ICARUS at Fermilab

Experimental Program and Status

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CAP Congress 2026
Ottawa, Ontario

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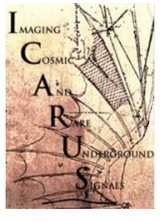
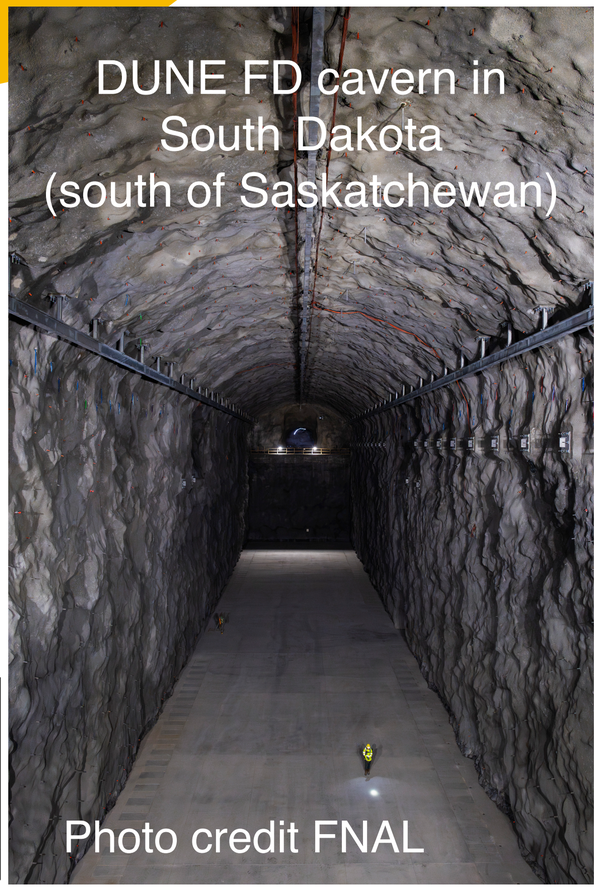
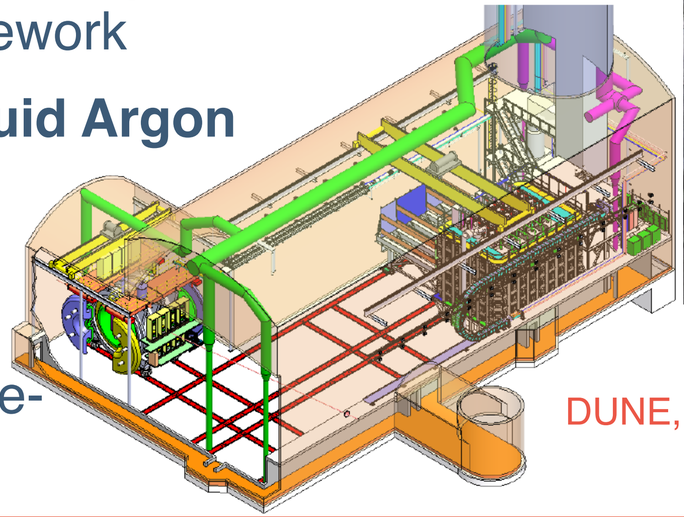
Fermilab



Where we're headed

- Gianfranco Ingratta just told us all about the Deep Underground Neutrino Experiment (DUNE):
  - Expected to provide unparalleled access to neutrino oscillation parameters:
    - Resolve neutrino mass ordering
    - High sensitivity to possible CP-violation
    - Measure several oscillation parameters in a single detector, test validity of three-flavour framework
  - As discussed in last talk, DUNE will use **Liquid Argon Time-Projection Chambers** (LAr TPCs)
  - A somewhat related open question in neutrino physics is: are there more neutrino states than the three flavours and is the three-flavour oscillation framework complete



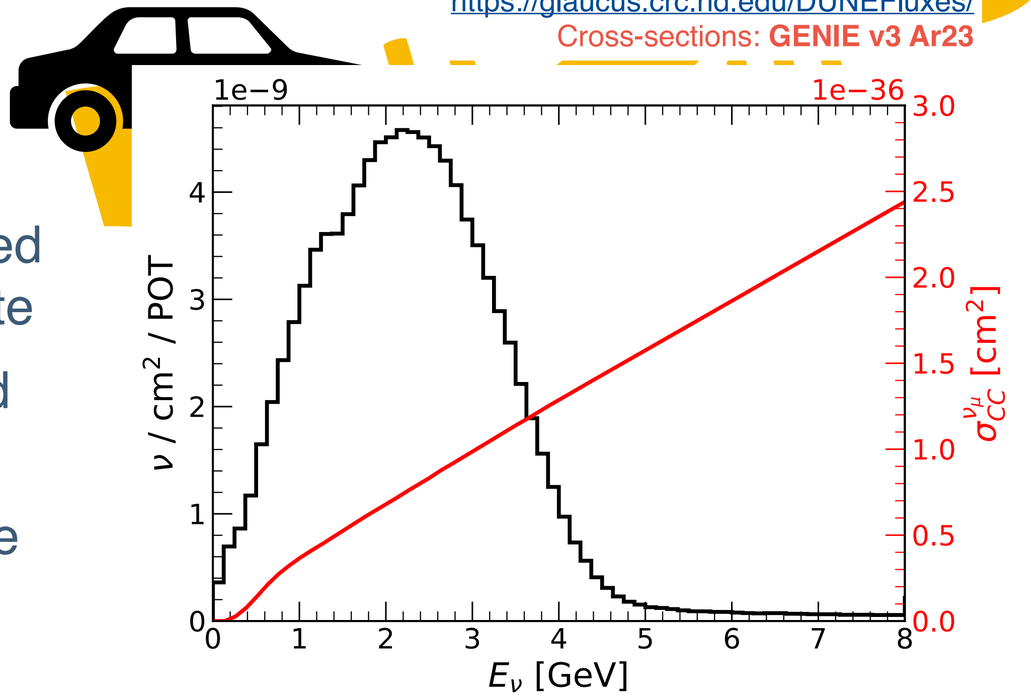


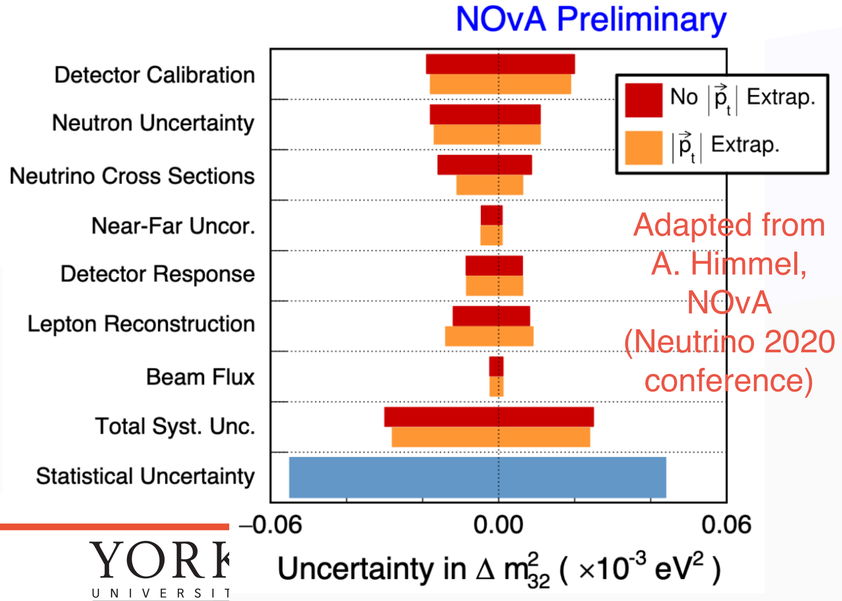
DUNE, arXiv:2408.12725

Where we're headed

- Neutrinos are interacting with complicated nuclei (Ar for DUNE, O for Hyper-Kamiokande) and in the several hundred MeV to few GeV range, several interaction modes contribute
  - Measurement at detector is convolution of flux (oscillated or unoscillated) and cross-section
  - Outgoing particles and kinematics have uncertainties due to not fully modelled cross-sections, contribute to uncertainties in oscillation measurements
  - Different models and generators, each with upsides and downsides: want to better model cross-sections!
  - Ways of mitigating some effects (e.g. DUNE's PRISM) but still would like better understanding of cross-sections
- DUNE will use large LAr TPCs: very sensitive detectors, but complicated. Cryogenics, many thousands of channels, light AND charge detection, event reconstruction, analysis, etc.

DUNE TDR-era flux:
https://glaucus.crc.nd.edu/DUNEFluxes/
Cross-sections: **GENIE v3 Ar23**

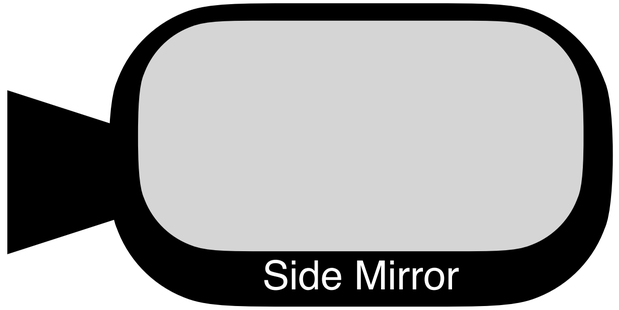


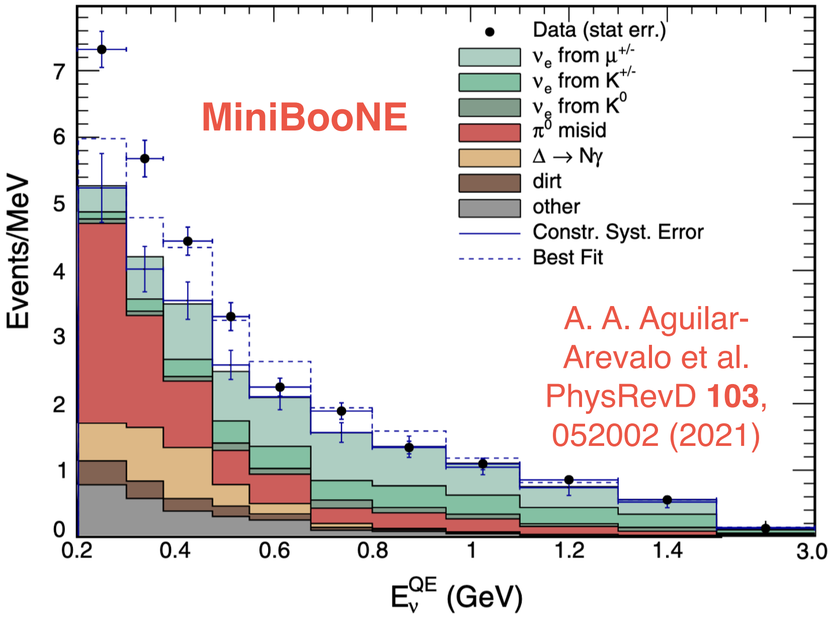


Adapted from A. Himmel, NOvA (Neutrino 2020 conference)

Where we've been:

- So, anything we can do with our current generation of detectors to help address these points will be incredibly useful for the next generation of experiments:
  - Operate large LAr TPC detectors to **gain critical experience in operating, modelling, and analyzing data**
    - And train highly qualified personnel to be prepared for leading efforts in DUNE
  - Leverage **neutrino interactions** from beams to better understand the **input models going into DUNE** measurements (and help lead to better ones)
- Also perform important measurements: anomalous results in previous experiments (MiniBooNE, LSND) point to unexpected excess in electron neutrino candidates at short distance, unexplainable with three-flavour oscillations of a muon neutrino beam (**unexpected extra neutrino states?**)





MiniBooNE: few hundred MeV, few hundred m
LSND: tens of MeV, tens of m

DUNE: ~2.5 GeV, 1300 km ~ 500 m/MeV
T2K/Hyper-K: 600 MeV, 300 km ~ 500 m/MeV

ICARUS collaboration

- ICARUS (Imaging Cosmic and Rare Underground Signals)
- Collaboration originally formed in Italy and worked to build the earliest operational liquid argon (LAr) time-projection chambers (TPCs)
  - Worked up to larger and larger prototypes and eventually operated the T600 detector (more on next slide) in a neutrino beam in Gran Sasso, Italy
  - Placed underground in INFN-Gran Sasso and detected neutrinos produced at CERN (hence a very appropriate name)
- Collaboration sent T600 detector to CERN for refurbishment in mid 2010s, then to Fermilab in Illinois
  - Now includes Italy, USA, Brazil, **Canada**, CERN, India, Mexico

P. Abratenko et al.
EPJC (2023) 83:467

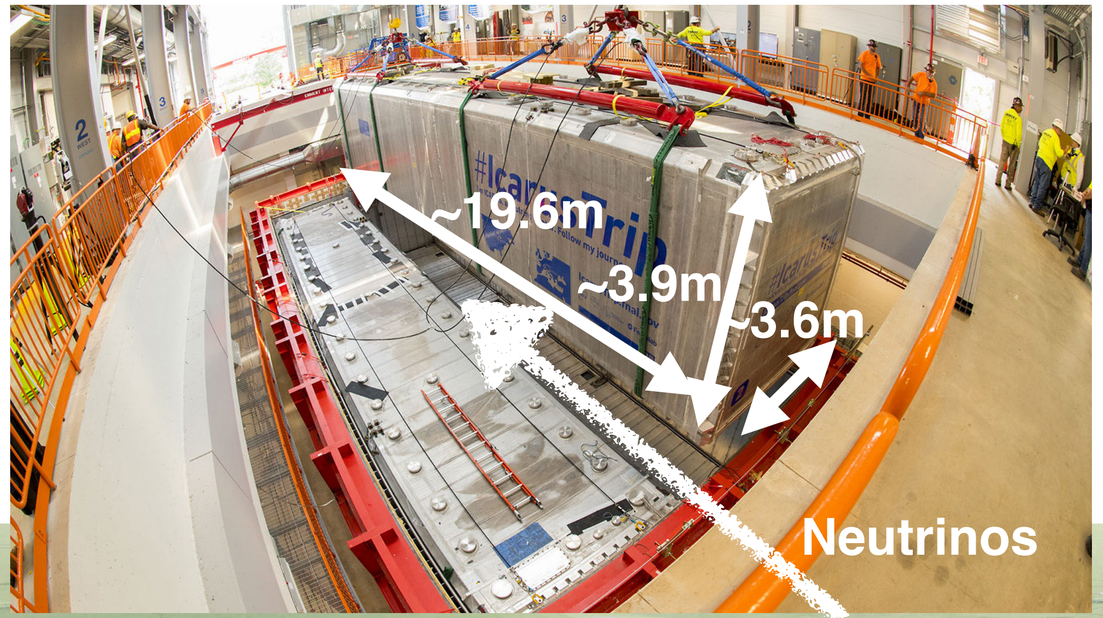
ICARUS detector

- Consists of 4 TPCs (each 1.5 x ~3.1 x ~19 m^3)
  - Though at surface, short drift distance minimizes field non-uniformity from “space-charge”
  - 3 wire planes (1 horizontal, 2 angled), wire spacing 3mm
- Each has 90 PMTs coated with a wavelength shifter (provides trigger on activity in-time with beam)
- External Cosmic Ray Tagger (CRT) covers detector faces: allows distinction of if activity is originating outside of the detector
- T600 has 760t LAr (476t active), **~1/20 of a DUNE module** (however, the first big LAr TPC to be operated and still one of the largest)

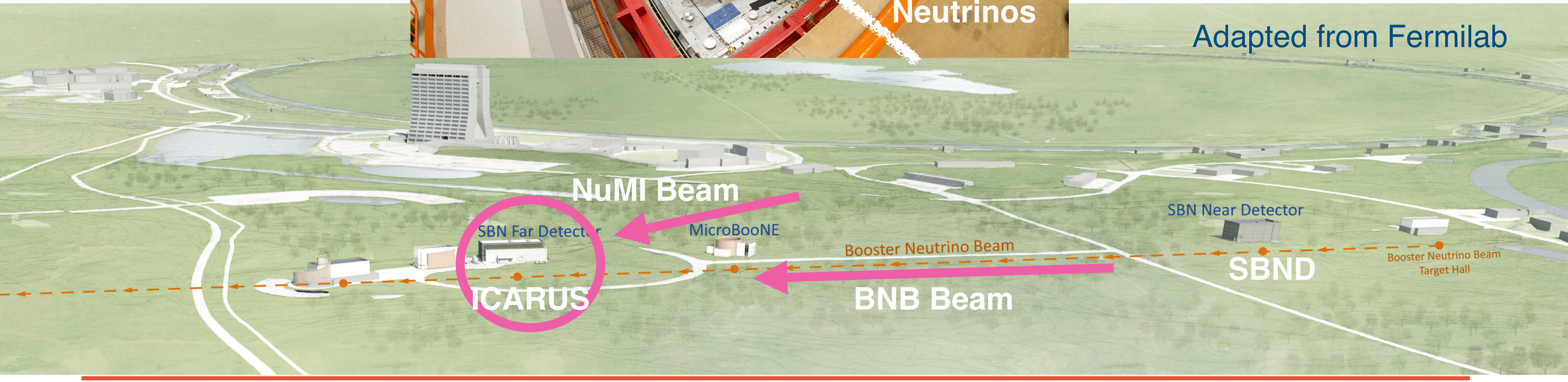
P. Abratenko et al.
EPJC (2023) 83:467

Where we are: ICARUS at Fermilab

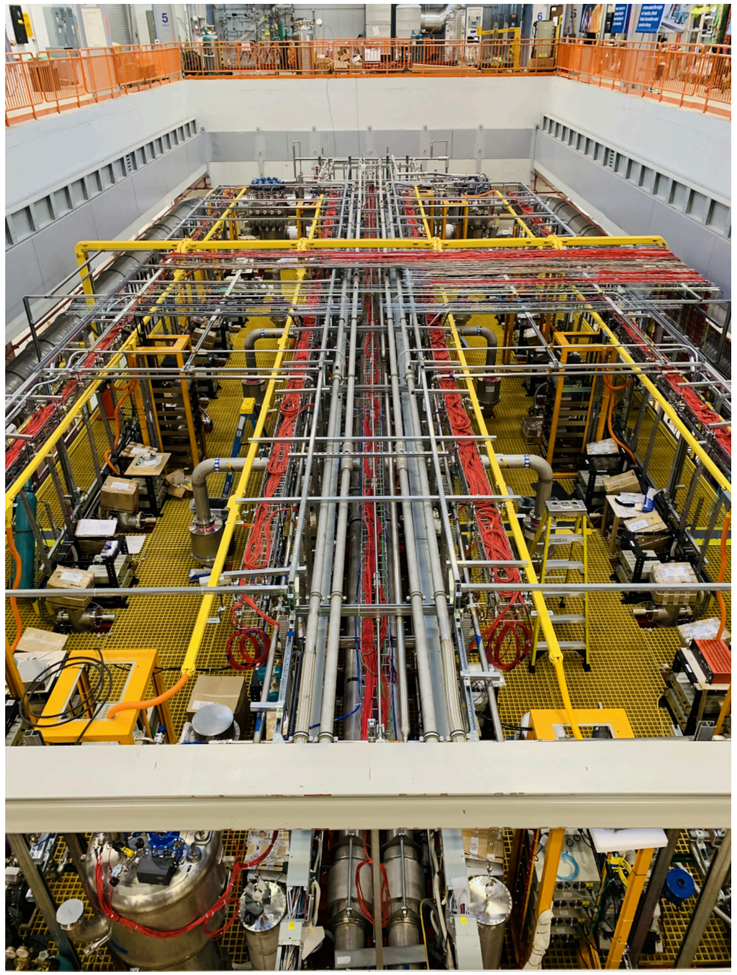
P. Abratenko et al.
EPJC (2023) 83:467



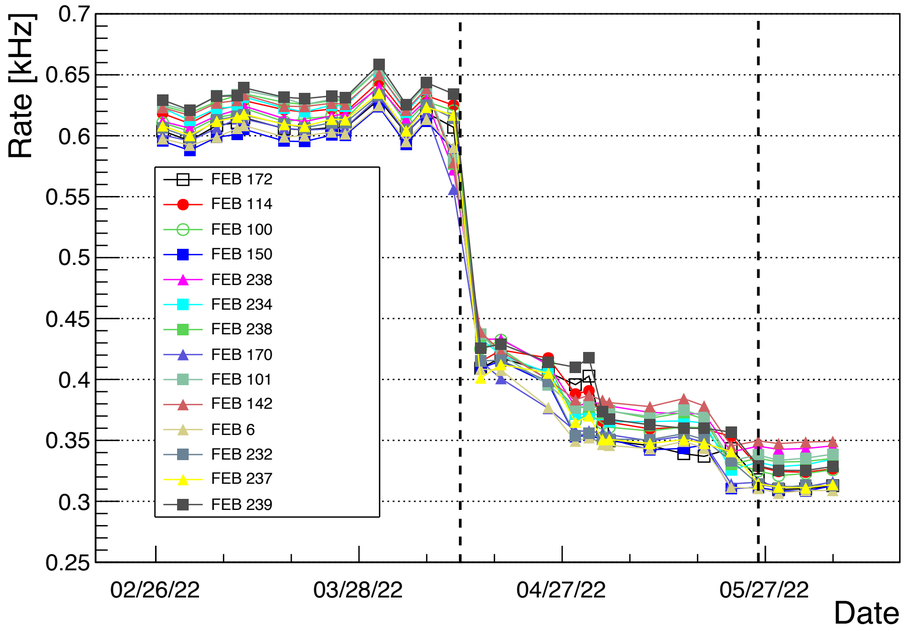
Adapted from Fermilab



ICARUS installation and operations at Fermilab



- Now concrete blocks above the silver cosmic-ray tagger modules
- Overburden (6 m.w.e.) reduces cosmic background

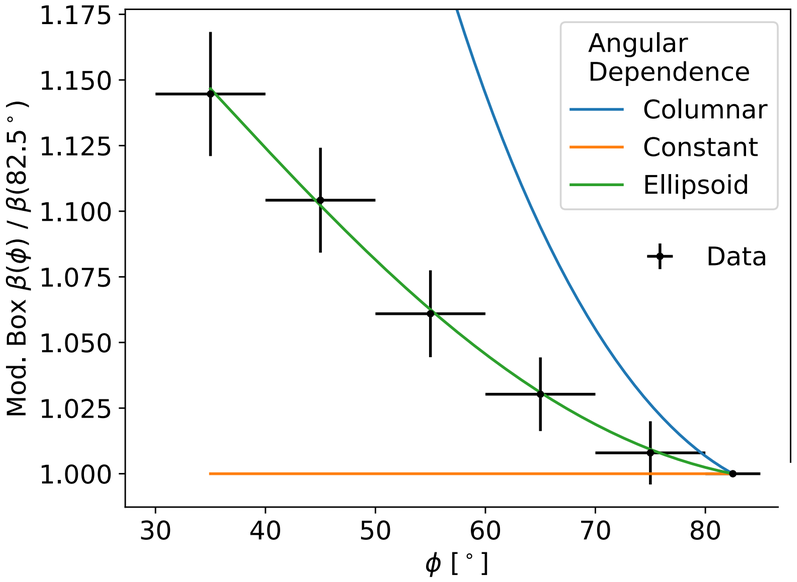


Abratenko, P., Aduszkiewicz, A., Akbar, F. *et al.* ICARUS at the Fermilab Short-Baseline Neutrino program: initial operation. *Eur. Phys. J. C* **83**, 467 (2023).

ICARUS installation and operations at Fermilab

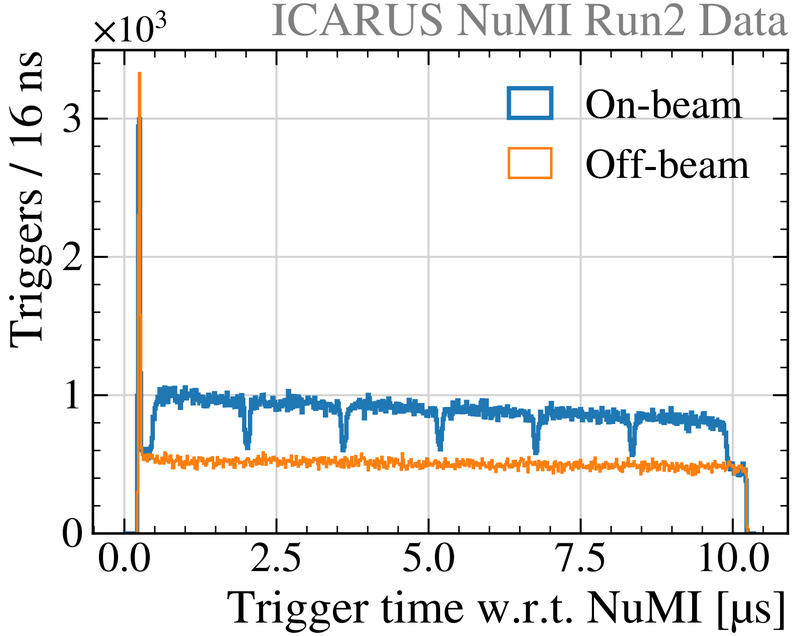
Lots of work on understanding performance & operation of detector

Developing & exercising procedures for characterizing the detector and detector effects with other LAr TPCs like ICARUS is an important step in preparation for future LAr TPCs.



JINST **20** P01033

JINST **20** P10044



Publications include

- Installation and first operations at Fermilab: EPJC **83**, 467
- Calibration: JINST **20** P01032
- Angular effects in electron-ion recombination: JINST **20** P01033
- Trigger: JINST **20** P10044
- and more published/in progress

ICARUS installation and operations at Fermilab

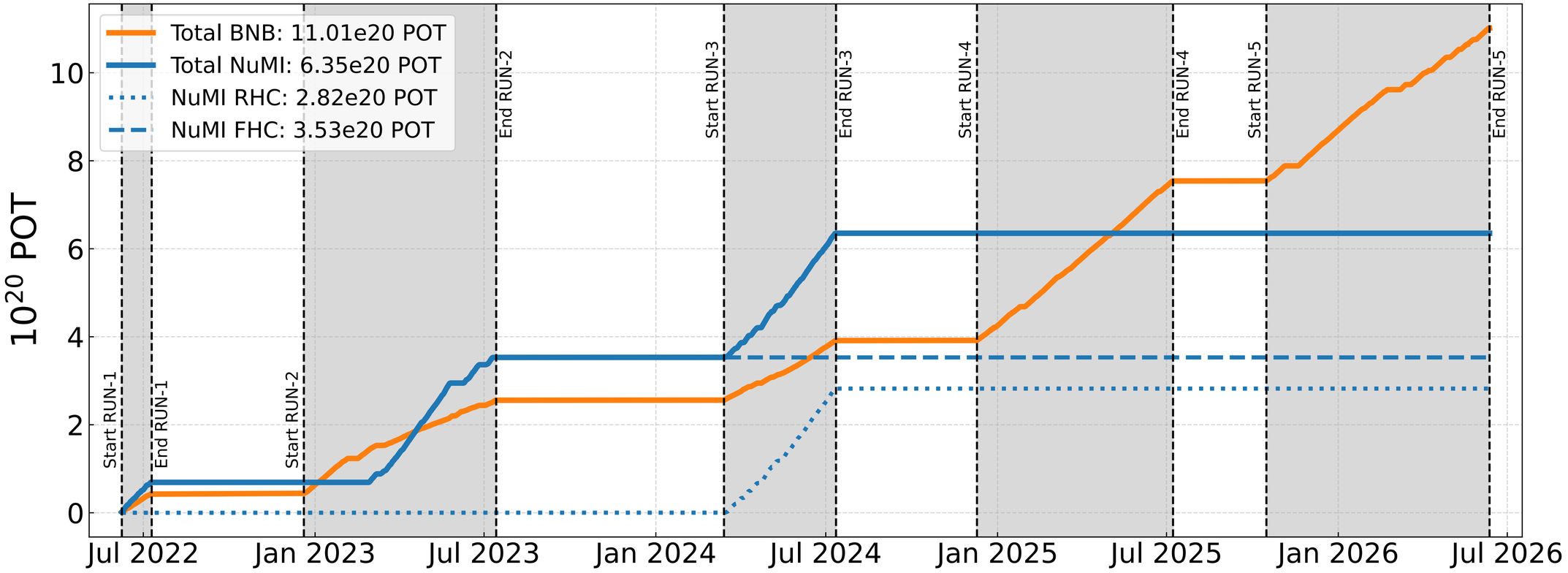
2020: initial fill, start of shifts, begin commissioning

2022: completion of cosmic-ray tagger installation

2022: start of physics data taking

Most recent beam operations period just ended few weeks ago

Excited for more stats!



BNB NuMI (ν)

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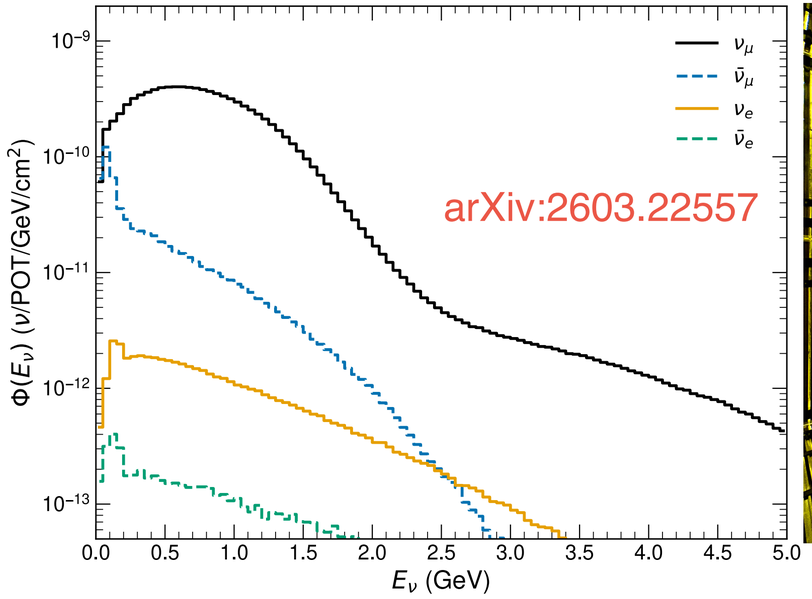
Short Baseline Neutrino (SBN) Program

BNB (Booster Neutrino Beam) → SBND 110 m → ICARUS 600 m

First data during 2024-2025 beam run

First physics data 2022



Flux as seen at ICARUS

SBND

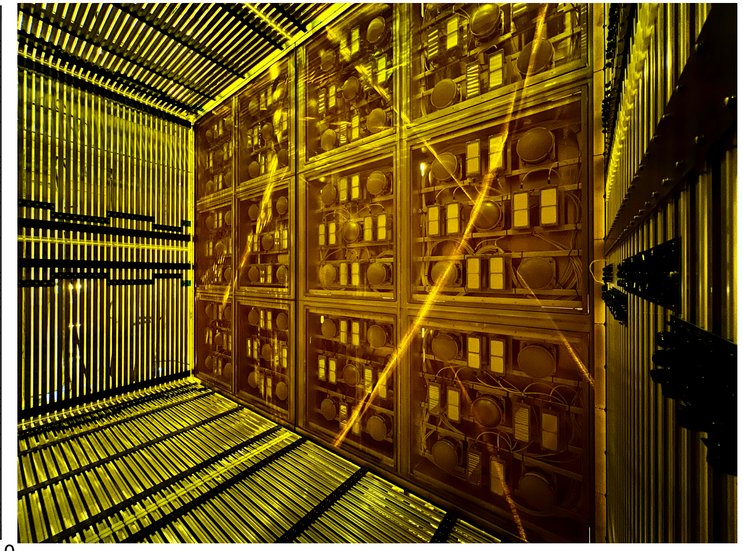
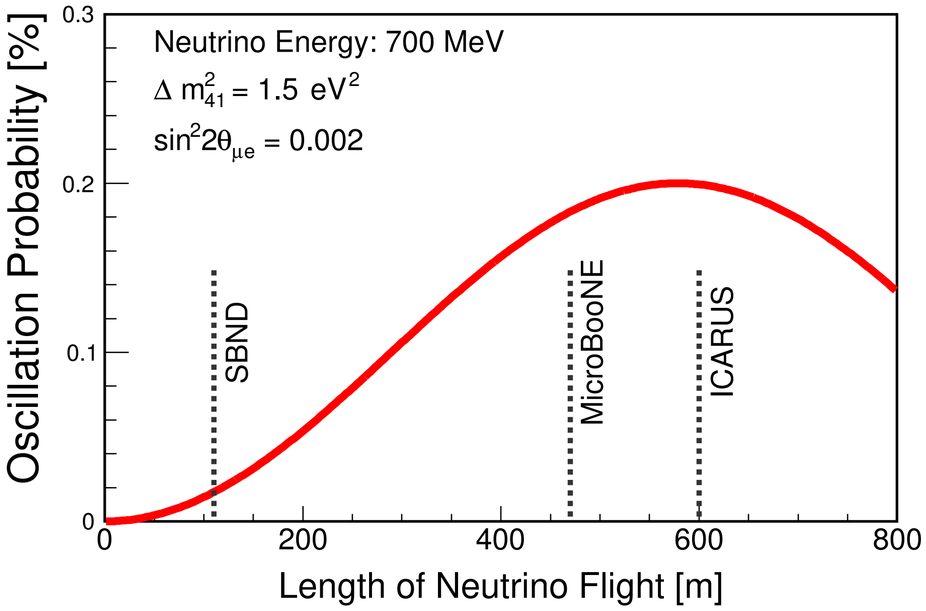


Photo credit: Mônica Nunes

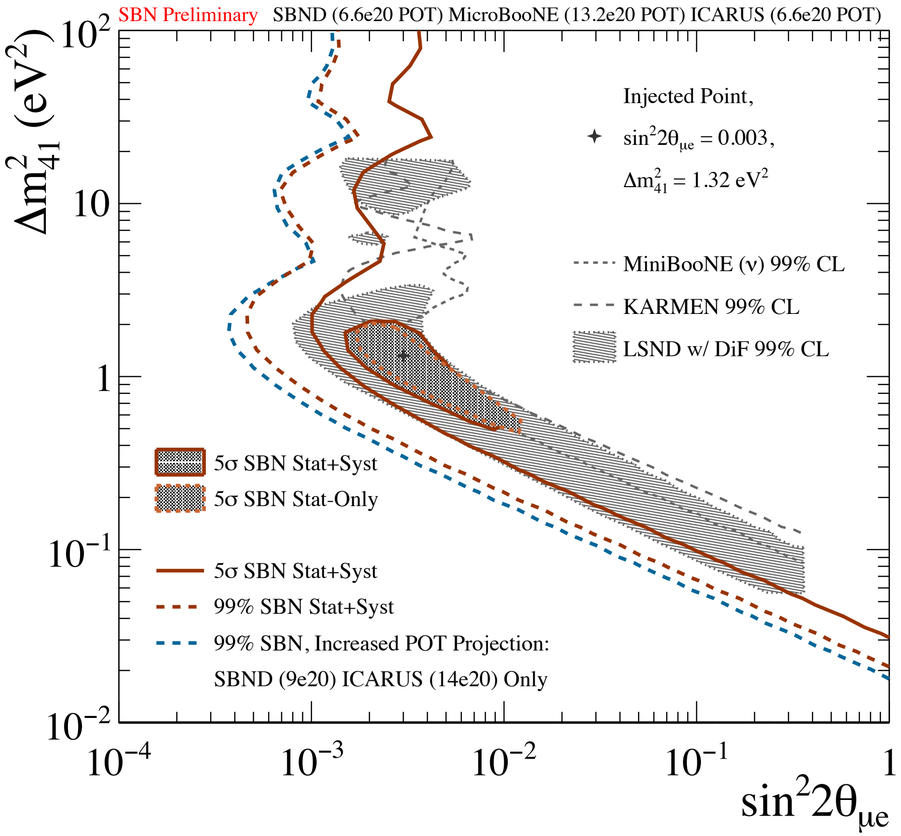
ICARUS

Adapted from CERN/Fermilab

SBN Program



P. Machado, O. Palamara, D. Schmitz. Annu. Rev. Nucl. Part. Sci. (2019) 69:363-87



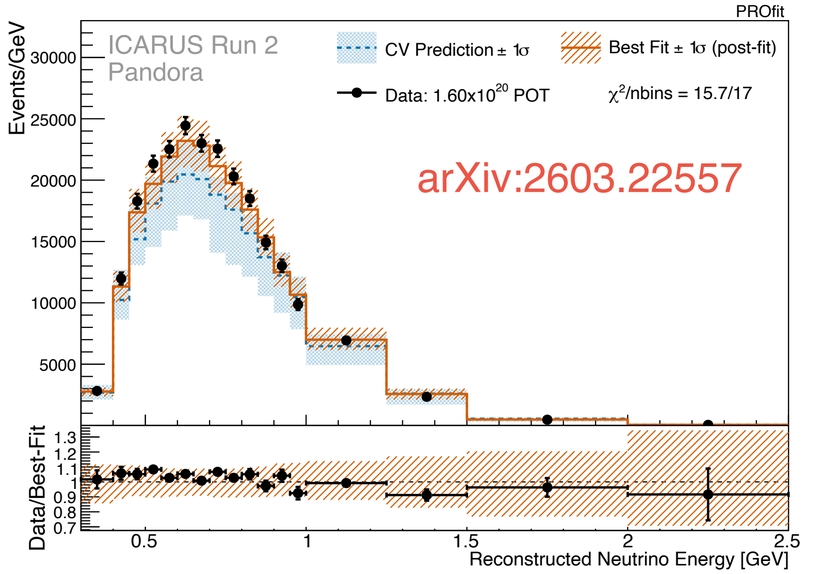
See: R. Acciarri et al. arXiv:2504.00245

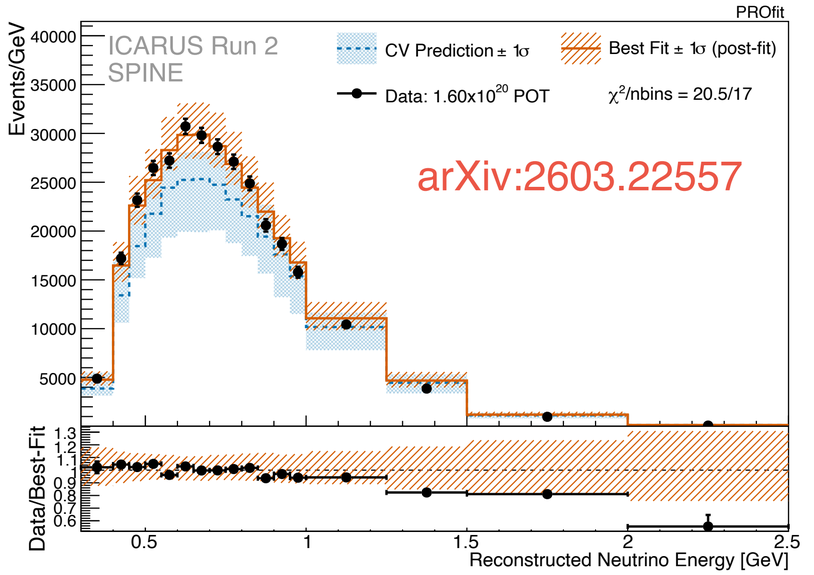
- This allows a two-detector oscillation style search a la DUNE
  - But VERY different L/E (~1 m/MeV in SBN, ~500 m/MeV in DUNE)
  - Targets the L/E range of previous anomalous results (MiniBooNE, LSND)
  - Also LAr TPC technology useful for electron/photon separation, clarify nature of the excess if found.

First oscillation result

- No time to go into details, ICARUS has recently released an ICARUS-only search for **muon neutrino disappearance**:
  - ~2.05x10^{20} protons-on-target (POT) exposure (fraction of total!)
  - Single detector: a first result and demonstrates framework
    - Affected by systematics differently than SBND + ICARUS (flux and cross-section uncertainties will be reduced)
    - Both detectors continually improving detector modelling to reduce systematic uncertainties here
  - Two event-level reconstruction packages: cross-validate results
- Sets stage for full two-detector oscillation searches with SBND and ICARUS
  - SBND now taking physics data
  - Joint analyses are in preparation (both disappearance and ultimately **appearance**)

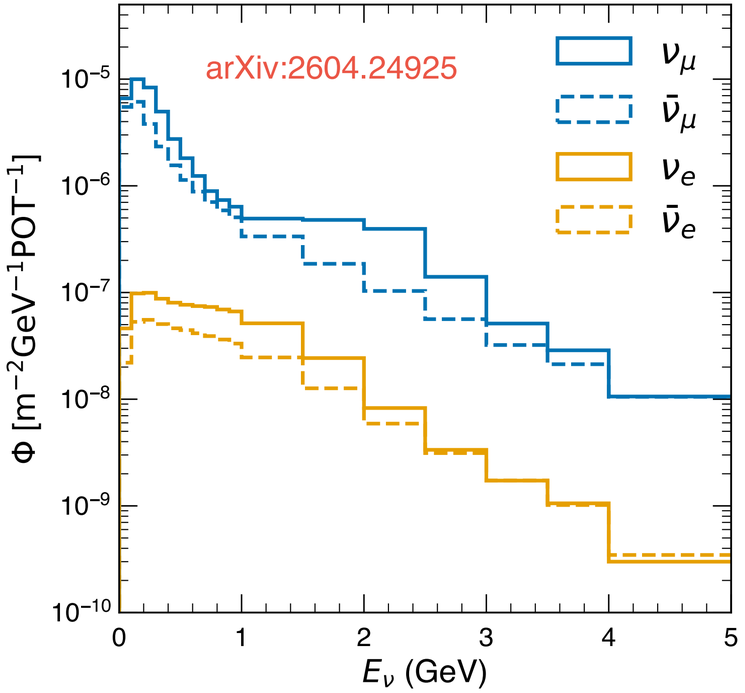
Null hypothesis fits in both reconstructions and selections





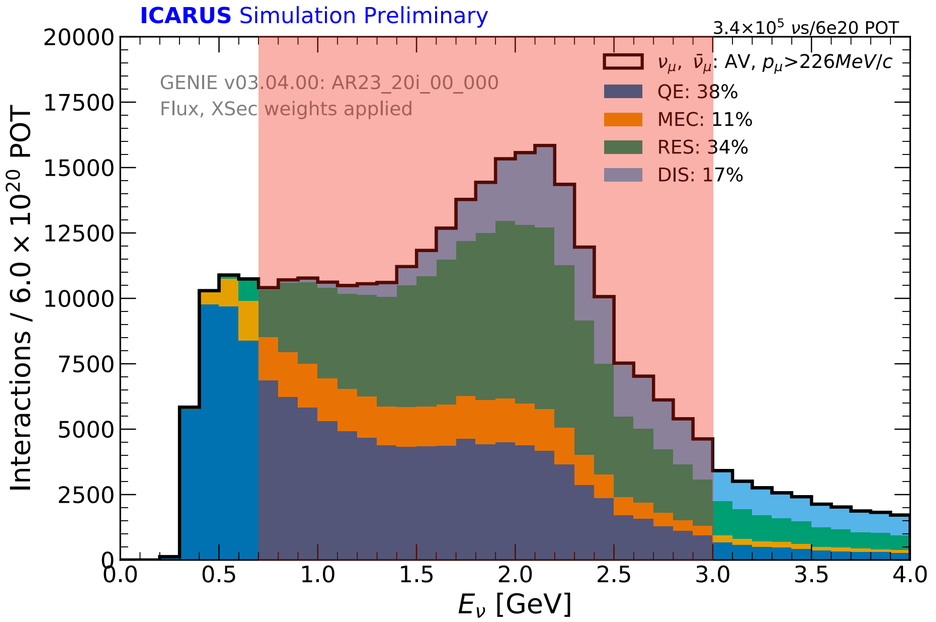
NuMI at ICARUS

Cross-section increasing with energy gives us a broad spectrum of interactions in ICARUS to use for studies!



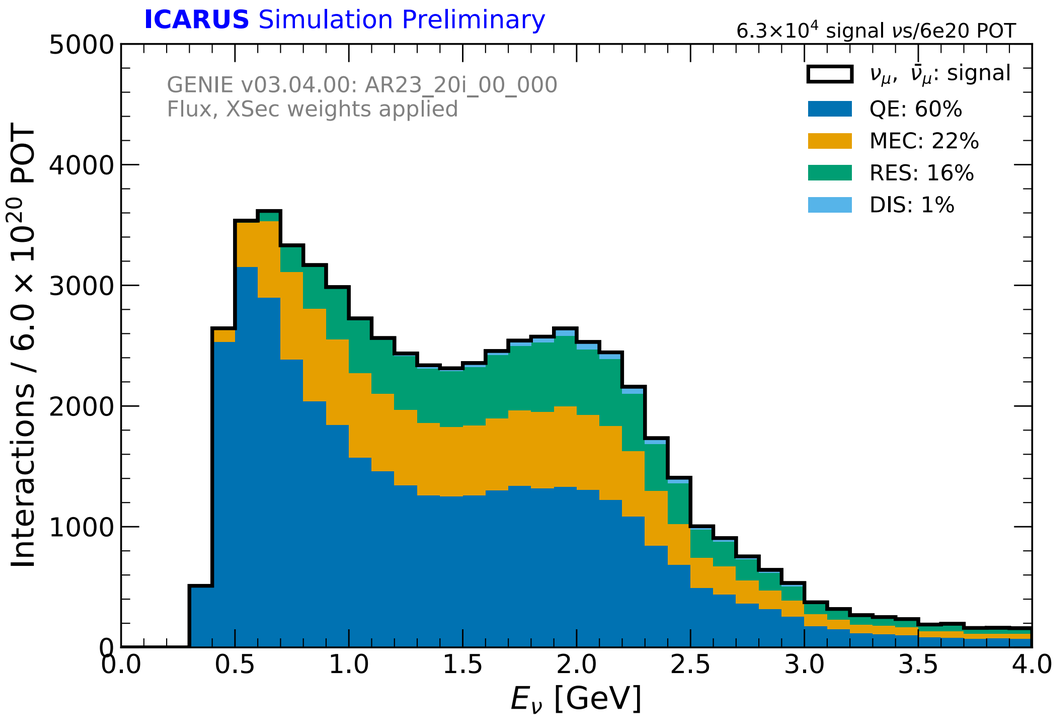
- 6 degrees off-axis, 800 m distance from target
  - Alters spectrum: kaon decay neutrinos swept to few GeV (DUNE range of interest)
  - Electron neutrino component enhanced relative to BNB beam (~5%)
  - NuMI runs in both neutrino & antineutrino mode
    - At our angle, benefit less from magnetic selection
    - However, a different and complementary flux, and work is ongoing to do antineutrino cross section with the antineutrino beam mode
- We are using GENIE (neutrino event generator) with its “AR23” as the model - same baseline model as DUNE
  - Some similar systematics packages in use in common between DUNE and SBN experiments

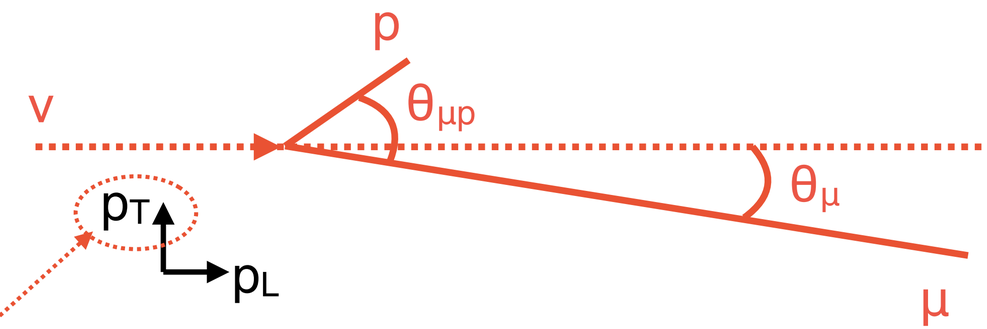
DUNE region of interest!



NuMI at ICARUS

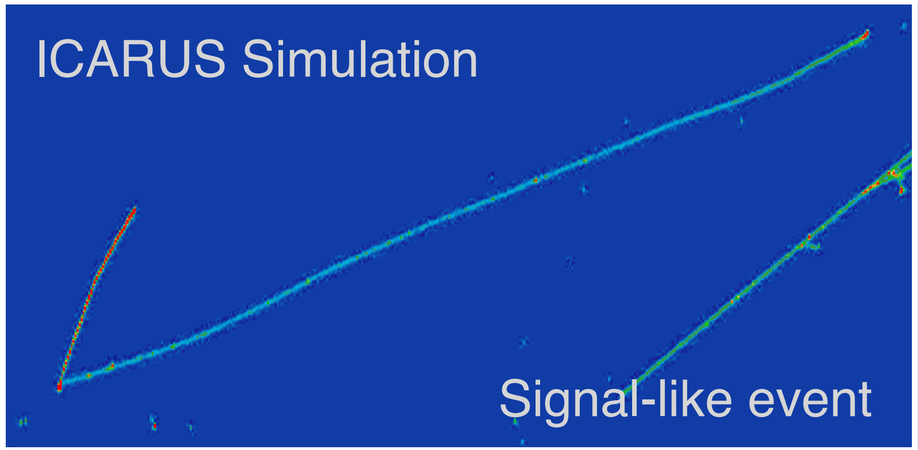
- First cross-section with NuMI at ICARUS: targeted a signature with 1 μ, at least 1 p, and no pions
  - Enhance quasi-elastic-like (QE-like) interactions
  - No pions could mean none produced, or could mean final state interactions (FSI)
- Placed signal region cuts to get events of interest:
  - Muon momentum > 226 MeV/c (~50 cm in Ar)
  - Leading proton between 0.4 GeV/c - 1.0 GeV/c
  - For variables using muon momentum, place signal definition for muon momentum < 800 MeV/c (we ask for muon to be contained in detector in selection)
- Variables chosen with aim of sensitivity to interaction kinematics & nuclear effects (e.g. initial nuclear state, FSI)
  - All selected signal events: muon angle, muon-proton angle
  - Contained muons: transverse kinematic imbalance (TKI)

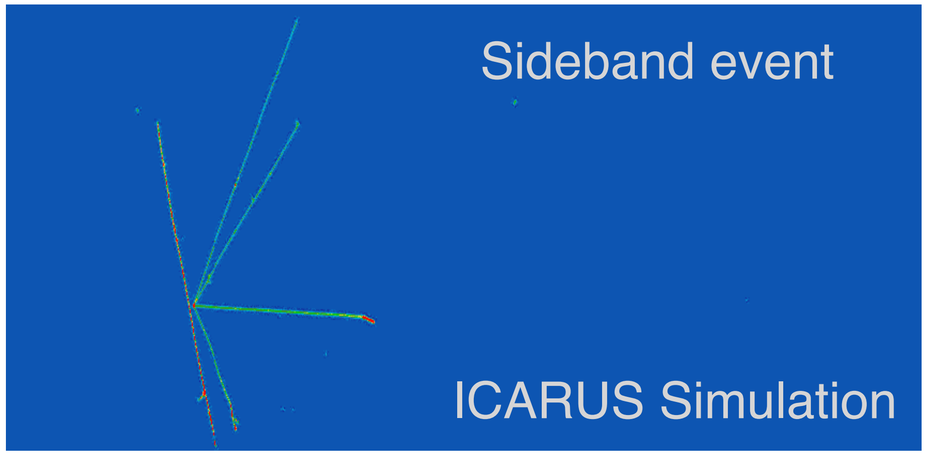




NuMI at ICARUS

- Signal-like selection picks things passing cuts on reconstructed interactions within a fiducial volume and not tagged as cosmic-ray-like, where reconstructed particles meet signal-like metrics, including:
  - A single muon (> 50 cm long) and no other minimally ionizing track near the vertex
    - Containment not required for angular variables, required for TKI (momentum from length)
  - N > 0 contained proton candidates, leading reconstructed momentum between 0.4-1.0 GeV/c
  - Photon-like cuts to reject neutral pions
- Sideband sample selected requiring at least one additional minimally ionizing track (length > 10 cm)



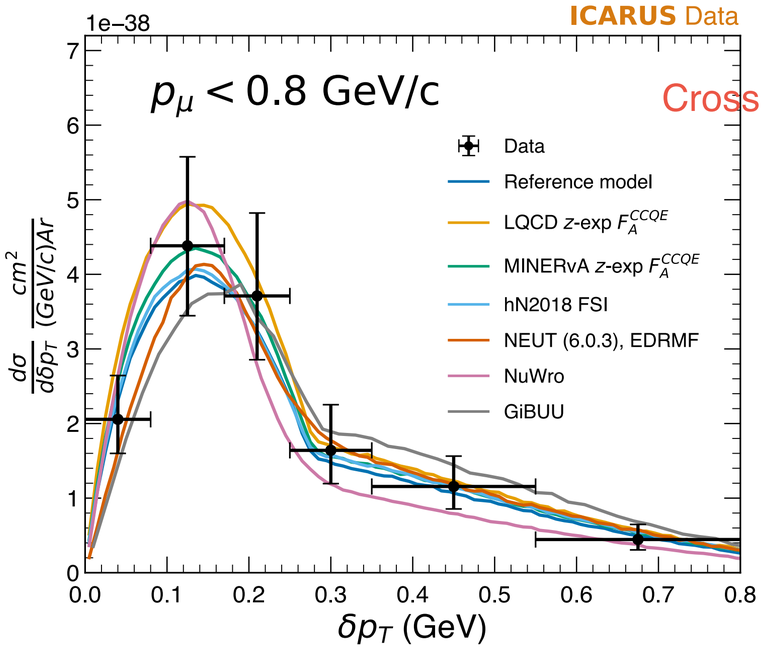


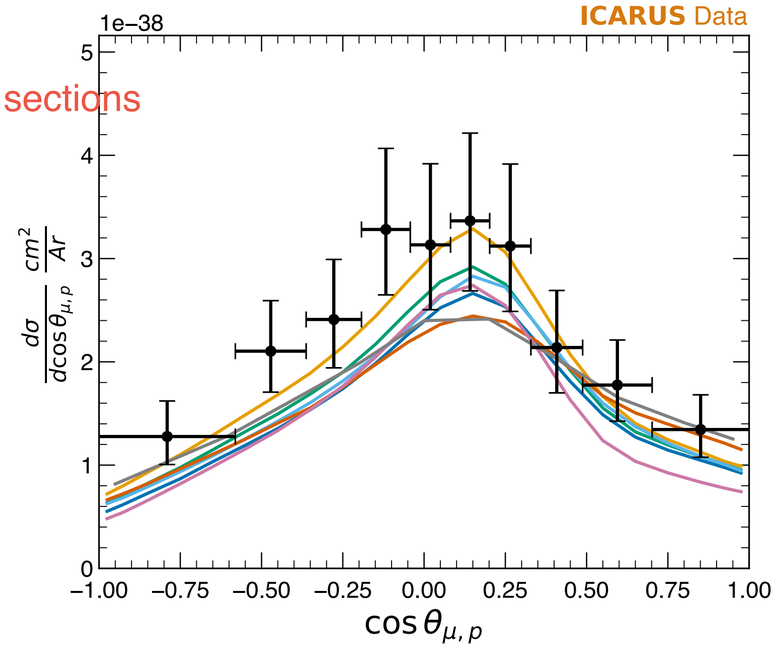
Figures adapted from **arXiv:2604.24925**

NuMI at ICARUS

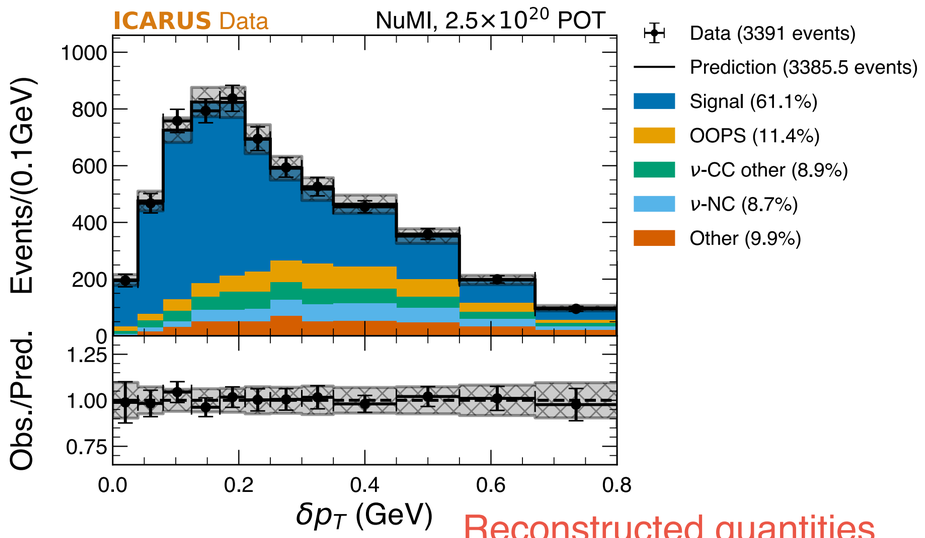
- Cross-section fit and extraction using the GUNDAM package originally created for T2K (GitHub)
  - Cross-sections computed in 1-dimension, BUT with simultaneous fits to 2 variables at a time (the 2 angular variables, or 2 TKI)
- Snapshot of some of the results (2 of four variables):

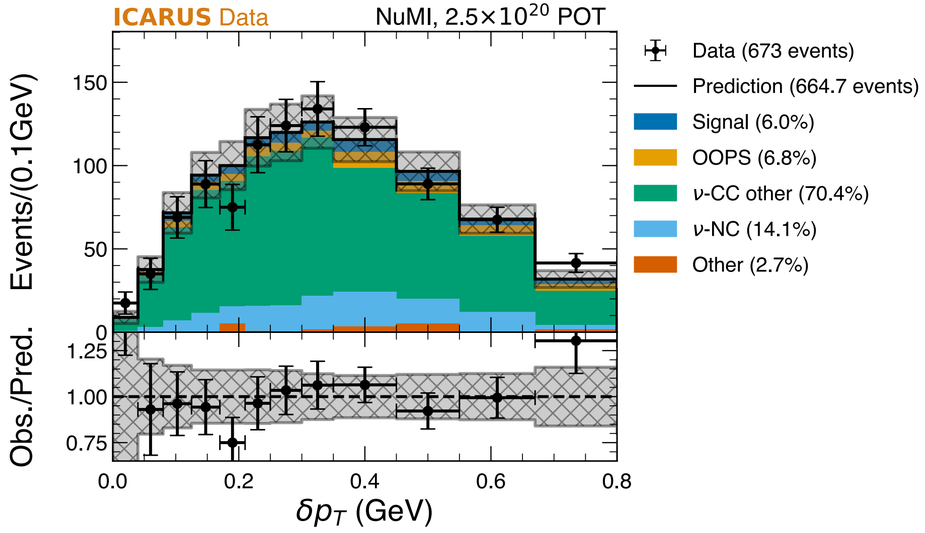
Cross sections





Reconstructed quantities





- Follow-up analysis aiming for better model separation and several different analyses in progress

Conclusions

- ICARUS is a Liquid Argon Time-Projection chamber in operation at Fermilab
- Does way more than I could possibly talk about in 12 minutes
- Sees neutrinos from two neutrino beams:
  - One beam services both SBND and ICARUS and is being used to study possible explanations of anomalous results in previous detectors
  - Other beam has primarily serviced other experiments, but ICARUS sees neutrinos from this beam off-axis (6 degrees):
    - Wide range of neutrino energies from this beam covering up to a few GeV
    - Neutrino interaction studies to help understand the limitations of current cross-section models and lead to development of improved models
    - Searches for non-standard physics (e.g. new particle production)
- Provides an invaluable opportunity to gain experience with this detector technology in advance of DUNE

Acknowledgments

Thanks to support for LAr TPC accelerator-based neutrino detector efforts in Canada from NSERC.

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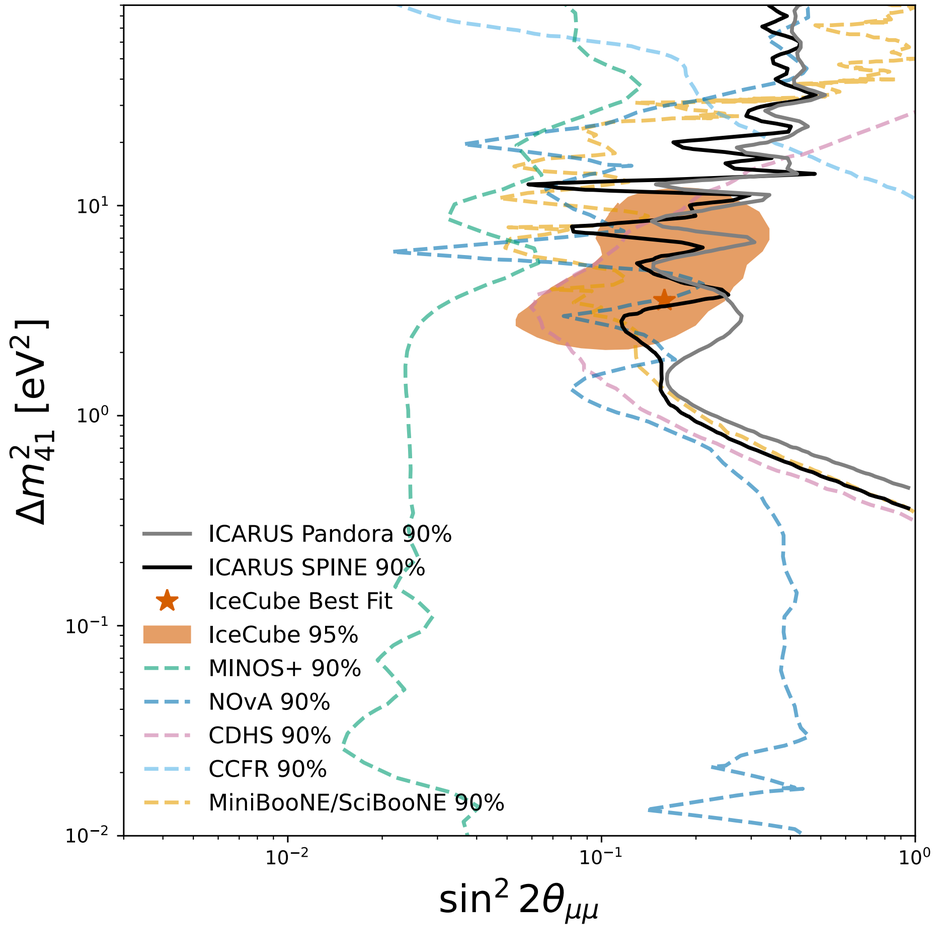
Backup

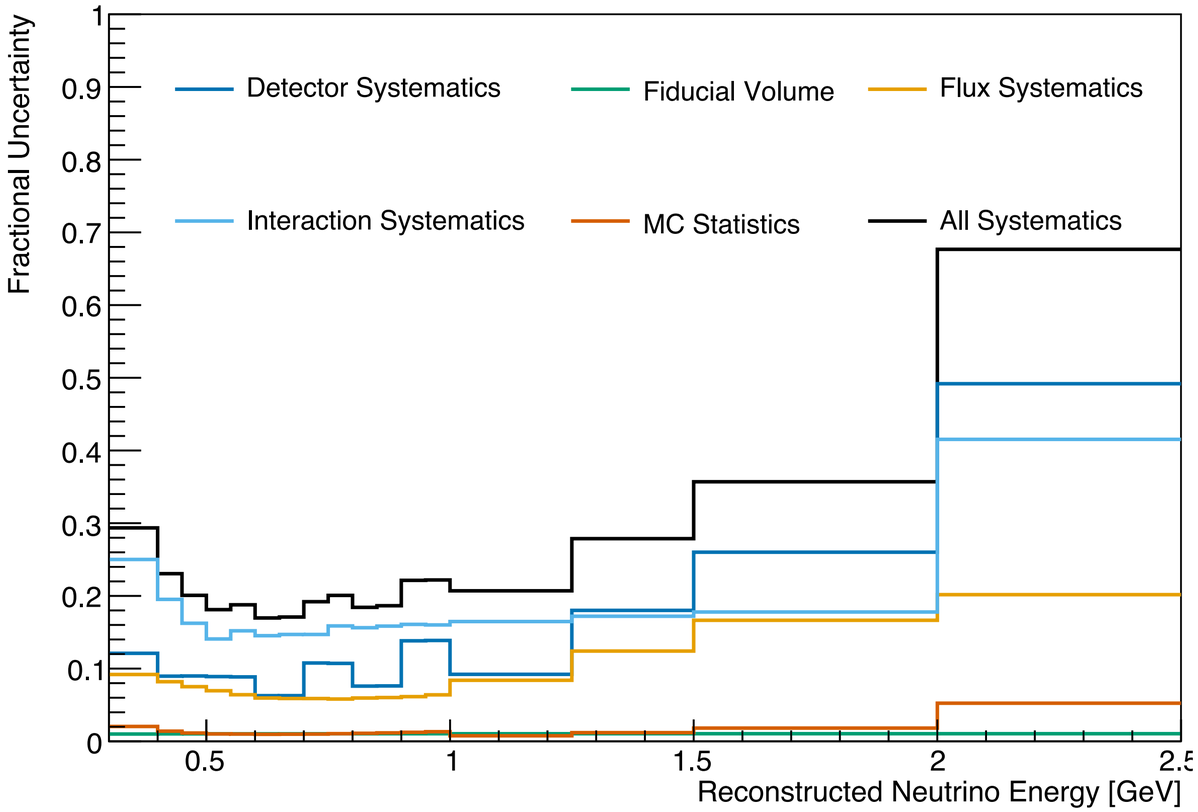
ICARUS-only oscillation study



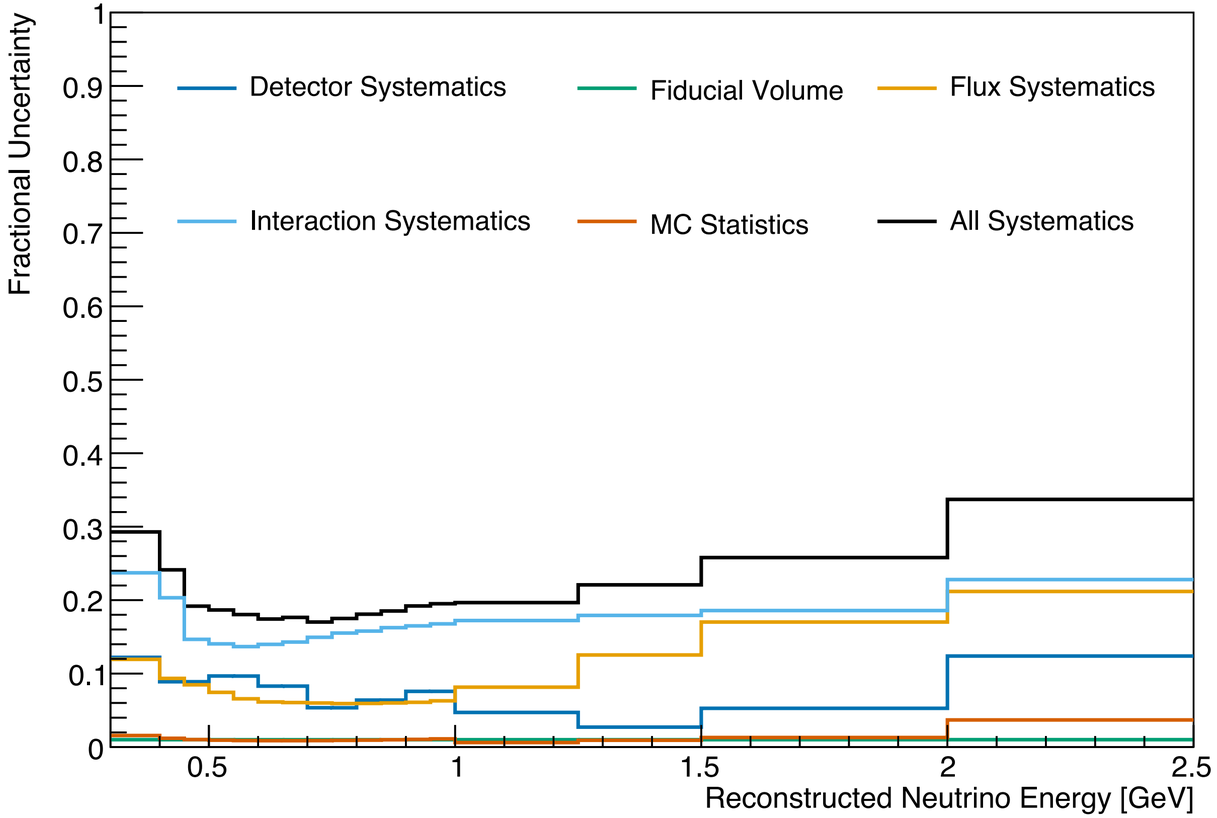
arXiv:2603.22557

ICARUS-only oscillation study

arXiv:2603.22557



Pandora-based analysis uncertainties

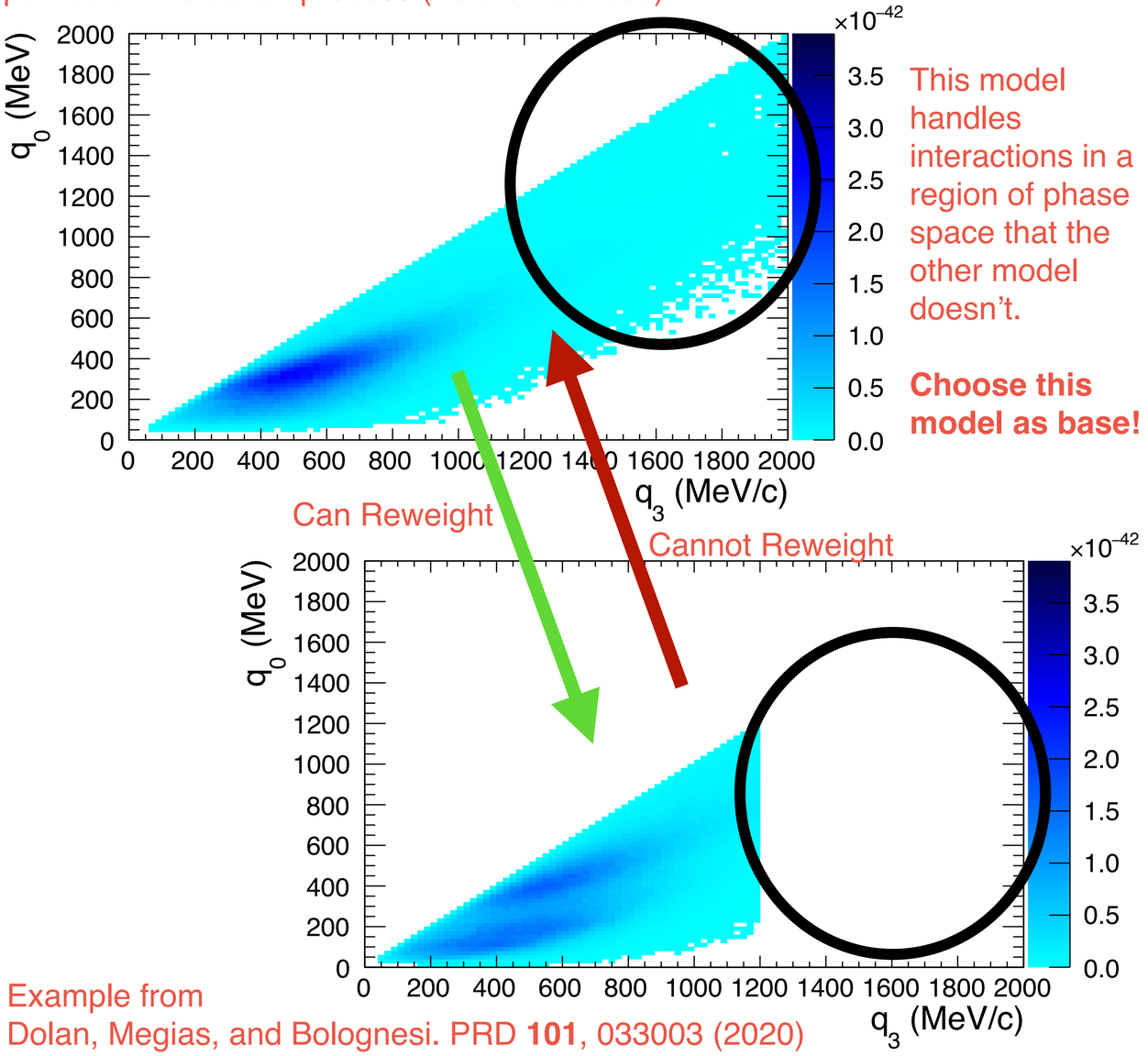


SPINE analysis uncertainties

NuMI at ICARUS

- We are using GENIE neutrino generator with its set of interaction models, predictions
  - Model choice is such that we match the same model as the baseline DUNE model (“AR23”)
  - Choice is guided by:
    - Ability to ascribe systematic uncertainties (GENIE enables calculating weights for interactions based on model uncertainties: enables reweighting events)
    - Similar systematics/same systematics available at ICARUS with nusystematics package as well
    - Make things reweightable where possible: i.e. given the choice of two models, if one is reweightable to the other and not vice-versa, chose the one that is

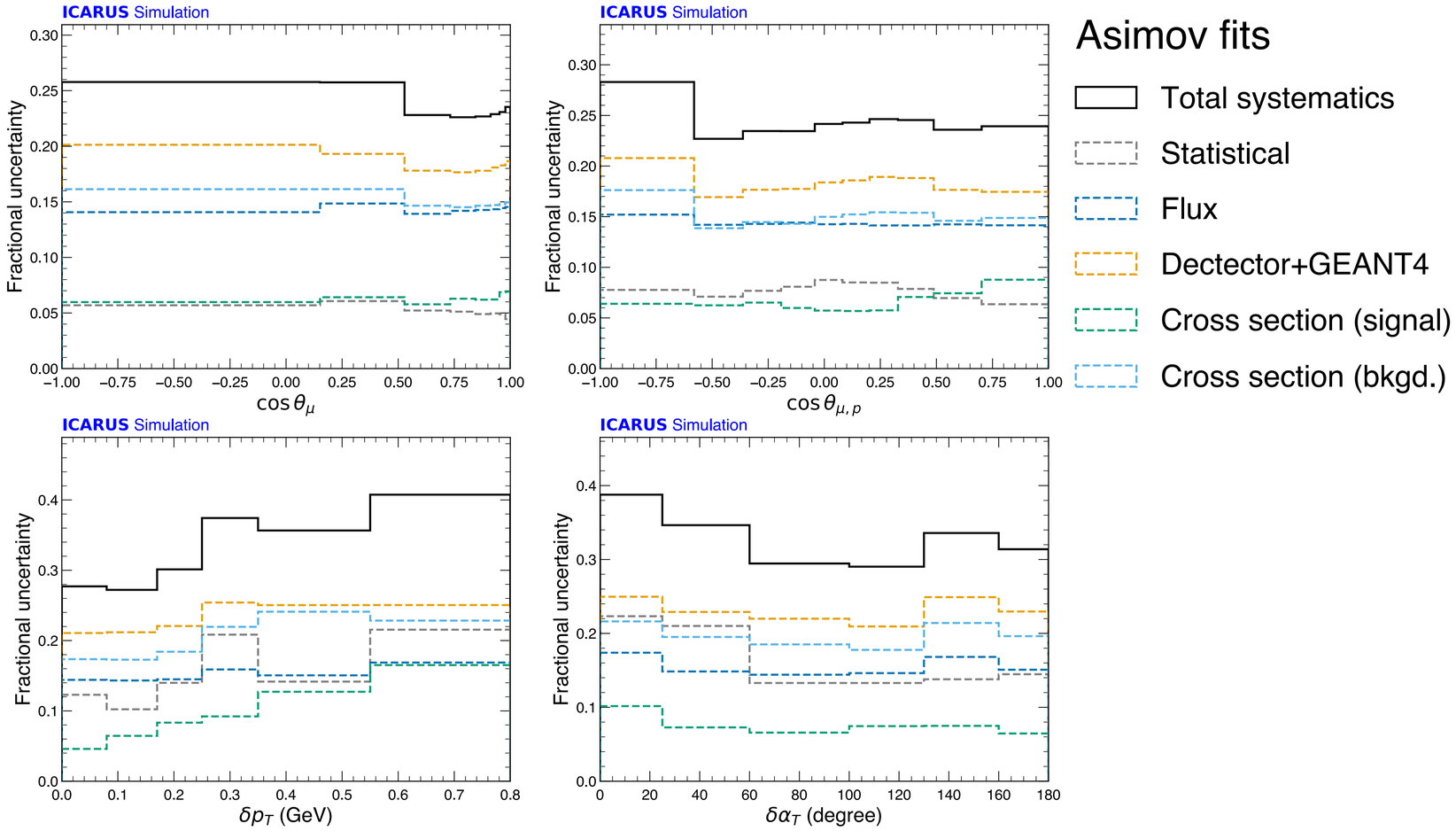
Event distributions for two different model choices available in GENIE for a particular interaction process (here on Carbon).



Example from
Dolan, Megias, and Bolognesi. PRD **101**, 033003 (2020)

Figures from **arXiv:2604.24925**

NuMI at ICARUS



More than I could possibly talk about in 12 minutes

- SBND now taking physics data fully unlocks the SBN Program!
  - First plan is for two-detector muon neutrino disappearance studies, building on the ICARUS-only measurement and exercising the two-detector fit
  - Additionally, work is ongoing to prepare for a full appearance + disappearance measurement that will utilize electron neutrinos (e.g. for appearance)
- Studying neutrino cross-sections and interaction properties with ICARUS will provide important tests of interaction models in the energy range of interest for next generation oscillation experiments. In addition to this first analysis:
  - Enhanced electron neutrino component off-axis
  - Neutrino and antineutrino cross-sections in various inclusive and exclusive channels
- NuMI is also an intense particle source close to our sensitive detector: looking for signatures of beyond Standard Model physics.
  - First result is a PRL (**134**, 151801 (2025)) and many more in the pipeline!