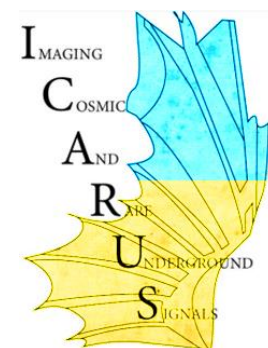


The first cross-section measurement from ICARUS

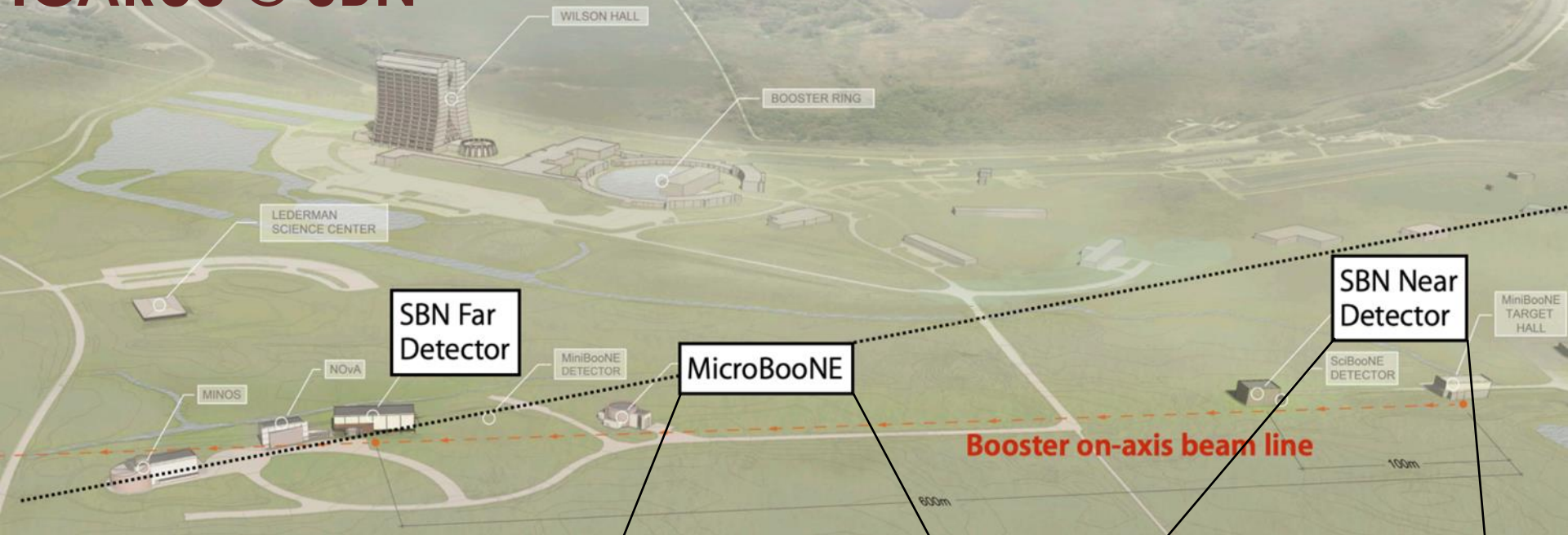


Stephen Dolan
For the ICARUS collaboration

stephen.joseph.dolan@cern.ch



ICARUS @ SBN



MicroBooNE



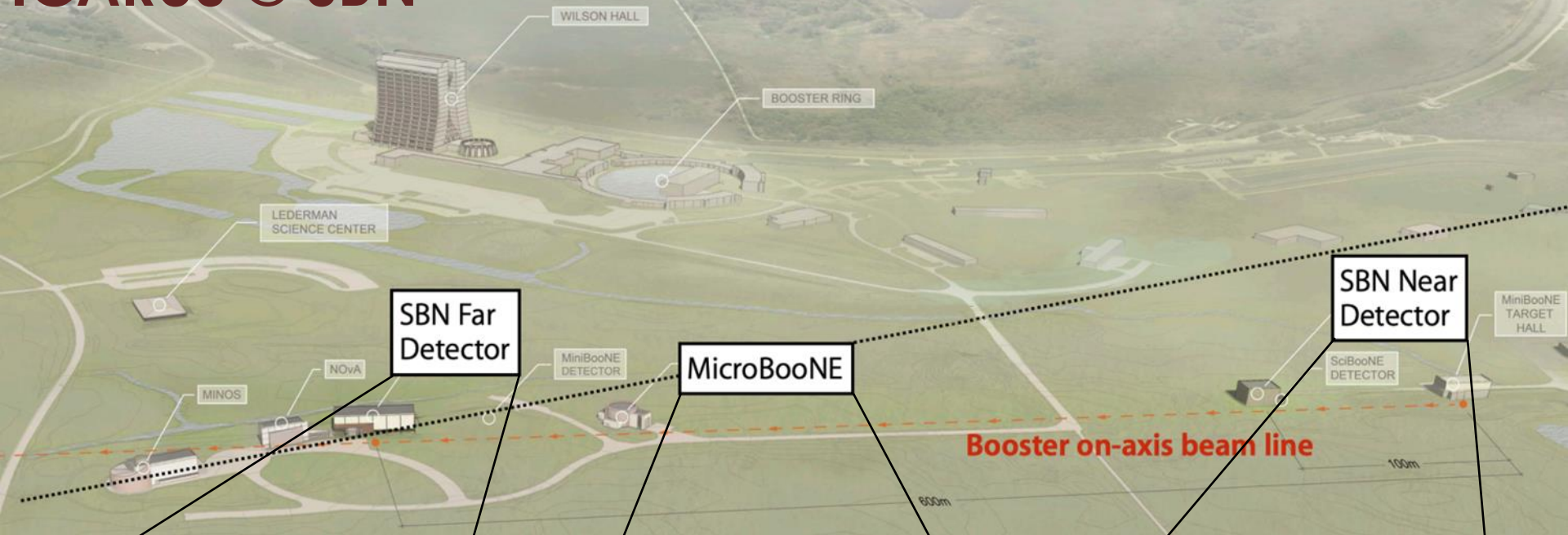
BNB baseline: 470 m
Total LAr: 170 ton
Active LAr: **90 ton**

SBND

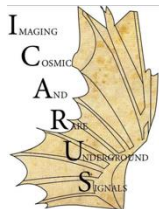


BNB baseline: 110 m
Total LAr: 270 ton
Active LAr: **112 ton**

ICARUS @ SBN



ICARUS-T600



BNB baseline: 600 m
Total LAr: 760 ton
Active LAr: **476 ton**

MicroBooNE



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SBND

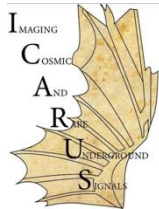


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SBN Physics Goals:

- Definitive search for SBL ev-scale sterile neutrinos
- Detailed studies of ν -Ar interactions
- New searches for BSM physics
- Advancement of large LAr TPC technology

ICARUS-T600



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Total LAr: 760 ton
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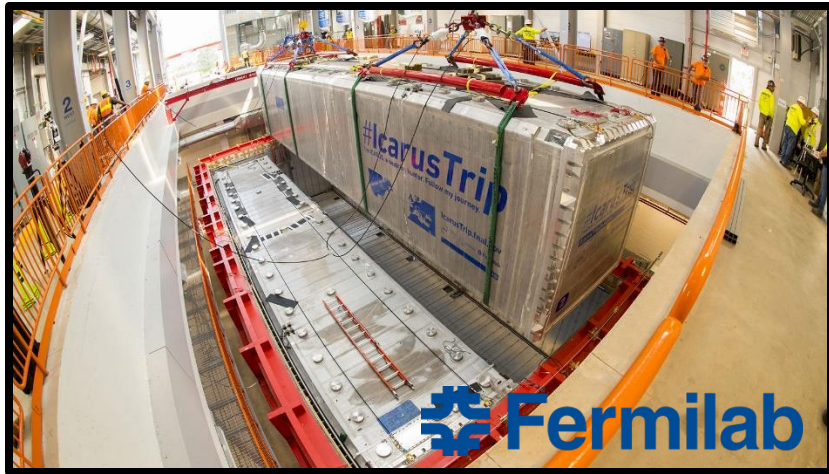
SBND



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The ICARUS experiment

The first large Liquid Argon Time Projection Chamber (LArTPC)



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
- Two identical modules, four TPCs, 476 tons total active mass
 - Sensitive volume: 18 m X 1.5 m X 3.16 m



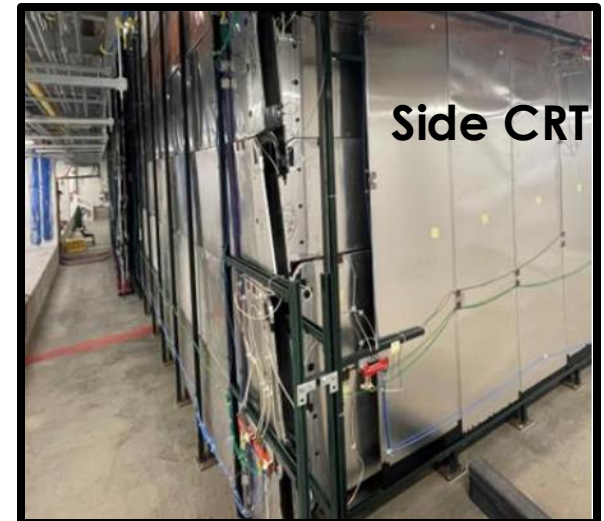
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 - ns resolution → spatial localisation of events < 50 cm



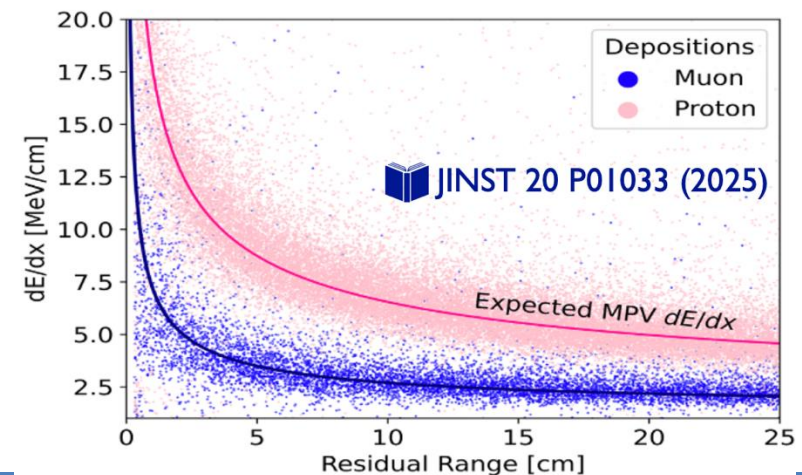
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 - Scintillator strips read out by SiPMs

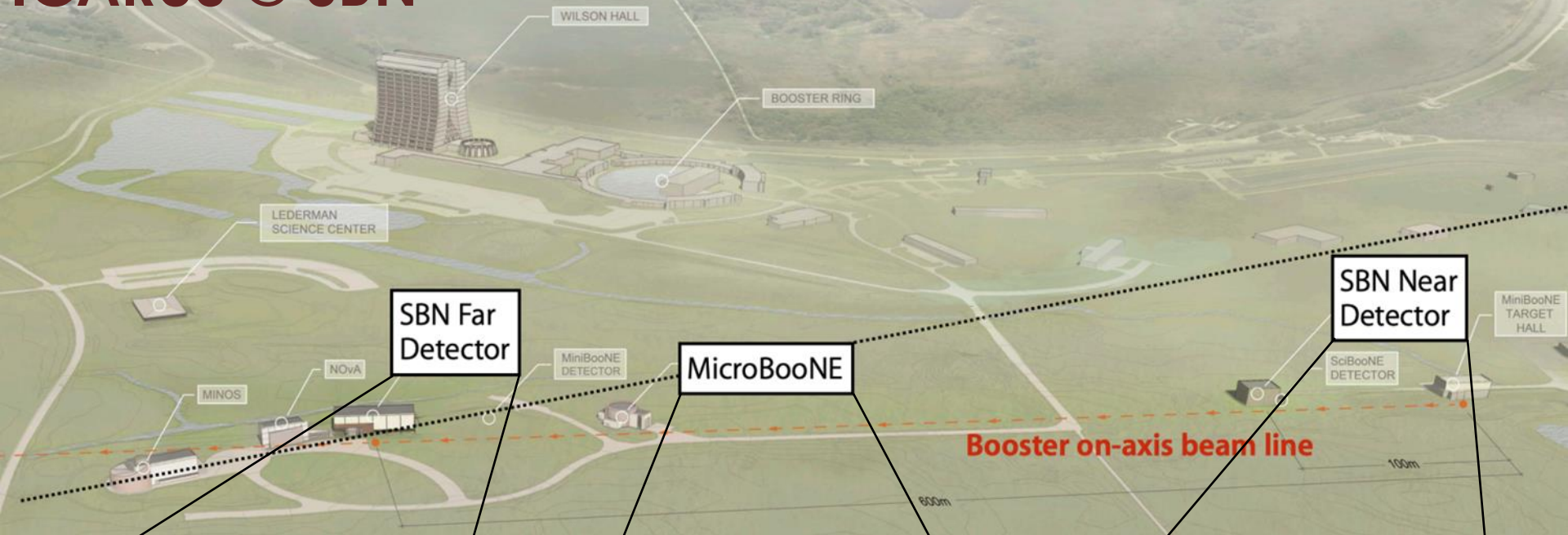


The ICARUS experiment

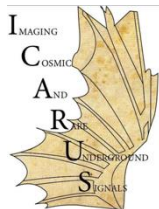
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- Well-validated detector performance using in-situ data taking
 - [arXiv:2301.08634](https://arxiv.org/abs/2301.08634)
 - [JINST 20 P01033 \(2025\)](https://arxiv.org/abs/2007.10333)
 - [arXiv:2501.03034](https://arxiv.org/abs/2501.03034)



ICARUS @ SBN



ICARUS-T600



BNB baseline: 600 m
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MicroBooNE



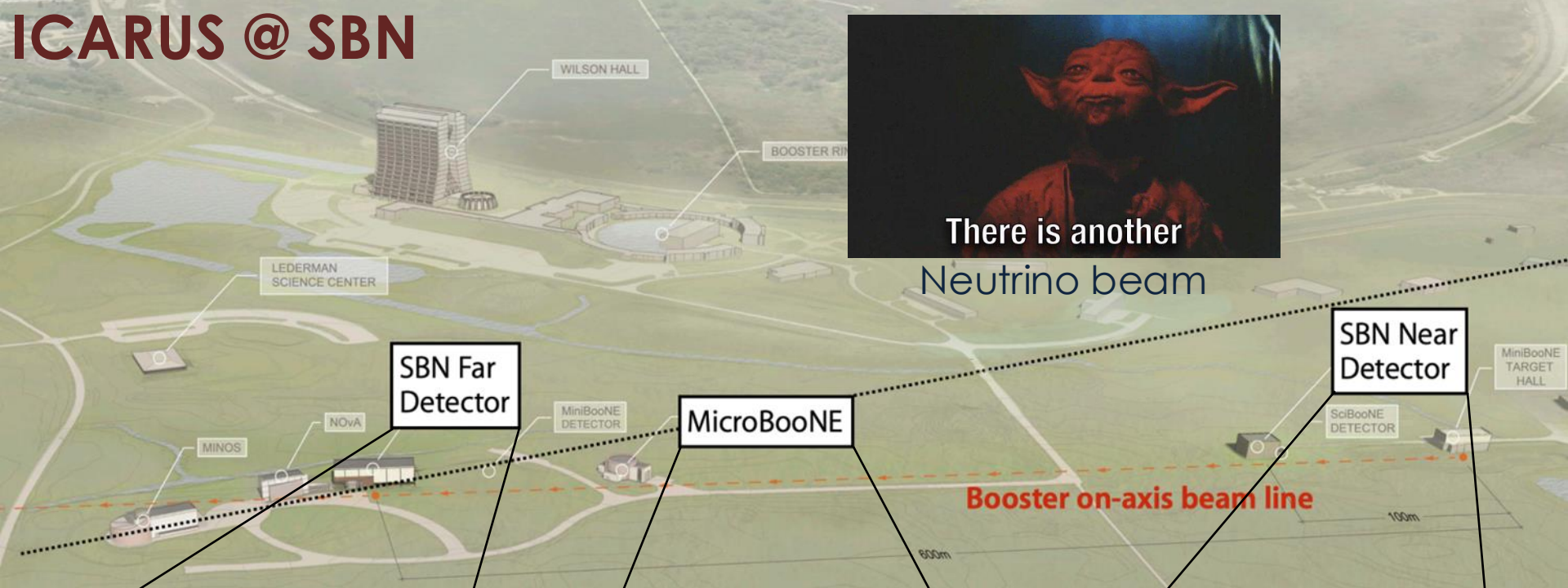
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SBND



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ICARUS @ SBN



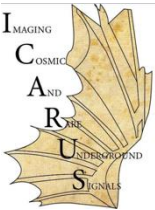
There is another
Neutrino beam

SBN Far
Detector

MicroBooNE


SBN Near
Detector

ICARUS-T600



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MicroBooNE



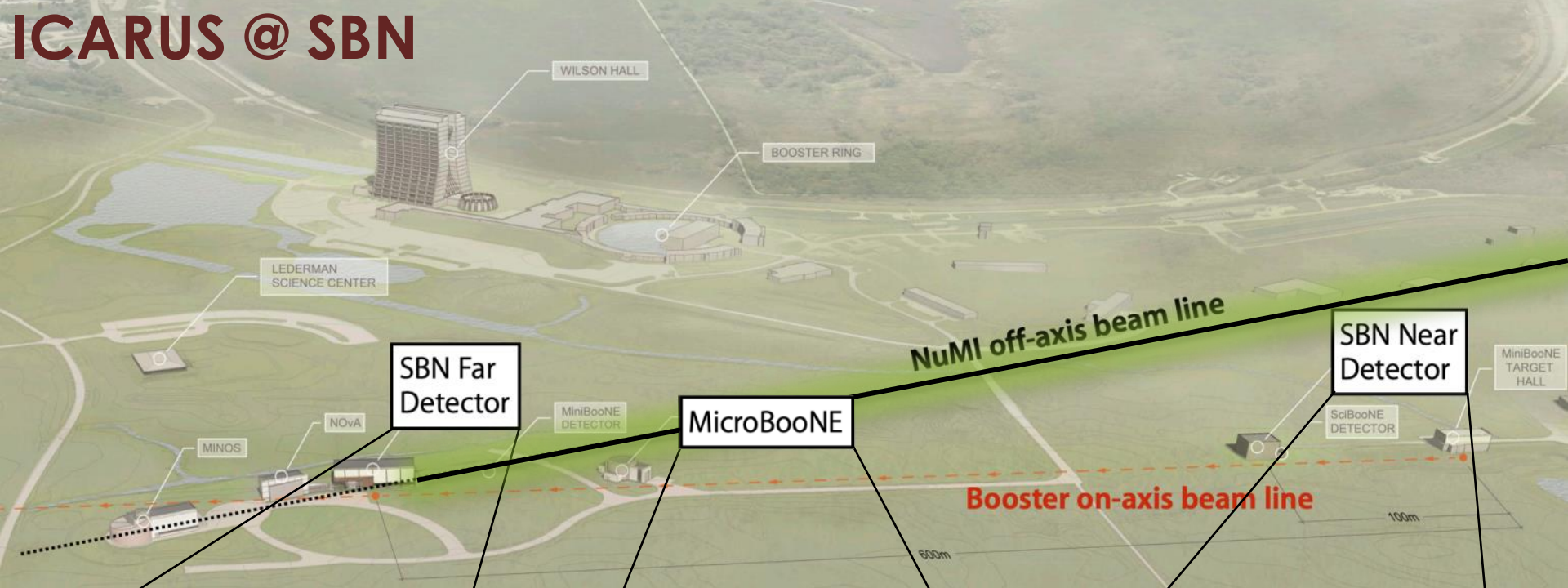
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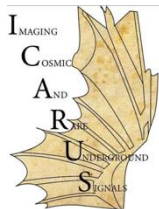


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ICARUS @ SBN



ICARUS-T600



BNB baseline: 600 m
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 Active LAr: **476 ton**
 NuMI off-axis angle*: 5.9°

MicroBooNE



BNB baseline: 470 m
 Total LAr: 170 ton
 Active LAr: **90 ton**
 NuMI off-axis angle*: 8°

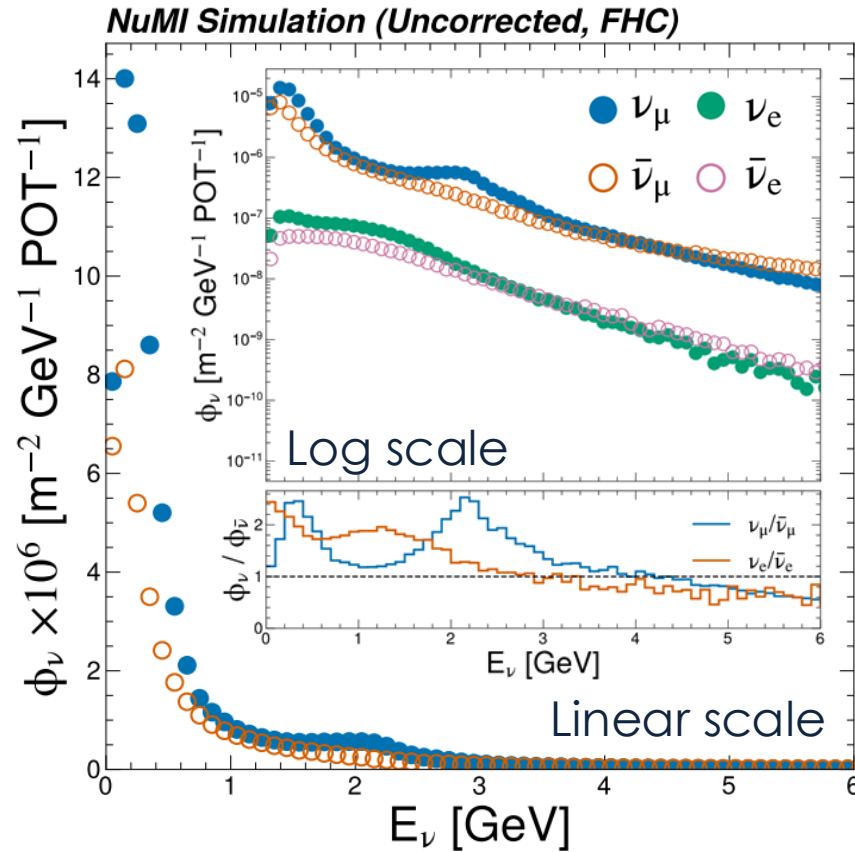
SBND



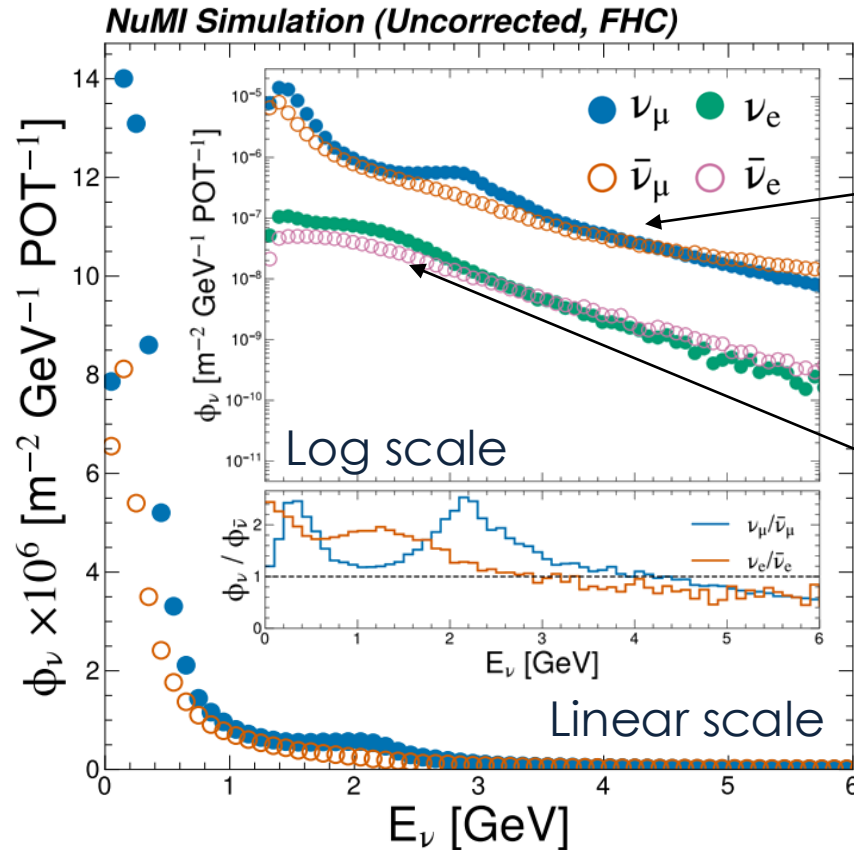
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 Total LAr: 270 ton
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* As measured from close to the target, observed neutrinos come from a wide range of angles

The NuMI beam at ICARUS



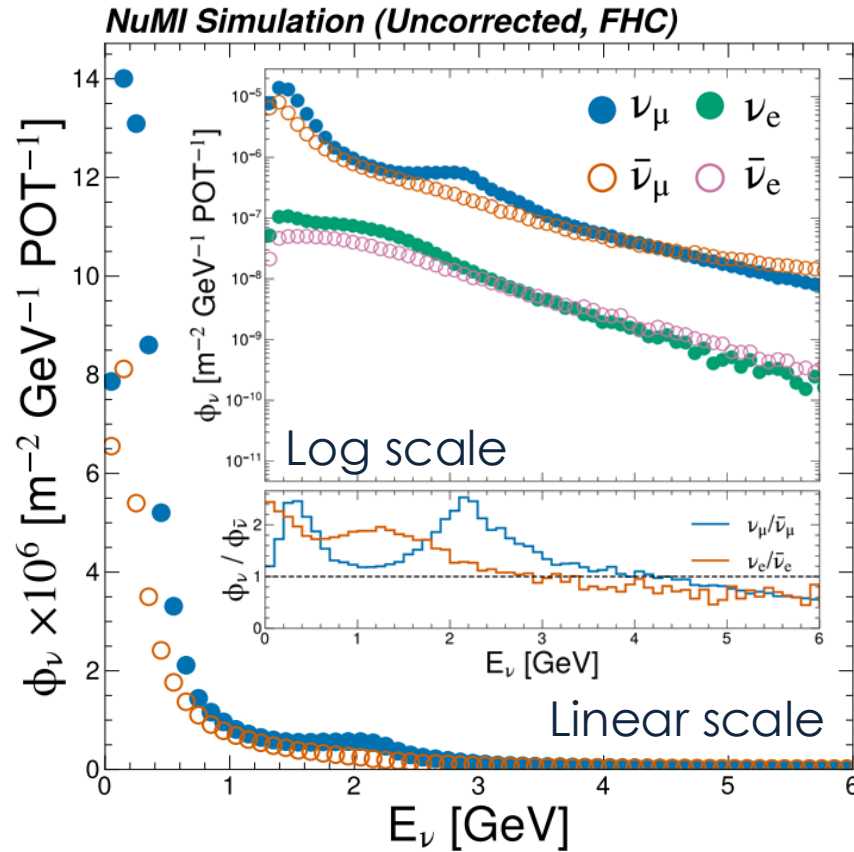
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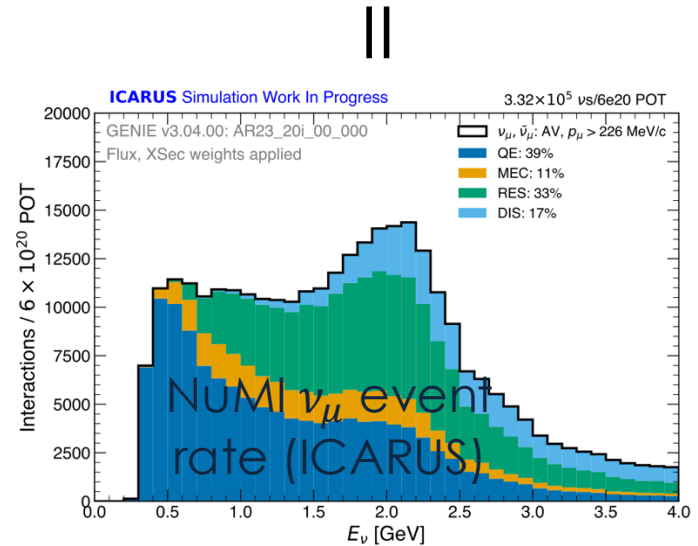
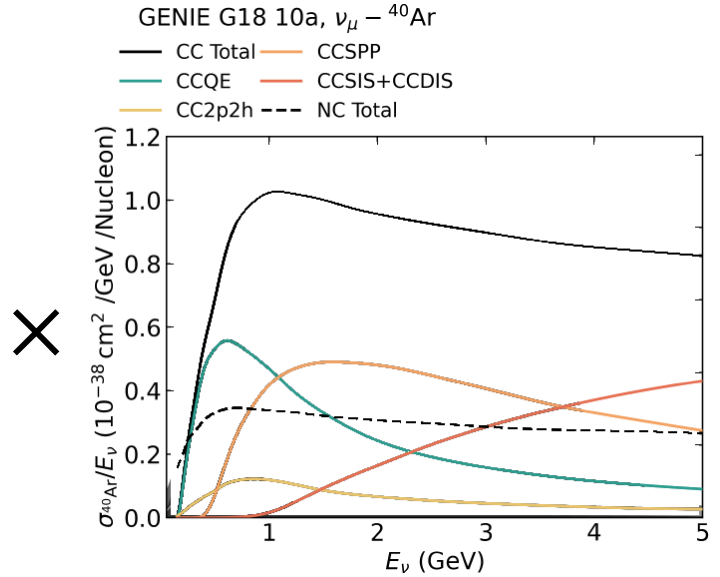
Integrated ν_μ flux comparable to Booster beam (BNB)

Integrated ν_e flux 6-7 times larger

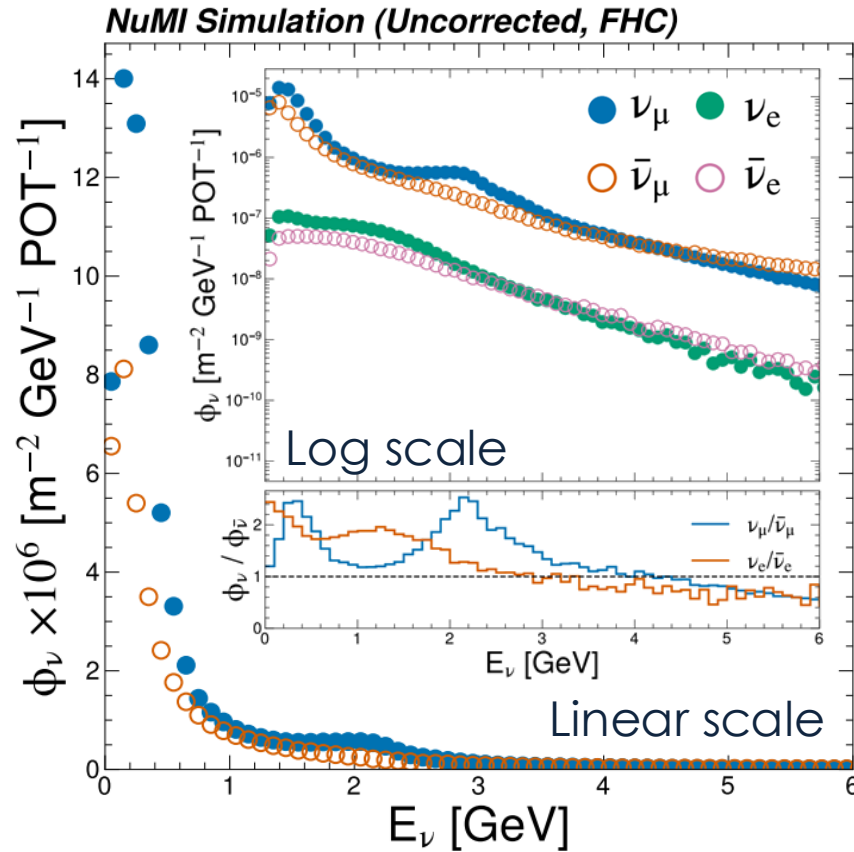
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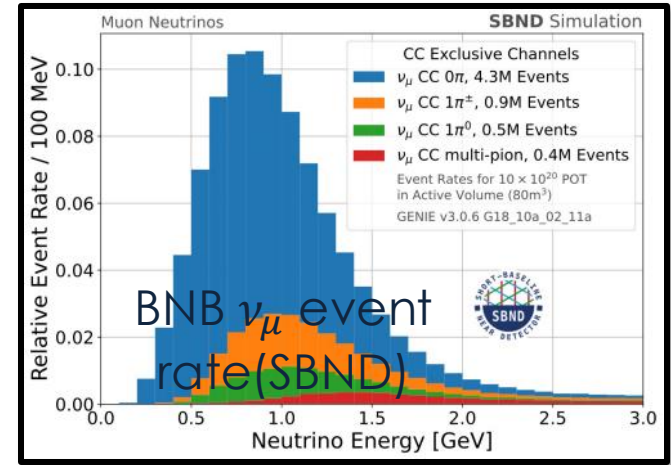
Different shape to BNB, different kinematic phase space coverage



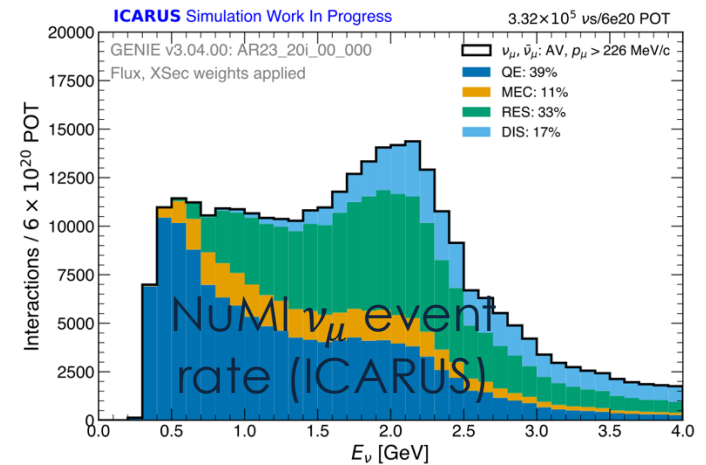
The NuMI beam at ICARUS



**Complimentary physics program
to μ BooNE and SBND**



**NuMI event rate spectra focussed
at larger E_ν than BNB**

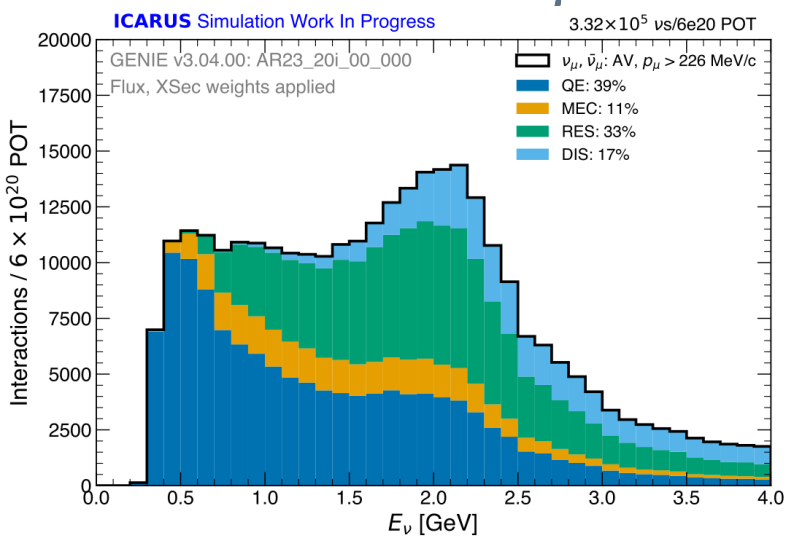


Physics with the NuMI beam

- A relatively high energy, high intensity beam
 - A unique chance to **probe the RES-SIS-DIS transition region on Argon**
 - Collected **~115k ν_μ** CC events for ν -mode NuMI running

Projected CC event rate spectra @ ICARUS

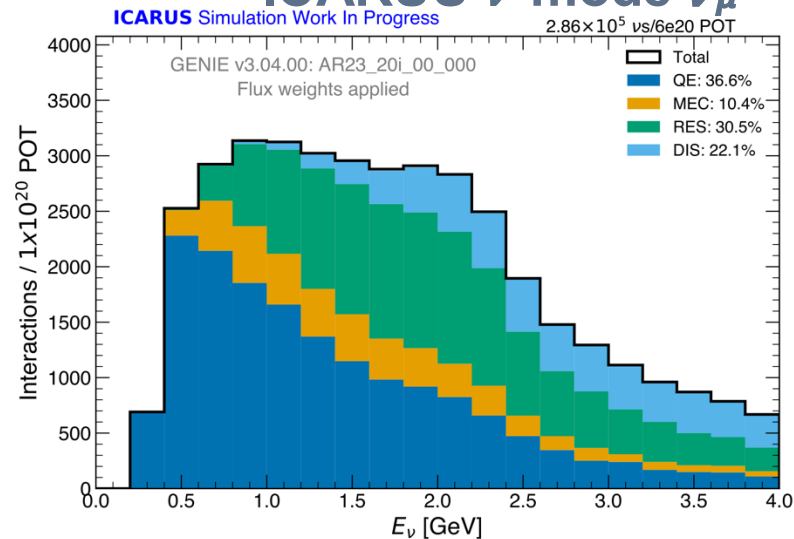
ICARUS ν -mode ν_μ



Available data

- ν -mode: 3E20 PoT (Runs 1+2)
- $\bar{\nu}$ -mode: 2.8E20 PoT (Run 3)

ICARUS $\bar{\nu}$ -mode ν_μ



Physics with the NuMI beam

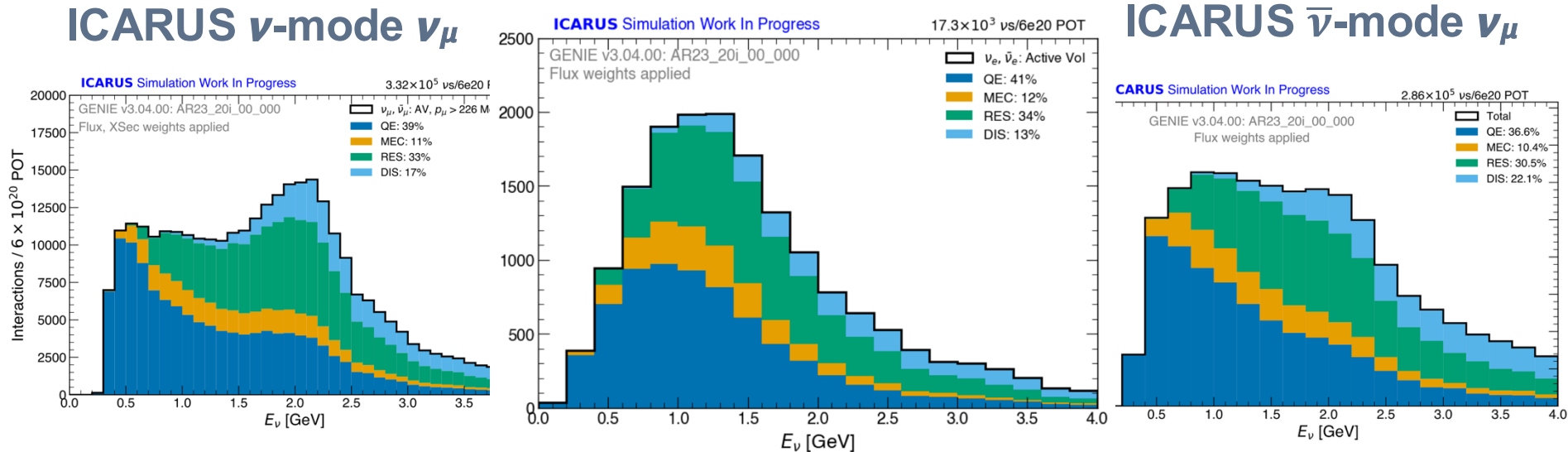
- A relatively high energy, high intensity beam
 - A unique chance to **probe the RES-SIS-DIS transition region on Argon**
 - Collected **~115k ν_μ** CC events for ν -mode NuMI running
- A large electron neutrino contribution
 - E.g. $\sim 8\%$ @ 1 GeV vs $\sim 3\%$ for BNB \rightarrow lower background analyses
 - **~7.5k ν_e** CC events for ν -mode NuMI running

Available data

- ν -mode: 3E20 PoT (Runs 1+2)
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Projected CC event rate spectra @ ICARUS

ICARUS ν -mode ν_e



Supporting DUNE

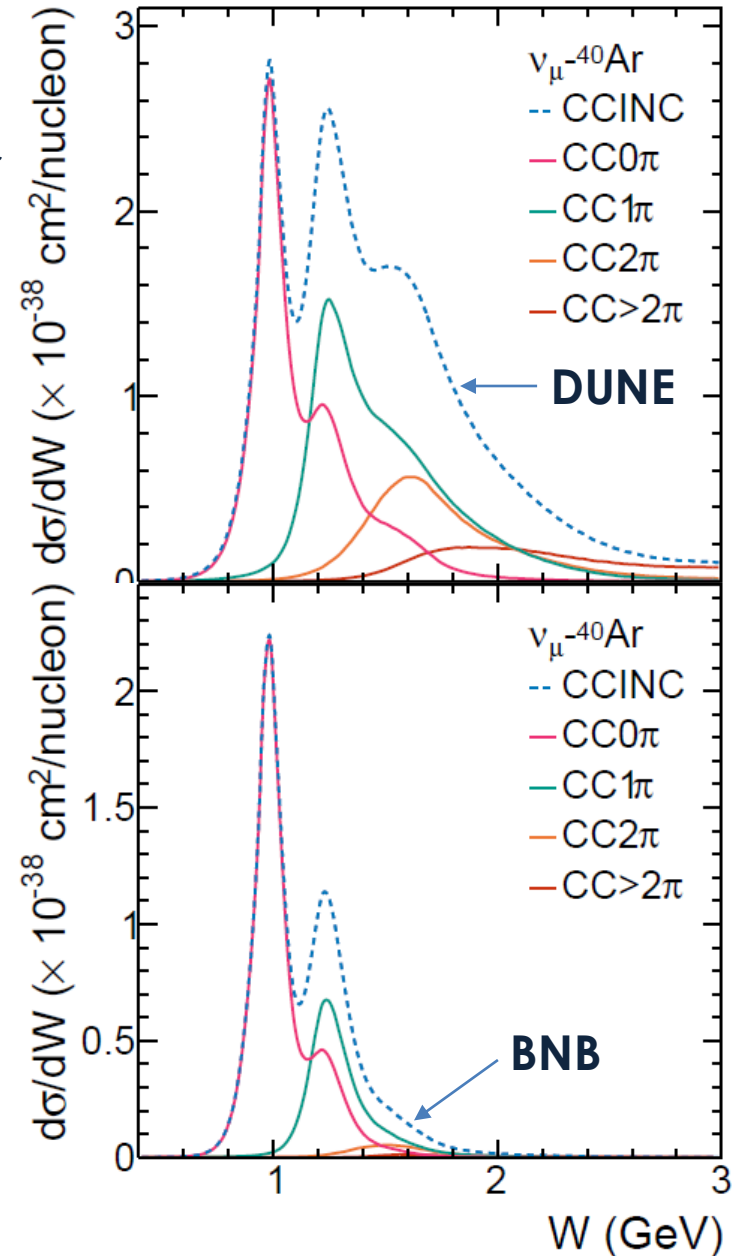
- DUNE faces a challenge from the lack of ν -Ar measurements at relevant kinematics
- BNB measurements can help, but the low energy means a significant amount of DUNE's phase space is uncovered*

See e.g. overlap in
hadronic invariant mass



- Little coverage in the notoriously difficult transition region ...

Plots from C. Wilkinson



*Enormous stats might allow some coverage from the far tails, but isolating this region in real event selections is challenging

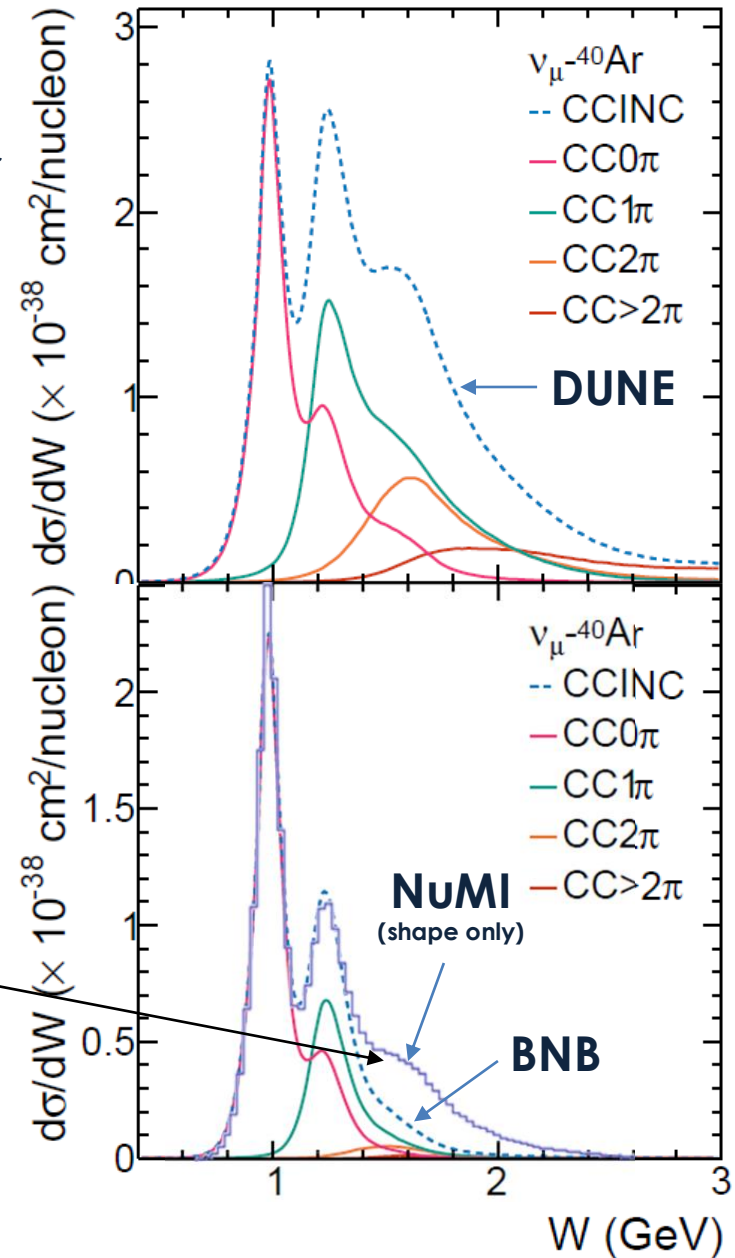
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- ICARUS NuMI measurements are uniquely positioned to fill at least some of this gap!



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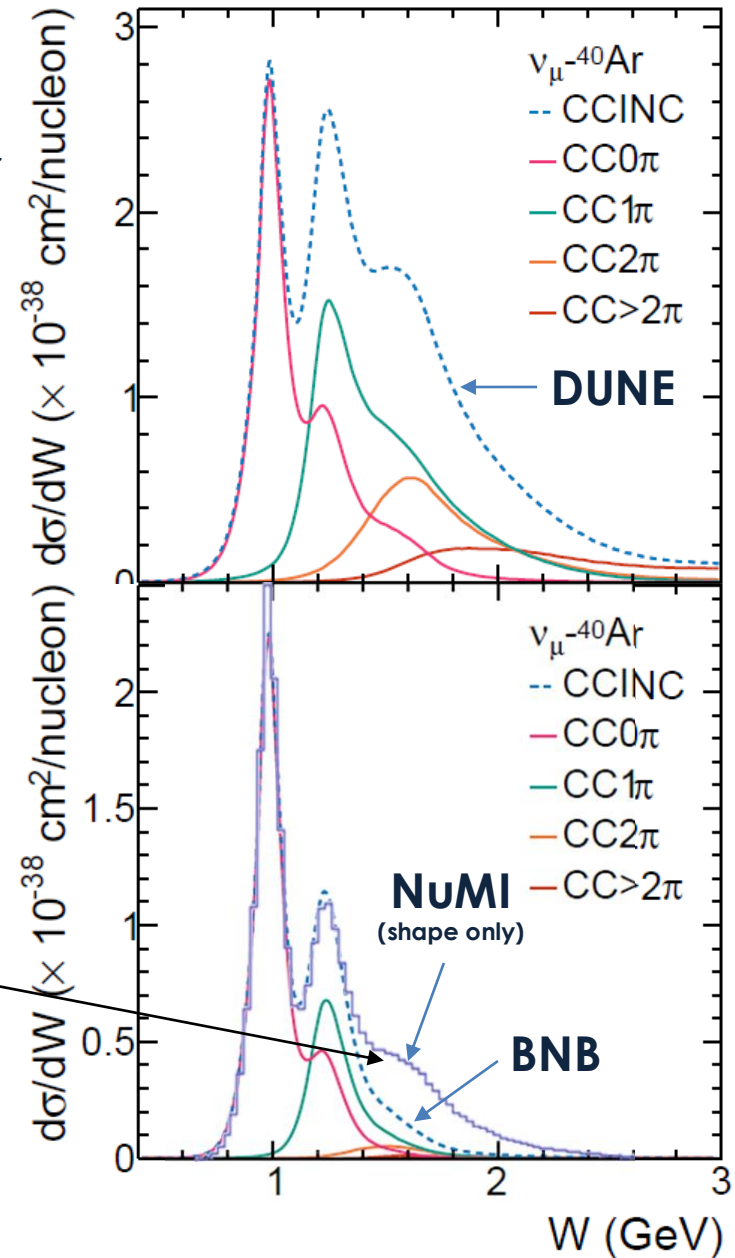
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See e.g. overlap in hadronic invariant mass →

- Little coverage in the notoriously difficult transition region ...
- ICARUS NuMI measurements are uniquely positioned to fill at least some of this gap!
- **Essential to take this step before DUNE turns on to start the model development journey**



*Enormous stats might allow some coverage from the far tails, but isolating this region in real event selections is challenging

Ongoing measurements

- **Detailed NuMI flux characterization**
 - Analysis complete, crucial input to measurements
- **CC0 π Np (N>0) cross section measurement**
 - Measurement of lepton+nucleon kinematics, including TKI
 - ***ICARUS' first cross-section analysis: just completed!***
- **CC0 π with two protons analysis**
 - Powerful probe of FSI and 2p2h
 - Analysis mature and ongoing
- **CC Inclusive**
 - Leverages NuMI energies: notable contributions from SIS transition region
 - Analysis ongoing
- **CC Charged and Neutral Pion Production**
 - Wide phase space coverage in hadronic invariant mass
 - Analyses ongoing
- **Electron neutrino analyses**
 - Leverages NuMI ν_e contributions
 - Analyses ongoing

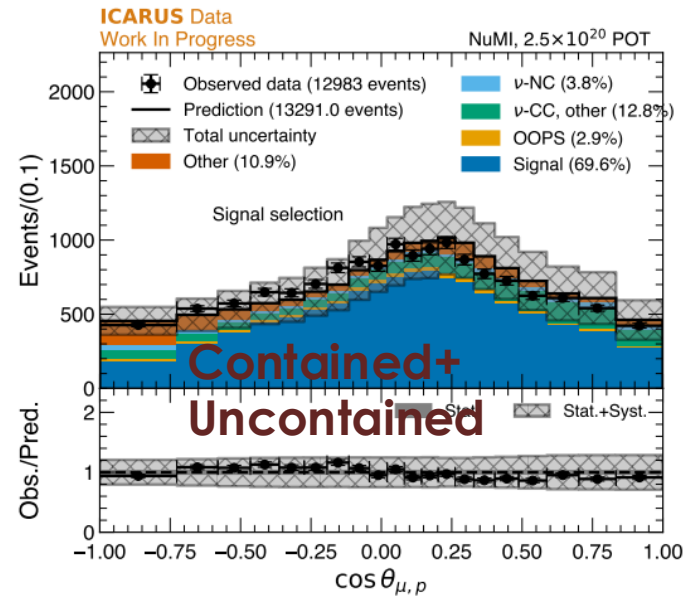
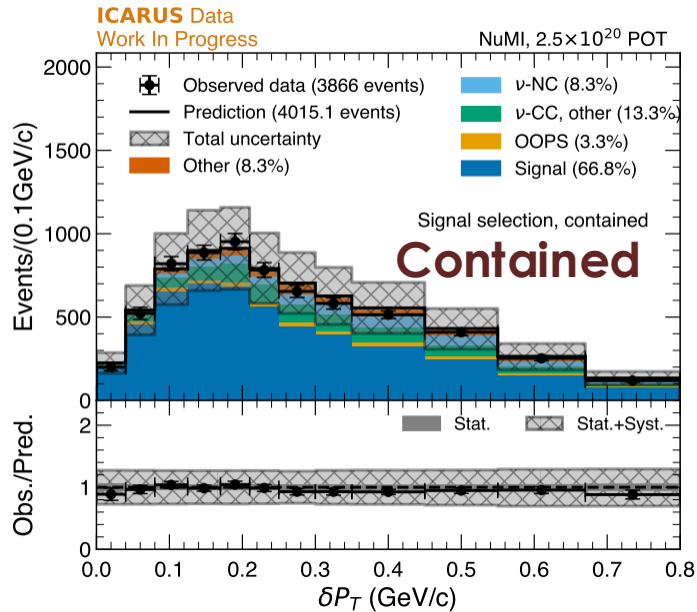
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↑
Focus of this talk

CC0 π Np measurement

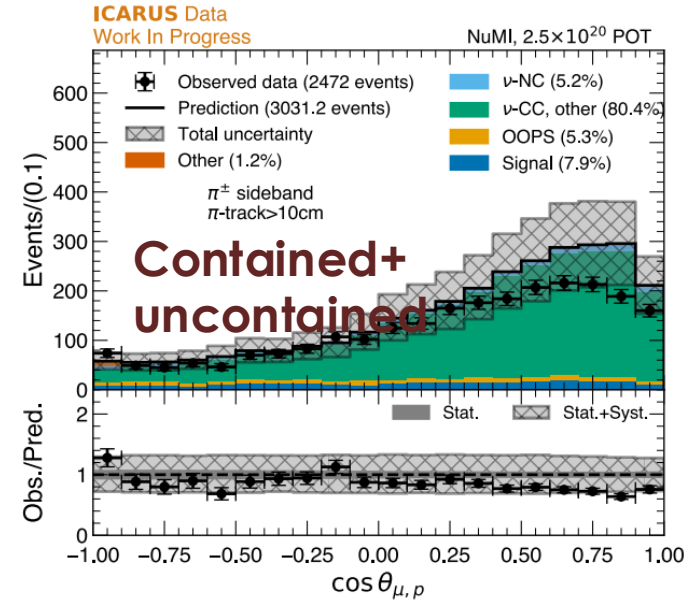
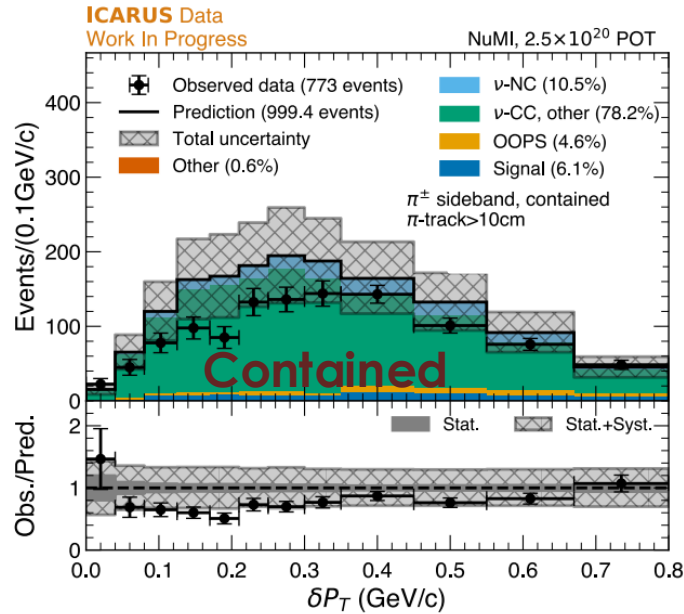
Signal event selections



- $\sim 10\%/36\%$ efficiency (for contained/all)
- $\sim 70\%$ purity
 - Largest background from CC1 π and cosmics
- Remarkable agreement between data and simulation (GENIE Ar23)

CC0 π Np measurement

Control region event selections



- High purity of representative background to the signal sample
- Reasonable agreement between data and simulation

CC0 π Np measurement

Cross section extraction

$$\left. \frac{d\sigma}{dx} \right|_i = \frac{N_i^{sig}}{\epsilon_i \Phi N_{tgts} (\Delta x)_i}$$

Incoming ν_μ flux

Number of targets (nucleons)

Bin width

The diagram shows the formula for cross-section extraction. The left side is $\left. \frac{d\sigma}{dx} \right|_i$. The right side is a fraction with N_i^{sig} in the numerator and $\epsilon_i \Phi N_{tgts} (\Delta x)_i$ in the denominator. A horizontal line is drawn under the denominator. Three colored boxes with arrows point to terms in the formula: a green box labeled 'Incoming ν_μ flux' points to Φ ; an orange box labeled 'Number of targets (nucleons)' points to N_{tgts} ; and a blue box labeled 'Bin width' points to $(\Delta x)_i$.

CC0 π Np measurement

Detector efficiency

Number of signal events, background subtracted + corrected for detector smearing

$$\left. \frac{d\sigma}{dx} \right|_i =$$

$$\frac{N_i^{sig}}{\epsilon_i \Phi N_{tgts}}$$

$$\frac{1}{(\Delta x)_i}$$

Bin width

Incoming ν_μ flux

Number of targets (nucleons)

Top priority: avoid input model dependence

CC0 π Np measurement

Diagram illustrating the formula for the differential cross-section $\frac{d\sigma}{dx} \Big|_i$ in a CC0 π Np measurement. The formula is:

$$\frac{d\sigma}{dx} \Big|_i = \frac{N_i^{sig}}{\epsilon_i \Phi N_{tgt} (\Delta x)_i}$$

The components are defined as follows:

- ϵ_i : Detector efficiency
- N_i^{sig} : Number of signal events, background subtracted + corrected for detector smearing
- Φ : Incoming ν_μ flux
- N_{tgt} : Number of targets (nucleons)
- $(\Delta x)_i$: Bin width

Top priority: avoid input model dependence

- Cross section extraction method adapted from T2K using the [GUNDAM likelihood fitter](#)
- **Free normalisation parameters** controlling N_i^{sig} are fit alongside those describing the flux, background and detector response to **signal and control region** data: **background model directly constrained by data**.
- Cross-section extracted with **no explicit regularisation** are provided: *minimal input model bias from unfolding*.

CC0 π Np measurement

The diagram shows the equation for the differential cross-section $\frac{d\sigma}{dx} \Big|_i$ with callouts for each term:

- Detector efficiency** (ϵ_i)
- Number of signal events, background subtracted + corrected for detector smearing** (N_i^{sig})
- Incoming ν_μ flux** (Φ)
- Number of targets (nucleons)** (N_{tgts})
- Bin width** ($(\Delta x)_i$)

$$\frac{d\sigma}{dx} \Big|_i = \frac{N_i^{sig}}{\epsilon_i \Phi N_{tgts} (\Delta x)_i}$$

Analysis output: two measurements

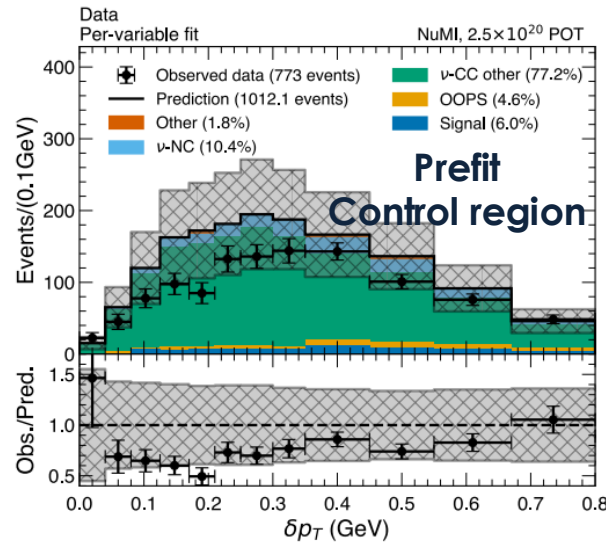
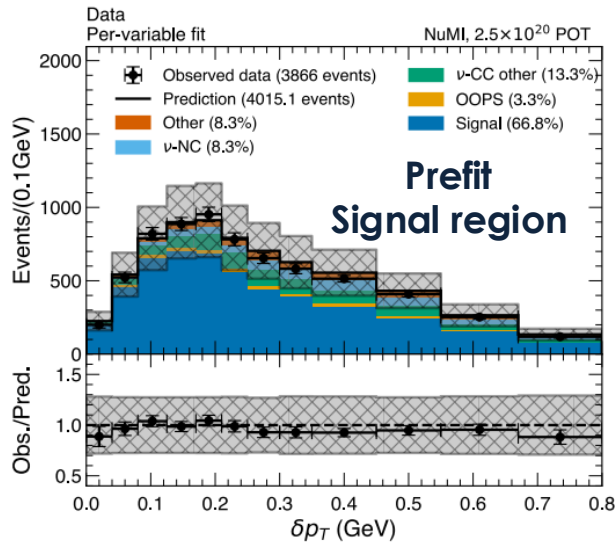
Contained μ analysis:

- Extract $d\sigma/d\delta p_T$, $d\sigma/d\delta\alpha_T$ and correlations between them

Contained + uncontained μ analysis: $\cos\theta_{\mu,\nu}$, $\cos\theta_{\mu,p}$

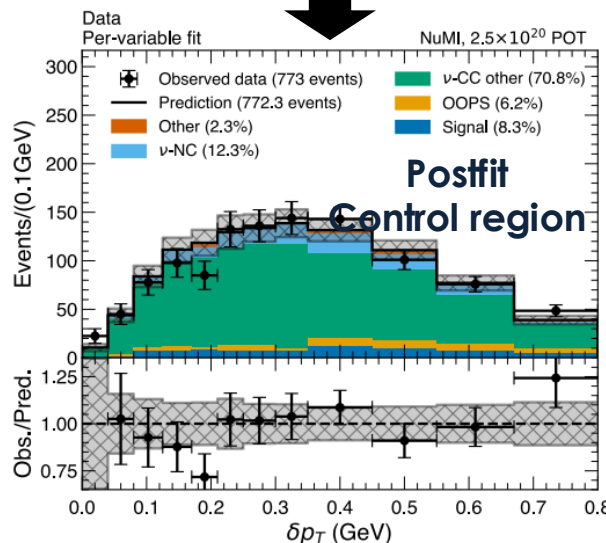
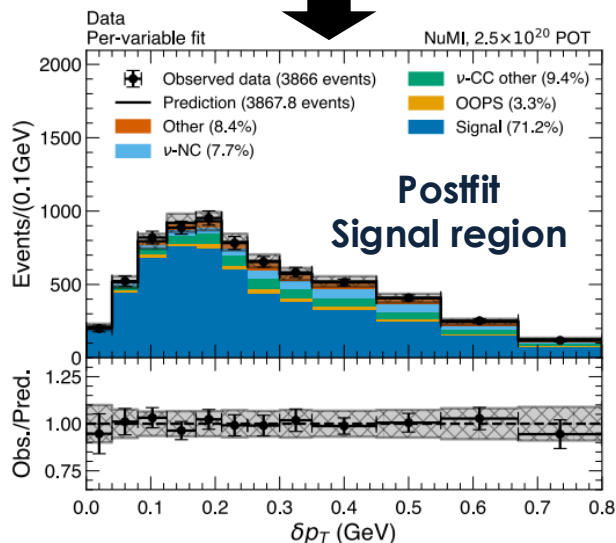
- Extract $d\sigma/d\cos\theta_{\mu,\nu}$, $d\sigma/d\delta\cos\theta_{\mu,p}$ and correlations between them

CC0 π Np measurement

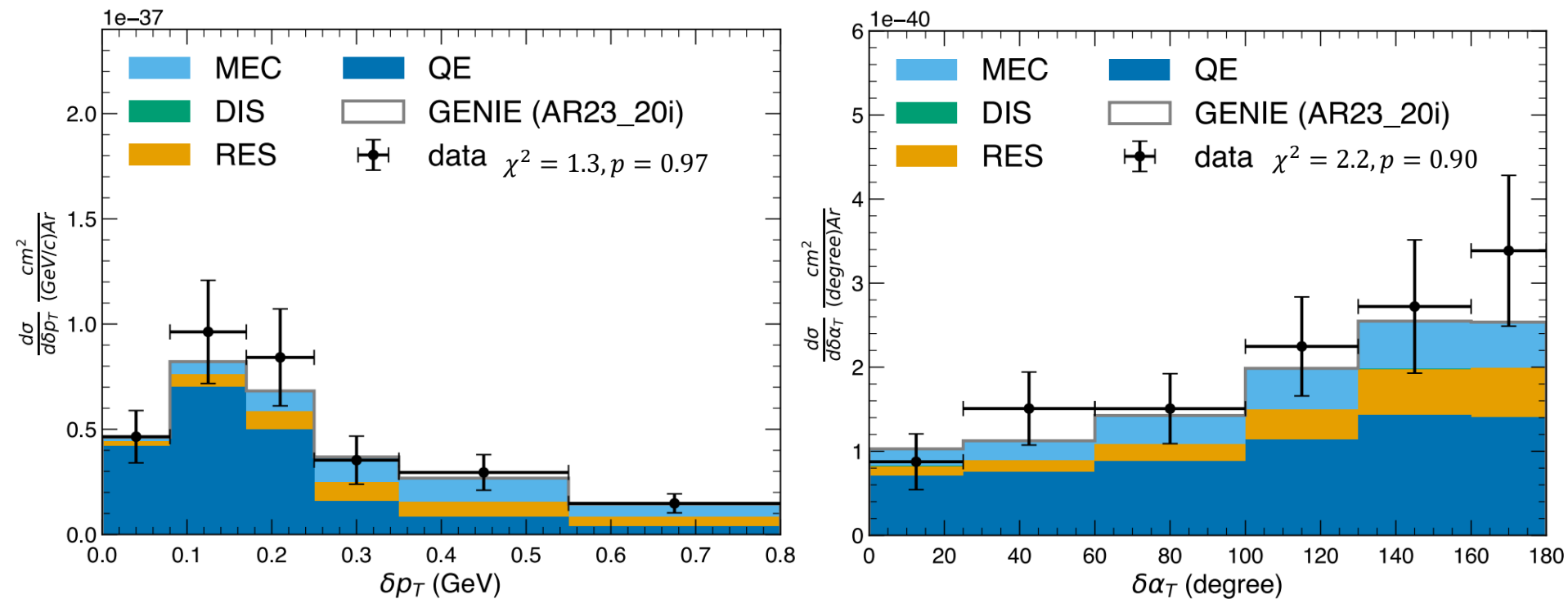


After the fit

- Background model better matches control sample data
- Associated systematic uncertainties are constrained
- A good p-value is obtained for all measurements



CC0 π Np measurement: Results



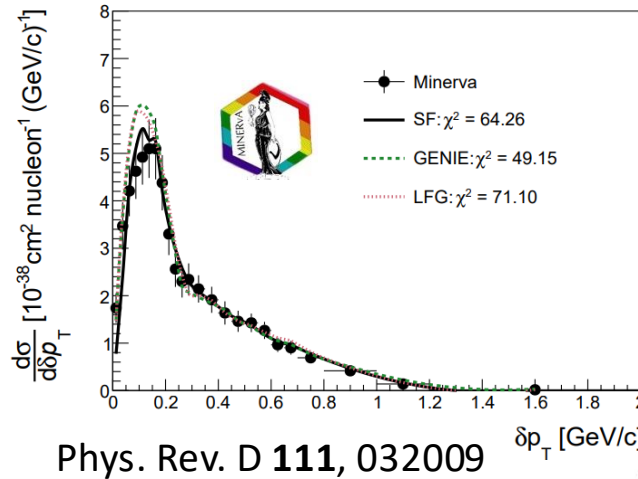
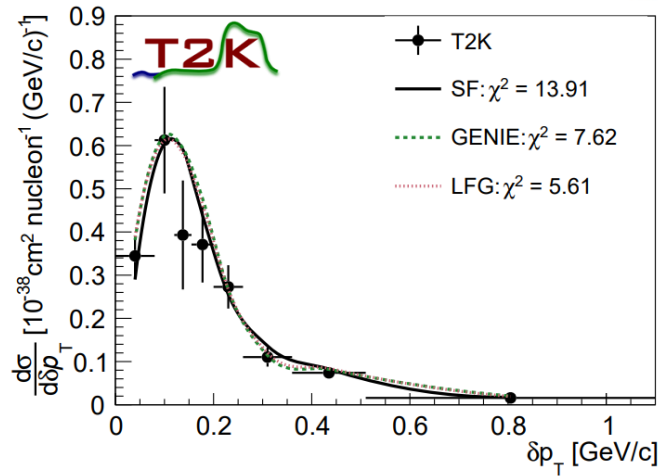
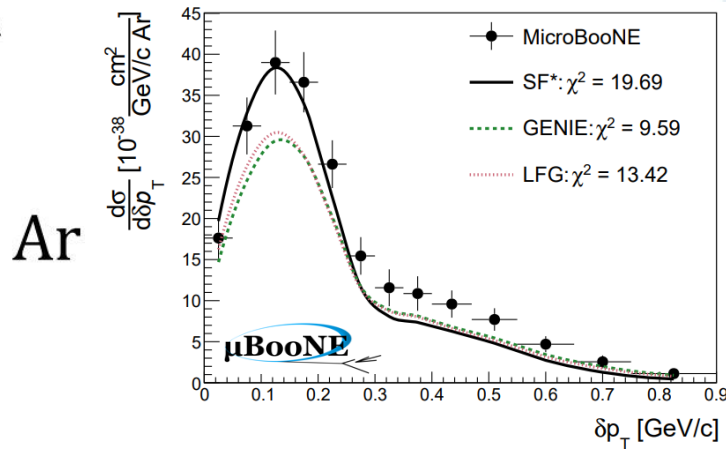
(Only showing the contained analysis today)

What can we learn?

L. Munteanu, NuFact 2024

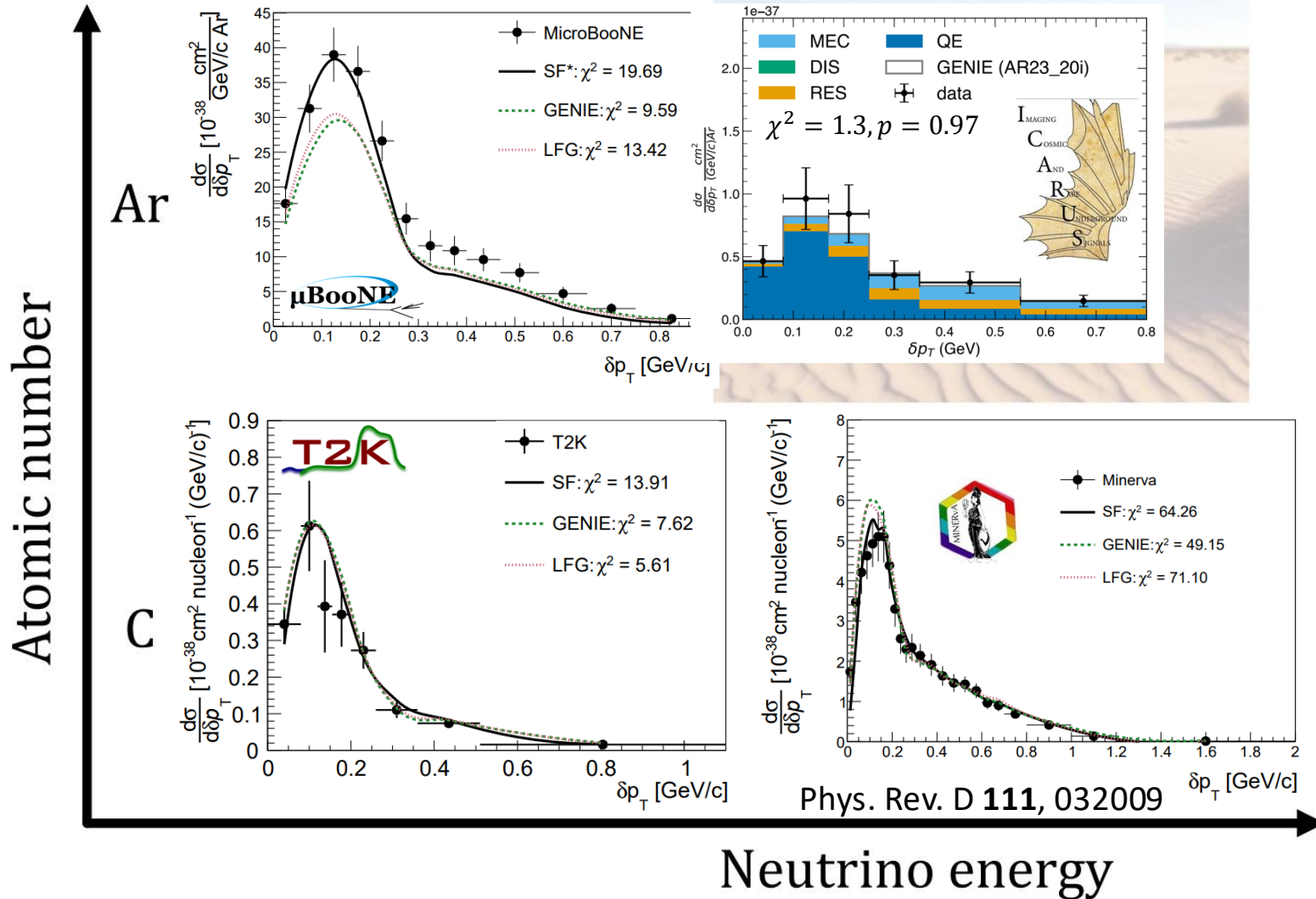


In all plots,
GENIE refers
to Ar23



Neutrino energy

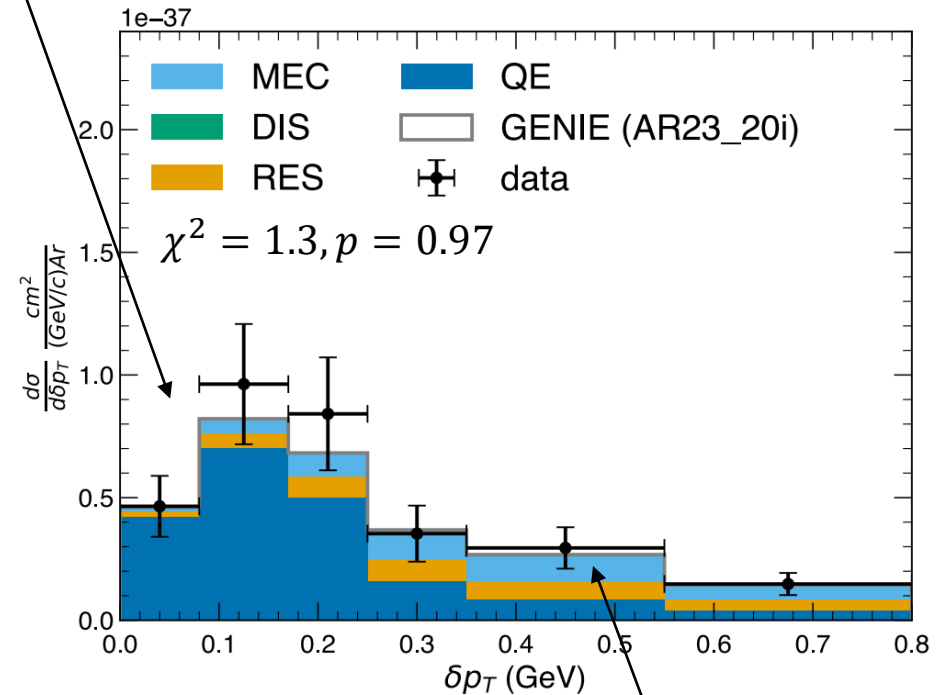
What can we learn?



In all plots, GENIE refers to Ar23

What can we learn?

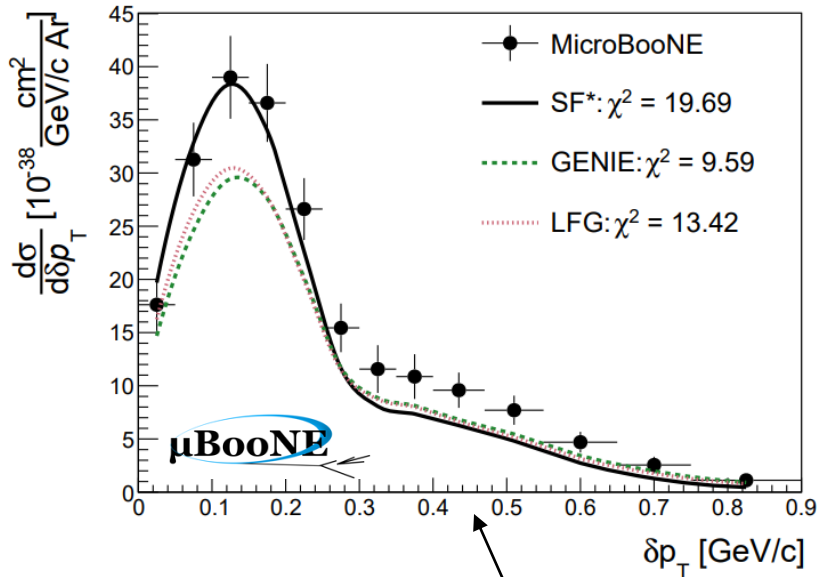
Ar23 describes the measurement



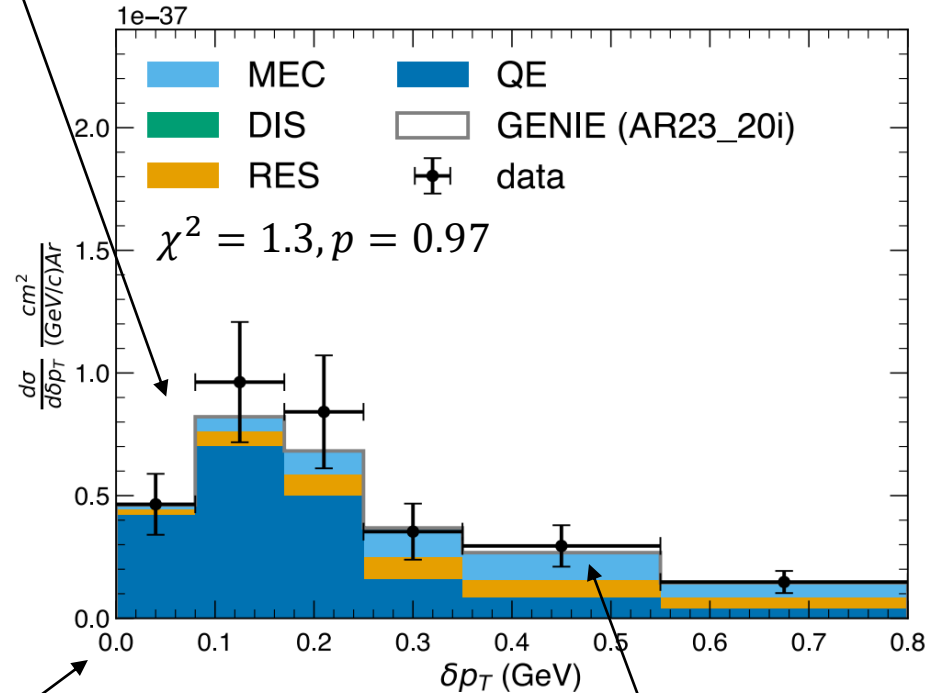
Clear need for 2p2h in the tail

What can we learn?

Consistent with what is seen by μ BooNE and T2K (but not MINERvA) ← Ar23 describes the measurement



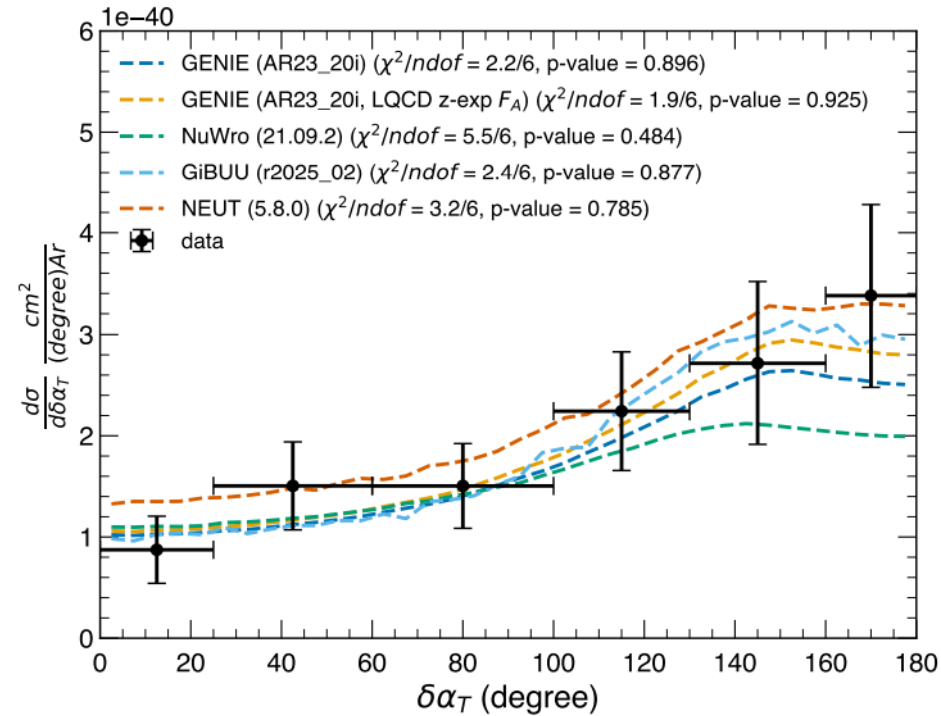
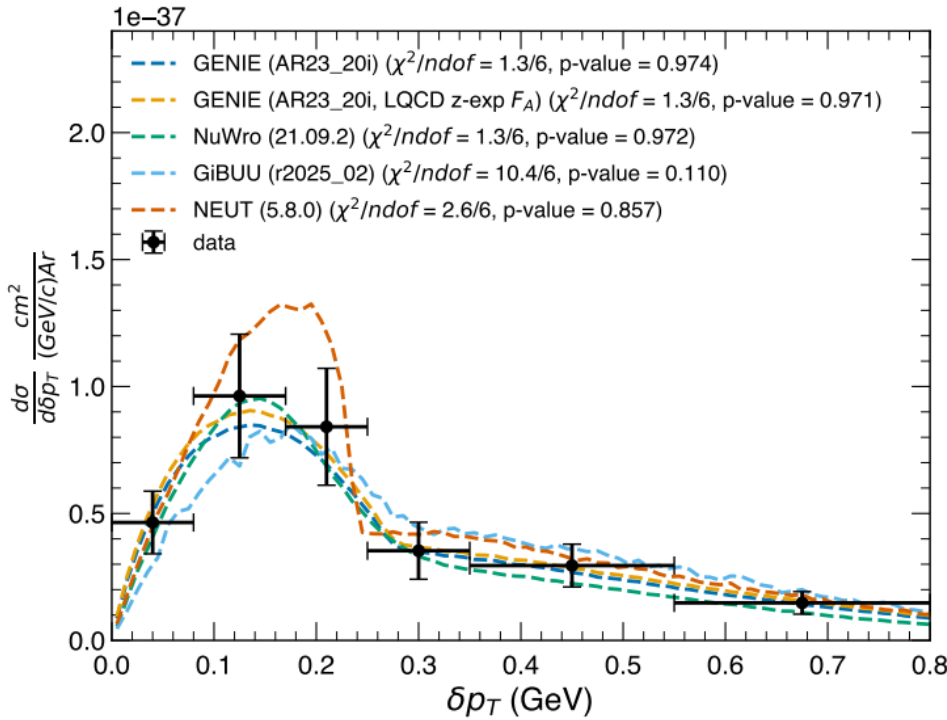
No overestimation of the bulk and tail seen by μ BooNE*



Clear need for 2p2h in the tail

* But note the different phase space covered by signal definitions and the μ BooNE result being in a smeared space

What can we learn?

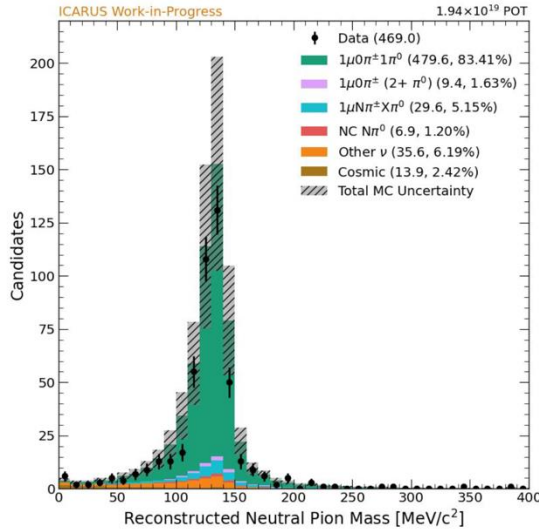


We have plenty more to study!

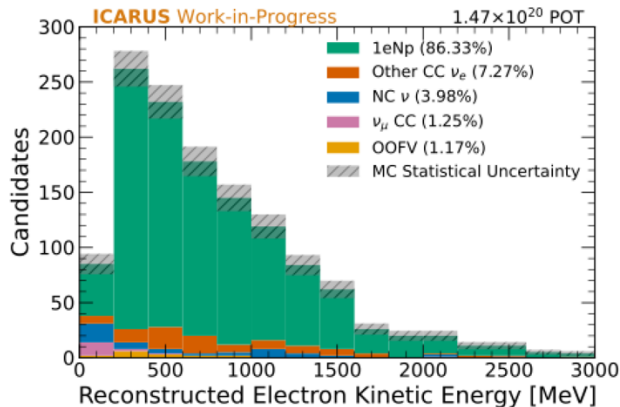
Expect a much deeper dive on interpretations in our paper

Other ICARUS measurements

CC π^0 production (BNB)



ν_e CCNp



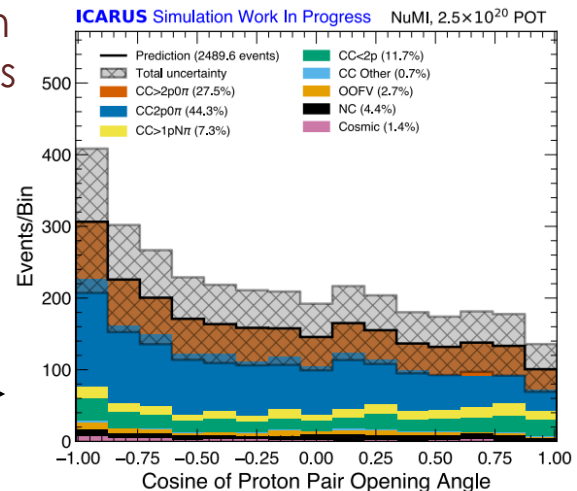
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 - Powerful probe of FSI and 2p2h
 - Analysis mature and ongoing
- **CC Inclusive**
 - Leverages NuMI energies: notable contributions from SIS transition region
 - Analysis ongoing
- **CC Charged and Neutral Pion Production**
 - Wide phase space coverage in hadronic invariant mass
 - Analyses ongoing
- **Electron neutrino analyses**
 - Leverages NuMI ν_e contributions
 - Analyses ongoing

Purity > 80%, efficiency > 70% in CC π^0 and ν_e CCNp selections

Enabled by SPINE reconstruction, see poster from D. Carber

Multi-proton analysis finds high purity signal rich in 2p2h interactions

CC $0\pi > 1p$

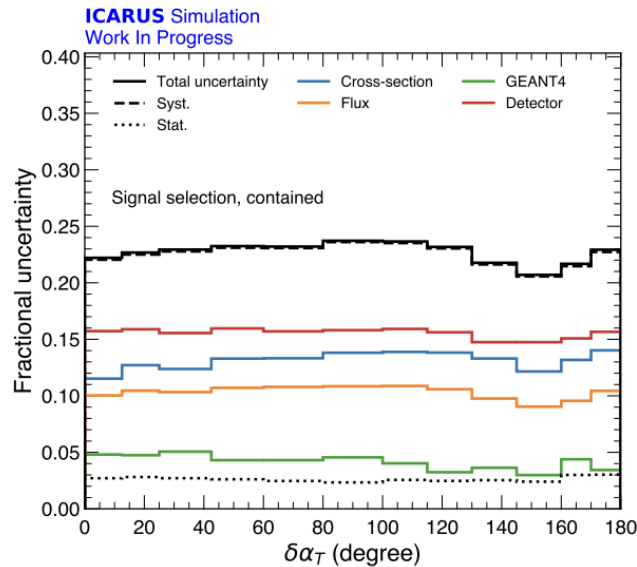
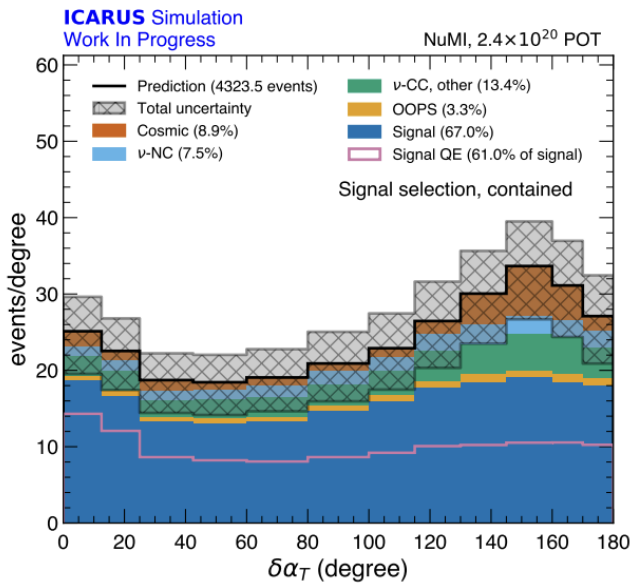
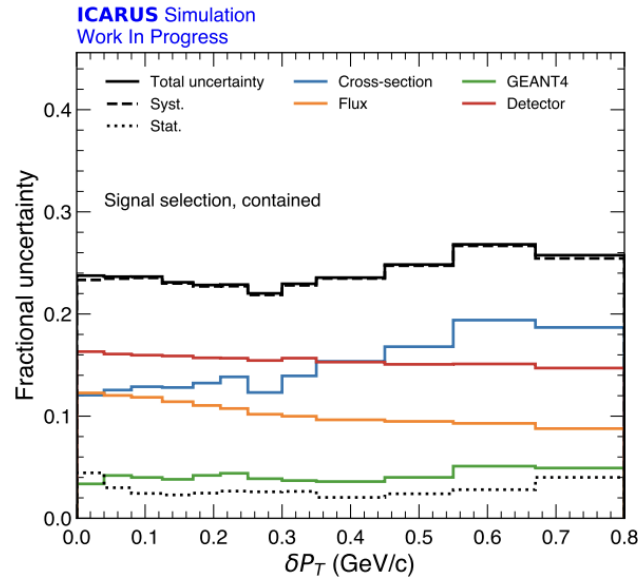
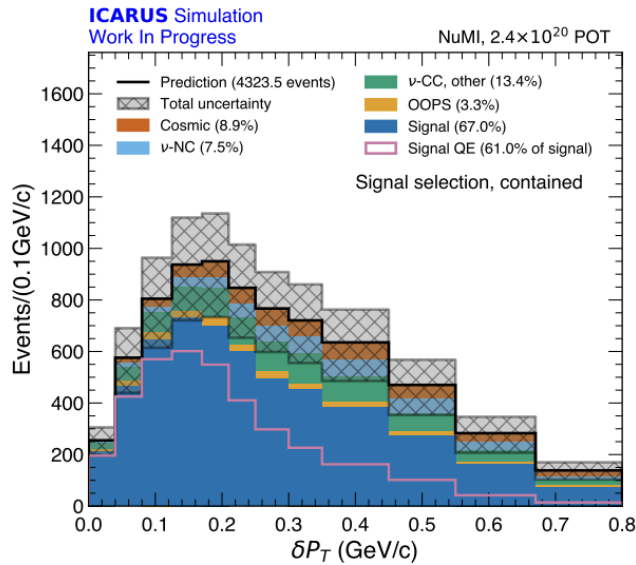


Summary

- Studying neutrino interactions in the NuMI beam at ICARUS has great physics potential:
 - Measurements at larger E_ν than BNB: **complementary to SBND**
 - **Large relative ν_e contributions**: allows low bkg measurements
- Our first analysis has just been completed
 - **CC0 π Np** measuring outgoing lepton and **nucleon kinematics**
 - Sophisticated analysis tool set **for low-model dependence**
 - Interesting results to complement those from other expts
- Many more analyses ongoing!

Backups

Event rate uncertainties



Uncertainties on the reconstructed event rates, not the cross section