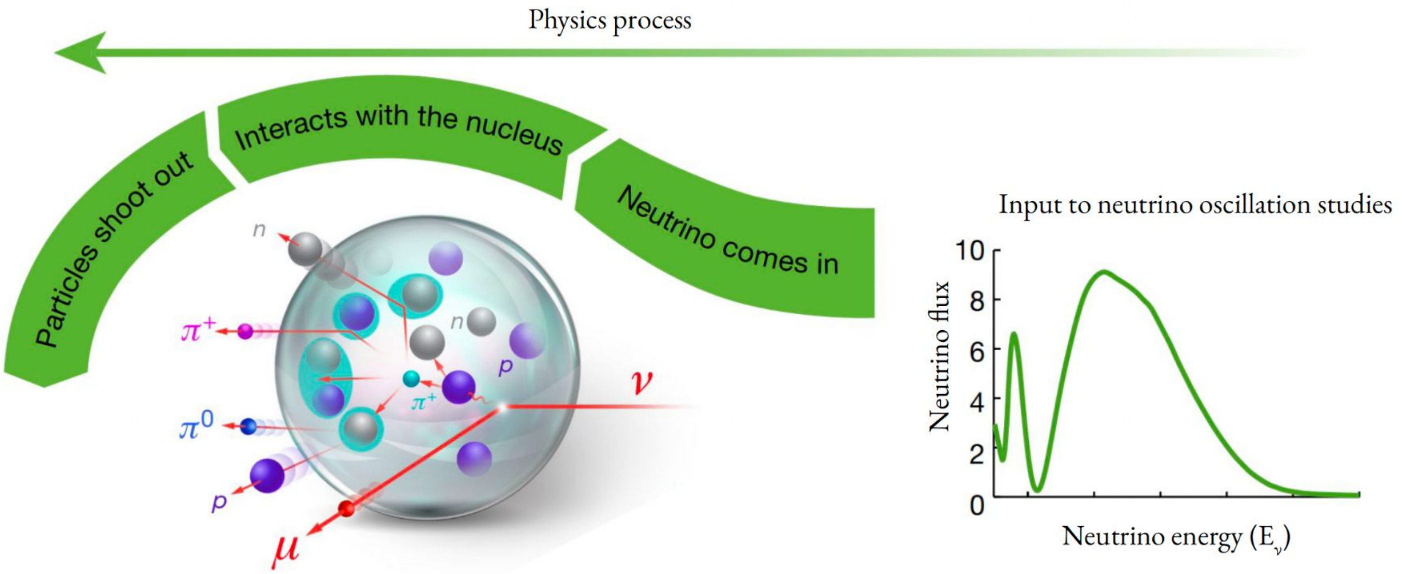
# Cross Section Overview and Prospects for the SBN Experiments at Fermilab

Erin Yandel on behalf of the SBND, MicroBooNE, and ICARUS Collaborations

Lepton Interactions with Nucleons and Nuclei 2025

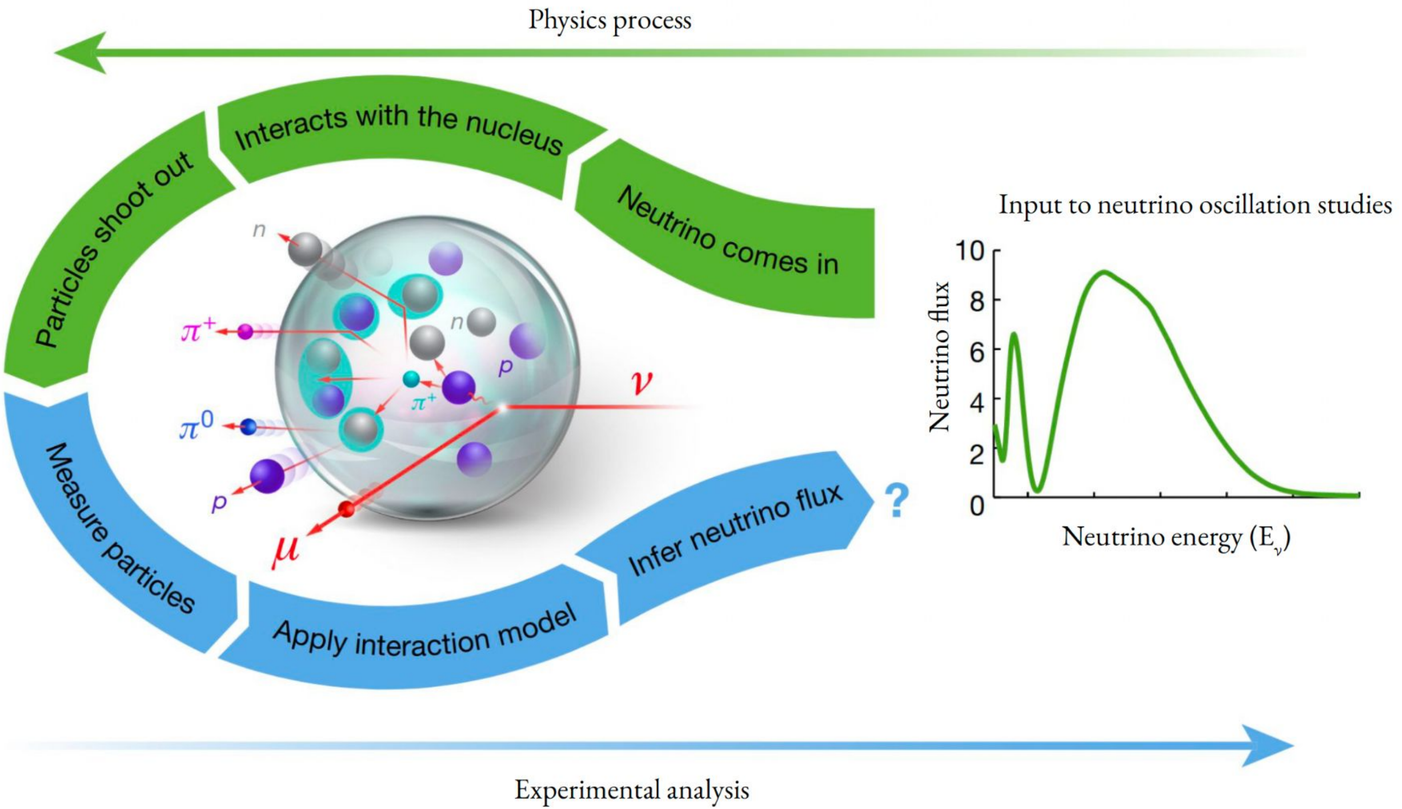
June 24th, 2025

# High-precision Neutrino Era



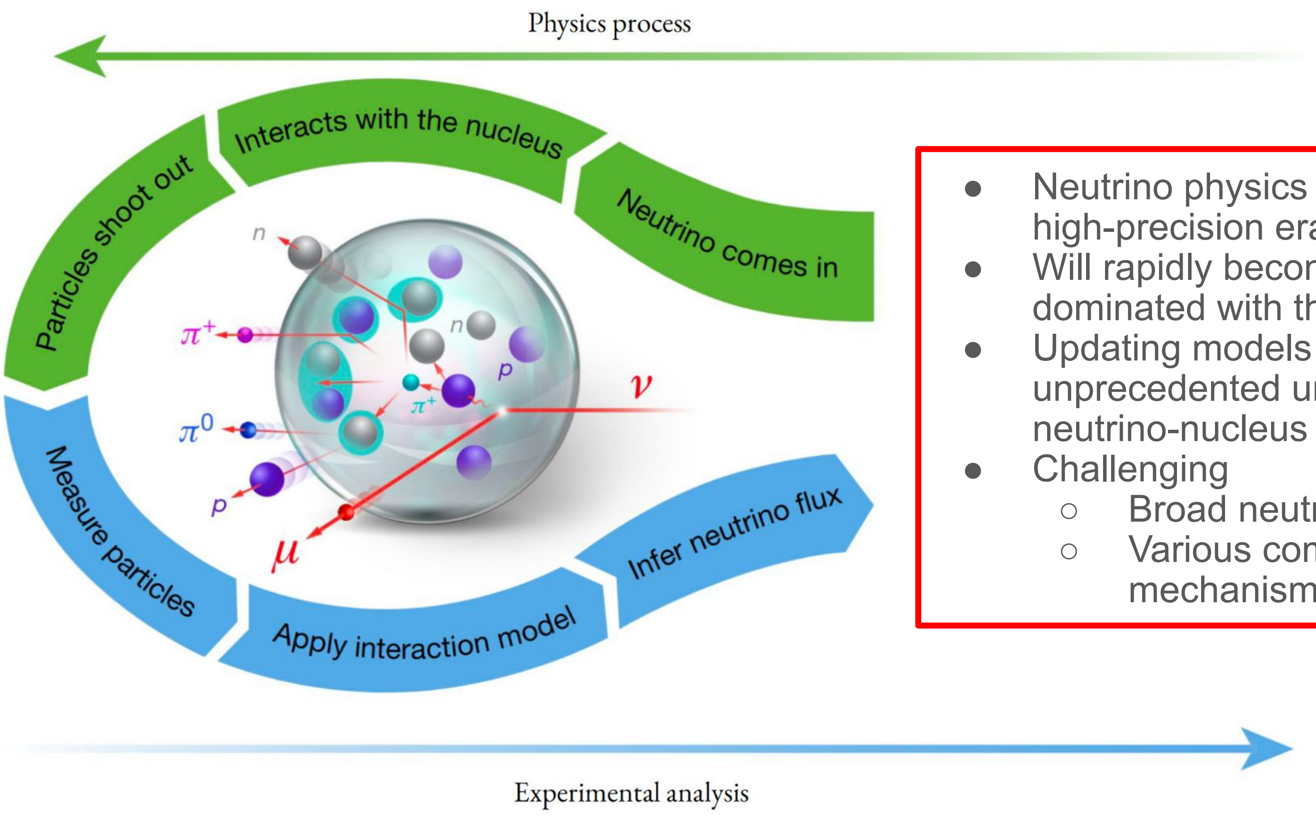

[Nature 599, 565–570 (2021)]

# High-precision Neutrino Era




Nature 599, 565–570 (2021)

# High-precision Neutrino Era

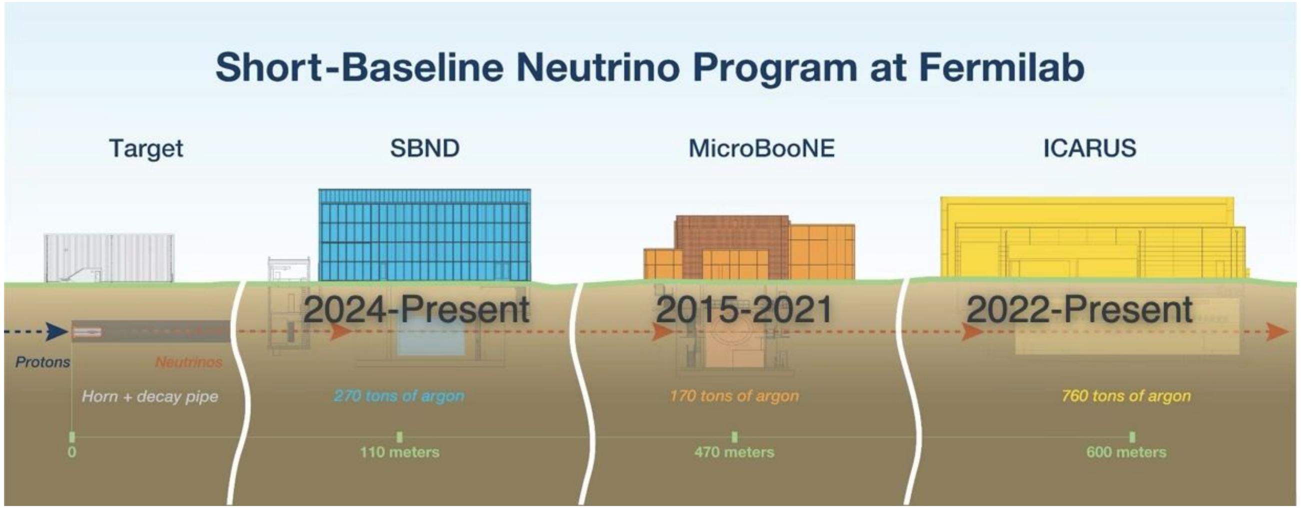



- Neutrino physics is entering a high-precision era
- Will rapidly become systematics dominated with the current models
- Updating models requires unprecedented understanding of neutrino-nucleus interactions
- Challenging
  - Broad neutrino spectra
  - Various complex interaction mechanisms

Nature 599, 565–570 (2021)

# The SBN Program

- Short-Baseline Neutrino (SBN)
- 3 detectors along the Booster Neutrino Beam (BNB, 8 GeV p) at Fermilab
  - MicroBooNE and ICARUS off-axis to the NuMI (120 GeV p) beamline as well
- Liquid Argon Time Projection Chamber (LArTPC) detectors

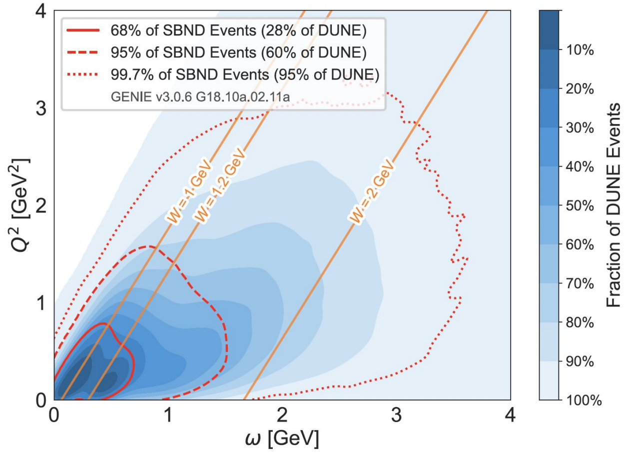


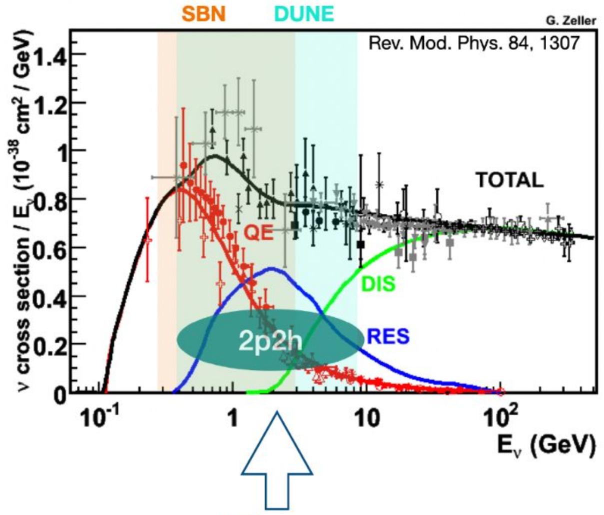

- 3 main physics goals:

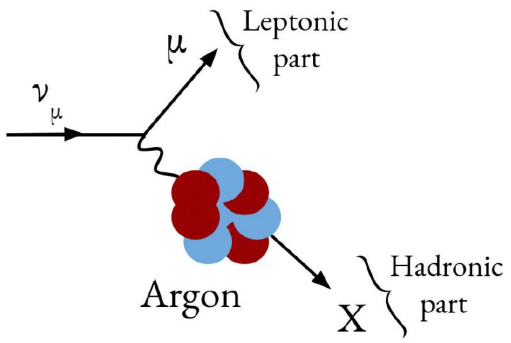
1. Investigate eV-scale sterile neutrino oscillations,
2. Search for beyond the Standard Model physics and study rare processes,
3. **Neutrino interaction measurements on argon**

# Updating Information for DUNE

- Same target (LAr) as DUNE
    - FSI, hadron production, etc.
- Combination of two beams covers critical phase spaces

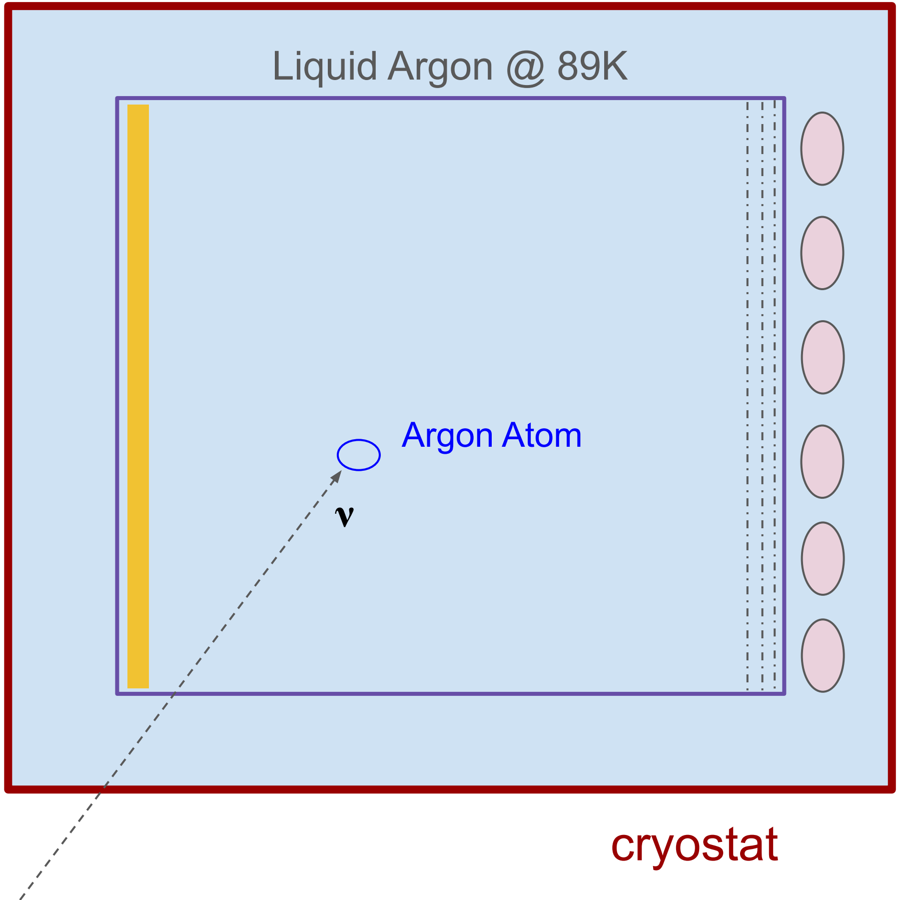


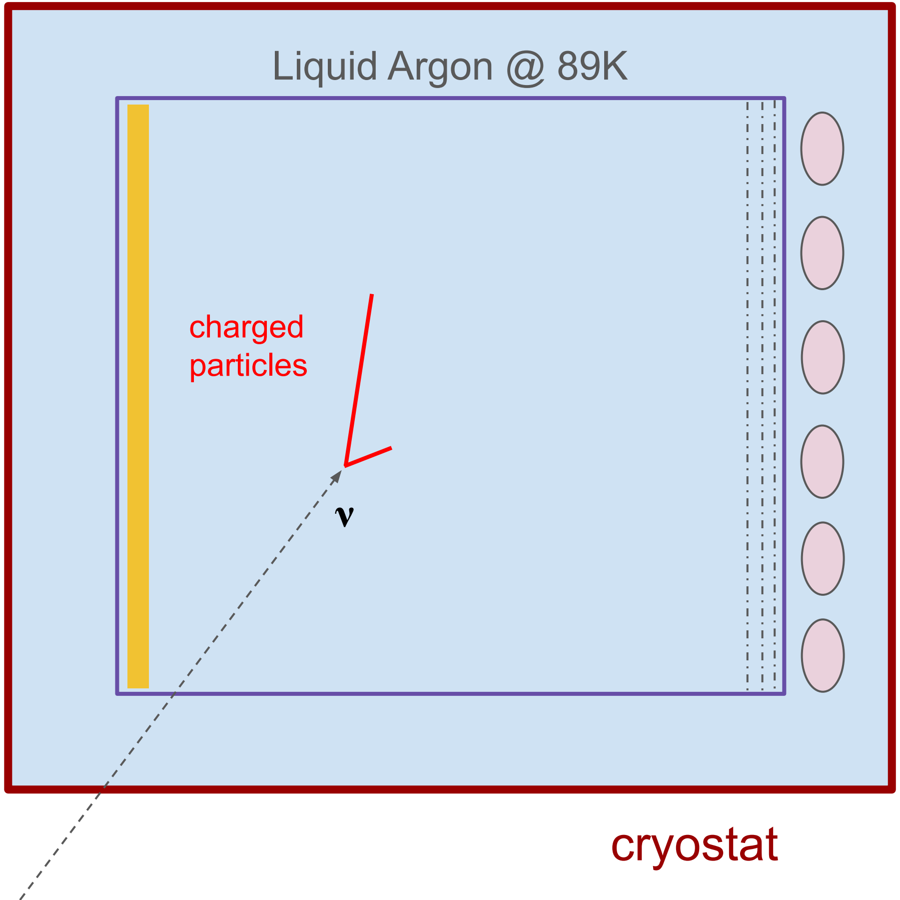




*High-precision measurements at SBN cover critical phase space relevant to DUNE's δCP sensitivity*

# LArTPC

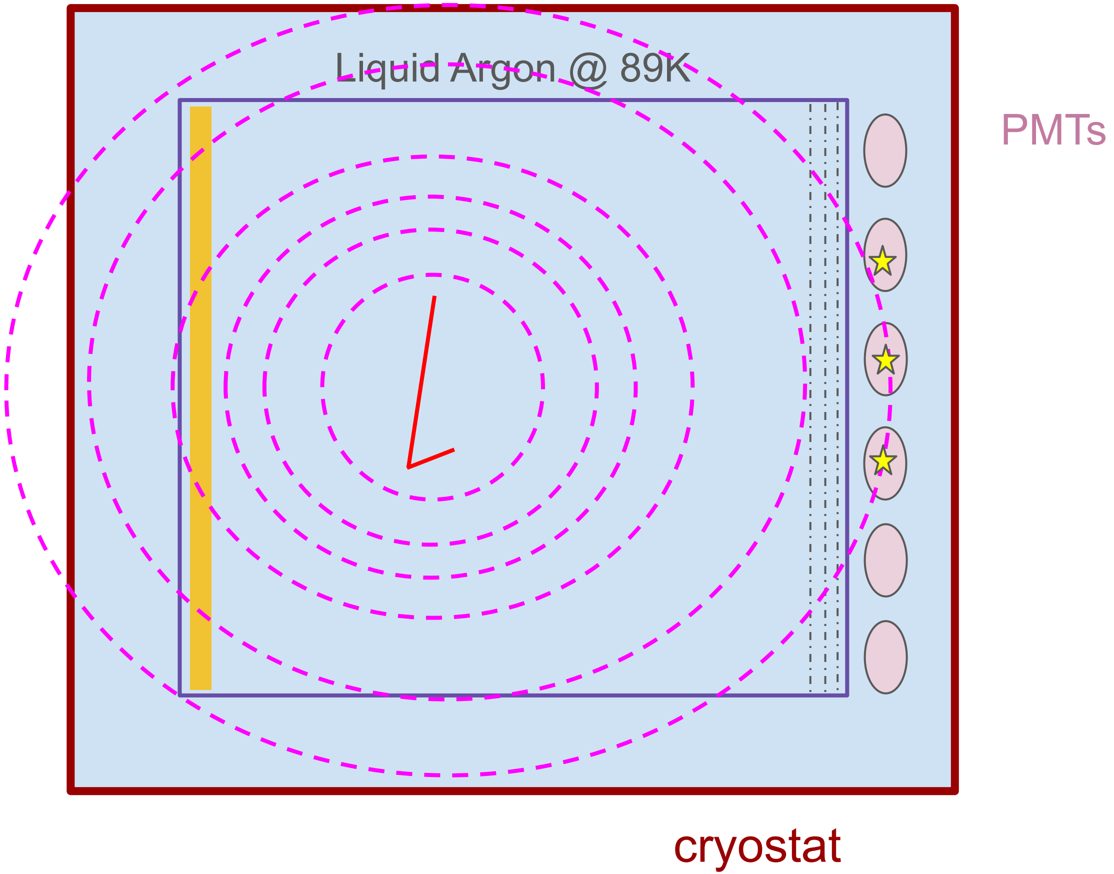


# LArTPC

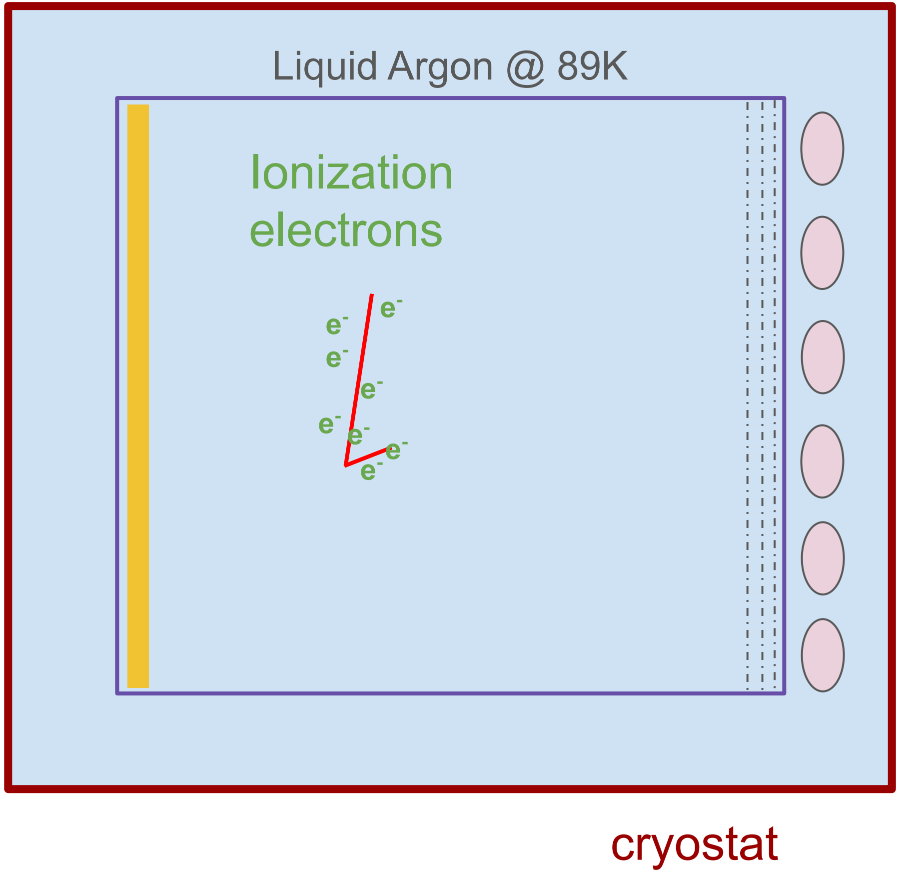


# LArTPC

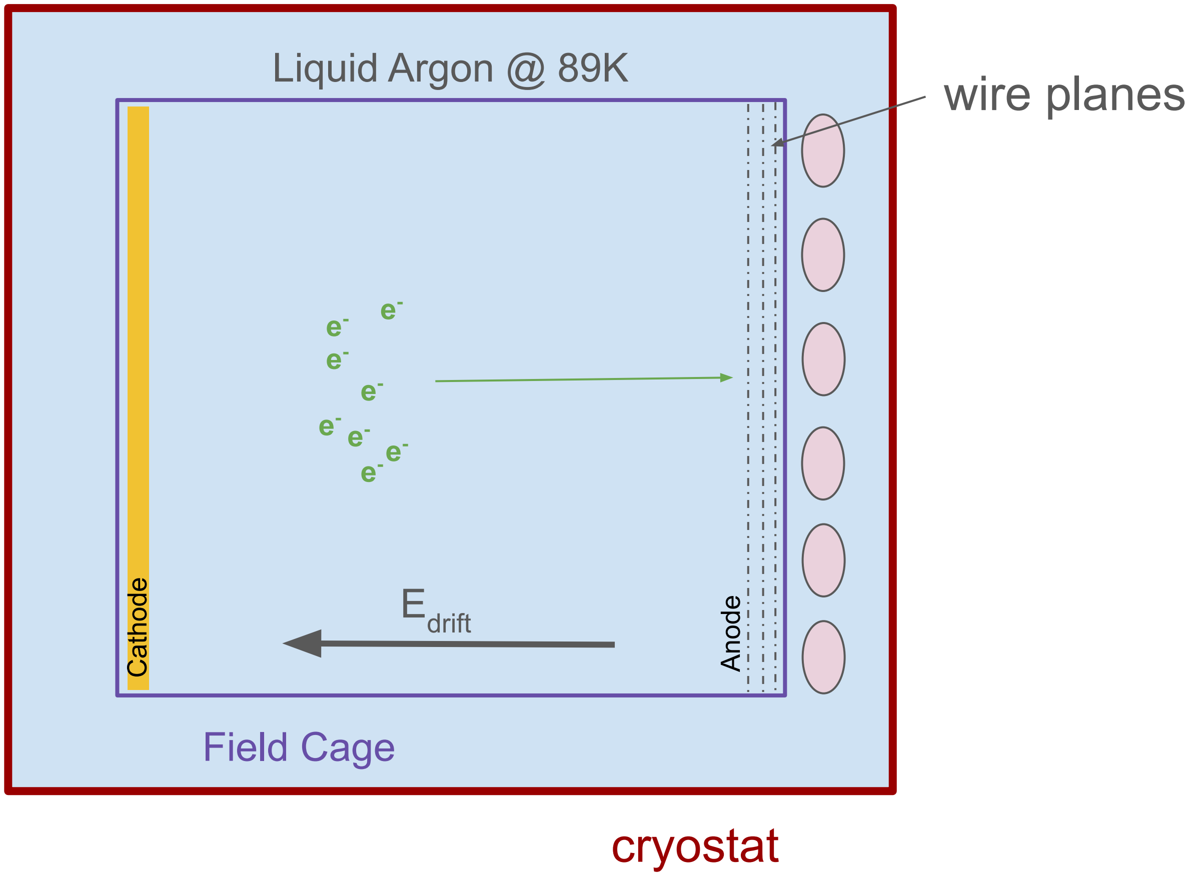
Scintillation Light



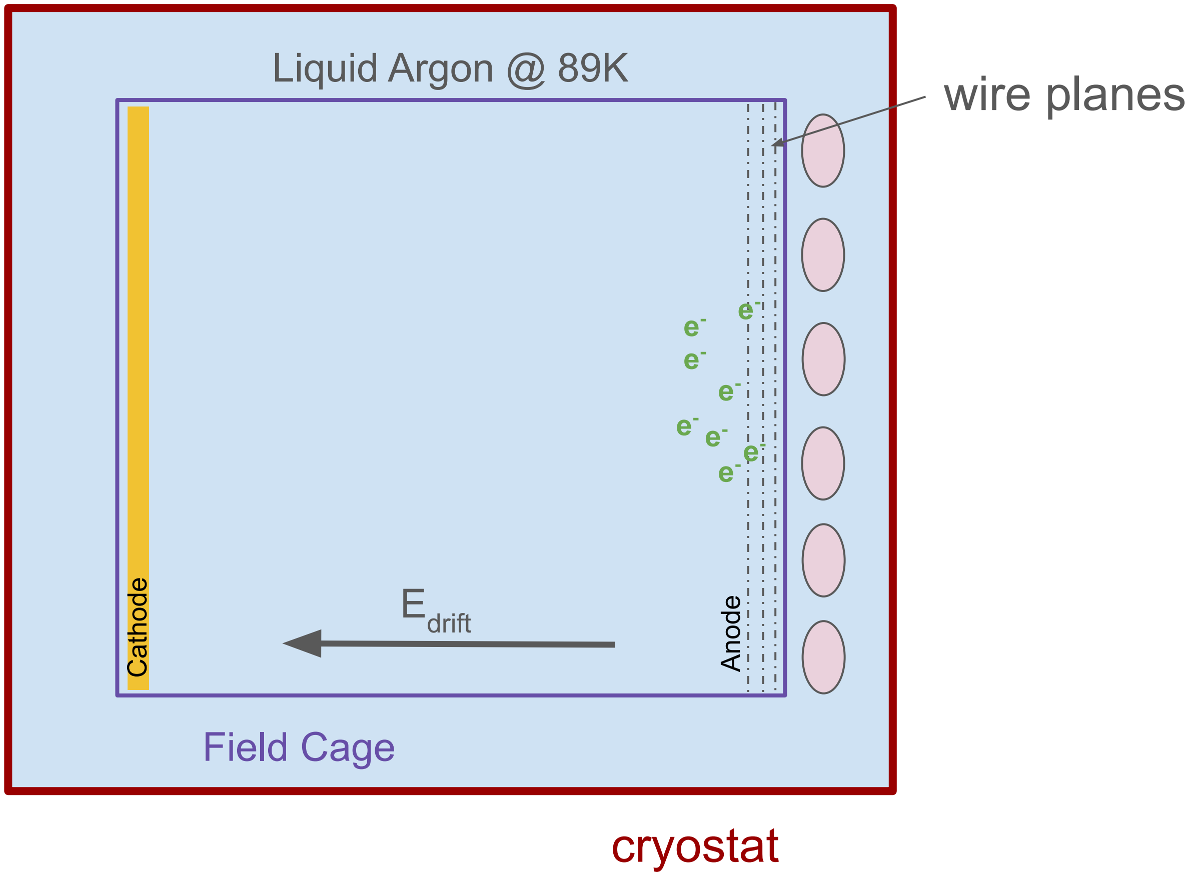
# LArTPC



# LArTPC


Liquid Argon @ 89K
wire planes
e-
e-
e-
e-
e-
e-
e-
e-
Cathode
E drift
Anode
Field Cage
cryostat

# LArTPC

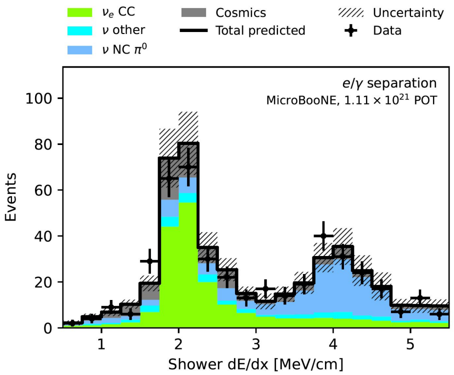


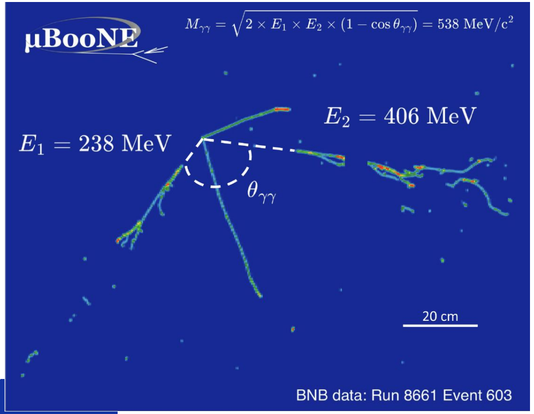
Liquid Argon @ 89K
wire planes
Cathode
Anode
e-
$E_{drift}$
Field Cage
cryostat

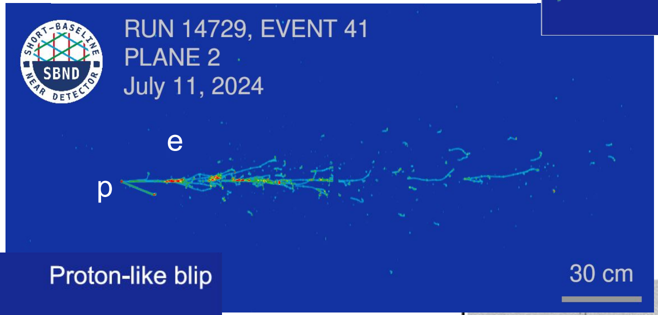
# LArTPC

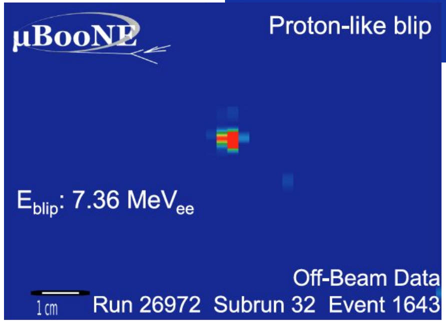
- Excellent particle identification
  - Can distinguish electrons, photons, muons, protons, pions, etc.
    - topological information
    - energy deposition per length (dE/dx)
  - Separate complicated topologies
  - Explore inclusive and exclusive channels in detail

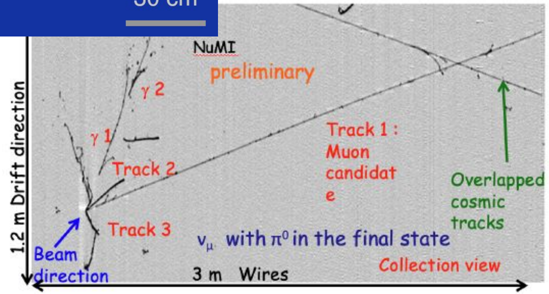
- MeV-level detection thresholds



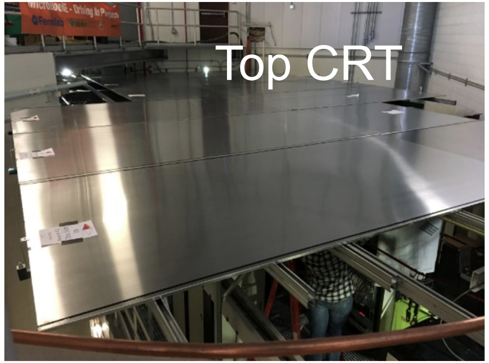



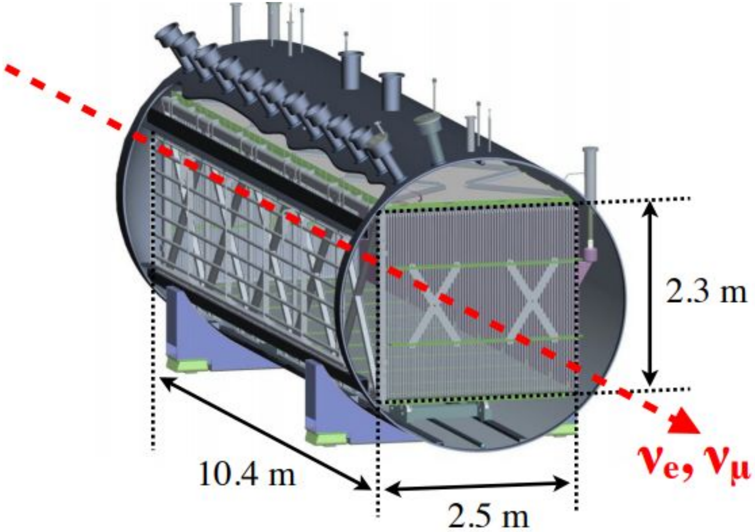



# MicroBooNE

JINST 12, P02017 (2017)

- Micro Booster Neutrino Experiment (MicroBooNE)
- Surface-level, 85 tonne LArTPC
- 3 planes of wires (vertical, +60°, -60°) with 3mm spacing
- 32 PMTs with TPB-coated wavelength shifting plates
- E-field of 273 V/cm, maximum ionization charge drift time of 2.3 ms
- Addition of a Cosmic Ray Tagger (CRT) in second run period to tag cosmogenic backgrounds

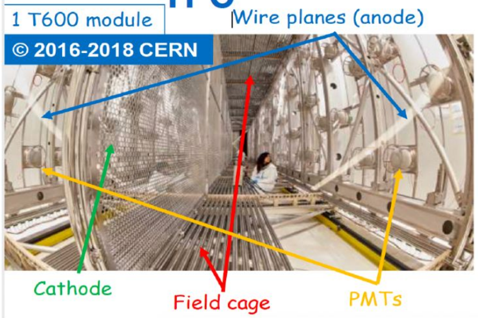


# ICARUS

- Imaging Cosmic and Rare Underground Signals (ICARUS)
- 2 Cryostats with 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 + 1 collection) per TPC, ~54000 wires at 0, ±60 degrees, 3 mm pitch
- 360 (8" PMTs): Scintillation light detected to provide ns event time and trigger
- CRT and overburden added when moved to Fermilab to reduce and tag cosmogenic backgrounds at new surface-level location

**TPC**




**PMT**

**side CRT**

**Top CRT**

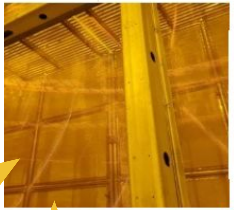

**3m concrete overburden**

# SBND

Short
Baseline
Near
Detector
(SBND)

**LArTPC**

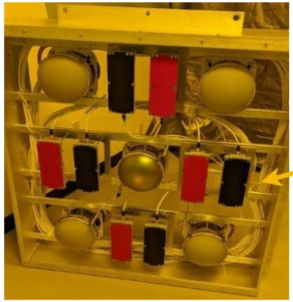
Active mass is 112 t
Active volume is 4×4×5 m³



**Anode Plane** on either side, each with three wire planes with 3 mm wire spacing and different orientation per plane

Total of 11,260 wires

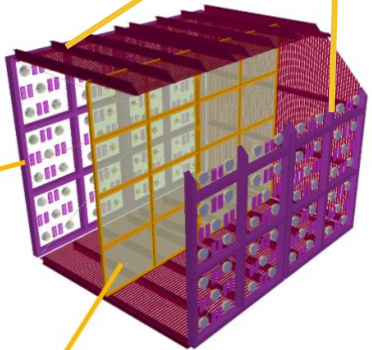
**Photon Detection System**



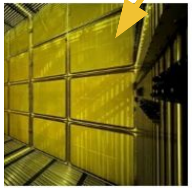
**24 PDS Boxes**
behind the anode wire planes

5×24 = **120 8″ PMTs**
80% TPB-coated,
20% uncoated

8×24 = **192 X-ARAPUCAs**
half with wavelength-shifting

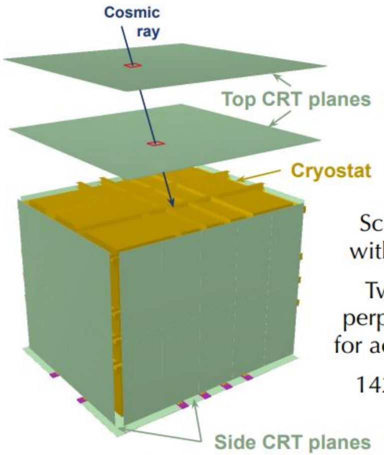


**Trigger System**



**Cathode Plane at −100 kV**
divides the detector into two drift volumes

Drift distance is 2 m,
max. drift time is ~1.28 ms




(160 m² active area)

Scintillator strips with SiPM readout

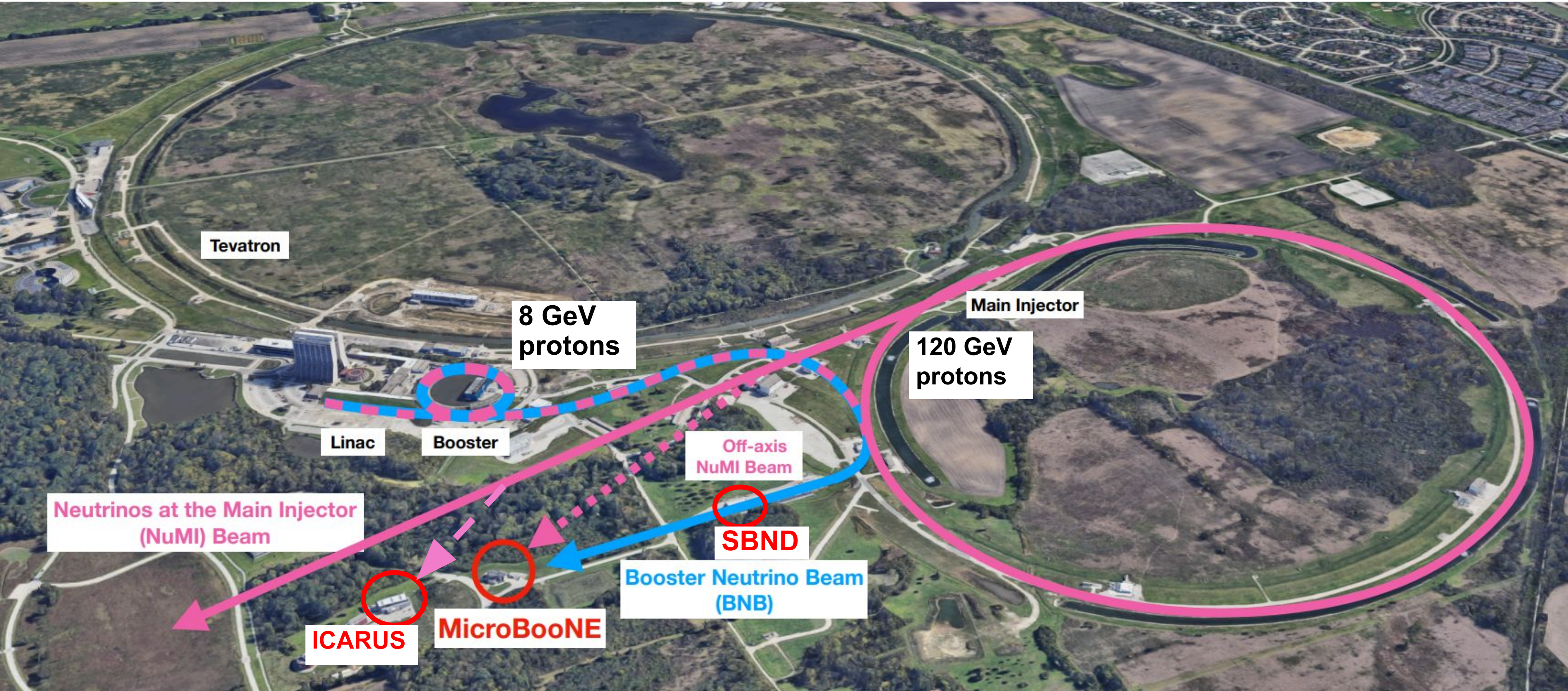
Two layers with perpendicular strips for accurate positions

142×32 channels

(225 m² active area)

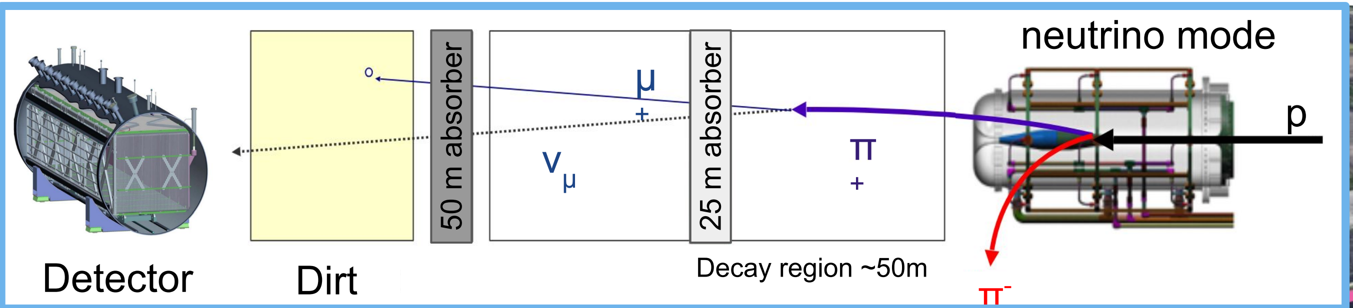
**Cosmic Ray Tagger**

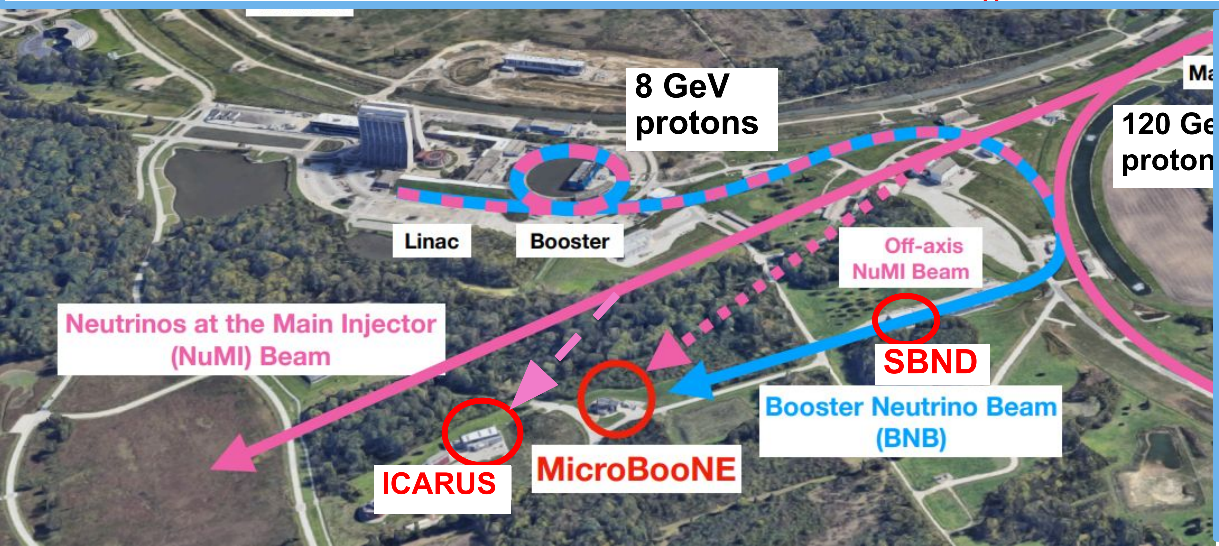
# The Beams

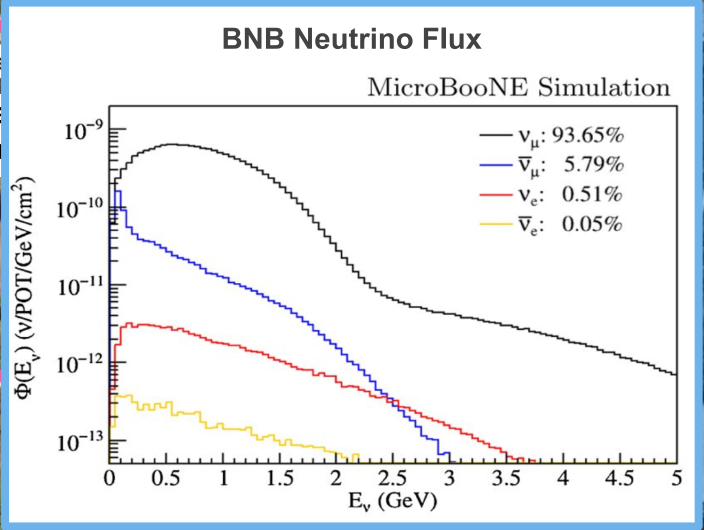


Tevatron
8 GeV
protons
Main Injector
120 GeV
protons
Linac
Booster
Off-axis
NuMI Beam
Neutrinos at the Main Injector
(NuMI) Beam
SBND
Booster Neutrino Beam
(BNB)
ICARUS
MicroBooNE

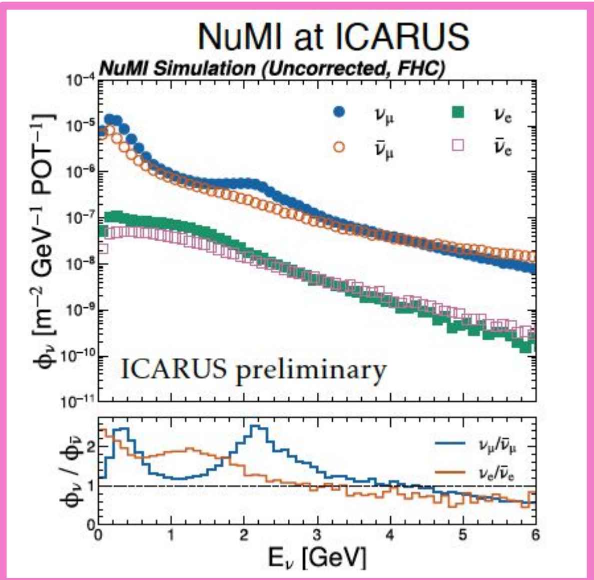
# The Booster Neutrino Beam (BNB)

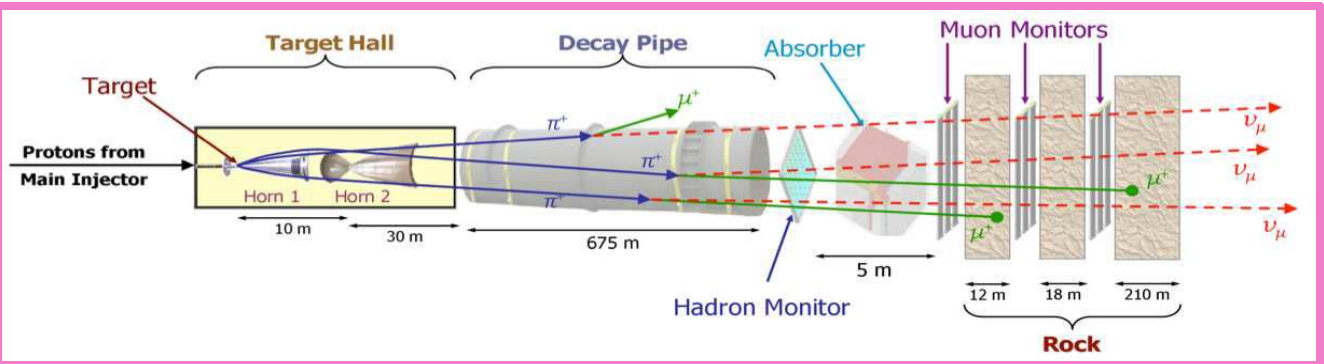


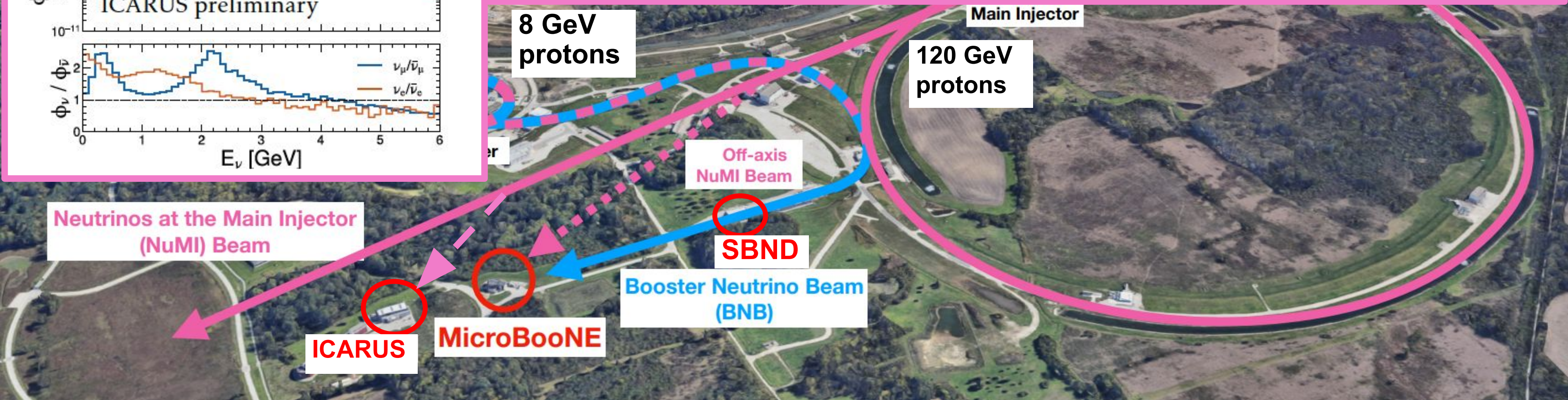



# Neutrinos at the Main Injector (NuMI)

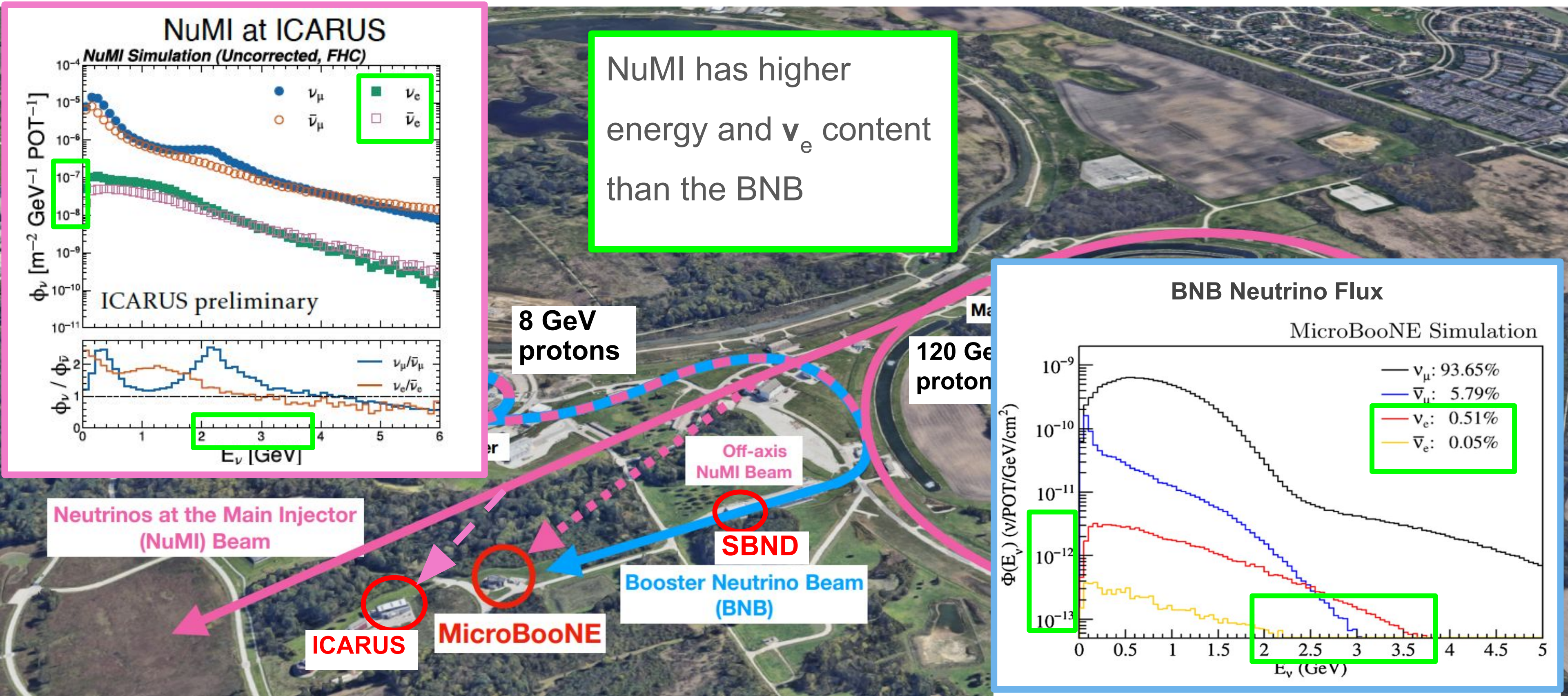


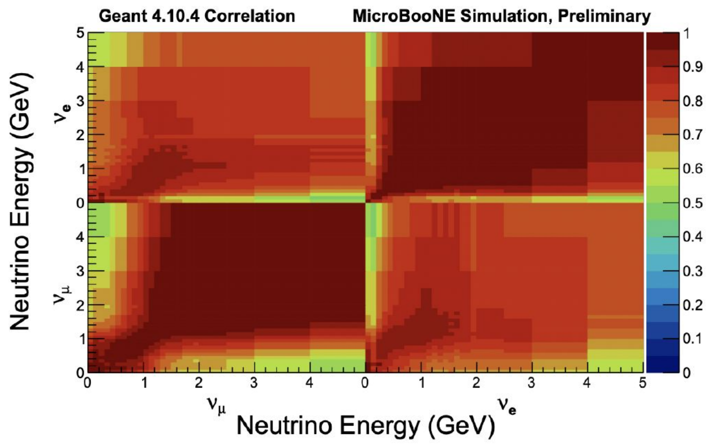
# Neutrinos at the Main Injector (NuMI)

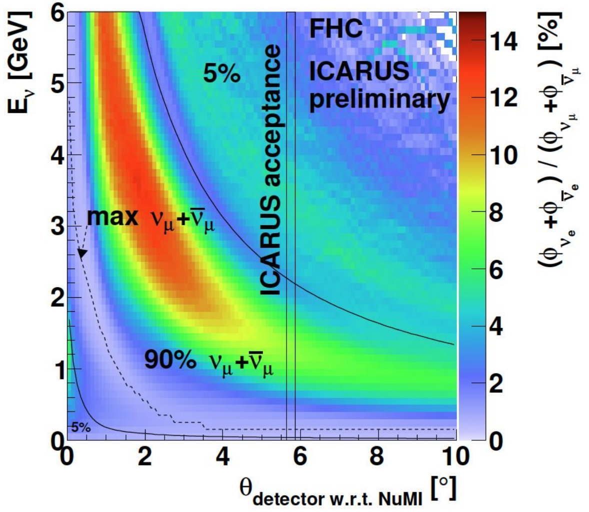
NuMI has higher energy and $\nu_e$ content than the BNB

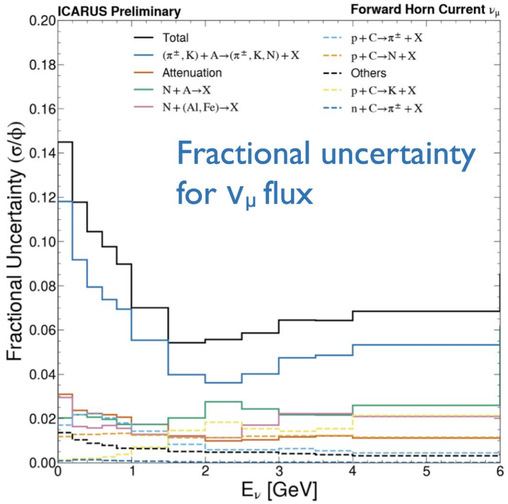


# NuMI Flux

- ICARUS and MicroBooNE see the NuMI beam at large off-axis angles (6° and 8°, respectively)
- Each have reevaluated the NuMI neutrino flux prediction for it's off-axis position
- Flux tuned with hadron production data via PPFX (MINERvA, Phys. Rev. D 94, 092005)
- New base model (G4.10.4) : better agreement with $\pi$, *K* production data from NA49
- Achieved flux uncertainties of 6-10%

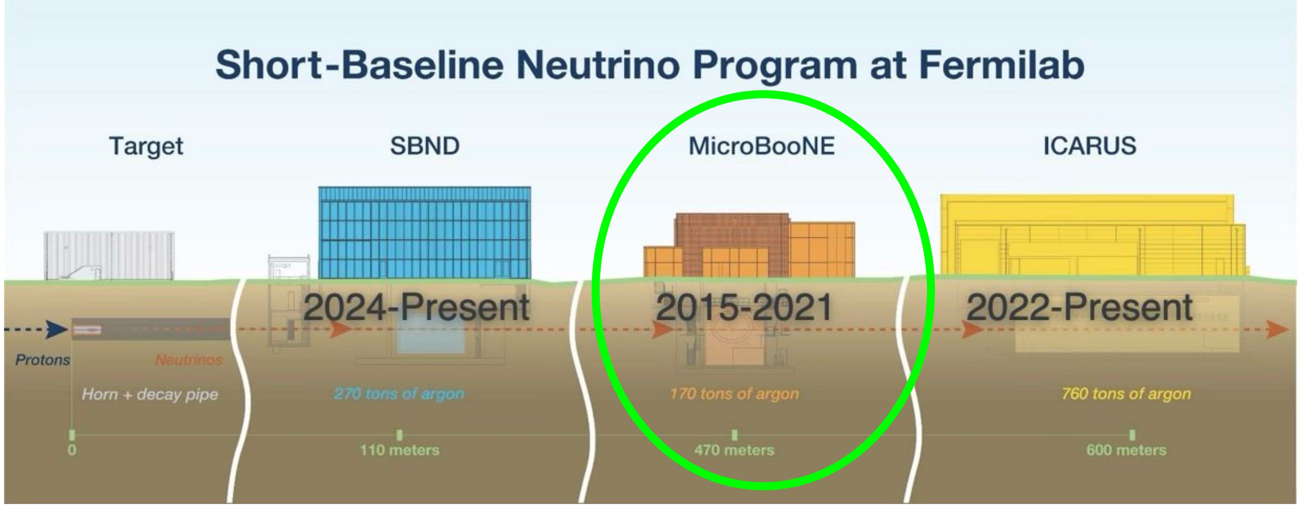


# The SBN Program: MicroBooNE

- 470m downstream from the neutrino production target
- 8° off-axis of the NuMI beam
- Collected data 2015 - 2021
- ~0.5M neutrino events
- Decommissioned


# MicroBooNE Cross Sections

## Published

**CC inclusive**

- 1D $\nu_\mu$ CC inclusive @ BNB, PRL 123, 131801
- 1D $\nu_\mu$ CC E$\nu$ @ BNB, PRL 128, 151801
- 3D CC $E_\nu$ @ BNB, arXiv:2307.06413
- 1D $\nu_e$ CC Inclusive @ NuMI, PRD 104 052002, PRD 105 L051102
- 2D $\nu_\mu$ CC0pNp inclusive @ BNB, arXiv:2402.19216, arXiv:2402.19281

**Rare channels & novel techniques**

- η production @ BNB, PRL 132, 151801
- Λ production @ NuMI, PRL 130, 231802
- K+ production @ BNB, arXiv:2503.00291
- Neutron identification, arXiv:2406.10583

**CC0π**

- 1D $\nu_e$ CCNp0π @ BNB, PRD 106, L051102
- 1D & 2D $\nu_\mu$ CC1p0π TKI @ BNB, PRL 131, 101802, PRD 108, 053002
- 1D & 2D $\nu_\mu$ CC1p0π GKI @ BNB, PRD 109, 092007
- 1D $\nu_\mu$ CC1p0π @ BNB, PRL 125, 201803
- 1D $\nu_\mu$ CC2p @ BNB, arXiv:2211.03734
- 1D $\nu_\mu$ CCNp0π @ BNB, Phys. Rev. D 102, 112013
- 2D $\nu_\mu$ CCNp0π @ BNB, arXiv:2403.19574

**Pion production**

- $\nu_\mu$ NC$\pi^0$ @ BNB, PRD 107, 012004
- 2D $\nu_\mu$ NC$\pi^0$ @ BNB, arXiv:2404.10948
- $\nu_\mu$ CC$\pi^0$ @ BNB, arXiv:2404.09949

## Ongoing

**CC inclusive**

- $\nu_\mu$ CC inclusive @ NuMI
- $\nu_e/\nu_\mu$ ratios @ BNB, NuMI
- 3D $E_\nu$, $E_\mu$, $E_{had}$ @ NuMI & BNB
- anti-$\nu_e$ @ NuMI

**Pion production**

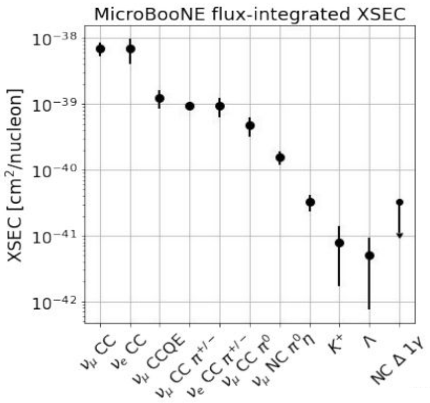
- $\nu_\mu$ CC1π+ @ BNB & NuMI
- $\nu_\mu$ CCNπ @ NuMI
- 1D $\nu_\mu$ CCπ0 @BNB
- 2D $\nu_\mu$ CC/NC π0 @ BNB
- 2D $\nu_{e,\mu}$ NCπ0 @ BNB

**CC/NC 0π**

- 2D $\nu_\mu$ CC1p0π GKI @ BNB
- 1D & 2D $\nu_\mu$ CC0π @ BNB
- 2D $\nu_\mu$ CCNp0π @ BNB
- 1D $\nu_e$ CC0πNp @ NuMI
- 1D $\nu_\mu$ NC1p0π @ BNB

**Rare channels & novel techniques**

- MeV-scale physics
- Low-energy neutrons @ BNB

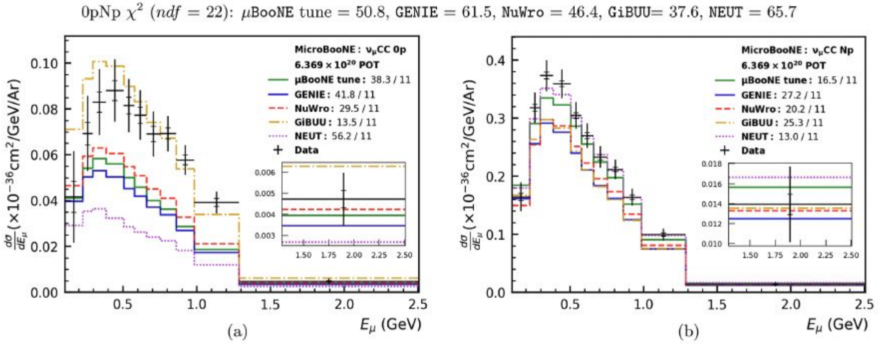


# $\nu_\mu$ CC Kinematics

## BNB Inclusive 0p/Np

PRD **110**, 013006 (2024)

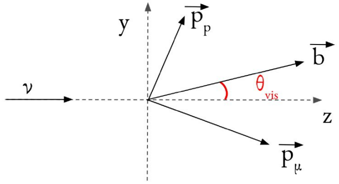
- Probing $\nu_\mu$ CC channel split by final state protons
- High statistics → differential (1D, 2D, 3D)
- Modeling better in Np
- Prefers strong FSI, in-medium corrections

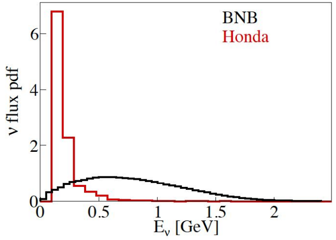


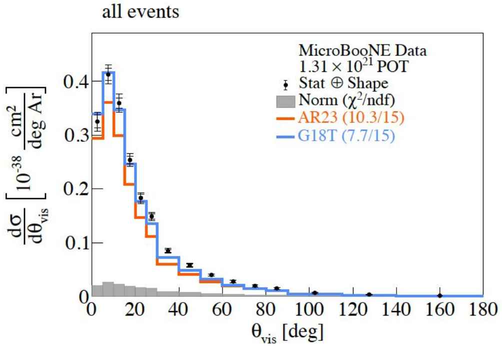

## 1μ1p Neutrino Directional Resolution for DUNE Atmospherics

arXiv:2504.17758

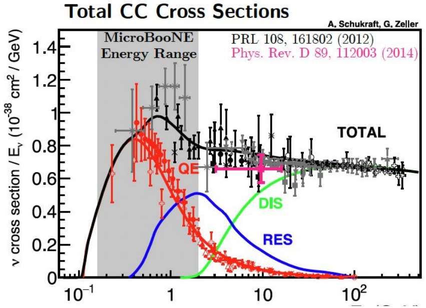
- Leverage known BNB beam direction to study angular distributions for the DUNE atmospheric flux
- Data-driven predictions for DUNE
- 1μ1p differential cross sections sensitive to FSI and hadron reinteractions



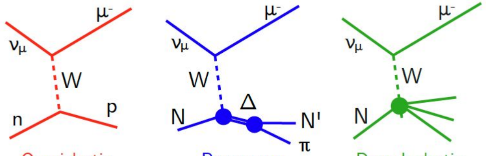



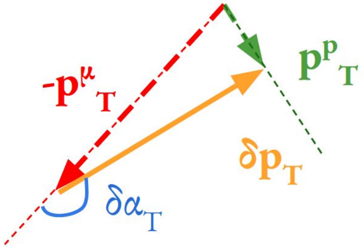
# Nuclear Effect Studies

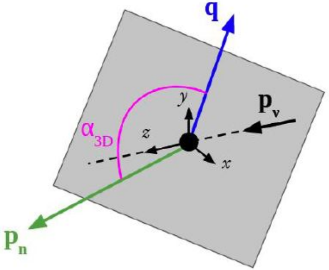



Using various $\nu_\mu$ CC final states to probe nuclear modeling and final state interactions across models




Quasielastic Scattering (QE) | Resonance Production (RES) | Deep Inelastic Scattering (DIS)



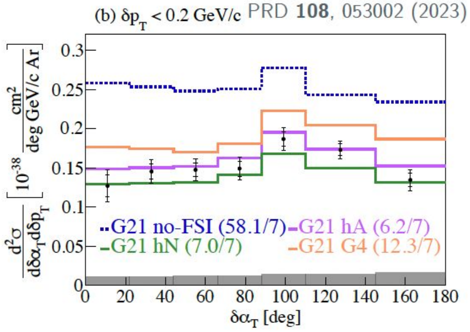

**1p:**

- Transverse Kinematic Imbalance (TKI)
  - PRL 131, 101802 (2023)
  - PRD 108, 053002 (2023)
- Generalized Kinematic Imbalance (GKI)
  - PRD 109, 092007 (2024)

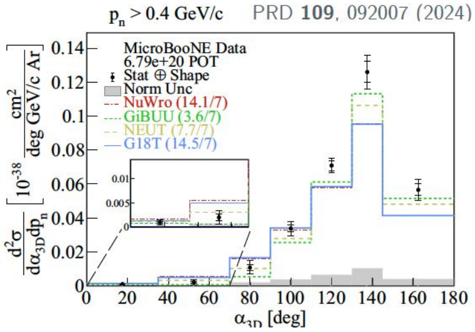
**Np:**

- TKI
  - arXiv:2403.19574

TKIs in $p_T$ slices, kinematic $\nu_\mu$CCQE-like

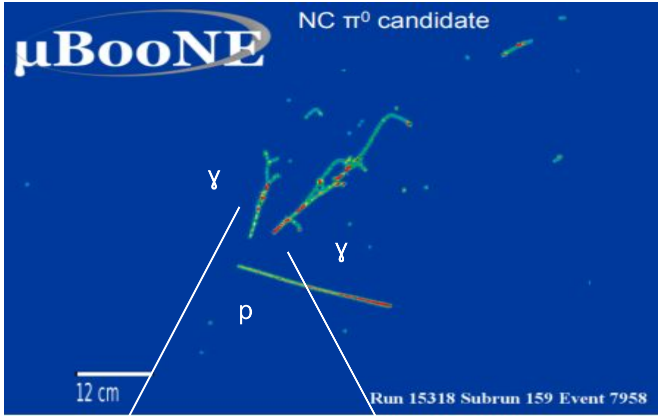


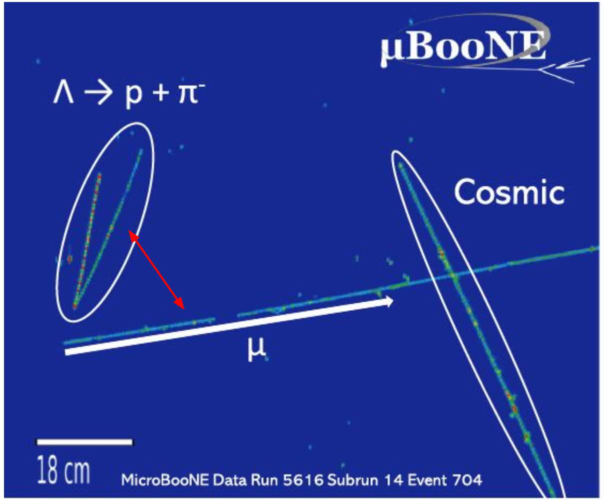

GKIs ($q \cdot p_n$) in $p_n$ slices, $\nu_\mu$CC1μ1p

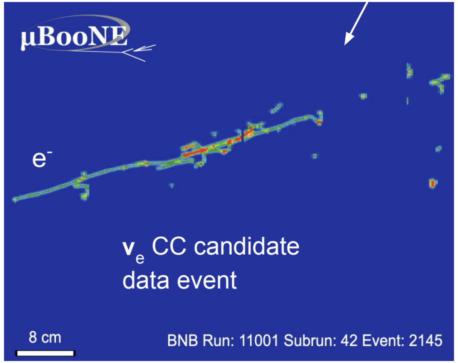


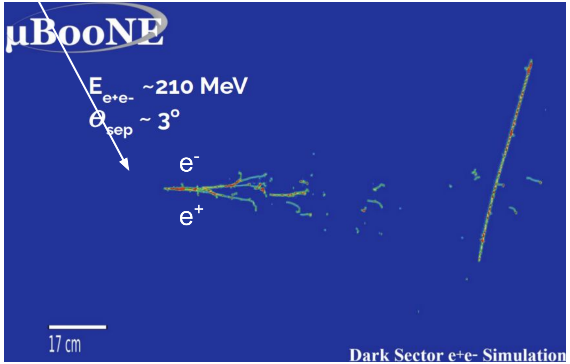
# Pions

Major backgrounds for $\nu_\mu$ CC and $\nu_e$ CC used in oscillation measurements as well as BSM searches (single photon, $e^+e^-$, $\mu\pi$)



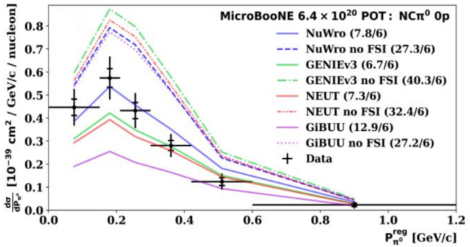



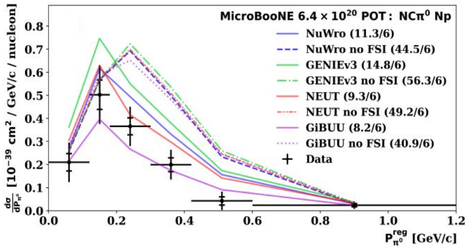



# Pions

## BNB 2D NC $\pi^0$ 0p/Np PRL **134**, 161802 (2025)

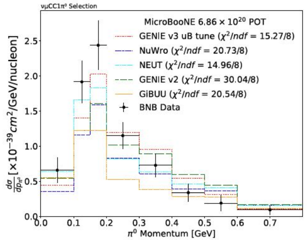
- First 2D NC $\pi^0$ on Ar
- $\pi^0$ kinematics
- Split by final state protons
- Sensitive to FSI and form factors
- Prefers a stronger $Q^2$ dependence

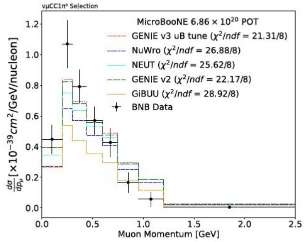



## BNB $\nu_\mu$ CC $1\pi^0$ PRD **110**, 092014 (2024)

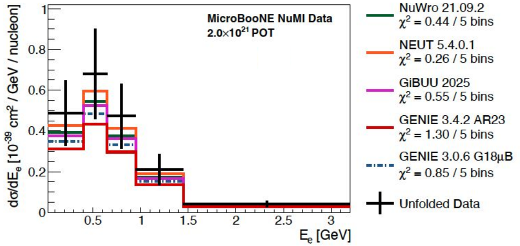
- 1D and 2D in μ and $\pi^0$ kinematics
- Shows a low-*q* suppression for resonant pion production and impact of pion FSI treatments

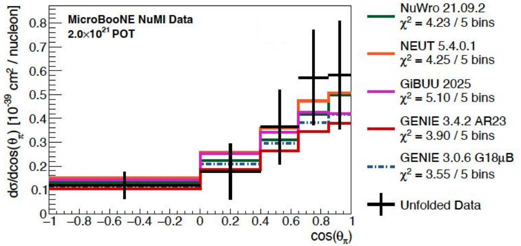



## NuMI $\nu_e$ CC $1\pi^\pm$ arXiv:2503.23384

- First differential $\nu_e$ $1\pi^\pm$ on Ar
- e and $\pi$ kinematics
- Showing good model agreement
- Limited statistics



# Pions

## BNB 2D NC $\pi^0$ 0p/Np PRL **134**, 161802 (2025)

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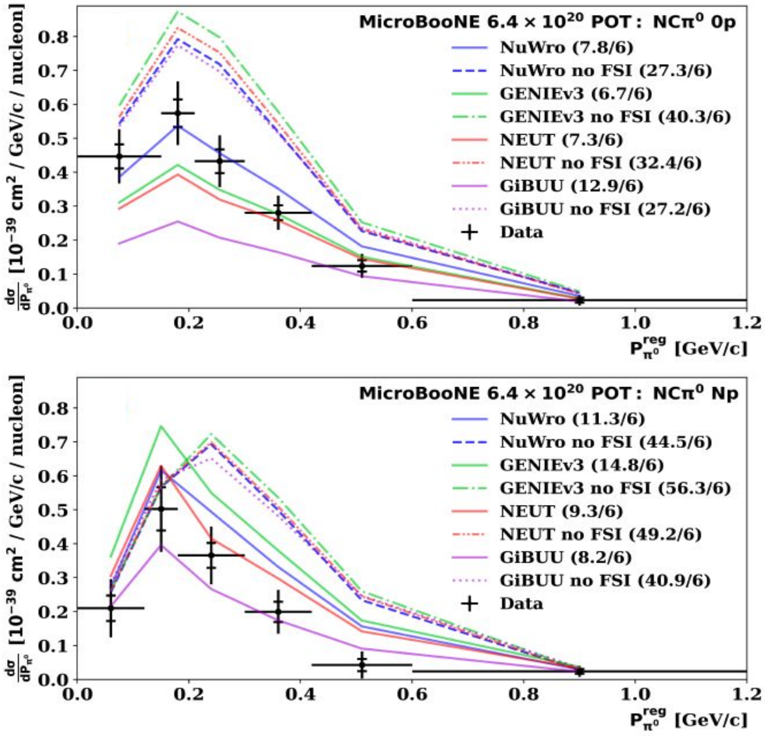
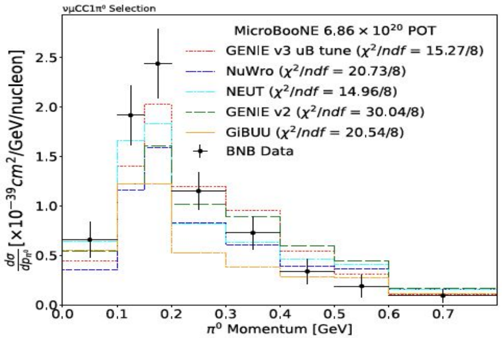
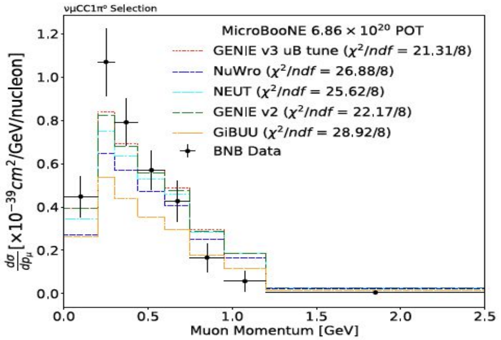


# Pions

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- 1D and 2D in μ and $\pi^0$ kinematics
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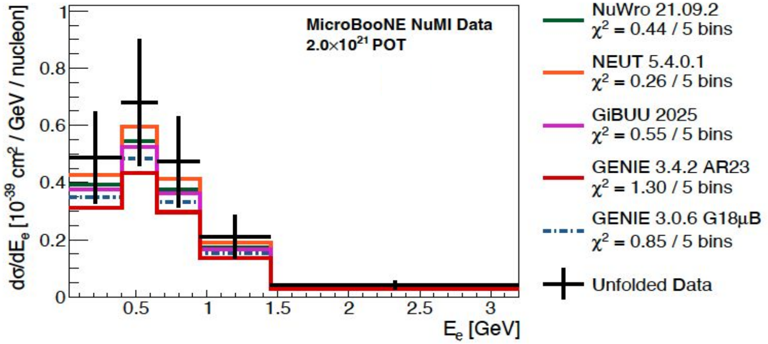
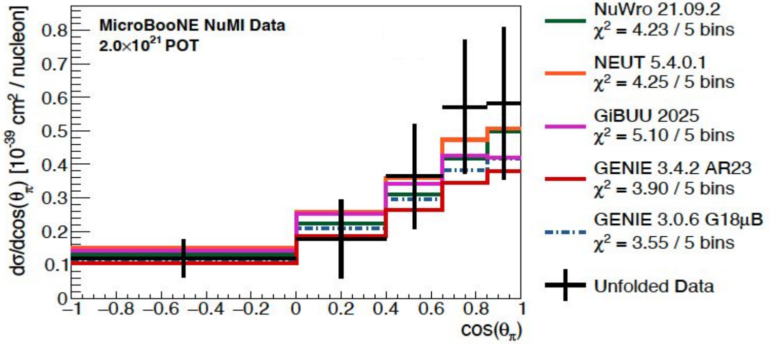
# Pions

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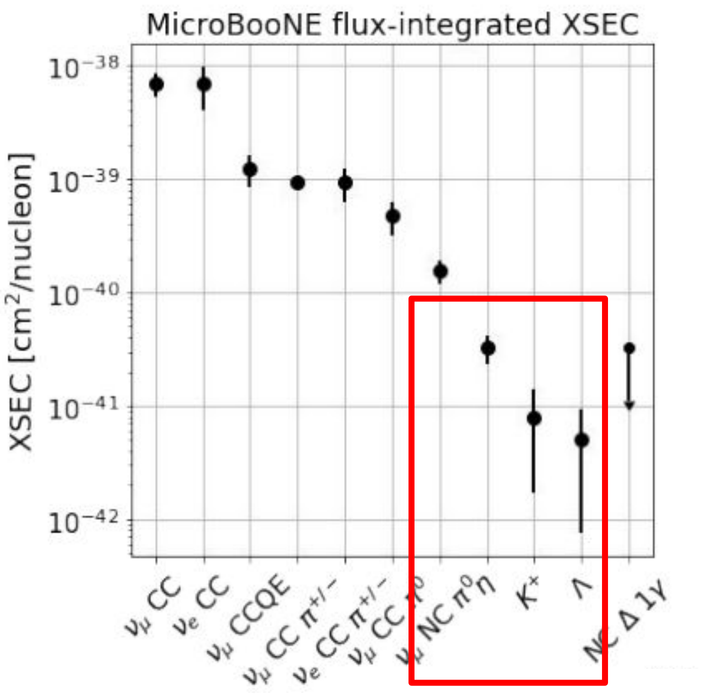
# Rare Channels

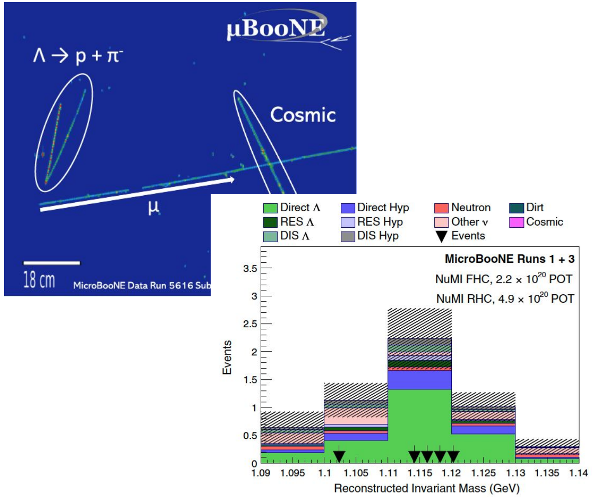


# Rare Channels

## NuMI Λ Production PRL **130**, 230802 (2023)

- Cabibbo-suppressed inclusive $\nu_\mu$ CC $\Lambda + X$ production
- Sensitive to nuclear details and nucleon decay search backgrounds
- 5 candidate events

$$\sigma = 2.0^{+2.2}_{-1.7} \times 10^{-40}\,\mathrm{cm}^2$$



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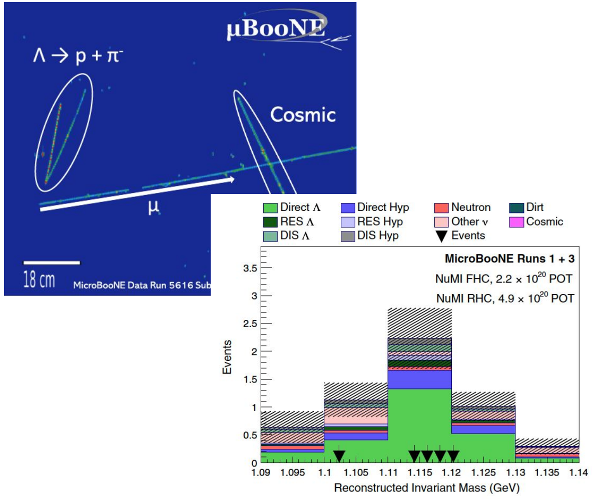
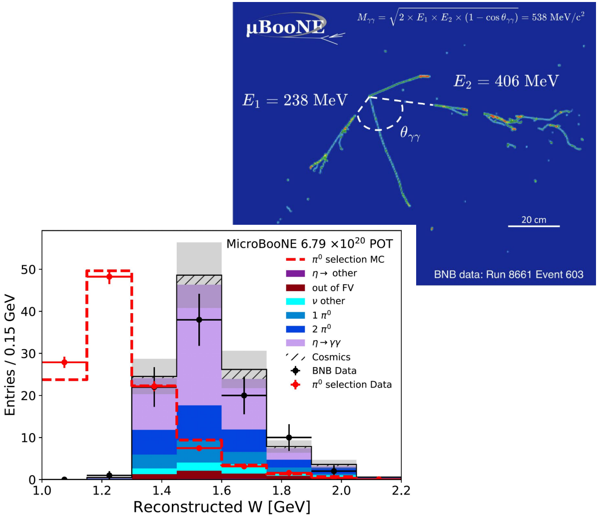



## BNB η Production PRL **132**, 151801 (2024)

- Inclusive CC+NC η production
- Probing resonances above the Δ(1232) mass
- η invariant mass and W

$$\sigma = (3.22 \pm 1.20) \times 10^{-41}\,\mathrm{cm}^2$$



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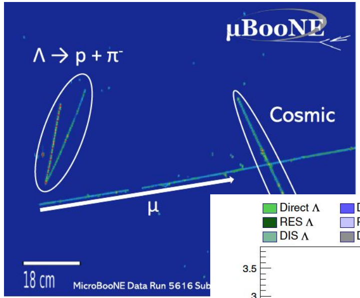


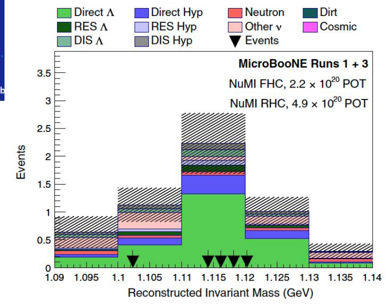


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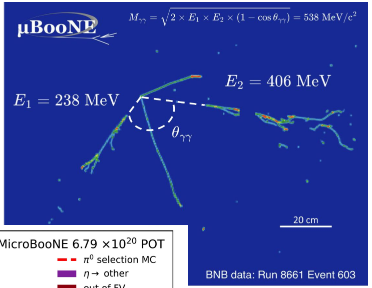
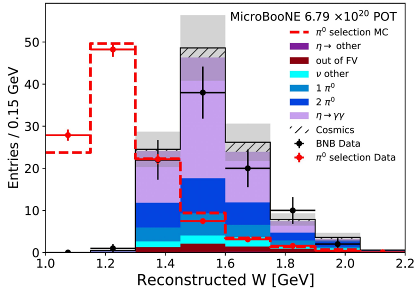
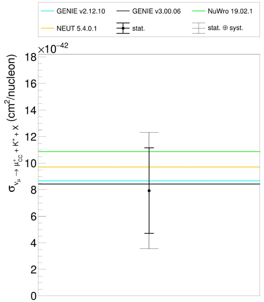


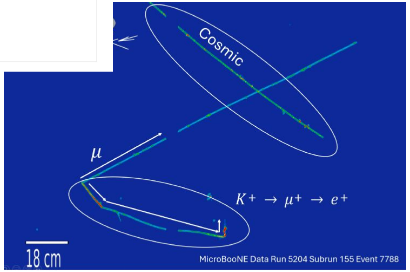




## BNB $\nu_\mu$ CC $K^+$ arXiv:2503.00291

- First ν $K^+$ production on Ar
- Probing strange production and nucleon decay backgrounds
- 10 candidate events

$$\sigma = (7.93 \pm 4.38) \times 10^{-42}\,\mathrm{cm}^2$$

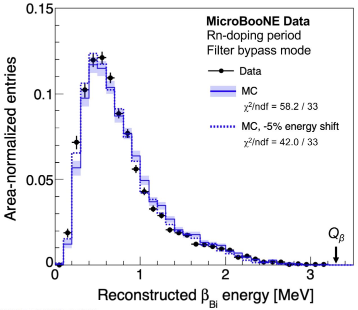


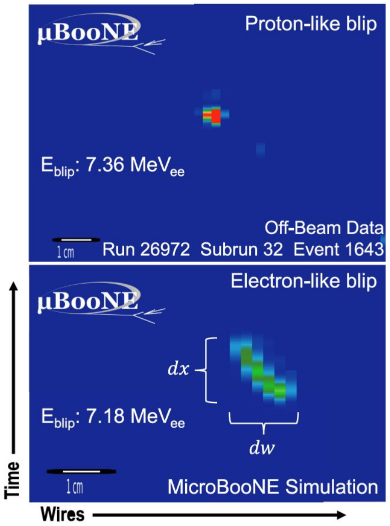



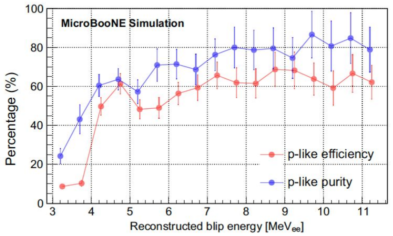
# Low-Energy Regime

## MeV-Scale "Blips" PRD **111**, 032005 (2025), PRD **109** 052007 (2024)

- Ability to reconstruct activity down to 150 keVee
- Perform α and β calorimetry
- Using on- and off-beam data + a special Rn doping run done in 2021
- Applications: improved calorimetry, lower particle thresholding, BSM searches (e.g. millicharged particles), muon/pion charge sign tagging, gamma spectroscopy, neutron tagging, etc.

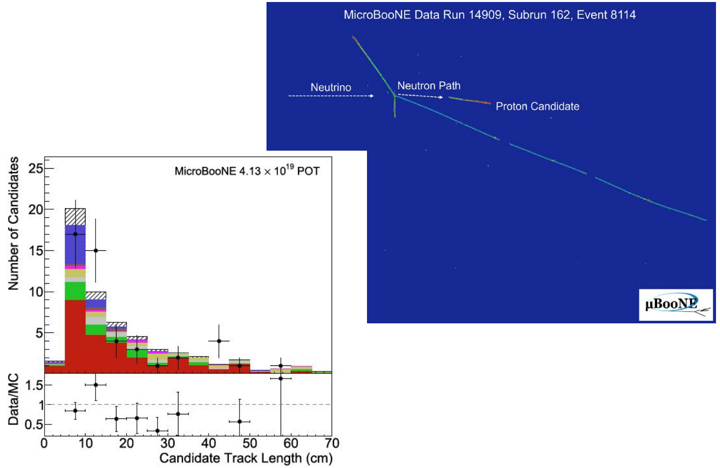



## Neutron-induced Protons EPJC **84**, 1052 (2024)

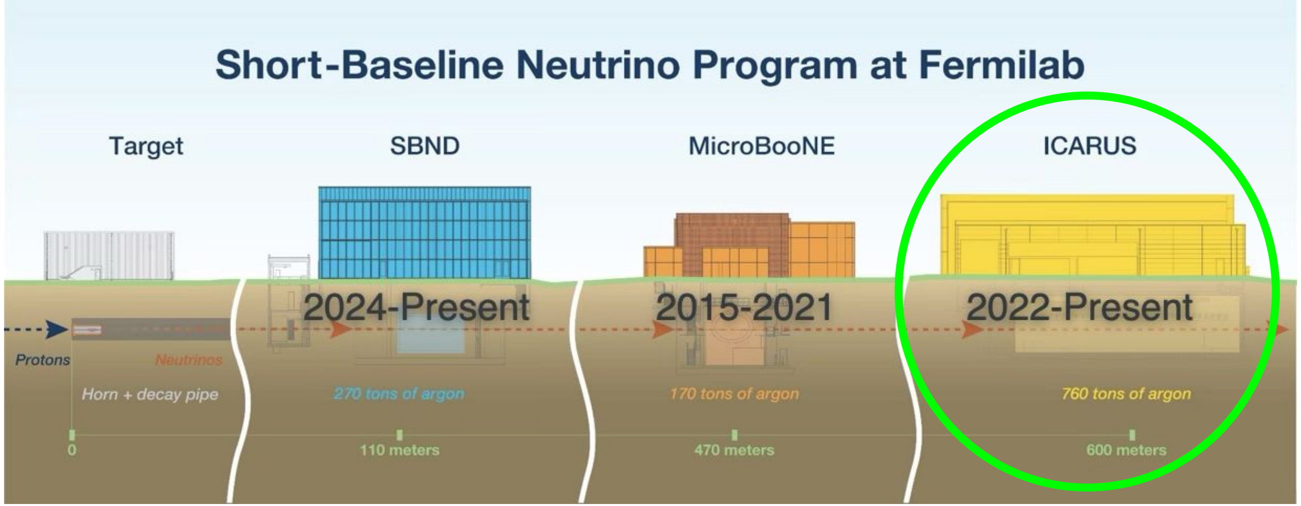
- Capability to identify and reconstruct neutrons > ~100 MeV via n-Ar inelastic single-proton production
- New insights into poorly-constrained neutral hadron production important to modelling and neutrino oscillation measurements
- Work underway to combine with blips to extend toward low-energy neutrons



# The SBN Program: ICARUS

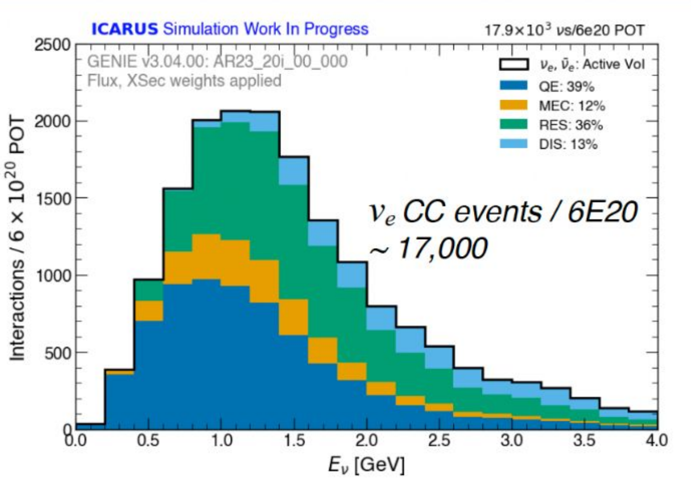
- First commissioned in Gran Sasso, refurbished and shipped from Gran Sasso to Fermilab to be part of the SBN program
- 600m downstream from the neutrino production target
- 6° off-axis of the NuMI beam
- Collecting data since June of 2022

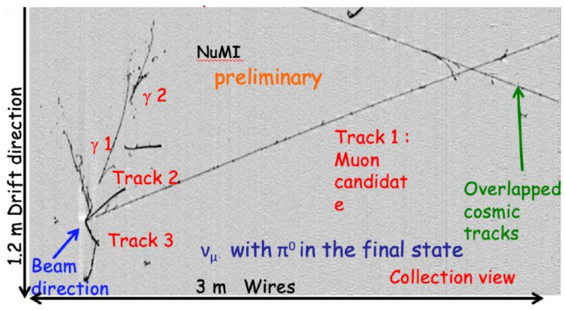
| Collected POT ($\times 10^{20}$) | BNB | NuMI ($\nu$) | NuMI ($\bar{\nu}$) |
|---|---|---|---|
| Run 1 | 0.41 | 0.68 | — |
| Run 2 | 2.06 | 2.74 | — |
| Run 3 | 1.36 | — | 2.82 |
| Run 4 (Ongoing) | 1.37 | — | — |
| Total | 5.19 | 3.42 | 2.82 |

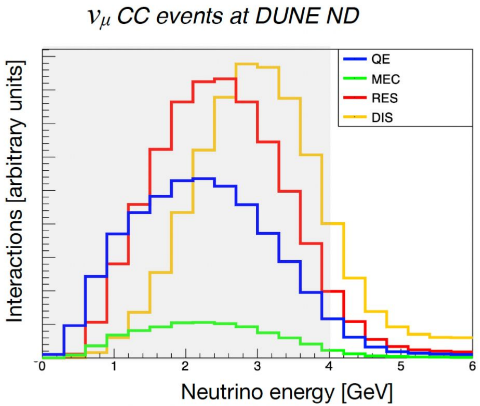


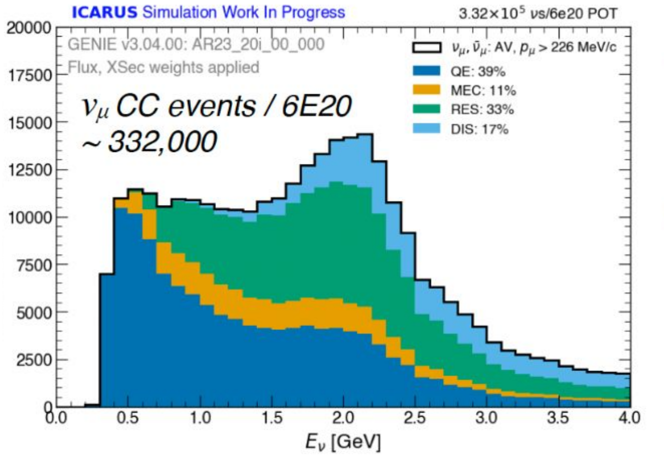

# NuMI at ICARUS

- ICARUS sees the NuMI beam at a smaller off-axis angle (6°) than MicroBooNE (8°)
  - Higher energy beam, closer to DUNE's first oscillation maximum
  - Higher statistics
- Currently, ~3.4 x $10^{20}$ POT of neutrino and ~2.8 x $10^{20}$ POT of anti-neutrino NuMI data collected by ICARUS
- High-statistics sample enables precise QE and **π** production measurements for both $\mathbf{v}_\mu$ and $\mathbf{v}_e$
- With available statistics, study of resonance and DIS also possible



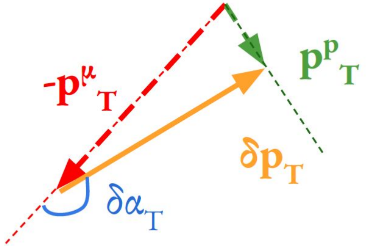



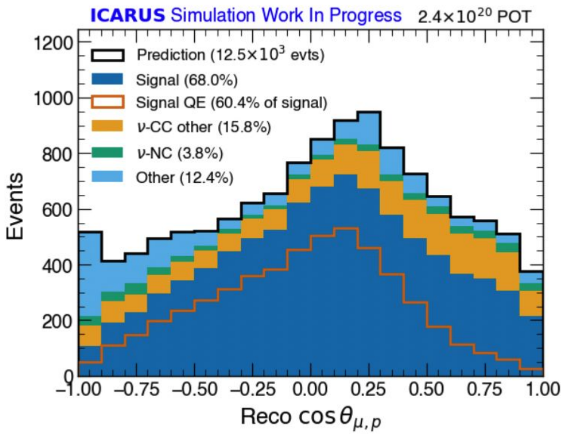



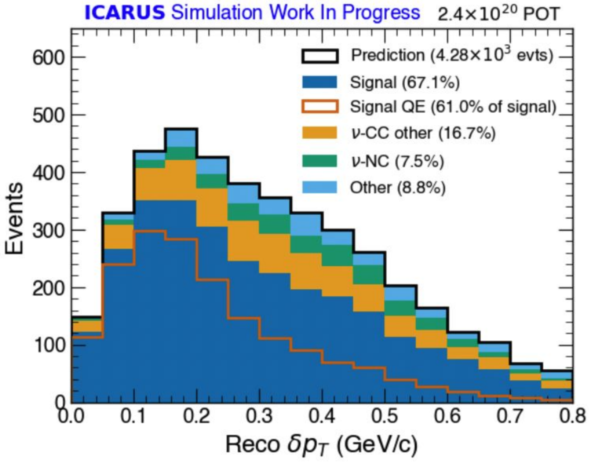
# $\nu_\mu$ CC Np 0$\pi$

- Using first 2 physics runs → 2.4 x $10^{20}$ POT
- Target a QE-like signal definition
  - Muon with p > 226 MeV/c (~50 cm long track)
  - ≥1 proton with 400 MeV/c < p < 1 GeV/c
  - Any number of additional nucleons
  - No additional mesons of any energy
- Muon and proton angular observables and TKI variables
- Probe QE, 2p2h, FSI modeling
- ~35% efficiency overall (~10% for fully contained)

**Full analysis is ready and expected to be shown later this summer**

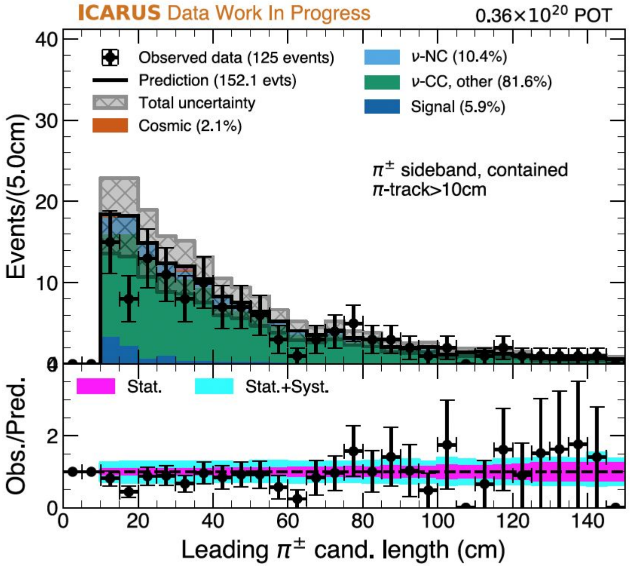


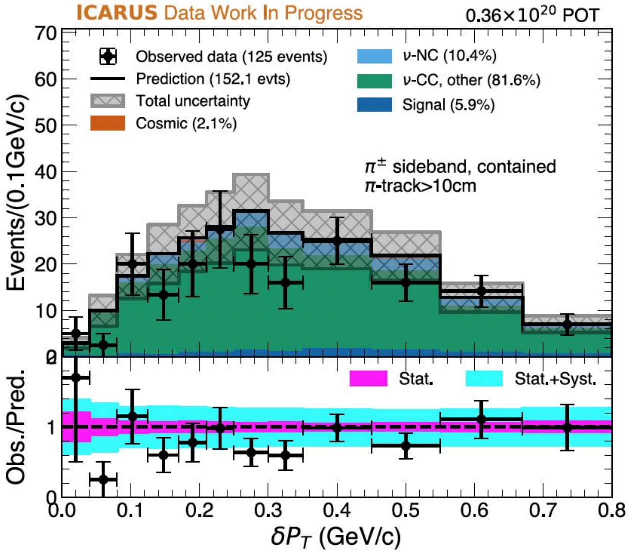



# $\nu_\mu$ CC Np N$\pi$

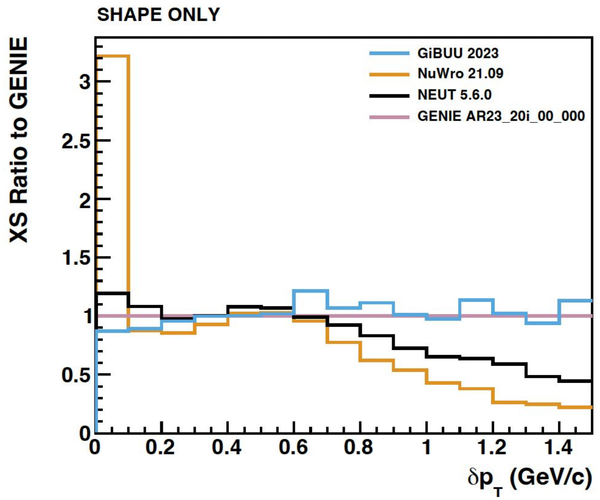
- Sideband selection for $\nu_\mu$ CC Np 0$\pi$ analysis
- Constrain pion backgrounds
- Evaluate $\pi^{\pm}$ kinematics
- 15% of data shown here (100% sample has been unblinded)

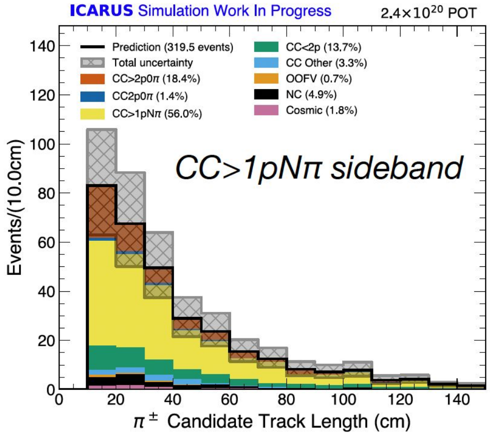


# Multi-proton analysis

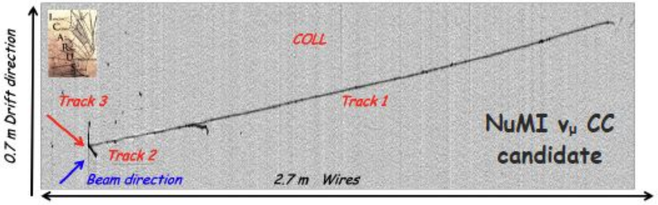
- Extension of the $\nu_\mu$ CC Np $0\pi$ selection: ≥**2** protons with p > 350 MeV/c
  - Uses the vector sum of the leading two protons
- Enhanced sensitivity to non-QE processes like 2p2h and FSI-induced pion absorption
  - Significantly more prominent in the NuMI flux than in the BNB
- Most neutrino event generators (e.g. GENIE, NuWro, NEUT) lack theory-driven modeling of the momentum sharing in multi-nucleon events
- >70% purity
  - 45% 2p
  - 27% >2p
- >1ppN$\pi$ sideband to constrain

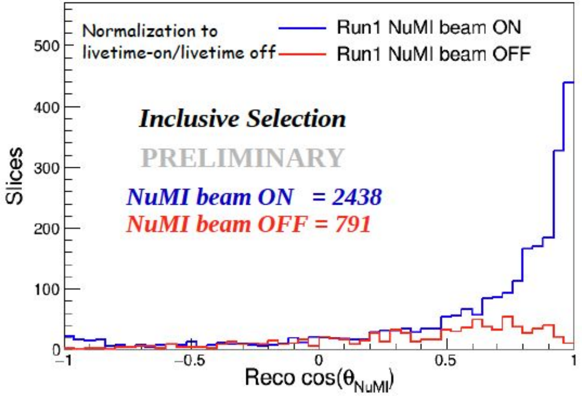


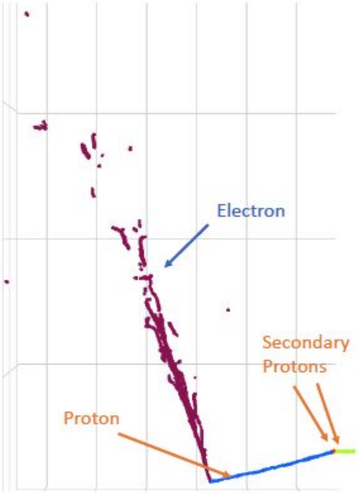



# More Analyses In-Progress

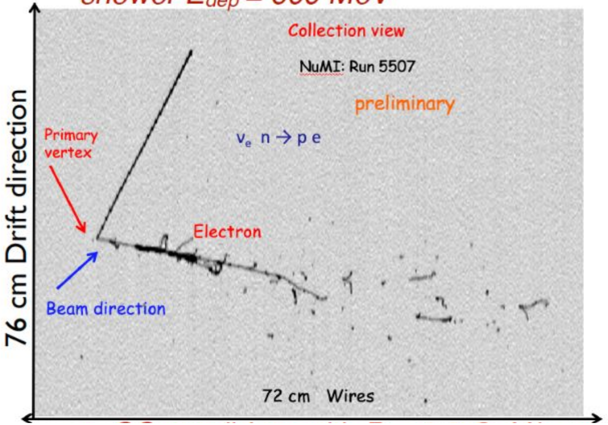
- $\nu_\mu$ CC Inclusive
- $\nu_\mu$ CC $1\pi^\pm$
- $\nu_\mu$ CC $1\pi^0$
- $\nu_e$ CC Inclusive
- $\nu_e$ CC Np



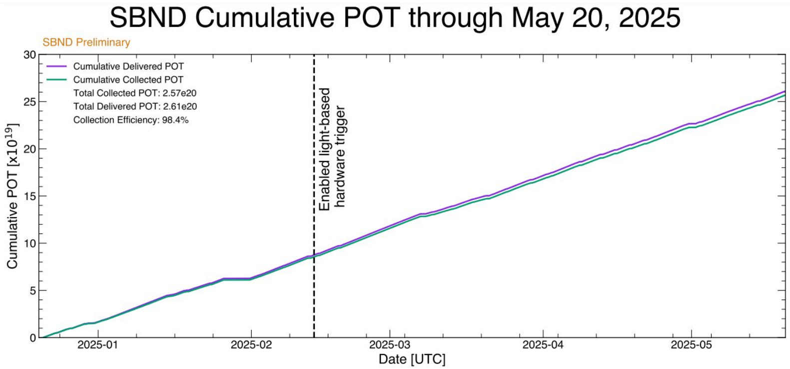



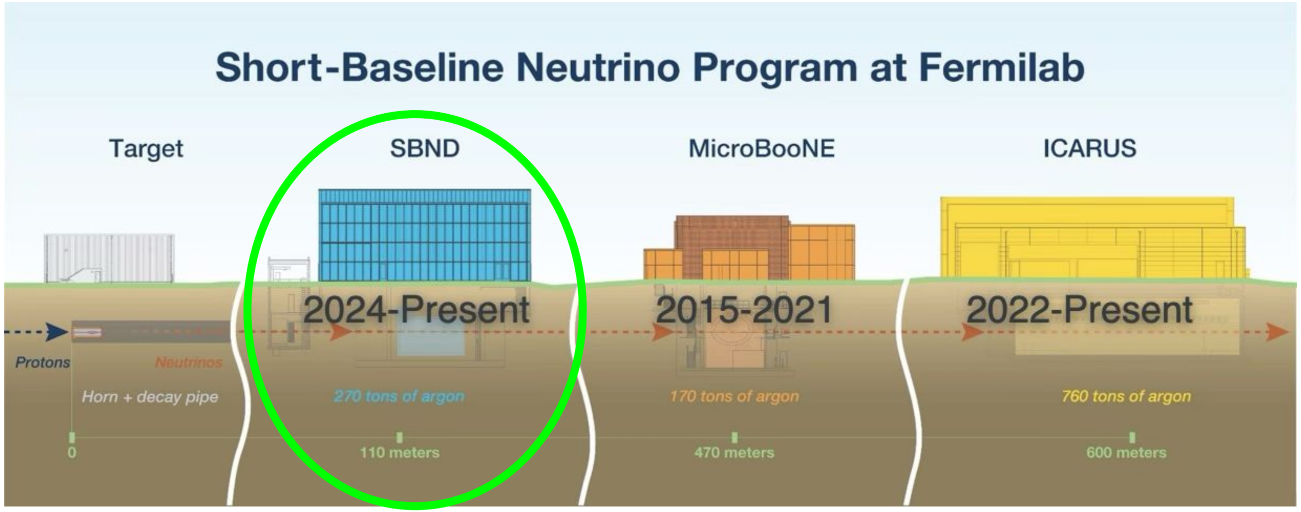

$\nu_e$ CC candidate with electromagnetic shower $E_{dep}$ = 600 MeV



# The SBN Program: SBND

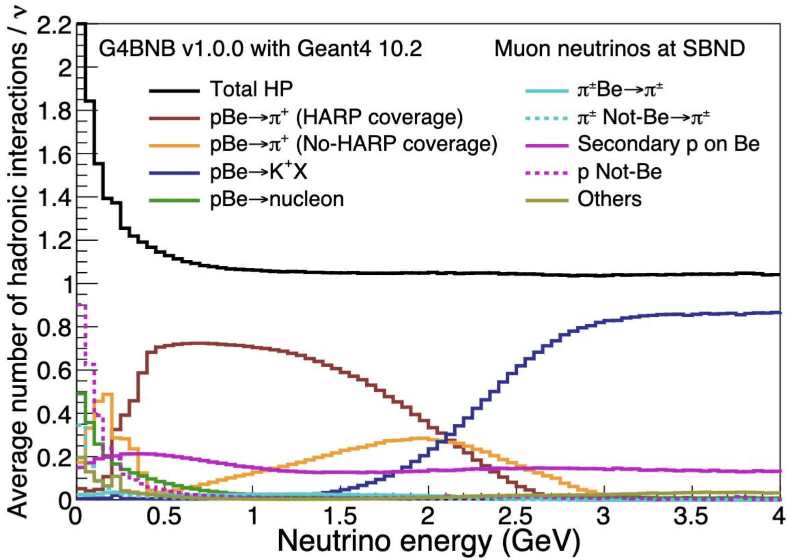
- Collected first neutrino data July 2024
- In the midst of first physics run period
- Large flux: only 110m from the BNB target
- Expects on average more than 5000 neutrino events per day
    - Expect O(10M) neutrino interactions in total by end of running
    - Has already surpassed the full 5 year dataset from MicroBooNE
    - Allows for multi-dimensional and rare process studies



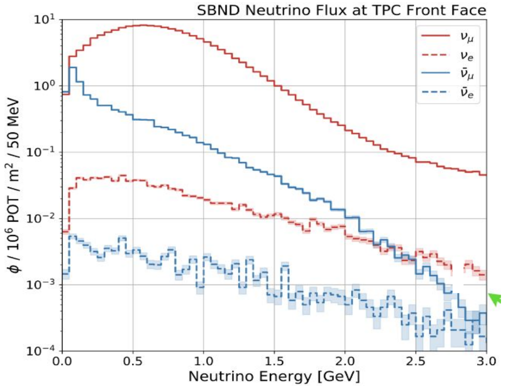

# The BNB at SBND

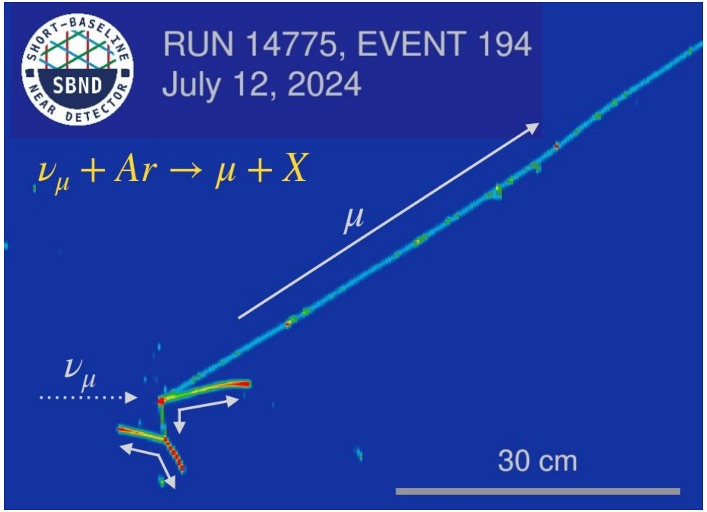
- BNB flux measurements and uncertainties traditionally used MiniBooNE studies
- SBND is working to update and reevaluate the BNB flux and lower flux uncertainties → crucial for precise cross section measurements at SBND
- Development of G4BNB
  - Enables a complete record of hadronic interaction flux within a modern Geant4 framework
  - Calculate more precise flux uncertainties, incorporating current and future data
  - Reevaluating the extension of data coverage, that account for secondary interactions
- Improvements in flux uncertainties are possible by hadron production (HP) experiments
  - EMPHATIC (Fermilab)
  - NA61/SHINE (CERN)

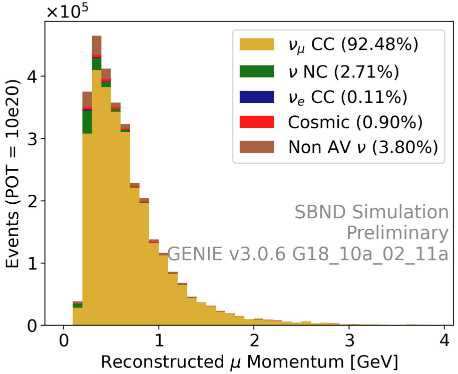


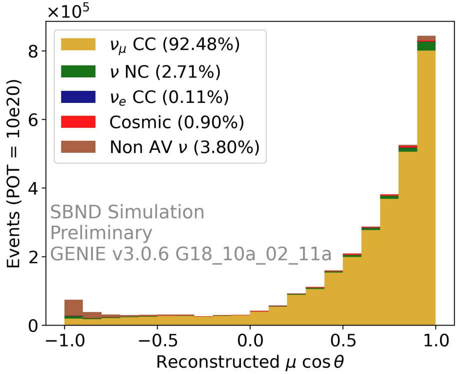
# $\nu_\mu$ CC Inclusive

- Majority (~94%) of BNB flux is muon neutrinos
  - Expect ~2 million $\nu_\mu$ CC interactions every year
- Early measurement that can demonstrate detector performance
- High statistics and low model bias
- Multi-dimensional differential in muon kinematics
- High performance selection
  - 92% pure with 46% efficiency
  - No threshold requirements on particle kinematics

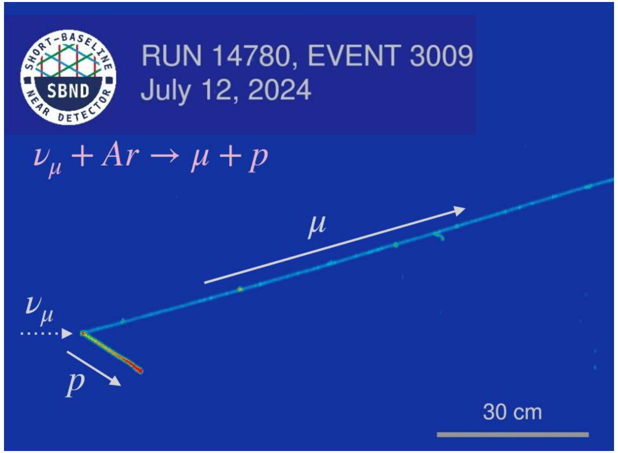


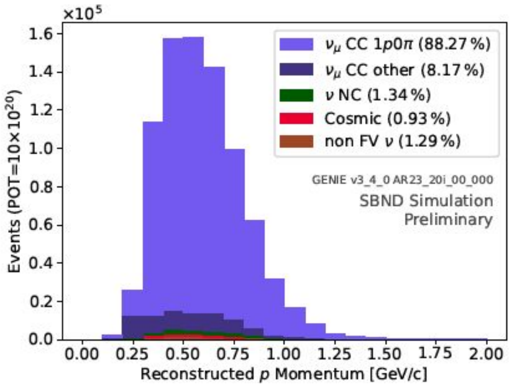



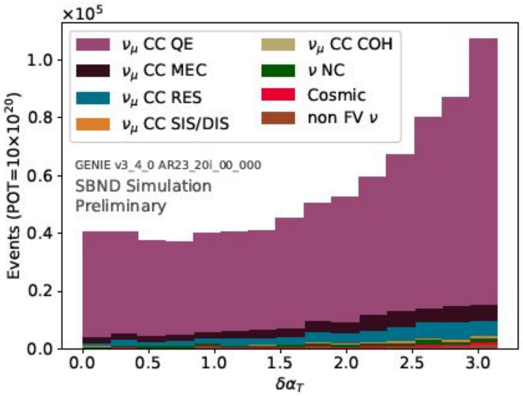



# $\nu_\mu$ CC 1p 0π




- Target the QE interaction mode
  - Muon with p > 220 MeV/c
  - Exactly 1 proton with p > 300 MeV/c no other protons with p > 200 MeV/c
  - No charged pion with momentum > 70 MeV/c
  - No neutral pions
- Enables observations of low $Q^2$ effects

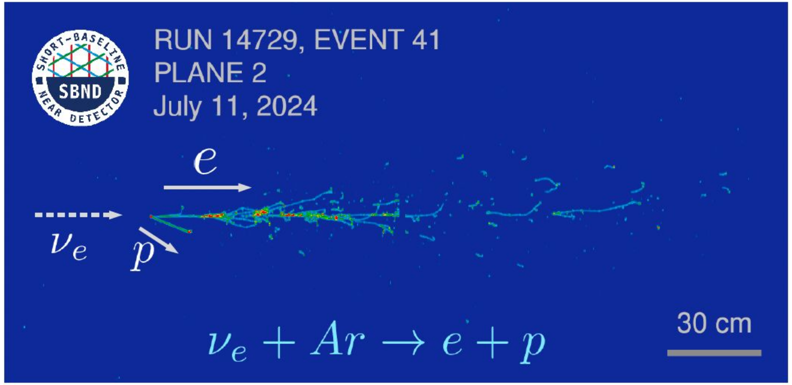


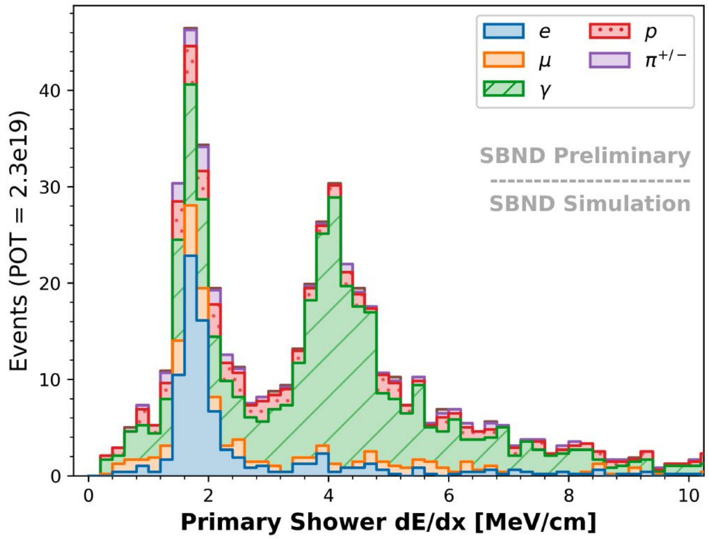




- Measurements in muon and proton kinematics + kinematic imbalance variables in multiple dimensions
- Event selection: 88% purity, 38% efficiency
  - ~900,000 signal events with 3 years of data

# $\nu_e$ CC Inclusive

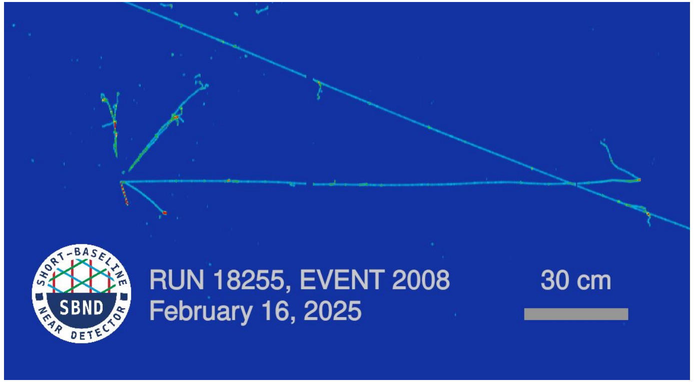
- Only 0.5% of beam flux (~15000 events per year)
- Important for current SBN sterile search as well as future DUNE oscillation analyses
- Selection uses cuts on shower opening angle, distance between vertex and shower start, and cuts on dE/dx to help select electrons
- For electron energy > 500 MeV: purity of 78% at 31% efficiency
    - No threshold requirements on particle kinematics

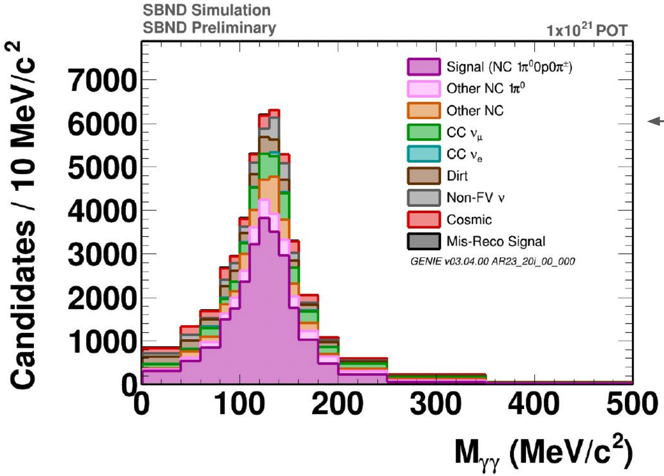


# NC $\pi^0$

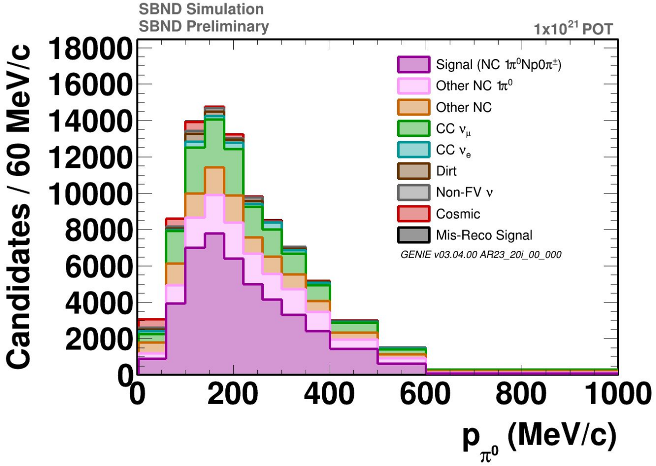
- No $\pi^{\pm}$ with p > 150 MeV/c
- Important background to $\nu_e$ CC
- Measurement will use kinematics of the $\pi^0$ (invariant mass, momentum)
- Two parallel selections: with and without final state protons
  - Proton p > 400 MeV/c
- 53% purity, 22% efficiency



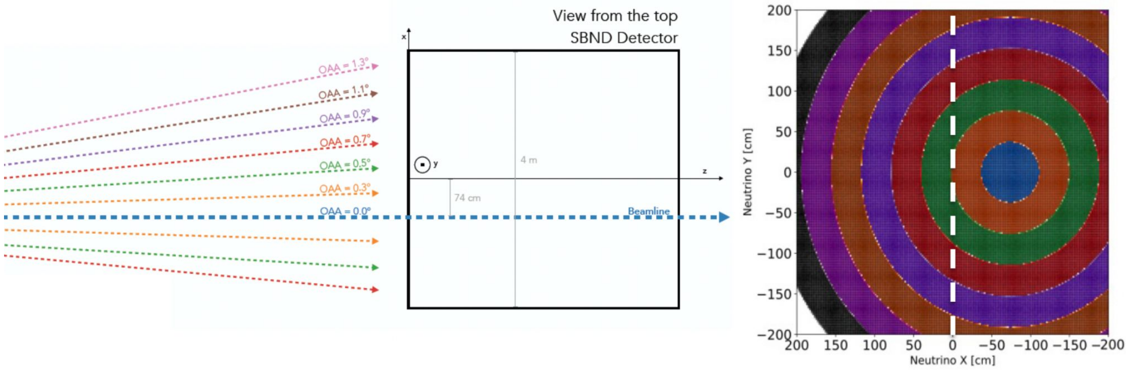

0 proton selection

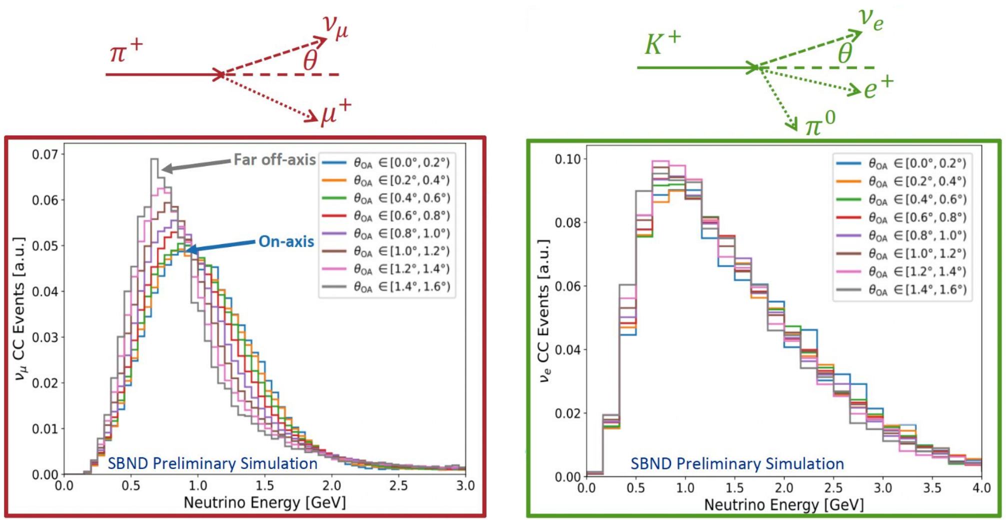
N proton selection



# SBND-PRISM

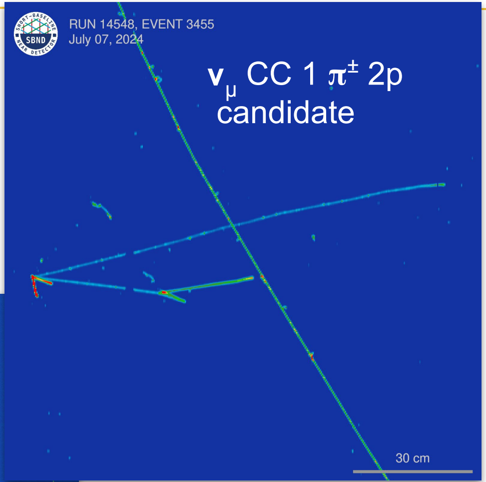
- Very close to beam target (~110 m) and detector center is offset relative to beam center → ~74 cm off-axis
- Achieve a “prism” effect where slices of the detector see different angles
- Similar concept to DUNE PRISM but “for free” (no need to move the detector!)
- Potential for interaction model energy dependence and muon-to-electron neutrino cross section dependence

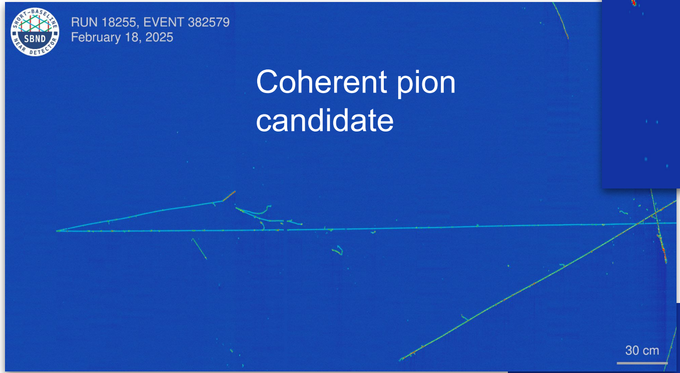


# More Future Measurements

- In progress
  - Coherent pion production
  - $\nu_\mu$ CC 1 $\pi^\pm$
  - η meson resonant production
- Getting started
  - $\nu_\mu$ CC 2p 0 $\pi$
  - $\nu_\mu$ CC 1 $\pi^0$
  - $\nu_\mu$ CC SIS
  - $\bar{\nu}_\mu$ CC QE hyperon
  - $\Lambda^0$, $\Sigma^0$, $\Sigma^-$
  - Cluster production (deuterium, tritons, alphas)
  - Neutrino-electron elastic scattering
  - Muon decays at rest (μDAR)
  - Giant resonances

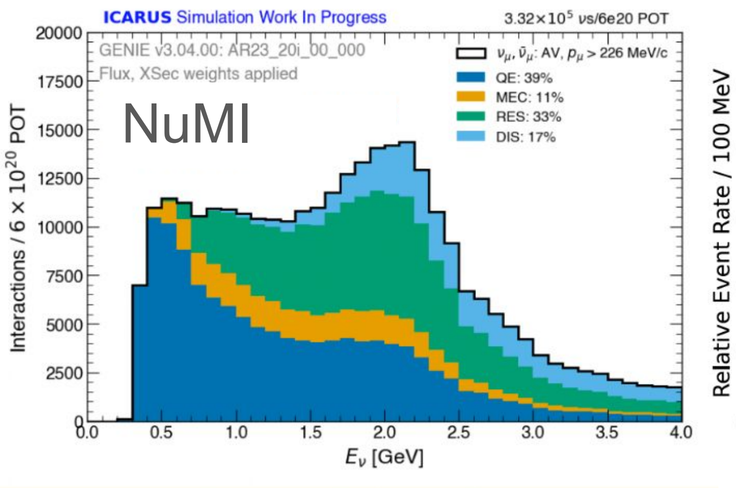


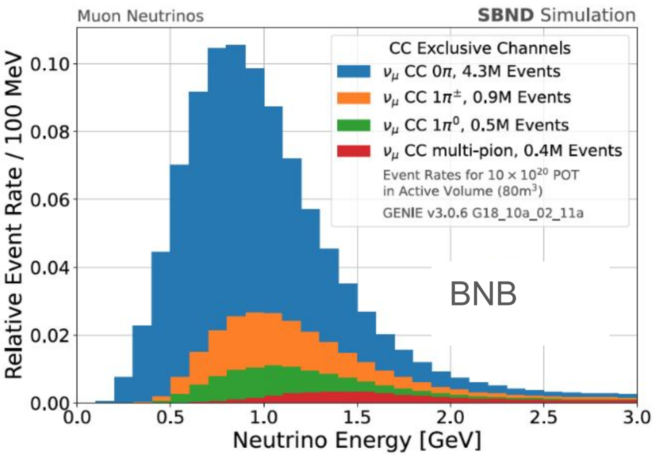



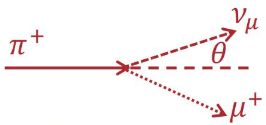

# Multi-Detector Analyses

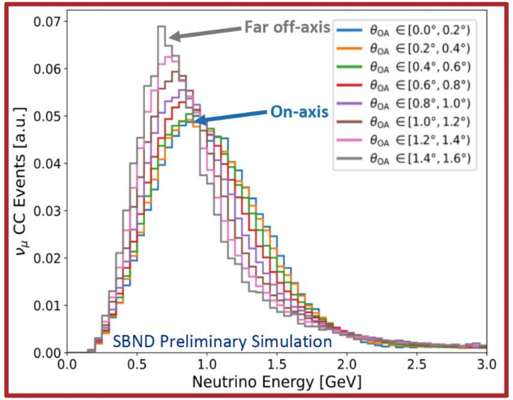
## Ongoing efforts to combine the three SBN experiments

- Reduce systematics, share tools
- Joint, high-stat NuMI+BNB xsec analyses possible by combining detectors
- Study energy dependence across a wider range



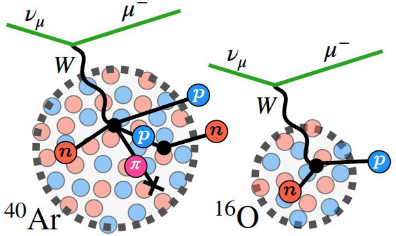



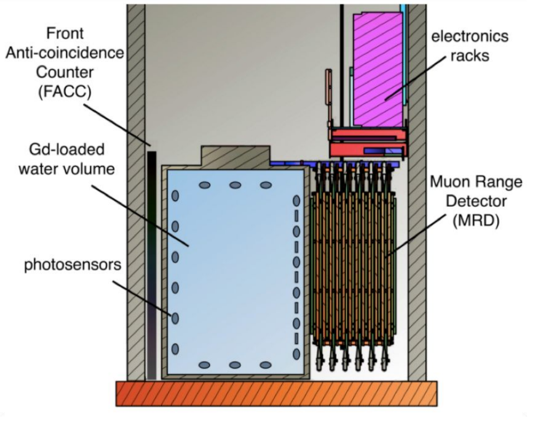
# Multi-Detector Analyses

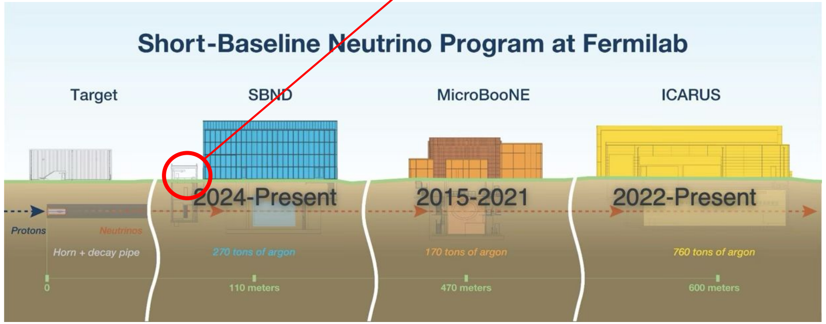
Additionally, work is underway to leverage information from other BNB experiments like ANNIE

- ANNIE is a 26-ton water-based neutrino detector at Fermilab on the BNB
    - will be able to detect neutrons which are largely invisible in LArTPCs
- Unique opportunity for precision, multi-target measurements of cross sections and hadron production using both water and argon
    - Same neutrino flux → precision test of A scaling
        - Nuclear effects scale with size → large impact on neutrino energy reconstruction
    - Correlations in hadron production




## ANNIE



# Summary

- Fermilab's SBN detectors comprise three LArTPC experiments, all with exciting recent and upcoming precision cross section measurements on Ar.
- MicroBooNE has finished it's physics running and is leveraging it's existing dataset across two neutrino beams to measure cross sections that span from high statistics kinematic studies of muon neutrinos to rare event searches.
- ICARUS is currently running and working to analyze its first few runs of data with a particular focus on cross sections with the NuMI beam. First measurements are expected this summer!
- SBND turned on last year and in the midst of its first physics run. With it's large flux from the BNB, high statistics cross section measurements are already underway.

***More Exciting Results Coming Soon!***

# Thank you!

SHORT-BASELINE NEAR DETECTOR
SBND

μBooNE

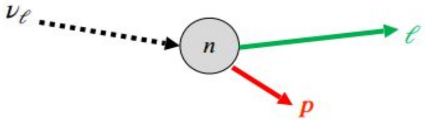
IMAGING
COSMIC
AND
RARE
UNDERGROUND
SIGNALS


# Backup

# The MicroBooNE Tune

## The four parameters for the "MicroBooNE Tune"

### CCQE axial mass $M_A$




$$q^2 \equiv (p_\nu - p_\ell)^2 \quad Q^2 \equiv -q^2$$

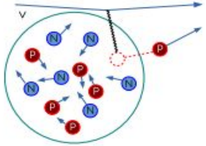
$$F_A(Q^2) = \frac{g_A}{(1 + Q^2/M_A^2)^2}$$

Standard quantity used in the description of v-N QE ($M_A \approx 1$ GeV)

Form factor: nucleons have internal structure!

DUNE uses $^{+0.25}_{-0.15}$ GeV Eur. Phys. J C 80, 978 (2020)

### Strength of CCQE RPA corrections

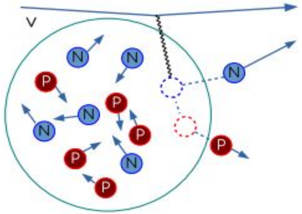


QE cross section modified by in-medium effects

Treated via the **R**andom **P**hase **A**pproximation

$$\frac{d\sigma}{d\mathbf{x}} = (1-k)\frac{d\sigma^{\text{RPA}}}{d\mathbf{x}} + k\frac{d\sigma^{\text{no RPA}}}{d\mathbf{x}}$$

### CC 2p2h normalization



Scale nominal total cross section by a constant factor

### CC 2p2h shape

Smoothly morph the leptonic differential cross section between two competing models

Renormalize each so that the total cross section is unaffected

$$P(T_\ell, \cos\theta_\ell) = (1-k)\frac{1}{\sigma^{\text{Valencia}}}\frac{d\sigma^{\text{Valencia}}}{dT_\ell\, d\cos\theta_\ell} + k\frac{1}{\sigma^{\text{Empirical}}}\frac{d\sigma^{\text{Empirical}}}{dT_\ell\, d\cos\theta_\ell}$$

Phys. Rev. D 105, 072001 (2022)

# The MicroBooNE Tune

## Fit to T2K data

Phys. Rev. D 105, 072001 (2022)

- Series of 4 fits, final uncertainties inflated to approximately cover intermediate variations

| | MaCCQE fitted value | CC2p2h Norm. fitted value | CCQE RPA Strength fitted value | CC2p2h Shape fitted value | T2K $\chi^2/N_{bins}$ |
|---|---|---|---|---|---|
| Nominal (untuned) | 0.961242 GeV | 1 | 100% | 0 | 106.7/58 |
| Fit MaCCQE + CC2p2h Norm. | 1.14±0.07 GeV | 1.61±0.19 | 100% (fixed) | 0 (fixed) | 71.8/58 |
| Fit MaCCQE + CC2p2h Norm. + CCQE RPA Strength | 1.18±0.08 GeV | 1.12±0.38 | (64±23)% | 0 (fixed) | 69.7/58 |
| Fit MaCCQE + CC2p2h Norm. + CCQE RPA Strength + CC2p2h Shape | 1.10±0.07 GeV | 1.66±0.19 | (85±20)% | $1^{+0}_{-0.74}$ | 52.5/58 |

# The MicroBooNE Tune

## Fit to T2K data

Phys. Rev. D 105, 072001 (2022)

- Series of 4 fits, final uncertainties inflated to approximately cover intermediate variations
- Adopted **parameter values and uncertainties**:
  - CCQE axial mass: 1.1 ± 0.1 GeV
  - RPA strength: 85 ± 40% of Valencia correction
  - CC 2p2h normalization: 1.66 ± 0.5 times nominal
  - CC 2p2h shape: k = 1 → Empirical (uncertainty is taken to be the full [0,1] range)