Prospects for measuring ν-Ar cross-section and ν_μ event selection using the NuMI neutrino beam @ ICARUS

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On behalf of the ICARUS collaboration

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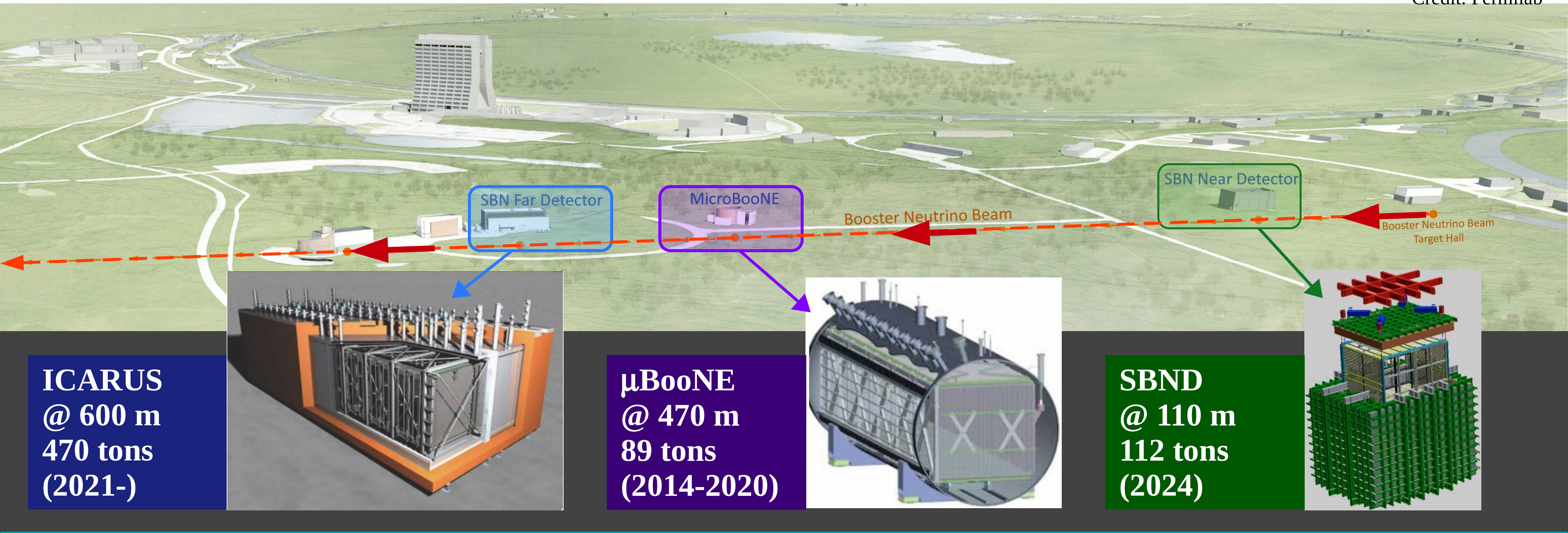
SBN Program at Fermilab

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.***

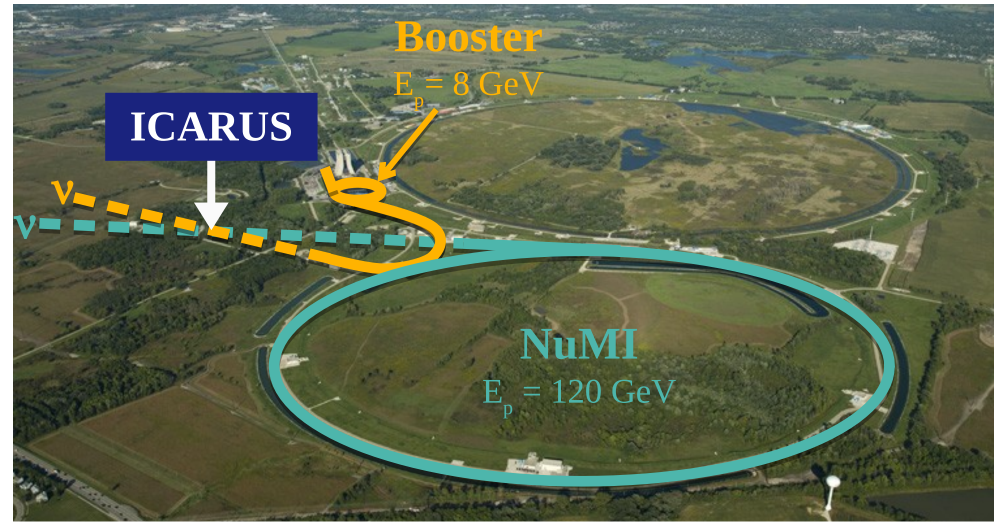
Credit: Fermilab

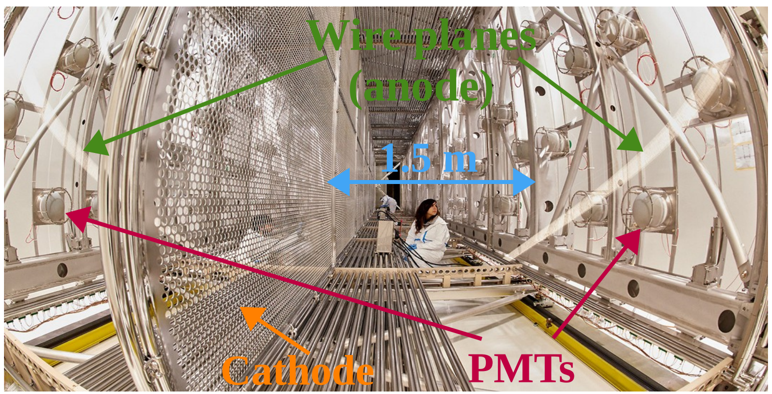


ICARUS

Imaging Cosmic And Rare Underground Signals

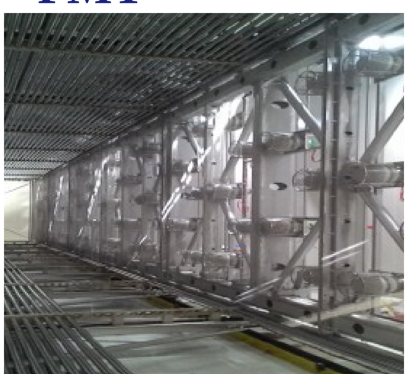
ICARUS is the **far detector in the SBN program**, is located **on-axis with the Booster** beamline and **6° off-axis from the NuMI** beamline, this will allow it to get a lot of data sets of ν-Ar interactions.





TPC

PMT



CRT

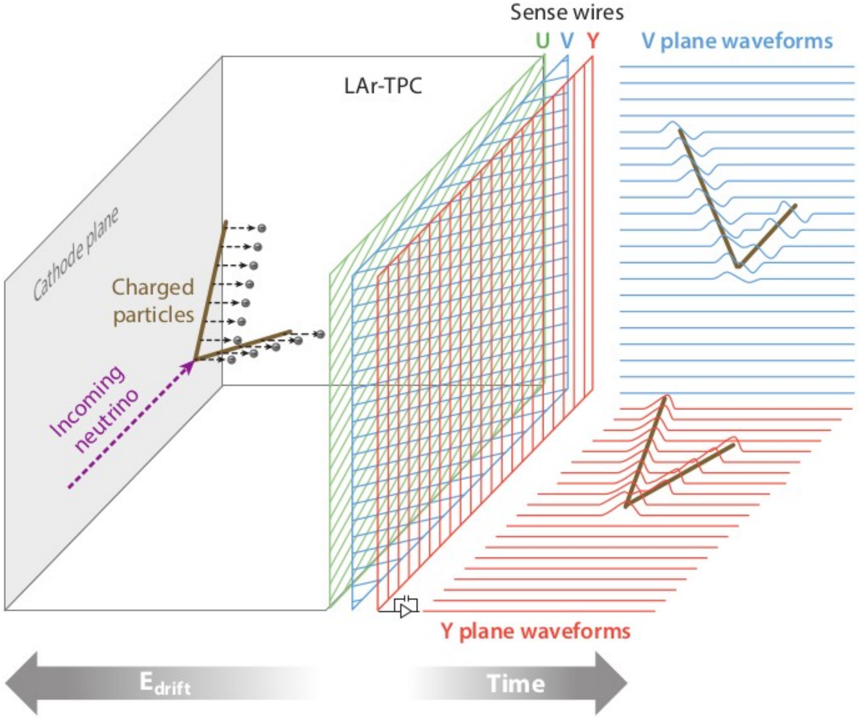
- **2 identical modules.**
- **2 TPCs per module** with central cathode.
- **3 readout wire planes** (2 induction + 1 collection) per TPC.
- **360 PMTs** for trigger and timing.
- **Cosmic Ray Tagging System** (CRT) at the bottom, sides, and top.

LAr TPCs

Why LAr TPCs?

Liquid argon technology for ν physics was proposed by C. Rubbia

- 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, O. Palamara, and D. Schmitz. Annu. Rev. Nucl. Part. Sci. (2019)

LAr TPCs

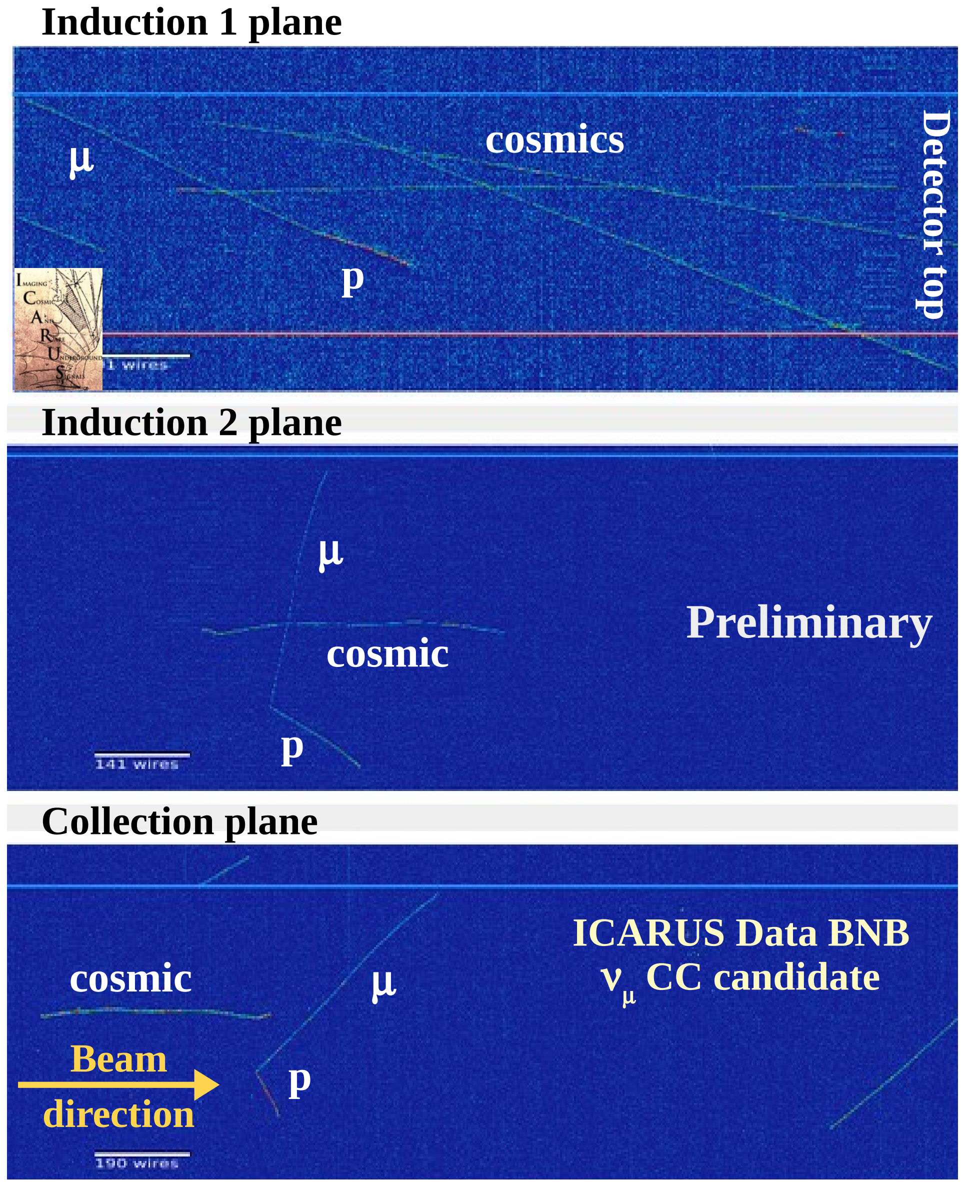
Why LAr TPCs?

- 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.

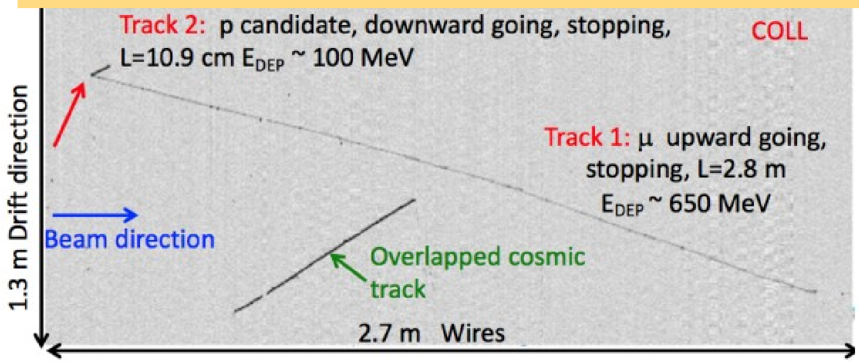
Thus, using this technology we will be able to study ν_μ and ν_e with high precision.



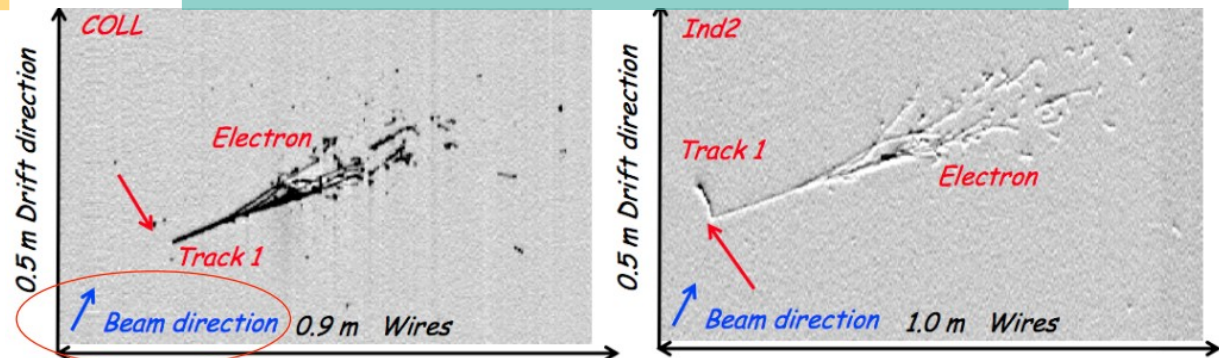
ICARUS
Current Status

Started collecting data taking with the BNB & NuMI beams since March 2021, in parallel with **commissioning** activities. **Cosmics, ν_μ , and ν_e samples were collected** for trigger, calibration, event reconstruction studies, etc.

Contained **BNB ν_μ** CC candidate: $\boldsymbol{\nu_\mu + n \rightarrow \mu^- + p}$



Contained **NuMI ν_e** CC candidate: $\boldsymbol{\nu_e + n \rightarrow e^- + p}$

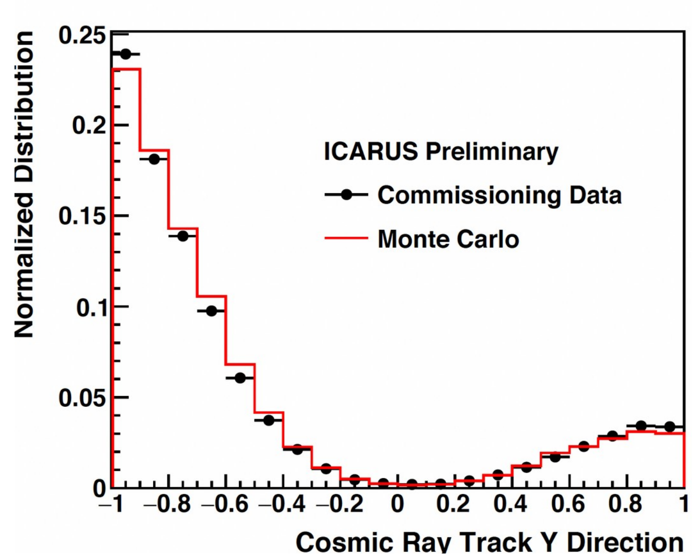


The commissioning period is over and **the physics run started** this June 9th 2022! And a new taking neutrino data is happening since this October 2022

Event reconstruction

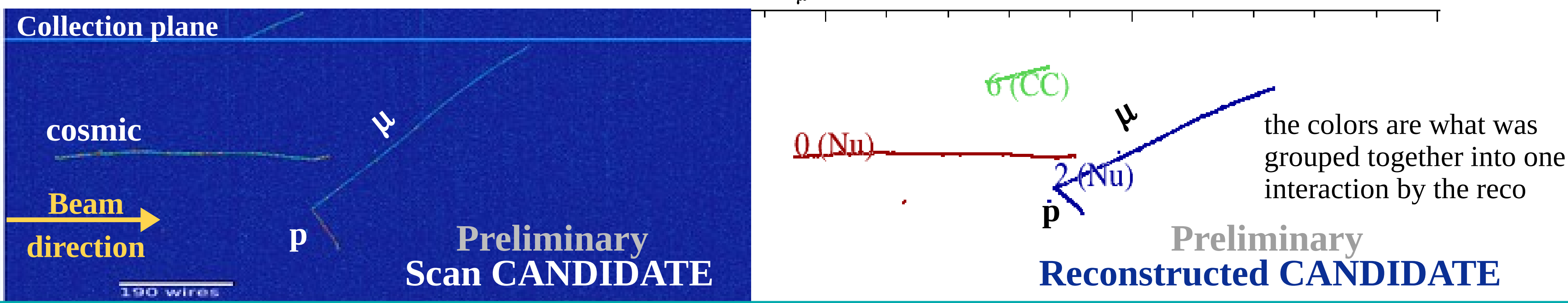
TPC tracks reconstruction algorithm is based on the pre-processing, the wire signals identification/reconstruction (hits), and the track/shower reconstruction. The TPC event reconstruction uses Pandora pattern-recognition software with LArSoft interface to:

- **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, $\pi\pm$, K$\pm$) or **shower-like** (e, γ)



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



Cross-Section
Neutrino Interactions

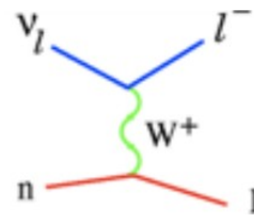
The ν oscillation experiments, require precise understanding of ν–Ar interaction cross section for a correct interpretation of the experimental result.

The ν cross section depends on:

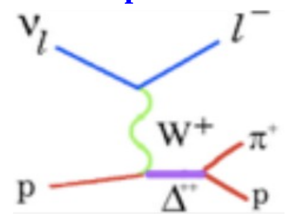
- **ν interaction type** (CC or NC)
  For CC
  - **QE:** nucleon changes, but NOT breaks up
  - **RES:** nucleon excites to resonance state
  - **DIS:** nucleon breaks up
  - **MEC:** classified in 2p-2h effect
- **ν target** (e, nucleus, nucleon, q)
- **ν energy** (MeV, GeV)

ICARUS will provide a large data set of ν–Ar interactions from BNB and off-axis NuMI. **Is particularly expected to have high statistics for ν_e cross section measurement using the NuMI off axis.**

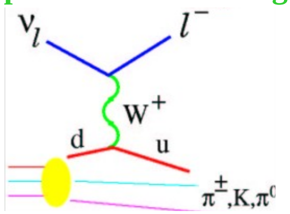
Quasi-elastic scattering (QE)

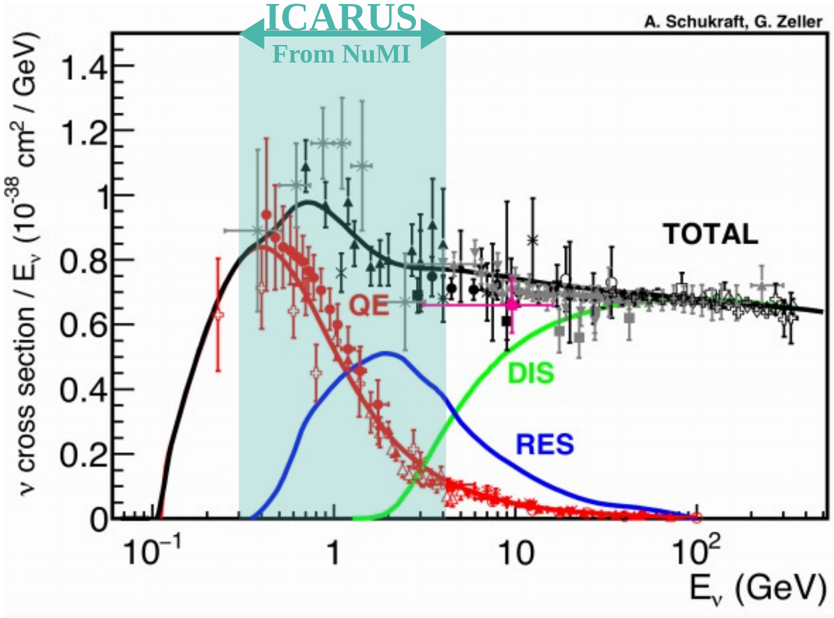


Resonance production (RES)



Deep Inelastic scattering (DIS)



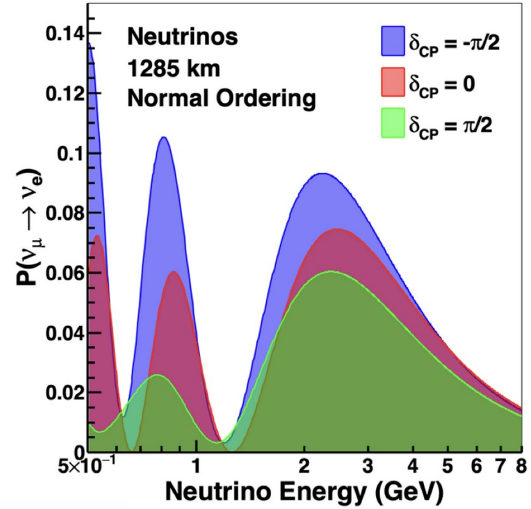


In few GeV energy range, historically very few data

Cross-Section

Neutrino Interactions from NuMI Off Axis

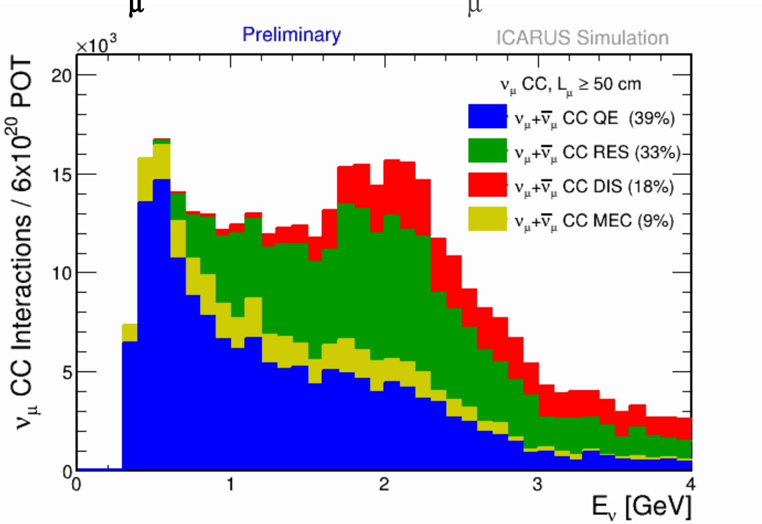
ICARUS has an **important statistic of ν_μ and ν_e interaction modes in the few hundred MeV to few GeV range from the NuMI beam**. This allows be used for osc SBN and DUNE studies. Also the **ν-Ar measurements help to constrain cross-section systematics** and nuclear effects for the analysis of oscillations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

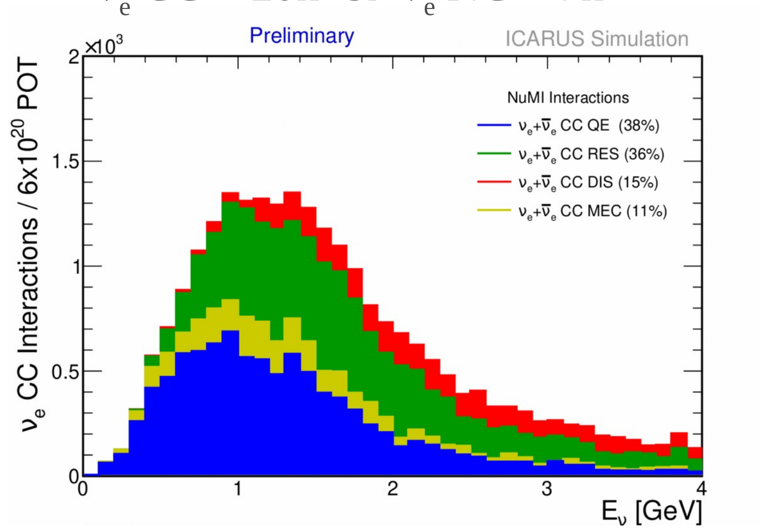


The expected number of events from NuMI off axis per 6×10^{20} POT (~ 1 year):

ν_μ CC ≈ 433k & ν_μ NC ≈ 191k

ν_e CC ≈ 20k & ν_e NC ≈ 7k





Cross-Section

Strategy for a first cross section measurement

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)

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

Bin-width

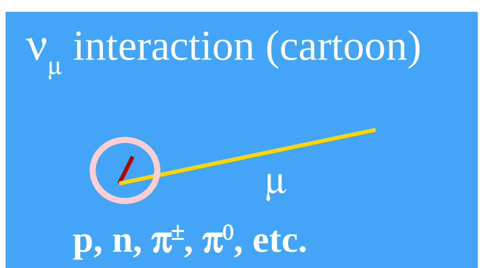
Acceptance

Flux

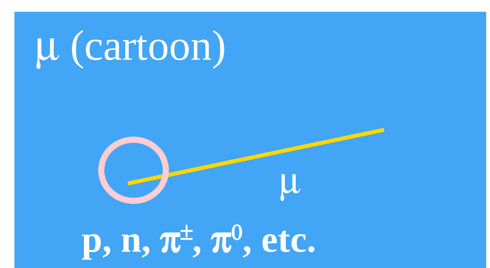
Targets

Cosmic background will be constrained with cosmic data.

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)***.



We will focus only on μ



Selection of ν_μ events

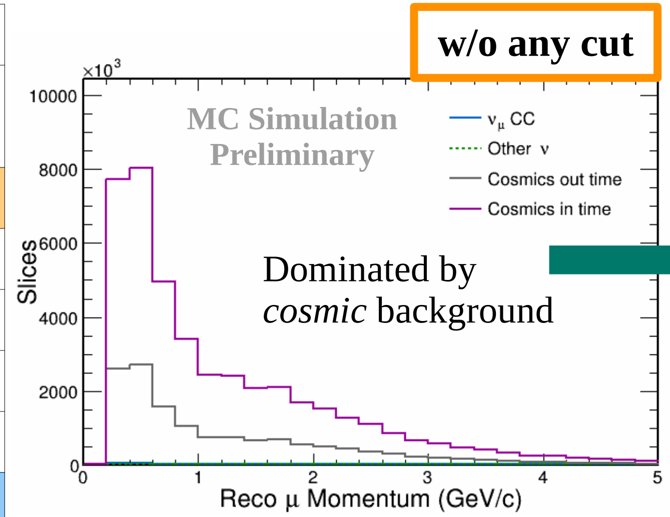
Selection Criteria

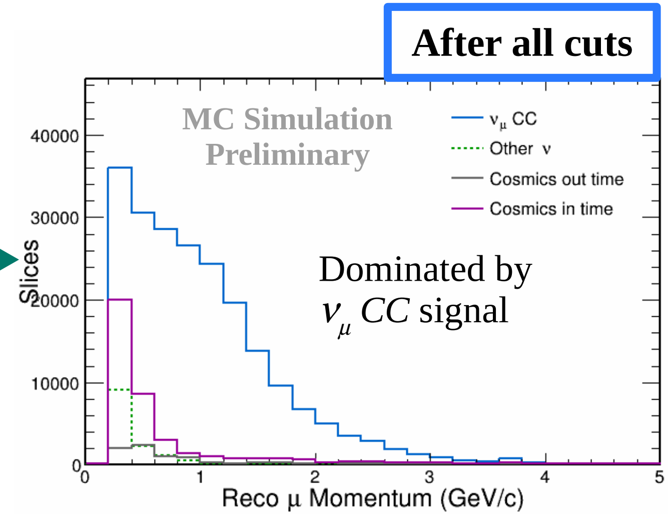
- **For geometry**: vertex contained in fiducial volume
- **For PMT**: the charge flash matching associates ionized electrons (slow to read-out) with scintillation photons (fast to read-out). The main goals are to provide T_0 for each activity, identify a neutrino interaction from cosmics.
- **For reconstruction**: Longest track's Y-direction, remove everything that is a clear cosmic, μ like track.

If we apply the selection criteria sequentially, the purity of the signal and background will be:

Purity = selected [signal or bkgd] / (selected signal + selected background)

	MC Simulation	
	Purity (sig)	Purity (bkg)
No cut	0.01	0.99
Fiducial Volume (FV)	0.02	0.98
FlashM Score (FS)	0.22	0.78
FlashM Time (FT)	0.37	0.63
CRLTrackDirY (TD)	0.52	0.48
Everything	**0.77**	**0.23**

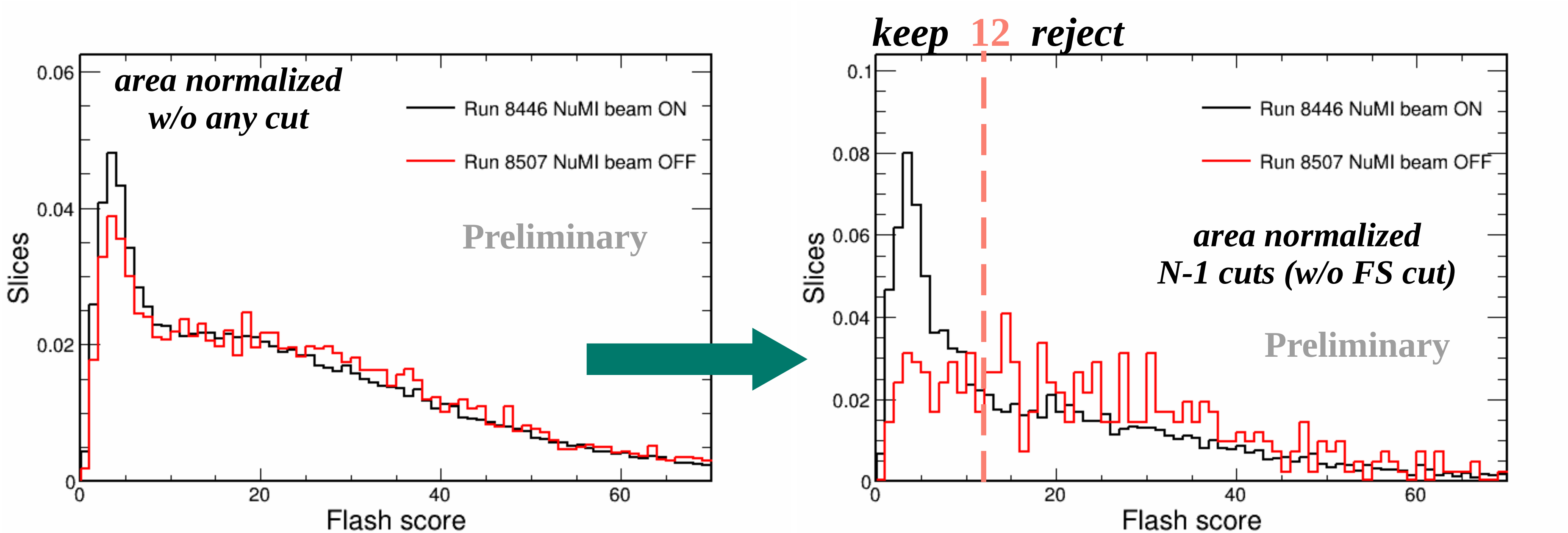




Selection of ν_μ events

First look at run 1 data

A first selection study with data from a couple of runs of run1 where the NuMI beam is **on** and **off** shows that after the selection criteria we applied we can **start to distinguish the signal from the background**.



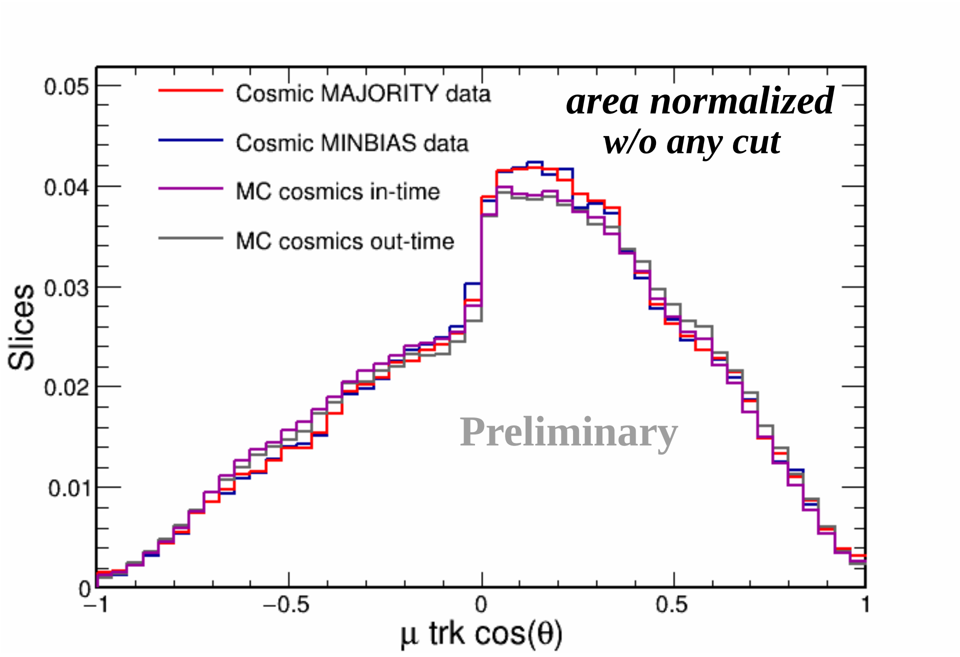
	NuMI beam ON (Eff)	NuMI beam OFF (Eff)
No cut	574666.0 (1.00)	76292.0 (1.00)
Everything	2175.0 (0.00)	110.0 (0.00)

Selection of ν_μ events

Cosmic: Data vs MC

The dominant background is cosmic. After our selection, 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%)].

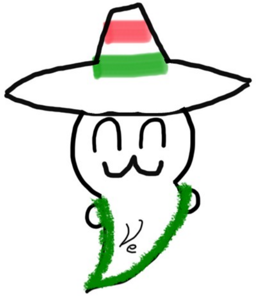
An initial study where we compared in and out time cosmic background MC simulation samples with cosmic data samples, showed:



- similar shapes for reconstructed vertices, track angle, and longest track direction,
- but some disagreement for the track length [we are currently studying it].

Conclusions

- 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.
- The ν_μ selection cut applied removed a great amount of cosmics (which is our principal background). However, this is still a preliminary event selection, an optimization and tuning will be done in the near future.
- A new round of ICARUS taking neutrino data is happening now since this October 2022. A lot of neutrino data awaits us, stay tuned… more to come!!!




¡Muchas gracias!

Backup

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 ≈ 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:

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

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

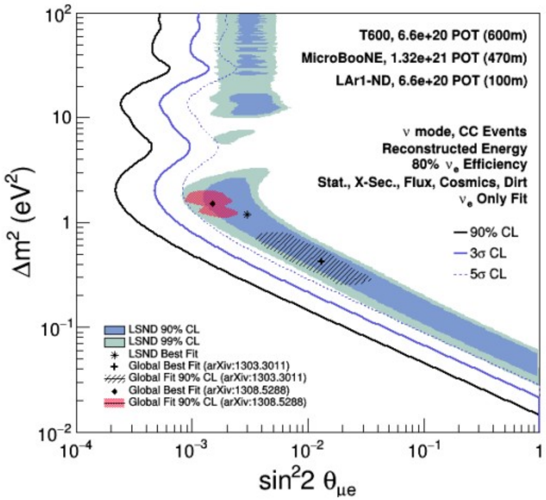
$$\nu_\mu \rightarrow \nu_\mu : \ \sin^2 2\theta_{\mu\mu} \equiv 4|U_{\mu 4}|^2(1 - |U_{\mu 4}|^2) \quad \text{(no anomaly observed)}$$

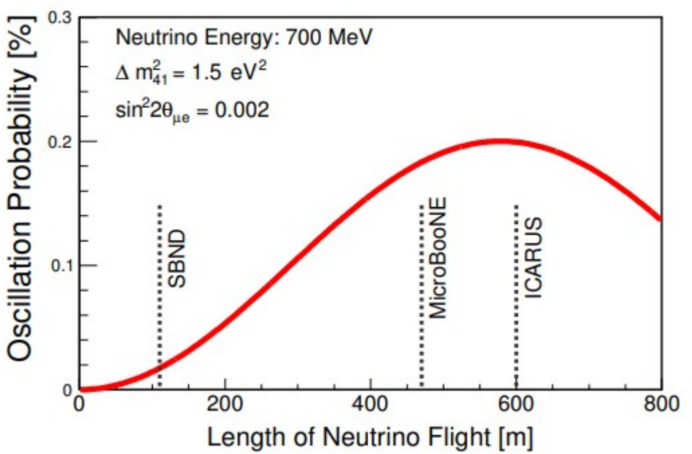
ICARUS Main Motivations

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