. Events with exactly three reconstructed tracks traversing at least four spectrometer magnets were accepted as 3μ candidates. The transverse distance between the tracks of any muon pair at the vertex plane was required to be less than 15 cm. All muons were required to have momenta above 5 GeV/c at the vertex, after the correction for energy losses (≈ 1 GeV) in the calorimeter. A cut on the quality of muon momentum reconstruction in the spectrometer ($\chi^2_\mu/\text{ndf} \leqslant 5$) was also applied. These criteria were identical to those used in an earlier CHORUS publication [11]. In addition, the number of reconstructed muon tracks starting from the second magnet should be equal to three. Such a requirement protects against events with fake muons due to shower leakage from the calorimeter into the spectrometer. Furthermore, at least fourteen spectrometer scintillation counters out of a total twenty-four are required to have a hit along each muon trajectory. This criterion being effective in the rejection of overlay muons. Forty-two $\mu^-\mu^-\mu^+$ and three $\mu^-\mu^+\mu^+$ events survived all these cuts. No $\mu^-\mu^-\mu^-$ and $\mu^+\mu^+\mu^+$ events passed the selection criteria.

The total number of dimuon events observed with the selections equivalent to those used for trimuons is 15111 for $\mu^-\mu^+$, 2107 for $\mu^-\mu^-$ and 66 for $\mu^+\mu^+$ sign combinations. It was checked that the dimuon trigger efficiency is the same for 2μ and 3μ events (0.86 ± 0.05 and 0.85 ± 0.11, respectively). This sample corresponds to 17×10^6 deep-inelastic CC events with $10 \leqslant E_\nu \leqslant 200$ GeV in the fiducial volume [12]. Correcting for the energy cuts, the total number of CC interactions is then 18.0×10^6, in good agreement with the estimate of $(18.4 \pm 1.7) \times 10^6$ obtained from the number of observed dimuon events and assuming an average ratio of dimuons to total CC cross-section of 0.0050 ± 0.0003 [13]. The observed ratio of number of $\mu^-\mu^-\mu^+$ and single μ^- events as a function of visible neutrino energy is shown in Fig. 1. A direct comparison with the available experimental results is difficult since different selection criteria have been adopted. However the results obtained in this paper are in agreement with those quoted in Ref. [3a], provided similar selection criteria are applied. In particular, requiring that the muon momentum be larger than 4.5 GeV/c and removing the selection on the quality of the fit, for $E_\nu \geqslant 30$ GeV, we obtain $3\mu/1\mu = (2.6 \pm 0.2) \times 10^{-5}$ to be compared with the CDHS result of $(3.3 \pm 0.4) \times 10^{-5}$, before any background subtraction.

It is expected that the decays of light neutral mesons and resonances, muonic decays of charmed particles with an additional pion or kaon decay, and internal bremsstrahlung contribute to trimuon production. Therefore we studied whether these sources could account for the observed events.

4. Simulation

A detailed MC simulation was performed to clarify the origin of trimuon events. Physical event generation was done with the CHORUS JETTA [14] package derived from LEPTO [15] and JETSET [16]. GEANT 3.21 [17] was used for modelling the neutrino beam as well as for simulation of the detector response in the complete set-up. MC events were then processed with the CHORUS reconstruction program. The following sources of $\mu^-\mu^-\mu^+$ production were considered:

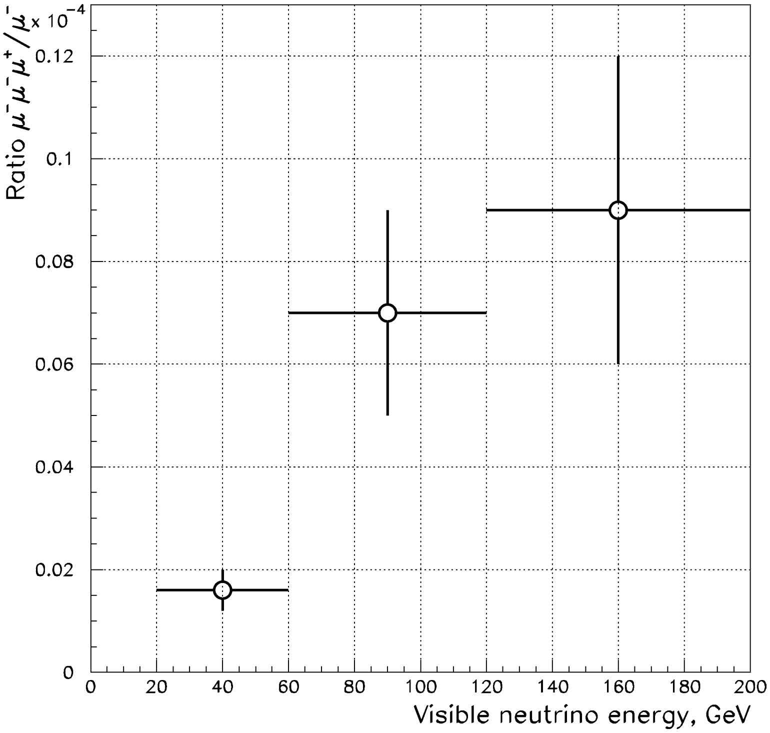

Fig. 1. Ratio of number of $\mu^-\mu^-\mu^+$ and single μ^- events survived the cuts as a function of visible neutrino energy. The visible energy is defined as a scalar sum of muon momenta and shower energy.

Table 1

Yields and muonic branching ratios of neutral mesons and resonances together with the number of trimuon events from this source in ν_μCC interactions. The rates for processes where the reference is given as 'MC' are obtained from the model in Ref. [14]

Meson	N/N_{CC}	Ref.	Decay	$BR \times 10^5$	$(N_{3\mu}/N_{\text{CC}}) \times 10^6$
$\eta(548)$	0.196 ± 0.056	[21]	$\gamma\mu^-\mu^+$	31 ± 4	61 ± 20
$\rho(770)$	0.196 ± 0.020	[20]	$\mu^-\mu^+$	4.60 ± 0.28	9.0 ± 1.0
$\omega(782)$	0.130 ± 0.031	[21]	$\mu^-\mu^+$	9.0 ± 3.1	11.7 ± 4.9
$\omega(782)$	0.130 ± 0.031	[21]	$\pi^0\mu^-\mu^+$	9.6 ± 2.3	12.5 ± 4.3
$\eta'(958)$	0.043 ± 0.005	MC	$\gamma\mu^-\mu^+$	10.4 ± 2.6	4.5 ± 1.2
$\phi(1020)$	0.0057 ± 0.0005	MC	$\mu^-\mu^+$	28.7 ± 2.0	1.64 ± 0.18

1. ν_μCC events with rare decays of light neutral mesons and resonances into a muon pair.
   Experimental data on production of $\eta(548)$, $\rho(770)$ and $\omega(782)$ in neutrino interactions and on their muonic branching ratios [18] are currently available, see Table 1.[16] Several bubble chamber experiments [19] and NOMAD [20] studied inclusive production of ρ^0. BEBC WA59 [21] also measured η and ω yields, albeit with a worse precision. There is still no experimental evidence for neutrino production of $\eta'(958)$ and $\phi(1020)$ states which also can decay into a $\mu^-\mu^+$-pair.

---

[16] At the time when CDHS and HPWF reported their results on trimuons this was not the case.

We forced $\eta \to \gamma\mu^-\mu^+$ and $\rho \to \mu^-\mu^+$ decay modes at the generation stage.[17]
It should be noted that BEBC [21] and NOMAD [20] observed a discrepancy between experimental ρ rates and those estimated with JETSET [16]. NOMAD [20] proposed to retune some of the parameters used within JETSET to obtain better agreement. Therefore, for the purpose of this analysis events were simulated both with the default setting and with the setting proposed by NOMAD of key JETSET parameters, taking an average between them as a result and half a difference as a systematic error. We used experimental rates of light neutral mesons and resonances where available (Table 1) for normalization purposes. The uncertainty introduced by the JETSET parameter settings (which amounts to 20% at most) affects only the production of the η' and ϕ for which no experimental data are available. This uncertainty is reflected in the error quoted in the table. However, since the contribution from η' and ϕ is small, the overall effect is less important.

2. Charm dimuon ν_μCC and $\bar{\nu}_\mu$CC events, with a leptonic decay of the charmed particle and an extra muon from a leptonic $\pi^\pm$ or $K^\pm$ decay, as well as ordinary charged-current events with two extra muons from $\pi^\pm$ or $K^\pm$ decays.
   To estimate the contribution from this source to the total 3μ rate and to validate the MC, large samples of 2μ events were generated and passed through the same selection chain as 3μ events (see above). The merged MC sample consists of (18.6 ± 1.9)% CC events with one extra pion or kaon decay and 81.4% CC events with charm production and its subsequent leptonic decay. These numbers were estimated with the MC sample of ordinary charged-current events, by counting the number of muons from pion and kaon decays accepted by the selection criteria used for this analysis. Dimuon events from this sample were compared with the CHORUS data. The average dimuon selection efficiency is 0.13 ± 0.01. The observed distributions of the muon momenta and the angles with respect to the initial neutrino direction for $\mu^-\mu^+$ events, shown in Fig. 2, are well described by the MC. The predicted and the observed relative rates of $\mu^-\mu^-$, $\mu^+\mu^+$ and $\mu^-\mu^+$ events agree, see Table 2. Since the like sign dimuon events are dominated by decays of pions and kaons, this agreement validates our calculations of the trimuon events from this source.

More exotic sources of trimuons could be associated-charm production ($c\bar{c}$) with both charmed particles decaying muonically and $J/\psi \to \mu^+\mu^-$ production in CC interactions. Recently, one event with a topology compatible with $c\bar{c}$ production was detected in the CHORUS emulsion target [22]. Based on Ref. [23] we estimated the total rate of $c\bar{c}$ (including muonic branching ratio) to be as small as $\approx 3 \times 10^{-7}$ of the total ν_μCC cross-section. This process is therefore negligible. Recent estimates based on the non-relativistic QCD approach [24], as well as older calculations [23], indicate that J/ψ production in CC also has a too small cross-section to be observed in CHORUS.

5. Results and conclusions

The absolute normalization of the data and the MC samples is based on the number of $\mu^-\mu^+$ events which survived the cuts. We took the average ratio of 2μ and total CC cross-sections at our energies as $\sigma(2\mu)/\sigma(\mathrm{CC}) = 0.0050 \pm 0.0003$ following Ref. [13]. Note that this is physical ratio, i.e., before any experimental cuts applied. Normalization factors obtained in this manner are in 5% agreement with those found with an alternative method using CC interaction rates [12] measured in CHORUS as a starting point.

The MC predicts $8.3 \pm 2.8\mu^-\mu^-\mu^+$ events from charm dimuon events with an additional π^-/K^- decay. The error is dominated by MC statistics. A systematic error due to uncertainties in parton distributions and fragmentation functions is 10%.

The contribution from CC interactions with two extra muons from $\pi^\pm$ or $K^\pm$ decays is estimated to be less than one event [10].

---

[17] JETSET does not contain muonic decays of ω, η' and ϕ. Instead we forced $\omega \to \pi^-\pi^+$, $\omega \to \pi^-\pi^+\pi^0$, $\eta' \to \gamma\rho \to \gamma\mu^-\mu^+$ and $\phi \to K^-K^+$ decay modes and replaced by hand pions or kaons with muons. Mass effects in the rates which are significant in the case of $\phi \to K^-K^+$ have been corrected for.

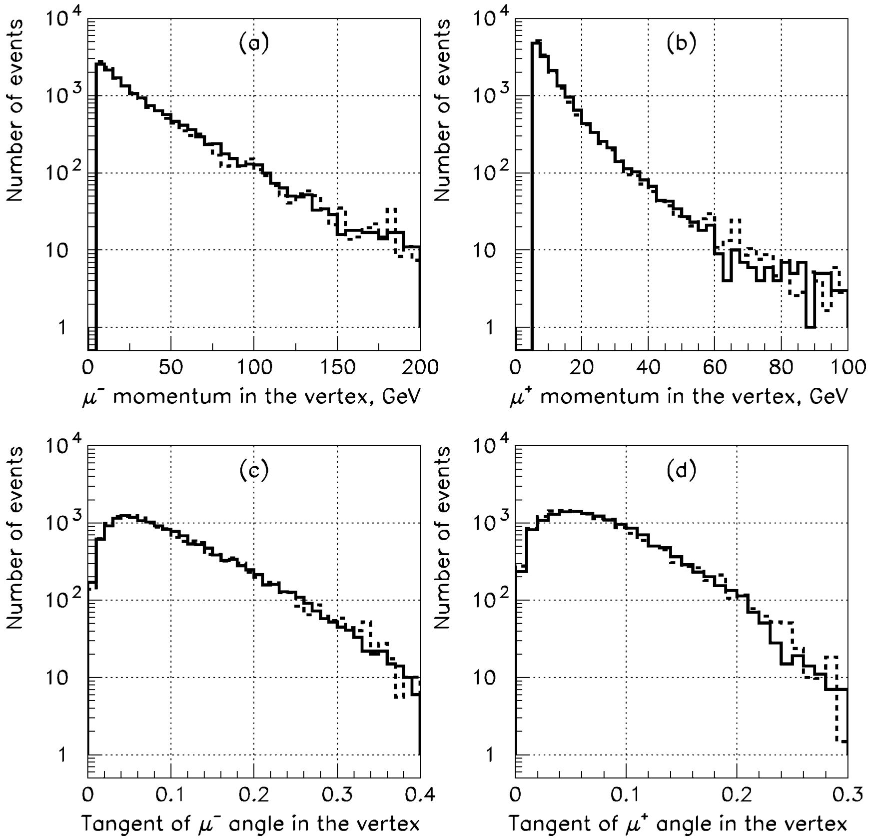

Fig. 2. Kinematical distributions of $\mu^-\mu^+$ events (solid histograms are the data and dashed histograms are the MC predictions): (a) μ^- momentum; (b) μ^+ momentum; (c) μ^- angle; (d) μ^+ angle. The merged MC sample was normalized to the data sample to have the same number of events survive the cuts.

In principle, the vector meson production and muon bremsstrahlung processes would be more naturally normalised to the number of inclusive CC events. However, since the two methods agree within 5% we have chosen to normalise to the inclusive dimuon rate. This has the advantage that the dimuons and trimuons share the same trigger conditions, and therefore this method can be considered as "internal normalisation".

The expected numbers of trimuons from muonic decays of light neutral mesons and resonances are summarized in Table 3. The total contribution from this source is 23.1 ± 5.0 events. The selection efficiency is given in the table and varies from 1.0% for η to 2.7% for ϕ. The errors include uncertainties in the branching ratios and yields, the MC systematic errors, and the uncertainty of the normalization (10%). The MC systematics was evaluated by varying the JETSET key parameters as described in Section 4.

Table 2
Relative rates of dimuon events

Sample	N^{--}/N^{-+}	N^{++}/N^{-+}
Present data	0.139 ± 0.007	0.0044 ± 0.0005
Combined MC	0.121 ± 0.013	0.0034 ± 0.0015

The sources of trimuon events discussed so far account for all but 10.6 of the observed events. To investigate the consistency of this result with the expectation from the internal bremsstrahlung process, we use the fact that its kinematics has a characteristic feature. Fig. 3(a) shows the distribution of the angle

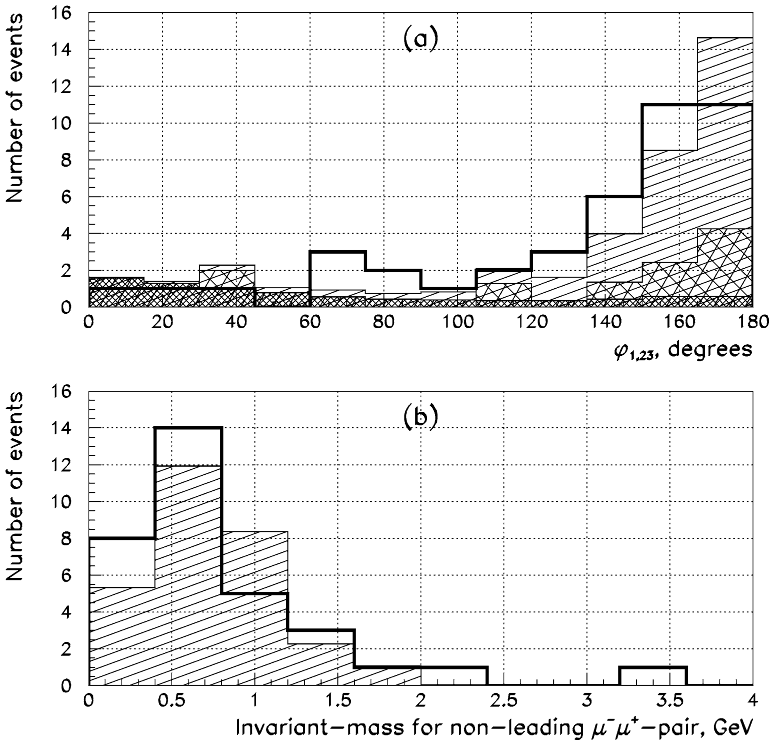

Fig. 3. (a) Angle $\phi_{1,23}$ between the leading μ^- and the vector sum of momenta of the two other muons in the plane perpendicular to the initial neutrino direction in $\mu^-\mu^-\mu^+$ events. The solid hatched histogram shows the data and the filled histograms are the MC predictions (see text). The bottom hatched histogram is only internal bremsstrahlung, the middle hatched histogram is internal bremsstrahlung plus charm and π/K muonic decays, and the top hatched histogram represents all sources. (b) Invariant-mass for the non-leading $\mu^-\mu^+$-pair in $\mu^-\mu^-\mu^+$ events having $\phi_{1,23} \geqslant 90°$ (solid unhatched histogram is the data and hatched histogram is the MC). Here the internal bremsstrahlung contribution was neglected.

Table 3
Number of expected trimuon events ($N_{3\mu}$) and their selection efficiency ($\epsilon_{3\mu}$) from the MC

Decay	$N_{3\mu} \pm \Delta N_{3\mu}$	$\epsilon_{3\mu} \pm \Delta\epsilon_{3\mu}$
$\eta \to \gamma\mu^-\mu^+$	11.2 ± 4.5	0.010 ± 0.002
$\rho \to \mu^-\mu^+$	2.8 ± 0.7	0.017 ± 0.004
$\omega \to \mu^-\mu^+$	3.8 ± 1.7	0.018 ± 0.003
$\omega \to \pi^0\mu^-\mu^+$	3.0 ± 1.0	0.013 ± 0.002
$\eta' \to \gamma\mu^-\mu^+$	1.5 ± 0.5	0.018 ± 0.004
$\phi \to \mu^-\mu^+$	0.8 ± 0.2	0.027 ± 0.005

$\phi_{1,23}$ between the leading μ^-[18] and the vector sum of momenta of the two other muons in the plane perpendicular to the initial neutrino direction. As was shown in Refs. [5, 3a], about two thirds of the events from internal bremsstrahlung have $\phi_{1,23} \leqslant 90°$. Using this feature, we normalized the theoretical curve quoted in Ref. [3a] to 5.7 ± 3.0 events in the interval $\phi_{1,23} \leqslant 90°$, which are left after subtraction of the expected contribution from charm dimuon events with an additional π^-/K^- decay and light neutral meson decays. The estimated contribution of internal bremsstrahlung at $\phi_{1,23} \geqslant 90°$ is 2.9 ± 1.5 events.

The invariant-mass distribution for the non-leading $\mu^-\mu^+$-pair is shown in Fig. 3(b). The cut $\phi_{1,23} \geqslant 90°$ was applied to suppress the contribution from the internal bremsstrahlung. The MC describes the data reasonably well.

In conclusion, 42 neutrino-induced $\mu^-\mu^-\mu^+$ events were observed and their origin accounted for. Detailed GEANT-based MC simulations showed that

---

[18] Following Ref. [3a] “we take as the leading muon that negative muon for which the sum of the absolute values of transverse momenta of the other negative muon and the positive muon with respect to the direction of the virtual W-boson is minimal”.

23.1 ± 5.0 events are expected to come from rare muonic decays of neutral mesons and resonances, mostly from η and ω. Therefore, rare decays of light mesons, abundantly produced in neutrino–nucleon interactions, are an important source of $\mu^-\mu^-\mu^+$ events, accounting for more than a half of all trimuons and almost three quarters of those having a hadronic origin. Another 8.3 ± 2.8 events are predicted to be from muonic decays of charmed particles with an additional π/K decay. Finally, the contribution from internal bremsstrahlung of virtual photons into a muon pair is estimated as 8.6 ± 4.5 events. Associated-charm production with subsequent decays of both charmed particles into muons is negligible.

Acknowledgements

We gratefully acknowledge the help and support of the neutrino-beam staff and of the numerous technical collaborators who contributed to the detector construction and operation. The experiment has been made possible by grants from the Institut Interuniversitaire des Sciences Nucléaires and the Interuniversitair Instituut voor Kernwetenschappen (Belgium); the Israel Science Foundation (grant 328/94) and the Technion Vice President Fund for the Promotion of Research (Israel); CERN (Geneva, Switzerland); the German Bundesministerium für Bildung und Forschung (Germany); the Institute of Theoretical and Experimental Physics (Moscow, Russia); the Istituto Nazionale di Fisica Nucleare (Italy); the Promotion and Mutual Aid Corporation for Private Schools of Japan and Japan Society for the Promotion of Science (Japan); the Korea Research Foundation Grant KRF-2003-005-C00014 (Republic of Korea); the Foundation for Fundamental Research on Matter FOM and the National Scientific Research Organisation NWO (The Netherlands); and the Scientific and Technical Research Council of Turkey (Turkey). We gratefully acknowledge their support.

References

[1] B.C. Barish, et al., Phys. Rev. Lett. 38 (1977) 577;
A. Benvenuti, et al., Phys. Rev. Lett. 38 (1977) 1110.
[2] M. Holder, et al., CDHS Collaboration, Phys. Lett. B 70 (1977) 393;
P.C. Bosetti, et al., Phys. Lett. B 73 (1978) 380.
[3] T. Hansl, et al., CDHS Collaboration, Nucl. Phys. B 142 (1978) 381;
T. Hansl, et al., CDHS Collaboration, Phys. Lett. B 77 (1978) 114.
[4] A. Benvenuti, et al., HPWF Collaboration, Phys. Rev. Lett. 42 (1979) 1024.
[5] J. Smith, Nucl. Phys. B 157 (1979) 451;
J. Smith, Phys. Lett. B 85 (1979) 124, and references therein.
[6] E. Eskut, et al., CHORUS Collaboration, Nucl. Instrum. Methods A 401 (1997) 7.
[7] S. Buontempo, et al., Nucl. Instrum. Methods A 349 (1994) 70;
E. Di Capua, et al., Nucl. Instrum. Methods A 378 (1996) 221.
[8] A. Artamonov, P. Gorbunov, CHORUS Internal Note 97029, 23 February 1998, updated on 12 March 1999, http://choruswww.cern.ch/Publications/Notes/spec1mu_new.pdf.
[9] M.G. van Beuzekom, et al., Nucl. Instrum. Methods A 427 (1999) 587.
[10] I. Tsukerman, et al., CHORUS Internal Notes 2000023 and 2000025, 16 March 2004, http://choruswww.cern.ch/Publications/Notes/datamc2munew.pdf, http://choruswww.cern.ch/Publications/Notes/rhoetaaugnew.pdf.
[11] CHORUS Collaboration, E. Eskut, et al., Phys. Lett. B 503 (2001) 1.
[12] R. Oldeman, PhD Thesis, University of Amsterdam, The Netherlands, 2000, http://choruswww.cern.ch/Internals/Reference/Theses/oldeman.ps.gz.
[13] G. De Lellis, A. Marotta, P. Migliozzi, J. Phys. G 28 (2002) 713;
G. De Lellis, A. Marotta, P. Migliozzi, J. Phys. G 28 (2002) 1515, Erratum.
[14] P. Zucchelli, PhD Thesis, University of Ferrara, Italy, 1992/1994.
[15] G. Ingelman, LEPTO version 6.1, Preprint TSL/ISV-92-0065, Uppsala University, May 1992.
[16] T. Sjostrand, Comput. Phys. Commun. 82 (1994) 74;
T. Sjostrand, PYTHIA 5.7 and JETSET 7.4, physics and manual, CERN Program library long writeup W5035/W5044.
[17] GEANT 3.21, CERN Program library long writeup W5013.
[18] K. Hagiwara, et al., Phys. Rev. D 66 (2002) 010001.
[19] G.T. Jones, et al., Z. Phys. C 51 (1991) 11;
G.T. Jones, et al., Z. Phys. C 51 (1991) 205;
P. Allen, et al., Nucl. Phys. B 194 (1982) 373;
H. Grassler, et al., Nucl. Phys. B 272 (1986) 253;
H. Grassler, et al., Nucl. Phys. B 268 (1986) 1;
V.V. Ammosov, et al., Sov. J. Nucl. Phys. 46 (1987) 80;
J. Berge, et al., Phys. Rev. D 22 (1980) 1043;
M. Derrick, et al., Phys. Lett. B 91 (1980) 307;
V.V. Ammosov, et al., Sov. J. Nucl. Phys. 45 (1987) 457;
V.V. Ammosov, et al., Sov. J. Nucl. Phys. 46 (1987) 998;
W. Wittek, et al., Phys. Lett. B 187 (1987) 179.
[20] P. Astier, et al., NOMAD Collaboration, Nucl. Phys. B 601 (2001) 3, and references therein.
[21] W. Wittek, et al., Z. Phys. C 44 (1989) 175.
[22] A. Kayis-Topaksu, et al., CHORUS Collaboration, Phys. Lett. B 539 (2002) 188.
[23] K. Hagiwara, Nucl. Phys. B 173 (1980) 487.
[24] B.A. Kniehl, L. Zwirner, Nucl. Phys. B 678 (2004) 258.