Exclusive Muon Neutrino Charged Current Pion-less Topologies. ArgoNeuT Results and Future Prospects in LAr TPC Detectors

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(Received February 29, 2016)

Results from the analysis of charged current pion-less (CC 0-pion) muon neutrino events in argon collected by the ArgoNeuT experiment on the NuMI beam at Fermilab are presented and compared with predictions from Monte Carlo simulations. A novel analysis method, based on the reconstruction of exclusive topologies, fully exploiting the Liquid argon Time Projection Chamber (LAr TPC) technique capabilities, is used to analyze the events, characterized by the presence at the vertex of a leading muon track eventually accompanied by one or more highly ionizing tracks, and study nuclear effects in neutrino interactions on argon nuclei. Multiple protons accompanying the leading muon are visible in the ArgoNeuT events, and measured with a proton reconstruction threshold of 21 MeV kinetic energy. Measurements of (anti-)neutrino CC 0-pion inclusive and exclusive cross sections on argon nuclei are reported. Prospects for future, larger mass LAr TPC detectors are discussed.

**KEYWORDS:** Neutrino Interactions, Neutrino Cross Sections, Nuclear Effects

1. Introduction

The analysis and interpretation of the present and future neutrino oscillation experiments strongly rely on the quantitative understanding of neutrino and antineutrino interactions with nuclei in the GeV energy range. In this energy range the most important interaction channel is the charged current (CC) quasi elastic (QE) scattering, historically referring to the emission of a charged lepton and a single nucleon. For this reason, a lot of effort has been devoted to measurements of neutrino- and antineutrino-nucleus "QE like" cross-sections in a broad kinematical domain.

Nuclear effects, however, play a key role in neutrino-nucleus interactions in nuclear targets. Due to intra-nuclear re-scattering of hadrons produced in the initial state as they exit the nucleus (FSI) and effects of correlation between target nucleons, a genuine QE interaction can often be accompanied by the ejection of additional nucleons (multi-nucleon knock-out), emission of many de-excitation \(\gamma\)'s and sometimes by soft pions in the final state. On the other hand, an interaction which is not a CCQE process can change due to nuclear effects and mimic its signature, leading to its acceptance in the final CCQE event sample. This is especially common in case of pion absorption in the nucleus. Nuclear effects can drastically alter what was initially produced by a neutrino interaction and are an important source of perturbation for the kinematic of quasi elastic neutrino interactions. Neutrino interaction channel definitions are largely ill defined and all the measurements of specific interaction channels largely rely on Monte Carlo simulation.

An approach based on the event categorization in terms of exclusive topologies is here reported for data analysis and cross section measurement of muon neutrino charged current pion-less (\(\nu_\mu\) CC 0-pion) events from the ArgoNeuT LAr TPC data. Prospects for future larger mass detectors are...
discussed.

2. Exclusive topologies in LAr TPC detectors

LAr TPC detectors provide full 3D imaging, precise calorimetric energy reconstruction down to very low threshold, efficient particle identification and background rejection.

Taking advantage of the reconstruction capabilities of LArTPCs, individual neutrino events can be categorized in terms of exclusive topologies observed in the final state and used to explore the evidence of nuclear effects in neutrino-argon interactions from detailed studies of the hadronic part of the final states.

CC muon neutrino events can be classified in CC 0-pion topologies ($\mu+Np$, where $N=0,1,2,...$ characterized by the presence at the vertex of a leading muon track eventually accompanied by one or more highly ionizing tracks), one pion topologies ($\mu+Np+1\pi$), etc. CC 0-pion events exclusive topologies can be selected and fully reconstructed, measurements of proton multiplicity at the neutrino interaction vertex and reconstruction of proton kinematics in events with different proton multiplicity can be performed with very low proton energy threshold, ultimately allowing for most precise reconstruction of the incoming neutrino energy from lepton and proton kinematics.

3. $\nu_\mu$ CC 0-pion events. ArgoNeuT results

The ArgoNeuT detector, 170 l active volume LArTPC, collected \~7000 CC muon neutrino events running in the NuMI LE beam at Fermilab in both $\nu$-mode (collecting 8.5x10$^{18}$ POT) and anti-$\nu$-mode (collecting 1.20x10$^{20}$ POT). The detector was positioned just upstream of the MINOS Near Detector, which provided charge and momentum reconstruction of muons exiting ArgoNeuT. A detailed technical description of the ArgoNeuT detector, its performances and the off-line event reconstruction can be found in [1].

The analyzed sample is the CC 0-pion sample collected in the anti-$\nu$-mode run. It contains both neutrino and anti-neutrino events, for a total of about 600 reconstructed events.

3.1 Event selection and reconstruction

The procedure for the selection and topological classification in terms of final state proton multiplicity of the $\nu_\mu$ CC 0-pion events proceeds through different steps. Muon neutrino CC events are inclusively selected by requiring a negatively charged muon in MINOS-ND matching a track originating from an interacting vertex in the ArgoNeuT detector. From this sample, the main class of ($\mu+Np$) is then extracted. In this class of events the leading muon can be accompanied by any number ($N=0, 1, 2, 3, \geq 4$) of protons in final state. Very efficient particle identification and proton/pion separation is performed through energy deposition versus range measurement.

The three momentum of the muon is determined from the matched track in ArgoNeuT and MINOS-ND, the sign of the muon is provided by MINOS-ND. The reconstruction of the individual proton kinematics (kinetic energy and 3-momentum) is determined by ArgoNeuT with good angular resolution and down to a low proton kinetic energy threshold of 21 MeV. Details of the reconstruction procedure can be found in [1]. In principle, neutrons can also be emitted in these events, however ArgoNeuT has a very limited capability to detect neutrons emerging from the interaction vertex. This is because the detector size is too small to have significant chances to allow neutrons to convert into visible protons in the LArTPC volume before escaping.

All proton tracks are required to be fully contained inside the fiducial volume of the TPC and above the energy threshold [we note that $\mu+Np$ events where a proton is below threshold fall in the $\mu+(N-1)p$ sample]. From detector simulation, the overall acceptance for the $\mu+Np$ sample is estimated to be around 50% (neutrinos) and around 70% (anti-neutrinos), dominated by the requirement of
proton containment in the fiducial volume.

3.1.1 Neutrino energy reconstruction

A precise reconstruction of the incoming neutrino energy is important for the analysis of any experiment which detect neutrinos. Proton identification and reconstruction in neutrino events allows full kinematic reconstruction of the incoming neutrino energy, improving energy reconstruction.

An estimate of the incident neutrino energy in $\nu_\mu$ CC 0-pion events is inferred from the final state particles (muon and protons) measured kinematics. The incident neutrino energy for the ($\mu + Np$) events is given by $E_v = (E_\mu + \sum T_{pi} + T_X + E_{\text{miss}})$ [2], where $E_\mu$ is the reconstructed muon energy, and $T_{pi}$ is the kinetic energy of the proton $pi$. The last two terms are small corrections: the residual nuclear system is undetectable, however a lower bound for its recoil kinetic energy can be calculated using the measured transverse missing momentum as $T_X \approx (P_{\text{miss}}^T)^2/2M_X$. The missing energy $E_{\text{miss}}$ includes two terms, namely the nucleons separation energy for argon and the actual excitation level of the residual nucleus.

3.1.2 Systematic uncertainties and resolutions

The ArgoNeuT CC 0-pion analysis is statistically limited, but systematic uncertainties are included in the analysis, as reported in Tab. I. The most significant contribution (11%) comes from the uncertainty in the neutrino flux. Tab. I also shows the relevant experimental resolutions.

Table I. Systematic uncertainties and experimental resolutions included in the analysis

<table>
<thead>
<tr>
<th>Uncertainty</th>
<th>Uncertainty</th>
</tr>
</thead>
<tbody>
<tr>
<td>NuMI beam Flux [3]</td>
<td>11%</td>
</tr>
<tr>
<td>NC background</td>
<td>&lt;1%</td>
</tr>
<tr>
<td>Wrong sign background (muon wrong sign reconstruction from MINOS ND)</td>
<td>&lt;1%</td>
</tr>
<tr>
<td>Background from events with $\pi^0$ with both $\gamma$ that do not convert in LAr</td>
<td>&lt;1%</td>
</tr>
<tr>
<td>Proton identification</td>
<td>97% efficiency</td>
</tr>
<tr>
<td>Muon momentum resolution</td>
<td>5-10%</td>
</tr>
<tr>
<td>Proton angular resolution</td>
<td>1-1.5°, depending on the track length</td>
</tr>
<tr>
<td>Proton energy resolution</td>
<td>6-10%, depending on proton energy</td>
</tr>
<tr>
<td>Neutrino energy reconstruction</td>
<td>dominated by muon momentum resolution</td>
</tr>
</tbody>
</table>

The overall resolution in neutrino energy reconstruction is dominated by muon momentum resolution, as in CC interactions the muon takes the largest fraction on the incident neutrino energy.

3.1.3 Inclusive and exclusive neutrino and anti-neutrino CC 0-pion cross sections

The number of CC 0-pion events with different proton multiplicity are obtained after applying corrections for efficiency and acceptance and subtracting backgrounds.

The inclusive and exclusive cross section are respectively given by:

\[
\sigma_{CC0\pi}^{\nu_\mu} = \frac{N_{CC0\pi}}{\phi \times Exp \times NFID},
\]

\[
\sigma_{CC0\pi,Np}^{\nu_\mu} = \frac{N_{CC0\pi,Np}}{\phi \times Exp \times NFID}.
\]
and the inclusive cross section as a function of the neutrino energy is given by:

$$\sigma^{\nu}_{CC0}(E_{\nu}) = \frac{N_{CC0}(E_{\nu})}{\phi \times Exp \times NFID}. \quad (3)$$

where $N_{CC0}$ is the measured total number of CC 0-pion events, $N_{CC0, Np}$ is the measured number of CC 0-pion events with proton multiplicity N, and $N_{CC0}(E_{\nu})$ is the measured number of CC 0-pion events at energy $E_{\nu}$, all after efficiency and acceptance correction and background subtraction. $\phi$ is the total (anti-)neutrino flux, Exp is the total exposure and NFID is the number of argon nuclei in the fiducial volume.

The measured cross sections for $\nu_\mu$ and $\bar{\nu}_\mu$ CC 0-pion events are reported in Fig. 1 and Tab. II. Inclusive cross sections and exclusive cross sections at different proton multiplicity (N=0, 1, 2, 3, 4) are shown. Proton multiplicity of 4 is the highest multiplicity found in the data.

Table II. ArgoNeuT CC 0-pion events. Inclusive and exclusive antineutrino and neutrino cross sections. Statistical and systematics error are reported.

<table>
<thead>
<tr>
<th>Proton Multiplicity</th>
<th>$\bar{\nu}<em>\mu$ Cross Section (10$^{-38}$cm$^2$/nucleon) at $&lt;E</em>\nu&gt;=3.6 \pm 1.5$ GeV</th>
<th>$\nu_\mu$ Cross Section (10$^{-38}$cm$^2$/nucleon) at $&lt;E_\nu&gt;=9.6 \pm 6.5$ GeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>$0.39 \pm 0.02 \pm 0.008$</td>
<td>$0.17 \pm 0.02 \pm 0.001$</td>
</tr>
<tr>
<td>1</td>
<td>$0.14 \pm 0.02 \pm 0.002$</td>
<td>$0.43 \pm 0.05 \pm 0.005$</td>
</tr>
<tr>
<td>2</td>
<td>$0.035 \pm 0.007 \pm 0.002$</td>
<td>$0.19 \pm 0.04 \pm 0.001$</td>
</tr>
<tr>
<td>3</td>
<td>$0.008 \pm 0.004 \pm 0.002$</td>
<td>$0.05 \pm 0.02 \pm 0.003$</td>
</tr>
<tr>
<td>4</td>
<td>$0.005 \pm 0.004 \pm 0.001$</td>
<td>$0.03 \pm 0.02 \pm 0.003$</td>
</tr>
<tr>
<td>Total</td>
<td>$0.58 \pm 0.03 \pm 0.06$</td>
<td>$0.87 \pm 0.08 \pm 0.04$</td>
</tr>
</tbody>
</table>

Fig. 1. ArgoNeuT CC 0-pion events. Inclusive and exclusive (N=0, 1, 2, 3, 4 protons, with 21 MeV kinetic energy threshold) $\bar{\nu}_\mu$ (Left) and $\nu_\mu$ (Right) cross sections, at the average energy of 3.6±1.5 and 9.6±6.5 GeV respectively. Argon isoscalar target.

A comparison of the measured antineutrino cross sections as a function of the proton multiplicity with predictions from GENIE [4] and GiBUU [5] neutrino event generators are show in Fig. 2. The total cross section predicted by GENIE, $\sigma^{\bar{\nu}_\mu}_{CC0}(GENIE) = 0.71 \cdot 10^{-38} \text{cm}^2$, is 22% higher than
ArgoNeuT data, with large difference at high proton multiplicity. The total cross section predicted by GiBUU, \( \sigma_{CC0}^{\nu}(GiBUU) = 0.48 \cdot 10^{-38} \text{cm}^2 \), is 17\% lower than ArgoNeuT data, with large difference at 0 proton. As can be seen also in Tab. III, Monte Carlo generators predict varying amounts of proton emission.

![Graph](image_url)

**Fig. 2.** \( \bar{\nu}_\mu \) CC 0-pion events. Comparison of ArgoNeuT exclusive (N=0,1, 2, 3, 4 protons, with 21 MeV kinetic energy threshold) cross sections with predictions from the GENIE (Left) and GiBUU (Right) neutrino event generators. The 2p2h component in GiBUU predictions has large uncertainties. Argon isoscalar target.

### Table III. \( \bar{\nu}_\mu \) CC 0-pion events. Comparison of ArgoNeuT measured fractions of events at different proton multiplicity with different Monte Carlo generators (GENIE, GiBUU and NUWRO [13])

<table>
<thead>
<tr>
<th>Proton Multiplicity</th>
<th>ArgoNeuT data (%)</th>
<th>GENIE (%)</th>
<th>GiBUU (%)</th>
<th>NUWRO (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>67</td>
<td>61</td>
<td>61</td>
<td>65</td>
</tr>
<tr>
<td>1</td>
<td>24</td>
<td>18</td>
<td>24</td>
<td>23</td>
</tr>
<tr>
<td>2</td>
<td>6.0</td>
<td>7.3</td>
<td>9.5</td>
<td>8.0</td>
</tr>
<tr>
<td>3</td>
<td>1.3</td>
<td>4.9</td>
<td>3.5</td>
<td>2.8</td>
</tr>
<tr>
<td>( \geq 4 )</td>
<td>12</td>
<td>1.8</td>
<td>1.6</td>
<td></td>
</tr>
</tbody>
</table>

A comparison of the measured neutrino cross sections as a function of the proton multiplicity with predictions from GENIE neutrino event generator is show in Fig. 3. The total cross section predicted by GENIE, \( \sigma_{CC0}^{\bar{\nu}}(GENIE) = 1.42 \cdot 10^{-38} \text{cm}^2 \), is 64\% higher than ArgoNeuT data, with large difference at 1p and high multiplicity events.

The measured cross sections as a function of the neutrino energy reconstructed from the observed final state particles kinematics, as described in Sect. 3.1.1, are reported in Fig. 4 (Left) for the \( \nu_\mu \) and the \( \bar{\nu}_\mu \) CC 0-pion event samples. A comparison with predictions from GENIE [4] neutrino event generator is show in Fig. 4 (Right). Predictions for anti-neutrino (yellow) and neutrino (red) CC 0-pion events (continuous line), QE only events (dash line) and for CC 0-pion events with proton multiplicity \( \leq 4 \) (long dash line) are reported to guide the comparison. A quite large disagreement can be seen, in particular for neutrinos, in the higher energy region.
Fig. 3. $\nu_\mu$ CC $0$-pion events. Comparison of ArgoNeuT exclusive ($N=0, 1, 2, 3, 4$ protons, with $21$ MeV kinetic energy threshold) cross sections with predictions from the GENIE neutrino event generator. Argon isoscalar target.

Fig. 4. CC $0$-pion events. $\nu_\mu$ (black) and $\bar{\nu}_\mu$ (red) ArgoNeuT measured cross sections as a function of the reconstructed neutrino energy. One-side errors are added to the data to account for systematic from neutrino energy reconstruction (according to GENIE underestimation of $E_\nu$ is $10\%$ for $\nu$ and $4\%$ for $\bar{\nu}$). Argon isoscalar target. Comparison of ArgoNeuT neutrino (blue) and anti-neutrino (pink) data with GENIE predictions. Predictions for anti-neutrino (yellow) and neutrino (red) CC $0$-pion events (continuous line), QE only events (dashed line) and for CC $0$-pion events with proton multiplicity $\leq 4$ (long dashed line) are reported.

4. Future prospects in LAr detectors

Nuclear effects significantly alter cross sections and final state particle topology and kinematics. The main reason for the disagreement between ArgoNeuT data and Monte Carlo predictions is the treatment of nuclear effects in the Monte Carlo generators. LAr data can provide an important discriminator among models. Pion absorption in the nucleus is a dominant effect for CC $0$-pion events. Important measurements of charged pion interaction cross section in LAr will come soon from the LArIAT experiment [7] at Fermilab.

LAr TPC detectors in the Short Baseline Neutrino (SBN) program [8] will provide huge data sets of $\nu$-Ar interactions from the Booster Neutrino Beam (BNB, $<E_\nu> = 800$ MeV). Large samples in MicroBooNE (82 t instrumented volume) [9] are coming. MicroBooNE experiment will record 50,000 $\nu_\mu$ CC per year [10]. SBND experiment (112 t instrumented volume) [11] will record 1.5
million $\nu_\mu$ CC and 12,000 $\nu_e$ CC interactions per year [12]. At the BNB CC 0-pion is the dominant channel. MicroBooNE accumulates the total ArgoNeuT $\nu_\mu$ CC 0-pion statistics in only 15 days and SBND will accumulate 3.5 Million $\nu_\mu$ and 22,000 $\nu_e$ CC 0-pion in 3 years. High statistics measurements will allow to quantify nuclear effects in neutrino-Ar scattering. As an example, ArgoNeuT has recently reported the measurement of short range correlated nucleon pairs in LAr [2]. High precision measurements of these processes will allow more precise comparisons with with theory models with nucleon-nucleon correlation [13].

5. Conclusion

Neutrino oscillation experiments are limited, among others, by the knowledge we have of neutrino-nucleus cross section and nuclear effects. Measurements of these effect in LAr target are particularly important since LAr TPC is the chosen technology for future short- and long-baseline experiments and acquire experimental data is mandatory in order to tune the existing Monte Carlo generator models. Nuclear matter perturbs the initial state of the interaction through many different effects. Several kinematical variables, like pure leptonic variables, are only marginally affected by nuclear effects. Hadronic variables, like proton multiplicity and the reconstructed kinematics of the protons are very sensitive to nuclear effects and can be used to tune Monte Carlo generators.

ArgoNeuT is the first experiment which has shown the capability of a LArTPC detector to identify and reconstruct exclusive neutrino interaction topologies, down to a very low proton threshold of 21 MeV Kinetic Energy. Muon and proton(s) kinematics and proton multiplicity at the neutrino interaction vertex in LAr have been measured. The first model independent measurement of (anti-) neutrino Argon cross section at different proton multiplicities and also for the combined 0+1+ 2 ... + N proton samples, less sensitive to nuclear affects, is presented. Disagreement of the individual cross sections for different proton multiplicities, indicates that the treatment of nuclear effects in the generator need to be further tuned.

In spite of the limited statistics, the ArgoNeuT CC 0-pion event sample shows that LAr data are indeed helpful for nuclear effects understanding. Accurate and extremely detailed Monte Carlo neutrino generators are needed for comparison with LAr data. Nuclear effects in Monte Carlo codes represent the most difficult present challenge and present neutrino generators predict vastly varying amounts of proton emission in $\nu_\mu$ CC 0-pion events.

Future larger mass and high statistics LAr TPC detectors will allow to quantify nuclear effects in neutrino-Ar scattering and provide important hints to tune Monte Carlo generators and discriminate among models.

References

[12] C. Adams, "SBND: Neutrino Interactions at Fermilab’s Short Baseline Near Detector", this proceedings.