Fermi National
Accelerator Laboratory

Summer internship

Final report

Neutrino event rates and $\mu + 2p$ events in SBND experiment

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Contents

Abstract

This note presents the expected neutrino event rate in the SBND experiment, the near detector in the SBN program at Fermilab, focusing on a particular final state topology in order to study the nuclear effects in neutrino-argon interactions. Expectations are evaluated with a GENIE Monte Carlo simulation and for the full exposure of SBND, $6.6 \cdot 10^{20}$ POT. SBND is currently expected to collect more than 1.5 million neutrino-argon interaction events per year. Thanks to the capabilities of the liquid argon TPC detector it's possible to perform exclusive measurement of different final states for ν_μ and ν_e events with high precision. This will allow precise studies on nuclear effects by comparing data with MonteCarlo simulations.

Chapter 1

Introduction to the SBND Experiment

SBND (Short Baseline Near Detector) is a Time Projection Chamber based on Liquid Argon. This type of detector is well suited for great variety of experiments: from those which look for rare events (as the interaction of Dark Matter with ordinary matter) because of the powerful background rejection, to the study of neutrino physics, thanks to its spatial resolution, calorimetric information, and triggering capability.
The detector is under construction; it will be located at 110 m from the target of the Booster Neutrino Beam (BNB), with $< E_\nu >= 800\,\mathrm{MeV}$ at Fermilab. Together with MicroBooNE and ICARUS-T600, SBND will perform studies sterile neutrino oscillation in order to resolve some anomalies found in previous experiments on the short baseline neutrino beam component; thanks to the high expected statistic it will be able to perform studies on the neutrino-Argon interactions too; in addition, it's an opportunity for further development of the liquid argon based detector technology for the future long-baseline neutrino physics program.
This chapter presents the SBN phyisics program, focusing on the current anomalies in neutrino short baseline oscillations; then there's a brief description of SBND.

1.1 SBN Physics Program

The Short Baseline Neutrino (SBN) physics program brings together three Liquid Argon Time Projection Chambers located on the Booster Neutrino Beam axis in order to investigate and resolve a class of anomalies found in previous experiments, which will be explained in next section; these unex-

plained results can be linked to the existance of new neutrino mass states.
SBN detectors will perform the most sensitive search-to-date for sterile neutrios, by looking at both appearance and disappearance oscillation channels, in the $1\,\mathrm{eV}^2$ mass range.
In addiction, SBN Program includes the study of neutrino-Argon cross sections with millions of interactions and thanks to the detectors' technology.
SBN detectors will also record events from the off-axis flux of the NuMI neutrino beam, wich has higher electron neutrino content and different energy spectrum.
Finally, the SBN Program plays an important role for study and developement of liqud argon TPC detectors technology for the future long-baseline neutrino program [1].

1.1.1 Experimental Anomalies found in neutrino physics

In recent years, experimental anomalies ranging in significance $(2.8\sigma - 5.9\sigma)$ have been detected from different experiments studying neutrinos over baselines less than 1 km.
Two classes of anomalies pointing at additional physics beyond the Standard Model in the neutrino sector can be distinguished:

- the apparent *disappearance signal in low energy electron anti-neutrinos* from nuclear reactors and from radioactive electron neutrino sources in the calibration of experiments originally designed to detect solar neutrinos beyond the expected oscillation effect;
- evidence for an *electron-like excess* in interactions coming from muon neutrinos and anti-neutrinos from particle accelerators).

In particular, the first class of anomalies refers to a deficit found in $\bar{\nu}_e$ events in the analysis of the antineutrino flux produced by nuclear power reactors in various reactor experiments (the "reactor anomaly") and calibration runs with ^{51}Cr and ^{37}Ar radioactive sources in the Gallium solar neutrino experiments GALLEX and SAGE, which have shown a deficit in the electron neutrino event rate over very short distances (the "Gallium anomaly").
The second class of anomalies involves results from the LSND and MiniBooNE short-baseline $\nu_e/\bar{\nu}_e$ appearance experiments; the anomalies which have been detected cannot be described by oscillations between the three neutrino flavours within the Standard Model (the so-called "LSND anomaly").
All these anomalies with their significance are summarized in the table 1.1:

Experiment	Channel	Significance
LSND	$\bar{\nu_\mu} \to \bar{\nu_e}$	3.8σ
MiniBooNE	$\nu_\mu \to \nu_e$	3.4σ
MiniBooNE	$\bar{\nu_\mu} \to \bar{\nu_e}$	2.8σ
GALLEX/SAGE	ν_e disappearance	2.8σ
Reactors	ν_e disappearance	3.0σ

Table 1.1: Summary of the experimental anomalies found in previous experiments with their significance.

Since none of these results can be described by oscillations between the three Standard Model neutrinos, they could be related to hints for neutrino physics beyond Standard Model: the most common interpretation involves the existence of at least one fourth non-standard, *sterile*, neutrino state with masses at or below the few eV range, which drives neutrino oscillation at *small distance*. The minimal model consists of a hierarchical $3 + 1$ neutrino mixing, acting as a perturbation of the standard three-neutrino model dominated by the three $(\nu_e, \nu_\mu, \nu_\tau)$ neutrinos with only small contributions from sterile flavors.
While the Standard Model neutrino mass states are responsible of measured and estabilished oscillations $\Delta m^2_{21} = 7.5 \cdot 10^{-5}\text{eV}^2$ and $\Delta m^2_{13} = 2.4 \cdot 10^{-3}\text{eV}^2$, which are mostly dominated by the SM flavour states $(\nu_e, \nu_\mu, \nu_\tau)$, the results previously shown can lead to oscillations between new mass states which mostly involve sterile flavour contributes with small active flavour content.
The explainations of these anomalies bring to the idea of oscillations in the mass range $\Delta m^2_{41} \approx (0.1 \div 10)\text{eV}^2$.

1.1.2 SBN Neutrino Beam and Detectors

The Booster Neutrino Beam (BNB) operates in both neutrino and antineutrino mode producing ν_μ and $\bar{\nu}_\mu$ by extracting protons from the Booster accelerator at 8 GeV kinetic energy and which impact on a Beryllium target to produce a secondary beam of hadrons, mainly pions. Charged secondaries are focused by a single toroidal aluminum alloy focusing horn that surrounds the target; the horn can be pulsed with either polarity, thus focusing either positives or negatives and de-focusing the other. Then mesons travel in a 50m air-filled tunnel where the majority will decay to produce muon and electron neutrinos/antineutrinos.
The SBN program includes three Liquid Argon Time Projection Chamber (LAr-TPC) detectors, as shown in figure 1.1, namely the Short-Baseline Near Detector(SBND), Micro Booster Neutrino Experiment (MicroBooNE), and

Imaging Cosmic And Rare Underground Signals (ICARUS) experiments, located on-axis on the BNB and ground-based. The use multiple detectors along the beam axis has the advantage of reducing systematic uncertainties in the measurement of short baseline neutrino oscillations.
The size and position of the three detectors allow to characterize the beam before oscillations in the near detector and to measure simultaneously the channels of ν_e appearance and ν_μ disappearance. The detectors' parameters are shown in the table 1.2.

Detector	Distance from the BNB (m)	Active LAr Mass (t)
SBND	110	112
MicroBooNE	470	86
ICARUS T-600	600	470

Table 1.2: SBN Detctors' parameters.

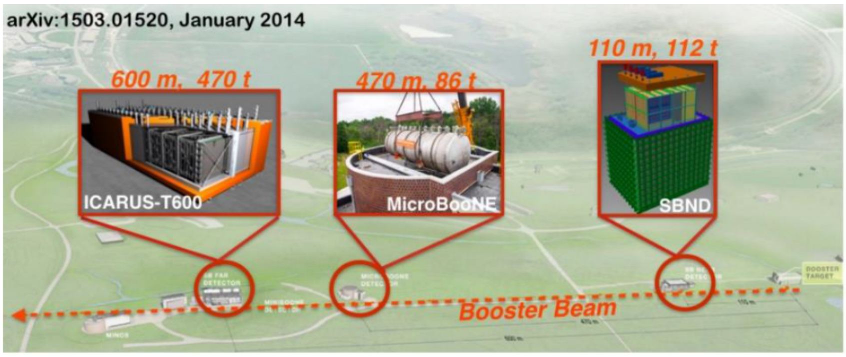


Figure 1.1: Scheme of the three detectors in SBN.

1.1.3 The Near Detector: SBND

SBND (Short-Baseline Near Detector) is a 112 t liquid Argon Time Projection Chamber (LArTPC) detector under construction at the Fermilab; it will be operating in 2020. The SBND LAr TPC gives full 3D imaging with millimetre granularity, allowing for precise measurement of topological and calorimetric information.
It has an active volume of $5\,\mathrm{m} \times 4\,\mathrm{m} \times 4\,\mathrm{m}$, composed of a membrane-style cryostat which will house a CPA (Cathode Plane Assembly) and four APAs (Anode Plane Assemblies) to read out ionization electron signals. It has two drift regions, with the CPA at the centre, and the two wire readout planes (APA, Anode Plane Assembly) on each side, as shown in figure 1.2.

Each wire readout plane consists of two interconnected steel APA frames, which hold 3 planes of wires with 3 mm wire spacing. TPC signals are then read out with banks of cold electronics boards at the top and two outer vertical sides of each detector half. The total number of readout channels is 2,816 per APA (11,264 in the entire detector) [2].
The CPA has the same dimensions as the APAs and is centered between them. It is made of a stainless-steel framework, with an array of stainless-steel sheets mounted over the frame openings.
Each pair of facing CPA and APA hence forms an electron-drift region. The open sides between each APA and the CPA are surrounded by 4 FCAs (Field Cage Assemblies), to create a uniform drift field. The drift distance between each APA and the CPA is 2 m such that the cathode plane will need to be biased at -100 kV for a nominal 500 V/cm field.
In addition it will include a light collection system for detecting scintillation light produced in the argon volume made by three different technologies: Hamamatsu photomultiplier tubes (PMT) with a wavelength shifting material (tetraphenyl butane, TPB); ARAPUCA, a novel photon collection device which is composed of dichroic filters on a highly internally reflective box, read out by a Silicon PhotoMultiplier (SiPM); light guide bars, which are composed of TPB coated acrylic strips, read out by an array of SiPMs. The photon detection system is both a test-bed for new technology, and an excellent calorimetric tool with fast timing capabilities.

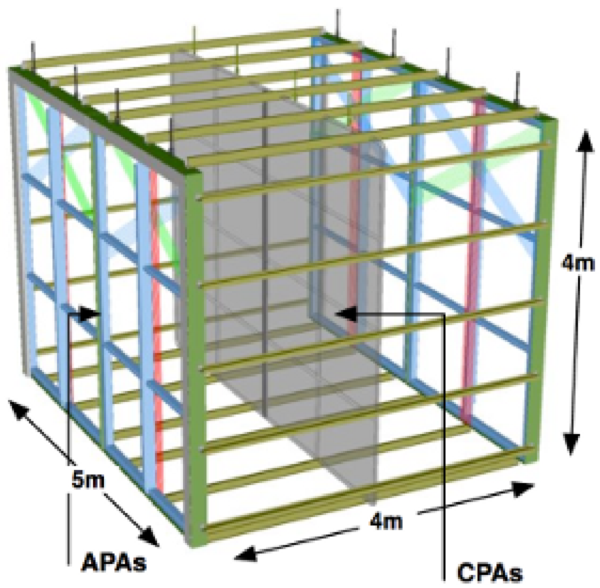


Figure 1.2: SBND conceptual design [1].

Chapter 2

Expected Statistics at SBND

To estimate the physics sensitivities of an experiment it's crucial to simulate what we expect to happen inside the detector and all the surrounding effects; this is performed by a simulation software.
Real data are than analysed and compared with the predictions; so it's important to build analysis algorithms and to get a universal approach in order to compare results of different experiments, and to obtain a well grounded analysis of the physics.
This chapter is organized as follows: there is a brief introduction on the event generator used to calculate the expected statistic at SBND and on the reconstruction software; then it's presented the first part of the work done during the internship, which has been to calculate the expected statistic at SBND for the full exposure, matching new neutrino flux files with new GENIE model configuration, with the comparison between the results of this analysis and the expected statstic calculated at the time of the proposal, in 2012.
At the end, there's a section focused on the $\nu_\mu - Ar$ charged current (CC) events without pions in the final state ($CC\,1\mu\,0\pi$ topology) related to the multiplicity of protons in the final state, and there's a look on their relation with new interactions included in the simulations.

2.1 Data Simulation and Reconstruction: LAr-Soft Project

Thanks to the capabilities of the LAr-TPC detectors, as explained in previous chapter, it's possible to categorize the events both in terms of final state interactions and by final state topologies. This allows for precise topological cross-section measurements to be made.

So, it's crucial match the data which will be taken with the simulations in order to know what do we expect from the experiment and to write reconstuction and analysis algorithms.
In addiction, an universal approach to select each final state is necessary to compare different experiments' results and to obtain a systematically-consistent program of cross-section measurements; by propagating the method to the SBN experiments it's possible to produce a well-grounded analyses of neutrino oscillations.
LArSoft (Liquid Argon Software) is a common software infrastructure made for Liquid Argon detector data simulation, reconstruction and analysis; it is a powerful framework used by liquid argon detector based experiments.
The LArSoft collaboration consists of a group of experiments and software computing organizations contributing and sharing data simulation, processing and analysis code for Liquid Argon TPC experiments.

Event production chain

To produce a sample of simulated events one must take in account of the flux of incident particles on target (in this case neutrino flux), and on the simulation software; for the analysis it was used LArSoft [3], which was discussed previously. The event chain production consists in four "steps":

1. Simulation of neutrino-Argon interactions at a true level, i.e. without considering the surrounding matter and detector effects: this is performed by GENIE, one of the most common neutrino event generator; it plays the leading role in the development of comprehensive physics models for the simulation of neutrino interactions, and performs a highly-developed global analysis of neutrino scattering data. It uses cross-section data acquired from available neutrino scattering data to build neutrino-nuclear interaction models and simulate neutrino interactions on argon;

2. To take in account of the passage of the particles through the matter, GEANT4 propagates the particles which leave the nucleus through the medium (argon) and simulates the subsequent interactions of the final state particles;

3. DetSim simulates the drift of the electrons, their behaviour through the detector and when they arrive at the anode plane, the response from the wires;

4. For the pattern recognition, calorimetry, particle identification, the reconstruction takes hits from the readout of the wires and builds up a

picture of the neutrino event in the detector. This is applied to both simulated events and data.

2.2 SBND expected statstic

Neutrino-nucleus interactions are a fundamental element to understand neutrino oscillations. Together with the MicroBooNE and ICARUS experiments, SBND will make the world's highest statistics cross section measurements for many $\nu - Ar$ scattering processes, in the GeV energy range. Figure 2.1 shows the expected rates in the SBND experiment of ν_μ and ν_e events separated into their main experimental topologies for an exposure of $6.6 \cdot 10^2$ protons on target (POT) at the time of the proposal [1]. Since that time, some changes have been made in the flux files and in the GENIE model configuration.
The first part of the work done at the Fermilab was to calculate the new expected statistic at SBND, matching the new flux configuration and the use of a sample of 10^6 simulated events generated at true level (without taking in account of the surrounding matter effects) with a new GENIE model configuration (v_02_12_10); it was considered the full exposure of SBND ($6.6 \cdot 10^2$ protons on target (POT)). The results are shown in figure 2.2.
A novel approach based on the event categorization in terms of exclusive topologies can be used to analyze data and provide precise cross section measurements in many different exclusive channels: besides MC based classification of the event rates in terms of interaction channel (QE, RES, DIS, etc), neutrino events in LAr can be directly categorized in terms of final state topology based on particle multiplicity.
With the imaging LAr-TPC detector these exclusive topologies can be fully reconstructed, measurements of particle multiplicity at the neutrino interaction vertex and reconstruction of particle kinematics in events with different proton multiplicity can be performed down to very low energy threshold.
So, in both the tables are shown the processes divided by final state topologies and by physical process from Monte Carlo truth information.

Process		No. Events
	ν_μ *Events (By Final State Topology)*	
CC Inclusive		5,212,690
CC 0 π	$\nu_\mu N \to \mu + Np$	3,551,830
	$\cdot\ \nu_\mu N \to \mu + 0p$	793,153
	$\cdot\ \nu_\mu N \to \mu + 1p$	2,027,830
	$\cdot\ \nu_\mu N \to \mu + 2p$	359,496
	$\cdot\ \nu_\mu N \to \mu + \geq 3p$	371,347
CC 1 $\pi^\pm$	$\nu_\mu N \to \mu +$ nucleons $+ 1\pi^\pm$	1,161,610
CC $\geq 2\pi^\pm$	$\nu_\mu N \to \mu +$ nucleons $+ \geq 2\pi^\pm$	97,929
CC $\geq 1\pi^0$	$\nu_\mu N \to \mu +$ nucleons $+ \geq 1\pi^0$	497,963
NC Inclusive		1,988,110
NC 0 π	$\nu_\mu N \to$ nucleons	1,371,070
NC 1 $\pi^\pm$	$\nu_\mu N \to$ nucleons $+ 1\pi^\pm$	260,924
NC $\geq 2\pi^\pm$	$\nu_\mu N \to$ nucleons $+ \geq 2\pi^\pm$	31,940
NC $\geq 1\pi^0$	$\nu_\mu N \to$ nucleons $+ \geq 1\pi^0$	358,443
	ν_e *Events*	
CC Inclusive		36798
NC Inclusive		14351
Total ν_μ and ν_e Events		7,251,948

	ν_μ *Events (By Physical Process)*	
CC QE	$\nu_\mu n \to \mu^- p$	3,122,600
CC RES	$\nu_\mu N \to \mu^- \pi N$	1,450,410
CC DIS	$\nu_\mu N \to \mu^- X$	542,516
CC Coherent	$\nu_\mu Ar \to \mu Ar + \pi$	18,881

Figure 2.1: Estimated event rates using GENIE (v2.8) in the SBND active volume (112 t) for for $6.6 \cdot 10^{20}$ POT. We assume an energy threshold on proton kinetic energy of 21 MeV.

Process		No. Events
ν_μ *Events (By final state topology)*		
CC inclusive		5,173,249
CC 0 π		3,969,756
	$\nu_\mu N \rightarrow \mu + 0p$	692,301
	$\nu_\mu N \rightarrow \mu + 1p$	1,999,237
	$\nu_\mu N \rightarrow \mu + 2p$	799,449
	$\nu_\mu N \rightarrow \mu + \geq 3p$	478,768
CC 1 π	$\nu_\mu N \rightarrow \mu + 1\pi +$ nucleons	1,098,110
CC 1 $\pi^\pm$	$\nu_\mu N \rightarrow \mu + 1\pi^\pm +$ nucleons	817,419
CC $\geq$ 1 π^0	$\nu_\mu N \rightarrow \mu + \geq 1\pi^0 +$ nucleons	363,622
CC $\geq$ 2 $\pi^\pm$	$\nu_\mu N \rightarrow \mu + \geq 2\pi^\pm +$ nucleons	22,450
NC inclusive		1,627,284
NC 0 π	$\nu_\mu N \rightarrow$ nucleons	1,276,715
NC 1 $\pi^\pm$	$\nu_\mu N \rightarrow \pi^\pm +$ nucleons	97,307
NC $\geq$ 1 π^0	$\nu_\mu N \rightarrow \geq 1\pi^0 +$ nucleons	251,024
NC $\geq$ 2 $\pi^\pm$	$\nu_\mu N \rightarrow \geq 2\pi^0 +$ nucleons	2,236
	ν_e *Events*	
CC inclusive		38,377
NC inclusive		11,633
Total ν_μ and ν_e events		6,850,544
ν_μ *Events (By Physical Process)*		
CC QE		2,518,203
CC RES		1,160,108
CC DIS		362,195
CC COH		14,936
CC MEC		1,117,804

Figure 2.2: Expected statistics in SBND active volume (112 t) expressed in terms of final state configurations and final state interactions for ν_μ and ν_e with the updated flux files and the new GENIE model configurations (v_02_12_10) for $6.6 \cdot 10^{20}$ POT. We assume an energy threshold on proton kinetic energy of 21 MeV.

We can notice that:

- The numbers of events in the tables are comparable with each other and are very huge: we expect to get more than $2 \cdot 10^6$ neutrino-argon events per year in the full active volume, to see both a lots of $\nu_\mu - Ar$ events and also a big sample of ν_e CC interactions with Argon. Comparison between ν_μ and ν_e cross sections is very important: by lepton universality, the cross sections should be the same after correcting for the outgoing charged-lepton mass. A difference in the cross sections would indicate a new process that violates lepton universality;

- The largest event sample corresponds to ν_μ Charged Current interactions with $0\,\pi$ in the final states: in these topologies there is an outgoing muon and a certain number of recoil nucleons;

- From the NC elastic scattering, events identified by a single nucleon recoil track, it's possible to make a a competitive measurement of Δs, the strange quark contribution to the proton spin, if the recoil proton events can be cleanly separated from the recoil neutron events;

- A new type of interaction has been introduced in the simulations: the*Meson Exchange Current* interaction. Its contribute brings a lot of statistcs and leads sensible variation in some channels; in particular in the CC $0\pi\,2p$ final state configuration the number of expected events is almost twice the proposal one.

2.2.1 MEC interaction component in $CC\,0\pi\,Np$ channels

CC $0\pi\,Np$ channels are identified by looking at those final states which have 1 muon, N protons (with $N = 0, 1, 2, \ldots$) and no pions or kaons.
Those final state topologies are interesting because the cross section for neutrino scattering off nuclei largely depends on final state interactions and other nuclear effects and SBND data will allow the study of those effects with high precision.
The GENIE simulations take in account of a new type of interaction that contributes to the neutrino-argon cross section: the Meson Exchange Current interaction (MEC) [5].
MEC is an interaction involved in 2 nucleons, or 2-body current, and it is classified in "2 particle-2 hole (2p-2h)" effect. A weak boson from the leptonic current is exchanged by a pair of nucleons (2-body current), and it's believed to lead to 2-nucleon emission. The importance of this process in neutrino interactions was first pointed out shortly after the MiniBooNE experiment showed their Charged Current Quasi Elastic (CCQE) double differential cross section. Several theoretical calculations successfully are able to reproduce the

MiniBooNE CCQE or neutral current elastic (NCEL) cross section data by adding the MEC in their models. To understand whether the MEC is the responsible process for enhancement of recent neutrino data, it's needed to compare more kinematic details of the data with simulations.
The huge data sample which is expected to be collected at SBND will allow the study of the MEC contribution in neutrino-argon interactions and the tuning of neutrino event generator.
So, the introduction of the MEC process in the simulations brings some changes in the number of expected events in some channels. By looking at the distribution of the expected events at a true level in function of the proton multiplicity for every type of interaction, which is shown in figure 2.3, we can notice that the MEC interaction component (shown in green) gives a huge contribution in the CC $0\pi\, 2p$ channel; this will be discussed in next chapter.

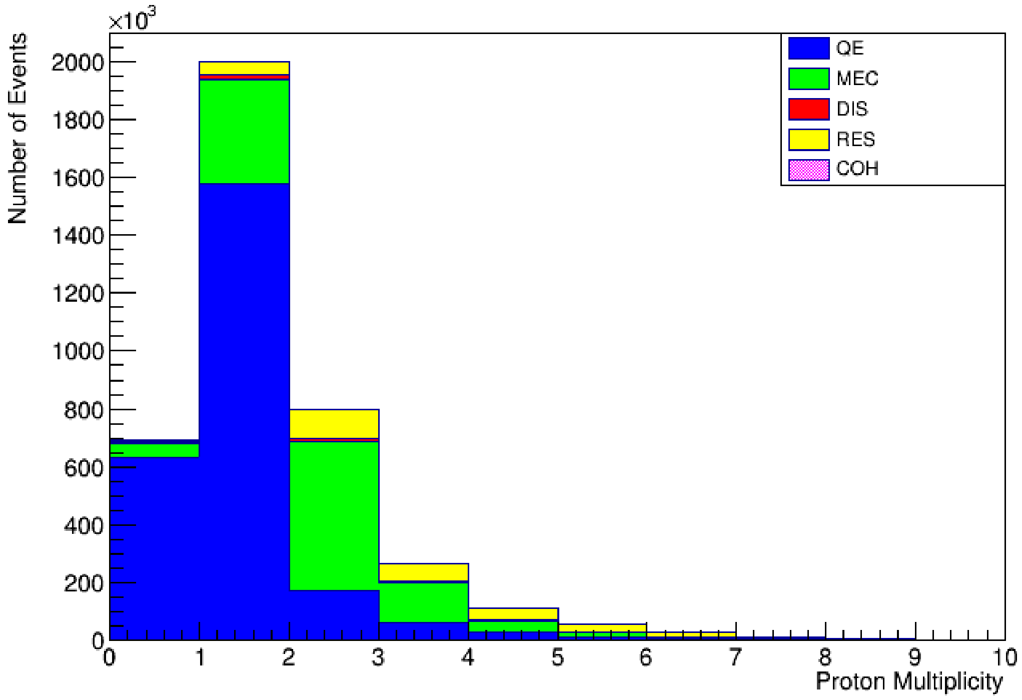


Figure 2.3: Event rate vs proton multiplicity.

Chapter 3

CC $0\pi 2p$ channel

The systematic study of the impact of nuclear effects in the determination of neutrino cross sections in the few-GeV energy range and on neutrino oscillation parameters, has developed into a very active field of theoretical and experimental research over the last decade. Direct experimental investigations on the nature of those effects and their impact on the predicted rates, final states, and kinematics of neutrino interactions are very compelling.
LAr-TPC detectors provide calorimetric information and 3-D reconstruction of the detected particle track with high resolution and robust background rejection power, allowing for exclusive topologies selection and direct exploration of nuclear effects from identification/reconstruction of specific classes of neutrino events with extraordinary sensitivity.
Nuclear effects in heavy nuclear targets play a big role in neutrino interactions. The realization of consistent models including all these nuclear effects is now being actively pursued together with the inclusion of them in Monte-Carlo generators.
This chapter describes the analysis on a sample of MC generated and reconstructed events in order to investigate the nuclear effects included in the simulations. More specifically, the events selected have 1 muon, 0 pions and 2 protons in the final state; this is because the 2 nucleon final state topology can be related to 2 nucleons correlated initial states: the so-called *Nucleon Nucleon Short Range Correlations* (NN-SRC). They will be briefly described in the first part of the chapter; in section 3.2 are shown the results of ArgoNeuT since they are the starting point of the analysis. Then it's presented the complete analysis done in the second part of the internship on the kinematic variables of the final state particles, in order to look for angular correlations related to correlated initial nuclear states.

3.1 Two Nucleon knock-out topology

The Charged Current events with the leading muon, 2 protons and no pions or kaons in the final state are very interesting because their topology can be related to:

- *Nucleon Nucleon Short Range Correlations* (NN-SRC);
- *Meson Exchange Currents* (MEC);
- *Final State Interactions* (FSI);
- interference between all the previous processes.

So they may provide information on NN-SRC in the target nucleus when the protons of the pair appear with high-momentum (exceeding the Fermi momentum) and in strong angular correlation.
Nucleon nucleon correlations are essential components of modern potentials describing the mutual interaction of nucleons in nuclei. The strong, repulsive short-range correlations (NN-SRC) cause the nucleons to be promoted to states above the Fermi level in the high-momentum tail of the nucleon momentum distribution. Thus, SRC cause nucleon to form pairs with large relative momentum and small center-of-mass momentum, i.e. pairs of nucleons with large, back-to-back momenta. Nucleon Nucleon Short Range Correlations in nuclei (NN-SRC) are very interesting not only because they carry important information on nuclear structure and dynamics, but also for the study of nuclear effects in neutrino-nucleus interaction.
Two-nucleon knock-out from high energy scattering processes is the most appropriate venue to probe NN correlations in nuclei. NN-SRC have been extensively probed through two-nucleon knock-out reactions in both pion and electron scattering experiments [4]. In particular, in analogy with results those experiments, a neutrino CC-QE interaction on a neutron in a SRC pair is expected to produce back-to-back protons in the CM frame of the interaction, whereas a CC pionless resonance reactions (CC RES) involving a SRC pair may produce back-to-back protons in the Lab frame.
Neutrino scattering experiments have never attempted to directly explore SRC states through detection of two knock-out nucleons, except for ArgoNeuT, an experiment which took data for a short period and found a few events that can provide hints for NN-SRC states [6].
Considering the following neutrino CC interactions with a NN-SRC pair leading two-proton knock-out:

- *CC RES pionless mechanisms involving a pre-existing SRC np pair in the nucleus.* For example, via nucleon RES excitation and subsequent two-body absorption of the decay charged pion by a SRC pair (Fig. 3.1 [Left]), or from RES formation inside a SRC pair (hit nucleon in the pair) and de-excitation through multi-body collision within the $A-2$ nuclear system (Fig.3.1 [Center]). Initial state SRC pairs are commonly assumed to be nearly at rest. The detection of back-to-back pp pairs in the Lab frame can be seen as a "snapshot" of the initial pair configuration in the case of RES processes with no or low momentum transfer to the pair.

- *CC QE one-body neutrino reactions, through virtual charged weak boson exchange on the neutron of a SRC np pair* (Fig 3.1 [Right]). The high relative momentum will cause the correlated proton to recoil and be ejected. The identification of the struck neutron requires a large momentum transfer such that the momentum of the proton emitted in this type of event is much larger than the momentum of the spectator proton in the pair; in this case with both protons exceed the Fermi momentum too, the struck nucleon being the higher in momentum and the lower identified as the recoil spectator nucleon from within the SRC.

Two nucleons can be naturally emitted by other two-body mechanisms: MEC interactions, probing two nucleons correlated b meson exchange currents, and "Isobar Currents" (IC), intermediate state Δ, N^* excitation of a nucleon in a pair with the pion from resonance decay reabsorbed by the other nucleon. It should be noted that the NN pairs in these two-body processes may or may not be SRC pairs.
One-body interactions can also lead to two-nucleon ejection. This happens when the struck nucleon is in a SRC pair and the high relative momentum in the pair would cause the correlated nucleon to recoil and be ejected.
It should also be noted that in both cases final state interactions (FSI), momenta or charge exchange and inelastic reactions, between the outgoing nucleons and the residual nucleus may alter the picture.

3.2 Previous results in ArgoNeuT

The ArgoNeuT (Argon Neutrino Test) detector is a Liquid Argon Time Projection Chamber of $47 \times 40 \times 90\text{cm}^3$ with $\approx 240\,\text{kg}$ of Liquid Argon in the active volume; it was located along the NuMI (Neutrinos at the Main Injector) beam, with $< E_\nu >= 3.9\,\text{GeV}$ and $< E_{\bar{\nu}} >= 9.6\,\text{GeV}$, at the MINOS near detector hall, at Fermilab. ArgoNeuT collected, during its run from

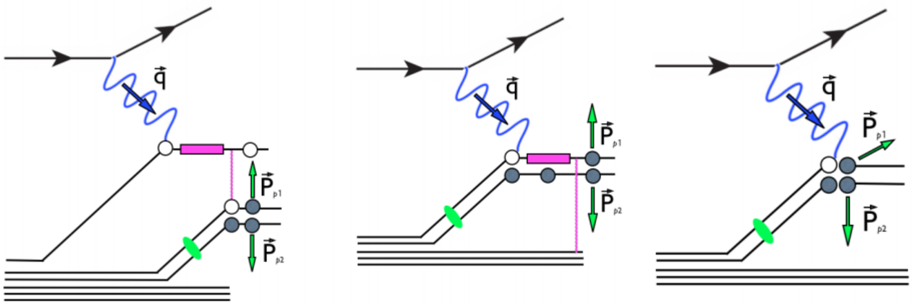


Figure 3.1: Diagrams of examples of two-proton knockout CC reactions involving np SRC pairs. Short range correlated (green symbol) nucleons in the target nucleus are denoted by open-full dots (n-p), wide solid lines (purple) represent RES nucleonic states, (purple) lines indicate pions.

September 2009 to February 2010, several thousands of ν_μ and $\bar{\nu}_\mu$ interactions, with an average neutrino energy of 4 GeV and antineutrino energy of 10 GeV. The capabilities of the detector allow 3D imaging of the ionization tracks in the LArTPC volume and the calorimetric reconstruction of the energy deposited by individual charged particles along their ionization trail. For particles slowing down and stopping inside the active volume (contained tracks), the energy loss as a function of distance from the end of the track is used as a powerful method for particle identification.

$CC\,0\pi$ event selection in ArgoNeuT

Muon neutrino CC events were inclusively selected by requiring a negatively charged muon in MINOS-ND matching a track originating from an interacting vertex in the ArgoNeuT detector; in addition the events selected were required to be pionless, and to have one leading muon and N protons identified in the final state (with $N = 0, 1, 2, \ldots$). In principle, neutrons can be emitted in these events too; but ArgoNeuT has a very limited capability to detect neutrons emerging from the interaction vertex due to the small size of the detector to have significant chances to allow neutrons to convert into visible protons in the LArTPC volume before escaping. The reconstruction of the individual proton kinematics (kinetic energy and 3-momentum) is determined with good angular resolution and down to a low proton kinetic energy threshold of 21 MeV.

Results in ArgoNeuT

ArgoNeuT has recorded a sample of 30 fully reconstructed charged current events with 2 proton in the final state accompaining the leading muon, and no pions or kaons: 19 were collected from anti-neutrino beam mode and 11 in neutrino beam mode. Experimentally measurable observables are the 3-momentum of the muon, determined from the matched track in ArgoNeuT and MINOS-ND, the sign of the muon provided by MINOS-ND, and the energy and direction of propagation of the two protons measured by ArgoNeuT. Both proton tracks are required to be fully contained inside the fiducial volume of the TPC and above the energy threshold; 19 events had the protons above the Fermi momentum of the Ar nucleus ($\approx 250\,\text{MeV}$) as we can see in the scatter plot of the higher vs lower momentum of the pp pair, in figure 3.3a.
Out of them, *four are found with the two protons in a strictly back-to-back high momenta configuration directly observed in the final state* and can be associated to nucleon resonance pionless mechanisms involving a pre-existing short range correlated np pair in the nucleus; the signature of these events gives the appearance of a hammer, with the muon forming the handle and the back-to-back protons forming the head; as an example, the 2D views from the two wire planes of the LArTPC for one of these "hammer" events is reported in Fig. 3.2. In all four events, both protons in the pair have momentum significantly above the Fermi momentum, with one almost exactly balanced by the other, and they show a rather large miss ing transverse momentum; these features look compatible with the hypothesis of CC RES pionless reactions involving pre-existing SRC np pairs. The solid angle between the two detected proton tracks at the interaction vertex (γ) is directly measured in the Lab reference frame. The scatter plot in fig 3.3b shows the cosine of the angle γ vs. the momentum of the least energetic proton in the pair. It is interesting to note that four of the nineteen $2p$-events above the Fermi momentum are found with the pair in a back-to-back configuration ($cos(\gamma) < -0.95$).

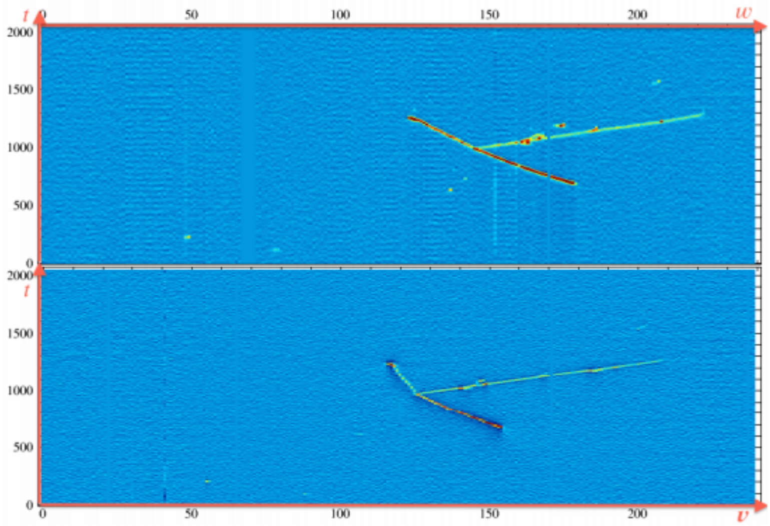
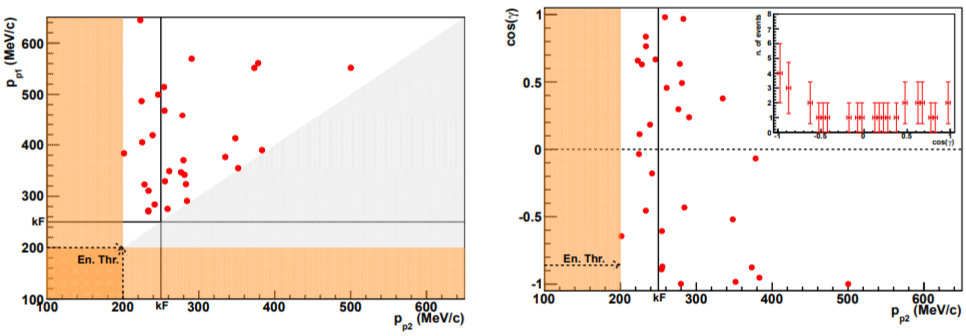


Figure 3.2: Event display of a "hammer" event in ArgoNeuT.



(a) (b)

Figure 3.3: Left: momentum of the most energetic proton (p_{p1}) in the pair vs. momentum of the other (least energetic) proton(p_{p2}); the Fermi momentum in argon (line) and the momentum corresponding to the detection threshold in ArgoNeuT (dashed) are also indicated.
Right: cosine of the angle between the two protons (Lab frame) vs. the momentum of the least energetic proton in the pair.

Another fraction of four events of the remaining 15 events *have a reconstructed back-to-back configuration of a np pair in the initial state*, a signature compatible with one-body Quasi Elastic interaction on a neutron in a SRC pair.

3.3 Event Selection in SBND analysis

The statistic collected in ArgoNeuT is unfortunately too poor to obtain a significant physical result for the study of the NN-SRC. The high expected statistic in SBND with high precision will make possible to explore the evidence of nuclear effects in neutrino-argon interactions. The analysis presented in next sections is made on a sample of 15317 simulated events at SBND; in table 3.1 there is the selection made for the CC inclusive channel and for the $CC\,0\pi\,2p$ channel.

Process	True event	Reconstructed	Signal
CC inclusive	13083	13082	-
CC $0\pi\,2p$	2103	406	328

Table 3.1: Number of true, reconstructed and signal events for the selection of CC inclusive and the cannel we're interested processes.

Where the signal events are those events which are both true and reconstructed. By defining the purity and the efficiency as follows:

$$Efficiency = \frac{\sum signal(topology)}{\sum true(topology)} = 0.14$$

$$Purity = \frac{\sum signal(topology)}{\sum selected(topology)} = 0.84$$

The purity is good, which means that the background rejection is high, as we expect for TPC detectors, while the efficiency is very low: the number of the reconstructed events is small compared to the number of the true events; this issue can be related to the criteria of the selection, which will be discussed afterwards, and will be object of further studies on the reconstruction algorithms.
To select a $CC\,0\pi\,2p$ event the requirements to be made are:

- If *all tracks are contained*, the muon is identified by requiring the minumum χ^2_μ or the longest track is 1.5 times longer than other tracks; protons are identified by requiring the minimum χ^2_p and other tracks are identified on the particle hypotesis[1] with smallest χ^2;

[1] The χ^2 is calculated by comparing the distribution for dE/dx vs range obtained from the simulated event with the theoretical one.

- If *one tracks escapes*, the escaping track is identified as the muon candidate, protons are identified by requiring the minimum χ^2_p and other tracks are identified on the particle hypotesis with smallest χ^2.

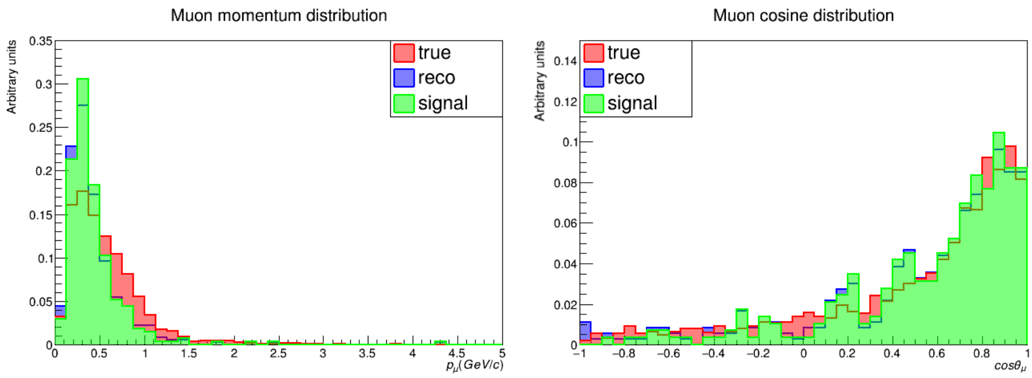
The cuts put for the event selection are:

- Neutrino vertex must be at least 50 cm far from the fiducial border, so that the escaping track can be detected;

- Proton candidates are required to have kinetic energy $E_{k_p} > 21\,\mathrm{MeV}$ so that reconstruction is possible; this is the same threshold used in the ArgoNeuT analysis, reported in the previous Section.

3.4 Particles Kinematics

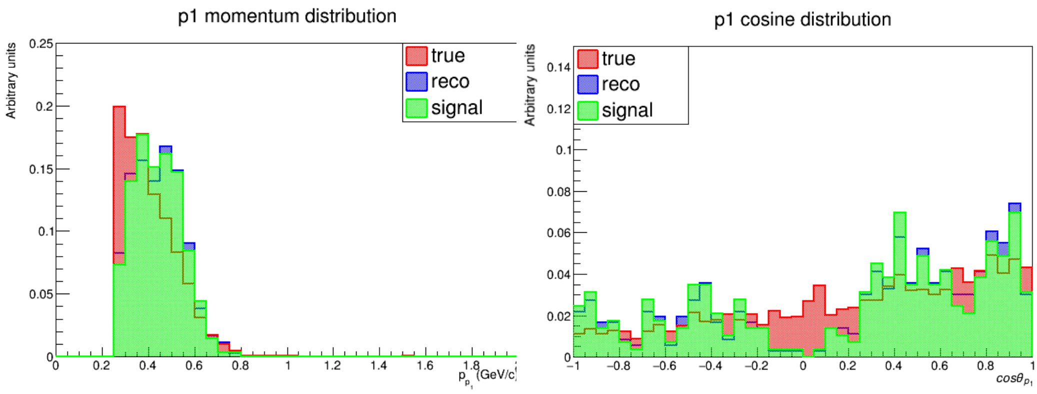
In figure 3.4a and 3.4b there are the distributions of the momentum and the angle with respect to the beam direction of the outgoing muon.
The distribution of the true muon momentum extends to larger momenta than the reconstructed one; this can be related to the misidentification, at the reconstruction stage, of two splitted tracks which were one long muon track; the peaks of the distribution are in the same position.
The cosine of the angle of the outgoing muon has a peak in the region of $cos(\theta_\mu) \approx 0.85 \div 0.9$, which corresponds to an angle $\theta_\mu \approx 26° \div 31°$, as we expect from previous analyses.



(a) (b)

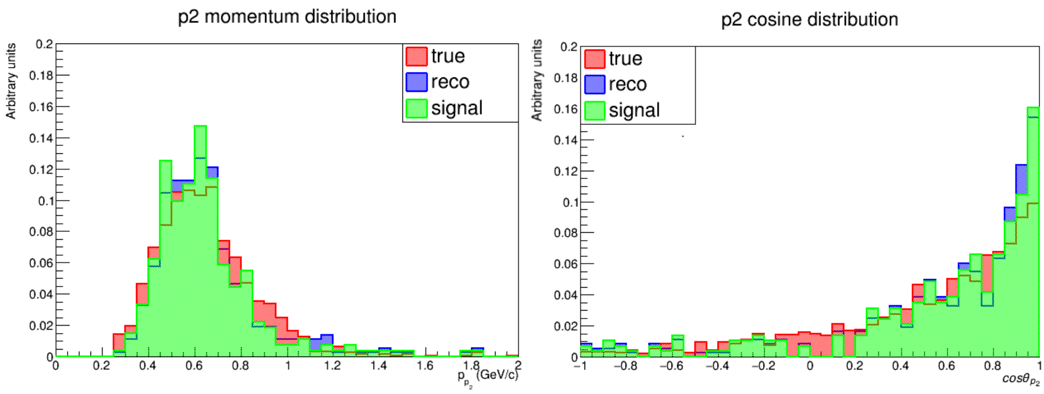
Figure 3.4: Left: Momentum distribution for the outgoing muon. Right: Distribution of the cosine of the angle between the outgoing muon and the beam axis. The distributions are area normalized.

In figure 3.5a, 3.5b, 3.6a and 3.6b there are the distributions of the momentum and the angle with respect to the beam direction of the outgoing protons, where p_{p_1} is chosen to be the least energetic of the pair and p_{p_2} is the most energetic outgoing proton.
As expected, we can see that the most enegetic proton is more collimated than the least energetic one, from the peak of the cosine in the region of $cos(\theta_{p_2} \geq 0.95$; in both cases we don't expect to have protons emitted at 90°.



(a) (b)

Figure 3.5: Left: momentum distribution for the least energetic proton, p_{p_1}. Right: distribution of the cosine of the angle between the outgoing proton and the beam axis. The distributions are area normalized.



(a) (b)

Figure 3.6: Left: momentum distribution for the most energetic proton, p_{p_2}. Right: distribution of the cosine of the angle between the outgoing proton and the beam axis. The distributions are area normalized.

Angular distributions of final state particles

The distribution of the cosine of the angle between the two outgoing protons in the LAB frame is shown in figure 3.7; differently from what measured from the ArgoNeuT data, there isn't a peak in the region where $cos(\theta_{p1p2} \geq -0.95)$. This is expected, considering the relative lower energy of the BNB compared with the NuMI beam. In SBND we do not expect most events to be back-to-back in the final state configuration because the rate of resonance events is low relative to the rate of quasi elastic events. By looking at the same distribution for true, reconstructed and signal events, respectively in figure 3.8a, 3.8b and 3.8c, we can see that the interaction are equally present in all the cosine range: there's not a predominance in the back-to-back region of MEC, for the reasons explained previously.

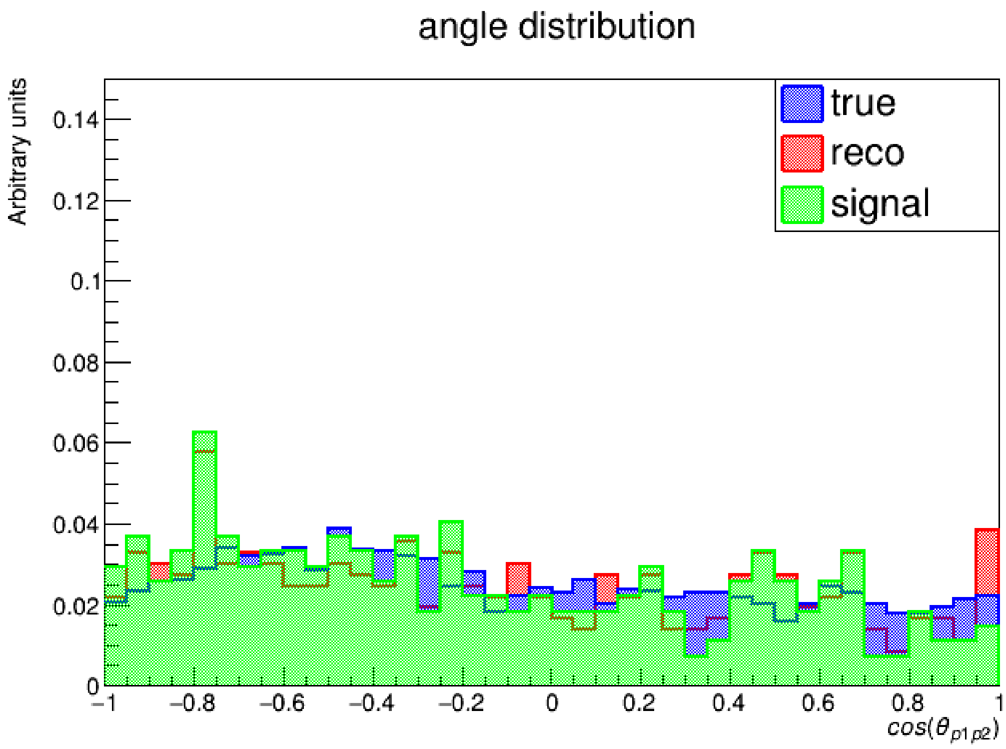
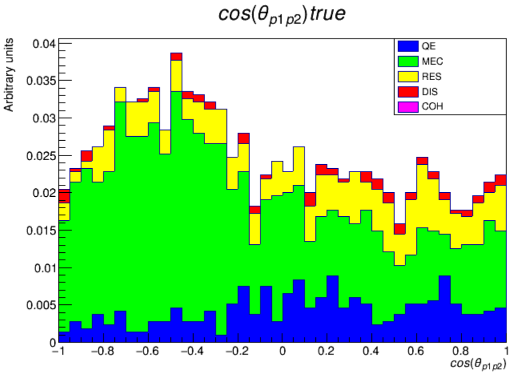
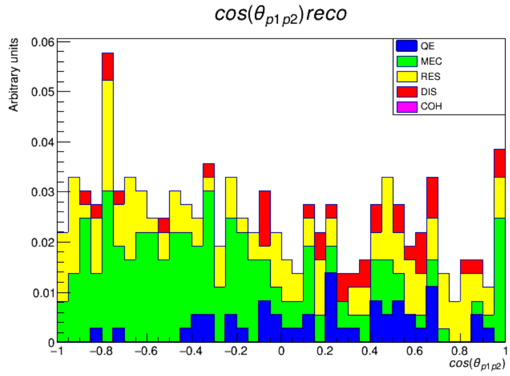


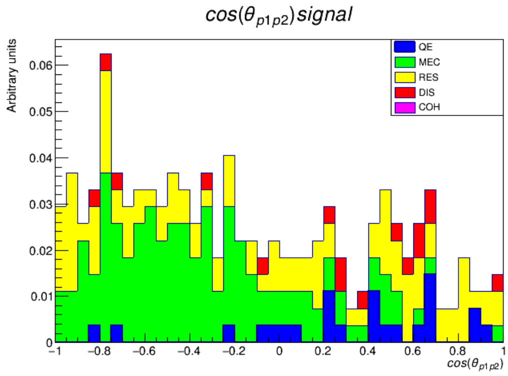
Figure 3.7: Distribution of the angle between the two protons; it is area normalized.



(a)



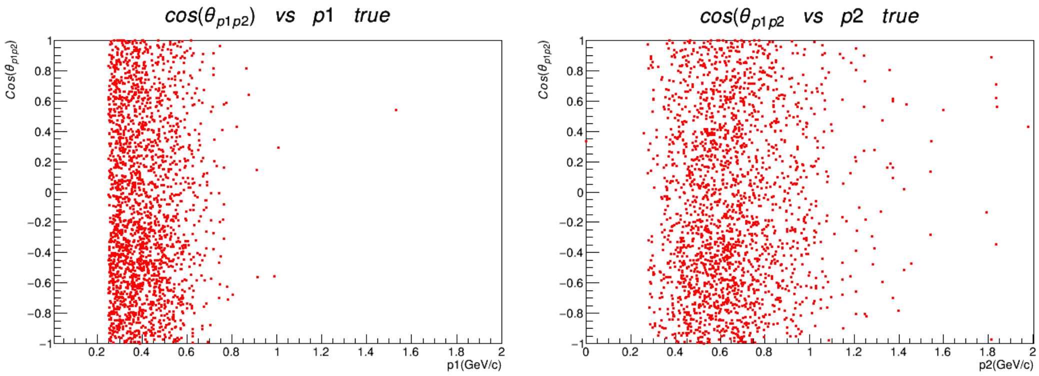
(b)



(c)

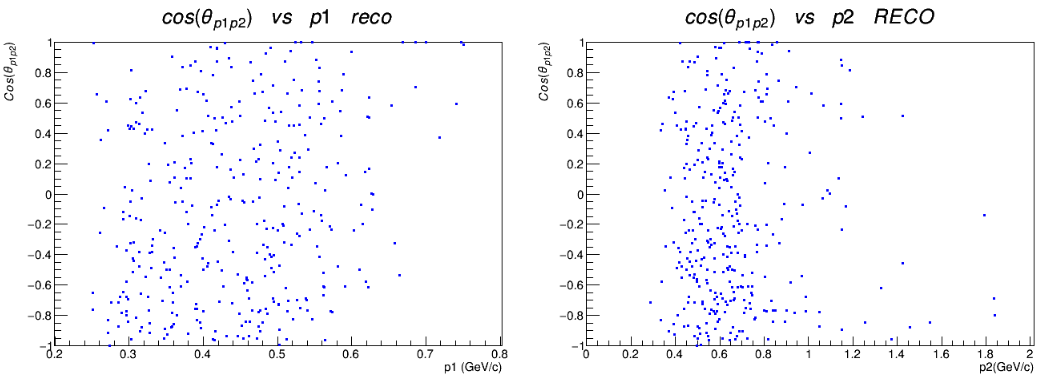
Figure 3.8: Distribution of the true (upper left panel), reconstructed (upper right panel) and signal (lower panel) angle between the two protons separating the components for each final state interaction considered in the analysis. The distributions are area normalized.

The same result is shown in the plots of the angle between the protons vs proton momenta for the true, reconstructed and signal events, shown in figure 3.9a, 3.9b, 3.10a, 3.10b, 3.11a and 3.11b. In none of those plots there is any accumulation of the events in a particular angular region.



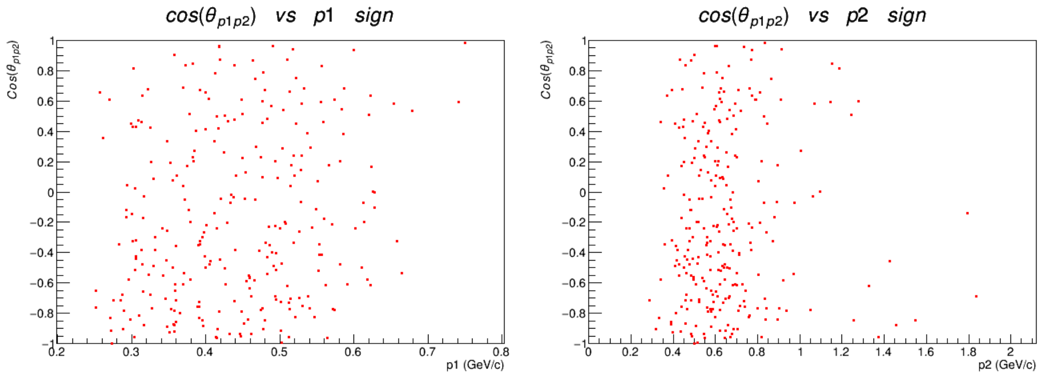
(a) (b)

Figure 3.9: True angle between the two final state protons vs. least energetic proton true momentum (left) and vs. most energetic proton true momentum (right). The distributions are area normalized.



(a) (b)

Figure 3.10: Reconstructed angle between the two final state protons vs. least energetic proton reconstructed momentum (left) and vs. most energetic proton reconstructed momentum (right). The distributions are area normalized.



(a) (b)

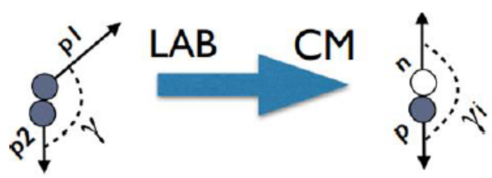
Figure 3.11: Signal angle between the two final state protons vs. least energetic proton signal momentum (left) and vs. most energetic proton signal momentum (right). The distributions are area normalized.

Angular distributions of initial state particles

To determine the initial momentum of the struck neutron the with an approach similar to the electron scattering triple coincidence analysis, that is the same used for ArgoNeuT analysis, we use the law of conservation of momentum:

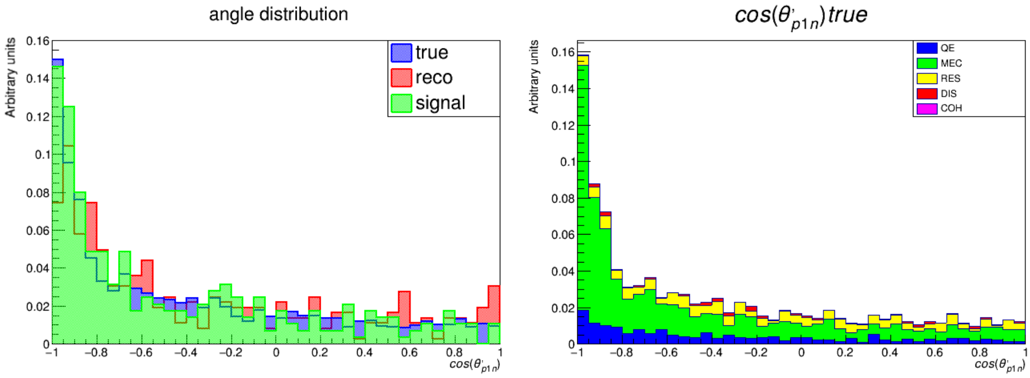
$$\vec{p}^{\,f}_{p2} = \vec{p}^{\,i}_{n} + \vec{q} \rightarrow \vec{p}^{\,i}_{n} = \vec{p}^{\,f}_{p2} - \vec{q}$$

where the struck nucleon p_2 being the higher in momentum and the lower p_1 identified as the recoil spectator nucleon from within the SRC; this procedure is applied to the subsample having both the protons above Fermi momentum. In most cases the reconstructed initial momentum is found above Fermi momentum.
In figure 3.12 there is a scheme of the reconstruction of the angle in the CM frame between the two initial nucleons; figure 3.13a shows the distribution of the angle between the initial nucleons.



[H]

Figure 3.12: Pictorial scheme of the reconstruction of the angle between the initial state pair nucleons in the CM frame.



(a) (b)

Figure 3.13: Right: distribution of the angle between the reconstructed struck neutron and the recoil proton in the initial pair in the CM frame. Left: distribution of the true angle between the reconstructed struck neutron and the recoil proton in the initial pair in the CM frame, separating the components for each final state interaction considered in the analysis. The distributions are area normalized.

It's clear that a significant part of the events is back to back; by looking at the same distribution where the interactions responsible of the final state are separated, shown in figure 3.13b, we can see that most of the events in the back to back region ($cos(\theta'_{p1n} \geq -0.95$) are produced by MEC interaction.

Conclusions

Taking advantage of the reconstruction capabilities of LArTPCs, individual events are categorized in terms of exclusive topologies observed in the final state and used to explore the evidence of nuclear effects in neutrino-argon interactions.
The sample of data which is expected for the full exposure of SBND is very high, and this allows to investigate and resolve different physics issues, from short baseline unexpected neutrino oscillation to the nuclear effects in neutrino interaction with argon.
The current state of the simulation softwares includes new types of interactions, which were not present at the time of the proposal; this leads changes in some channels expected event rate. From the studies that I performed during my internship on the to the $CC\,0\pi\,2p$ channel it turns out that these channel can give important contributions to specific experimental observables, that can be measured in SBND with high precision.
In conclusion, the main goal in the SBND experiment is the search for sterile neutrino at a mass scale where current and previous experiments have found some hints; in addition, high precision cross section measurements in terms of exclusive channels will help to reduce systematics effects in the oscillation measurement, and will allow to perform detailed studies of nuclear effects in neutrino-argon interactions. In particular, detailed studies of Short Range Correlation in neutrino-argon interactions will be performed for the first time, from the study of events with one muon and two protons in the final state.

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