

Hints on Nuclear Effects from ArgoNeuT data

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Abstract. Initial results from a topological analysis of CC "0 pion" muon neutrino events in LAr collected by the ArgoNeuT experiment on the NuMI LE beam at Fermilab (in the few GeV energy region) are presented and compared with predictions from MC simulations. A new analysis method, based on the reconstruction of exclusive topologies, fully exploiting the LArTPC technique capabilities, is used to analyze the events and study nuclear effects in neutrino interactions on Argon nuclei. Multiple protons accompanying the leading muon and the presence of vertex activity are clearly visible (and measured) in the events. Ratios among rates of different exclusive topologies provide indications of the size of nuclear effects in neutrino-nucleus interactions in LAr.

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LARTPC ANALYSIS APPROACH

The analysis and interpretation of 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 (FSI) and possible effects of correlation between target nucleons, a genuine QE interaction can hence often be accompanied by the ejection of additional nucleons, emission of many de-excitation γ 's and sometimes by soft pions in the Final State (after hadronization). Neutrino interaction channel definitions are largely ill defined given the effects of FSI and measurements of specific channels largely rely on MC simulation.

LArTPC detectors, providing bubble-chamber-like quality images and excellent particle ID and background rejection, allow for MC independent measurements, FSI exploration and exclusive topology recognition with extraordinary sensitivity. Instead of MC based classification of the events in the interaction channels (QE, RES, DIS etc), neutrino events in LAr can be classified in terms of final state topology based on particle multiplicity: CC 0 pion ($\mu+N$ proton, where $N=0,1,2,\dots$), CC 1 pion ($\mu+N$ proton+ 1π) events, etc.. In imaging LArTPC detectors, these exclusive topologies can be 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.

A first topological analysis of the CC 0 pion muon neutrino events in the few GeV energy region, has been currently developed and exploited in ArgoNeuT. The ArgoNeuT detector [1] [2], 170 l active volume LArTPC, collected ~ 10000 CC muon neutrino events running in the NuMI LE beam at Fermilab in both ν -mode (2 weeks, 8.5×10^{18} POT) and anti- ν -mode (6 months, 1.20×10^{20} POT). The detector was positioned just upstream of the MINOS Near Detector, which provided charge and momentum reconstruction of muons exiting ArgoNeuT.

Results from an analysis of exclusive $\mu+N_p$ topologies in ArgoNeuT are reported in [3]. Further details, focused on the study of nuclear effects in neutrino interactions in Argon nuclei are reported here.

IMPACT OF NUCLEAR EFFECTS

Due to FSI and possible effects of correlation between target nucleons, a genuine neutrino-nucleus QE interaction can often be accompanied by the ejection of additional particles. As an example, the results of a FLUKA [6] MC

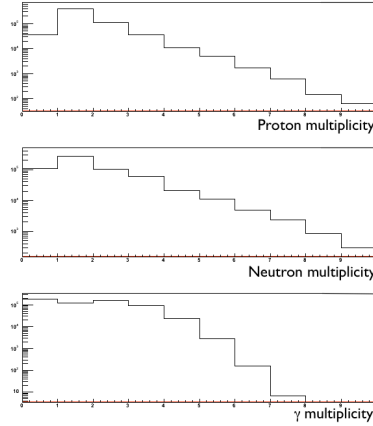


FIGURE 1. FLUKA simulation: multiplicity of protons, neutrons and γ s in CCQE ν_μ events in LAr from the NuMI beam LE beam (neutrino mode).

simulation of CCQE ν_μ events in LAr from the NuMI LE beam (neutrino mode)¹ are reported in Fig. 1. As can be seen from this figure, ejection of additional nucleons and many de-excitation γ 's is present in the final state.

These products are usually neglected because they are not detectable, unless a high quality, low energy threshold imaging detector is in use. As shown in Fig.2 in LArTPC one can actually "see" the recoil proton(s). Accurate and extremely detailed, nuclear physics based, MonteCarlo neutrino generators are therefore needed for comparison with LAr data. Available versions of MC neutrino generators include the treatment of FSI but not (yet) multi-nucleon correlations. FSI in MC codes represent the most difficult present challenge in MC development and present neutrino generators predict very different number of emitted protons .

RECONSTRUCTION OF EXCLUSIVE TOPOLOGIES IN ARGONEUT

The methods used for the selection and classification in terms of final state proton multiplicity of the ArgoNeuT CC 0 pion neutrino events² are described in [3].

By fully exploiting the LArTPC technique for 3D and calorimetric reconstruction, protons at the neutrino interaction vertex are identified through a very efficient particle identification method and counted, allowing for topology recognition with high sensitivity thanks to the good resolution for final states and p/π^\pm identification capability. Multi-proton accompanying the leading muon and the presence of vertex activity are clearly visible (see Fig.3), while in Cherenkov detectors all these classes of events are typically "CCQE like" events.

Reconstruction of proton events is challenging and requires accurate 3D and calorimetric reconstruction of low energy protons. A very low threshold of 21 MeV kinetic energy has been achieved by ArgoNeuT for proton identification. The kinematics of proton(s) are fully reconstructed through the calorimetric reconstruction procedure described in [1], [4].

In ArgoNeuT CC 0 pion muon neutrino events exclusive topologies are therefore identified, muon and proton(s) kinematics and proton multiplicity at the neutrino interaction vertex in LAr are measured for events with identified proton(s) with kinetic energy >21 MeV.

¹ Kindly from G. Battistoni (priv. comm.)

² Due to the small size of the detector the presence of additional neutrons can be identified (through $n \rightarrow p$ conversion) in only a very small fraction of the events.

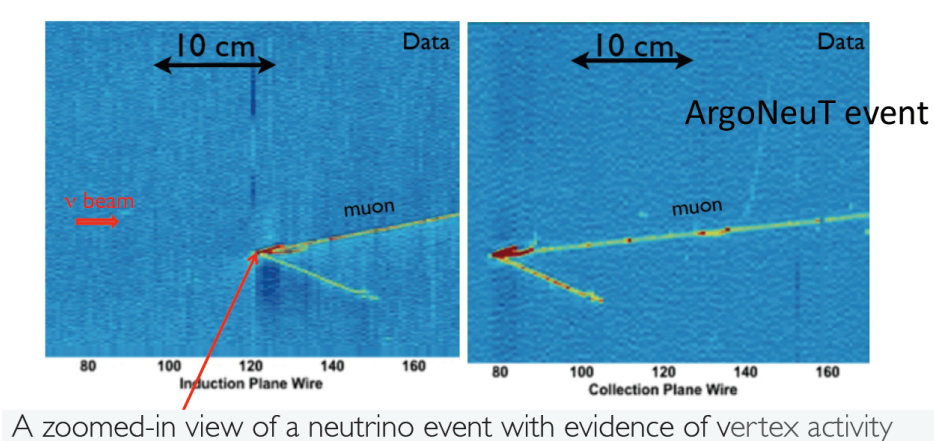


FIGURE 2. ArgoNeuT event (images recorded in the Collection and Induction wire planes, the horizontal coordinate corresponds to the wire coordinate in the plane and the vertical coordinate corresponds to the drift time) with evidence of vertex activity. The yellow trail corresponds to a MIP-like particle, the red trail signifies a more densely ionizing particle (proton).

DATA

Clear presence of FSI and/or other nuclear effects accompanying the leading muon is visible in ArgoNeuT CC muon neutrino events. An example is reported in Fig.3, where some ArgoNeuT events are shown. All these final state topologies do not exist in absence of nuclear effects and the presence of activity around the vertex (electrons from nuclear de-excitation γ conversion) is another indication of FSI effects.

MC predictions

GENIE [5] version 4370 is used as reference MC generators to make comparison with ArgoNeuT data. In parallel, predictions from FLUKA [6] and NUANCE [7] MC generator are also used for comparison.

Different MC generators (GENIE, FLUKA, NUANCE) generally agree on the total number of CCQE events given similar input model parameters, while they predict substantially different rates of different proton multiplicities in the CC 0 pion sample.

GENIE and FLUKA MC predictions for the fractions of events with different proton multiplicities in the ArgoNeuT $\mu+N_p$ sample (for the NuMI neutrino and antineutrino mode runs) are reported in Table 1. Contributions from non-CCQE interactions to each multiplicity are also shown. These are substantial contributions, in particular for high proton multiplicity events, overall as large as $\sim 30\%$ according to MC. Different MC are in reasonable agreement on the fractions of each multiplicity for neutrinos in neutrino mode, but predict very different contributions from non-CCQE (RES, DIS etc.) events. This is indeed an important information, that could be attributed to the different way of treating nuclear effects inside each MC neutrino generator. FSI models for Ar need to be cross-checked by comparison of different MC generators with data.

DATA-MC COMPARISONS: HINTS ON NUCLEAR EFFECTS

Measured rates of neutrino and anti-neutrino events with different proton multiplicities in ArgoNeuT CC 0 pion events together with GENIE MC predictions are reported in Tables and Figures in [3].

Fraction of events (% of total) as a function of proton multiplicity³, compared with GENIE predictions are also

³ Uncertainties on the neutrino flux not yet included. Efficiency for the selection of high multiplicity events not (yet) optimized and studies of background effects are ongoing and will be finalized soon.

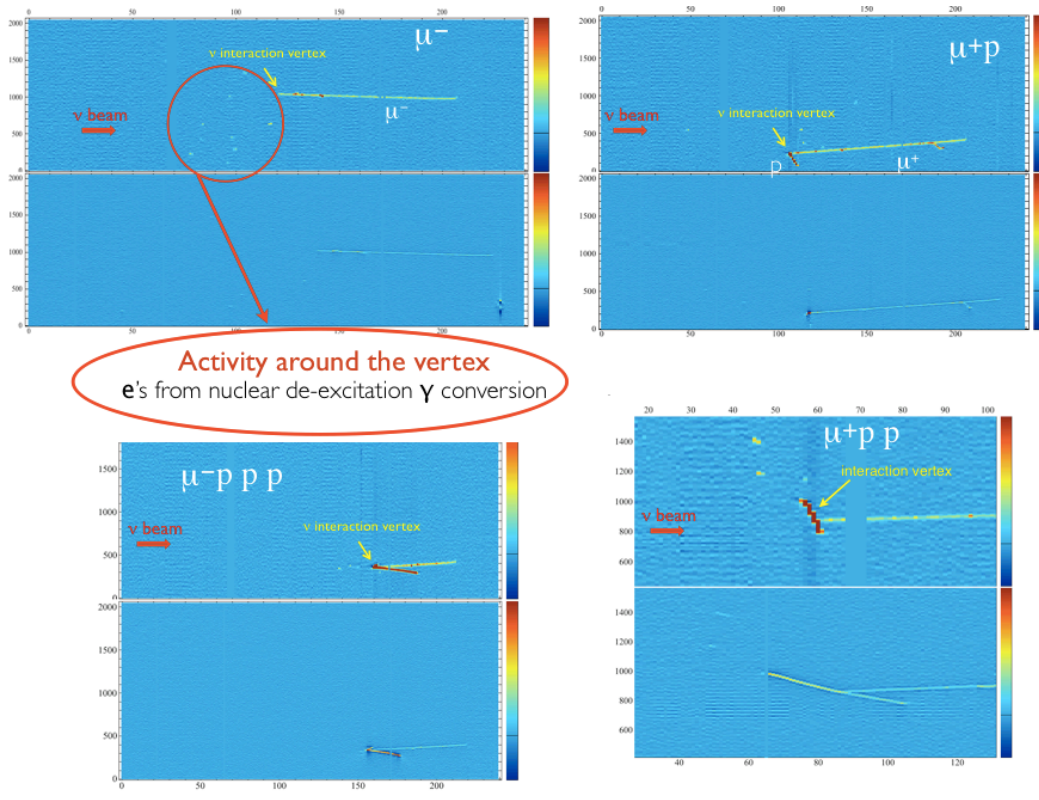


FIGURE 3. ArgoNeuT events (images recorded in the Collection and Induction wire planes, the horizontal coordinate corresponds to the wire coordinate in the plane and the vertical coordinate corresponds to the drift time) showing evidence of nuclear effects. Top Left: μ^- , no proton at the vertex. Top Right: μ^+p . Bottom: multi-proton events. Bottom Left: μ^-ppp . Bottom Right: μ^+pp . The yellow trail corresponds to a MIP-like particle, the red trail signifies a more densely ionizing particle (proton).

TABLE 1. Fractions of predicted events and fractions of non-CCQE (RES, DIS etc) events as a function of proton multiplicity in neutrino 0 pion events.

Left: GENIE [FLUKA] MC generator, NuMI beam neutrino mode.

Right: GENIE MC generator, neutrino (anti-neutrino) events, NuMI beam anti-neutrino mode.

Proton multiplicity	% of Total GENIE [FLUKA] ν events neutrino mode	% of non-CCQE GENIE [FLUKA] ν events neutrino mode	Proton multiplicity	% of Total GENIE ν (anti- ν) events anti-neutrino mode	% of non-CCQE GENIE ν (anti- ν) events anti-neutrino mode
0 p	16 [16]	0 [3]	0 p	14 (60)	3 (11)
1 p	47 [51]	8 [10]	1 p	48 (17)	6 (39)
2 p	13 [16]	57 [73]	2 p	14 (7)	60 (74)
3 p	8 [11]	80 [93]	3 p	7 (5)	76 (82)
4 p	5 [4]	85 [95]	4 p	5 (4)	83 (89)
5 p	3 [1]	65 [97]	5 p	4 (2)	86 (88)
6 p	0.6 [0.3]	100 [97]	6 p	3 (2)	86 (96)
7 p	1 [0]	100 [99]	7 p	2 (1)	97 (96)
8 p	2 [0]	100 [100]	8 p	1 (1)	79 (97)
9 p	1 [0]	100 [100]	9 p	1 (0.4)	94 (100)
10 p	0.3 [0]	100 [100]	10 p	1 (0.2)	100 (100)
			N p		32 (33)

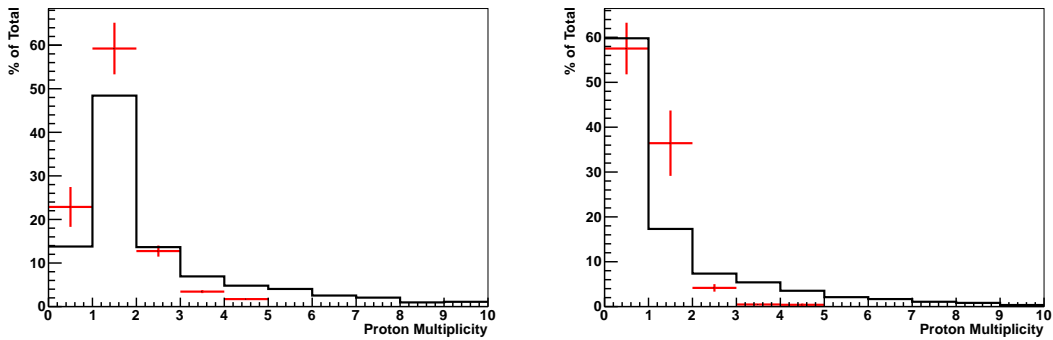


FIGURE 4. Fraction of events (% of total) as a function of proton multiplicity in ArgonneNuT neutrino CC 0 pion events (red), compared with GENIE predictions (black histogram) for NuMI anti-neutrino mode run. Left: neutrino events, Right: anti-neutrino events. Data error bars show statistical and systematic errors.

reported in Fig.4 (for the NuMI anti-neutrino mode run). Ratios among rates of different exclusive topologies provide indications of the size of nuclear effects in the data, to be compared with MC. As shown in Fig.4 the fractions of events with different proton multiplicities in GENIE MC do not agree with DATA, in particular for antineutrino scattering. As an example: the ratio $(1p/0p)_{DATA}=0.63$ while $(1p/0p)_{MC}=0.29$ for anti- ν , and $(0p/1p)_{DATA}=0.39$ while $(0p/1p)_{MC}=0.28$ for ν . These results indicate the need for improved treatment of nuclear effects in MC generators.

A lot of information on nuclear effects in Argon nuclei can be extracted from ArgonneNuT data-MC comparisons and detailed studies are in progress.

CONCLUSIONS

ArgonneNuT 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. This allows for MC independent measurements of neutrino-Argon nuclei interactions. Proton multiplicity at the neutrino interaction vertex with presence of secondary particles in ArgonneNuT events and ratios among rates of different exclusive topologies provide indications on the size of nuclear effects in LAr, like FSI (and multi-nucleon correlations) in the few GeV energy region. This analysis indicates that LAr data are indeed helpful for FSI understanding and can provide important hints to tune MC generators and discriminate among models.

Progressing with development of more and more accurate reconstruction tools for data analysis, in combination with larger mass LArTPC detectors (MicroBooNE and future LAr detectors like LBNE) is an important step for accurate topological analysis of neutrino events, on the type pioneered by ArgonneNuT.

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