# ICARUS, and the Short-Baseline Neutrino (SBN) Program at Fermilab

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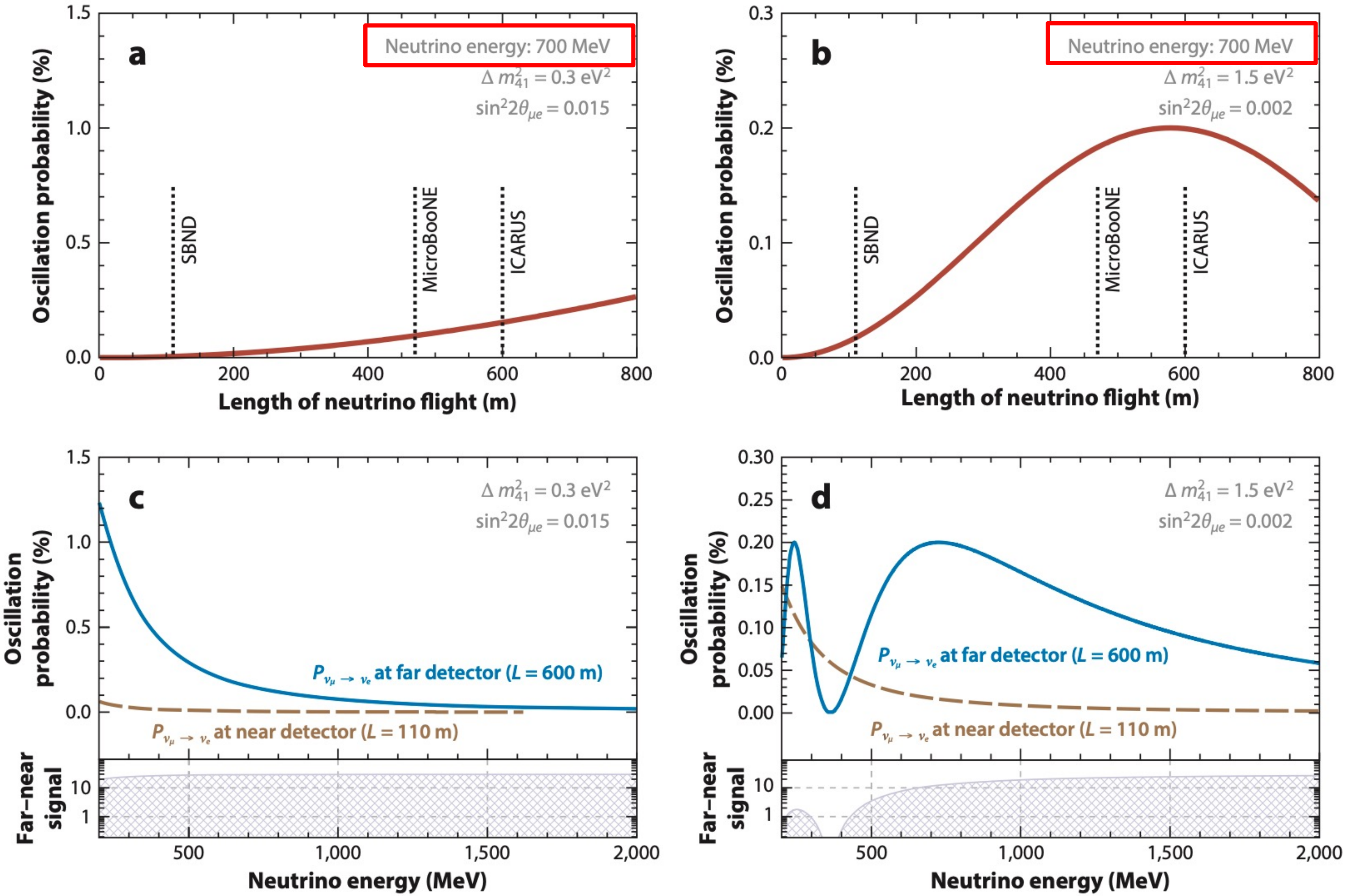
# The SBN Program at Fermilab


- **Same Technology:** Liquid Argon Time Projection Chamber (LArTPC)
- **Same Source:** Booster Neutrino Beam (BNB: 93.60% $\nu_\mu$ /5.86% anti-$\nu_\mu$ /0.52% $\nu_e$ and 700 MeV peak Energy)
  - **Near Detector** (**SBND**, 110 m, taking data since 2024): Measure neutrinos before they oscillate, provide precise information on the initial beam composition and energy
  - **Far Detector** (**ICARUS**, 600 m, taking data since 2022): Have non null oscillation probability
- **Main goal:** Search for sterile neutrinos, solve the sterile neutrino puzzle (+cross sections, BSM Searches)
- **Two Neutrino Beams:** BNB + NuMI (ICARUS only)

# SBN @FNAL: L/E Optimization

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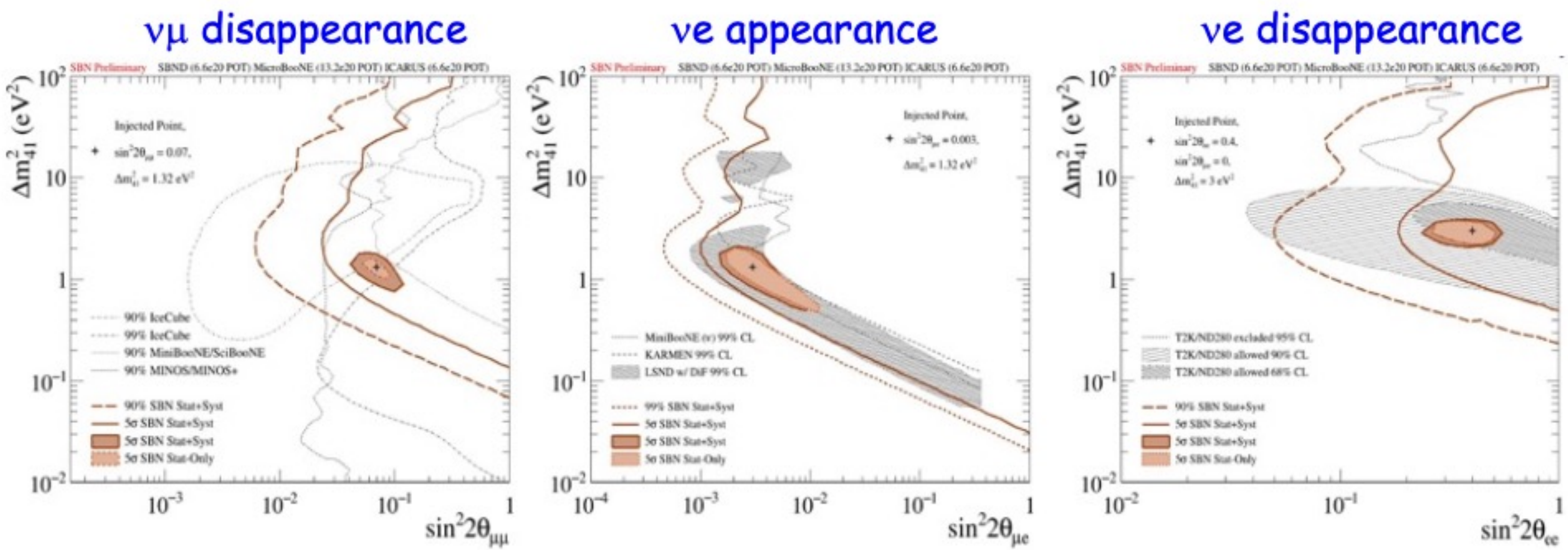
# Sterile neutrino sensitivity, 3 years ($6.6 \times 10^{20}$ pot)

Combined ICARUS (FD) and SBND (ND) data analysis using the same LArTPC event imaging greatly reduces expected systematics

- Initial BNB beam composition and spectrum provided by SBND
- High $\nu_e$ identification capability/NC background rejection provided by LArTPC

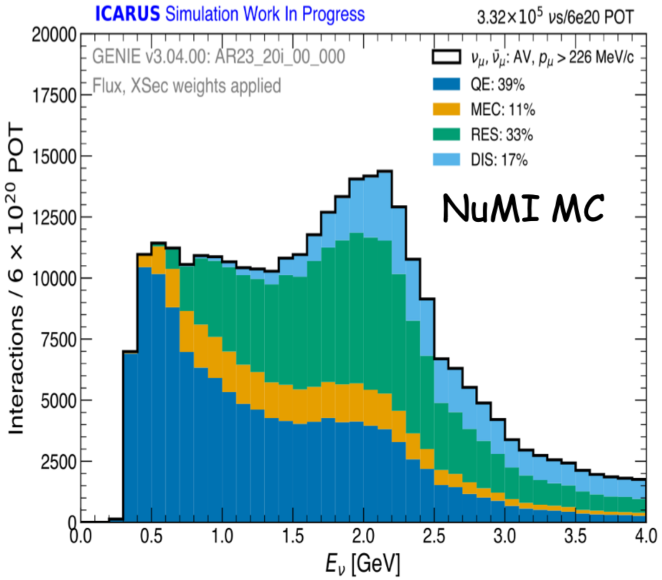



- 5σ coverage of the parameter area relevant to LSND anomaly

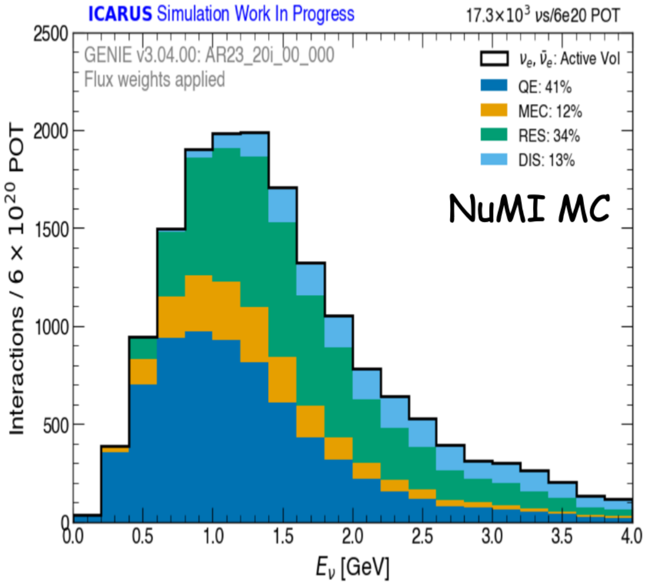
Unique capability to study neutrino appearance/disappearance simultaneously

# Neutrinos at the Main Injector (NuMI) Beam

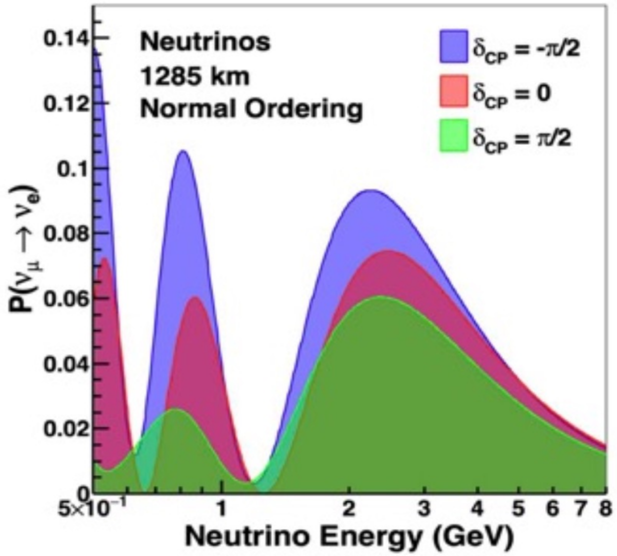
$\nu_\mu$ from NuMi to ICARUS




$\nu_e$ from NuMi to ICARUS




Oscillation Prob. at DUNE

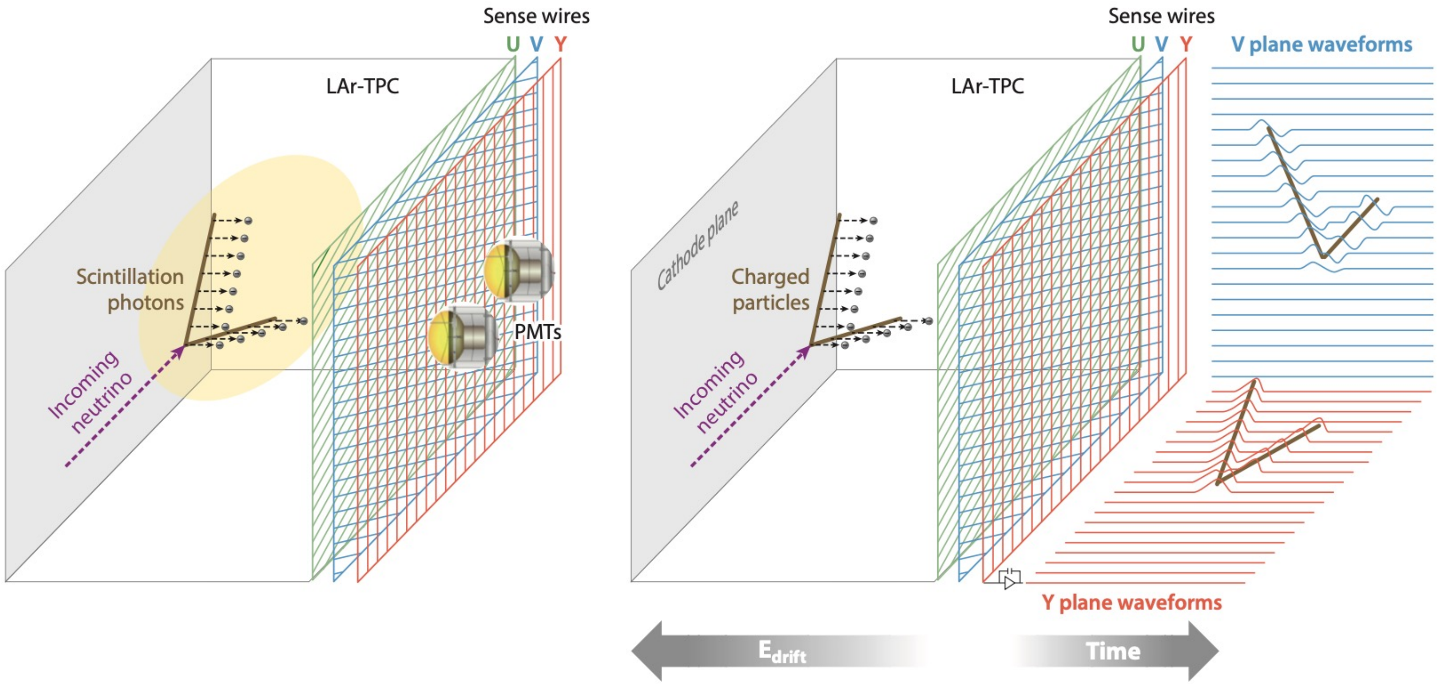



- Excellent statistics to measure cross sections

  Estimate of CC Events/6E20 pot: 332,000 $\nu_\mu$ / 17,000 $\nu_e$
- Neutrino energy spectrum from NuMI covers the first oscillation peak and has good coverage on the relevant phase space for DUNE
- Further exploitation of NuMI: rich BSM search program, Higgs portal scalar, $\nu$ tridents, light Dark Matter, Heavy Neutral Leptons, and more.

# Liquid Argon Time Projection Chambers

- From an idea of Carlo Rubbia (1977), LArTPCs are ideal detectors for ν physics: they allow to have simultaneously an **energetic reconstruction** of the events and a **3D image** of ν interactions




- Charged particles generate excited argon molecules that **emit light**
  - Fast component (τ < 2 ns): identify time of neutrino interaction (**Trigger**)
  - Slow component (τ ~ 2-3 μs): energy measurement
- Charged particles **ionize argon**: 42,000 $e^-$/MeV and the 500 V/cm Electric Field drifts the $e^-$ (1.6 m/ms) towards the anode where wire planes are used to generate **2D images** of charged particle tracks

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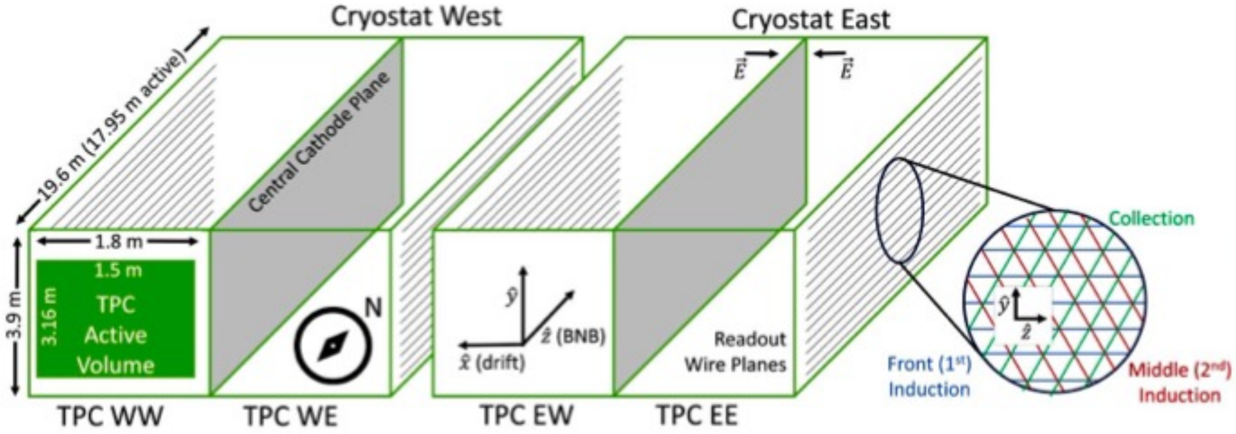
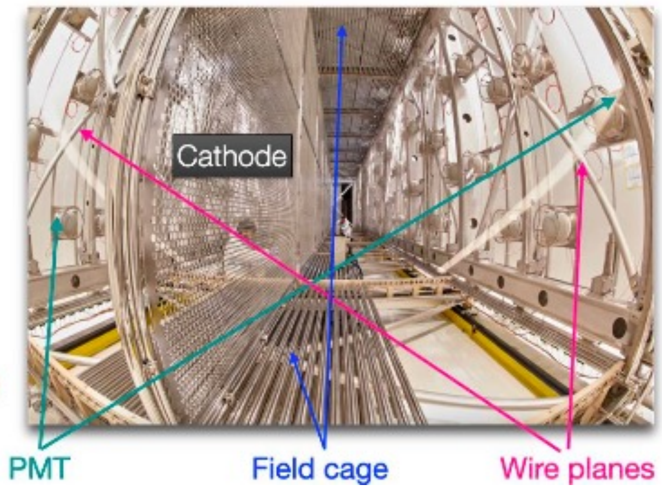
# ICARUS AT FERMILAB

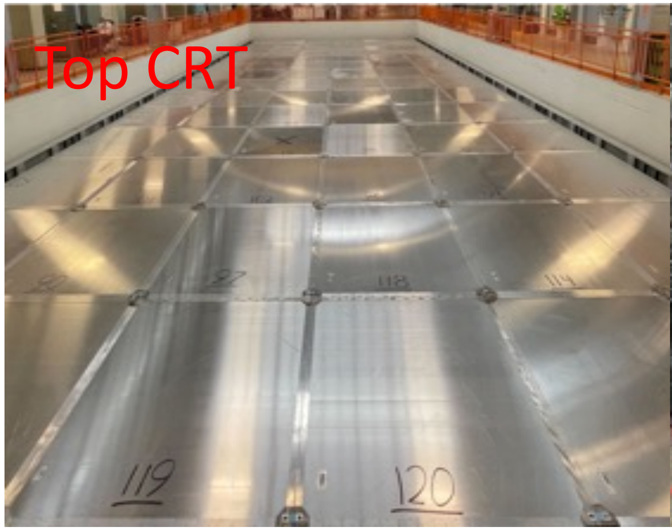



- **ICARUS T600:** the first large scale LArTPC ever built with 760 tons of pure LAr, **470 tons** active mass
- **2 cryostats** (3.6 x 3.9 x 19.6 $m^3$) with 2 TPCs each and a central cathode (1.5 m drift, $E_D$ = 500V/cm)
- **3 wire planes per TPC:** total of 54,000 wires at 0°, ±60°, 3mm pitch to measure ionization signal
- **360 PMTs** behind the wires to measure scintillation light and provide trigger (300 ps resolution)
- LAr/GAr purified by copper filters and molecular sieves for water absorption
- 2.85 m concrete **overburden** to suppress and external Cosmic Ray Tagger (**CRT**) to tag **cosmic rays background**
- After **3 yr physics run at LNGS** and **intensive overhaul at CERN**, ICARUS was moved to Fermilab

# Cosmic-ray background mitigation in ICARUS

- **ICARUS** exposed in a pit to cosmic rays: electrons produced by $\gamma$'s via Compton Scatt./Pair Prod. can mimic a genuine $\nu_e$ CC event
- Cosmic muons entering ICARUS are identified in time/position by $4\pi$ CRT 1000 $m^2$ double-layer scintillation bars equipped with SiPMs surrounding the LArTPC



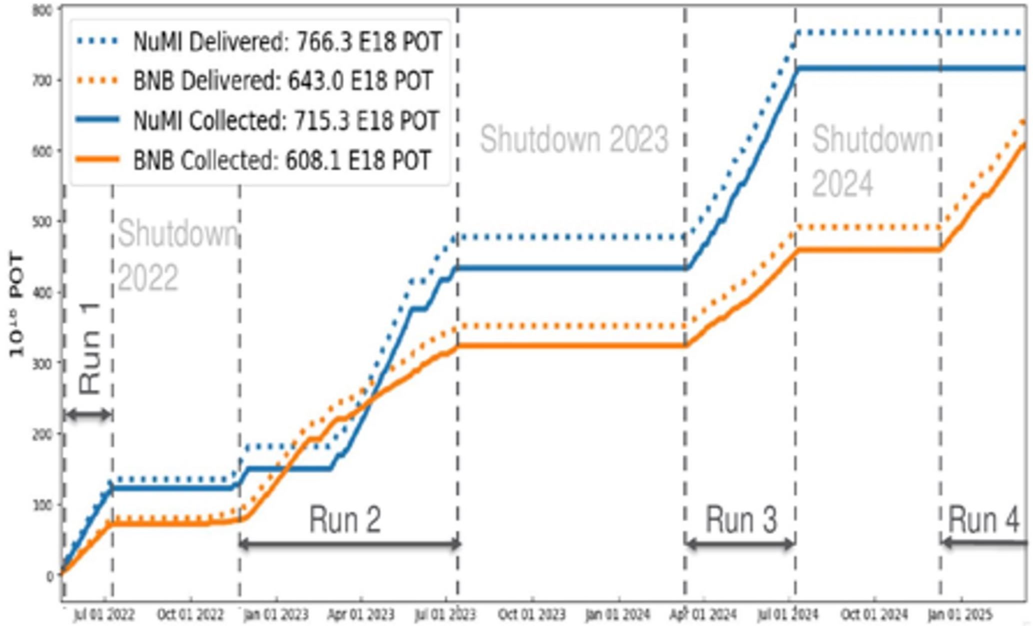


- Cosmic $\gamma$'s and neutrons suppressed by 2.85 m concrete overburden installed above the CRT

# ICARUS Operations and Data Collection at Fermilab

ICARUS data taking for physics started in June 2022

- **3 physics runs completed** + Run 4 ongoing since December 2024
- Steady data taking, **excellent stability** at BNB rates > 4 Hz, > 90% live time
- Highly pure liquid argon: **free electron lifetime 7-8 ms** -> full track detection efficiency in the 1.5 m drift (1 ms)
- Trigger: light signal registered by 4 PMT pairs in a 6 m detector slice in coincidence with BNB (1.5 μs), NuMI (9.5 μs) beams

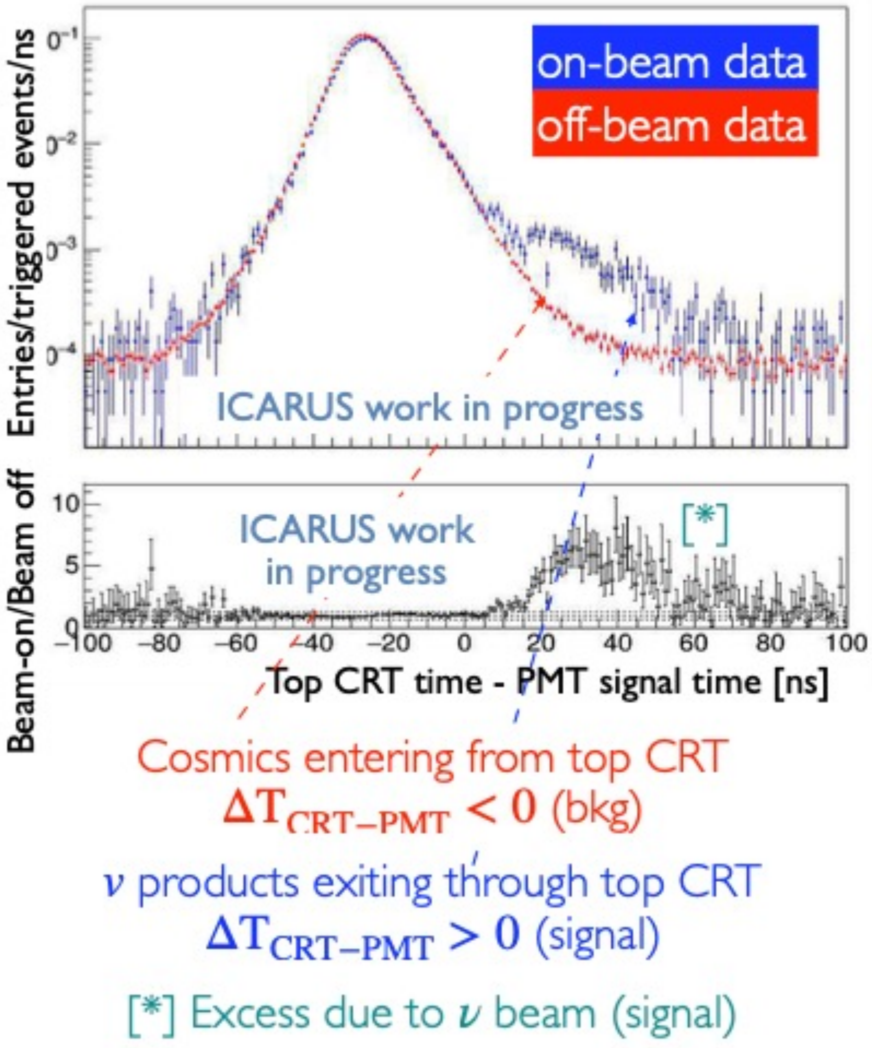



| Collected PoT | BNB (FHC) positive focusing | NuMI (FHC) positive focusing | NuMI (RHC) negative focusing |
|---|---|---|---|
| RUN-1 (Jun - Jul 22) | $0.41\ 10^{20}$ | $0.68\ 10^{20}$ | - |
| RUN-2 (Dec 22 - Jul 23) | $2.06\ 10^{20}$ | $2.74\ 10^{20}$ | - |
| RUN-3 (Mar - July 24) | $1.36\ 10^{20}$ | - | $2.82\ 10^{20}$ |
| RUN-4 (Dec 24 - today) | $2.58\ 10^{20}$ | - | - |
| TOTAL | $6.41 \times 10^{20}$ | $3.42 \times 10^{20}$ | $2.82 \times 10^{20}$ |

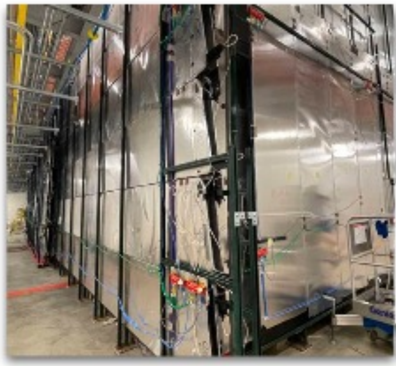
# Detector Performance

All ICARUS subsystems fully operational since the start of physics runs

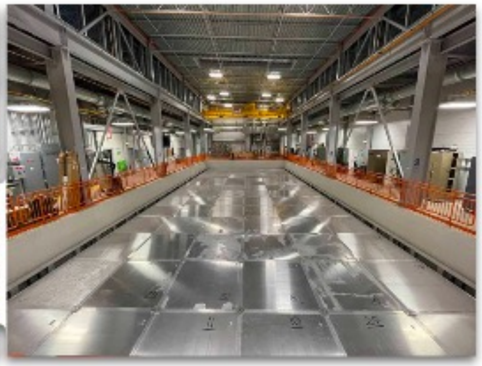
- External CRT tags incoming cosmics with 95% efficiency
- Inner PMTs have gain equalized within 1% to G = $5\times10^{6}$
- Measurement of the time of flight (ToF) with signals from CRT & PMT system to reject cosmics ray background




Side CRT



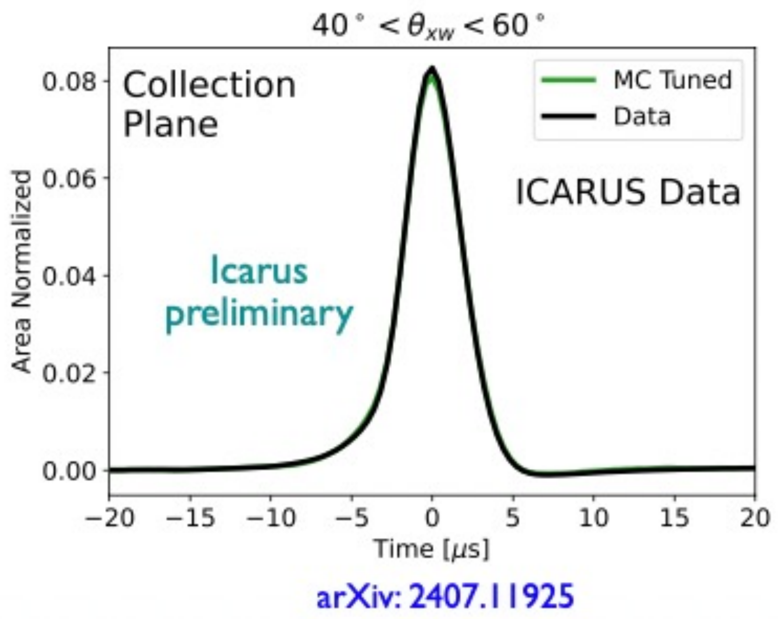
Top CRT

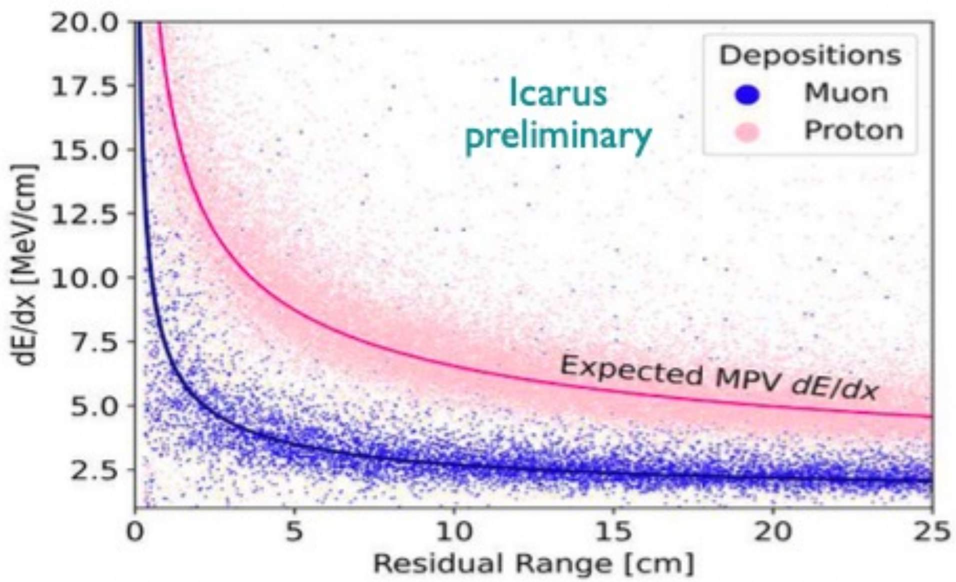


Bottom CRT

# Detector Calibration and Modelling

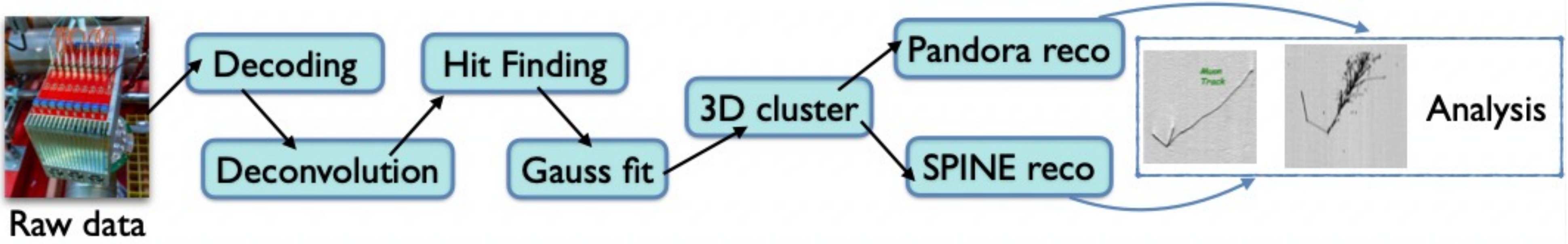
- Accurate modelling of the signal from TPC wires and new angular dependent **recombination model** (arXiv:2407.12969)
- Detector response **calibration** extracted from cosmic muons and protons from ν interactions, and the energy reconstruction validated comparing calorimetric and range-based reconstructions
- Use energy loss per unit length (**dE/dx**) vs residual range for particle identification (PID)



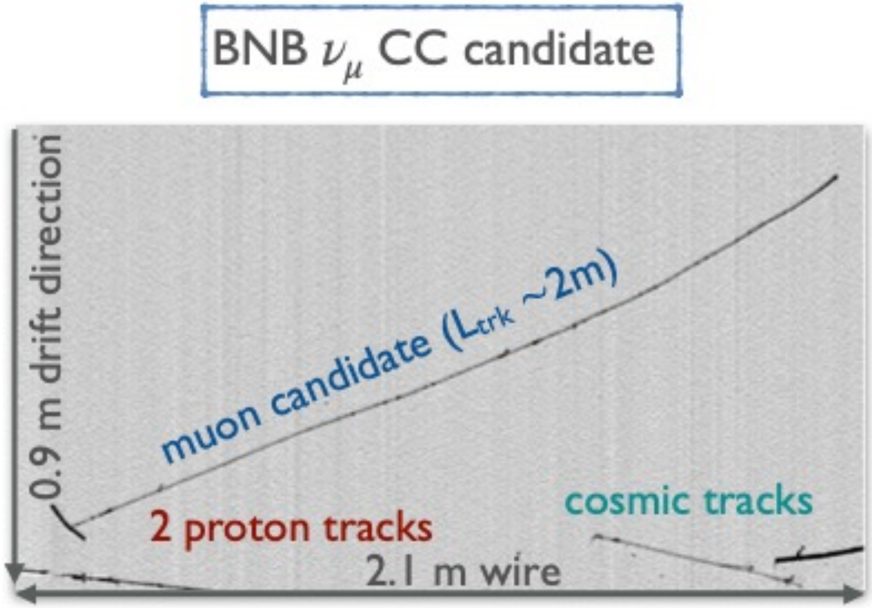




**Average signal response** for a track angular bin

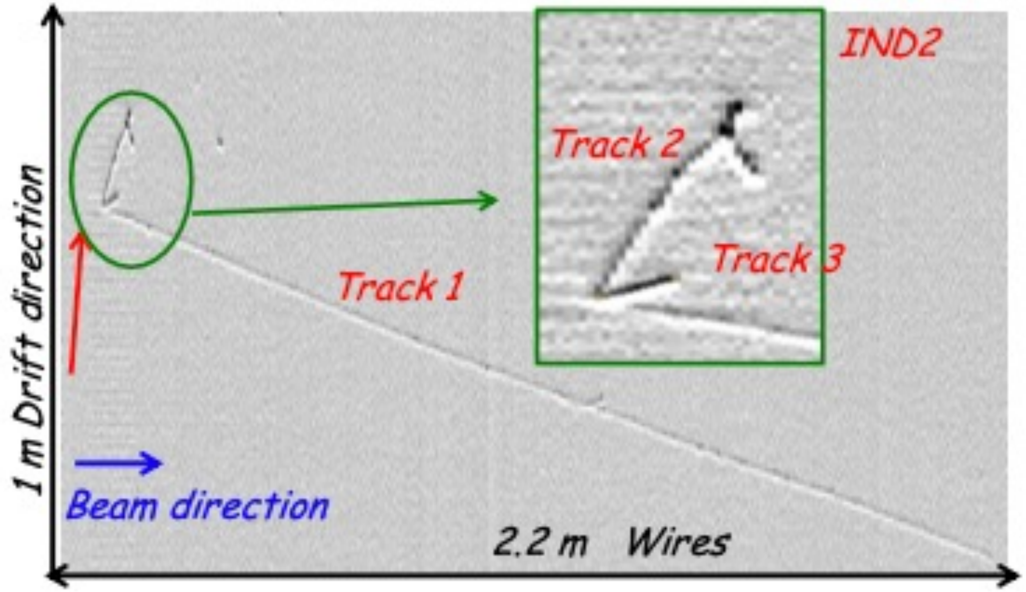
# Neutrino Candidates Reconstruction

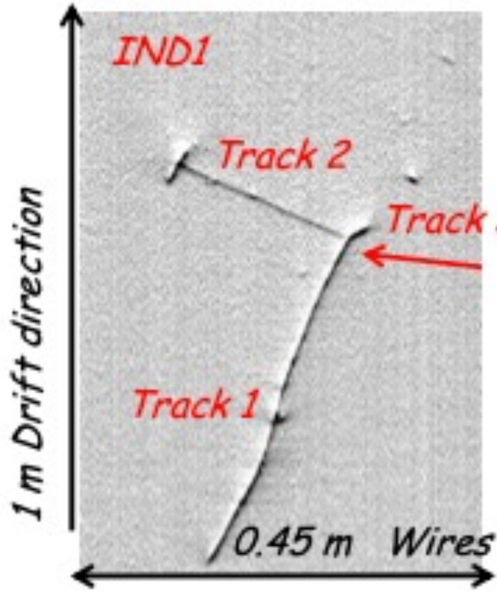


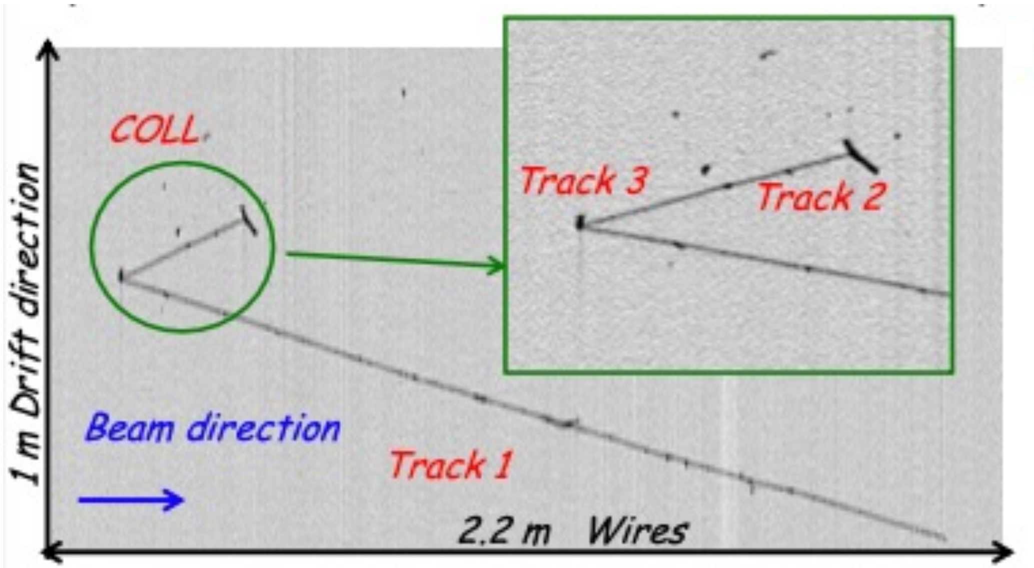

- Two reconstruction frameworks to characterize ν events
  - **Pandora**, pattern recognition software widely used in LArTPC
  - **SPINE**, entirely based on ML techniques
- Continuous effort to improve reconstruction and data/MC agreement
- Validation using **visual scanning**
  - Interaction point (vertex) reconstruction
  - Agreement between light and charge signal barycenters along longitudinal (beam) direction within 1 m



# $\nu_\mu$ CC candidate: 1 Event, 3 pictures

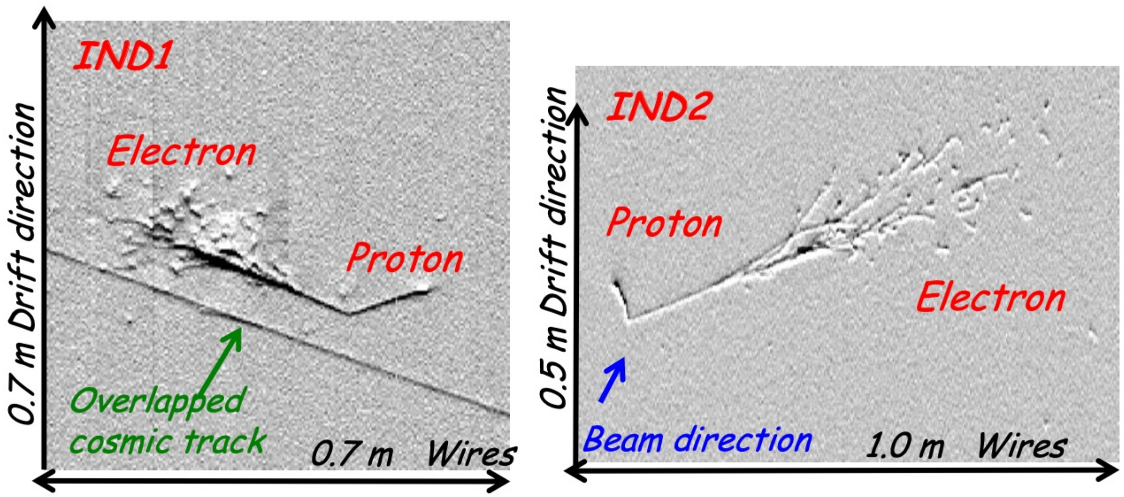


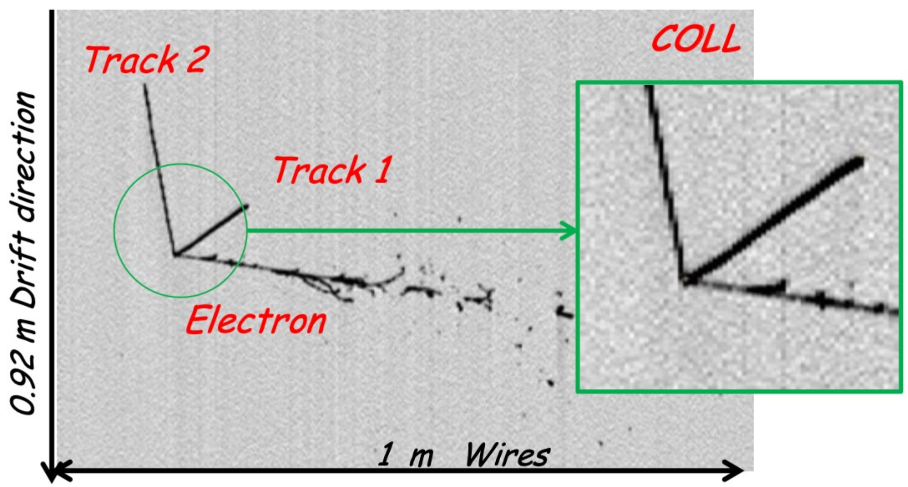




- **Three tracks at the primary vertex**
- Track 1 (**muon**): downward going, crossing the cathode and stopping in the detector (L = 6.4 m)
- Track 2 (**hadron**): downward going, interacting in the detector and producing two short protons
- Track 3 (**proton**): upward going (L = 3.4 cm)

# NuMI $\nu_e$ CC candidates

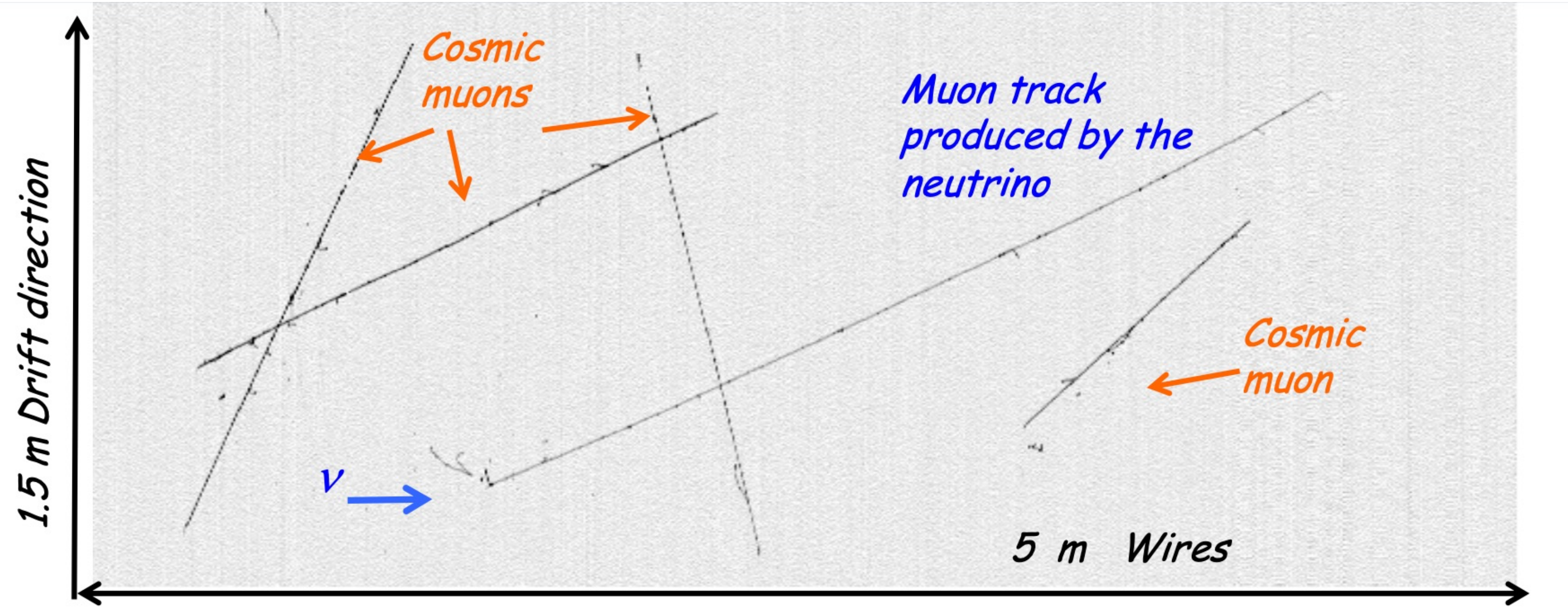


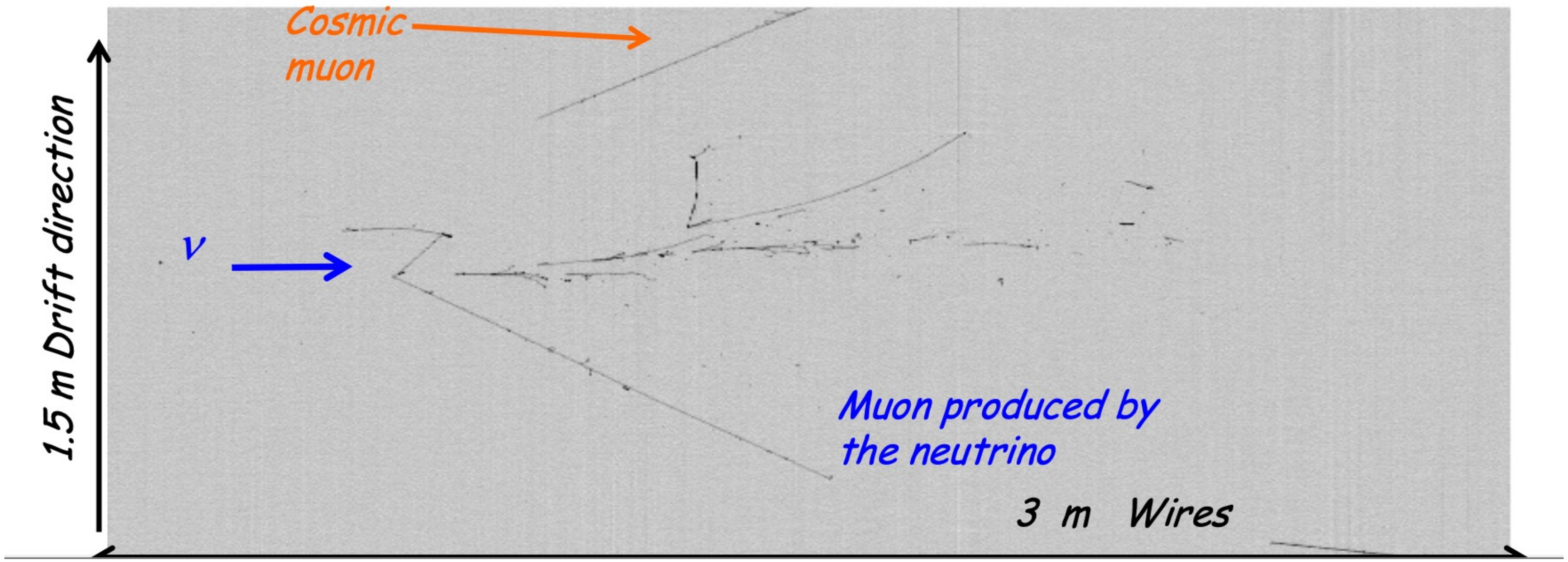

- **Two tracks at the primary vertex**
- QE $\nu_e$ CC candidate fully contained in active LAr, ($E_{dep}$ = 870 MeV)
- Electron shower: downward going
- Track 1 (**proton**): upward going and stopping (L = 13 cm)




- **Three tracks at the primary vertex**
- $\nu_e$ CC candidate fully contained in active LAr, ($E_{dep}$ = 830 MeV)
- Electron shower: downward going ($E_{dep}$ 570 MeV
- Track 1 (**proton**): upward going and stoppong (L = 23.7 cm)
- Track 2 (**hadron**): upward going and stopping (L = 33.4 cm)

# Neutrino Events + Cosmics: Real Life



# ICARUS Physics Program

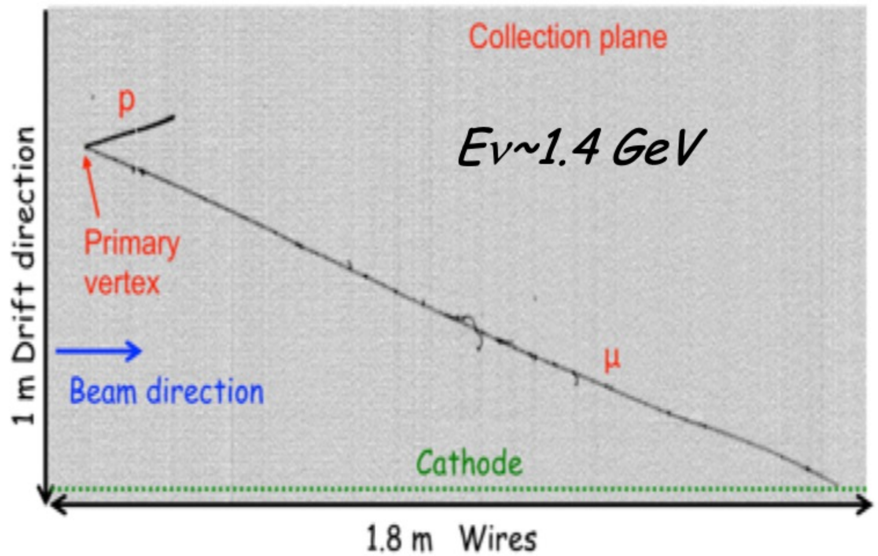
- **SBN joint (SBND+ICARUS) physics program**: address the question of **sterile neutrinos** with the BNB beam by comparing $\nu_e$ and $\nu_\mu$ interactions at different distances from the target, as measured by ICARUS and SBND LArTPCs

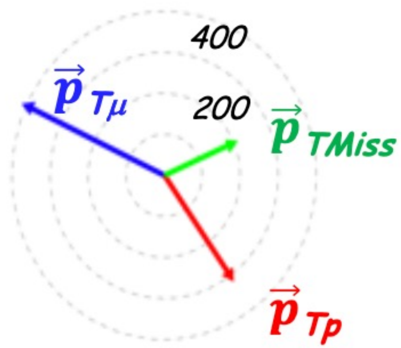
- Before performing the joint oscillation analysis with SBND, ICARUS is now focusing **on a standalone physics program**
  - Analysis of the $\boldsymbol{\nu_\mu}$ **disappearance** channel with BNB, to be complemented with $\boldsymbol{\nu_e}$ **disappearance from NuMI** beam data (enriched $\nu_e$ composition due to 6-degree off-axis): verify the **Neutrino-4 experiment claim**
  - Study $\nu_\mu$ and $\boldsymbol{\nu_e}$ interactions from the NuMI beam **to measure $\nu$-Ar cross sections** and optimize event reconstruction in the **DUNE** energy range
  - Search for evidence of physics Beyond Standard Model in other channels using NuMI data. A channel was already explored: **dark matter decay in a di-muon state** (Phys.Rev.Lett. 134 (2025) 15, 151801)

- Blinding policy established to ensure robust and unbiased interpretation of the collected data: analyses are initially validated with a subset of collected data

# $\nu_\mu$ Disappearance Analysis with BNB Beam Data

- Selection of **fully contained $\nu_\mu$CC events with 1$\mu$+N protons** in the final state (event kinematics extracted from range measurements)
  - PMT light signal within 1.6 $\mu$s beam spill in coincidence with reconstructed TPC tracks, no CRT signal
  - A muon with $L_{trk}$ > 50 cm, N > 1 protons with $E_K$ > 50 MeV ($L_{trk}$ > 2.3 cm)
  - No additional $\pi$ or $\gamma$
- Residual cosmic background < 1%
- **Two independent analysis streams**, respectively based on
  - **Pandora:** pattern recognition algorithm
  - **SPINE:** Machine Learning (ML) base reconstruction code
- A **further visual selection of $\nu$ candidates** is used to validate the event selection/reconstruction

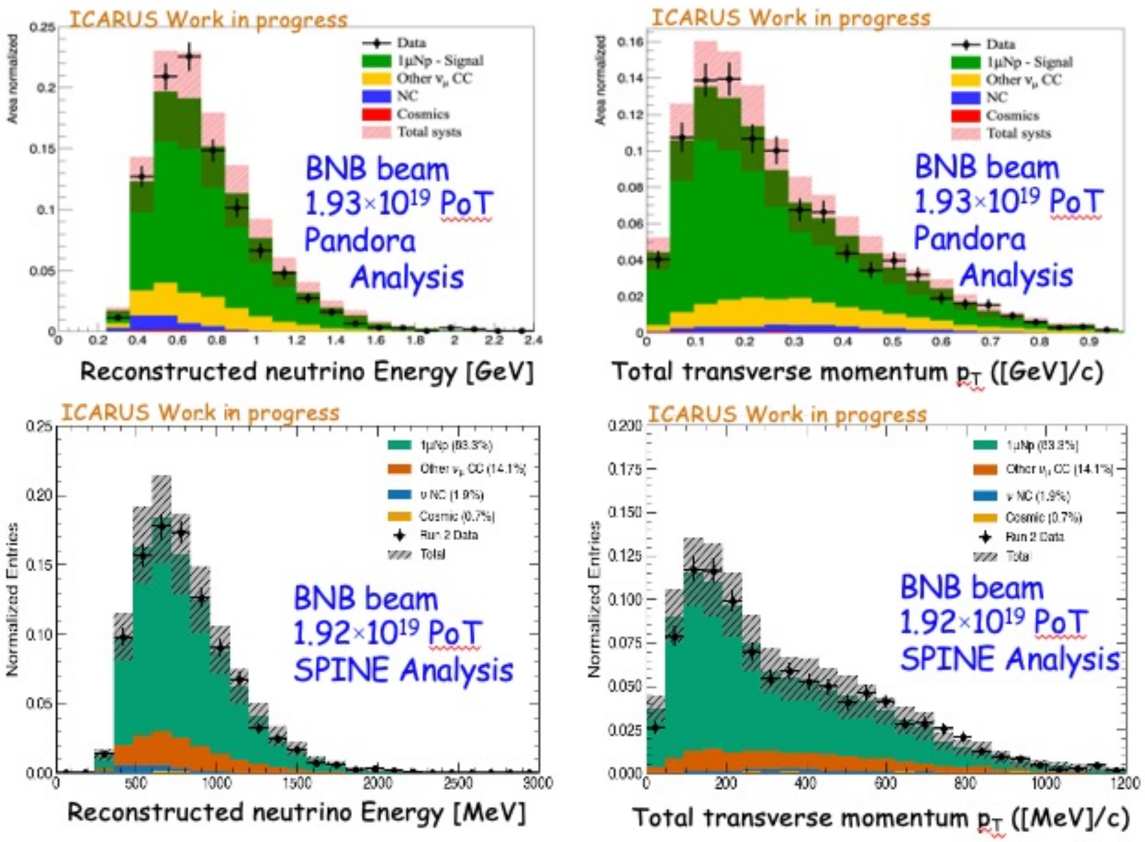



Momentum in the transverse plane (MeV/c)

# $\nu_\mu$ Disappearance Analysis: Preliminary Results

- **10% of Run-2 data analysed** ($2x10^{19}$ pot, about 20x data available) showing data/MC agreement within systematic effects for all studied kinematic variables




**Pandora-based** reconstruction
- 50% signal efficiency, 80% signal purity
- $1.93x10^{19}$ Proton on Target

(34,000 events expected in Run 1-3)

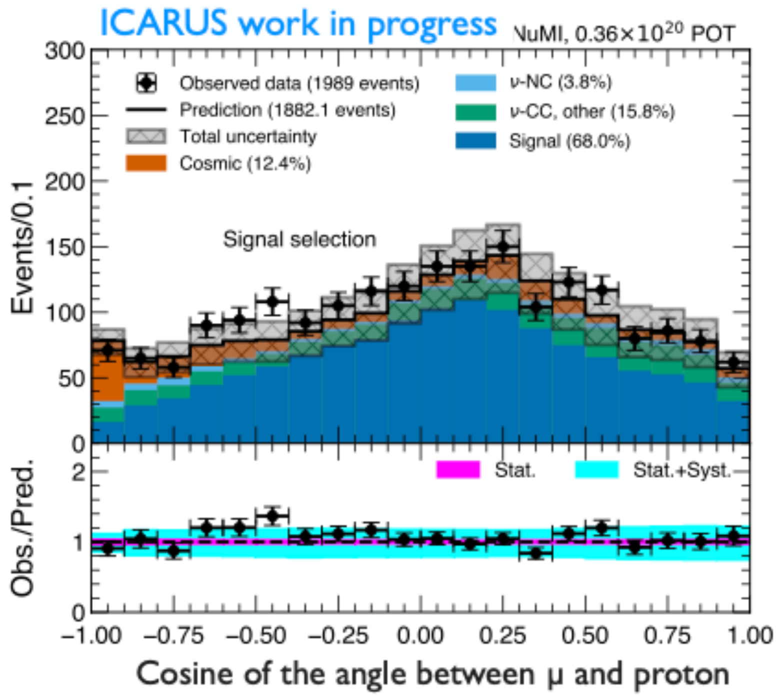
**SPINE-based** reconstruction
- 75% signal efficiency, 80% signal purity
- $1.92x10^{19}$ Proton on Target

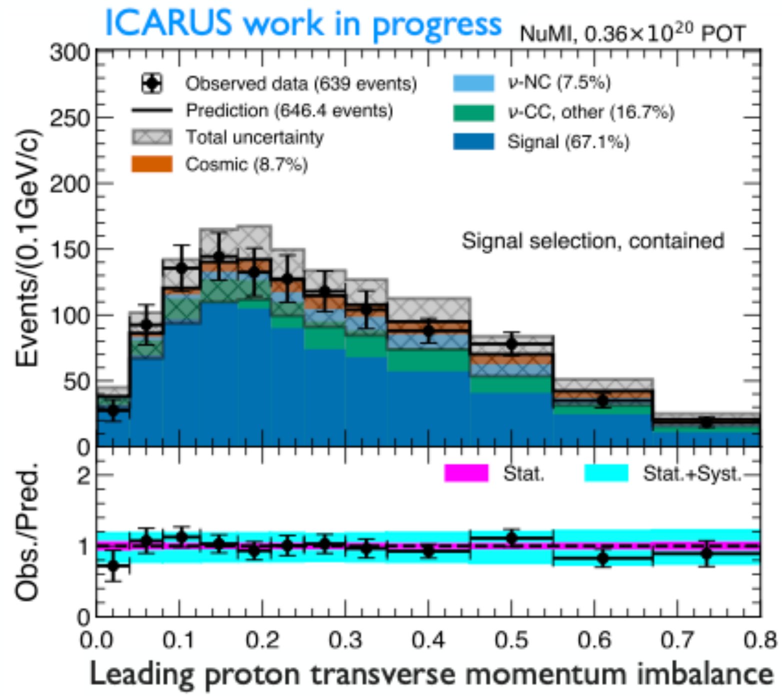
(47,000 events expected in Run 1-3)

- **Next analysis steps**
  - Enlarge the control sample to confirm the robustness of the analysis
  - Proceed to full data unblinding and oscillation fit

# Cross Section Measurements with NuMI Data

- Huge statistics to measure $\nu_\mu$ and $\nu_e$ cross sections with different types of interactions (with 6 x $10^{20}$ PoT: estimated 332,000 $\nu_\mu$ and 17,000 $\nu_e$)
- **First analysis targets 1$\mu$+Np+0$\pi$ in the final state:**
  - **Signal definition:** 1$\mu$ with p > 226 MeV/c, any proton with 400 MeV/c < p < 1 GeV/c, no pion in the final state
  - Flux, interaction model, and detector systematic uncertainties included
  - Angle between $\mu$ and leadind p encodes information about Final State interactions
  - Transverse kinematic observables sensitive to Initial and Final State effects




Initial study with 15% of data, ready to enlarge statistics

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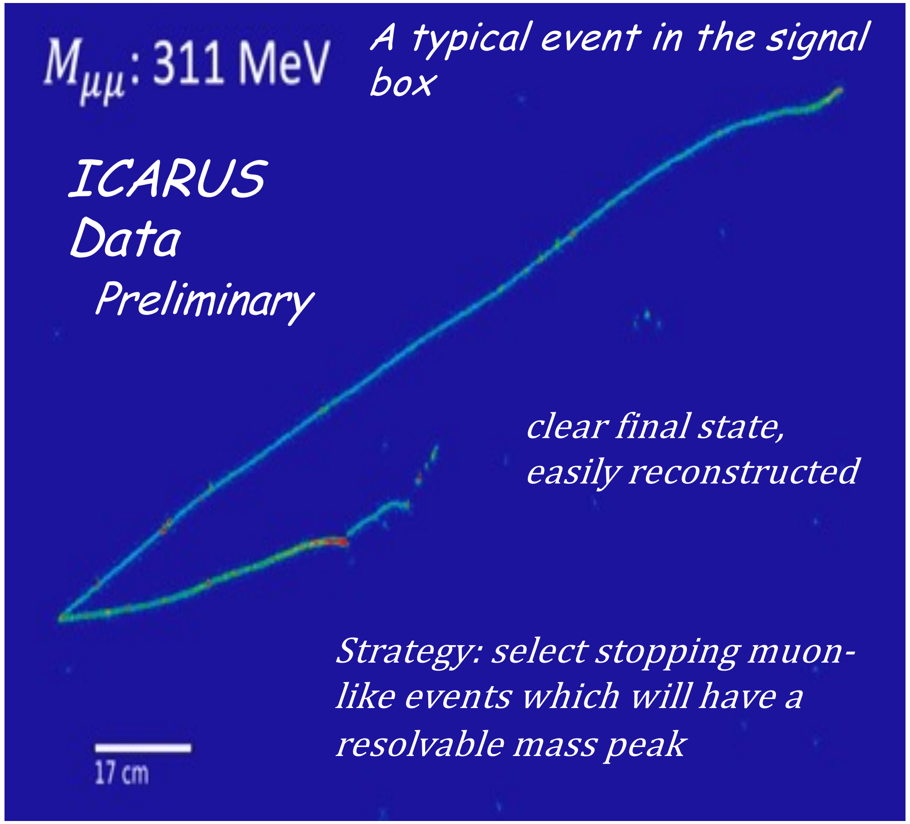
# Dark Sector models investigation with NuMI Data

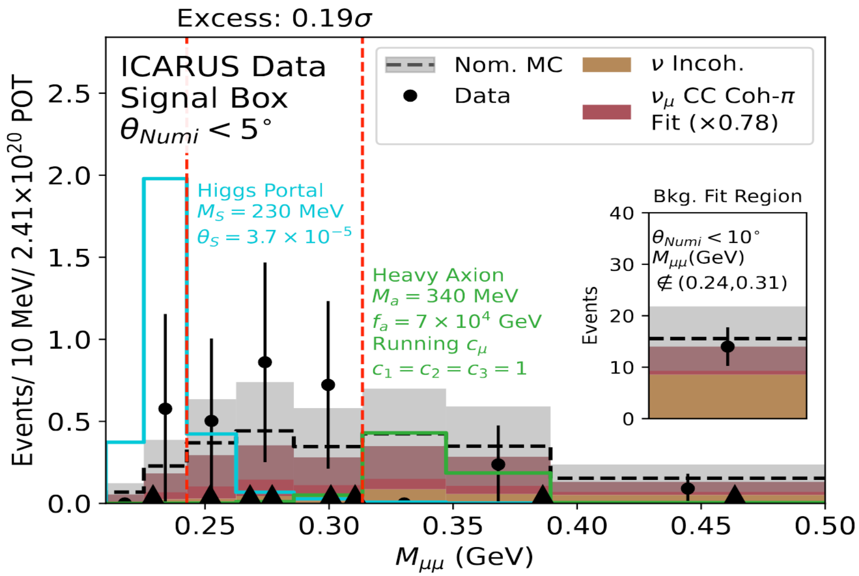
- Rich BSM search program (light DM, Heavy Neutral Leptons, Higgs Portal scalar, tridents and more) can be pursued by exploiting the off-axis NuMi beam
- Models considered so far involve dark particles coupling to SM particles via Scalar Portal Interactions:
  - Higgs Portal Scalar: Scalar dark sector particles, interactions by mixing with Higgs boson
  - Heavy QCD axion: Pseudo-scalar particles, interactions by mixing with pseudo-scalar mesons

- **ICARUS performed a first search for a new long-lived particle decaying into di-muon**
- Events with 2 stopping muons are selected to reconstruct the scalar mass peak
  - Signal expected at small angle from the beam ($\theta_{NuMI} < 5$ degree)
- Flux, interaction model and detector systematic uncertainties included

**Phys. Rev. Lett. 134, 151801 (2025)**

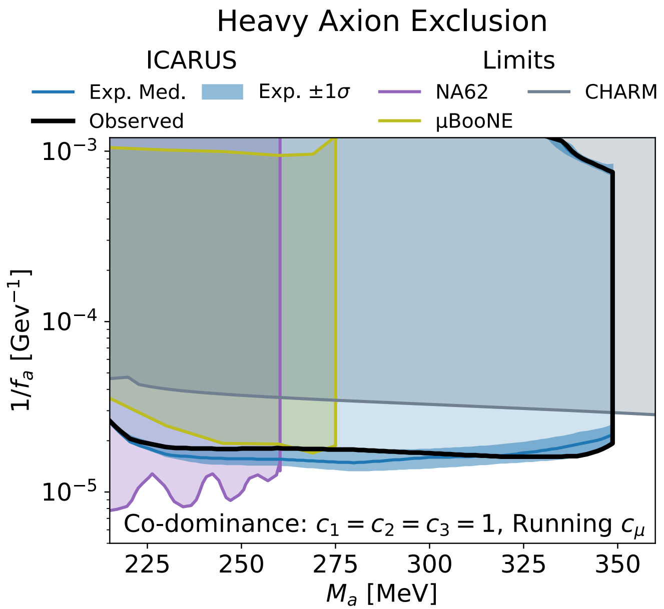


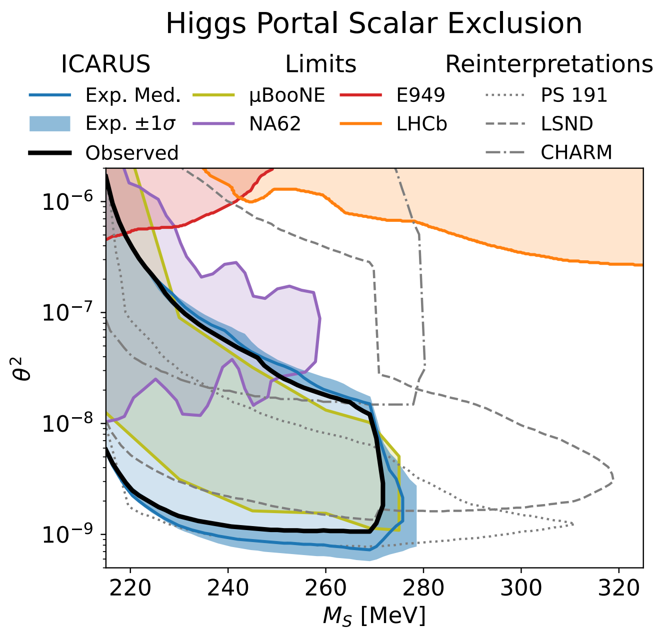
# BSM searches with NuMI Data: Results




- **Open box result:** 8 events observed, compared to MC expectations of 8 events mostly from $\nu_\mu$ CC coherent π production
- **No New Physics signal observed**

**Phys. Rev. Lett. 134, 151801 (2025)**



# ICARUS Pisa

| | | | | FTE | FTE - Totale |
|---|---|---|---|---|---|
| Giovanni | Chiello | Borsista | Università di Pisa | 1.00 | |
| Namitha | Chithirasreemadam | AdR | Università di Pisa | 0.80 | |
| Simone | Donati | PA | Università di Pisa | 0.50 | |
| Antonio | Gioiosa | RTT | Università del Molise | 0.40 | |
| Hussain | Kitagawa | Borsista | Università di Pisa | 0.40 | |
| Alessandro Maria | Ricci | AdR | Università di Pisa | 0.80 | 3.90 |
| X | Y | PhD 2025/2026 | Università di Pisa | 1.00 | 4.90 |

| | | | | |
|---|---|---|---|---|
| Master Theses | | | | |
| G. Chiello | Muon Momentum Reconstruction in ICARUS-T600 LArTPC via Multiple Scattering | Physics | Università di Pisa | March, 2025 |
| | | | | |
| Conferences | | | | |
| A.M. Ricci | Improving ICARUS track reconstruction algorithms | IFAE 2025 | Cagliari | April, 2025 |
| A.M. Ricci | Latest Results from the ICARUS Experiment at the Short Baseline Neutrino Program | ICNFP 2025 | Crete | July, 2025 |
| A.M. Ricci | Improving ICARUS track reconstruction algorithms | ICNFP 2025 | Crete | July, 2025 |
| A. Gioiosa | High Voltage Control System for the ICARUS Experiment at Fermilab | IPRD 2025 | Siena | September, 2025 |
| G. Chiello | Muon Momentum Reconstruction in ICARUS-T600 LArTPC via Multiple Scattering | SIF 2025 | Palermo | September, 2025 |

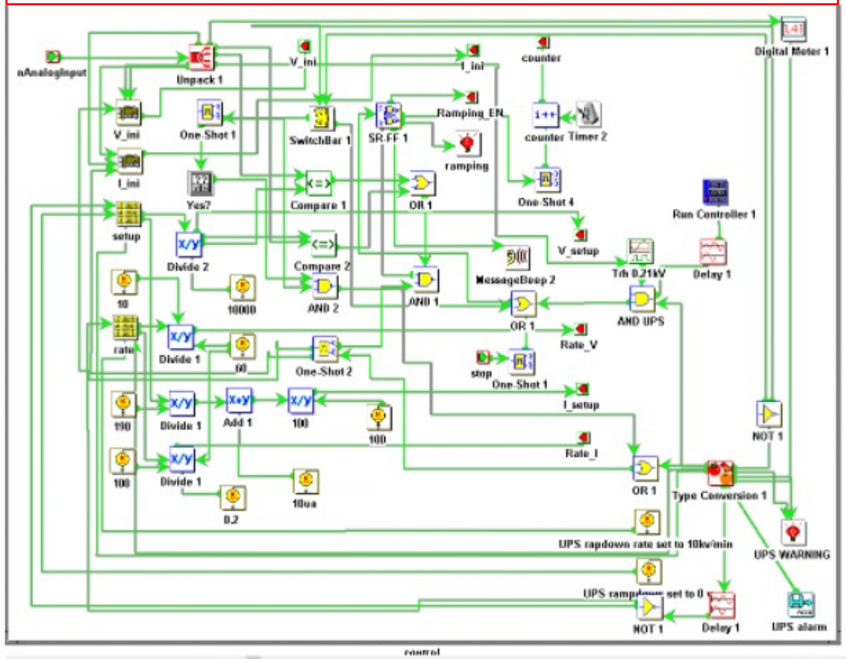
# High Voltage Control Software

- **ICARUS demands a High-Voltage (HV) system with exceptional stability and precise control**
- **HV Control System based on EDAS - 1000**
  - Multifunction Ethernet DAQ board, designed for high-speed analog data acquisition, digital I/O control and network integration
  - It offers power, flexibility and modularity for industrial and testing environments
  - It can be easily programmed and configured with full software support (Visual Designer, Net Link): no need for low-level coding

- **Since 2023, Antonio Gioiosa** has developed fully automated procedures to:
  - Configure voltage settings
  - Configure ramp rates
  - Configure precise safety thresholds
  - Perform automatic ramp down during an UPS warning
  - Perform automatic ramp stop
  - Control alarm
- Achieved HV stability within 25V at -75kV

**Antonio Gioiosa**, Convener of the HV Team

**High Voltage Control System**



# Slow Control and Data Quality Monitor

- **Slow Control:**
  - PMT Monitor voltage/currents (EPICS)
  - EPICS framework data storage system
- **Online Monitor pages** (used by Shifter/Experts on call):
  - PMT
  - Wire Bias
  - Ground impedance

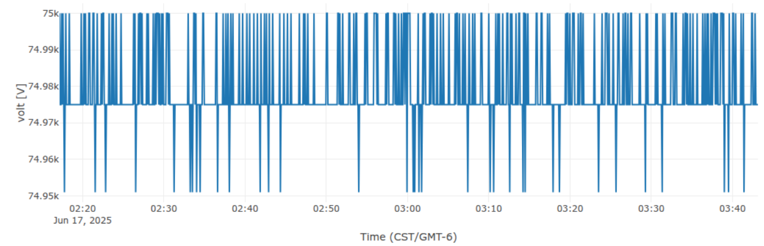
Jamie C. Dyer (FNAL), **Antonio Gioiosa**, Gianluca Raselli (INFN-PV), Geoffrey Savage (FNAL), Donatella Torretta (FNAL), Matteo Vicenzi (BNL)

**Archiver Engine Summary**

| | |
|---|---|
| State | RUNNING |
| Uptime | 19.24 days |
| Last Written | 2023/03/28 07:44:38 |
| Memory | 75.5 MB of 228.0 MB used (33.1 %) |

| Group | Enabled | Channels | Connected | State | Alarm Sev. | Time Last Archive |
|---|---|---|---|---|---|---|
| beam | Enabled | 28 | 0 | Disconnected | INVALID | 2023-03-09 01:05:04 |
| cathodehv | Enabled | 8 | 8 | ok | ok | 2023-03-28 07:44:33 |
| cryo | Enabled | 104 | 0 | Disconnected | INVALID | 2023-03-09 01:05:04 |
| electrical | Enabled | 12 | 12 | UDF_ALARM | INVALID | 2023-03-28 07:44:35 |
| pmthv | Enabled | 2186 | 2180 | UDF_ALARM/Disconne | INVALID | 2023-03-28 07:42:32 |
| pmttemperature | Enabled | 6 | 6 | UDF_ALARM | INVALID | 2023-03-09 01:19:34 |
| pmtvme | Enabled | 24 | 24 | ok | ok | 2023-03-09 13:46:25 |
| timing | Enabled | 23 | 0 | Disconnected | INVALID | 2023-03-09 01:05:04 |
| tpcps | Enabled | 1248 | 1248 | UDF_ALARM | INVALID | 2023-03-28 07:44:37 |
| wirebias | Enabled | 12 | 12 | ok | ok | 2023-03-28 07:44:33 |

| | |
|---|---|
| IOC last execution | 2023-03-28 07:45:01 |




| PV Name | icarus_cathodehv_set/volt |
|---|---|
| Description | None |
| Last Sample Time | 2025-06-17 03:41 |
| Last Sample Value | 74975.000 |
| Channel ID | 165 |
| DataType | None |
| Group ID | 8 |
| Group Name | cathodehv |
| Group Description | None |
| Engine ID | 4 |

Display Options

Start Time __/__/____ __:__

End Time __/__/____ __:__

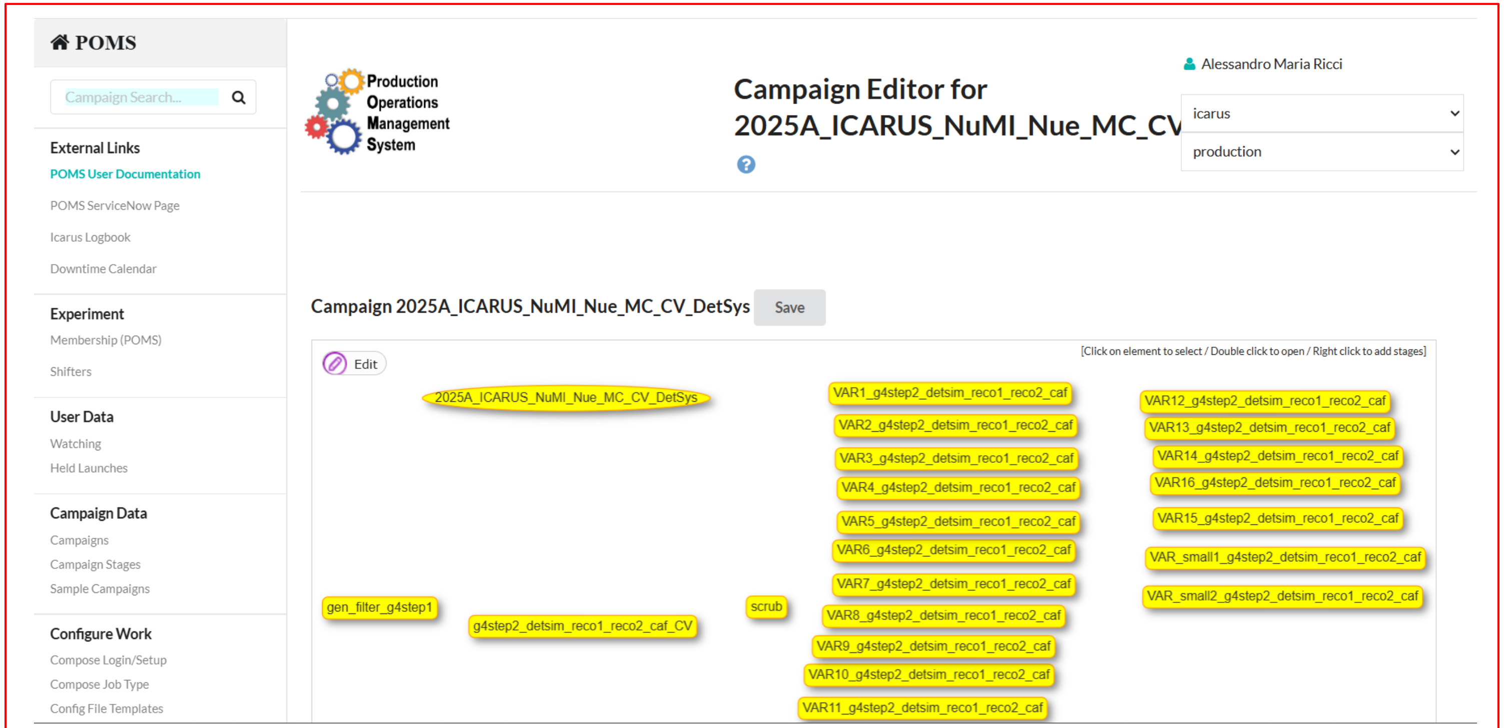
Live | Last Hour | Last 8 Hrs | Last Day | Last Week | Lookback

Download Data

**Cathode HV Monitor**

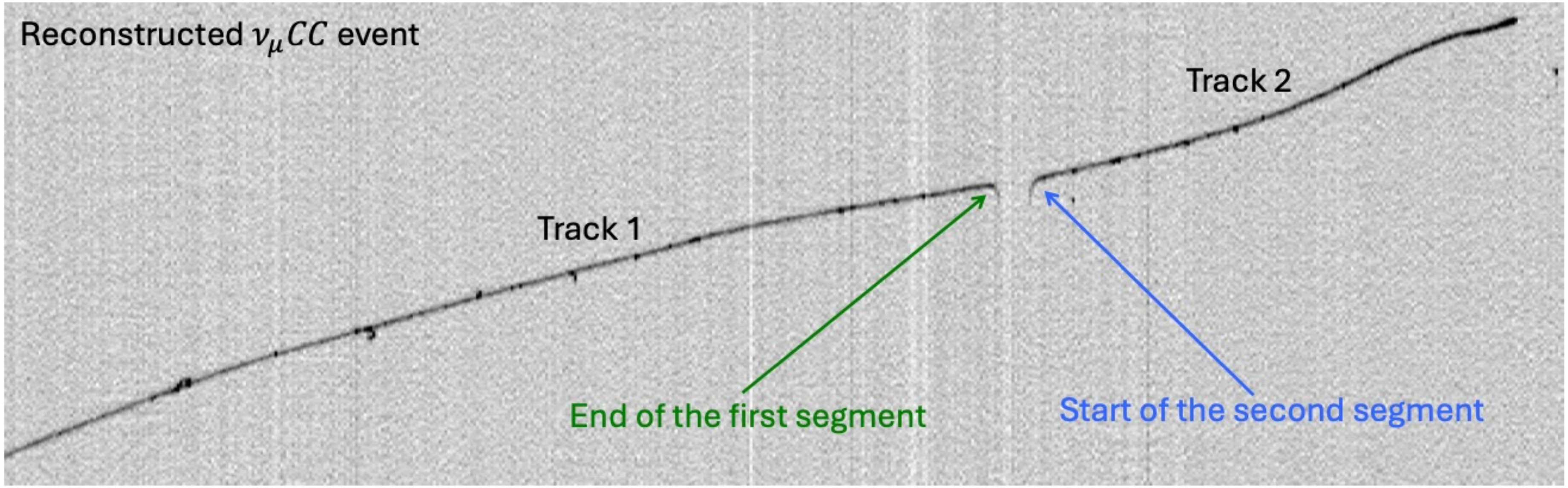
# MC Production/Data Processing with POMS

- **Production Teams at FNAL and CNAF**
  - **Responsible** for handling the requests and setting up MC simulations or data processing campaigns
  - **Responsible** for defining the required stages and their configurations according to the intended goals (calibration, signal and/or background studies, or data analysis)
  - Once configured and tested, the campaigns are submitted to the Computing Centers (**Fermilab, NERSC - operated by LBNL, and CNAF**)
- **Alessandro Maria Ricci, Antonio Gioiosa** are providing **leading contribution** to this effort



# Improving Track Reconstruction Algorithms (I)

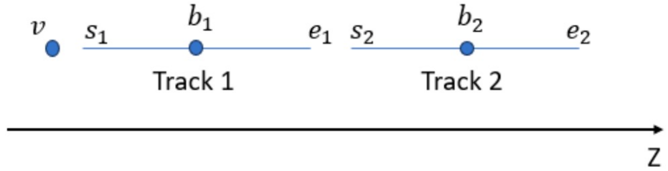
- **Pandora may erroneously break and lose a significant fraction of the particle's track**
- These cases of poor reconstruction are caused by
  - hit inefficiencies
  - kinks in particles trajectories
  - or particles crossing the cathode or the wire support structure of Induction 1 wires
- **This effect impacts a few % of the $\nu_\mu$ CC sample, increases the uncertainty in momentum reconstruction**, a feature that is still poorly modelled in the Monte Carlo)




**Alessandro Maria Ricci** has developed a "stitching algorithm" to repair these tracks

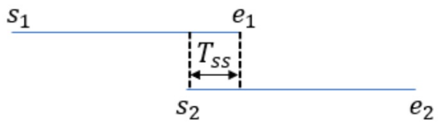
# Improving Track Reconstruction Algorithms (II)

- **Simple and quick:**
- Treat the VSS case (SVS disregarded)



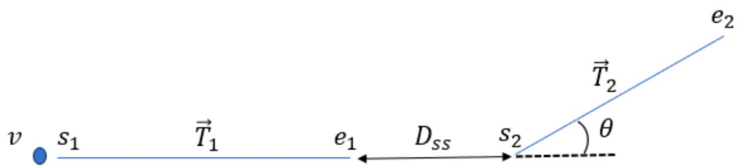

- Align barycenters, start- and end-point along the z (beam) axis
- Check overlap between segments

$$T_{ss} = \frac{|z_{s_2} - z_{e_1}|}{\min(D_{z,1}, D_{z,2})} < 0.7, \qquad D_{z,i} = |z_{e_i} - z_{s_i}|$$

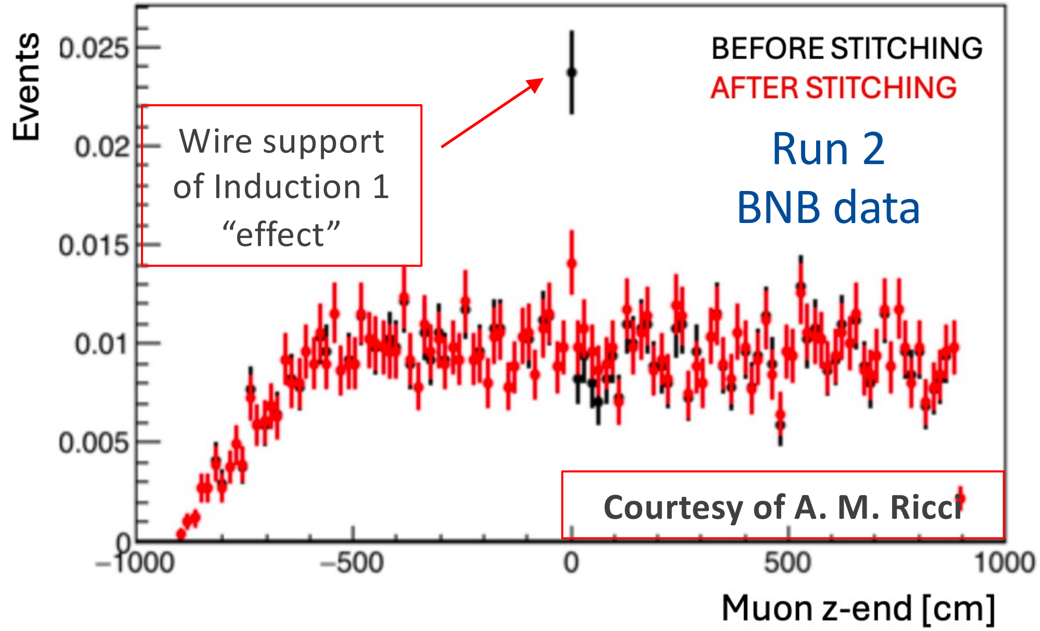



- Check angle/distance between segments

$$D_{ss} = \frac{\sqrt{\Delta x^2 + \Delta y^2 + \Delta z^2}}{\min(D_{se,1}, D_{se,2})} < 0.7, \qquad D_{se,i} = |\vec{T}_i| = |\vec{e}_i - \vec{s}_i|$$




- Monte Carlo: Efficiency = 73%, Purity = 89%

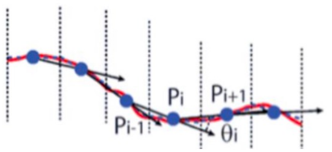



In a sample of 1,700 $\nu_\mu$ CC (Run 2)
3.2% of muon tracks can be repaired
Significant effects at z = 0
and at the Cathode (|x| = 210 cm)

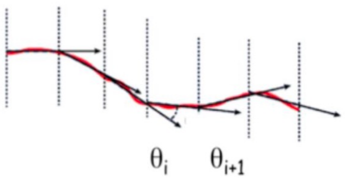
# Muon Momentum Reconstruction via Multiple Scattering

- **ICARUS typically exploits two ways to reconstruct charged particles' energy**
  - **Calorimetric energy reconstruction** from $e^-$ ionization charge collected on TPC wires
  - **Range-based energy reconstruction** (continuous slowing-down approximation)
- This is **feasible** only for **fully contained** particles
- **Additional method for uncontained muons: exploit Multiple Coulomb Scattering (MCS)**
  - 2 state-of-the-art MCS based algorithms
    - **Gran Sasso** algorithm
    - **MicroBooNE** algorithm

- **Gran Sasso** algorithm:
  - Use 2D, or 3D hits
  - Divide $\mu$ track into N segments and measures deflections
  - Build a **$\chi^2$-like** function to estimate momentum




- Polygonal approach



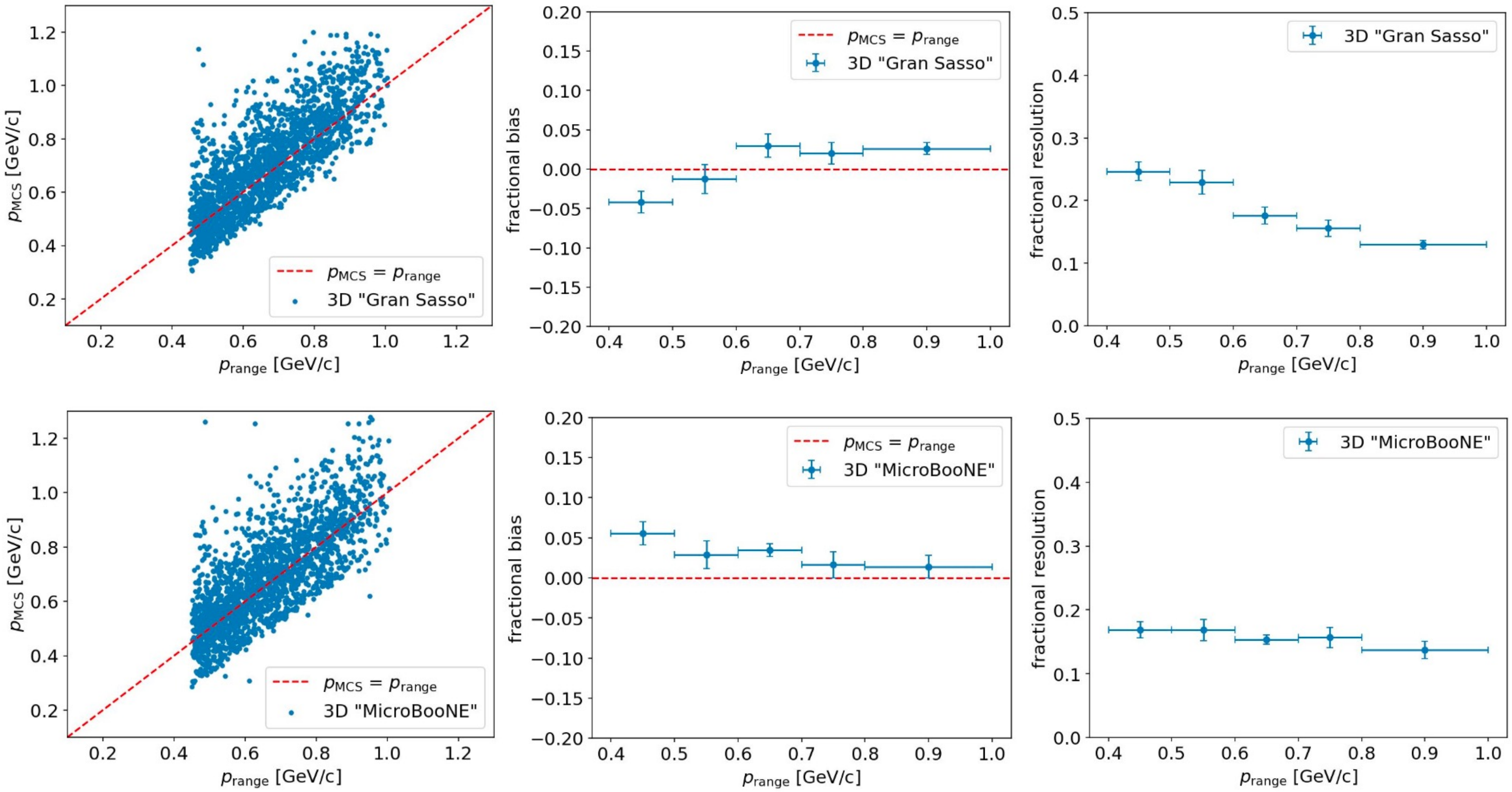

- Linear-fit approach

- **MicroBooNE** algorithm:
  - Use 3D hits only
  - Divide $\mu$ track into N segments and measures deflections
  - Build a **likelihood** function to estimate momentum
  - Only uses linear-fit approach

**Giovanni Chiello's Master Thesis in Physics at the Università di Pisa, March 2025**


Fermilab

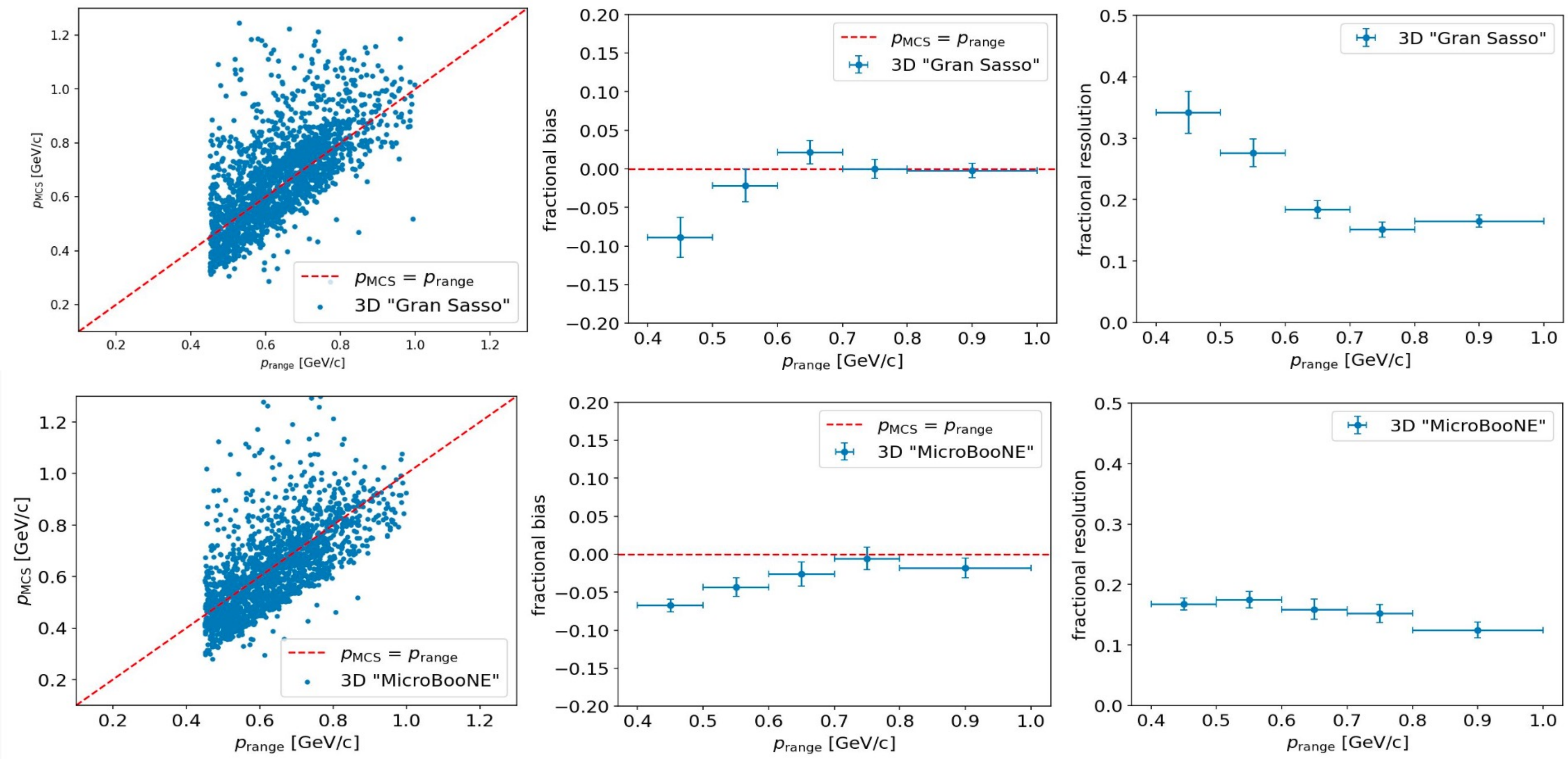
# Monte Carlo: Results (3D Algorithm)




- **Efficiency: close to 100%**
- **Fractional bias: few %**
- **Resolution: 16% at high momentum**

Courtesy of Giovanni Chiello

# Real Data: Results (3D Algorithm)




- **Efficiency: 90%** (slightly lower in data than in MC)
- **Fractional bias: few %**
- **Resolution: 14% at high momentum** (slightly worse for Gran Sasso algorithm)
- **MCS momentum algorithm: 2x increase in statistics for BNB and 3x for NuMi, crucial for oscillation studies and searches for sterile $\nu$**

# Participate in the $\nu_\mu$ Disappearance Analysis

- **Namitha Chithirasreemadam** will contribute to the study of **Detector Systematics** and the development of the **Oscillation Fitting Procedure**
- **Systematics**
  - **Neutrino flux systematics** (mostly Fermilab colleagues)
  - **Neutrino interaction model systematics** (mostly Fermilab colleagues)
  - **Detector Systematics: a lot of effects already being studied**
    - Recombination
    - Diffusion
    - Electron Lifetime
    - Space Charge
    - Scintillation Model
    - TPC Signal
    - TPC Noise
    - TPC Intransparency
    - Cathode Bending
    - Induction 1 Wire Gap
    - Trigger Efficiency
      - Additional Sources
- **Oscillation Fitting Procedure**
    - Learn, use and develop PROfit framework

# Long-Standing Collaboration with the $\nu$ Community

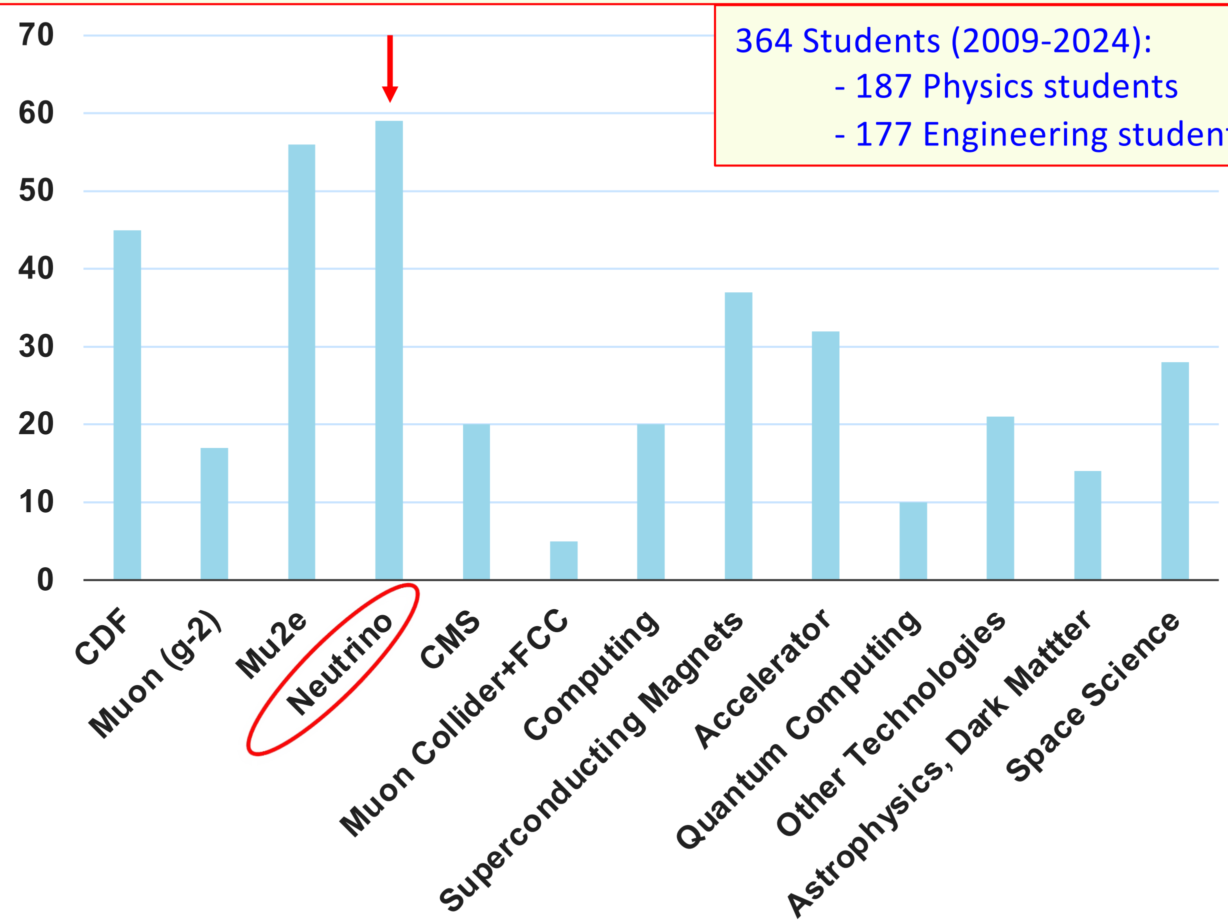
| | | | | |
|---|---|---|---|---|
| **NEWS** | H2020-MSCA-RISE-2018 | **INFN-PI** | UNIPI | 2017-2023 |
| **INTENSE** | H2020-MSCA-RISE-2018 | INFN-PI | **UNIPI** | 2019-2024 |
| **INTENSE** | H2020-MSCA-ITN-2019 | INFN-PI | **UNIPI** | 2020-2024 |
| **PROBES** | H2020-MSCA-RISE-2020 | **INFN-PI** | UNIPI | 2022-2026 |
| **SENSE** | HORIZON-MSCA-2021-SE-01 | INFN-PI | **UNIPI** | 2022-2026 |
| **PICO** | HORIZON-MSCA-2023-CITIZENS-01 | INFN-PI | | 2024-2026 |
| **BEYOND** | HORIZON-MSCA-2024-SE-01 | **INFN-PI** | | 2026-2029 |

**Thanks to the Ufficio Fondi Esterni of Infn Pisa**

# Long-Standing Collaboration with the ν Community

The Italian Summer Students Program at Fermilab and other US Laboratories

364 Students (2009-2024):
- 187 Physics students
- 177 Engineering students




**Neutrino Experiments are highly popular among students**

# Backup