ICNFP, Crete, Greece, July 17th-25th, 2025

Latest Results from the ICARUS Experiment at the SBN Program

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University of Pisa and INFN Pisa

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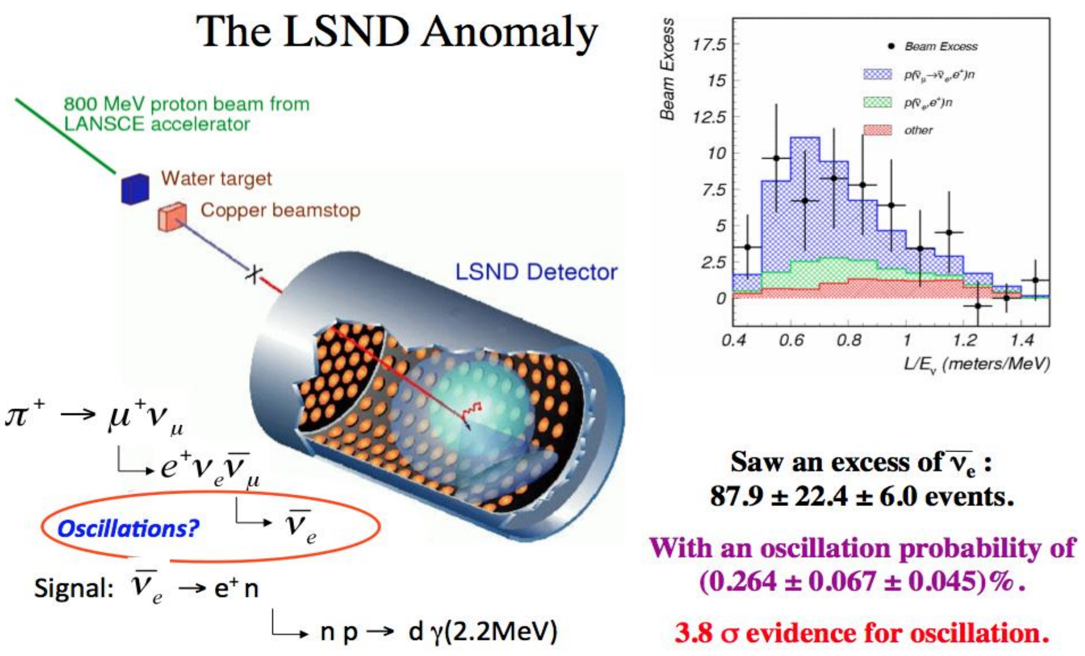
01

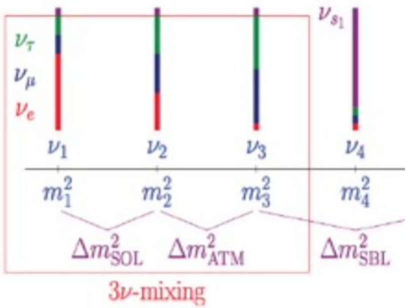
Sterile Neutrino

Persisting anomalies in the neutrino sector

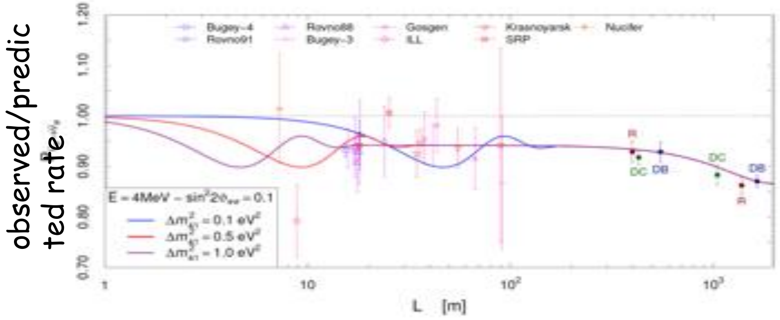
- $\bar{\nu}_e$ appearance: LSND experiment with $\bar{\nu}_\mu$ beam saw an excess $\bar{\nu}_e \rightarrow e^+ n$ at 3.8 σ.
- ν_e disappearance: SAGE, GALLEX experiments with Mega-Curie K-capture calibration sources showing an observed/predicted $R = 0.84 \pm 0.05$, recently confirmed at 4σ by BEST exp.
- $\bar{\nu}_e$ disappearance: in near-by nuclear reactor experiments RAA, $R = 0.934 \pm 0.024$, but study of fuel burnup cycle from Daya Bay, RENO, STEREO to reconstruct contribution of main isotopes: hint of $\nu_{sterile}$ reduced to $1\ \sigma$.



...pointing to $\nu_{sterile}$ hypothesized by Bruno Pontecorvo in a 1957 seminal paper...

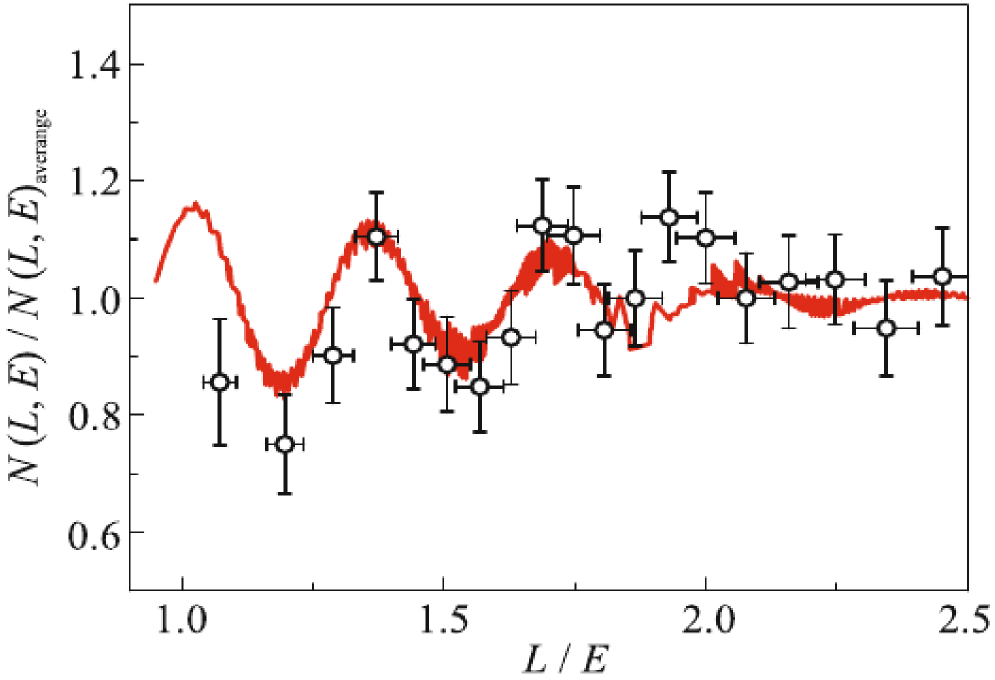


$$U = \begin{bmatrix} U_{e1} & U_{e2} & U_{e3} & U_{e4} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} & U_{\mu 4} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} & U_{\tau 4} \\ U_{s1} & U_{s2} & U_{s3} & U_{s4} \end{bmatrix}$$



New evidence for $\nu_{sterile}$ at reactor?

- In 2019 Neutrino-4 experiment (A.P. Serebrov et al.) at Dimitrovgrad SM-3 reactor gave evidence of ν oscillation into $\nu_{sterile}$ showing a disappearance signal with a clear $L/E \sim 1-3\ m/MeV$ modulation.



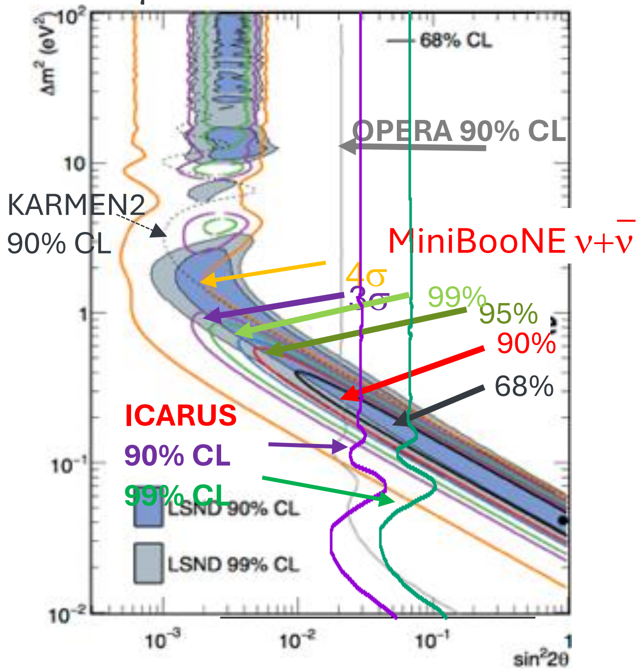
Combined analysis: Neutrino-4 (P.R. D 104, 032003, 2021), GALLEX, SAGE and BEST

$\Delta m^2_{14} = 7.3\ eV^2,\ \sin^2 2\theta_{14} = 0.36$ at $5.8\ \sigma$ C.L. (A.P. Serebrov et al. arXiv:2302.09958).

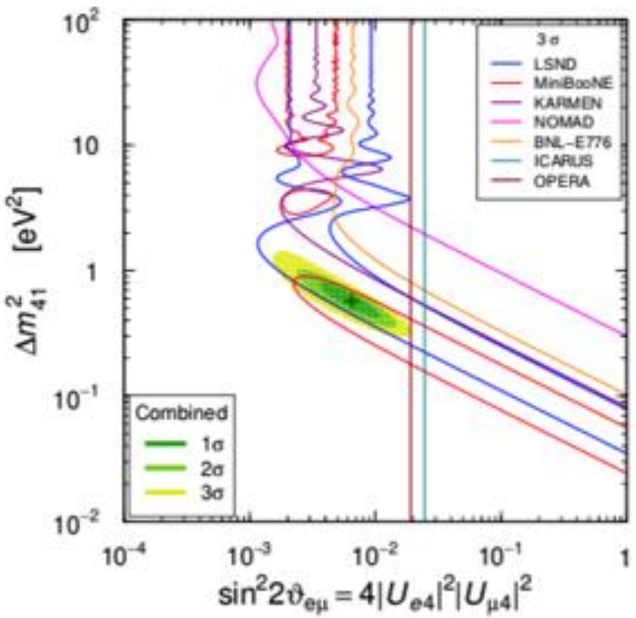
$\nu_{sterile}$ puzzle

- Several experiments at accelerators and reactors to study “ν anomalies” both in appearance/disappearance:
  - ➢ Large part of LSND parameters $(\nu_\mu \rightarrow \nu_e)$ excluded by ICARUS and OPERA at CNGS ν beam. MiniBooNE at FNAL saw a low energy ν_e event excess not confirmed by MicroBooNE.
  - ➢ No evidence in ν_μ disappearance experiments (IceCube, NOνA, MINOS/MINOS+,T2K).
- Clear tension between appearance/disappearance experiments characterized by different ν detection techniques and ν energy spectra.

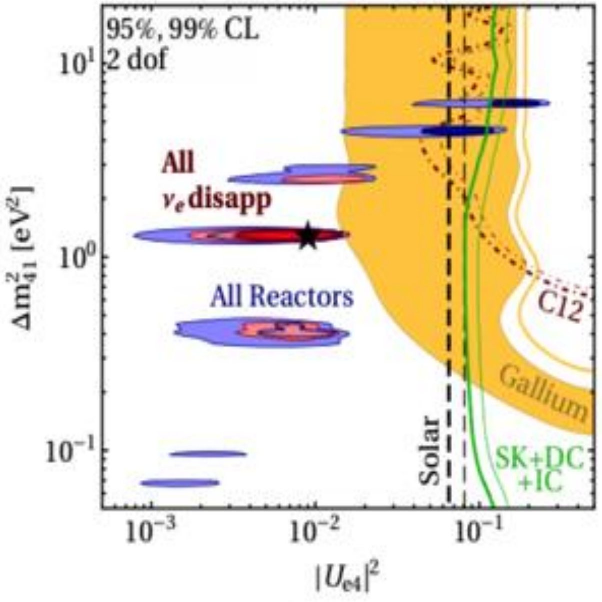
$\nu_\mu \rightarrow \nu_e$ Appearance



$\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ *Appearance*



$\bar{\nu}_e$ *Disappearance*



02

SBN Program at Fermilab

Short Baseline Neutrino (SBN) Program at FNAL

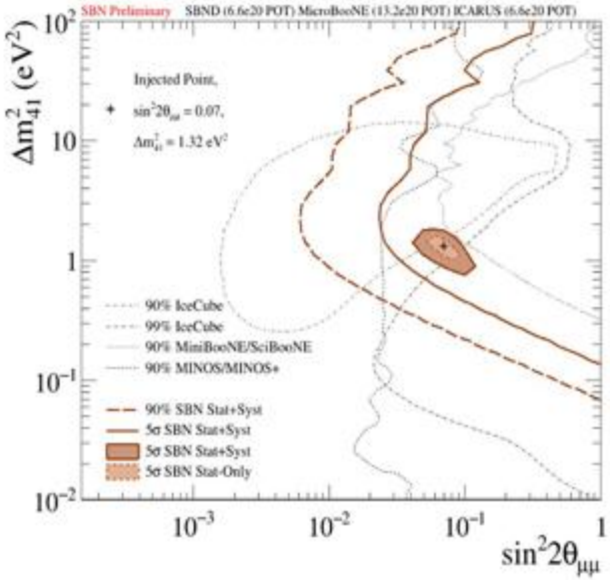
- **Same Technology:** Liquid Argon Time Projection Chamber (LArTPC)
- **Same Source:** Booster Neutrino Beam (BNB: $93.60\%\ \nu_\mu$ $/5.86\%\ \bar{\nu}_\mu$ $/0.52\%\ \nu_e$ and 700 MeV peak Energy)
- **Near Detector** (**SBND**, 110 m, taking data since 2024): Measure $\nu's$ before they oscillate, 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 $\nu_{sterile}$ and solve the $\nu_{sterile}$ puzzle (+ cross section measurements and BSM Searches)
- **Two ν Beams:** BNB + NuMI (ICARUS only)

$\nu_{sterile}$ sensitivity, 3 years (6.6×10^{20} pot)

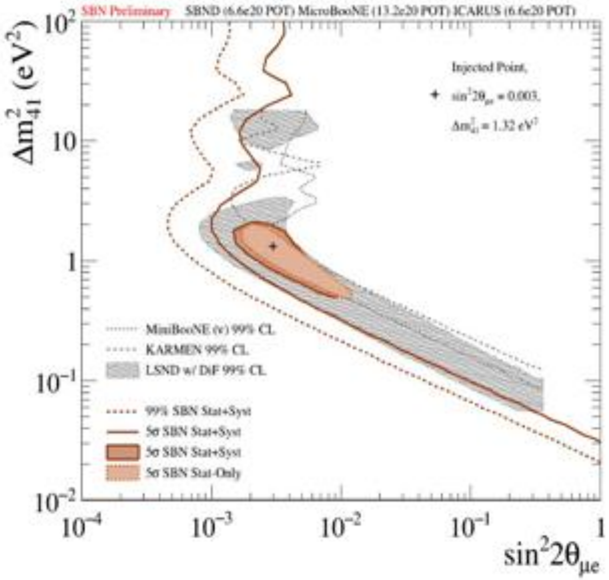
Combined ICARUS (FD) and SBND (ND) data analysis using the same LArTPC event imaging greatly reduces expected systematics:

- ➢ Initial BNB beam composition and spectrum provided by SBND
- ➢ High ν_e identification capability/NC background rejection provided by LArTPC

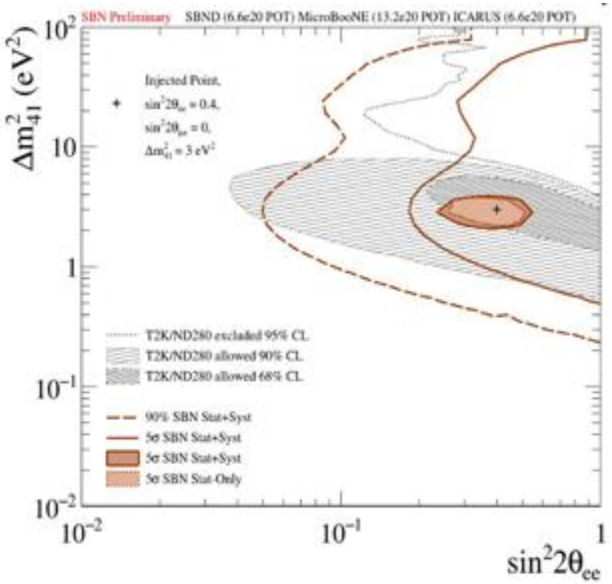
ν_μ disappearance



ν_e appearance



ν_e disappearance



- ✓ 5σ coverage of the parameter area relevant to LSND anomaly
- ✓ Probing the parameter area relevant to reactor and gallium anomalies

Unique capability to study ν appearance/disappearance simultaneously

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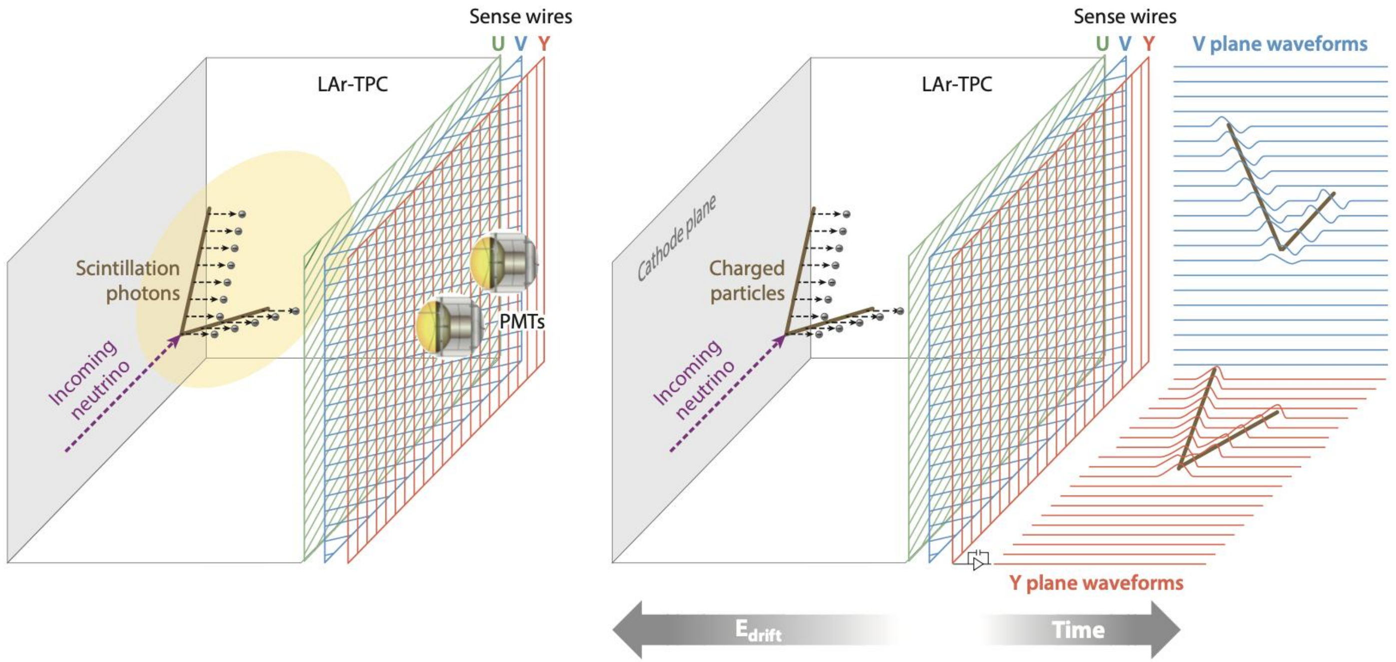
Imaging Cosmic And Rare Underground Signals

03

ICARUS at SBN Program

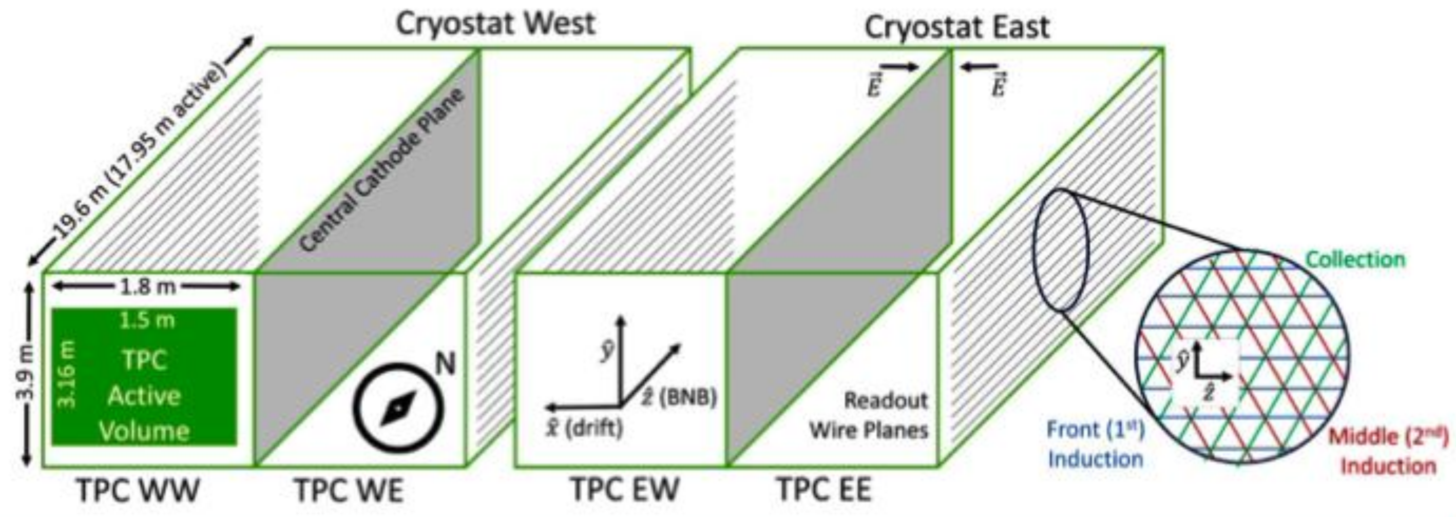
Liquid Argon Time Projection Chambers

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 ($t < 2$ ns): identify time of neutrino interaction (**Trigger: arXiv:2506.20137**).
  - Slow component ($t \sim 2 - 3\ \mu s$): energy measurement.
- Charged particles **ionize argon**: 42000 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.
- 2D images are combined into **3D trajectories** with mm resolution.

ICARUS at Fermilab



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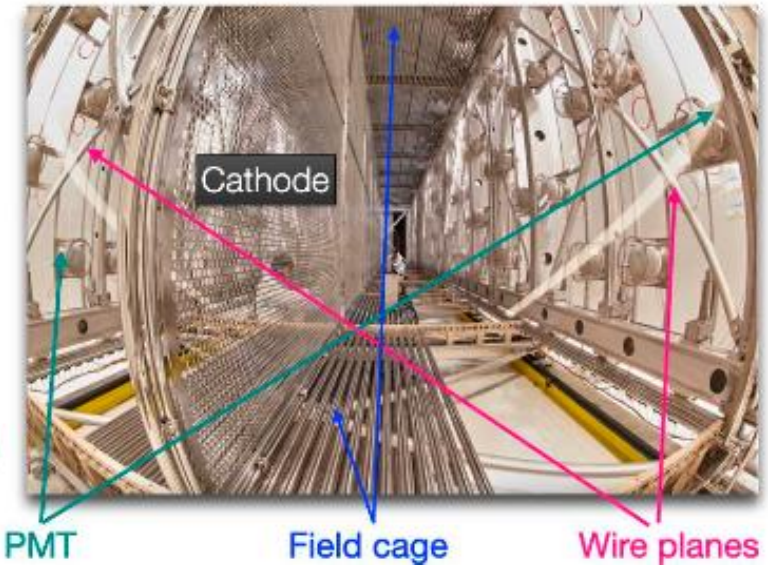

- **ICARUS T600:** the first large scale LArTPC ever built with 760 tons of pure LAr, **470 tons** active mass
- After **3-year physics run at LNGS** and **intensive overhaul at CERN**, ICARUS was moved to Fermilab
- **2 cryostats** ($3.6 \times 3.9 \times 19.6\, m^3$) with 2 TPCs each and a central cathode (1.5 m drift, $\mathrm{E_D} = 500$ V/cm)
- **3 wire planes per TPC:** total of 54000 wires at $0^{\circ}, \pm 60^{\circ}$ with 3 mm 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 ray background**

See my talk "Improving ICARUS track reconstruction algorithms" for further information.

Cosmic ray background mitigation

A new experimental challenge: a LAr-TPC on surface

- ICARUS exposed in a pit to cosmic rays:
  - e^- produced by $\gamma's$ via Compton Scattering or Pair Production can mimic a genuine $\nu_e CC$ event ⇒ Cosmic $\gamma's$ and neutrons suppressed by 2.85 m concrete overburden installed above the Cosmic Ray Tagger (CRT).
  - Cosmic $\mu's$ can mimic a genuine $\nu_\mu CC$ event ⇒ they are identified in time/position by 4π CRT double-layer scintillation bars $(1000\ m^2)$ with an efficiency of 95%.

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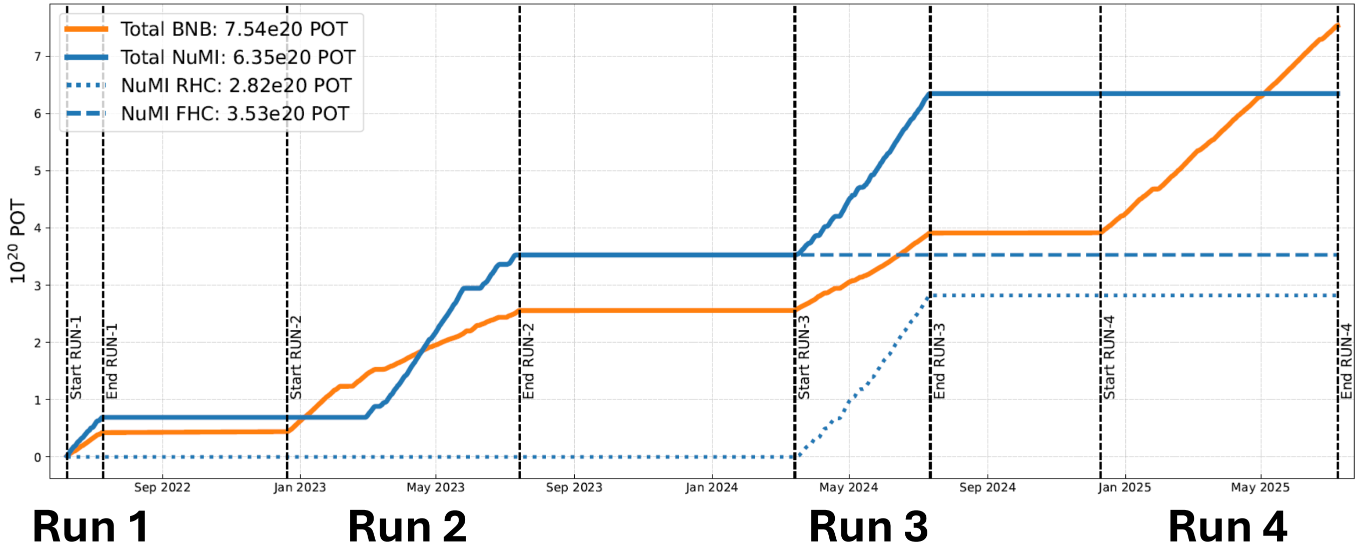
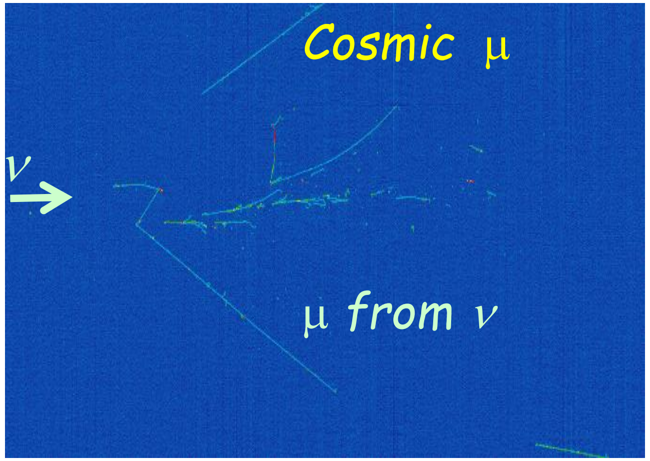
ICARUS Operations and Data Collection at Fermilab

ICARUS data taking for physics started in June 2022:

- 4 physics runs completed.
- Steady data taking, excellent stability at BNB rates $> 4\ Hz, > 90\%$ live time.
- Highly pure liquid argon: free e^- lifetime $7-8\ ms \Rightarrow$ 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 ms), NuMI (9.5 ms) 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)	3.71×10^{20}	-	-
TOTAL	7.54×10^{20}	3.42×10^{20}	2.82×10^{20}

Imaging Cosmic And Rare Underground Signals

04

ICARUS Physics Results

ICARUS Research Program

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

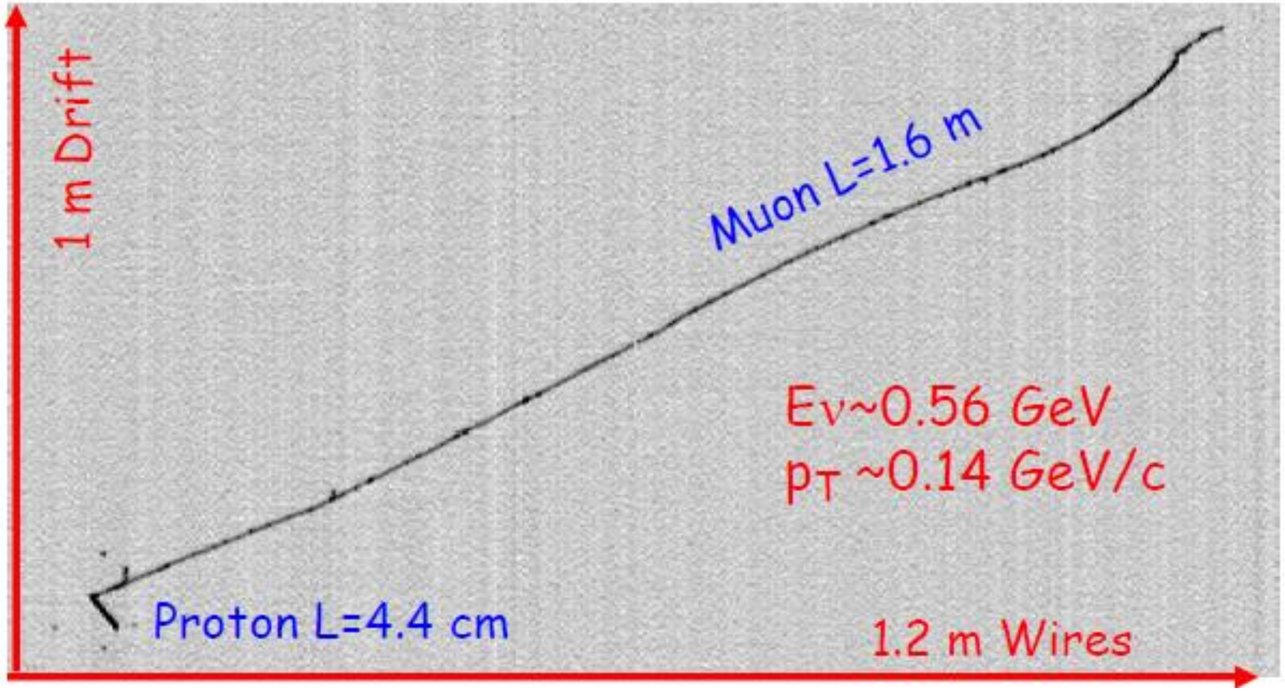
- Before performing the joint oscillation analysis with SBND, ICARUS is now focusing **on a standalone physics program**:
  - Analysis of the $\boldsymbol{\nu_\mu}$ **disappearance** channel **with BNB**, to be complemented with $\boldsymbol{\nu_e}$ **disappearance from NuMI** beam data to verify the **Neutrino-4 experiment claim**;
  - Study of $\boldsymbol{\nu_\mu}$ and $\boldsymbol{\nu_e}$ interactions from the NuMI beam **to measure $\boldsymbol{\nu}$-Ar cross-sections** and optimize event reconstruction in the **DUNE** energy range.
  - Search for evidence of Beyond Standard Model physics 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.

ν_μ Disappearance Analysis with BNB Beam Data

- **Selection of fully contained $\nu_\mu CC$ events** with 1μ+N protons in the final state (event kinematics extracted from range measurements):
  - PMT light signal within 1.6 ms beam spill in coincidence with reconstructed TPC tracks, No CRT signal;
  - A muon with $L_{trk} > 50$ cm;
  - $N \geq 1$ protons with $E_k > 50$ MeV ($L_{trk} > 2.3$ cm);
  - No additional π or γ.

Residual cosmic background $< 1\%$!



- Flux, cross section and **detector systematic uncertainties** have been included:
  - Preliminarily, the impact of detector systematics is evaluated comparing calibrated and uncalibrated MC samples; the ongoing simulation improvements reducing residual Data/MC discrepancies are expected to reduce also detector systematics;
  - Substantial cancellation of cross section and flux uncertainties and of common detector systematics is expected in the joint SBN analysis.

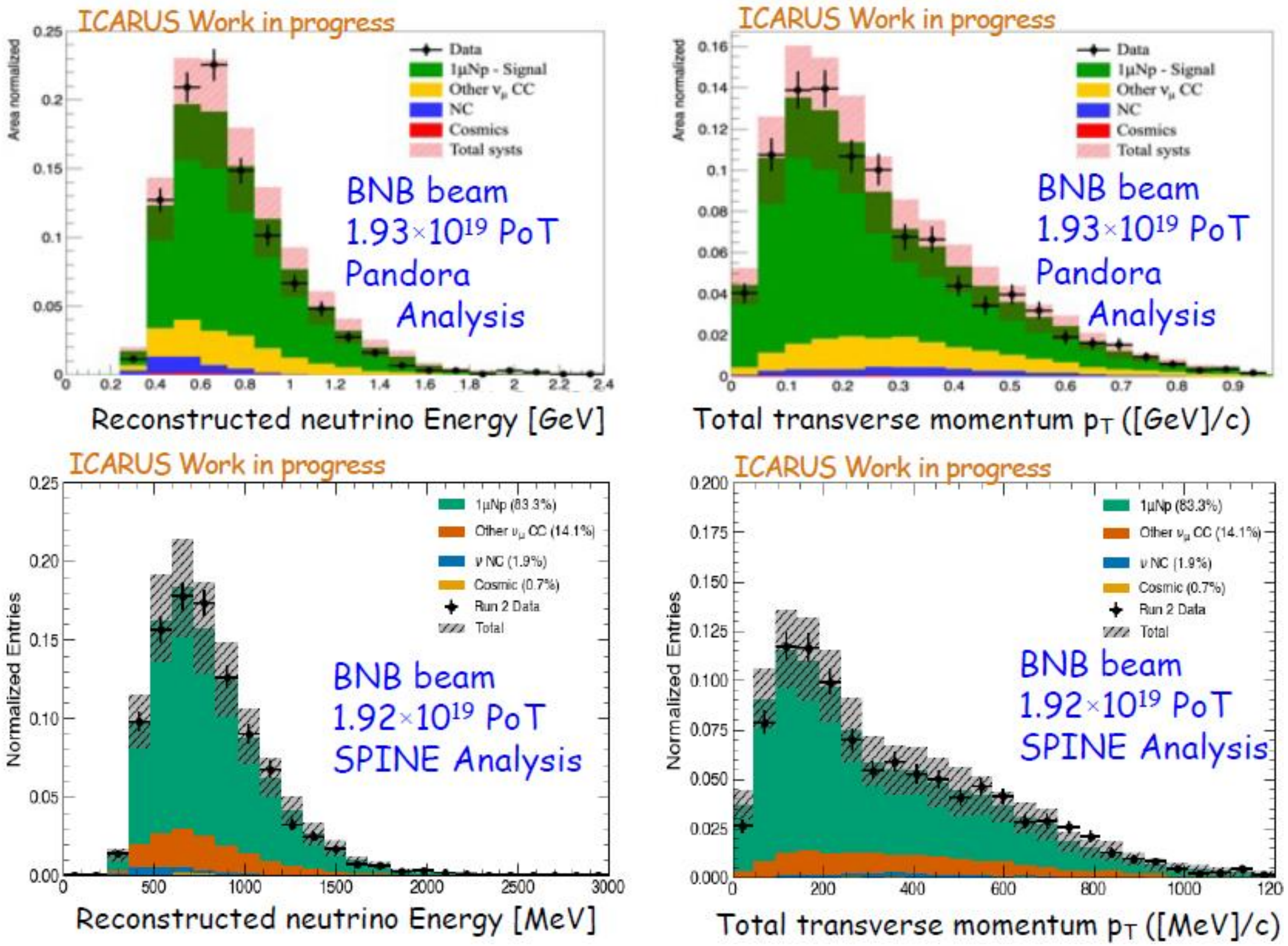
ν_μ Disappearance Analysis with BNB Beam Data

- Two independent analysis streams considered, respectively based on:
  - ➢ Pandora pattern recognition ($\sim 50\%$ efficiency and $\sim 80\%$ purity for the signal;
  - ➢ Machine Learning (ML) SPINE reconstruction code: $\sim 75\%$ efficiency and $\sim 80\%$ purity for the signal.

- 10% of RUN-2 data analyzed.

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

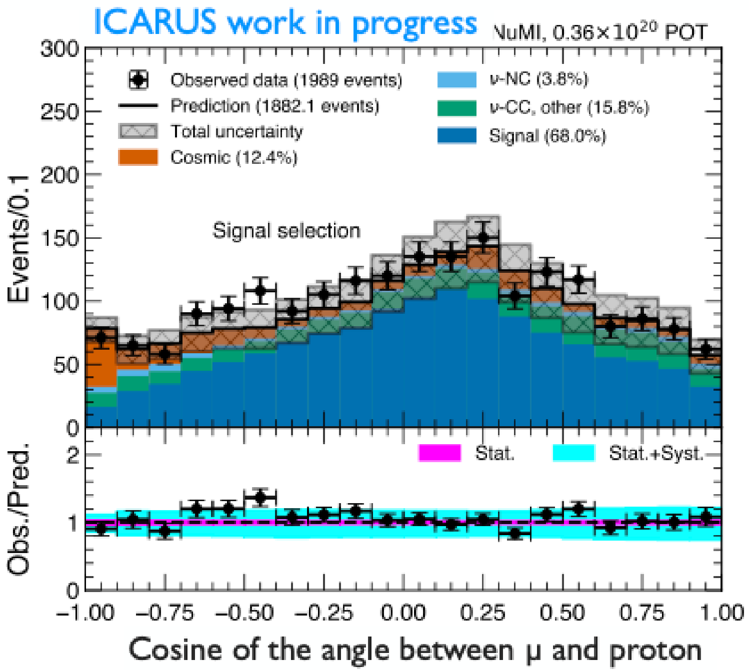
- Next analysis steps: full dataset unblinding and oscillation fit.

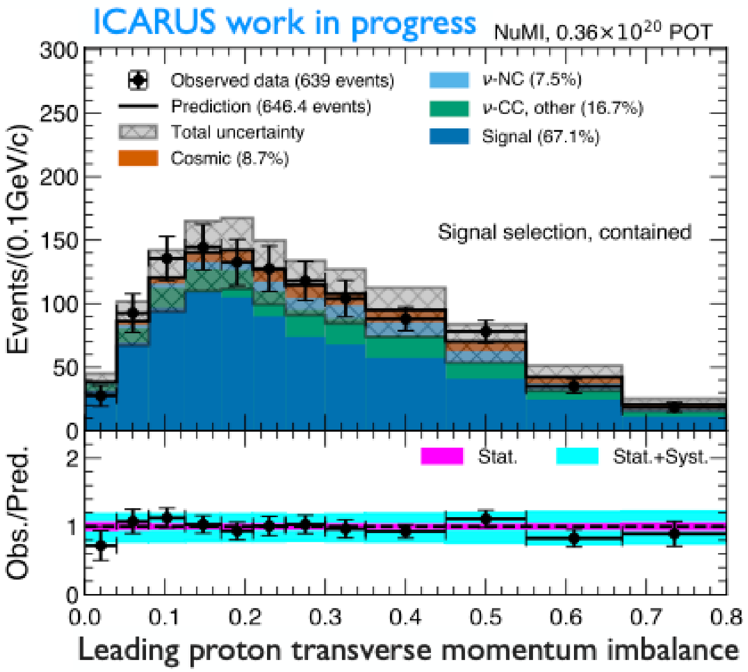


Cross-Section Measurements with NuMI Data

- Huge statistics to measure ν_μ and ν_e cross-sections with different types of interactions (available data $\sim 3.42 \times 10^{20}$ POT for physics analysis now: expected 188000 ν_μ and 9600 ν_e events).
- **First analysis targets $1\mu + Np + 0\pi$ in the final state:**
  - **Signal definition:** 1μ with $p > 226$ MeV/c, any proton with $400\ MeV < p < 1\ GeV$, no pion in the final state;
  - Flux, interaction model, and detector systematic uncertainties included;
  - Angle between μ and leading 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



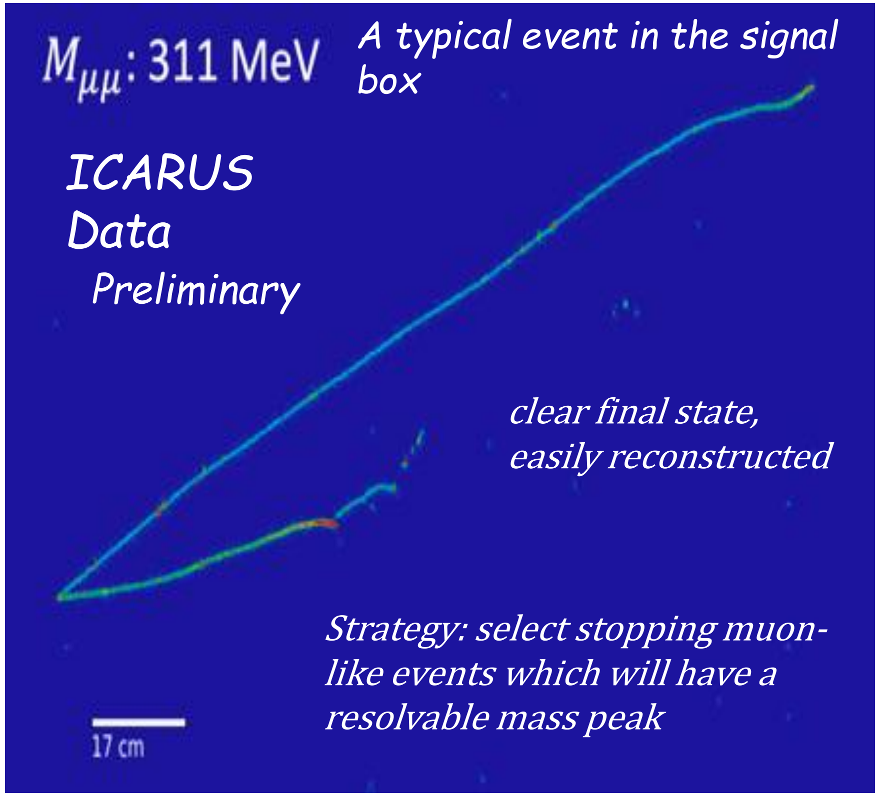


Investigation of Dark Sector Models with NuMI Data

- 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

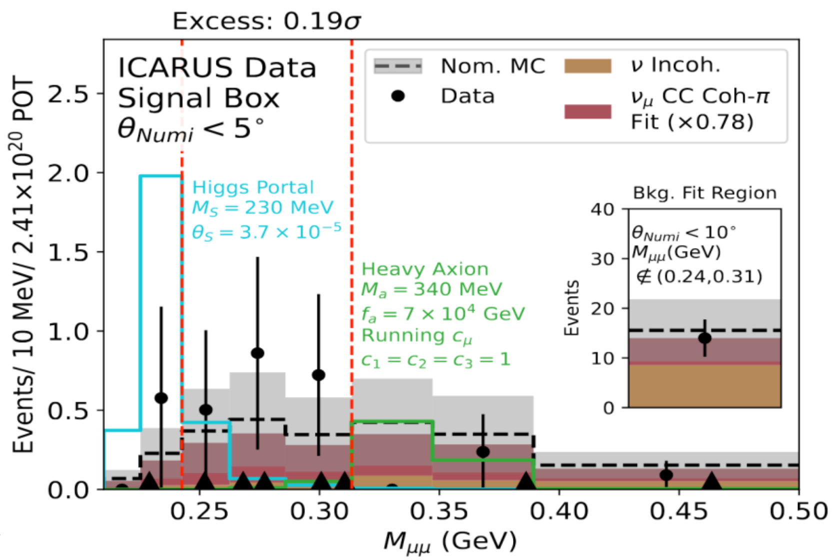
- ICARUS performed a first search for a new particle decaying into $\mu\mu$.
- Events with 2 stopping muons are selected to reconstruct the scalar mass peak.
- Signal expected at small angle to the beam ($\theta_{NuMI} < 5$ degree).
- Flux, interaction model and detector systematic uncertainties included.

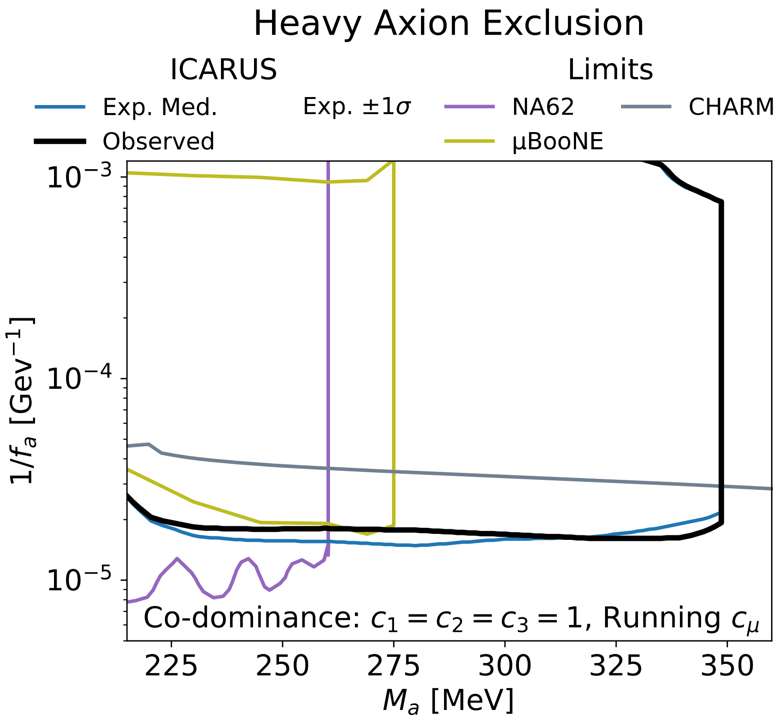
Phys. Rev. Lett. 134, 151801 (2025)

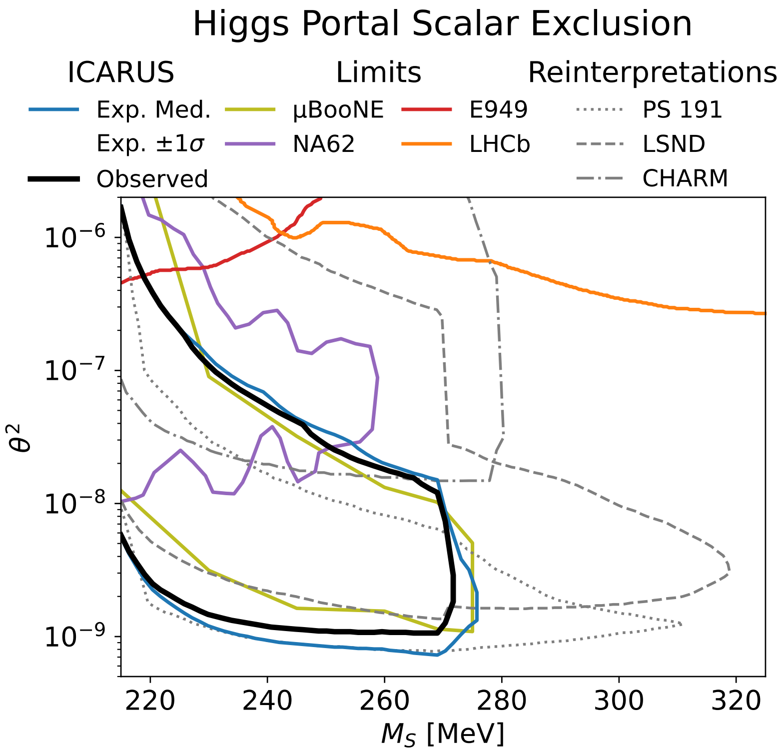


BSM searches with NuMI Data: Results

- **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)

Conclusions

- ICARUS is smoothly running in physics mode since June 2022, exposed to the BNB and NuMI ν beams, already collected $> 7 \times 10^{20}$ POT with BNB and $\sim 3 \times 10^{20}$ POT with NuMI both positive and negative focusing.

- The detector is calibrated with cosmic muons and protons from ν interactions, 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:

  A. Study of ν_μ disappearance with the BNB beam (Neutrino-4 claim), almost ready for the full signal unblinding;

  B. Measurement of ν_μ-Ar cross-sections with NuMI beam (for DUNE), almost ready for the full signal unblinding;

  C. Search for Sub-GeV Dark Matter candidates in NuMI beam. A first analysis with di-muon final state topology has been completed **(Phys. Rev. Lett. 134 (2025), 151801)**.

ICARUS Collaboration at SBN

P. Abratenko[19],N. Abrego-Martinez[3], F. Akbar[23], L. Aliaga Soplin[24], M. Artero Pons[15], W.F. Badgett[5], L.F. Bagby[5], B. Baibussinov[15], B. Behera[4], V. Bellini[7], O. Beltramello[2], R. Benocci[13], J. Berger[4], S. Bertolucci[6], M. Betancourt[5], K. Biery[5], M. Bonesini[13], T. Boone[4], B. Bottino[8], J Bremer[2], S. Brice[5], V. Brio[7], C. Brizzolari[13], J. Brown[5], H.S. Budd[23], A. Campani[8], A. Campos[27], D. Carber[4] , M. Carneiro[1], I. Caro Terrazas[4], H. Carranza[24], R. Castillo Fernandez[24], S. Centro[15], G. Cerati[5], M. Chalifour[2], A.Chatterjee[26], D. Cherdack[21], S. Cherubini[11], N. Chitirasreemadam[25], M. Cicerchia[15], T. Coan[18], A. Cocco[14], M. R. Convery[17], L. Cooper-Troendle[22], S. Copello[16], A. De Roeck[2], S. Di Domizio[8], D. Di Ferdinando[6], L. Di Noto[8], M. Diwan[1], S. Dolan[2], S. Donati[25], R. Doubnik[5], F. Drielsma[17], J. Dyer[4], S. Dytman[22], C. Fabre[2], A. Falcone[13], C. Farnese[15], A. Fava[5], N. Gallice[1], C. Gatto[14], M. Geynisman[5], D. Gibin[15], A. Gioiosa[25], W. Gu[1], M. Guerzoni[6], A. Guglielmi[15], G. Gurung[24], S. Hahn[5], H. Hausner[5], A. Heggestuen[4], B. Howard[5], J. Hrivnak[2], C. James[5], W. Jang[24], Y.-J. Jwa[17],L. Kashur[4],W. Ketchum[5], J.S. Kim[23], D.H. Koh[17], J. Larkin[1], G. Laurenti[6],Y. Li[1], G. Lukhanin[5], C. Mariani[27], C. Marshall[23], S. Martynenko[1], N. Mauri[6], A. Mazzacane[5], K.S. McFarland[23], D.P. Mendez[1], A. Menegolli[16], G. Meng[15], O.G. Miranda[3], D. Mladenov[2], N. Moggi[6], N.Montagna[6], A. Montanari[6], C. Montanari[5,b], M. Mooney[4], G. Moreno Granados[3], J. Mueller[4], M. Murphy[27], D. Naples[22], T. Nichols[5], S. Palestini[2], M. Pallavicini[8], V. Paolone[22], L. Pasqualini[6], L. Patrizii[6], L. Paudel[4], G. Petrillo[17], C. Petta[7], V. Pia[6], F. Pietropaolo[2,a], F. Poppi[6], M. Pozzato[6], A. Prosser[5], G. Putnam[20], X. Qian[1], A. Rappoldi[16], G.L. Raselli[16], R. Rechenmacher[5], S. Repetto[8], F. Resnati[2], A.M. Ricci[25], E. Richards[22], A. Rigamonti[2], M. Rosemberg[19], M. Rossella[16], P. Roy[27], C. Rubbia[9], M. Saad[22], S. Saha[22], G. Savage[5], A. Scaramelli[16], D. Schmitz[20], A. Schukraft[5], D. Senadheera[22], S.H. Seo[5], F. Sergiampietri[2], G. Sirri[6], J. Smedley[23], J. Smith[1], A. Soha[5], L. Stanco[15], H.Tanaka[17], F. Tapia[24], M. Tenti[6], K.Terao[17] , F. Terranova[13], V.Togo[6], D.Torretta[5], M.Torti[13], R. Triozzi[15], Y.T. Tsai[17], T. Usher[17], F.Varanini[15], S. Ventura[15], M.Vicenzi[1], C. Vignoli[10], P. Wilson[5], R.J. Wilson[4], J. Wolfs[23], T. Wongjirad[19],A.Wood[21], E. Worcester[1], M. Worcester[1], H. Yu[1], J. Yu[24], A. Zani[12], J. Zennamo[5], J. Zettlemoyer[5], S. Zucchelli[6], M. Zuckerbrot[5]

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12 INFN groups, 12 US institutions, CERN, 1 Mexican institution, 1 Indian Institution

a On Leave of Absence from INFN Padova
b On Leave of Absence from INFN Pavia

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05

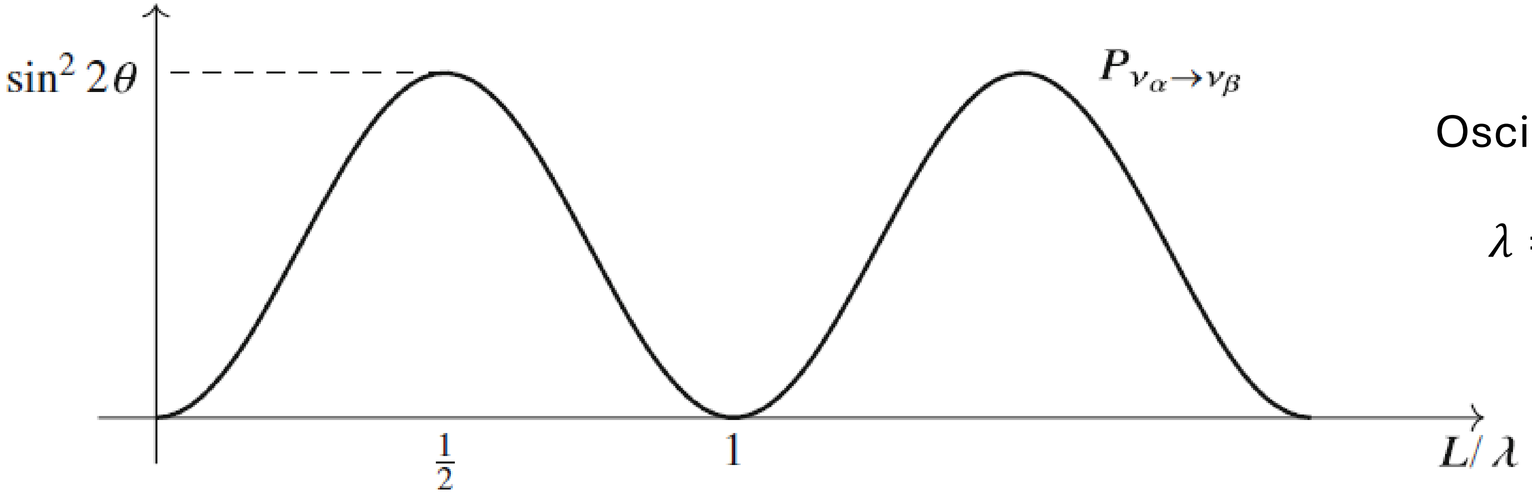
Backup

Neutrino oscillations

- Two-Generation Mixing $\nu_\alpha \rightarrow \nu_\beta$ over a distance L: lepton flavor violation process is described by the mixing probability of the mass eigenstates ν_1, ν_2 as a function of the quadratic mass difference $|\Delta m^2| = m_1^2 - m_2^2$ and the coupling amplitude $\sin^2 2\theta$.

$$P(\nu_\alpha \rightarrow \nu_\beta) = \sin^2(2\theta)\sin^2\left(1.27\frac{\Delta m^2 L}{E}\frac{[eV^2][Km]}{[GeV]}\right)$$

- $P(\nu_\alpha \rightarrow \nu_\beta)$ is an oscillating function. At any distance $L + n\lambda$, n being an integer number, the transition probability acquires the same value. The mass splitting determines the frequency and the mixing angle the amplitude.



Oscillation length:

$$\lambda = 2.47\frac{E}{\Delta m^2}$$

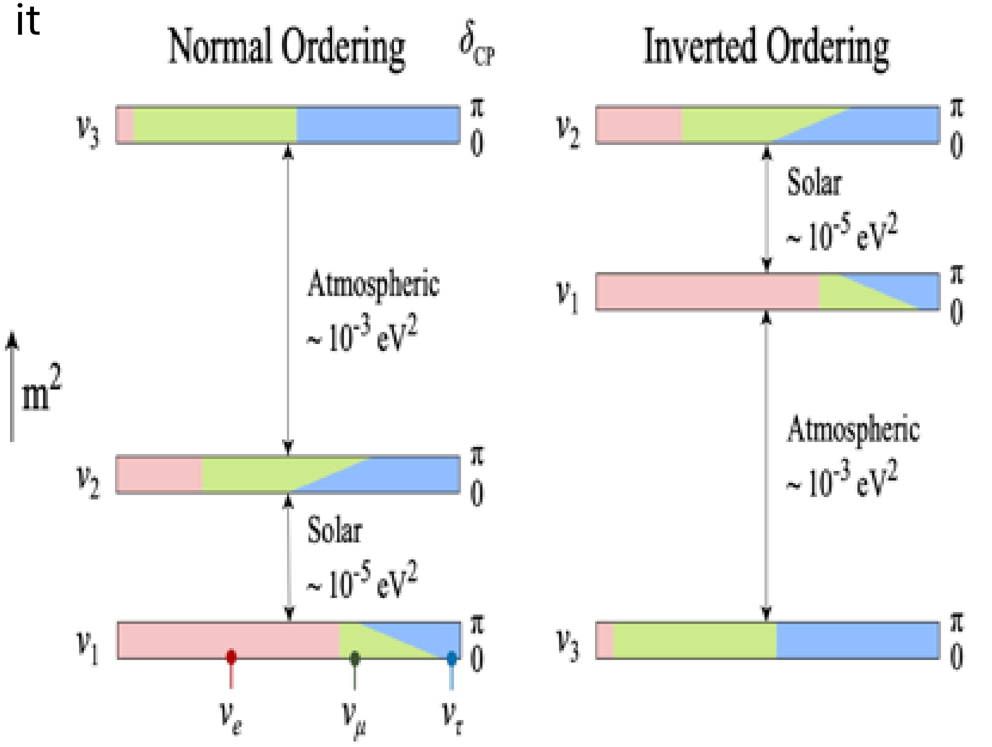
Neutrino Oscillations

- Transition probability $\nu_\alpha \rightarrow \nu_\beta$ over a distance L: a ν produced in one flavor eigenstate (e, μ, τ) will oscillate to another as it propagates:

$$P(\nu_\alpha \rightarrow \nu_\beta) = \sin^2(2\theta)\sin^2\left(1.27\frac{\Delta m^2 L}{E}\frac{[eV^2][Km]}{[GeV]}\right)$$

- 3-flavour Lepton Mixing Matrix of Pontecorvo-Maki-Nagatawa-Sakata (like CKM matrix): 3 Euclid mixing angles θ_{ij} + 1 CP-violating phase δ.

$$\Delta m^2 = m_2^2 - m_1^2$$



$$U_{\text{PMNS}} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \times \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix} \times \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

atmospheric reactor solar

$$c_{ij} = \cos\theta_{ij} \qquad s_{ij} = \sin\theta_{ij}$$

ν mass hierarchy?

δ_{CP} matter-antimatter asymmetry?

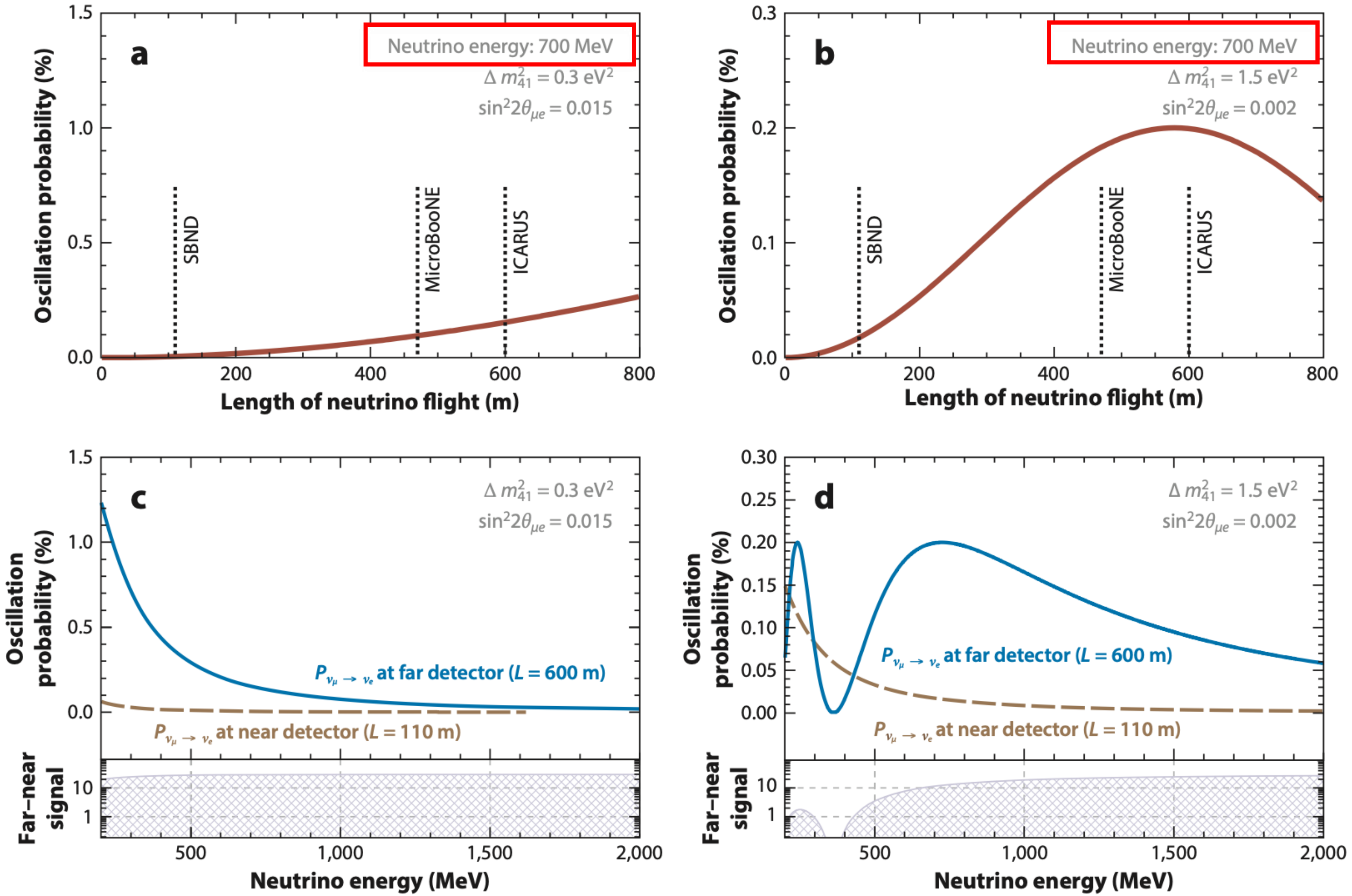
$\sin^2 2\theta_{12} \sim 0.3$, $\sin^2 2\theta_{23} \sim 0.5$, $\sin^2 2\theta_{13} \sim 0.1$ determined in 20 years experiments!

Possible experiments

- Assuming a pure beam of known flavour, we distinguish two kinds of experiments:
  - Disappearance experiment: look to see how many $\nu's$ have disappeared. The key issue are:
    - Incoming ν flux;
    - Efficiency with the event detection.
  - Appearance experiment: search the number of $\nu's$ of a different flavour at the detector. The ν flavour is defined by the charged lepton which is produced in its charged current interactions. The key issues are:
    - Incoming ν flux;
    - Efficiency with the event detection;
    - Energies kinematically above the lepton mass threshold.
- Both kinds of experiments require probabilities large enough than events can be observed in a reasonable amount of time $\Rightarrow$ Maximize $P\left(\nu_\alpha \to \nu_\beta\right)$:

$$\frac{L}{\lambda} = \frac{1}{2} = \frac{1.2}{\Delta m^2}$$

SBN @FNAL: L/E Optimization



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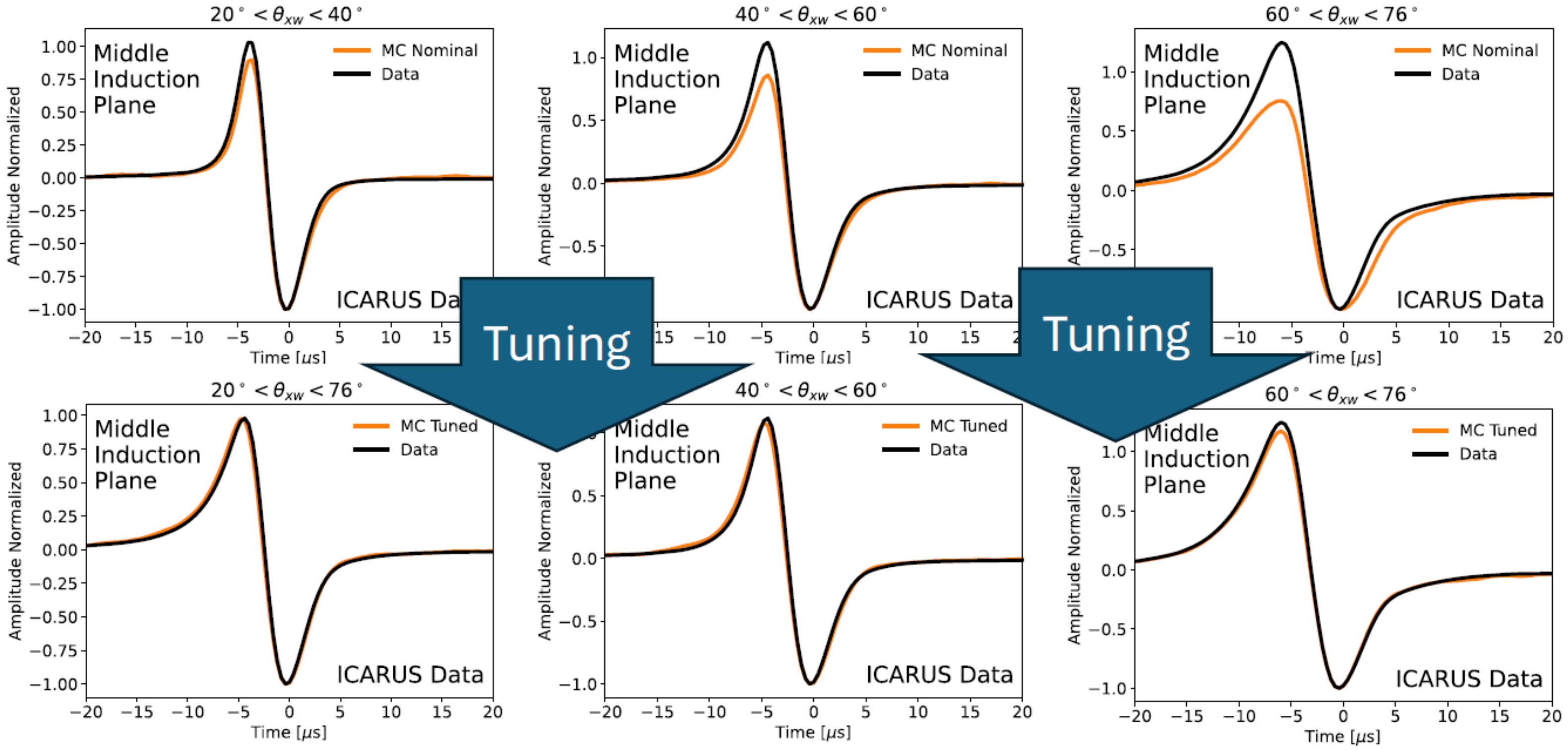
Detector Calibration and Modelling

- Comparison of simulated and measured TPC signal shapes across different angles between the track and the drift coordinate (larger angle, more extended signal).



This is like simulating the lens distortion incorrectly!

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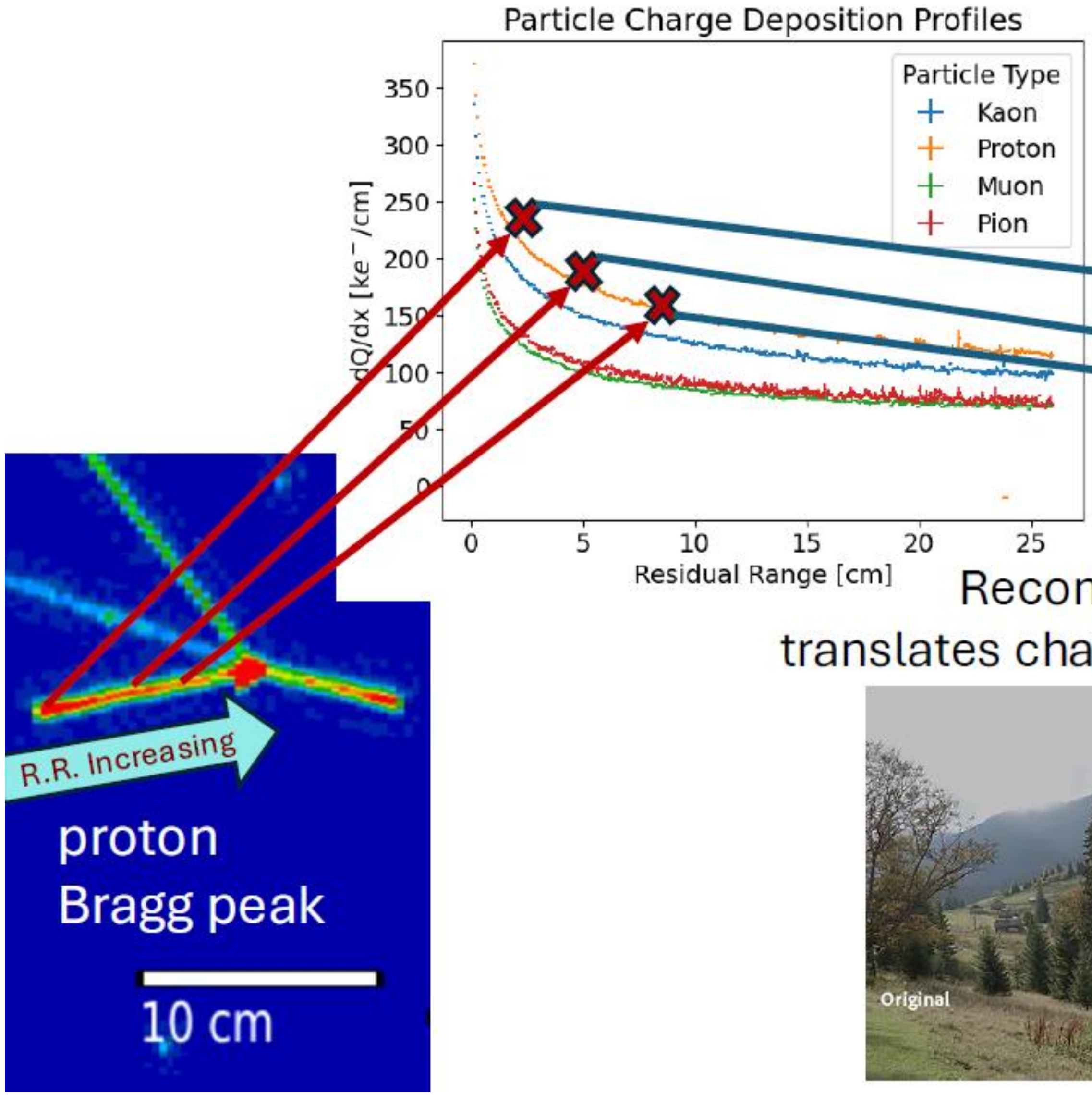
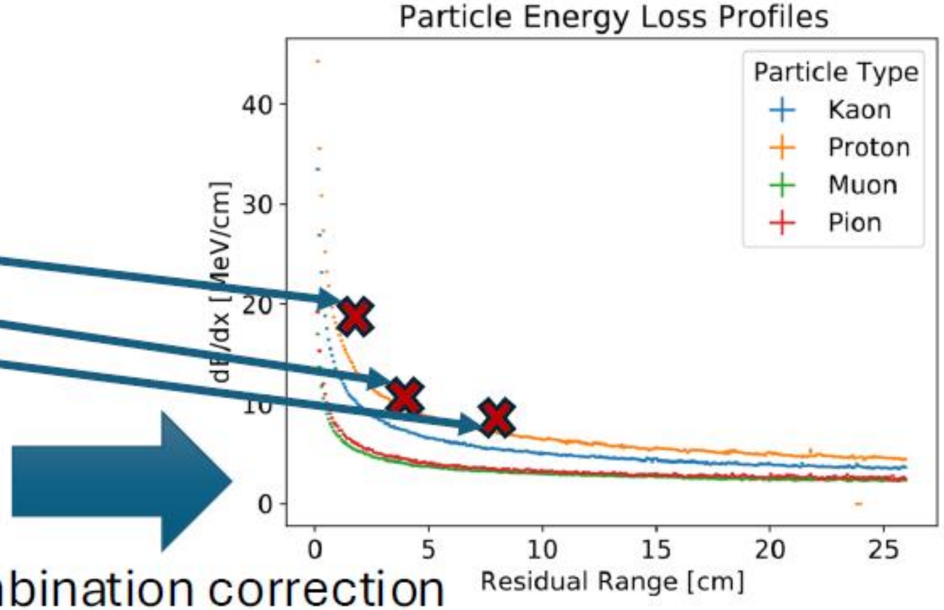
Detector Calibration and Modelling





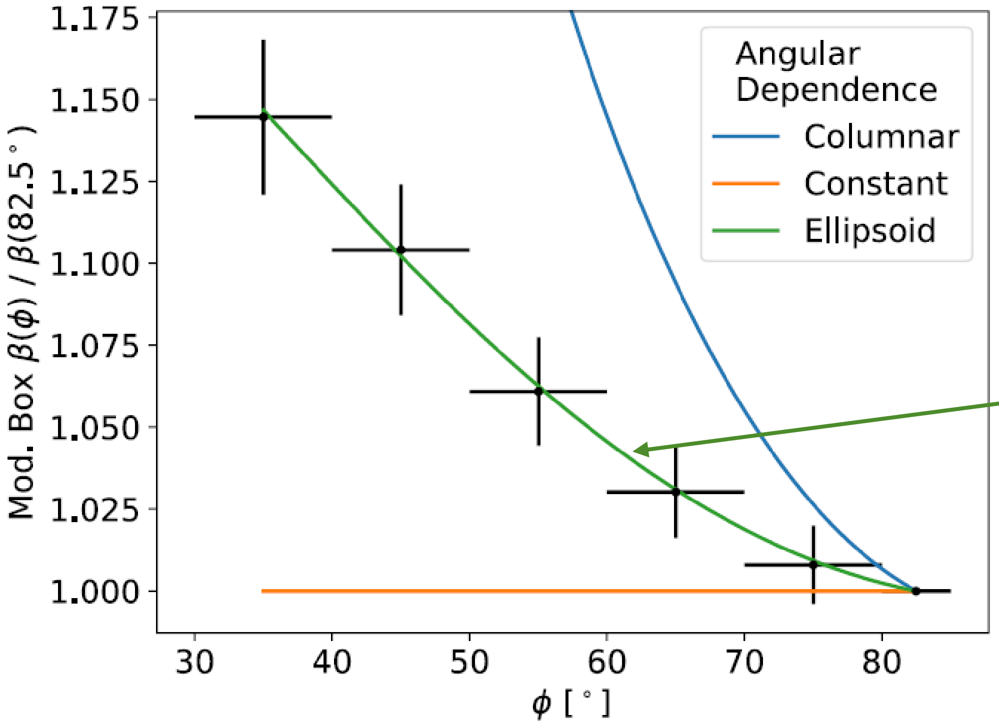
Recombination correction
translates charge (dQ/dx) to energy (dE/dx)

This is like performing color correction on an image!

Detector Calibration and Modelling

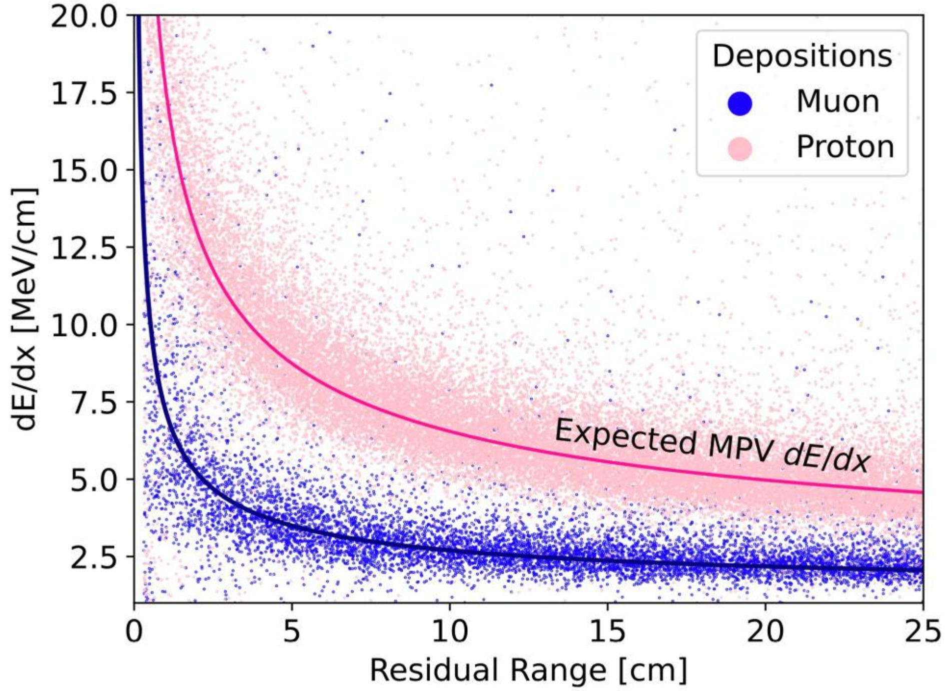
- Detector response is calibrated with cosmic μ and p from ν interactions including a new angular dependent ellipsoidal recombination model (EMB).

Modified Birks' law taking into account the angle between the track and the drift coordinate (Modified Box Recombination)



$$\frac{dx}{dQ} = \frac{1}{G}\frac{\log(\alpha+\beta(\phi))\frac{dE}{dx}}{\beta(\phi)W_{ion}}$$

Angular dependence of recombination β parameter



$\frac{dE}{dx}$ vs Residual Range for μ and p used for PID

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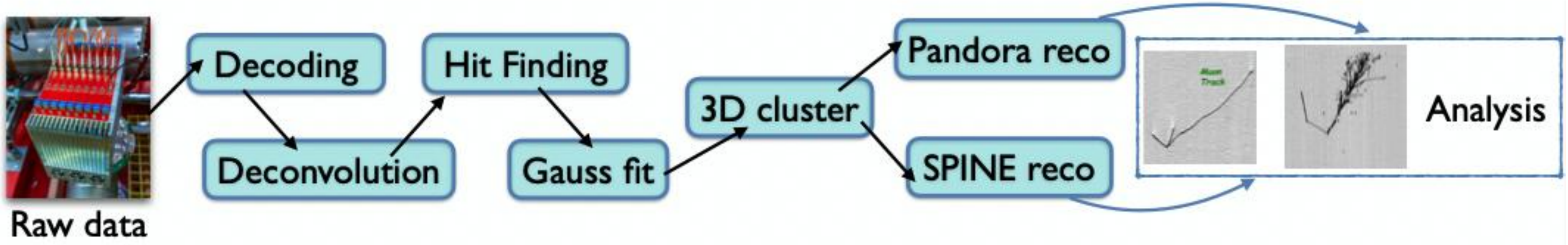
Neutrino Candidate Reconstruction



- 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.