Fermilab

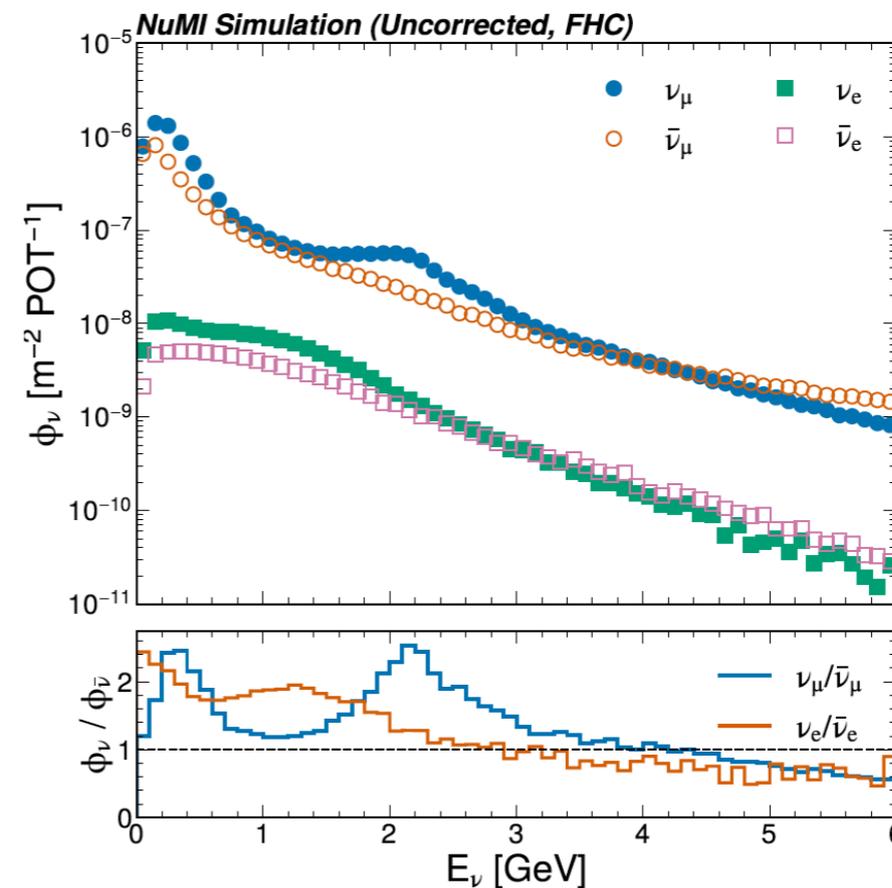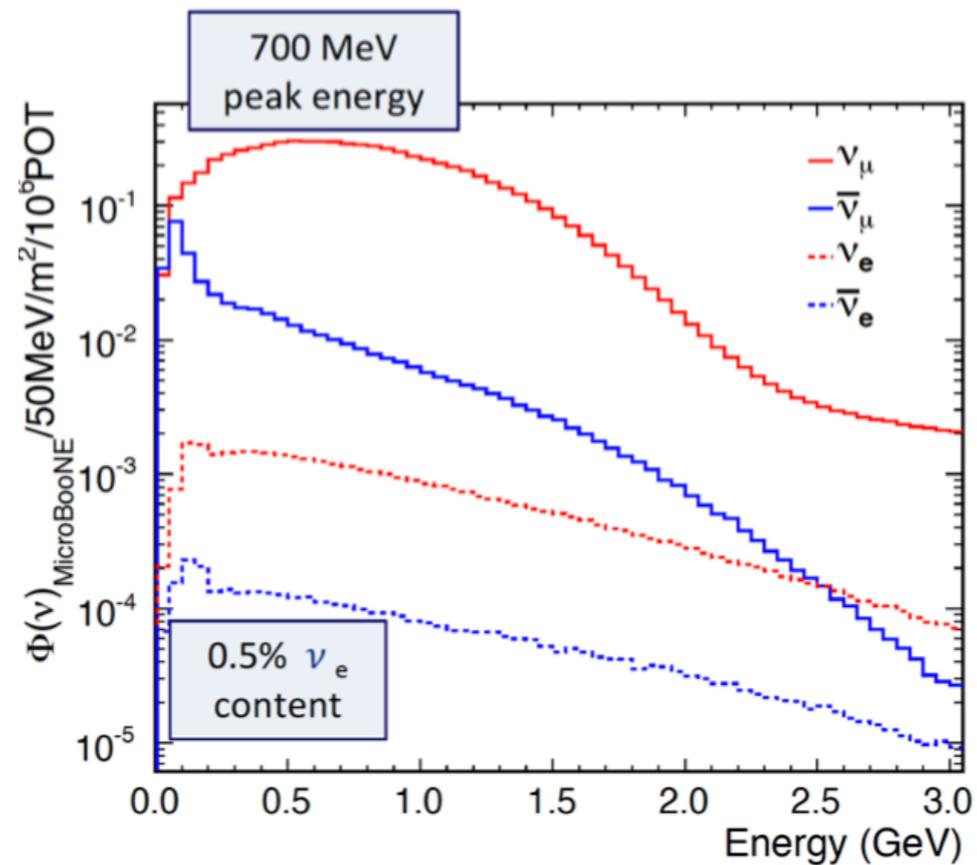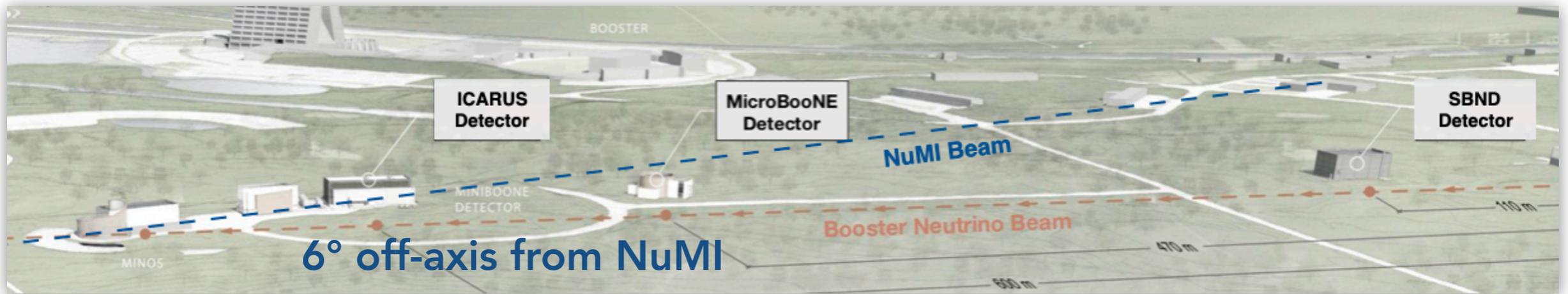# Future Statistics and Constrains from ICARUS using NuMI

Minerba Betancourt (Fermilab) on behalf of the ICARUS collaboration

02 Nov 2023
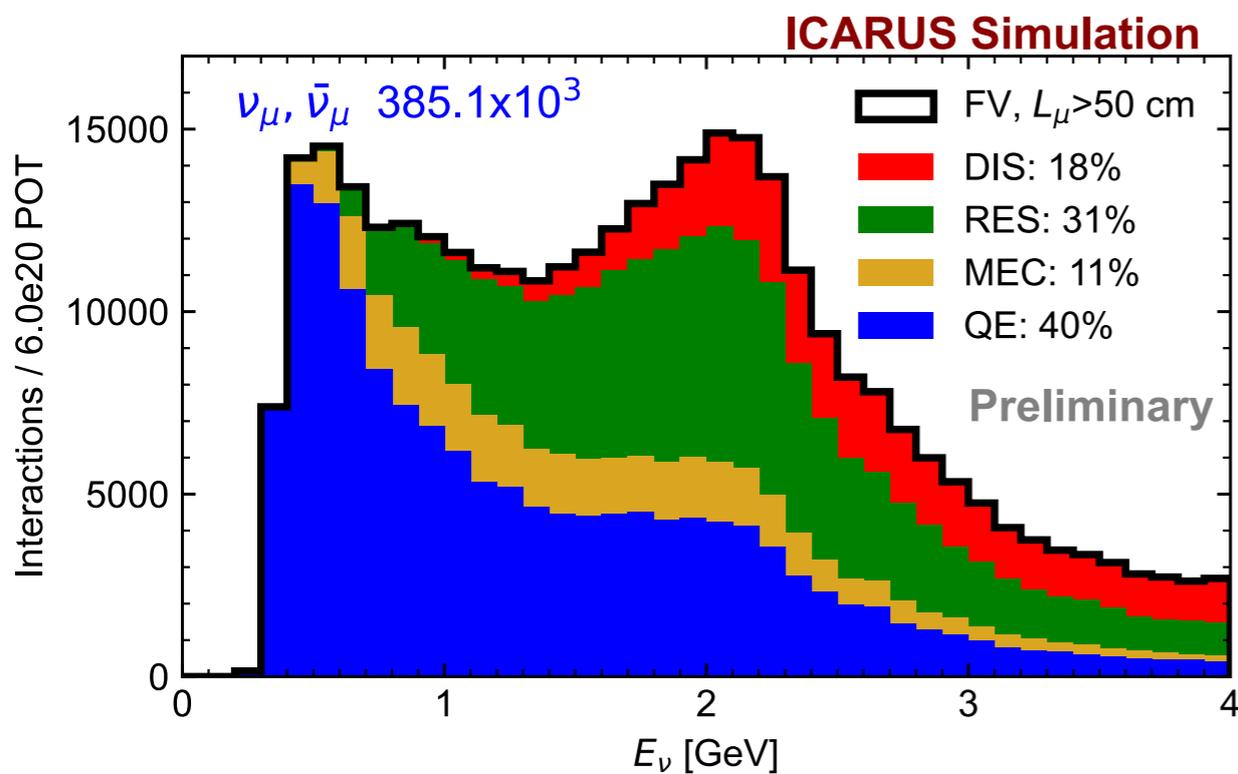
INT Workshop 2023

ICARUS at FNAL

- The ICARUS detector is located on-axis from the Booster beam and 6° off-axis from the NuMI beam
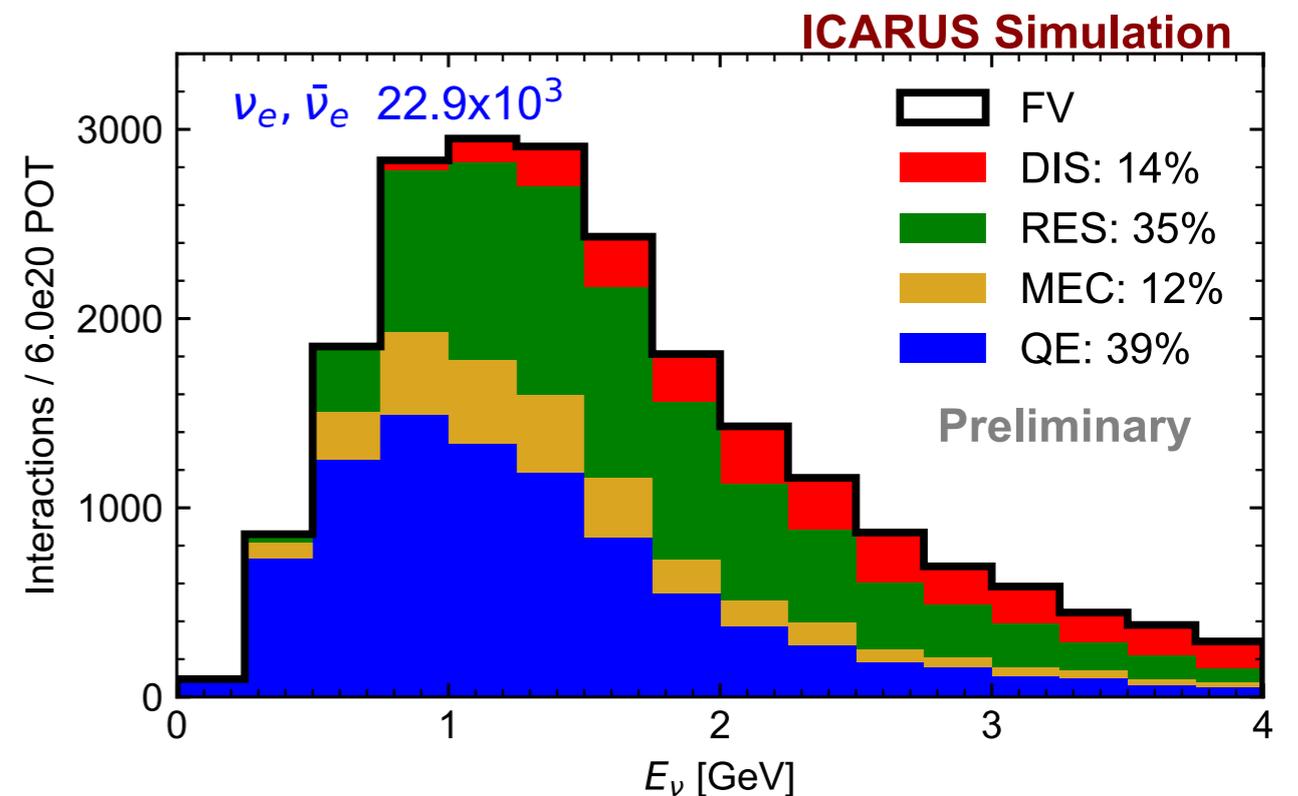
Neutrino Interactions from NuMI off axis at ICARUS

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

Muon Neutrino

ICARUS Simulation

$\nu_\mu, \bar{\nu}_\mu$ 385.1x10^3

FV, L_μ>50 cm
DIS: 18%
RES: 31%
MEC: 11%
QE: 40%

Preliminary

Interactions / 6.0e20 POT

E_ν [GeV]

Electron Neutrino

ICARUS Simulation

$\nu_e, \bar{\nu}_e$ 22.9x10^3

FV
DIS: 14%
RES: 35%
MEC: 12%
QE: 39%

Preliminary

Interactions / 6.0e20 POT

E_ν [GeV]

Expected event rates for 1 year

Muon neutrino	CCQE	CCMEC	CCRES	CCDIS
6E20 POT	186400	40262	142780	77060
Electron neutrino	CCQE	CCMEC	CCRES	CCDIS
6E20 POT	8256	2000	7905	3678

CC Events/year
ν_μ 446,000
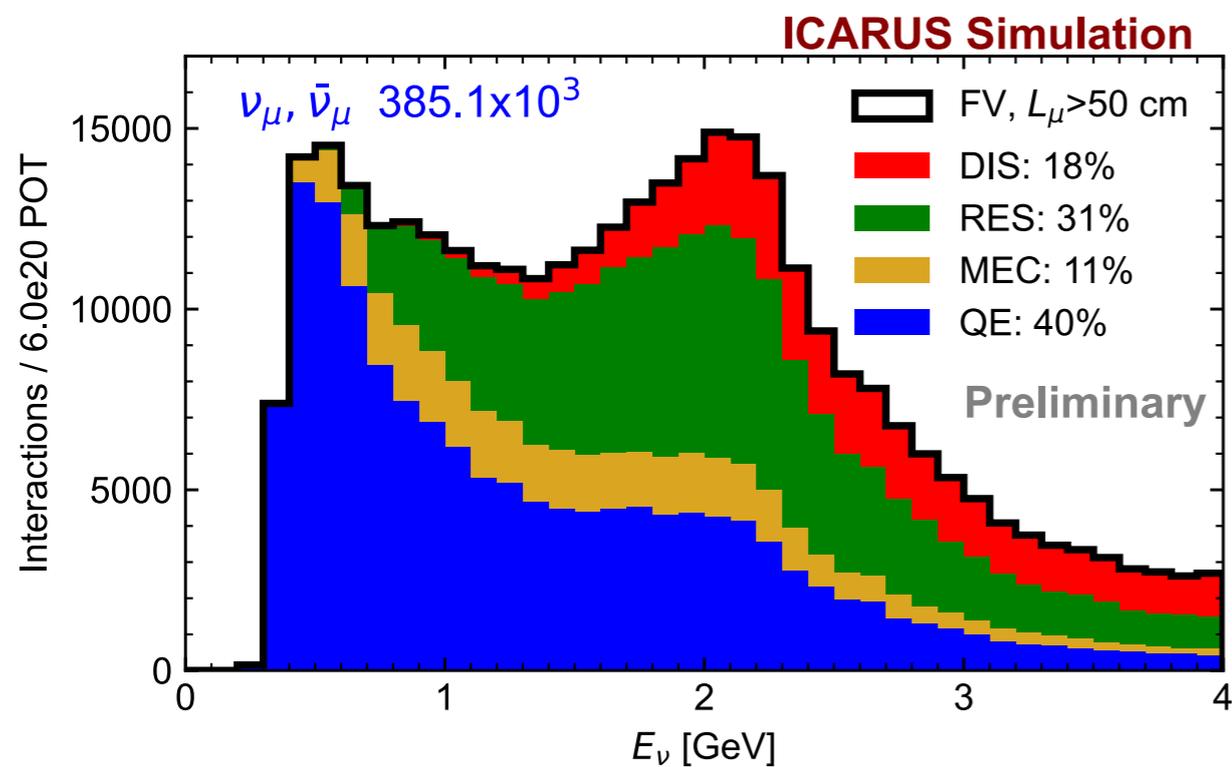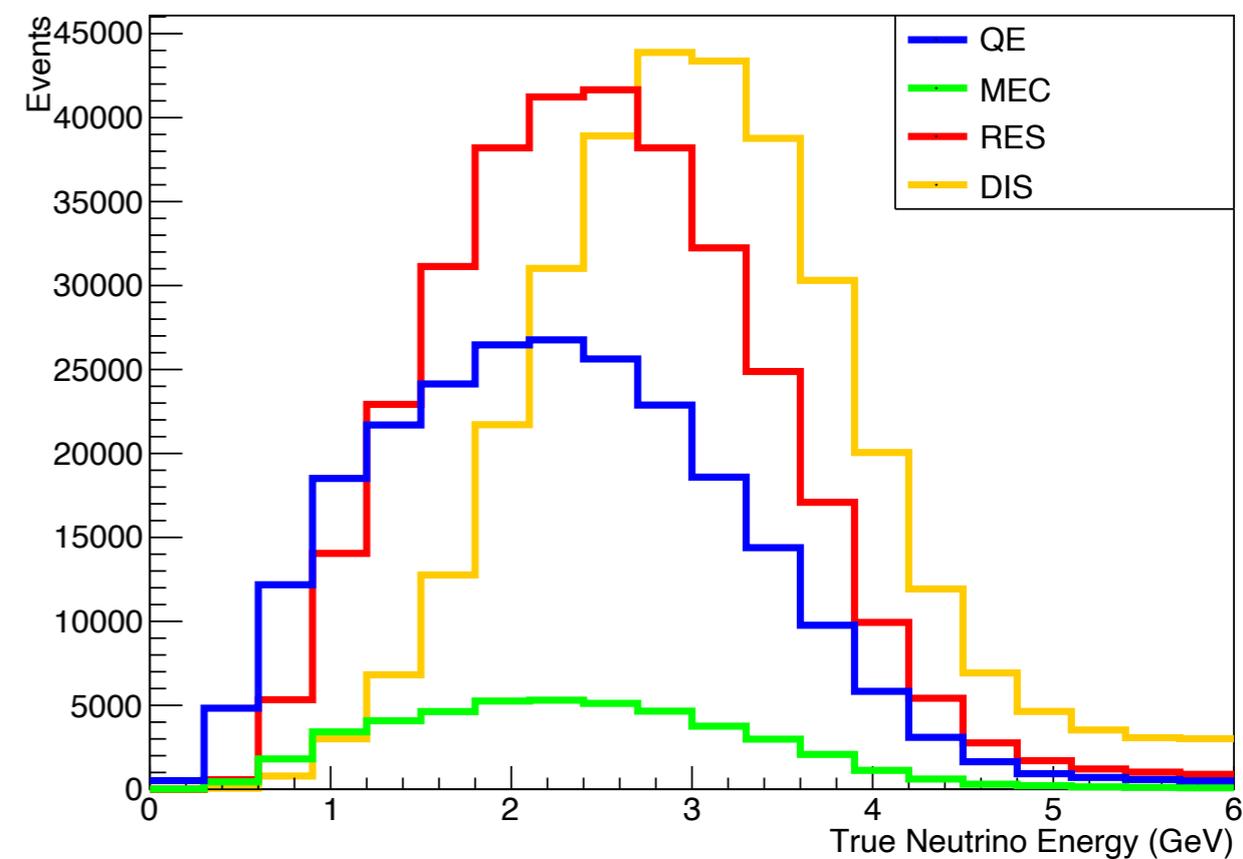ν_e 22,000

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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

ICARUS Simulation

$\nu_\mu, \bar{\nu}_\mu$ 385.1×10^3

	FV, $L_\mu > 50$ cm
DIS:	18%
RES:	31%
MEC:	11%
QE:	40%

Preliminary

Interactions / 6.0e20 POT

E_ν [GeV]

ICARUS Simulation

$\nu_e, \bar{\nu}_e$ 22.9×10^3

	FV
DIS:	14%
RES:	35%
MEC:	12%
QE:	39%

Preliminary

Interactions / 6.0e20 POT

E_ν [GeV]

True Neutrino Energy (GeV)

Muon neutrino	CCQE	CCMEC	CCRES	CCDIS
6E20 POT	186400	40262	142780	77060

CC Events/year
ν_μ 446,000

Fermilab
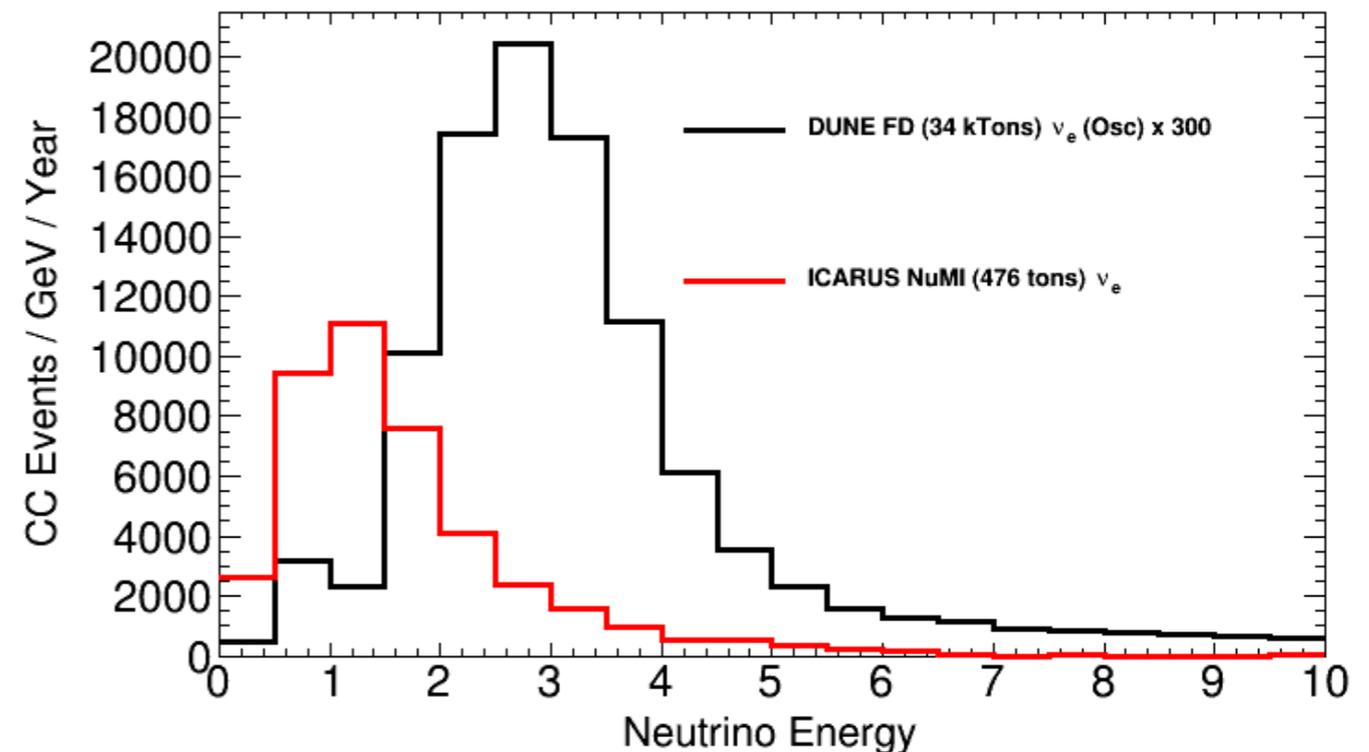
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Relevance for DUNE

- 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
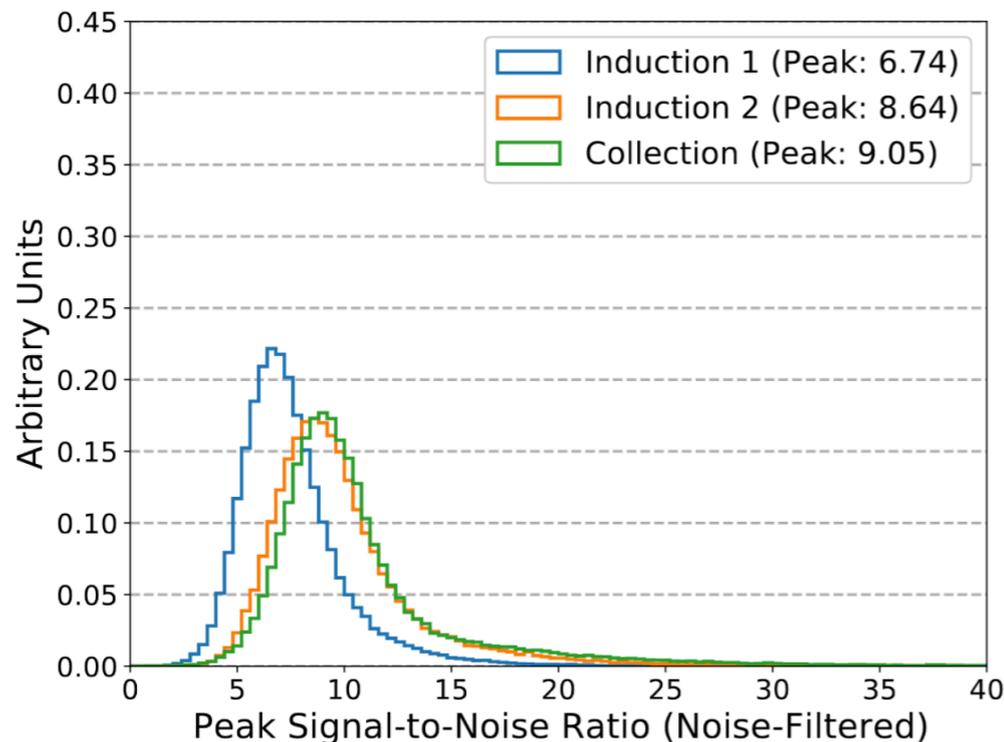
Electron Neutrinos from NuMI
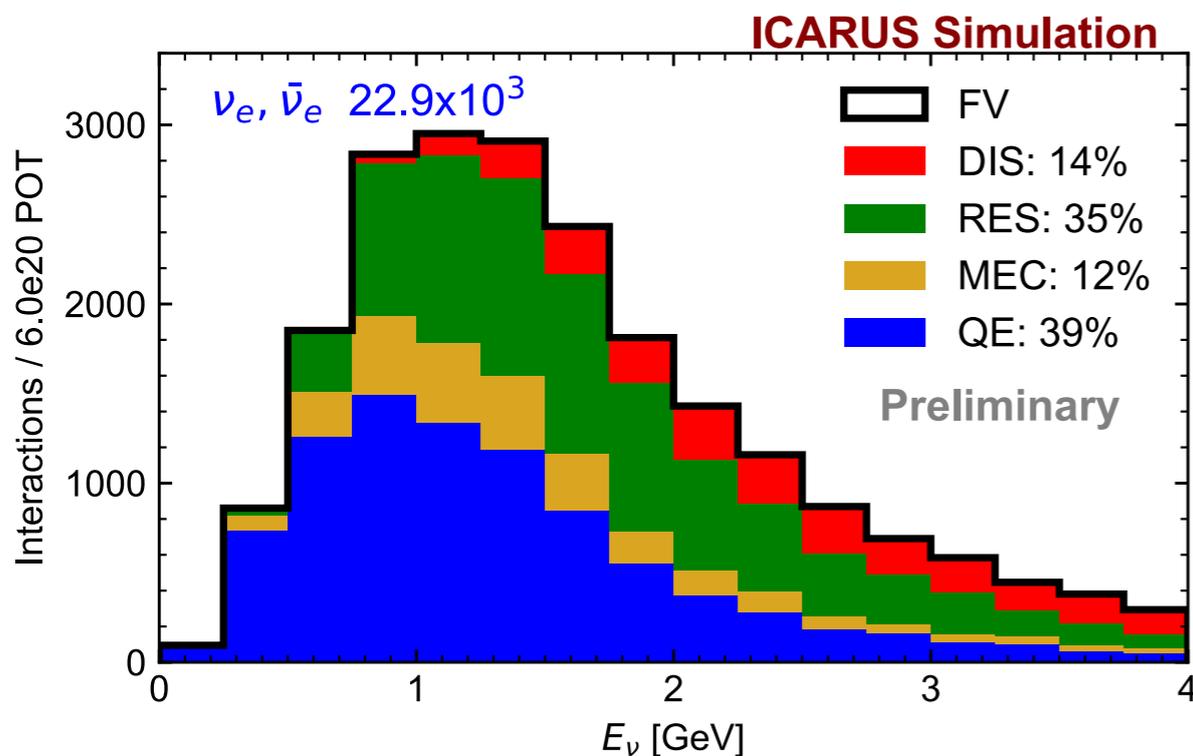
Electron Neutrino in ICARUS and DUNE

CC Events/year: ν_e 22,000

- 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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ICARUS at FNAL

- ICARUS began commissioning in 2020
- First ICARUS physics runs collected spring NuMI and Booster neutrino beams
- Commissioning and physics data have been used to perform the calibration tuning reconstruction and start the first analysis with neutrino data
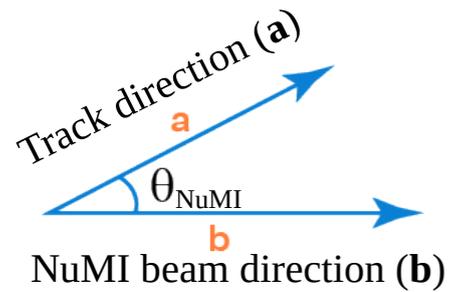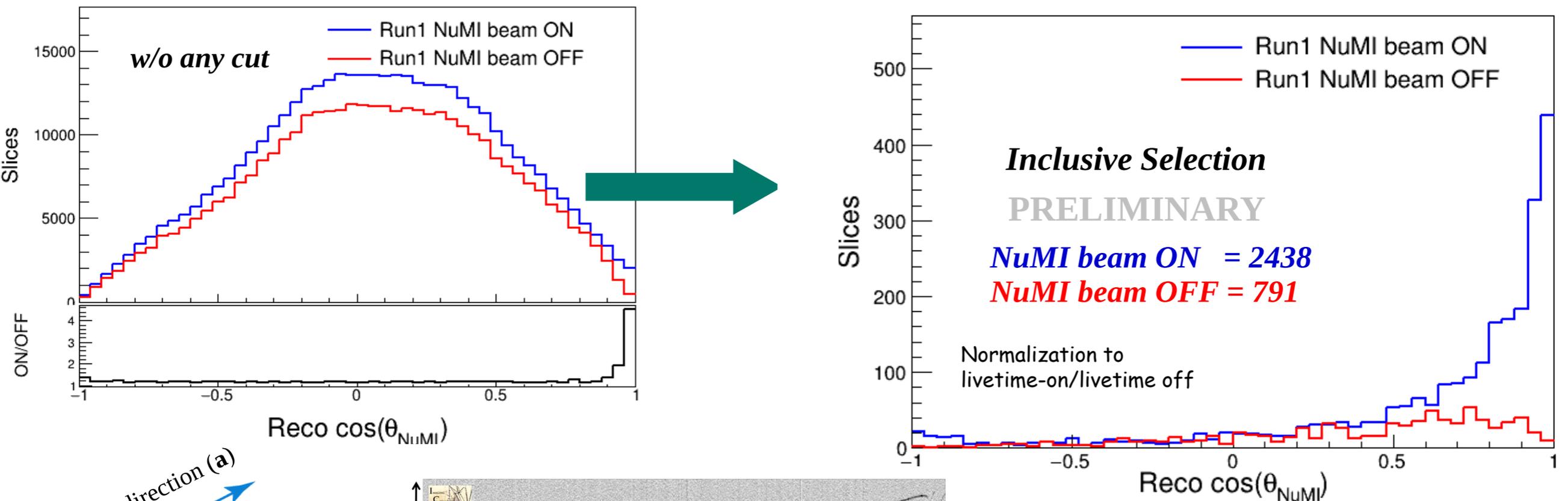- The signal-to-noise ratio was extracted from a sample of anode-to-cathode crossing cosmic muons
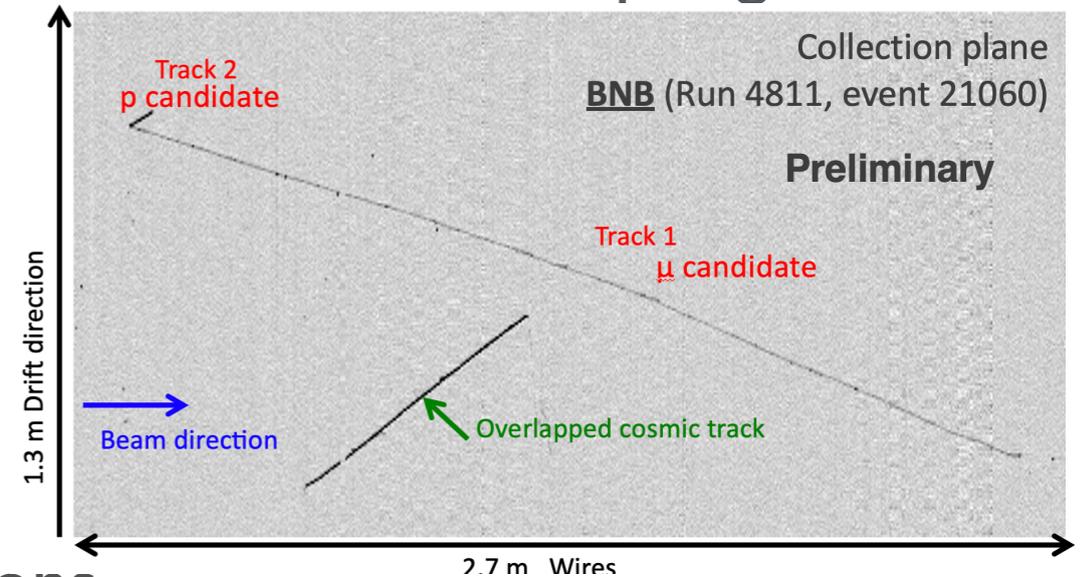
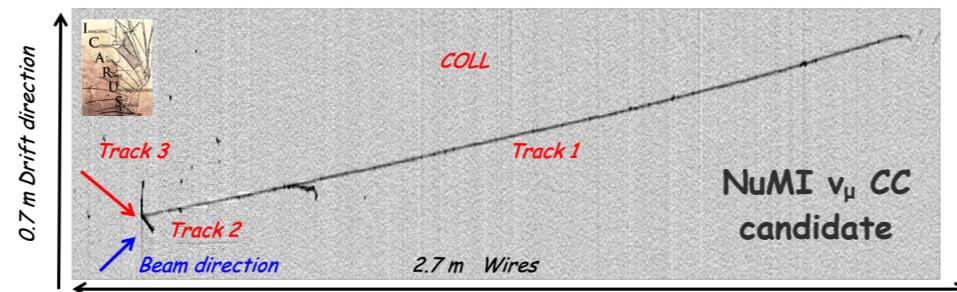Results of ionization drift velocity measurement using cosmic muon data
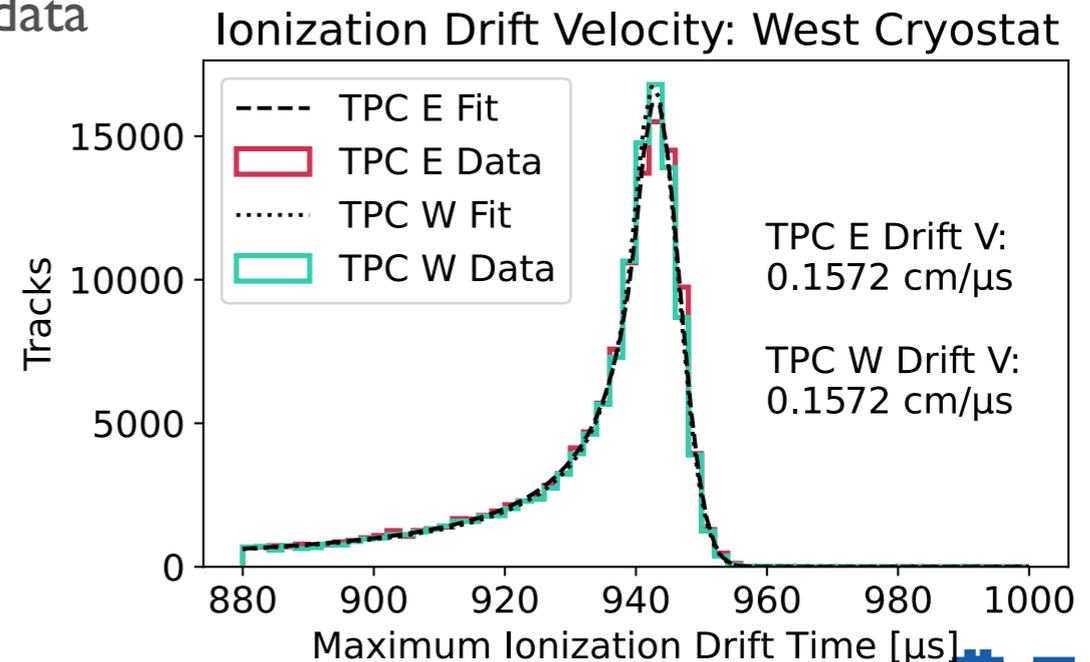
Muon Neutrino from NuMI beam at ICARUS

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

lection Criteria

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

w/o any cut

Run1 NuMI beam ON
Run1 NuMI beam OFF

Slices

ON/C=F

Angle

AnEdenP
Angle Between
Formula
Formula

$MI)$

$cos(\theta_{NuMI}) \xrightarrow{Trac}$

le m

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

Run8446, NuMI, 6e20 POT

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

Events/1.0

Data/MC

Flash matching score

NuMI ν_μ CC candidate

Track direction (a)

θ_{NuMI}

NuMI beam direction (b)

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

est track Y direction (under cosmic ray hypothesis)

is a Pandora clear cosmic,

Slices

Inclusive Selection

PRELIMINARY

NuMI beam ON   = 2438
NuMI beam OFF = 791

Normalization to livetime-on/livetime off

Run1 NuMI beam ON
Run1 NuMI beam OFF

Reco cos(θ_{N})

Inclusive selection cuts

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

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%)

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%)

a·b

a| |b|

x b

Num beam direction (b)

ICARUS Simulation

/ 6x10^{20} POT

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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

eno

ICARUS Simulation

ν_μ CC, $L_\mu \geq 50$ cm

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

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

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

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

440k ν_μ CC events in 1 year

E [GeV]

ICARUS S

NuMI Interac

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

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

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

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

ν_e CC Interactions / 6x10^{20} POT

Building a Cross Section Analysis for 1μ+Nproton+0π

- First analysis targets 1**μ**+Nproton+0**π**

  - 1**μ**+Nproton+0**π** enhanced in quasi-el

- Building up cross-section analysis to co

- Angle between the muon candidate and   he phase
  space somewhat broadly and would be   t FSI for
  all events

- Transverse kinematic imbalances observa   s

- Expect ~20K selected events at current se
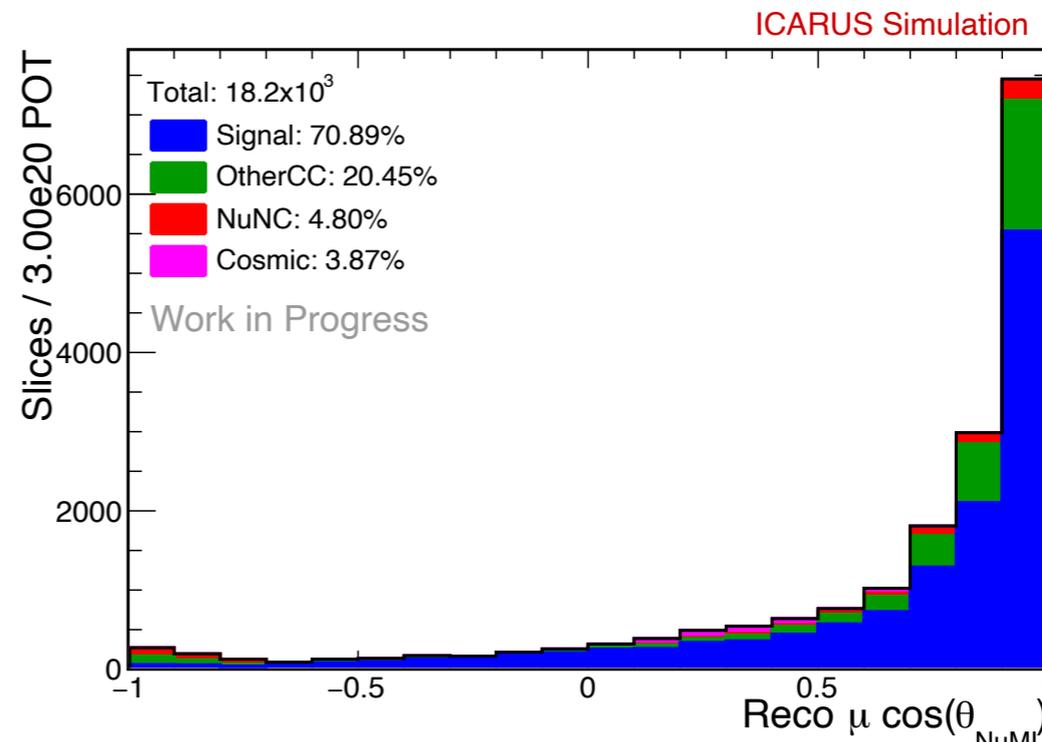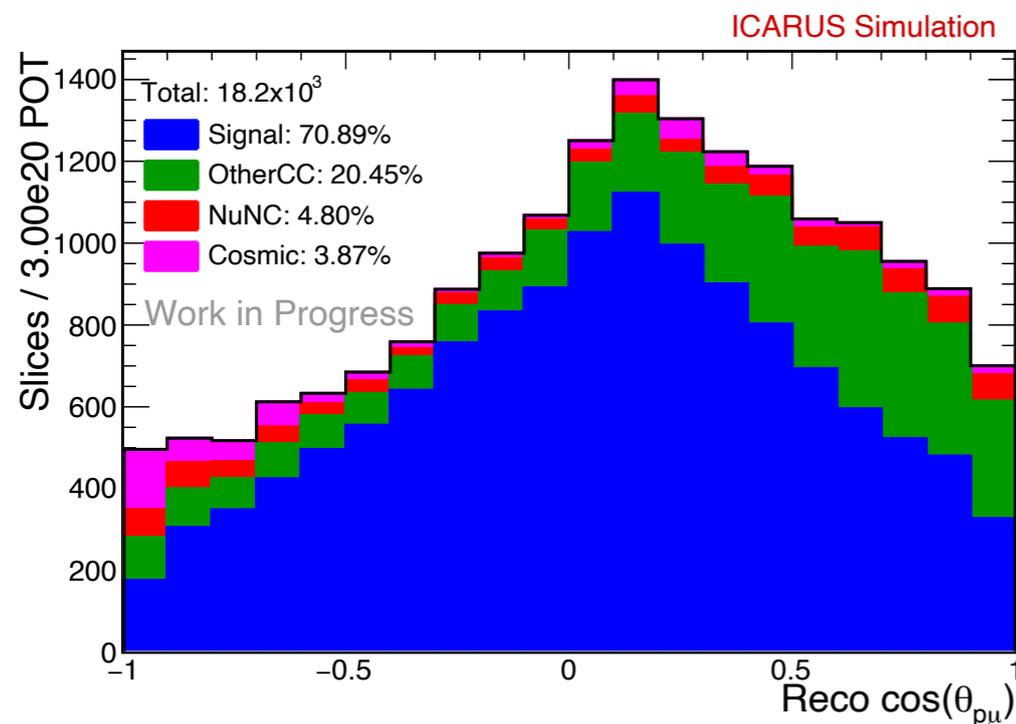
NuMI Cross Section

- Developing the cross section with small set of the data
- A selection targeting 1μ+Nproton + 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
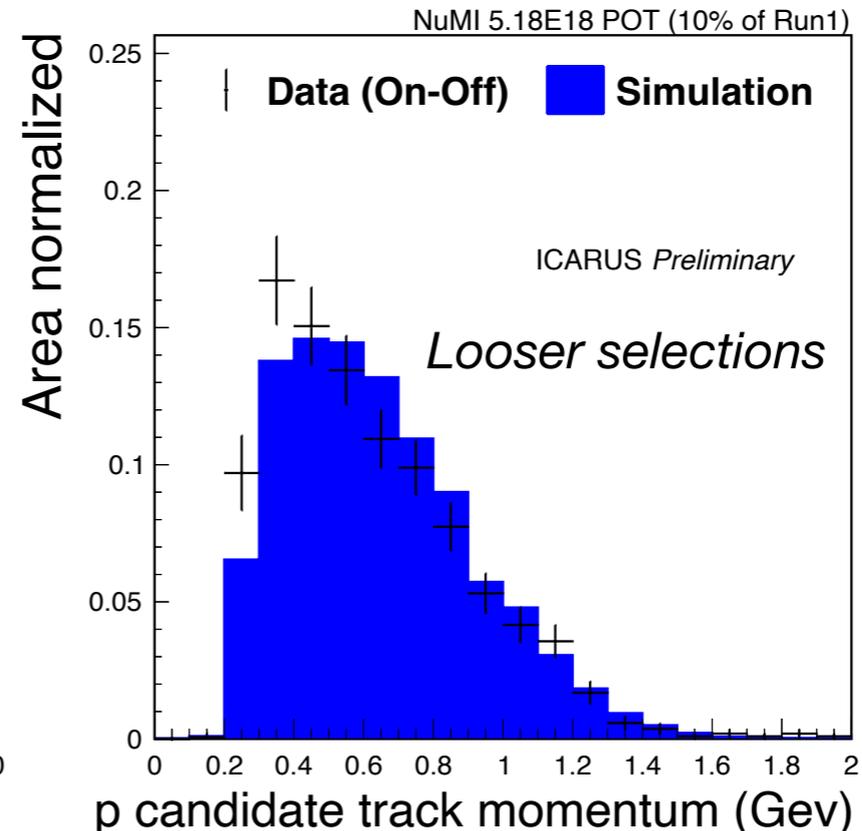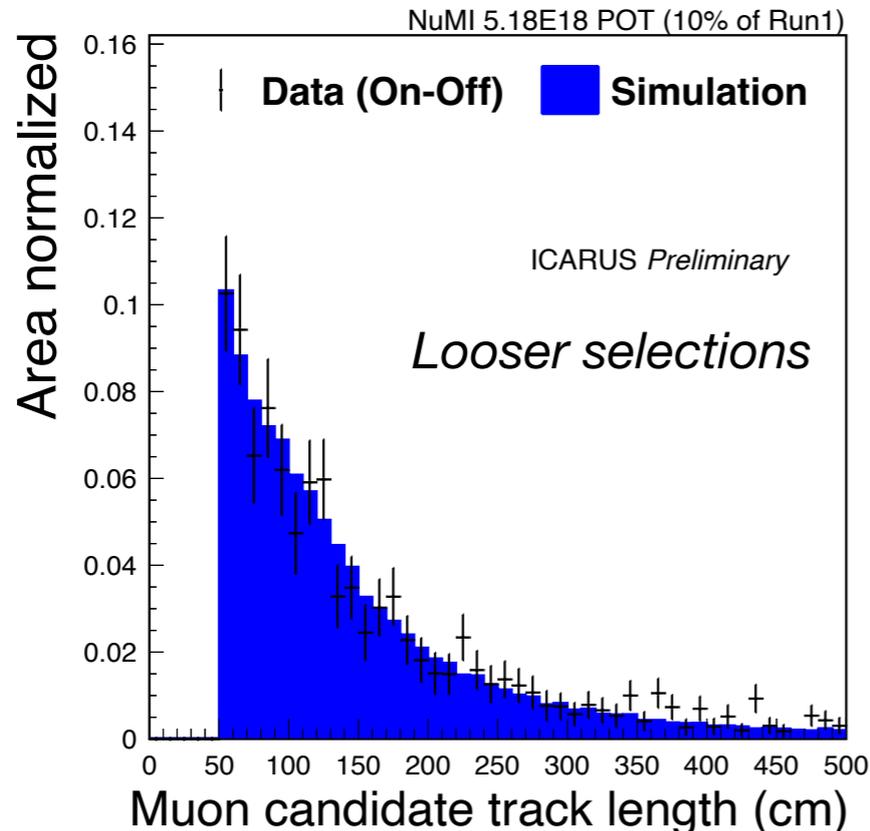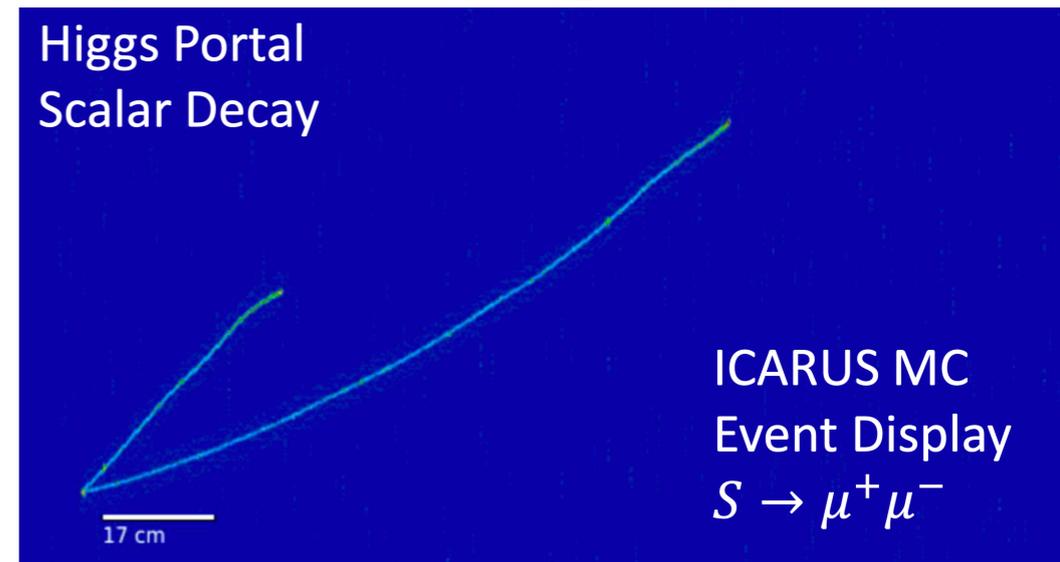
BSM Searches with NuMI

- Certain BSM searches benefit from sitting off-axis such as kaon coupled Higgs portal scalars

PRD 100, 115039 (2019)
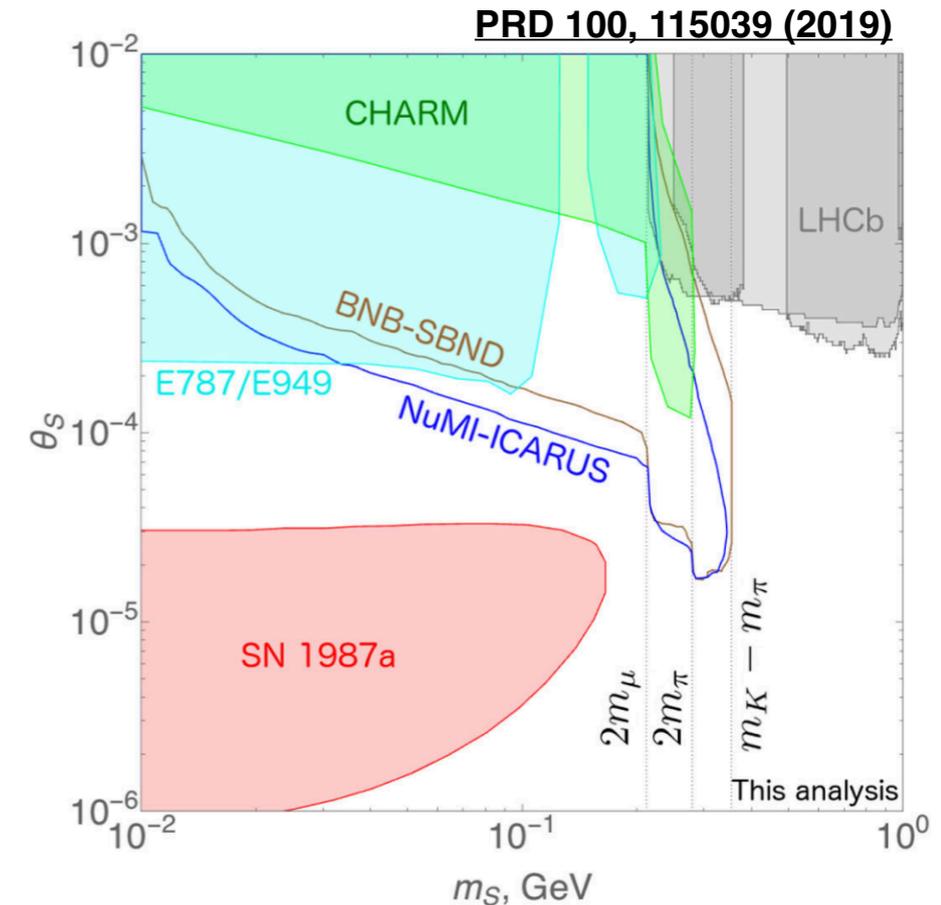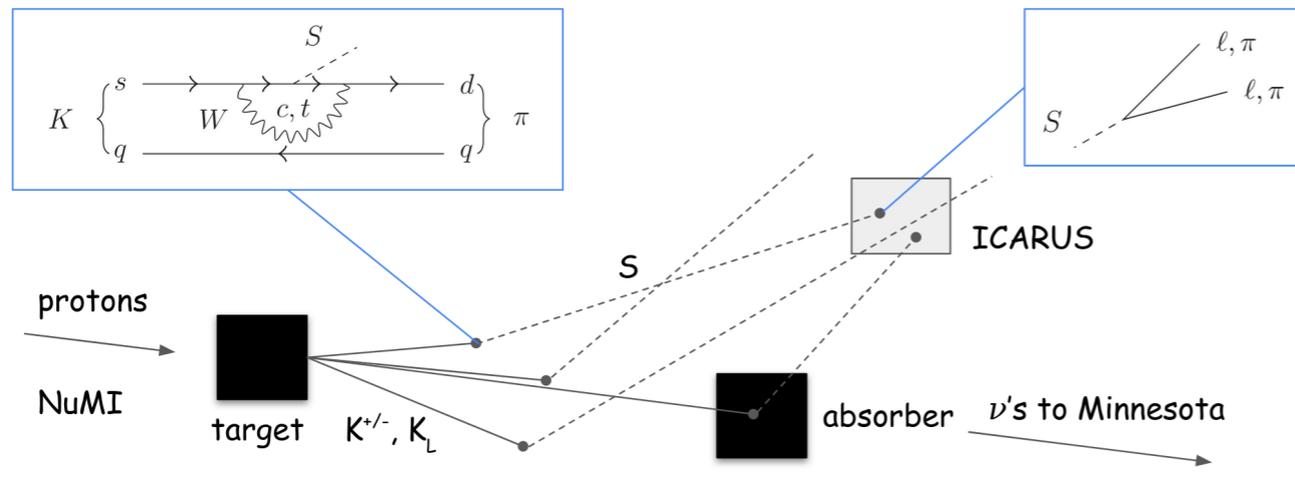
- Phenomenological studies have shown great promise for a search like this

- Looking for light dark matter, Higgs portals scalar and other long lived particles $l, \bar{l}$

- Early analysis on Higgs portal scalar to $\mu^+\mu^-$ is well on the way and a number of other analyses are progressing $\mu, \bar{\mu}$

Higgs Portal Scalar Decay

ICARUS MC Event Display $S \rightarrow \mu^+\mu^-$

17 cm

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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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