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ICARUS Cross-Section Measurements

Minerba Betancourt (Fermilab) on behalf of the ICARUS collaboration

April 04 2024

Short-Baseline Experiment/Theory Workshop

Short Baseline Science Program

Near detector (SBND)

Far detector (ICARUS)

Neutrino Energy: 700 MeV

$\Delta m_{41}^2 = 1.2 \ eV^2$

$sin^2(2\theta) = 0.003$

Oscillation Probability [%]

SBND

MicroBooNE

ICARUS

Length of Neutrino Flight [m]
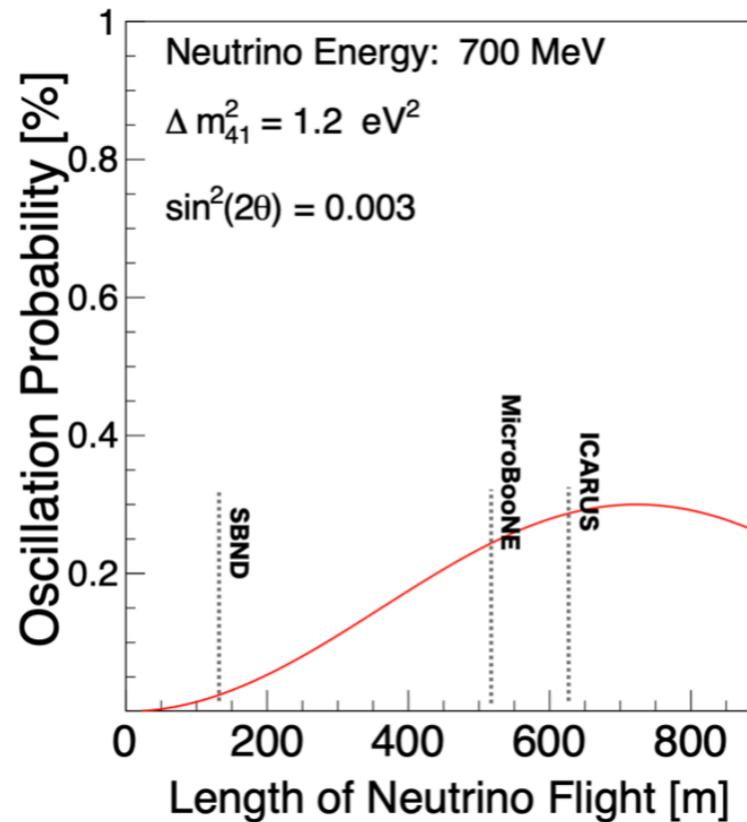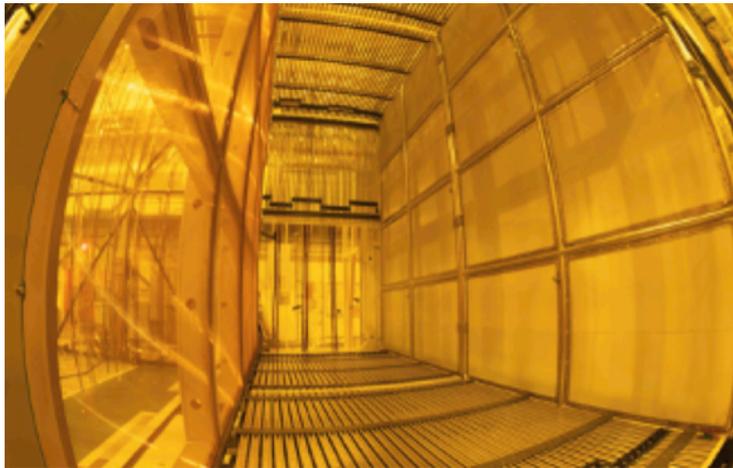
- **Search for Sterile Neutrinos**
  - ν_μ disappearance, ν_e appearance and ν_e disappearance

- **Neutrino cross section measurements**
  - Millions of neutrino interactions for ν_μ and hight statistics for ν_e, see Henry's talk for SBND

- **Search for Beyond Standard Model physics**, detector locations and technology will enable many searches , see Jose and Jamie's talks
  - Dark neutrinos, light dark matter, axion-like particles, heavy neutral leptons, higgs portal scalar, transition magnetic moment and millicharged particles

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ICARUS at FNAL

- The ICARUS detector is located on-axis from the Booster beam and 6° off-axis from the NuMI beam
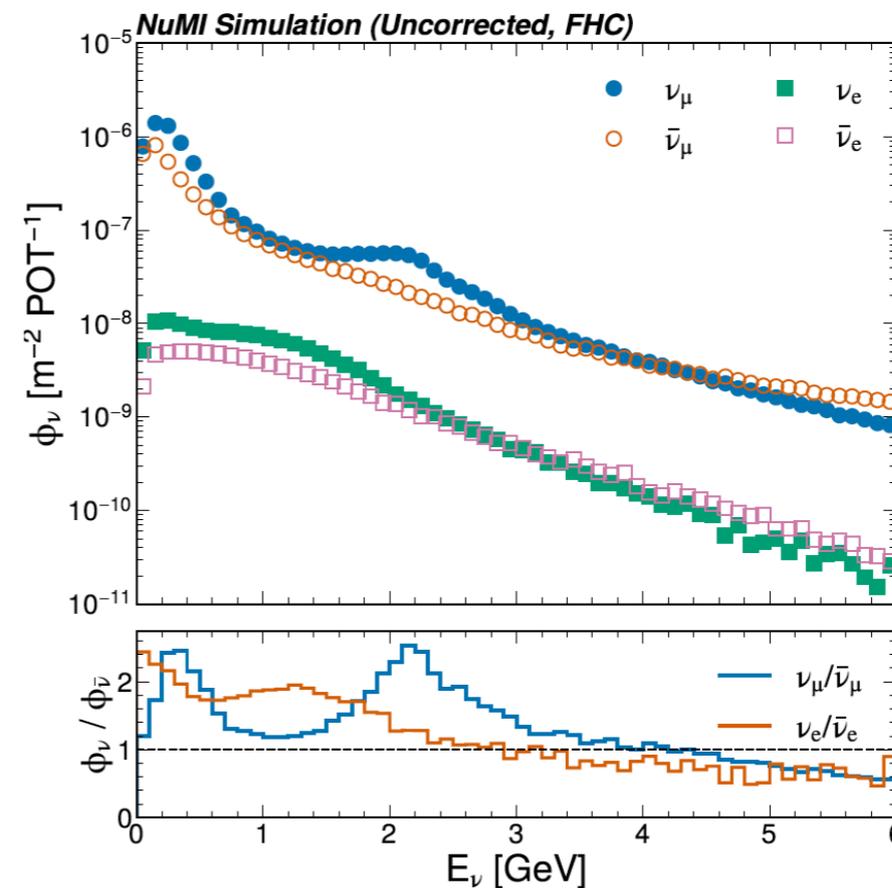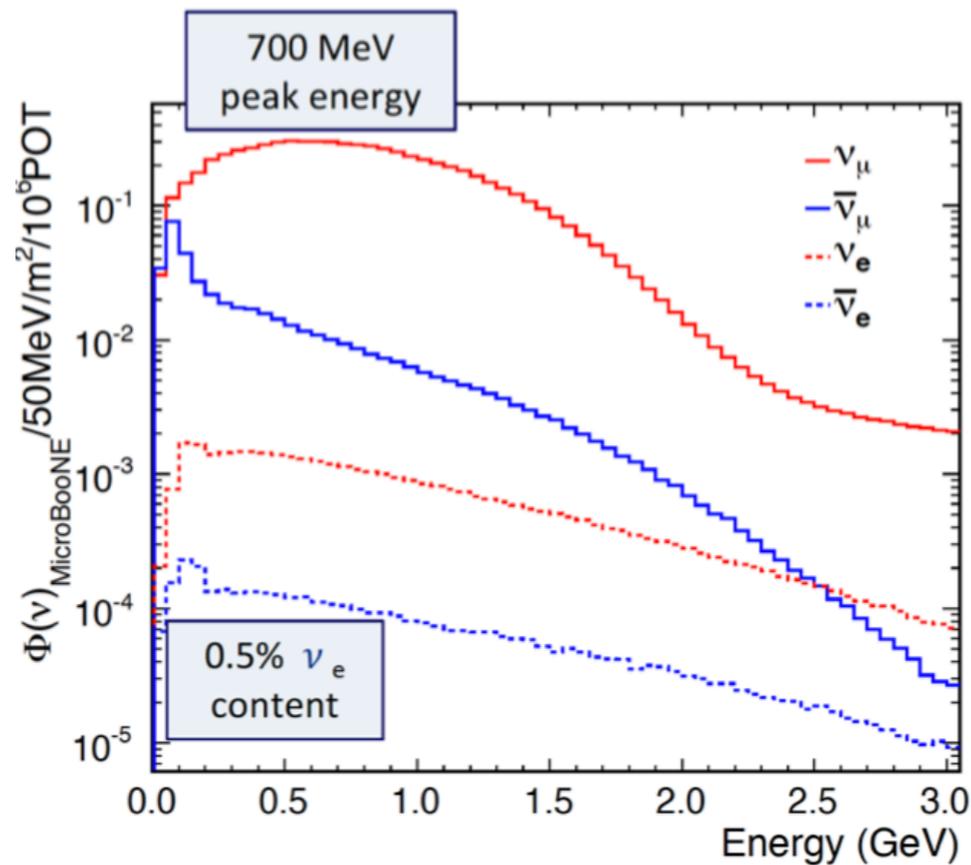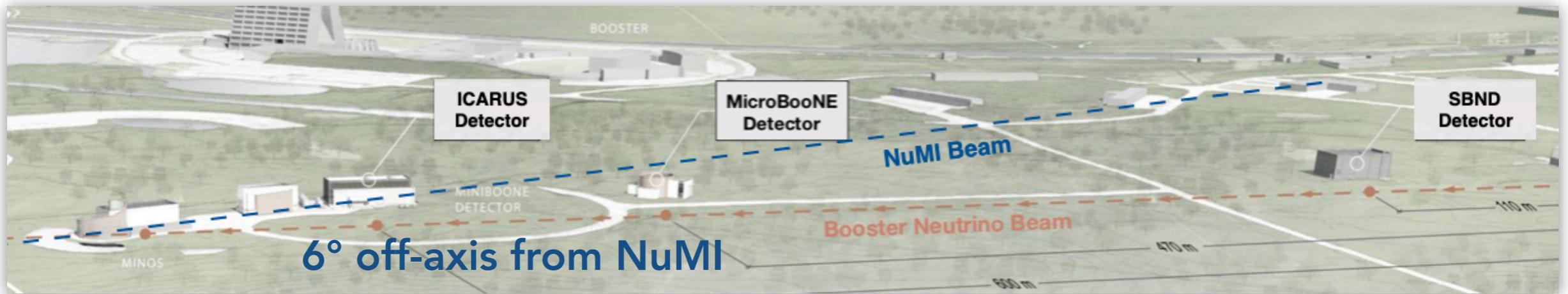
ICARUS (Imaging Cosmic And Rare Underground Signals)

- Tracking device: precise 3D event topology with ~mm³ resolution for ionizing particle

- Charged particles from neutrino interactions ionize the LAr, production ionization electrons drifting in 1 ms toward readout sense wires

- 2 TPCs per module with central cathode, 1.5 m drift, E_D=0.5 kV/cm, Δt~1 ms

- 3 readout wire planes (2 induction+collection) per TPC, ~54000 wires at 0, 60 degrees, 3 mm pitch: a continuous read-out

- 360 (8'' PMTs): Scintillation light detected to provide ns event time and trigger

neutrino

Electric field

VUV scintillation γ

Ar+

e-

Anodic planes

Photomultiplier tubes (PMTs)

Reconstructed image

Signal on wires

1 T600 module

Wire planes (anode)

© 2016-2018 CERN

Cathode

Field cage

PMTs

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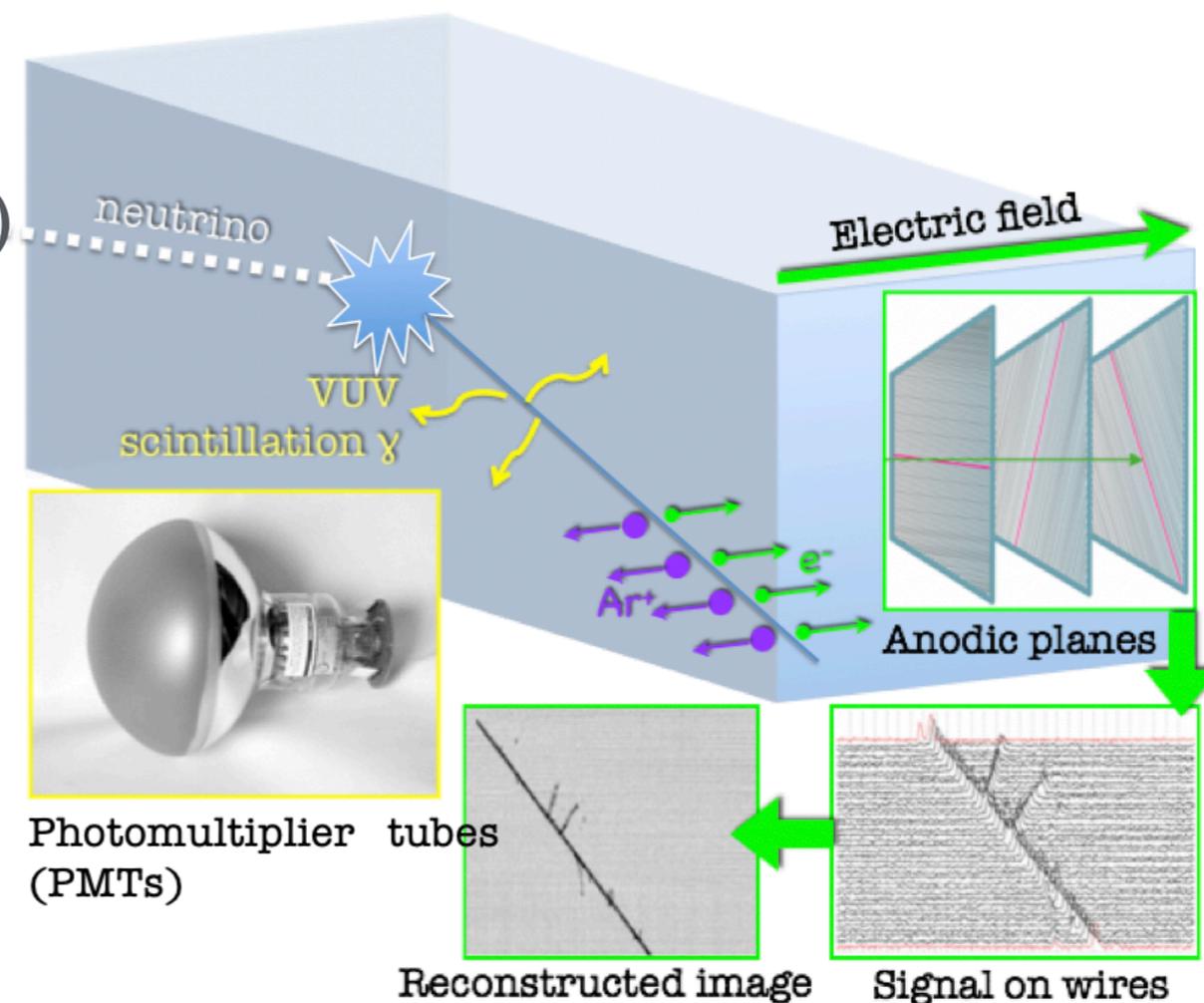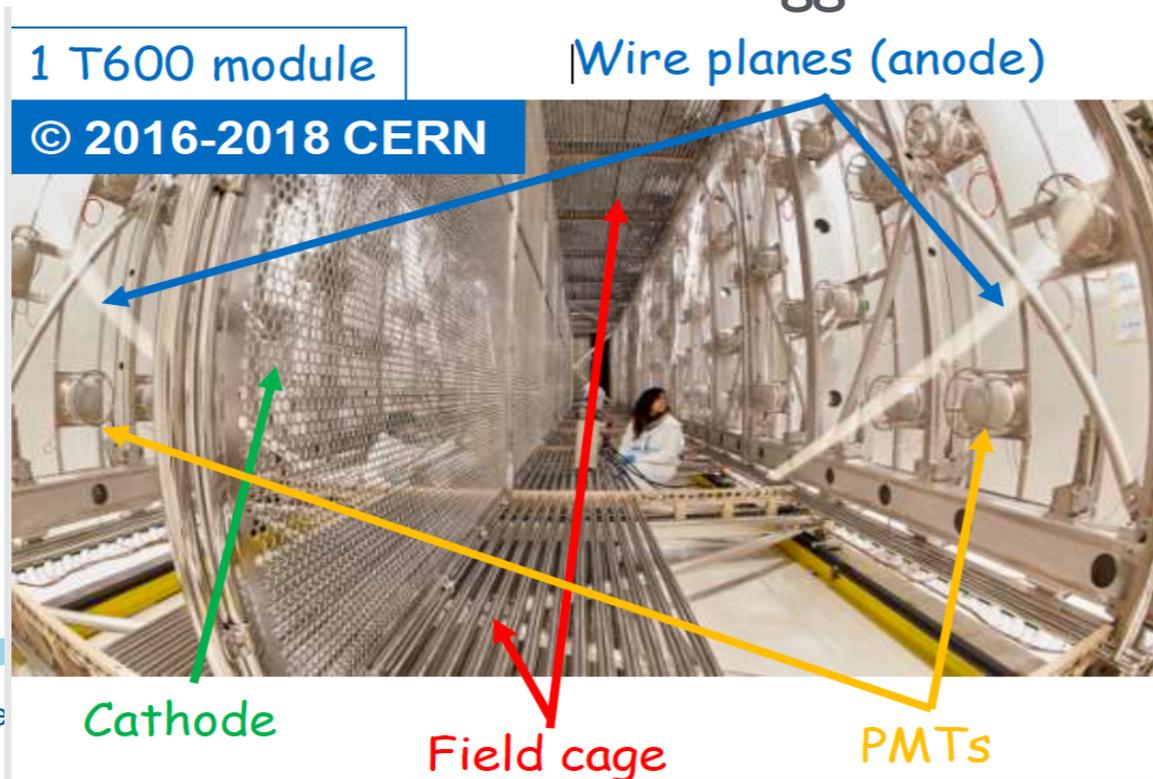
ICARUS at FNAL

- Several technology improvements were introduced, aiming to further improve the achieved performance ICARUS previous runs: new cold vessels, improvement of the cathode planarity, higher [...] and upgrade of the PMT system

- ICARUS is located on th[...] [over]burden has been installed to reduce and tag the ab[...]

TPC

1 T600 module
© 2016-2018 CERN
Wire planes (anod[...]
Cathode
Field cage
PM[T]

PMT

Top - horizontal
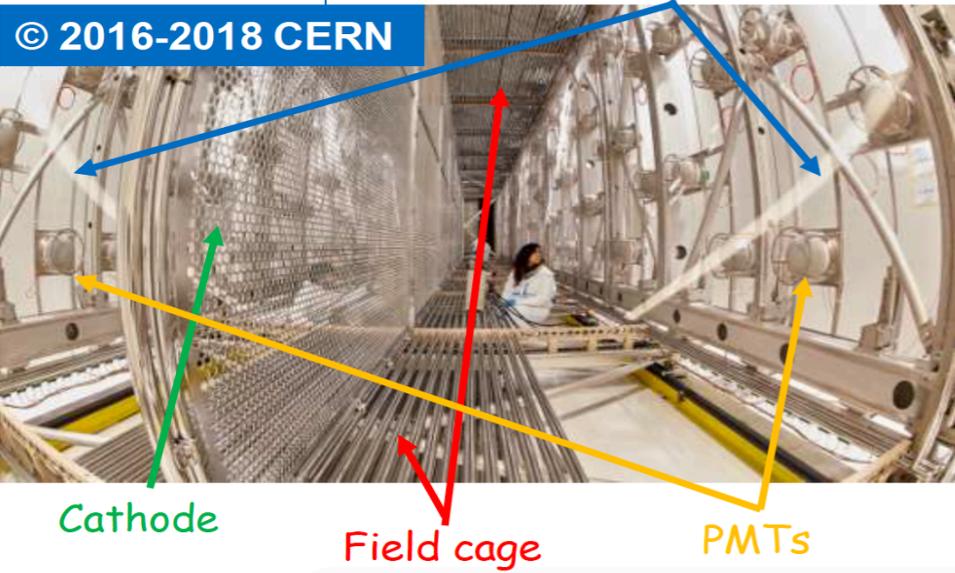
side CRT

Top CRT
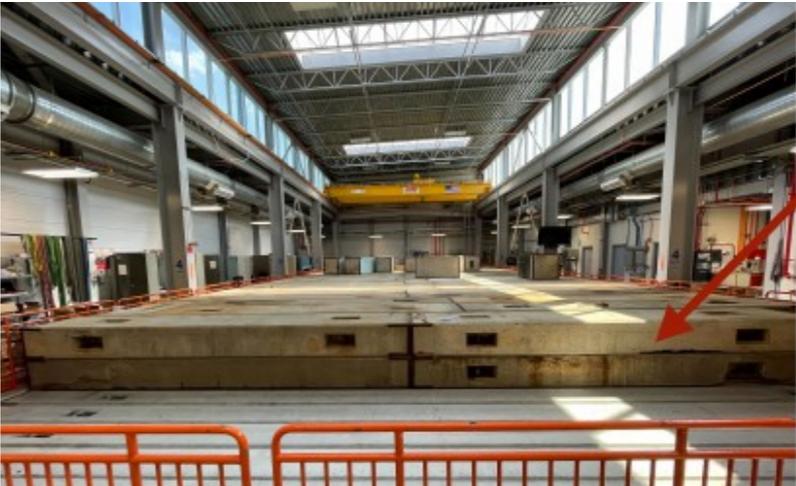
3m concrete overburden

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Status

- ICARUS began commissioning in 2020 with cosmic data
- First ICARUS physics runs collected last June 2022 and December 2022 (Run1) and 2023 (Run 2)
- Collected two successful physics runs from NuMI (3e20POT) and Booster neutrino beams (2.4e20POT)
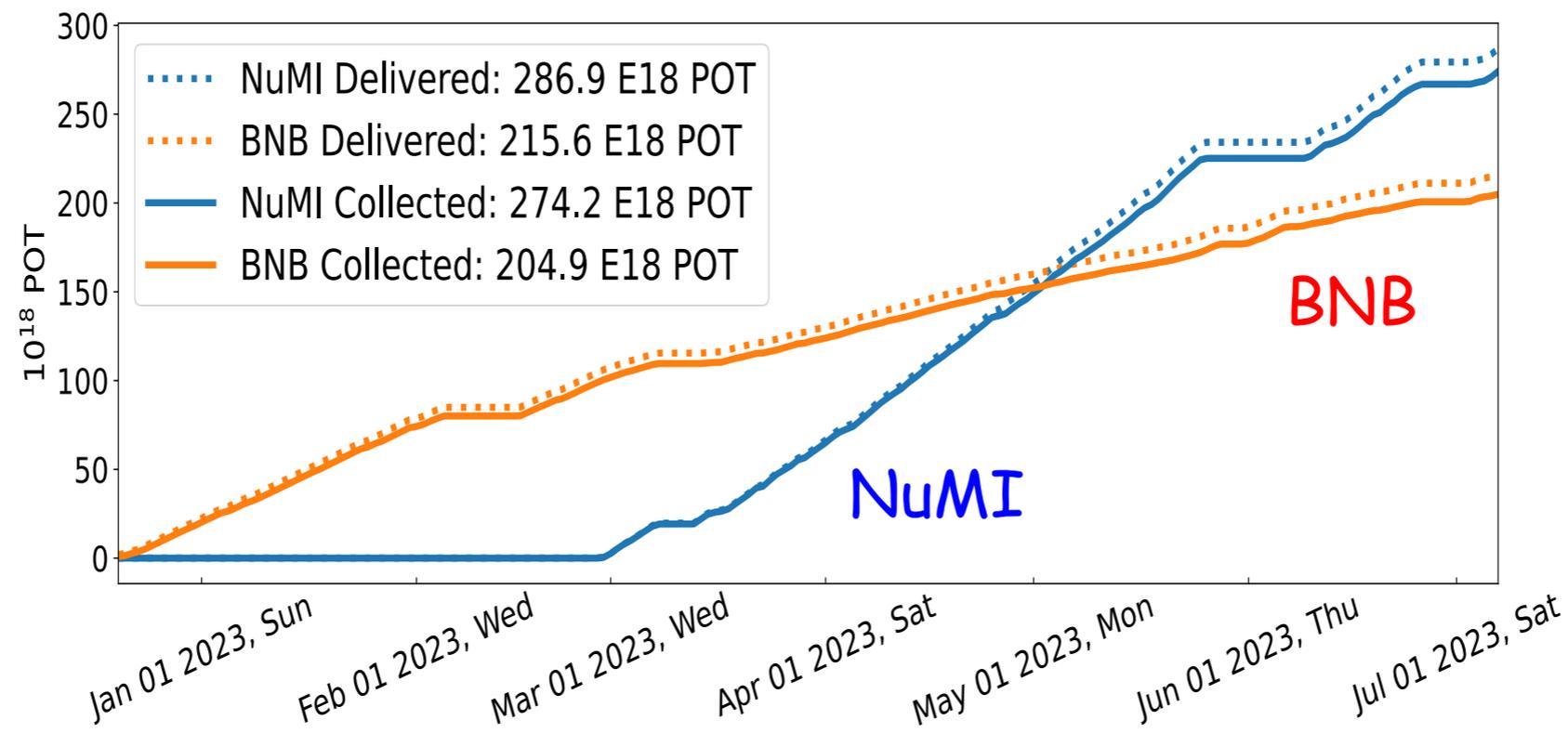
- Commissioning and physics data have been used to perform the calibration, tune the reconstruction and start the first analyses with neutrino data

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Calibration

- The full calibration has been developed, including: measurement of the drift velocity, equalization of electronic changes and detector response across the wire plane
- The measured ionization density dQ/dx is studied in bins of residual range, track angle and drift time for cosmic muon stopping/decaying in the LAr

Stopping Muons
dE/dx vs. Residual Range

— Predicted MPV dE/dx

Double Gaussian Fit:
σ_1: 4.7%
μ_1: 0.3%

σ_2: 14.5%
μ_2: 0.8%

ICARUS Commissioning Data

P. Abrateenko et al, Eur. Phys. Journal C 83, 467 (2023)

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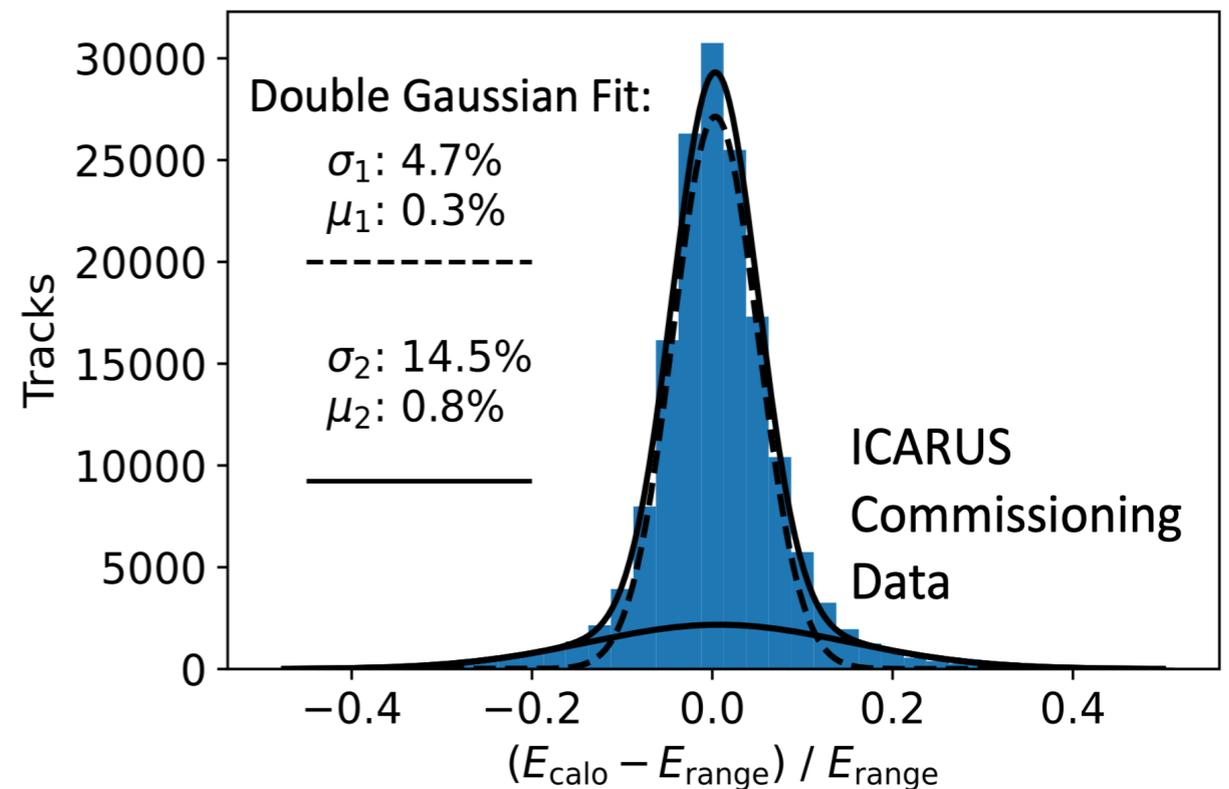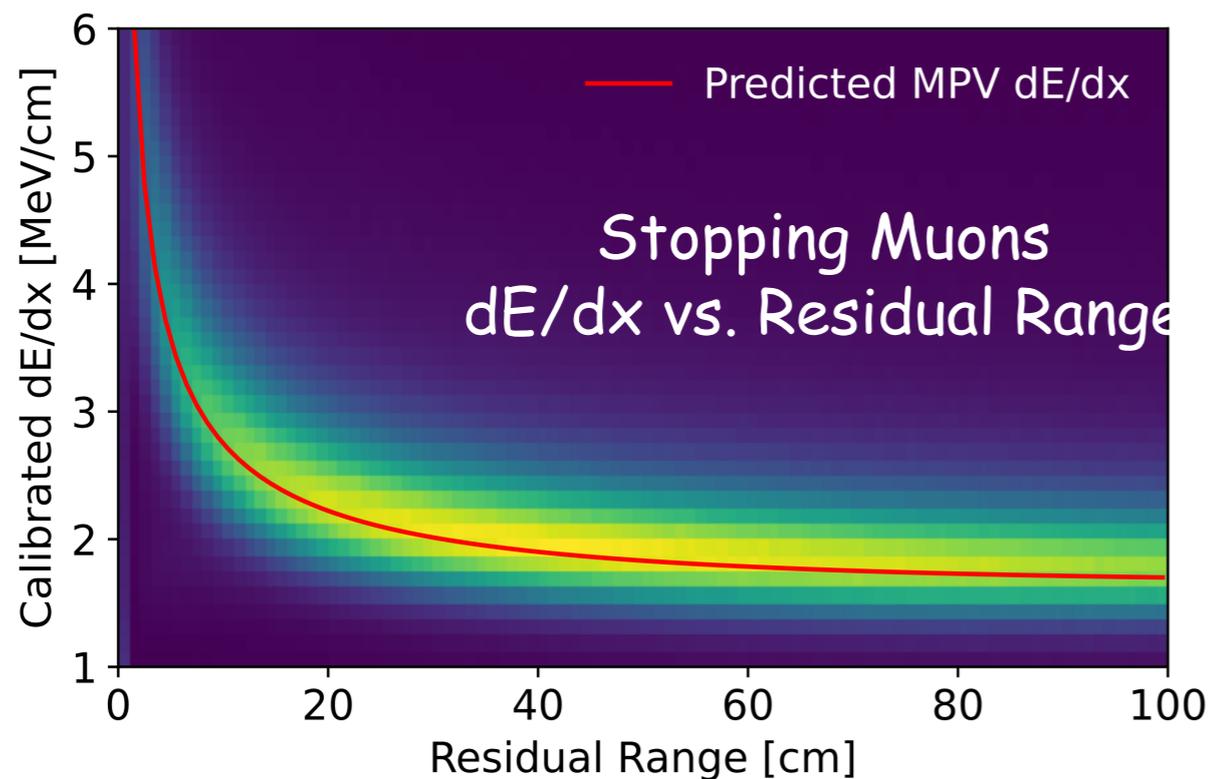
TPC Commissioning

- The signal-to-noise ratio was extracted from a sample of anode-to-cathode crossing cosmic muons
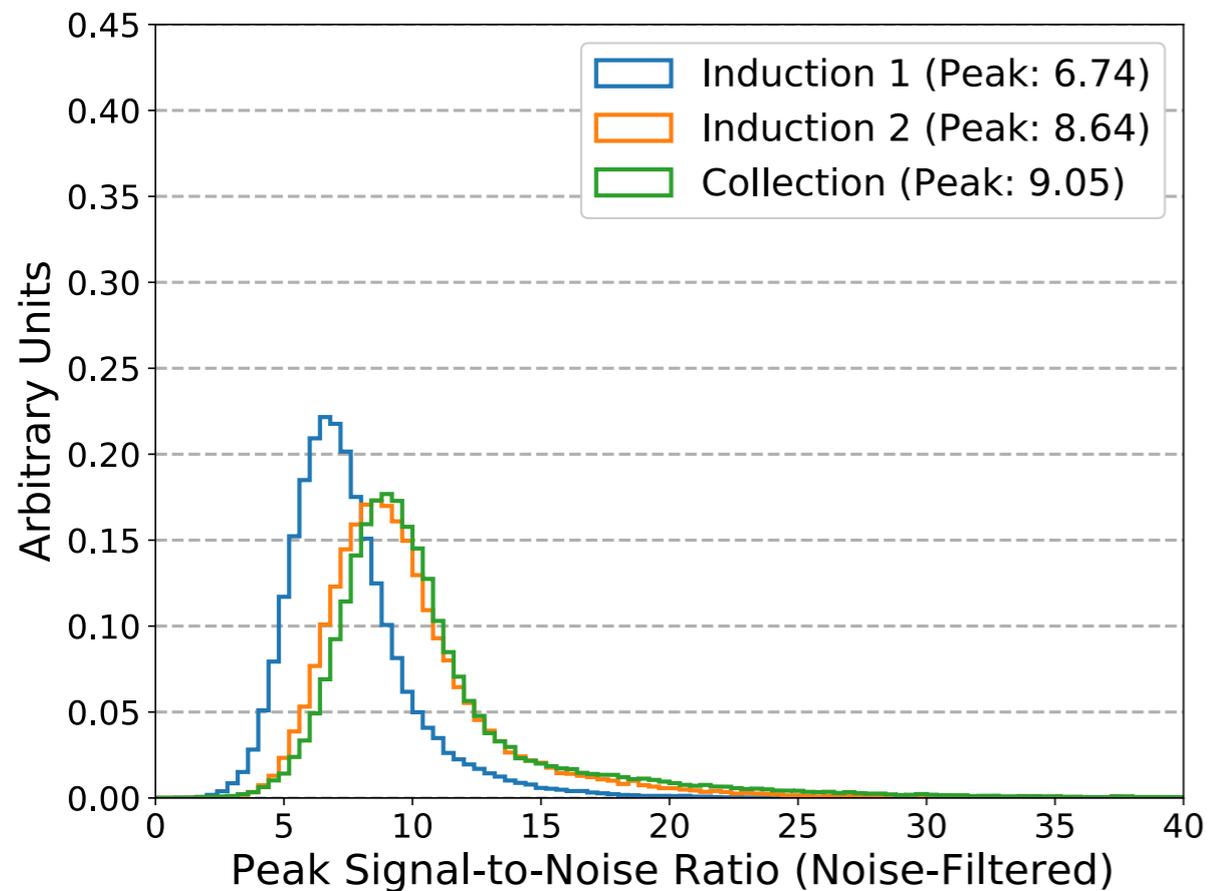
- Results of ionization drift velocity measurement using cosmic muon data
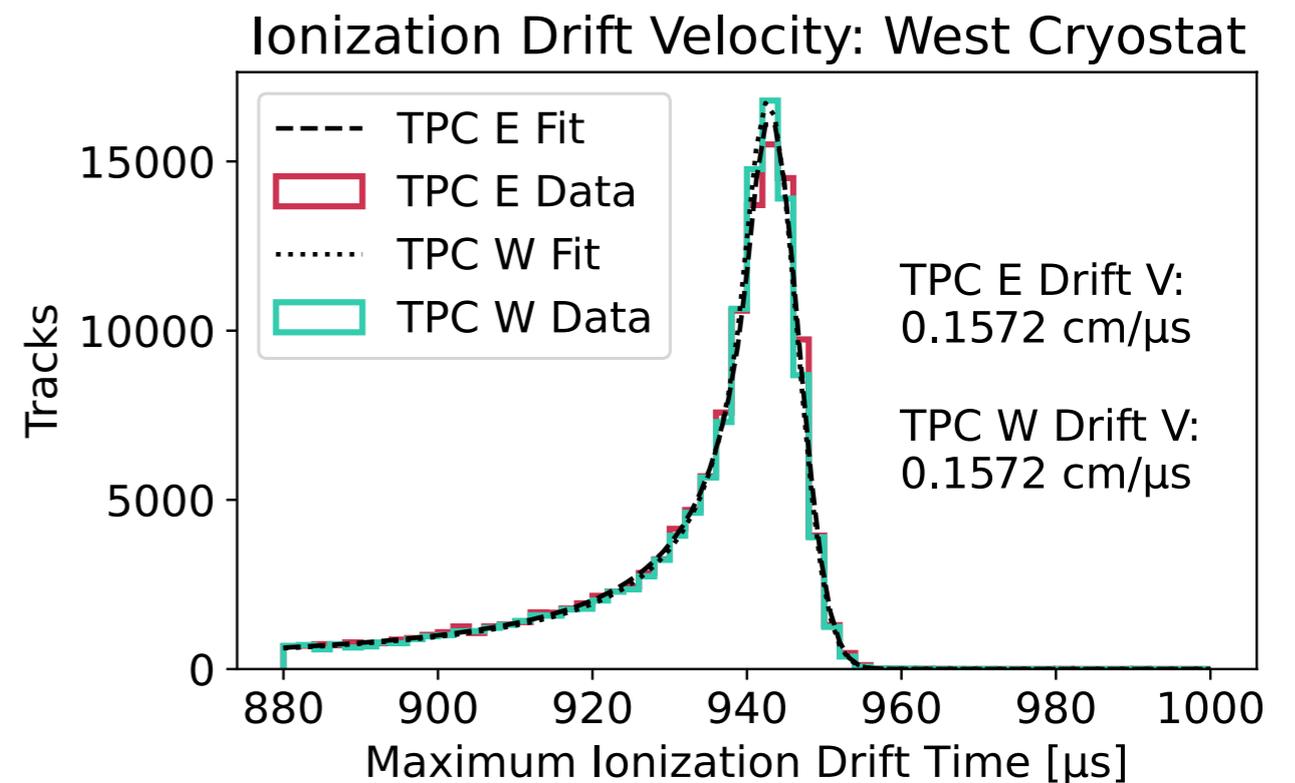
P. Abrateenko et al, Eur. Phys. Journal C 83, 467 (2023)

TPC Track Reconstruction

- Comparison of cosmic events reconstructed in data and simulation in TPC
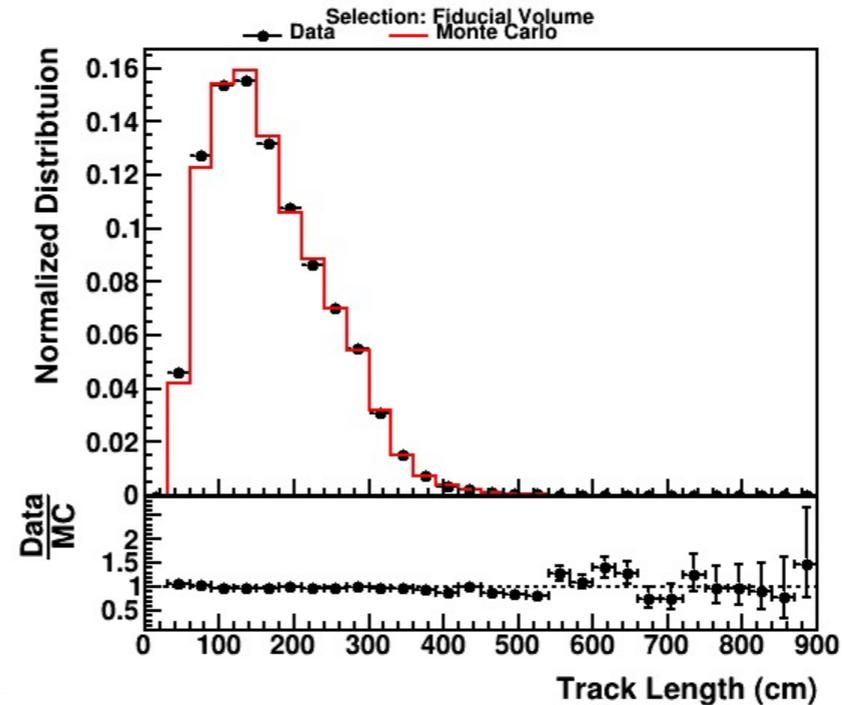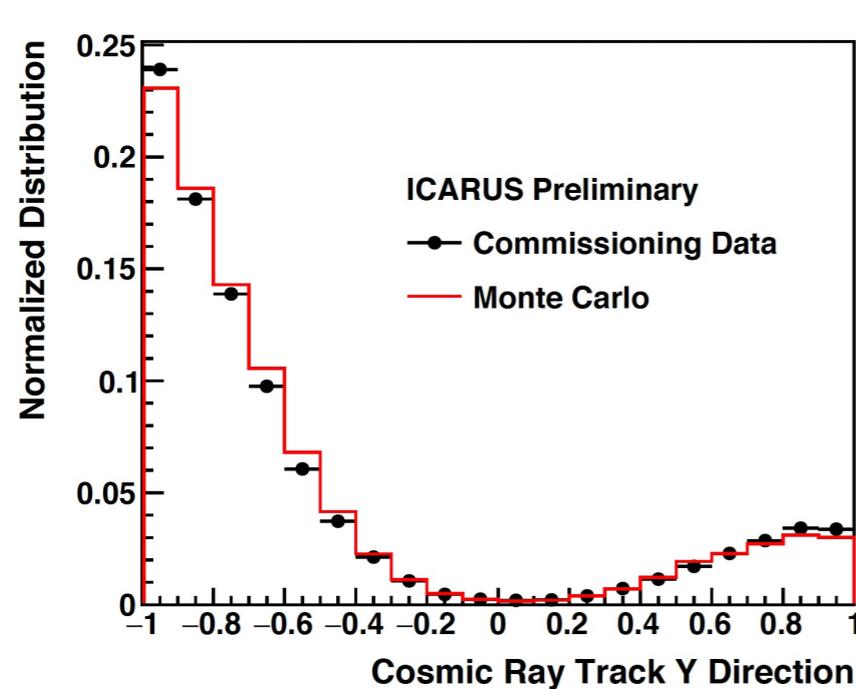
See Alice Campani's LArTPC track reconstruction talk

- Visual study of ~600 neutrino candidates from BNB

Difference between the reconstructed and scanned z position

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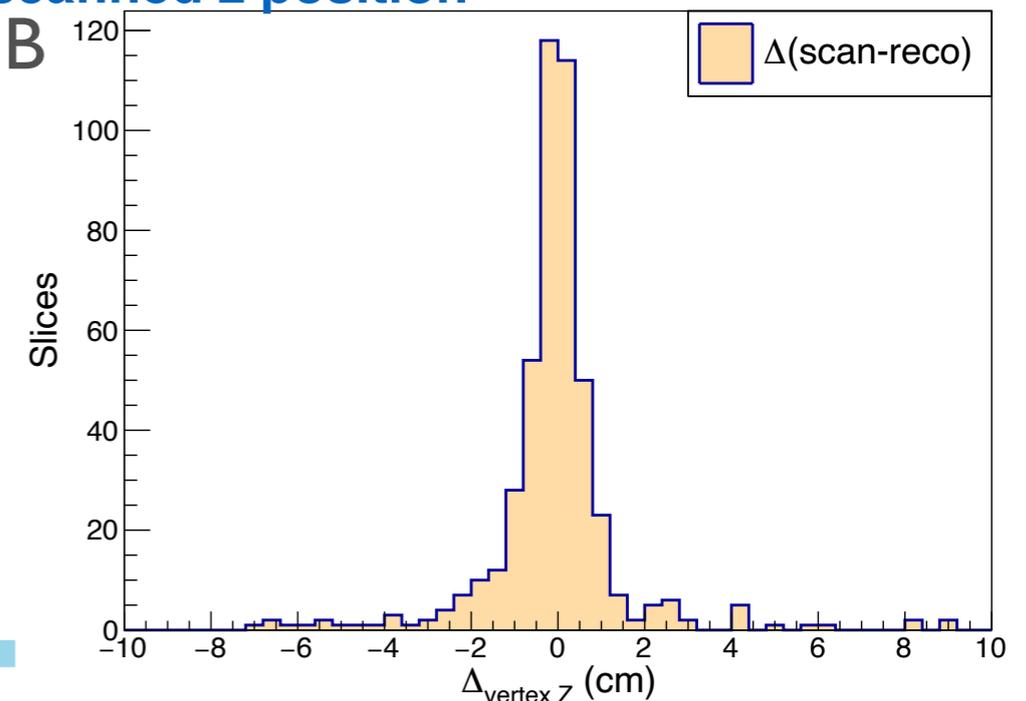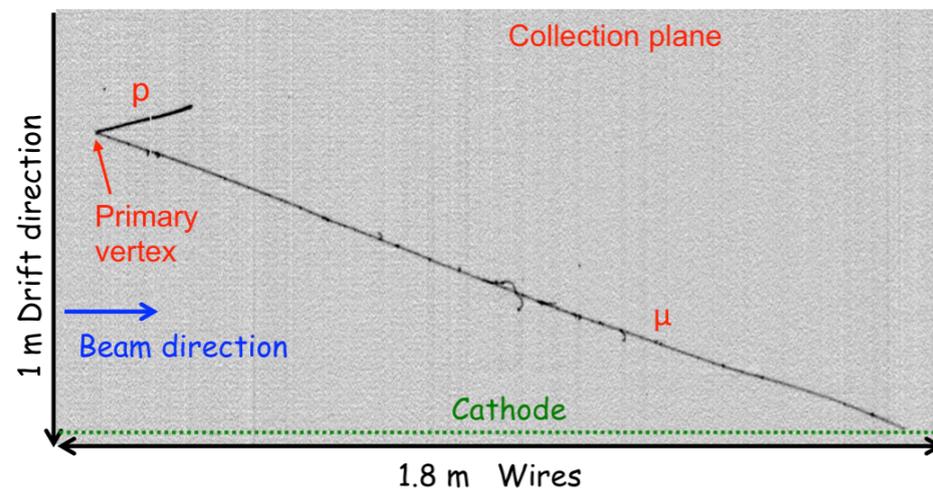
Reconstruction from PMT and CRT Systems

- CRT hit time relative to the neutrino gate start time for the NuMI beam

From CRT

BNB data, Run 8515

CRT Hit time - Gate start time [µs]

NuMI data, Run 8515

ICARUS Preliminary
~ 32k events

NuMI gate: 9.6 µs

Gate start time [us]
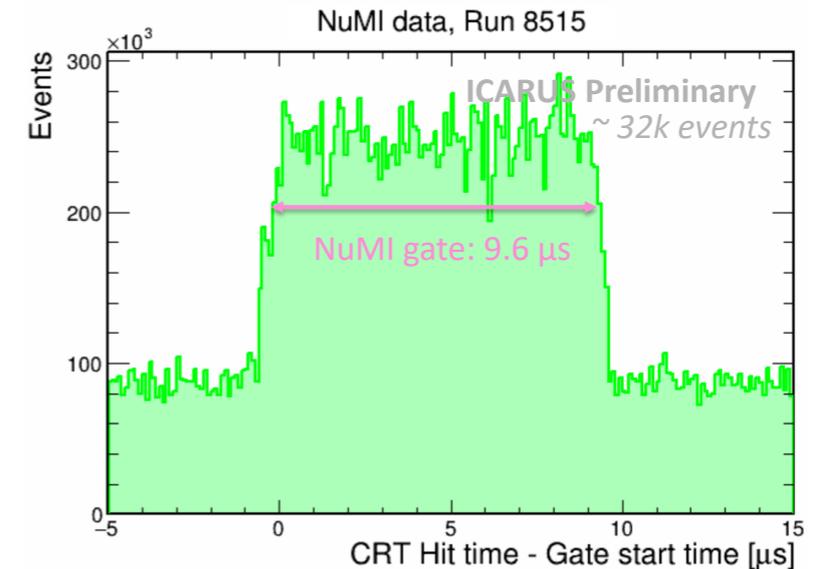
- Preliminary evaluation from the top CRT a

Cosmic entering

T_{CRT}

T_{PMT}

CRT walls

PMTs

Top - horizontal

BNB, Side, South
bin size = 0.2 µs

Hit T0-gate start time (µs)

| Mean | −27.12 ± 0.08 |
| Sigma | 8.101 ± 0.080 |

Top CRT Hit timestamp - Optical Flash [ns]

SBN Program

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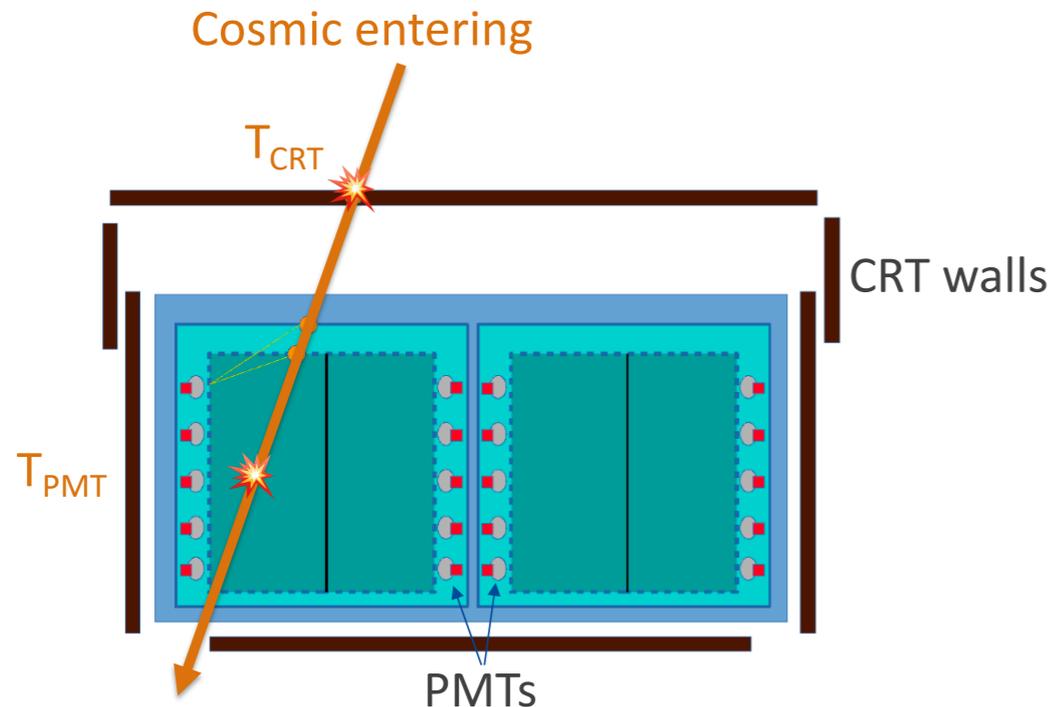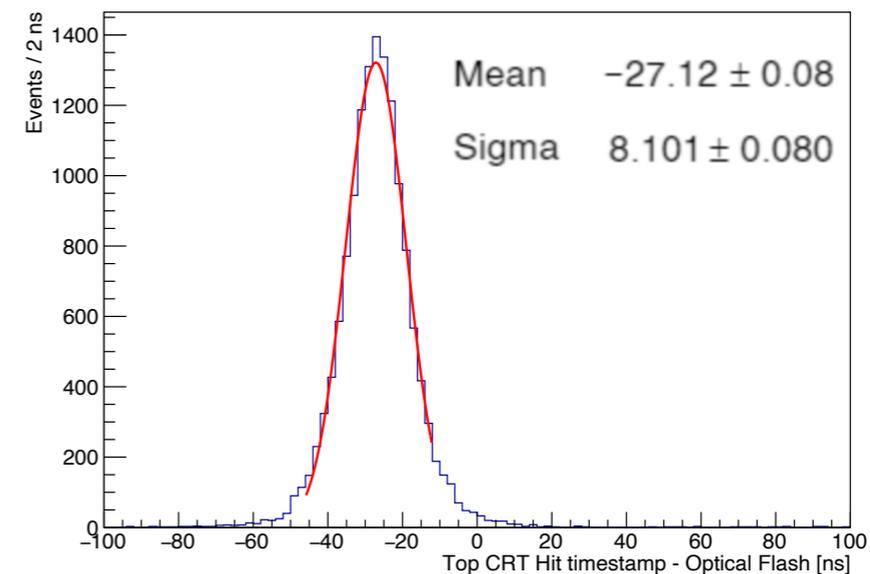
NuMI off Axis at ICARUS

- The ICARUS detector is located 6° off-axis from the NuMI beam

Data events from NuMI off axis
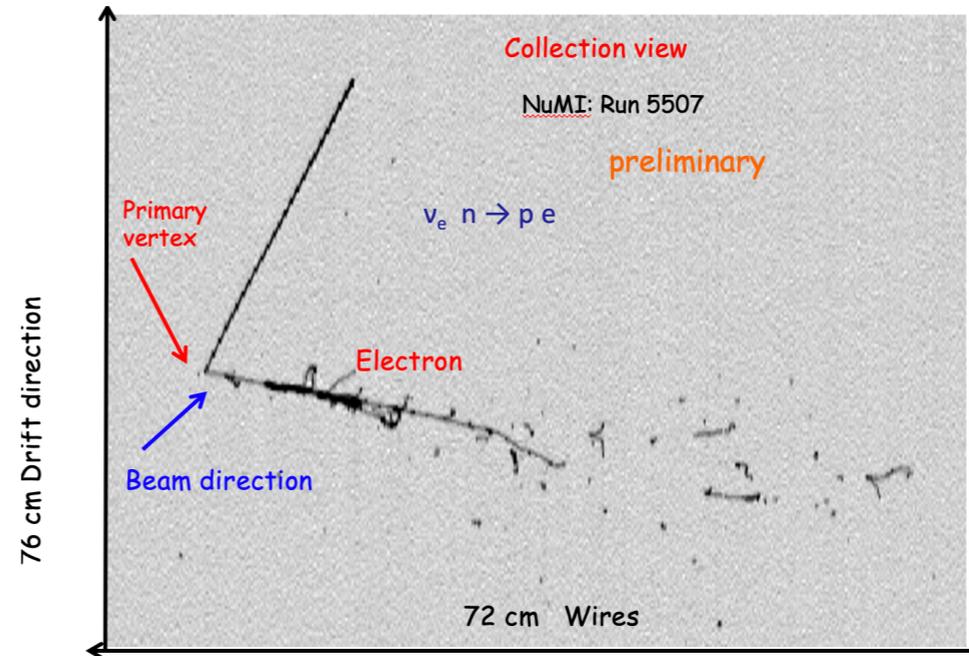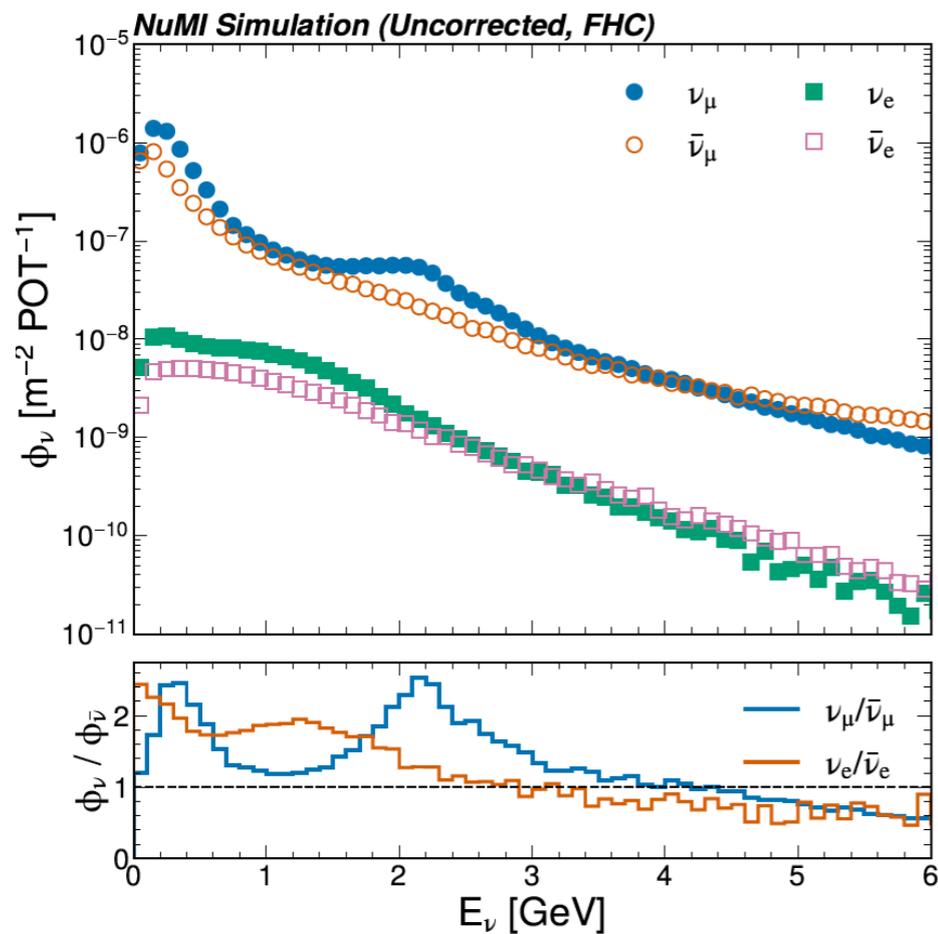
Electron neutrino candidate with electromagnetic shower E_{dep}=600 MeV
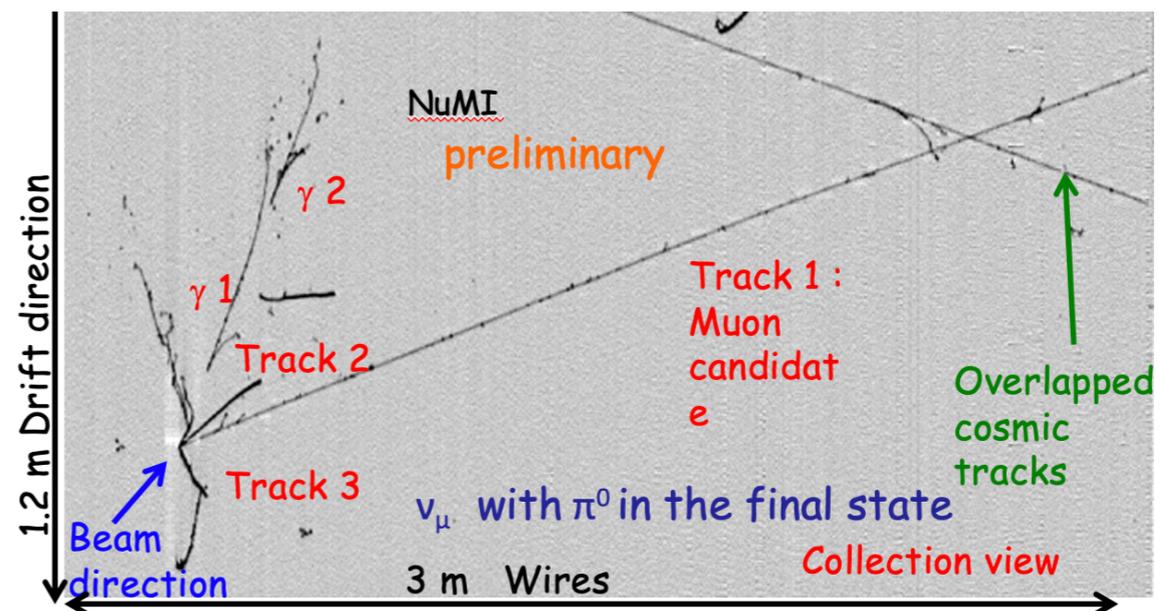
Muon neutrino candidate with muon candidate p~1.3 GeV/c and π0 candidate with photons of 200 and 240 MeV

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Neutrino Interactions from NuMI off axis at ICARUS

• Excellent statistics to make cross section measurements for quasi-elastic and pion production scattering, for both electron and muon neutrinos

Muon Neutrino
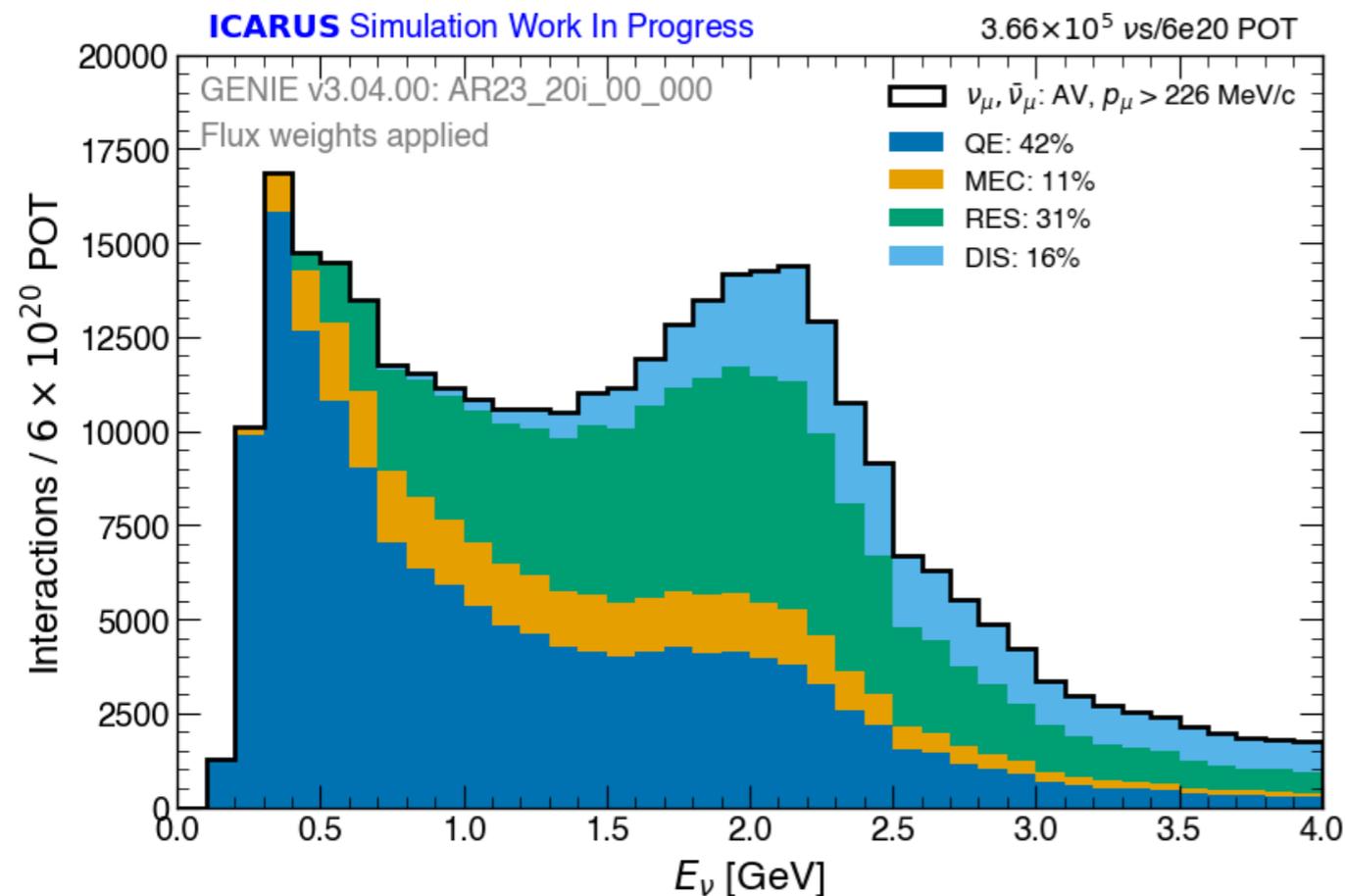
Electron Neutrino

CC Events/year: ν_μ 366,000 and ν_e 17,000

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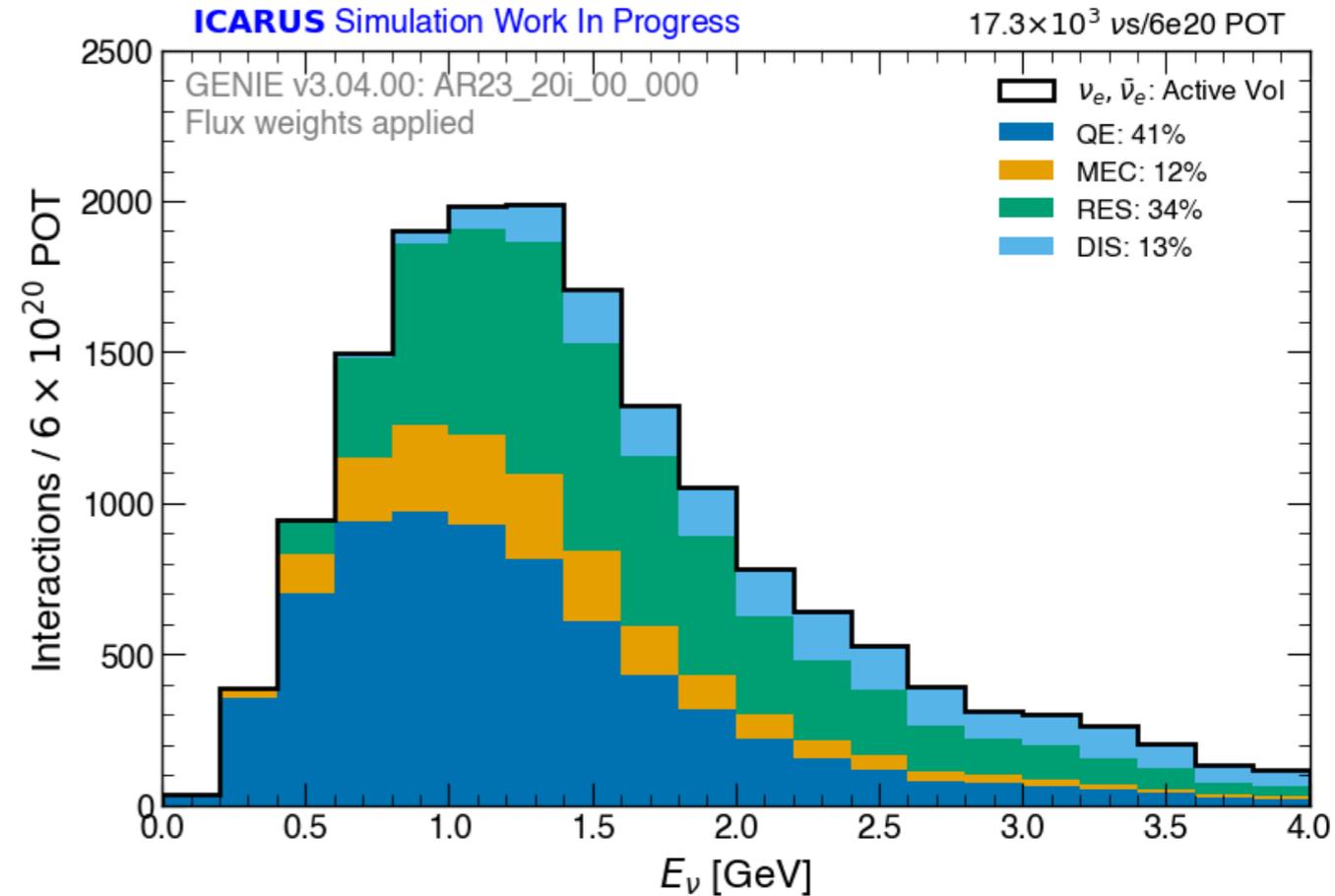
Relevance for DUNE

- NuMI at ICARUS offers excellent coverage for ν_μ

Muon Neutrinos from NuMI
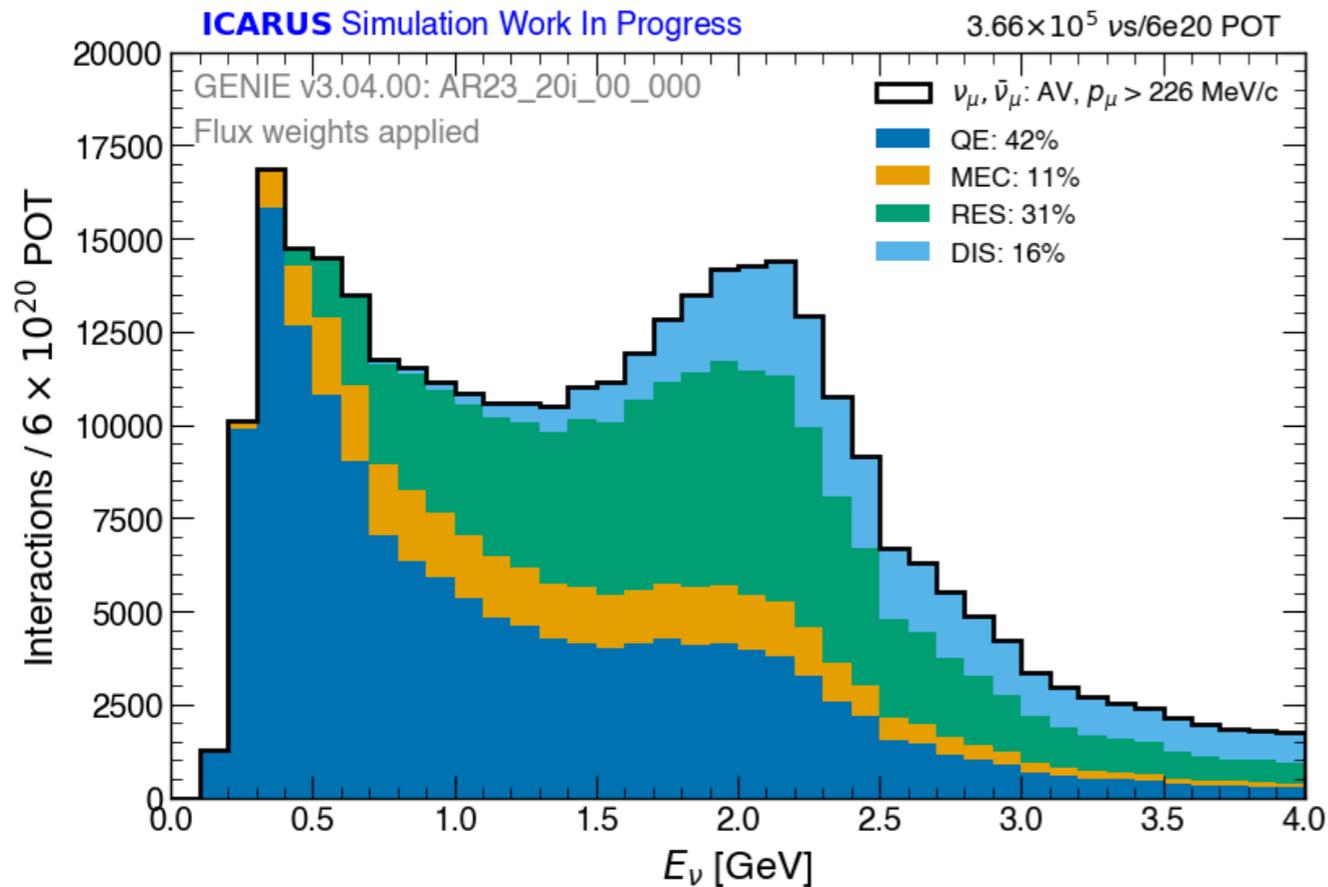
Spectrum at DUNE Near Detector

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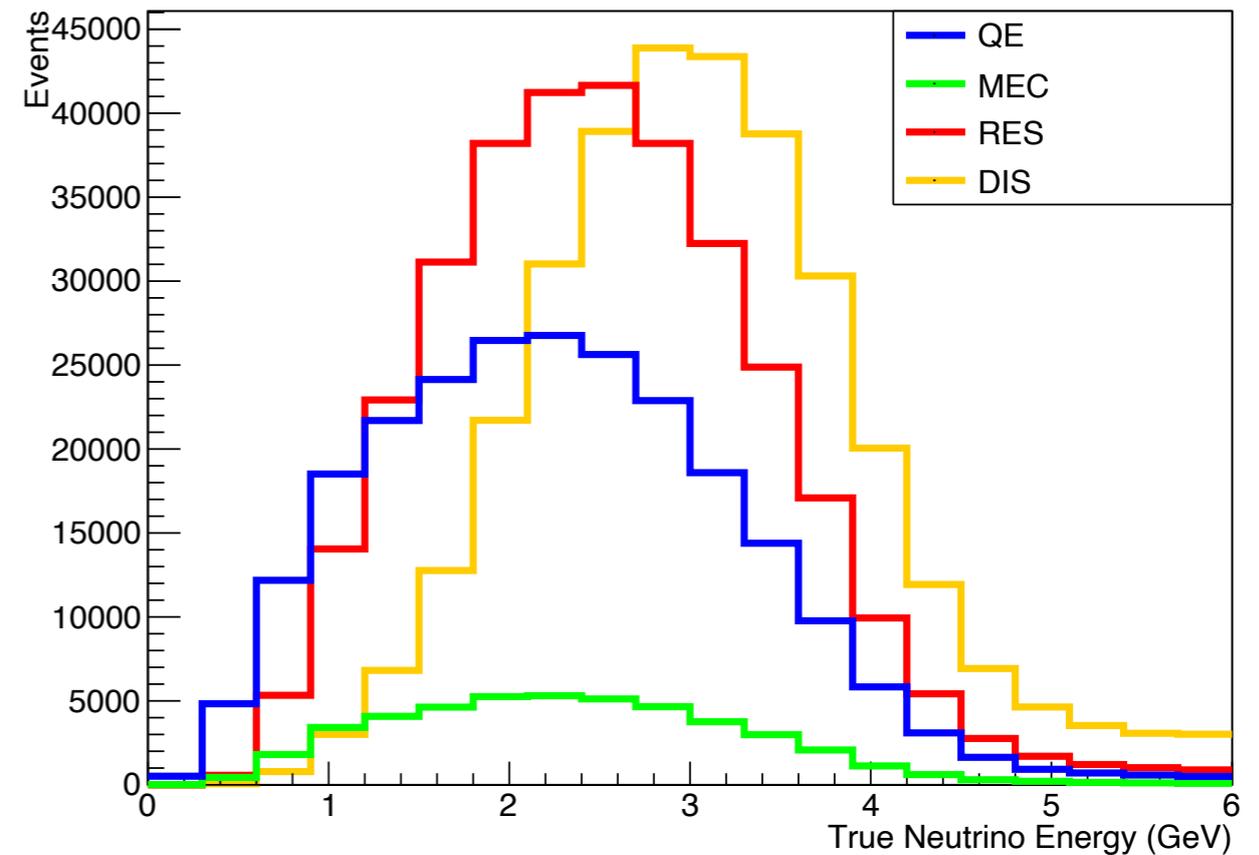
Relevance for DUNE

- Electron neutrino spectrum from NuMI at ICARUS covers the first oscillation peak and the tail covers the majority of the relevant phase space for the DUNE experiment

Electron Neutrinos from NuMI
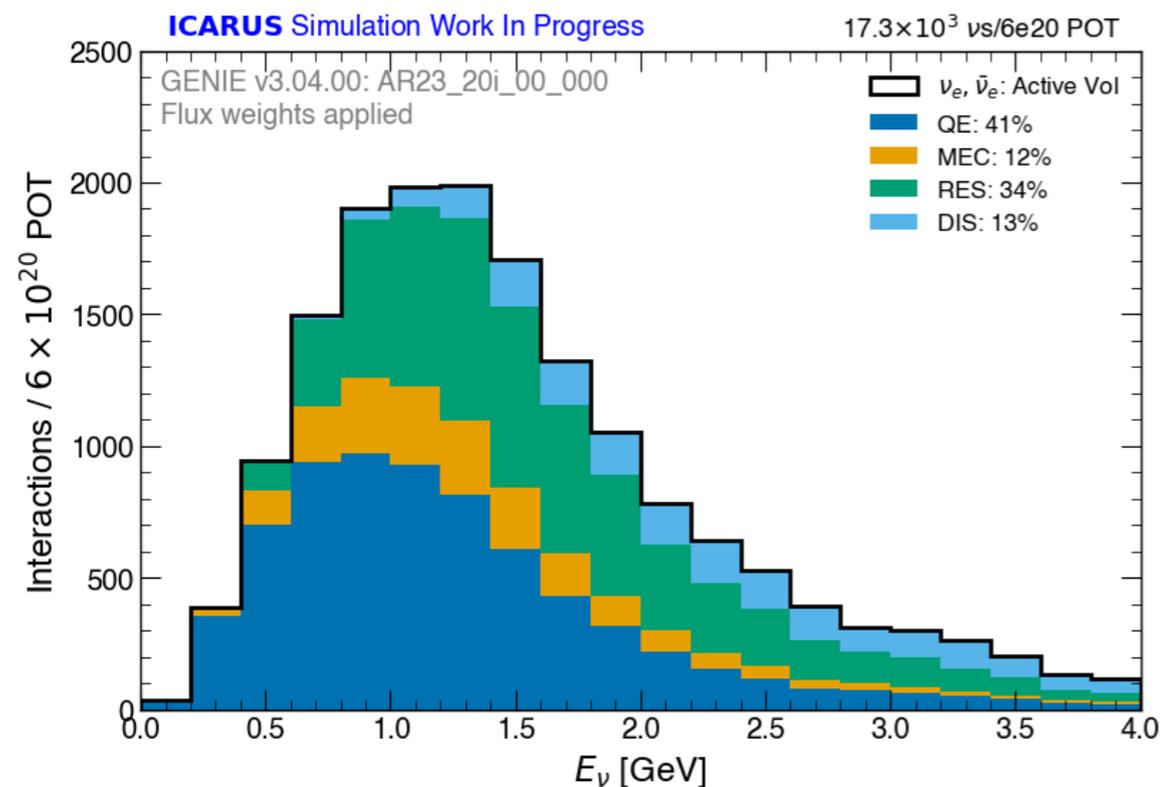
Electron Neutrino in ICARUS and DUNE
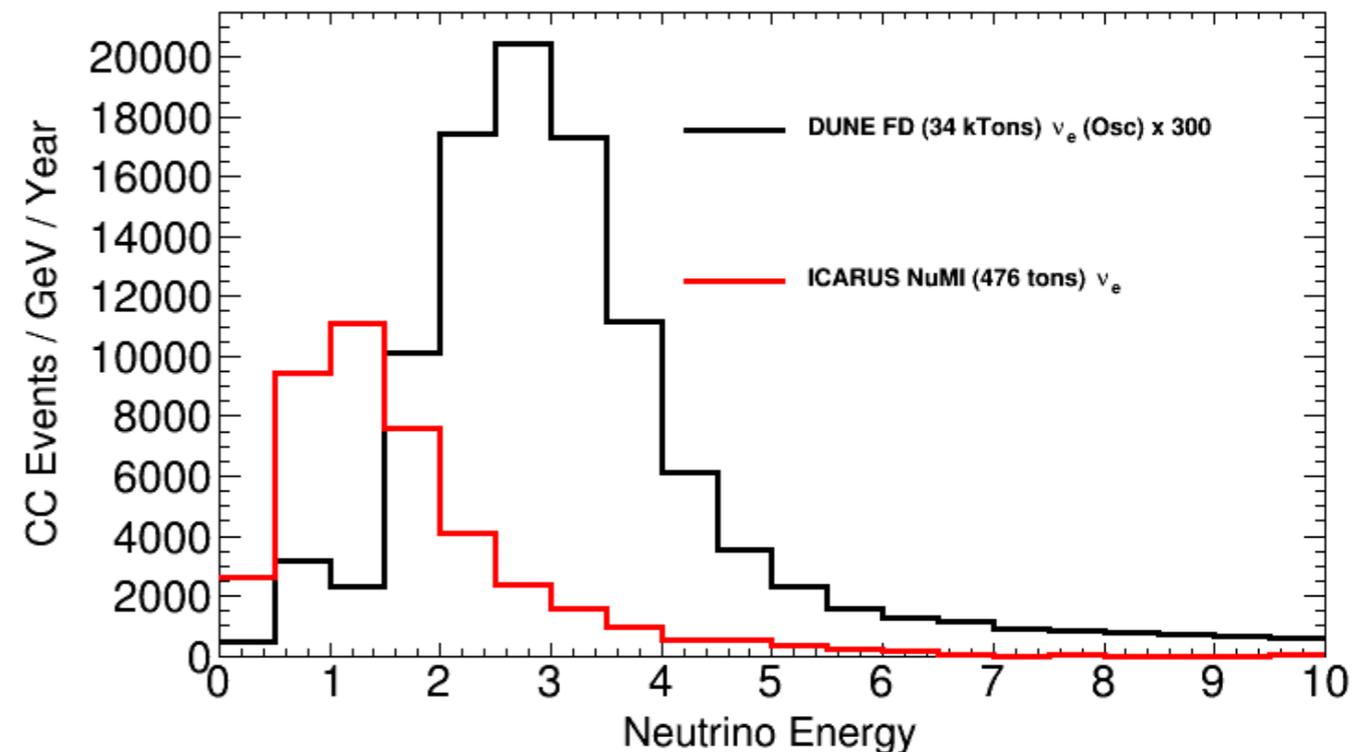
- ν_e flux is excellently distributed to probe regions of kinematic phase space in which we expect the largest ν_e/ν_μ differences (which is the dominant systematic for DUNE-CP violation measurements)

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- Neutrino cross section measurement with NuMI
- Developing and optimizing muon neutrino event selection

lection Criteria

Distributions with the **beam OFF**, we are scaling as slide 4

Data from NuMI

Run1 NuMI beam ON
Run1 NuMI beam OFF

w/o any cut

Slices

15000

10000

5000

ON/C--E

Angle

AnEdenF

Angle Between

Formula   Formula

×10³   Run8446, NuMI, 6e20 POT

Events/1.0

250

200

150

100

50

ClearCosmic FMTime
- ν_μ**CC**
- ν_μ**NC**
- ν_e
- **Cosmic**

Data/MC

2
1.5
1
0.5
0
0   10 20 30 40 50 60 70 80 90 100

Flash matching score

Slices

500

400

300

200

100

0.2
.15
0.1
.5

Inclusive Selection

PRELIMINARY

NuMI beam ON   = 2438
NuMI beam OFF = 791

Normalization to
livetime-on/livetime off

Track direction (a)

θ_{NuMI}

NuMI beam direction (b)

$cos(\theta_{NuMI}) = \frac{\vec{a} \cdot \vec{b}}{|\vec{a}||\vec{b}|}$

Reco $cos(\theta_{N})$

Run1 NuMI beam ON
Run1 NuMI beam OFF

NuMI ν_μ CC candidate

is a Pandora clear cosmic,

Inclusive selection cuts

- Vertex in fiducial volume
- Longest track's Y direction
- Requiring PMT-TPC matching

Muon candidate

$cos(\theta_{NuMI})$

Track

NuMI beam direction (b)

est track Y direction (under cosmic ray hypothesis)

- Available NuMI data: Run I=2.4E20 POT and Run2=0.5E19 POT

ν_μ CC, $L_\mu \geq 50$ cm
- $\nu_\mu + \bar\nu_\mu$ CC QE (39%)
- $\nu_\mu + \bar\nu_\mu$ CC RES (33%)
- $\nu_\mu + \bar\nu_\mu$ CC DIS (18%)

POT / 6x10²⁰

1.5

NuMI Interactions
- $\nu_e + \bar\nu_e$ CC QE (38%)
- $\nu_e + \bar\nu_e$ CC RES (36%)
- $\nu_e + \bar\nu_e$ CC DIS (15%)
- $\nu_e + \bar\nu_e$ CC MEC (11%)

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Muon Neutrino from NuMI beam at ICARUS

- Starting to study events with one muon and N Protons

- One muon and N $_{proton}$ event selection
  - Vertex in fiducial volume

NuMI Neutrino Data and NuMI beam off Data

Selection Criteria

Distributions with the **beam OFF**,
we are scaling as slide 4

Data from NuMI

eno

ICARUS Simulation

ν_μ CC, $L_\mu \geq 50$ cm

$\nu_\mu + \bar{\nu}_\mu$ CC QE (39%)

$\nu_\mu + \bar{\nu}_\mu$ CC RES (33%)

$\nu_\mu + \bar{\nu}_\mu$ CC DIS (18%)

$\nu_\mu + \bar{\nu}_\mu$ CC MEC (9%)

440k ν_μ CC events in 1 year

E_ν [GeV]

$\times 10^3$

ν_e CC Interactions / 6×10^{20} POT

Slices

ICARUS S

NuMI Interac

$\nu_e + \bar{\nu}_e$ CC Q

$\nu_e + \bar{\nu}_e$ CC R

$\nu_e + \bar{\nu}_e$ CC D

$\nu_e + \bar{\nu}_e$ CC M

CC 0π Event Selection

- First analysis targets 1μ+Nproton+0π

  - 1μ+Nproton+0π enhanced in quasi-elastic and 2p2h interactions

- Building up cross-section analysis to conduct model investigations
- Angle between the muon candidate and leading proton candidate populates the phase space somewhat broadly and would be expected to encode information about FSI for all events
- Signal definition: One muon with momentum > 226 MeV/c, any proton with momentum between 400 MeV/c and 1 GeV/c, no charged or neutral pions
- Events with contained and exiting muons
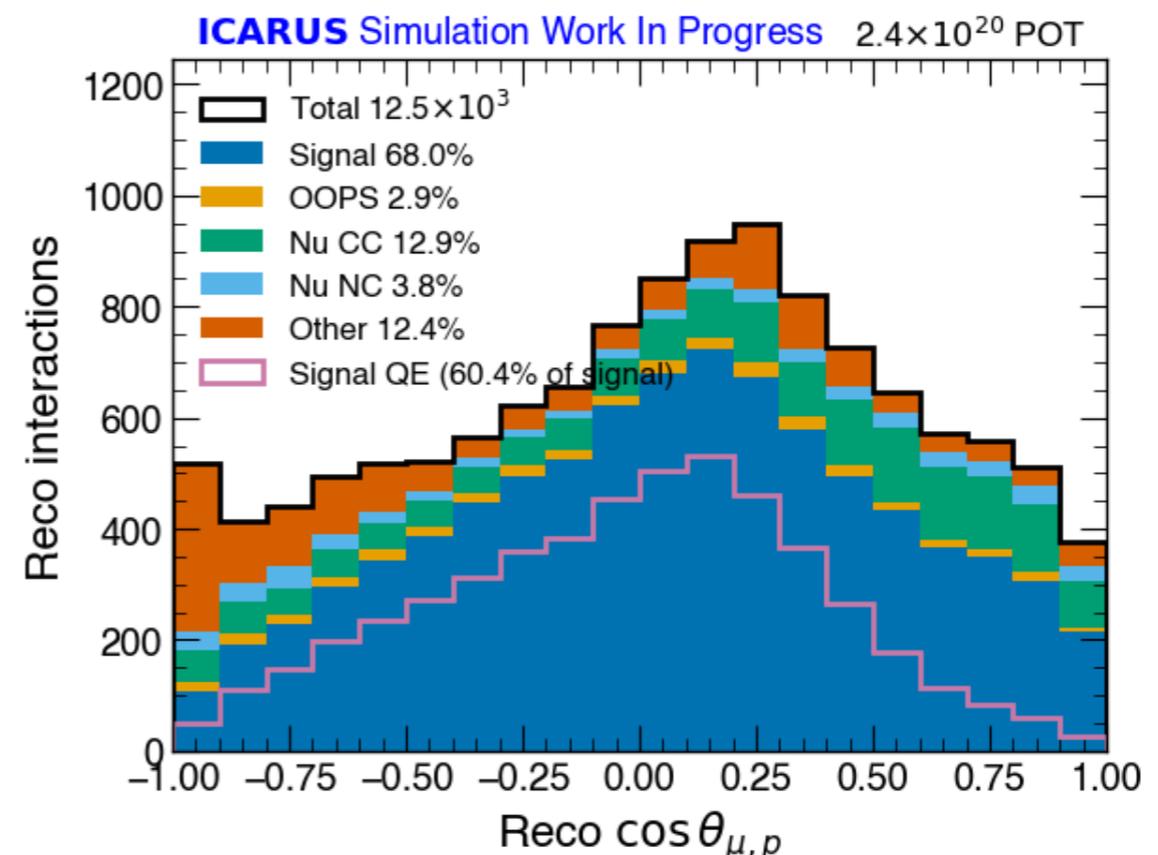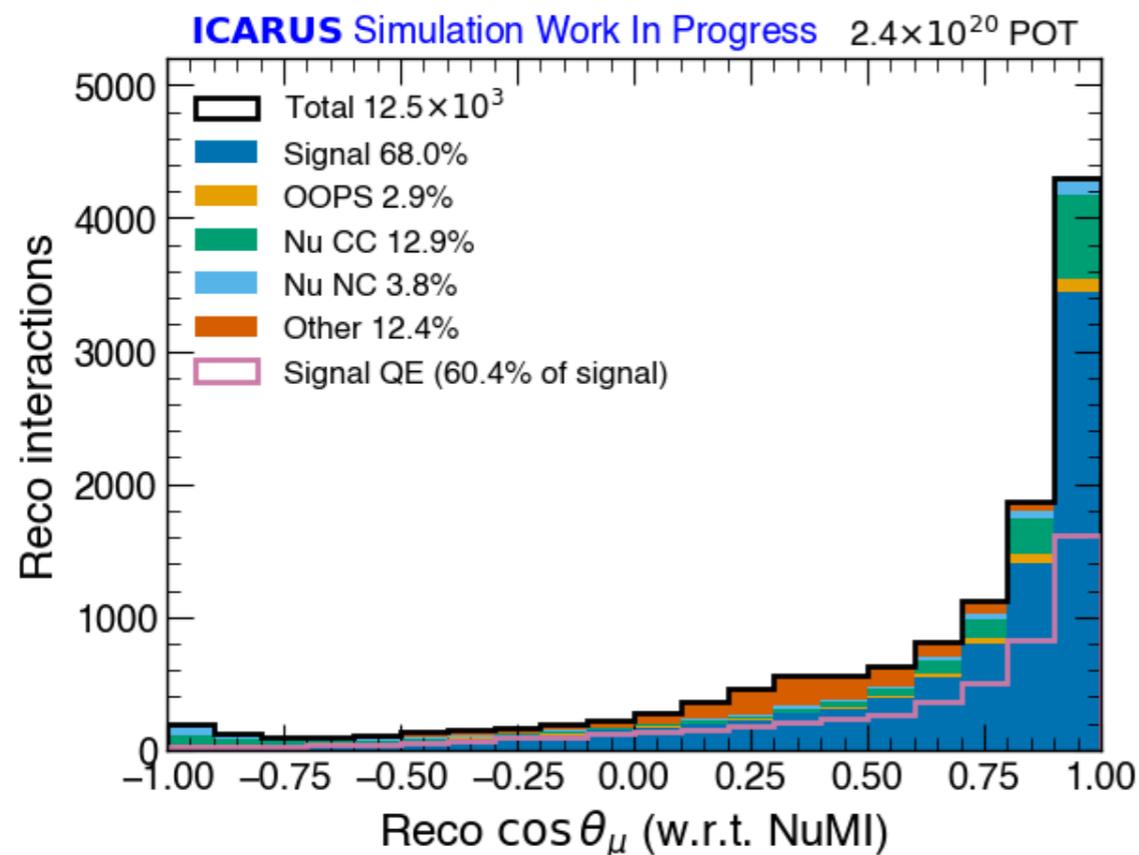
CC 0π Event Selection for fully contained Events

- Transverse kinematic imbalances observables δP_T and $\delta \alpha_T$ for fully contained events

- Signal definition: One muon with momentum > 226 MeV/c, any proton with momentum between 400 MeV/c and 1 GeV/c, no charged or neutral pions

- Events with contained muons and protons

OOPS: Out of phase space; signal but fails **μ**/p momentum thresholds
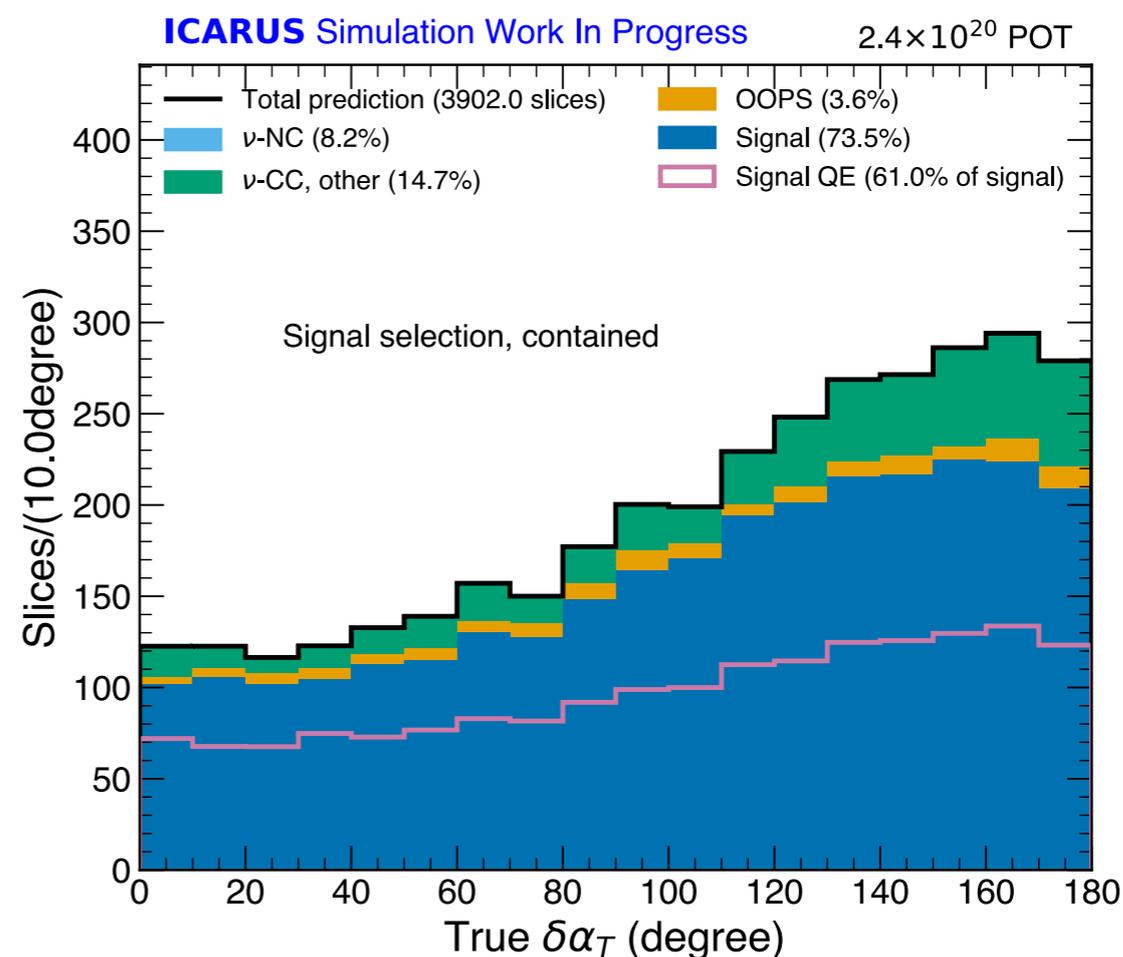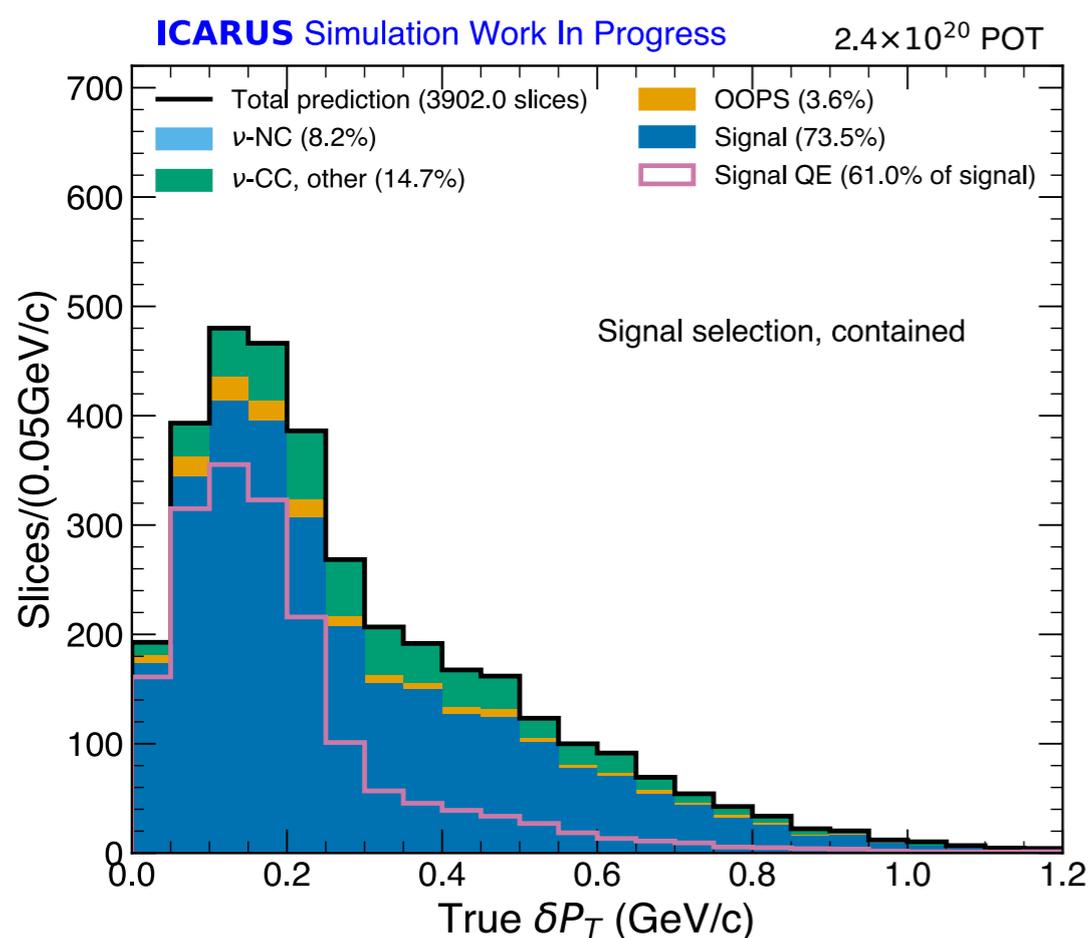
Systematic Uncertainties

- Excellent progress with the systematic uncertainties evaluation: Detector, flux, cross-section, FSI and GEANT4 systematics

- Developing sideband and using external data sets from MINERvA to constrain the main background CC pion
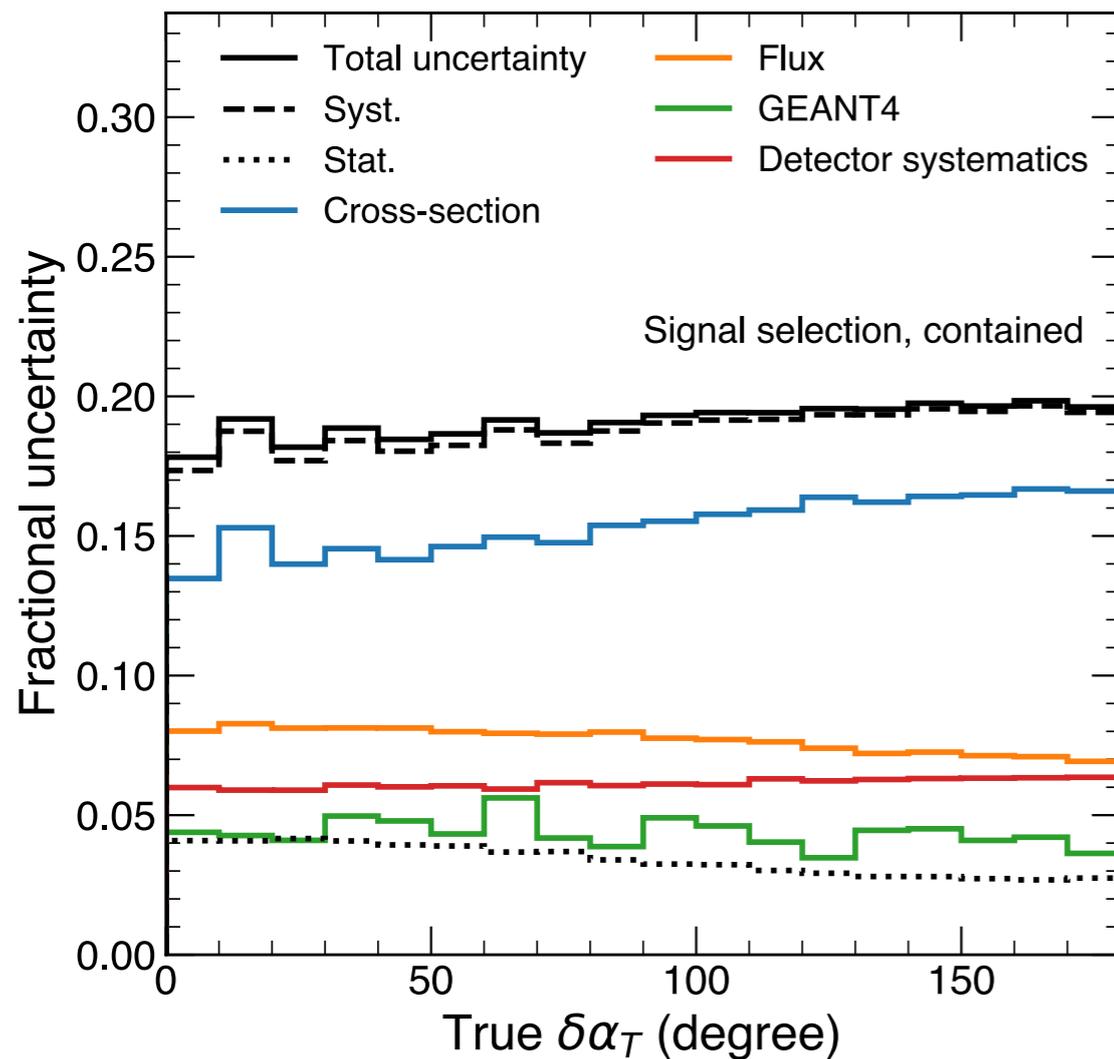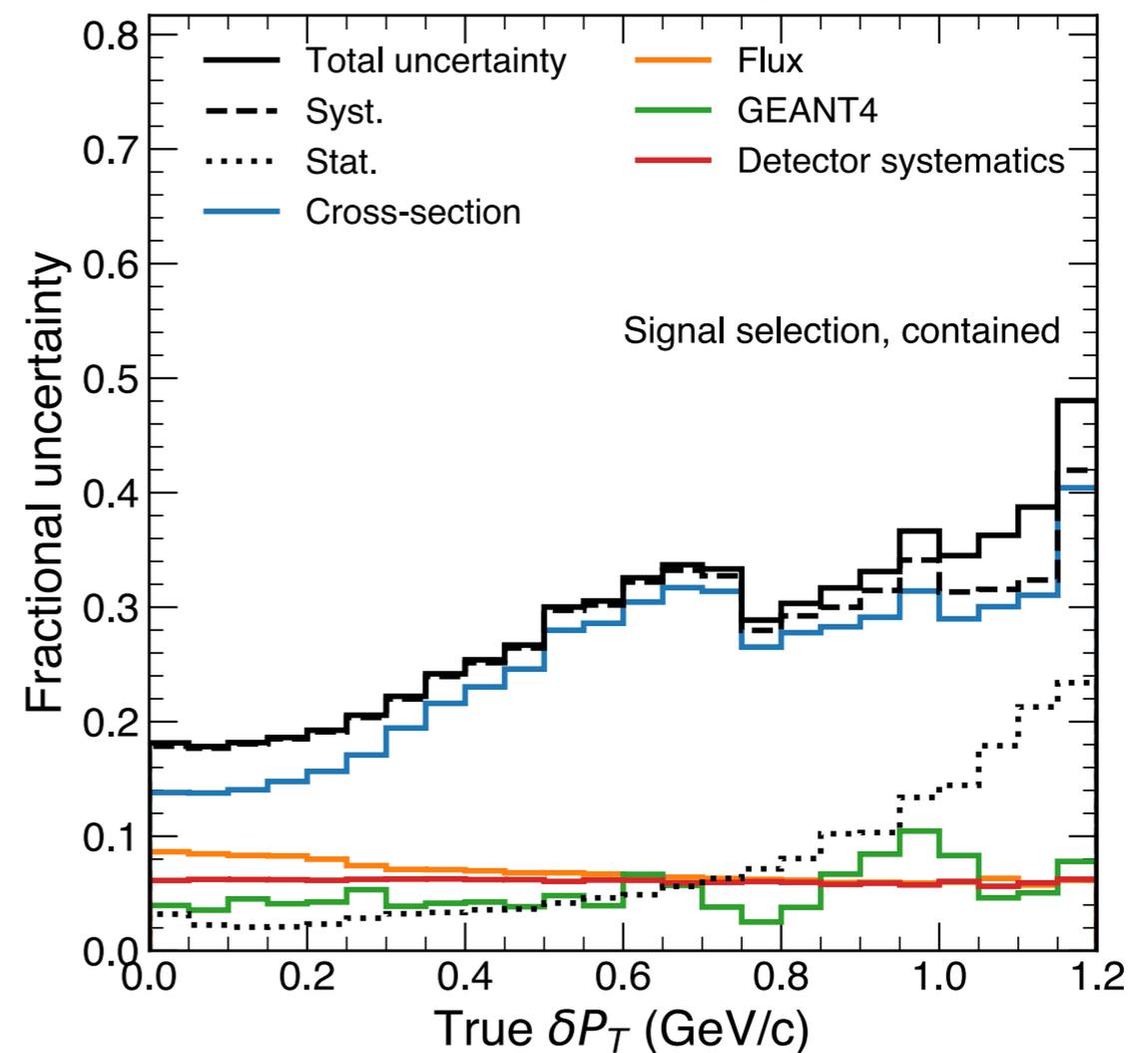
NuMI Cross Section

- Developing the cross section extraction with small set of the data
- A selection targeting 1μ+Nproton + 0π anything with some differences in cuts with data samples to highlight cosmic rejection and selected beam events
- Data versus MC studies ongoing: shown here some relaxed cuts area normalized, fairly reasonable comparisons
- Measuring backgrounds/sidebands for analysis (e.g. charged pions)
- Developing and evaluating systematic uncertainties, using GENIE v3.04.00 with the latest development shared from DUNE
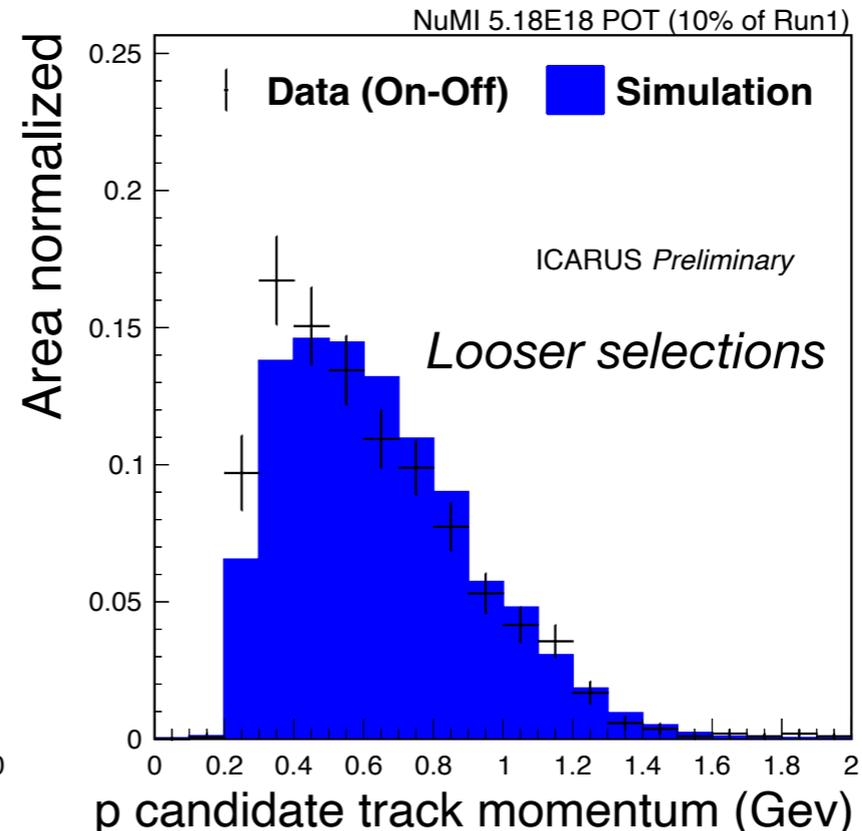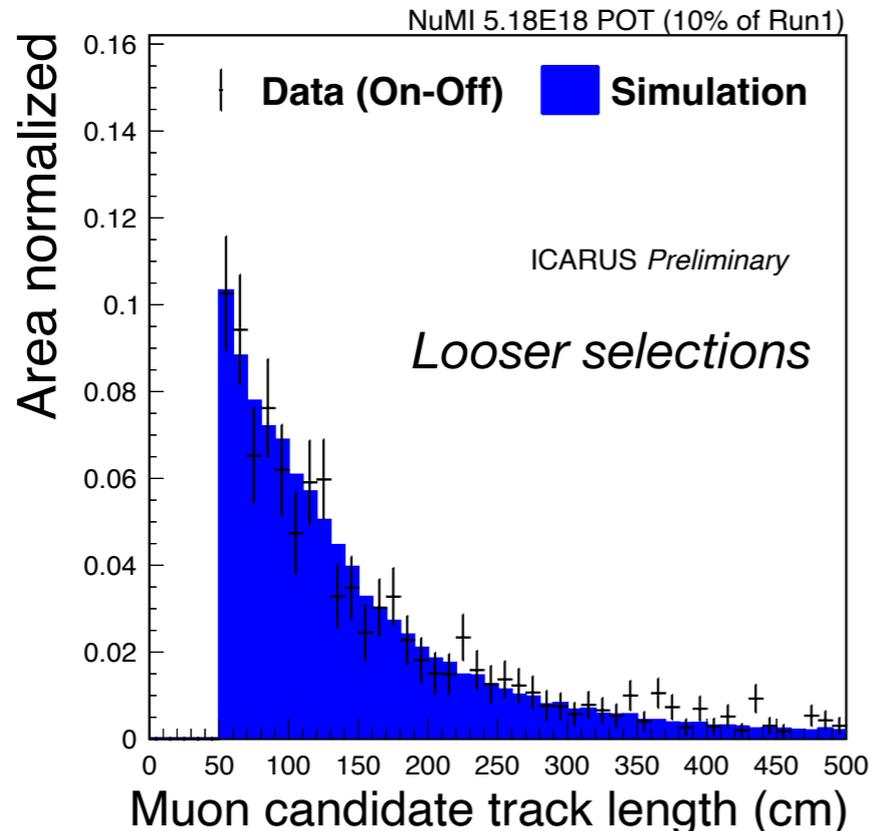
Summary

- Rich physics program of neutrino-argon scattering measurements and BSM physics using NuMI
  - Conducting neutrino cross-section and interaction measurements using neutrinos from NuMI beam in a similar kinematic regime as DUNE
    - Opportunity to test and constrains models for use in DUNE
- ICARUS at Fermilab underwent a period of commissioning and first operations as captured in recent paper: P. Abrateenko et al, Eur. Phys. Journal C 83, 467 (2023)
- Actively using forward analyses with the data collected 3E20 POT from NuMI
  - Ongoing work to conduct 1μ+Nproton+0π cross section analysis
- ICARUS results will be quantitatively useful when DUNE is building and tuning its interaction model for real data analysis
- We would love to use the latest models development discussed in this workshop and work together to benchmark the models and uncertainties with new data

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