# ICARUS at the Short-Baseline Neutrino program: first results

Maria Artero Pons Università degli Studi di Padova and INFN Padova

On behalf of the ICARUS Collaboration

XIII International Conference on New Frontiers in Physics

Kolymbari, 4th September 2024

Imaging Cosmic And Rare Underground Signals

ICNFP

Università degli Studi di Padova

INFN Padova

European Commission

Intense RISE

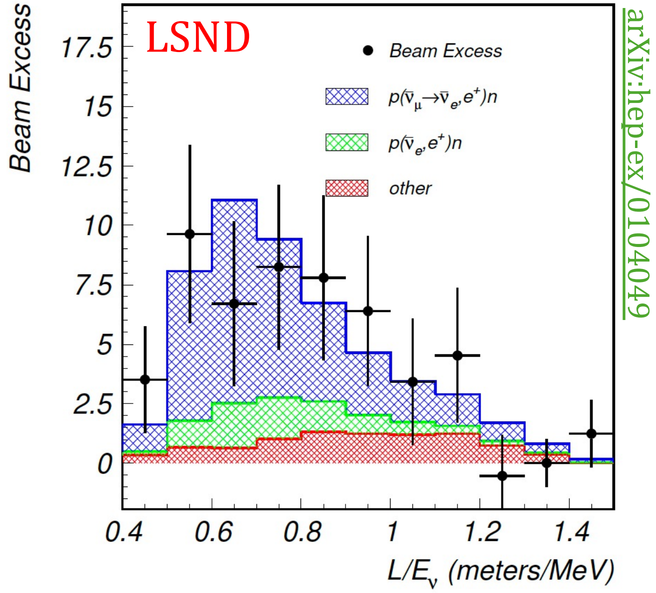
H2020-MSCA-RISE-2018

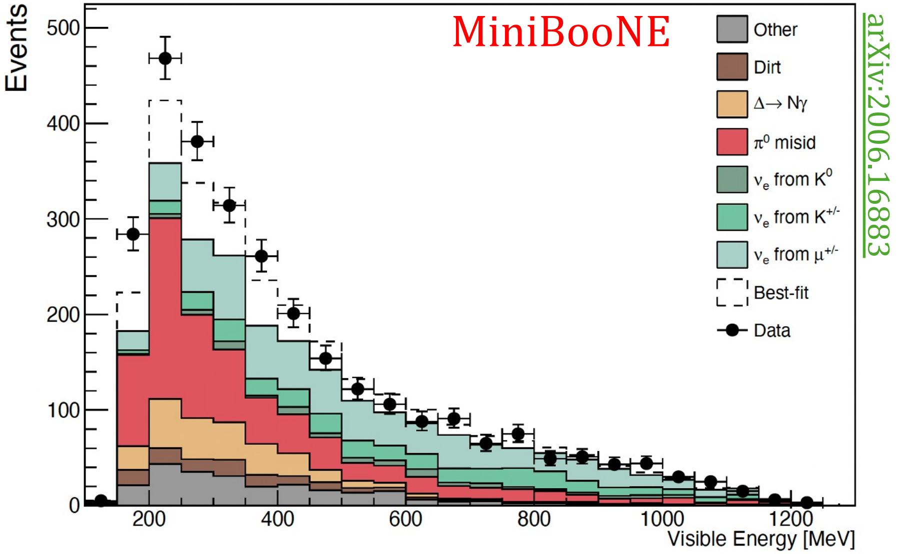
G.A. 822185

maria.arteropons@pd.infn.it

# The sterile neutrino puzzle

- Accelerator experiment anomalies: $\nu_e$ excess in a $\nu_\mu$ beam



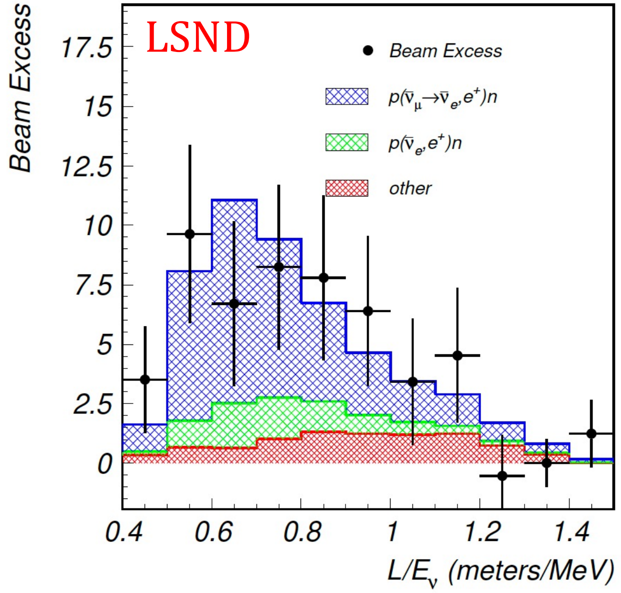




| Best fit | $\sin^2(2\theta)$ | $\Delta m^2_{23}$ $[eV^2]$ |
|---|---|---|
| LSND | 0.003 | 1.2 |
| MiniBooNE | 0.807 | 0.043 |

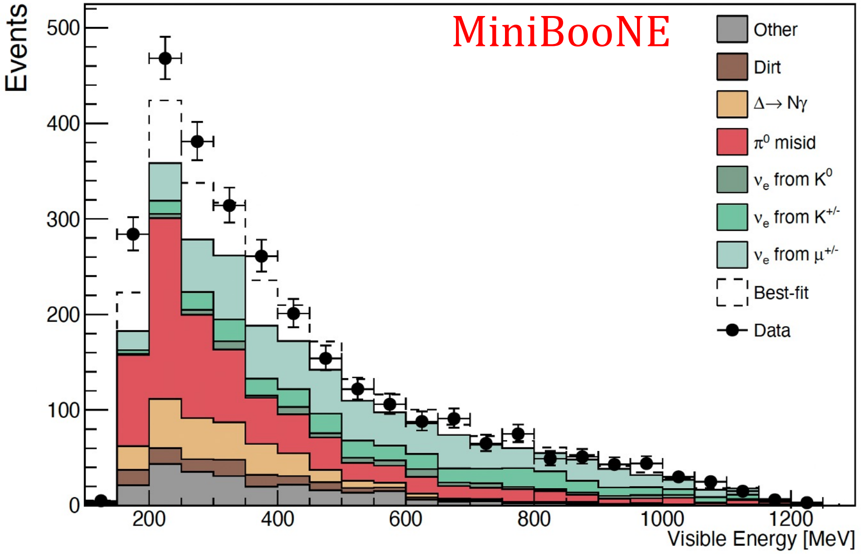
New sterile $\nu$ flavor
at $\Delta m^2 \sim eV^2$ !

# The sterile neutrino puzzle

- Accelerator experiment anomalies: $\nu_e$ excess in a $\nu_\mu$ beam

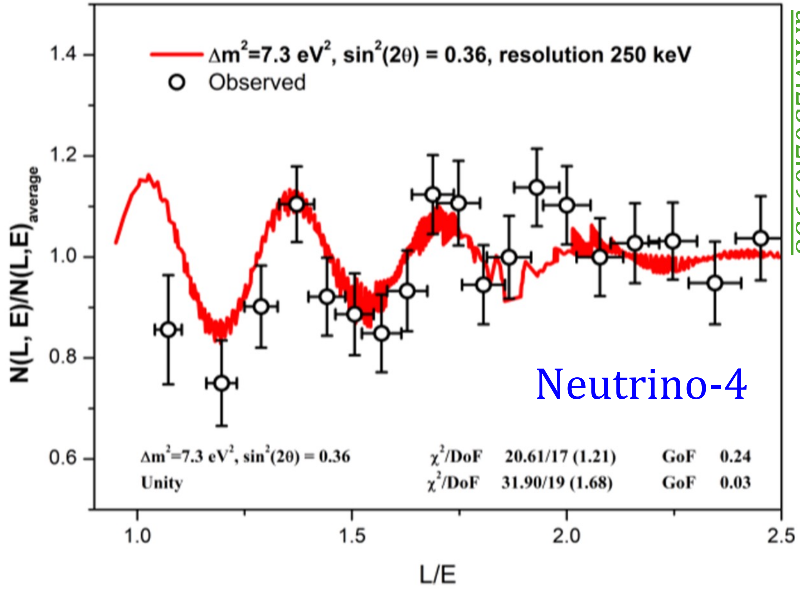



arXiv:hep-ex/0104049




arXiv:2006.16883

- Reactor $\bar{\nu}_e$ disappearance signal




arXiv:2302.09958

| Best fit | $\sin^2(2\theta)$ | $\Delta m^2_{23}$ $[eV^2]$ |
|---|---|---|
| LSND | 0.003 | 1.2 |
| MiniBooNE | 0.807 | 0.043 |

New sterile $\nu$ flavor at $\Delta m^2 \sim eV^2$ !

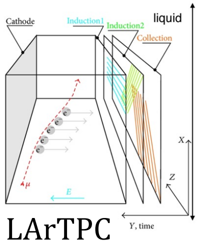
Oscillation signature at $5.8\sigma$ CL when results are combined with other experiments

# The sterile neutrino puzzle

Tension between appearance and disappearance results in global constraint plots

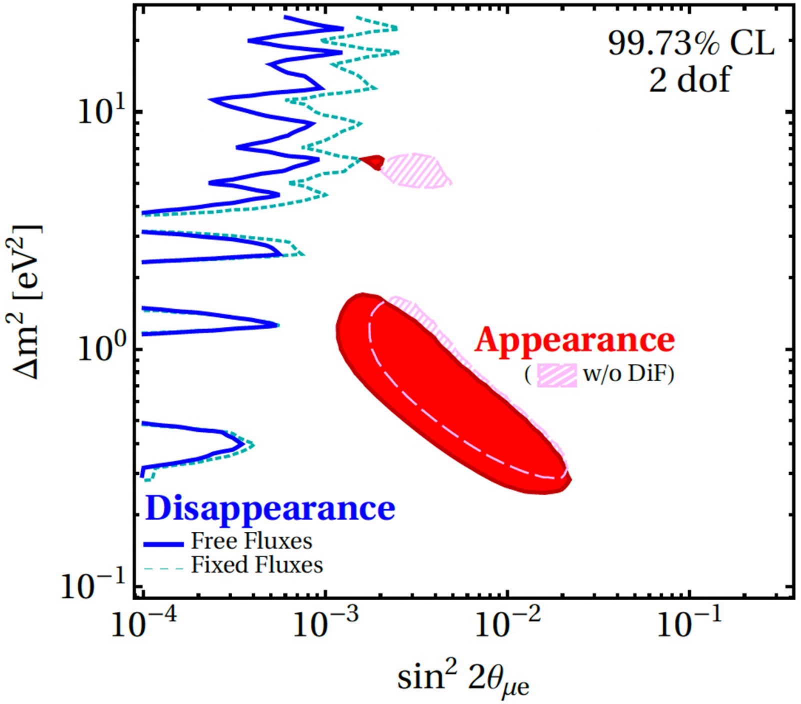
Measure both channels with the same experiment

The Short-Baseline Neutrino program is searching for sterile neutrinos at $\sim eV^2$ mass scale



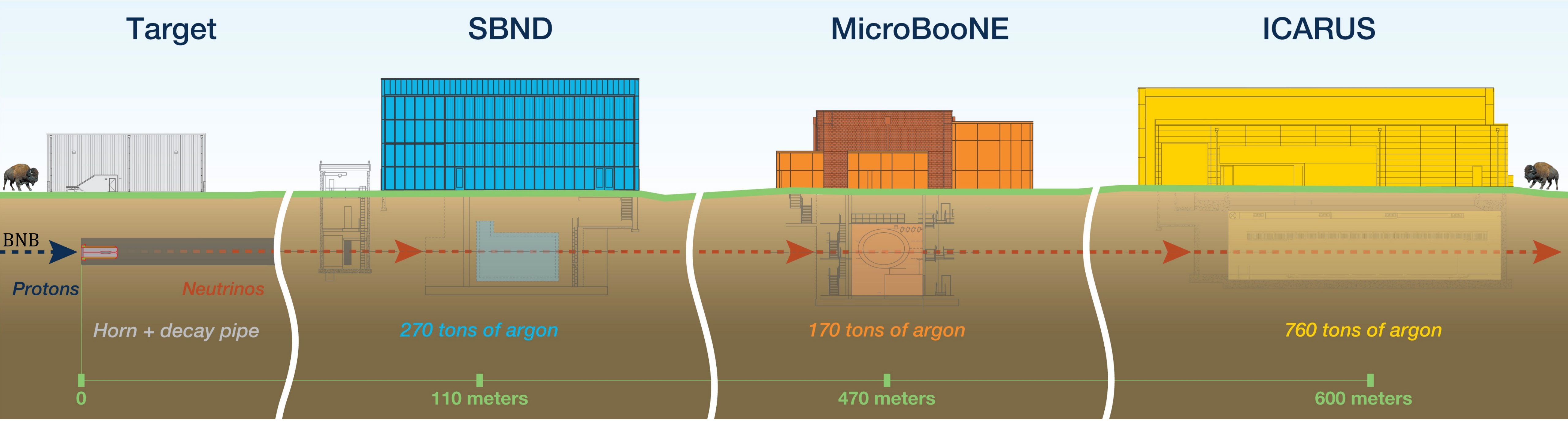
LArTPC

LAr Time Projection Chambers (LArTPC) @ Fermilab sampling the same $\nu$ beam at different distances




JHEP08 (2018) 010

# The Short-Baseline Neutrino program




- Shared detector technology, nuclear target and beam to reduce the systematic uncertainties to % level

Flux and $\nu -$ Ar cross section constraints from the near detector

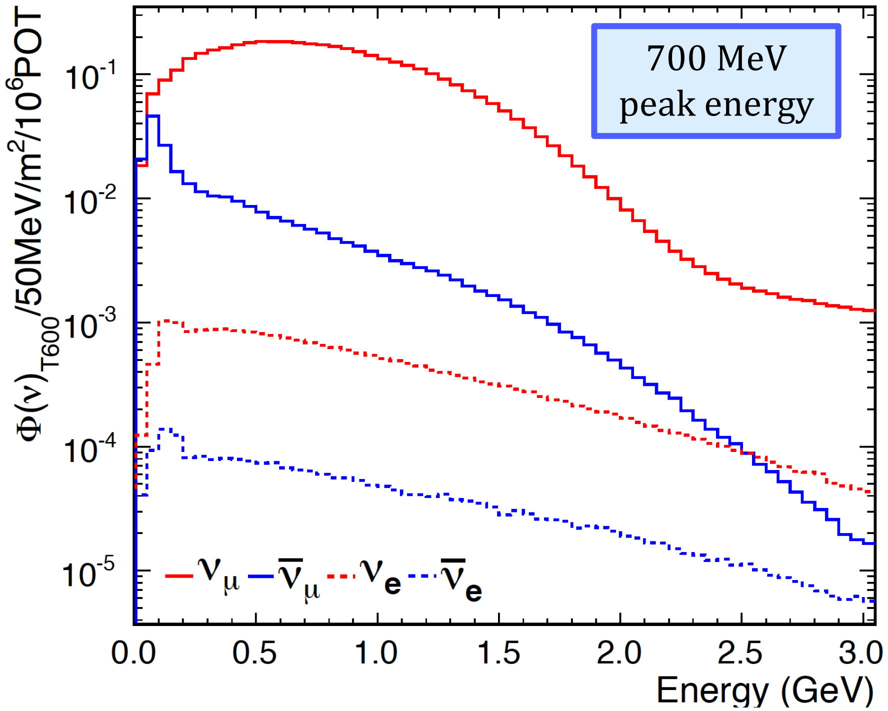
Commissioning phase

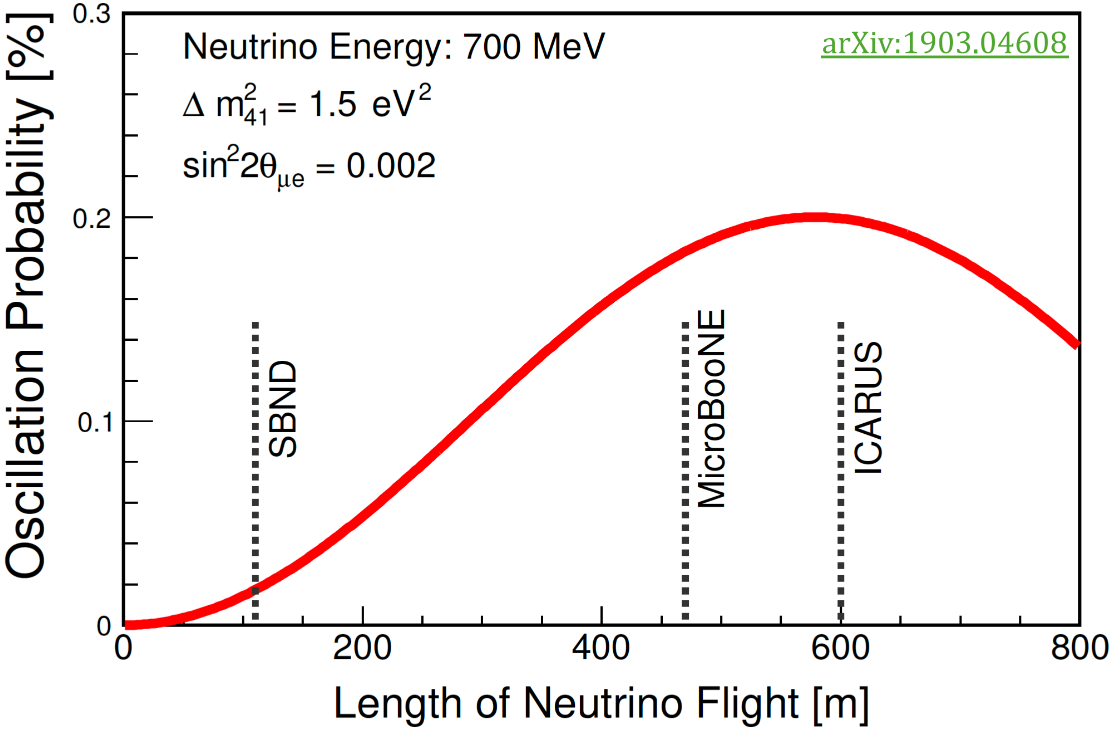
Oscillated neutrino spectrum measurement at the far detector

Taking data

# ICARUS beams

- **BNB** is a well characterized $\nu_\mu$-beam, able to produce $\nu$ and $\bar{\nu}$ beams with low $\nu_e$ contamination

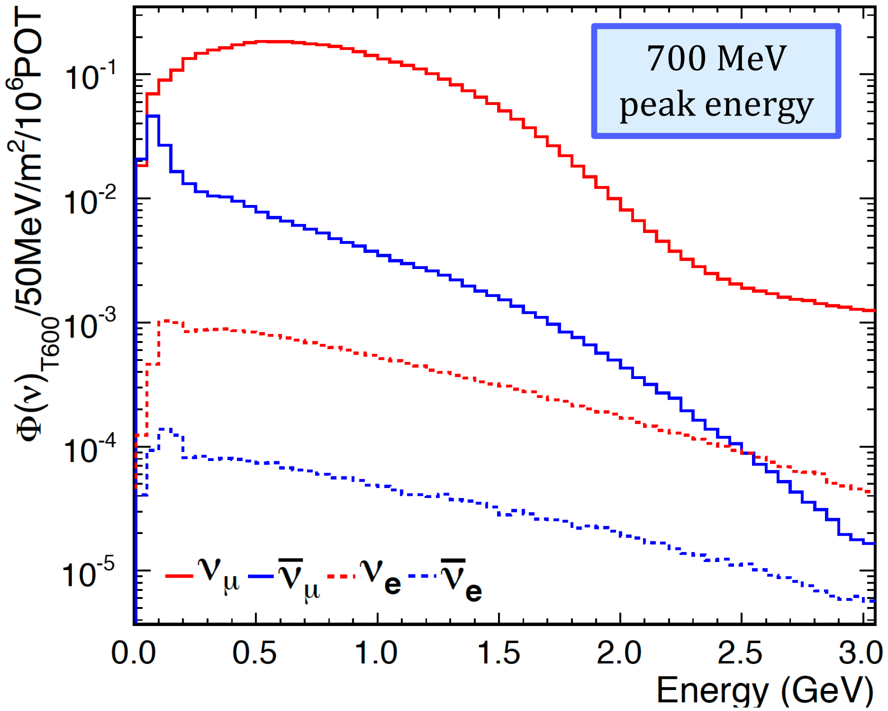


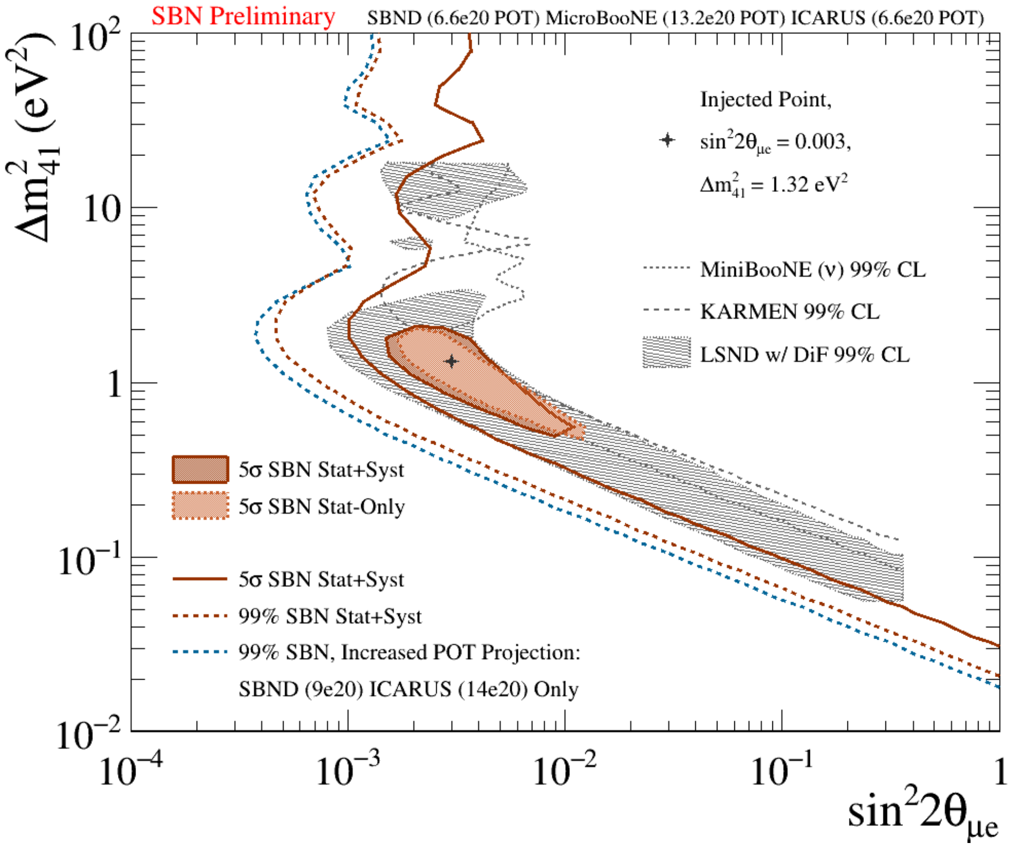
# ICARUS beams

- **BNB** is a well characterized $\nu_\mu$-beam, able to produce $\nu$ and $\bar{\nu}$ beams with low $\nu_e$ contamination

  ➔ Sensitive search in the $\nu_\mu$ disappearance & $\nu_e$ appearance channels

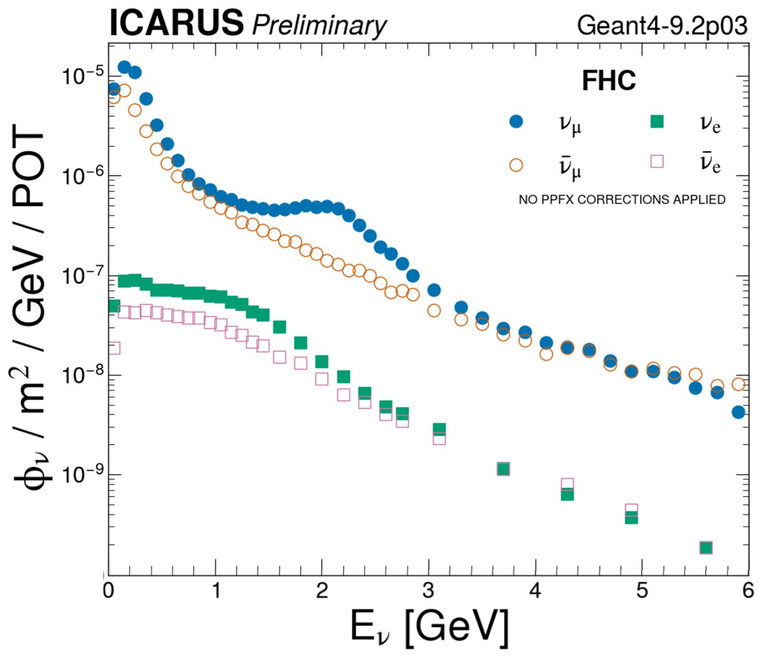


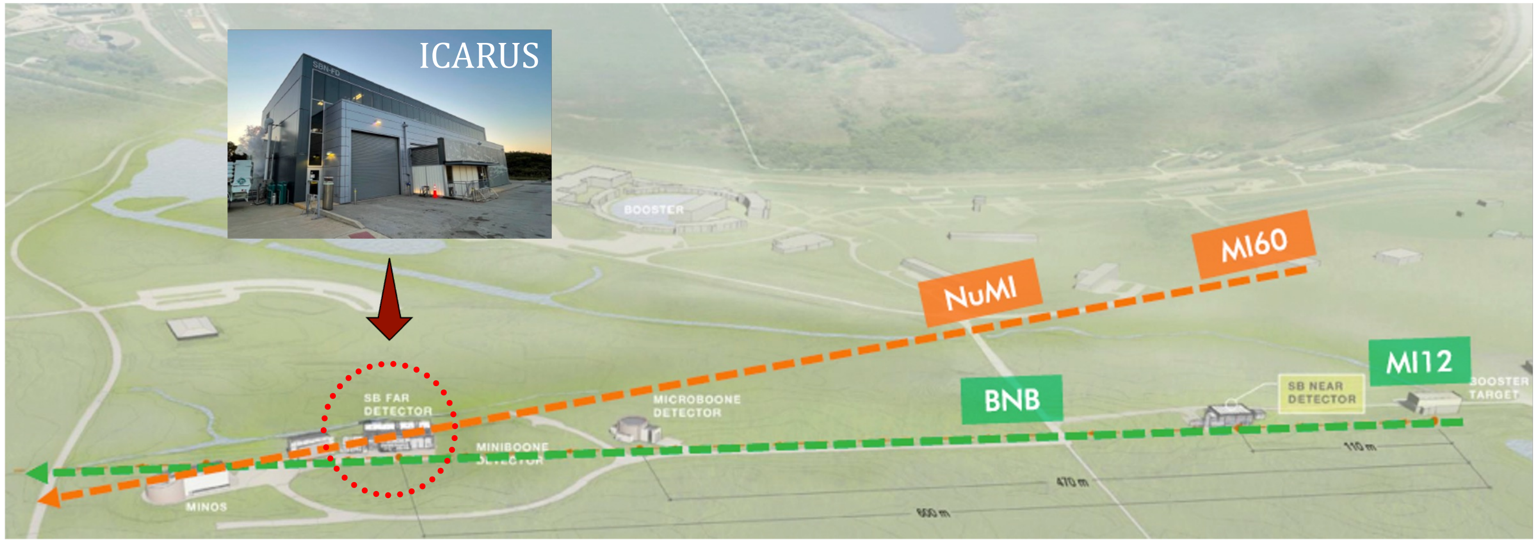

SBN $\nu_e$ appearance sensitivity



# ICARUS beams

- BNB is a well characterized $\nu_\mu$-beam, able to produce $\nu$ and $\bar{\nu}$ beams with low $\nu_e$ contamination
- ICARUS is also exposed $\sim 6°$ off-axis to the **NuMI** beam and can access the $\nu_e$ rich component of the spectrum




arXiv:1503.01520

# Standalone ICARUS physics program

- Before the start of near-far joint operation, ICARUS standalone physics program includes

01

$\nu_\mu$ disappearance investigation with BNB beam

→ $\nu_e$ disappearance studies leveraging the NuMI beam will follow

02

$\nu-$Ar cross section measurements and software optimization of reconstruction & identification tools with NuMI beam

→ within DUNE's interest energy range

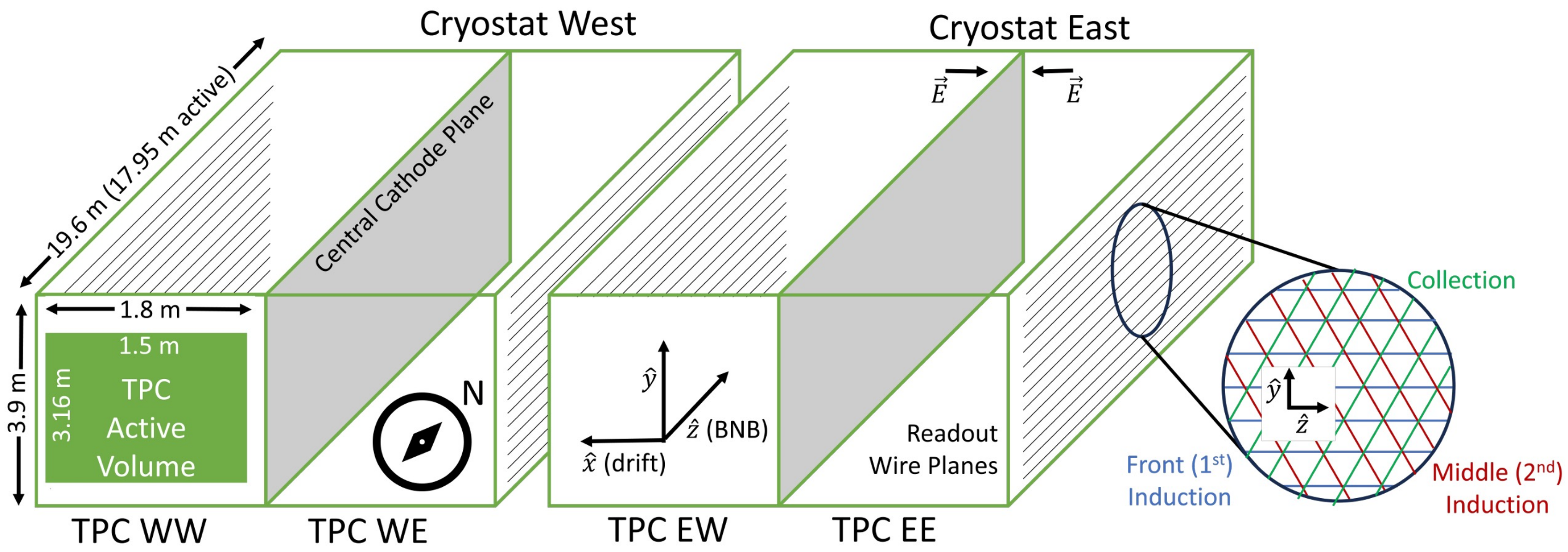
03

Search for sub-GeV Beyond Standard Model (BSM) signatures

→ Exploiting off-axis NuMI beam

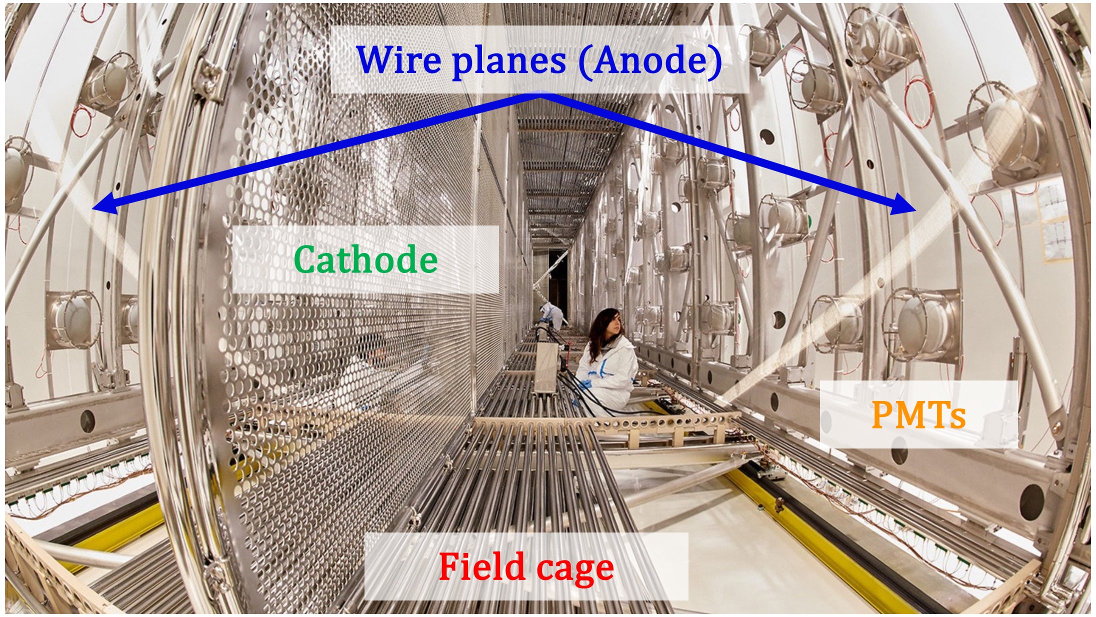
# ICARUS LArTPC

- ICARUS T600 is the first large scale LArTPC




- 2 Identical cryostats with 4 TPCs
- Total active mass 476 ton
- 3 readout wire planes per anode at 0 and $\pm 60°$
- 500 V/cm $\vec{E}$ field, with 1.5 m drift length
- Warm front-end electronics

# ICARUS Detector Subsystems

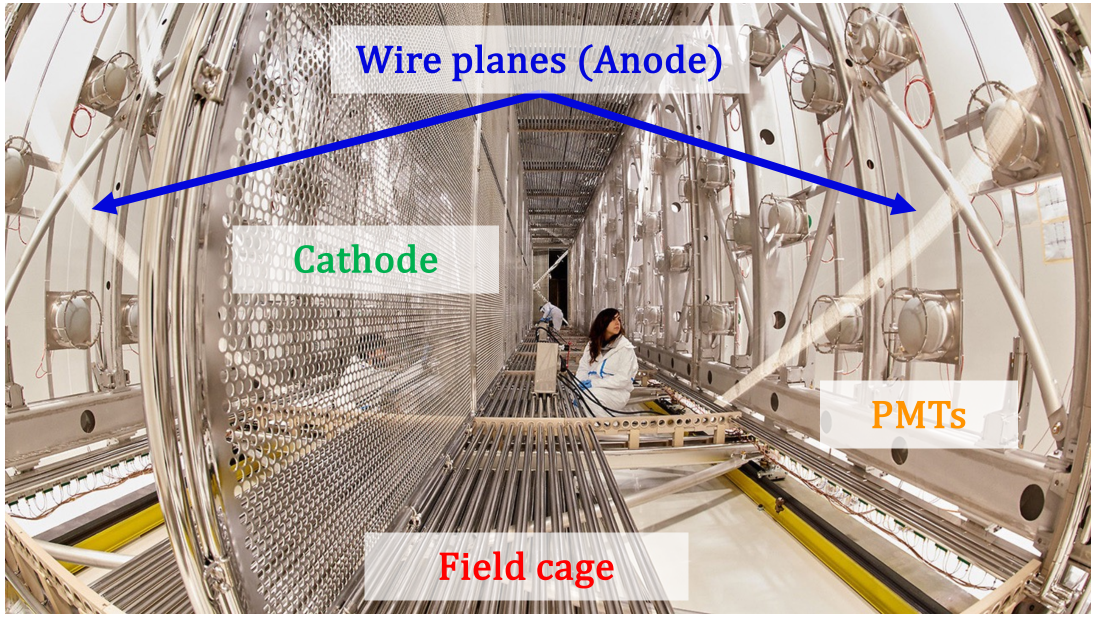




- Time Projection Chambers (TPC)
  - ~ 54k channels at different orientations and 3 mm pitch
- Photon Detection System (PDS)
  - 360 PMTs, TPB coated to detect scintillation light
  - Event timing and triggering purposes
- Cosmic Ray Tagger (CRT)
  - ~ $4\pi$ scintillator panels with SiPM readout for cosmic tagging
  - Protected by ~ 2.85 m thick concrete overburden for external $\gamma$/n suppression

*ICARUS operates at shallow depth

# ICARUS Detector Subsystems



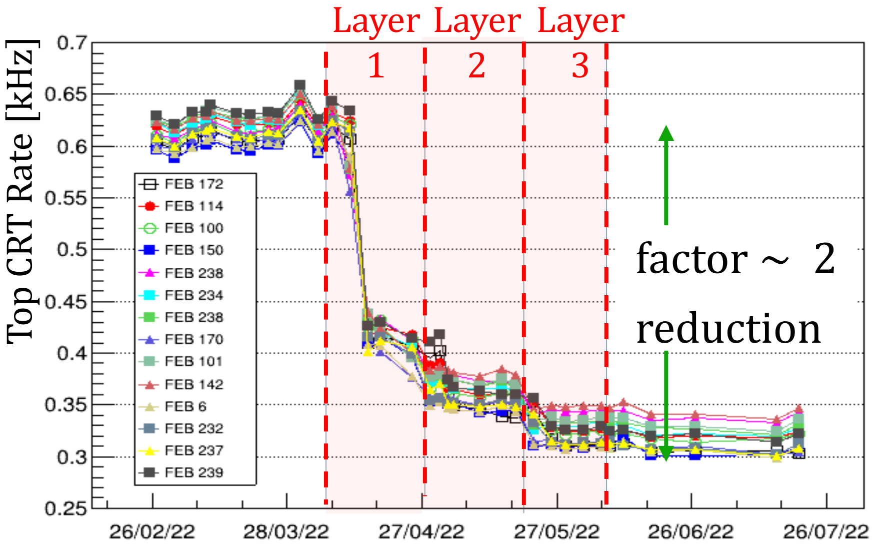


## Installation and activation

- September 2020: Start of TPC and PMT operations
- December 2021: CRT installation

~ 95% tagging efficiency

- June 2022: Overburden installation




Eur. Phys. J. C 83, 467 (2023)

# Physics runs

See R. Triozzi's talk!

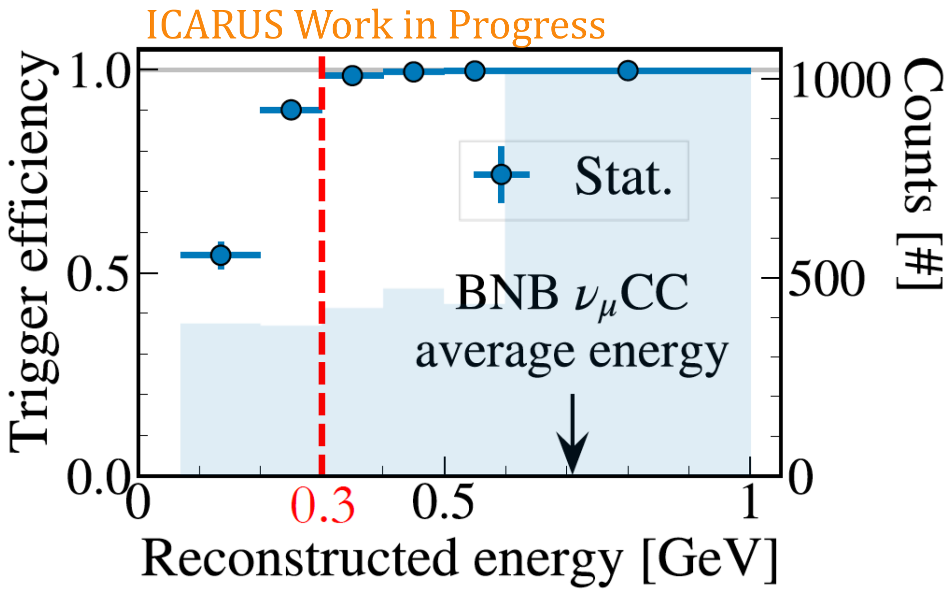
First physics data taking after overburden completion

Recording events whose scintillation light is detected in coincidence with the proton beam extraction

At least 5 fired PMT pairs inside a 6 m longitudinal slice

No beam periods allowed LAr refilling and detector improvement operations

>97% data collection efficiency



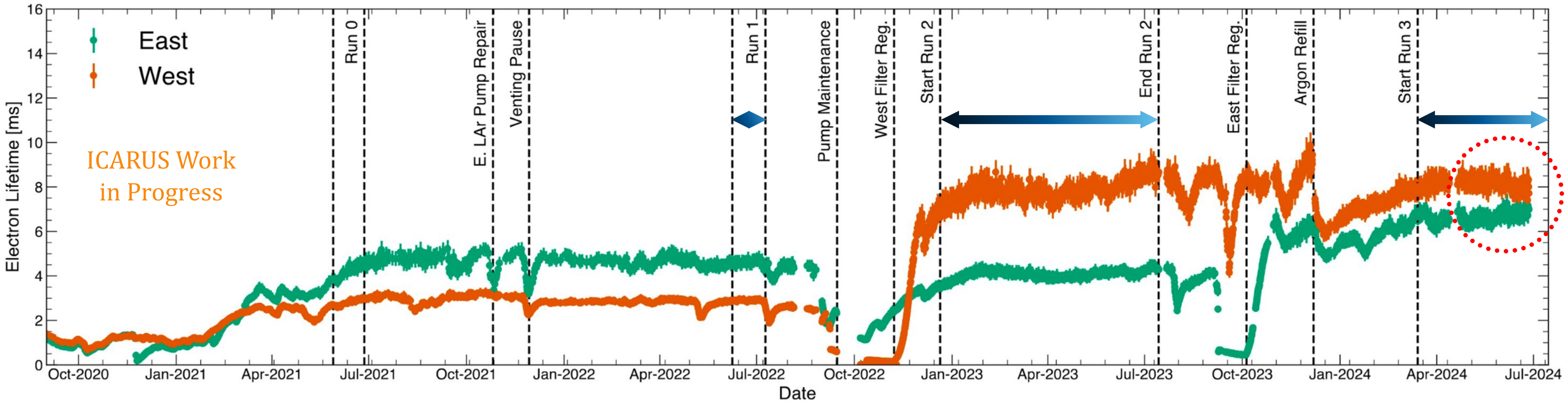

Run-2 DATA

| Collected Protons on Target | BNB + focusing | NuMI + focusing | NuMI - focusing |
|---|---|---|---|
| Run-1 (Jun 9$^{th}$ – Jul 10$^{th}$ 22) | $0.41 \cdot 10^{20}$ | $0.68 \cdot 10^{20}$ | – |
| Run-2 (Dec 20$^{th}$ 22 – Jul 14$^{th}$ 23) | $2.05 \cdot 10^{20}$ | $2.74 \cdot 10^{20}$ | – |
| Run-3 (Mar 15$^{th}$ - Jul 12$^{th}$ 24) | $1.36 \cdot 10^{20}$ | - | $2.82 \cdot 10^{20}$ |
| Total | $3.82 \cdot 10^{20}$ | $3.42 \cdot 10^{20}$ | $2.82 \cdot 10^{20}$ |

*+(-) focusing indicates forward (reverse) Horn Current

# ICARUS Data taking

- Free electron lifetime stable and adequate for physics runs thanks to the cryogenic and purification systems

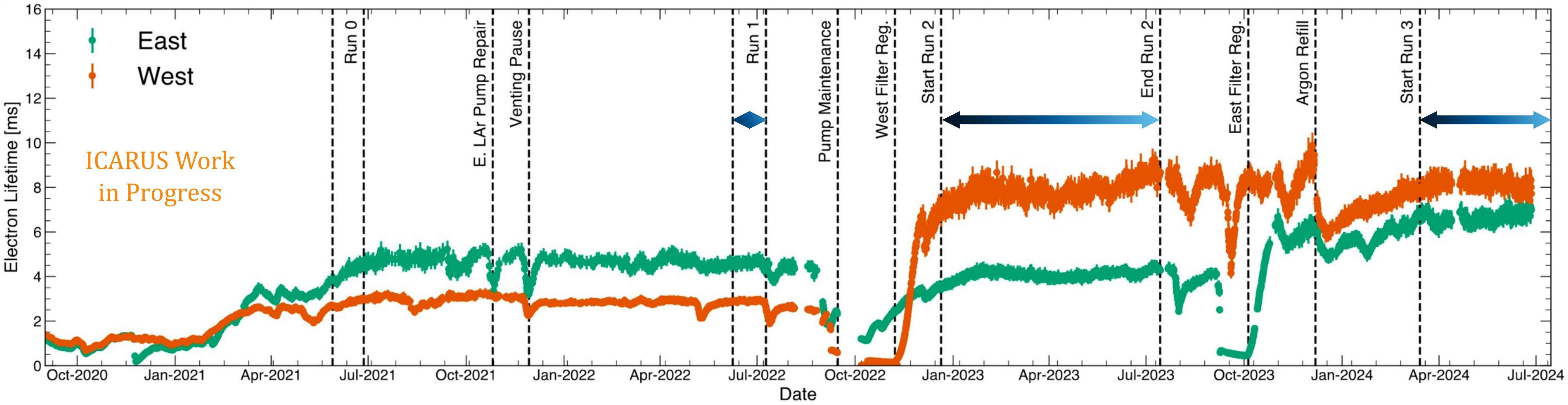



Values ~ 7-8 ms allowing an almost full track detection efficiency in the whole 1.5 m drift ( ~ 1 ms)

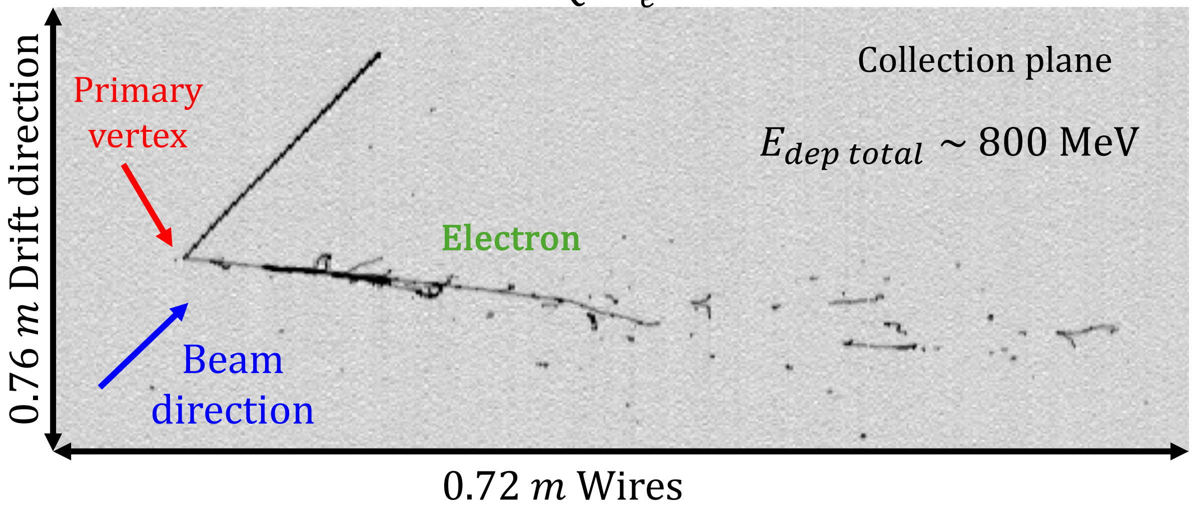
*residual impurities in LAr at ~ 40 p.p.t. of $[O_2]$ equivalent

# ICARUS Data taking

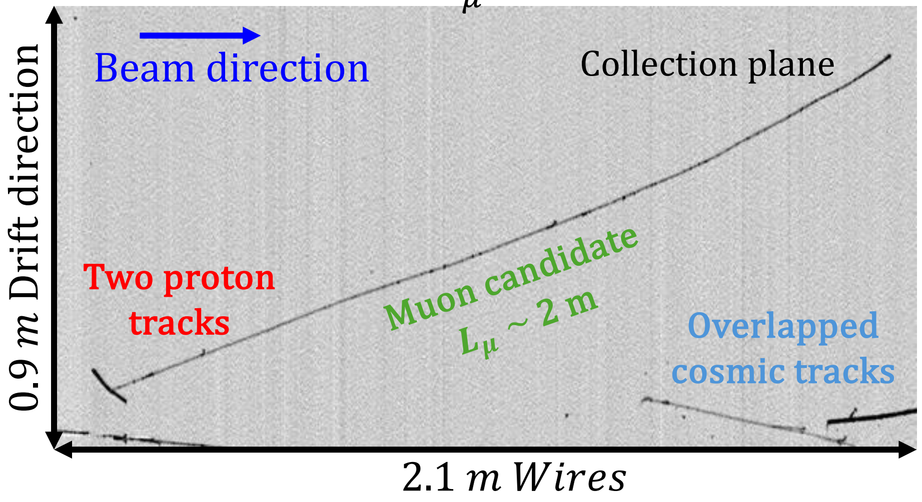
- Free electron lifetime stable and adequate for physics runs thanks to the cryogenic and purification systems




NuMI CCQE $\nu_e$ candidate

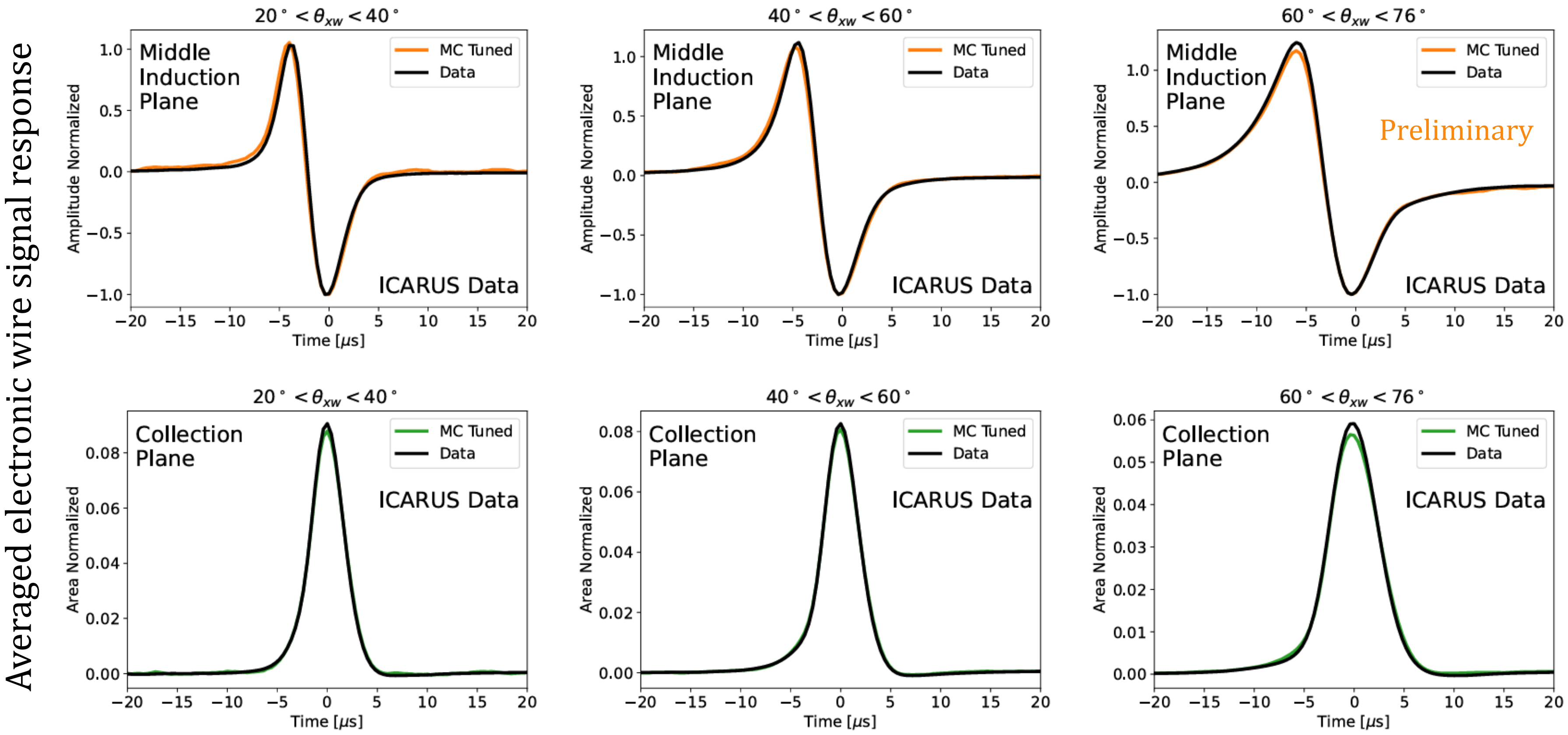



BNB CC $\nu_\mu$ candidate



# Detector calibration

- To pursue ICARUS' standalone physics program a full detector calibration is mandatory
- Accurate characterization and modeling of TPC wire signals in MC using cosmic muon data




arXiv:2407.11925

# Detector calibration

- Detector response calibration with cosmic muons and protons from neutrino events, essential for PID
  - Electronics gain factors
  - New angular dependent recombination model (EMB)
  - Electron lifetime correction

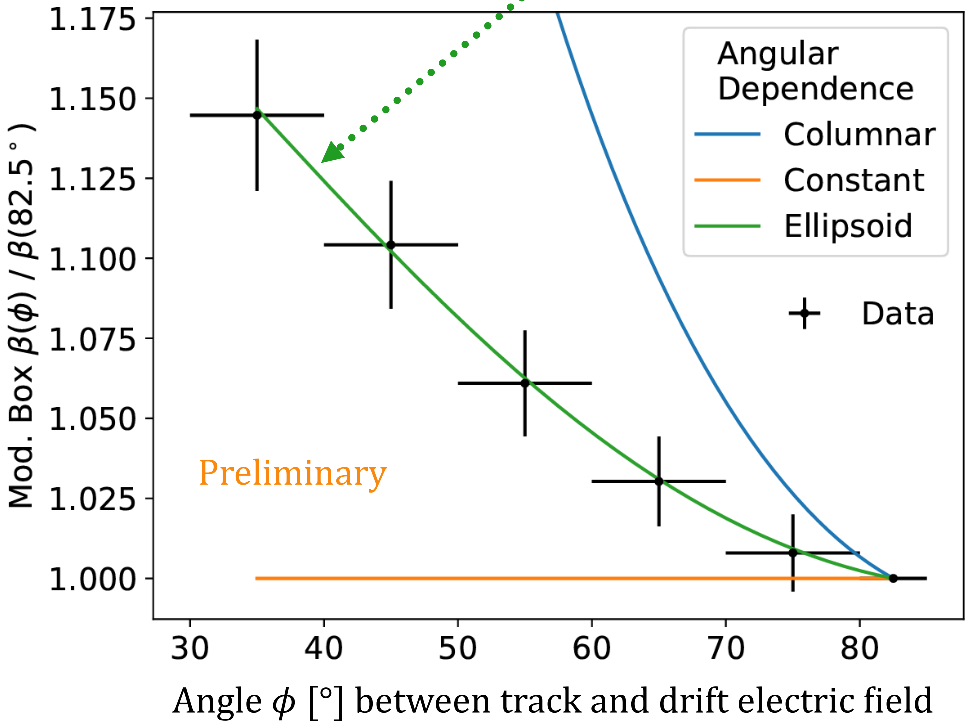
arXiv:2407.12969

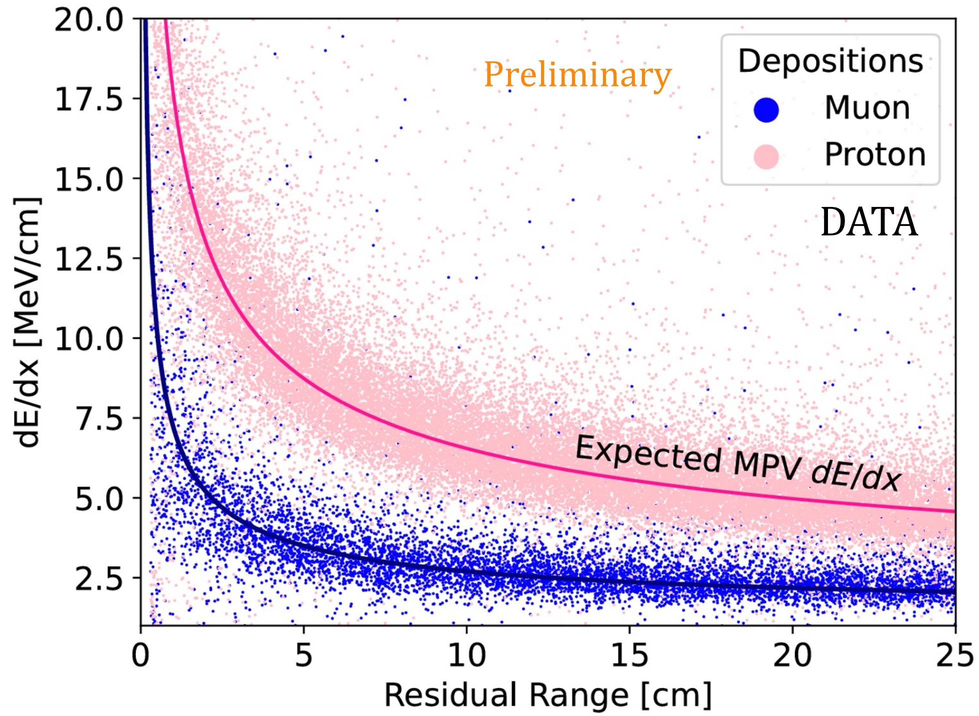
$$\frac{dQ}{dx} = \frac{\log\left(\alpha + \mathcal{B}(\phi)\frac{dE}{dx}\right)}{\mathcal{B}(\phi) W_{\text{ion}}} \qquad \mathcal{B}(\phi) = \frac{\beta_{90}}{\mathcal{E}\rho\sqrt{\sin^2\phi + \cos^2\phi / R^2}}$$

$\alpha$: 0.904 ± 0.008 $\quad R$: 1.25 ± 0.02

$\beta_{90}$: 0.204 ± 0.008 (kV/MeV)(g/mL)

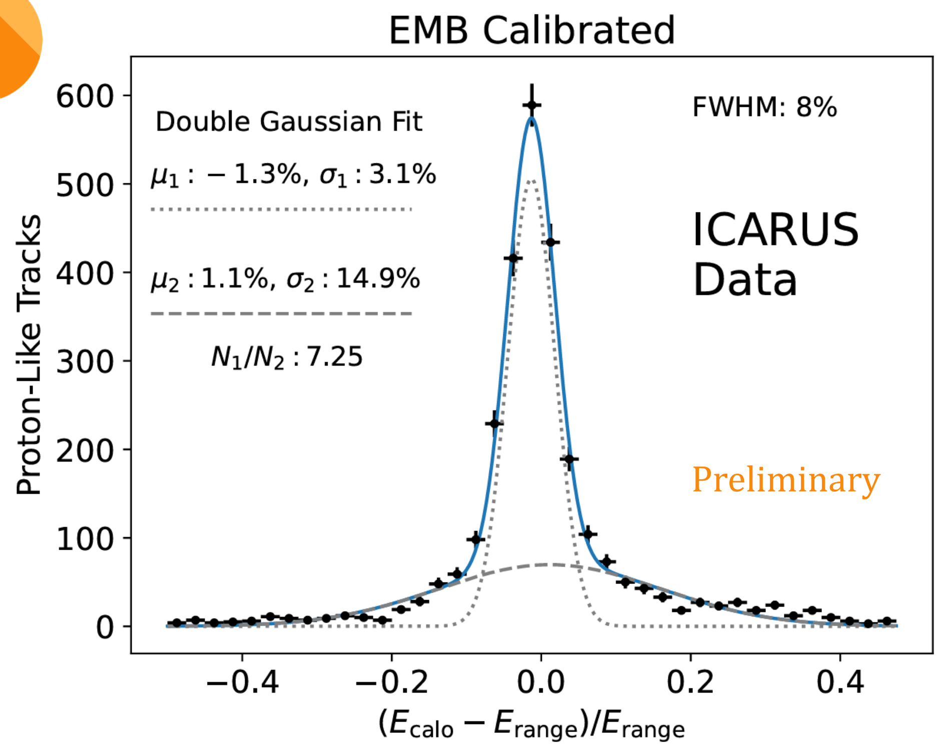
*$\mathcal{E}$ being the electric field and $\rho$ the Ar density



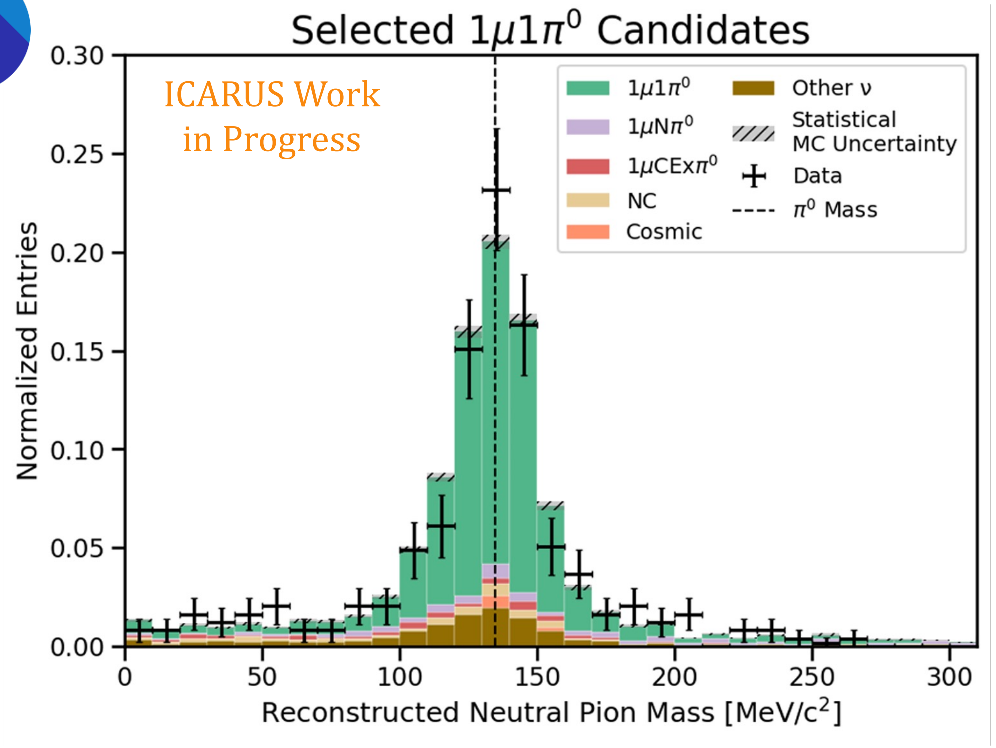
# Detector validation

- Deposited energy was used to validate the calibration and calorimetric reconstruction




- stopping protons from NuMI $\nu_\mu$CC
- $\sim 3\%$ resolution

arXiv:2407.12969

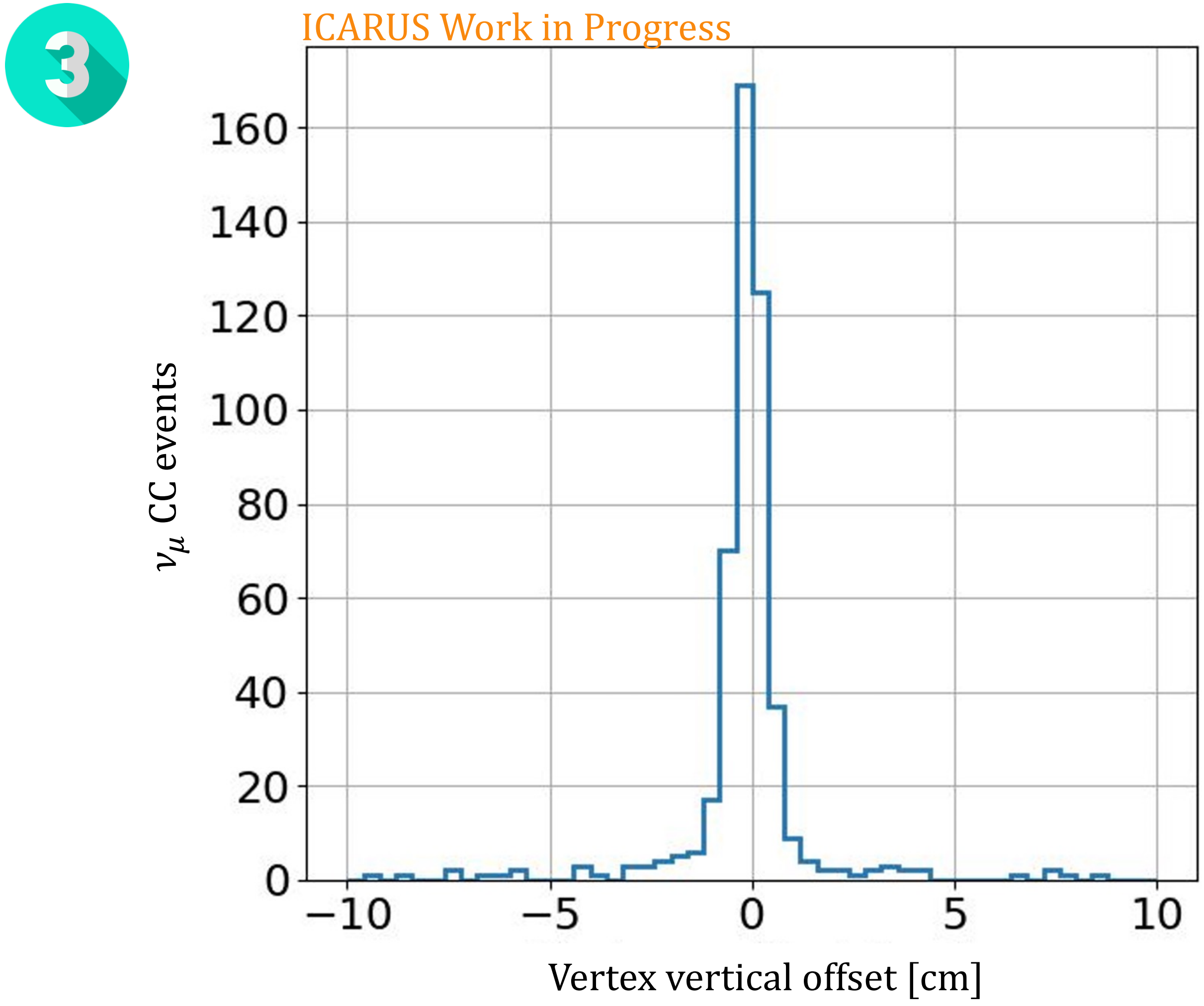



- $\pi^0$ from BNB $\nu_\mu$CC
- $\sim 10\%$ resolution

More details here

# Detector validation

- Visually selected events exploited to evaluate the automatic reconstruction resolution

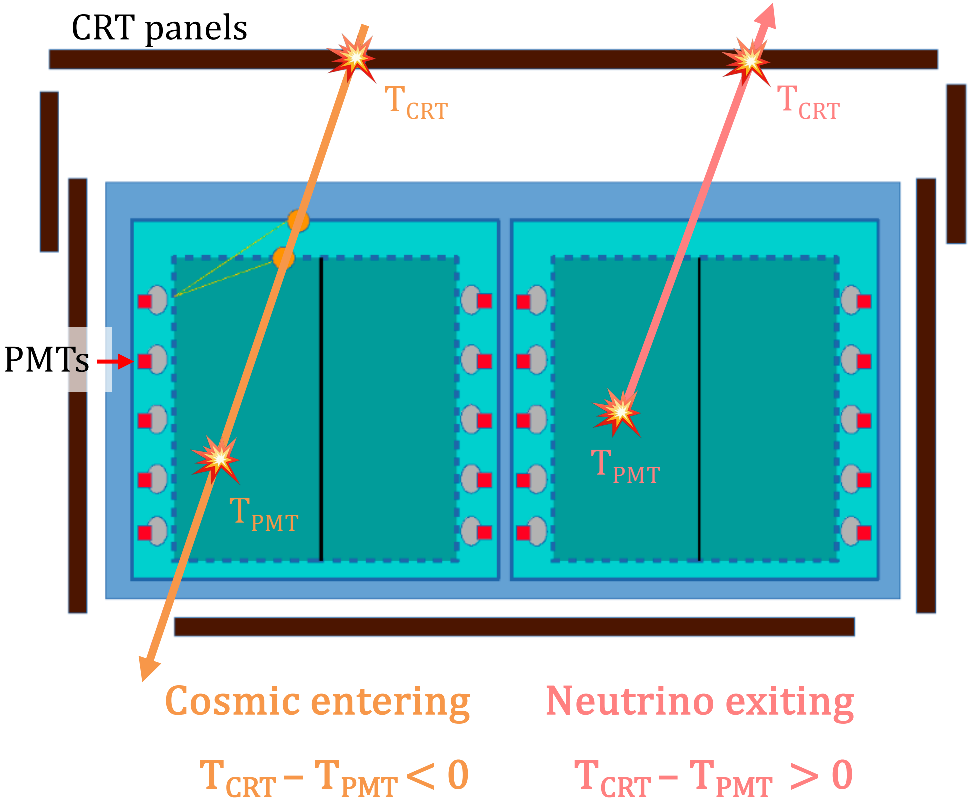


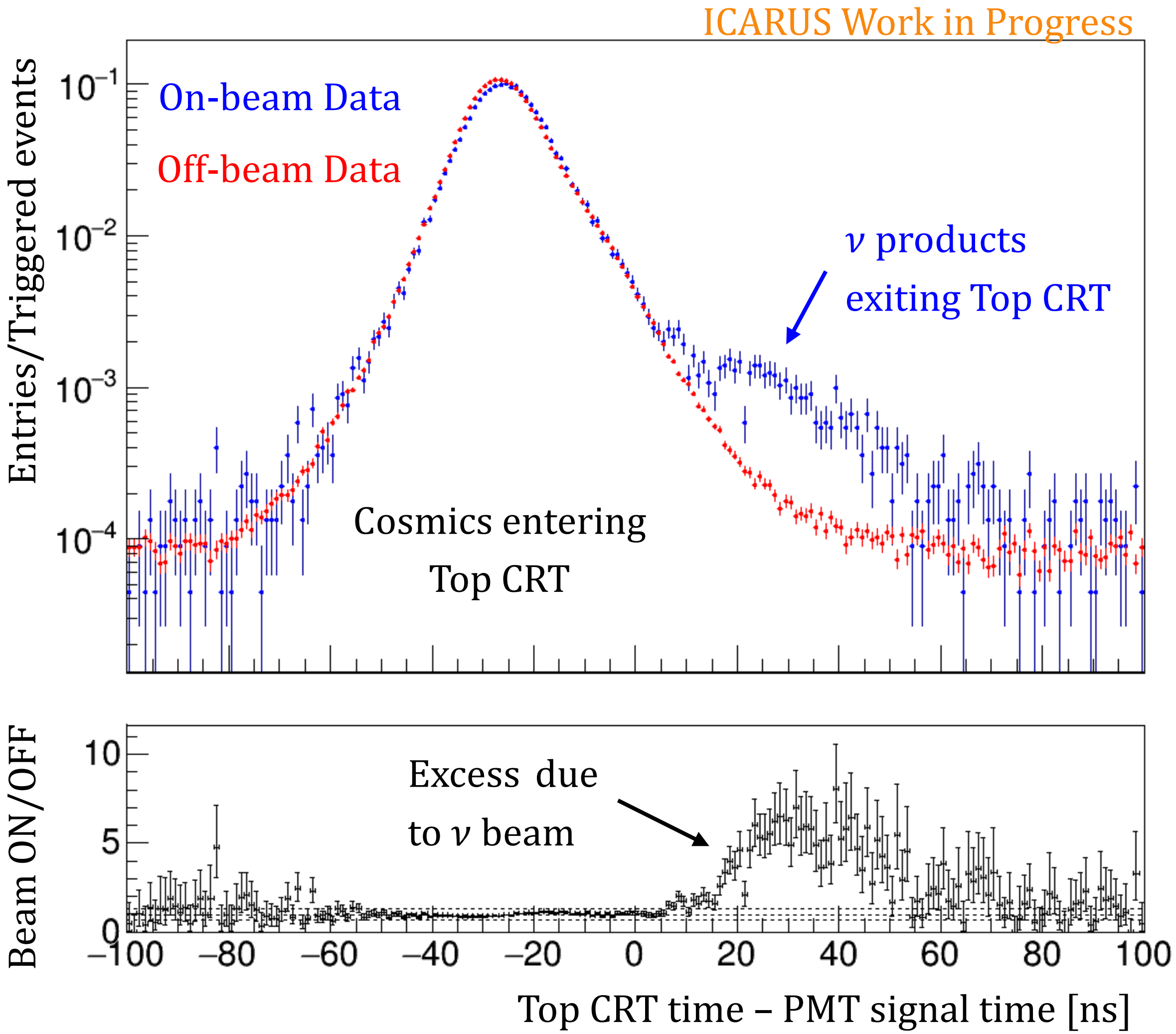

- ~ 500 $\nu_\mu$CC from BNB
- Automatic – visual vertex reconstruction
- few mm resolution !!

# Detector performance

- Effective rejection of incoming cosmics using their time of flight

Leveraging the correlation between CRT and PMT signals

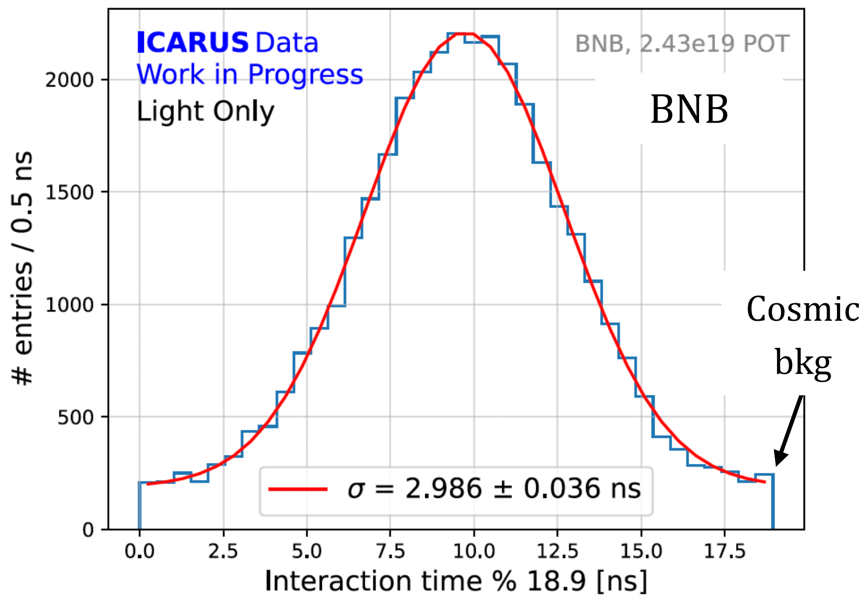


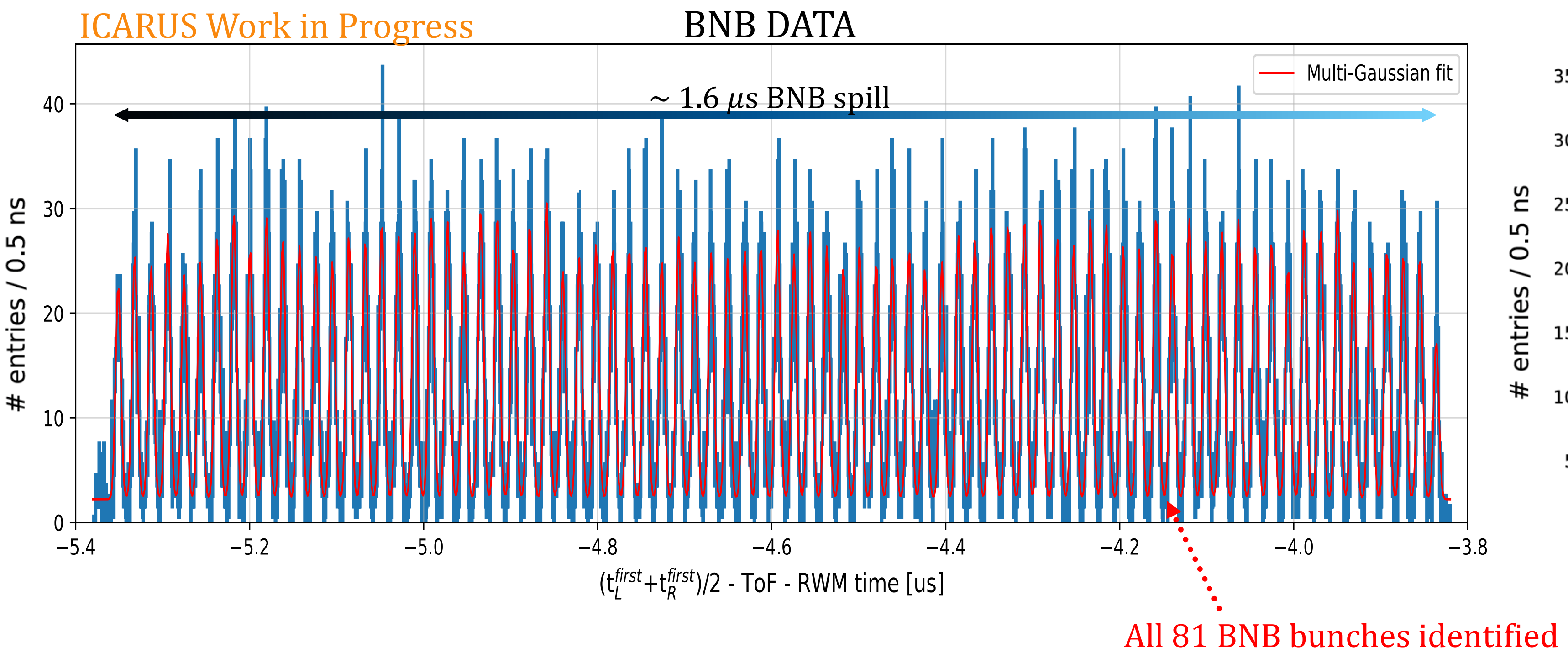



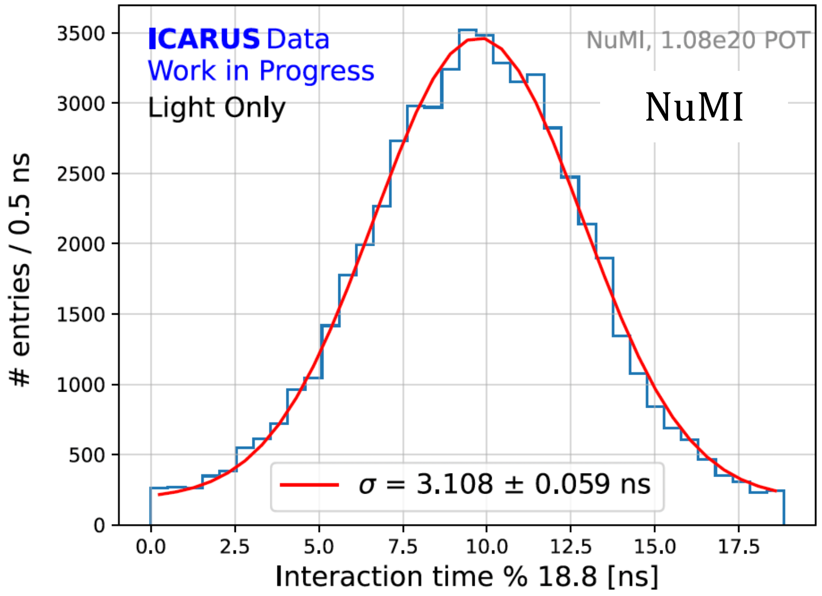
# Detector performance

More details here

- Reconstruction of BNB and NuMI beams bunch structures
  - Rejecting incoming cosmic activity (CRT filter) + $\nu$ time of flight correction
  - Using light information only
    - Charge information expected to improve resolution
  - $\nu$ event time wrt proton beam extraction time (RWM counters)




*Resistive Wall Monitors (RWM)

# Status of ICARUS physics program

- Before the start of near-far joint operation, ICARUS standalone physics program includes

01 $\nu_\mu$ disappearance investigation with BNB beam

$\nu_e$ disappearance studies leveraging the NuMI beam will follow

Event selection ready and validated

02 $\nu-\text{Ar}$ cross section measurements and software optimization of reconstruction & identification tools with NuMI beam

within DUNE’s interest energy range

Selection ready and sidebands studied for a subset of data

03 Search for sub-GeV Beyond Standard Model (BSM) signatures

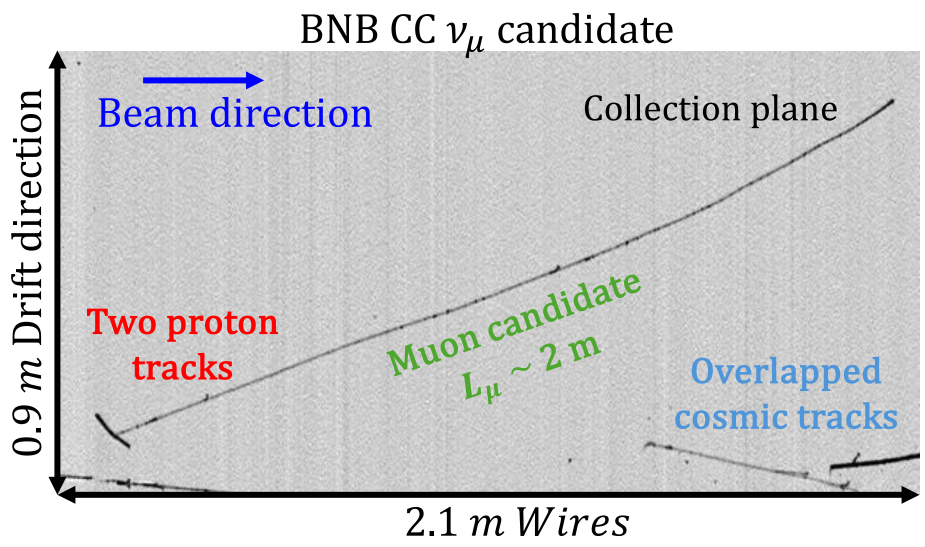
Exploiting off-axis NuMI beam

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

# $\nu_\mu$ CC event selection

- Fully contained $\nu_\mu$ CC events with 1 muon + N protons are studied

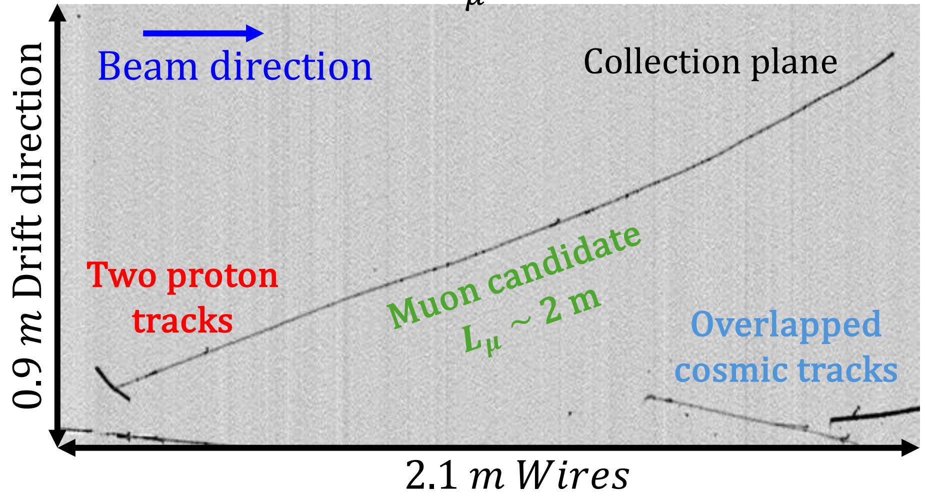
  - TPC track associated with PMT light and no CRT signal inside the beam spill window
  - A muon ($L_\mu > 50$ cm)
  - At least 1 proton $L_p > 2.3$ cm ($E_k > 50$ MeV)
  - Correctly identified by the PID tool (based on dE/dx)
  - Fully contained particles
  - no additional $\pi$ or $\gamma$'s



# $\nu_\mu$ CC event selection

- Fully contained $\nu_\mu$ CC events with 1 muon + N protons are studied
  - TPC track associated with PMT light and no CRT signal inside the beam spill window
  - A muon ($L_\mu > 50$ cm)
  - At least 1 proton $L_p > 2.3$ cm ($E_k > 50$ MeV)
  - Correctly identified by the PID tool (based on dE/dx)
  - Fully contained particles
  - no additional $\pi$ or $\gamma$'s

BNB CC $\nu_\mu$ candidate

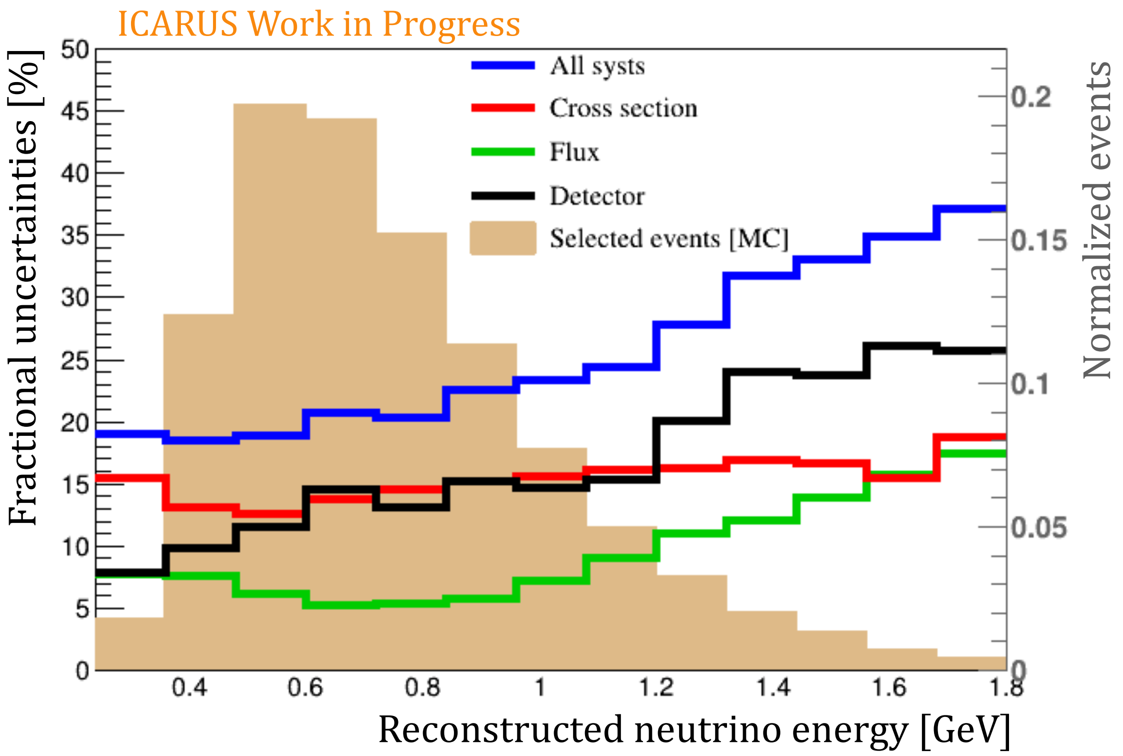



- Two independent reconstruction approaches:
  - Pandora patter recognition algorithm
  - Machine learning - SPINE

- Cosmic backgrounds below 1%
- Validation through visual studied $\nu$
- Event kinematic by range measurements

# $\nu_\mu$ CC event selection - Systematics

- Systematics are evaluated comparing calibrated vs uncalibrated MC samples




- Kinematic variables might help reducing cross section systematics
- Cancellations in the joint SBN analysis:
  - cross section and flux uncertainties
  - common detector systematics
- Simulation improvements ongoing to reduce Data-MC discrepancies

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

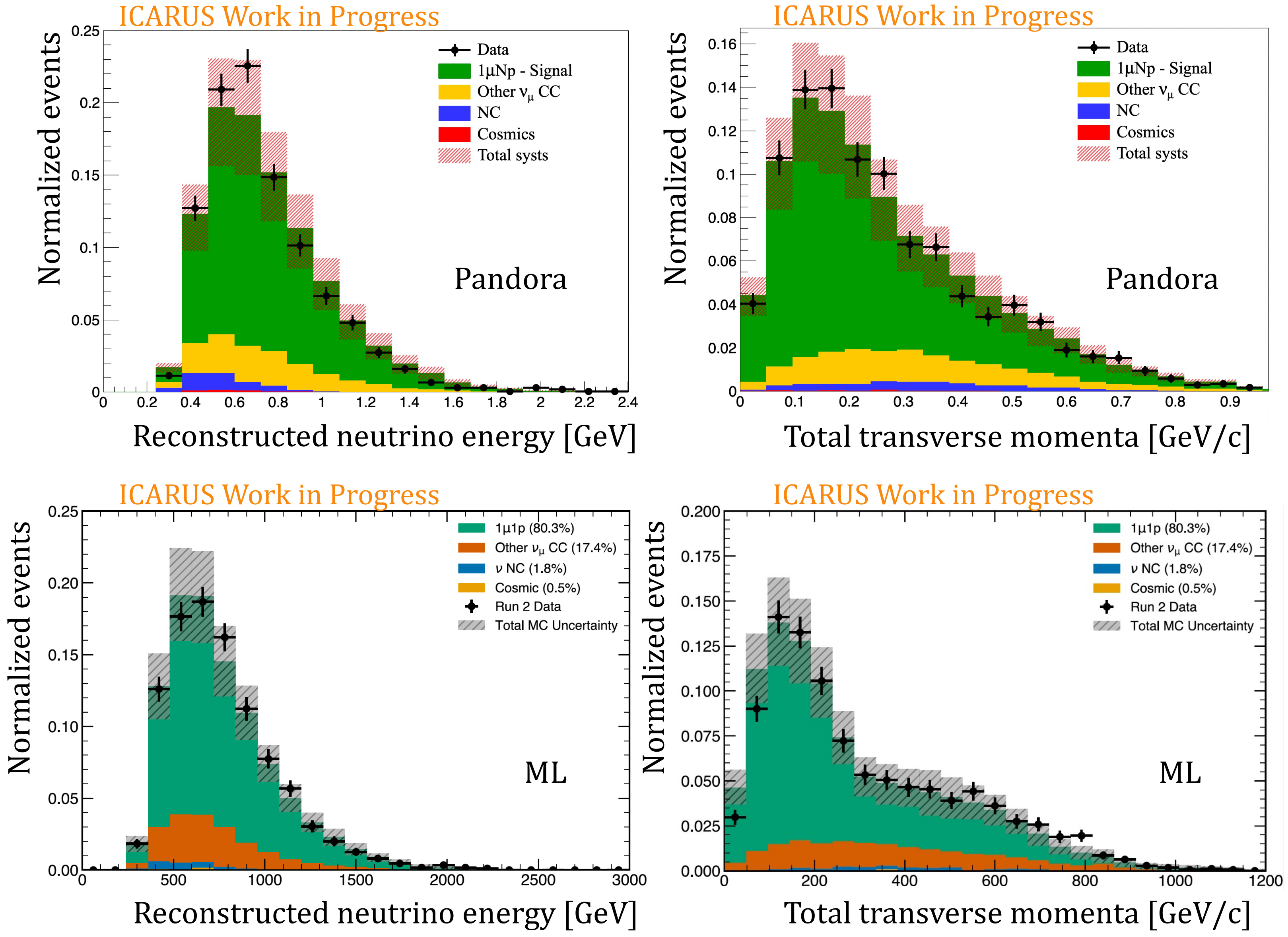
# 01 $1\mu$Np selection – first results BNB

- Data-MC agreement in 10% of Run-2 unblinded data

| | Pandora | SPINE |
|---|---|---|
| Efficiency | 50% | 75% |
| Purity | 80% | 80% |
| *Total events | 34 k | 47 k |

- Next steps:
  - Enlarge control sample
  - Unblind full dataset
  - Single detector oscillation fit

*Considering Run 1-2-3 POT

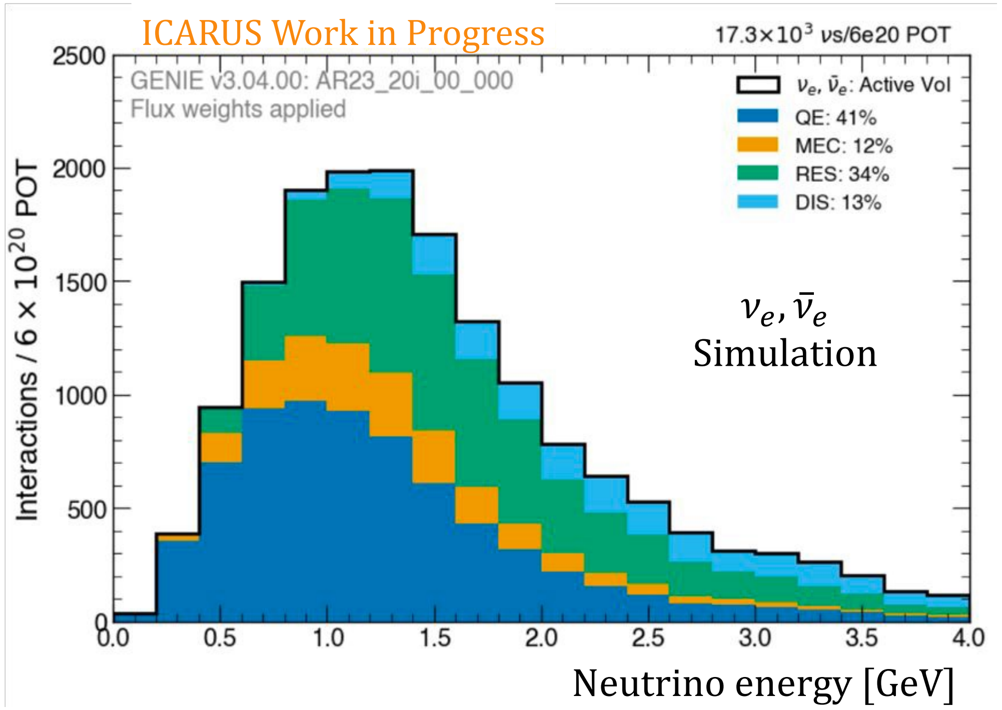


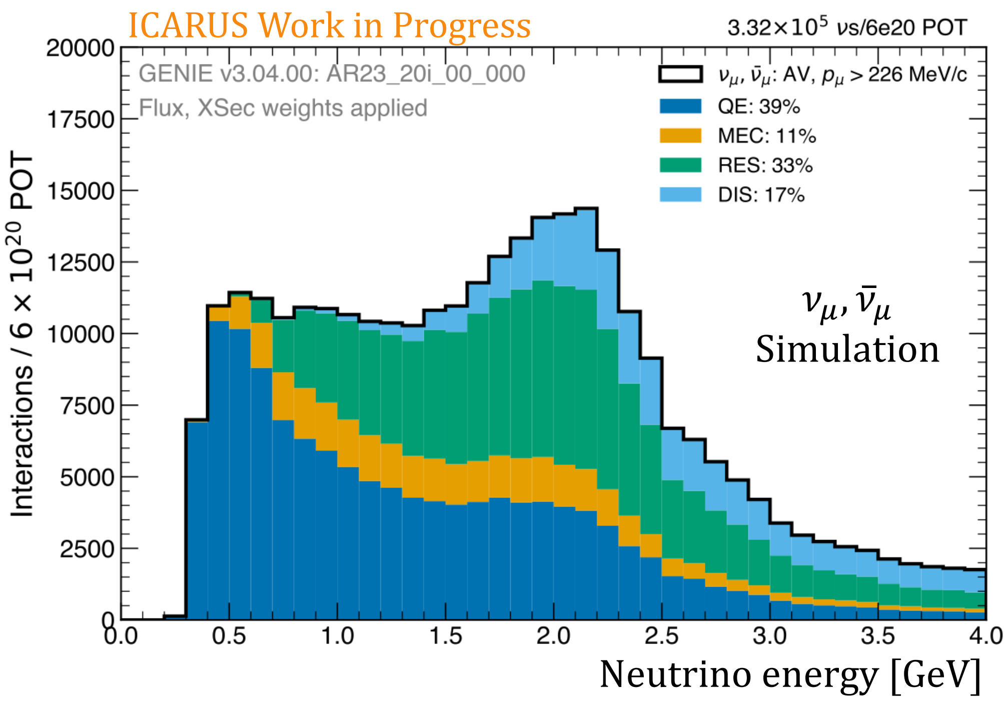
# Interactions @ ICARUS

- Cross section measurements thanks to NuMI high statistics

  332 k $\nu_\mu$CC and 17 k $\nu_e$CC interactions in $6 \cdot 10^{20}$ POT

- Available data $\sim 3.42 \cdot 10^{20}$ POT




More details here

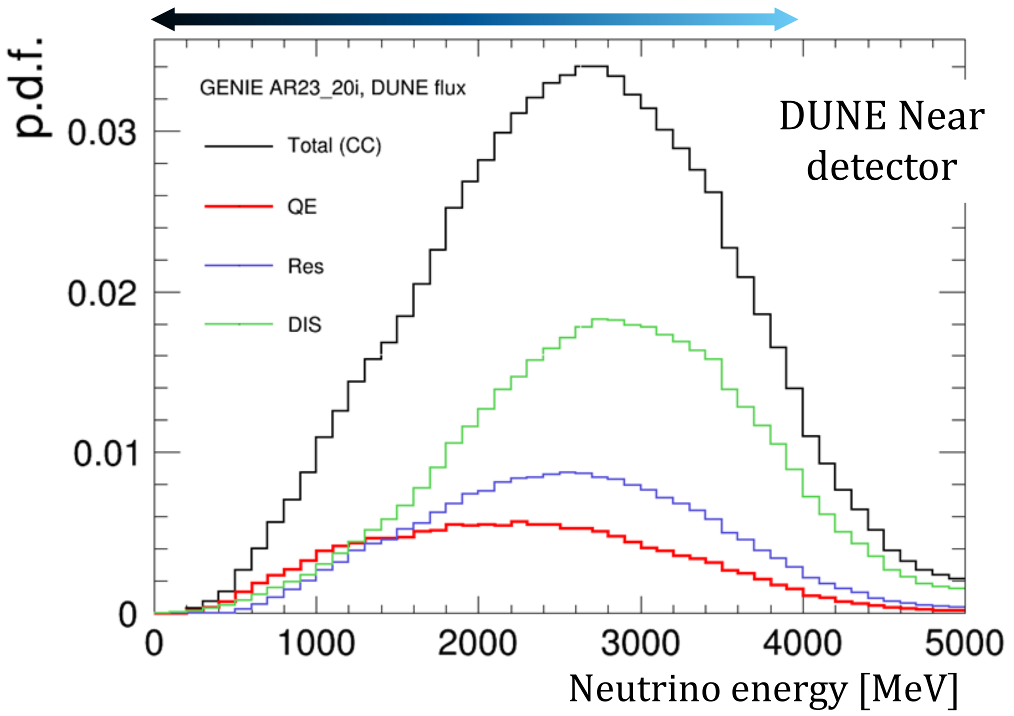
# 02 Interactions @ ICARUS

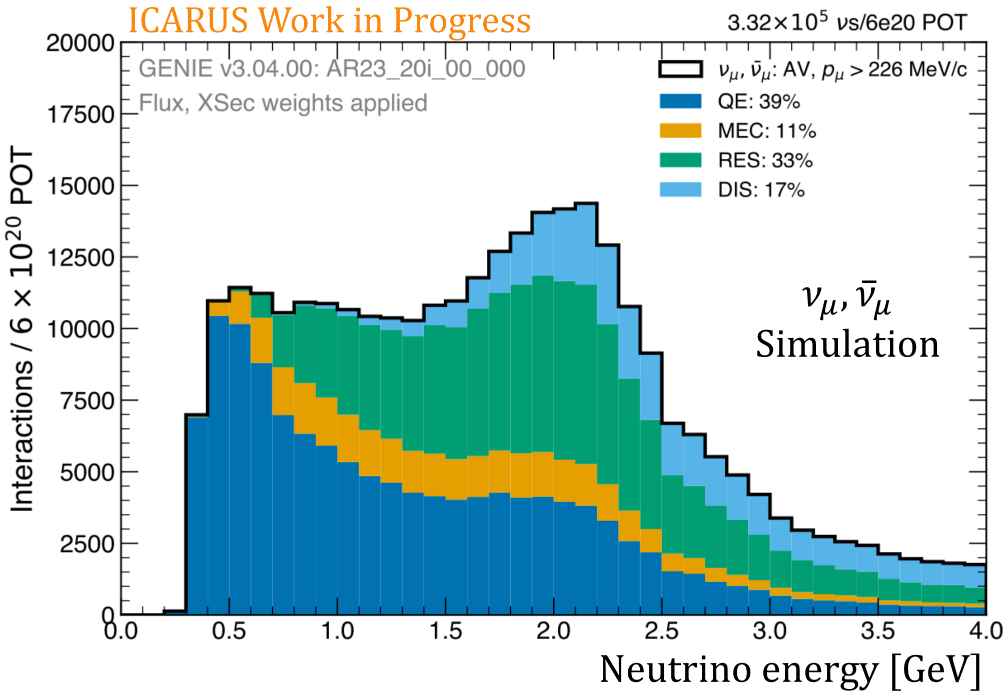
- Cross section measurements thanks to NuMI high statistics

  ➔ 332 k $\nu_\mu$CC and 17 k $\nu_e$CC interactions in $6 \cdot 10^{20}$ POT

- Available data ~ $3.42 \cdot 10^{20}$ POT

- Relevant overlap between ICARUS and DUNE energy spectrum



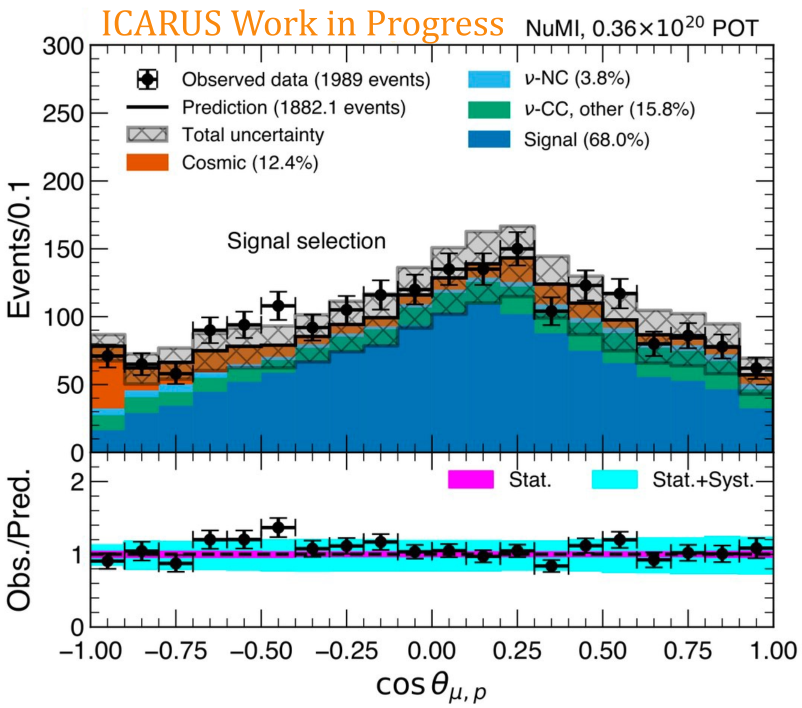

More details here

# 1$\mu$Np0$\pi$ selection - NuMI

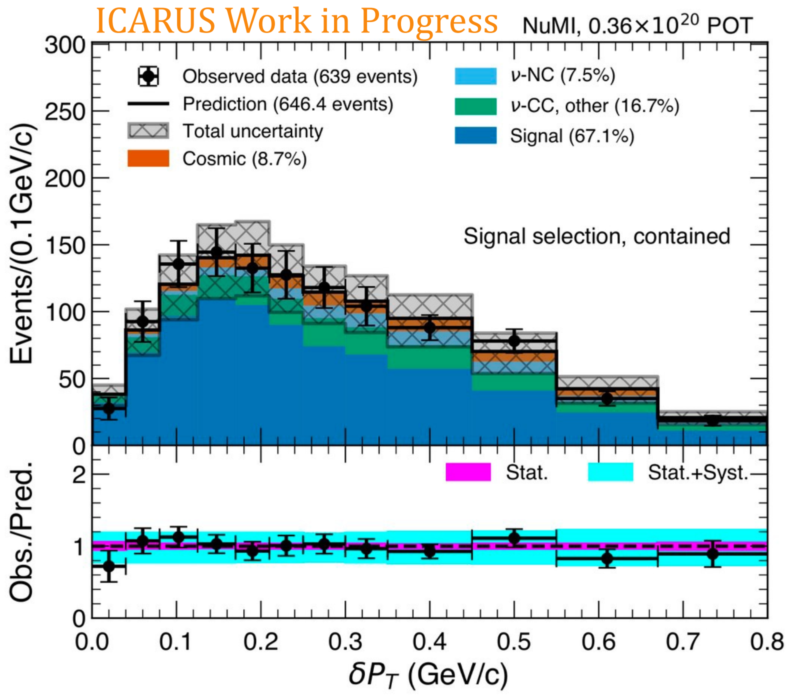
- Targeting 1$\mu$Np0$\pi$ topology

Enriched in quasi-elastic and 2p2h interactions

Flux, cross section and detector systematics included




- Signal definition
  - One $\mu$ with $p_\mu > 0.226$ GeV/c
  - At least one proton with $p_\mu \in [0.4, 1]$ GeV/c
  - no additional $\pi^\pm$ or $\pi^0$

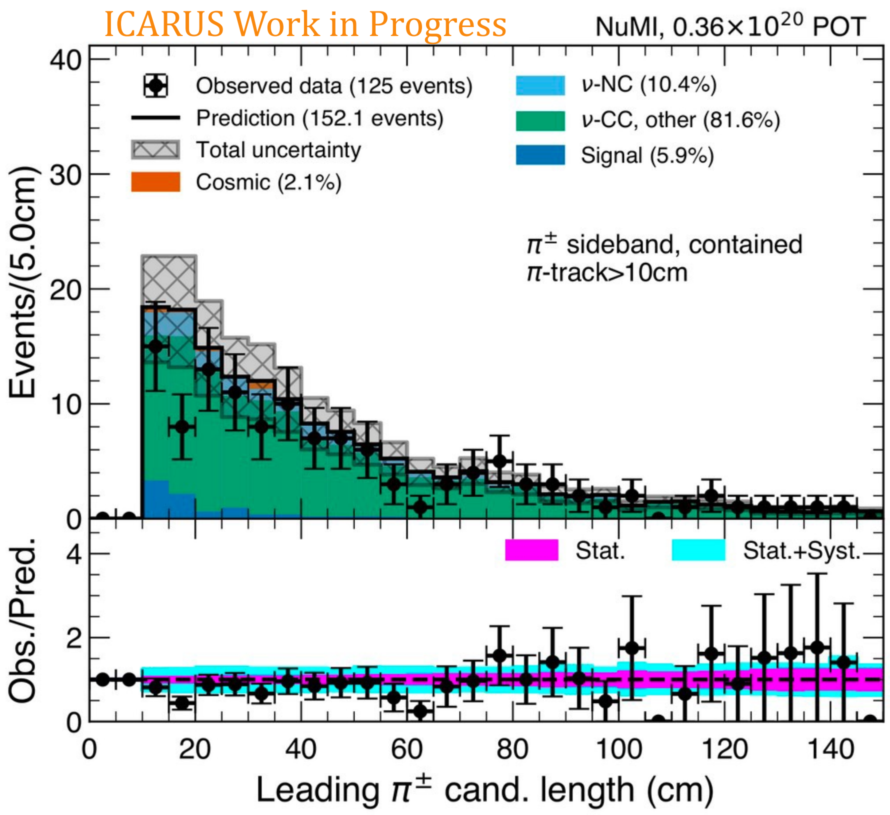


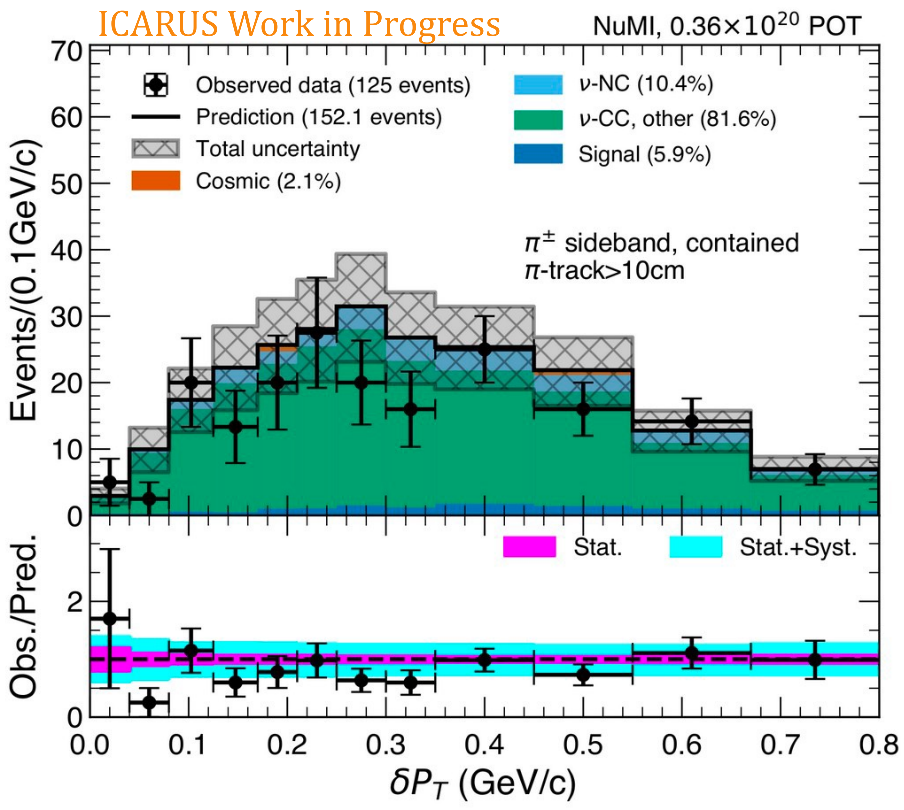

Angles and transverse kinematic variables as a proxy for initial and final state information

- Using 15% of Data

# $\pi^{\pm}$ control sample

- Major background: undetected or misidentified pions
- Control sample studied requiring two muon-like tracks
- Good agreement between 15% data-MC

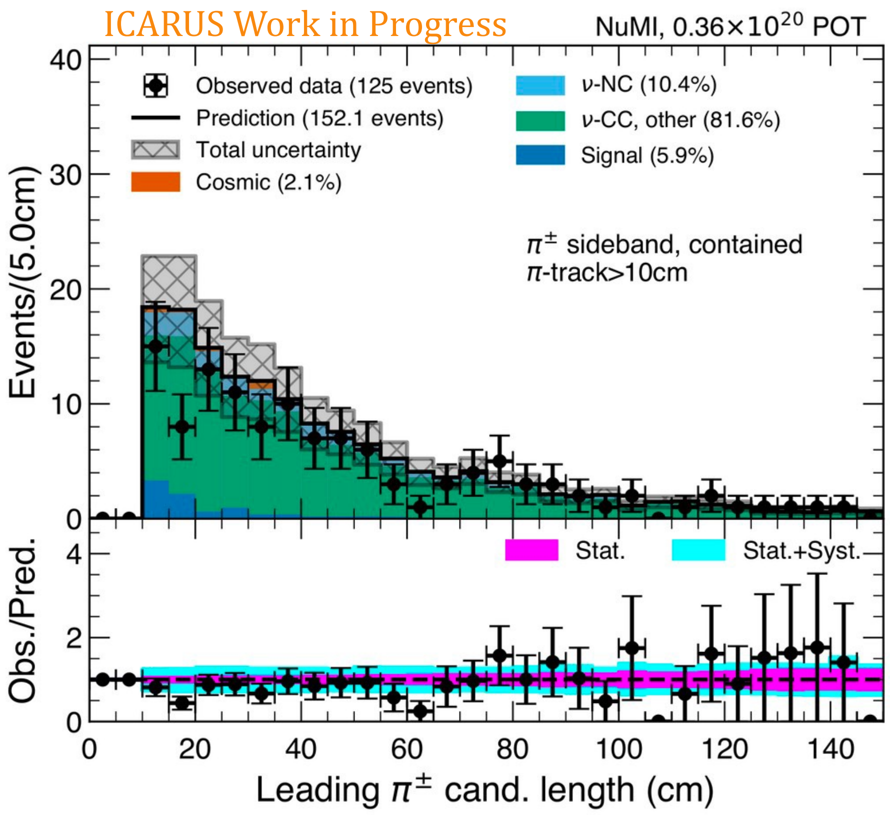


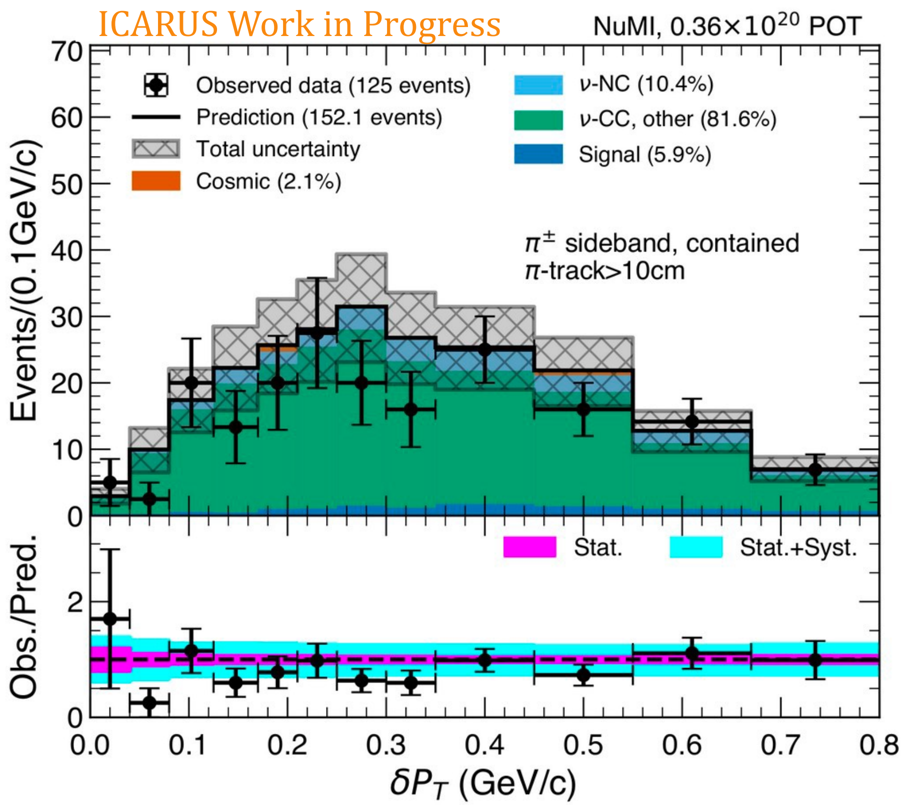



# $\pi^{\pm}$ control sample

- Major background: undetected or misidentified pions
- Control sample studied requiring two muon-like tracks
- Good agreement between 15% data-MC


Ready to study 100% data sideband



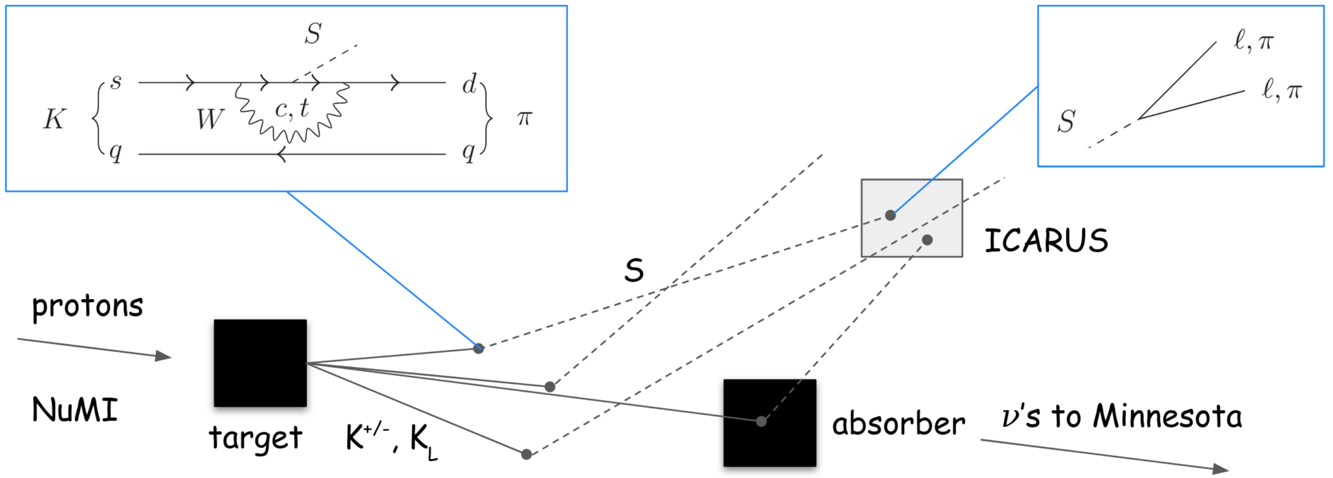



# 03 BSM Physics - NuMI

- Rich BSM research program within the off-axis NuMI beam
- Explored 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

Phenomenology diagram of HPS at ICARUS

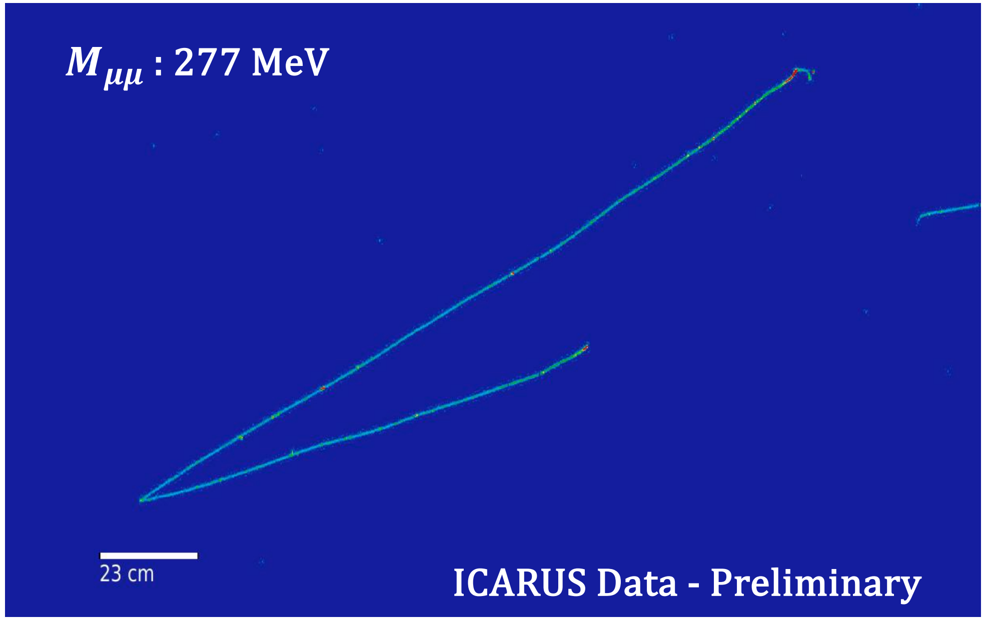


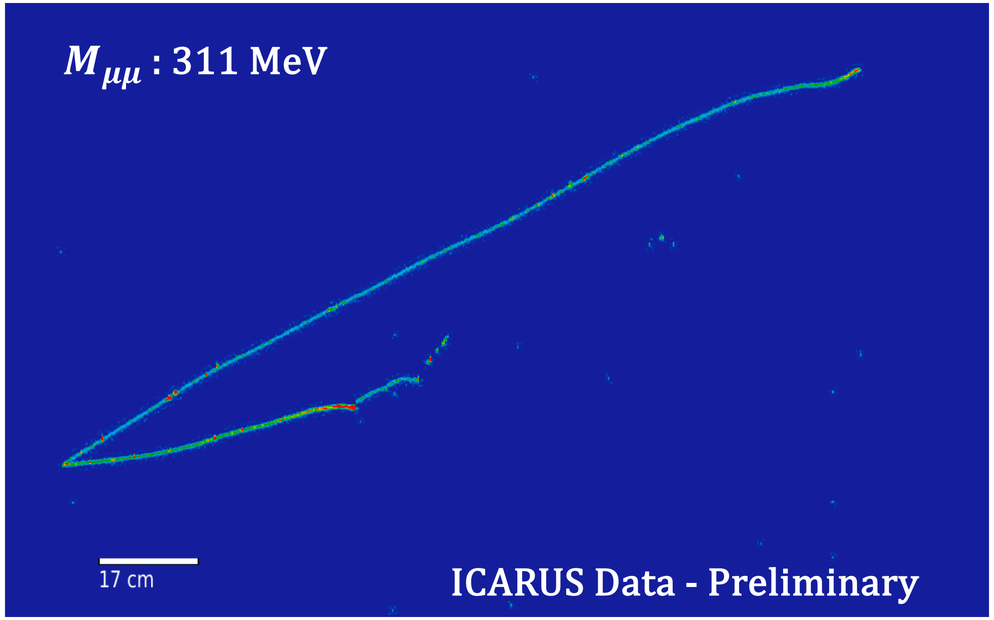

First analysis completed!

Signal: contained di-muon final state topology

# HPS and ALP search results

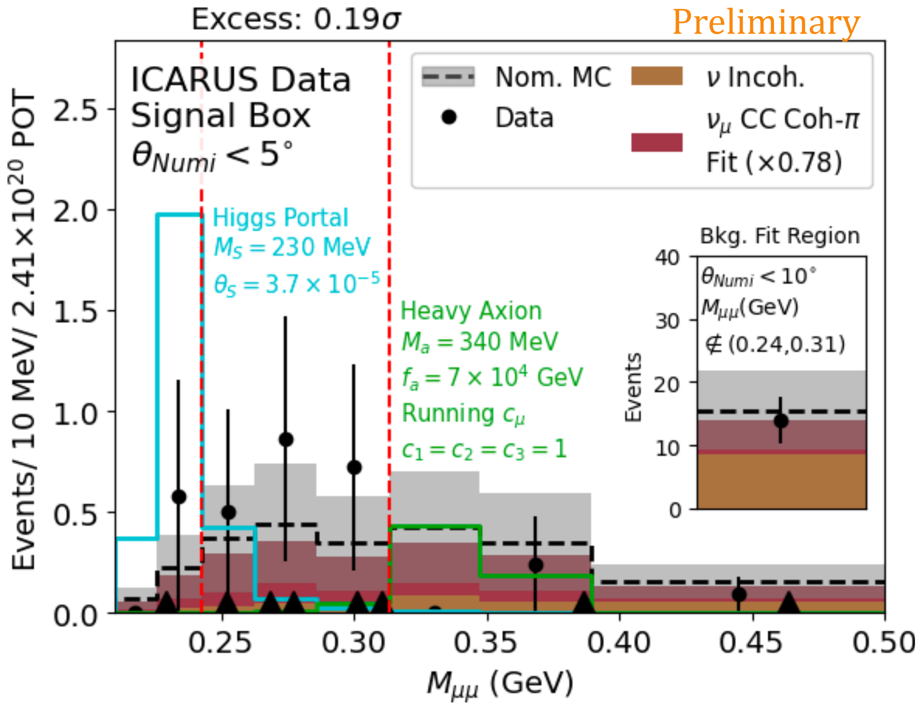
- The Scalar mass ($M_{\mu\mu}$) peak is reconstructed using the two stopping muons
- Signal is expected at small angle to the beam direction $\theta_{\mathrm{NuMI}} < 5°$
- 8 candidate events were found in all ICARUS Run-2 NuMI data

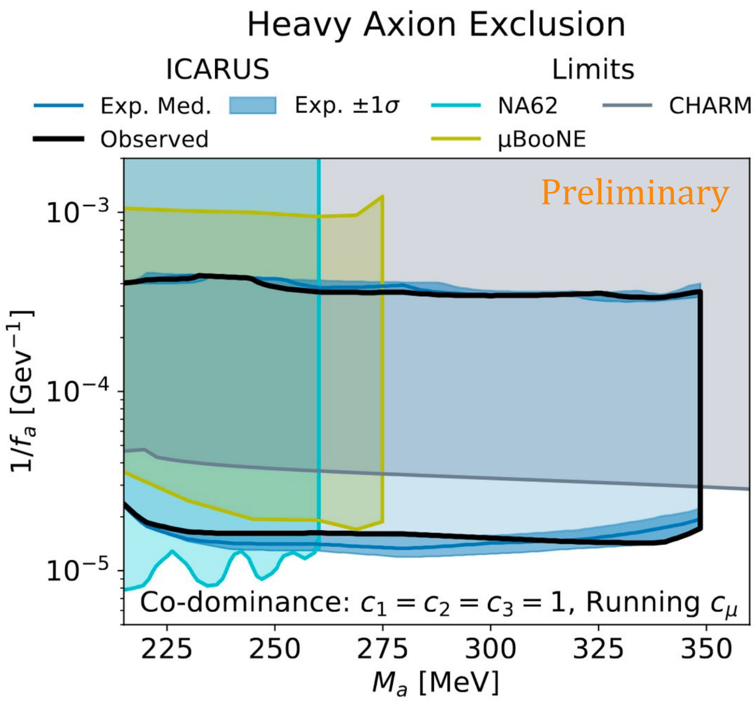


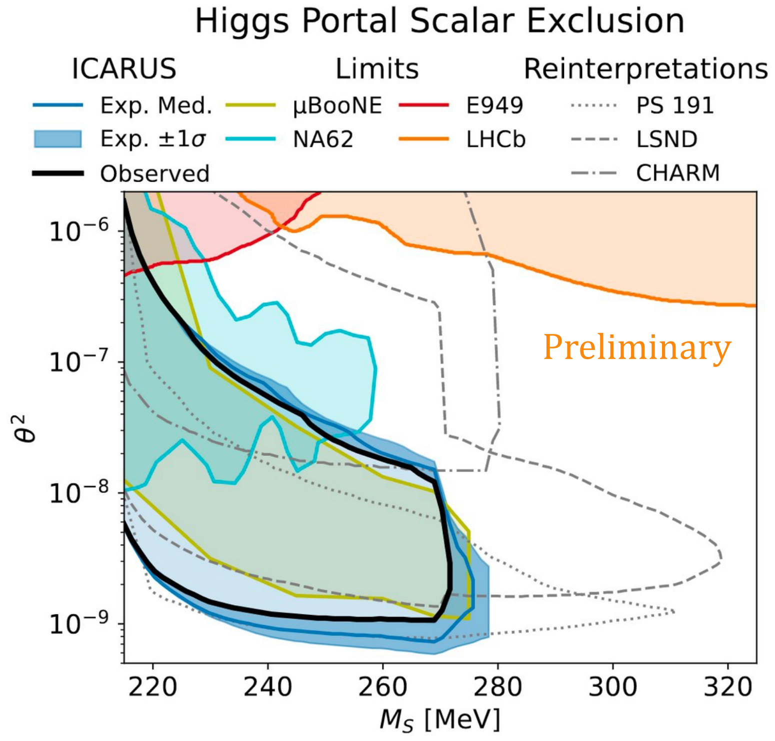



# HPS and ALP search results

- The result is compatible with **no** new physics signal (0.19 $\sigma$)
  - Background: 8 events from $\nu_\mu$ CC coherent pion production
- Exclusion contour plots (90% C.L.) and paper in progress




*Full systematic treatment included

More details here

# Conclusions

- ICARUS is smoothly running in physics mode since June 2022

- Detector performance evaluated with cosmic muons and protons from $\nu$
  - Huge effort to calibrate and model detector response → Papers available in arXiv

- ICARUS well on the way to first physics results
  - Single detector $\nu_\mu$ disappearance with BNB beam
  - $\nu_\mu - Ar$ cross-section measurements with NuMI beam

  → Ready to enlarge control samples

  - Sub-GeV dark matter candidates with NuMI beam → Completed contained di-muon search

SOON Looking forward for the SBN joint analysis!

# Conclusions


- ICARUS is smoothly running in physics mode since June 2022
- Detector performance evaluated with cosmic muons and protons from $\nu$
  - Huge effort to calibrate and model detector response → Papers available in arXiv

- ICARUS well on the way to first physics results
  - Single detector $\nu_\mu$ disappearance with BNB beam
  - $\nu_\mu -$ Ar cross-section measurements with NuMI beam

  → Ready to enlarge control samples

  - Sub-GeV dark matter candidates with NuMI beam → Completed contained di-muon search


Looking forward for the SBN joint analysis!

# ICARUS Collaboration at SBN

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

Spokesperson: C. Rubbia, GSSI

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]

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

1. Brookhaven National Lab., USA
2. CERN, Switzerland
3. CINVESTAV, Mexico,
4. Colorado State University, USA
5. Fermi National Accelerator Lab., USA
6. INFN Bologna and University, Italy
7. INFN Catania and University, Italy
8. INFN Genova and University, Italy
9. INFN GSSI, L'Aquila, Italy
10. INFN LNGS, Assergi, Italy
11. INFN LNS, Catania, Italy
12. INFN Milano, Milano, Italy
13. INFN Milano Bic. and University, Italy
14. INFN Napoli, Napoli, Italy
15. INFN Padova and University, Italy
16. INFN Pavia and University, Italy
17. SLAC National Accelerator Lab., USA
18. Southern Methodist University, USA
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