ICARUS: Status and Outlook

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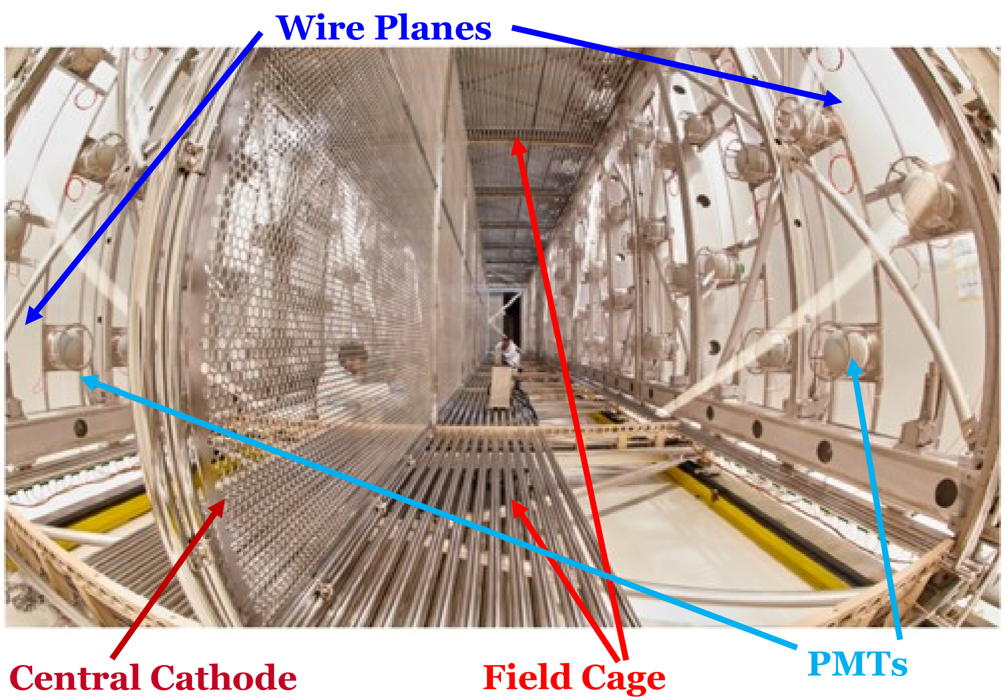
Introduction

- **ICARUS:** far detector of SBN Program @ Fermilab, originally operating at LNGS underground lab at Gran Sasso in Italy (shipped to US in 2018)
- Primary physics goal is to study anomalous neutrino oscillations (e.g. sterile neutrinos) at short baselines (L ~ 600 m) and L/E ~ 1 m/MeV using **BNB**
- Uses liquid argon time projection chamber (LArTPC) technology

<u>Primary Detector Subsystems</u>

- **TPC:** ~54,000 channels across two cryostats (four drift volumes) for imaging neutrino interactions
- **PDS:** 360 PMTs behind anode wire planes (90 per anode) for event triggering/timing w/ light
- **CRT:** top/side cosmic ray tagger panels (scintillator + SiPM readout) for tagging cosmics



Inner View of an ICARUS TPC

ICARUS Collaboration

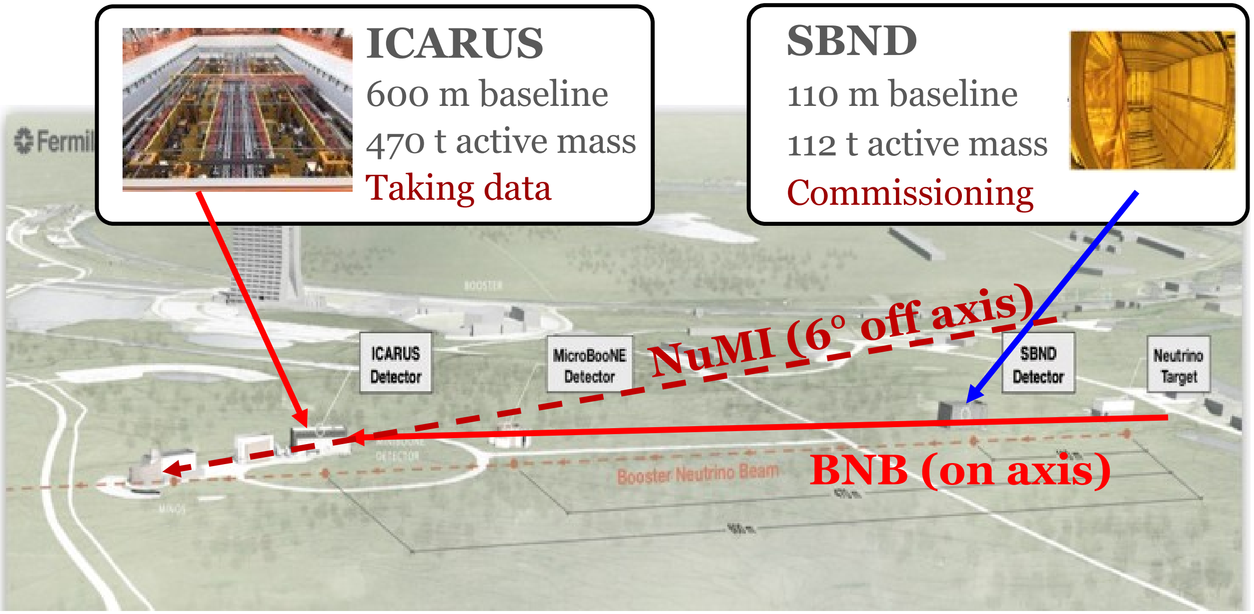
P. Abratenko[19],N. Abrego-Martinez[3], F. Akbar[23], L. Aliaga Soplin[24], M. Artero Pons[15], W.F. Badgett[5], L.F. Bagby[5], B. Baibussinov[15], B. Behera[4], V. Bellini[7], O. Beltramello[2], R. Benocci[13], J. Berger[4], S. Bertolucci[6], M. Betancourt[5], K. Biery[5], M. Bonesini[13], T. Boone[4], 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[23], 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[5], 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]

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

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

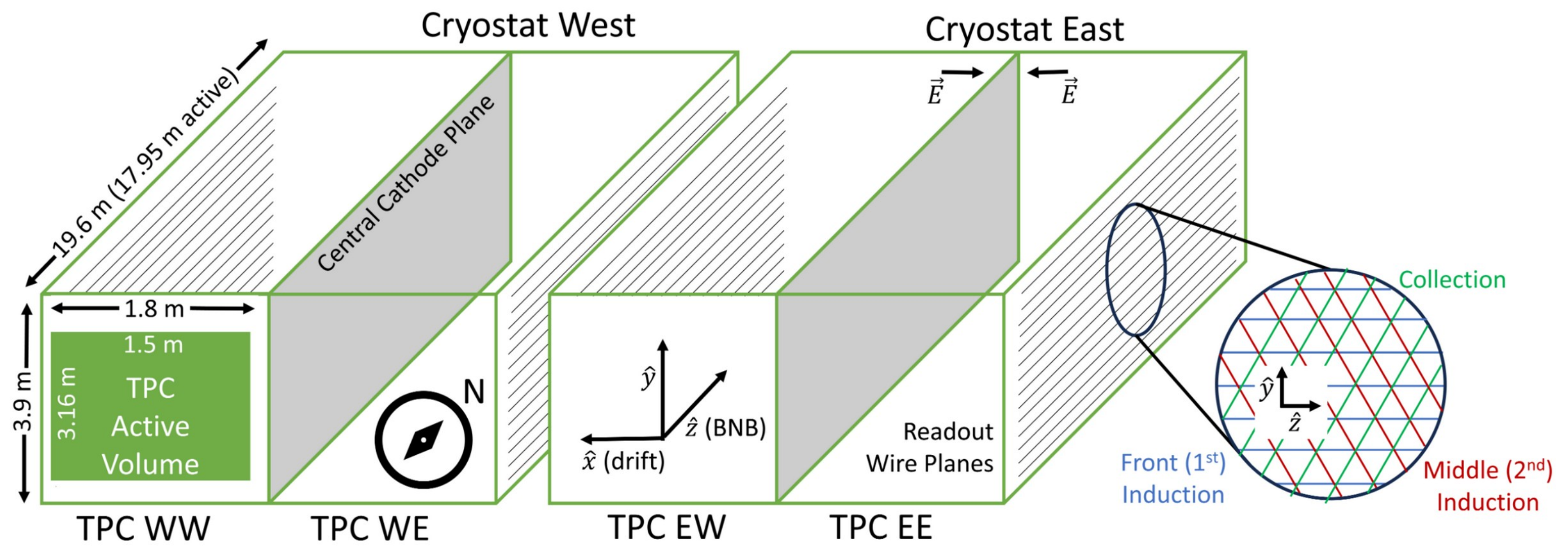
Spokesperson: C. Rubbia, GSSI

ICARUS and SBN Program

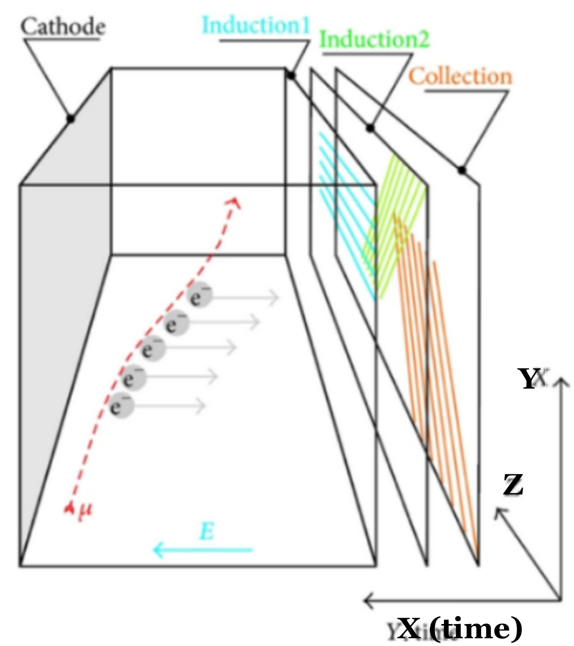


- SBN Program: two LArTPC detectors @ Fermilab on BNB
  - <u>SBND</u>: near detector; provides flux and ν-Ar xsec constraint
  - <u>ICARUS</u>: far detector; measures oscillated neutrino spectrum
- Measure **ν_μ disappearance + ν_e appearance** *at same experiment*
- ICARUS also sees NuMI neutrinos → extra handle on ν-Ar xsec
  - NuMI target, absorber: sources for BSM physics searches

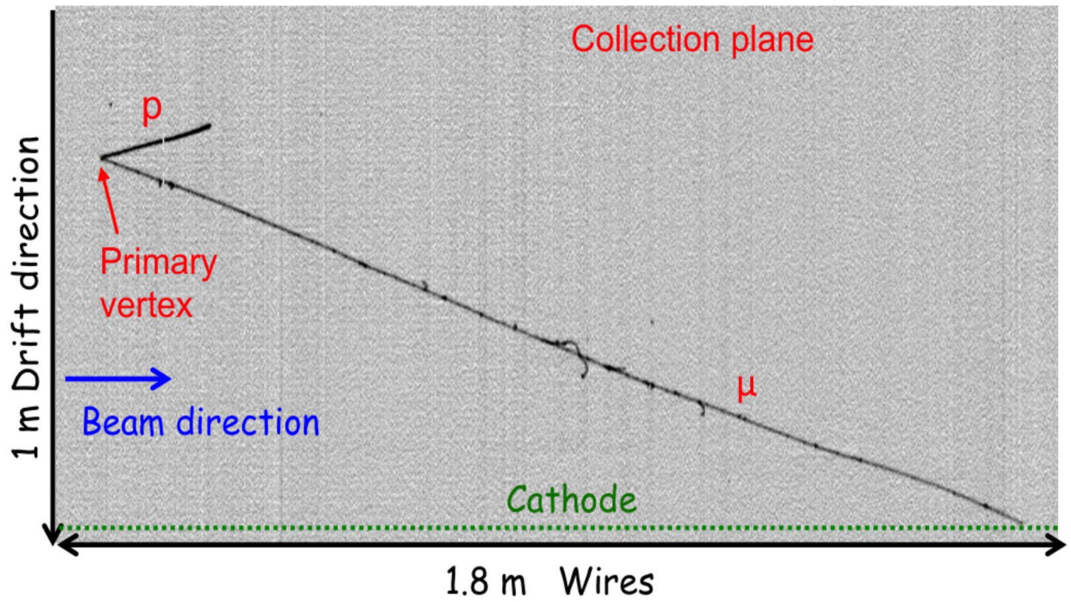
ICARUS LArTPCs

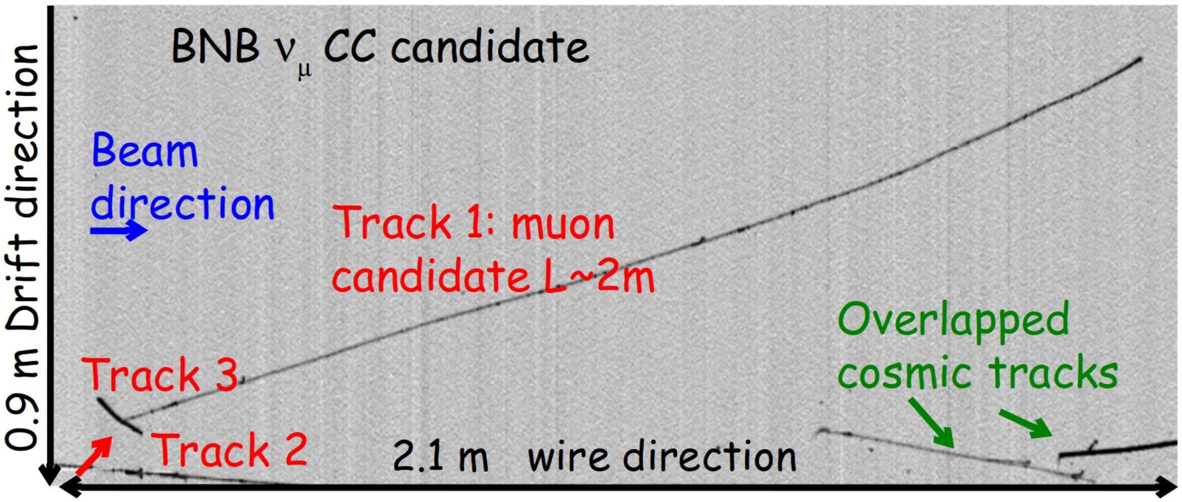


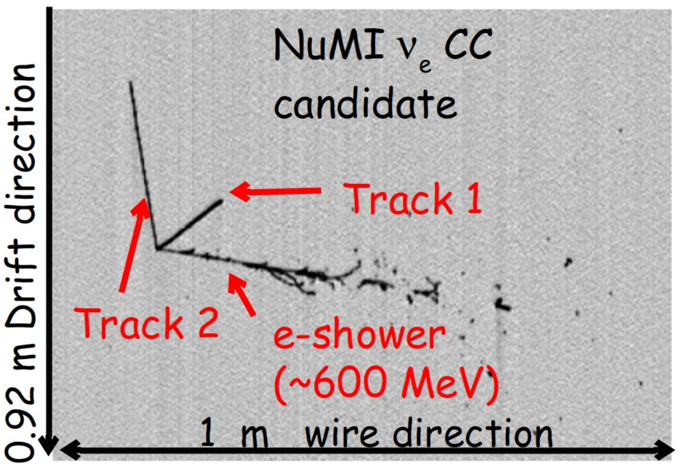
- Three wire planes per anode (two induction, one collection) → image in 3D
- Front induction plane wires horizontal, others @ 60° angles
- 500 V/cm E field, 1.5 m max drift
- Warm front-end electronics (not in LAr like MicroBooNE/SBND)



Imaged Neutrinos @ ICARUS

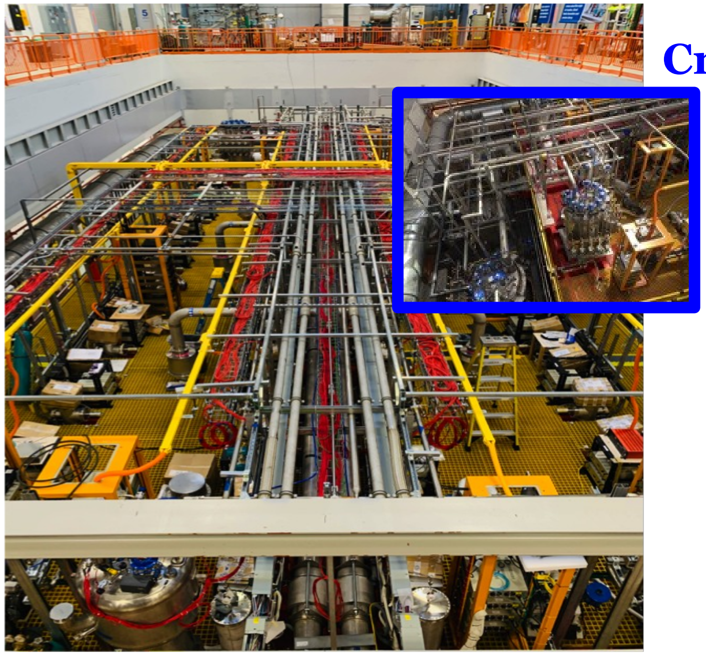






Installation

Detector in Pit Before CRT Installed

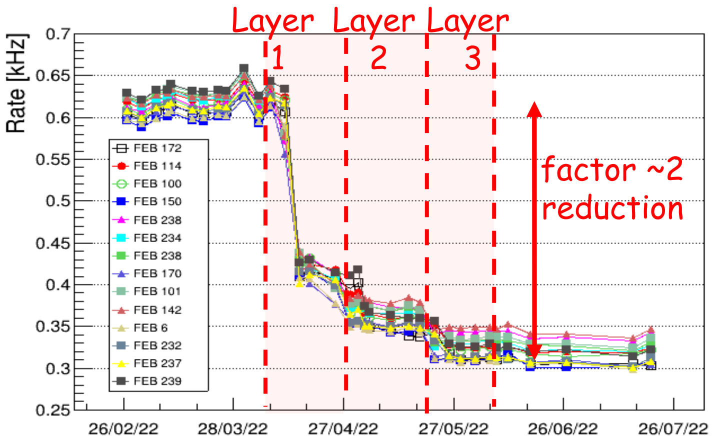


Cryo Plant

- Detector installation: 2018-2020
- CRT installed in 2021-2022
  - ~95% cosmic tagging efficiency

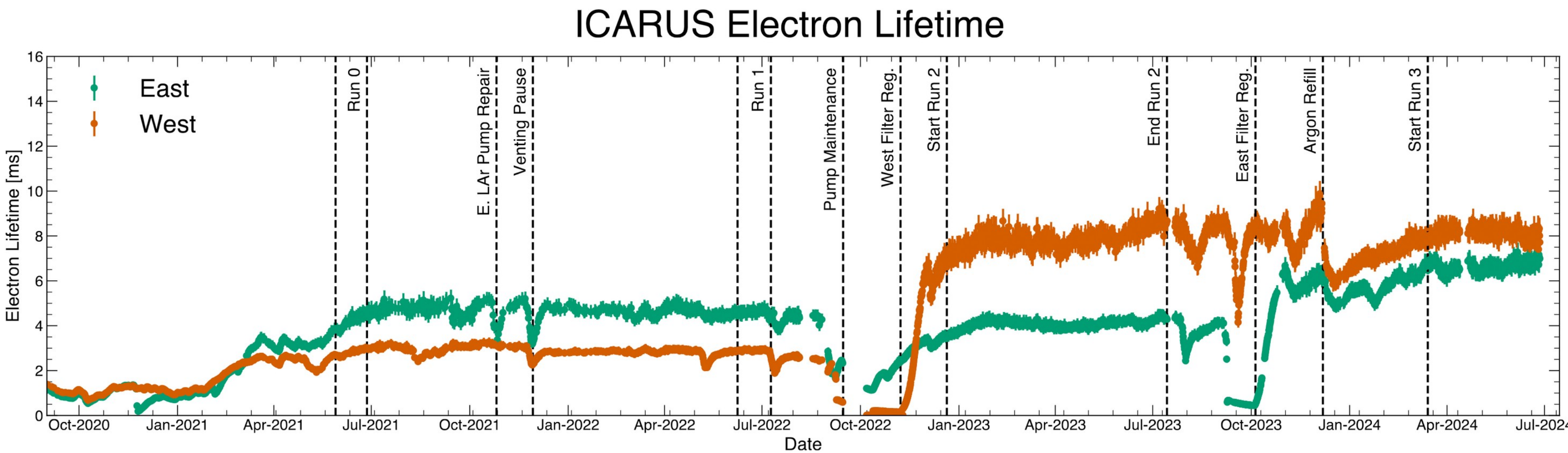
Top CRT

Side CRT

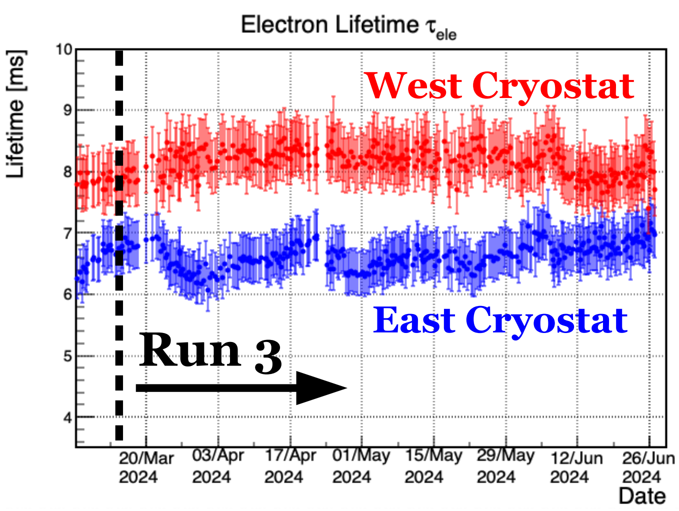


- Concrete overburden (~3 m) for cosmic γ/n suppression

Data-taking @ ICARUS



- Cold commissioning in September 2020
- Started taking physics data in June 2022
- Electron lifetime high enough for quality physics, now in 6-9 ms range (for Run 3)
  - Max charge loss @ cathode: 10-15%
- Run 1/2/3 BNB POT ($\times 10^{20}$): 0.4/2.1/1.4
- Run 1/2/3 NuMI POT ($\times 10^{20}$): 0.7/2.7/2.8 (FHC/FHC/RHC)



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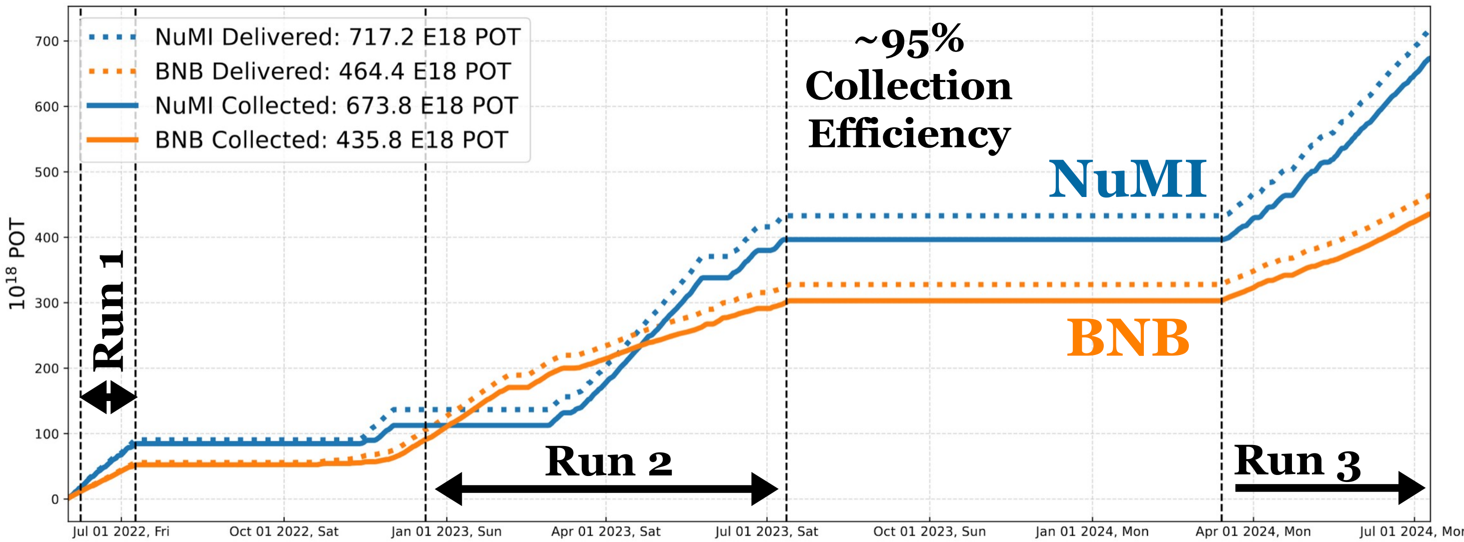

ICARUS Total Projected POT
(Depending on Accelerator Operations)

BNB:
10-14×10²⁰

NuMI:
11-18×10²⁰

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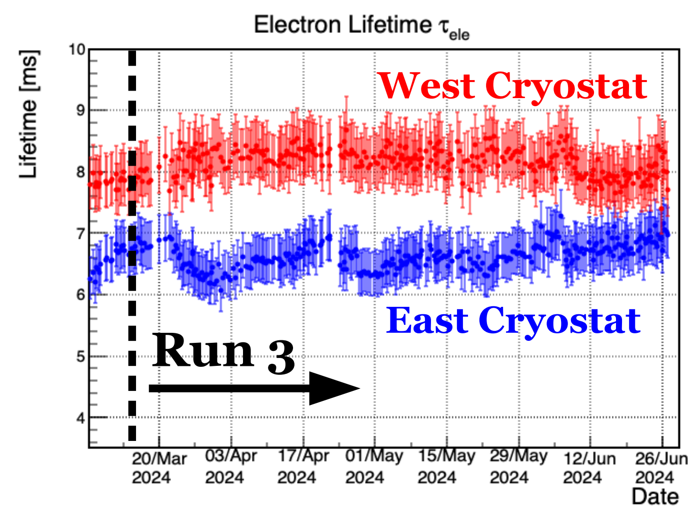
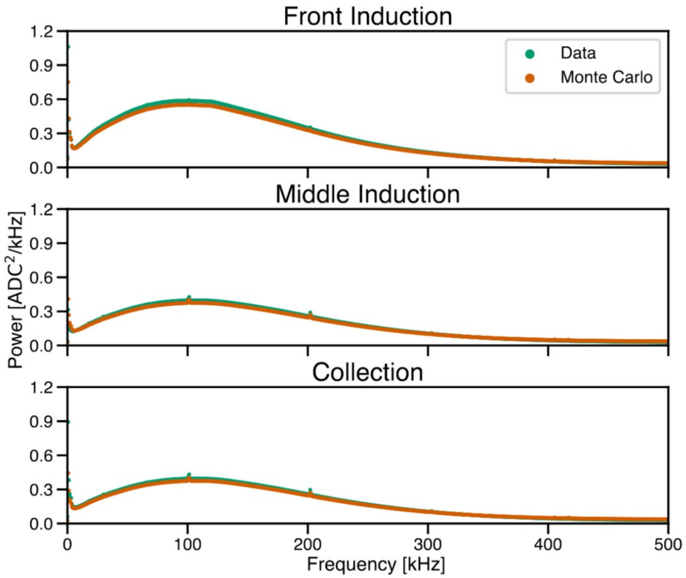
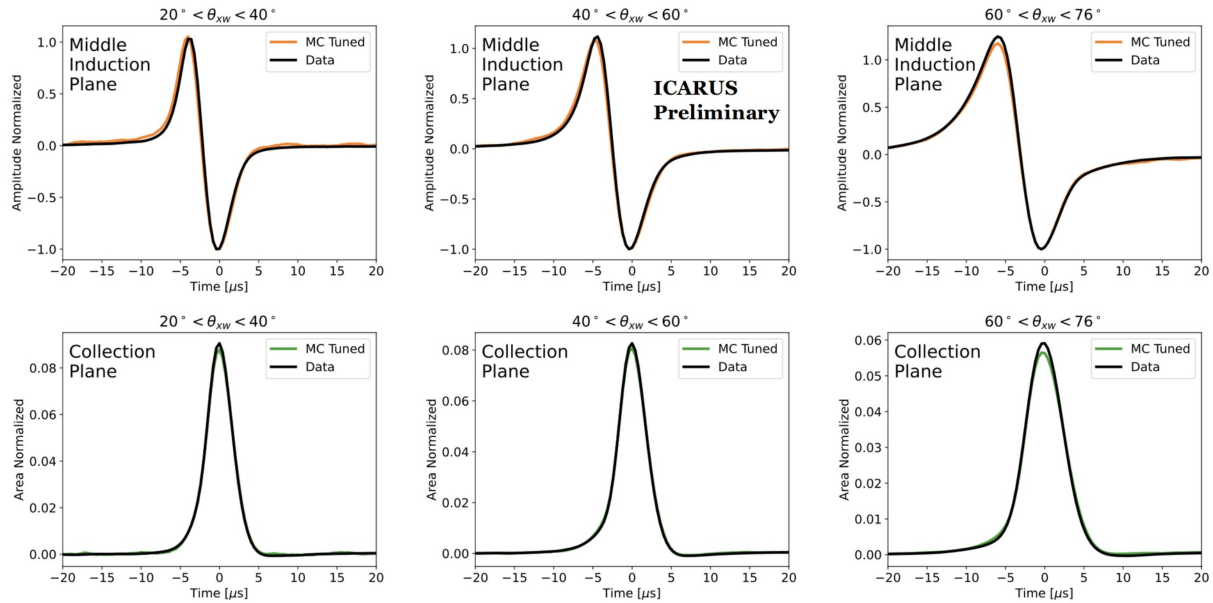


Detector Calibration

TPC Noise FFTs – Data vs. MC



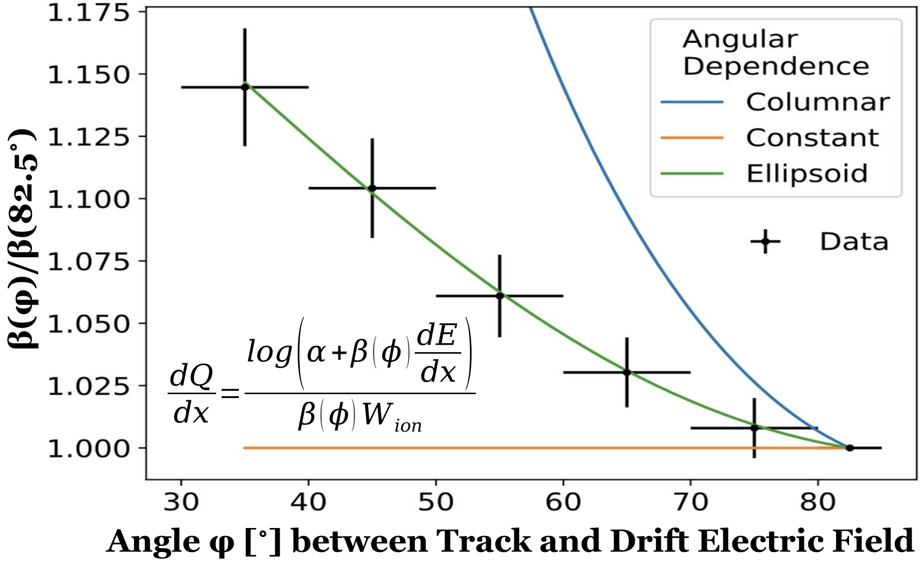
Wire Signal Response (After Calibration) – Data vs. MC



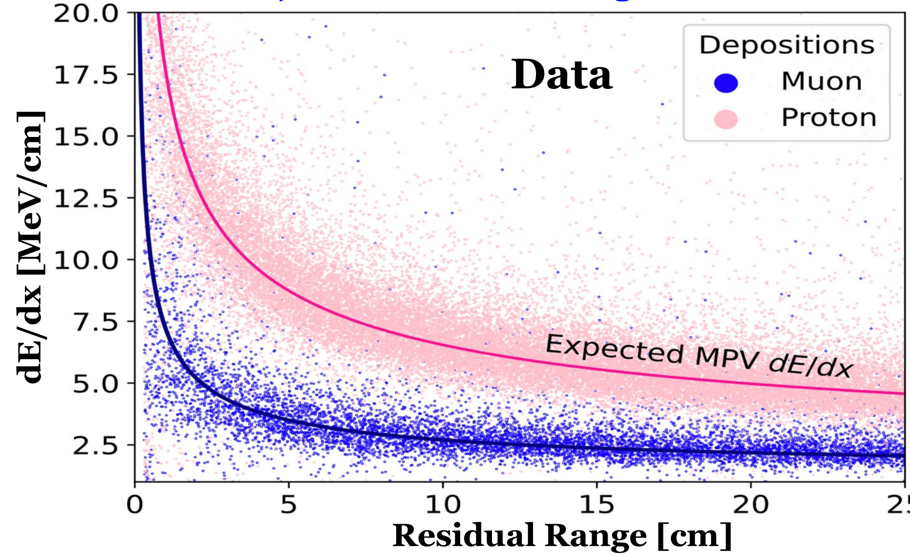
- Tuned noise model and wire signal response in MC simulation using minimum bias data and cosmic muon data, respectively
- Extracted electronics gain factors, electron lifetime correction, and electron-ion recombination correction using cosmic data
- Two forthcoming ICARUS papers describing calibrations
  - Other detector physics publications (e.g. diffusion) also forthcoming

Detector Calibration

Dependence of Recombination on Track Angle



dE/dx vs. Residual Range (for PID)



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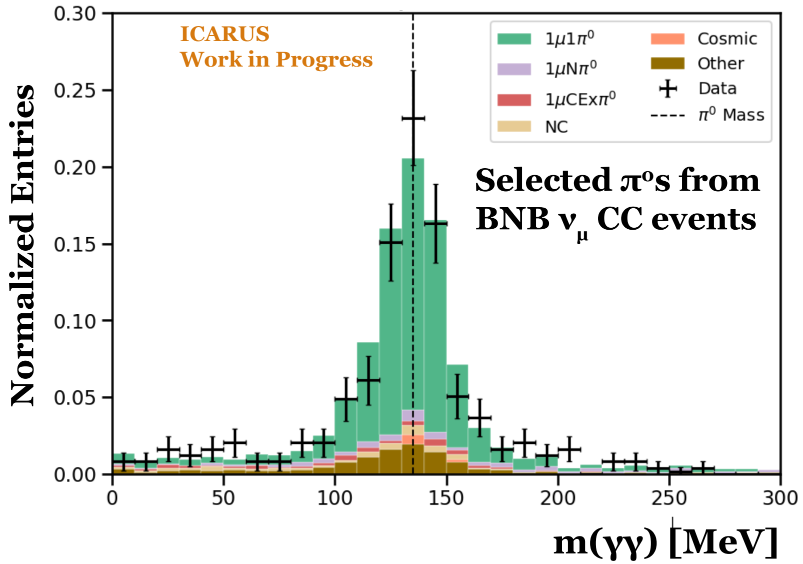
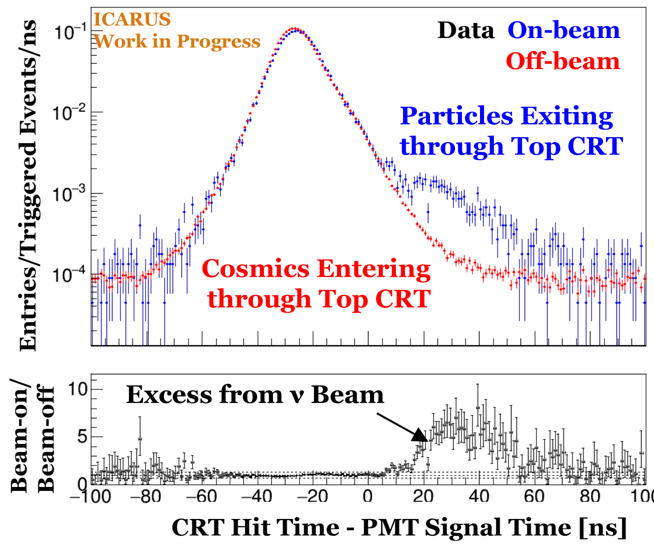
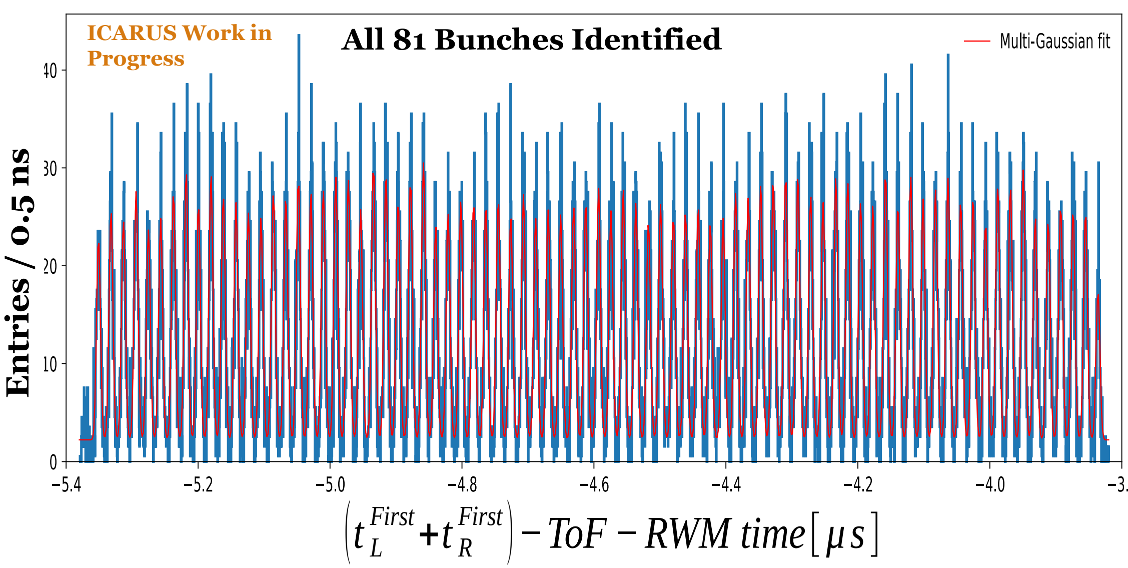
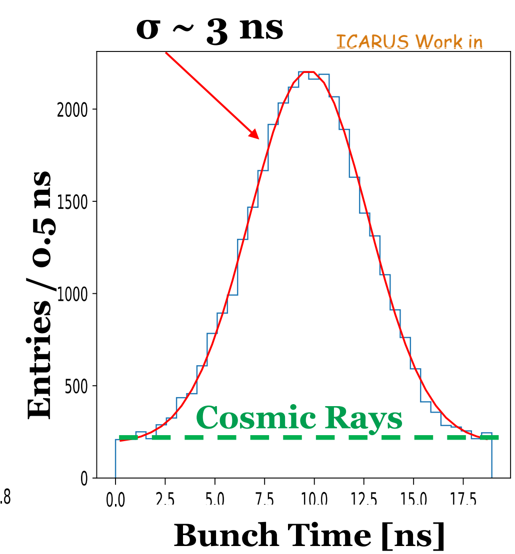
Event Selection Studies



Cosmic Rejection w/ CRT+PMTs (TOF)







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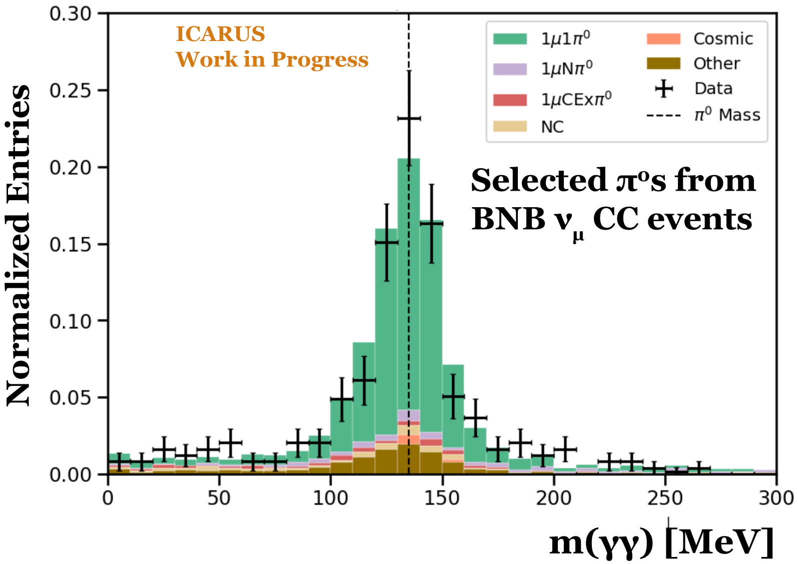
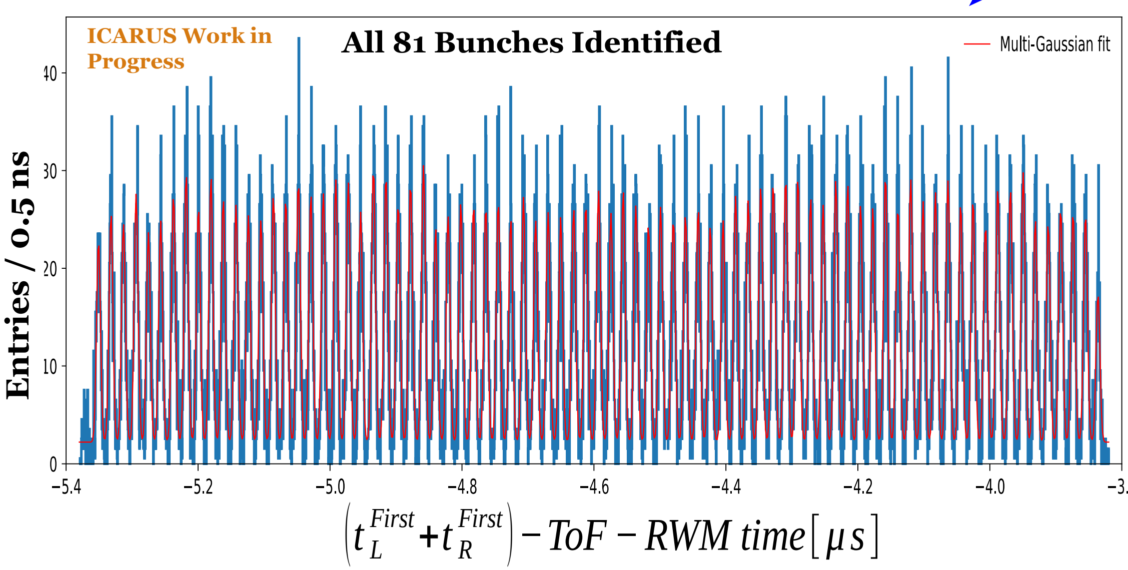
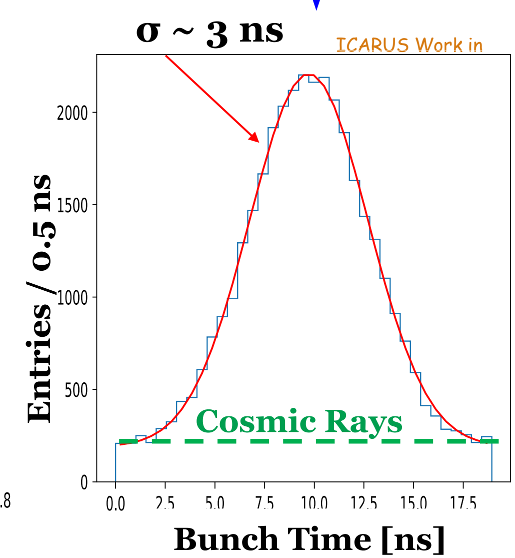


Poster by Matteo Vicenzi





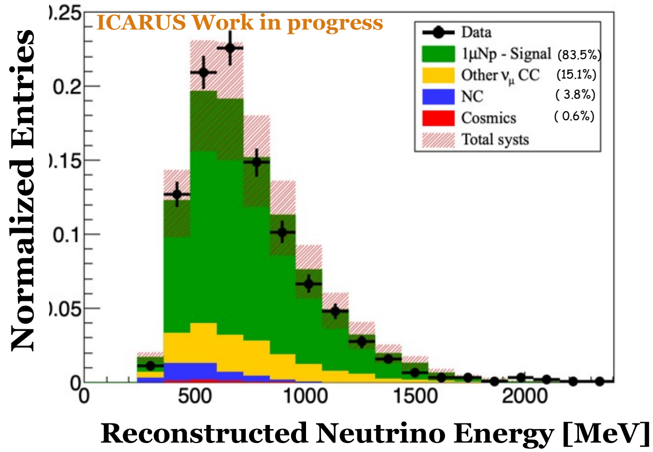
Neutrino Oscillation Physics

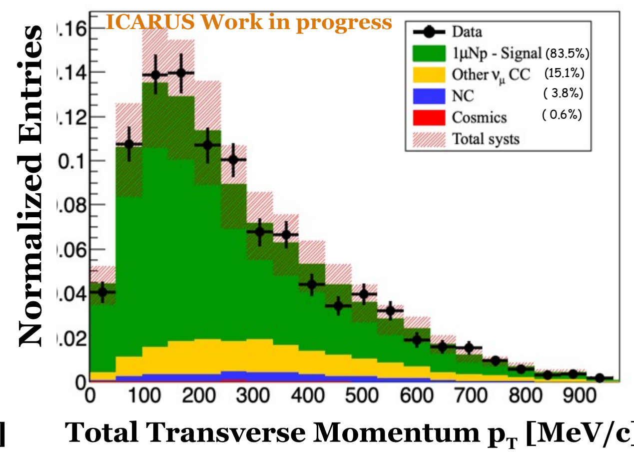
- Ultimate goal for ICARUS is to provide oscillated neutrino spectrum as far detector of SBN Program
  - Measure ν_μ disappearance + ν_e appearance w/ **two detectors**
  - BNB ν_μ/ν_e data for SBND/ICARUS, NuMI ν_μ/ν_e data for ICARUS
- While SBND progresses through commissioning, ICARUS is pursuing **single-detector** neutrino oscillation physics with first focus on muon neutrinos – targeting *end of calendar year*
  - Pathway for tool developments (e.g. fitter, systematics) in preparation for two-detector measurements of full SBN Program
  - May consider electron neutrino modes if ready on this timescale
- Considering $1\mu1p0\pi/1\mu Np0\pi$ BNB final states – two approaches:
  - **Pandora** – traditional reconstruction approach (used at MicroBooNE)
  - **ML (SPINE)** – machine-learning-based reconstruction chain
    - GitHub: **https://github.com/DeepLearnPhysics/spine**

First BNB Studies w/ Data

Pandora
1μNp0π Selection

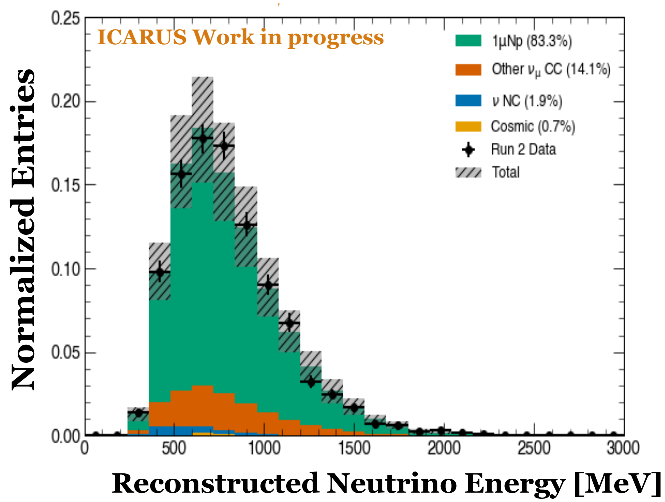
Efficiency ~ 50%
Purity ~ 80%

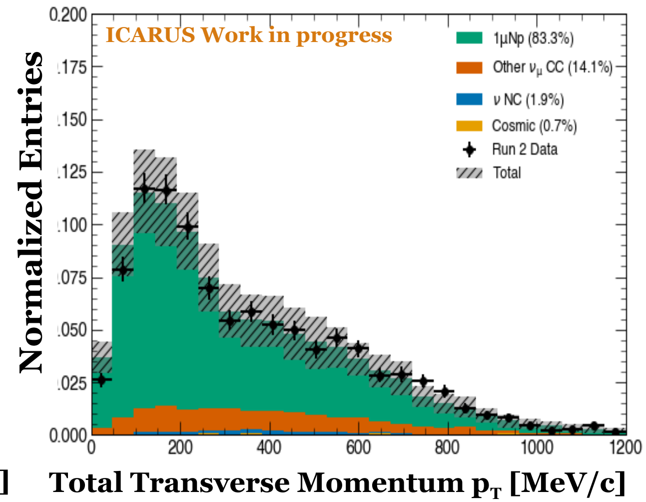




ML (SPINE)
1μNp0π Selection

Efficiency ~ 75%
Purity ~ 80%





- Excellent data/MC agreement seen in 10% unblinded Run 2 data
- Current systematics: flux/xsec/detector ~ 10%/15%/15%

First BNB Studies w/ Data

Pandora 1μNp0π Selection

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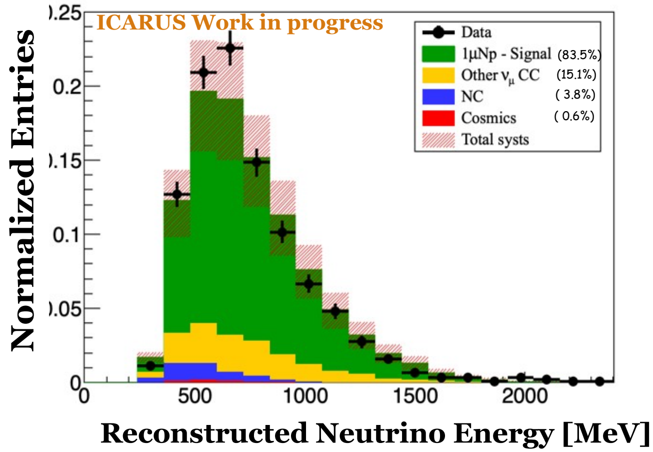

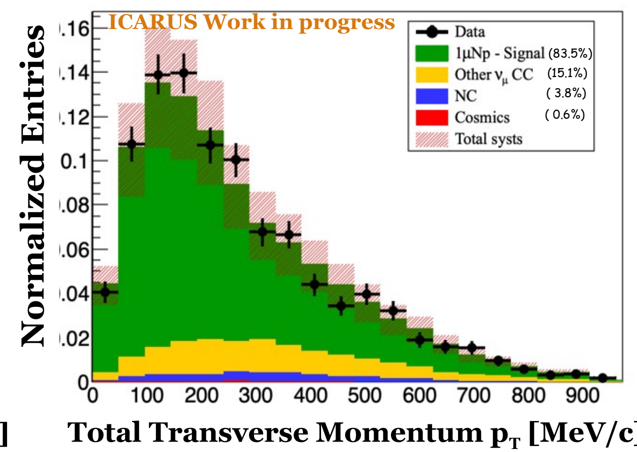

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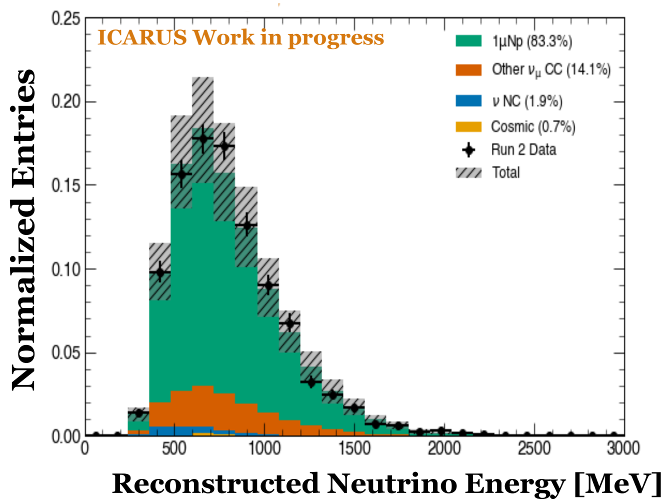
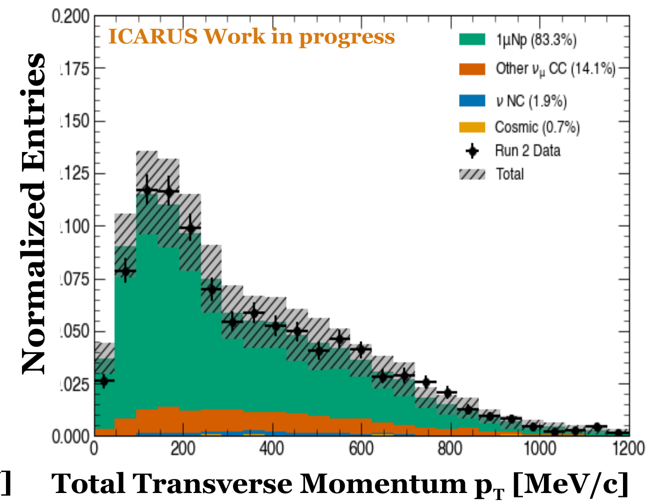




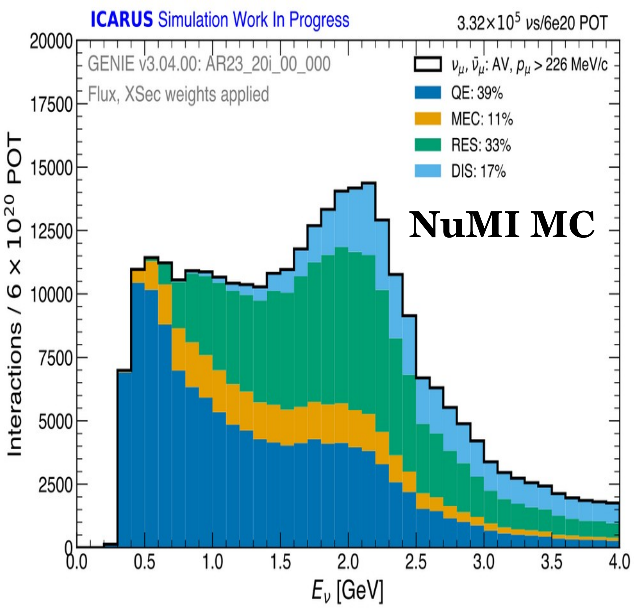
Poster by Jacob Zettlemoyer

- Current **systematics**: flux/xsec/detector ~ 10%/15%/15%

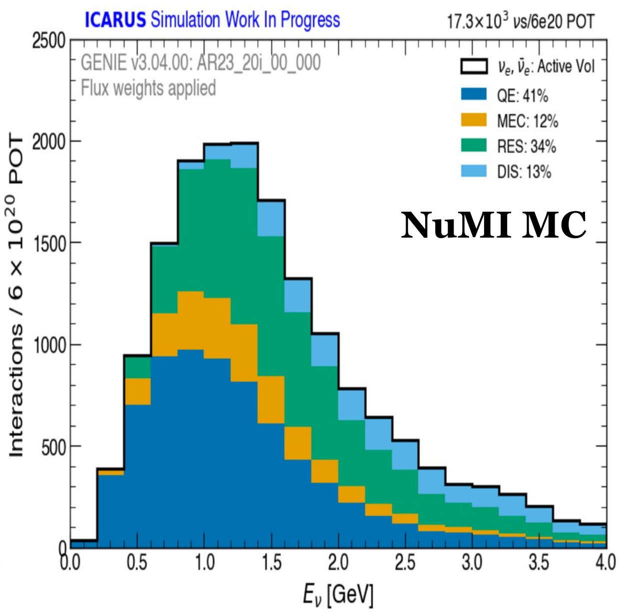
Cross Section Physics

- High statistics w/ NuMI beam for cross section measurements
  - Muon neutrinos: **~330k** for 6×10^{20} POT
  - Electron neutrinos: **~17k** for 6×10^{20} POT
- Relevant for first oscillation maximum of DUNE (high neutrino energy, so low L/E)

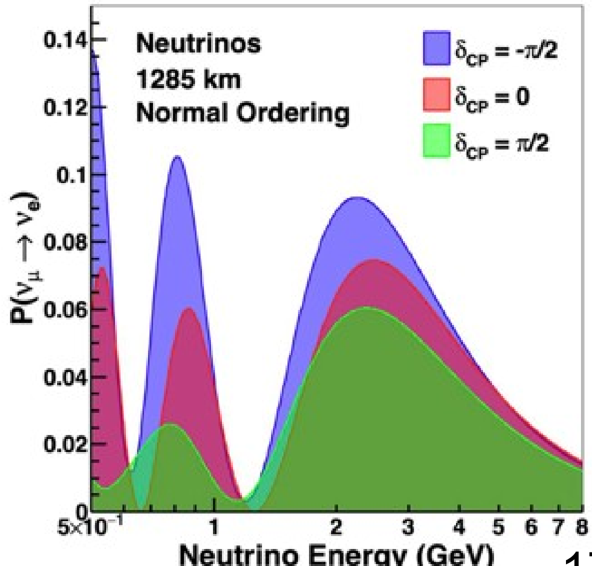
Muon Neutrinos @ ICARUS



Electron Neutrinos @ ICARUS

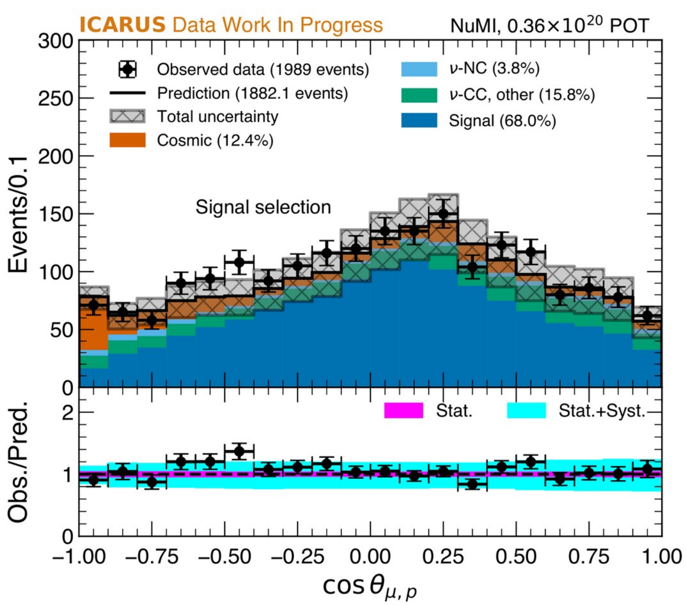


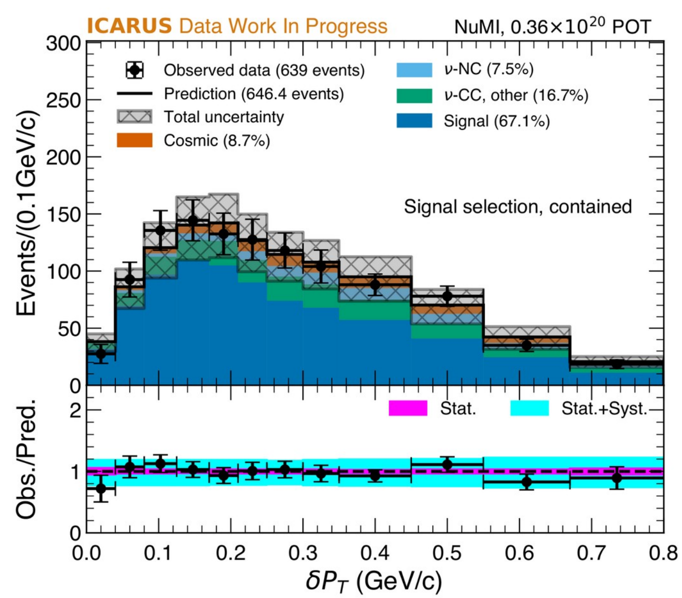
Oscillation Probability at DUNE



1μNp0π NuMI Analysis

- First NuMI cross section measurement: **1μNp0π** final state
  - Enriched in quasi-elastic and 2p2h interactions
  - Select events w/ one muon-like track and *at least* one proton-like track
- Study angles, transverse kinematic variables sensitive to FSI
- Use of charged pion control sample in fit (handle on π→p mis-ID)
  - Instead require *two* muon-like (pion-like) tracks





Poster by Jack Smedley

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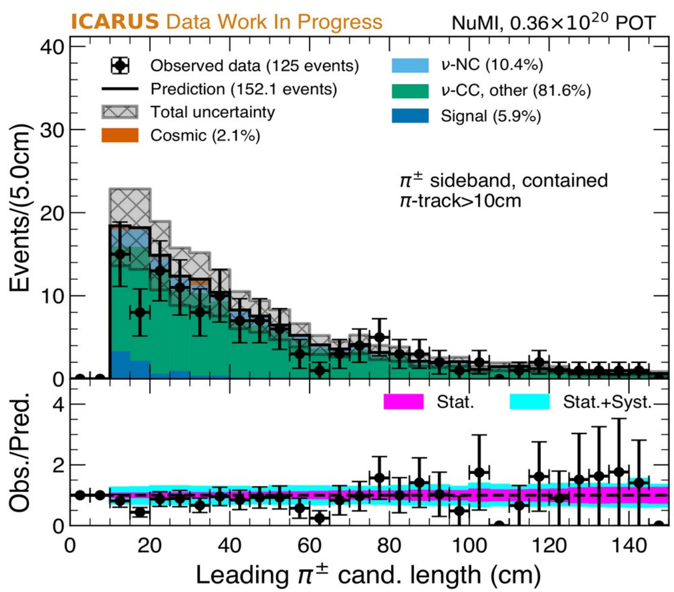
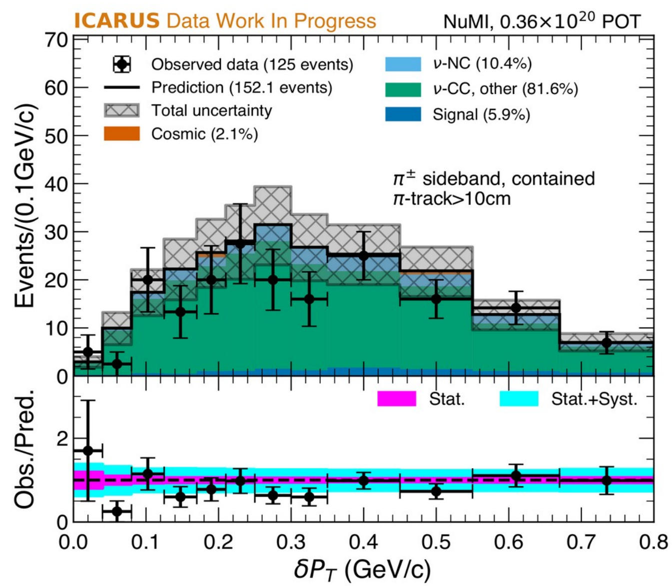


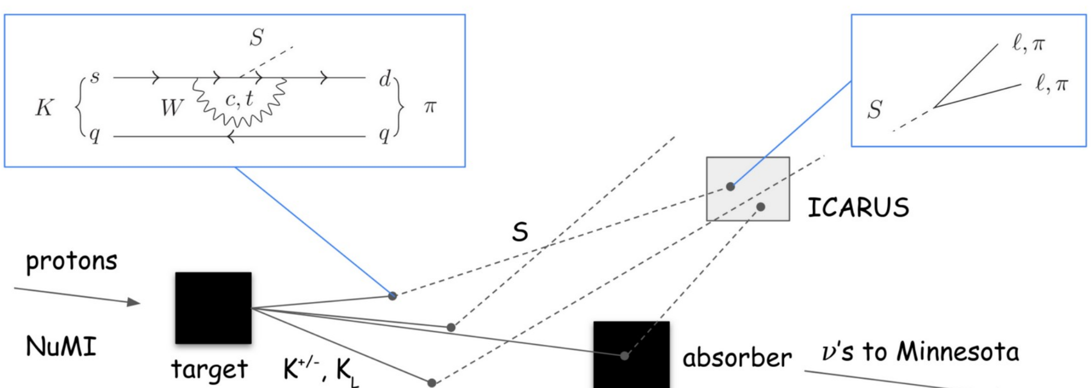


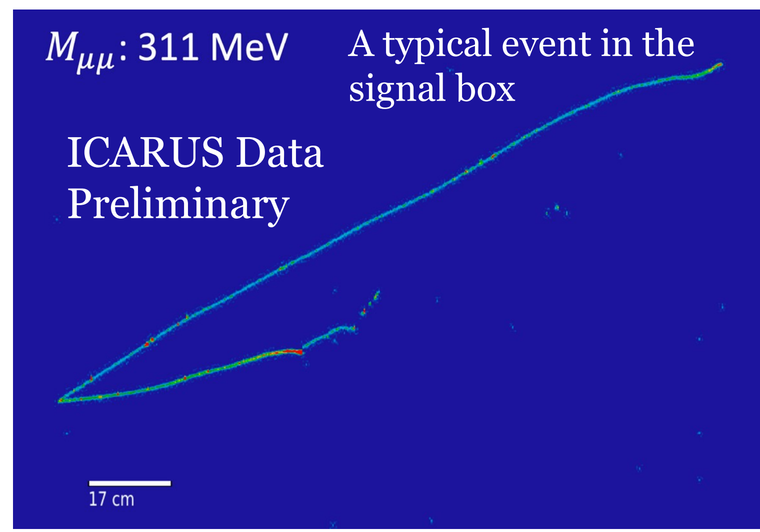
Poster by Jack Smedley

BSM Physics

- Rich BSM physics program at ICARUS w/ off-axis NuMI beam
- BSM models considered so far, both involving *kaon decay* and contained *dimuon final states* (for first analysis):
  - **Higgs Portal Scalar (HPS)**: Scalar dark sector particles that undergo mixing with Higgs boson
  - **Heavy QCD Axion** or **Axion-Like Particle (ALP)**: Pseudoscalar particles that undergo mixing with pseudoscalar mesons

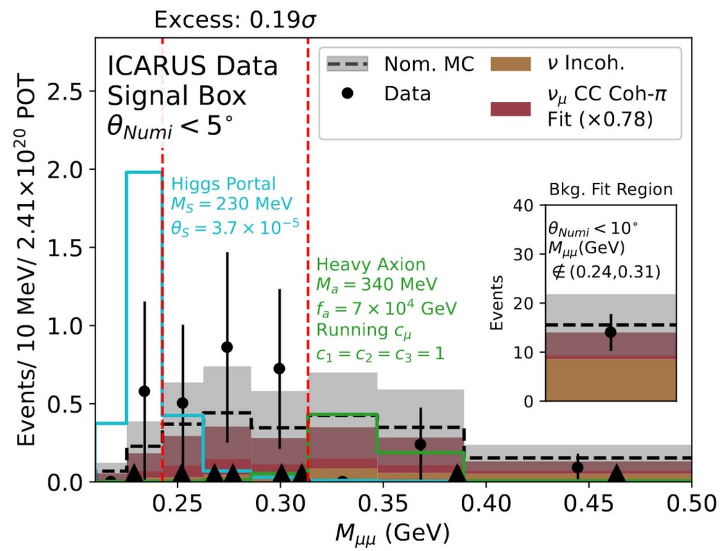
Below: Production and decay of a Scalar particle (the Higgs Portal Scalar) in ICARUS with the NuMI beam.

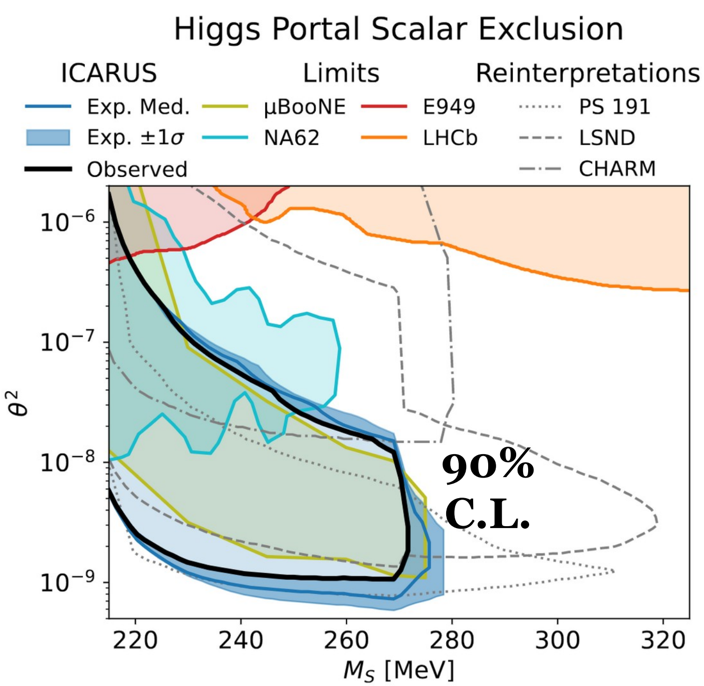


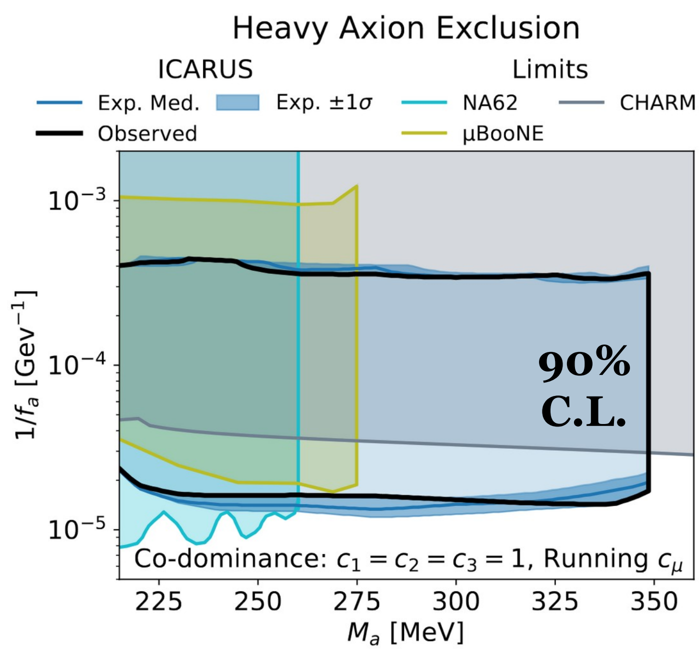


HPS/ALP Search Results

- HPS/ALP search: look for resonance ("bump") at specific value of M(μμ)
- Using ICARUS Run 2 NuMI data, **no new physics signal observed**
- Full results in forthcoming paper







Poster by Gray Putnam

Summary

- ICARUS well on the way to first physics results, including:
  - Single-detector neutrino oscillation physics w/ BNB (and NuMI) data
  - Cross section measurements, BSM physics searches w/ NuMI data
  - Detector physics results w/ cosmic muon data
- Goal is end of year for first ICARUS single-detector neutrino oscillation measurement – *key step toward SBN-wide physics*
  - ICARUS data in hand: ~4×10^{20} BNB POT, ~6×10^{20} NuMI POT
  - Ultimate dataset: 10-14$\times10^{20}$ BNB POT, 11-18$\times10^{20}$ NuMI POT
- Near-term ICARUS priority is reducing detector systematics
  - Achieving 5-7% should be straightforward with studies in hand
  - SBN Program goal of 2-3% achievable on longer timescale
- **Thanks to all the Fermilab support** that got us here
  - Fermilab cryogenic support, computing, accelerator division, human resources… we couldn't do it without you!

Thanks!