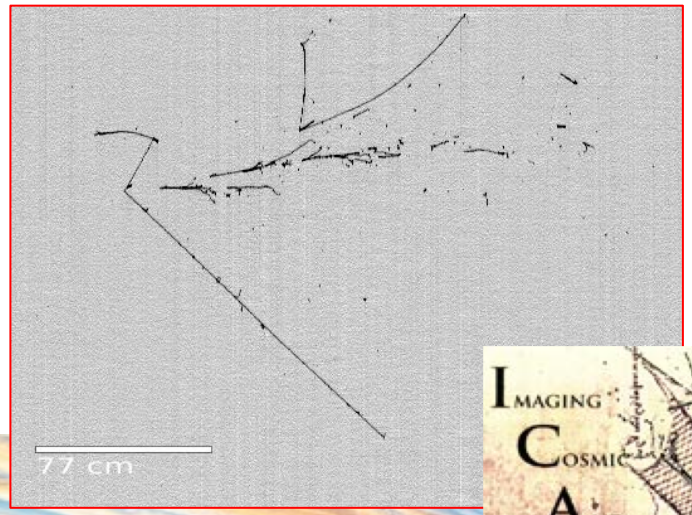
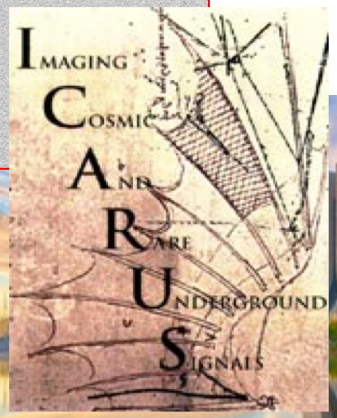
The ICARUS experiment at Fermilab



Alberto Guglielmi
INFN Padova



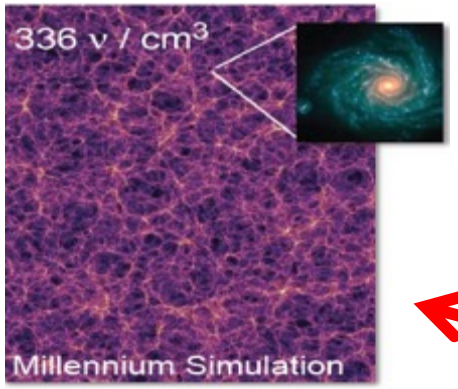
European Commission

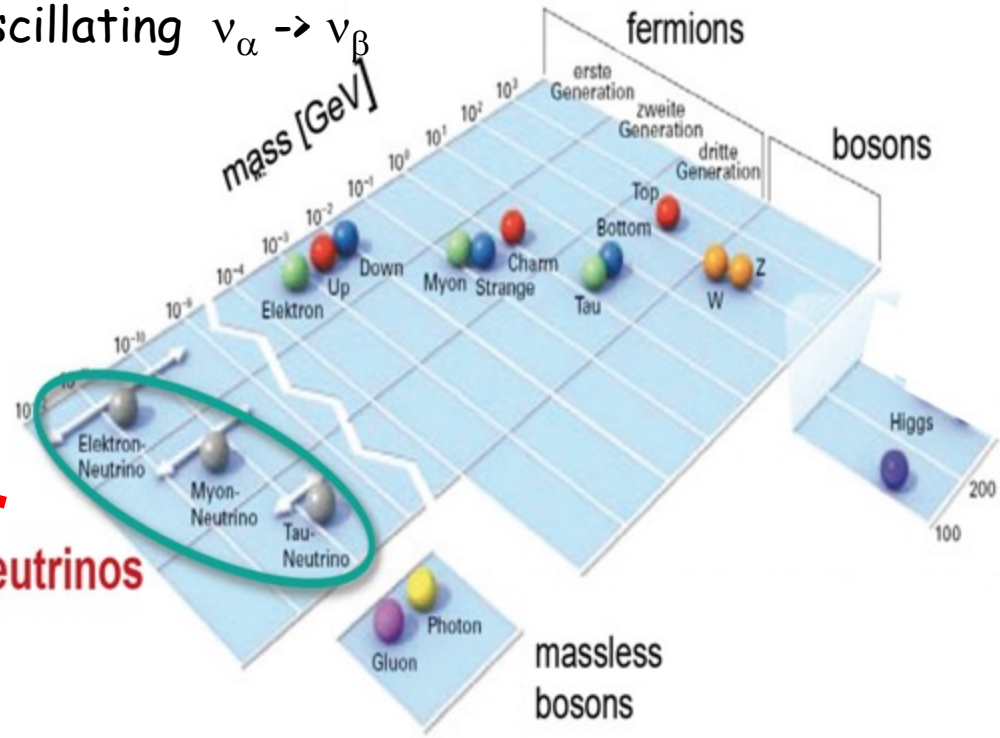
H2020, M. Sklodowska-Curie
R&I No. 822185, 858199,
101003460, 101081478

June 4th 2025

The high energy frontier

- The discovery of Higgs bosons has completed the Standard Model (SM) of elementary particles that describes the fundamental matter components and their interactions
  - 3 different neutrinos; ν_e ν_μ ν_τ, m_ν < eV oscillating ν_α -> ν_β





νs: the most abundant massive particles in the Universe, 336 ν/cm³

neutrino masses and flavor oscillations represent today a main experimental evidence of physics beyond SM. Being some of their fundamental properties still unknown, νs are naturally one of main portals towards beyond-SM physics.

The incredible smallness of ν masses compared to other elementary fermions points to some specific scenario awaiting to be elucidated.

Neutrino oscillations

- 2 neutrino ν_α -> ν_β over a distance L: lepton flavor violation process described by the mass states ν_1, ν_2 mixing probability as a function of $|\Delta m^2| = m_1^2 - m_2^2$ mass difference and $\sin^2 2\theta$ coupling amplitude

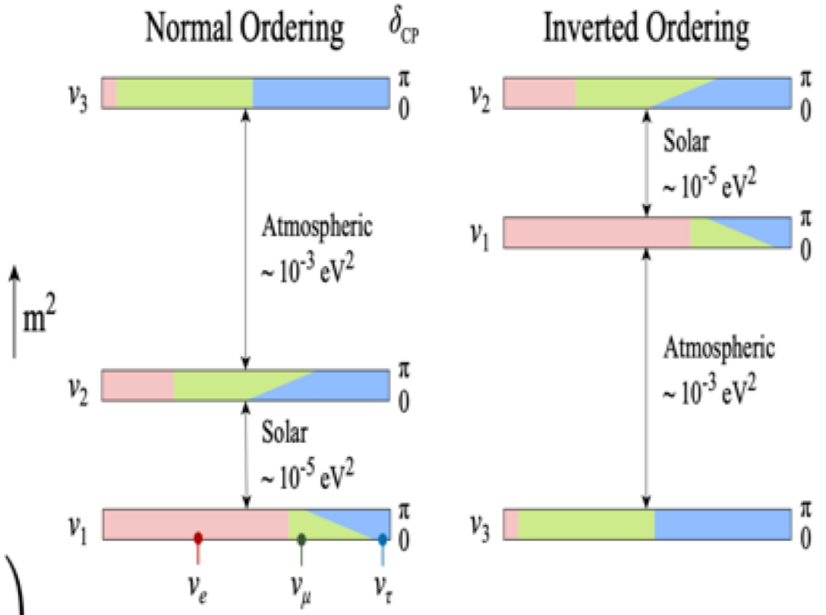
$$P(\nu_\alpha \to \nu_\beta) = \sin^2(2\theta)\sin^2\left(\frac{\Delta m^2 L}{4E_\nu}\right)$$

$\lambda = 4\,E_\nu/\,\Delta m^2$: ν oscillation length, E_ν ν–energy

- 2 different small mass-difference regimes of oscillations have been discovered with:

  - *solar ν osc $\Delta m^2_{21} \sim 8 \times 10^{-5}$ eV^2 and*
  - *atmospheric ν osc $\Delta m^2_{31} \sim 2.5 \times 10^{-3}$ eV^2*
  - *+ sub-leading $\nu\mu$ -> νe*

-> 3ν oscillation coherent picture: lepton-mixing matrix of Pontecorvo-Maki-Nagatawa-Sakata, 3 mixing angles + 1 CP-violating phase



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

C_{ij}: cos θ_{ij} S_{ij}: sin θ_{ij}

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

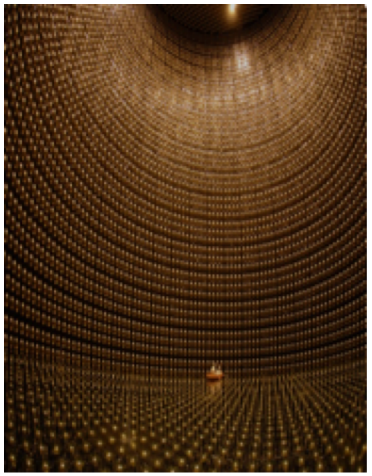
but ν mass hierarchy ? δ_{CP} matter-antimatter asymmetry ?

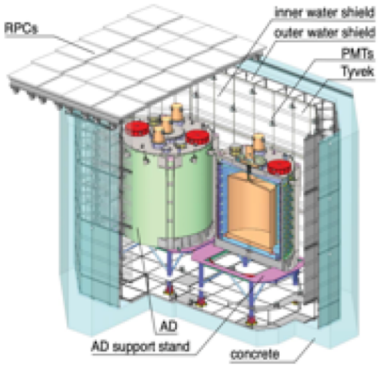
Present neutrino saga…

- Still open questions: *mass hierarchy, δ_{CP}, ν mass and Dirac/Majorana ν ?*
  - Several ongoing experiments/projects addressing neutrinos with nuclear reactors, radioactive sources, neutrino beams from proton accelerators and cosmic νs with large ice/water Cherenkov counter telescopes

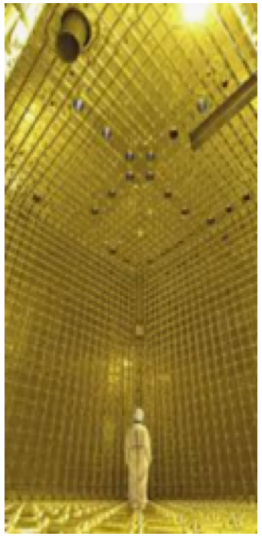
SK: Atmospheric/solar $\nu\mu$ –> ν_τ , ν_e

T2K--> Hyper-K
+ NuMI, NovA LBL

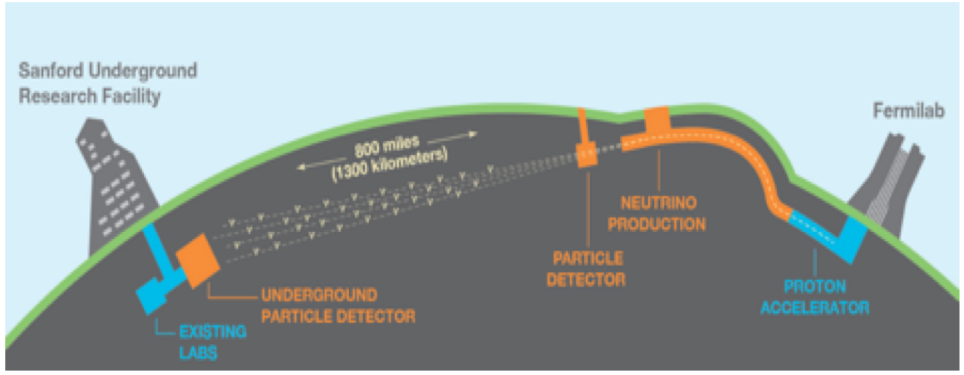




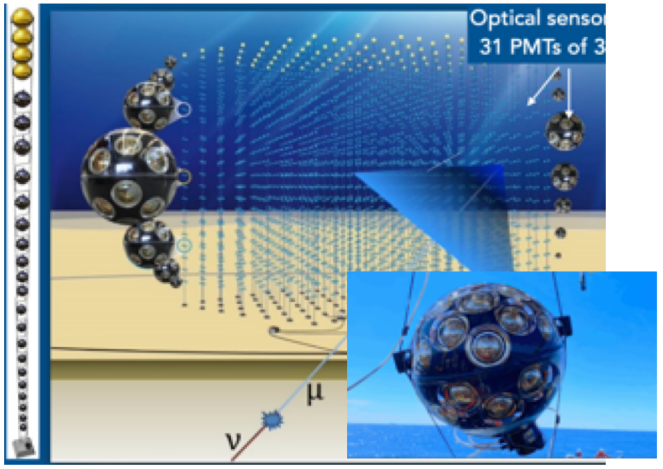
Reactors:
Reno, Daya Bay ,…Juno
…subleading $\nu\mu$ –> ν_e



DUNE Liquid Argon program



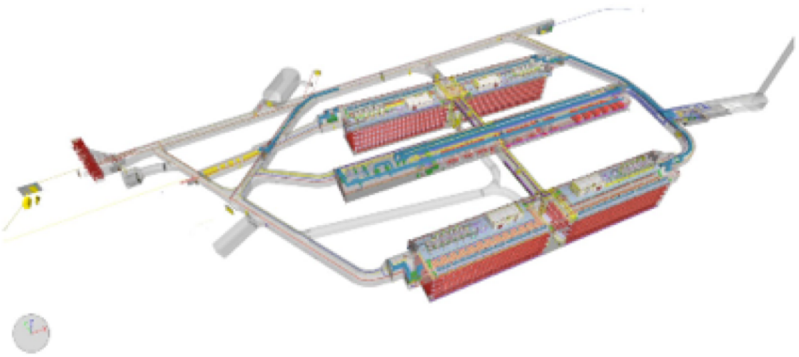
KM3NeT-ARCA cosmic νs

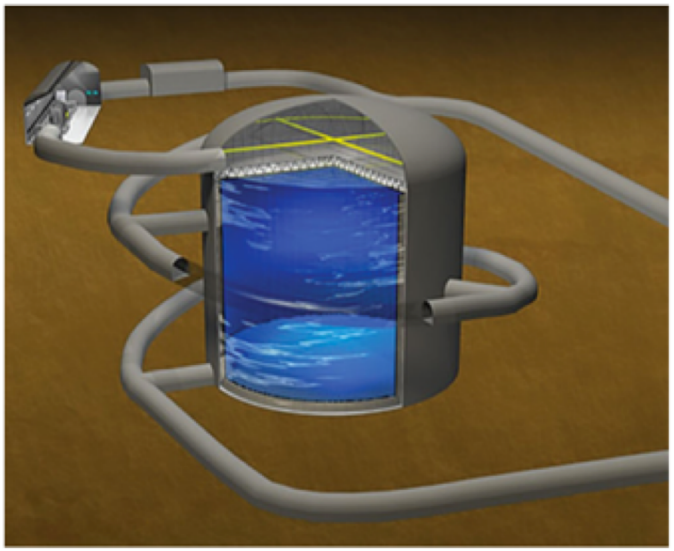


Matter-antimatter asymmetry?

- *Mass hierarchy, δ_{CP} will be solved by DUNE, HK comparing $\nu\mu$->νe oscillation in $\nu\mu$ and anti-$\nu\mu$ beams:*

$$A_{\alpha\beta} \equiv \frac{P(\nu_\alpha \to \nu_\beta) - P(\bar{\nu}_\alpha \to \bar{\nu}_\beta)}{P(\nu_\alpha \to \nu_\beta) + P(\bar{\nu}_\alpha \to \bar{\nu}_\beta)}$$





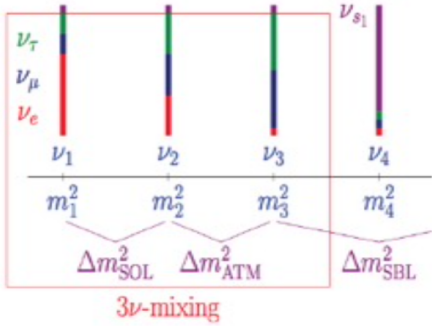
- DUNE: *4x 17 kt LAr-TPC, 1.2 -> 2 MW proton beam*
  - Very long baseline → large matter effect → unambiguous mass ordering and CPV
  - Broadband neutrino beam → high statistics over full oscillation period
  - Reconstruct E_ν over broad range → imaging + calorimetry → LArTPC technology
  - Highly-capable near detector to constrain systematic uncertainties
- Hyper-K: *260 kt water-Ch, 1.2 MW proton beam*
  - Shorter baseline → small matter effect
  - Off-axis location & narrowband beam → very, very high statistics at oscillation maximum, less feed-down
  - Lower energy and mostly CCQE → very large water Cherenkov detector
  - Highly-capable near detector to constrain systematic uncertainties

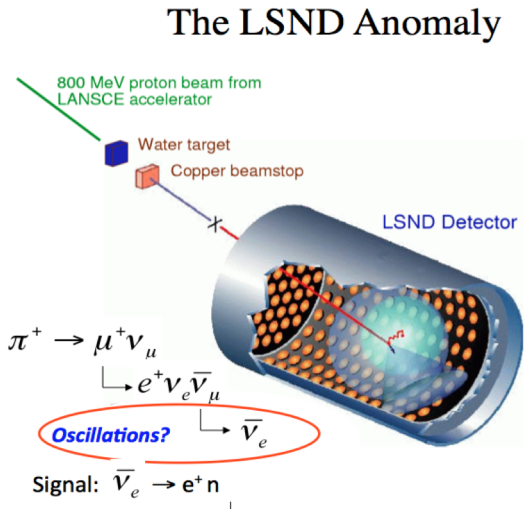
Persisting anomalies in the neutrino sector

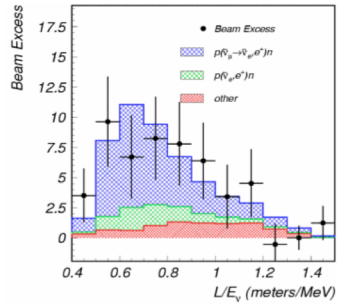
- Despite the well-established 3-flavour ν mixing, several anomalies collected so far hinting to additional ν states driving oscillations at small distance with $\Delta m^2_{new} \sim 1\ eV^2$, small $\sin^2 2\theta_{new}$:

  - *anti–ν_e appearance: in anti-νμ accelerator LSND experiment where anti-ν_e -> e⁺ + n with neutron resulting n + p into d + γ.*
  - *ν_e disappearance: SAGE, GALLEX experiments with Mega-Curie K-capture calibration sources showing an observed/predicted R = 0.84±0.05, recently confirmed at 4σ by BEST exp.*
  - *anti-ν_e disappearance of near-by nuclear reactor experiments RAA, R = 0.934±0.024, but poor knowledge of U fuel processes consumption*

…pointing to sterile ν hypothesized by Bruno Pontecorvo in a 1957 seminal paper…



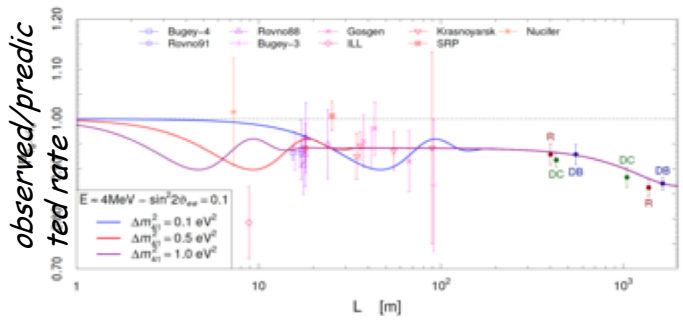




Saw an excess of $\bar{\nu}_e$: 87.9 ± 22.4 ± 6.0 events.

With an oscillation probability of (0.264 ± 0.067 ± 0.045)%.

3.8 σ evidence for oscillation.



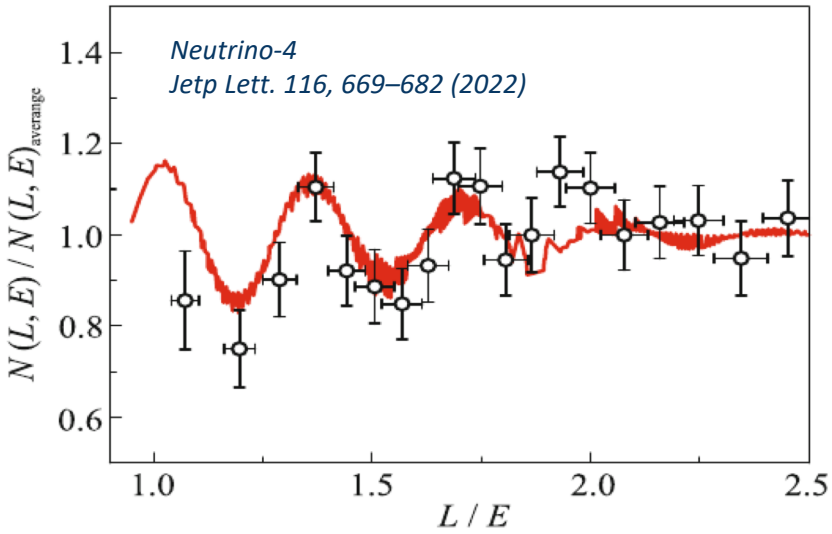
$$U = \begin{bmatrix} U_{e1} & U_{e2} & U_{e3} & U_{e4} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} & U_{\mu 4} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} & U_{\tau 4} \\ U_{s1} & U_{s2} & U_{s3} & U_{s4} \end{bmatrix}$$

New evidence for oscillations of sterile neutrinos at reactor ?

- In 2019 Neutrino-4 experiment *(A.P. Serebrov et al.)* at Dimitrovgrad SM-3 reactor gave evidence of neutrino oscillation into sterile-νs showing a disappearance signal with a clear L/E ~ 1-3 m/MeV modulation

- 3 years data taking moving the segmented liquid scintillator detector from 6.4 to 11.9 m from reactor core in 24 steps:

Neutrino signal compared with expectation for $\Delta m^2 \sim 7.25\ eV^2$, $\sin^2 2\theta \sim 0.26$ *as a function of L/E*



Reactor On - Off : 223 events/day with Signal/Background ~ 0.54

$\Delta m_{14}^2 = 7.25 \pm 1.09\ eV^2$ *with* $\sin^2(2\theta_{14}) = 0.26 \pm 0.08\ stat \pm 0.05$

sterile ν as candidate for Dark Matter ?

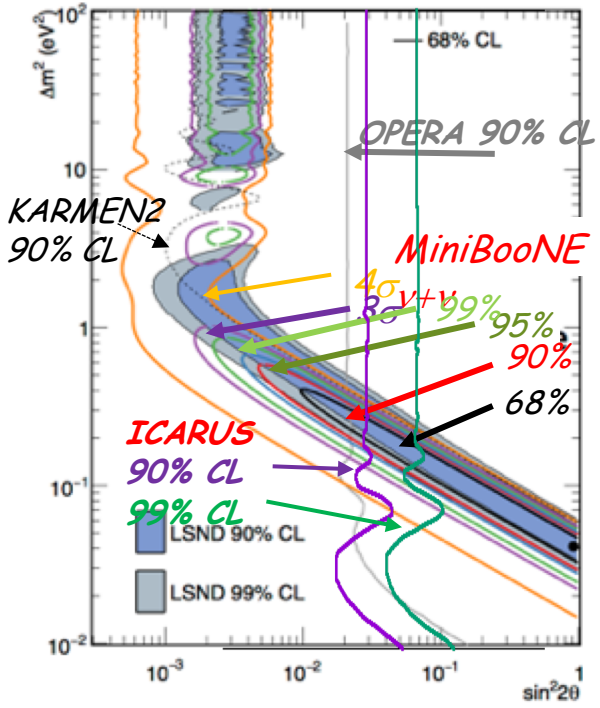
a quite obvious contribution due to the high density of relic sterile-νs with $m\nu_4$ = 2.7 eV.

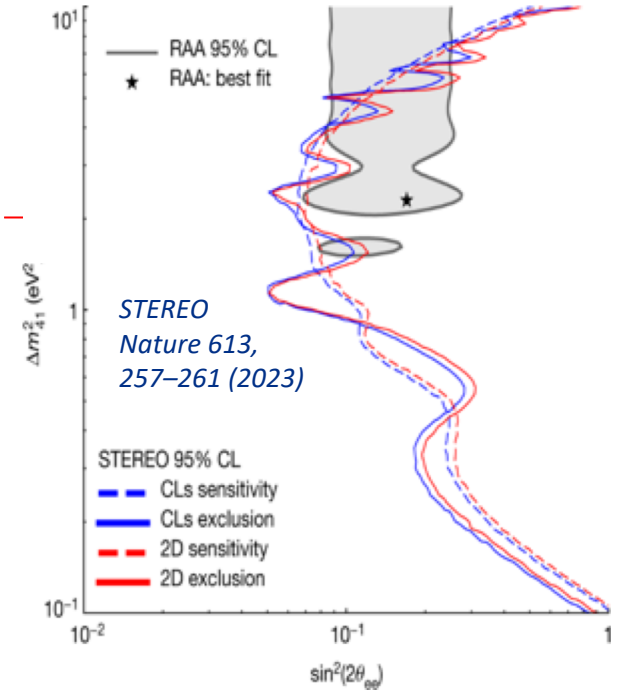
Combined analysis: Neutrino-4 (*P.R. D 104, 032003, 2021*), GALLEX, SAGE and BEST

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

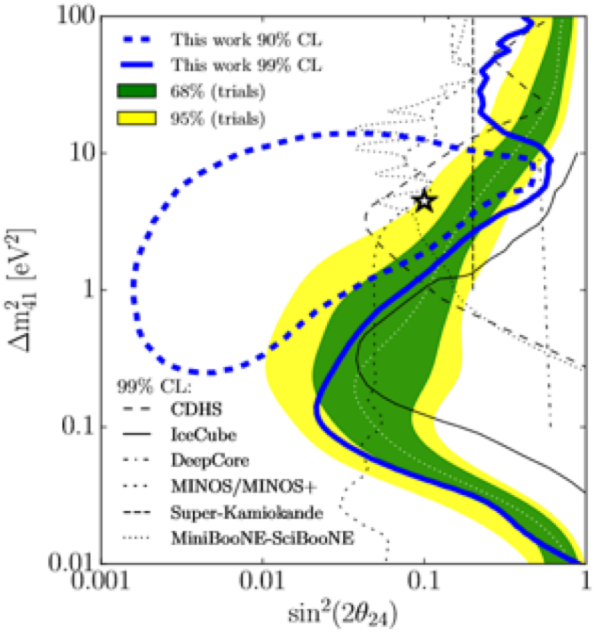
- Several experiments at accelerators and reactors to study "ν anomalies" both in appearance/disappearance:
  - Large part of LSND parameters excluded by ICARUS and OPERA $\nu_\mu \rightarrow \nu_e$ at CNGS ν beam; MiniBooNE $\nu_\mu \rightarrow \nu_e$ at FNAL low energy νe event excess not confirmed by MicroBooNE
  - Recent anti-ν_e measurement at reactors: study of fuel burnup cycle from *Daya Bay, RENO STEREO* to reconstruct contribution of main isotopes: hint of sterile ν reduced to 1 σ;
  - No evidence in νμ disapp. exps (*IceCube, NOνA, MINOS/MINOS+, T2K)*

$\nu_\mu \rightarrow \nu_e$





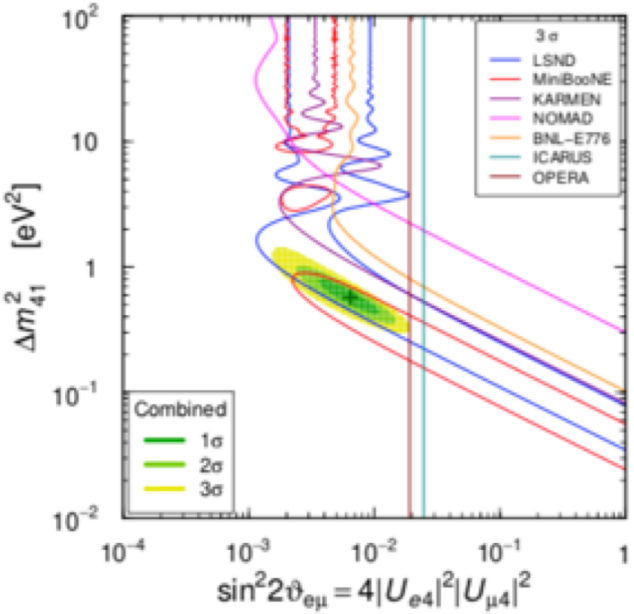
IceCube
Phys.Rev.Lett. 125 (2020) 14, 141801



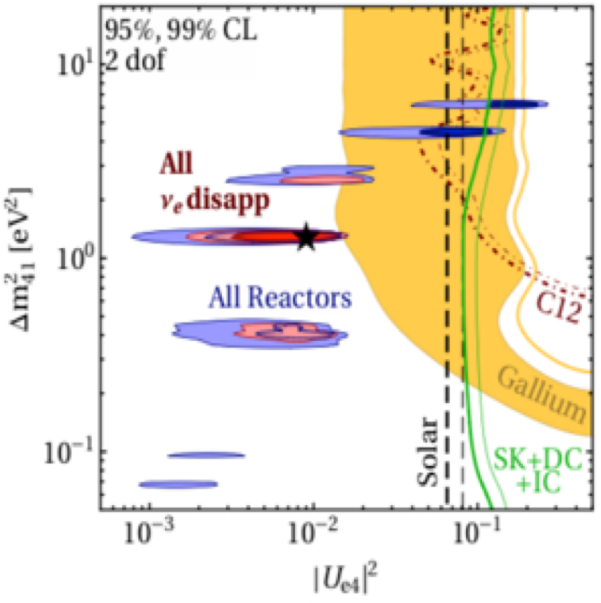
A long-standing puzzle in neutrino oscillation sector

- Clear tension between appearance/disappearance experiments characterized by different neutrino detection techniques and ν energy spectra:

(anti-)$\nu_\mu \rightarrow \nu_e$ Appearance



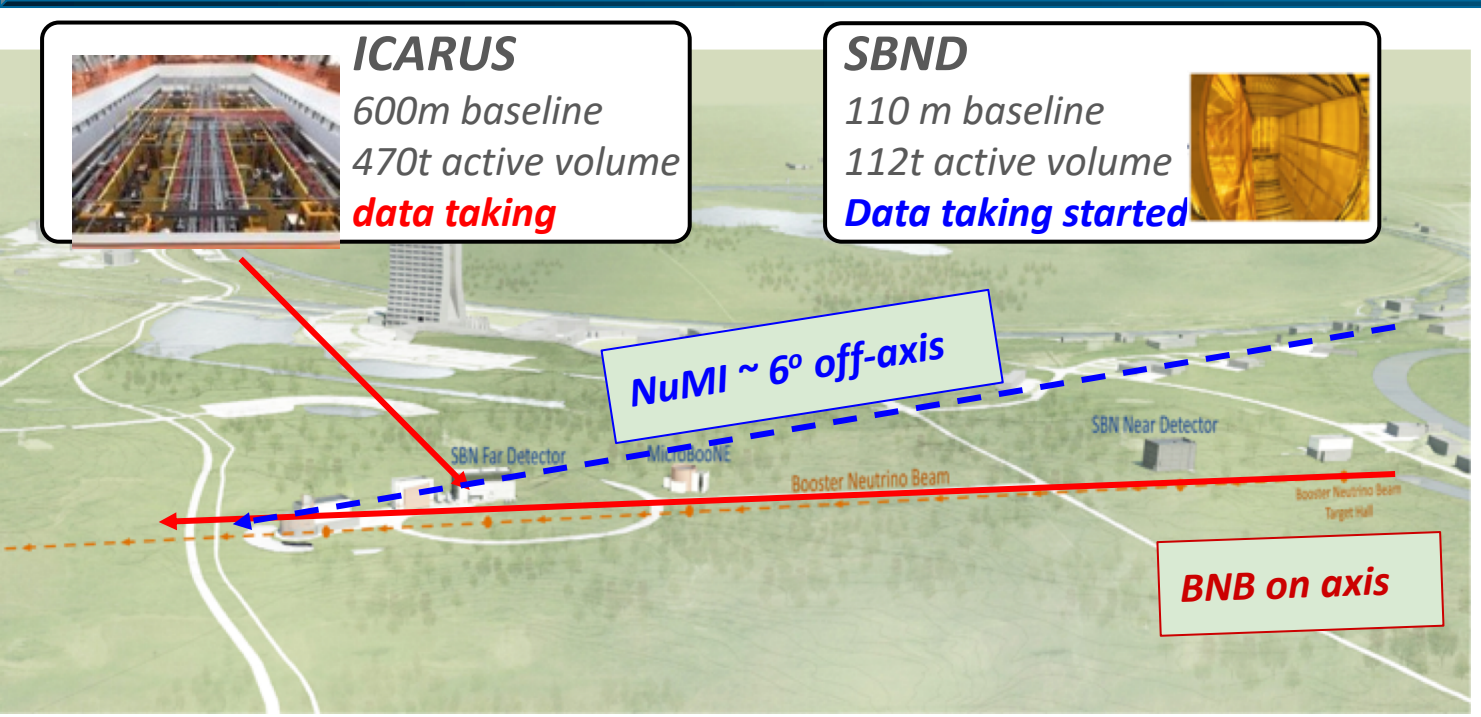
(anti-)ν_e Disappearance

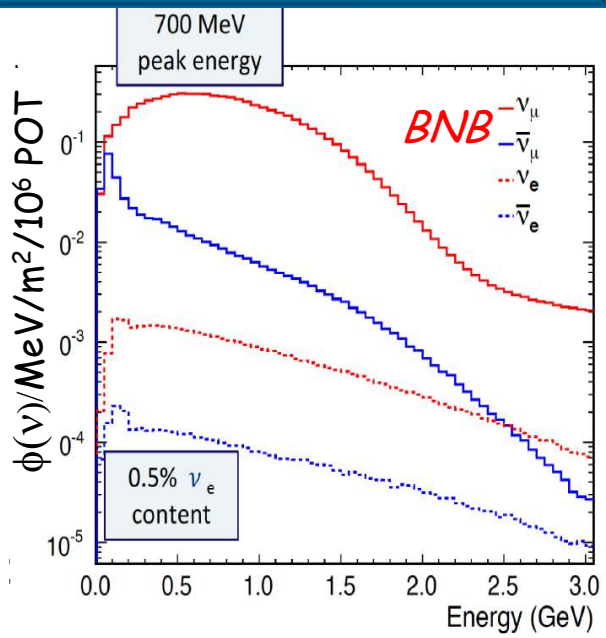


(arXiv:2106.05913)

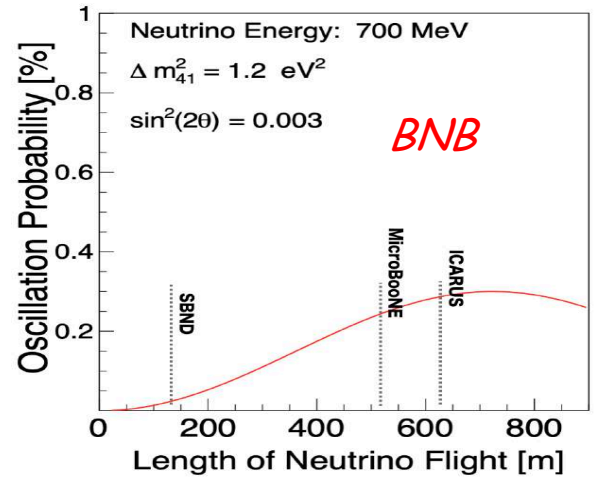
- ✓ *Measuring both ν app./disapp. in the same experiment with a detector with an optimal neutrino identification/backgr rejection is mandatory*
- ✓ *Far to near detector neutrino spectra comparison: crucial for the control of backgr and beam/detector systematics.*

Short Baseline Neutrino (SBN) at FNAL BNB and NuMi beams: *a definitive answer to sterile neutrinos ?*



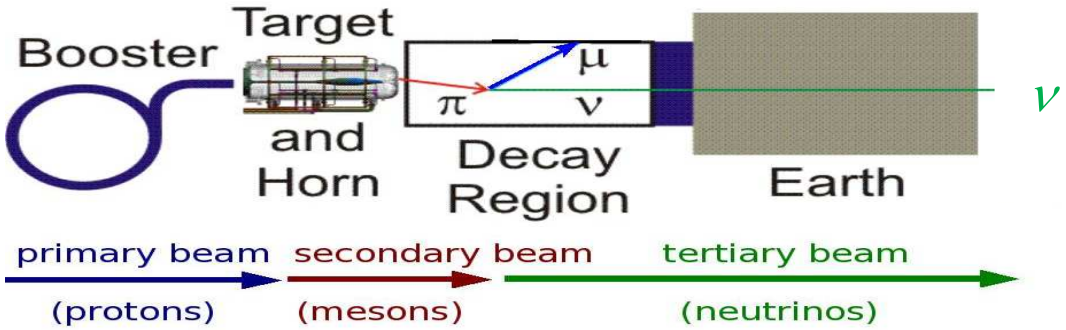


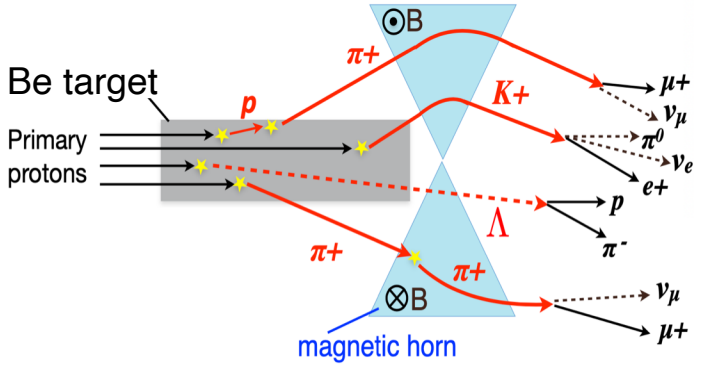
- ICARUS and SBND LAr-TPC's installed at 600 and 110 m from the BNB target, searching for sterile-ν oscillations both in appearance and disappearance channels.
- High-statistics ν-Ar cross-section measurements and event identification/reconstruction studies:
  - 10^6 evt/y in SBND <1 GeV from Booster (Eν ~ 0.8 GeV)
  - 10^5 evt/y in ICARUS >1 GeV from 6^0 off-axis NuMI (Eν~2 GeV)

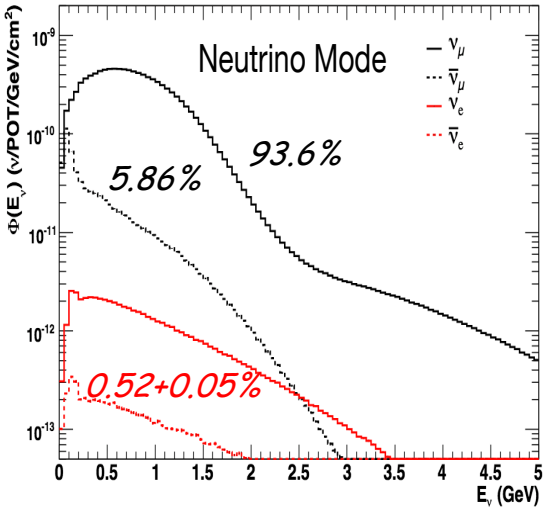


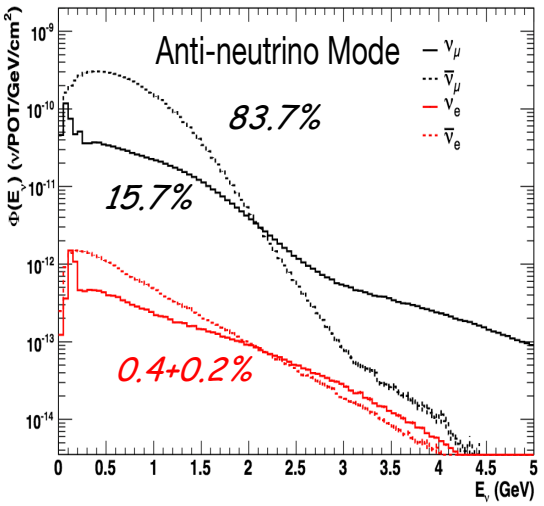
BNB neutrino beam

- ✓ 8 GeV protons on Be target, ~5×10^{12} p/spill, 1.6 μs spill: 81 x 2 ns bunches 19 ns apart, ~5 Hz.
- ✓ Positive (*negative*) secondary particles are focused (*defocused*) by a magnetic horn according to I circulation versus.
- ✓ 50 m decay tunnel where focused mesons propagate/decay producing neutrino.









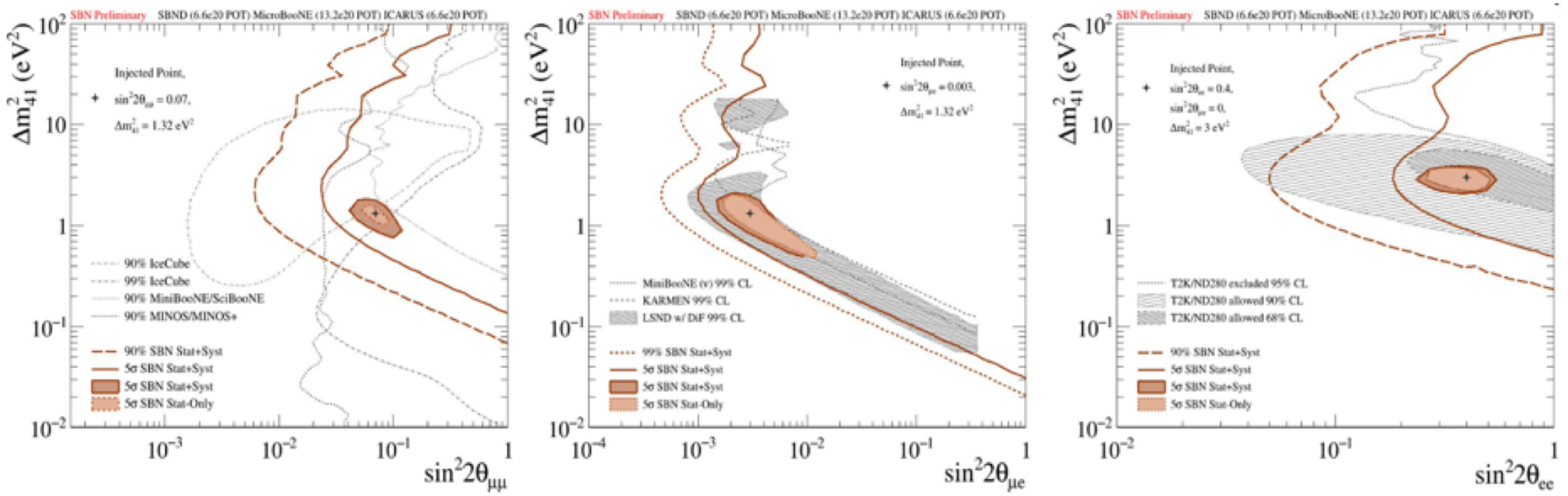
Anti-neutrino beam: secondary negative particles are focused by reversing the Horn current

MiniBooNE Collab. Phys. Rev. D 79, 072002. 2009

SBN Program: sterile neutrino sensitivity, 3 years (6.6 x10^{20} pot)

- Combined analysis of events collected far by ICARUS at far site and by SBND at near using the same LAr-TPC event imaging technology greatly reduces the expected systematics:
  - High νe identification capability of LAr-TPCs rejecting NC event background;
  - "Initial" BNB beam composition and spectrum provided by SBND detector.

νμ disappearance | *νe appearance* | *νe disappearance*



5σ coverage of the parameter area relevant to LSND anomaly

Probing the parameter area relevant to reactor and gallium anomalies.

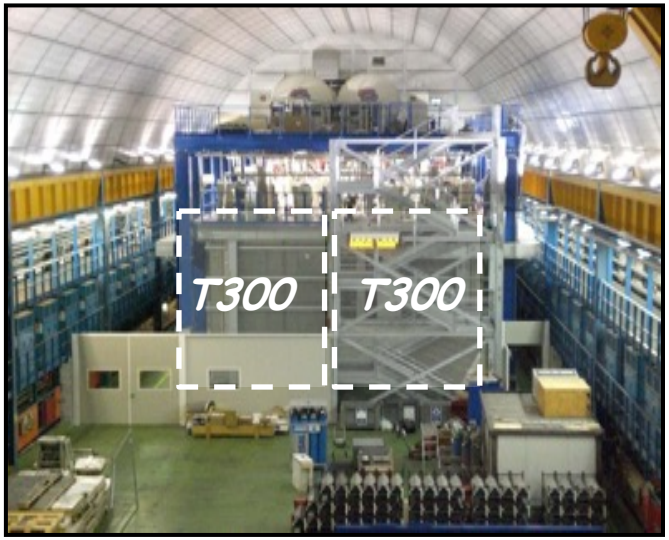
Unique capability to study neutrino appearance and disappearance simultaneously

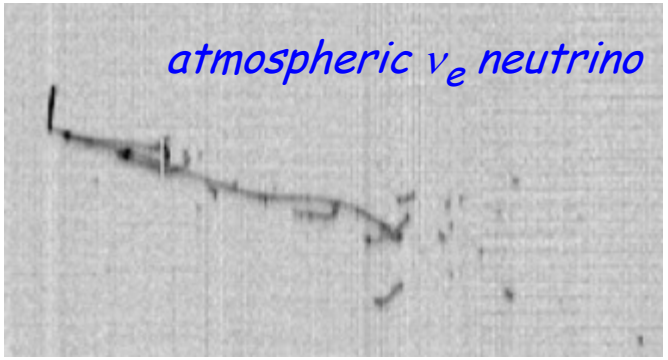
The remarkable evolution of ν-detectors: the ICARUS LAr-TPC

- Liquid Argon Imaging technology LAr-TPC, an "electronic bubble chamber" to unambiguously reconstruct each ionizing track in complex neutrino events, was first proposed by C. Rubbia in 1977 as an alternative to Cherenkov detectors:

  A long R&D culminated in the first large-scale successful experiment ICARUS-T600, 0.76 kt ultra-pure LAr at Gran Sasso INFN Lab exposed underground to CNGS ν beam investigating sterile neutrinos!

  - Tracking device: 3D event topology with $\Delta x \sim$ mm, e- by charged particles can drift undisturbed for meters with E_D= 0.5 kV/cm if LAr is sufficiently pure
  - Full sampling homogeneous calorimeter: E measurement by charge signal integration;
  - Measurement of local energy deposition dE/dx: remarkable e/γ separation, 0.02 X_0 sampling, X_0=14 cm, a powerful PID by dE/dx vs range. Momentum of not contained μ is measured by Multiple Coulomb Scattering
  - Scintillation light by charged particles provides fast signals for timing/triggering.

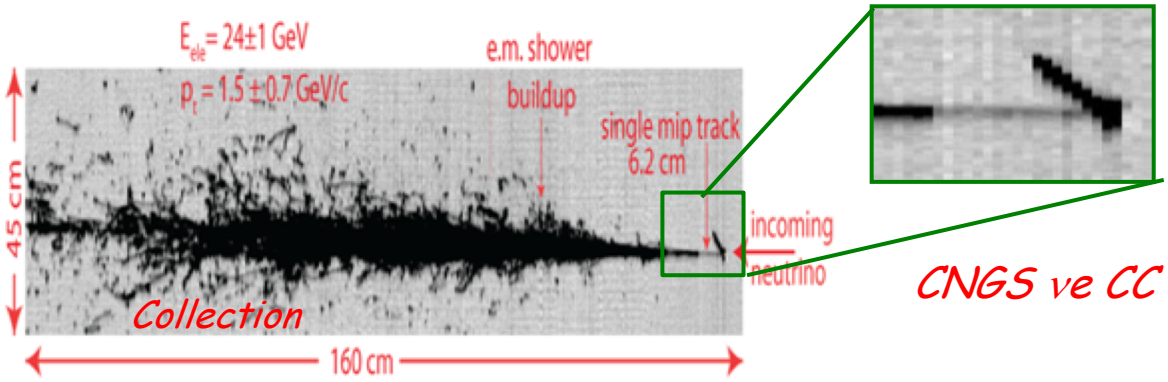




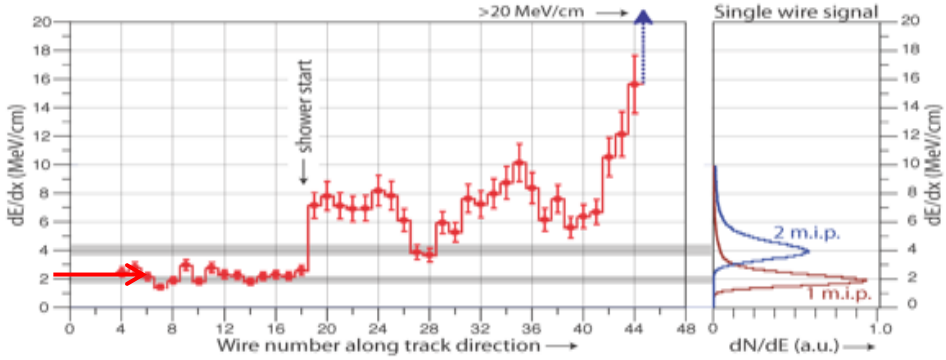
… paving the way for Long-Baseline DUNE experiment!

ICARUS T600: a powerful detector for neutrino experiments

- ICARUS concluded in 2013 a successful 3 years long run exposed to CNGS beam and cosmic rays with several physics/technical achievements:
  - *Demonstrating the unique LAr-TPC capability to identify νe and reject π^0 background*
  - *Performing with OPERA a sensitive search for νμ ->νe appearance constraining LSND and MiniBooNE νe signals to a narrow region, EPJ C (2013) 73:2599*

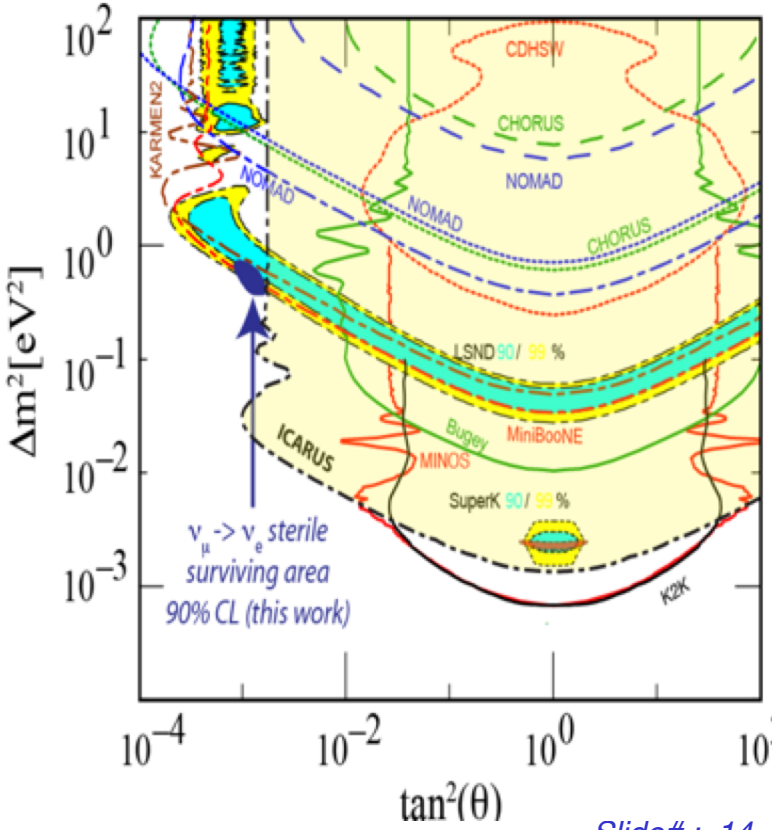


CNGS νe CC



Single mip

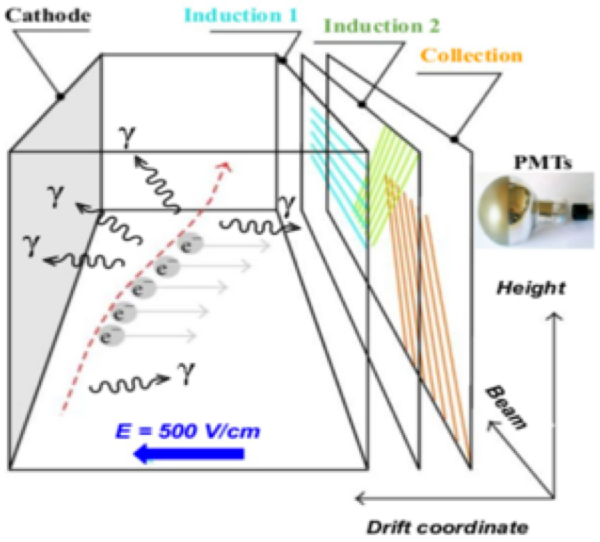
Evolution from single e-mip to EM shower is evident from dE/dx on individual wires.



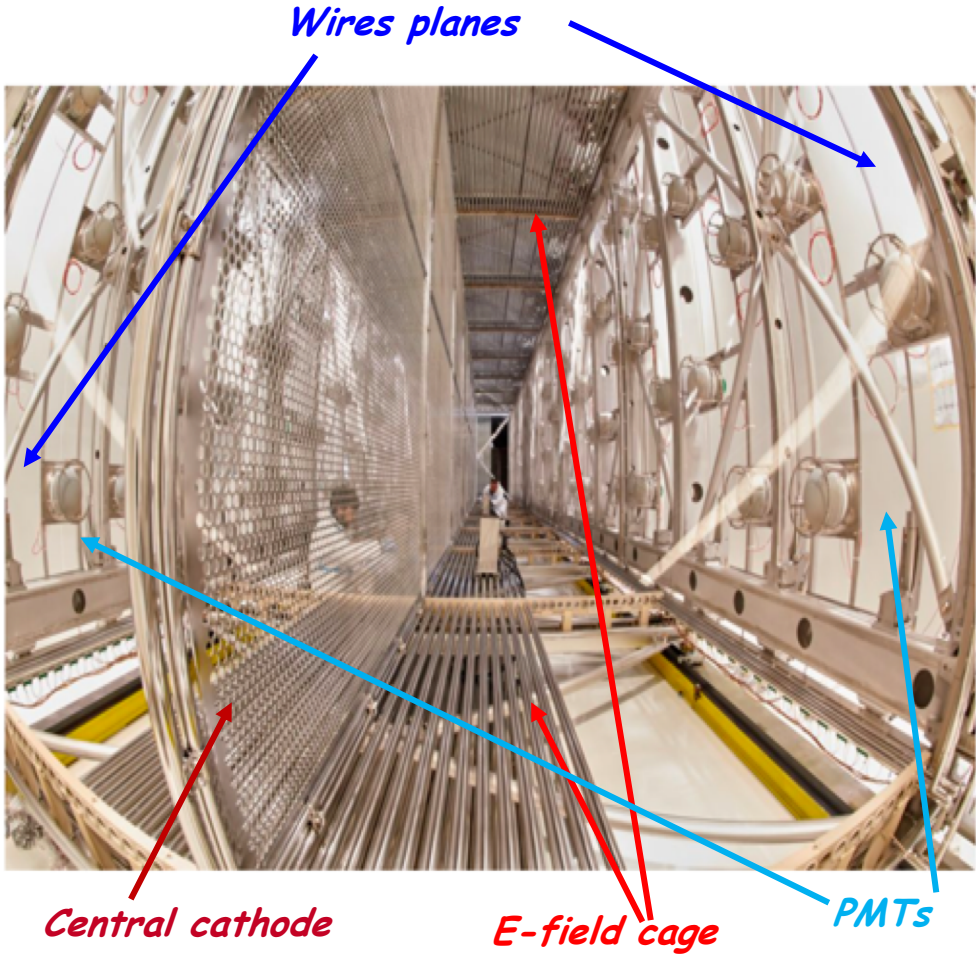
ICARUS at Fermilab

- 2015-18: extensive overhauling in view of shallow depth operations at Fermilab to explore $\Delta m^2 \sim 1\ eV^2$ region and fix the sterile neutrino question.

  - 2 modules, 2 TPC chambers per module with a central cathode (1.5 m drift, E_D= 0.5 kV/cm);
  - 3 readout wire planes per TPC, 54000 wires at 0, $\pm$ 60^0, 3 mm pitch, in total;
  - 360 8" photomultipliers, TPB coated, to detect the scintillation light;
  - LAr/GAr purified by copper filters and molecular sieves for water absorption.

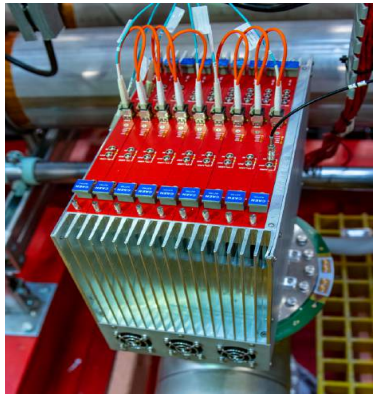


Structure of one module with 2 TPC chambers

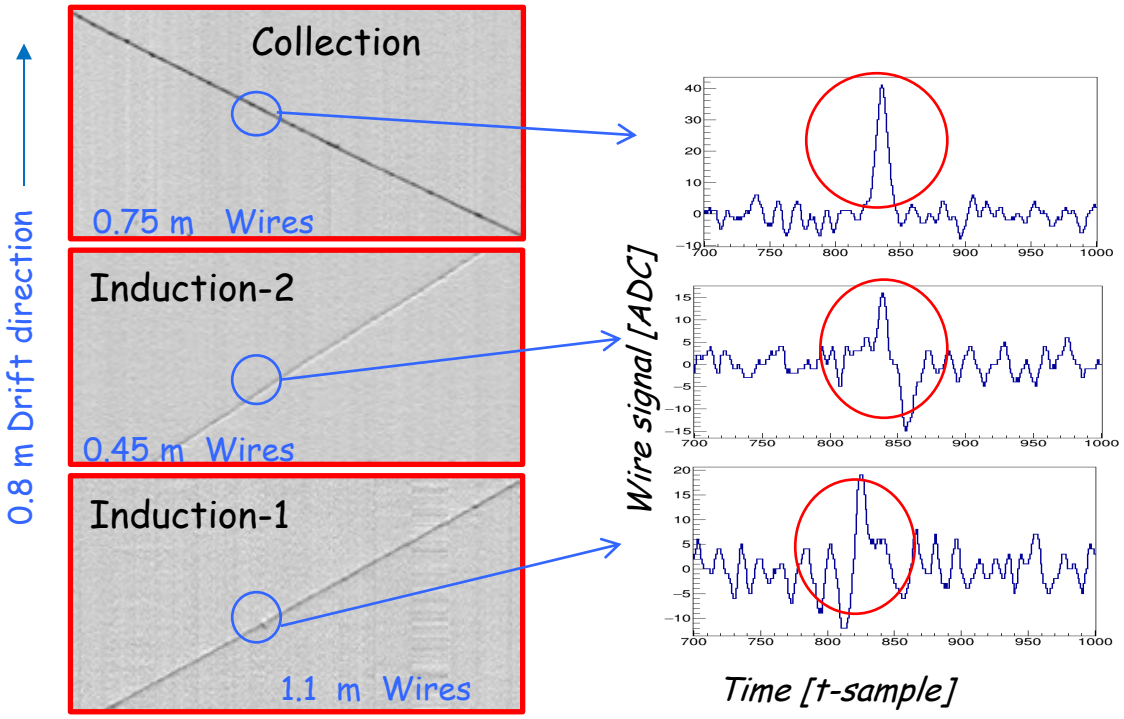


TPC wire readout

- 54000 chs: front-end based on analogue low noise, charge sensitive pre-Amp;
- Signal shaping ~1.3 μs matching e- transit time between Induction-1, 2 and Collection wire planes (3 mm apart) improving hits position resolution;
- Compact layout with both analog/digital electronics in a single board.

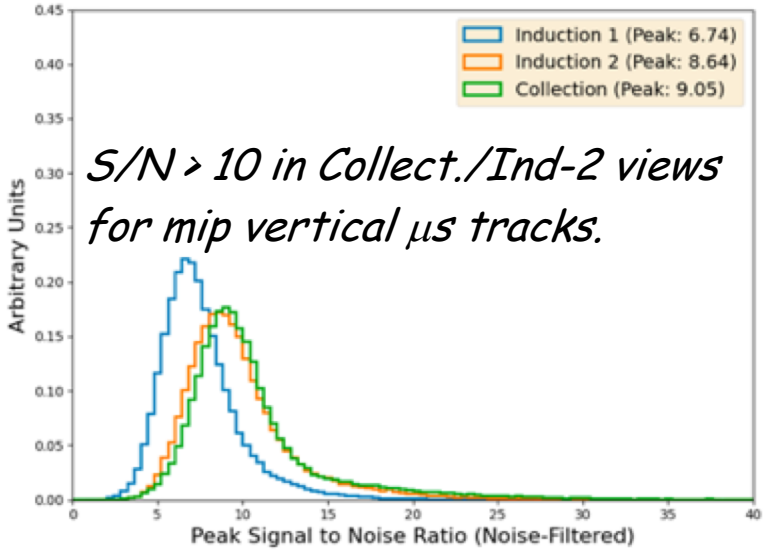


10 liter mini-crate on a feed-through hosting 9 boards (576 wires).



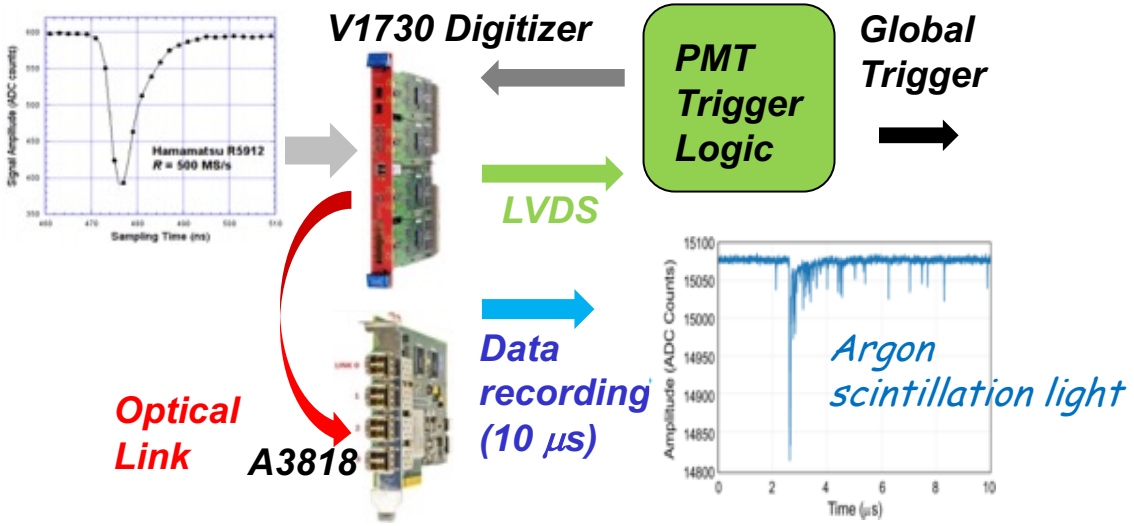
Recorded cosmic muon track:
bipolar shape of e-signals traversing wire planes recognized in Inducion.-1, 2 views.

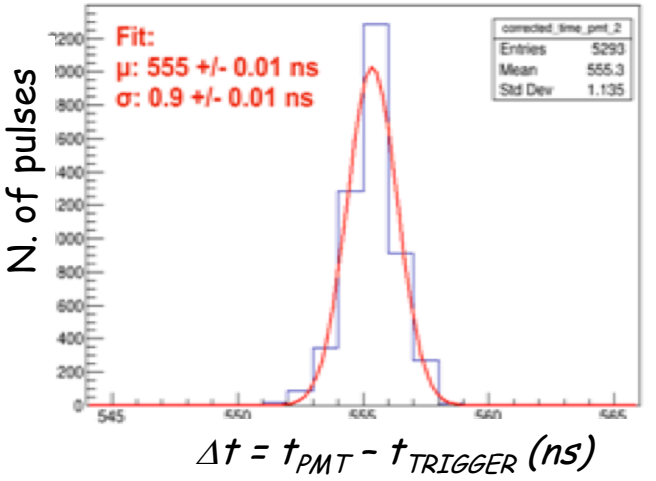
ICARUS Signal to Noise ratio



Upgrade of the light collection system

- 360 Hamamatsu 8" PMT (5% coverage, 15 phe/MeV) installed behind the wire planes, 90 PMTs per TPC chamber:
  - Continuous read-out, digitization, discrimination and waveform recording of PMTs signals (V1730 digitizers);
  - PMT signals sampled every 2 ns, recorded in 10 μs windows.

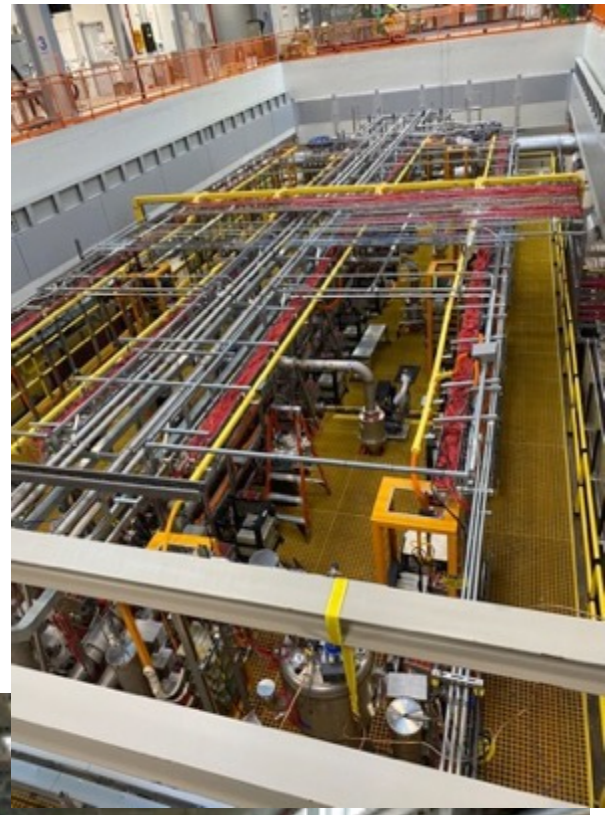




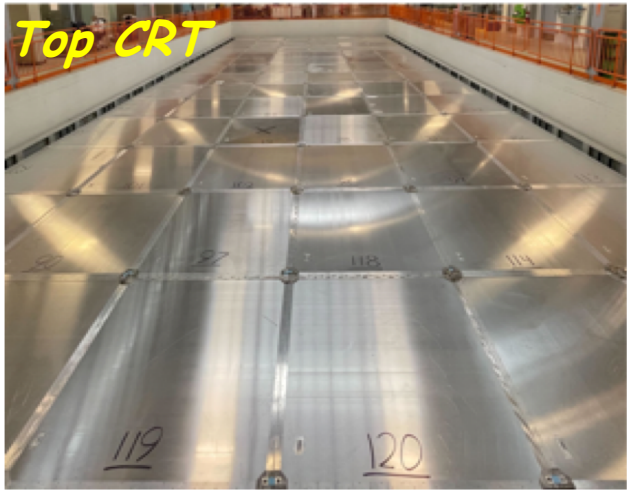
- PMT gain equalized at ~ 0.45 $10^7 \pm 1\%$ with $\lambda \sim 405$ nm laser and measuring ~4 mV PMT response to single photoelectron;
- PMT timing to Trigger signal with 1 ns resolution by laser to perfectly determine the time of collected events.

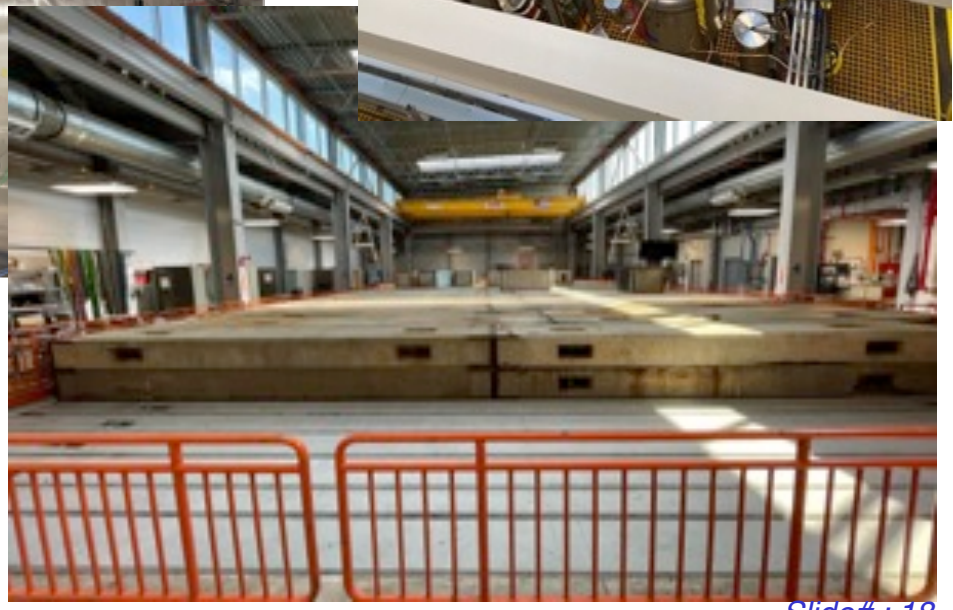
Cosmic-ray background mitigation in ICARUS

- ICARUS exposed in a pit to cosmic rays: electrons produced by γ's via Compton Scatt./Pair Prod. can mimic a genuine ν_e CC event:



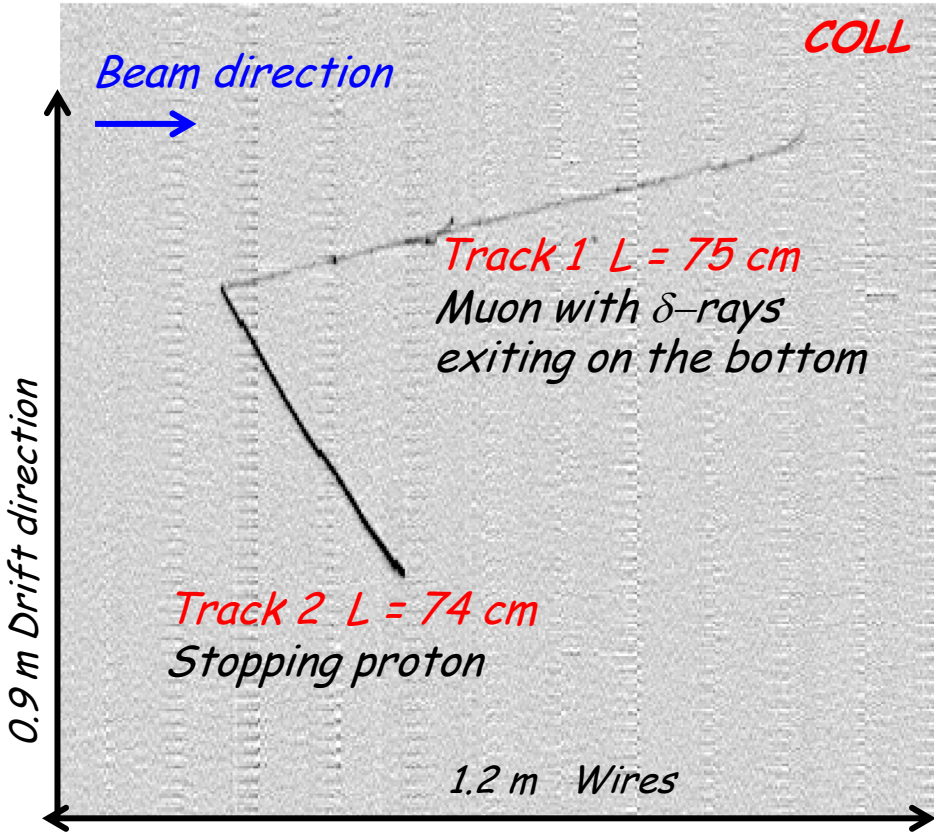
  - Cosmic μs entering ICARUS are identified in time/position by 4π Cosmic Ray Tagger (CRT) ~1000 m^2 double-layer scintillation bars equipped with SiPMs surrounding LAr-TPCs;





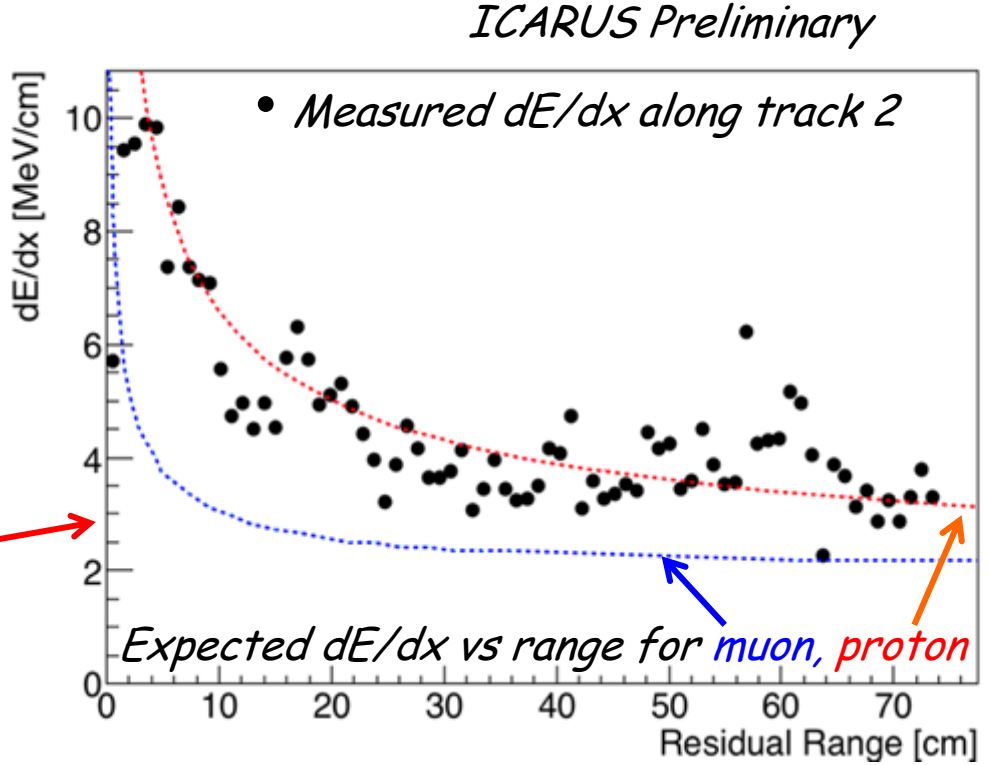
  - Cosmic γ's and neutrons suppressed by 2.85 m concrete overburden installed above CRT.

First collected neutrino events: a BNB QE νμ CC candidate

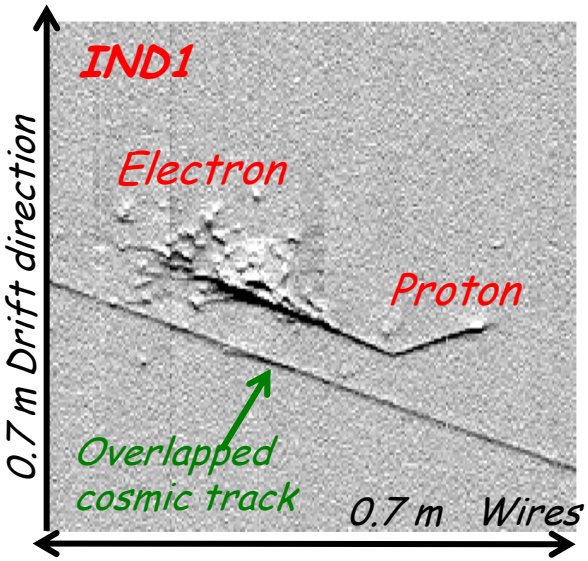


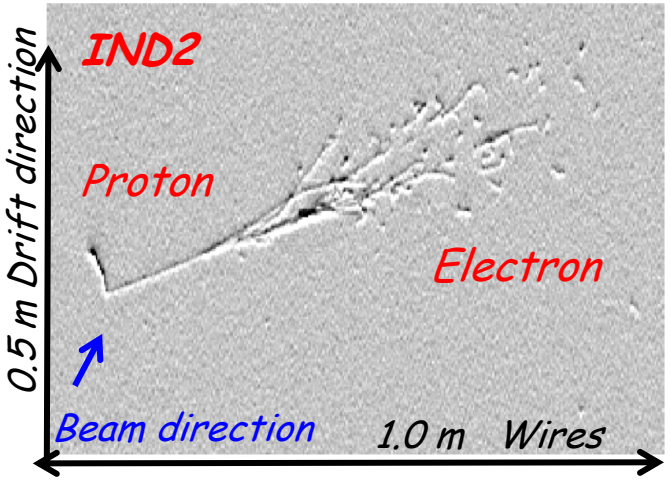
- Neutrino interaction vertex well inside the active LAr volume. Two tracks are produced:
  - ✓ Track 1: downward going muon candidate, exiting on bottom (confirmed by δ rays)
  - ✓ Track 2: stopping proton.

- From the study of dE/dx *vs* range, track 2 is compatible with a proton: E_{DEP}~ 340 MeV, E_K =370 MeV (if evaluated from range).

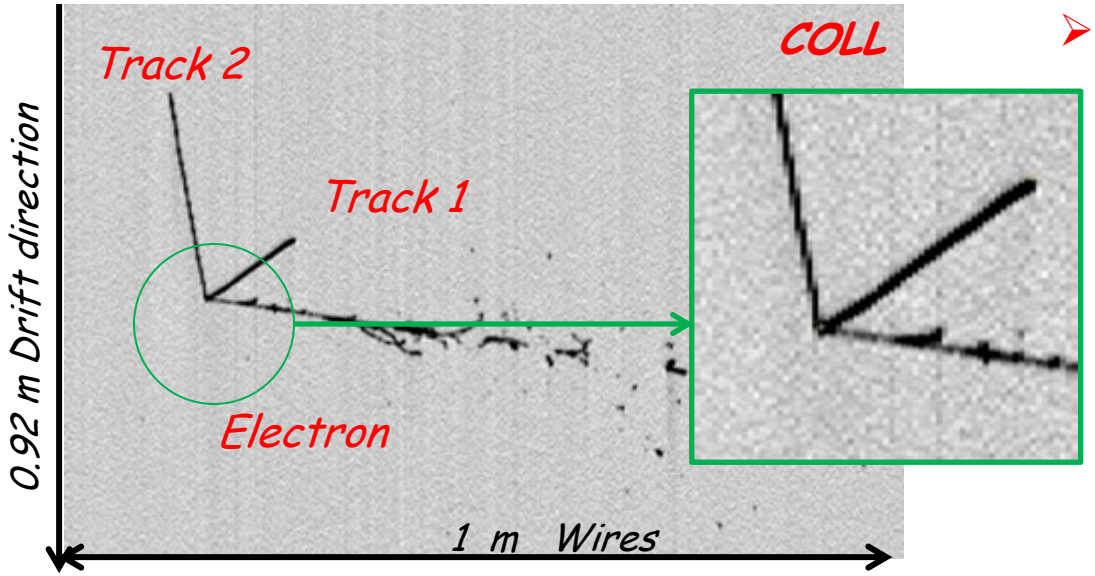


NuMI νe CC candidates





- QE νe CC event contained candidate, E_{DEP}~870 MeV:
  - ✓ proton candidate is upward going/stopping L= 13 cm;
  - ✓ e-shower is downward going.

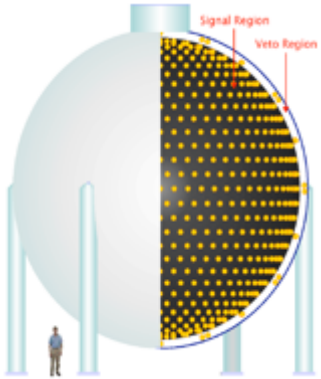


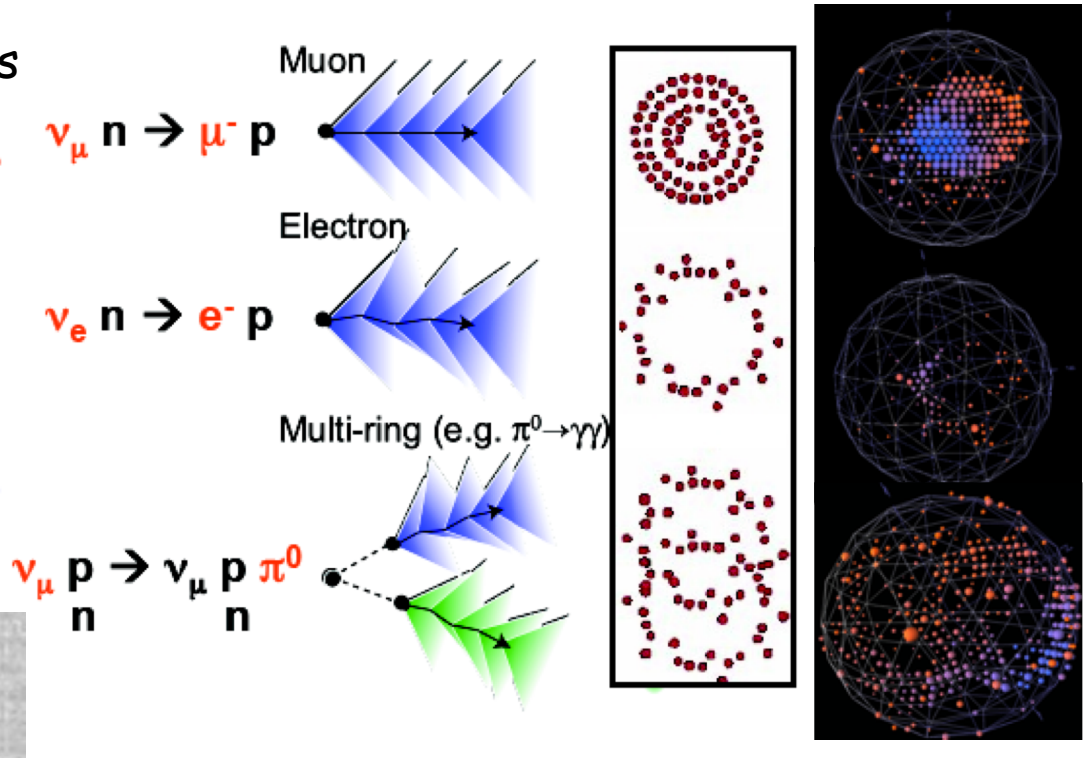
- νe CC event candidate fully contained in active LAr, E_{DEP}~830 MeV:
  - ✓ The electron shower, E_{DEP}~570 MeV is downward going;
  - ✓ Track 1: upward going, stopping proton candidate, L = 23.7 cm;
    Track 2: stopping hadron, L = 33.4 cm.

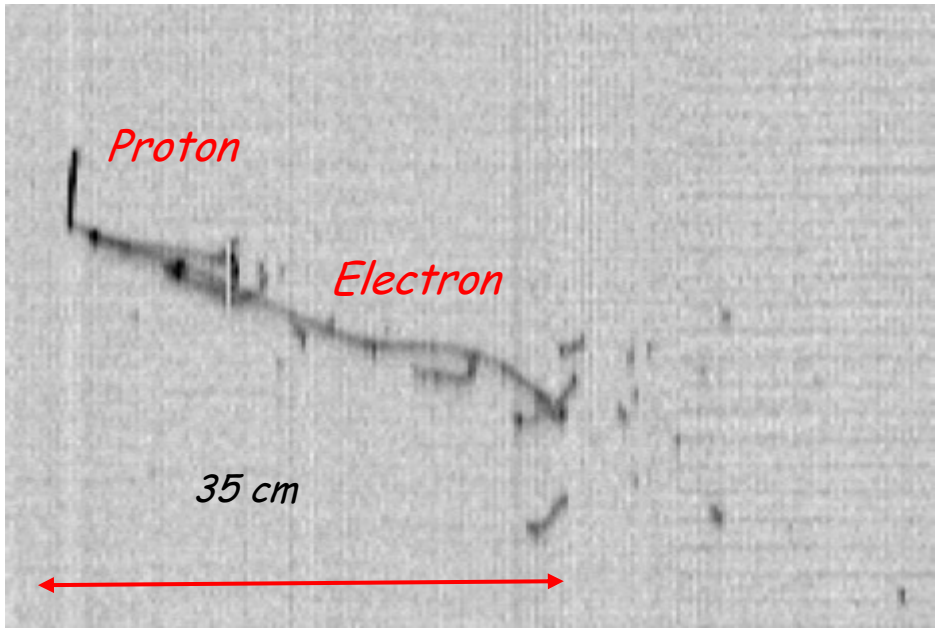
LAr-TPC *vs* Cherenkov?

- MiniBooNE: 800 ton liquid scintillator, primarily Cherenkov light by 1280 PMTs

difficult e/γ separation:
π^0 background!





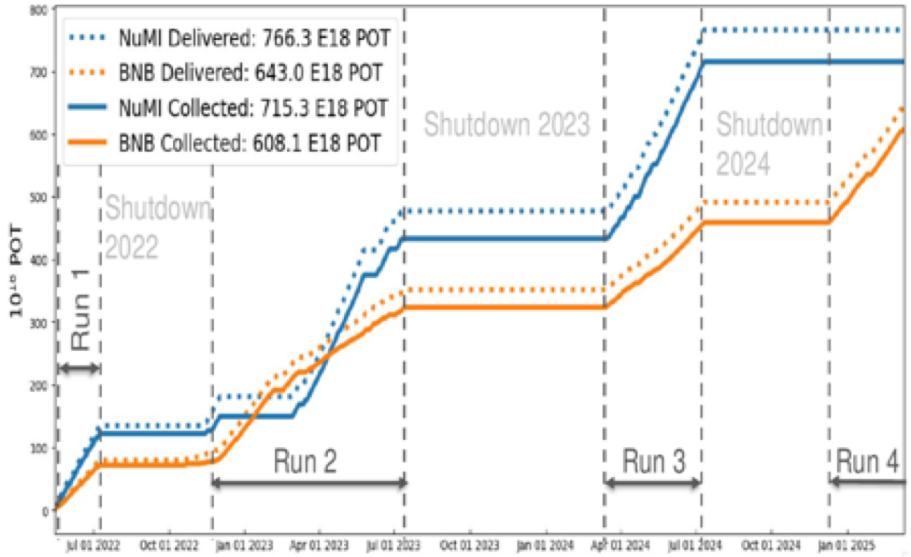


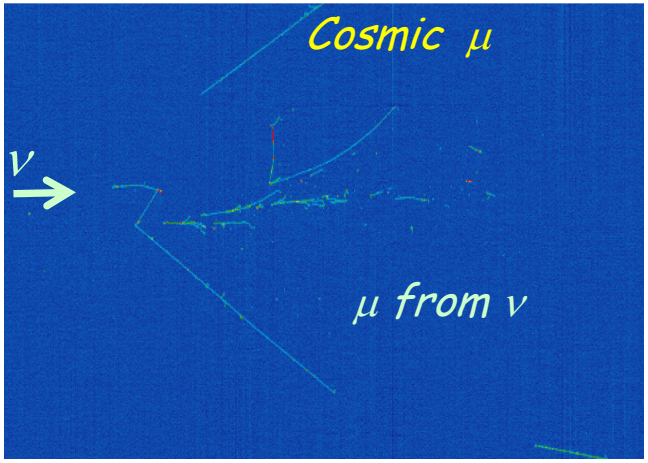
- ICARUS LAr-TPC ν_e atmosph. neutrino event

superb e/γ separation and
π^0 background rejection

ICARUS operations and data collection @FNAL

- ICARUS data taking for physics started in June 2022: 3 physics runs completed since then + fourth run ongoing since December 2024.
  - Steady data taking with excellent stability at BNB rates > 4Hz, >90% live time.
  - Highly pure liquid argon: free electron lifetime $\tau_e \approx$ 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 (1.6 μs), NuMI (9.5 μs) beams



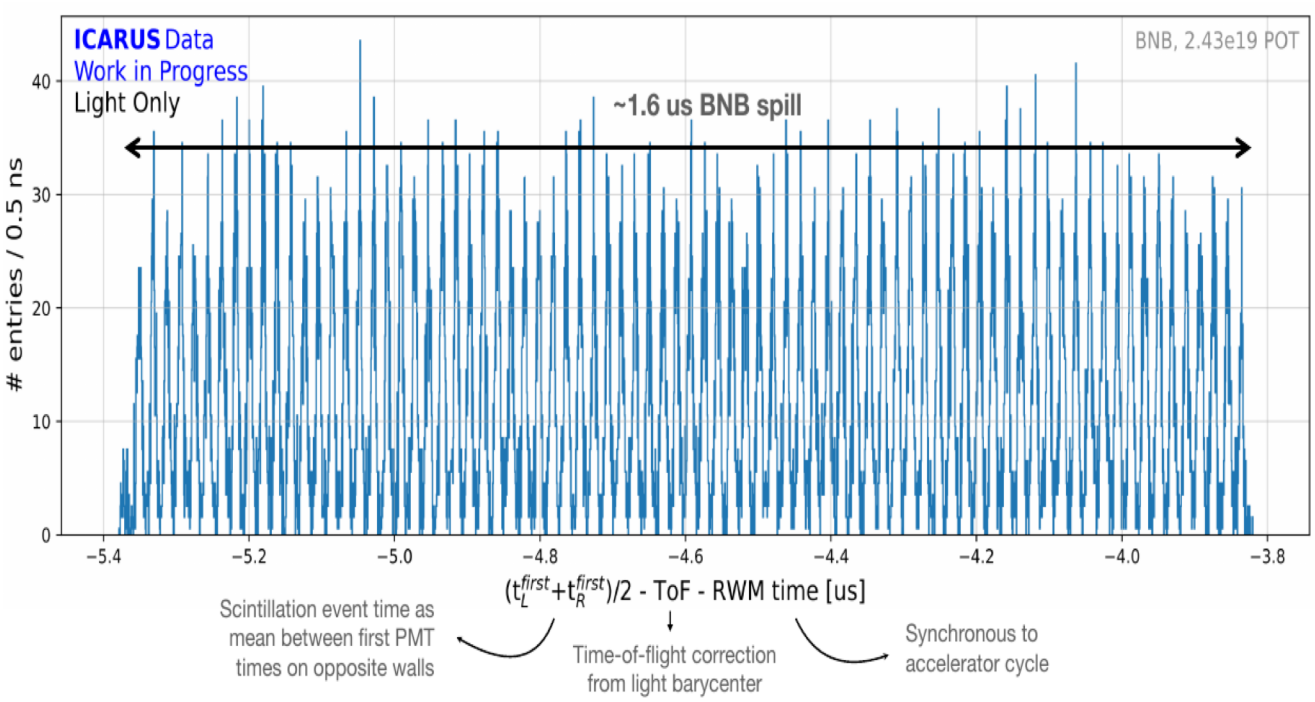


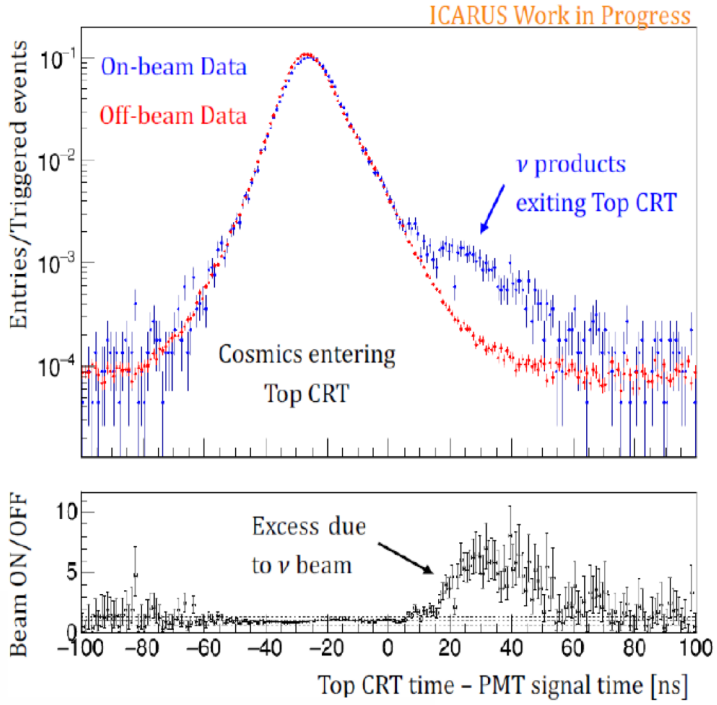
Collected PoT	BNB (FHC) positive focusing	NuMI (FHC) positive focusing	NuMI (RHC) negative focusing
RUN-1 (Jun-Jul 22)	0.41 10^{20}	0.68 10^{20}	-
RUN-2 (Dec 22-Jul 23)	2.06 10^{20}	2.74 10^{20}	-
RUN-3 (Mar -July 24)	1.36 10^{20}	-	2.82 10^{20}
RUN-4* (Dec 24 -today)	2.58 10^{20}	-	-
TOTAL	6.41 10^{20}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

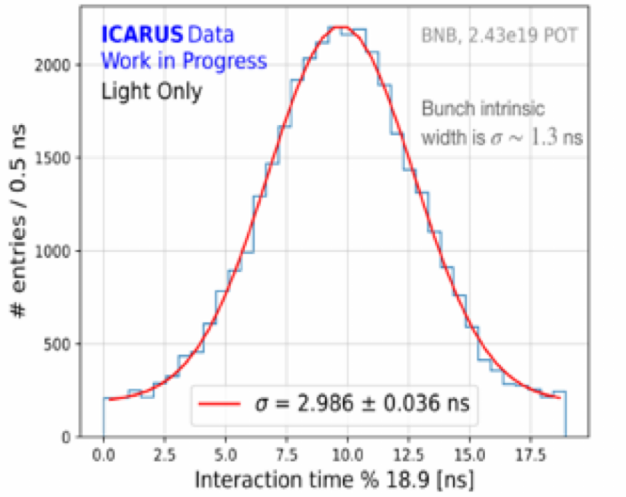
ICARUS performance: timing

- Rejection of incoming cosmics by means of time-of-flight between *external CRT* and *inner PMTs*.

- Reconstruction of BNB, NuMI beam bunch structures: neutrino event time (PMTs only) w.r.t the proton beam extraction time (RWM counters) after cosmics rejection (CRT) and ν flight distance correction.







ICARUS performance: calibration

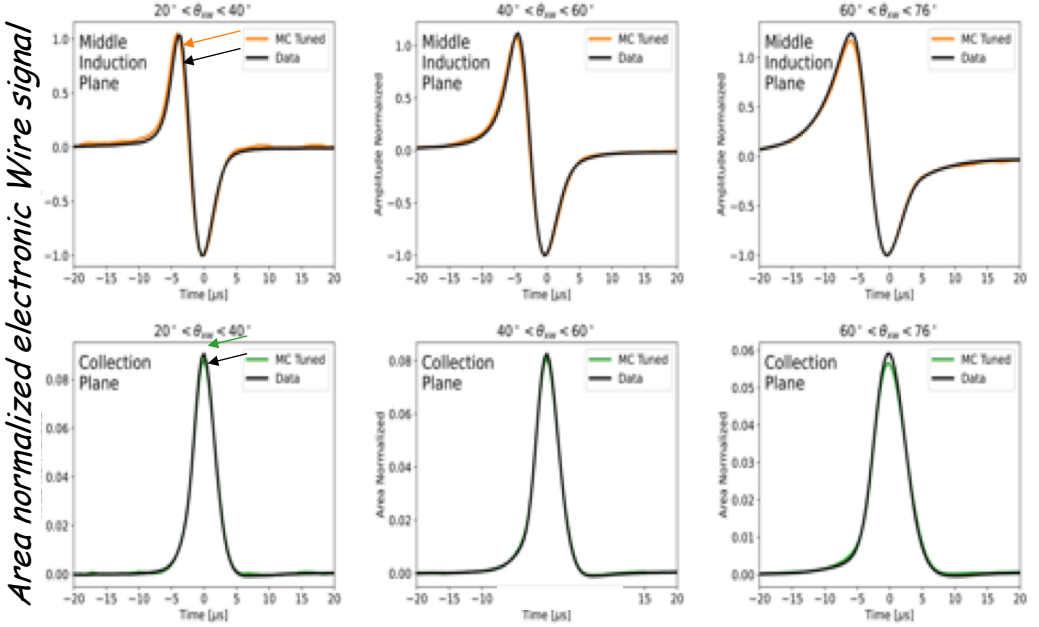
- TPC wires signals have been accurately characterized and modeled in Monte Carlo
- Detector response is calibrated with cosmic μ and p from ν interactions including a new angular dependent ellipsoidal recombination model (EMB)

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

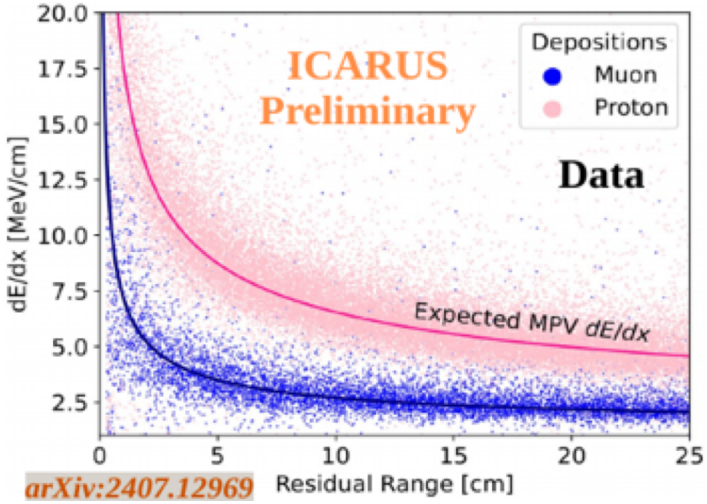
$$\frac{dx}{dQ} = \frac{1}{G}\frac{log(\alpha+\beta(\phi))\frac{dE}{dx}}{\beta(\phi)W_{ion}}$$

JINST 20 P01033 (2025)

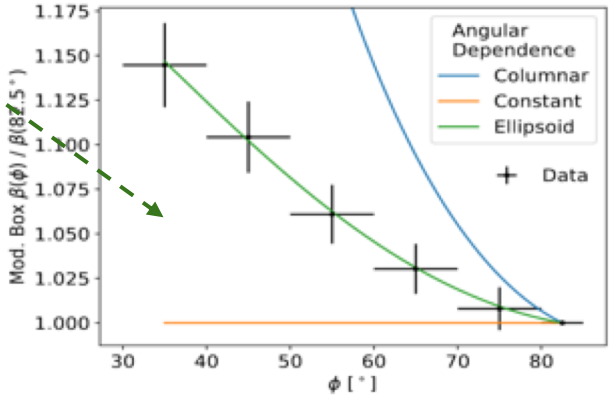
Signal response Coll. and Ind2 (Data/tuned MC) in 3 track angular bins



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

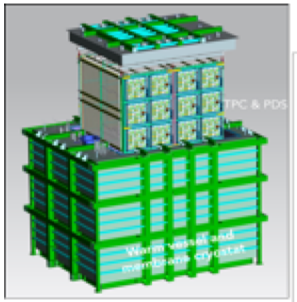


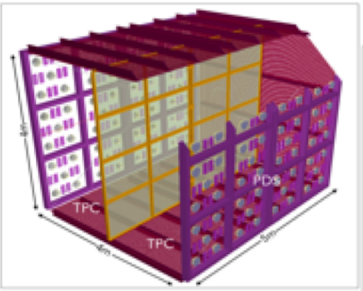
Angular dependence of recombination β parameter



SBN Near detector: SBND at 110 m from target

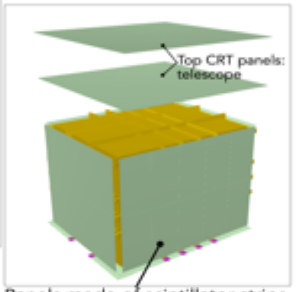
- Two LAr-TPCs with central Cathode, 112 t LAr active volume equipped with cold electronics;
- Photon detection systems of scintillation light produced by charged particles in LAr;
- The cryostat is surrounded by a Cosmic Tagger system for cosmic ray rejection.





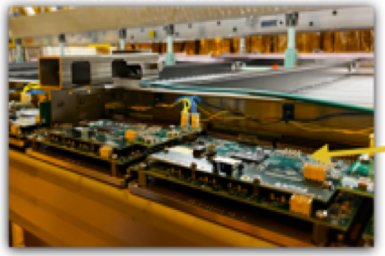
Two Time Projection Chambers and Photon Detection systems

Cryostat surrounded by a Cosmic Ray Tagger system for cosmic ray rejection

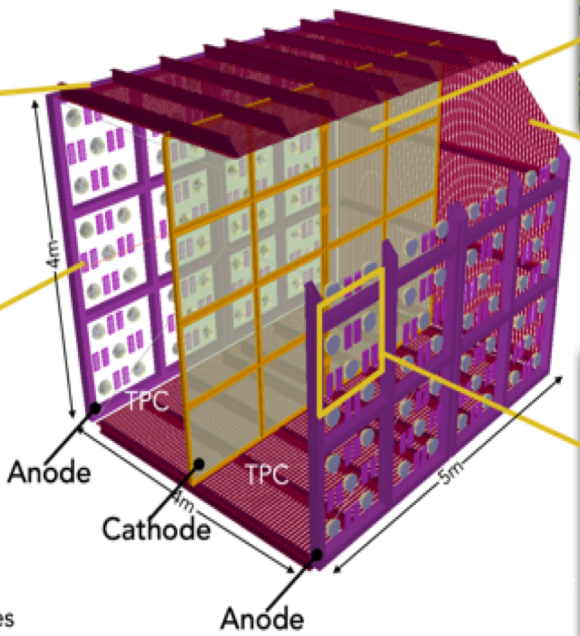


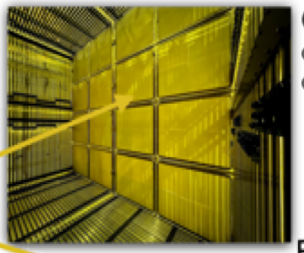
Panels made of scintillator strips

TPC Cold electronics



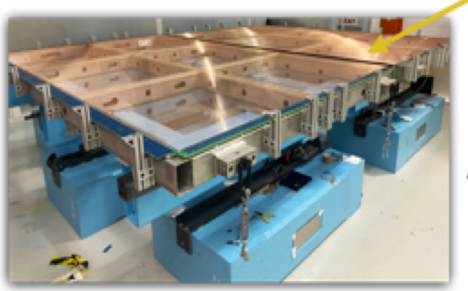
Two Time Projection Chambers
Total dimension: 4m x 4m x 5m





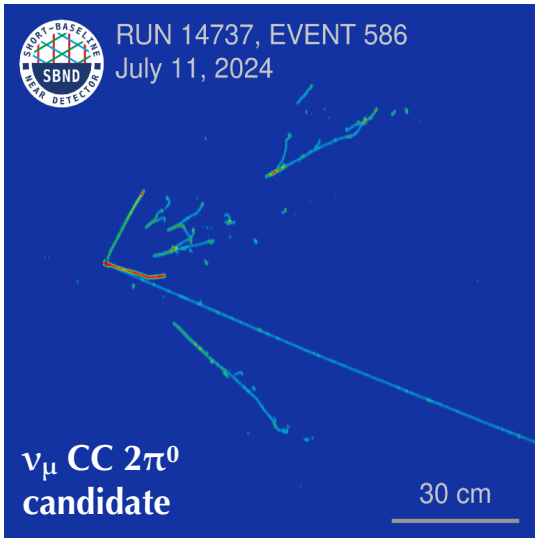
CPA-Cathode
covered with TPB
coated reflectors

Field Cage



APA-Wire Planes- 3 planes, ~11000 wires

Photon Detection Systems: 120 PMTs, 192 X-Arapucas



Started data taking: December 2024

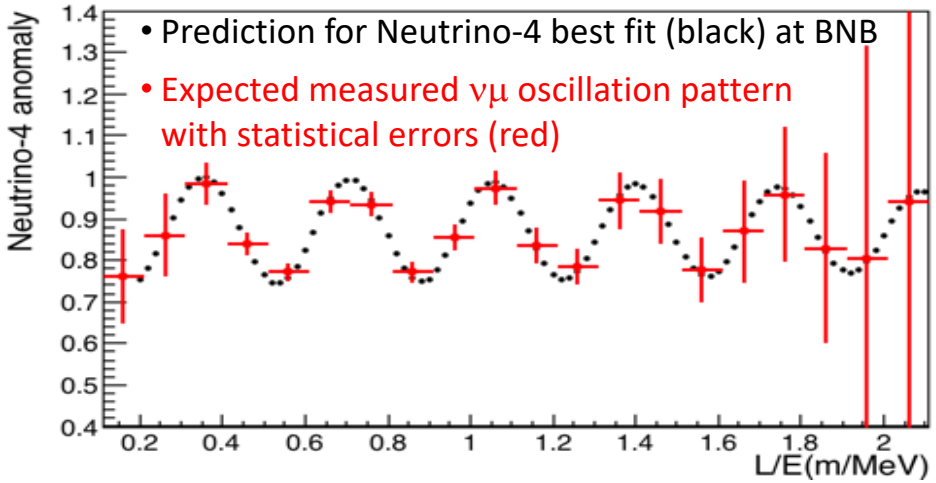
ICARUS Research Program

- The SBN program is addressing the question of sterile neutrinos with the BNB beam comparing ν_e and ν_μ interactions at different distances from target as measured by ICARUS and SBND LAr-TPCs.
- ICARUS is initially focused on standalone program before joint analysis with SBND:
  - Investigation of ν_μ disappearance with BNB ν beam, later complemented by the study of ν_e disappearance with off-axis NuMI beam, addressing Neutrino-4 claim;
  - Study of ν_e, ν_μ events from off-axis NuMI beam, to measure ν-Ar interaction cross sections and optimize ν reconstruction/identification in an energy range of interest for DUNE;
  - Exploit the off-axis NuMI beam to investigate sub-GeV Beyond Standard Model signatures: 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.

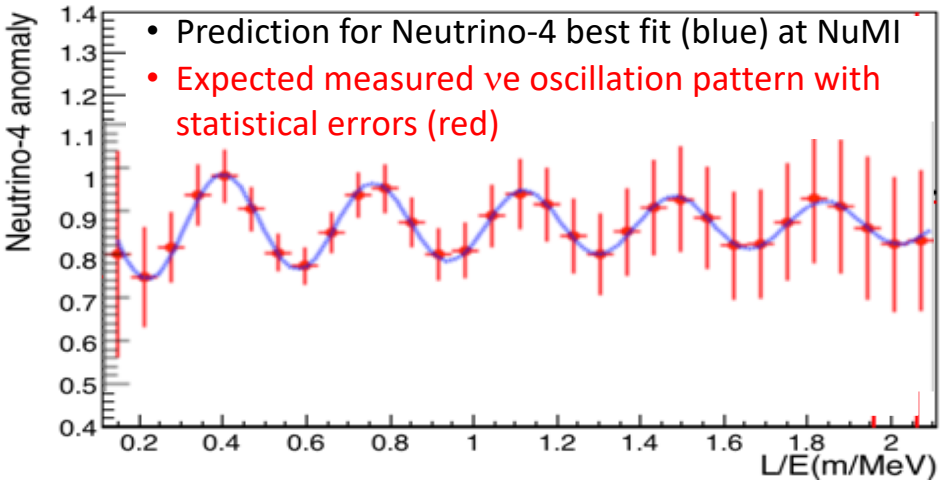
ICARUS search for Neutrino-4 claims at FNAL

- Remarkable ICARUS similarities to NEUTRINO-4 allow to settle sterile-ν claims with well-defined QECC νμ, νe fully contained events:
  - Oscillations should produce disappearance pattern of νμ in BNB and νe in NuMI in the same L/E ~ 1-3 m/MeV range but with events collected with ~100 times the energy;
  - L/Eν effect mostly related to Eν with L large/~constant for both BNB and NuMI 6^0 off-axis where νe are mostly produced by kaons decaying close to target at ~800 m distance.

Δm^2_{14}=7.25 eV^2, sin$^2 2\theta_{14}$=0.26



νμ survival oscillation probability at Booster:
~8500 QE events with >50 cm contained μ track,
~8.4 x 10^{19} pot ΔE/E ~3 %.



νe survival oscillation probability at NuMI:
~ 5200 QE events with contained E.M. shower,
~9 x 10^{20} pot .

Analysis complemented with a beam-off event sample (collected in parallel with the beam on) will allow to observe the Neutrino-4 modulation!

ν_μ event selection for disappearance analysis at BNB

- Fully contained $\nu\mu$CC events with 1μ+N protons are studied requiring:

  a) PMT light signal inside 1.6 μs p beam spill window correlated with TPC tracks with no CRT signal;

  b) A muon (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;

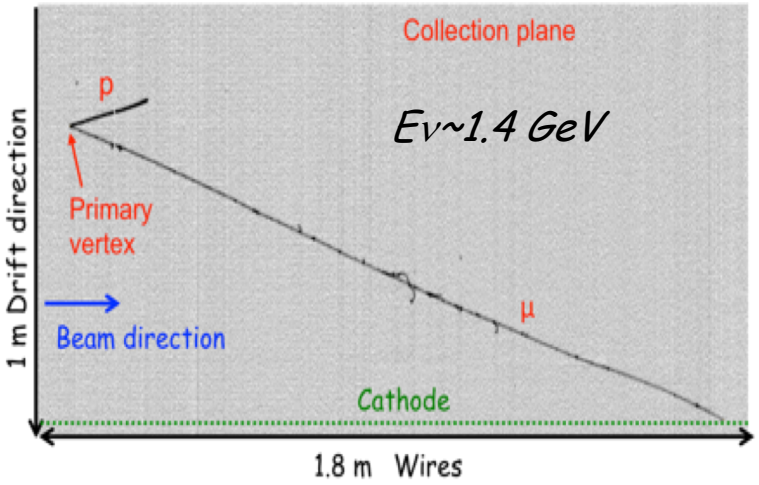
  c) No additional p, γ.

Residual cosmic backgrounds < 1%

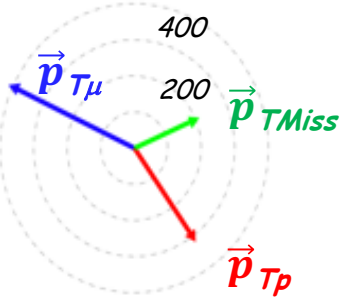
- Two independent analysis streams, respectively based on:
  - ✓ Pandora: pattern recognition algorithm
  - ✓ SPINE: Machine Learning-based (ML) reconstruction code

A visual selection of ν candidates is used to validate the event selection/reconstruction.

Global event kinematics obtained from range measurement of μ and p.

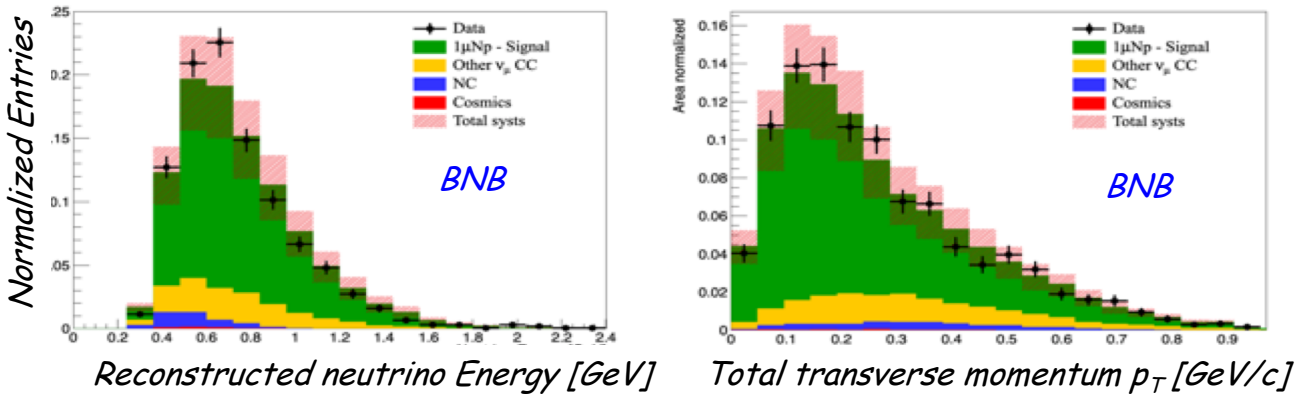


Momentum in the transverse plane (MeV/c)

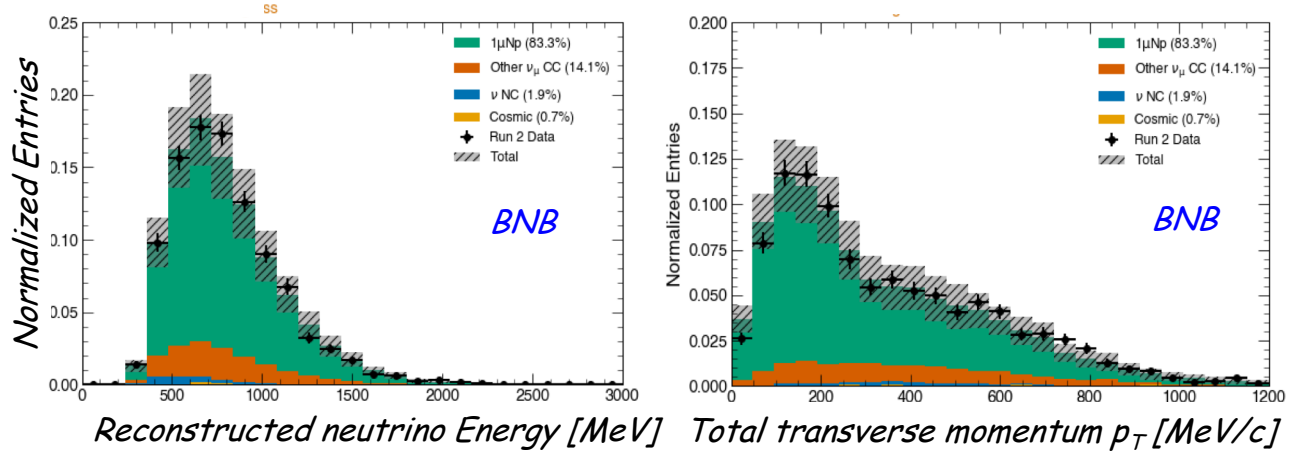


1μNp analysis – event selection results

- *Data-MC agreement within systematics for all studied event kinematic variables in ~10% of RUN-2 data analyzed (2·10[19] pot):*



ICARUS Work in progress



- *Pandora based analysis ~50% efficiency for the signal: (~34 k events for 3.89 10[20] pot)*
- *SPINE ML based analysis >50% efficiency for the signal: (~42 k events for 3.89 10[20] pot)*

- *Next analysis steps: enlarge the control sample, full dataset unblinding foreseen soon.*

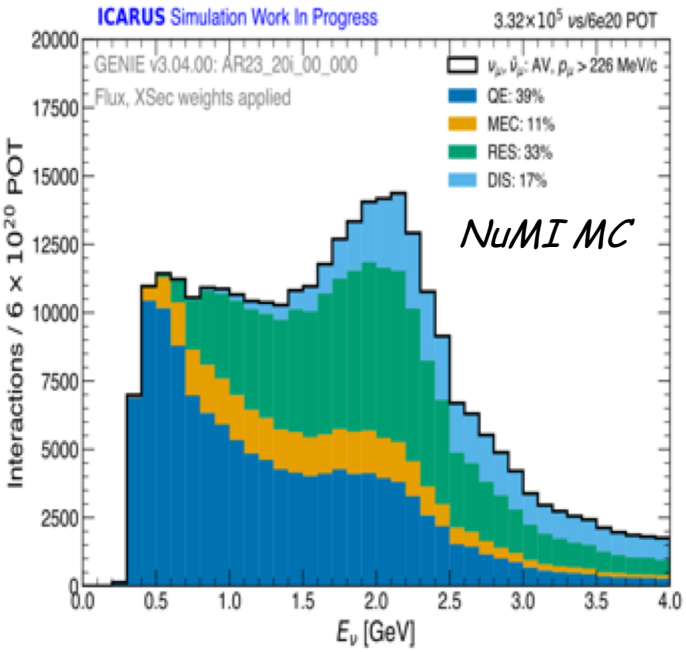
Neutrino Interactions from NuMI off axis at ICARUS

- Excellent statistics to measure ν-Ar cross section for quasi-elastic, resonance and deep inelastic scattering, for both electron and muon neutrinos:

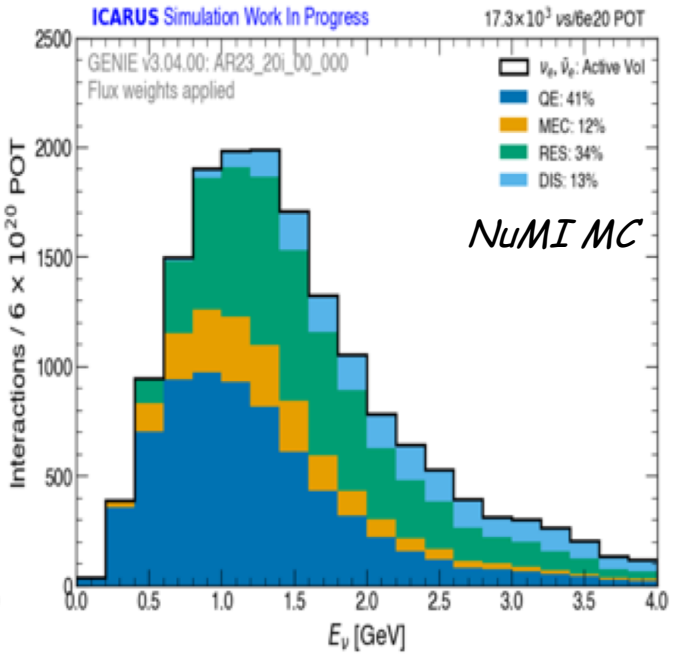
  CC events/6 10^{20} PoT : ν_μ 332,000 and ν_e 17,000.

- Neutrino energy spectrum from NuMI at ICARUS covers the 1st oscillation peak and good coverage of the relevant phase space for DUNE experiment.

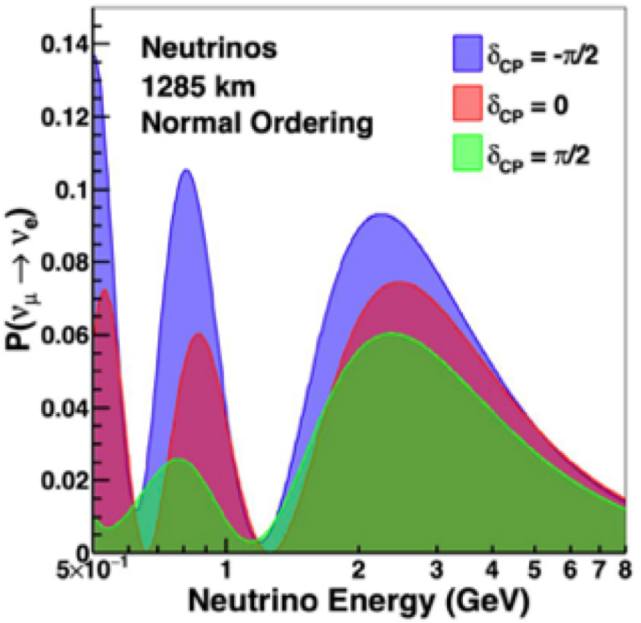
ν_μ, $\bar{\nu}_\mu$ from NuMI at ICARUS



ν_e, $\bar{\nu}_e$ from NuMI at ICARUS



Oscillation probability at DUNE

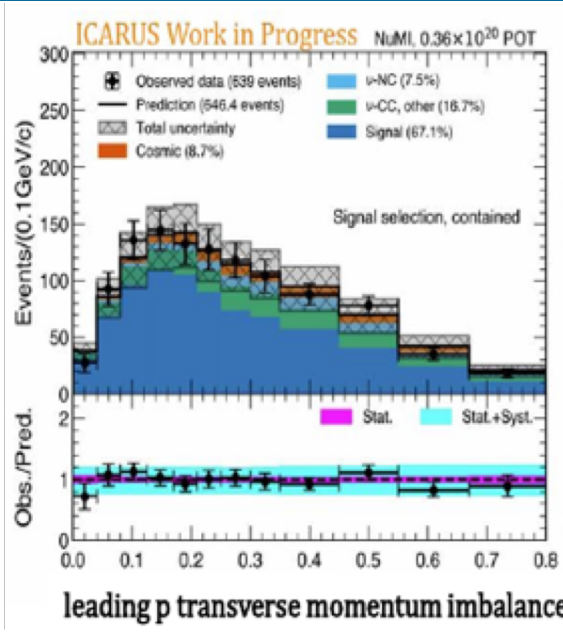


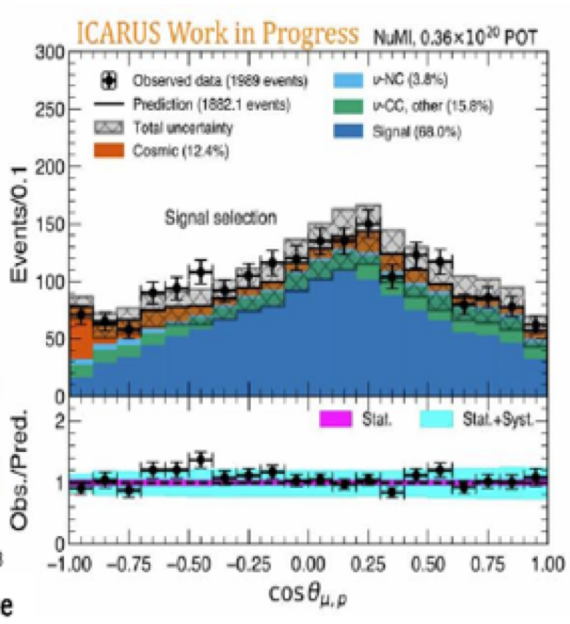
Available data ~3.42 10^{20} PoT for physics analysis now

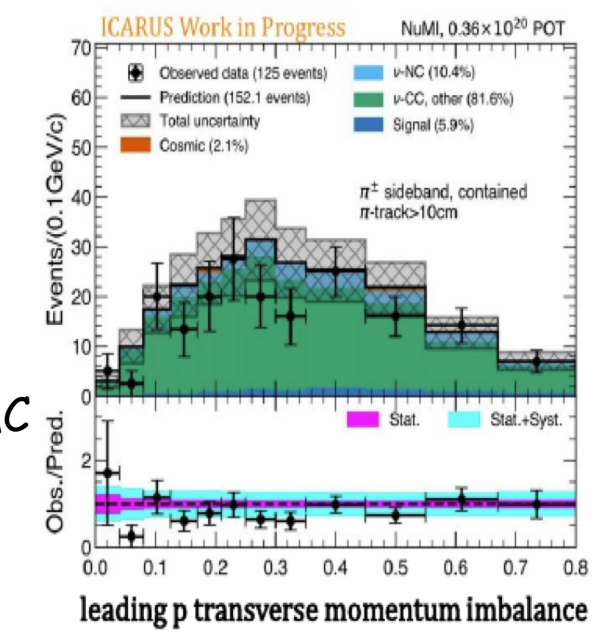
Neutrino CC 0π cross section analysis results: NuMI beam

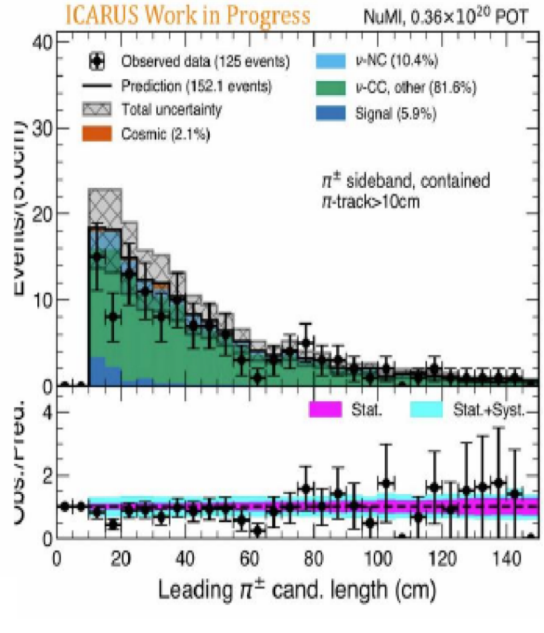
- First analysis targets 1μ Np 0π events
  - Signal: 1μ with p_μ > 0.226 GeV/c + >1 proton with 0.4< p_μ <1 GeV/c, no $\pi^\pm$, π^0 in the final state
  - Flux, interaction model and detector systematics included
  - Angles and transverse kinematics observables are expected to encode to Initial and Final State effects
- Major background: events with undetected/misidentified pions
  - Event control-sample with $\pi^\pm$ candid. studied to characterize this backg (requiring secondary μ-like track): good agreement between 15% data/MC

Results for the full dataset soon !





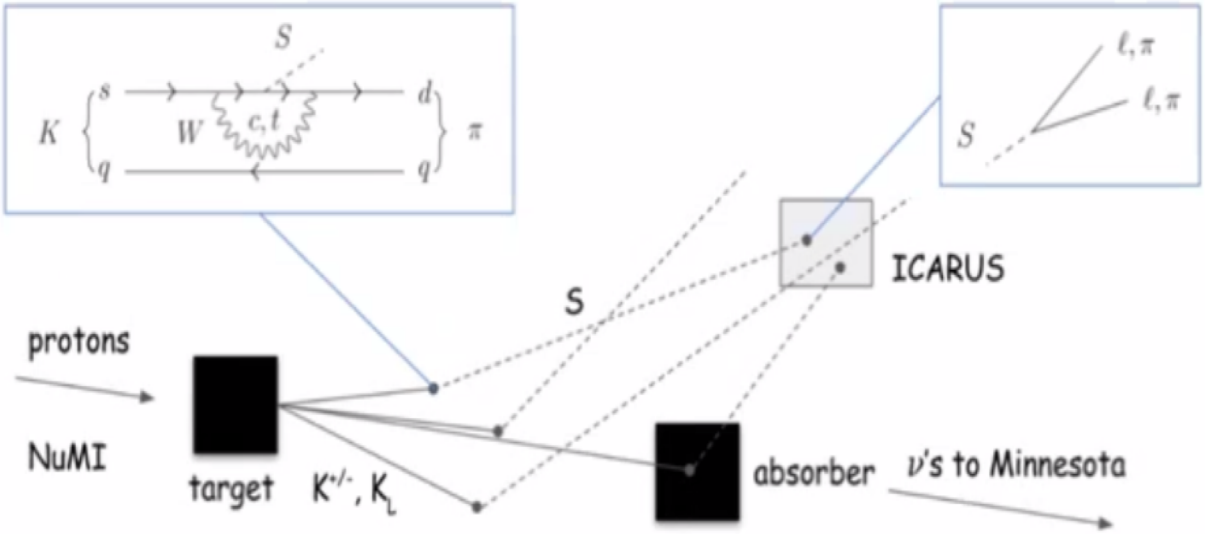


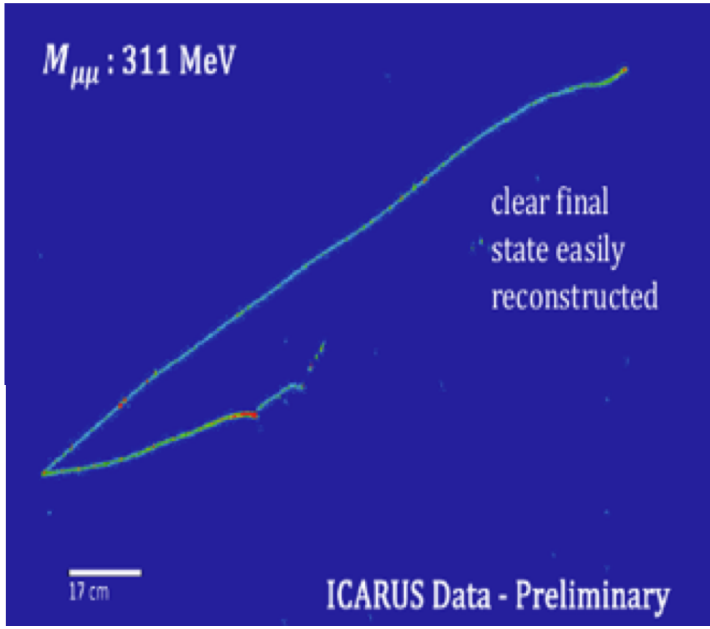


BSM searches with NuMI

- *Models involving dark particles coupling to SM particles through Scalar Portal Interactions:*
  - **Higgs Portal Scalar (HPS)** → Scalar dark sector particles, undergo mixing with Higgs boson
  - **Heavy QCD axion (ALP)** → Pseudoscalar particles, undergo mixing with pseudoscalar mesons

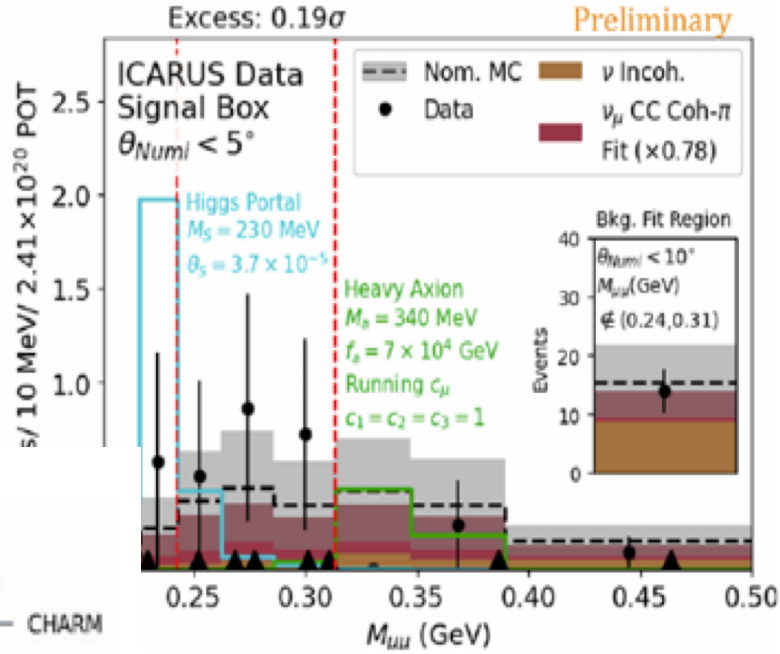
- *Scalar Decays in $\mu^+\mu^-$ with RUN2 NuMI beam.*
  - Scalar mass $M_{\mu\mu}$ peak reconstructed with 2 stopping μ;
  - Signal expected at small angle w.r.t. beam $\theta_s < 5°$

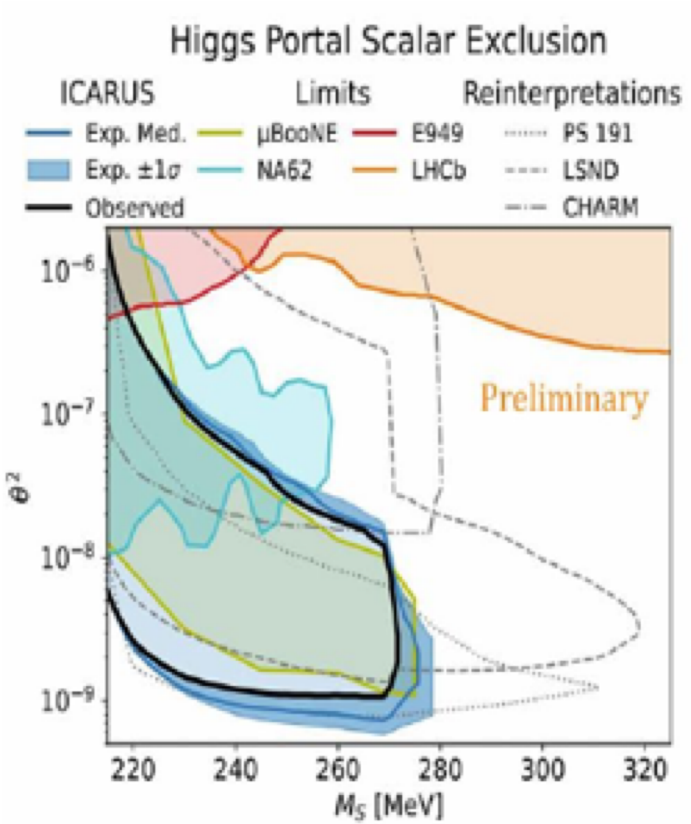


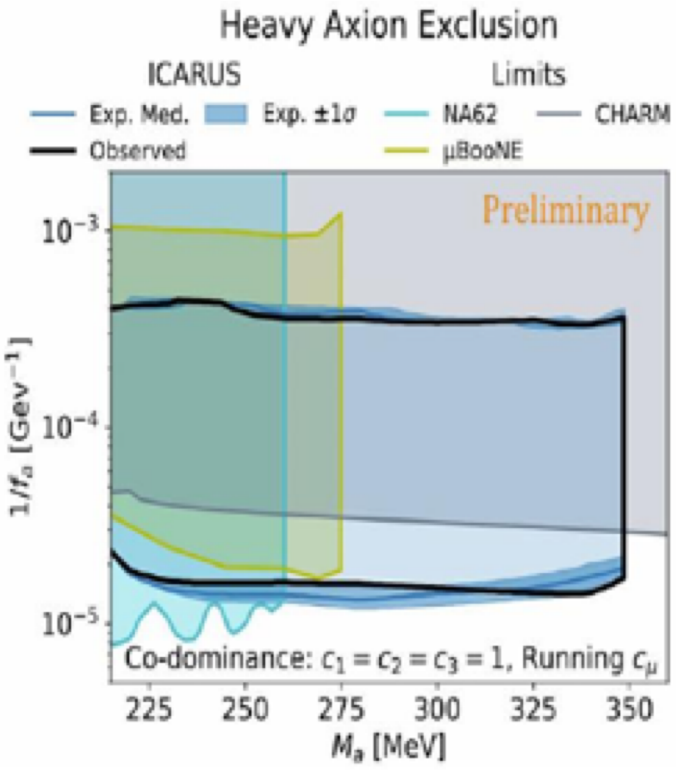


BSM searches with NuMI:results

- *Scalar Decays in μ⁺μ⁻: results*
  - 9 candidates found to be compared with 8 backg MC events expectation (from νμ CC coherent π prod.):







no significant new physics signal

Phys. Rev. Lett. **134**, 151801
https://arxiv.org/abs/2411.02727

What next

- ICARUS is smoothly running since June 2022, exposed to BNB and NuMI beams, already collected > 6 x 10^{20} pot with BNB and ~ 3 x 10^{20} pot with NuMI both positive and negative focusing.
- The ICARUS data taking foreseen to continue for ~ 3 years together SBND near detector operational since December 2024.
- ICARUS only is carrying on several analyses with data collected before the start of the joint operation within SBN: ν_μ disappearance with BNB (Neutrino-4 claim), ν–Ar cross section measurements with NuMI and search for sub-GeV dark matter, interesting results expected soon!
- *Exciting ICARUS time: new INFN contributions are welcome !*

ICARUS Collaboration at SBN

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12. INFN Milano, Milano, Italy
13. INFN Milano Bic. and University, Italy
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15. INFN Padova and University, Italy
16. INFN Pavia and University, Italy
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19. Tufts University, USA
20. University of Chicago, USA
21. University of Houston, USA
22. University of Pittsburgh, USA
23. University of Rochester, USA
24. University of Texas (Arlington),USA
25. INFN Pisa and University, Italy
26. Ramanujan Faculty Phys. Res. India
27. Virginia Tech Institute

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

- *Importante impegno dei gruppi INFN nello studio dei neutrini, in particolare nello sviluppo della TPC ad argon liquido con ICARUS al Gran Sasso ed ora al Fermilab impegnati sia nell'hardware TPC, PMT, CRT, Trigger, che nel software e nell'analisi dati finalizzata allo studio delle oscillazioni.*

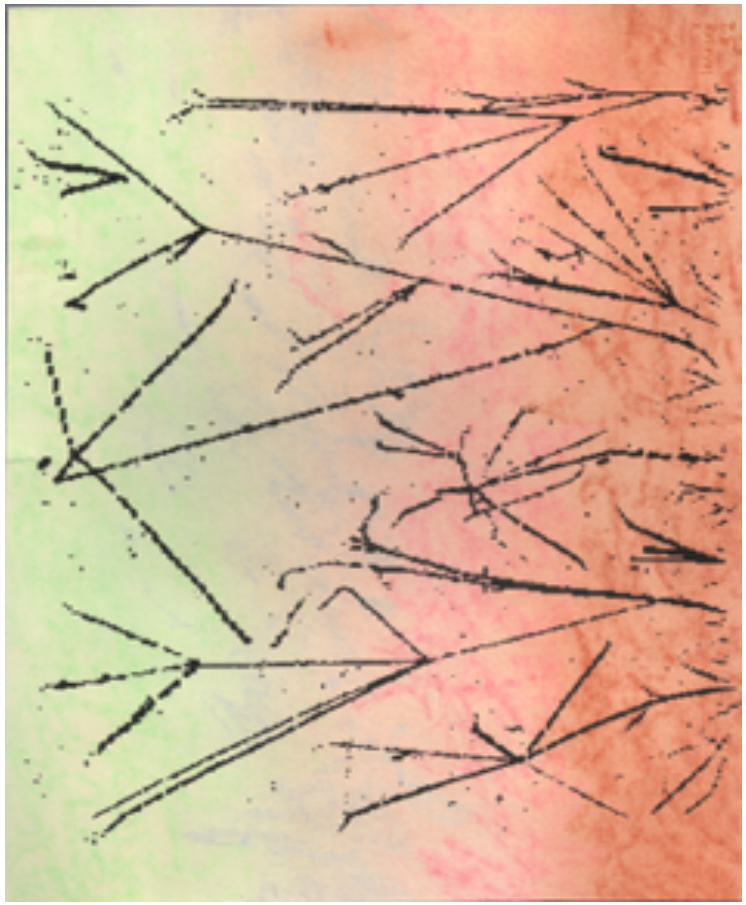
- *Il gruppo di Pisa e' attualmente impegnato nella ricostruzione e analisi degli eventi di neutrino oltre che nella data production; in particolare:*

  - *Miglioramento degli algoritmi di tracking e sviluppo algoritmi per la misura del momento dei muoni basati sul Multiple Coulomb Scattering: Alessandro M. Ricci, Giovanni Chiello e Namitha Chitirasreemadam, Simone Donati;*
  - *Improving lo Slow Control: Antonio Gioiosa*
  - *Data production: Alessandro M. Ricci e A. Gioiosa*

Grande opportunita' per i giovani:

ICARUS: un giardino fiorito …

DUNE: la prospettiva prossima



Giardino adronico (E. Iarocci)