

The Short Baseline Neutrino Far Detector ICARUS: status and first results

12^o Symposium on Large TPCs for
low-energy rare event detection
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on behalf of the
ICARUS collaboration

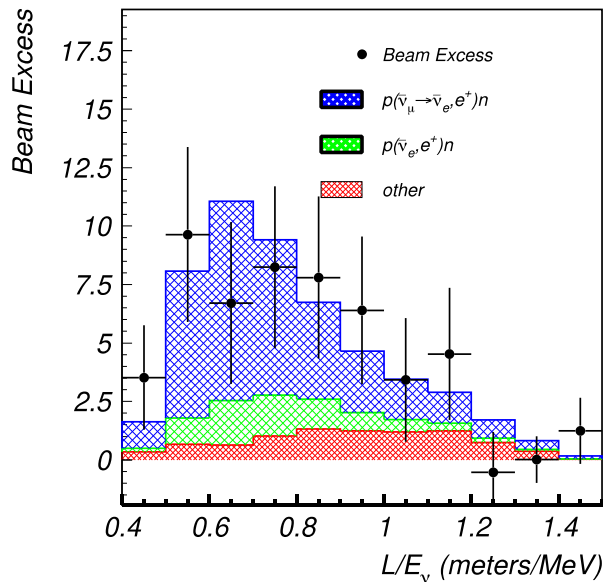


Short Baseline Neutrino (SBN) Program

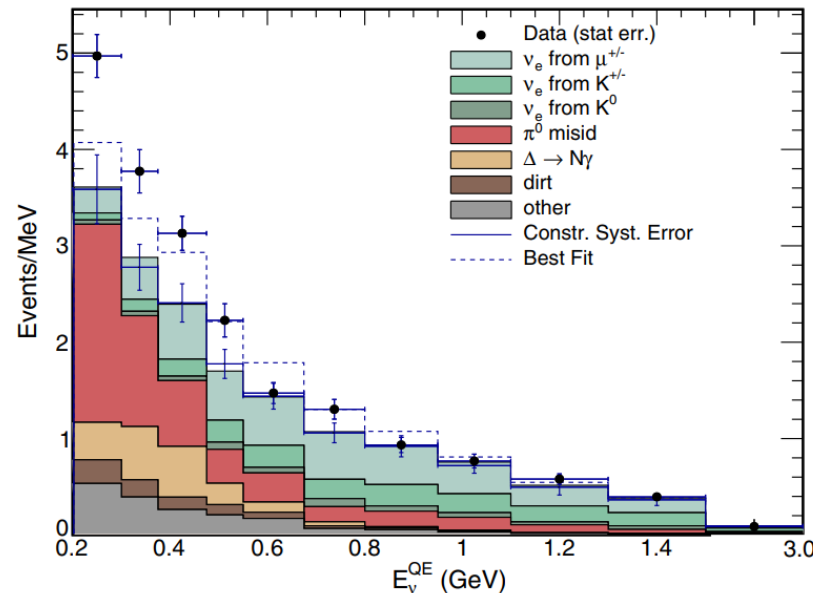
[arXiv/SBNProposal](#)

Several persisting anomalies are hinting to oscillations at low distances due to additional neutrino states with $\Delta m^2 \sim O(eV^2)$

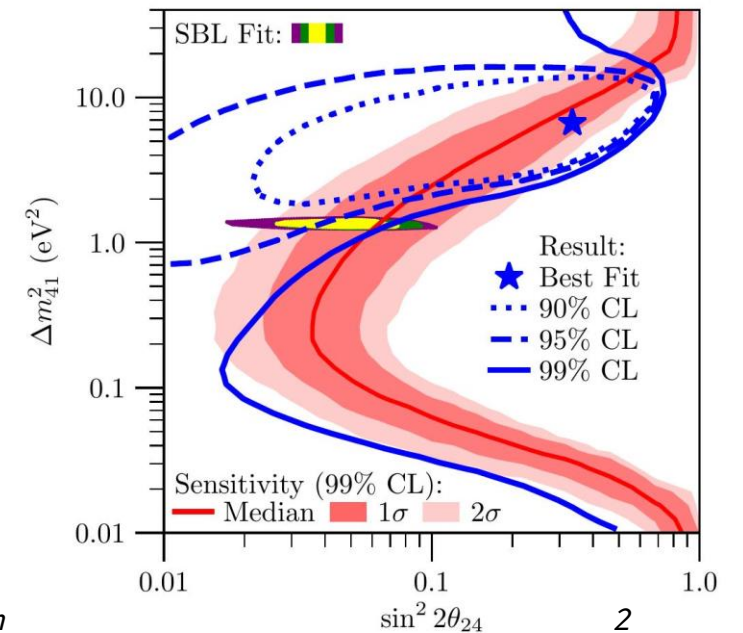
LSND anomaly:
 $\bar{\nu}_e$ appearance in $\bar{\nu}_\mu$ beam



MiniBooNE Low Energy Excess:

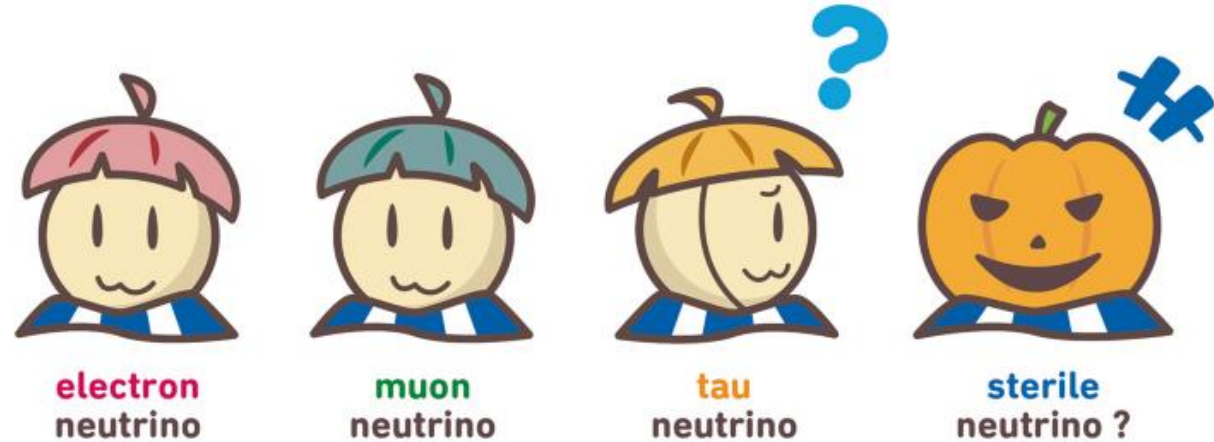


IceCube:
 ν_μ disappearance signal

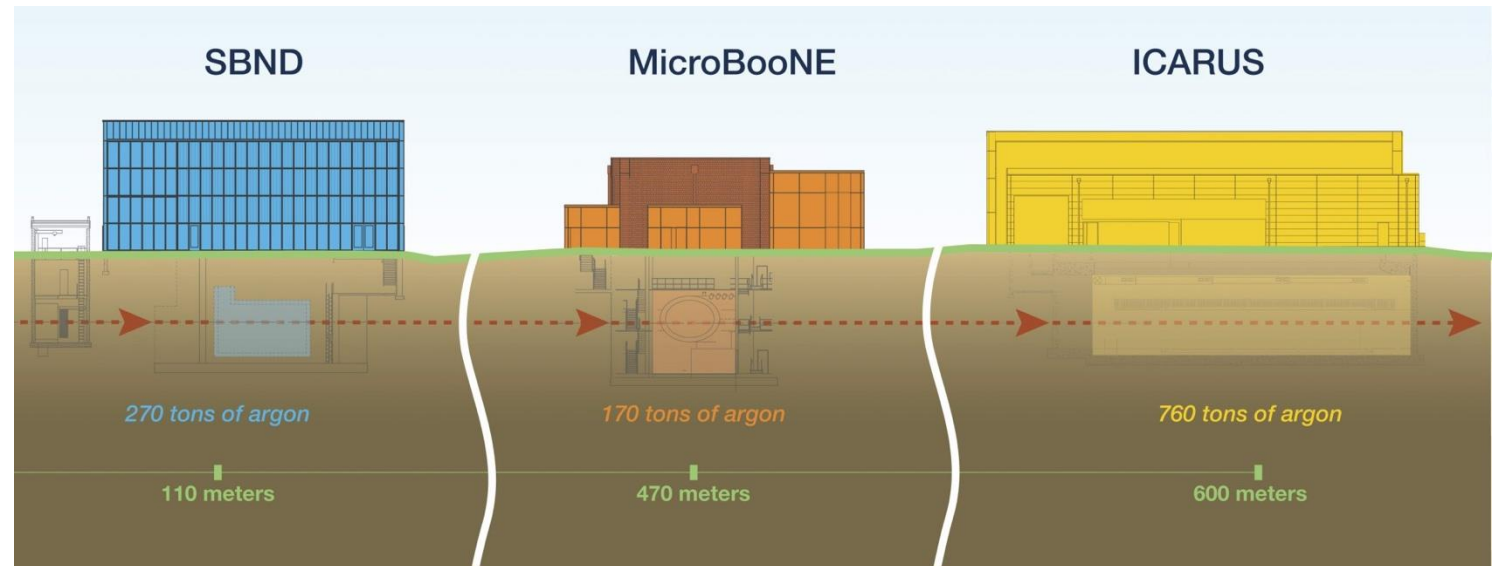


Short Baseline Neutrino (SBN) Program

Are there additional sterile neutrino states?



SBN is going to try to provide an answer by means of several LAr TPC detectors along the Booster Neutrino Beam (BNB).

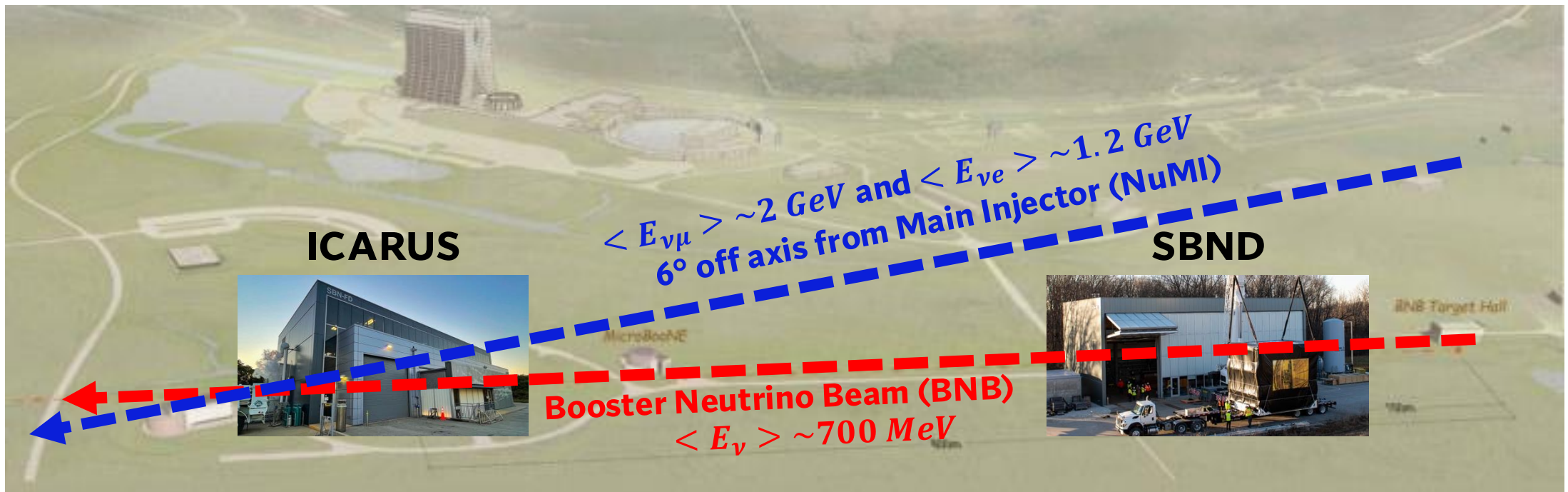


ICARUS Research Program

The SBN program is online and the first combined SBND + ICARUS results are expected for 2026, addressing the sterile neutrino puzzle.

In preparation for the SBN analyses, ICARUS is able to:

- Investigate the muon neutrino disappearance along BNB, complemented with electron neutrino disappearance study with the off-axis NuMI beam;
- Study ν_e and ν_μ interactions on argon and measure cross sections in the energy range of DUNE;
- Exploit the off-axis NuMI beam to investigate sub-GeV BSM signals.



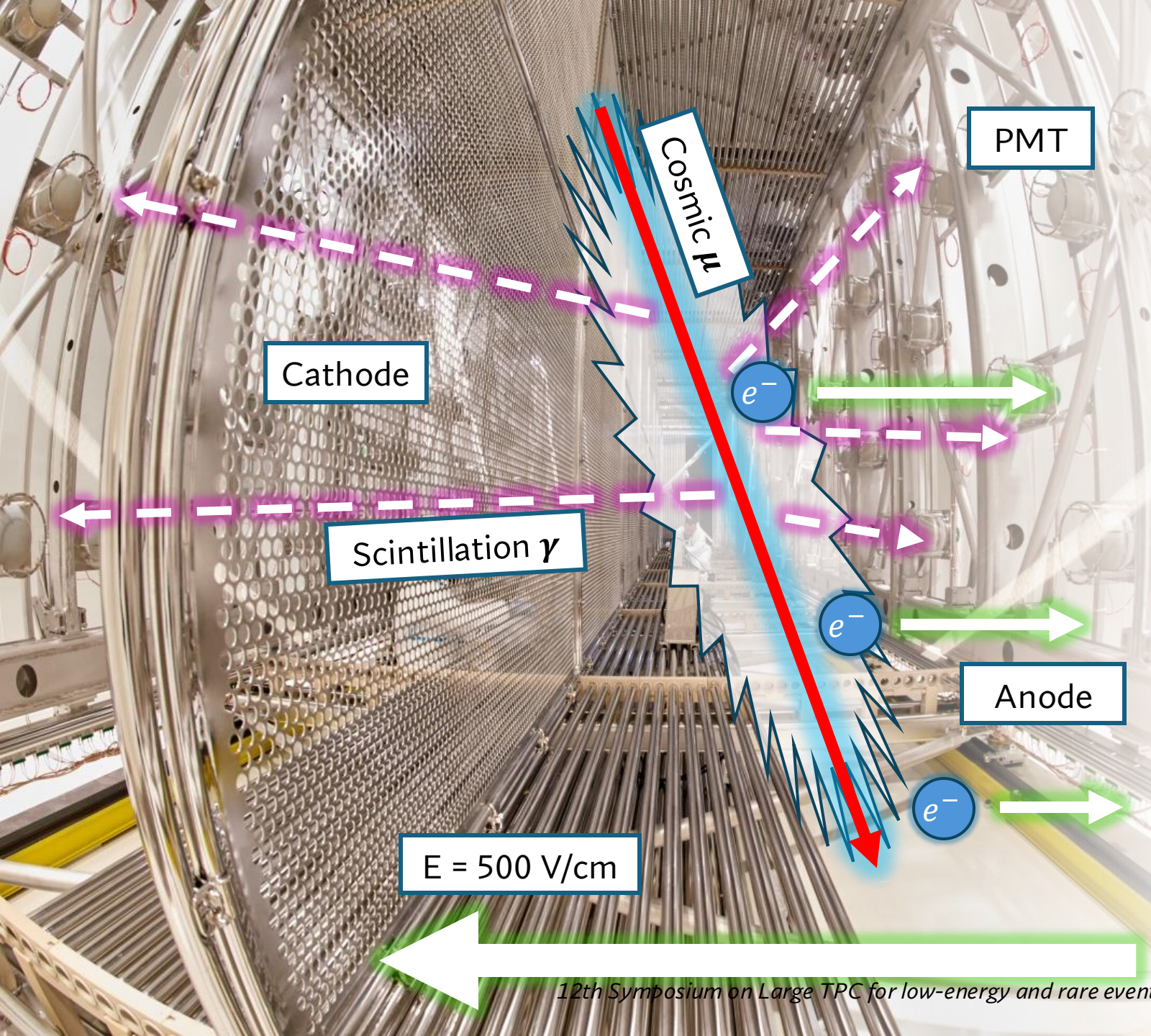
The SBN Far Detector: ICARUS-T600

ICARUS pioneered the LAr-TPC detectors, proposed by C. Rubbia in 1977

- Total (active) mass of 760 (476) LAr tons.
- Two modules:
3.6 m X 3.9 m X 19.9 m, total of 53248 wires.
- Drift time of 0.96 ms (500 V/cm).
- Photon Detection System (PDS) composed of 360 PMTs.

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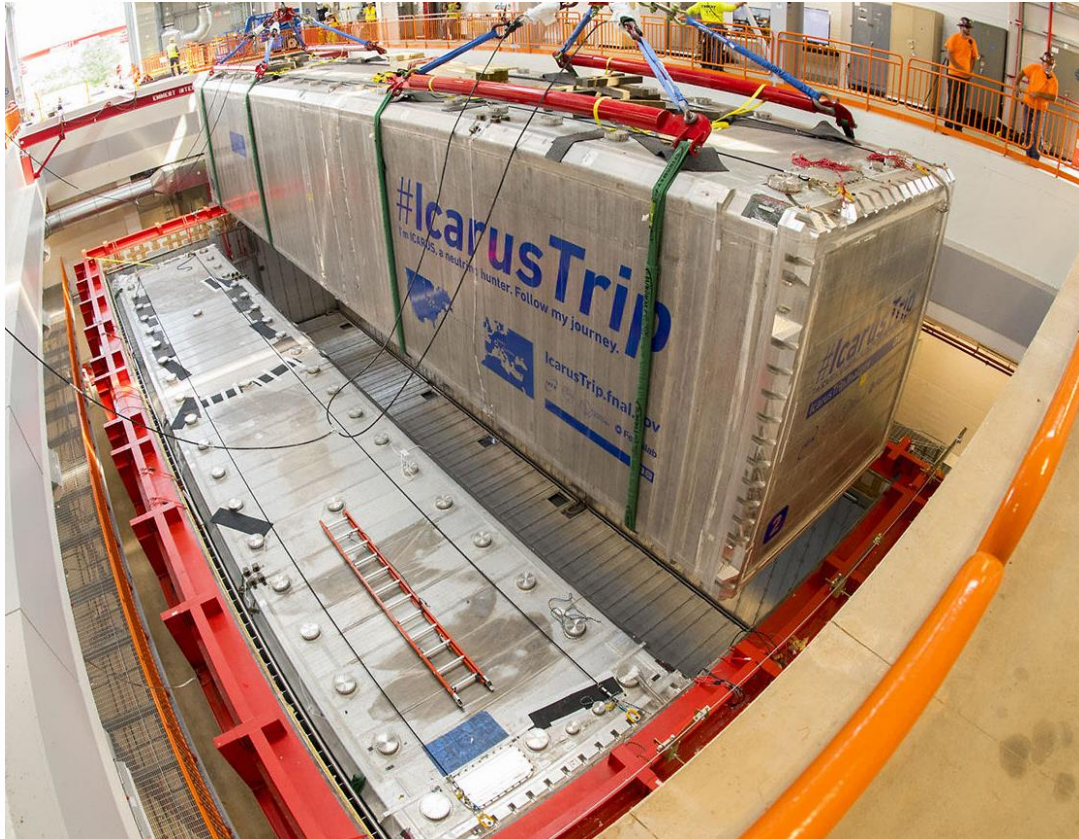
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ICARUS T600: Cosmic Rejection

* *BNB spill* = $1.6 \mu s$
NuMI spill = $9.6 \mu s$



ICARUS is installed at shallow depth and exposed to a large cosmic activity:

- 1 ν every 180 (53) spills* for BNB (NuMI)
- 1 cosmic μ every 55 (6) spills* for BNB (NuMI)

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A Cosmic Ray Tagger System (CRT) encloses the detector, providing good spatial ($\sim\text{cm}$) and timing ($\sim\text{ns}$) information of the entering cosmic.



Before and after the Top CRT installation

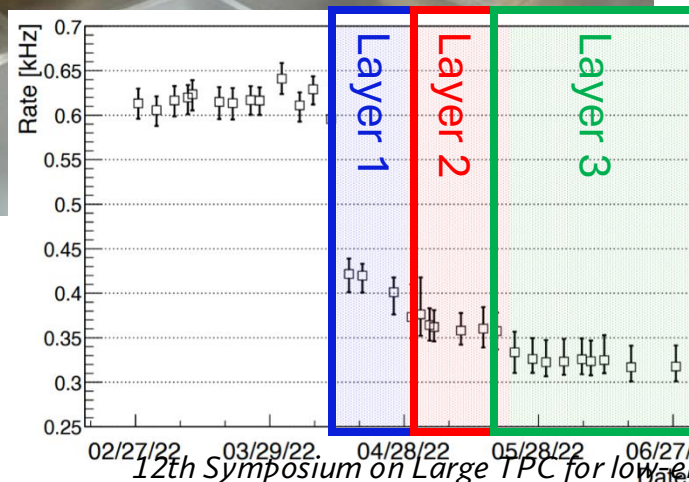
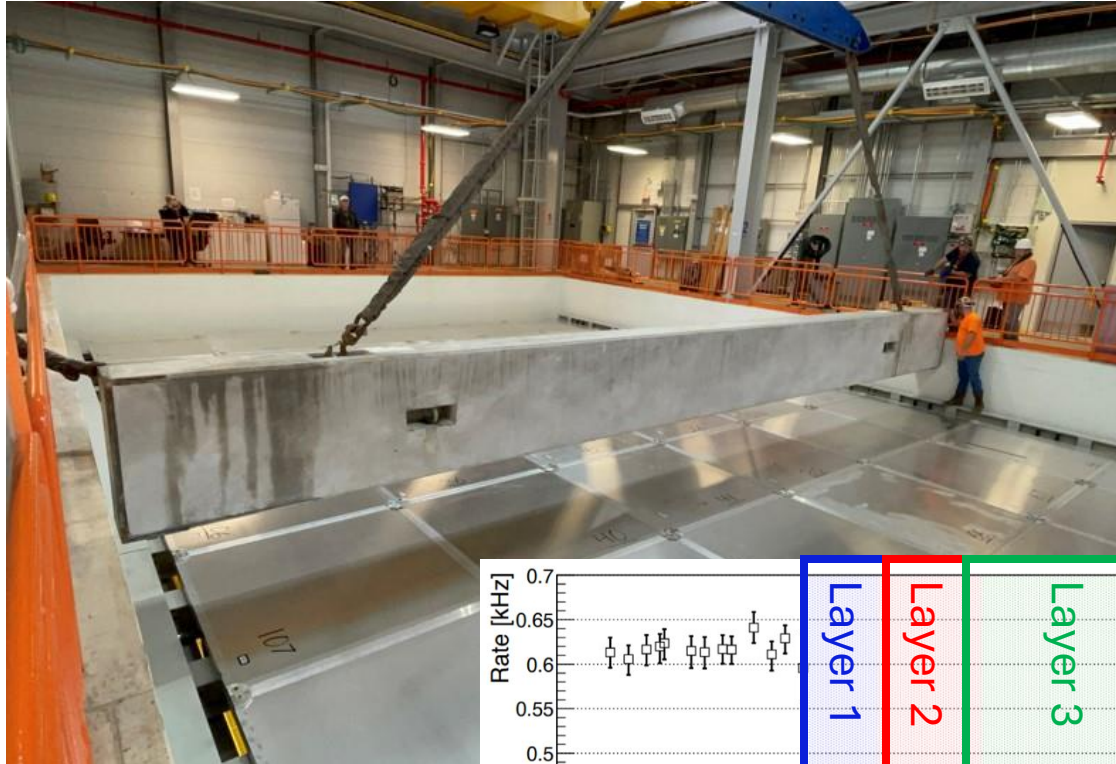


Side CRT

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First layer of concrete overburden



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Cosmic γ 's and neutrons are suppressed by a 3m (6 m water equivalent) thick concrete overburden on top of the CRT.

The cosmic ray rate per Top CRT module decreased from 600 Hz to 330 Hz along with the concrete deployment.

[A. Aduszkiewicz et al 2025 JINST 20 T04002](#)

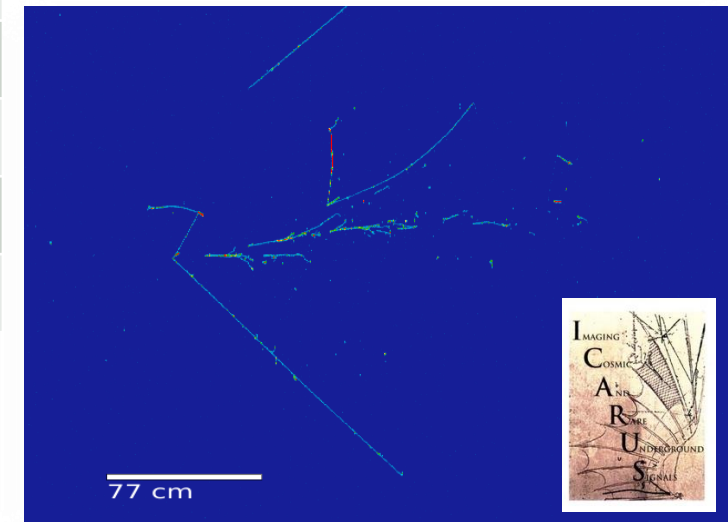
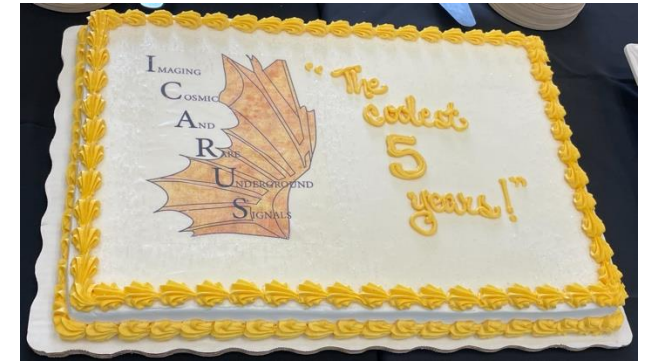
ICARUS Operations: neutrino collection

[Eur. Phys. J. C 83, 467 \(2023\)](#)

ICARUS has been in continuous operations since 2020 with remarkable stability!

Collected Protons on target (PoTs)	BNB (FHC)	NuMI (FHC)	NuMI (RHC)
Run-1 (June - July '22)	$0.42 \cdot 10^{20}$	$0.69 \cdot 10^{20}$	-
Run-2 (December '22 – July '23)	$2.13 \cdot 10^{20}$	$2.84 \cdot 10^{20}$	-
Run-3 (March – July '24)	$1.36 \cdot 10^{20}$	-	$2.82 \cdot 10^{20}$
Run-4 (December '24 – July '25)	$3.63 \cdot 10^{20}$	-	-
Run-5 (October '25 - ongoing)	$0.80 \cdot 10^{20}$	-	-
Total	$8.34 \cdot 10^{20}$	$3.53 \cdot 10^{20}$	$2.82 \cdot 10^{20}$

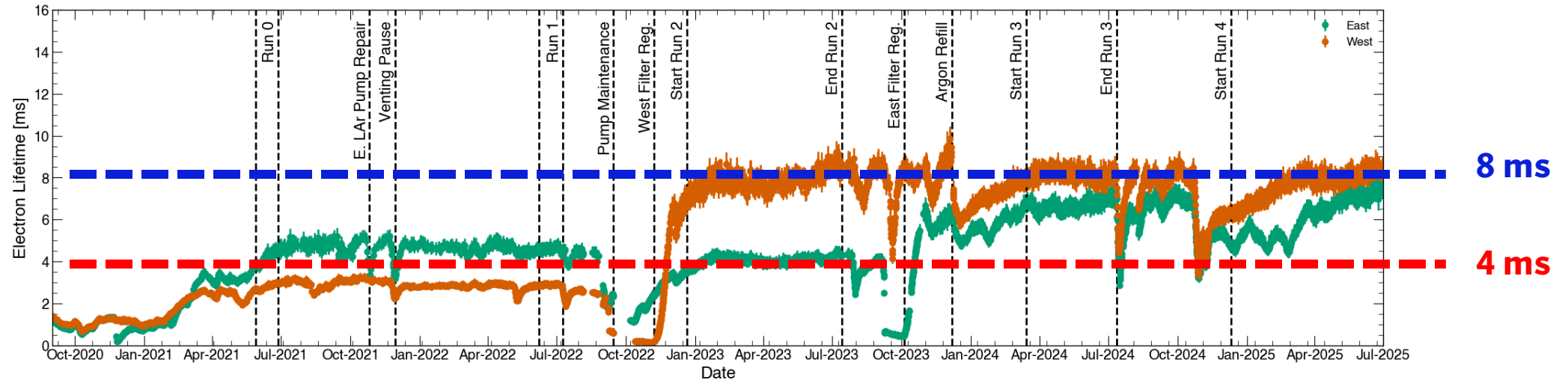
Data taking has been on-going smoothly with beam efficiency > 98%, with an overall dataset of ~ 1 milion of neutrino CC interactions.



ν_{μ} CC candidate with shower activity from BNB

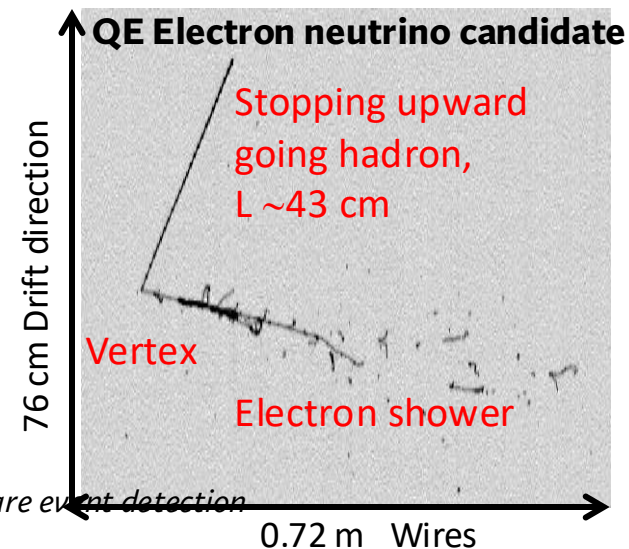
Detector performance: cryogenics

Measured electron lifetime since beginning of operations



The cryogenic/purification system performed smoothly with good electron lifetime during physics runs.

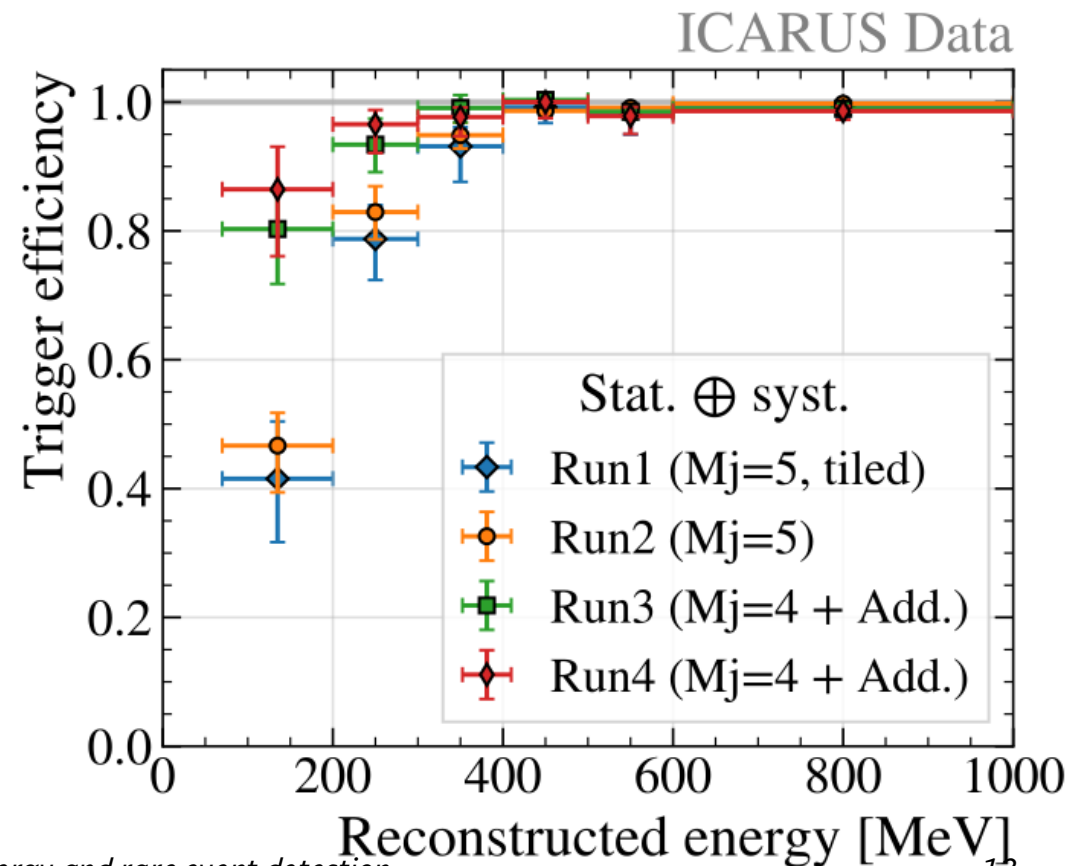
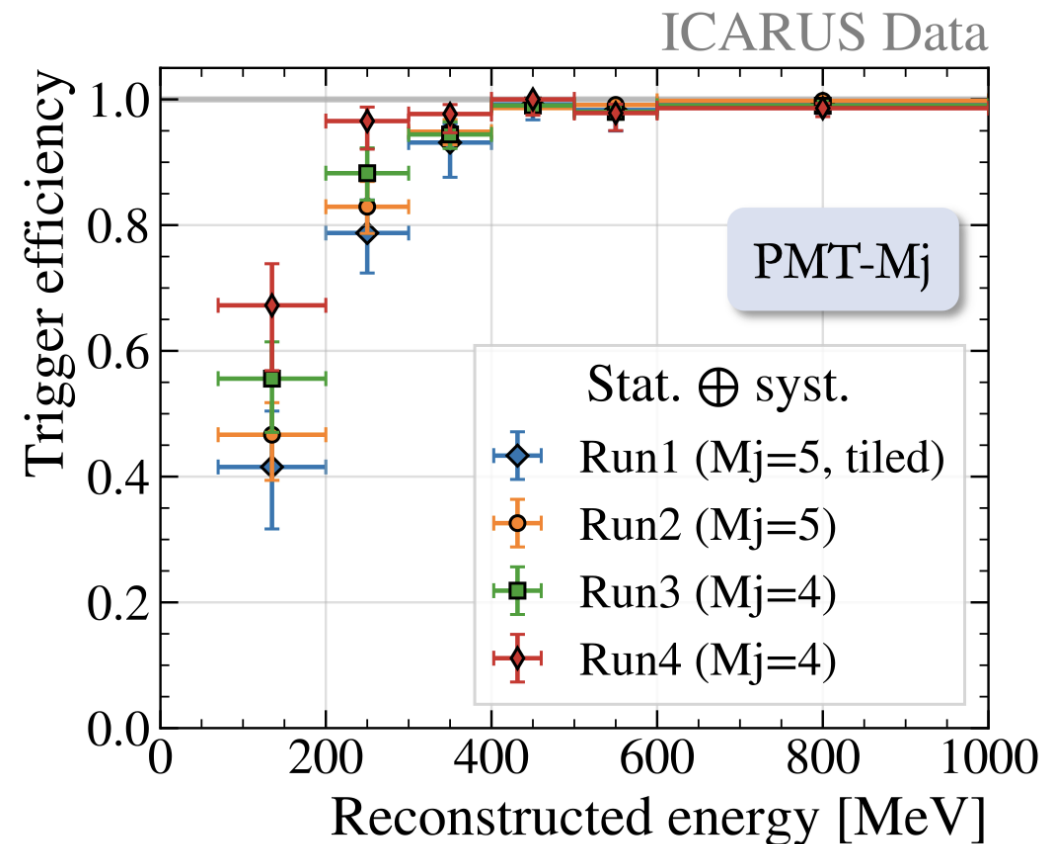
This allows excellent track detection and good calorimetry in the whole drift volume.



Detector performance: trigger

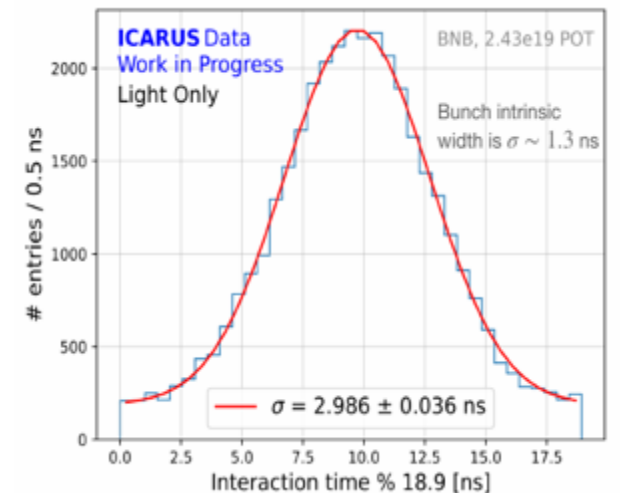
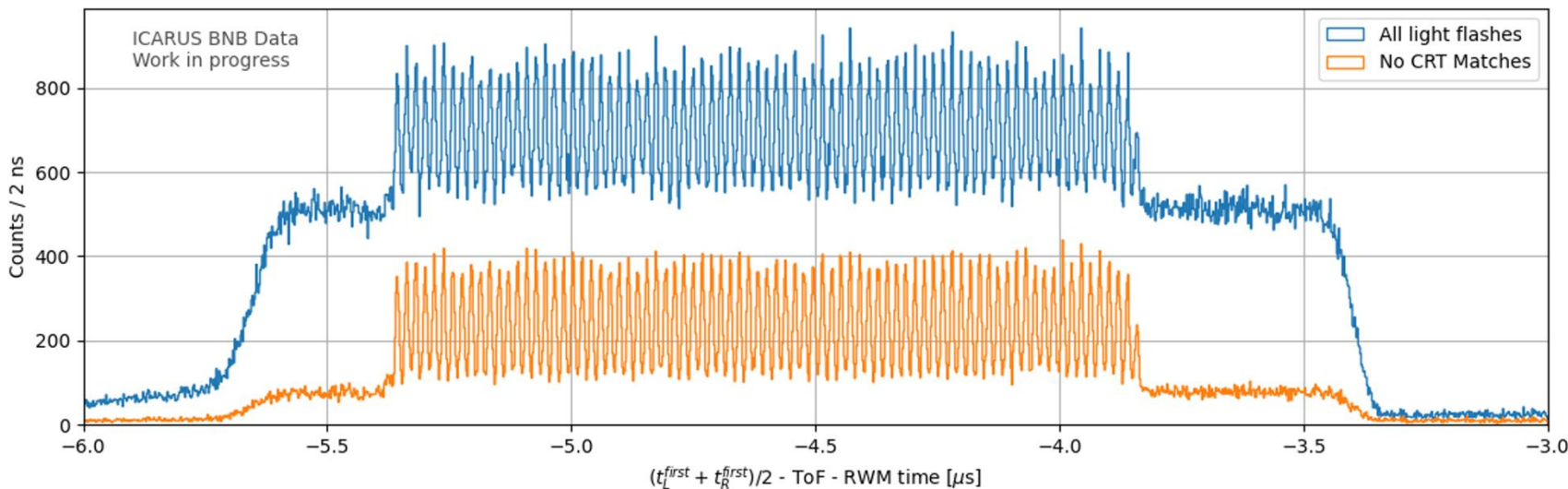
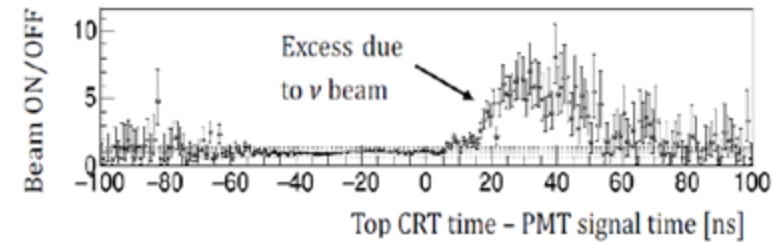
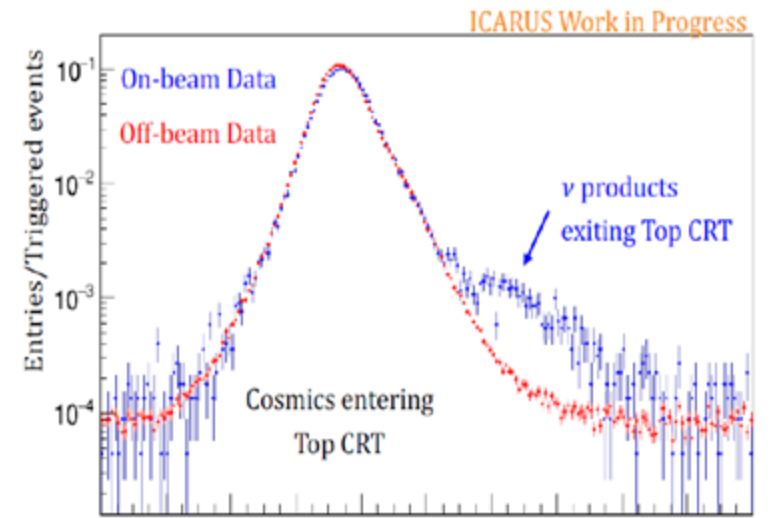
The event trigger system is based on a majority requirements of 5 fired PMT pairs in coincidence with the beam spills. The trigger efficiency saturates at 100% above 400 MeV.

A complementary trigger (based on the total light signal) was included from Run3 to increase efficiency at low energy.

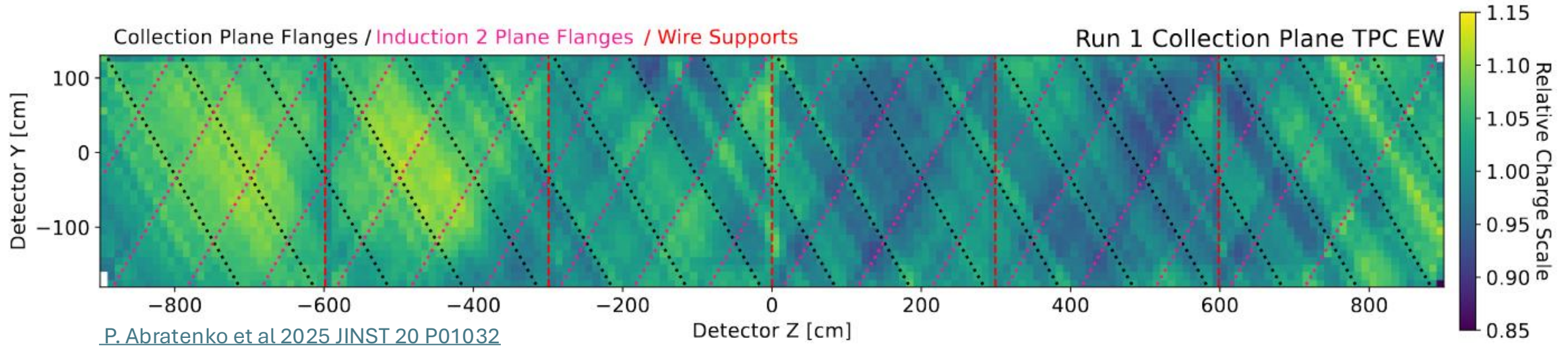


Detector performance: timing

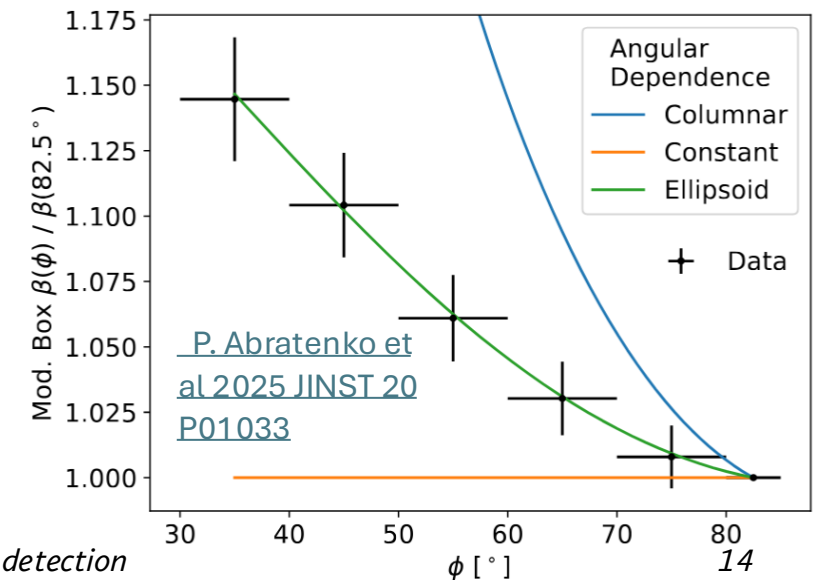
- The good resolution of the light (inner PMTs) and CRT system and their relative synchronization allows to distinguish entering and exiting particles by means of the time of flight.
- The recording of the RWM signals from the beam in combination with the light allows to fully reconstruct the bunched beam structure.



Detector performance: TPC



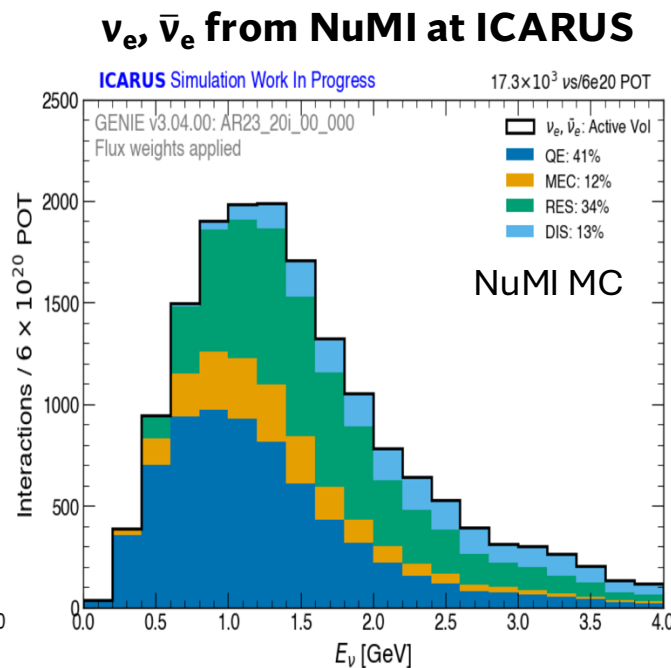
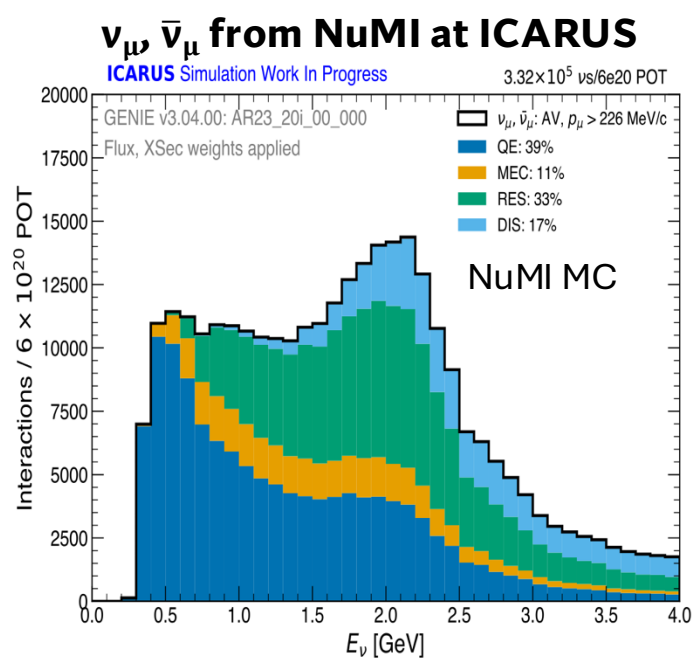
- A run-dependent calibration is performed to determine noise levels and equalize TPC gains. Non-uniformities along the wire plane (intransparency) have been characterized and equalized. A data driven noise and intransparency maps have been included in the simulation.
- Signal shape has been studied and a data driven model shape has been included in the simulation.
- An new angular dependent measurement of electron-ion recombination was performed, improving calorimetric reconstruction for protons and muons.



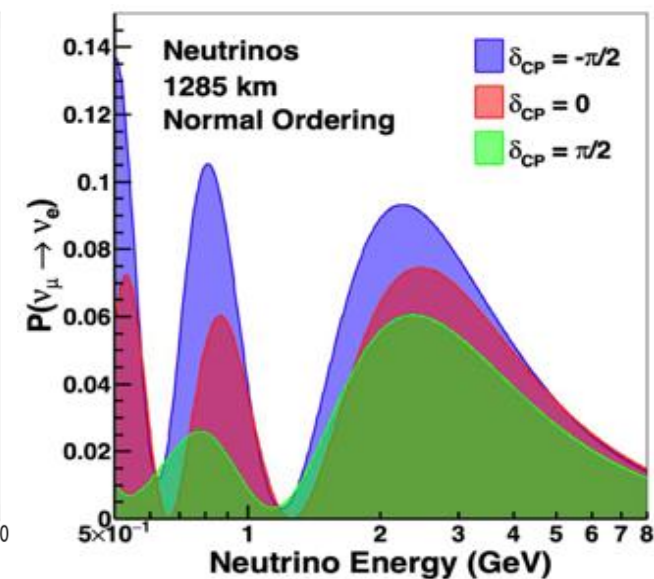
ICARUS First results: Cross Section

The NuMI off axis flux at ICARUS allows to record high statistic of quasi-elastic, resonance and deep inelastic scattering for both ν_e and $\bar{\nu}_\mu$. With the available statistics ($3.53 \cdot 10^{20}$ pots in FHC) we expect $\sim 200k$ ν_μ and $\sim 10k$ ν_e . At ICARUS we are able to cover the first oscillation peak expected at the DUNE far detector.

In our first analysis we targeted ν_μ CC candidates with $1\mu Np0\pi$ in the final state.



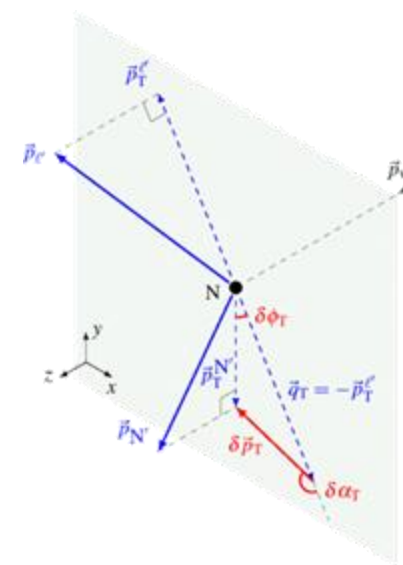
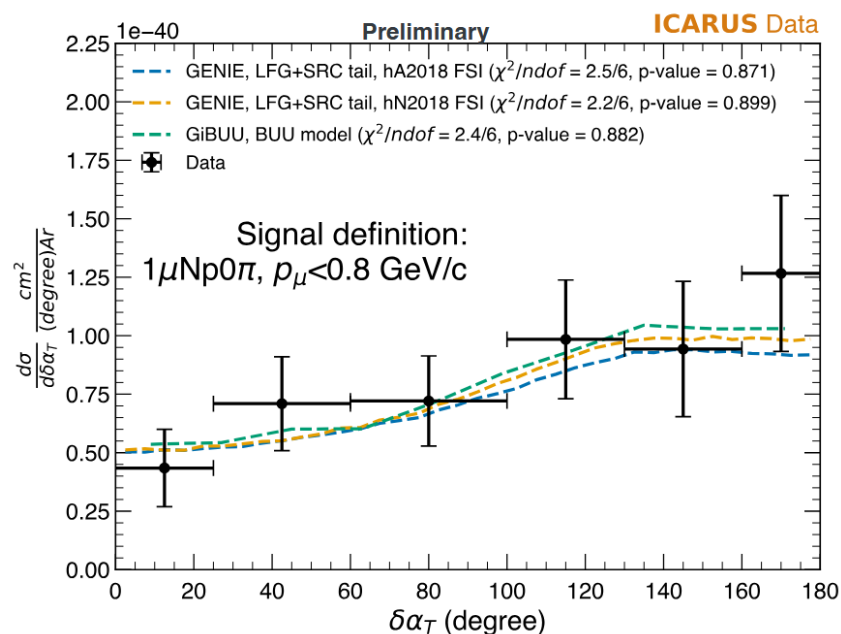
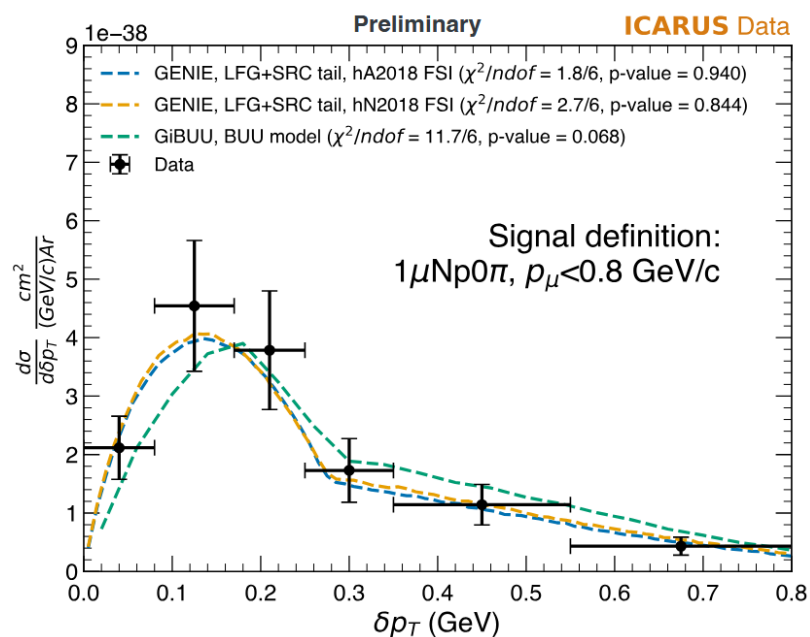
Oscillation probability at DUNE



ICARUS First results: Cross Section

The signal box was opened, with an overall exposure of $2.5 \cdot 10^{20}$ pots in FHC.

The cross section was measured as a function of the transverse kinematic imbalance variables ($\delta\vec{p}_T$ and $\delta\alpha_T$). This measurement at higher energy on argon fills a still missing gap.



$$\delta\vec{p}_T \equiv \vec{p}_T^{\ell'} + \vec{p}_T^{N'}$$

$$\delta\alpha_T \equiv \cos^{-1} \frac{-\vec{p}_T^{\ell'} \cdot \delta\vec{p}_T}{p_T^{\ell'} \delta p_T}$$

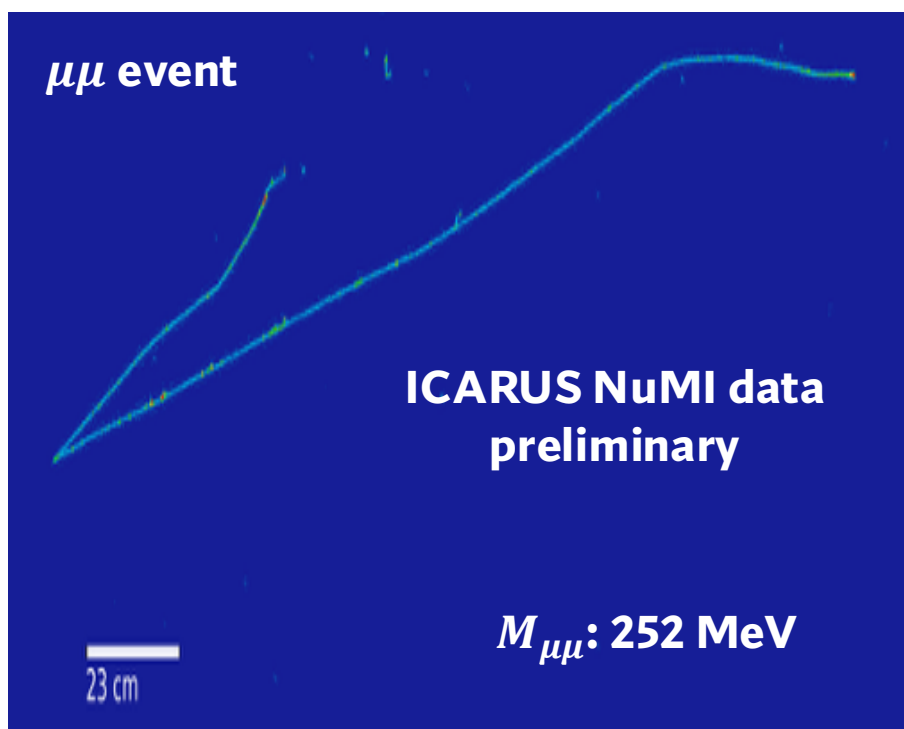
Note: more models and variables have been tested, the final paper is under submission.

For those who have access to FNAL database: [docid=43825](#) (colloquium from J. Kim and B. Howard)

ICARUS First results: Dark Sector

The NuMI off-axis beam allows to pursue searches in many BSM models.

The first focus has been dark particles coupling to SM through Scalar portals (Higgs portal and Heavy QCD axions). A first set of searches have been performed targeting BSM particles decaying into di-muon channels.

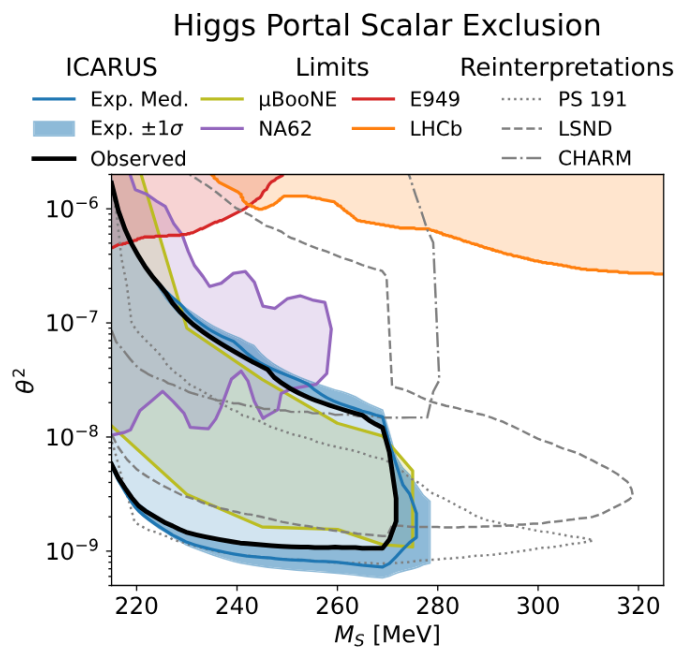
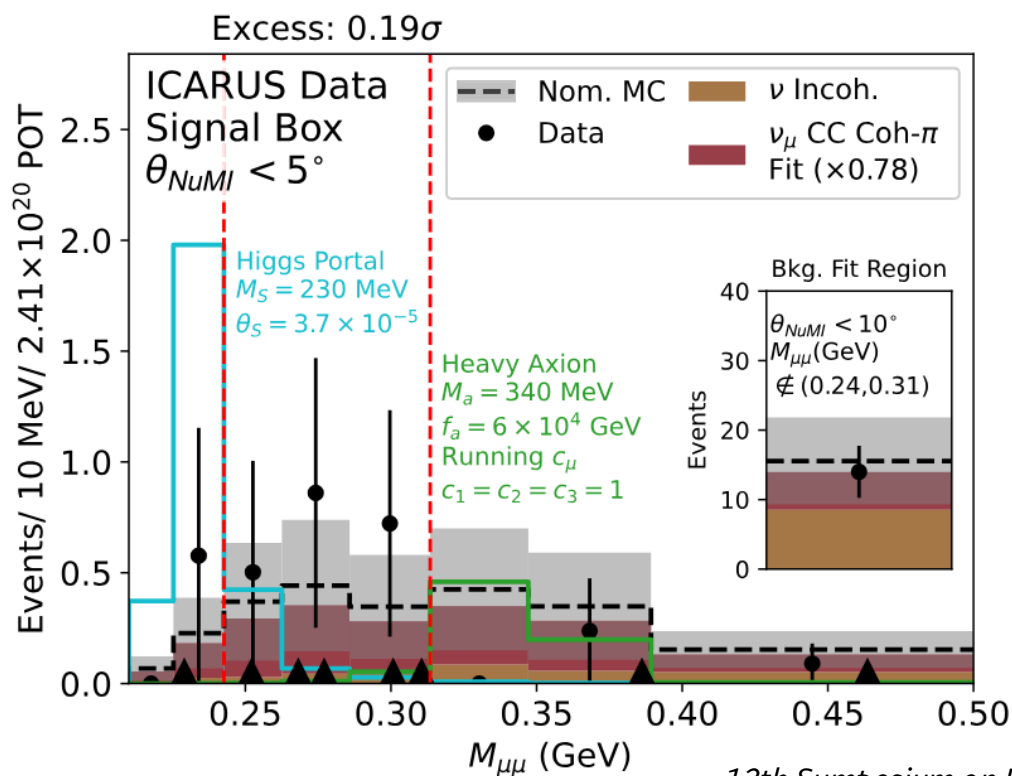


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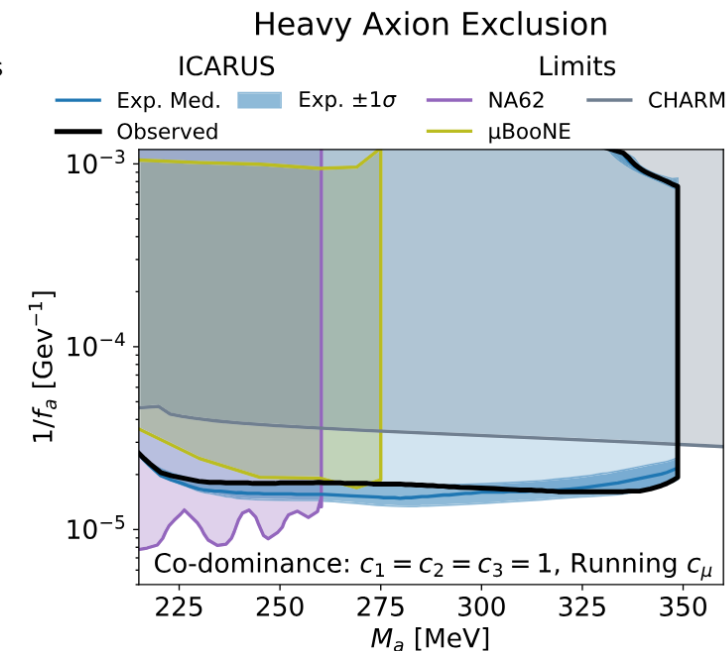
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Signal box opening



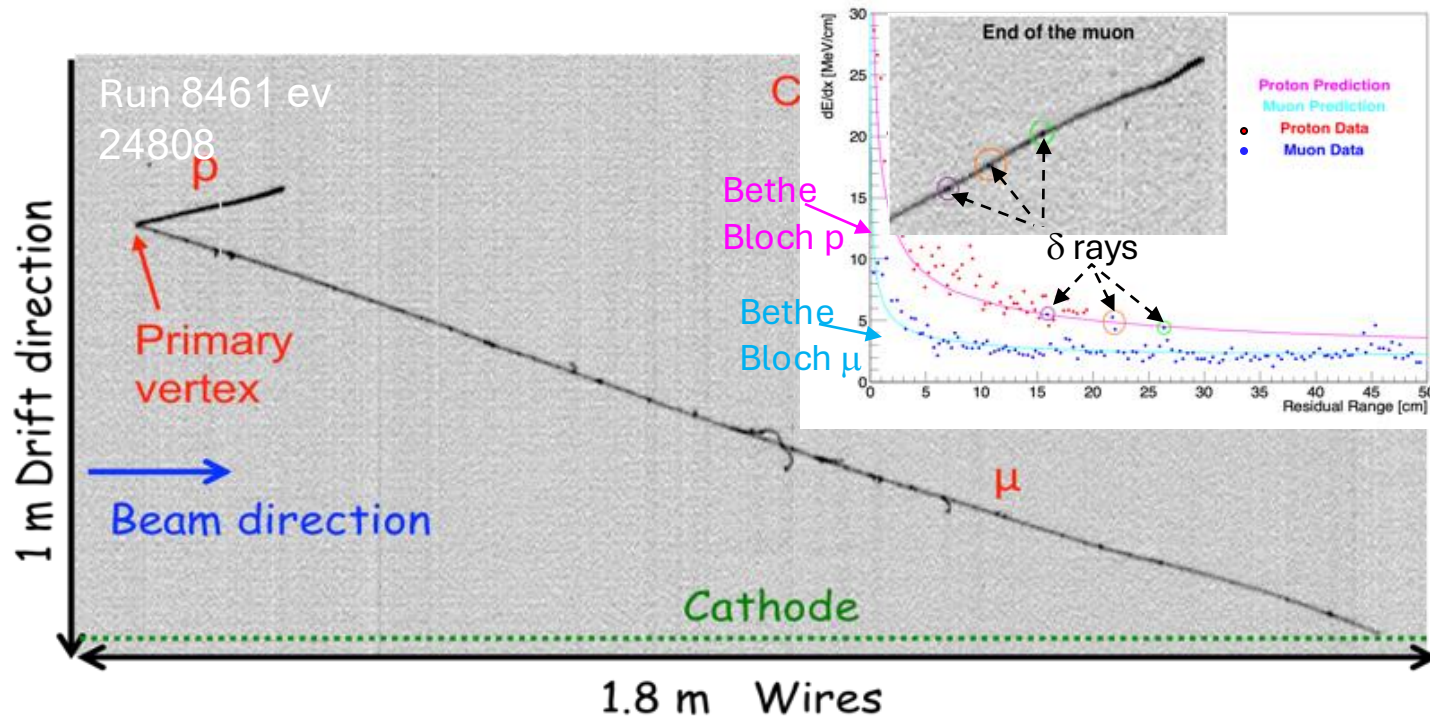
[PhysRevLett.134.151801](https://arxiv.org/abs/1304.1518)



ICARUS First results: ν_μ disappearance

ICARUS standalone data taking on BNB can be used to perform a ν_μ disappearance analysis, this was done with Run2 Data.

The selection targeted QE-like ν_μ interactions with $1\mu Np$ in the final state topologies and fully contained particles.



We performed two almost independent selections: Pandora (semi-analytical reconstruction) and SPINE (Machine Learning based). Both selections achieved good level of purity, with SPINE being the most efficient.

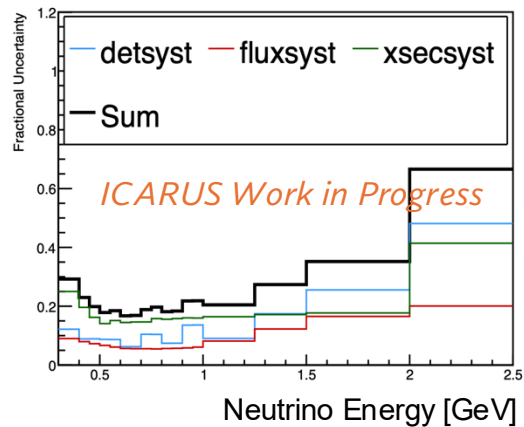
Pandora: efficiency 48.5%, purity 82%.

SPINE: efficiency 82%, purity 91.5%.

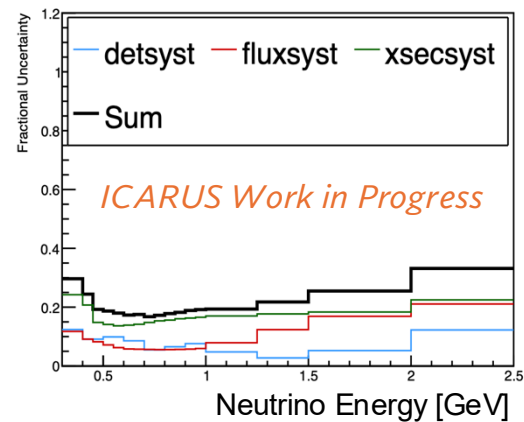
ICARUS First results: ν_μ disappearance

With a single detector analysis, the resulting systematics are dominated by cross section and flux.

Pandora

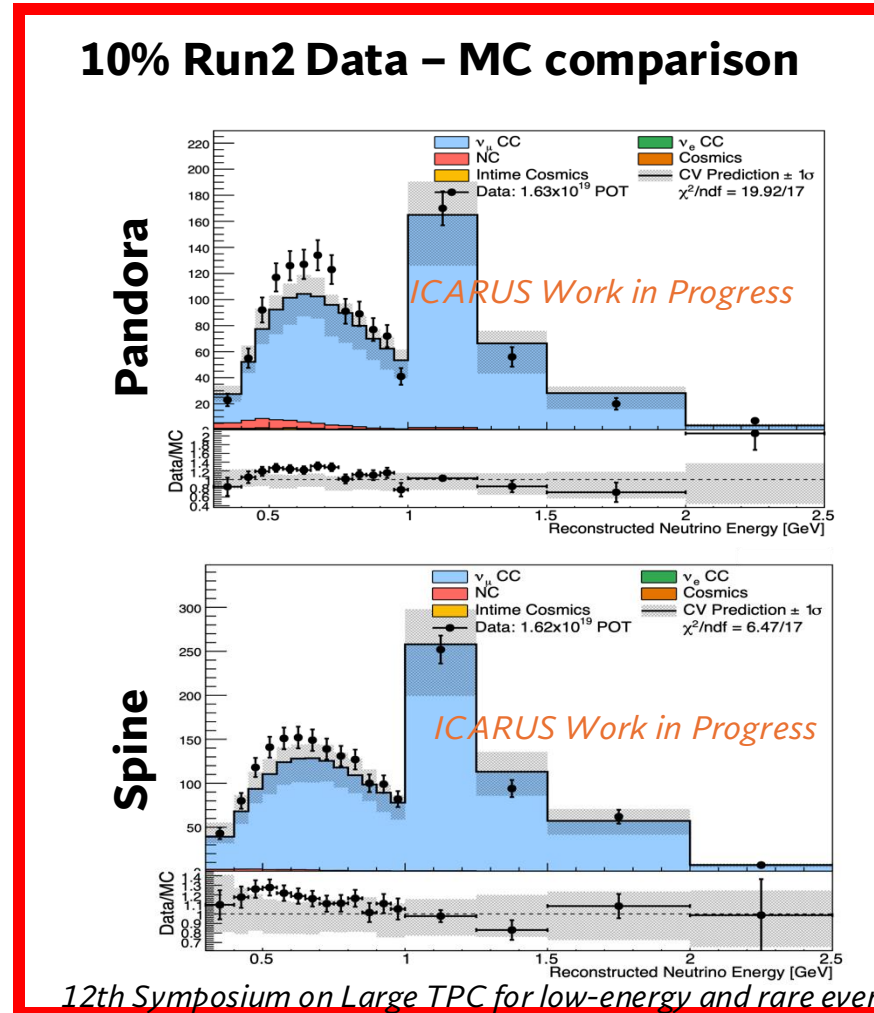
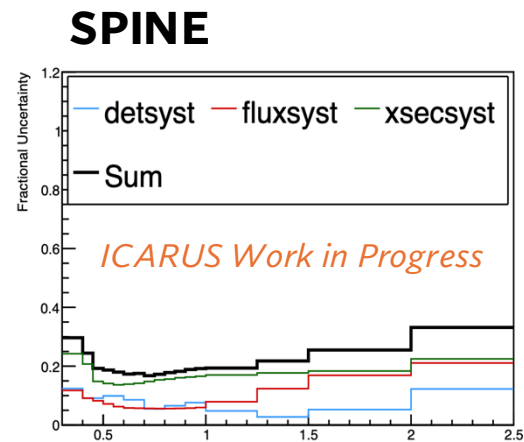
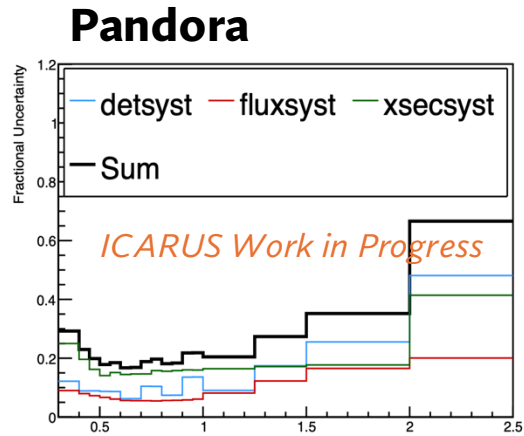


SPINE



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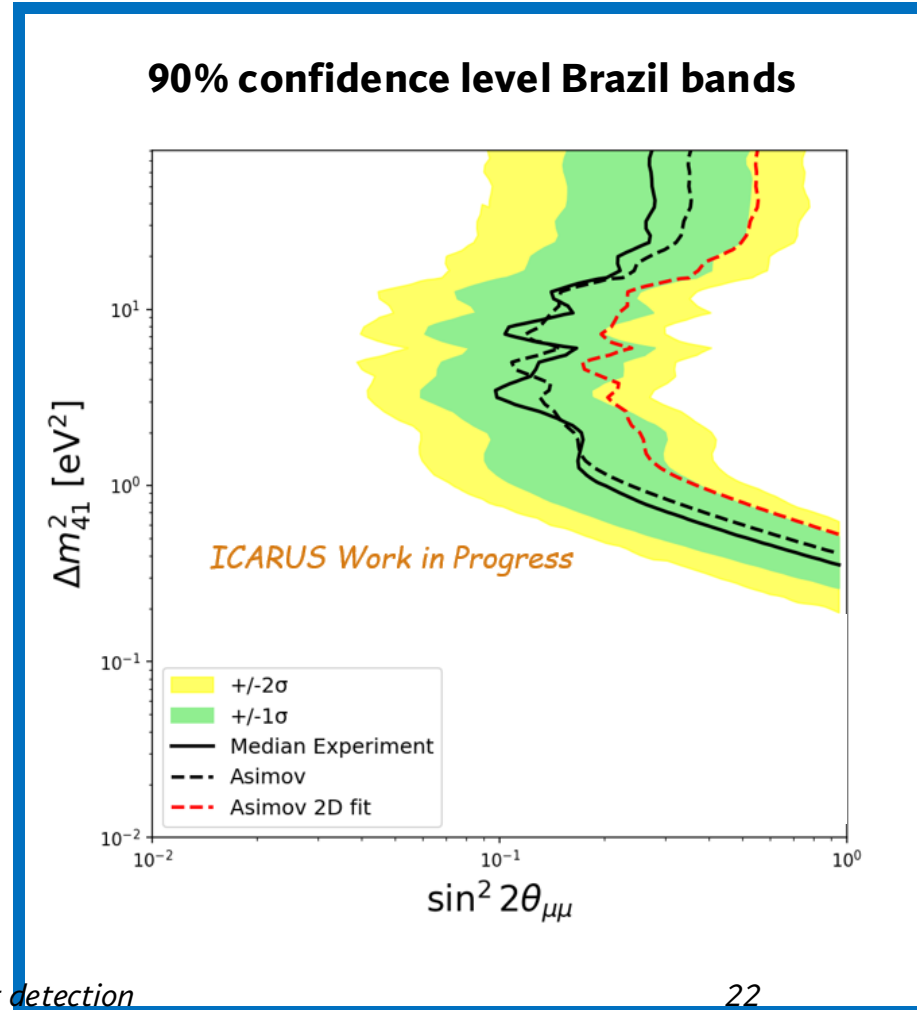
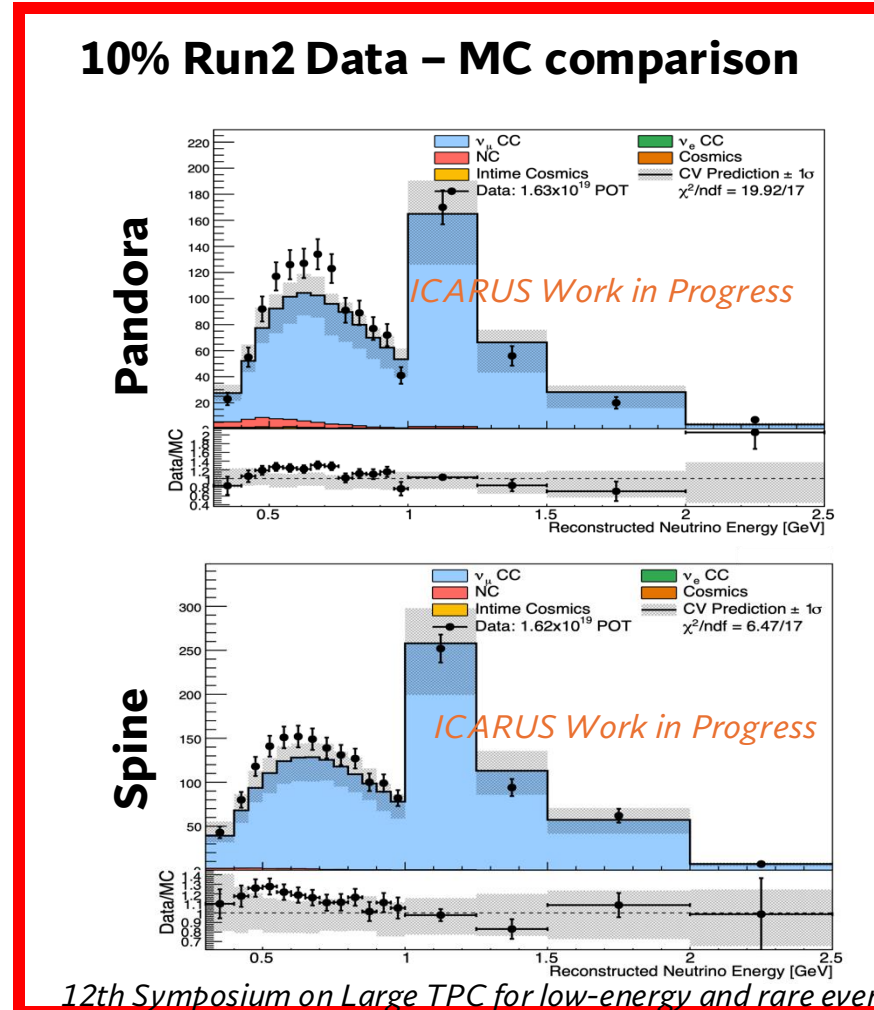
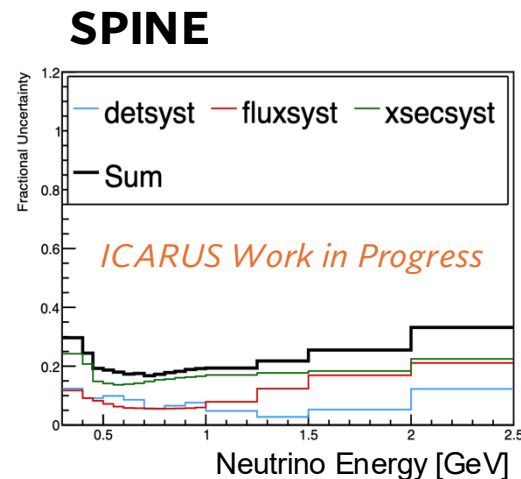
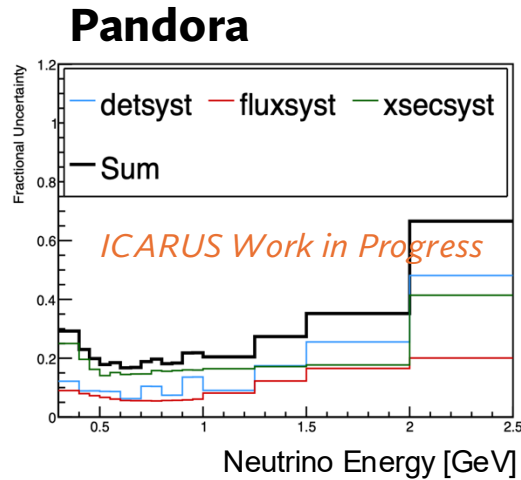
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12th Symposium on Large TPC for low-energy and rare event detection

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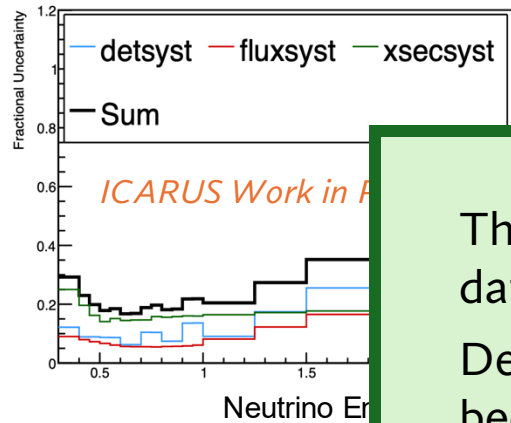
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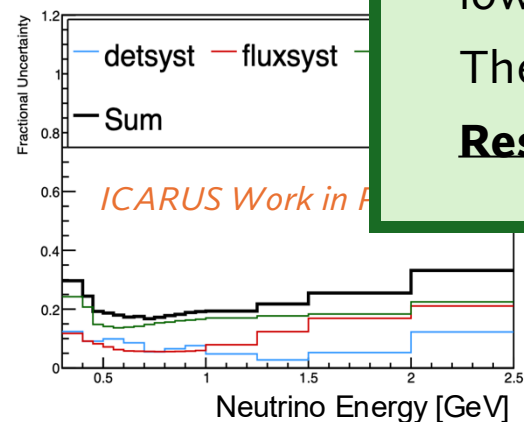
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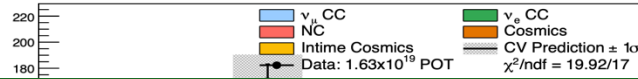
Pandora



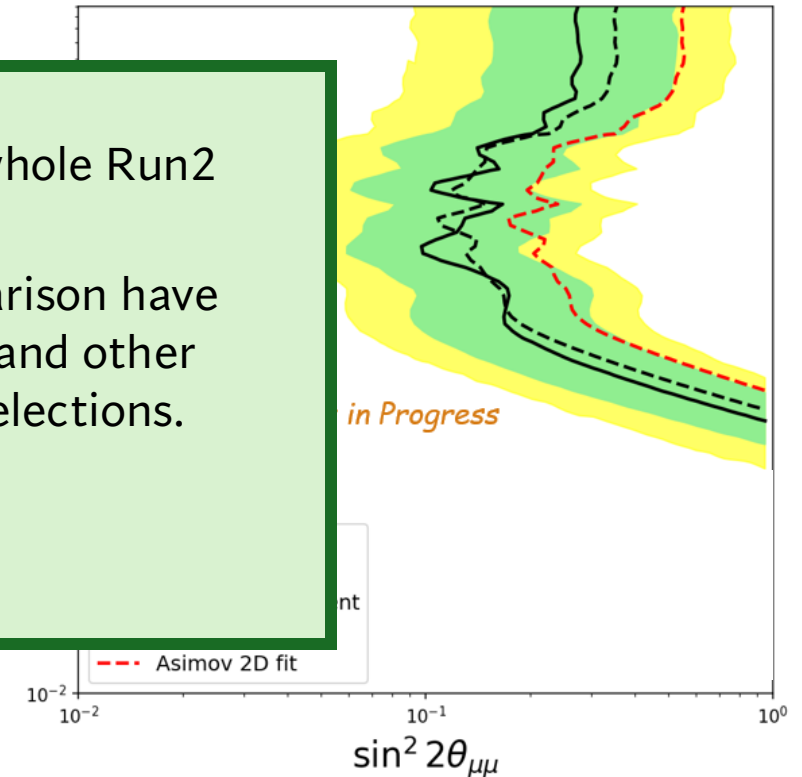
SPINE



10% Run2 Data – MC comparison



90% confidence level Brazil bands

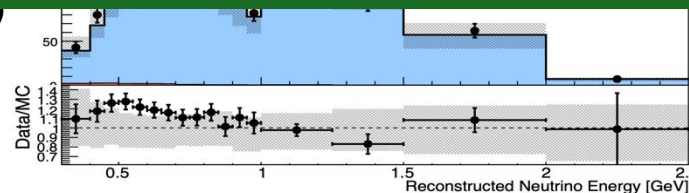


The signal unblinding has been completed on the whole Run2 dataset.

Detailed studies of Data/Data and Data/MC comparison have been performed on reconstructed neutrino energy and other lower level variables for both SPINE and Pandora selections.

The oscillation fit has been performed.

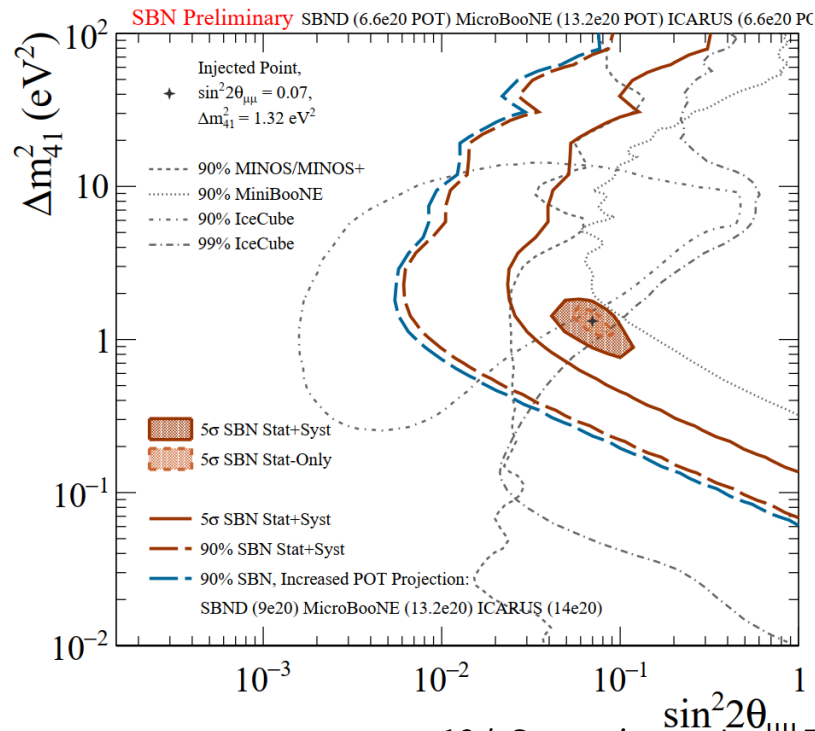
Results are expected soon.



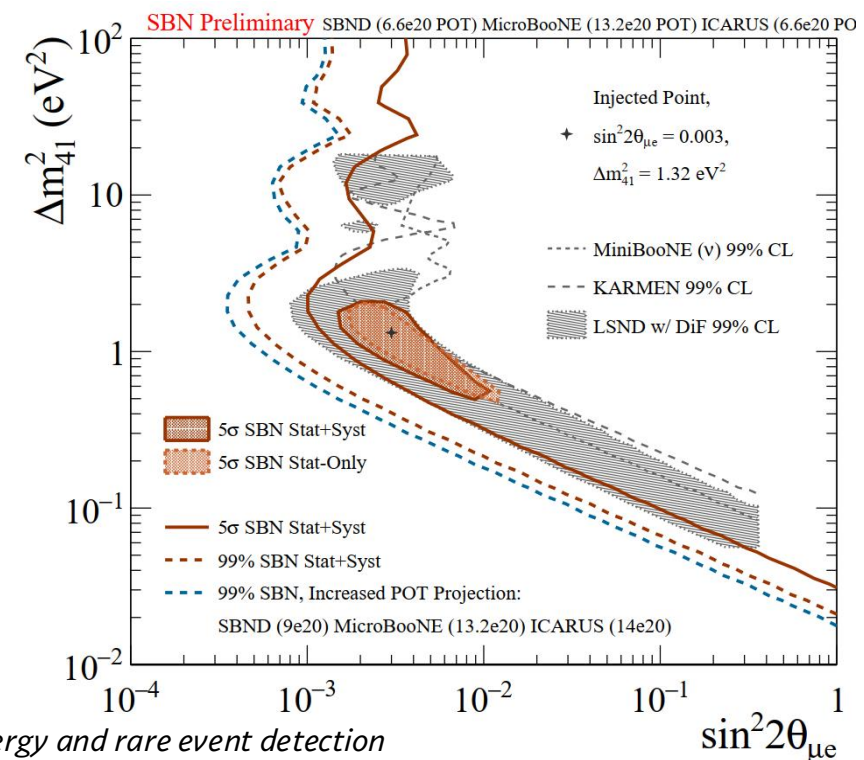
SBN: a near/far detector joint program

The next phase of the experiment is the combined analysis with SBND to achieve the world leading sensitivity in ν_μ disappearance and ν_e appearance channel, trying to provide a definitive answer to the sterile neutrino puzzle. In the joint program, detector systematics will become dominant.

Disappearance sensitivity



Appearance sensitivity



Conclusion

- The ICARUS detector has been in continuous operations since 2020, becoming the longest continuously operating LArTPC for more than 5 years and it is expected to keep running until 2028.
- The collaboration worked intensively to constantly improve our detector and our reconstruction, allowing a very efficient data collection.
- The enormous dataset collect so far is being studied and analyzed to produce physics results of great interest for the whole LAr community.
- The off-axis NuMI beam offers the opportunity to measure cross sections in the DUNE energy range, first measurements have been reported.
- A first study of Sub-GeV dark particles have been completed, the first exclusion plots have also been reported.
- A study of ν_μ disappearance along the BNB with ICARUS alone has been performed, the signal region has been fully unblinded and the fitting procedure completed; results are to be released soon.
- ICARUS and SBND are now able to move towards the next phase of the SBN program. Expect the first results in 2026.