Proceedings of the DIS'2004, Štrbské Pleso, Slovakia

NEUTRINO DIS MEASUREMENTS IN THE CHORUS EXPERIMENT

ALFREDO G. COCCO
Instituto Nazionale di Fisica Nucleare
Complesso Universitario Monte S.Angelo - I80126 Napoli, Italy
E-mail: alfredo.cocco@na.infn.it

The result of the analysis of neutrino induced charged current events in the lead scintillating fiber calorimeter of the CHORUS experiment is presented. A large statistics of neutrino interactions was collected in four years data taking on the Wide Band Neutrino Beam at CERN. Analysis on the production mechanism of dimuons and trimuons are reported in detail together with a study of the Z/A dependence of the charged current cross section performed using a dedicated setup.

1 The Chorus experiment

The CHORUS detector [1] was exposed to the Wide Band Neutrino Beam at CERN from 1995 until 1998. Neutrinos were produced at the SPS by a proton beam of 450 GeV; the average neutrino energy was of 27 GeV with a antineutrino contamination of about 6%. The 112 ton lead-scintillating fiber calorimeter, described in details in [2], has been used as an active target for neutrino induced charged current events. The calorimeter consists of three sections with decreasing granularity along the beam direction, for a total of 5.2 interaction lengths. A detailed test beam calibration of calorimeter performances was carried out [3]. A muon spectrometer composed of six magnetized iron toroids instrumented with drift chambers and scintillators is located further downstream to identify muons and determine their momentum; a resolution going from $\Delta p/p \sim 15\%$ at 20 GeV to $\Delta p/p \sim 19\%$ at 70 GeV was achieved, as measured with test beam muons [4]. The trigger system of the CHORUS experiment is described in [5]; a dedicated "dimuon" trigger setup was used to collect a large statistics of double track events used both in dimuons and trimuons analyses. A total of 4.9×10^{19} protons were accumulated on the Be target in the period 1995-1998; the overall CHORUS data collection efficiency was about 92% with a dead time of 5%.

2 Dimuons analysis

Events with two muons in the final state are mainly due to the production and decay of a single charm quark produced in deep inelastic scattering interactions. The dimuon sample was collected during four year of data taking with a dedicated trigger setup. A total of 6.6×10^6 events tagged as dimuons by the trigger were reduced to about 5.0×10^5 requiring that at least two muons were properly reconstructed by the muon spectrometer. Further cuts were applied in order to ensure a reliable event reconstruction: muon energy greater than 5 GeV and at least 2 muons within a distance of 15 cm in the vertex plane, fiducial volume ($|V_{y,z}| < 120$ cm and $295 < V_x < 394$ cm) and reconstructed shower energy ($5 < E_{sh} < 200$ GeV). An additional cut of events with $Q^2 < 4$ GeV^2 was performed in order to exclude quasi-elastic and resonances production, since these are not described by MonteCarlo.

The dimuon sample statistics after the cuts is the following $N^{--} = 2801$, $N^{-+} = 13132$, $N^{+-} = 1224$, $N^{++} = 70$; where the primary muon is assumed to be that one with the largest transverse momentum with respect to the neutrino beam direction. The efficiency of a correct identification of the primary muon was estimated to be about 96% for neutrino interactions.

A complete event generator named MCDIS and based on the leading order (LO) helicity formalism [6] to describe neutrino charged current cross section has been developed in the CHORUS Collaboration [7]. In this scheme neutrino charm production cross section is written as

$$\frac{d^2\sigma}{dxdy} = 2G_F^2 \frac{yQ^2}{\pi} \left(|V_{cd}|^2 d(\chi) + |V_{cs}|^2 s(\chi)\right) \left[\left(\frac{1+\cosh\psi}{2}\right)^2 + \frac{m_c^2}{2Q^2}\frac{\sinh^2\psi}{2}\right] \quad (1)$$

where the mass of the initial quark has been neglected. The scaling variable χ become the "slow rescaling" variable [8] in the limit $M^2/Q^2 \to 0$. Radiative corrections [9] and nuclear effects due to non isoscalarity of the lead target and Fermi motions are taken into account in the cross section evaluation.

Parton distribution functions used are GRV94LO and we parametrize the strange quark content of the nucleon with the parameter

$$\kappa = \frac{\int \left[xs(x,\mu_o^2) + x\bar{s}(x,\mu_o^2)\right] dx}{\int \left[x\bar{u}(x,\mu_o^2) + x\bar{d}(x,\mu_o^2)\right] dx} \quad (2)$$

where μ_o^2 is an arbitrary reference scale chosen to be 20 GeV^2. In a SU(3) flavor symmetric sea κ would be equal to one. Fragmentation of the charm quark is performed using the Peterson parametrization $D(z,\epsilon) \propto 1/z(1-1/z-\epsilon/(1-z))^{-2}$ where ϵ is a free parameter to be determined from data and z is the fraction of the charm quark longitudinal momentum take over by the charmed hadron $z = P_L(h_c)/P_L^{max}(h_c)$. Here $P_L(h_c)$ is the hadron longitudinal momentum relative to the W-boson direction in the boson-nucleon center of mass frame. Transverse momentum of charmed hadrons with respect to W-boson direction is assumed to be $dN/dp_t^2 \propto e^{-bp_t^2}$ with $b = 1.1$ as from [10]. MCDIS uses JETSET [11] for hadronization and the event is passed to the CHORUS full detector MonteCarlo in order to obtain an event that could undergo all the steps performed in the real data selection procedure.

The number of observed dimuon events depend on the charm quark mass m_c via the slow rescaling mechanism, the amount of strange quark sea (κ), the fragmentation parameter (ϵ) and on the branching ratio of charm into muon (B_μ). The background is mainly due to muonic decay of hadrons produced in the deep inelastic neutrino interaction. The amount of background was estimated using dimuon events in which both muons had identical charge (same-sign events). These events are mainly due to decay of pions and kaons whose contribution to opposite sign events should likely be the same. Background can thus be parametrized as $B^{-+} = (N_{CC}^{-+}/N_{CC}^{--})_{MC} N_{DATA}^{--}$ taking into account selection efficiencies and neutrino-antineutrino cross contamination. A total of 10^6 CC interactions were fully simulated through the whole analysis chain in order to establish $(N_{CC}^{-+}/N_{CC}^{--})_{MC} = 0.9 \pm 0.1$. After background subtraction a total of 10718 ± 288 leading μ^- and 420 ± 63 leading μ^+ where selected. This represents the largest sample of neutrino induced dimuons to date.

In order to extract information on the production mechanism of dimuon events, a maximum likelihood fit to the four parameters (m_c, κ, ϵ and B_μ) has been performed. The MonteCarlo is used to evaluate the event by event probability of the observables E_ν, $z = E_{\mu 2}/(E_{\mu 2} + E_{sh})$ and $x_{bjorken}$, as function of the four unknown parameters. The fit was performed using MINUIT simultaneously on the four parameters giving the following result: $m_c = 1.46 \pm\ 0.15$ (stat) $\pm$ 0.10 (syst) $\kappa = 0.56 \pm\ 0.05$ (stat) $\pm$ 0.045 (syst) $\epsilon = 0.040 \pm\ 0.003$ (stat) $\pm$ 0.015 (syst) $B_\mu = 0.098 \pm\ 0.005$ (stat) $\pm$ 0.014 (syst). Systematic errors include uncertainties on event normalization, background scale, hadronic energy measurement, radiative corrections, parton distribution functions and CKM matrix elements. More details can be found in [12]. In Fig. 1 is shown the result of the fit.

3 Trimuons analysis

The CHORUS analysis of events with three muons in the final state is reported in details in [13]. These events are found to be mostly of hadronic origin, with a small contribution from internal bremsstrahlung. 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.

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. This sample corresponds to 18.0×10^6 CC events with $10 \leq E_\nu \leq 200$ GeV. The observed ratio of number of $\mu^-\mu^-\mu^+$ and single μ^- events as a function of visible neutrino energy is shown in Fig. 2

A detailed MC simulation was performed to clarify the origin of trimuon events. The following sources of $\mu^-\mu^-\mu^+$ production were considered: (i) ν_μCC events with rare decays of light neutral mesons and resonances into a muon pair and (ii) 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.

In the first case experimental data on production of $\eta(548)$, $\rho(770)$ and $\omega(782)$ in neutrino interactions and on their muonic branching ratios have been taken into account. Decay of $\eta \to \gamma\mu^-\mu^+$ and $\rho \to \mu^-\mu^+$ were forced at the generation stage. The uncertainty introduced by the JETSET parameter settings amounts to 20% at most.

In the second case large samples of 2μ events were generated and passed through the same selection chain as 3μ events. The observed distributions of the muon momenta and the angles with respect to the initial neutrino direction for $\mu^-\mu^+$ events are well described by the MC. The predicted and the observed relative rates of $\mu^-\mu^-$, $\mu^+\mu^+$ and $\mu^-\mu^+$ events agree also. 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.

The MonteCarlo predicts 8.3±2.8 $\mu^-\mu^-\mu^+$ events from charm dimuon events with an additional π^-/K$^-$ decay, where 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. The expected numbers of trimuons from muonic decays of light neutral mesons and resonances is 23.1±5.0 events. The selection efficiency varies from 1.0% for η to 2.7% for ϕ. The contribution from internal bremsstrahlung of virtual photons into a muon pair is estimated to be of 8.6±4.5 events.

In conclusion, 42 neutrino-induced $\mu^-\mu^-\mu^+$ events were observed and their origin accounted for. Detailed GEANT-based MC simulations showed that these are expected to come (i) from rare muonic decays of neutral mesons and resonances, mostly from η and ω, (ii) from muonic decays of charmed particles with an additional π/K decay, (iii) from internal bremsstrahlung of virtual photons into a muon pair.

4 Z/A dependence of the CC cross section

The analysis of the Z/A dependence of the CC cross section in CHORUS is reported in details in [14]. Only part of the CHORUS detector was used, namely the trigger hodoscopes, the tracking system made of honeycomb chambers, the calorimeter and the muon spectrometer. The data used in this analysis were acquired in 1998 when a set of four targets consisting of polyethylene, marble, iron and lead was added to the CHORUS detector. Four targets (Marble, Iron, Lead, Plastic) were positioned with their mid-plane perpendicular to the neutrino beam and were arranged in two columns and two rows, transversely separated by 20 cm air gaps. The blocks had the same transverse cross-section (50×50 cm^2) and approximately the same mass ($\sim$ 100 kg). In this way comparable statistics and a clear separation of the interactions from each target could be obtained.

Five planes of scintillator hodoscopes were used for on-line triggering and analysis purposes. The on-line trigger system selects interactions in the four targets and in the calorimeter simultaneously. The trigger logic required signals consistent with a track in the calorimeter and the spectrometer. In total about 4.0×10^6 muon tracks are reconstructed and extrapolated to the four-target mid-plane.

Interactions by incident neutrinos are selected by requiring muons with negative charge. The muon momentum at the entrance of the spectrometer is required to be larger than 4 GeV/c (this implies an effective cut of $\approx$ 6 GeV/c at the interaction vertex since muons have to traverse the calorimeter before being measured in the spectrometer). It was checked with a simulation that the difference in energy loss in the different materials of the four targets has a negligible effect (less than 0.1% of the events) on this selection.

Experimentally, the neutrino CC total cross-section per nucleon may be written as $\sigma^A(\nu N) = N^\mu/(\Phi^\nu \rho_N)$, where N^μ is the number of muons produced in the target, Φ^ν is the number of incident neutrinos integrated over the energy spectrum and area, and ρ_N the thickness of the target in nucleons per cm^2. The integrated neutrino flux Φ^ν is not measured in this experiment, therefore it is not possible to obtain absolute cross-sections. Furthermore, relative knowledge of the neutrino flux is needed when taking the ratio $\sigma^{A_i}(\nu N)/\sigma^{A_j}(\nu N)$ for a given pair of targets A_i and A_j, since the neutrino fluxes collected during the periods with different configuration were not identical. This information can be obtained from the number of muons, M^μ, in the calorimeter sample. The flux is then expressed as $\Phi^\nu = M^\mu/(\sigma^{calo}(\nu N)\,\rho_N^{calo})$, where the denominator is a constant, C, equal for all four targets. The ratios (N^μ/M^μ) for all four target materials thus measure the cross-sections up to a common constant. The results for $\sigma^A(\nu N)/C$ are plotted as a function of Z/A in Fig. 3. The measurement of the Z/A-dependence is a direct experimental result and thus it is independent of models describing neutrino-nucleus cross-sections.

These experimental results can be interpreted in terms of an *effective* cross-section ratio $\sigma(\nu n)/\sigma(\nu p)$ sampled with the acceptance of the present detector. To obtain $\sigma(\nu n)/\sigma(\nu p)$ it is assumed that the neutrino-nucleus total cross-section is an incoherent weighted sum of the neutron and proton cross-sections. The cross-section per nucleon is then a linear function of Z/A with two parameters: $\sigma(\nu A)/\mathrm{A} = (\mathrm{Z/A})p1 + p2$, where $p1 = \sigma(\nu p) - \sigma(\nu n)$ and $p2 = \sigma(\nu n)$. The solid line in Fig. 3 represents the best linear fit to the four data points, from which the value $\sigma(\nu n)/\sigma(\nu p) = 1.71 \pm 0.22(stat) \pm 0.08(syst)$ for the effective neutron-to-proton cross-section ratio is obtained. The model calculation predicts for the neutron-to-proton cross-section ratio a value of 1.87 for our energy spectrum and for a detector with full acceptance.

References

1. E. Eskut *et al.*, Nucl. Inst. and Methods **A401** (1997) 7.
2. E. Di Capua *et al.*, Nucl. Inst. and Methods **A378** (1996) 221.
3. A.G.Cocco *et al.*, Chorus internal notes 2000019 and 2000020.
4. A. Artamonov and P. Gorbunov, CHORUS Internal note 97029 (1997).
5. M.G. van Beuzekom *et al.*, Nucl. Inst. and Methods **A427** (1999) 587.
6. M.A.G. Aivazis *et al.*, Phys. Rev. **D50** (1994) 3085; **D50** (1994) 3102.
7. A.G. Cocco, Chorus internal note; in preparation.
8. R.M. Barnett, Phys. Rev. Lett. **36** (1976) 1163.
9. D.Yu. Bardin and V.A. Dokuchaeva, Preprint JINR E2-86-260 (1986).
10. M. Aguilar-Benitez *et al.*, Phys. Lett. **B123** (1983) 98.
11. T. Sjostrand, Comput. Phys. Commun. **82** (1994) 74.
12. CHORUS Collaboration, "LO analysis of neutrino induced dimuon events", in preparation.
13. A. Kayis-Topaksu *et al.*, Phys. Lett. **B596** (2004) 44.
14. A. Kayis-Topaksu *et al.*, Eur. Phys. J. **C30** (2003) 159.

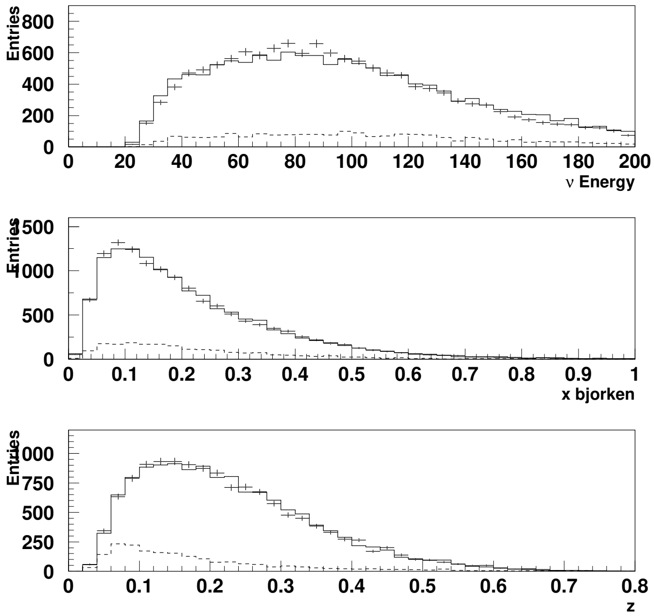

Figure 1. MonteCarlo (histogram) and Data (crosses) comparison for the result of the maximum likelihood fit to the dimuon sample. Contribution of events originated by π and K decay into muon is also shown.

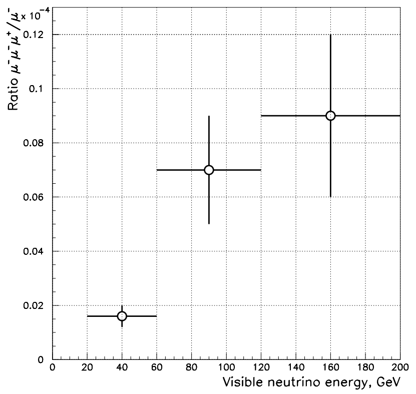

Figure 2. Ratio of number of $\mu^-\mu^-\mu^+$ and single μ^- events survived the cuts as a function of visible neutrino energy. The visible energy is defined as a scalar sum of muon momenta and shower energy.

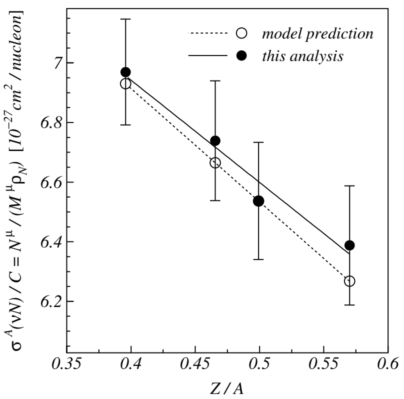

Figure 3. The measurements of the relative total cross-sections, $\sigma^A(\nu N)/C$, plotted as a function of Z/A (filled dots). The model predictions are superimposed (open dots) such that the points for marble coincide.