ICARUS at the Short-Baseline Neutrino program: First Results

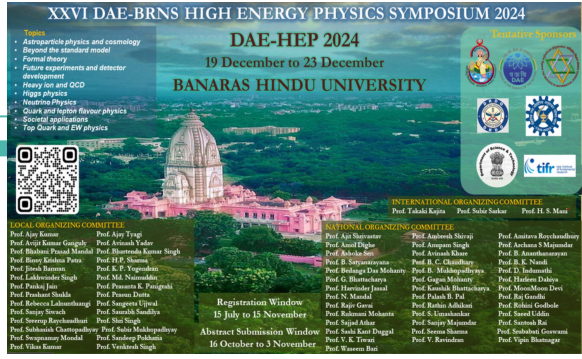
Promita Roy

Centre for Neutrino Physics, Virginia Tech

On behalf of the ICARUS collaboration

XXVI DAE-BRNS
High Energy Physics Symposium

December 19, 2024



Outline

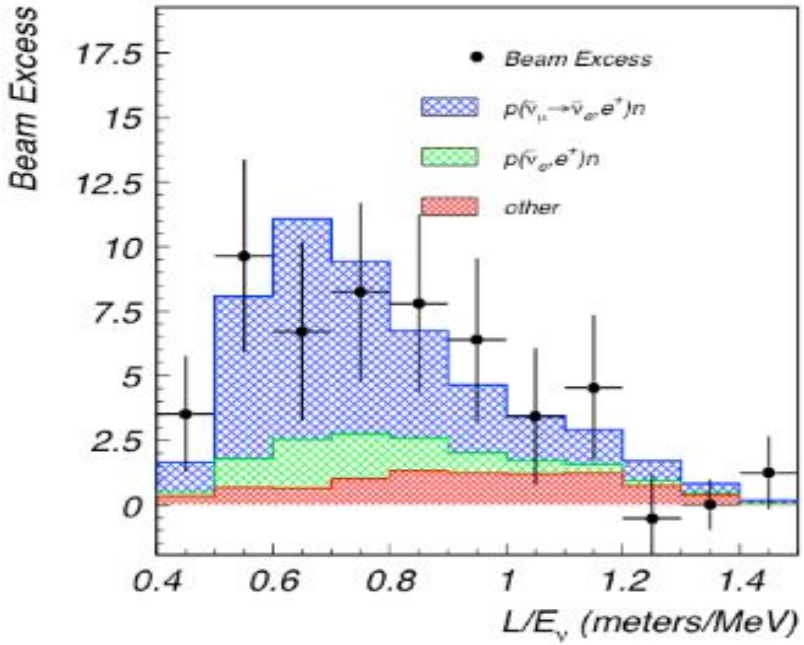
- The Sterile Neutrino Puzzle
- The SBN Program
- The ICARUS Detector in a nutshell
- ICARUS Physics Program
- Summary and Future prospect

Sterile neutrino puzzle / short baseline anomalies

While the 3ν-model aligns well with many experiments, some anomalies have been observed in short-baseline neutrino experiments, hinting at a new sterile neutrino flavor with $\Delta m^2 \approx 1\ eV^2$.

Accelerator experiments:

- LSND (baseline ~30m)
  $\bar{\nu}_e$ appearance in a $\bar{\nu}_\mu$ beam (~3σ) / observed ~87.9 excess $\bar{\nu}_e$ events



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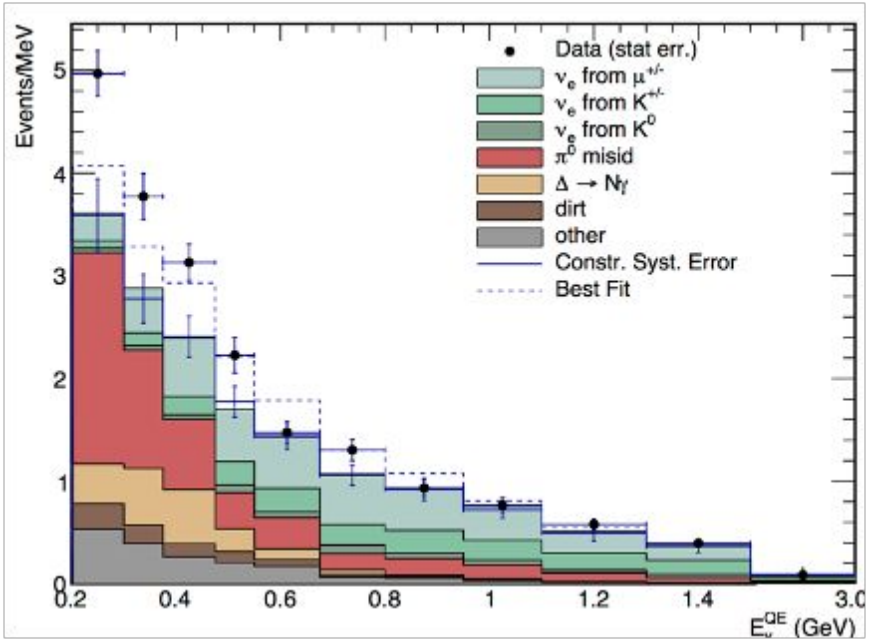
  $\bar{\nu}_e$ appearance in a $\bar{\nu}_\mu$ beam (~3σ) / observed ~87.9 excess $\bar{\nu}_e$ events

- MiniBoone (baseline ~540m)
  Excess in $\bar{\nu}_e$ mode, consistent with the LSND result, also observed excess in ν_e mode



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Radiochemical experiments:

- Gallium, SAGE, BEST
  Observed deficit in the detected ν_e (suggesting oscillations into sterile neutrinos)

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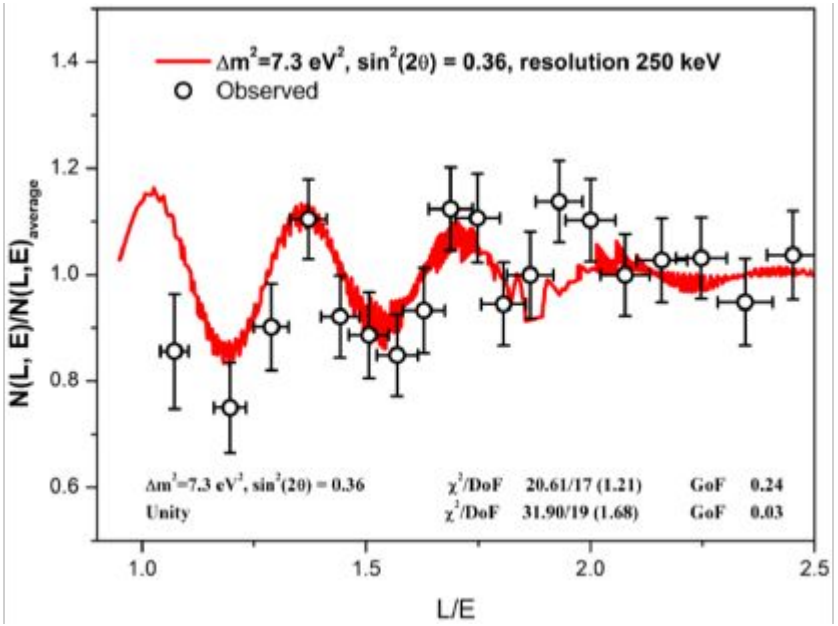
Radiochemical experiments:

- Gallium, SAGE, BEST
  Observed deficit in the detected ν_e (suggesting oscillations into sterile neutrinos)

Reactor experiment:

- Neutrino-4
  Independently observed ν oscillations with 2.9σ CL
  Later, combined analysis of Neutrino-4 with other experiments results in a best fit of
  $\boldsymbol{\Delta m^2_{14} = 7.3\ eV^2}$ ***and*** $\boldsymbol{\sin^2(2\theta_{14}) = 0.36}$ ***at 5.8 σ***



Sterile neutrino puzzle / short baseline anomalies

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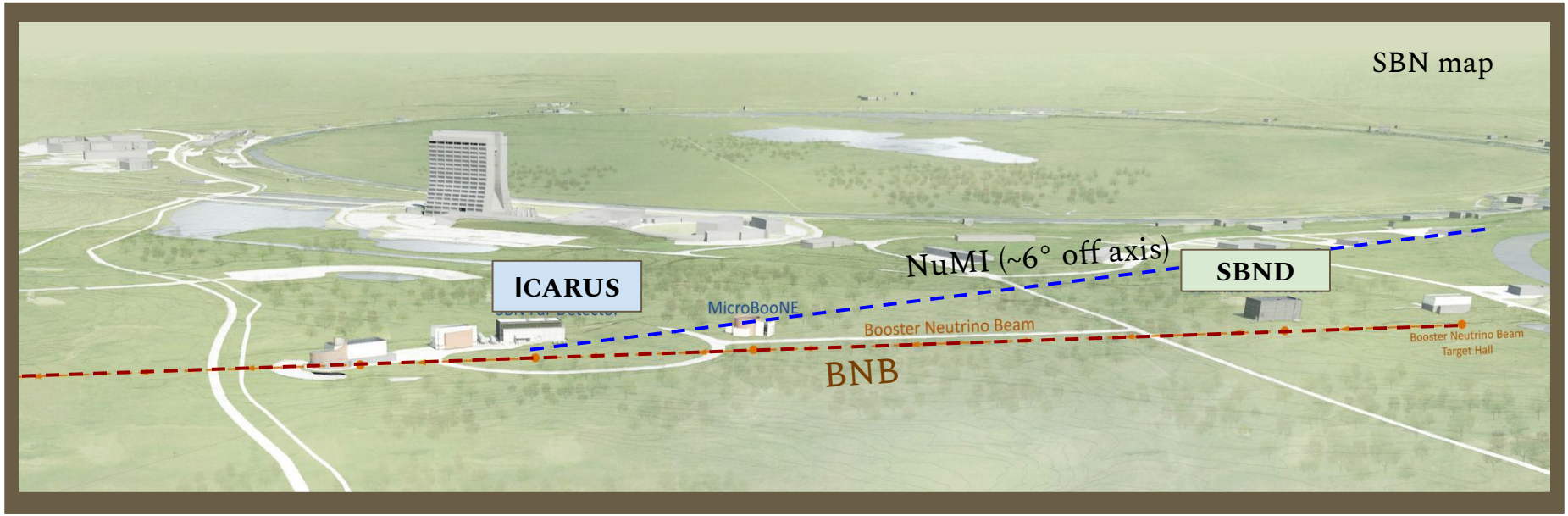
Several reactor and accelerator experiments, including the recent MicroBooNE, have explored these 'neutrino anomalies.'

However, a noticeable tension remains between appearance and disappearance experiments due to differences in the neutrino energy ranges they probe and the detection methods they utilize.

Here comes the SBN program !!

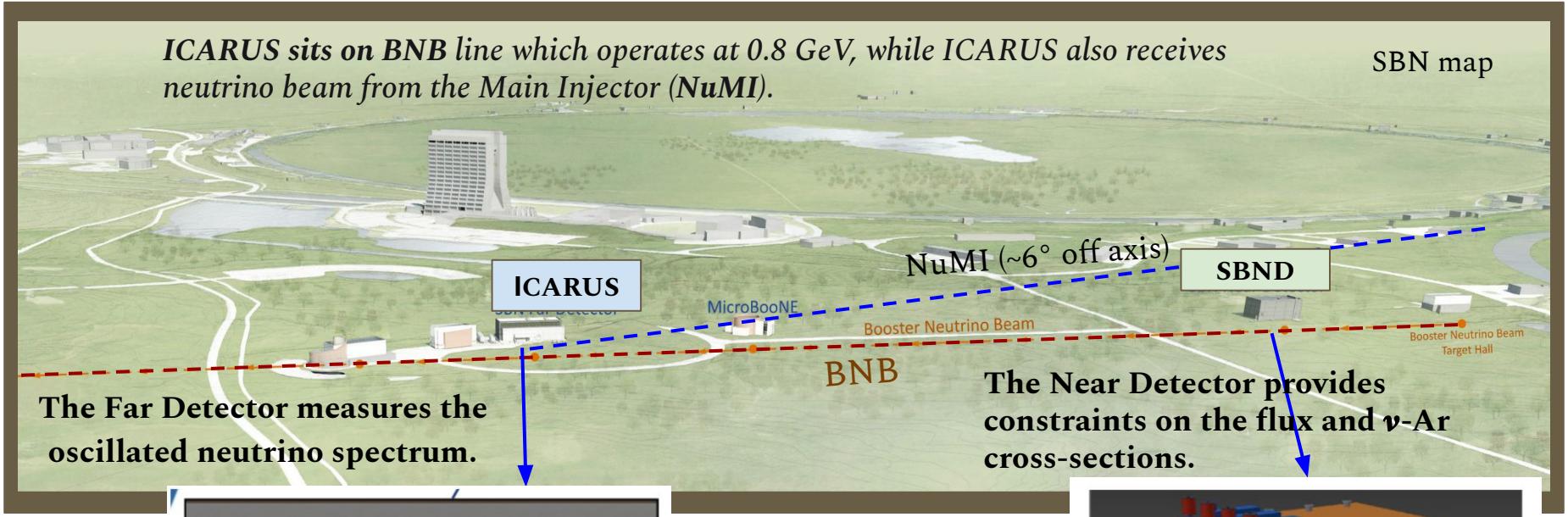
The SBN program at FERMILAB



The SBN program at FERMILAB

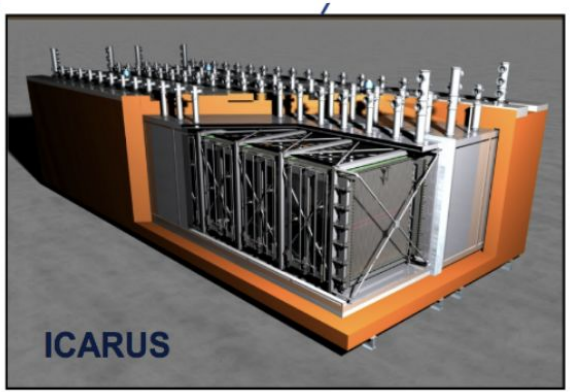
*ICARUS sits on BNB line which operates at 0.8 GeV, while ICARUS also receives neutrino beam from the Main Injector (**NuMI**).*

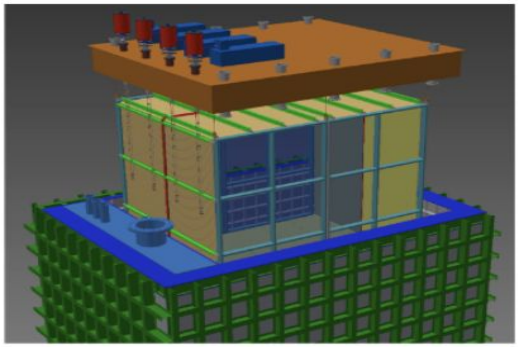
SBN map



The Far Detector measures the oscillated neutrino spectrum.

The Near Detector provides constraints on the flux and ν-Ar cross-sections.



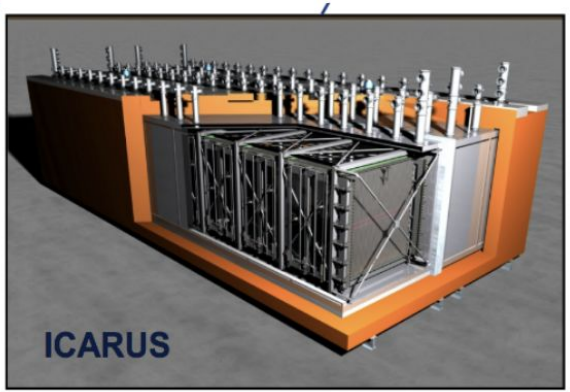


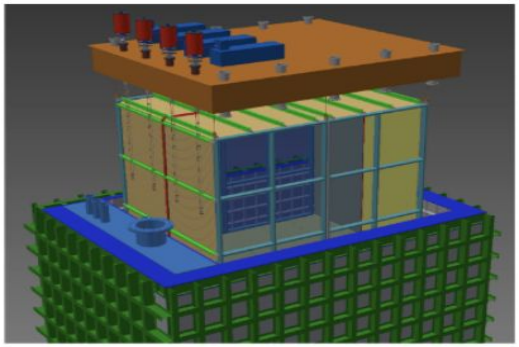
The SBN program at FERMILAB

ICARUS (SBN-FD) and SBND have same technology to minimize beam(BNB), background & detector systematics.

Main objectives:

- Definitive search for eV-scale sterile neutrinos by looking for muon neutrinos disappearance and electron neutrinos appearance oscillations.
- Perform detailed study of neutrino-Argon interactions at the GeV energy scale.
- Pursuit advancement of the liquid argon detector technology in view of upcoming multi-kiloTon long baseline DUNE experiment.
- Search for new/rare physics processes in the neutrino sector and beyond.





SBND

The ICARUS experiment in a Nutshell

Liquid Argon Time Projection Chambers (LArTPCs) first introduced by C.Rubbia in 1977

ICARUS T600 is the first large scale (760 Tonnes) LAr-TPC:

- 2 identical cryostats (3.6 x 3.9 x 19.6 m^3)

  Each of them have 2 TPCs with common cathode

- Active mass: 470 tons

Timeline

2013: concluded 3 year physics run at **LNGS**
2015-17: overhaul at **CERN**
2018: transportation to **Fermilab and start of installation**
2020: filling with LAr and start of commissioning
2022: **start of physics data taking**

arXiv:2301.08634v1

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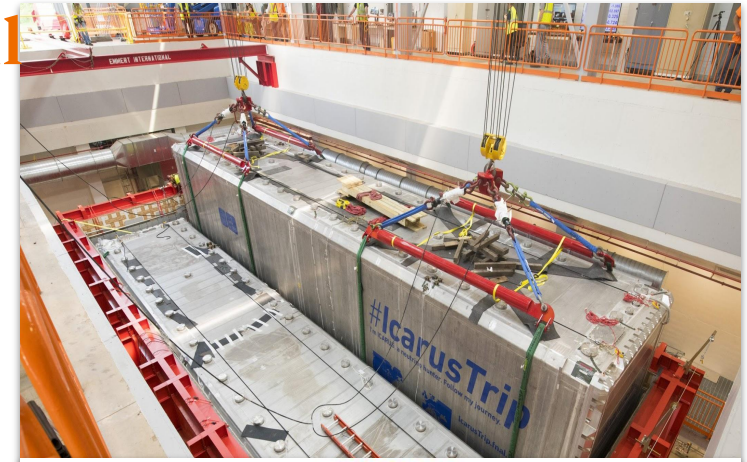


Time Projection Chambers:

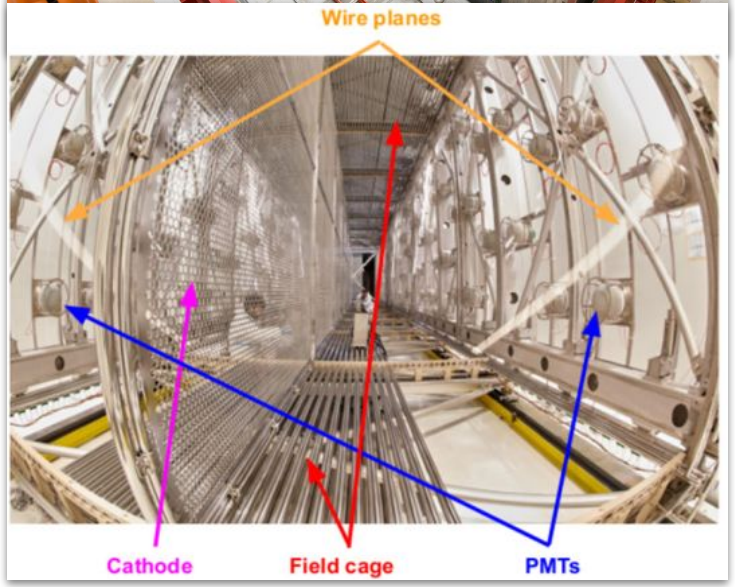
- - 3 wire planes per anode (0°,±60° w.r.t horizontal)
- - 500 V/cm E field (1.5 m drift)

Photon Detection System:

- - 360 PMTs coated with TPB behind anode wire planes (90 per anode) for event triggering/timing with light

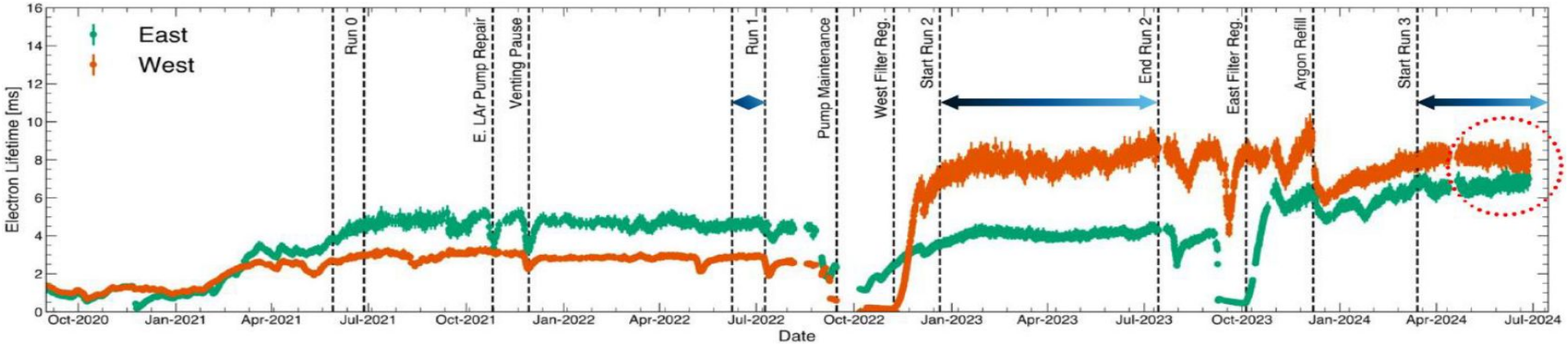
Cosmic Ray Tagger :

- Top, side and bottom cosmic ray tagger panels (scintillator + SiPM readout)



Detector operations and data acquisition

Data taking started in June 2022, 3 physics run since then: run 3 (both beams) 15 March - 12 July 2024



The cryogenic and purification systems performed smoothly, *maintaining a stable free electron lifetime of ~7-8 ms*, enabling nearly full track detection efficiency over the 1.5 m drift distance (~1 ms).

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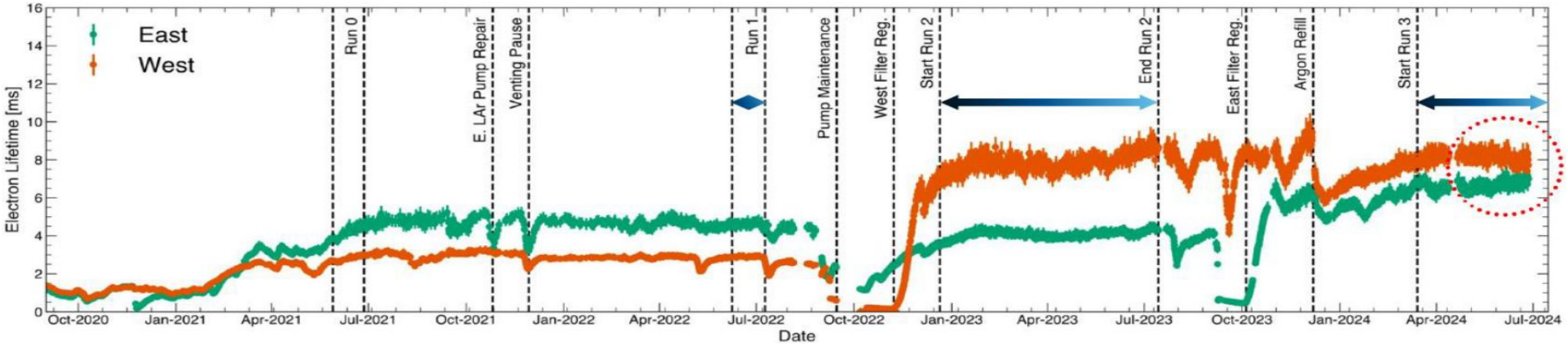

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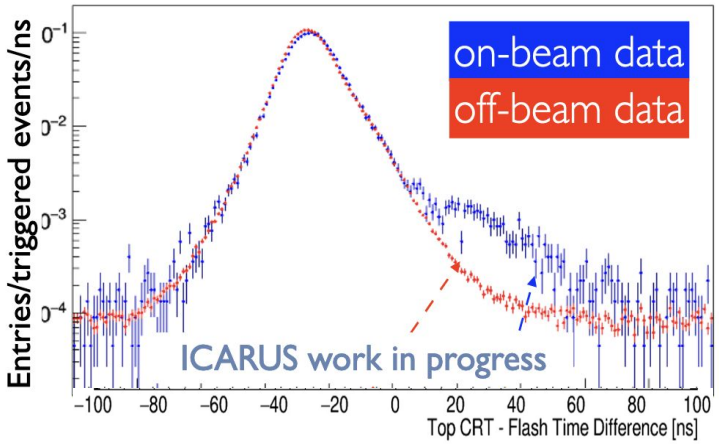
Collected Protons on target (PoT)		BNB (FHC) positive focusing	NuMI (FHC) positive focusing	NuMI (RHC) negative focusing
RUN-1	(Jun-Jul 22)	0.41 10^{20}	0.68 10^{20}	-
RUN-2	(Dec 22-Jul 23)	2.05 10^{20}	2.74 10^{20}	-
RUN-3	(Mar-Jul 24)	1.36 10^{20}	-	2.82 10^{20}
TOTAL	(PoT)	3.82 10^{20}	3.42 10^{20}	2.82 10^{20}

Detector performance and calibration

All subsystems are fully operational since the start of physics data taking

- CRTs tag incoming cosmics with 95% efficiency

- CRT & PMT timing information is used to reject cosmic background



Cosmics entering from top CRT

$\Delta T_{CRT-PMT} < 0$ (bkg)

ν products exiting through top CRT

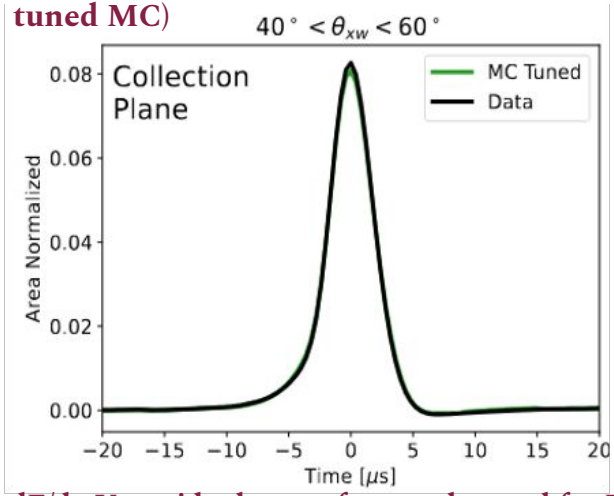
$\Delta T_{CRT-PMT} > 0$ (signal)

Detector performance and calibration

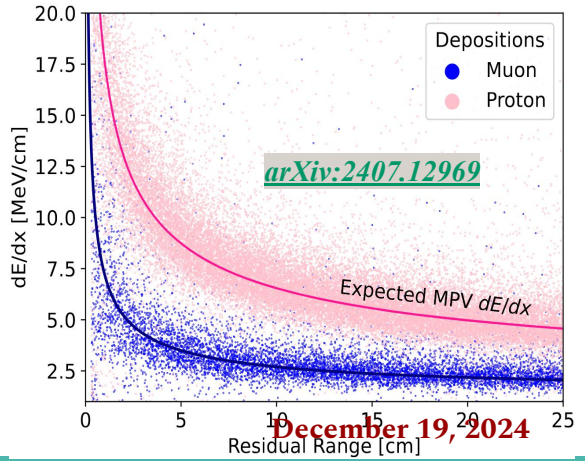
- TPC wire signals are accurately characterized and modeled in Monte Carlo simulation
- Detector response is calibrated using cosmic muons and protons from ν interactions, with a new angular-dependent ellipsoidal model (EMB).

  2407.12969
- Energy loss per unit length vs residual range for muons and protons PID
- Deposited energy is used to validate calibration and improve calorimetric reconstruction

Average signal response per plane (Data/ tuned MC)



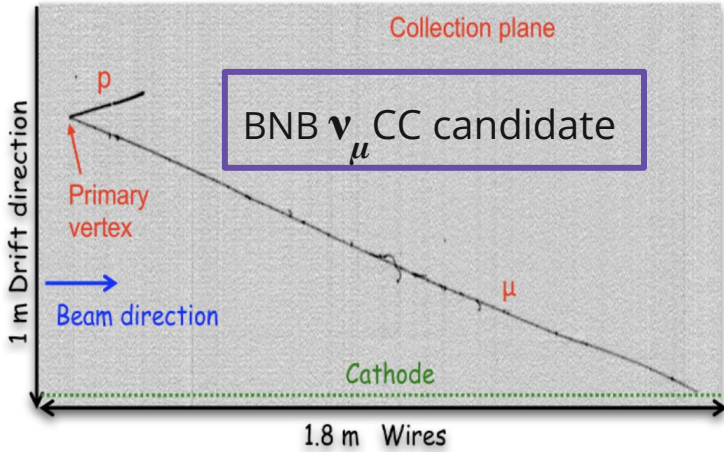
dE/dx Vs residual range for μ and p used for PID

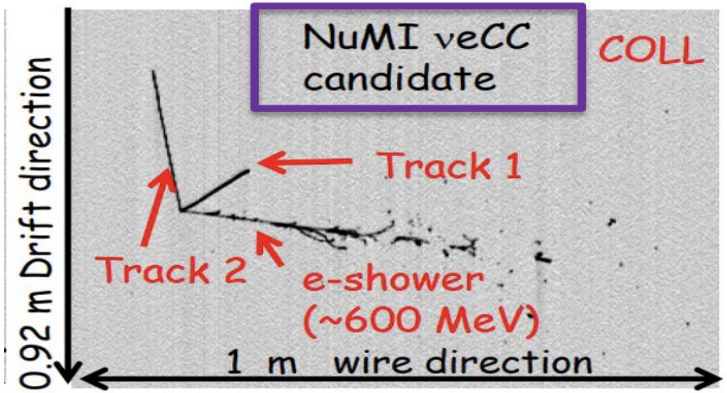


ICARUS Physics program

Before the joint-analysis with SBND, ICARUS focuses on a standalone physics program:

- Analysis of the ν_μ disappearance channel with **BNB**- *the goal is to confirm/refute the claim by Neutrino-4 experiment*
- Study of interactions from ***NuMI*** to measure **ν-Ar cross sections** and optimize reconstruction in the energy range that ***DUNE*** will explore
- Search for sub-GeV BSM signals using ***NuMI***



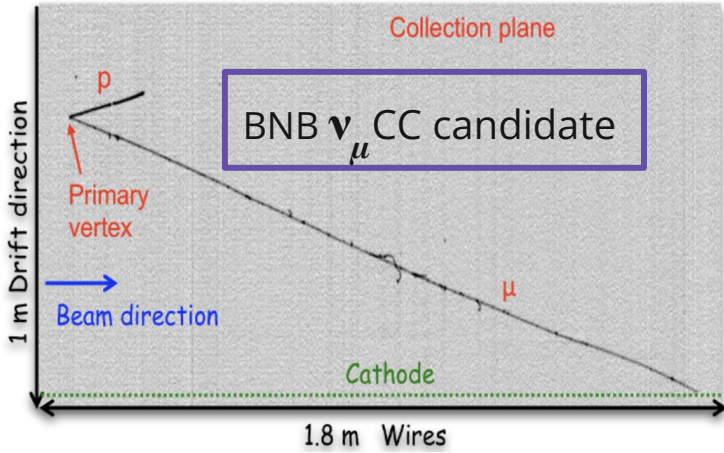


ICARUS Physics program

Event reconstruction criteria:

Two LArTPC event reconstruction frameworks:

- ***Pandora:*** pattern recognition software widely used in LArTPCs
- ***SPINE***: entirely based on Machine Learning techniques (arxiv)



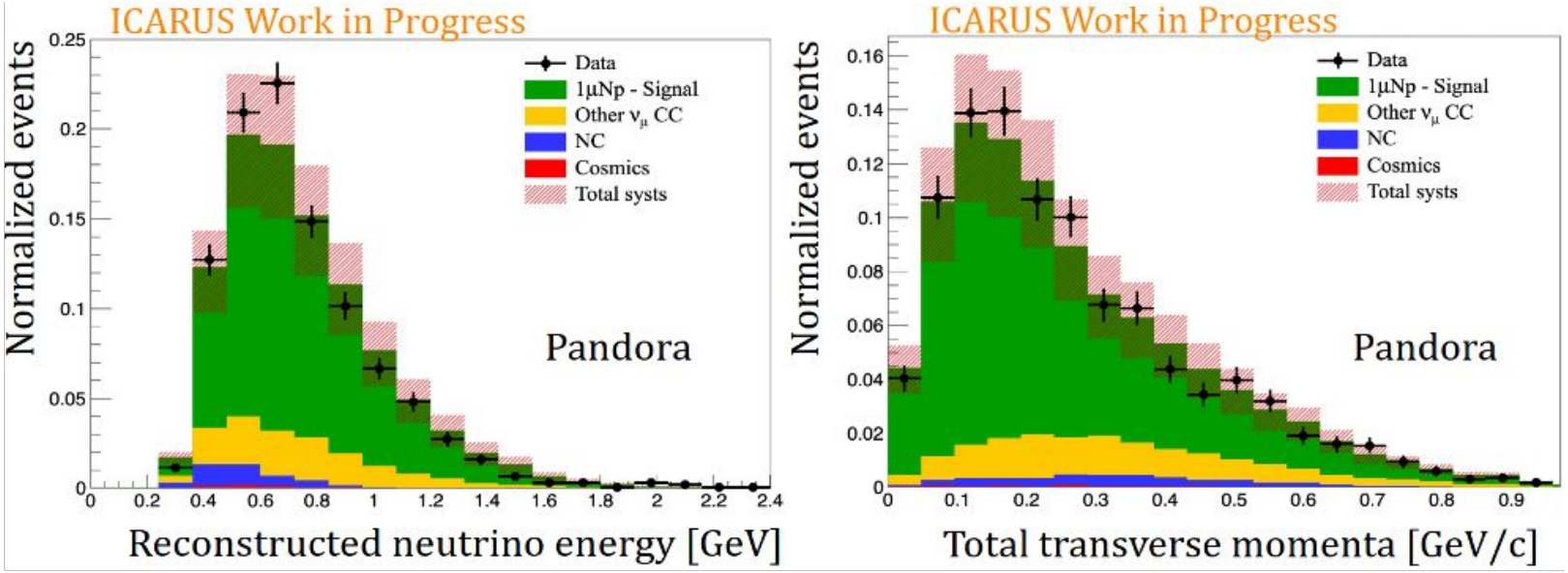
ν_μ disappearance analysis

Event selection criteria:

- **TPC - PMT matched tracks** and no corresponding CRT signal within beam spill window.
- Muon track with length L_μ>50 cm.
- At least 1 proton with L_p>2.3 cm (corresponding to E_k>50 MeV).
- Particles correctly identified by PID tool (based on dE/dx).
- Fully contained tracks

ICARUS Physics program

ν_μ disappearance analysis: Preliminary results

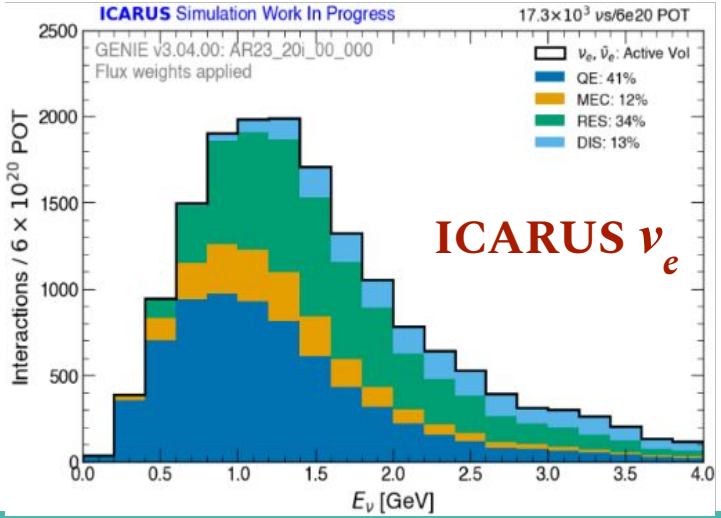


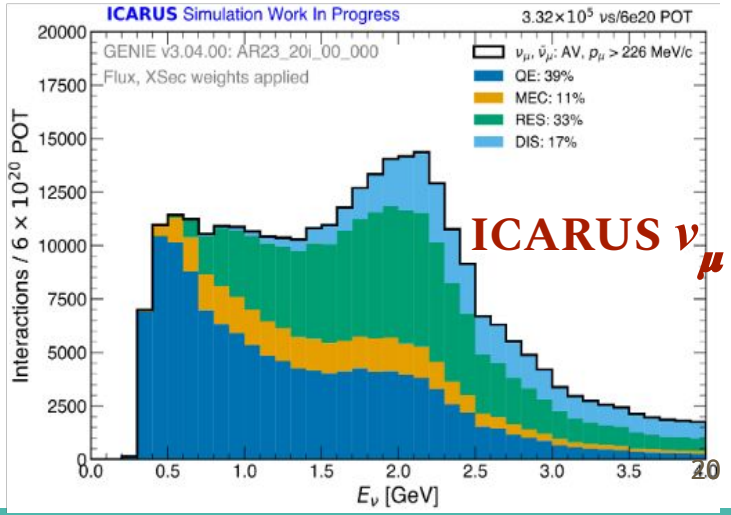
- **Pandora-based analysis on BNB beam**
- 50% signal efficiency, 80% signal purity
- 1.93 x 10^{19} Proton on Target (PoT)
- 34000 events (Run1-3)

Neutrino-Ar interaction with NuMI

- ICARUS has a large NuMI dataset for ν-Ar cross-section measurements:
  332k ν_μCC and 17k ν_eCC interactions with 6×10^{20} POT.
- Currently ***available data: ~3.42×10^{20} POT.***

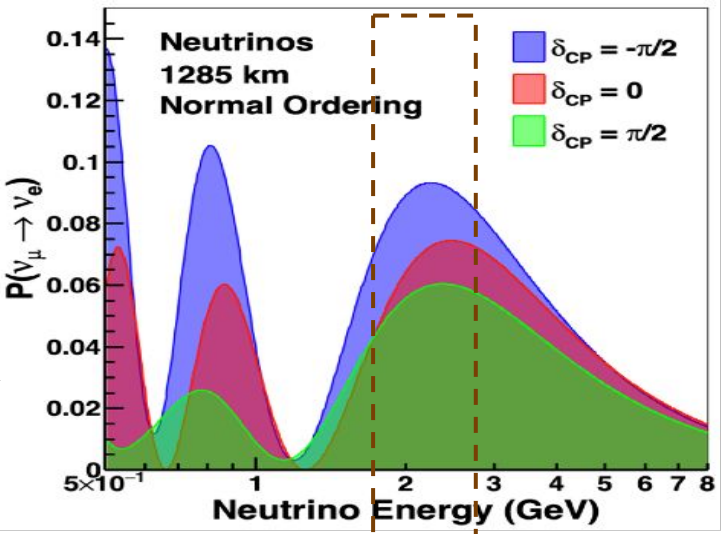
Larger statistics of ν_e **interactions with Ar** compared to previous experiments.

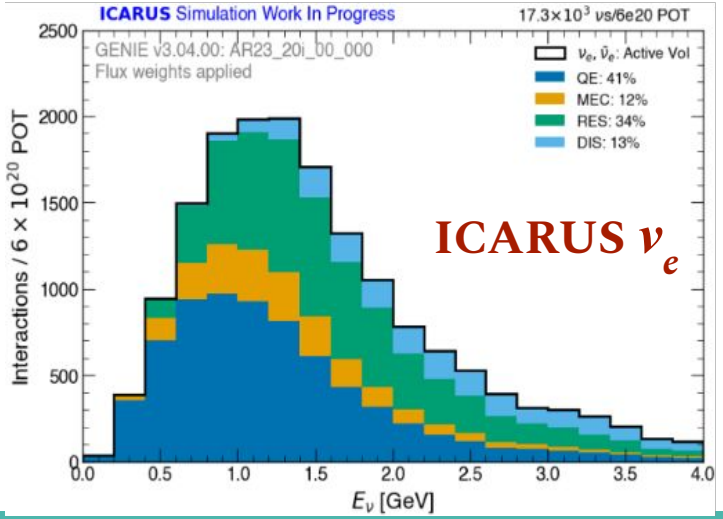


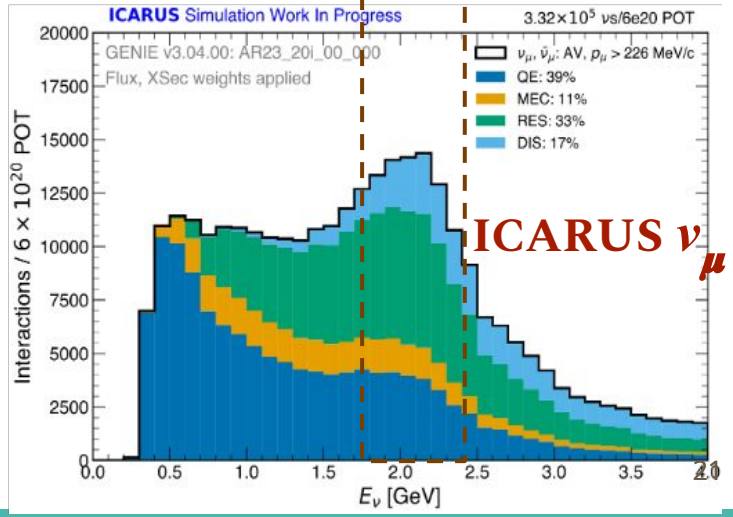


Neutrino-Ar interaction with NuMI

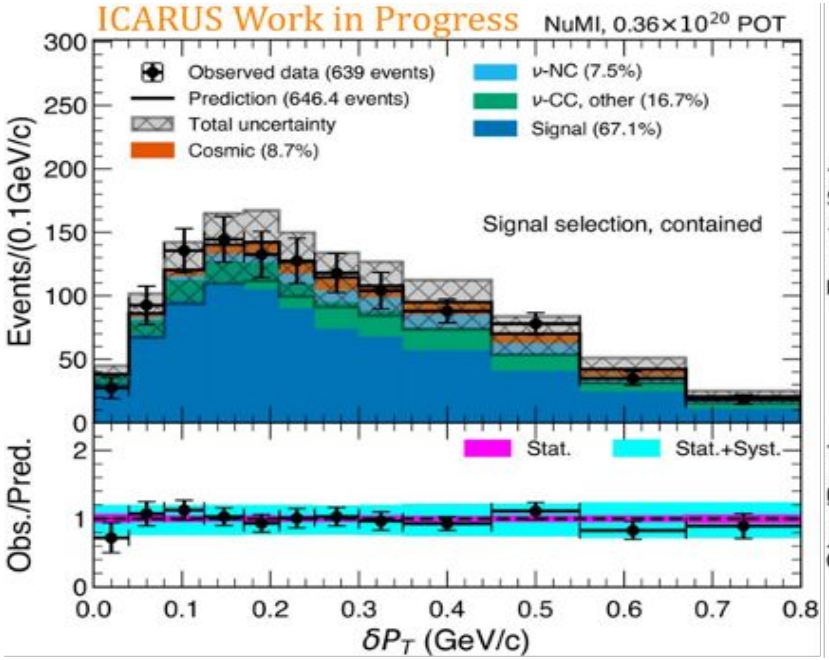
- ***NuMI's neutrino energy*** spectrum ranges from a few hundred MeV to a few GeV, ***covering the energy range relevant for the DUNE*** experiment.

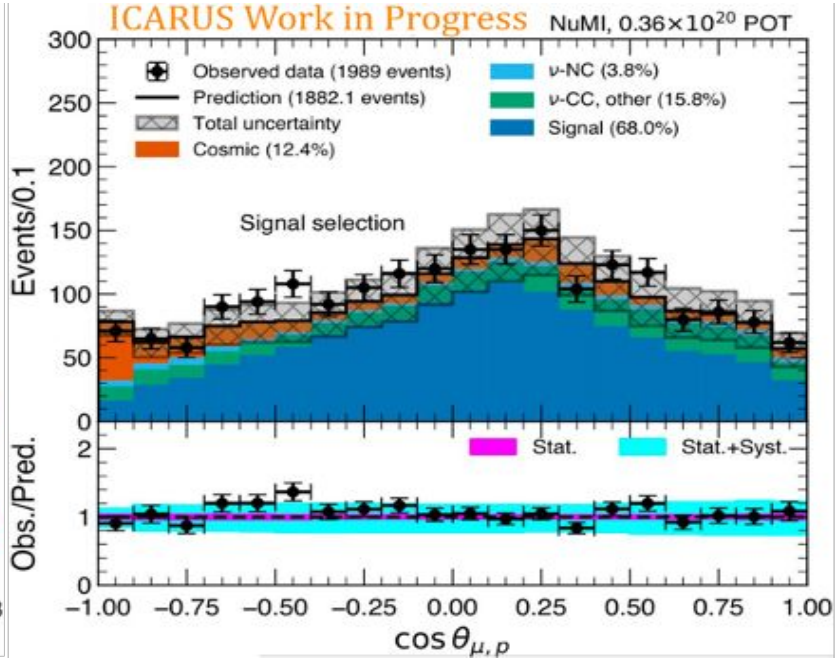






NuMI 1μNp0π Analysis: First cross-section analysis with ICARUS

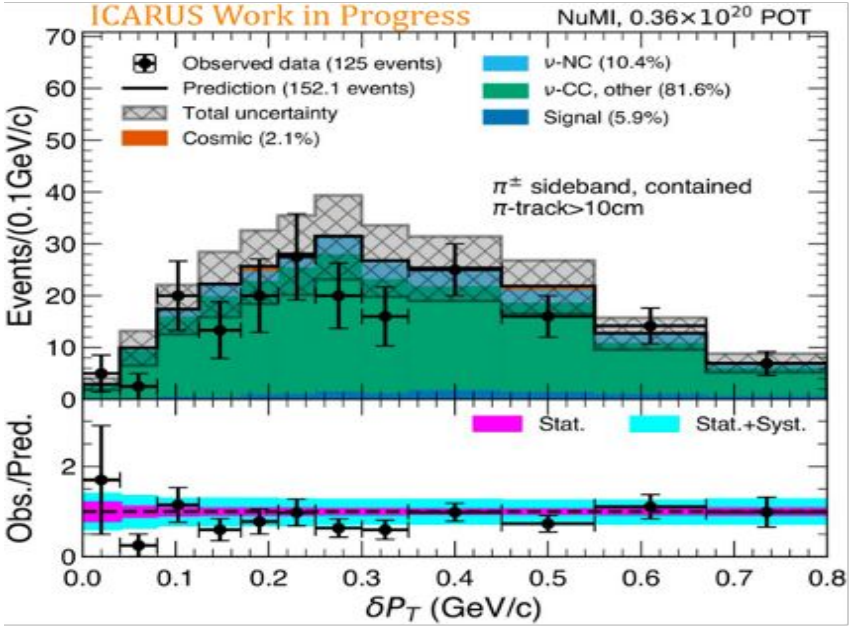


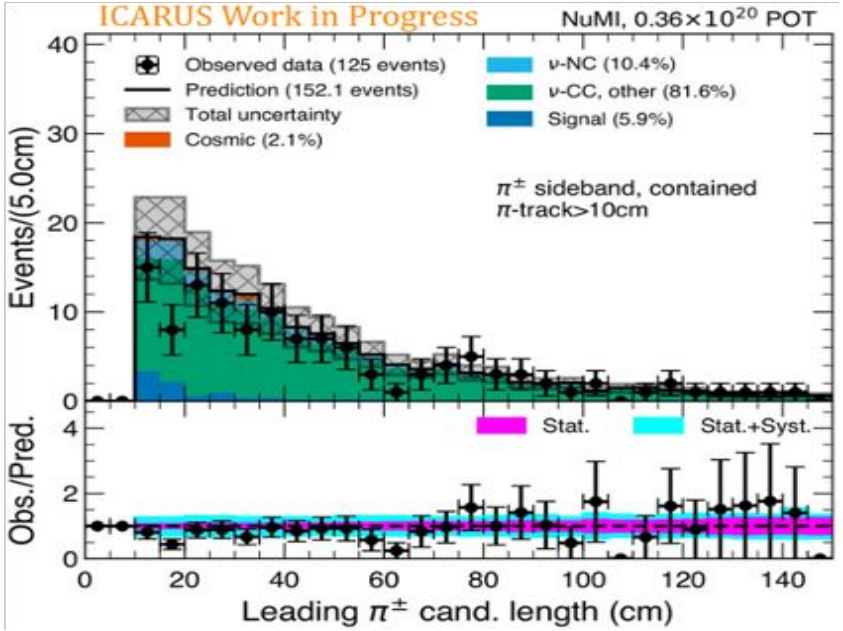


Signal:

- **One muon** with $p_{muon} > 226$ MeV/c
- **Any proton** with 400 MeV/c < p_{proton} < 1 GeV/c,
- **No charged or neutral pions in the final state.**

NuMI 1μNp0π Analysis: First cross-section analysis with ICARUS





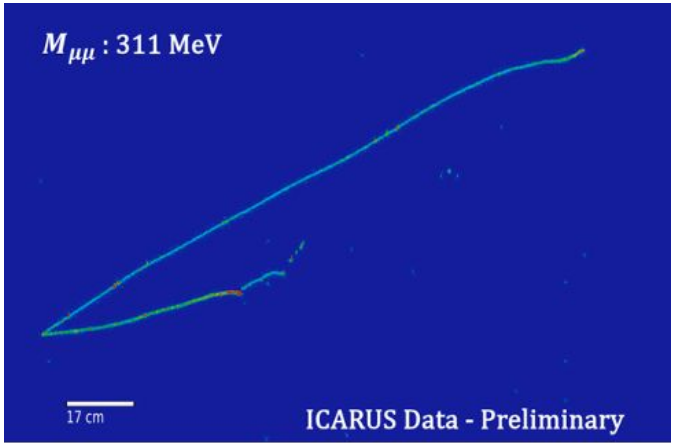
- *Major Backgrounds* (**Events with undetected or misidentified pions**)

BSM physics program with NuMI

- Rich BSM search program based on the ***off-axis NuMI*** beam.
- Models explored so far:

  Higgs Portal Scalar (scalar dark particles, interacting with SM particles with Higgs boson mixing),

  Heavy QCD axion (pseudo-scalar particles, interacting with SM ones via pseudo-scalar mesons)



Typical signal candidate

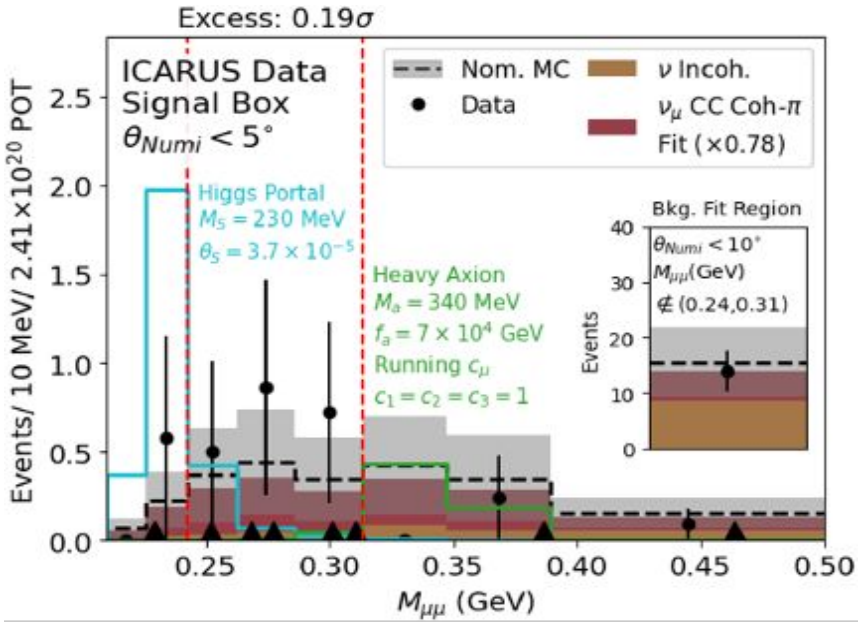
Di-lepton analysis

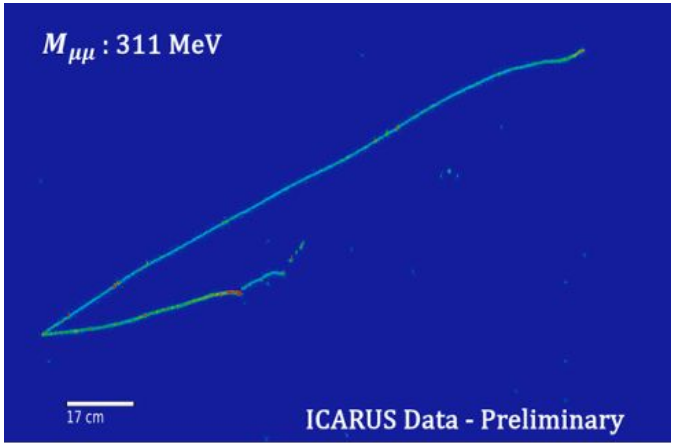
Event selection:

- **2 stopping μ-like particles** (fully contained) with resolvable mass peak, proxy of the scalar particle mass
- Signal peak is looked at small angles wrt beam ($\boldsymbol{\theta_{NuMI}}$ **< 5 degrees**)

BSM physics program with NuMI

Di-lepton analysis





A bump hunt search in the data against the scaled background prediction obtains an insignificant excess with **a global significance of 0.19σ,** in the range $0.24 < M_{\mu\mu} < 0.31$ GeV.

arXiv:2411.02727

Summary and next steps towards the goal

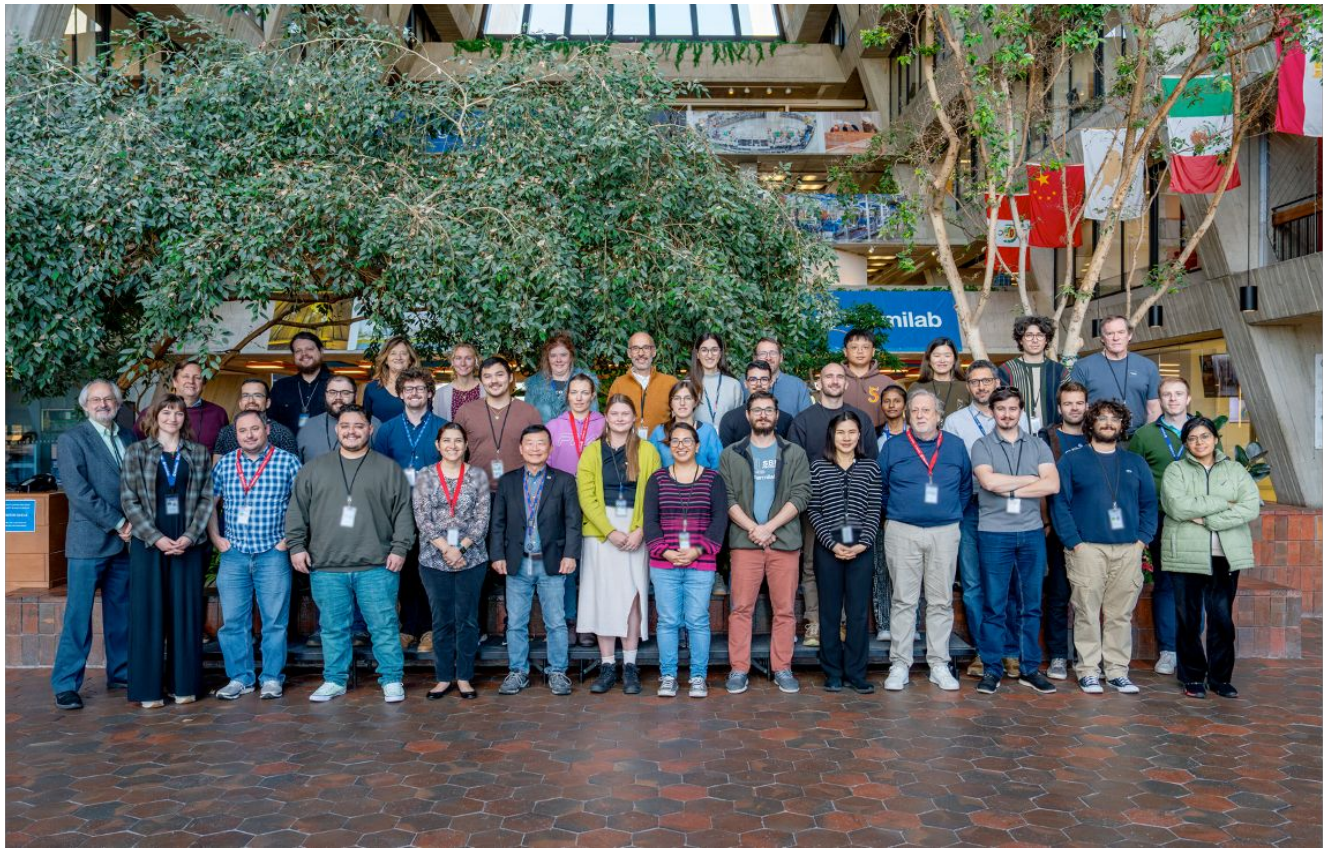
- ICARUS is running stably and has completed 3 physics run (Run1-Run3) since summer 2022, while being exposed to both on-axis BNB and off-axis NuMI neutrino beams.
- **Very recently ICARUS has started taking Run4 data with BNB.**
- Accurate detector calibration and response modelling is done using cosmic muons and protons from interactions and now they are fully embedded in our simulations.
- In the view of the upcoming joint-SBN analyses, several single detector studies are progressing and are quite advanced:

• **ν_μ- disappearance channel** with BNB: control sample will be enlarged to complete validation, full dataset will be unblinded and oscillation fit will be performed

• **ν-Ar cross section measurements with NuMI**: ready to study the sidebands with the full statistics

• **Search for μ^+/μ^- final state topology**: first results available, analysis completed.

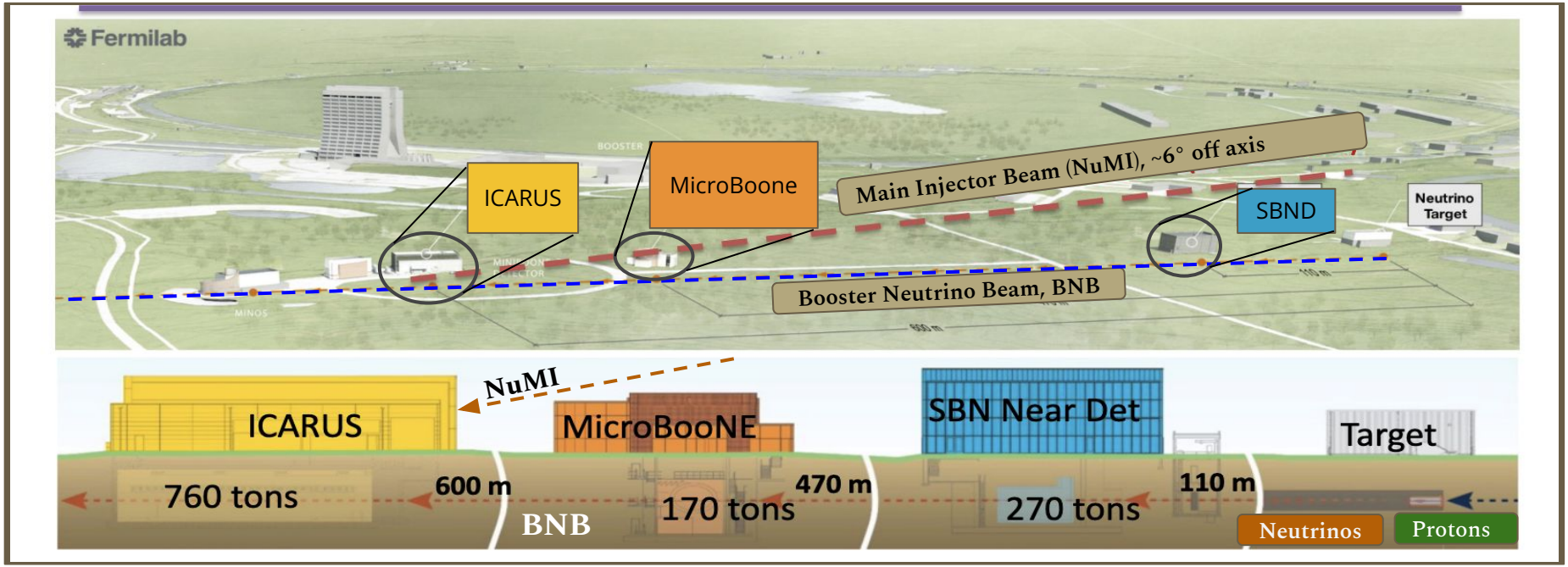
- Several other analyses with ICARUS BNB, NuMI data are going on, so stay tuned! :)



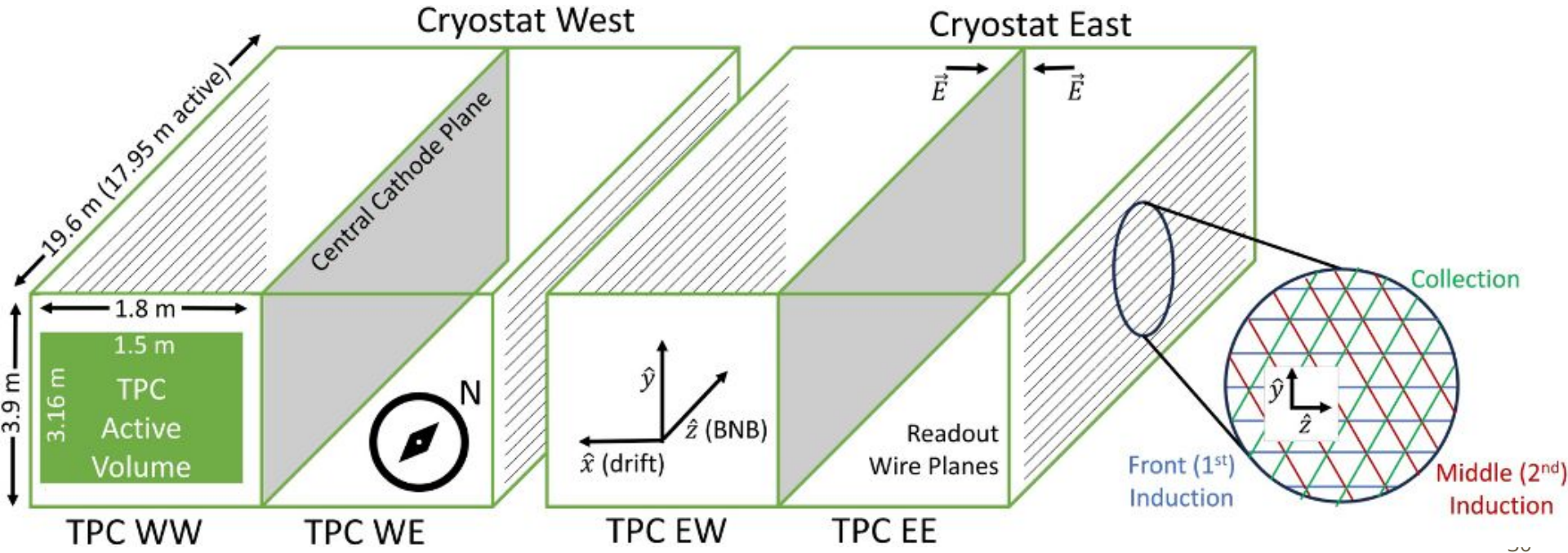
Thank you !!

Back up

The SBN program at FERMILAB

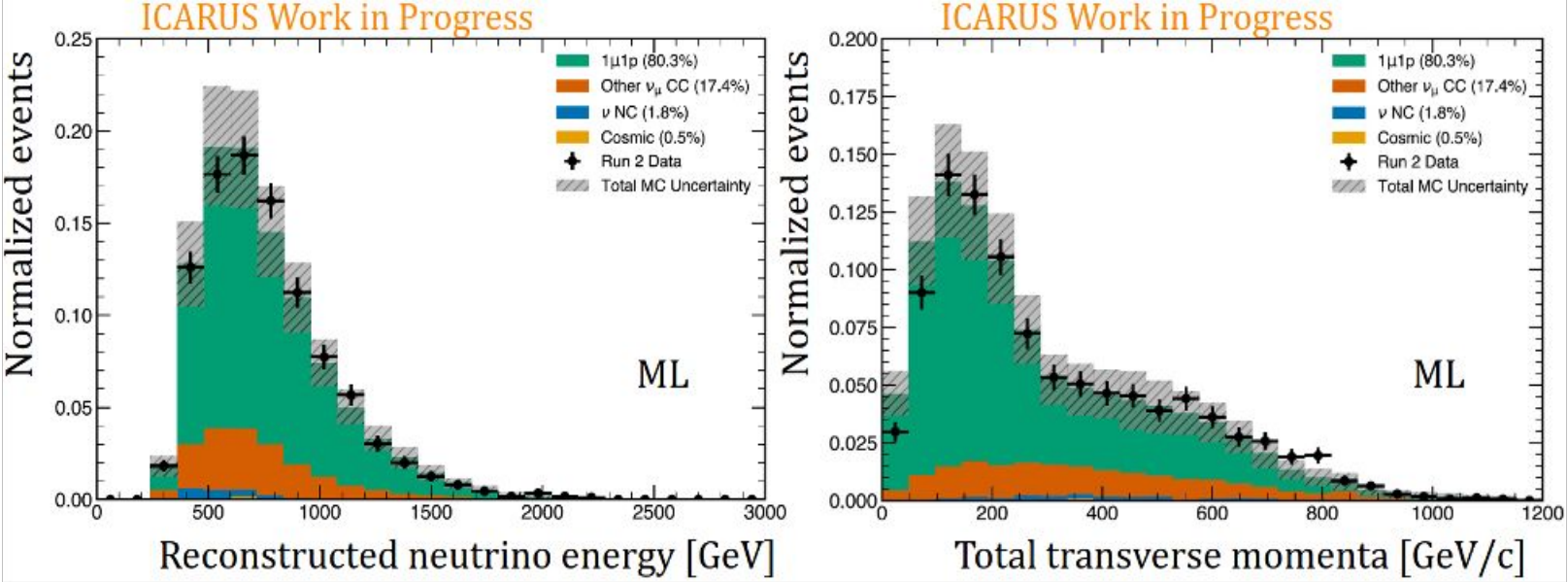


- ICARUS (SBN-FD) and SBND have same technology to minimize beam(BNB), background & detector systematics.
- BNB operates at 0.8 GeV, while ICARUS also receives neutrino beam from the Main Injector (NuMI).
- Capable of sensitive search in the $(\nu_\mu)\nu_e$ (dis)appearance channels to confirm/refute past anomalies in data


Cryostat West
Cryostat East
19.6 m (17.95 m active)
Central Cathode Plane
$\vec{E}$
$\vec{E}$
1.8 m
1.5 m
3.16 m
3.9 m
TPC Active Volume
N
$\hat{y}$
$\hat{z}$ (BNB)
$\hat{x}$ (drift)
Readout Wire Planes
Collection
Front (1st) Induction
Middle (2nd) Induction
TPC WW
TPC WE
TPC EW
TPC EE

ICARUS Physics program

ν_μ disappearance analysis: Preliminary results

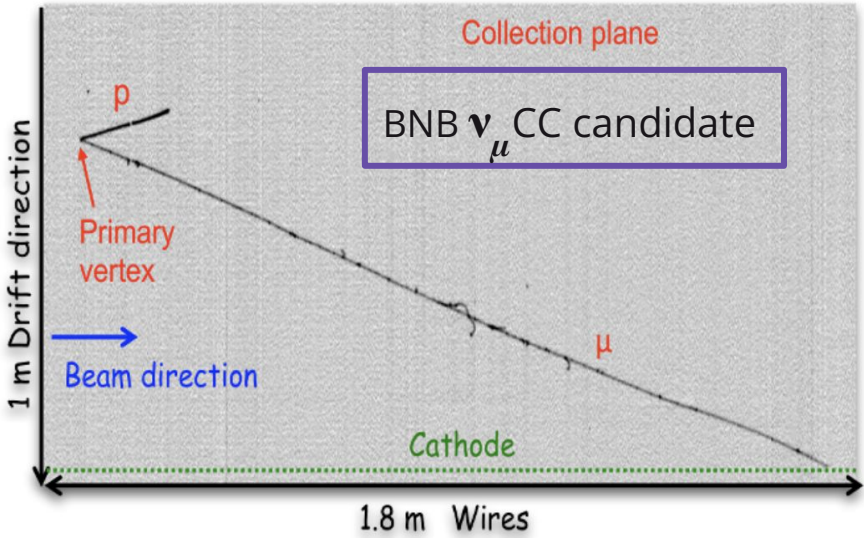


- **SPINE-based analysis on BNB beam**
- 75% signal efficiency, 80% purity
- 1.92 x 10^{19} PoT
- 47000 events (Run 1-3)

ICARUS Physics program

Event reconstruction criteria:
Two LArTPC event reconstruction frameworks:

- ***Pandora:*** pattern recognition software widely used in LArTPCs
- ***SPINE***: entirely based on Machine Learning techniques (arxiv)



ν_μ disappearance analysis

Systematics:

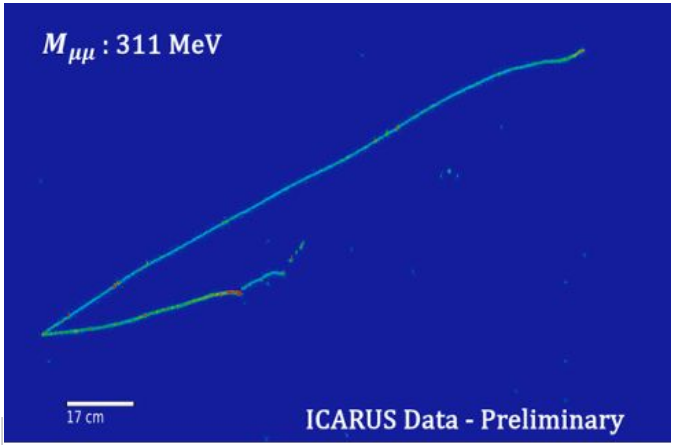
- Flux (~10%), cross-section (~15%) and detector systematics(~15%) included
- A reduction in the impact of detector systematics is expected from improved MC, while flux and cross-section systematics values should cancel with joint-SBN analysis

BSM physics program with NuMI

Models explored so far feature dark particles coupling to SM particles via Scalar Portal Interactions:

Higgs Portal Scalar (scalar dark particles, interacting with SM particles with Higgs boson mixing),

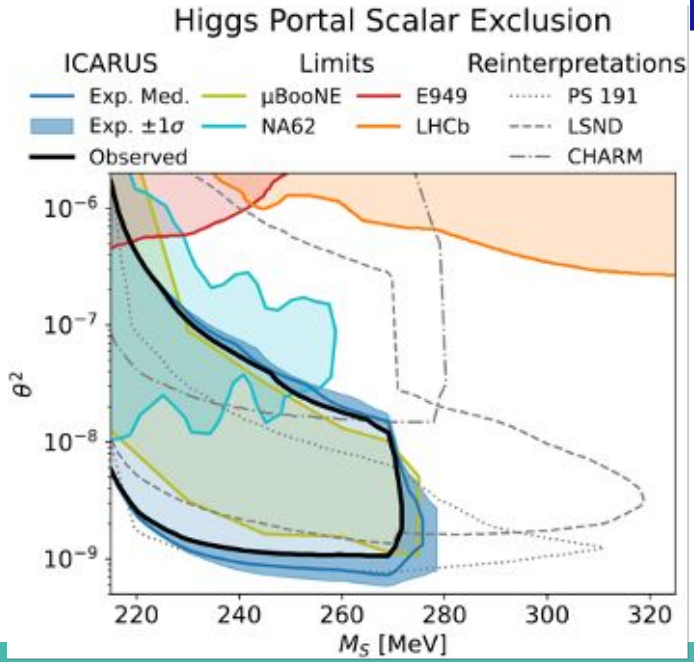
Heavy QCD axion (pseudo-scalar particles, interacting with SM ones via pseudo-scalar mesons)

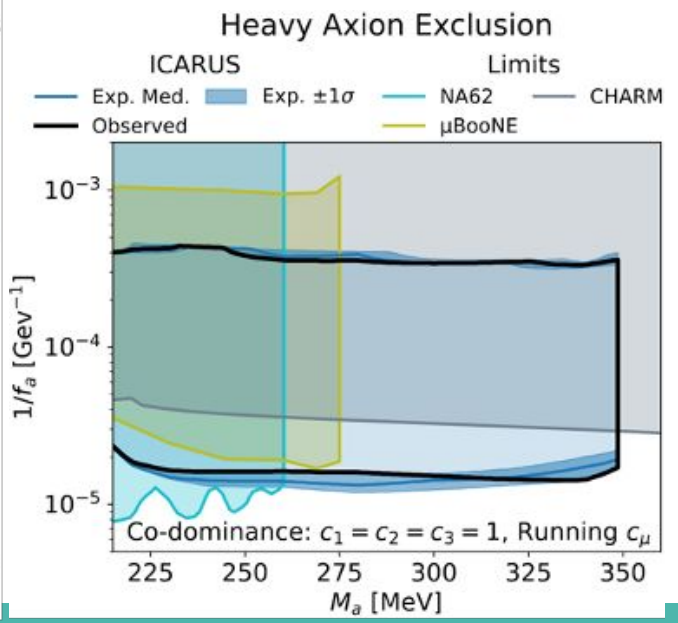


Di-lepton analysis

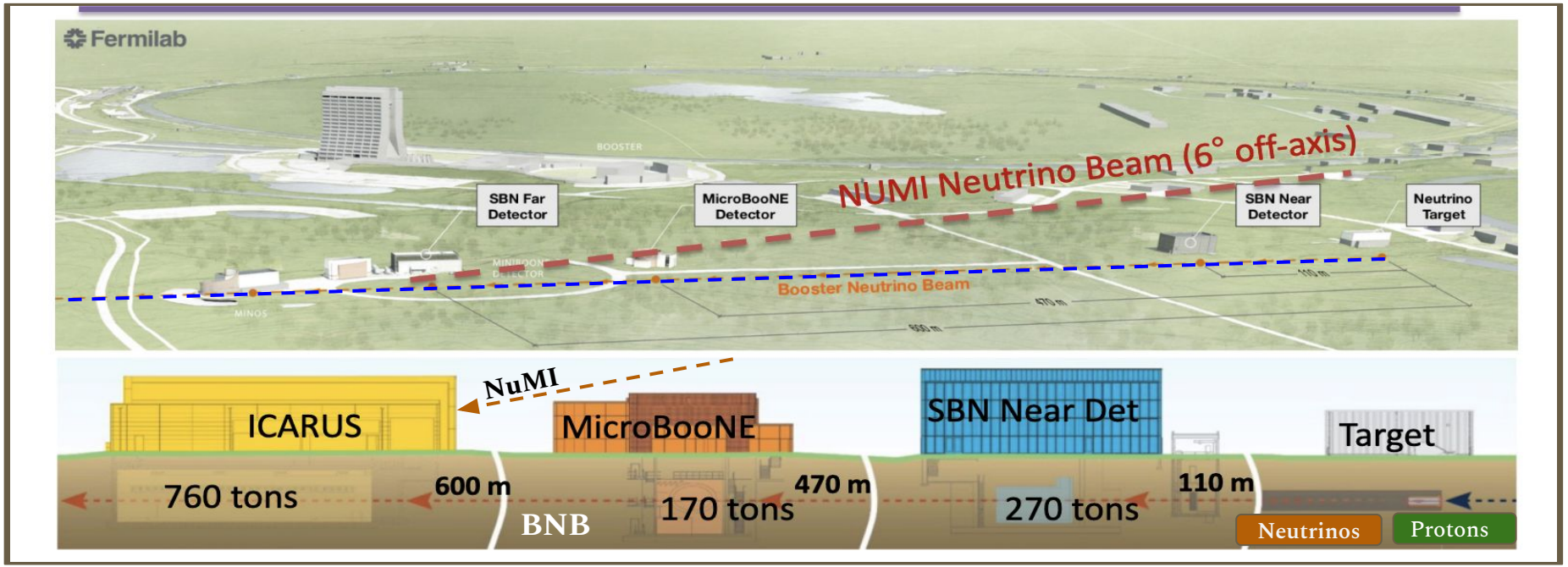
Limits on the Higgs Portal scalar and heavy axion models. Exclusions are computed with the CLs method at the 90% CL.

arXiv:2411.02727



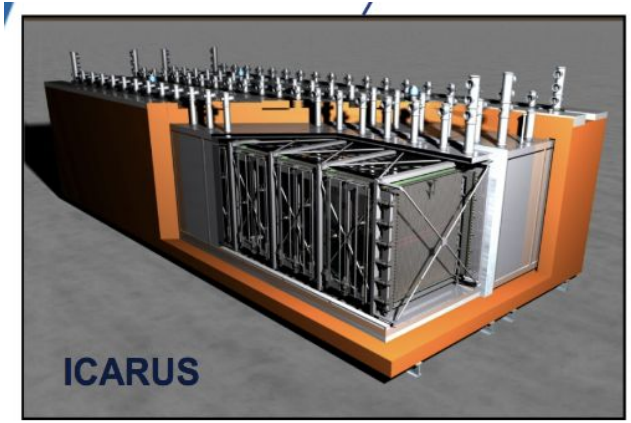


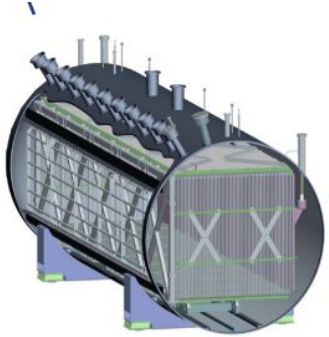
The SBN program at FERMILAB

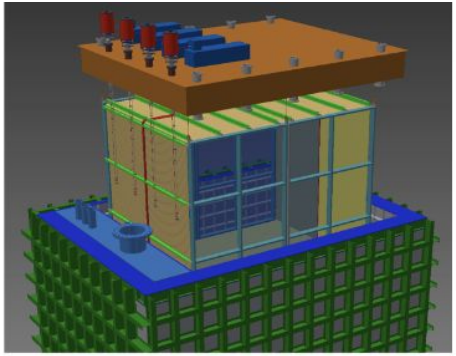


- ICARUS (SBN-FD) and SBND have same technology to minimize beam(BNB), background & detector systematics.
- BNB operates at 0.8 GeV, while ICARUS also receives neutrino beam from the Main Injector (NuMI).
- Capable of sensitive search in the $(\nu_\mu)\nu_e$ (dis)appearance channels to confirm/refute past anomalies in data.

The SBN program at FERMILAB

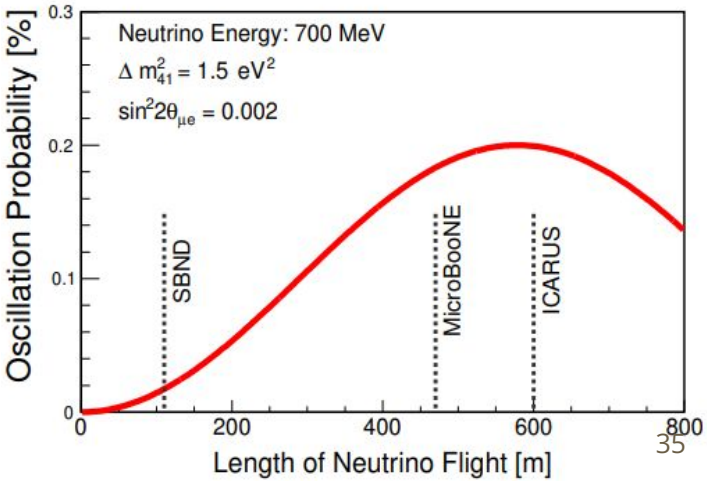






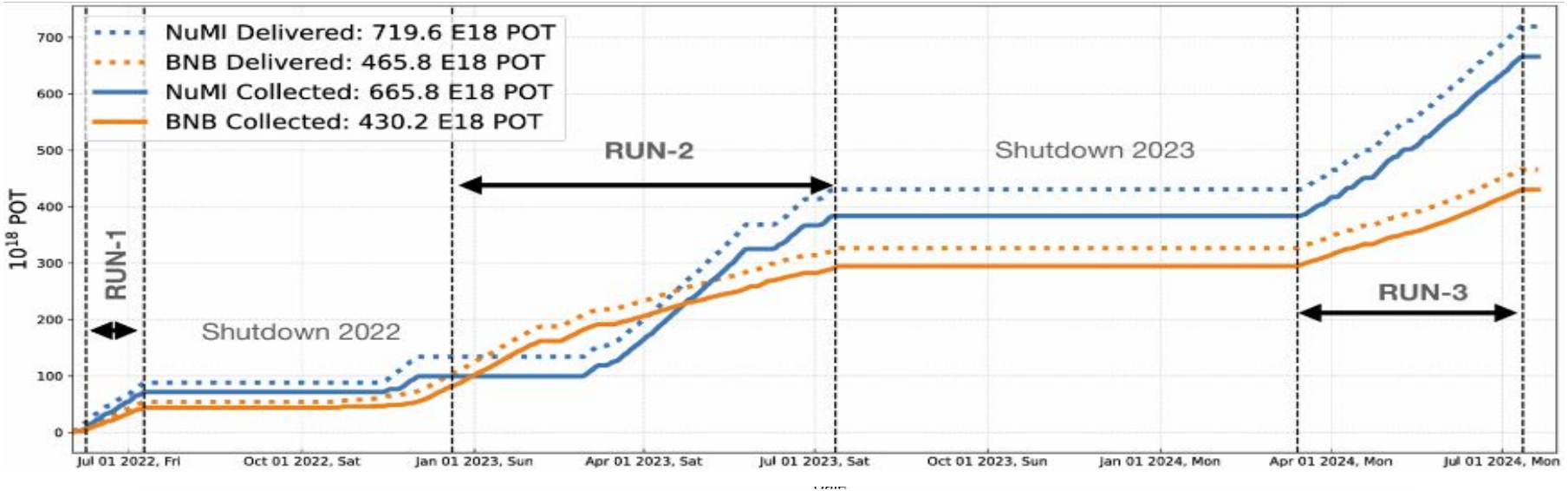
Main objectives:

- Search for eV-scale sterile neutrinos by looking for muon neutrinos disappearance and electron neutrinos appearance oscillations.
- Perform detailed study of neutrino-Argon interactions at the GeV energy scale.
- Pursuit advancement of the liquid argon detector technology in view of upcoming multi-kiloTon long baseline DUNE experiment.
- Search for new/rare physics processes in the neutrino sector and beyond.



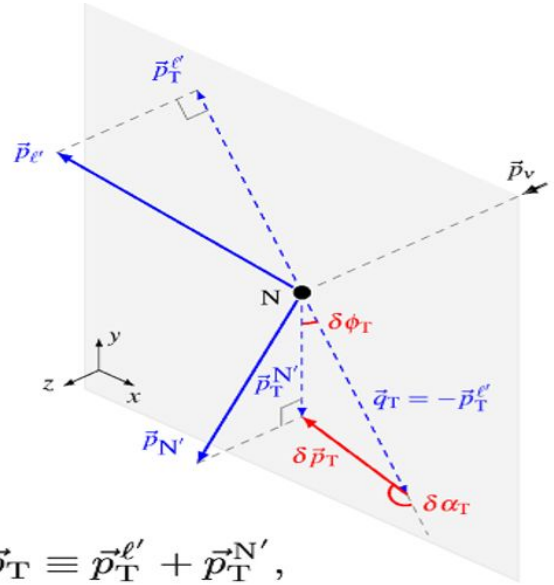
Detector operations and data acquisition

Data taking started in June 2022, 3 physics run since then: run 3 (both beams) 15 March - 12 July 2024



Collected Protons on target (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)	2.05 10^{20}	2.74 10^{20}	-
RUN-3	(Mar-Jul 24)	1.36 10^{20}	-	2.82 10^{20}
TOTAL	(PoT)	3.82 10^{20}	3.42 10^{20}	2.82 10^{20}

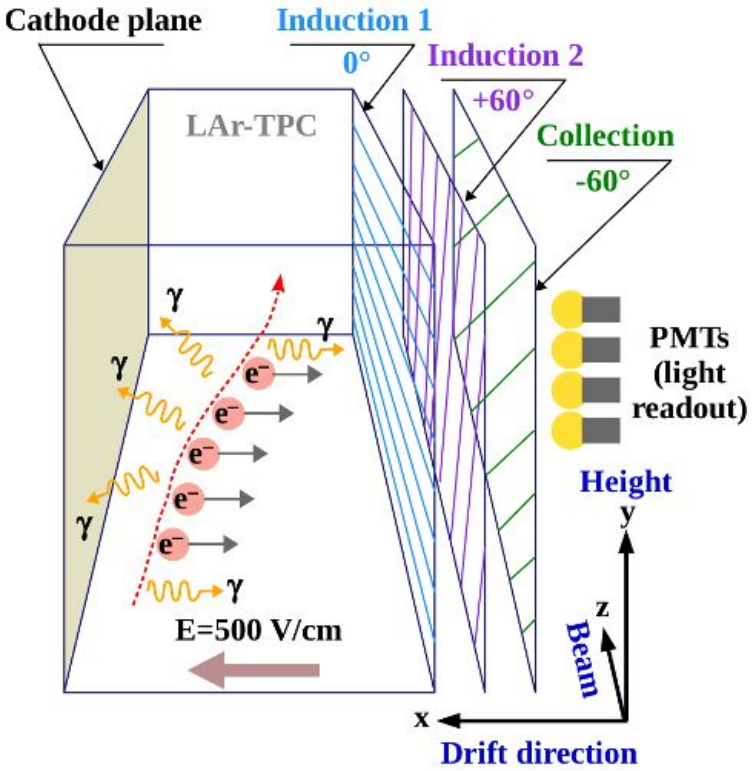
Transverse kinematics variables



$$\delta\vec{p}_{\mathrm{T}} \equiv \vec{p}_{\mathrm{T}}^{\,\ell'} + \vec{p}_{\mathrm{T}}^{\,\mathrm{N}'},$$

$$\delta\alpha_{\mathrm{T}} \equiv \arccos \frac{-\vec{p}_{\mathrm{T}}^{\,\ell'} \cdot \delta\vec{p}_{\mathrm{T}}}{p_{\mathrm{T}}^{\ell'}\delta p_{\mathrm{T}}},$$

These detectors ***are high-granularity, uniform, and self-triggering, with 3D imaging and calorimetric*** capabilities, making them ideal for neutrino physics.



- The ***n-Ar interactions produce tracks, with ions and photons along those***.
- ***Photons propagate inside the detector*** [the scintillation light is collected by the photomultiplier tubes (PMTs) for precise event timing and event calorimetry].
- ***The ionized electrons will slowly drift towards the anode*** by an applied electric field.
- ***The ionized electrons produce induction signals*** as they pass the first two wire planes and are collected on the last wire plane.