Neutrino-Argon interaction measurements using the NuMI beam at ICARUS

Stephen Dolan
For the ICARUS collaboration

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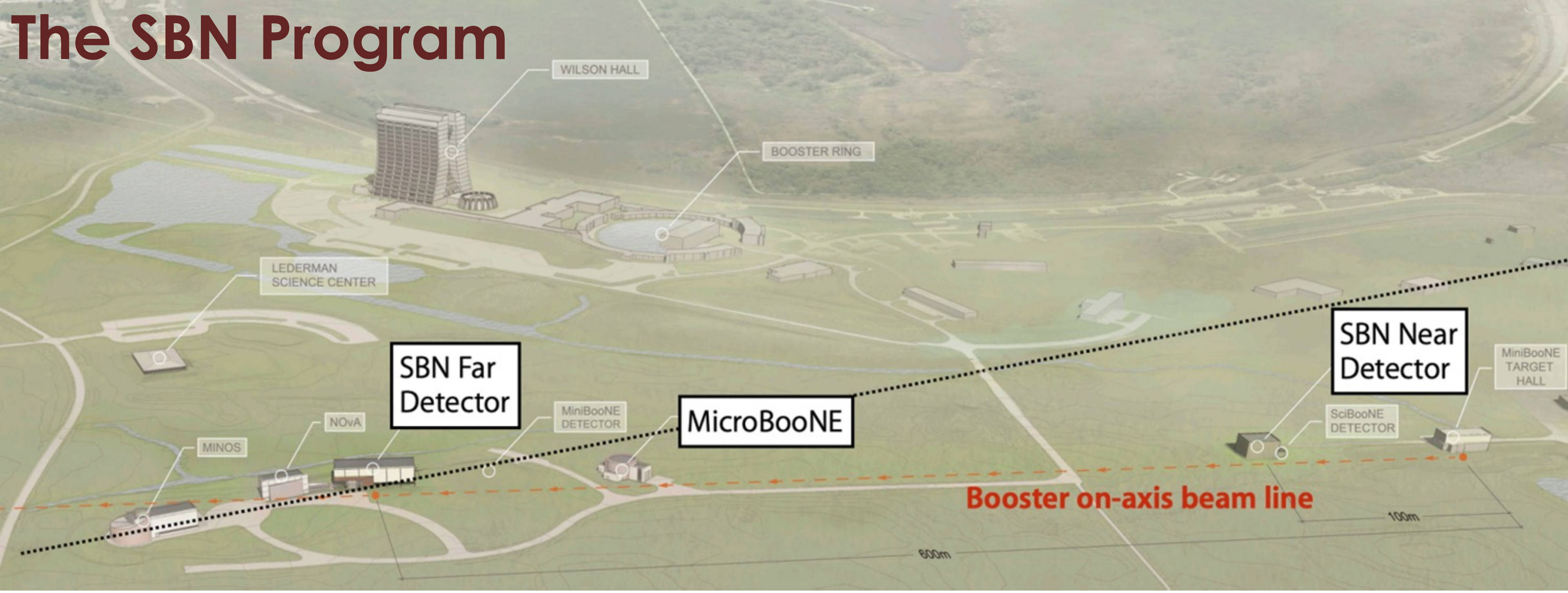
NuINT 2022

The 13th International Workshop on Neutrino-Nucleus Interactions in the Few GeV Regions

The SBN Program



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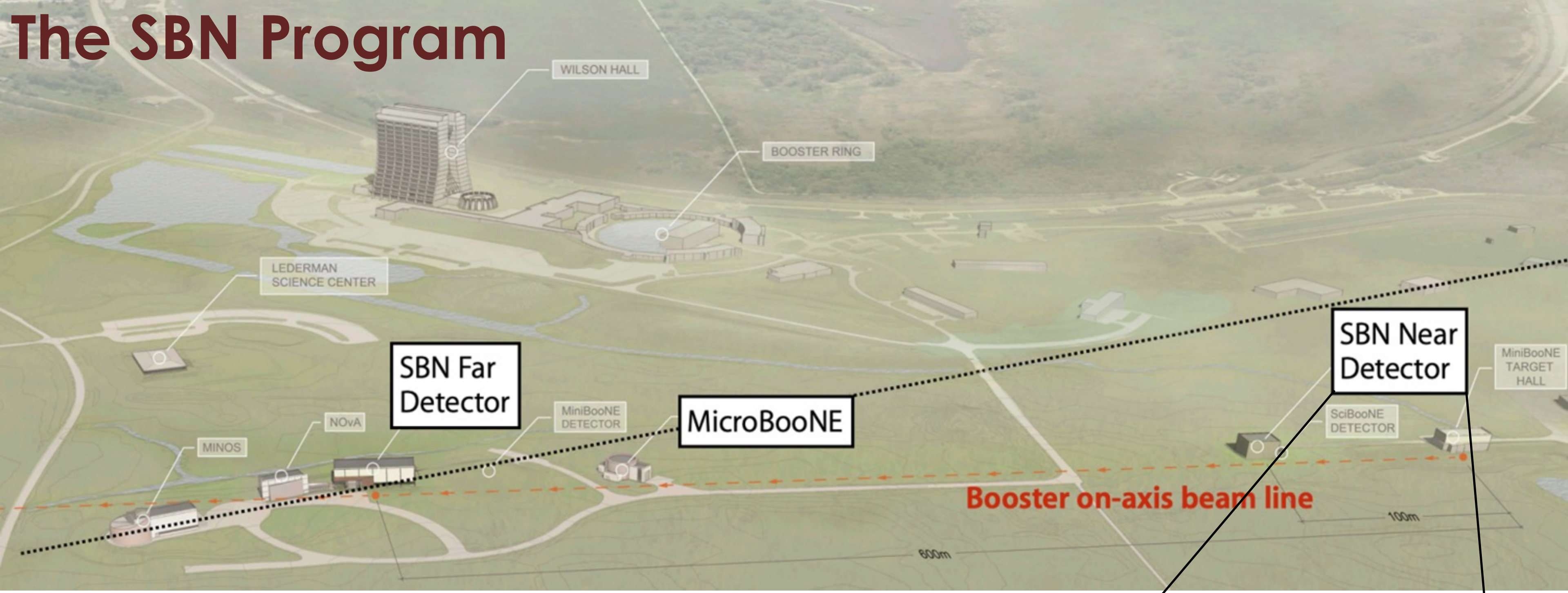
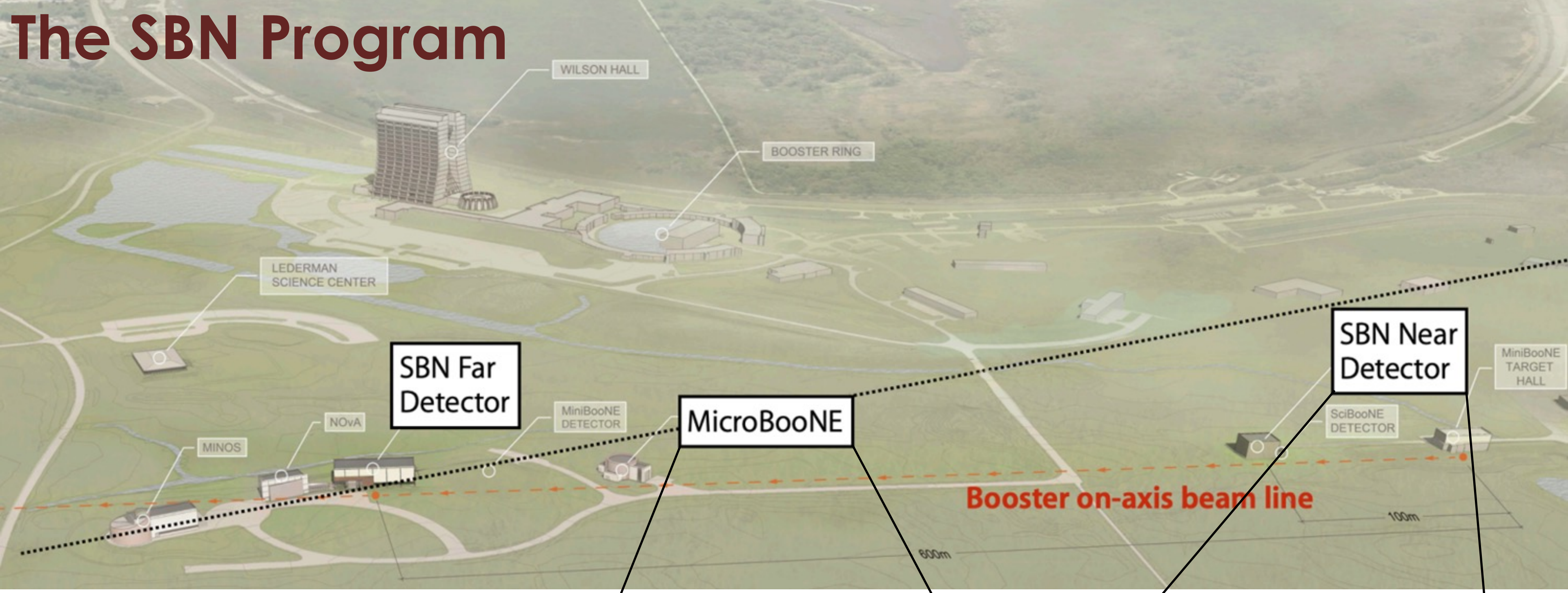


SBND

BNB baseline: 110 m
Total LAr: 270 ton
Active LAr: **112 ton**

The SBN Program



MicroBooNE

BNB baseline: 470 m
Total LAr: 170 ton
Active LAr: **90 ton**

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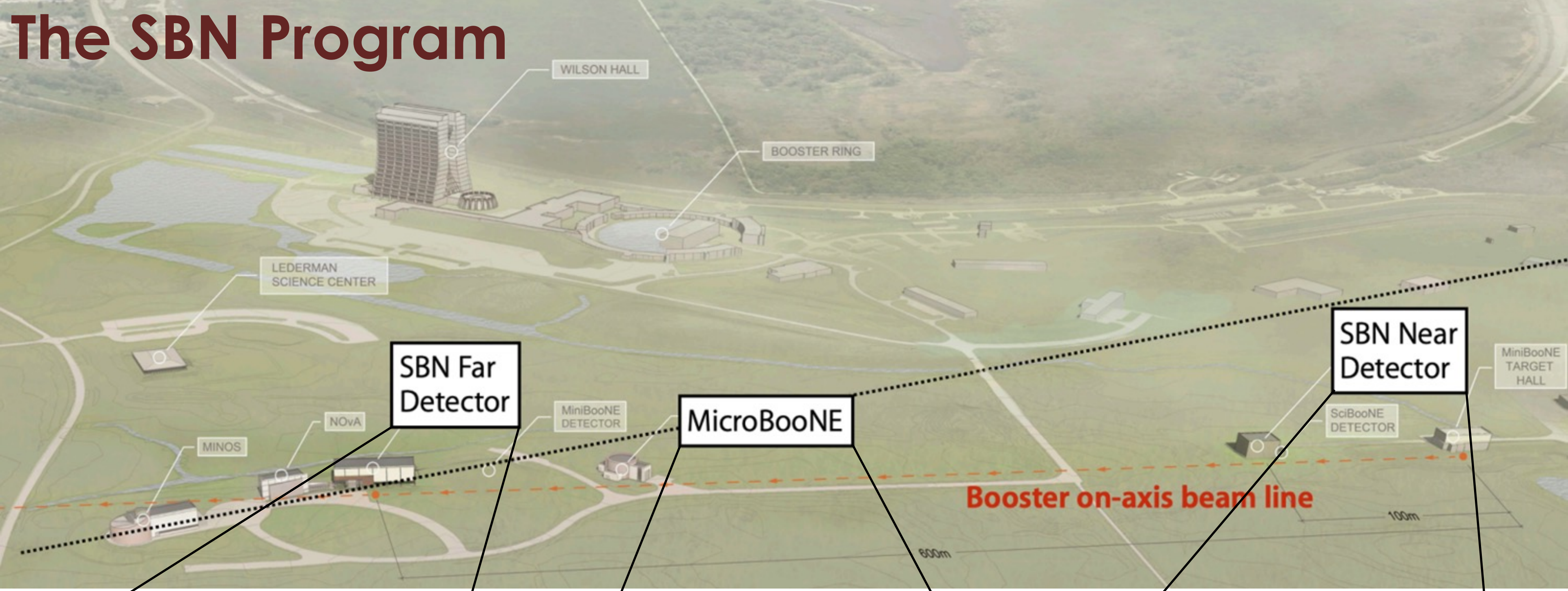

ICARUS-T600

Imaging Cosmic And Rare Underground Signals

BNB baseline: 600 m
Total LAr: 760 ton
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μBooNE

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Short-Baseline Near Detector

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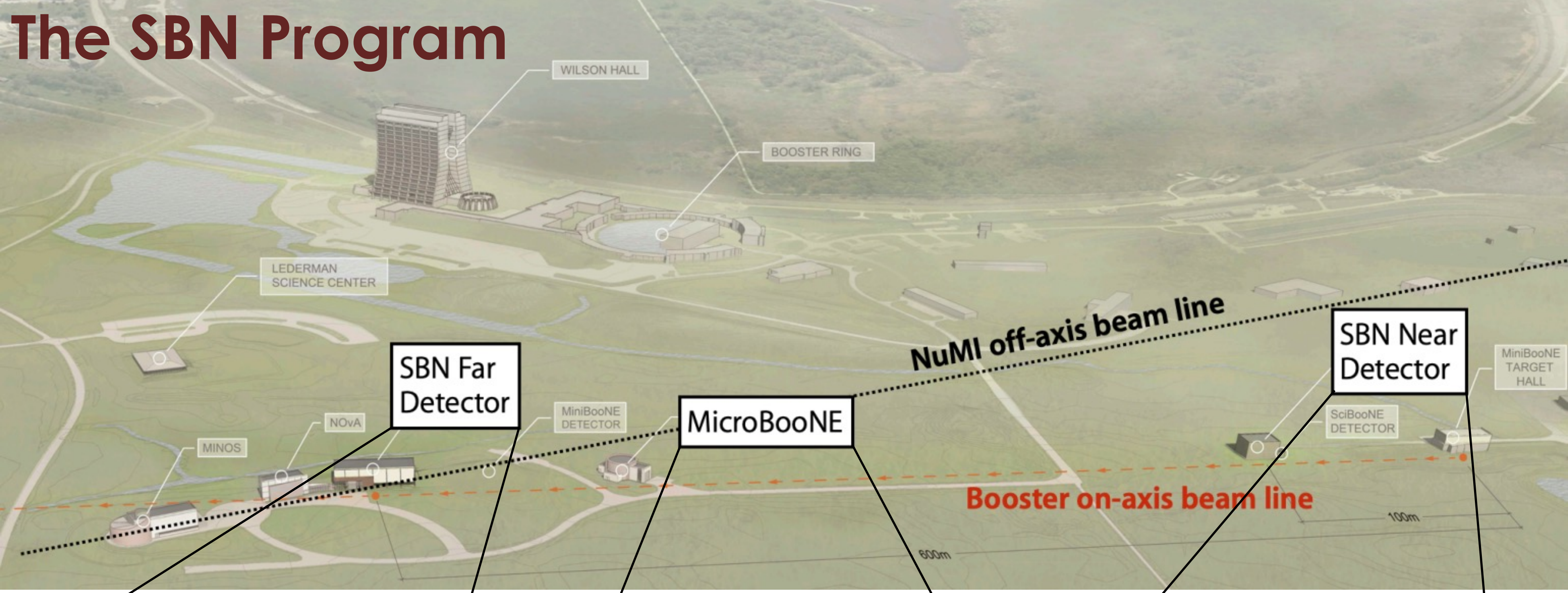

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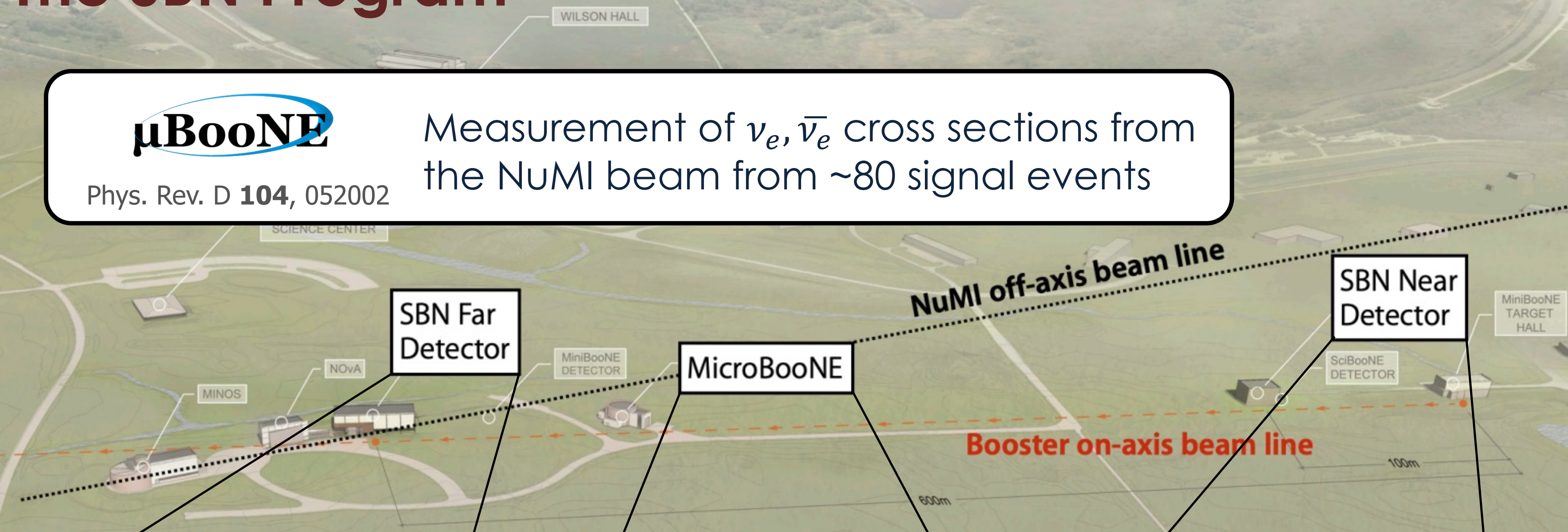
The SBN Program

μBooNE

Phys. Rev. D **104**, 052002

Measurement of $\nu_e, \bar{\nu}_e$ cross sections from the NuMI beam from ~80 signal events



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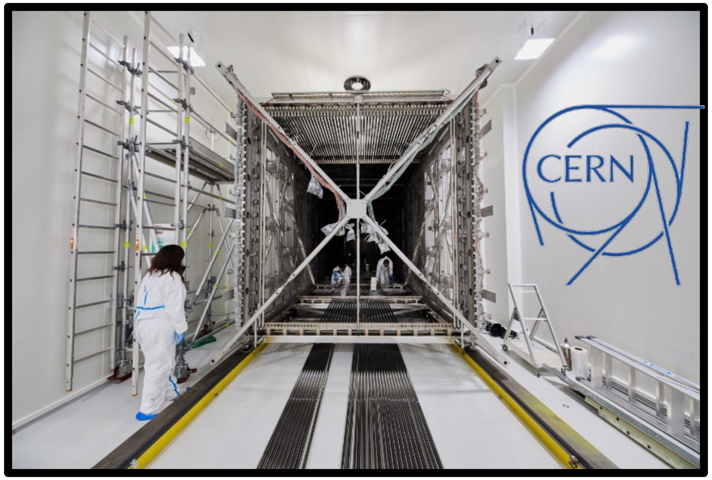
The ICARUS experiment

2010-2014: Data taking at Gran Sasso, Italy

The ICARUS experiment



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2014-2017: Refurbishment at CERN

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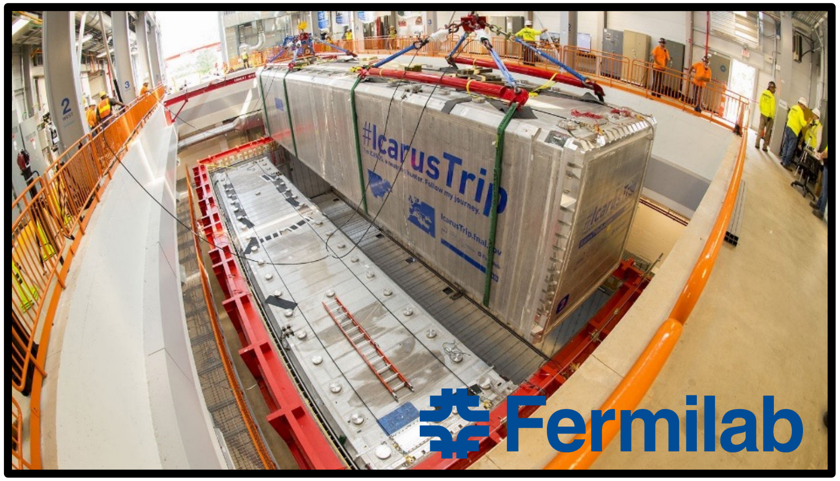
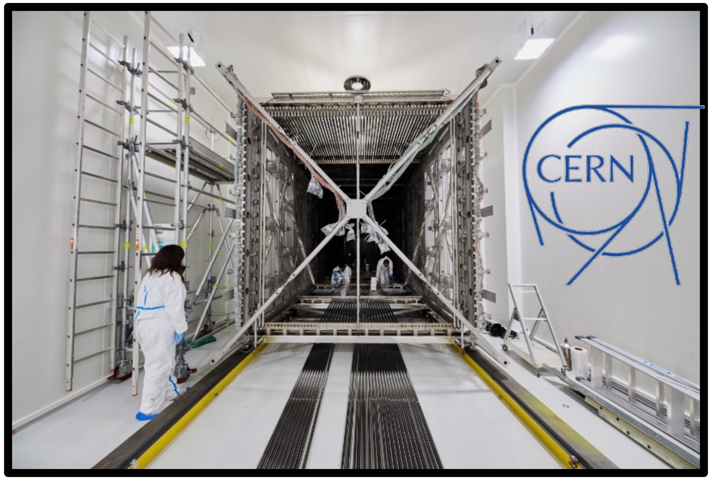




2010-2014: Data taking at Gran Sasso, Italy

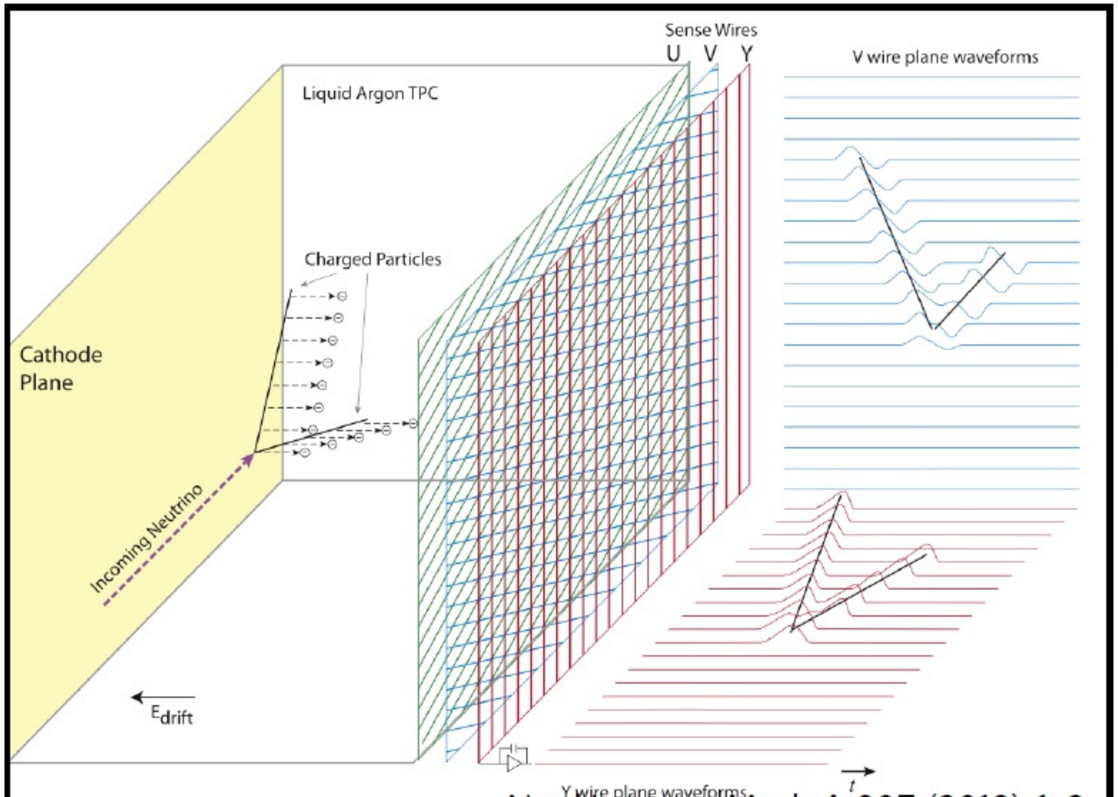
2014-2017: Refurbishment at CERN

July 2017: Transport to Fermilab

Since 2021: Data taking as part of SBN

The ICARUS experiment

- The first large Liquid Argon Time Projection Chamber (LArTPC)
  - Drift ionisation e^- from interaction products to three readout wire planes



Nucl.Instrum.Meth.A 907 (2018) 1-8

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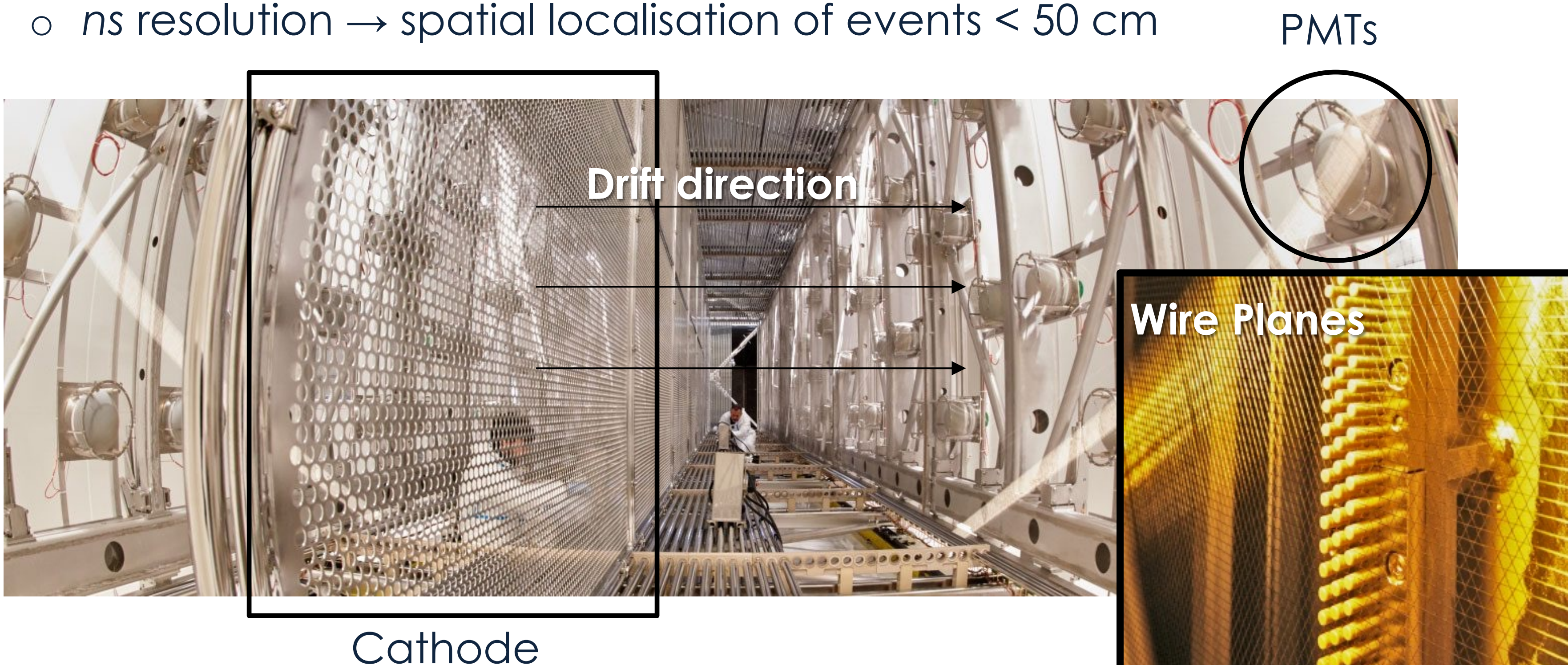
  - *ns* resolution → spatial localisation of events < 50 cm



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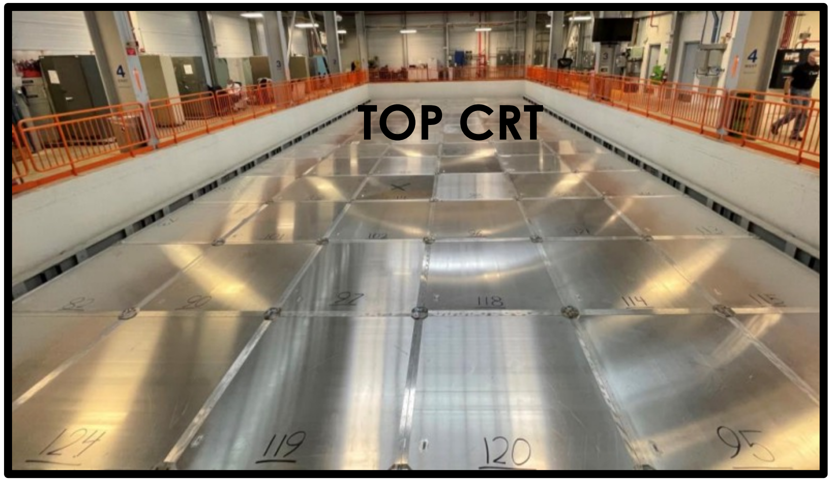
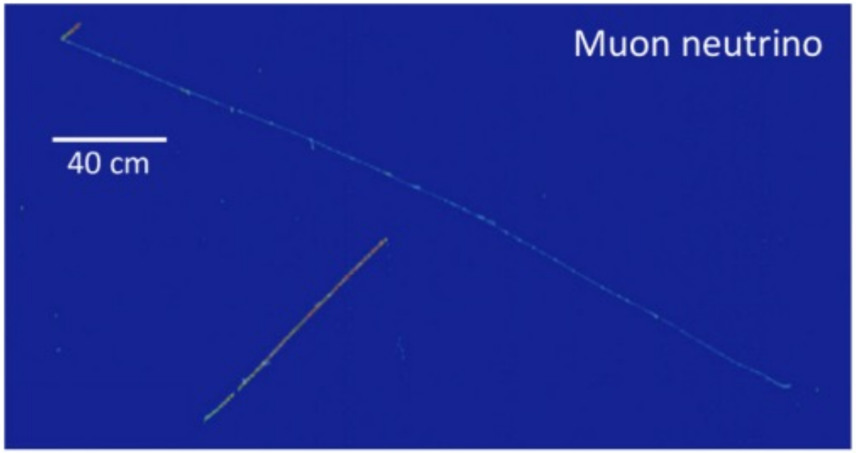
- Surrounded by a cosmic ray tagger (CRT)
  - Scintillator strips read out by SiPMs



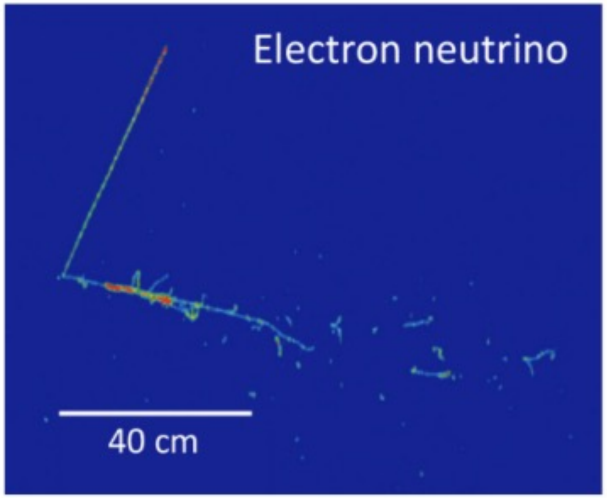
ICARUS Commissioning

- Collecting cosmic muon data since Summer 2020
- Collecting data from the Booster and NuMI beams since June 2021
- Characterising detector response and performances of automated reconstruction tools

Muon Neutrino candidate from data



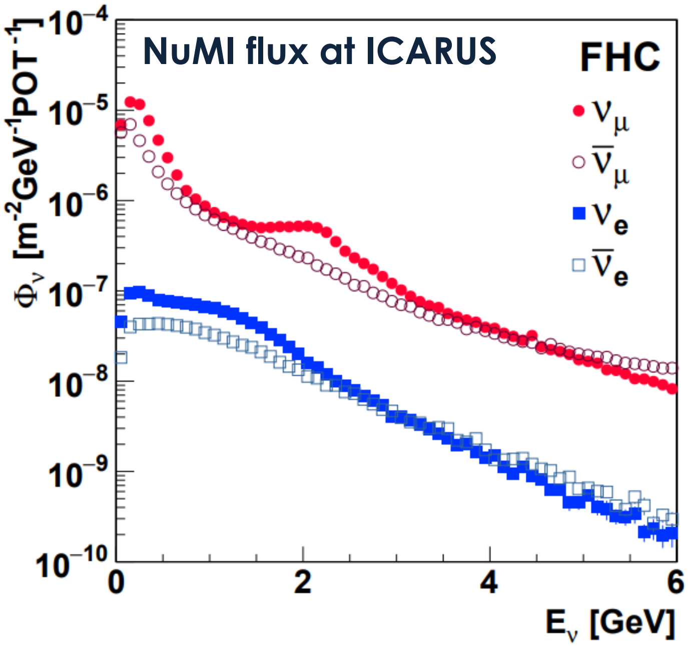
Electron Neutrino candidate

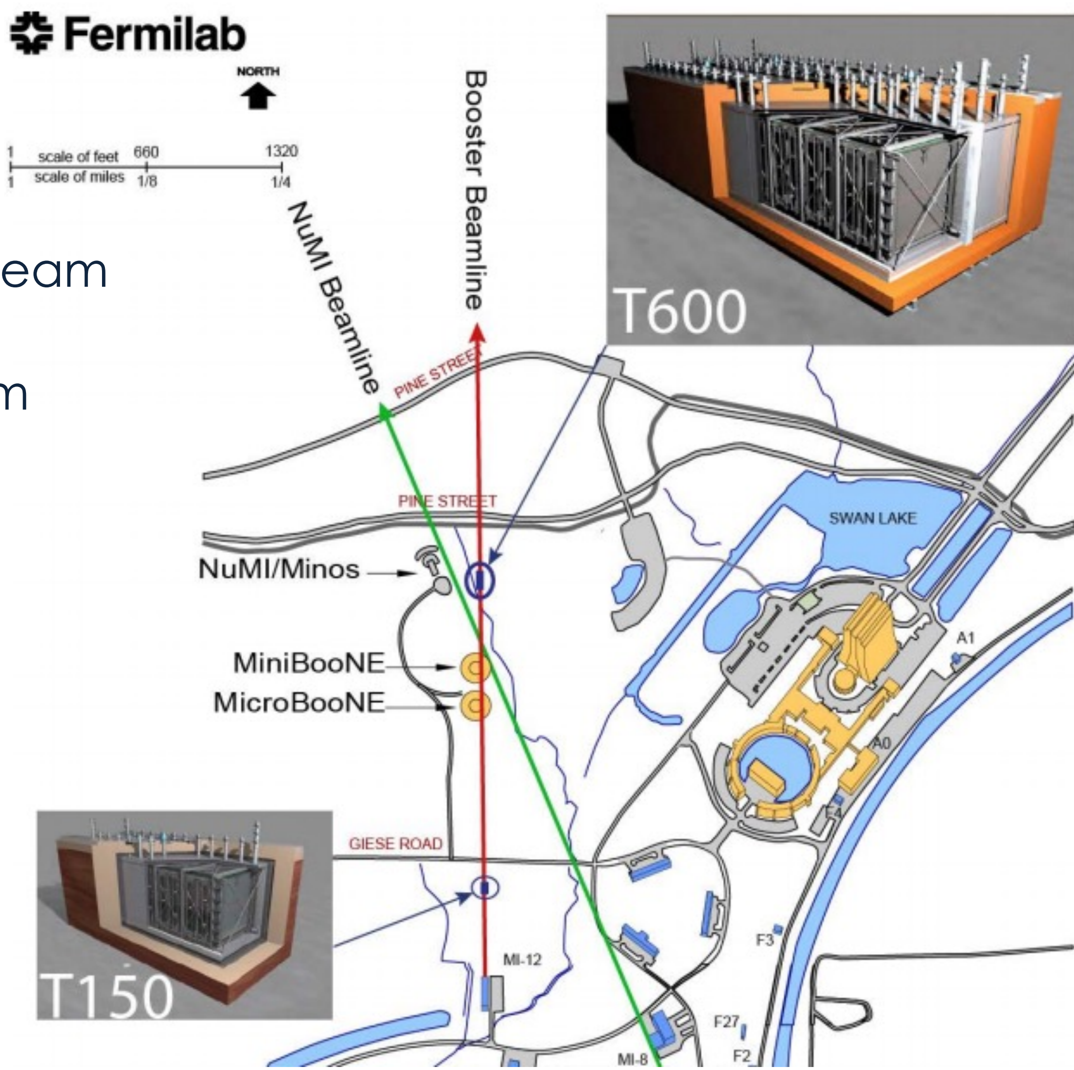


- Final stages of the trigger system and installation of the overburden was completed in May 2022. Begun physics-focussed data collection.

The NuMI beam at ICARUS

- NuMI is the primary beam for the MINERvA and NOvA
- ICARUS sees NuMI 5.9° off axis
- ν_μ flux comparable to Booster beam
- ν_e flux 6-7 times larger!
- Totally different energy spectrum





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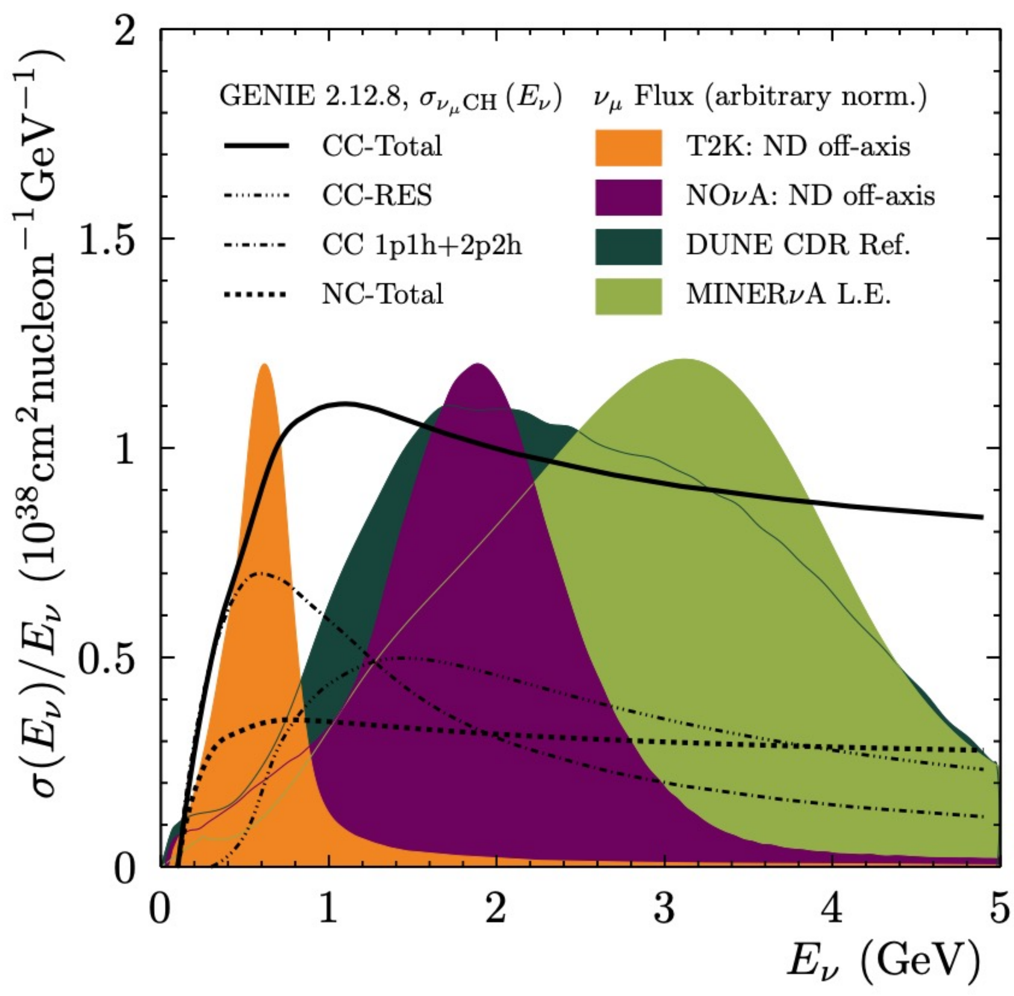

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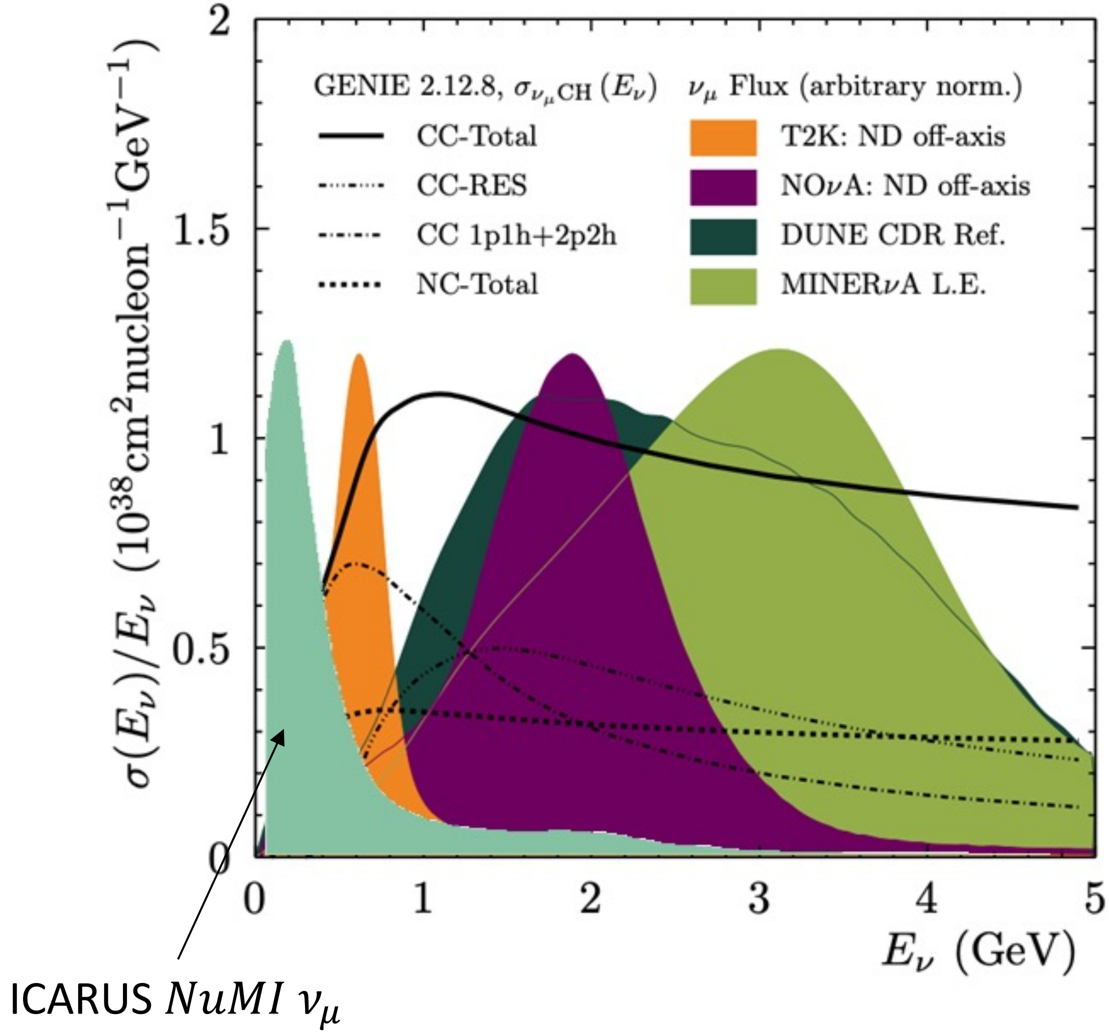

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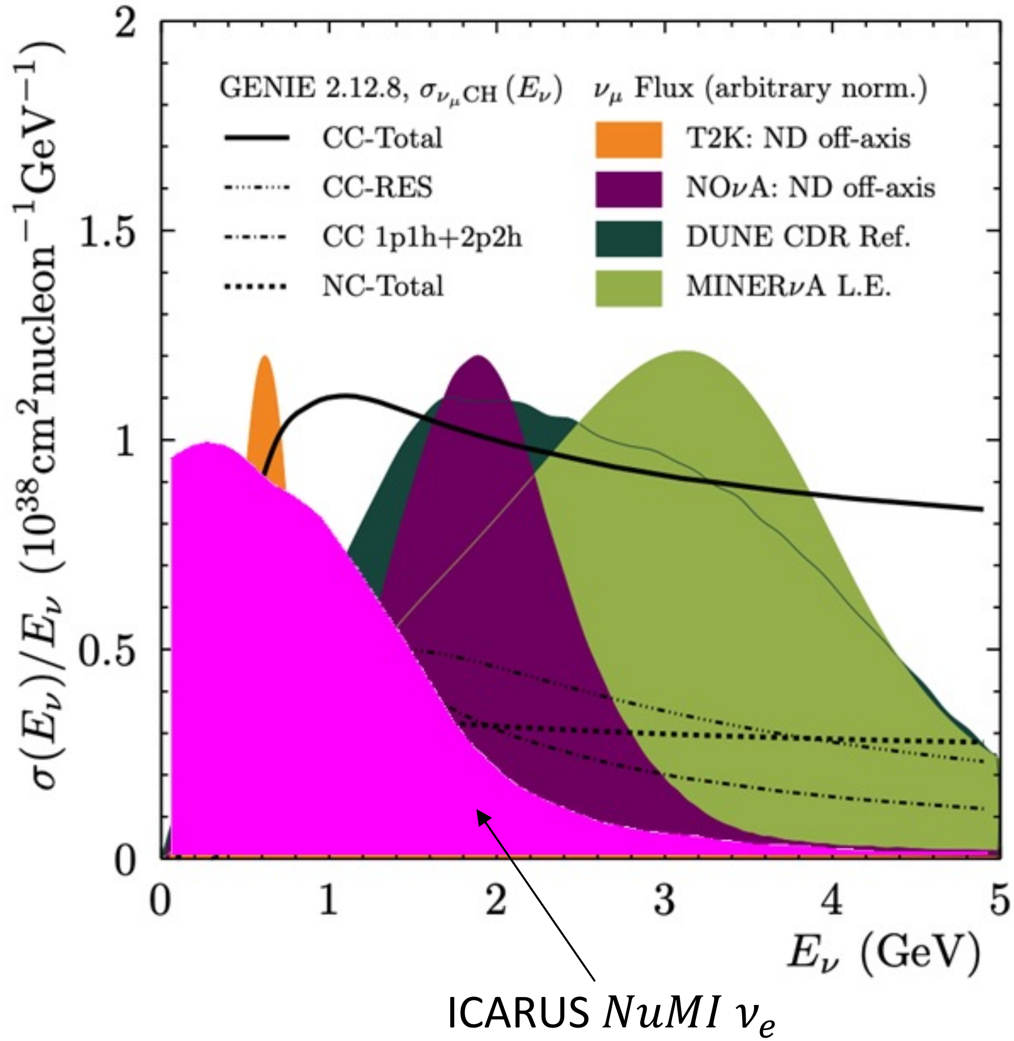


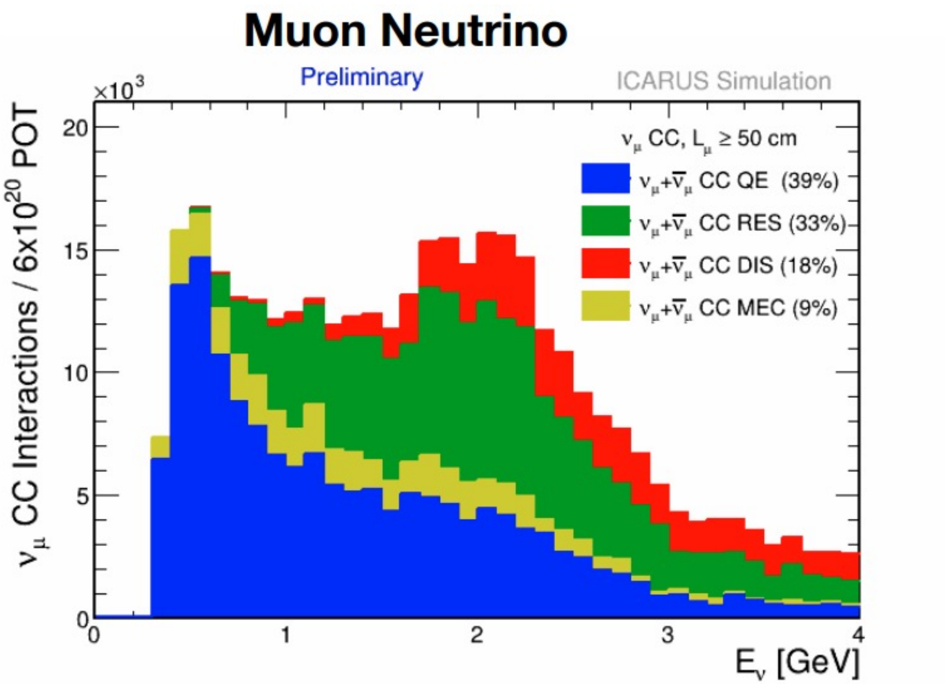
Neutrino interactions from NuMI

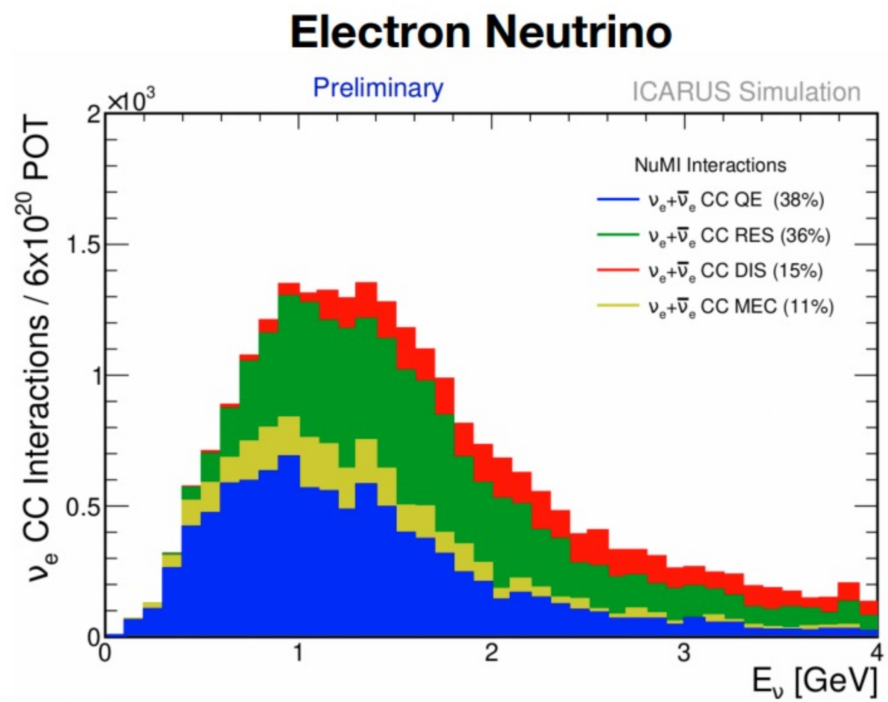
- High statistics neutrino cross-section measurements with unique fluxes
  - Especially promising ν_e measurements
- Primary channels are QE and single pion production

FHC	CC events/year*
ν_μ	446,000
ν_e	22,000

* 1 year = 6×10^{20} PoT

- Current focus: developing reconstruction and event selections

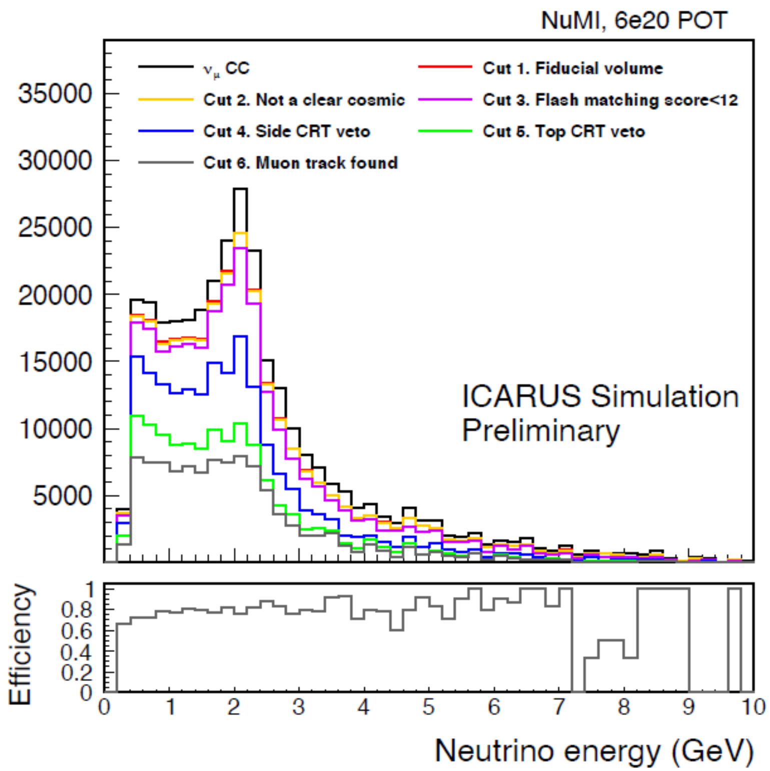


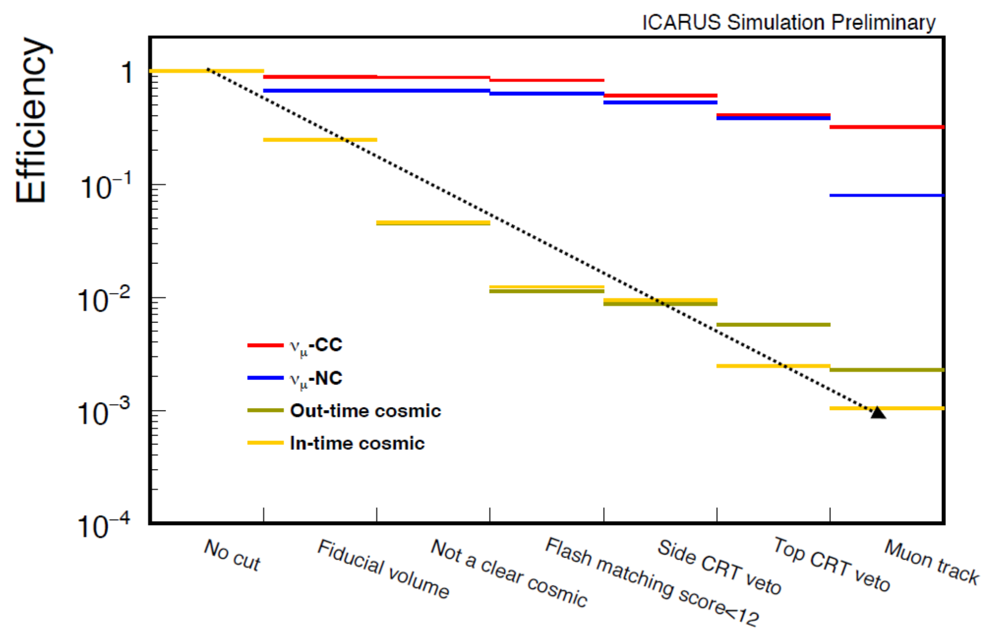


Muon neutrino selection

ν_μ CC Inclusive section

- Effective use of CRTs to reject cosmic-ray backgrounds
- Further cosmic ray rejection via TPC-PMT matching
- ~75% purity, ~70% efficiency
- Opportunities for significant improvement with CRT veto optimisation
- Further gains in purity moving to an exclusive CC$1\mu1p$ selection

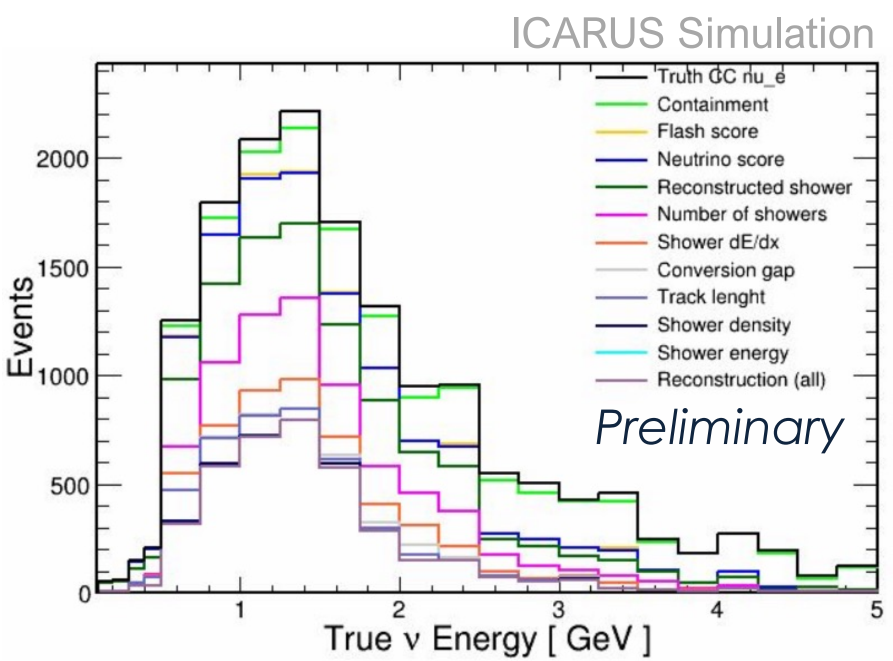


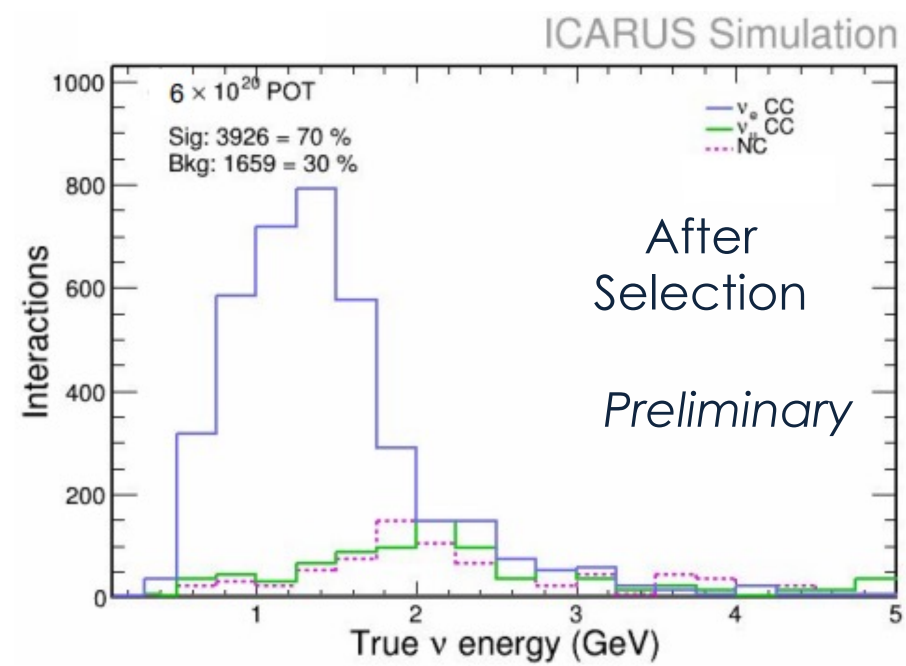


Electron neutrino selection

ν_e CC Inclusive section

- Particular focus on identifying events with a single electron
- Shower must be 1-MIP like, must start close to interaction vertex
- ~70% purity, ~15% efficiency: ~4000 ν_e/year!
- Plenty of scope for further optimisation





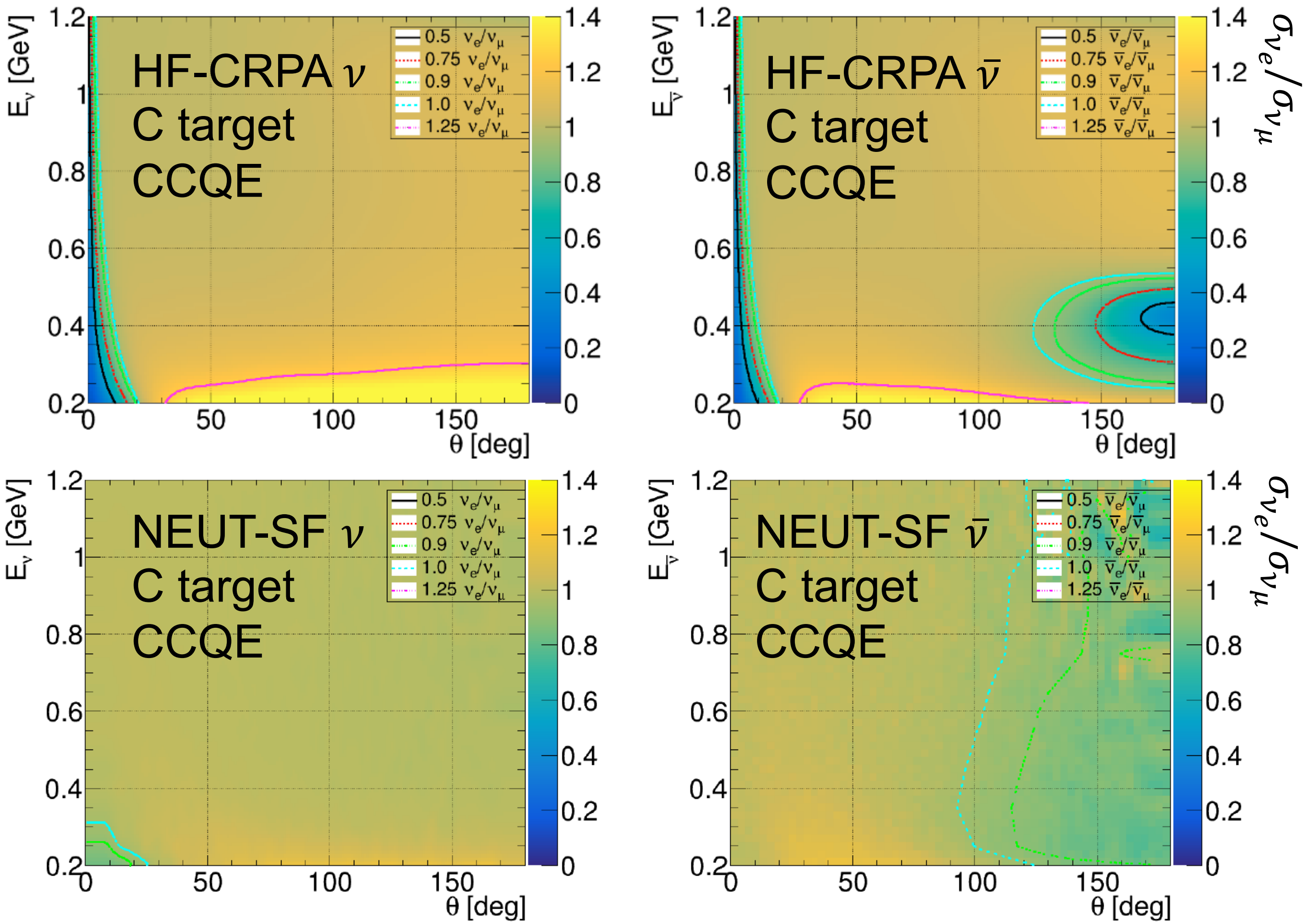
Future directions: ν_e/ν_μ

- Nuclear medium effects change the ν_e/ν_μ ratio
  - Changes the cross section close to phase space boundaries

More details in:
Dieminger et al.,
NEUTRINO 2022 poster

See also:
Nikolakopoulos et al.,
PRL **123**, 052501

Dolan et al.,
PRD **106**, 073001



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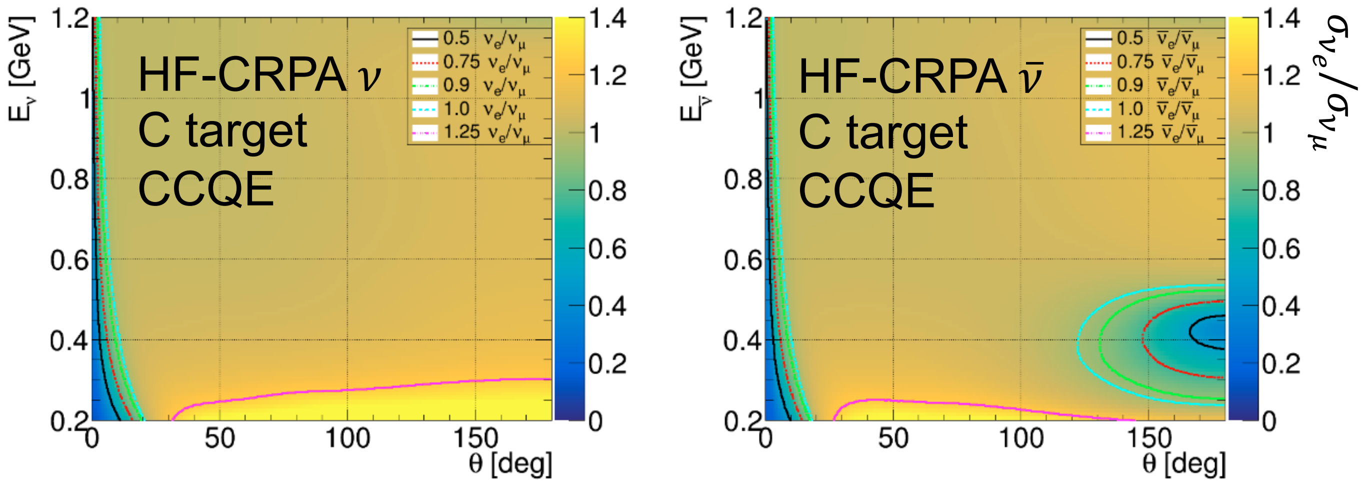
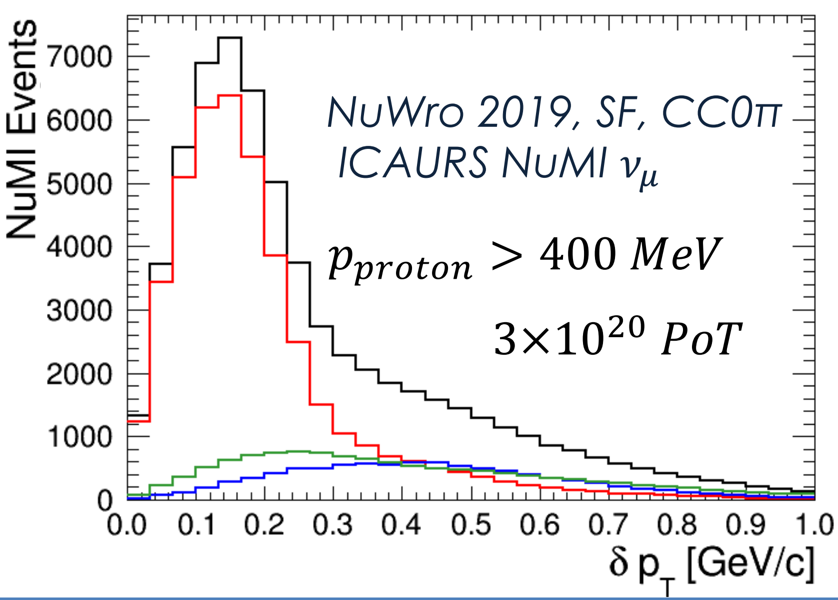


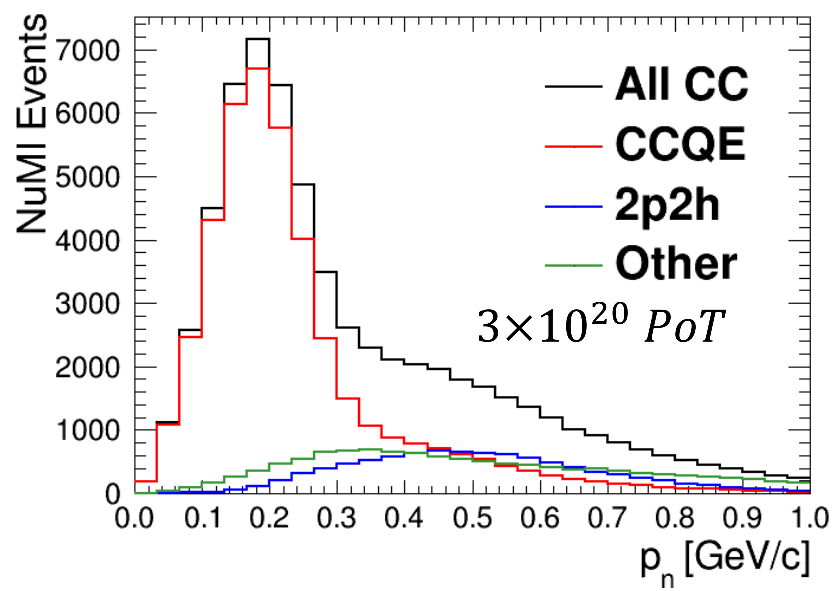
- The effect is much stronger for lower neutrino energies
  - ~2-3 % effect for T2K's oscillated flux
  - May be considerably larger for ICARUS' NuMI flux
  - Large ν_e statistics may allow an isolation of affected phase space
  - Expect some A-dependence: complementarity with CH experiments

Future directions: TKI

TKI details:
Lu, Pickering, Dolan et al., Phys. Rev. C **94**, 015503
Furmanski, Sobczyk, Phys. Rev. C **95**, 065501

- ICARUS is well suited to making measurements of transverse kinematic imbalances: relatively low proton tracking threshold, large statistics





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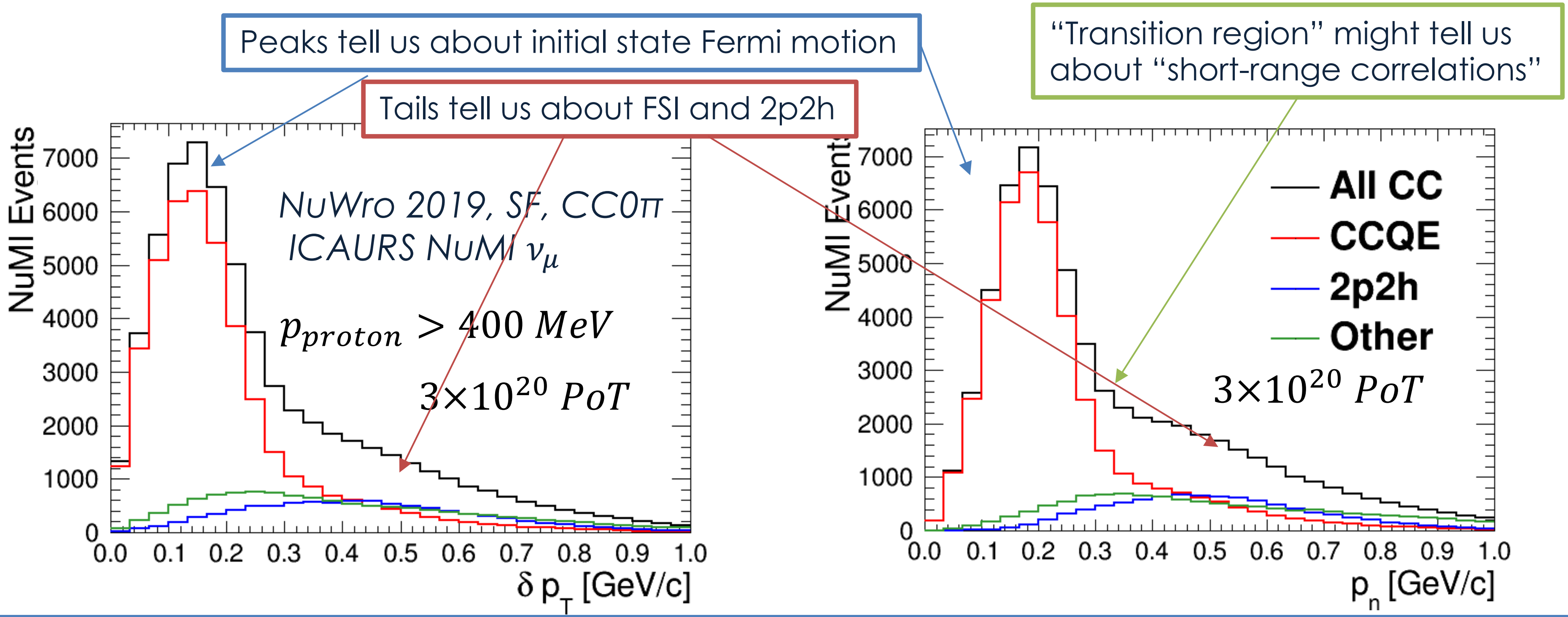

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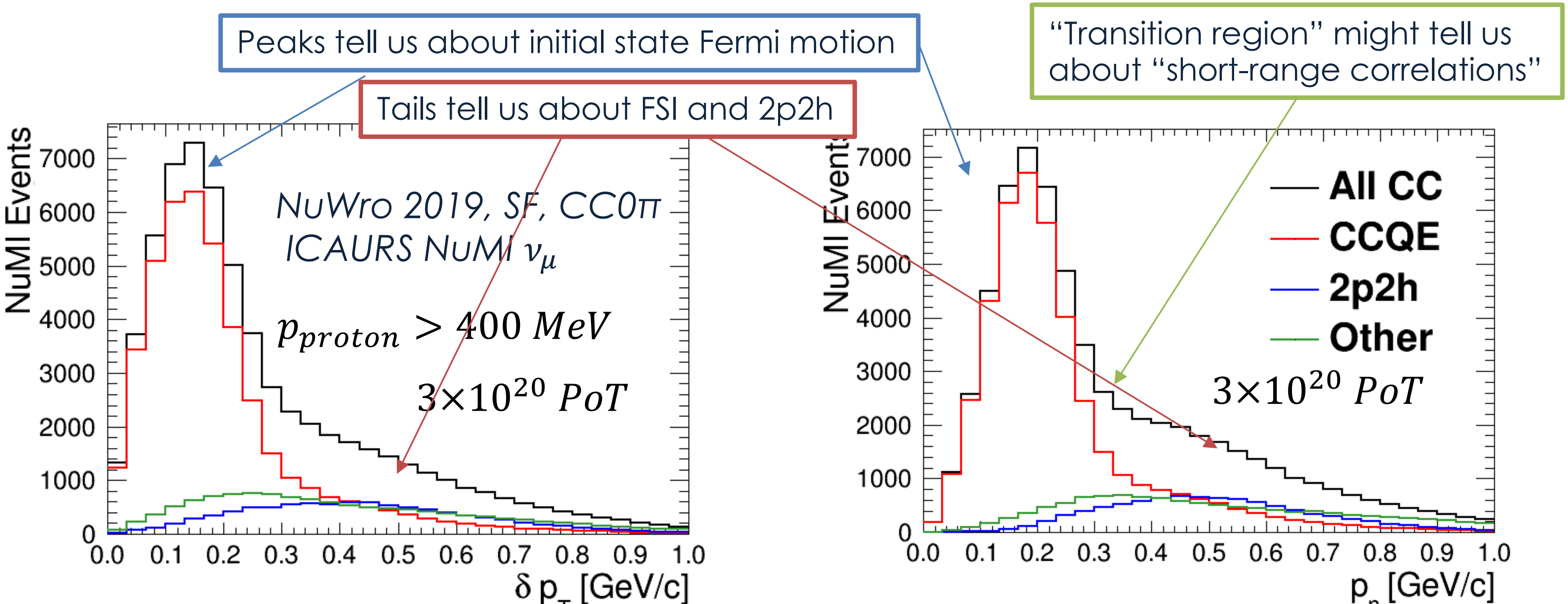
- Complementarity with existing measurements:
  - T2K+MINERvA: different target, different A-scaling of 2p2h and FSI — Phys. Rev. Lett. **121**, 022504; Phys. Rev. D **98**, 032003
  - MicroBooNE : different energy, same target → probe of energy dependence — MICROBOONE-NOTE-1108-PUB



Summary

- ICARUS has been commissioned as the far detector of the SBN experiment and it ready for physics analyses
- ICARUS sees neutrinos from both the Booster and NuMI neutrino beams
- The NuMI beam provides novel opportunities for characterising neutrino-Argon interactions
  - Especially with regards to ν_e measurements
- We have preliminary ν_μ and ν_e event selection, more exclusive analyses are on the way
- Exciting long-term prospects for ICARUS' analyses!

Backup

ICARUS Collaboration at SBN

P. Abratenko[19], A. Aduszkiewicz[21], F. Akbar[23], M. ArteroPons[15], J. Asaadi[24], M. Babicz[2], W.F. Badgett[5], L.F. Bagby[5], B. Baibussinov[15], C. Backhouse[25], B. Behera[4], V. Bellini[7], O. Beltramello[2], R. Benocci[13], J. Berger[4], S. Berkman[5], S. Bertolucci[6], M. Betancourt[5], K. Biery[5], M. Bonesini[13],T. Boone[4], B. Bottino[8], A. Braggiotti[15], J Bremer[2], S. Brice[5], V. Brio[7], C. Brizzolari[13], J. Brown[5], H. Budd[23], A. Campani[8], D. Carber[4], M. Carneiro[1], H. Carranza[24], D. Casazza[8], A. Castro[3], M. Cicerchia[15], S. Centro[15], G. Cerati[5], M. Chalifour[2], A.Chatterjee[27], D. Cherdack[21], S. Cherubini[11], N. Chitirasreemadam[26], T. Coan[18], A. Cocco[14], M.R. Convery[17], S. Copello[8], A. De Roeck[2], S. Di Domizio[8], D. Di Ferdinando[6], L. Di Noto[8], M. Diwan[1], S. Donati[26], J. Dyer[4], S. Dytman[22], S. Dolan[2],L. Domine[17], R. Doubnik[5], F. Drielsma[17], C. Fabre[2], A. Falcone[13], C. Farnese[15], A. Fava[5], A. Ferrari[12], F. Ferraro[8], N. Gallice[12], F. Garcia[17], M. Geynisman[5], D. Gibin[15], W. Gu[1], M. Guerzoni[6], A. Guglielmi[15], S. Hahn[5], A. Heggestuen[4], B. Howard[5], R. Howell[23], J. Hrivnak[2], C. James[5], W. Jang[24], L. Kashur[4], W. Ketchum[5], J.S. Kim[23], D.H. Koh[17], U. Kose[2],J. Larkin[1], G. Laurenti[6], G. Lukhanin[5], A. Maria[26], C. Marshall[23], S. Martinenko[1], N. Mauri[6], A. Mazzacane[5], K.S. McFarland[23], D.P. Mendez[1], G.Meng[15], A. Menegolli[16], O.G. Miranda[3], D. Mladenov[2],A. Mogan[4],N. Moggi[6], N. Montagna[6], A. Montanari[6], C. Montanari[5,b], M. Mooney[4], G. Moreno Granados[3], J. Mueller[4], D. Naples[22], M. Nessi[2], T. Nichols[5],S. Palestini[2], M. Pallavicini[8], V. Paolone[22], R. Papaleo[11], L. Pasqualini[6], L. Patrizii[6], 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], R. Rechenmacher[5], L. Rice[22], E. Richards[22], F. Resnati[2], A. Rigamonti[2], G.L. Raselli[16], M. Rosemberg[19], M.Rossella[16], C. Rubbia[9], P. Sala[12], G. Savage[5], A. Scaramelli[16], A. Scarpelli[1], D.Schmitz[20], A. Schukraft[5], F. Sergiampietri[2], G. Sirri[6], J. Smedley[23], A. Soha[5], L. Stanco[15], J. Stewart[1], N.B. Suarez[22], H.Tanaka[17], M. Tenti[6],K.Terao[17], F. Terranova[13], V.Togo[6], D.Torretta[5], M.Torti[13], F.Tortorici[7], Y.T. Tsai[17], S.Tufanli[2], T. Usher[17], F. Varanini[15], S. Ventura[15], M. Vicenzi[8], C. Vignoli[10], B. Viren[1], D. Warner[4], Z. Williams[24], P. Wilson[5], R.J. Wilson[4], J. Wolfs[23], T. Wongjirad[19], A. Wood[21], E. Worcester[1], M..Worcester[1], M. Wospakrik[5],H. Yu[1],J. Yu[24], A. Zani[12], C. Zhang[1], J. Zennamo[5], J. Zettlemoyer[5], S. Zucchelli[6], M. Zuckerbrot[5]

Spokesperson: C. Rubbia, GSSI

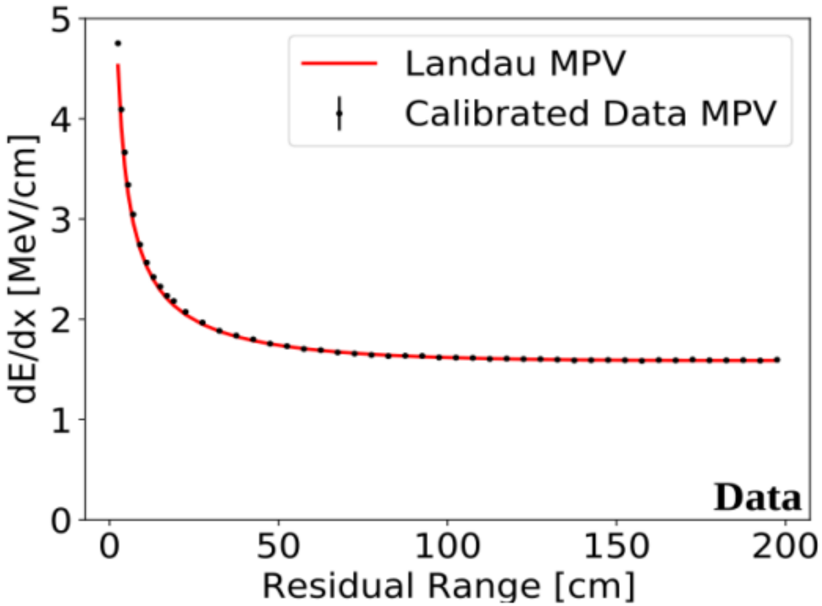
12 INFN groups, 11 US institutions, CERN, 1 Institution from Mexico, India and UK

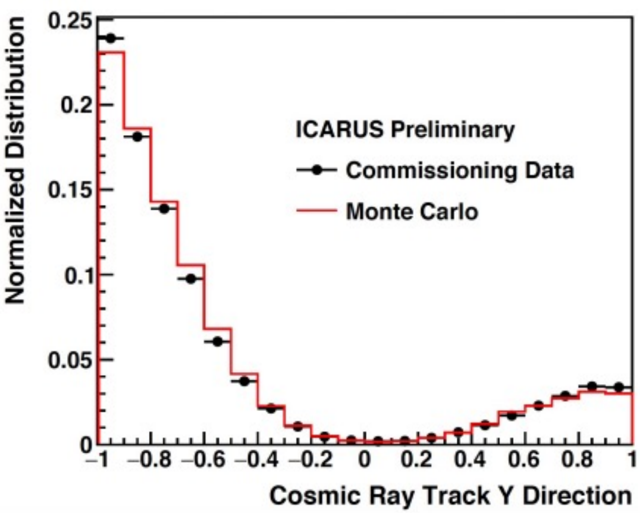
1. *Brookhaven National Lab., USA*
2. *CERN, Switzerland*
3. *CINVESTAV, Mexico,*
4. *Colorado State University, USA*
5. *Fermi National Accelerator Lab., USA*
6. *INFN Bologna and University, Italy*
7. *INFN Catania and University, Italy*
8. *INFN Genova and University, Italy*
9. *INFN GSSI, L'Aquila, 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. *University College London, UK*
26. *INFN Pisa and University, Italy*
27. *Ramanujan Faculty Phys. Res. India*

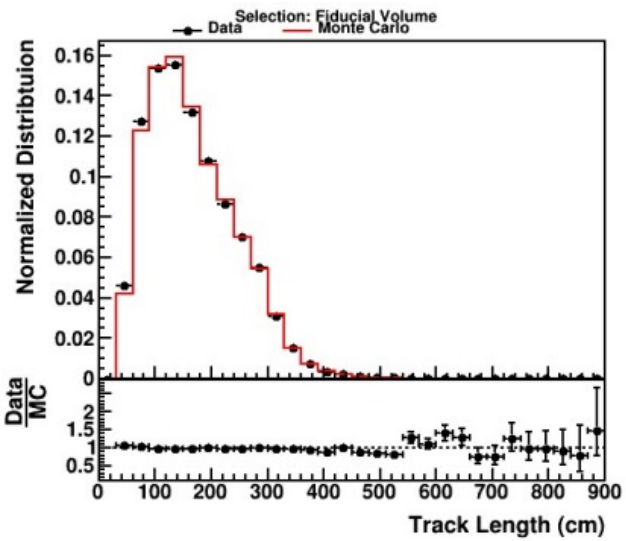
a On Leave of Absence from INFN Padova
b On Leave of Absence from INFN Pavia

Data analysis status

- Detector performance studied using cathode-crossing cosmic muons
- Good cosmic ray data-simulation agreement

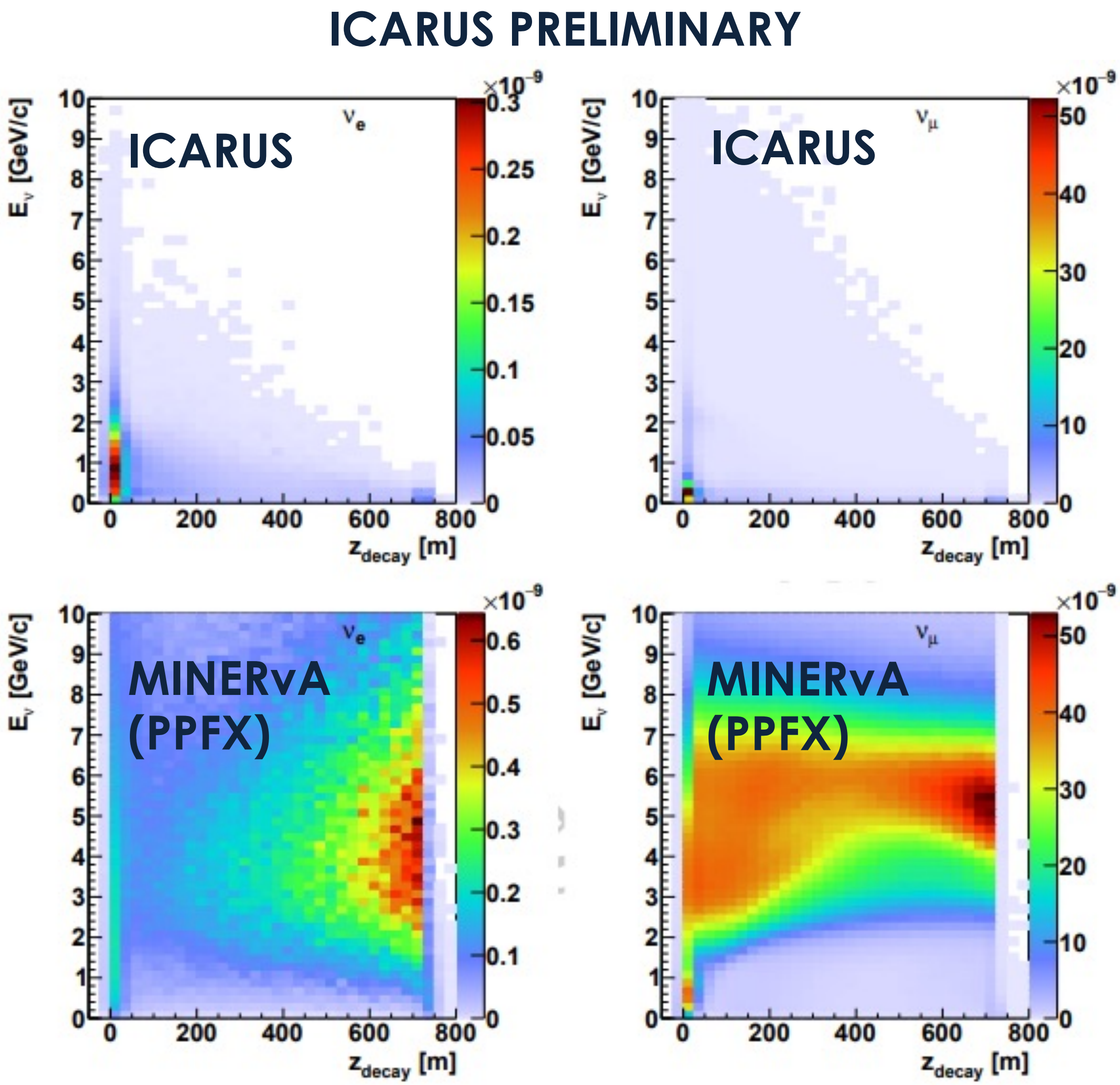






NuMI at ICARUS

- At ICARUS' off-axis angle, neutrino produced by NuMI usually originate from decays very close to the NuMI target
- Hadrons also tend to undergo more inelastic interactions before decaying to give neutrinos
- Hadrons have not been completely focussed, large wrong sign contamination
- Expect flux modelling uncertainties at the 10-15% level



NuMI at ICARUS

- The beam covers a wide range of off-axis angles
- Pions producing neutrinos must have a significant component of their momenta towards ICARUS to produce neutrinos with a large energy
- Kaons producing neutrinos can be closer to on-axis whilst still producing reasonably energetic neutrinos

ICARUS PRELIMINARY