

Prospects of neutrino cross-section measurements and ν_e selection with the NuMI off-axis beam at ICARUS

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On behalf of the ICARUS collaboration



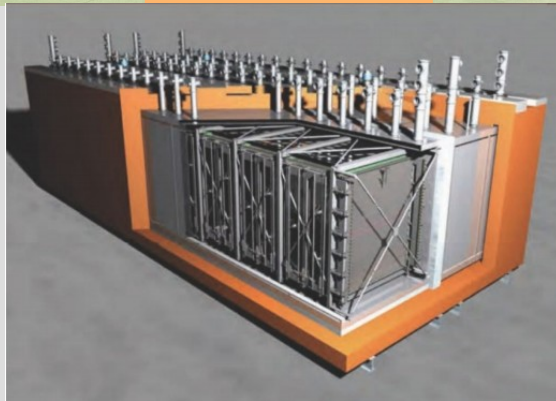
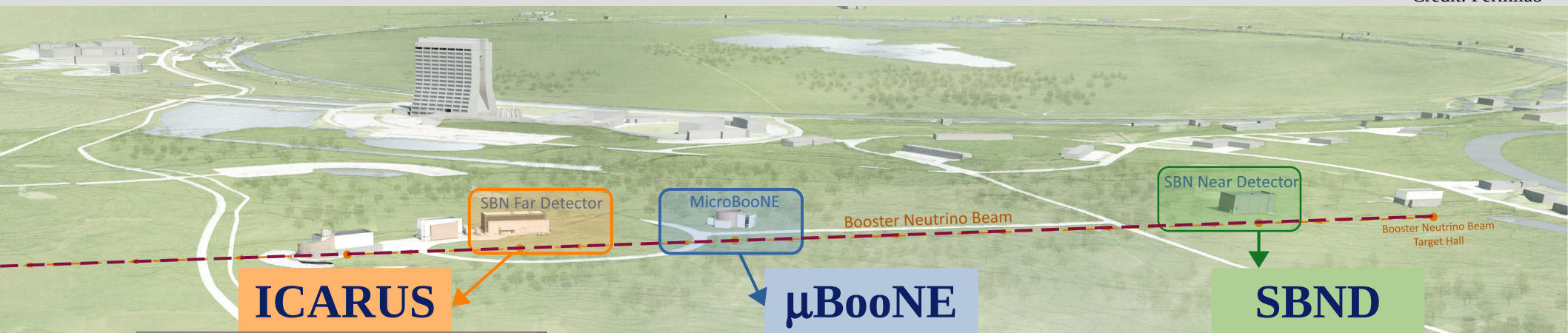
New Perspectives 2021, Fermilab

August 18, 2021

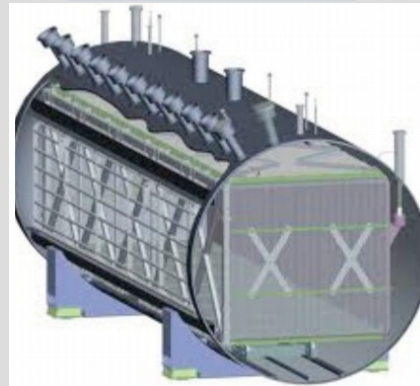
SBN Program at Fermilab

Three **L**iquid **A**rgon **T**ime **P**rojection **C**hamber (**LArTPC**) detectors in the **B**ooster **N**eutrino **B**eamline (**BNB**) at Fermilab.

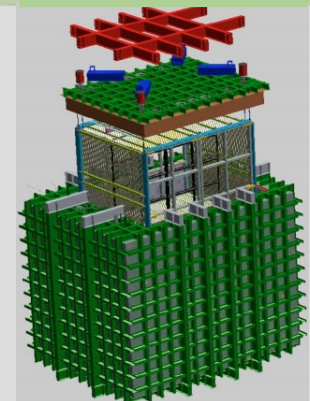
Credit: Fermilab



@ 600 m
476 tons



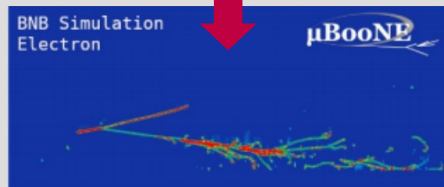
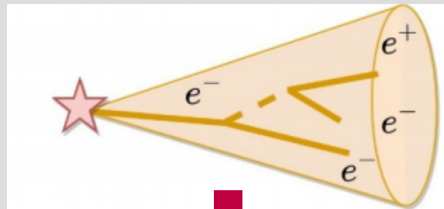
@ 470 m
85 tons



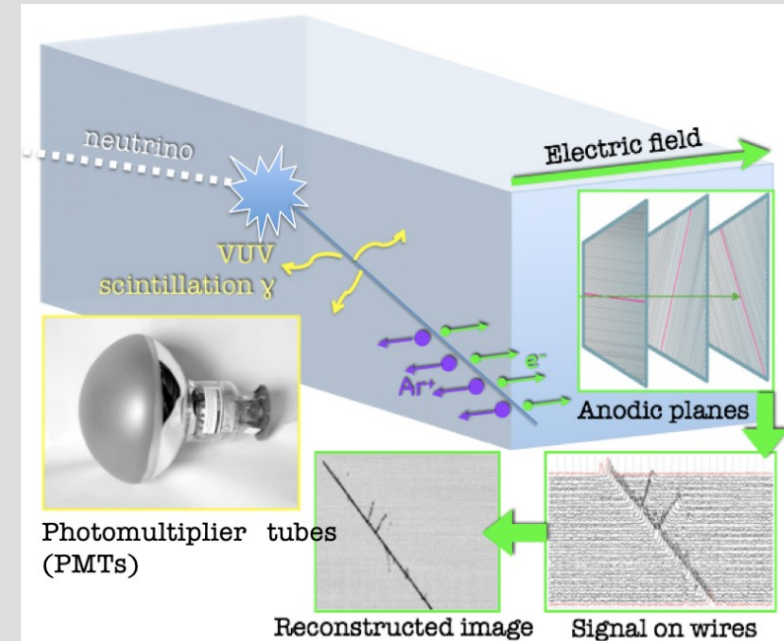
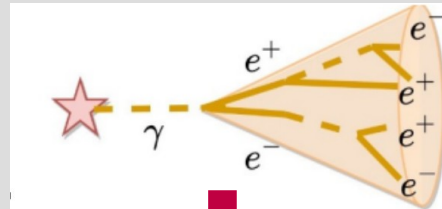
@ 110 m
112 tons

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**.



E. Worcester, Users Meeting Presentation



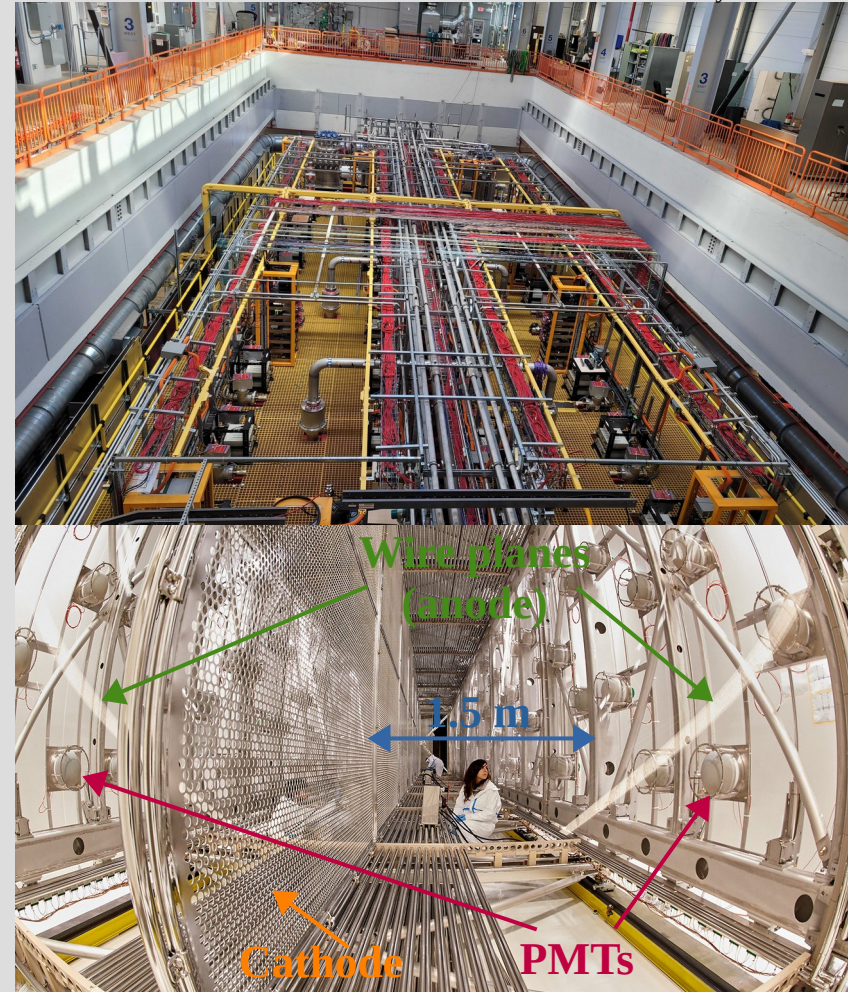
- **Has the capability to distinguish electrons from photons.** This by the gap between vertex and shower start for photons is $x_0 = 14$ cm and the dE/dx at shower start (e^- vs e^+e^-)

ICARUS

Imaging Cosmic And Rare Underground Signals

Credit: Tyler Boone

- **Far detector in the SBN program**
 - It was operational in LNGS from 2010-2013,
 - Then refurbished at CERN.
- **Two identical modules**
 - 19.6 x 3.9 x 3.6 m³ each,
 - **476 tons of LAr** active mass,
 - **at 600 m** from the neutrino source.
- **Two TPCs per module** with central cathode
 - 1.5 m drift lengths.
- **Three readout wire planes** (2 induction + 1 collection) per TPC
 - ~ 54000 wires
 - at 0° and ± 60°
 - with 3 mm pitch and plane spacing.
- **360 PMTs** for trigger and timing.
- **Cosmic Ray Tagging System (CRT)** at the bottom, side, and top.

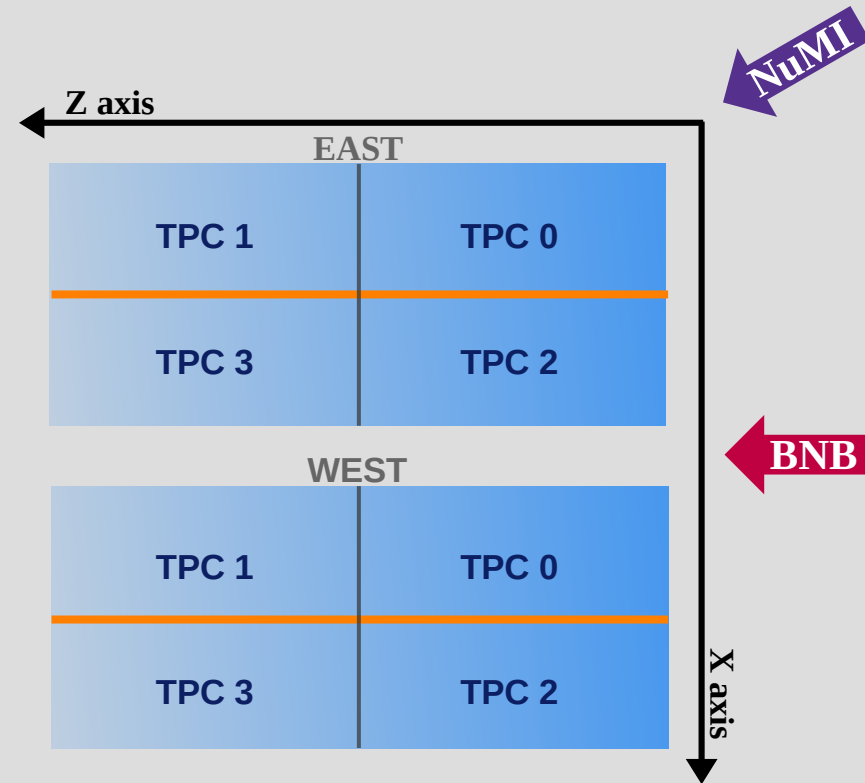
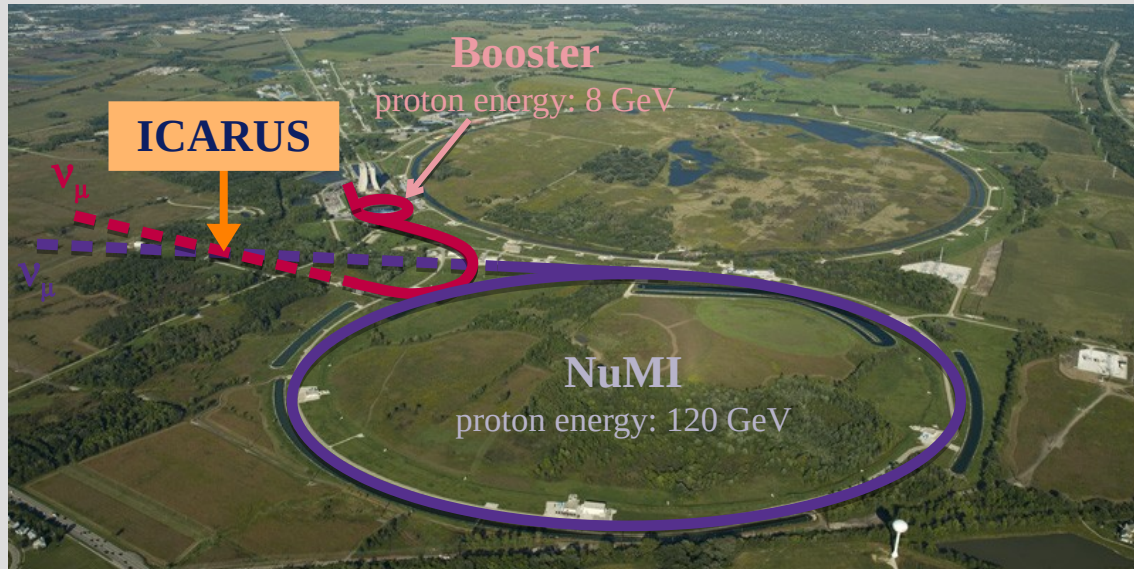


Credit: Symmetry Magazine / Courtesy of CERN

ICARUS

Two Neutrino Beams

ICARUS is located **on-axis with the Booster** beamline and **103 mrad off-axis from the NuMI** beamline, this will allow it to get a lot of data sets of ν -Ar interactions.

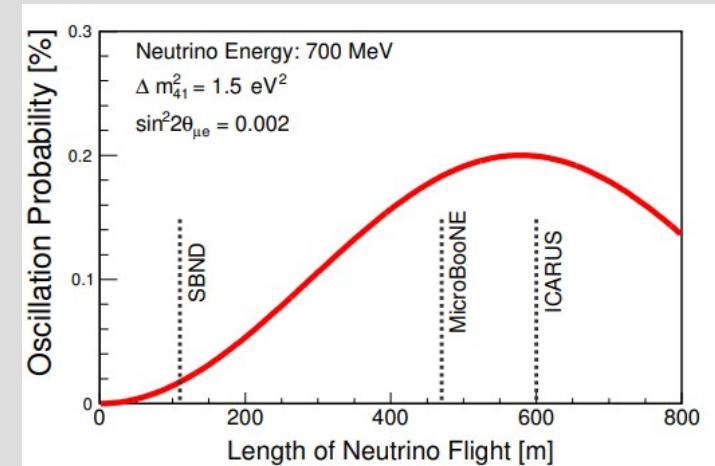
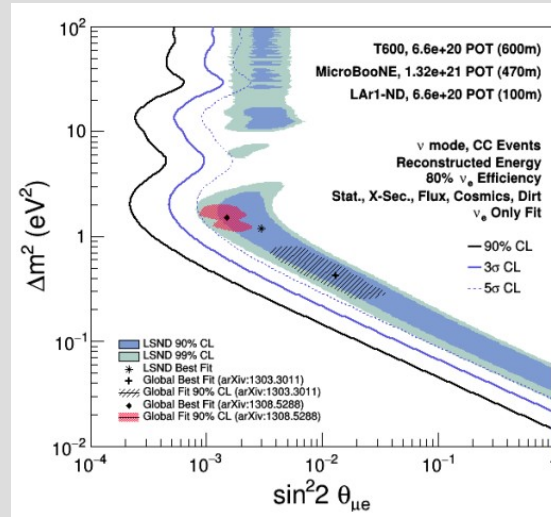


ICARUS Main Motivations

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 ($\sim 7 \text{ eV}^2$) and mixing angle ($\sin^2 2\theta \sim 0.26$).



*Phys. Atom. Nuclei 83, 930–936 (2020)

Cross-Section

Neutrino Interactions

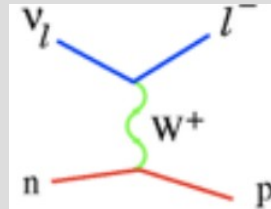
The ν oscillation experiments, require precise understanding of ν -Ar interaction cross section for a correct interpretation of the experimental result.

The ν cross section depends on:

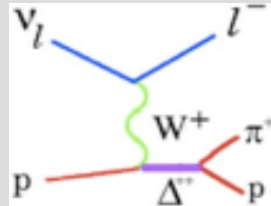
- **ν interaction type** (CC or NC)
For CC
 - **QE:** nucleon changes, but NOT breaks up
 - **RES:** nucleon excites to resonance state
 - **DIS:** nucleon breaks up
- **ν target** (e, nucleus, nucleon, q)
- **ν energy** (MeV, GeV)

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.**

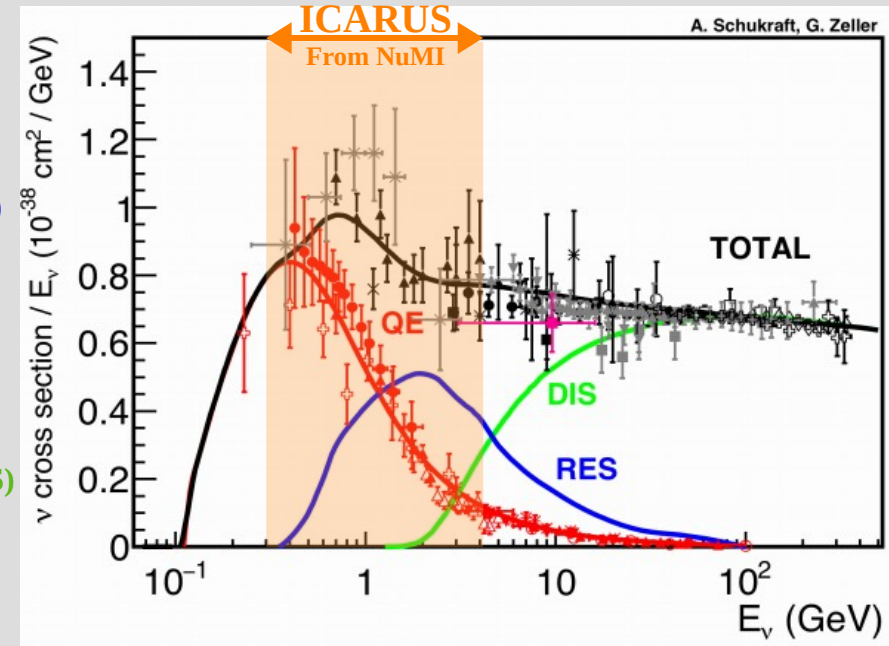
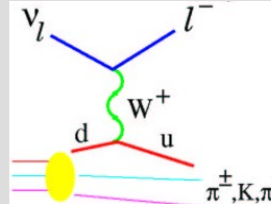
Quasi-elastic scattering (QE)



Resonance production (RES)



Deep Inelastic scattering (DIS)



In few GeV energy range, historically very few data

Cross-Section

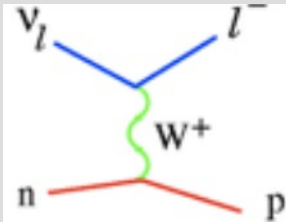
Neutrino Interactions from NuMI Off Axis

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

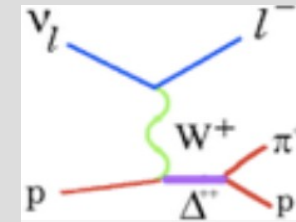
- ν_μ CC = 433056 & ν_μ NC = 191232
- ν_e CC = 20608 & ν_e NC = 7312

Mainly **Q**uasi-**E**lastic and **R**ESonance interactions are expected

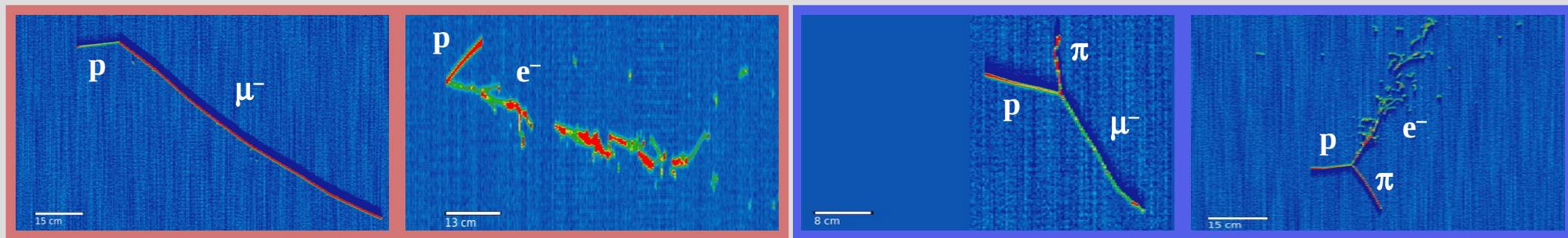
Quasi-elastic scattering (QE)



Resonance production (RES)



MC ν_μ and ν_e NuMI
off axis simulations

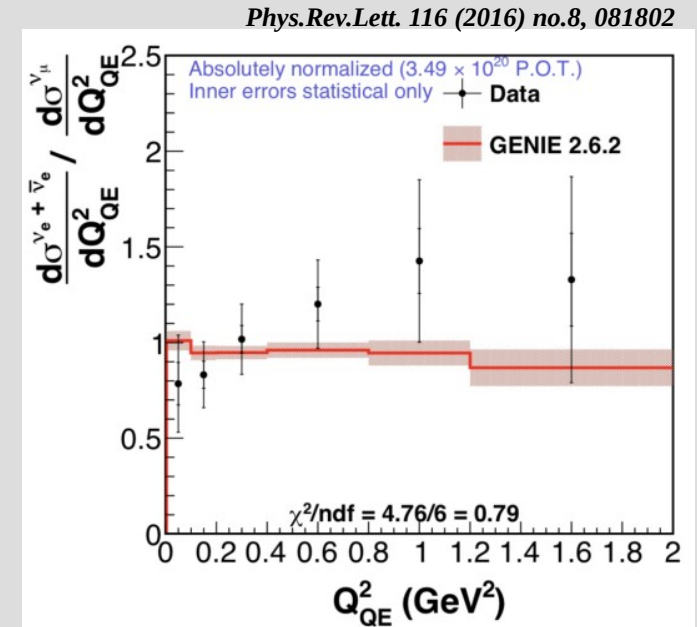


Cross-Section

Neutrino Interactions from NuMI Off Axis

Some examples of measurements that could be performed with the NuMI off axis in ICARUS include:

- to explore measurements of the electron neutrino cross section and muon to electron neutrino ratio cross section on Ar (since the statistic of these measurements is low),
- light dark matter searches
- CC non-standard interactions
- and so on.



Quasi-Elastic measurement from Minerva

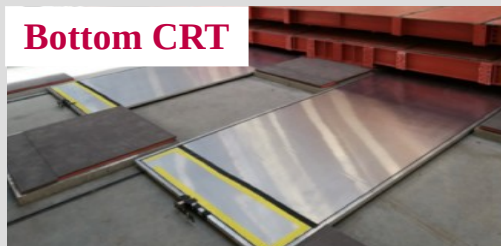
But, before measuring neutrino interactions, one needs to select the neutrinos...

ν_e Selected Events

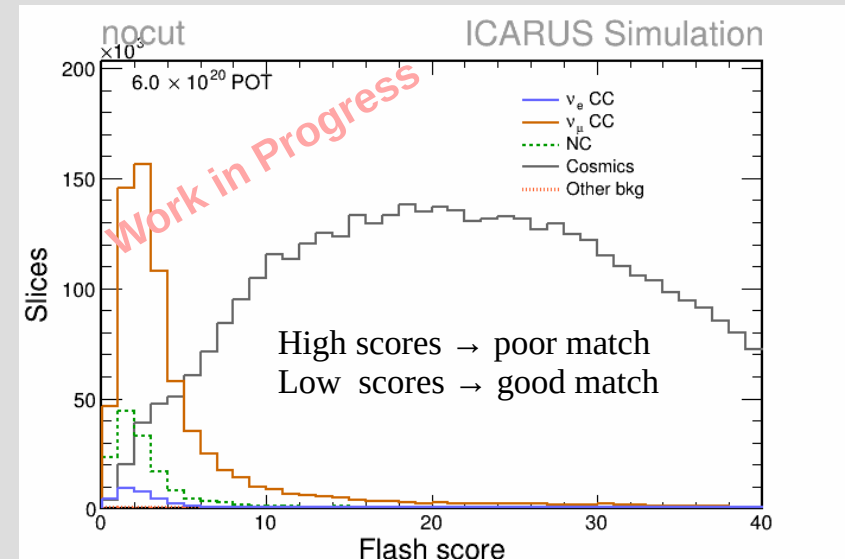
Cosmic Rejection

ICARUS, as a surface detector, faces an additional challenge to be constantly bombarded by cosmics. In order to decrease its incidence in the detector, we use the CRT system and the PMTs :

- **The CRT veto**, surrounds the cryostat with two layers of plastic scintillators, provides spatial and timing coordinates of the track entry point, match reconstructed CRT hits to activity in the TPC



- 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.

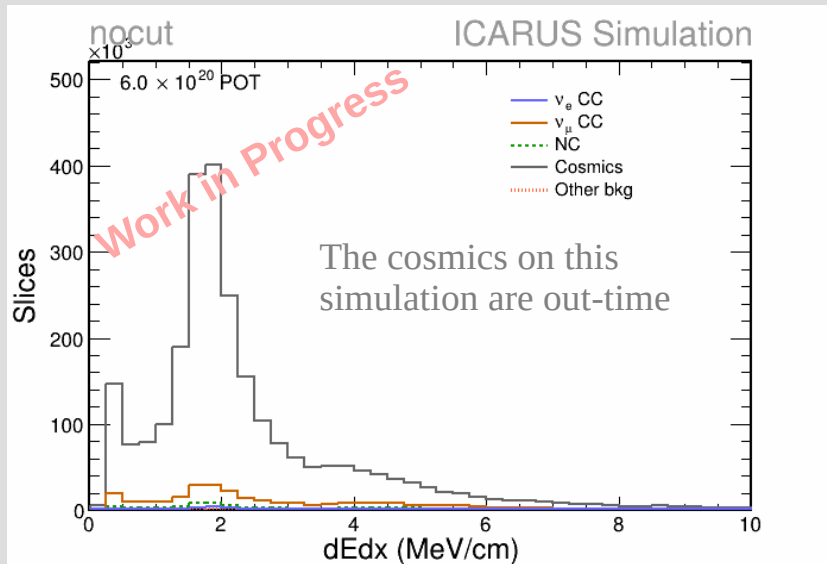


* This simple flash match was developed by I. de Icaza and M. Stancari for SBND

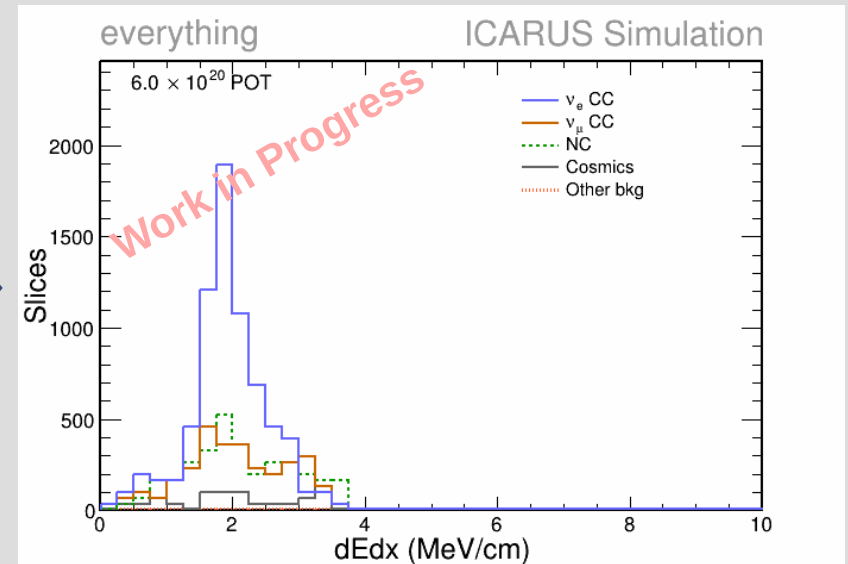
ν_e Selected Events

from NuMI Off Axis

In addition to the CRT veto and the cut on the Flash Score, other cuts are applied in the ν_e event selection, some of them in the Reconstruction, and in the fiducial volume.



After applying
all cuts



- After applying all the selection cuts*, there are **56% of ν_e CC** and **44% of background**** (of which ν_μ contributes with 14.6%, NC 28.1 % and cosmics are only 1.2%) in the sample.
- A similar analysis is ongoing for the BNB.

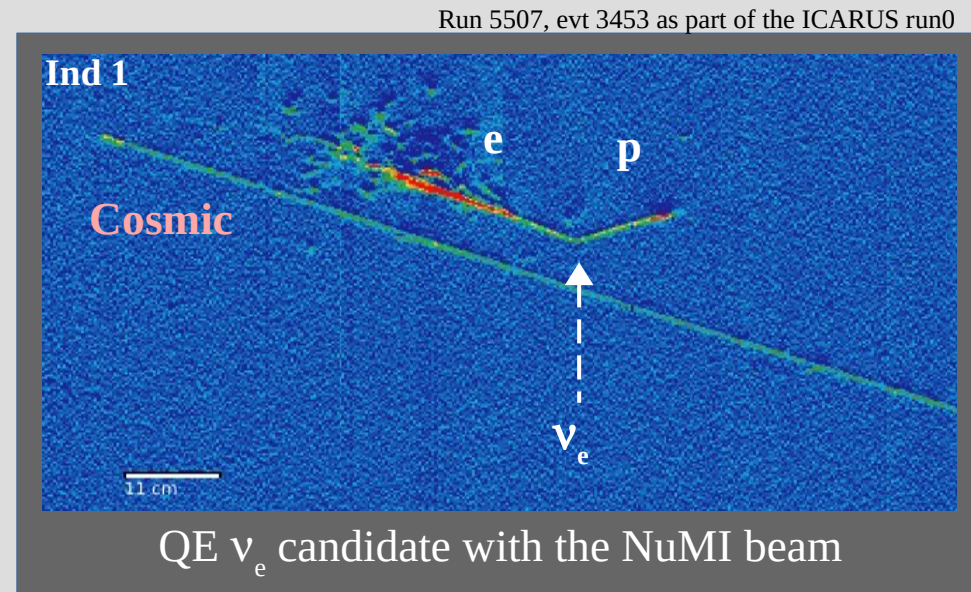
* This is a preliminary event selection, criteria must be improved.

** In this case, Background is all that is NOT ν_e CC (i.e. ν_μ , NC, cosmics).

ν_e Selected Events from NuMI Off Axis

Currently, we are in the process of improving the cuts and testing another cosmic simulations (in-time cosmics)

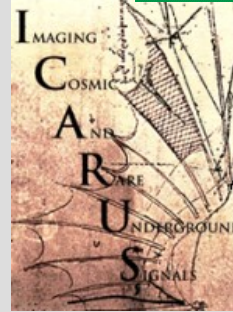
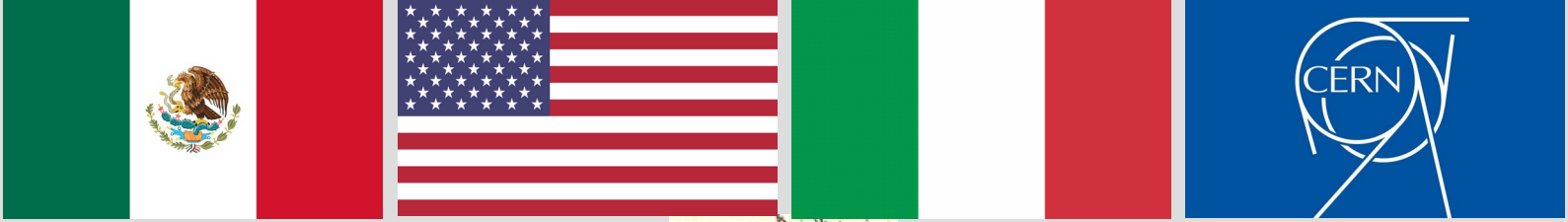
The next step will be to take this ν_e event selection to test in **real data!!**



(this candidate was got by visual scanning)

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.
- The ν_e 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.
- The next round of ICARUS taking neutrino data is expected for this fall 2021, a lot of neutrino data awaits us!!



THANKS

Collaboration meeting, March 2021

