Latest Results from the ICARUS Experiment at the Short-Baseline Neutrino Program

Imaging Cosmic And Rare Underground Signals

Matteo Tenti for the ICARUS Collaboration

180 people, 29 institutions: Italy, US, India, Mexico, Canada, Brazil + CERN

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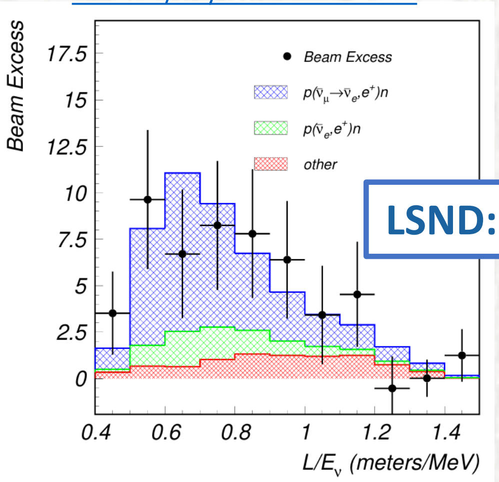
The Sterile Neutrino Puzzle

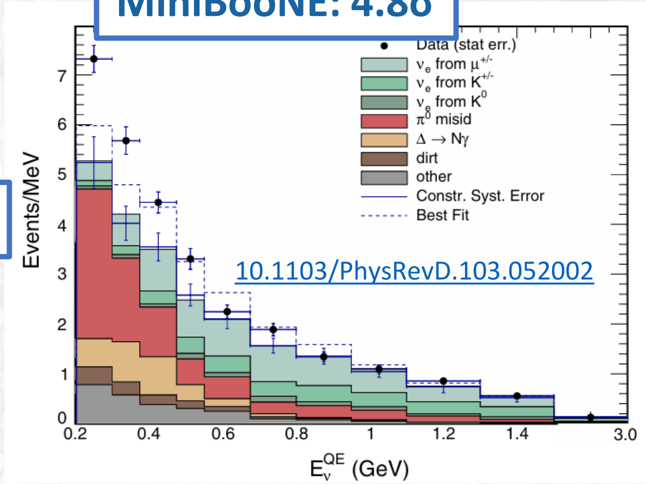
- Despite the well-established 3-flavour neutrino mixing model, several **anomalous results** have been collected over the past 25 years

10.1103/PhysRevD.64.112007

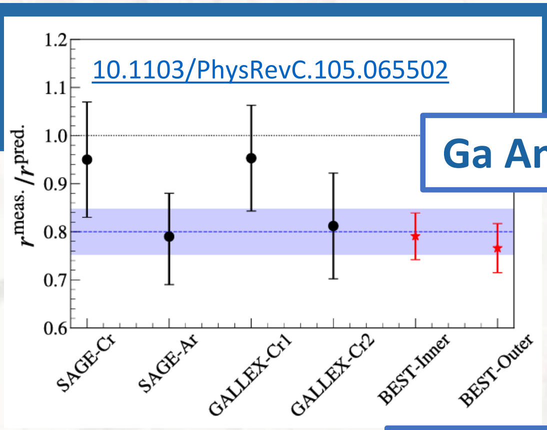


LSND: 3.8 σ

MiniBooNE: 4.8σ



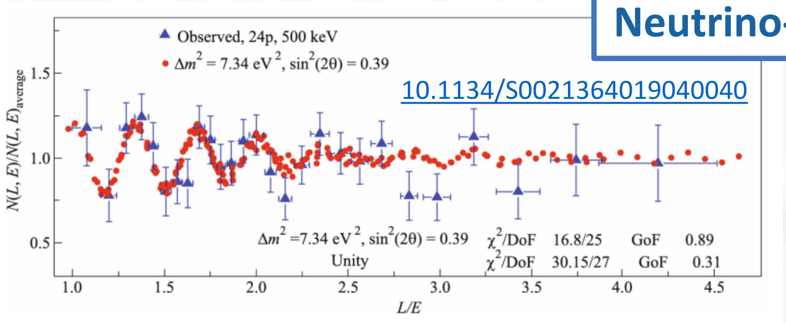
10.1103/PhysRevD.103.052002



10.1103/PhysRevC.105.065502

Ga Anomaly: 4σ

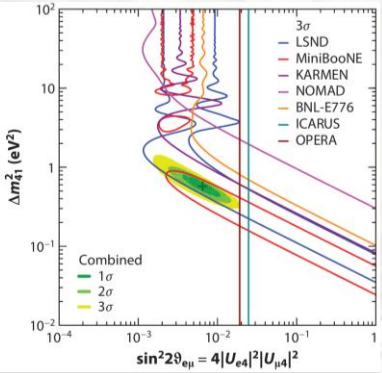
Neutrino-4: 2.8σ



10.1134/S0021364019040040

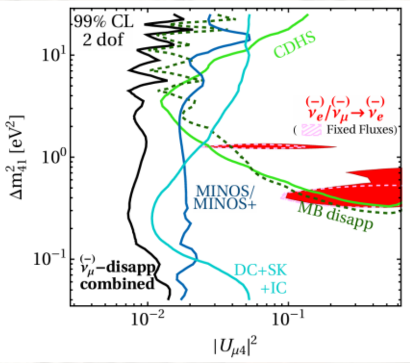
- Hints to additional **sterile ν** states with $\Delta m^2 \sim 1\ \text{eV}^2$ and $\sin^2 2\theta_{\mu e} = 4|U_{e4}|^2|U_{\mu 4}|^2 \sim O(10^{-2})$
- However, **no evidence in ν_μ disappearance** experiments: IceCube, NOνA, MINOS/MINOS+, T2K
- Clear **tension** between appearance and disappearance experiments, which are characterized by different ν energy range and detection technique, is evident

10.1146/annurev-nucl-101918-023755



ν_e appearance

10.1007/JHEP08(2018)010



ν_μ disappearance

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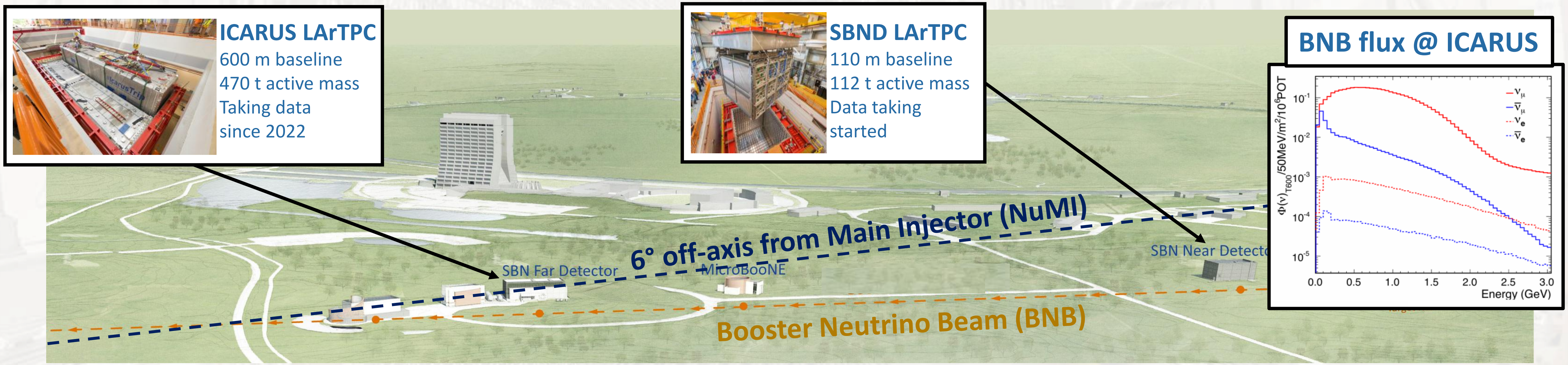
The Short Baseline Neutrino (SBN) at FNAL

- Measuring both **appearance /disappearance** in the **same experiment** with a detector capable to clearly identify neutrino events and reject the background is mandatory to disentangle physics scenario
- **Far to near** detector neutrino spectra comparison and **same technology** are crucial ingredients for the control of beam, cross-section and detector systematics
- The **Short Baseline Neutrino (SBN) program** at Fermilab satisfies these requirements: it could have a crucial role in solving the sterile neutrino puzzle!



- Two ν_μ beams: Booster Neutrino Beam (**BNB**, $E_\nu \sim 0.8$ GeV) and (ICARUS only) Neutrino at the Main Injector (**NuMI**, $E_\nu \sim 2$ GeV)

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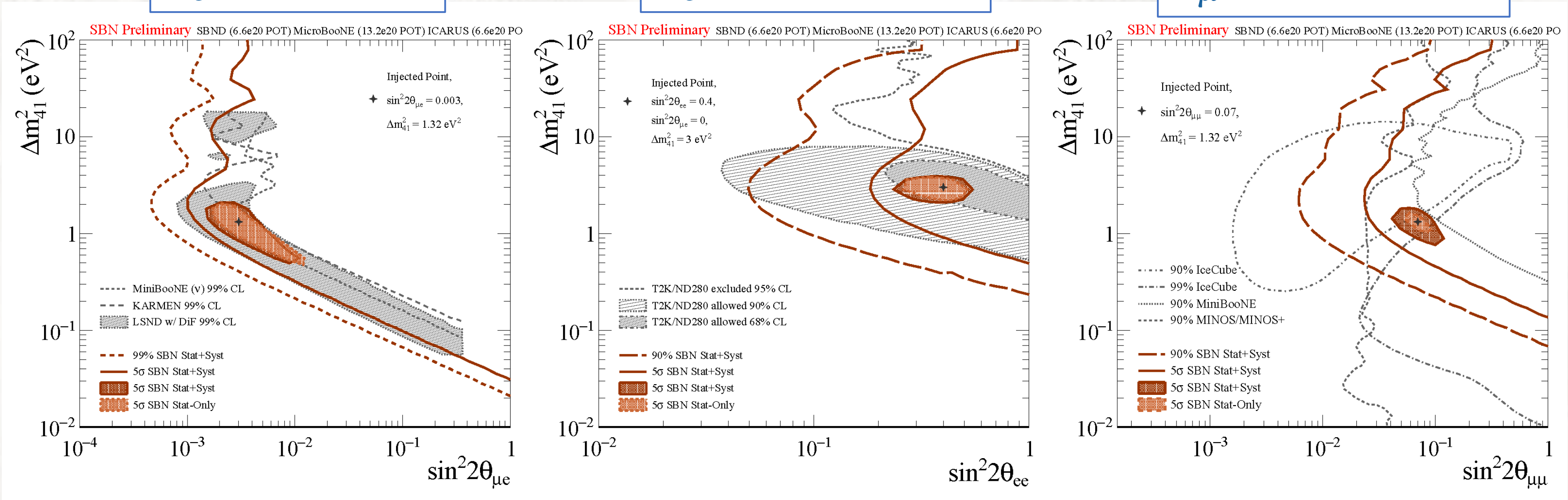
The SBN Physics Program

- Exploit the unique capability to study both neutrino **appearance and disappearance** channels simultaneously to search for sterile ν oscillations

ν_e apperance | ν_e disapperance | ν_μ disapperance



- **5σ sensitivity to LSND anomaly** in three years of data taking (6.6×10^{20} pot) gallium anomaly will be also probed

- In addition: high-statistics **ν-Ar cross-section** measurements in view of the DUNE exp.

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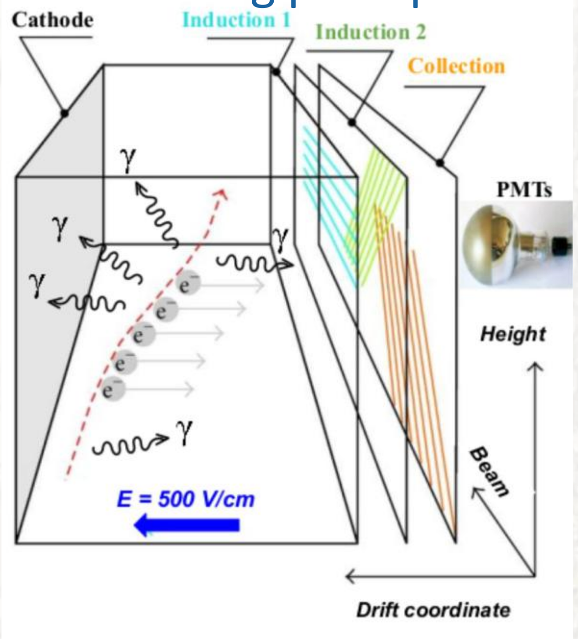
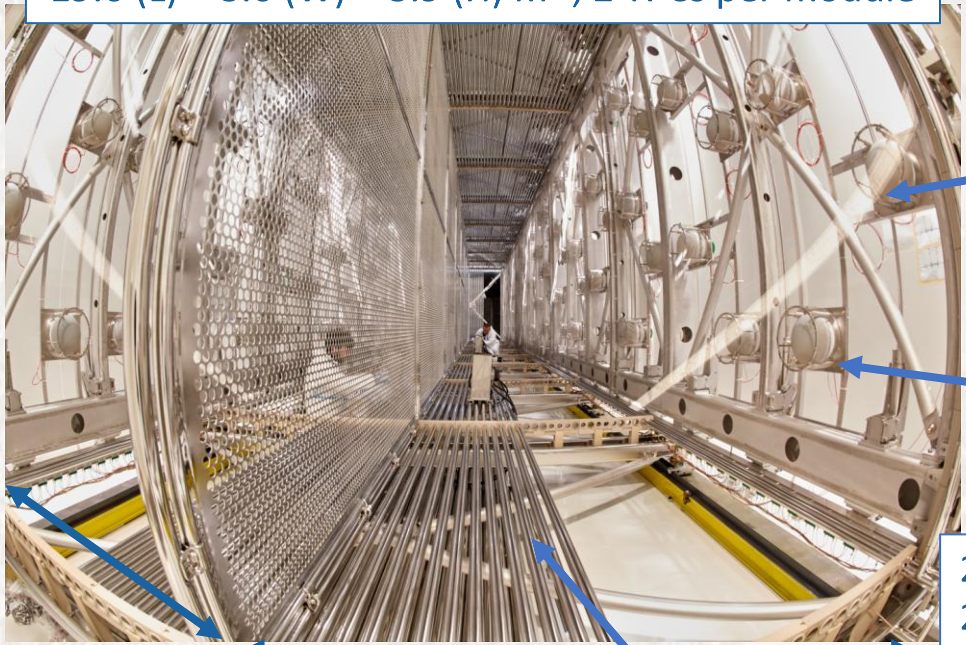
The ICARUS Detector: LArTPC

First proposed by C. Rubbia in 1977, LArTPCs are **high granularity uniform self-triggering** detectors with **3D imaging** and **calorimetric** capabilities, allowing to accurately reconstruct a wide variety of ionizing events with complex topology: **ideal detector for ν physics**

Working principle



Inner part of a module (2 modules in total)
19.6 (L) × 3.6 (W) × 3.9 (H) m^3 , 2 TPCs per module



3 readout **wire planes** per TPC, in total 54000 wires at 0, ± 60°, 3 mm pitch

360 8” **PMTs**, TPB coated detecting scintillation light by particles in LAr

1.5 m drift

punched stainless-steel central **cathode**

E-field cage, E = 500V/cm

2010-2012: Successful 3y physics run at LNGS
2014-2017: Intensive overhaul at CERN
2017-2021: Installation at FNAL and Commissioning
2022: Begin of physic run

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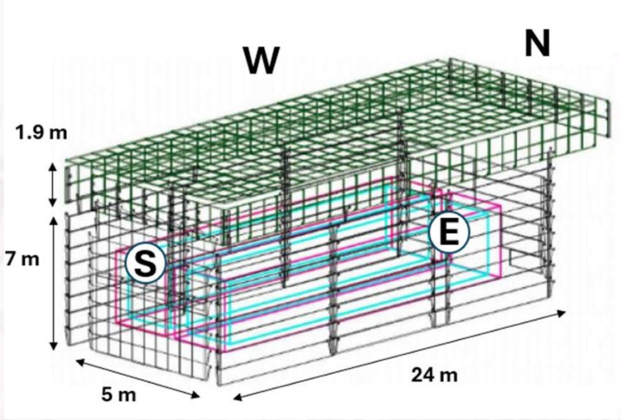
Cosmic Background Mitigation

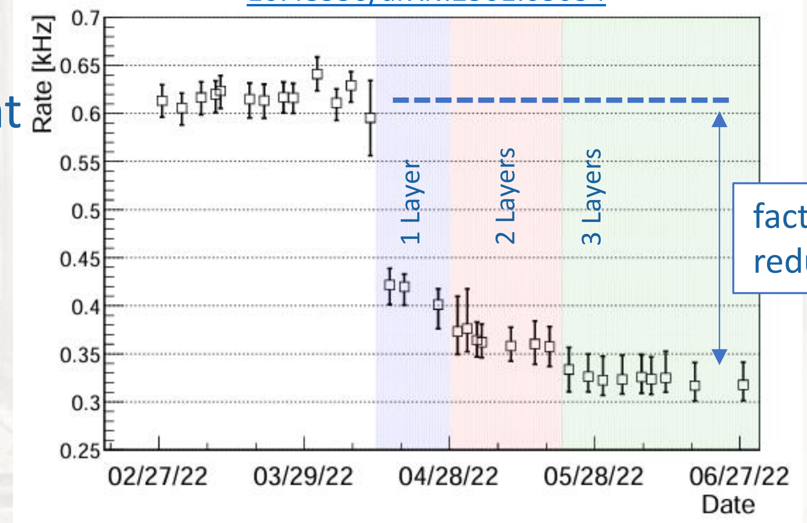


The ICARUS-T600 Liquid Argon Time Projection Chamber is operating at Fermilab at **shallow depth** and thus exposed to a high flux of cosmic rays that can fake neutrino interactions

A **Cosmic Ray Tagging (CRT) system** (~ 1100m^2), surrounding the cryostat with two layers of fiber embedded plastic scintillators, was developed to mitigate the cosmic ray induced background

- Tagging incoming cosmics with ~95% efficiency
- Offline vetoing cosmic-induced triggers

10.48550/arXiv.2501.03034



Cosmic γ's and neutrons are suppressed by **3 layers of concrete** (overall ~2.85 m thick) overburden installed on top of the CRT

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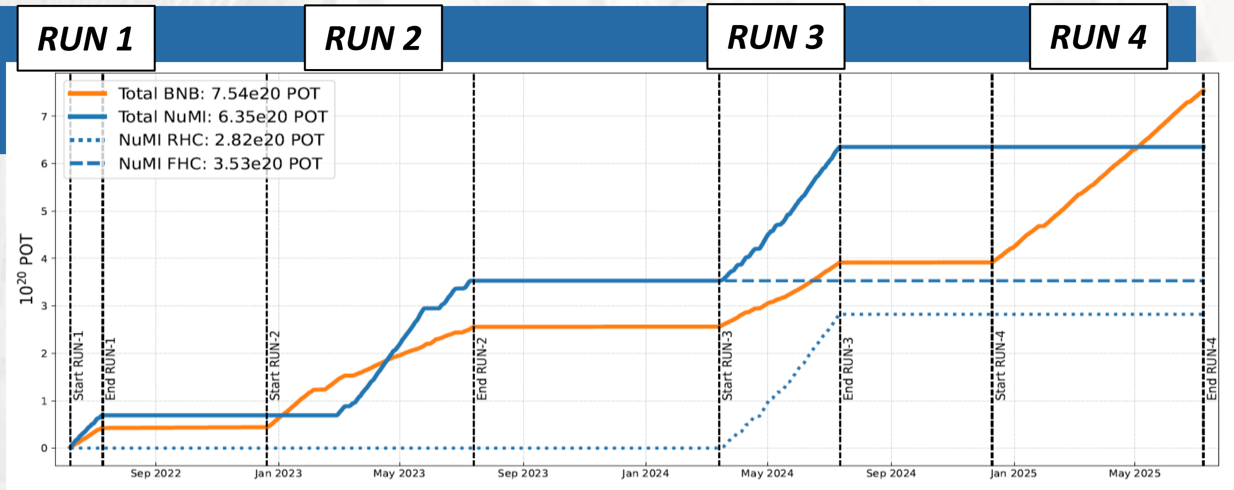
FNAL Operation

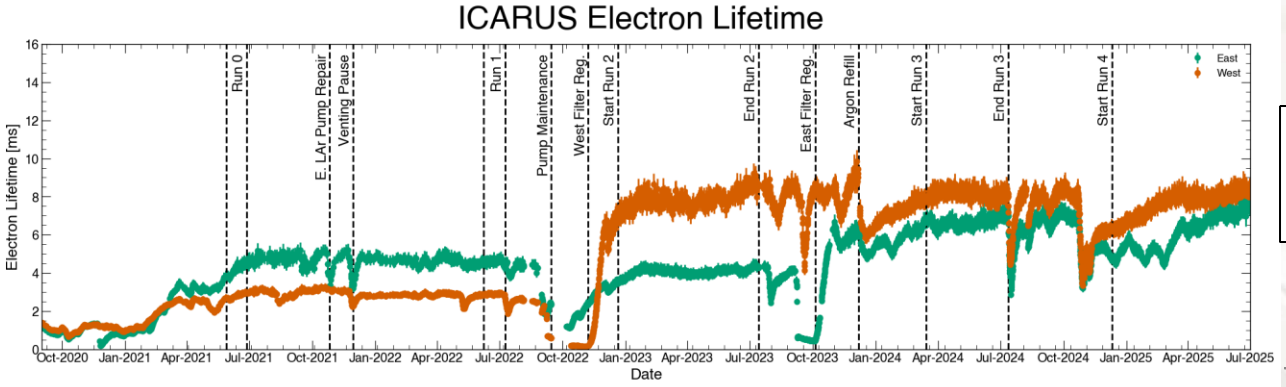


- **Data taking started** on June 9th 2022 with TPC, PMT and CRT systems fully operational
- 4 physics runs completed:
  - Detector lifetime > 90%,
  - DAQ collection efficiency > 97%
- Trigger requires at least 4 fired PMT pairs inside a 6 m longitudinal detector slice in coincidence with BNB, NuMI beam spills (efficiency > 90% for E_{dep} > 200 MeV)
  - TPC wires waveforms are amplified and sampled at 2.5 MHz with 12-bit ADC for 1.5 ms
  - PMT waveforms are sampled at 500 MHz with 14-bit ADC for 30 μs
  - CRT: autotrigger mode, coincidence of two-layers, hit timestamp and ADC

10.48550/arXiv.2506.20137

Collected p.o.t.	BNB (x 10^{20})	NuMI (x 10^{20})
RUN 1	0.41	0.68
RUN 2	2.06	2.74
RUN 3	1.36	2.82 (RHC)
RUN 4	3.71	-
Total	**7.54**	**6.24**

- Electron lifetime τ_{ele} ~ 7 - 8 ms, (maximal attenuation < 15%)



WEST: ~8 ms
EAST: ~7 ms

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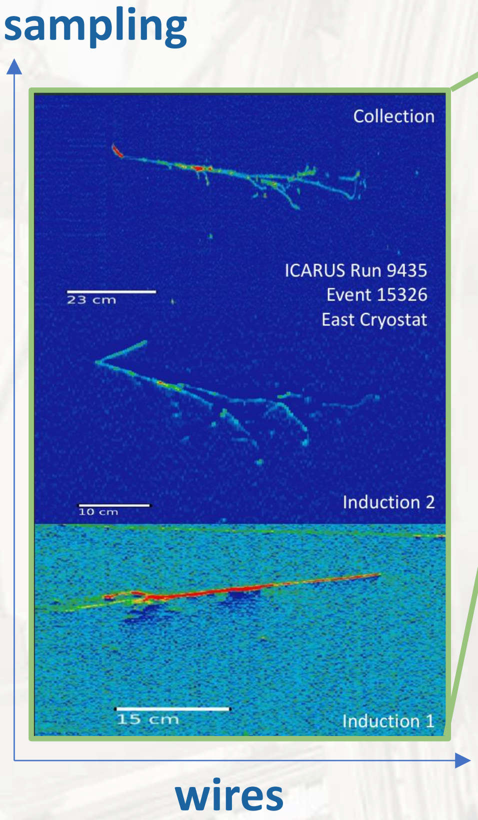
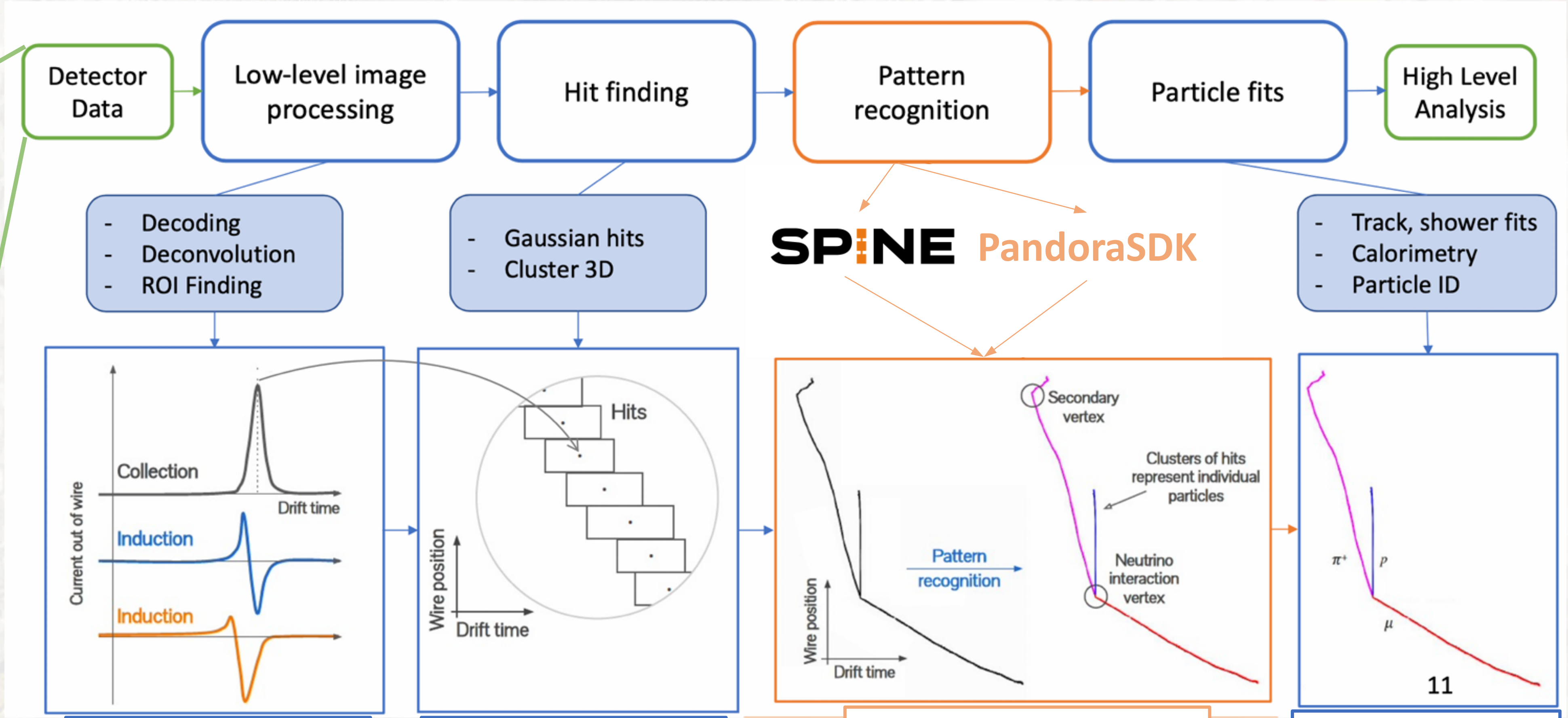
Event Reconstruction Chain





Includes electronic noise filtering; unipolar signals for all wire plane after this stage

A hit represents the identified signal induced by a track on a wire

Identifies primary & secondary vertexes; tracks/showers 3D reconstruction (organized in hyerachical order). Cosmic rays identification.

Objects for kinematic reconstruction and event analysis.

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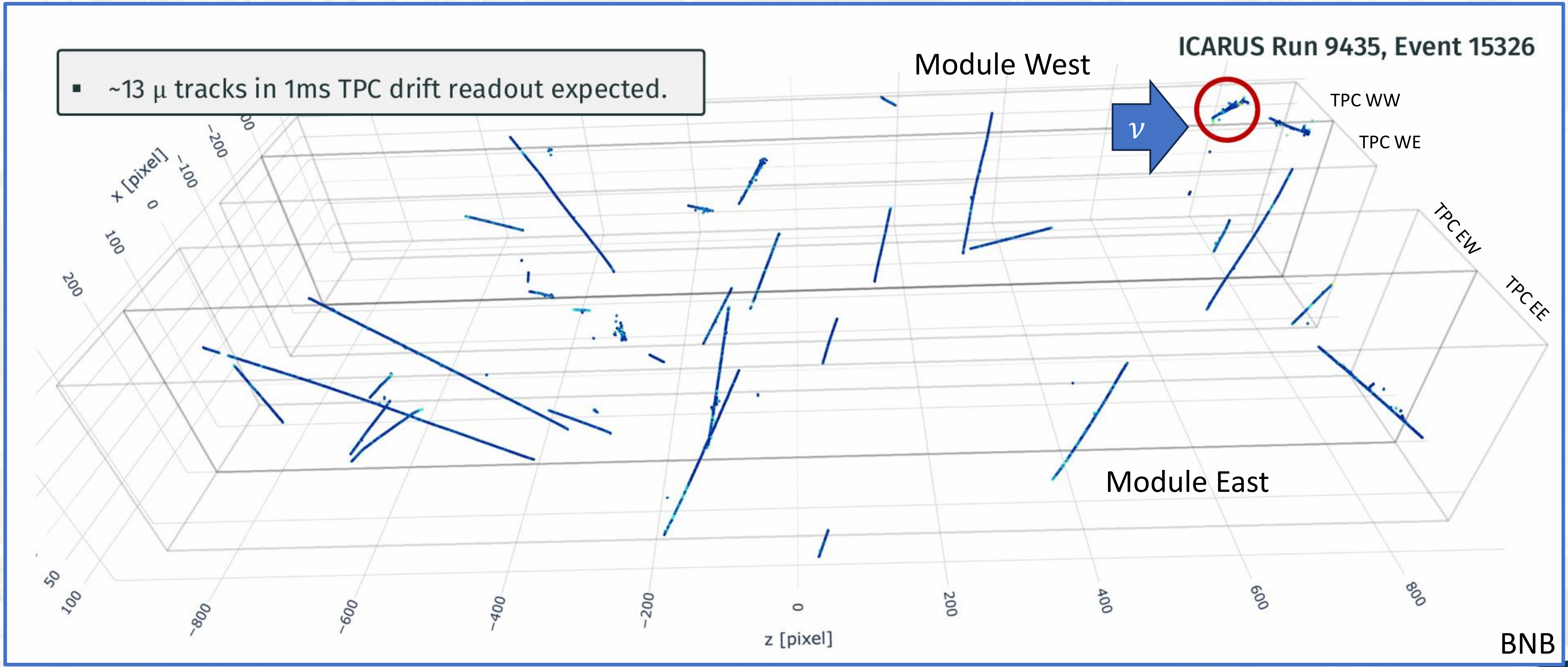
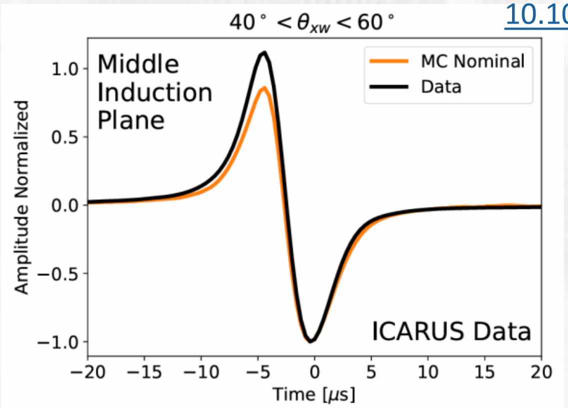
Example of Neutrino Event



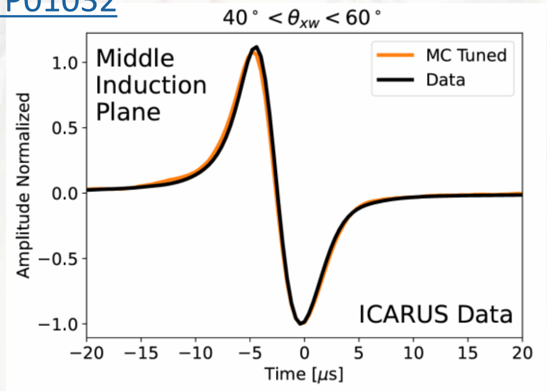
ICARUS Performance: Calibration

- **TPC wires signals have been accurately characterized and modeled in Monte Carlo**
- Detector response is calibrated with cosmic μ and p from ν interactions including a new **angular dependent ellipsoidal recombination model (EMB)**

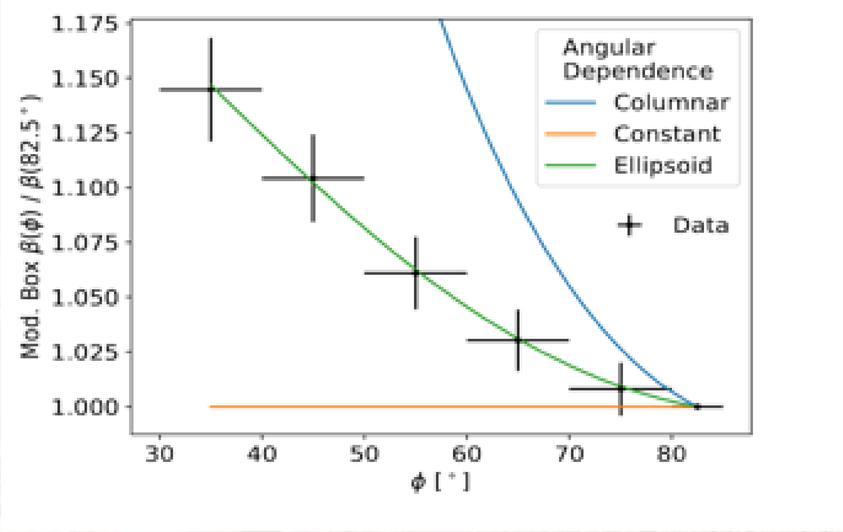
10.1088/1748-0221/20/01/P01032



MC signal shape tuning



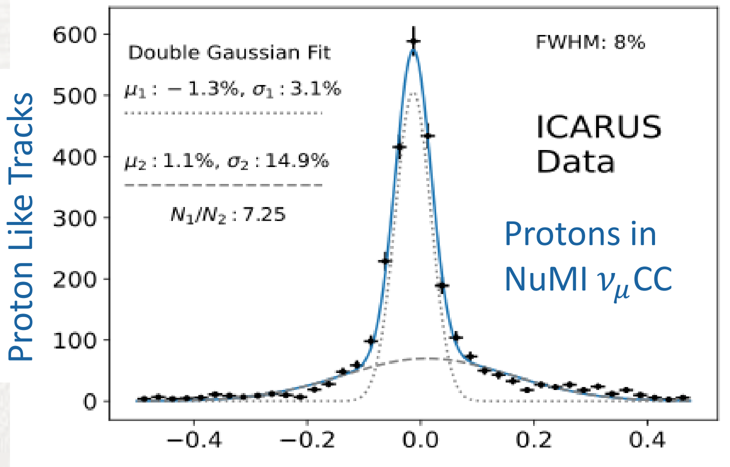
10.1088/1748-0221/20/01/P01033



$$\frac{dQ}{dx} = \frac{\log\left(\alpha + \mathscr{B}(\phi)\frac{dE}{dx}\right)}{\mathscr{B}(\phi) W_{\text{ion}}} \qquad \mathscr{B}(\phi) = \frac{\beta_{90}}{\mathscr{E}\rho\sqrt{\sin^2\phi + \cos^2\phi / R^2}}$$

Modified Birks' law taking into account the angle between the track and the drift direction

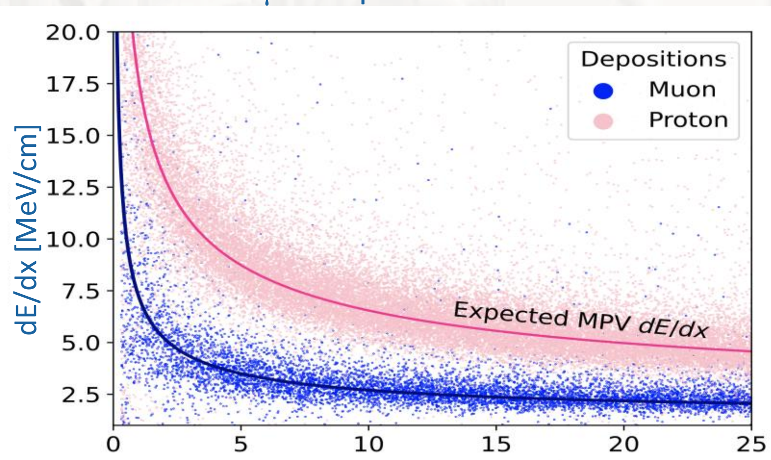
3% resolution



$(E_{calo}\text{-}E_{range})/E_{range}$

Difference between calorimetric and range measurement of the proton energy

dE/dx Vs residual range for μ and p used for PID



Residual Range [cm]

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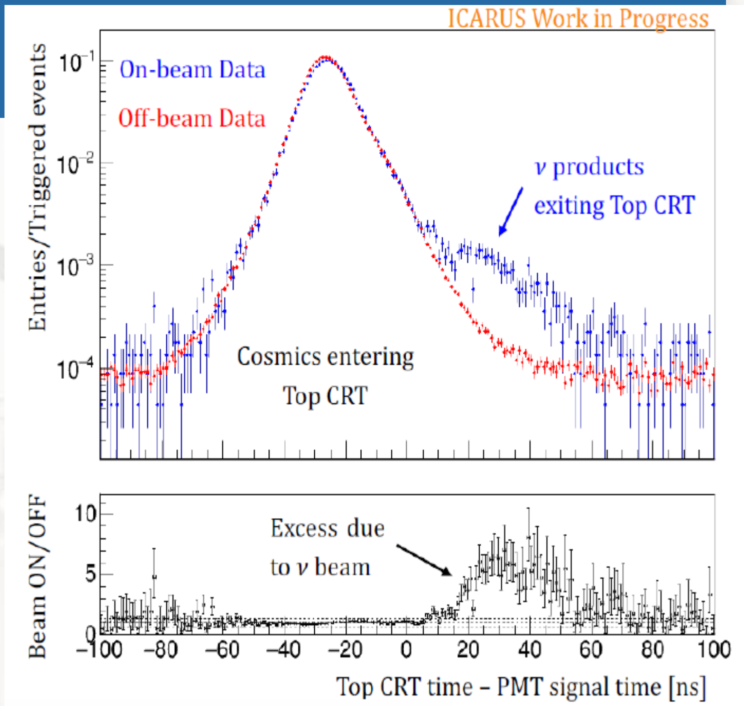
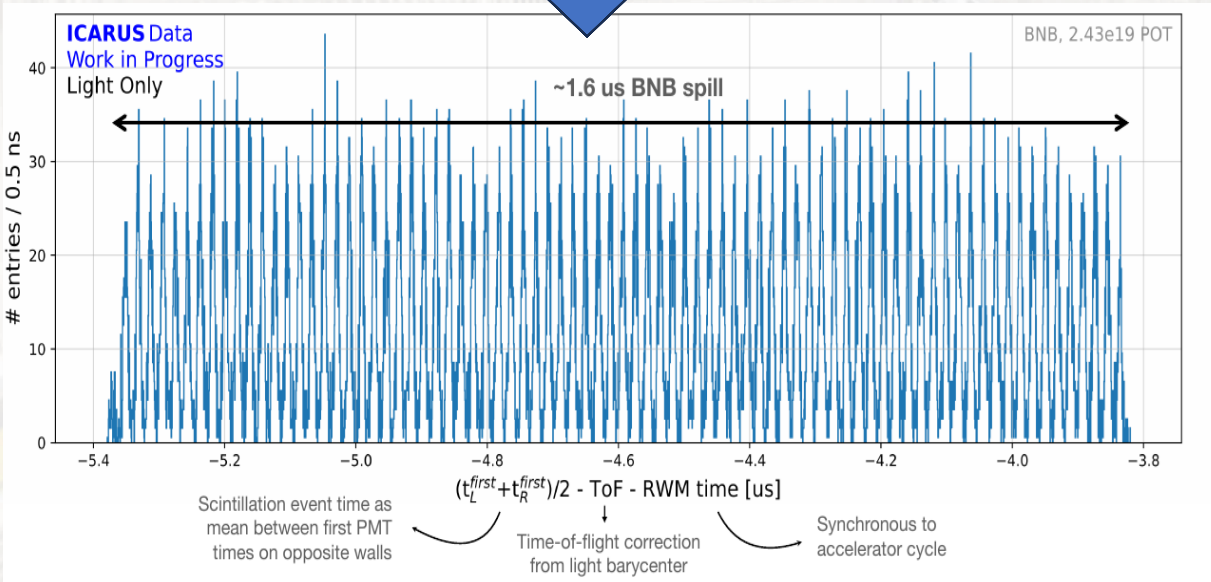
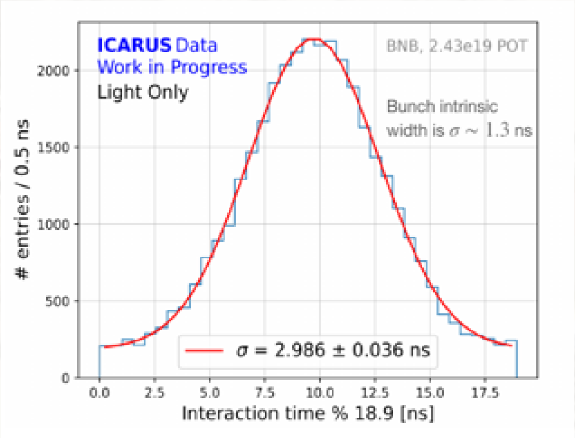
ICARUS Performance: Timing

- **Time-of-flight rejection of incoming cosmic rays** using the external CRT and the inner PMT system



- Reconstruction of **BNB and NuMI beam bunch structures**: **neutrino event time** (PMTs only) with respect to the proton beam extraction time (RWM counters) after rejecting incoming cosmics (CRT) and correcting for ν flight distance.

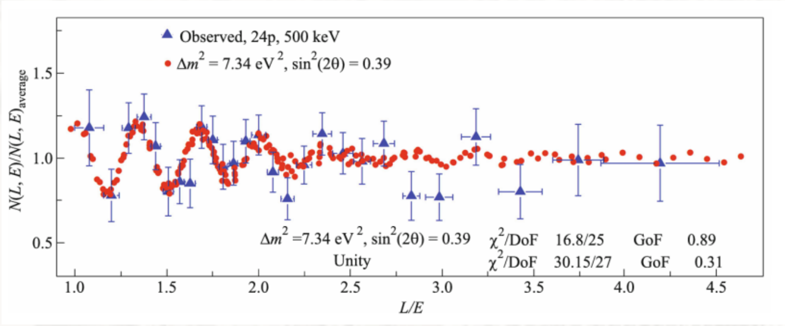




ICARUS Physics Program

- The main goal of the SBN program is addressing the issue of sterile neutrinos
- Before the start of joint operation ICARUS is focusing on **standalone physics program**:

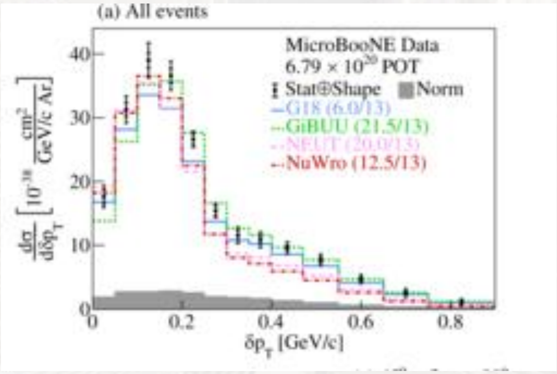
Neutrino-4 claim



ν_μ disappearance with BNB beam, and ν_e disappearance with off-axis NuMI beam

BNB ν_μ event selection: ready and validated

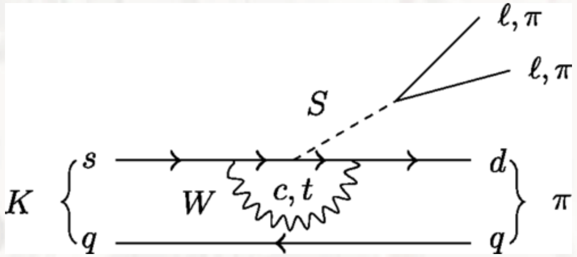
ν-Ar cross-section



Study of ν_e, ν_μ NuMI events to measure ν-Ar cross sections.

Event selection ready, sidebands studied for a subset of data

BSM search



Search for sub-GeV Beyond Standard Model signals in NuMI beam

Signal box opened for $\mu\mu$ decay channel

- ICARUS established a **blinding policy** to ensure robust and unbiased interpretation of the collected data; analyses are initially validated with a subset of collected data.

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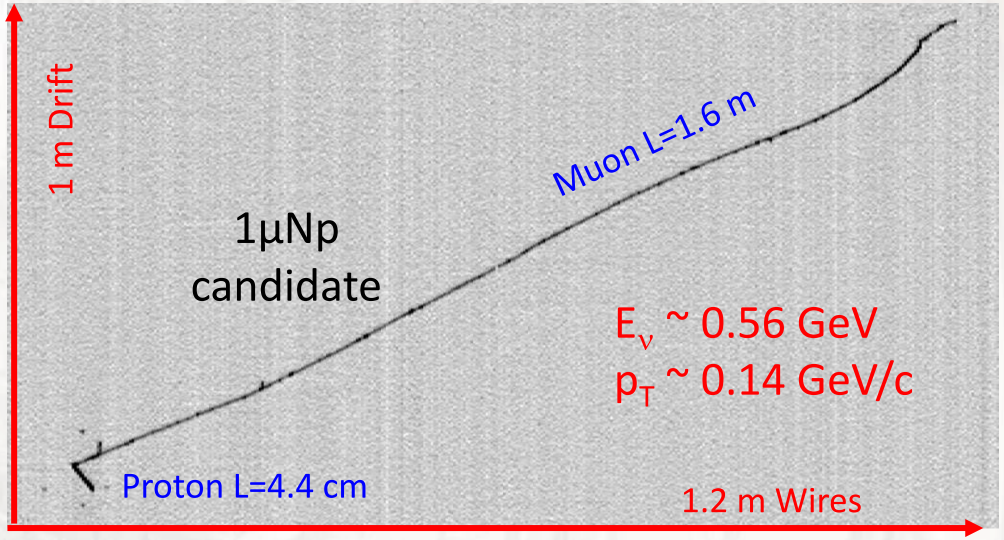
ν_μ event selection for disappearance analysis at BNB

- **Simple final-state topology** with selection criteria designed to minimize our sensitivity to imperfections in the detector calibration and event reconstruction algorithms
- **Fully contained ν_μCC events with 1 μ + N protons** (1μNp):
  - PMT light signal in the 1.6ms beam spill window correlated with TPC tracks, no CRT signal in coincidence
  - a muon with L_μ > 50 cm and at least one proton track with E_K > 50 MeV (L_p > 2.3 cm) fully contained and identified by PID scores based on dE/dx
  - no additional π, γ
- The global event kinematics is obtained from **range** measurement of μ and p.
- Residual **cosmic backgrounds** < 1%
- **Flux, cross section and detector systematic uncertainties** included:
  - Detector systematics evaluated comparing calibrated and uncalibrated MC samples

flux / cross section / detector ~ 10% / 15% / 15%

  - Substantial cancellation of cross section and flux uncertainties and of common detector systematics is expected in the joint SBN analysis;



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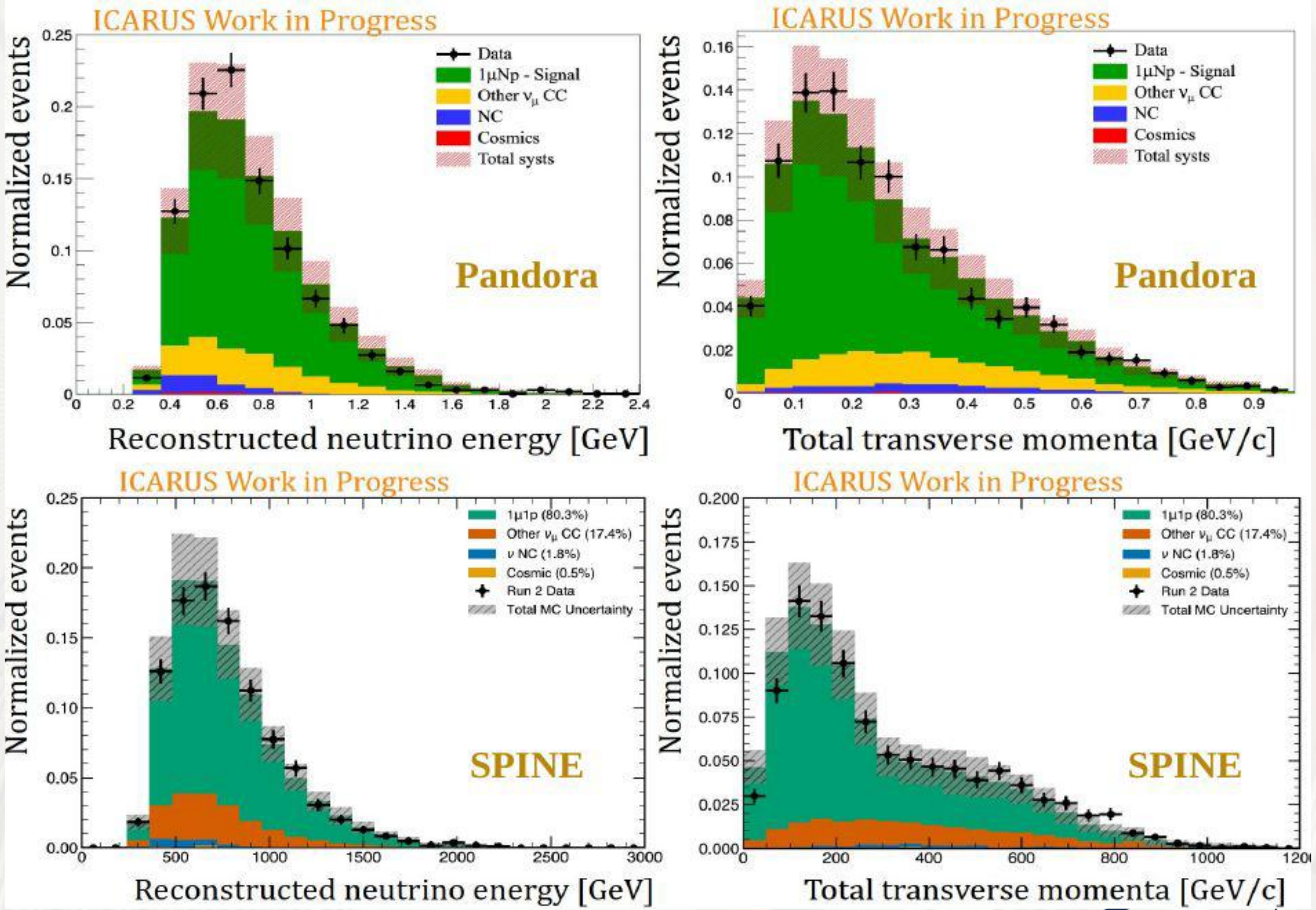
1μNp analysis

- 10% of RUN-2 data analyzed: $\sim 2 \times 10^{19}$ pot

- Two independent reconstruction approaches:
  - **Pandora**: pattern recognition algorithm
  - **SPINE**: Machine Learning-based reconstruction

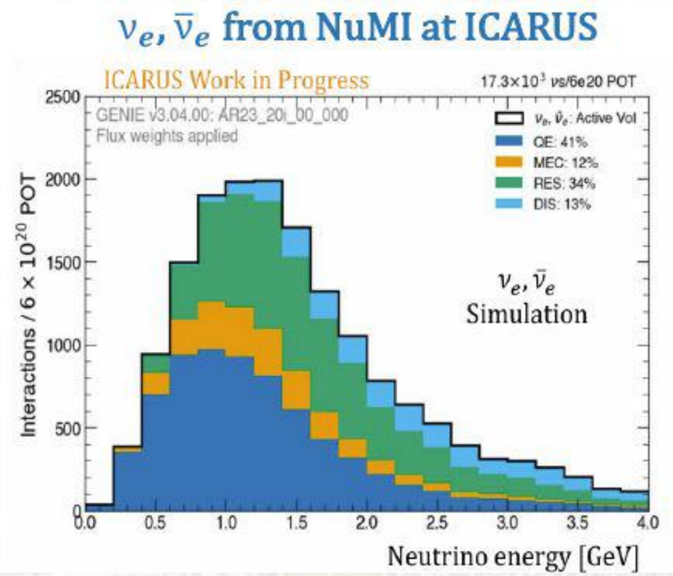
- Data-MC **agreement** for all studied event kinematic variables within systematics uncertainties

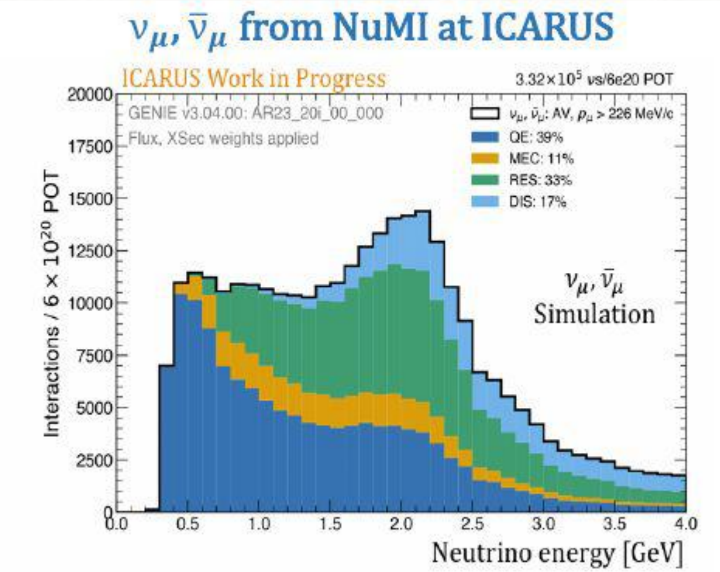
- Ongoing:
  - increase the studied data sample
  - dataset **unblind** foreseen soon

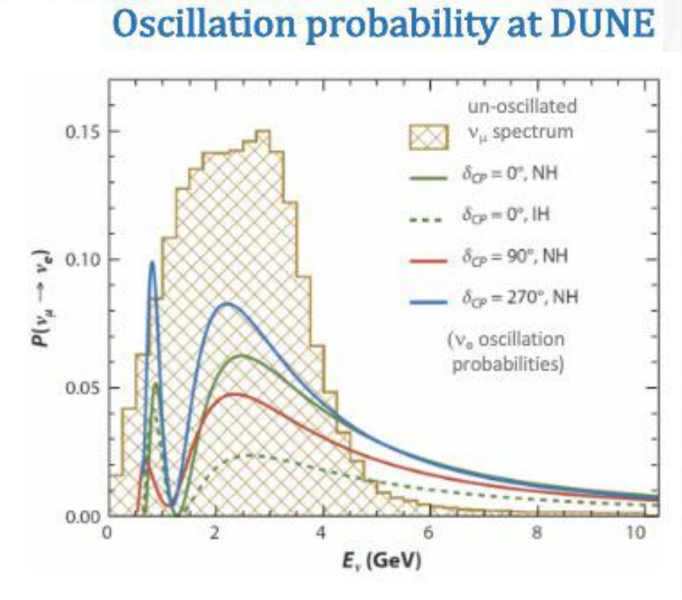


Neutrino cross-section measurements with NuMI

- High statistics from NuMI beam (currently available data 3.42×10^{20} pot) to measure ***ν*-Ar cross section**:
  - QE, resonance and DIS, for electron and muon neutrino
  - Expected 332k ν_μCC and 17k ν_eCC interactions in 6×10^{20} pot







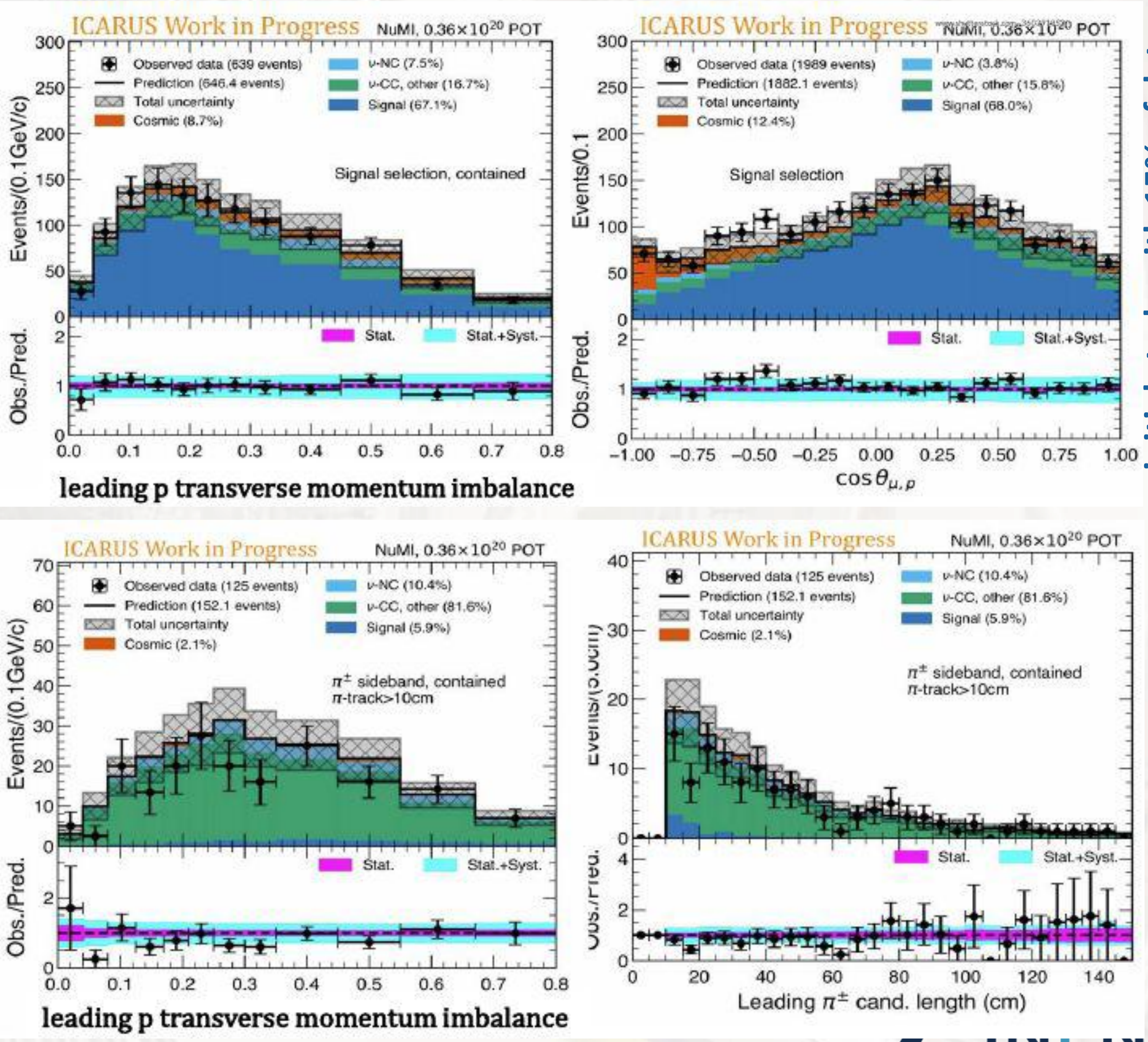
- Neutrino energy spectrum from NuMI covers the first oscillation peak and good coverage of the relevant phase space for DUNE experiment.

Neutrino CC0π cross section analysis results

- First analysis targets $1\mu + Np + 0\pi$ (CC0π) enhanced in QE and 2p2h interactions:
  - **Signal** definition:
    - 1μ with $p_\mu > 226$ MeV/c
    - any proton with 400 MeV/c $< p_p <$ 1 GeV/c
    - no π in the final state
  - Flux, interaction model and detector systematic uncertainties included
  - Transverse kinematic observables are sensitive to Initial and Final State effects.
- Main **background** source is due to events with undetected/misidentified pions
  - A control sample has been selected with charged pion candidates (requiring a secondary muon-like track)
- Good agreement between data/MC: Results for the **full dataset soon!!**

CC0π

Control sample



initial study with 15% of data

initial study with 15% of data

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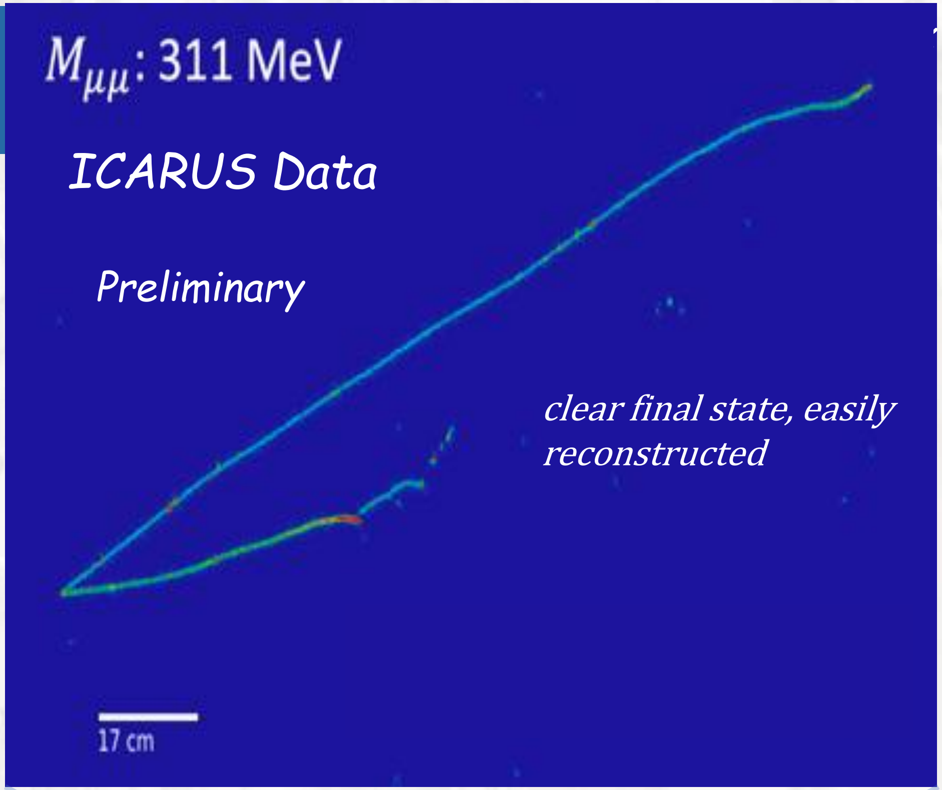
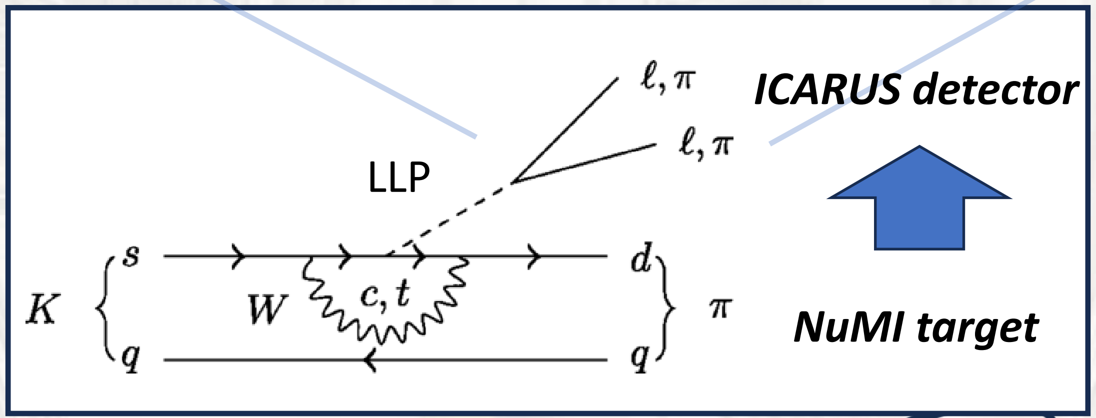
BSM searches with NuMI

- Several BSM models predict processes by which a kaon decays to a **long-lived particle** (LLP), which in turn decays to a $\boldsymbol{\mu\bar{\mu}}$**– pair**

- A first search for such events completed
  - Events with **2 stopping μs** selected
  - **Small angle** w.r.t. NuMI beam: $\theta_{NuMI} < 5°$
  - Observable: **dimuon invariant mass**, $M_{\mu\mu}$

- Flux, interaction model and detector **systematic uncertainties** have been included





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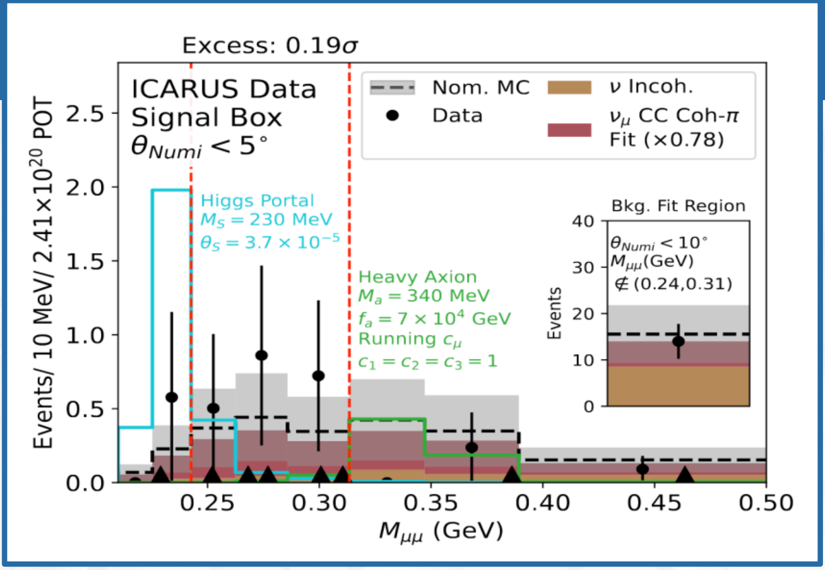
BSM: Results

- Data corresponding to exposure of 2.41×10^{20} pot (NuMI)

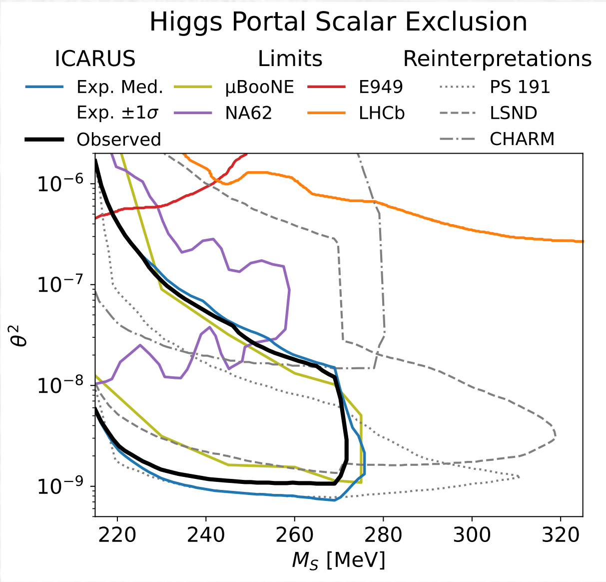


- Open box result: 9 candidate events found, **in accordance with background expectation** of 8 events (from ν_μCC coherent pion production)

10.1103/PhysRevLett.134.151801

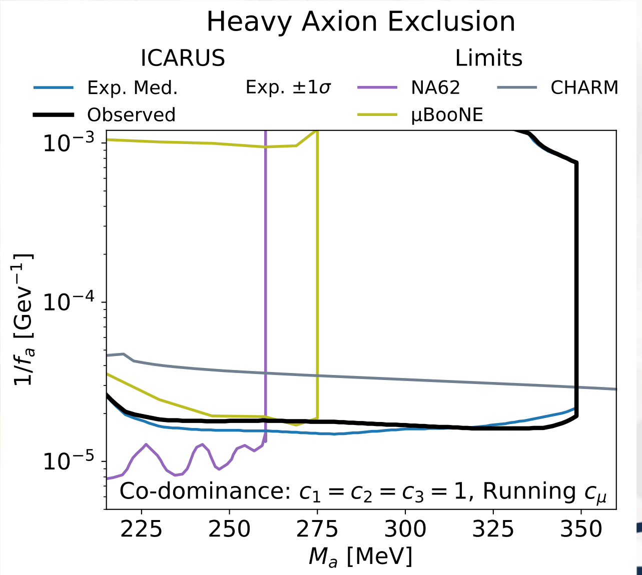
Higgs portal Scalar

Scalar dark sector particles, interactions by mixing with Higgs boson



Heavy QCD axion

Pseudo-scalar particles, interactions by mixing with pseudo-scalar mesons



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Conclusions

- ICARUS is smoothly **running in physics mode since June 2022**, exposed to the BNB and NuMI neutrino beams

- **The detector is calibrated** with cosmic muons and protons from neutrino interactions

- The **electronic response** and physical properties have been accurately qualified and are being fully modeled in simulation

- While waiting for the joint operation within SBN, **several single detector analyses** are quite advanced:
  - Study of ν_μ **disappearance** with the BNB beam
  - Measurement of ν_μ **cross-sections** with NuMI beam;
  - Search for **BSM physics** in NuMI beam

- Analyses are quite mature and ready to proceed to validation with larger control samples in view of the **full signal unblinding**.

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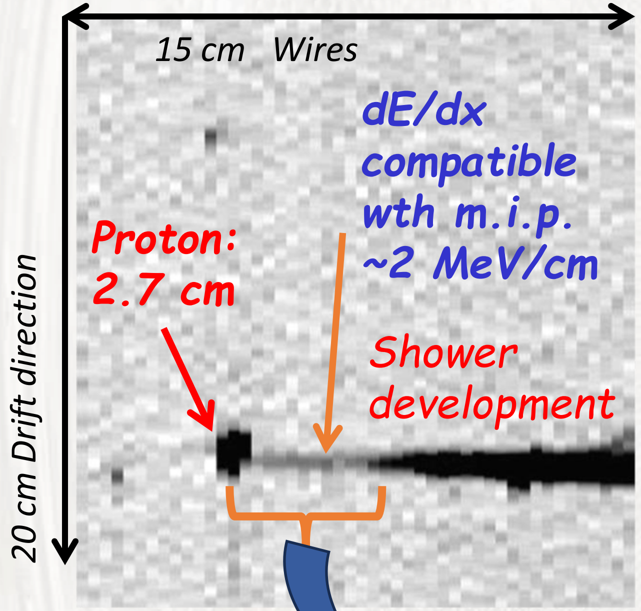
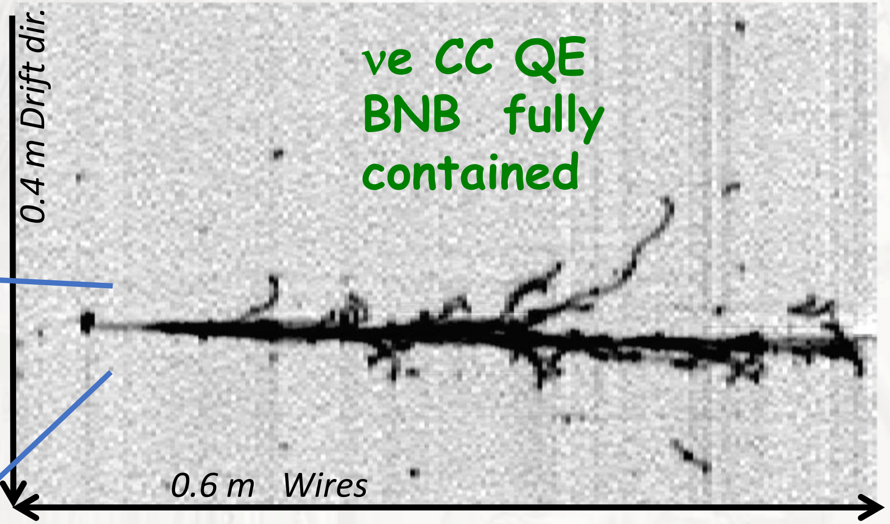
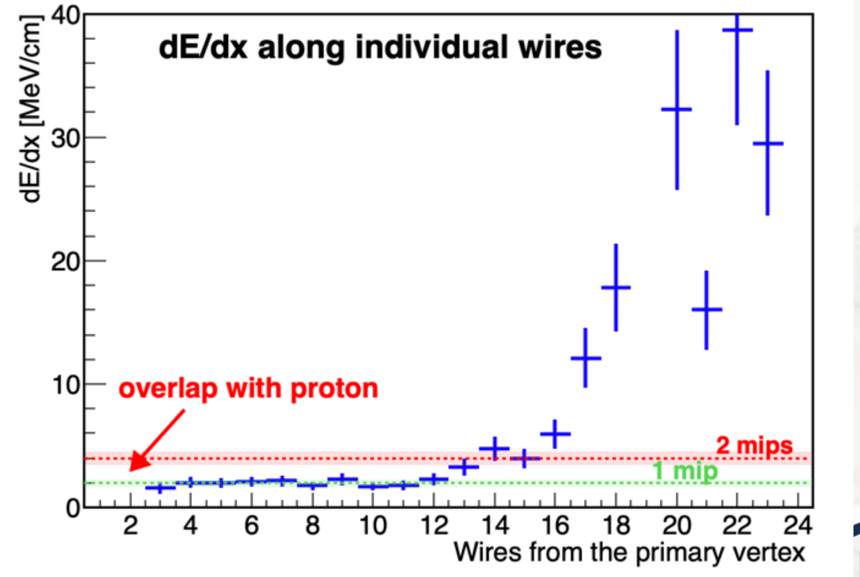
Search for electron neutrino events

The development of tools for the selection and reconstruction of the ν_e events is ongoing







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BSM search systematis

TABLE I. Uncertainty on the total event rate in the signal region for scalar signals and neutrino backgrounds. The scalar signal uncertainty is taken as the mean across the sampled mass points. It is nearly independent of the mass.

Systematic	Scalar sig. [%]	Neutrino bkg. [%]
Total detector uncertainty	11.0	20.2
Detector model variations	9.9	17.6
Cathode aplanarity	5.5	5.6
Energy scale	1.8	8.2
Flux	12.3	12.0
ν_μCC-Cohπ x-sec	...	62.9
Other ν interactions x-sec	...	4.1
Particle propagation	...	5.6
MC. statistics	...	4.6
Total	16.5	67.7

INFN BOLOGNA
Istituto Nazionale di Fisica Nucleare
Sezione di Bologna