Perspectives for measuring NuMI ν-Ar cross-section @ ICARUS and cosmic background constraints in the ν_μ inclusive selection

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On behalf of the ICARUS collaboration

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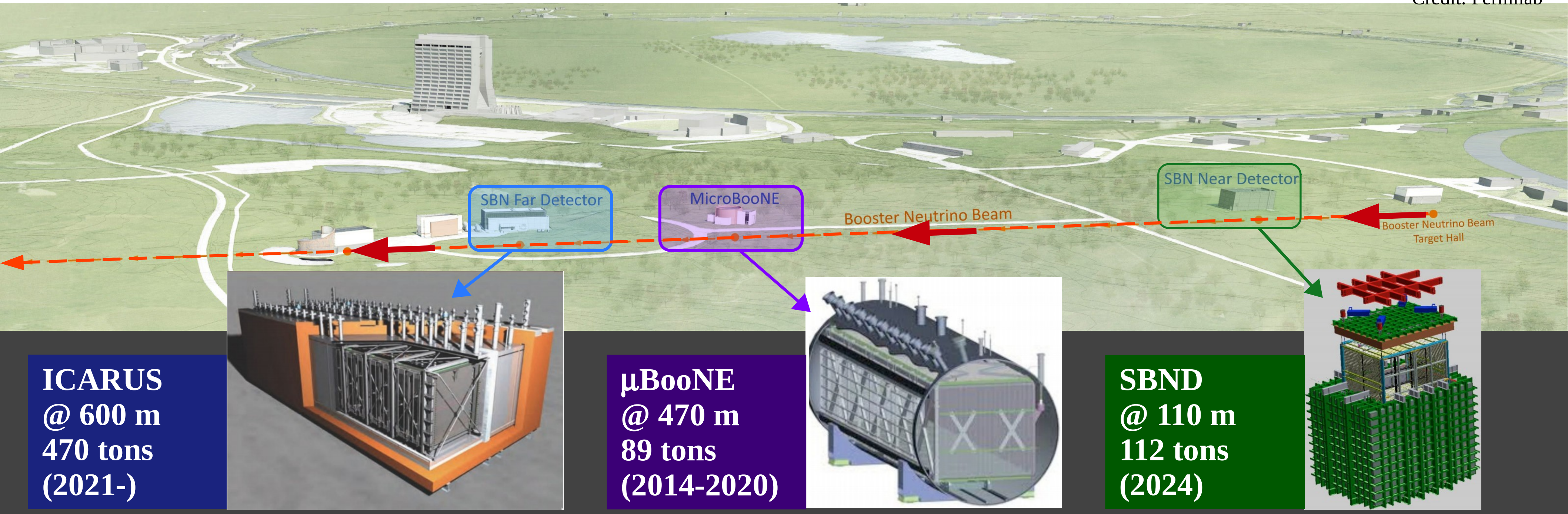
SBN Program at Fermilab

Three **L**iquid **Ar**gon **T**ime **P**rojection **C**hamber (**LArTPC**) detectors at different baselines from the **B**ooster **N**eutrino **B**eam (**BNB**) at Fermilab.

SBN has been designed to ***address the sterile neutrino interpretation*** of the experimental at short-baseline anomalies.
The SBN physics program includes ***the study of ν–Ar cross sections with unprecedented precision.***
The high sensitivity leads to ***invaluable opportunities for New Physics searches.***

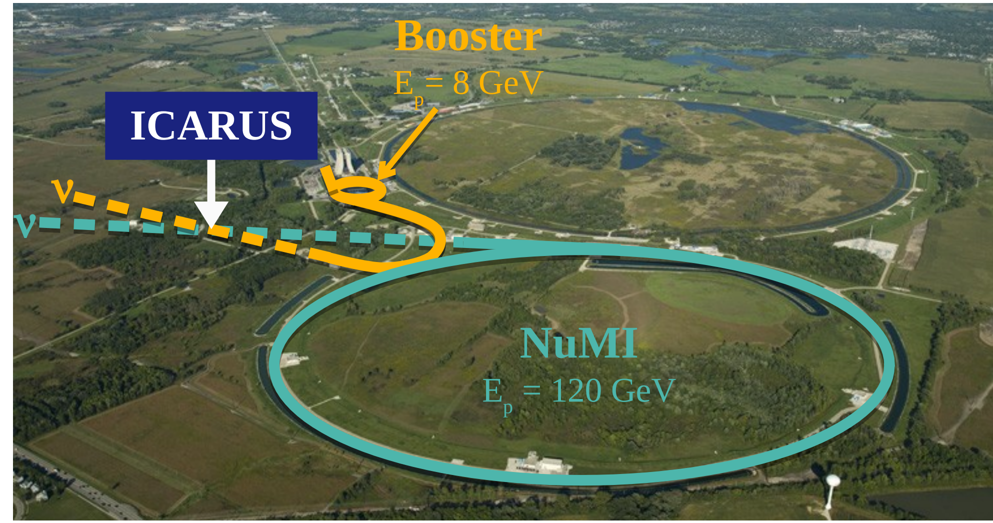
Credit: Fermilab

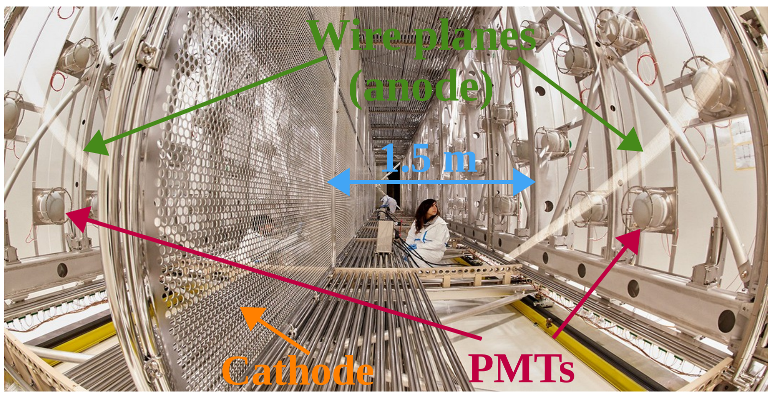


ICARUS

Imaging Cosmic And Rare Underground Signals

ICARUS is the **far detector in the SBN program**, is located **on-axis with the Booster** beamline and **5.7° off-axis from the NuMI** beamline, this will allow it to get a lot of data sets of ν-Ar interactions.





TPC

PMT

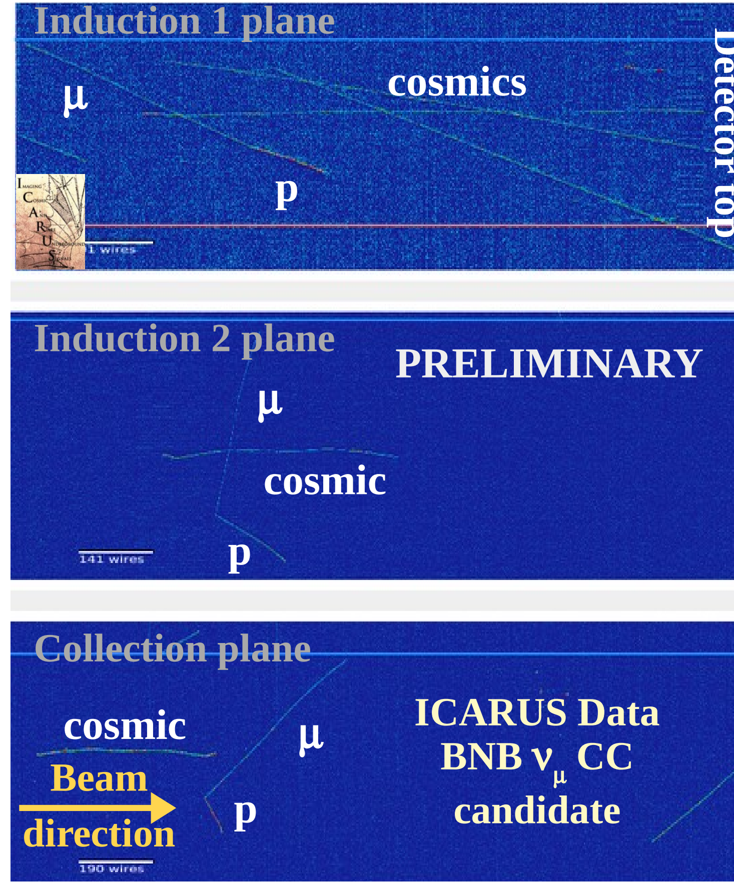
CRT

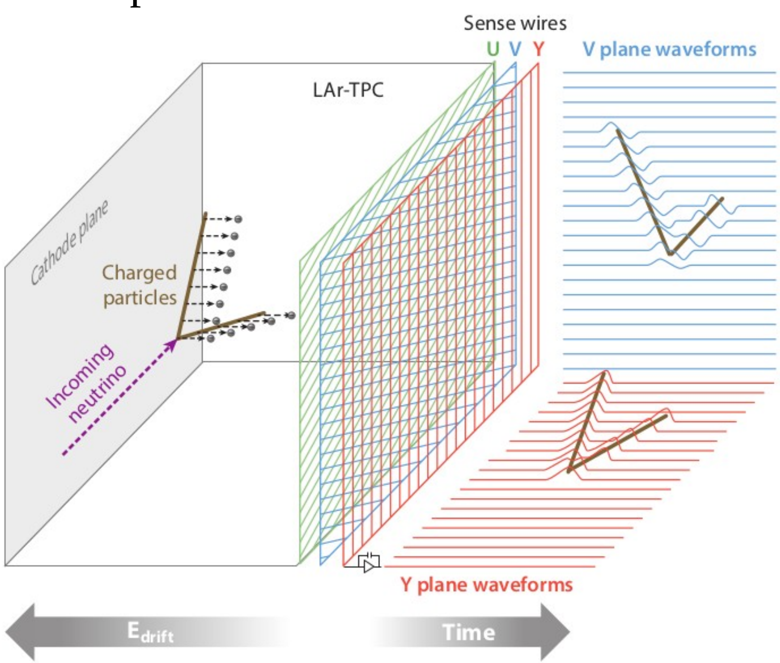
- **2 identical modules.**
- **2 TPCs per module** with central cathode.
- **3 readout wire planes** (2 induction + 1 collection) per TPC.
- **360 PMTs** for trigger and timing.
- **Cosmic Ray Tagging System** (CRT) at the bottom, sides, and top.

LAr TPCs

Why LAr TPCs?

- The ν-Ar interactions produce tracks, with ions and photons along those.
- Photons propagate inside the detector.
- The ionized electrons will slowly drift towards the anode by an applied electric field.
- The ionized electrons produce induction signals as they pass the first two wire planes and are collected on the last wire plane.





P. Machado, et. al. Rev. Nucl. Part. Sci. (2019)

LAr TPC detectors, provide **full 3D imaging, precise calorimetric energy reconstruction**, and efficient **particle identification**. The detailed images of particle trajectories provide **significant information about final states**. The **high spatial resolution** allows for background rejection.

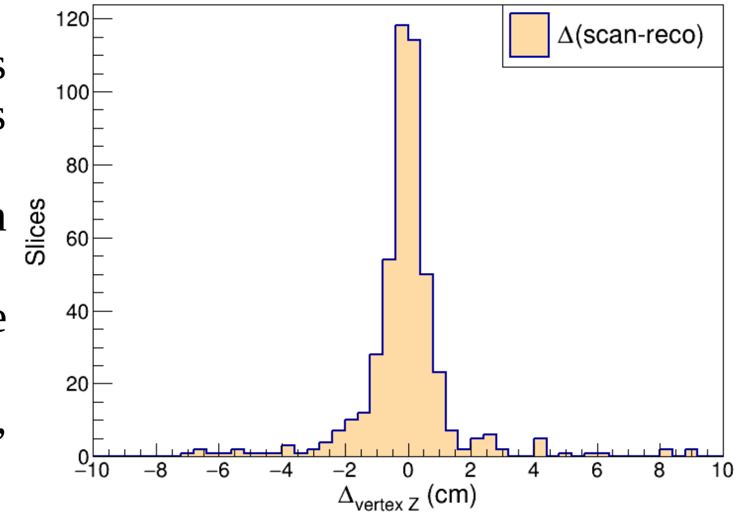
Thus, ***using the LArTPC technology we will be able to study ν_μ and ν_e with high precision.***

Event reconstruction

Abratenko, P. et al. Eur. Phys. J. C 83, 467 (2023)

TPC, PMT, and CRT reconstruction are performed on the interactions (ν, cosmic, etc.) present in each event. TPC event reconstruction uses Pandora to:

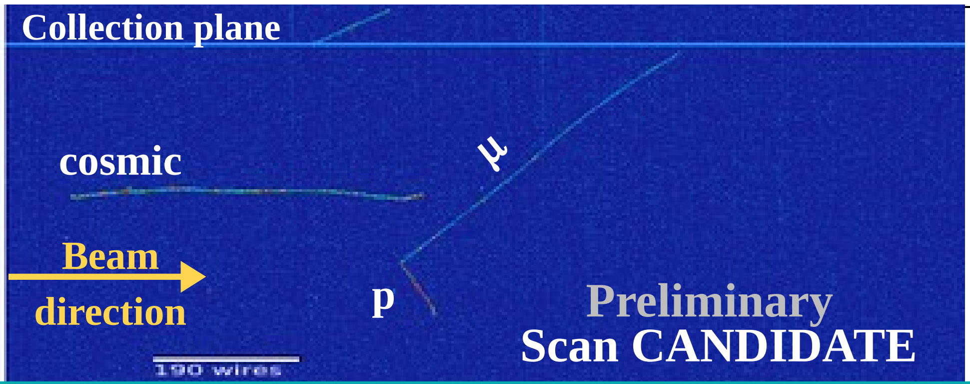
- **Reconstruct particle trajectories in 3D** starting from the hits in the TPC wire planes.
- **Reconstruct interaction vertices** (the common point where particles originate) and **particle hierarchy** (parent/child particles)
- **Classify particles as track-like** (μ, p, π±, K±) or **shower-like** (e, γ)

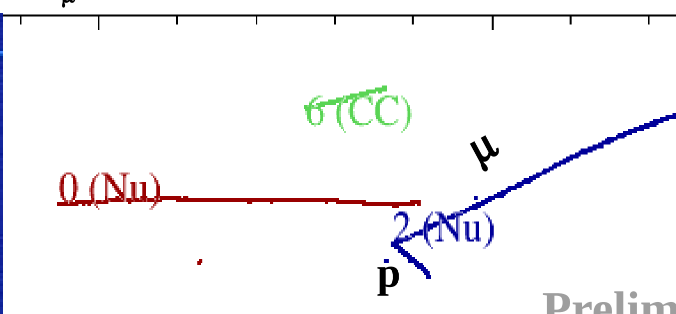


Selection considers the reconstructed output and looks for ν-like interactions with a μ-like track (ν_m) or e-like shower (ν_e).

Event selection by visual scan of collected data used to test and adjust automated software tools and compare data/MC samples.

ICARUS Data BNB ν_μ CC candidate





the colors are what was grouped together into one interaction by the reco

Preliminary

Reconstructed CANDIDATE

Neutrino Interactions

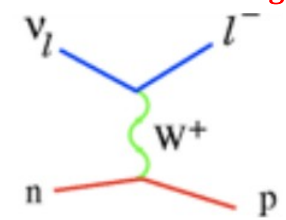
The ν oscillation experiments, require precise understanding of ν–Ar interaction cross section for a correct interpretation of the experimental result.

ν interaction type could be CC or NC:

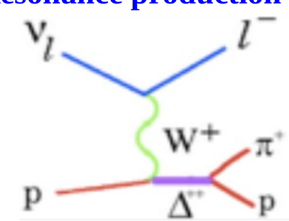
For CC

- **QE:** nucleon changes, but NOT breaks up
- **RES:** nucleon excites to resonance state
- **DIS:** nucleon breaks up
- **MEC:** classified in 2p-2h effect

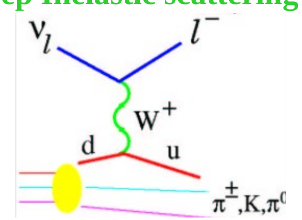
Quasi-elastic scattering (QE)

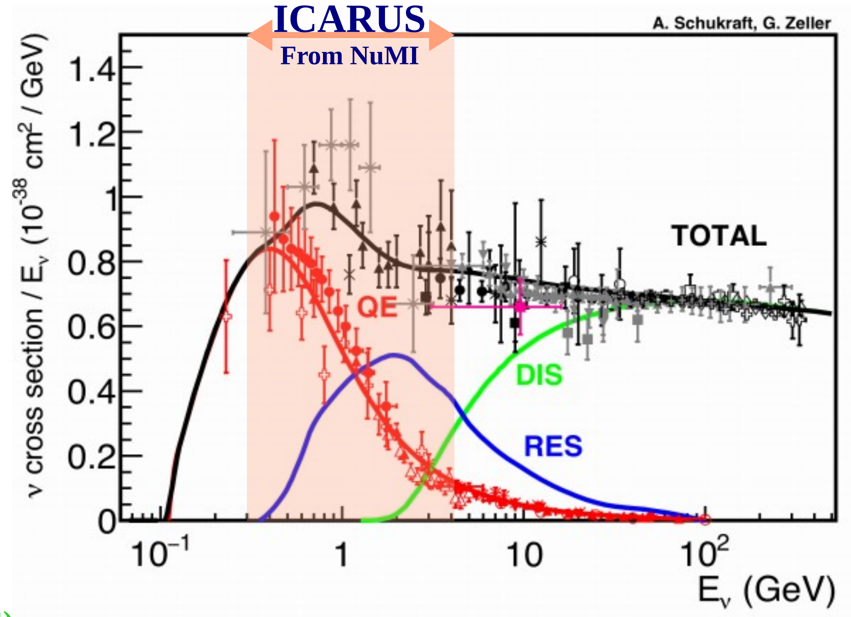


Resonance production (RES)



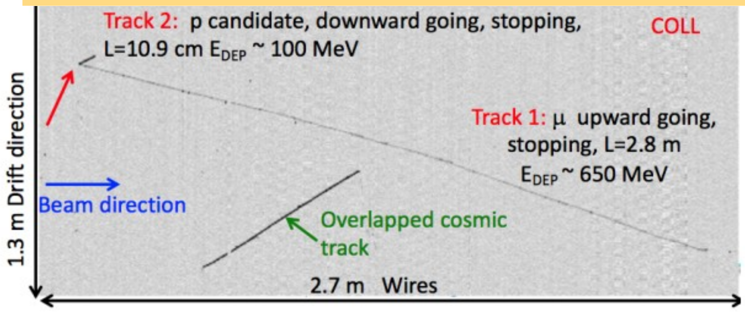
Deep Inelastic scattering (DIS)





We will have these kinds of interactions coming from the NuMI off-axis. **In the energy range where we will study, the QE is close to the RES, then we must distinguish between their topologies**.

Contained ν_μ CC candidate: $\nu_\mu + n \rightarrow \mu^- + p$



We will focus on the background located in signal regions.

Inclusive Selection

Strategy for measuring the cross section

The plan we have to extract the cross section of the NuMI beam neutrinos with the ICARUS Ar nuclei is using:

Events Selected

Signal is Charged Current: Quasi-elastic, Resonance and Deep inelastic

Unfolding

Backgrounds

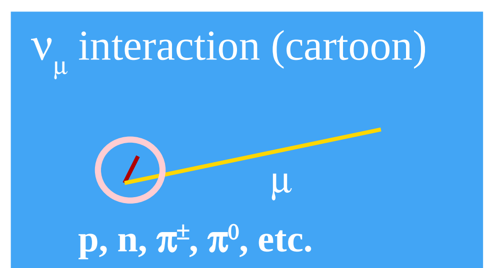
Neutral Current and cosmic background (the dominant is the cosmic)

$$\left(\frac{d\sigma}{dx}\right)_\alpha = \frac{\sum_j U_{j\alpha}(N_{data,j} - N^{bkgd}_{data,j})}{A_\alpha(\Phi T)(\Delta x)}$$

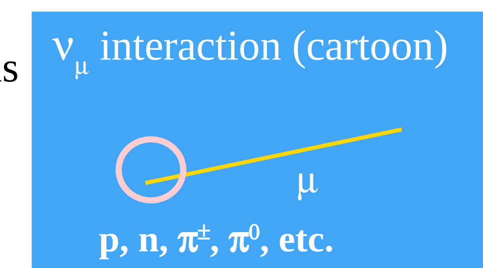
Acceptance Flux Targets Bin-width

First analysis using ν_μ CC Inclusive with μ kinematics. ***The idea of this study is tried to distinguish μ comes from ν_μ from the ones from the cosmic*** (not putting any constraints on the hadronic system).

The dominant background is due to cosmic. This background will be constrained with cosmic data.



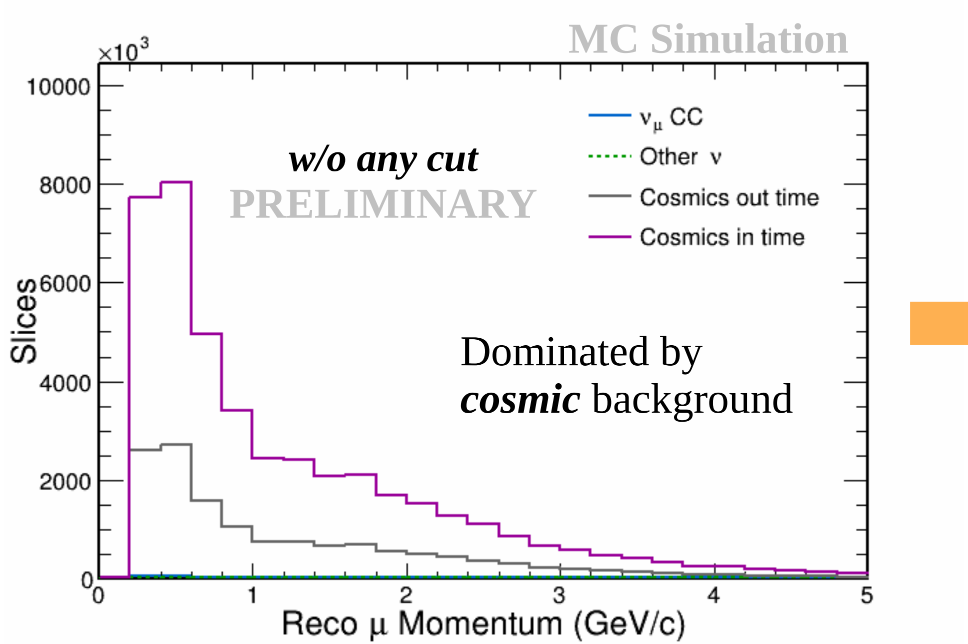
We will focus only on μ

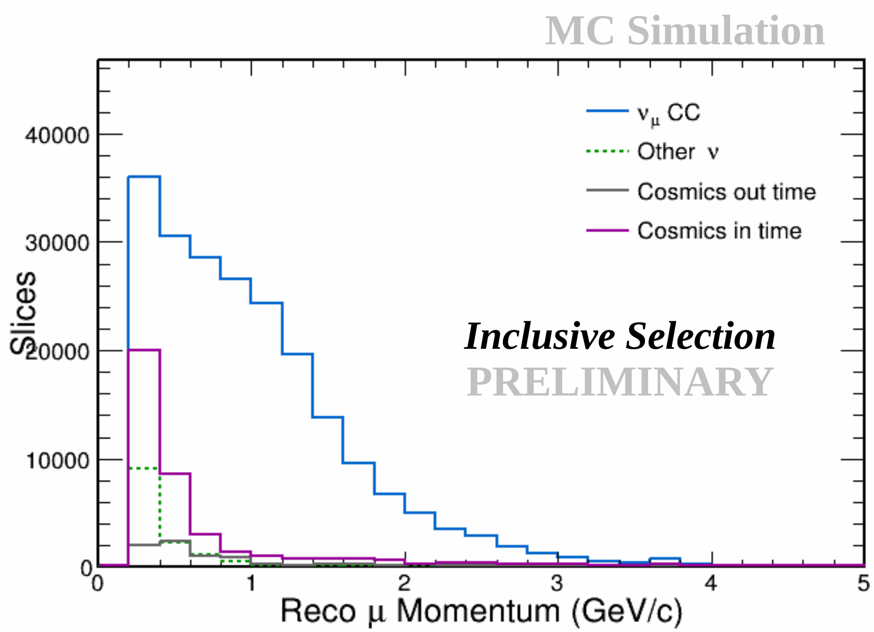


Let’s see closer this inclusive selection...

Inclusive Selection

MC Simulation

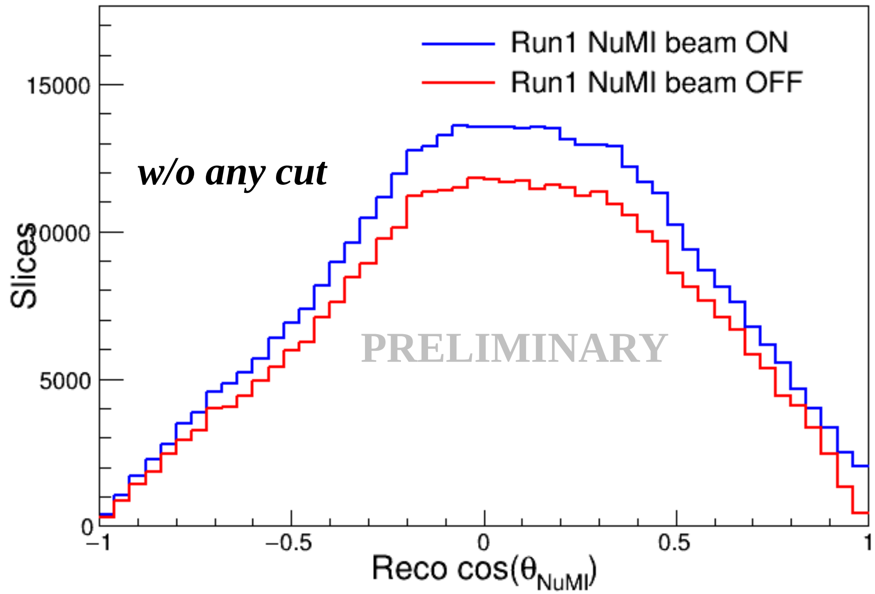




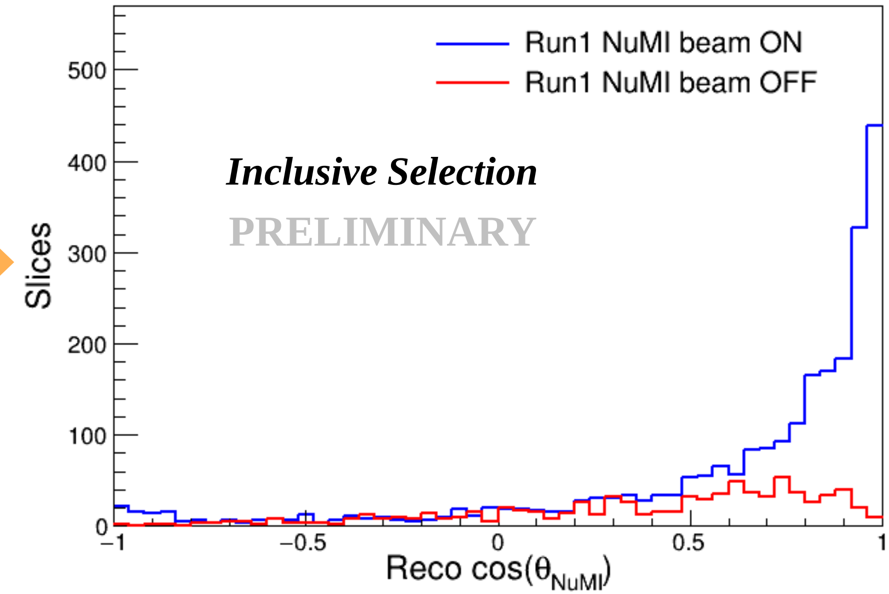
The ***dominant background is due to cosmic***. For one year with NuMI off axis $6x10^{20}$ POT and after our inclusive selection (which uses the TPC information and the geometry of the reconstructed interaction), we get ***77% of signal***, 7% other backgrounds (NC and ν_e) and ***16% of cosmic background*** [cosmics in time (13%) + cosmics out of time (3%)].

Purity = selected signal / (selected signal + selected background)

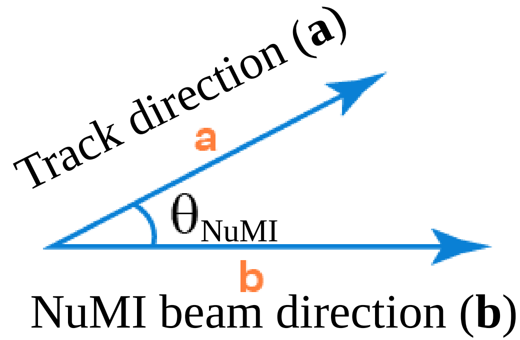
Inclusive Selection (NuMI Data, run 1)



Using TPC & PMT



$$cos(\theta_{NuMI}) = \frac{\vec{a}\cdot\vec{b}}{|\vec{a}||\vec{b}|}$$

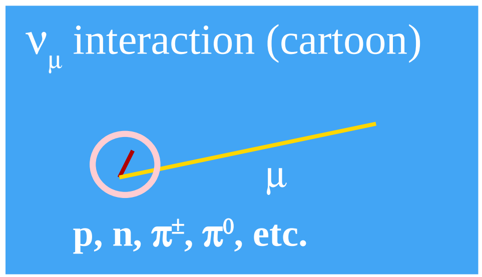


In this analysis, after applying a set of selection criteria, which uses the TPC information and the geometry of the reconstructed interaction (e.g. the vertex must be contained in the fiducial volume of the detector), we observe very few background events (red distribution).

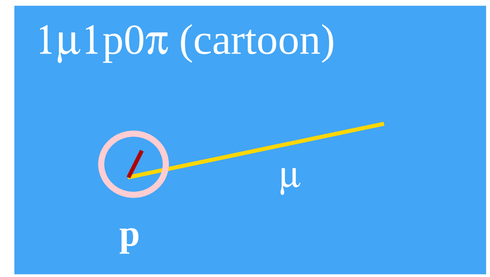
For the ***inclusive selection*** we already have the tools to select the signal and reject the background.

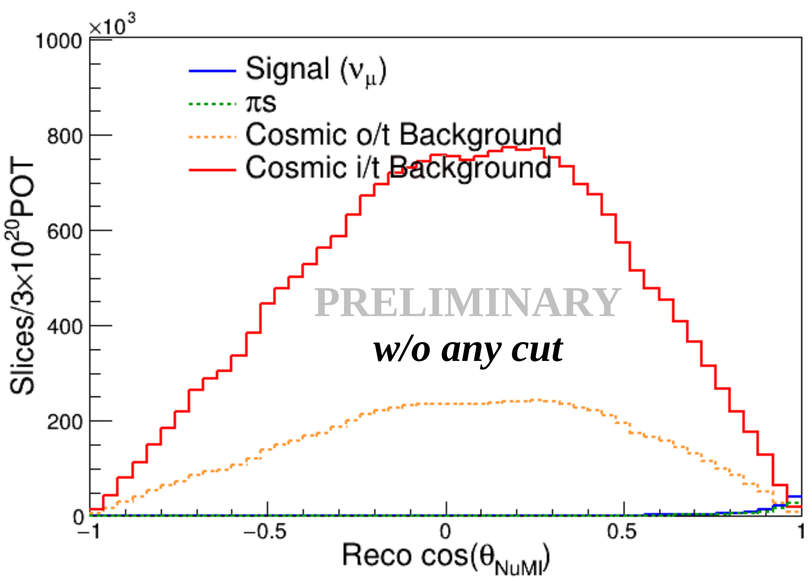
1μNp0π Selection

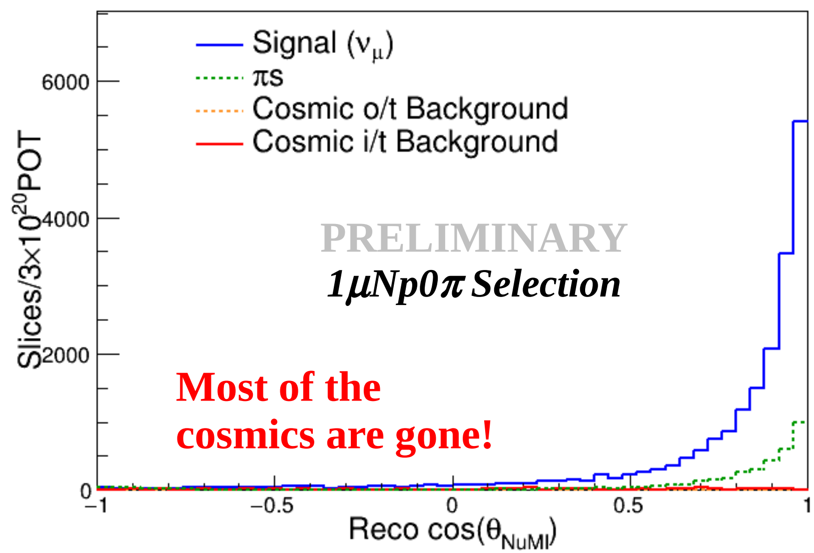
Currently, we started studying the background of the **1μNp0π** (*with a minimum p threshold*) sample. The signal is events without any pion in the final state. ***The dominant background is due to pions***.



We will focus on 1μNp0π







Summary

- ICARUS as the Far Detector of the SBN program, has the goal to search for sterile neutrinos via ν_e appearance.

- The understanding and characterization of neutrino interactions in Ar will be of great help in future experiments such as DUNE to investigate new and exciting physics.

- For the ***inclusive selection,*** we already have the **tools to select the signal and reject in a very good amount cosmic** background (which is the dominante background).

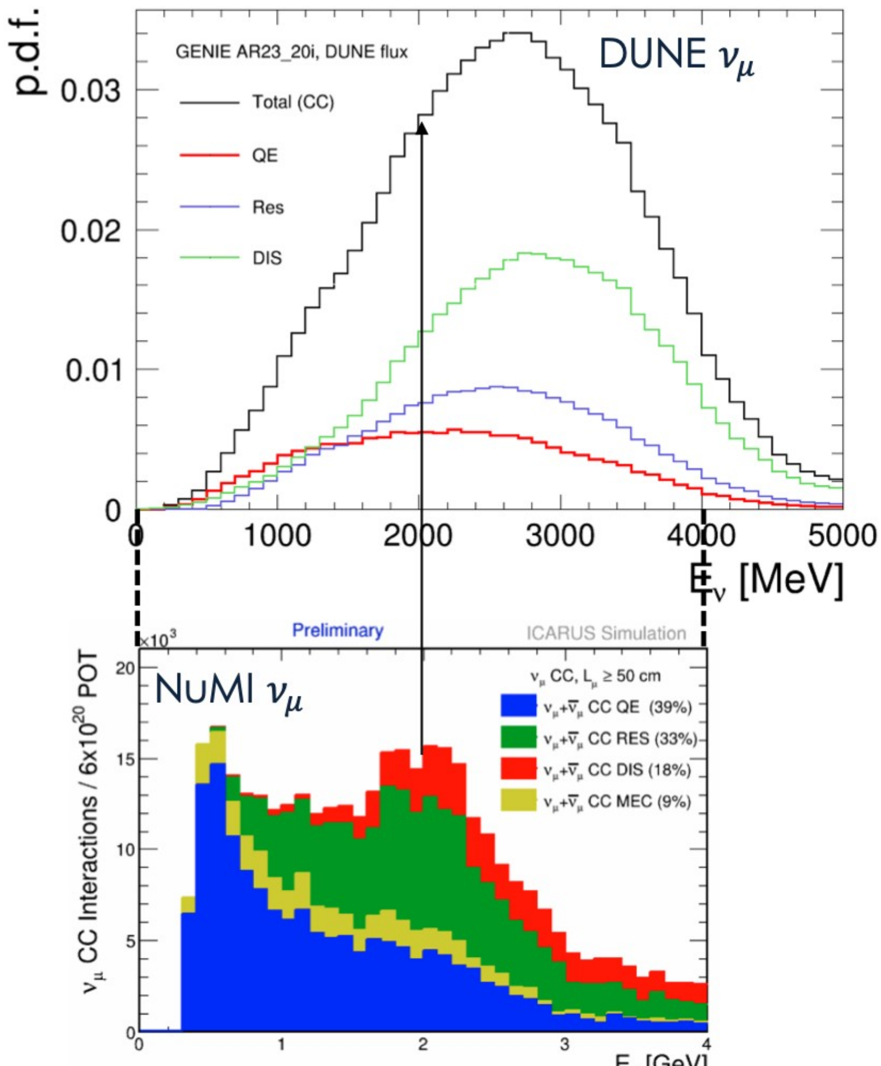
- In the **1μNp0π selection, we observe that**
  - **the dominant background is due to πs** (in particular due to π CC).
  - most of the cosmics are gone

- Currently, ICARUS is collecting physics-quality. A lot of neutrino data awaits us, **stay tuned… more to come!!!**

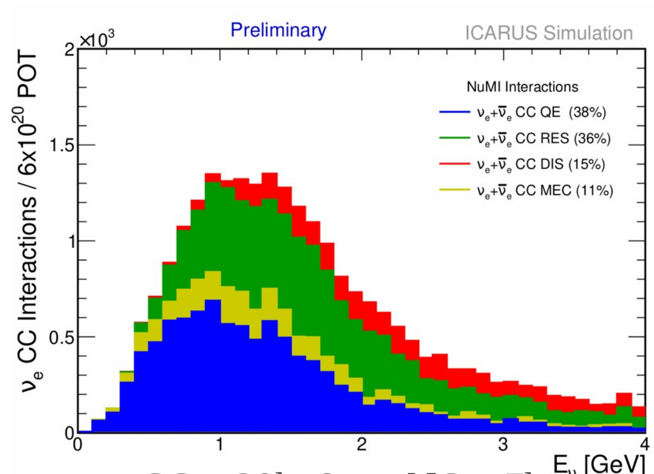
Imaging Cosmic And Rare Underground Signals

Backup

Neutrino Interactions from NuMI



ICARUS has an **important statistic of ν_μ and ν_e interaction modes in the few hundred MeV to few GeV range from the NuMI beam**. This allows be used for osc SBN and DUNE studies. Also the **ν-Ar measurements help to constrain cross-section systematics** and nuclear effects for the analysis of oscillations through event selection and energy estimates.



ν_μ CC ≈ 433k & ν_μ NC ≈ 191k

ν_e CC ≈ 20k & ν_e NC ≈ 7k

Motivation

Neutrino anomalies

Even though the 3νSM model has shown good agreement in many experiments, four main anomalies have been observed in neutrino experiments at short baseline, consistent with the mixing of the standard neutrinos with a fourth

Anomaly	Characteristics
LSND	Stopped π source with a detector optimized to probe $\bar{\nu}_e$ via inverse β decay. A 3.8σ excess of events over backgrounds was observed, compatible with $\bar{\nu}_\mu \to \bar{\nu}_e$ oscillations with $L/E \approx 1$ m MeV^{-1}.
MiniBooNE	Accelerator neutrino source with the capability of producing a dominant ν_μ or $\bar{\nu}_\mu$ beam. Excesses of ν_e ($\bar{\nu}_e$) events in ν_μ ($\bar{\nu}_\mu$) mode were observed over backgrounds, amounting to a 4.5σ (2.8σ) discrepancy from expectations. The observed excesses were found to be compatible with LSND within a sterile neutrino framework.
Reactor anomaly	A reevaluation of the $\bar{\nu}_e$ fluxes from nuclear reactors with improved theoretical uncertainties that led to a deficit in many past experiments in the total number of events with respect to theoretical expectations at the 3σ level. More recently, some spectral features have been observed that are consistent with sterile neutrino oscillations with $\Delta m^2 \sim eV^2$
Gallium anomaly	an overall deficit in the number of ν_e events from radioactive sources with respect to theoretical expectations at the 3σ level observed during calibration runs of solar neutrino experiments.

Motivation

(3+1)-Oscillation Scenario

One of the possible solutions to solve the short-baseline neutrino anomaly is the 3+1 scenario (one sterile neutrino is added to the neutrino spectrum).
Neutrino mixing amounts to the fact that the eigenstates produced by electroweak interactions (flavor states) are nontrivial linear combinations of mass eigenstates. For a 3+1 mixing matrix,

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \\ \nu_s \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} & U_{e4} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} & U_{\mu 4} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} & U_{\tau 4} \\ U_{s1} & U_{s2} & U_{s3} & U_{s4} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \\ \nu_4 \end{pmatrix}$$

and as long as $\Delta m^2_{41} >> |\Delta m^2_{31}|, \Delta m^2_{21}$, oscillations at short-baseline experiments can be well described by a two-flavor vacuum oscillation formula,

$$P_{\alpha\beta} = \delta_{\alpha\beta} - 4|U_{\alpha\beta}|^2(\delta_{\alpha\beta} - |U_{\alpha\beta}|^2)\sin^2\left(\frac{\Delta m^2_{41} L}{4E}\right)$$

Each oscillation channel $\nu_\alpha \rightarrow \nu_\beta$ is driven by a different effective mixing $\theta_{\alpha\beta}$ as:

$$\nu_\mu \rightarrow \nu_e : \ \sin^2 2\theta_{\mu e} \equiv 4|U_{\mu 4}|^2 |U_{e4}|^2 \qquad \text{(LSND, MiniBooNE anomalies);}$$

$$\nu_e \rightarrow \nu_e : \ \sin^2 2\theta_{ee} \equiv 4|U_{e4}|^2(1 - |U_{e4}|^2) \qquad \text{(reactor, gallium anomalies);}$$

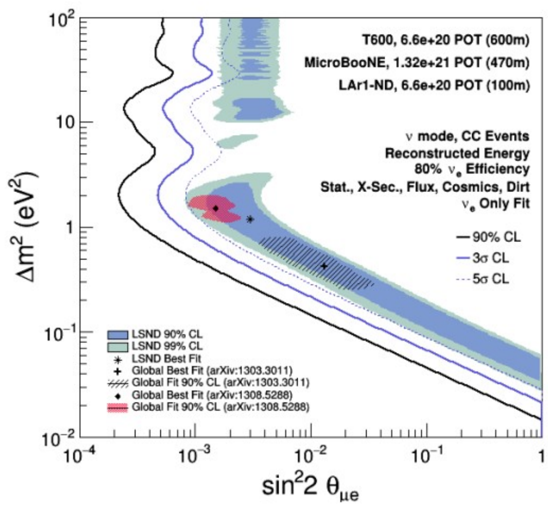
$$\nu_\mu \rightarrow \nu_\mu : \ \sin^2 2\theta_{\mu\mu} \equiv 4|U_{\mu 4}|^2(1 - |U_{\mu 4}|^2) \qquad \text{(no anomaly observed)}$$

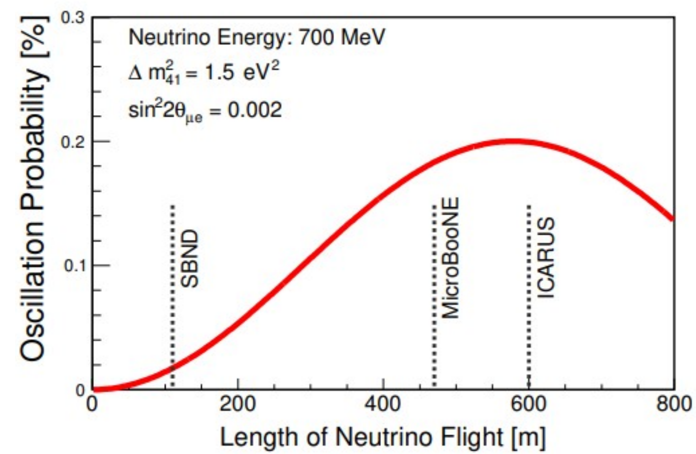
ICARUS Main Motivations

Physics Program

The SBN program has been designed specifically to address the sterile neutrino interpretation of the experimental at short-baseline anomalies.

- **ICARUS as the SBN far detector will primarily be dedicated to the search for sterile neutrinos via ν_e appearance**.
- The combined analysis, the near detector (SBND) and ICARUS, with 3 years of data will be able to cover the 99% C.L. allowed region of the LSND signal with a sensitivity of 5σ. Also, it will allow reducing both statistical and systematic uncertainties.
- Recently Neutrino-4 result, points to reactor anti-ν_e disappearance with large Δm^2 (~ 7 eV^2) and mixing angle ($\sin^2 2\theta$~0.26).





Phys. Atom. Nuclei 83, 930–936 (2020)

Cosmic Background

ICARUS, as a surface detector, **faces an additional challenge to be constantly bombarded by cosmics,** which can be classified into two types:

- ***In-time***: cosmic particles entering the detector during the beam spill.
- ***Out-of-time***: cosmic particles crossing the detector during the drift time.

In order to decrease as much as possible the cosmic incidence in the detector, have been implemented:

- a 4π coverage of the detector with **Cosmic Ray Tagging modules** (CRT): Bottom CRT, Side CRT and Top CRT
- a ICARUS' helmet: a **3 m concrete overburden** (6m water equivalent).

Cosmic Taggers

3 m Overburden