# SBND Cross Section Measurements

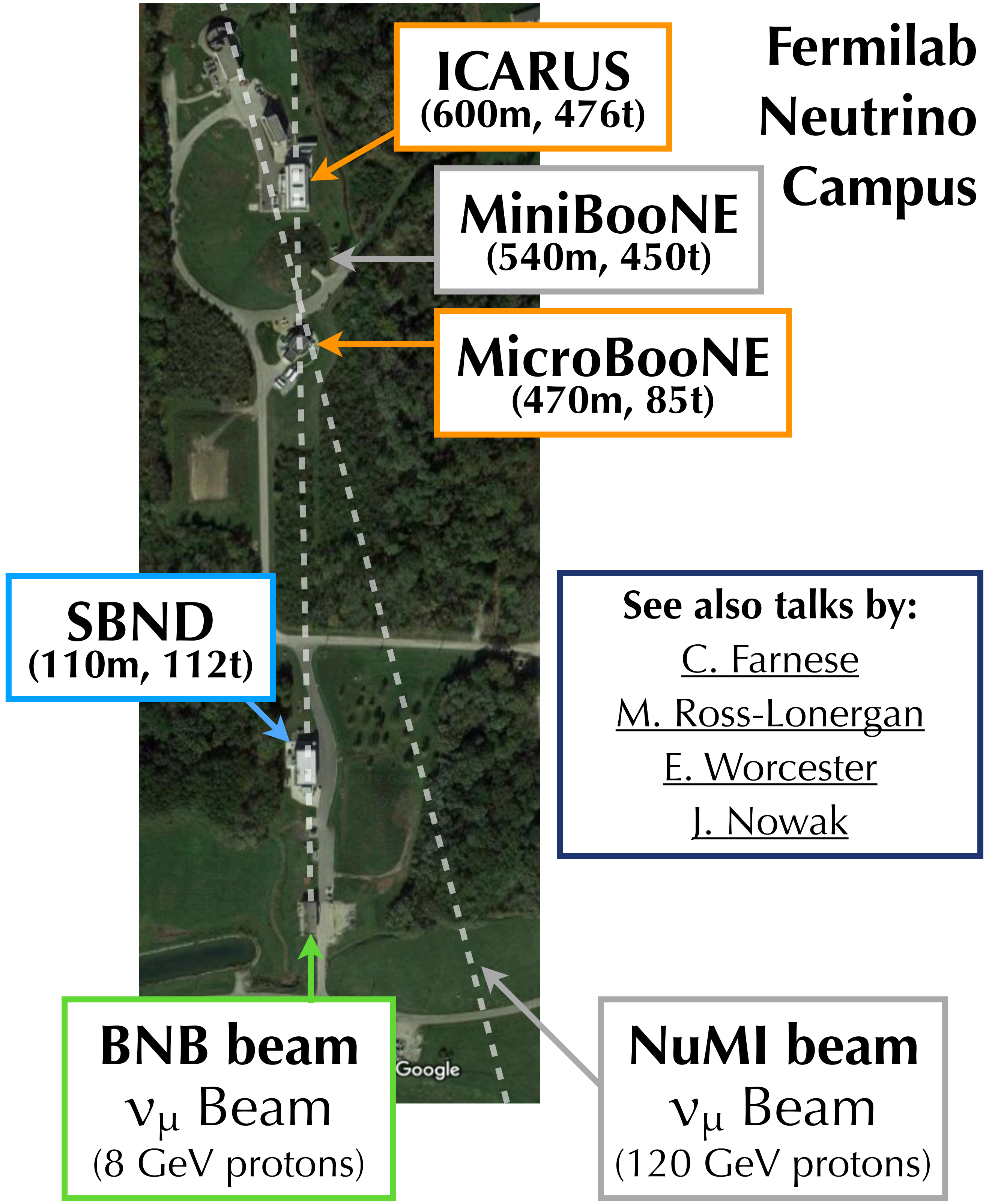
Lauren Yates (Fermilab)
On Behalf of the SBND Collaboration

NOW 2024 — Otranto, Lecce, Italy
September 7, 2024


FERMILAB-SLIDES-24-0221-PPD

# The Short Baseline Neutrino Program at Fermilab

- The Short Baseline Neutrino (SBN) Program at Fermilab consists of three LArTPC detectors, all in Fermilab's Booster Neutrino Beam (BNB) but at different baselines
- BNB is a primarily muon neutrino beam, with a mean $\nu_\mu$ energy of ~0.8 GeV and $\nu_\mu$ purity of ~94%
  - ~6% contamination from $\bar{\nu}_\mu$, ~0.5% $\nu_e+\bar{\nu}_e$
- SBN Program aims to conclusively address the possibility of eV-scale sterile neutrino oscillations
- SBND also has a rich single-detector physics program including neutrino–argon cross section measurements and new and rare physics searches
- Will lay important groundwork for future experiments using LArTPC detectors, such as DUNE




**See also talks by:**
C. Farnese
M. Ross-Lonergan
E. Worcester
J. Nowak

# The Short Baseline Neutrino Program at Fermilab

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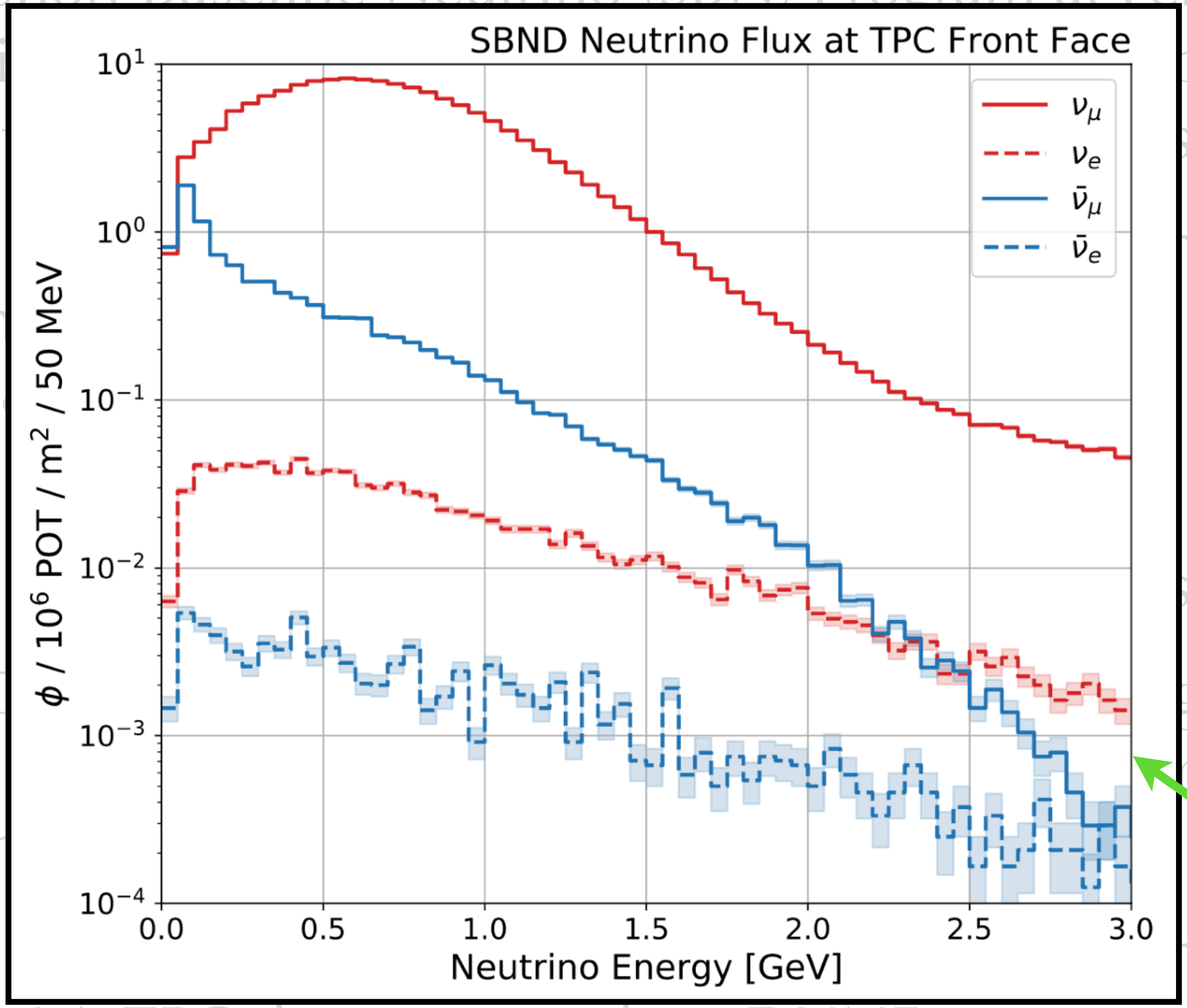
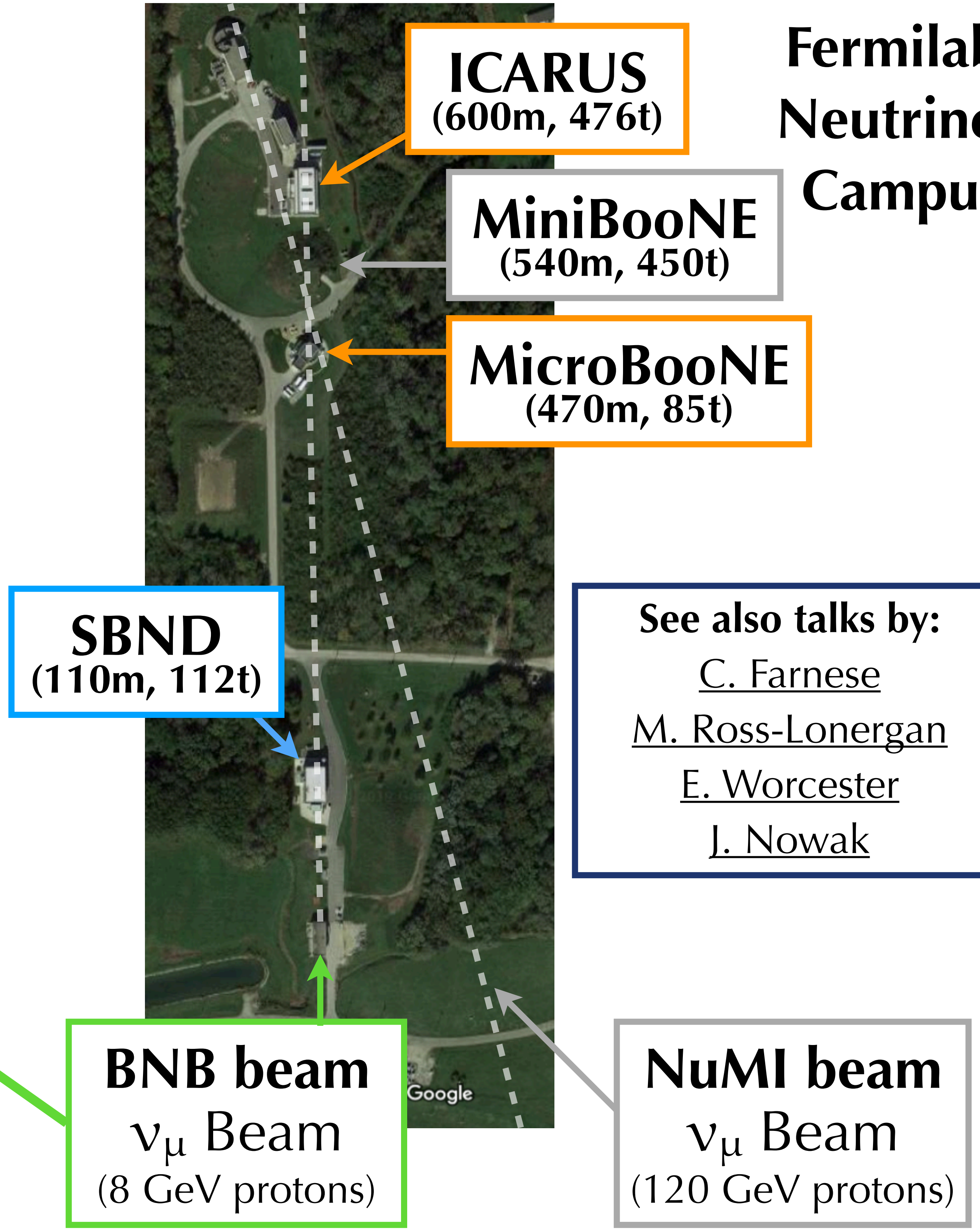
- BNB … …mean $\nu_\mu$ en…
  - ~6…
- SBN … possi… …s
- SBND … …gram inclu… …ents and r…
- Will … …ents using LArTPC detectors, such as DUNE

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# The Short Baseline Neutrino Program at Fermilab

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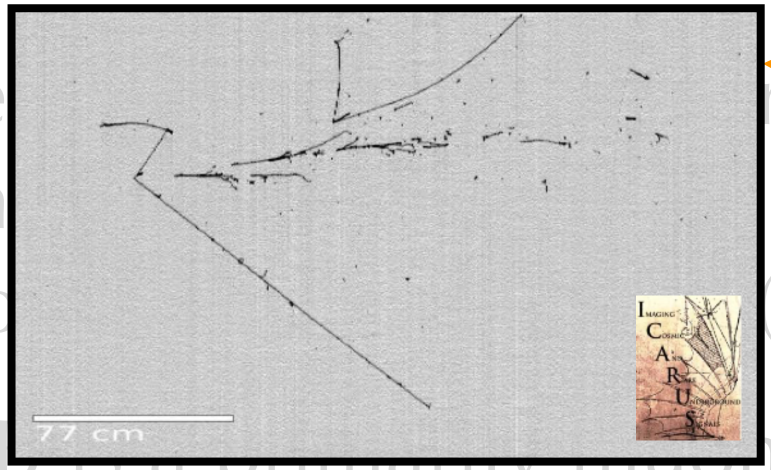
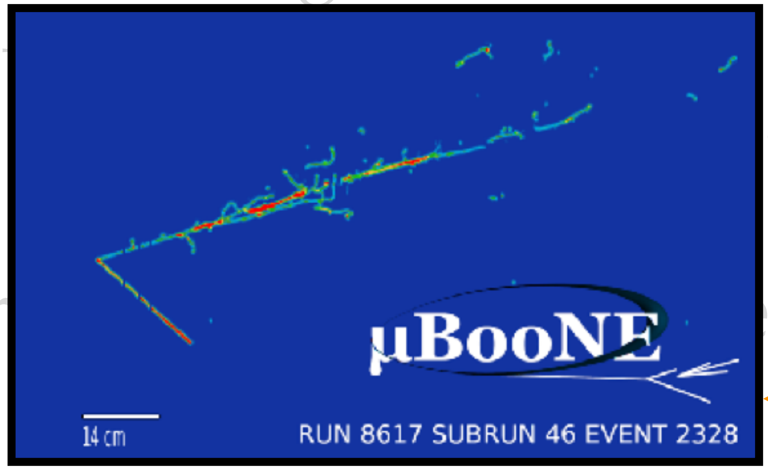
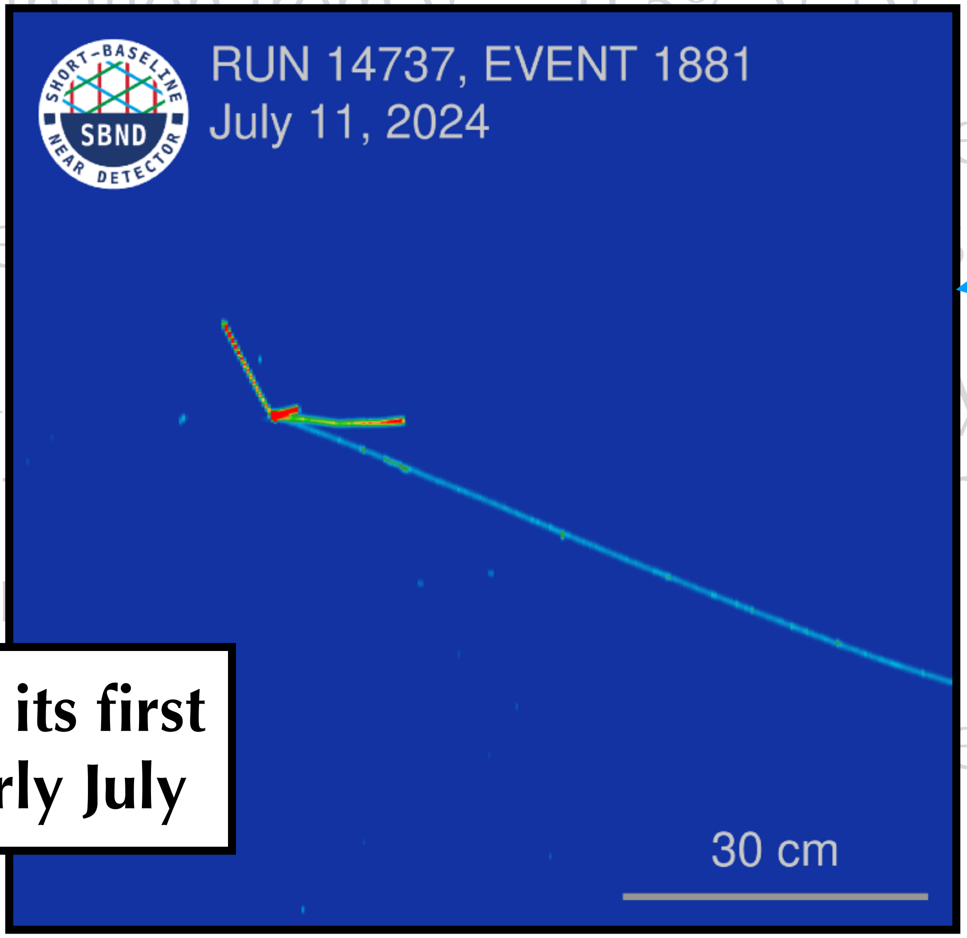
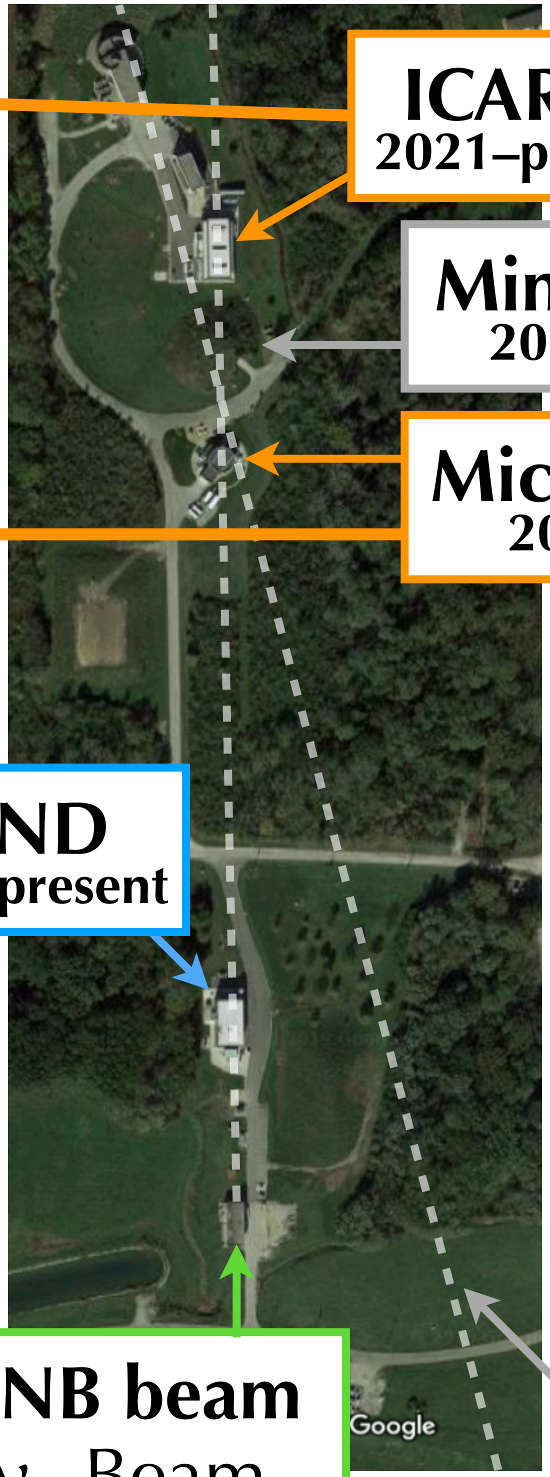
- BN... is a primary muon neutr... an $\nu_\mu$ energy of ~0.8 GeV and $\nu_\mu$ ...
  - ~6% contamination ...
- SBN Program ... ess the possibility of e... cillations
- SBND also ha... ysics program including neu... measurements and new and ...
- W... e experiments using LArTPC...




**SBND collected its first BNB data in early July**




**Fermilab Neutrino Campus**

**BNB beam**
$\nu_\mu$ Beam
(8 GeV protons)

**NuMI beam**
$\nu_\mu$ Beam
(120 GeV protons)

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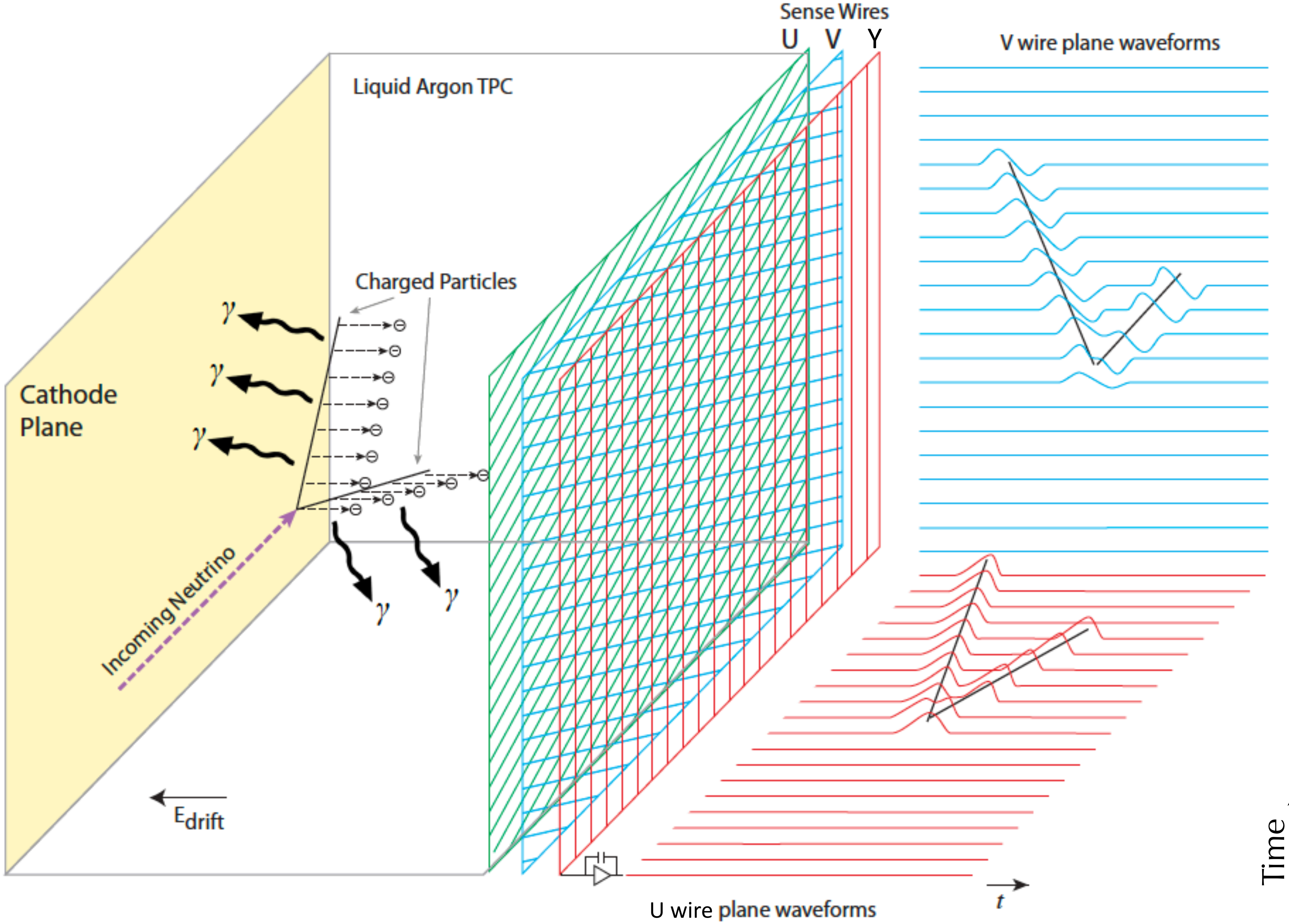
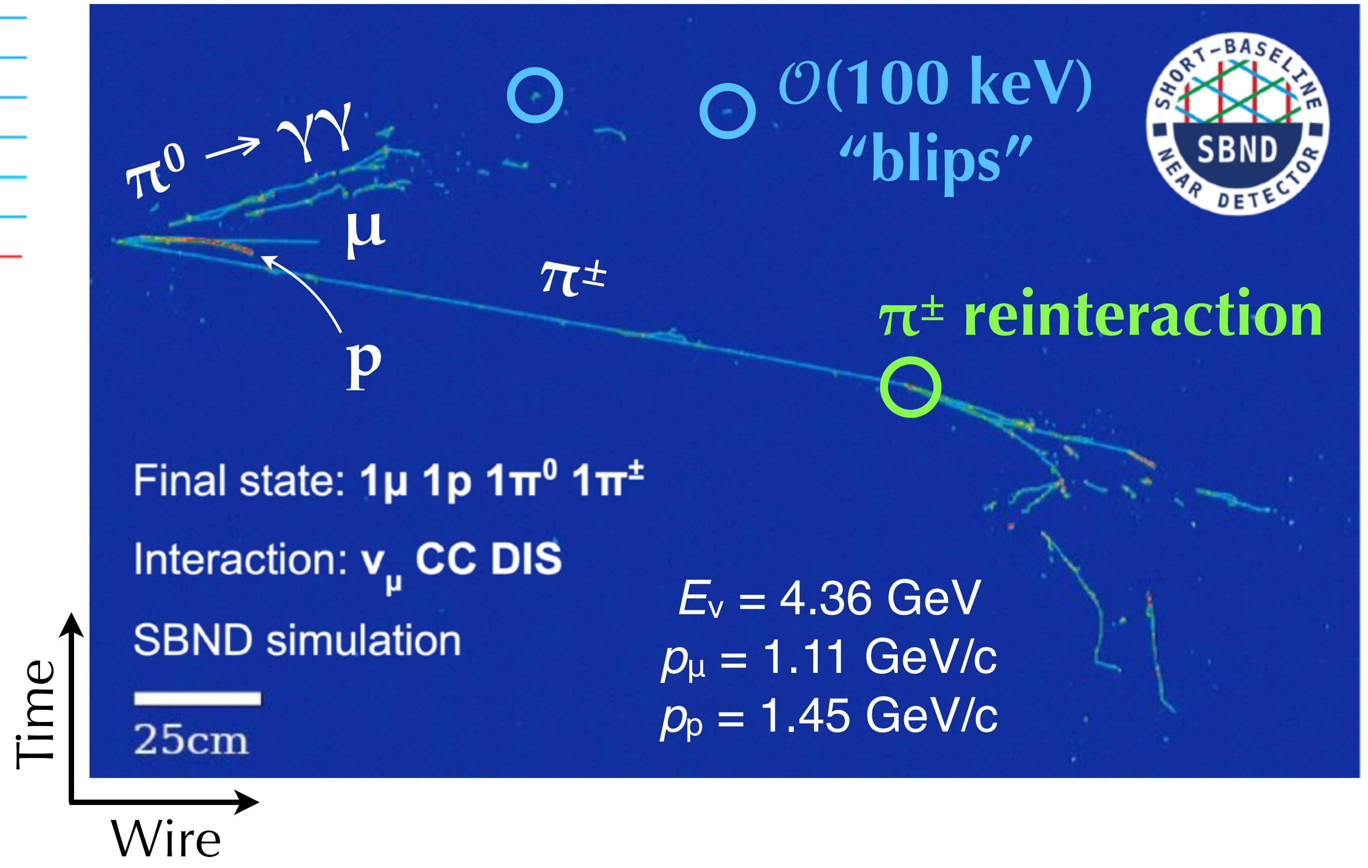
# Detecting Neutrino Interactions with a LArTPC



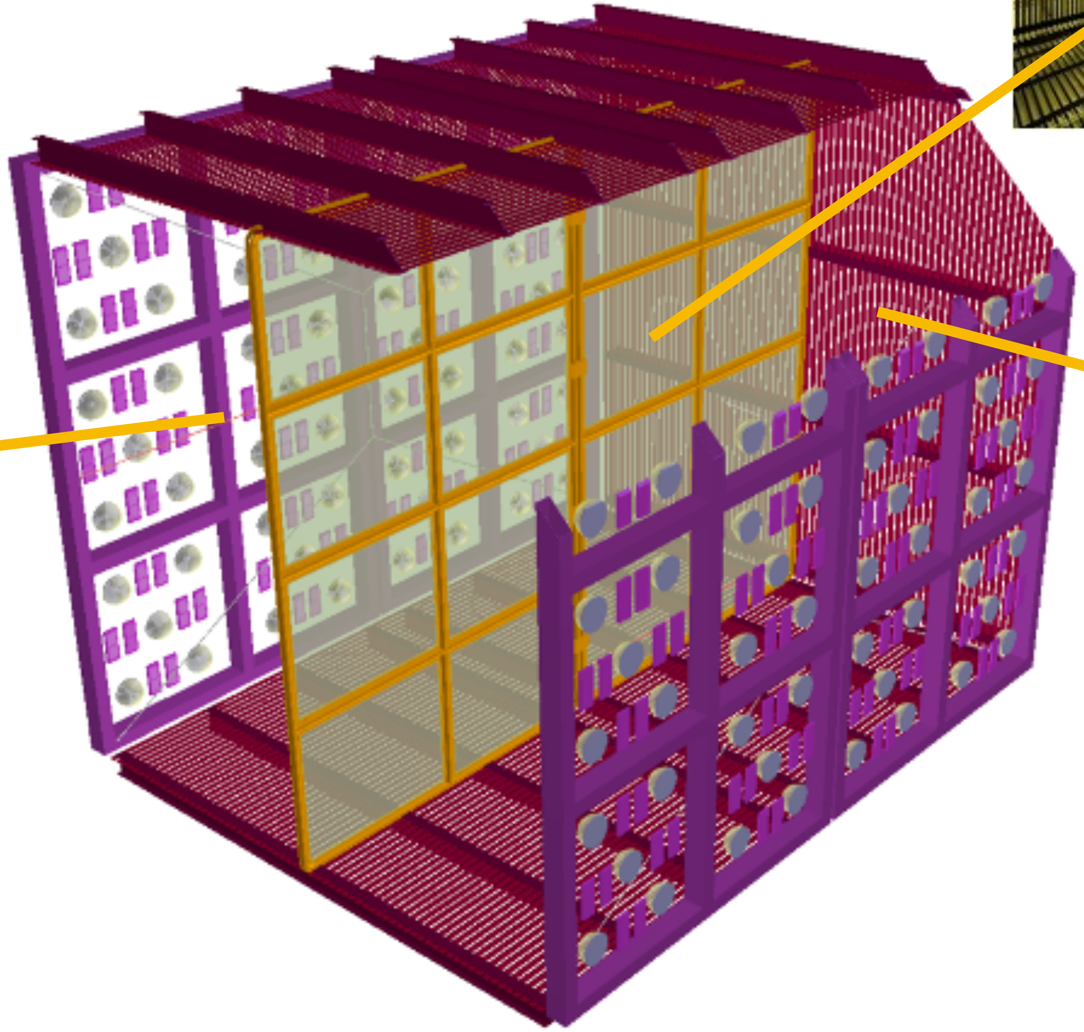

- LArTPC detectors are highly-capable, fully-active tracking calorimeters
- Enables disentangling complex final states with low thresholds and excellent particle identification
- Precise timing information also available via scintillation light

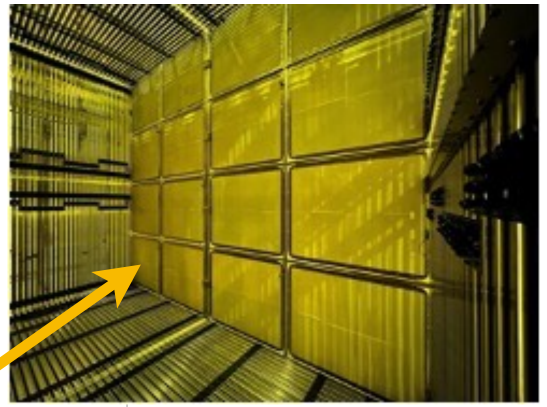


# The SBND Detector

**LArTPC**

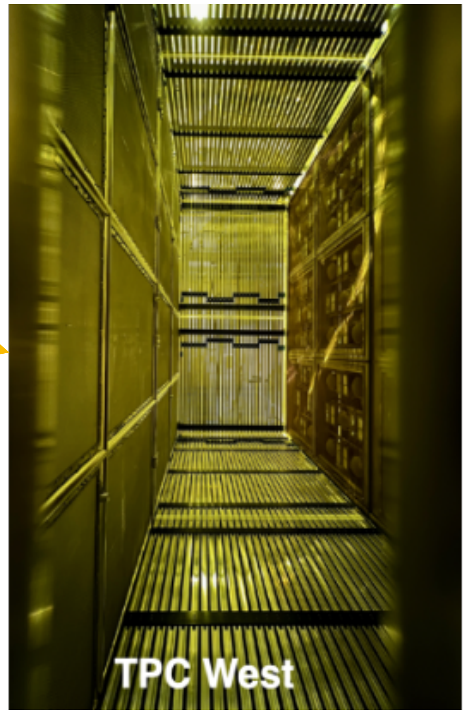
Active mass is 112 t
Active volume is 4×4×5 $m^3$



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

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



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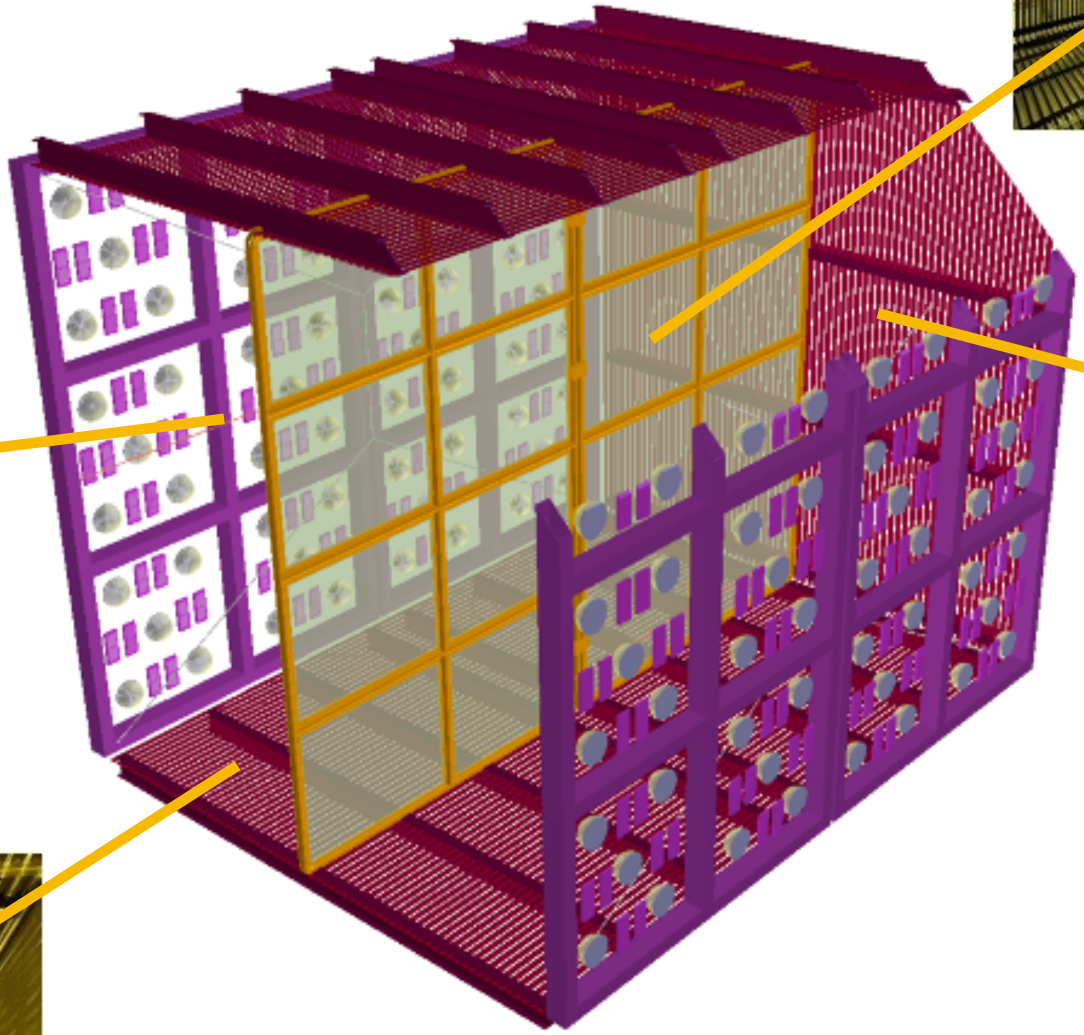

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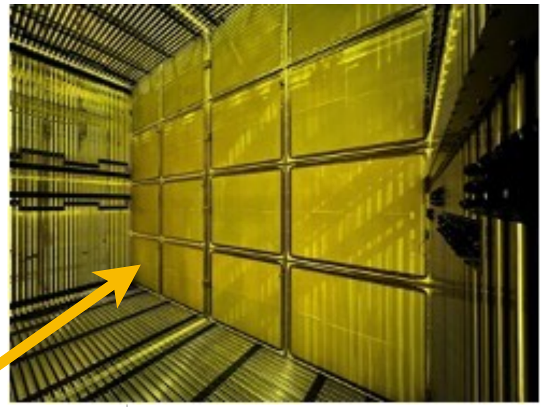

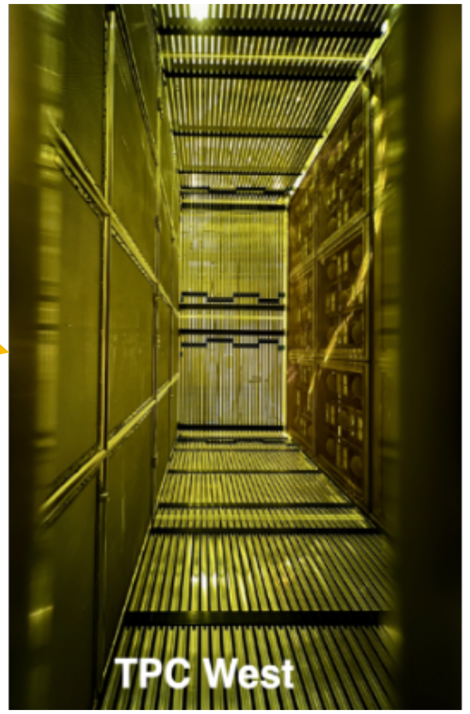


**Field Cage** wraps around the two TPCs to step down the voltage and ensure a uniform electric field of 500 V/cm

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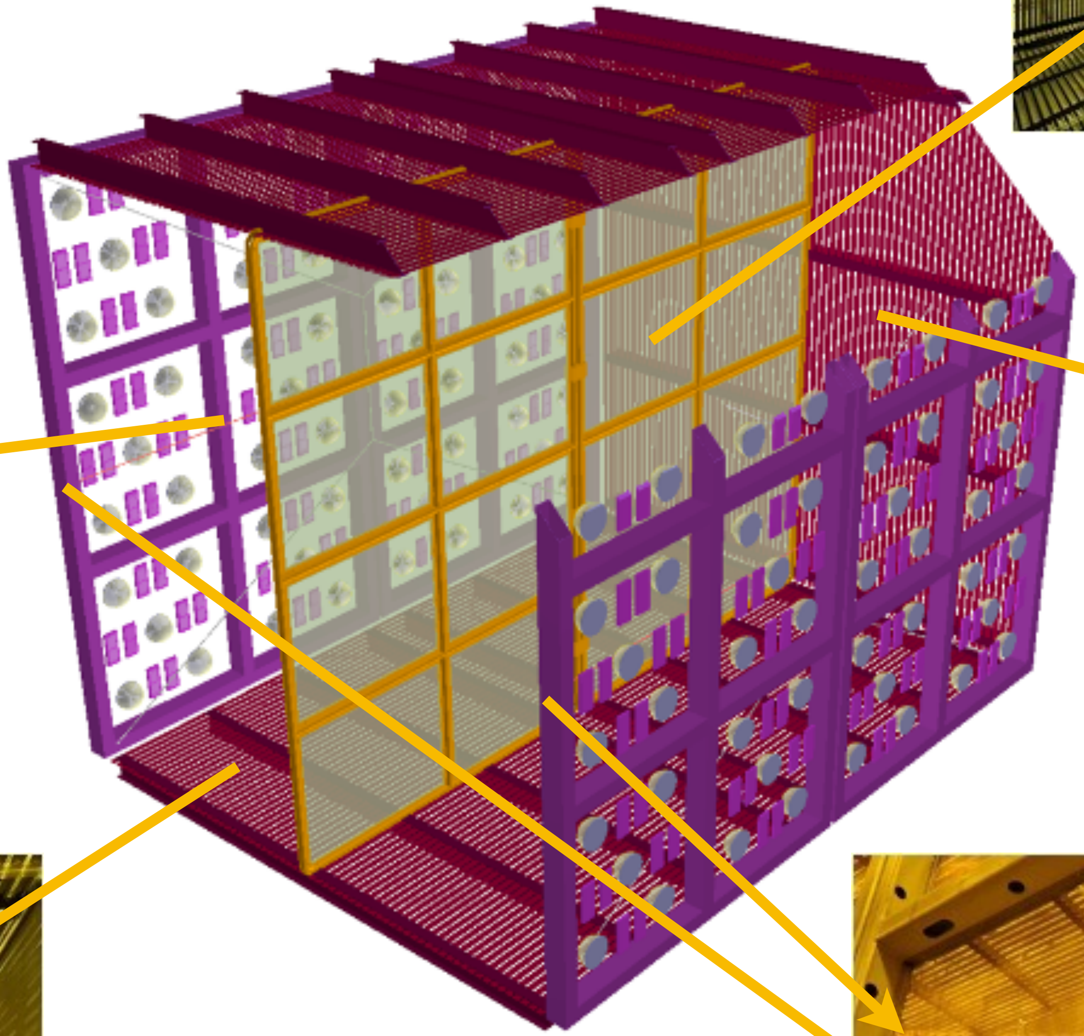


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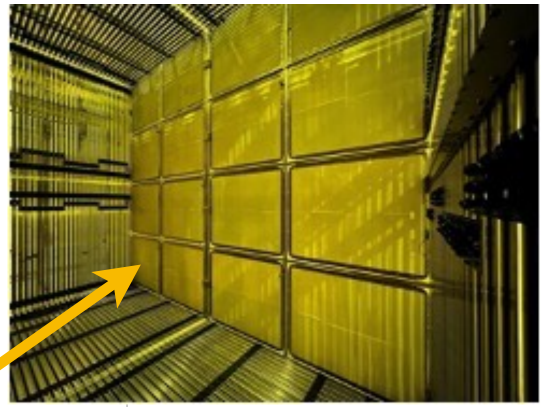

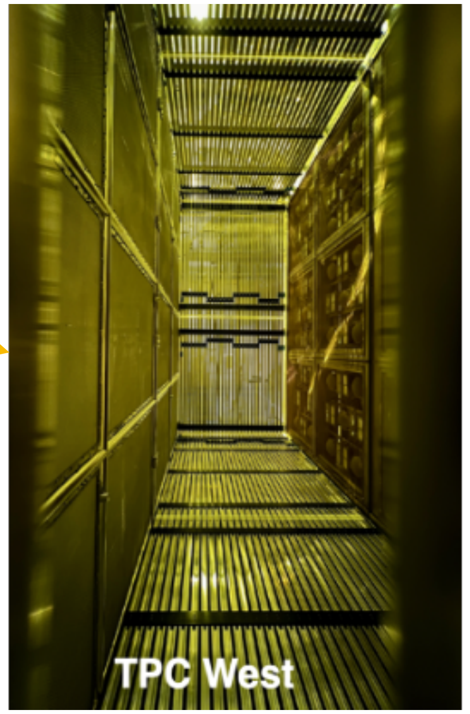


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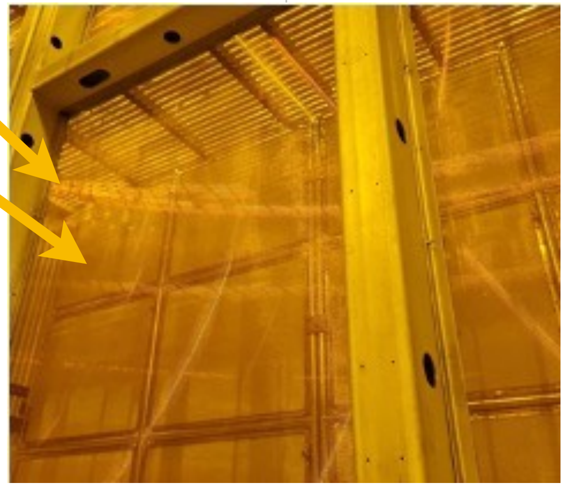


**Anode Plane** on either side, each with three wire planes with 3 mm wire spacing and different orientation per plane

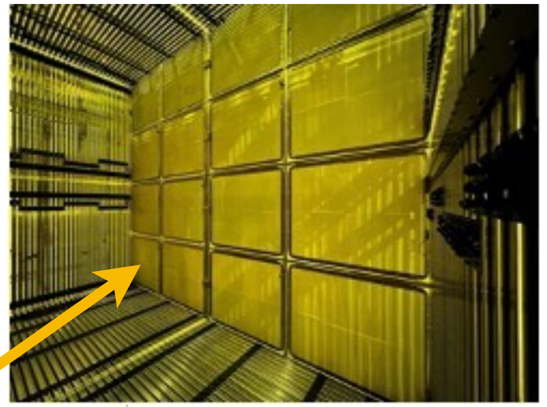
Total of 11,260 wires

# The SBND Detector

**LArTPC**

Active mass is 112 t
Active volume is 4×4×5 $m^3$

**Cold Electronics (in LAr)**
pre-amplify and digitize
TPC wire signals



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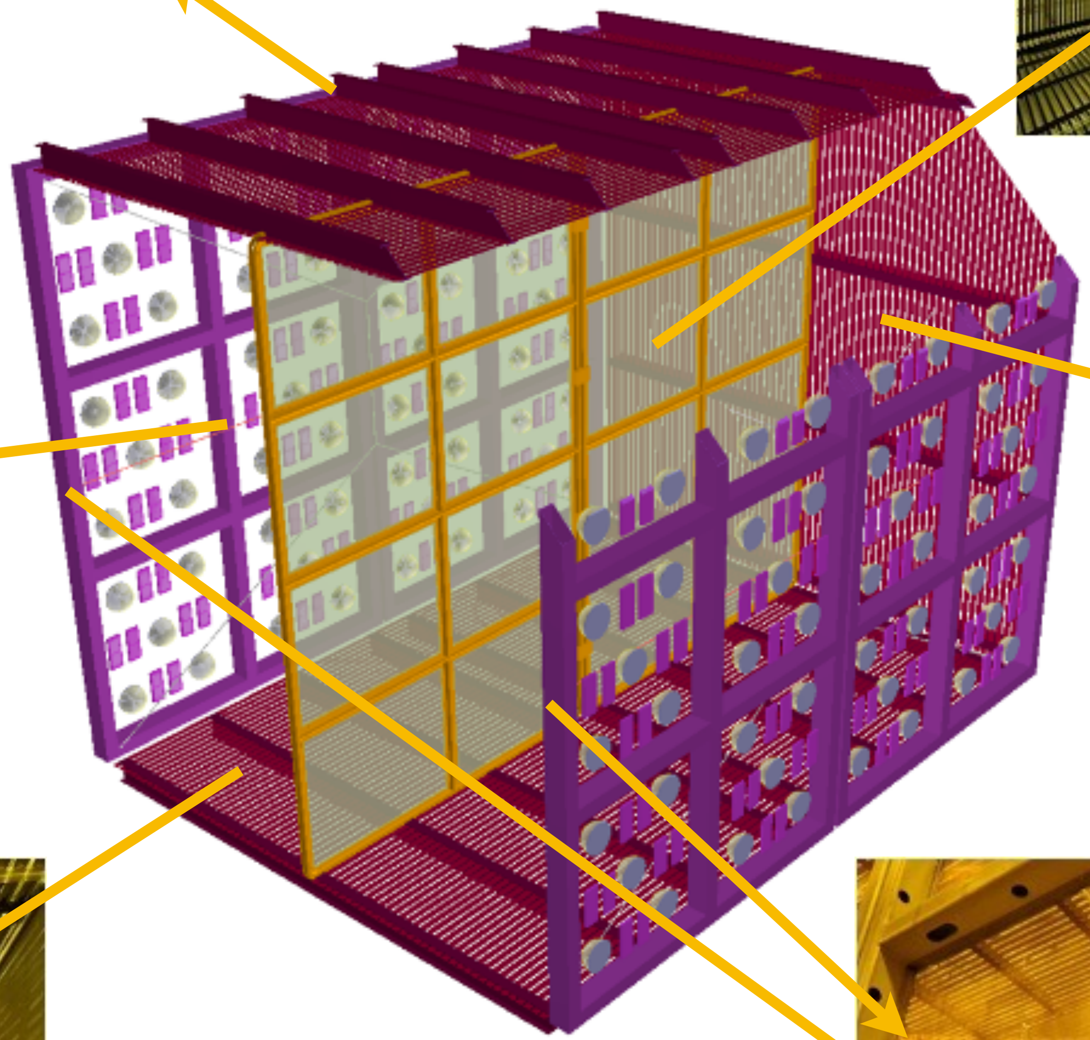

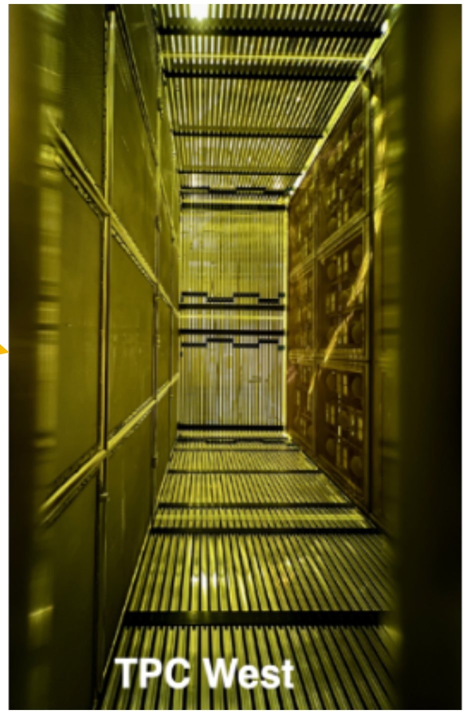


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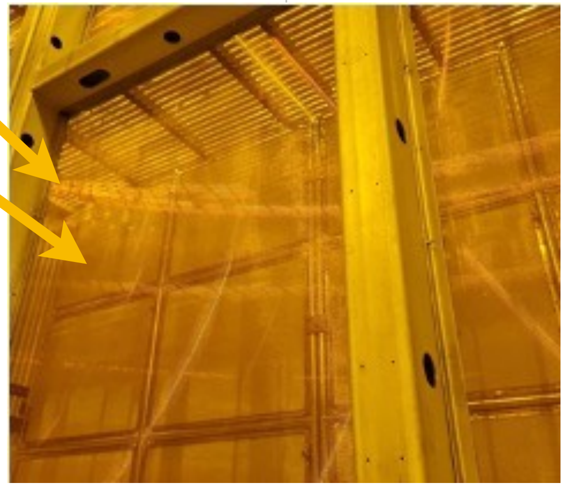

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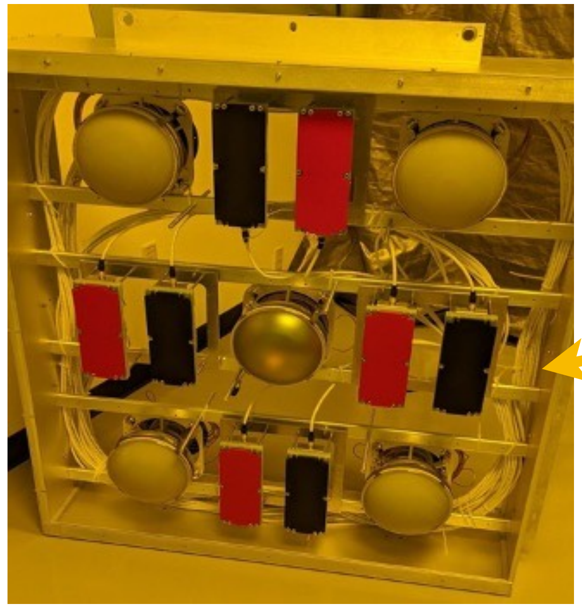
# The SBND Detector

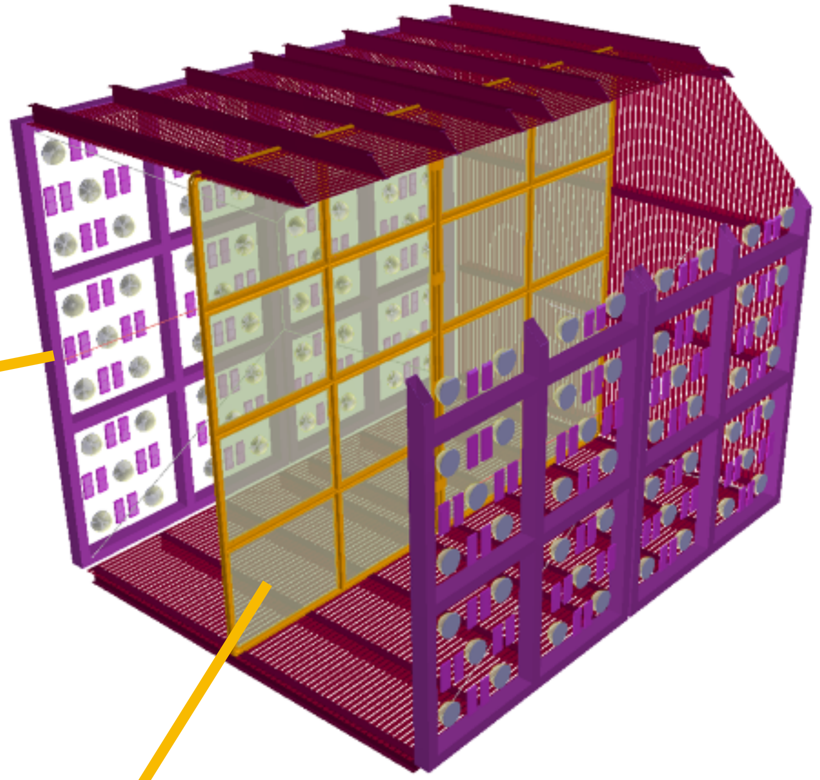
**Photon Detection System**

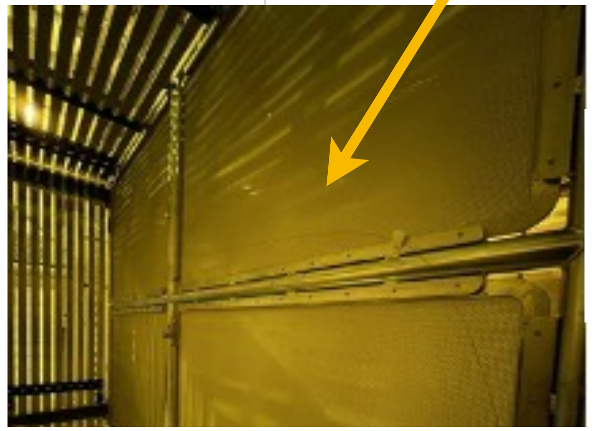


**24 PDS Boxes**
behind the anode wire planes

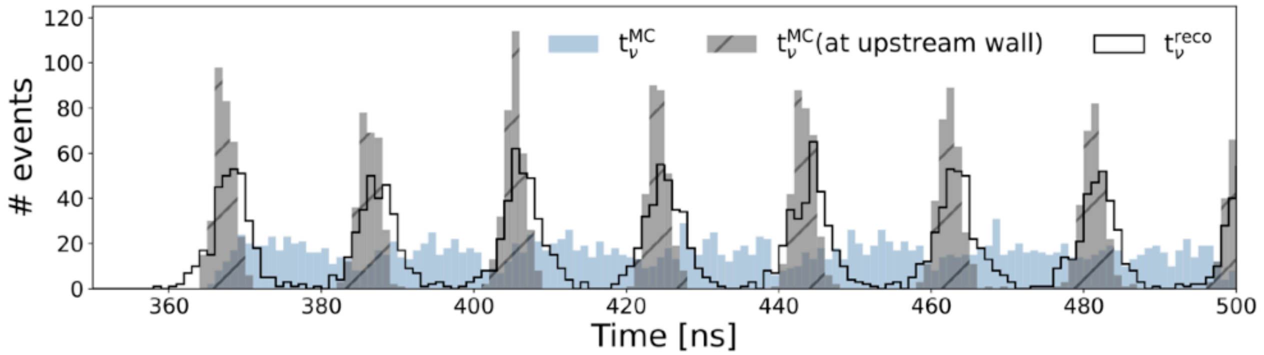
5×24 = **120 8″ PMTs**
80% TPB-coated,
20% uncoated

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





**Cathode Plane** with
TPB-coated reflective foils
mounted behind mesh panels

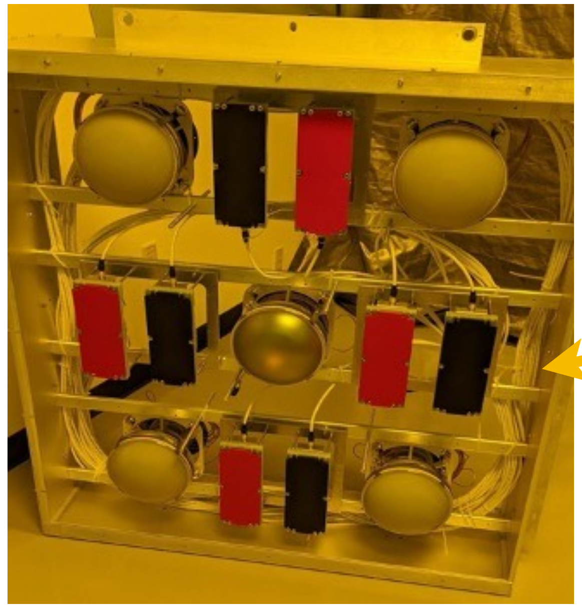


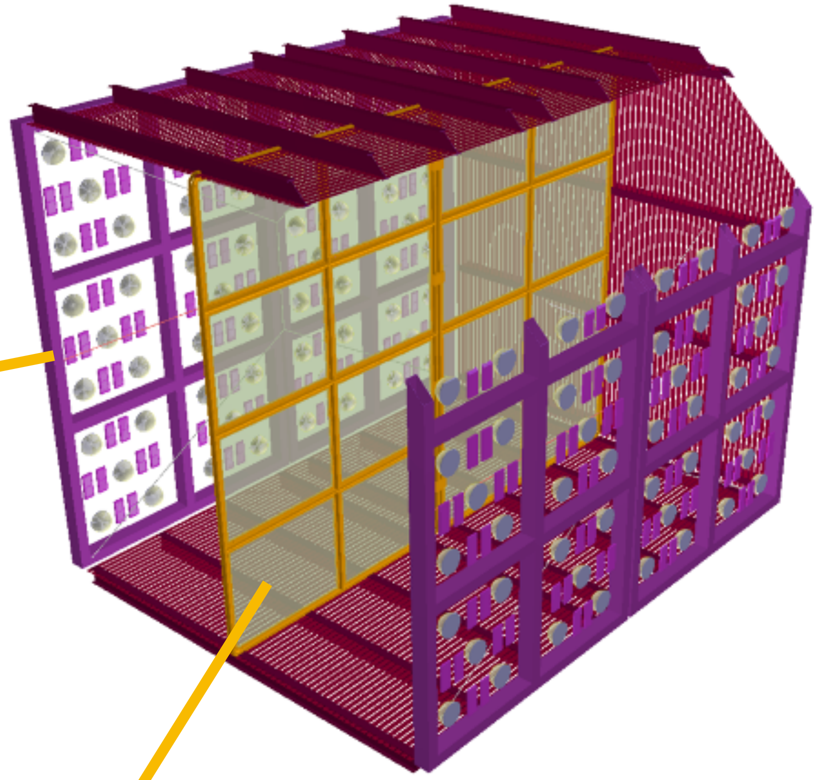

Sophisticated PDS
reconstruction techniques
developed on simulation
demonstrate ns-scale timing

arXiv:2406.07514

# The SBND Detector

## Photon Detection System





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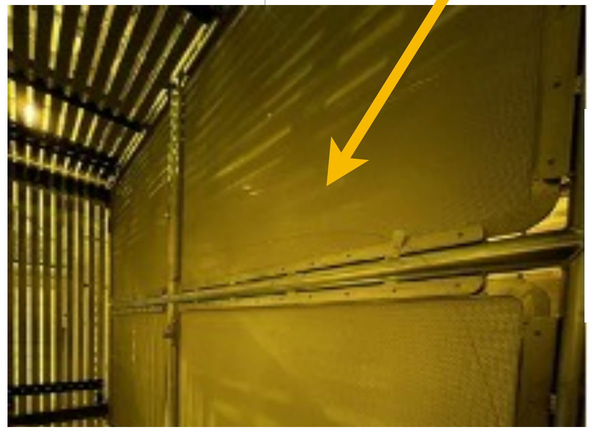

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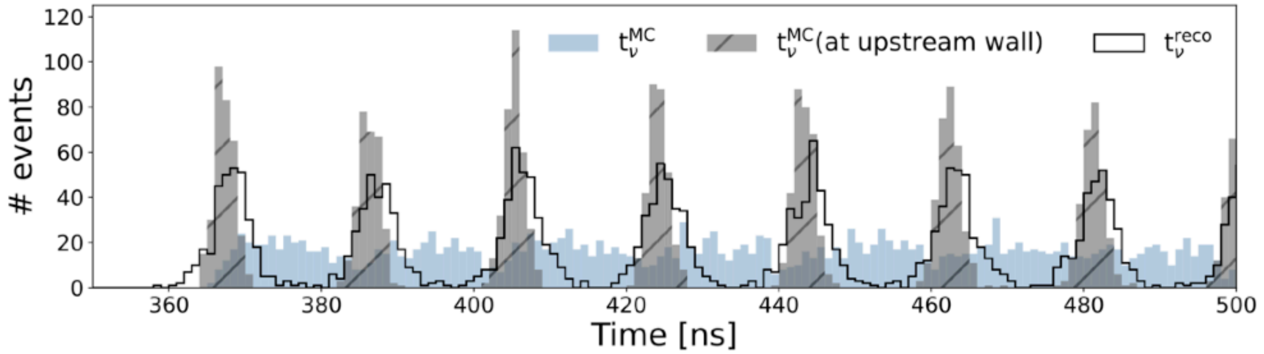


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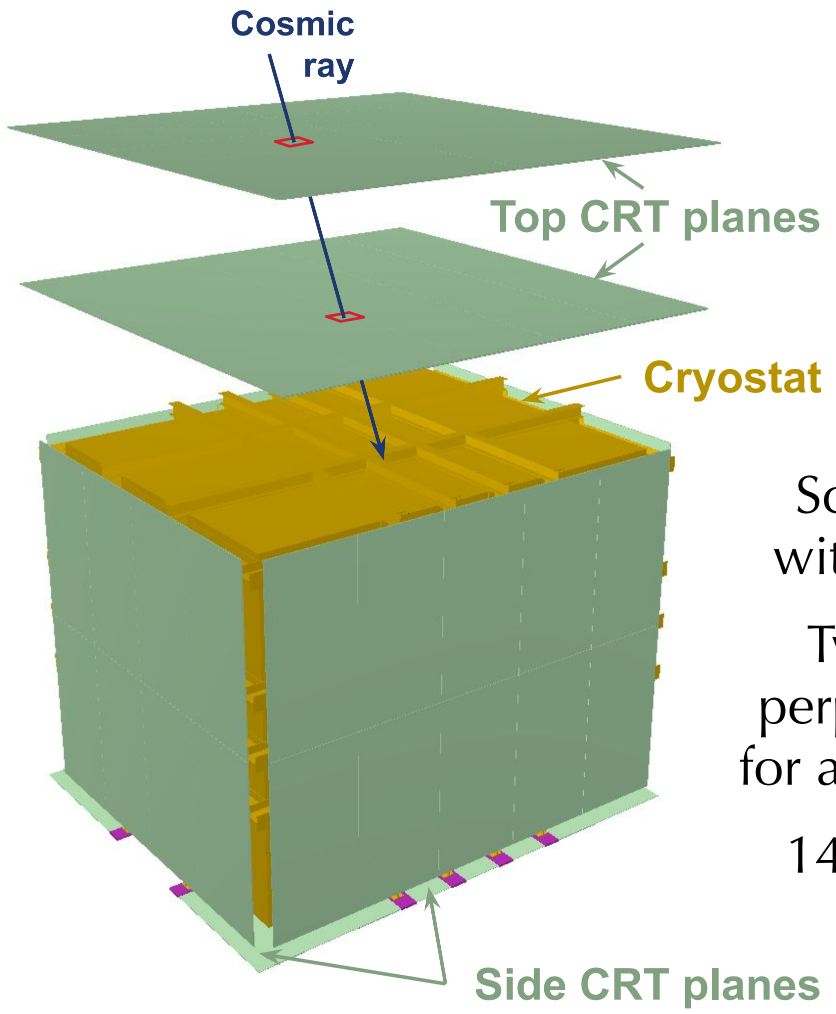



Top CRT planes (160 m² active area)

Scintillator strips
with SiPM readout

Two layers with
perpendicular strips
for accurate positions

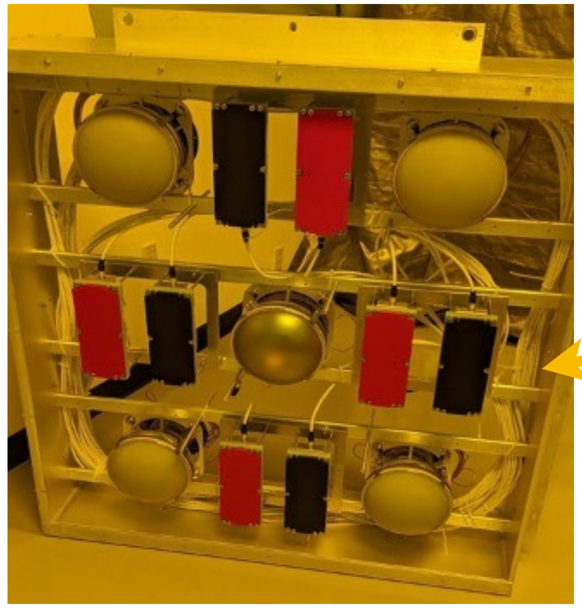
142×32 channels

Side CRT planes (225 m² active area)

**Cosmic Ray Tagger**

# The SBND Detector

## Photon Detection System



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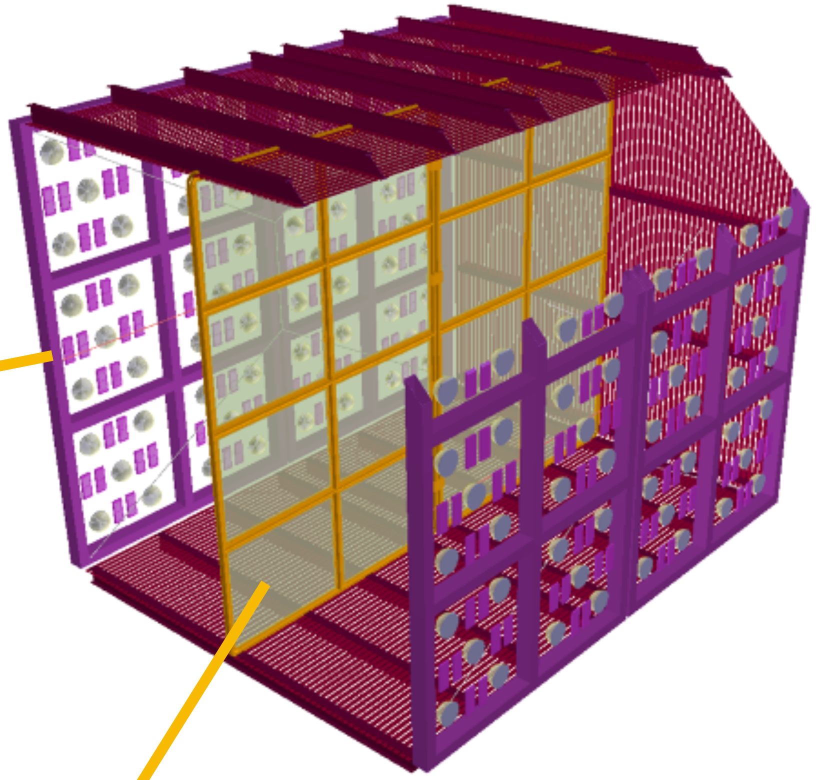

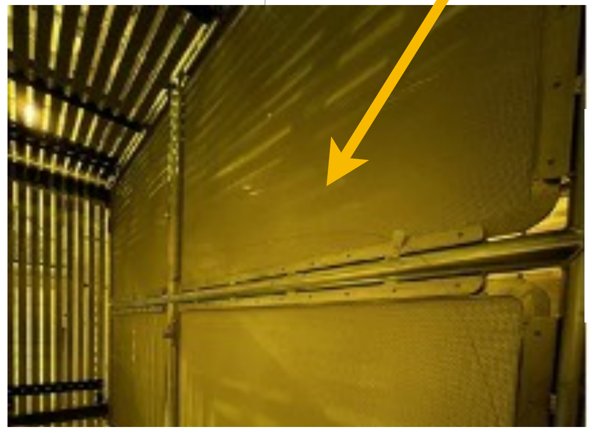

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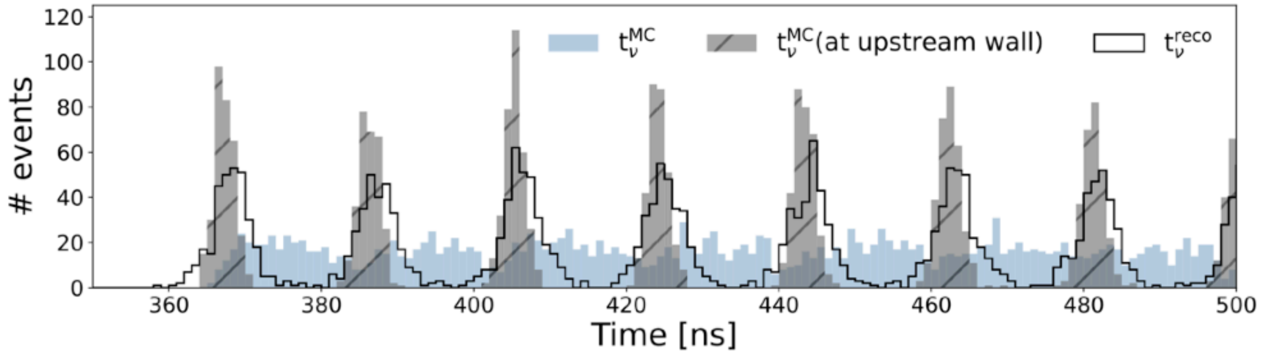
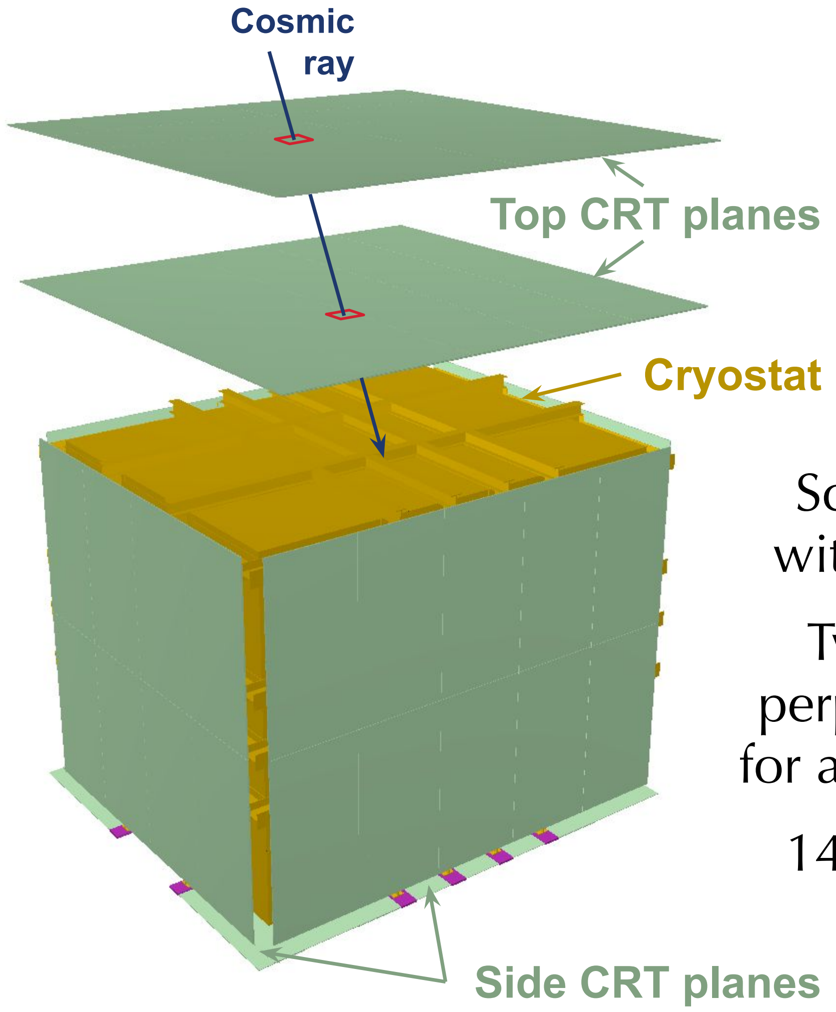



Sophisticated PDS
reconstruction techniques
developed on simulation
demonstrate ns-scale timing

arXiv:2406.07514

Hardware trigger
system capable of
incorporating inputs
from PMTs and CRT,
plus beam signals


## Trigger System




(160 m² active area)

Scintillator strips
with SiPM readout

Two layers with
perpendicular strips
for accurate positions

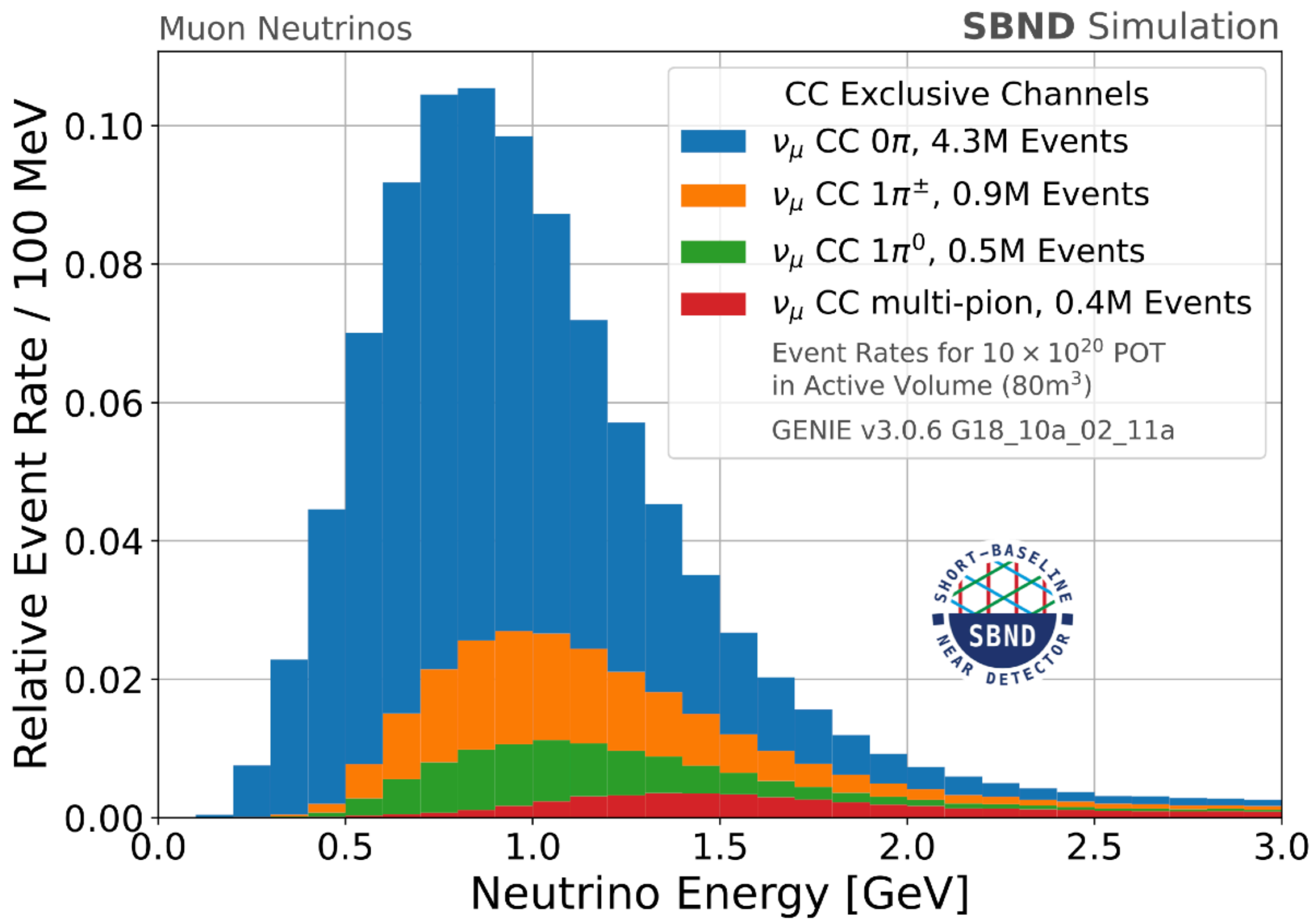
142×32 channels

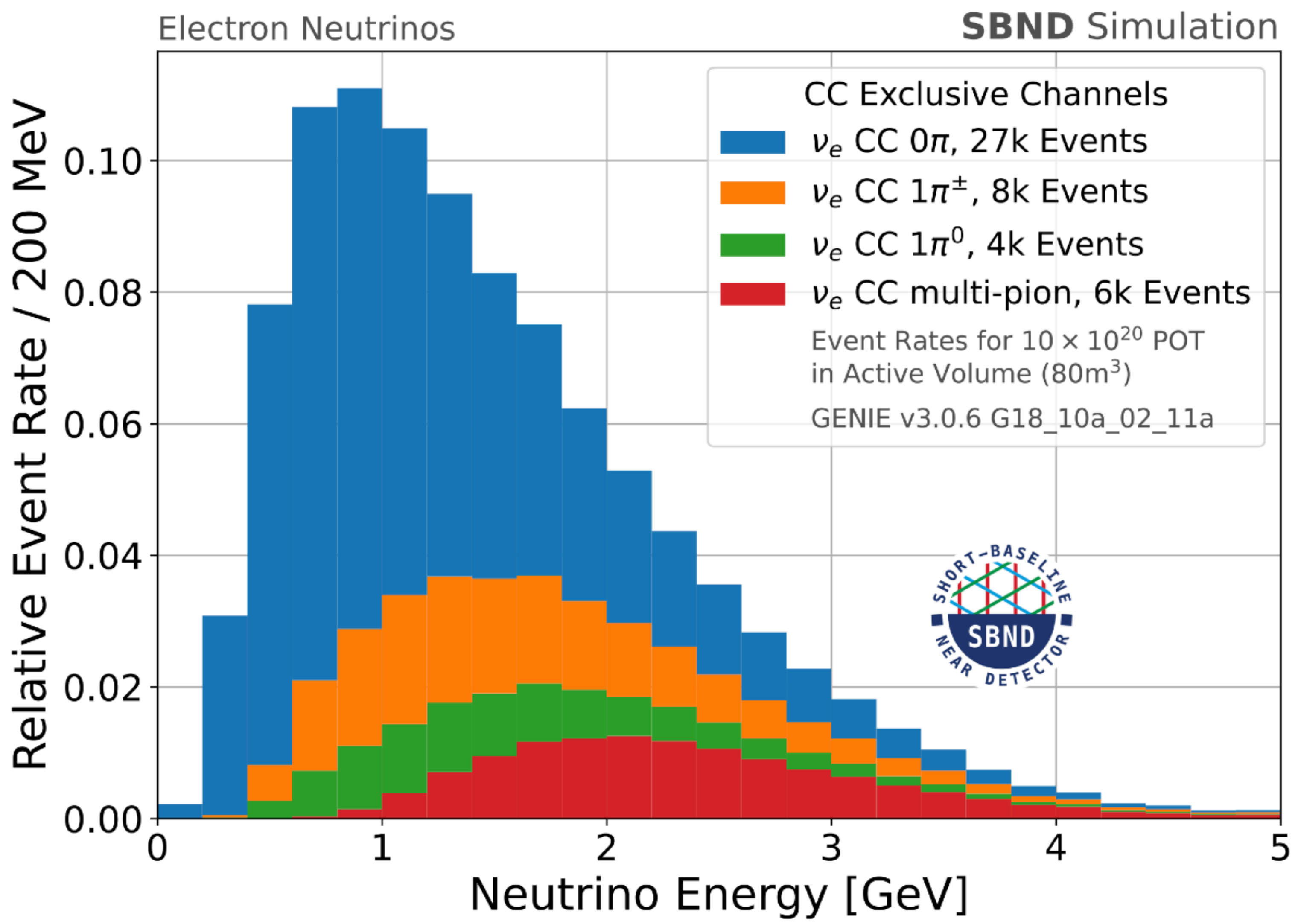
(225 m² active area)

## Cosmic Ray Tagger

# Neutrino Interaction Rates in SBND

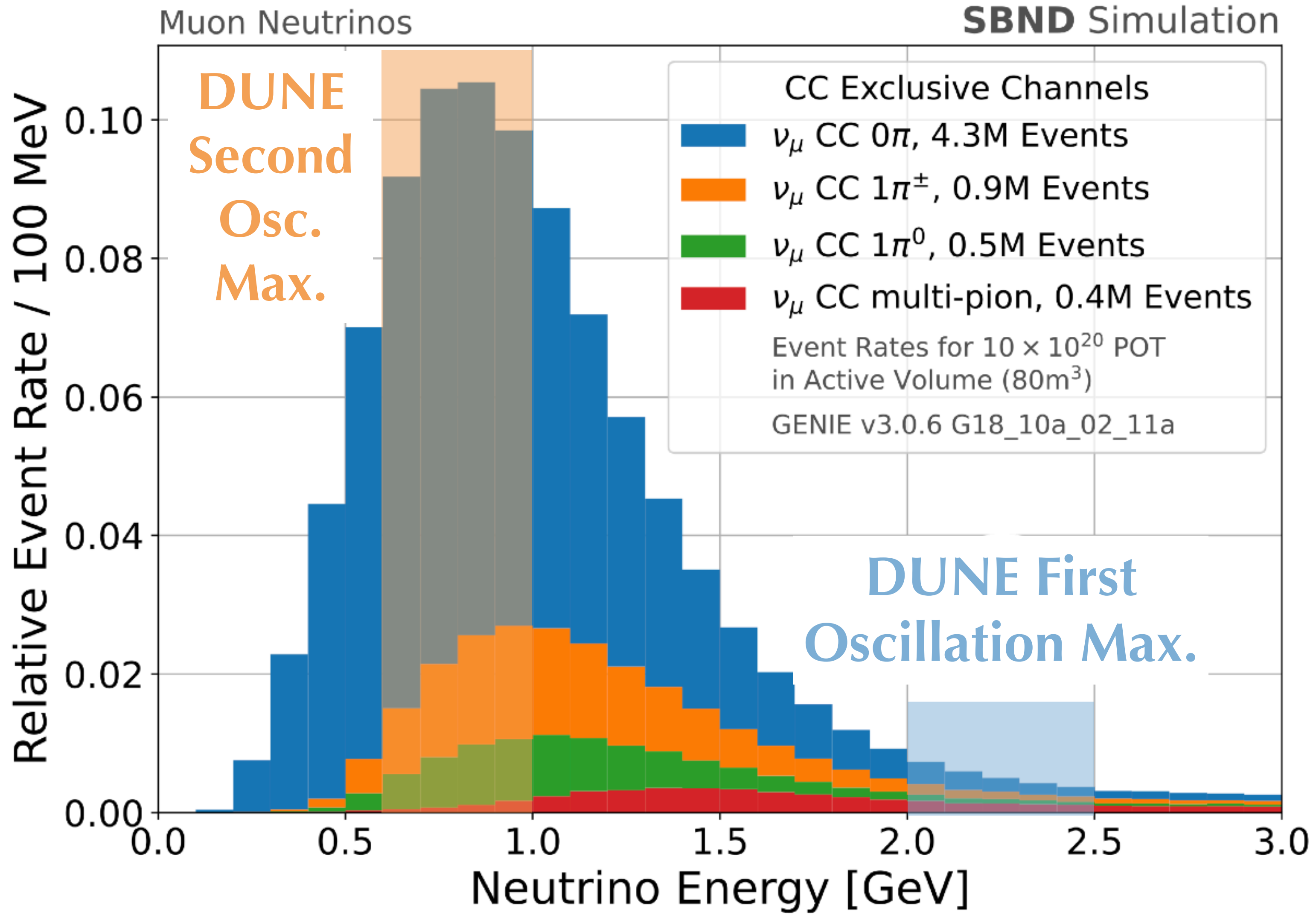
- SBND expects approximately 2 million $\nu_\mu$ CC and 15,000 $\nu_e$ CC interactions per year, and will collect beam neutrino data over the course of a ~3 year run
- Will record an order of magnitude more neutrino–argon interactions than currently available
- Enables a generational advance in the study of neutrino–argon interactions in the GeV energy range

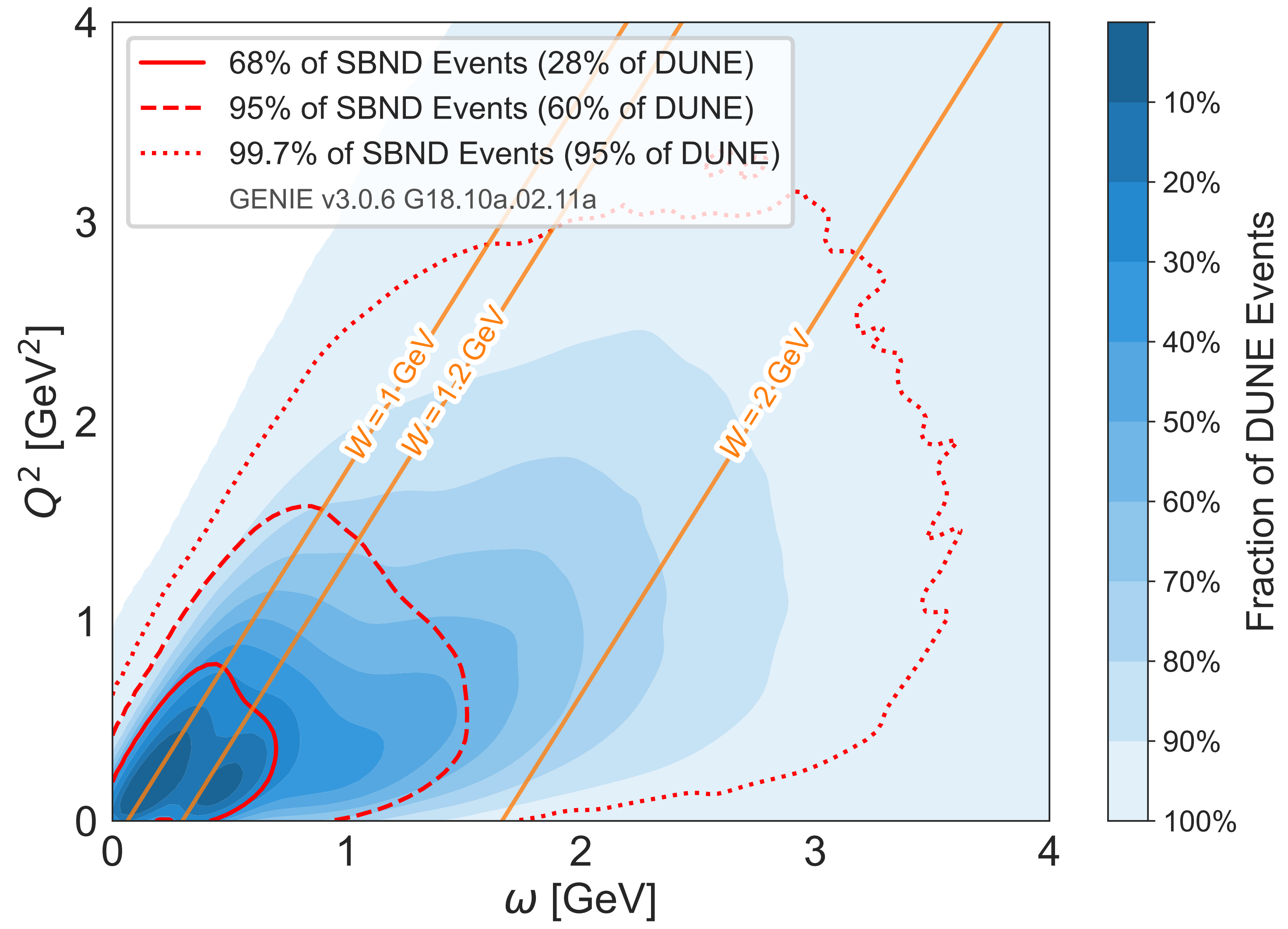


# SBND Interactions vs. the DUNE Phase Space

- SBND interactions will cover significant parts of kinematic phase space relevant for DUNE, including energy range spanning first and second oscillation maxima
- Have the opportunity to map out the argon nuclear response to neutrino probes from the quasielastic region to the resonance region and beyond



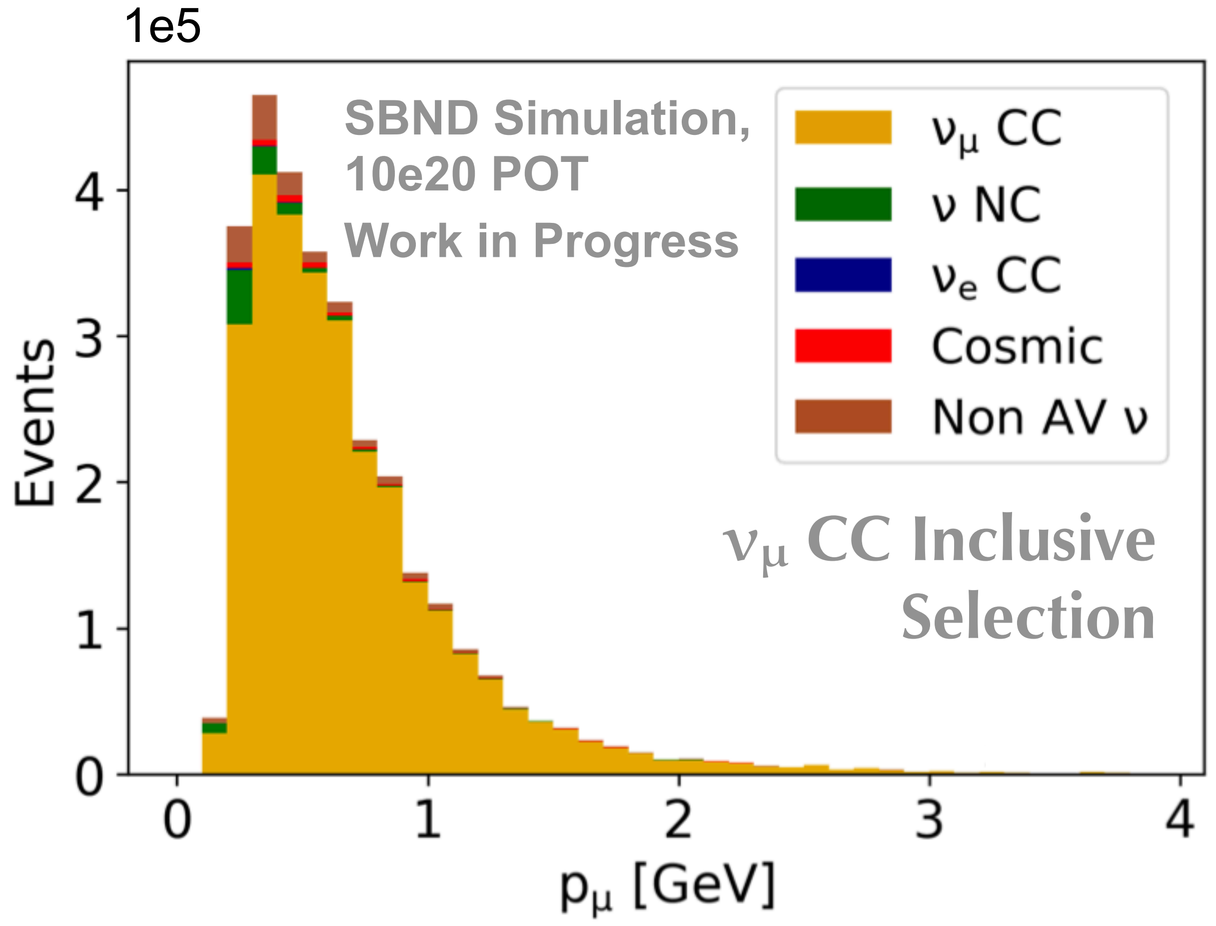



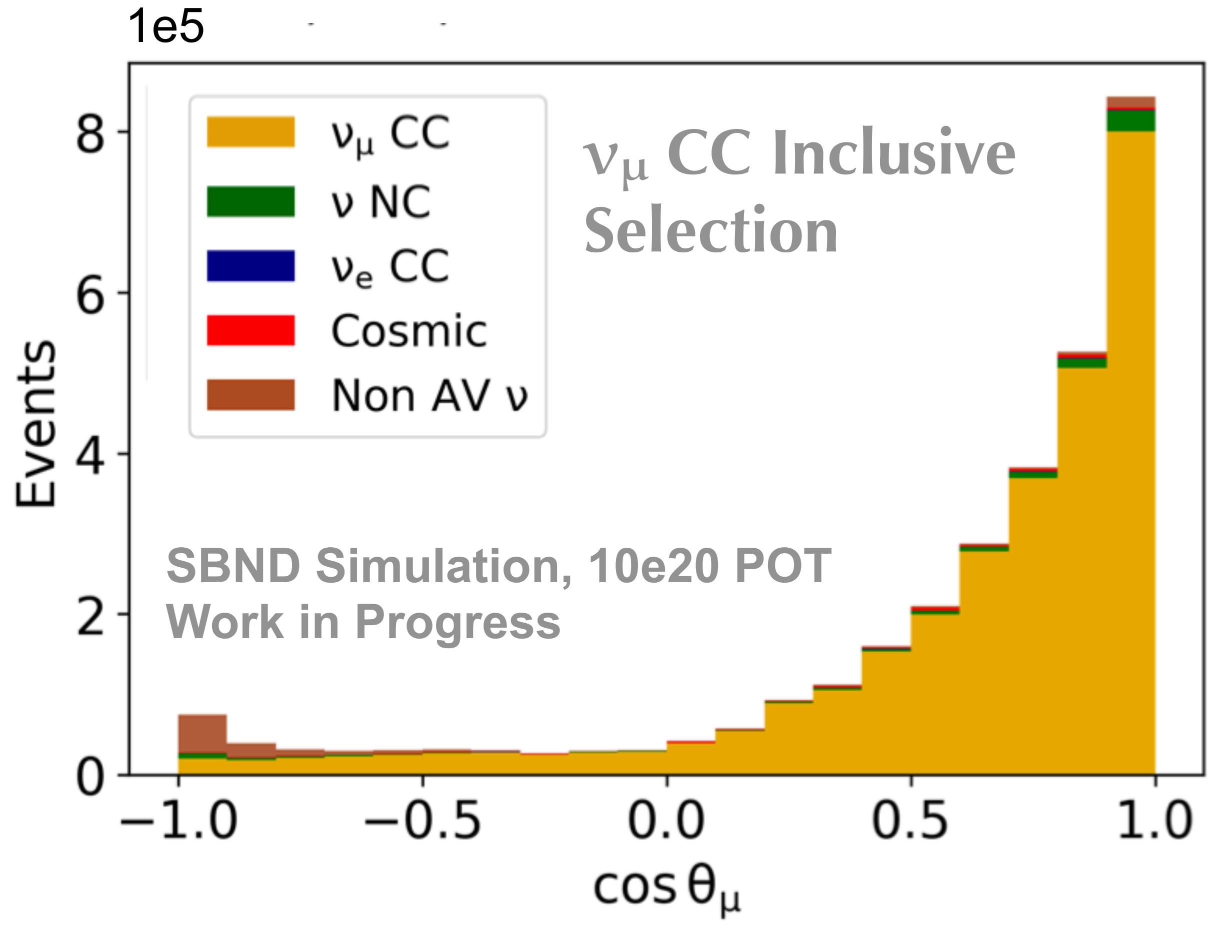
# Neutrino Interaction Measurements in SBND

- High statistics in SBND will allow a wide variety of neutrino interaction measurements
  - For **more common channels**, SBND can make multi-dimensional differential measurements
  - For **rare channels**, SBND can make measurements that are not possible in other existing experiments
- A quick sampler of measurement channels that are being worked on…
  - **$\nu_\mu$ CC inclusive**
  - **$\nu_\mu$ CC Np $0\pi$**
  - **$\nu_\mu$ CC Np $1\pi^0$**
  - **$\nu_\mu$ CC Np $1\pi^\pm$**
  - **$\bar{\nu}_\mu$ CC quasielastic hyperon production ($\Lambda^0$, $\Sigma^0$, $\Sigma^-$)**
  - **$\nu_\mu$ CC inelastic kaon production ($K^+ + \Lambda^0$)**
  - **$\nu_e$ CC inclusive**
  - **NC Np $0\pi$**
  - **NC Np $1\pi^0$**
  - **NC Np $1\gamma$**
  - **Neutrino–electron elastic scattering**
  - … more to come!
- Measurements will provide inputs for theory, generators, and future experiments

# Highlights: $\nu_\mu$ Charged-Current Inclusive

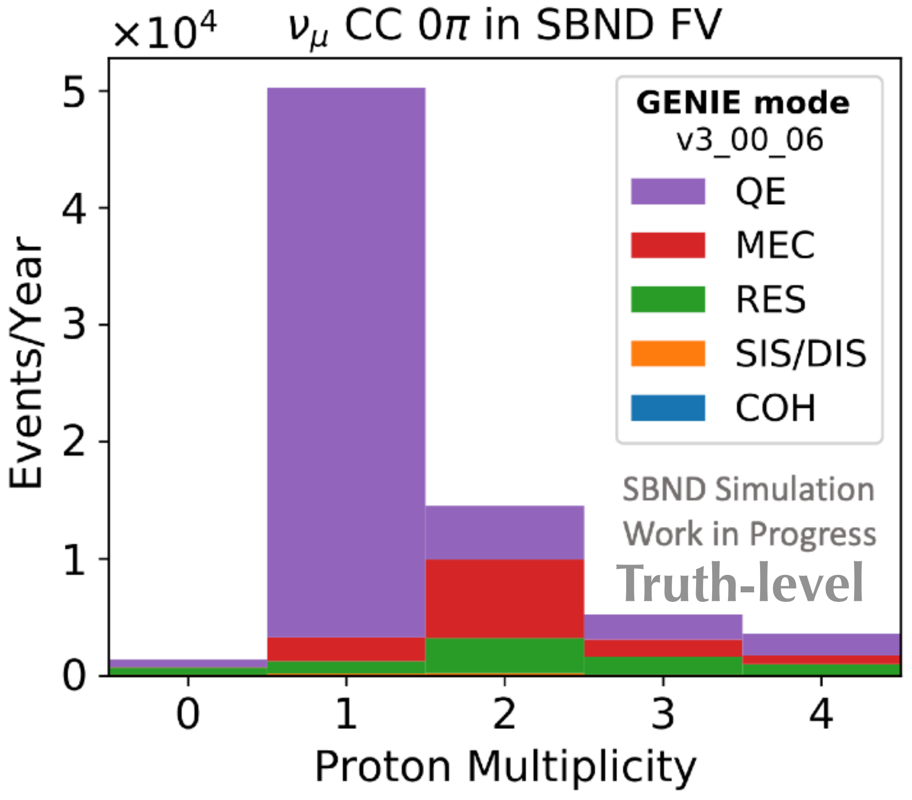
- The $\nu_\mu$ CC inclusive analysis can be used to study muon kinematics, and to make detailed comparisons to neutrino–argon interaction models leveraging SBND's high statistics
- In SBND, this selection can also be used to help us benchmark detector performance and understand BNB flux effects
- Current selection achieves 50% efficiency for $\nu_\mu$ CC interactions in the fiducial volume

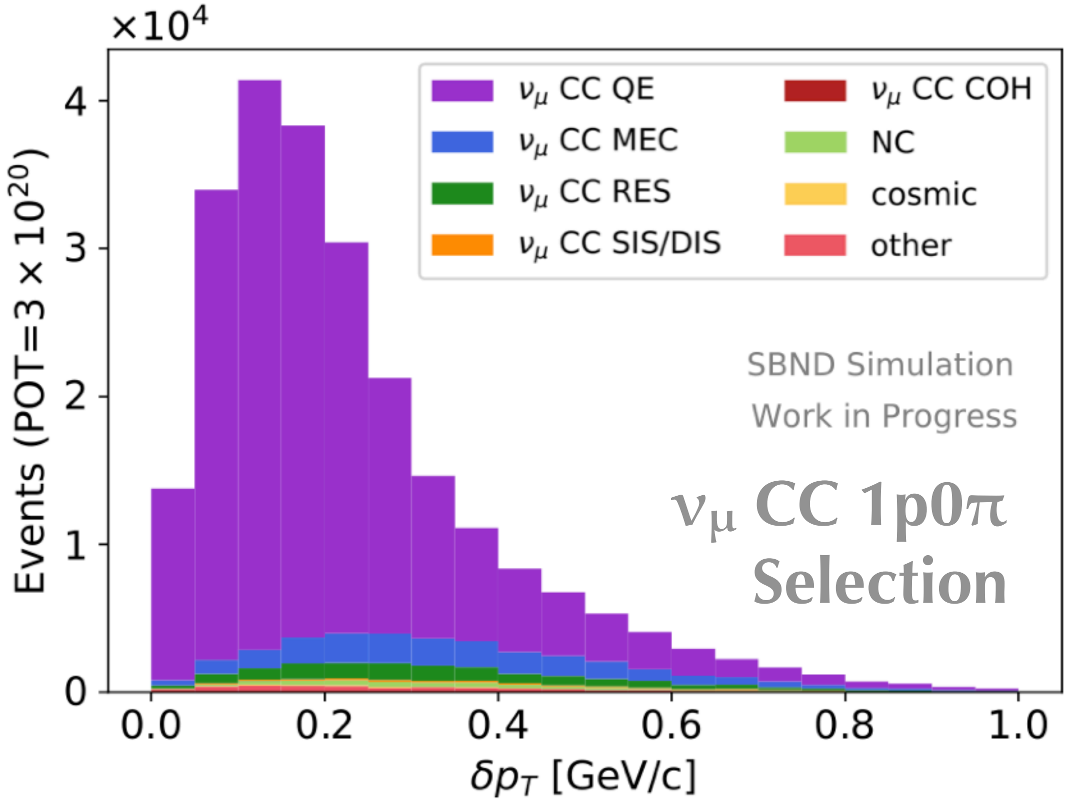


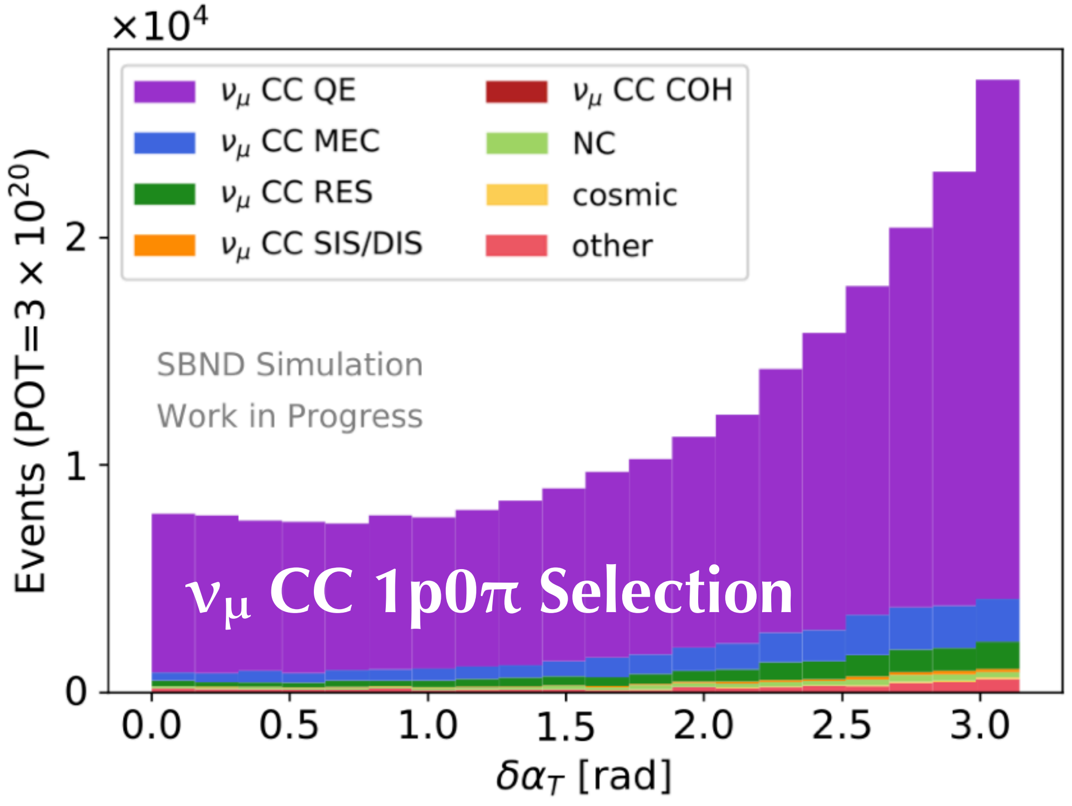



# Highlights: $\nu_\mu$ Charged-Current, Pionless Final States

- The $\nu_\mu$ CC $0\pi$ final state targets quasielastic and 2p2h (MEC) interaction modes that are dominant in the 1p and 2p final states, respectively
- The $1p0\pi$ final state is particularly good for studying transverse kinematic quantities, and more generally for studying nuclear effects
- Selection for $1p0\pi$ events is in place on SBND simulation, achieves 38% efficiency
  - Translates to an expectation of ~300,000 events per year of BNB data



# A Closer Look at the Booster Neutrino Beam

- SBND is so close to BNB target that it sees neutrinos from a range of off-axis angles (OAAs)
  - Off-axis angles are calculated with respect to the BNB target position

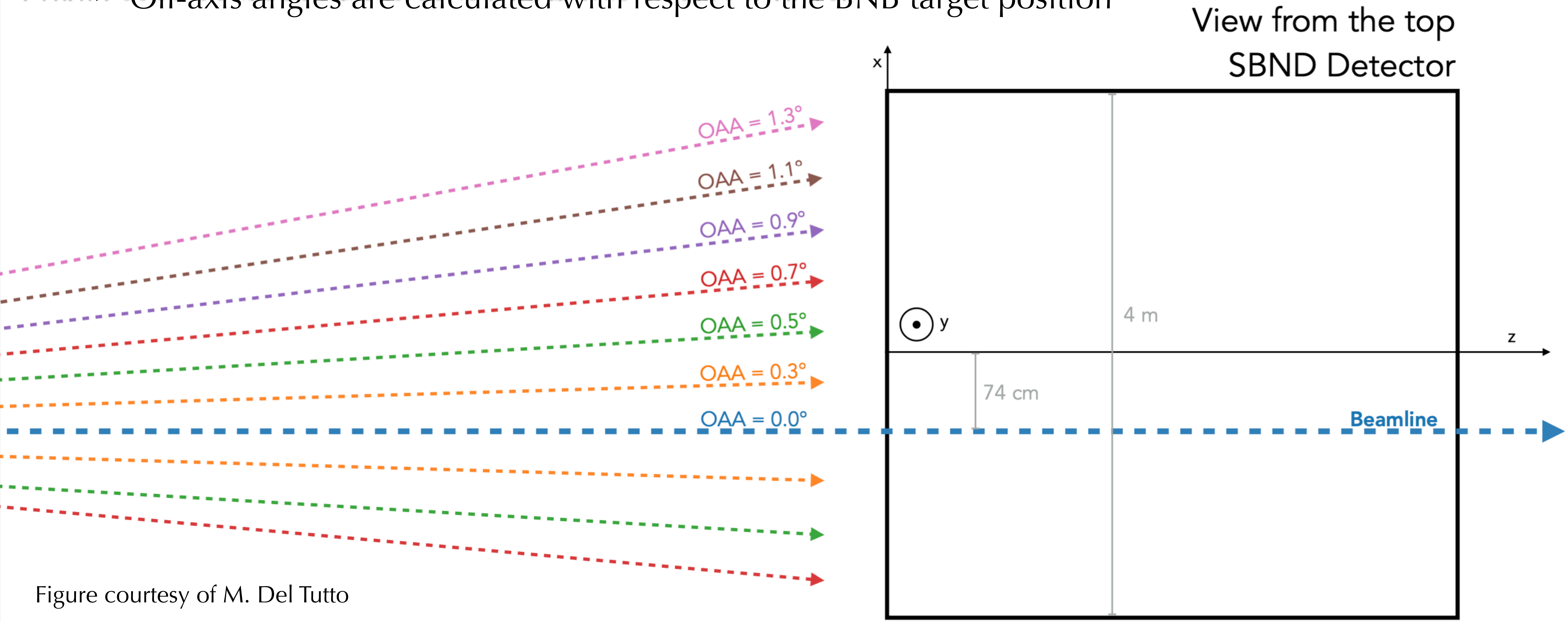
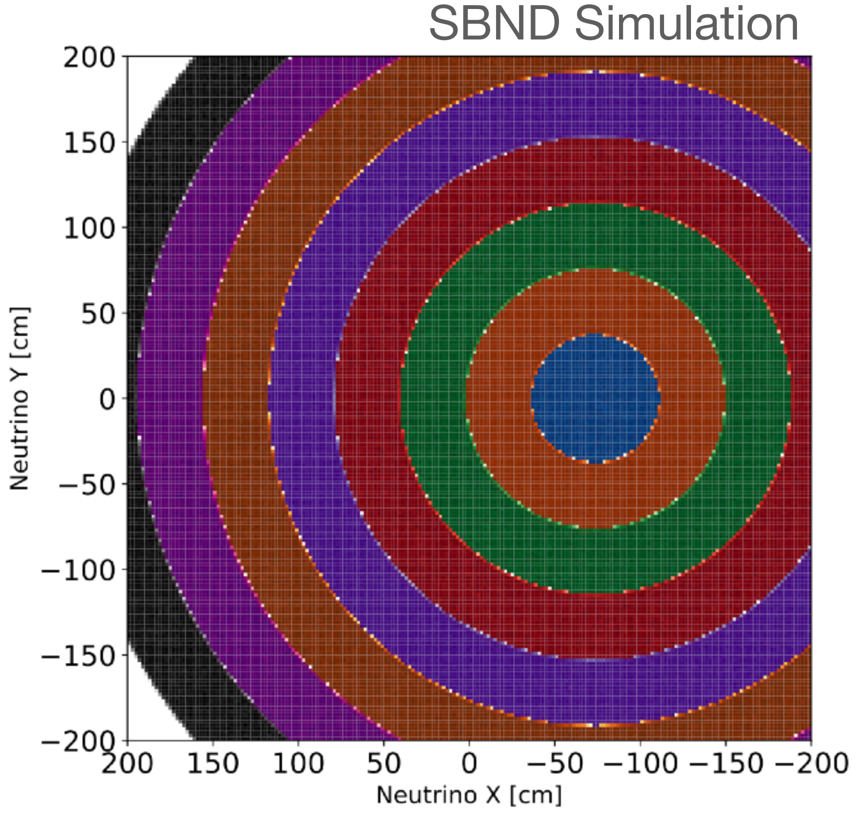


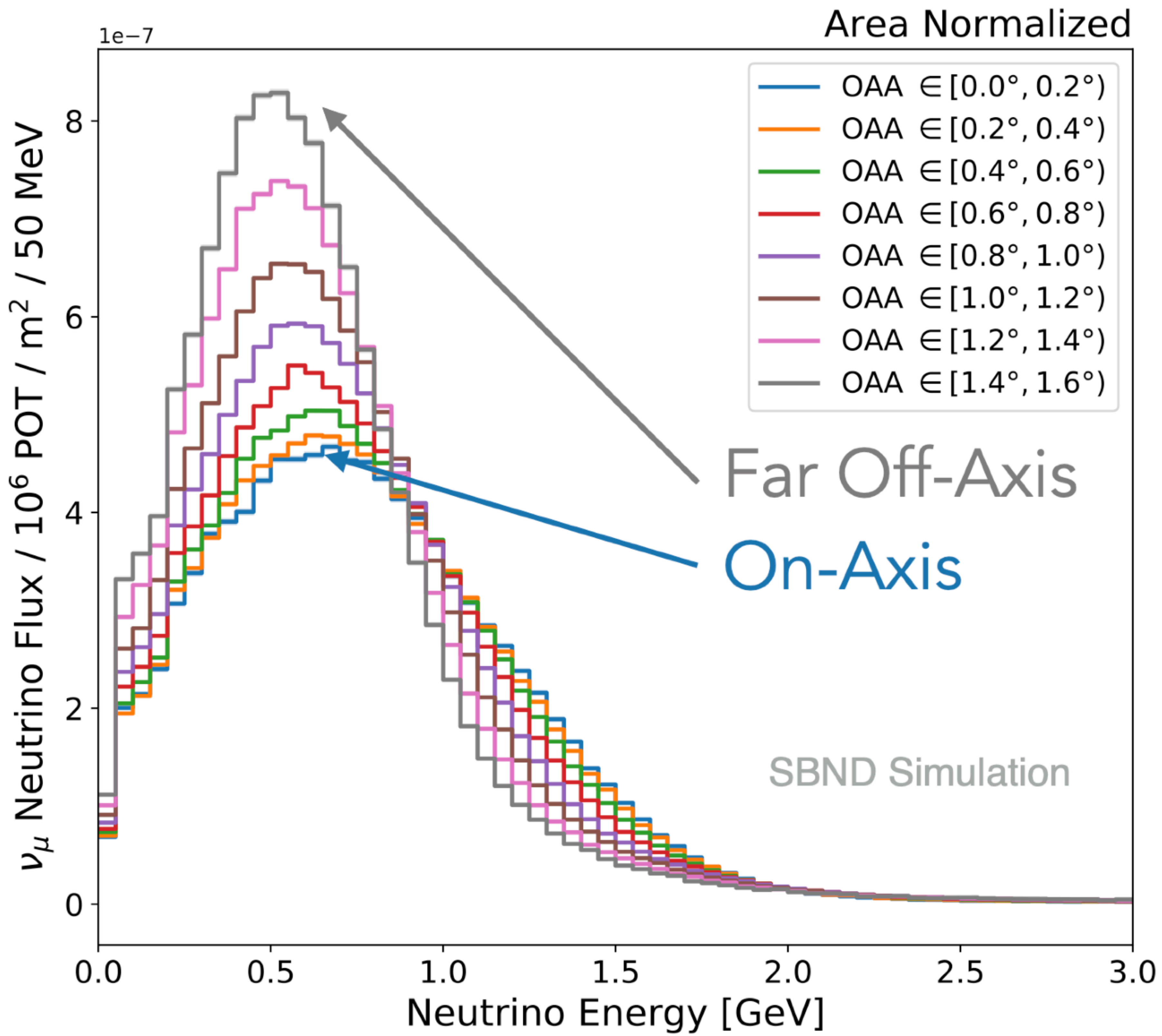

Figure courtesy of M. Del Tutto

# SBND-PRISM

nuPRISM proposal:
arXiv:1412.3086
Also similar to DUNE-PRISM

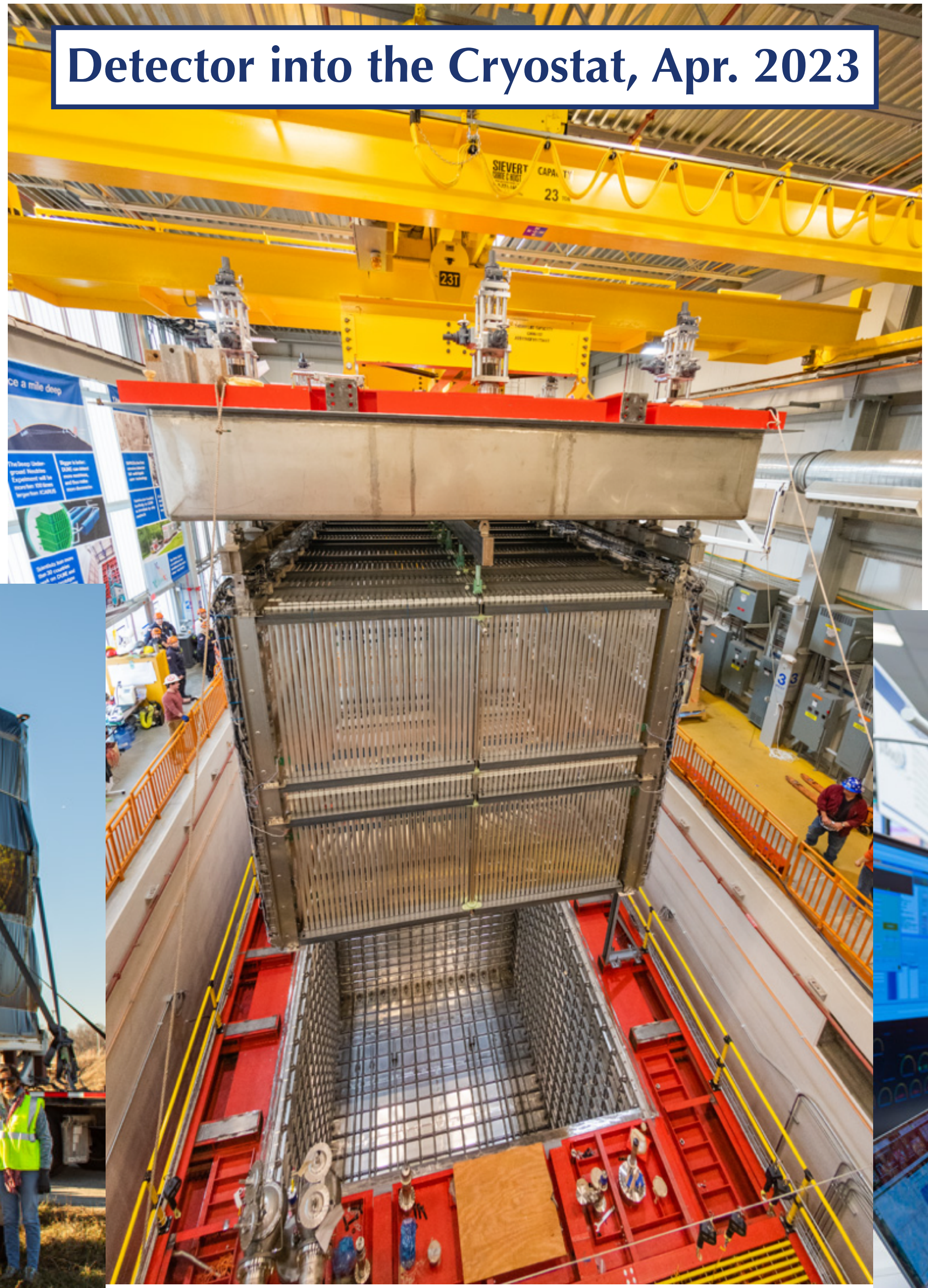
- Off-axis angle corresponds to neutrino interaction vertex position
- The flux spectrum evolves as a function of the off-axis angle
  - Further off-axis fluxes peak lower and tighter
- Offers opportunity to test energy dependence of the neutrino–argon interactions



# SBND Assembly, Installation, and Commissioning

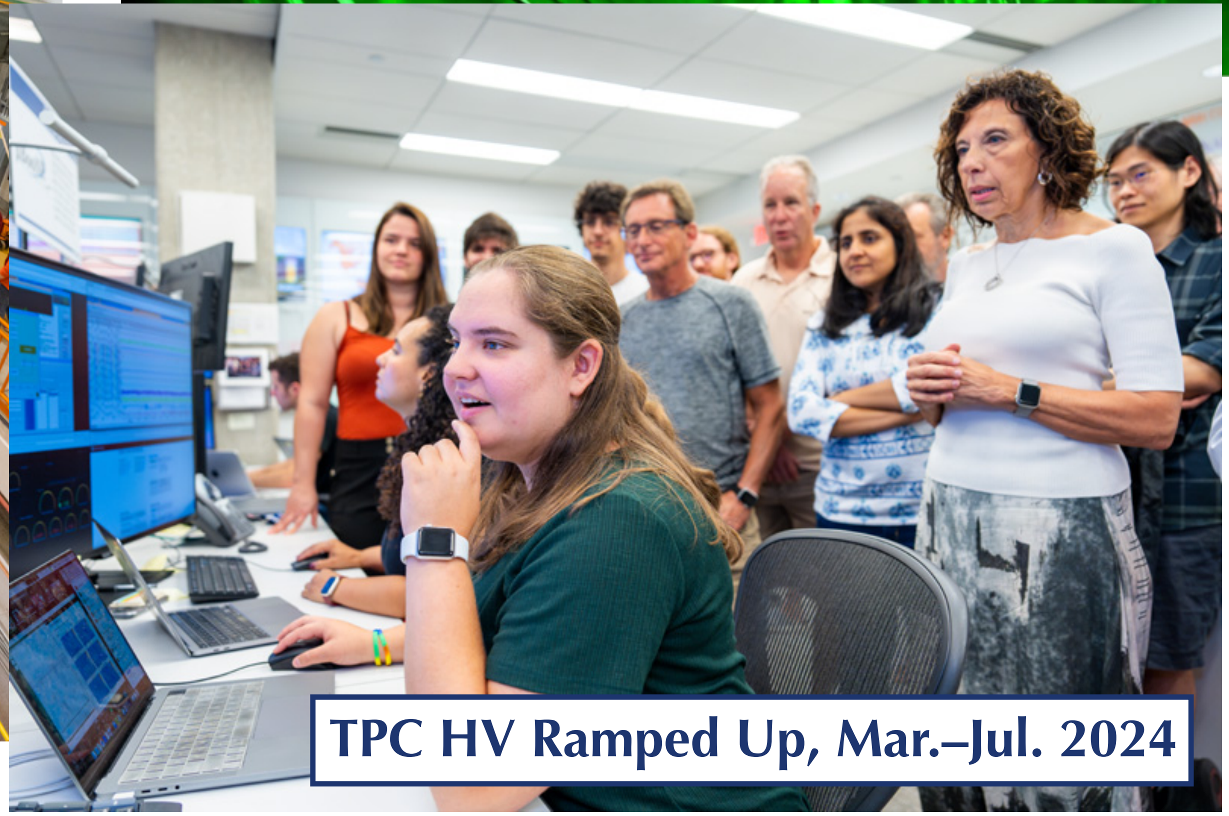
Detector Assembly, Dec. 2018–Sep. 2022



Detector into the Cryostat, Apr. 2023

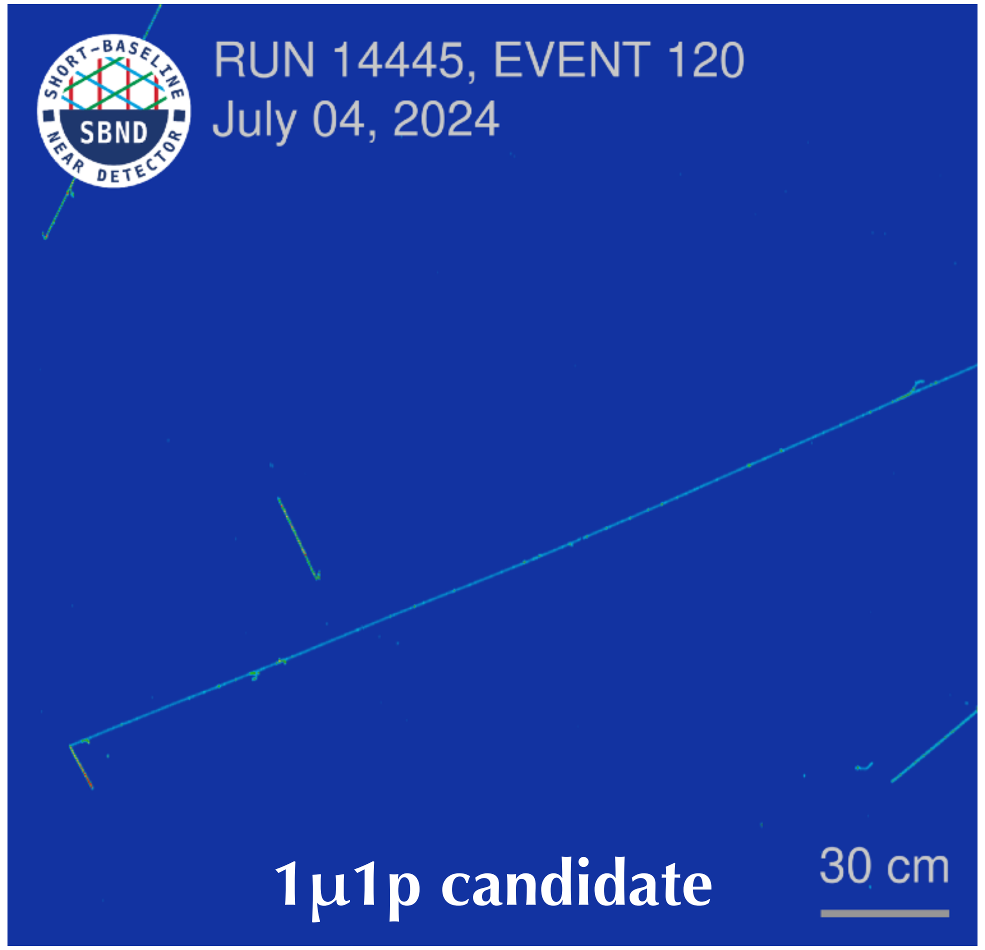
LAr Filling, Feb.–Mar. 2024

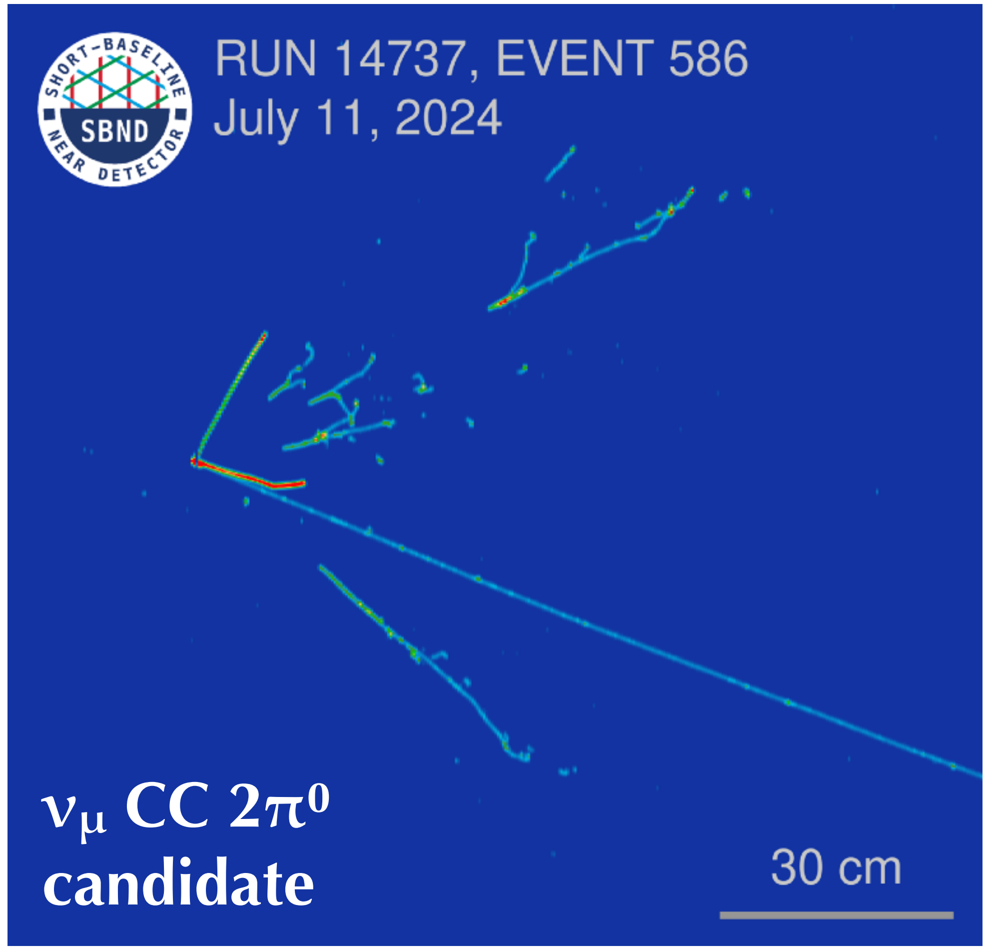
Detector to SBND, Dec. 2022



TPC HV Ramped Up, Mar.–Jul. 2024

# SBND Assembly, Installation, and Commissioning



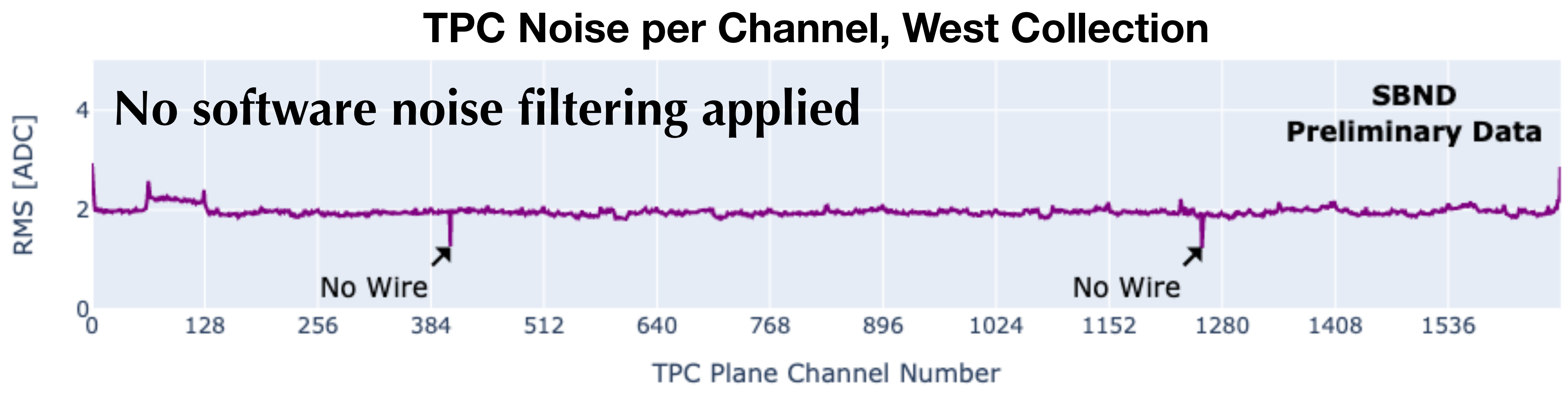



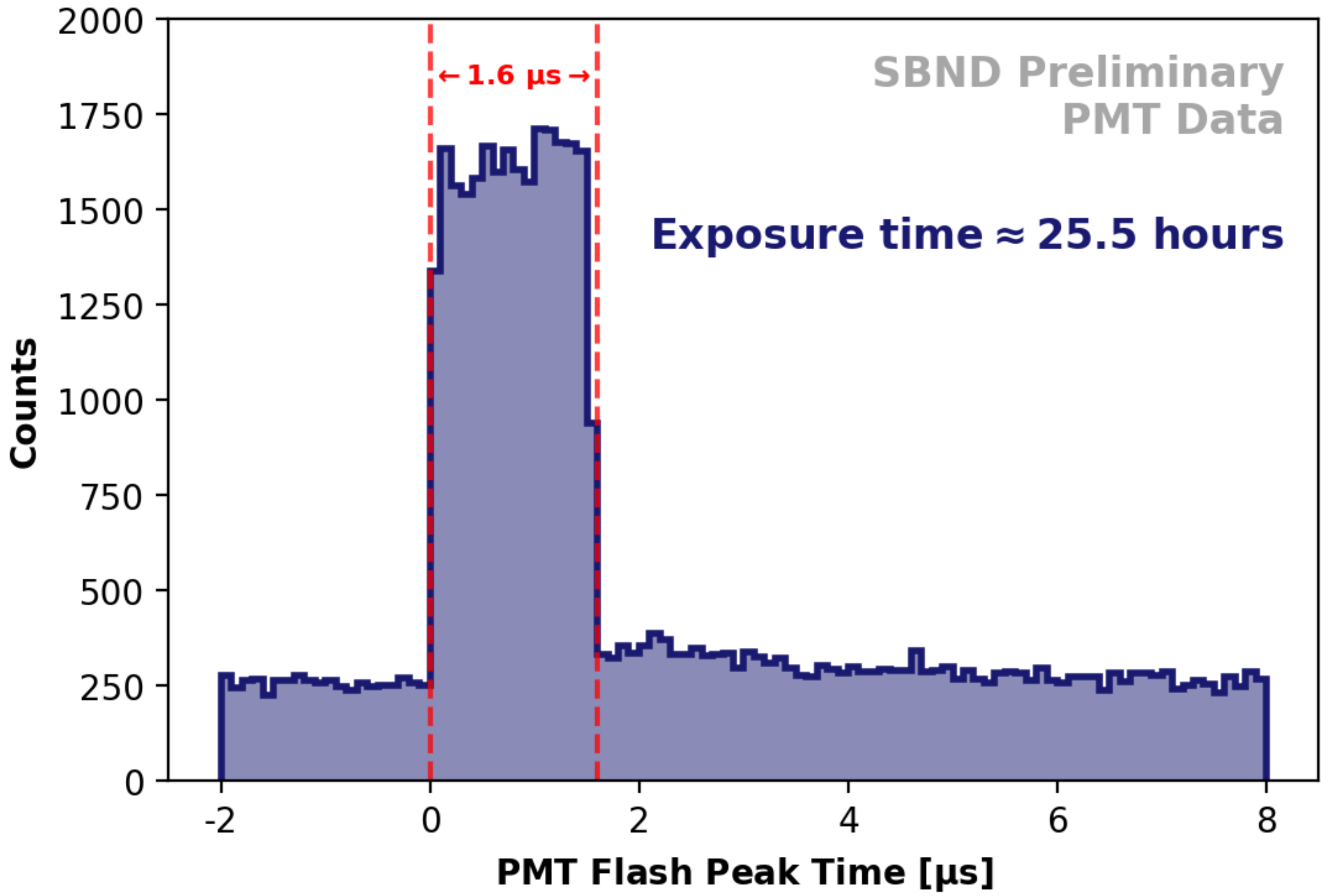


- Post-LAr-fill detector commissioning proceeded this spring, culminating in the collection of an initial BNB neutrino dataset in early July
- Currently working on installation and commissioning of the top CRT layers
- Installation, integration, and commissioning of the X-ARAPUCA light detector readout is also in progress and is expected to finish before the end of this year

# Initial Detector Performance

- TPC high voltage system has been operating stably since early July
- TPC noise is small, and resulting signal-to-noise ratio is great
  - Intrinsic noise is for a 4m-long wire is ~1.94 ADC, observed is top plot
- Initial PMT gain equalization done
- Verified synchronization of trigger, PMTs, and CRT with BNB spills
- Initial looks at our reconstruction performance on data are promising
- Observed drift electron lifetime meets design requirement of >3ms



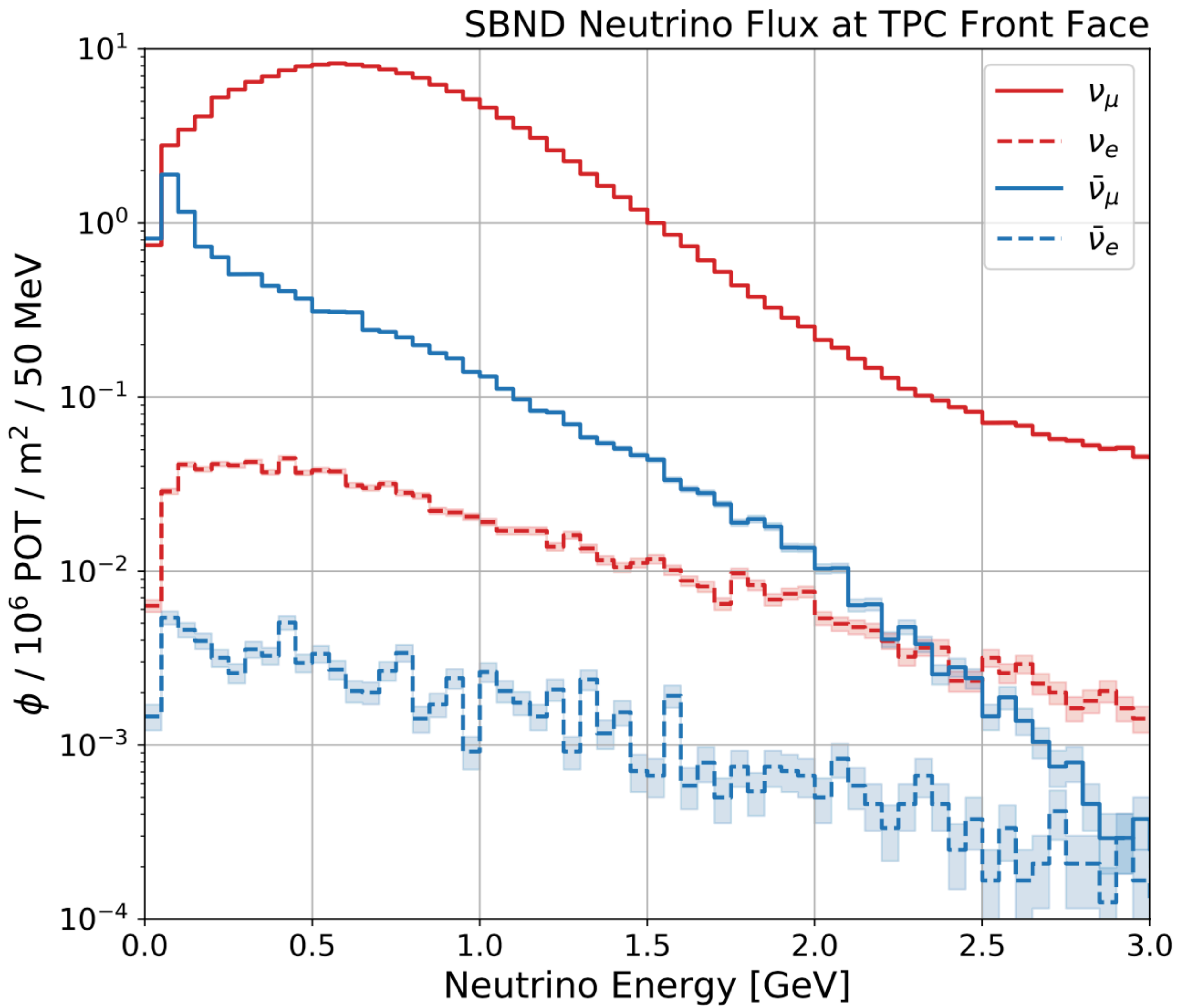
# Summary & Outlook

- The highly-capable LArTPC detector technology combined with SBND's close proximity to the BNB target and resulting high statistics will enable a wide variety of measurements
- SBND-PRISM provides a unique opportunity to probe different neutrino fluxes within the same stationary detector
- SBND's neutrino–argon interaction physics program will include:
    - Precise multi-dimensional differential measurements of high-statistics channels
    - World-first or world-leading measurements in rare channels
    - Constraining neutrino interaction uncertainties for SBN oscillation searches and other BSM studies
- Reconstruction, selection, and analysis tools for cross section measurements are already well-developed on SBND simulation
- SBND experiment has already collected an initial BNB neutrino dataset, is in the final stages of commissioning, and is looking forward to the return of BNB beam

# Thank you! Grazie!

# Additional Slides

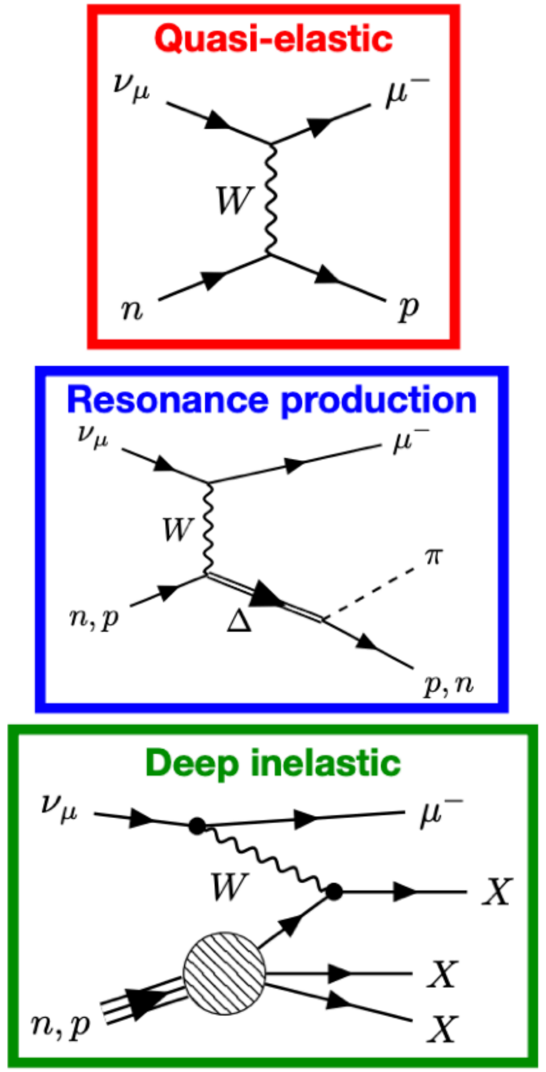
# Booster Neutrino Beam Flux at SBND



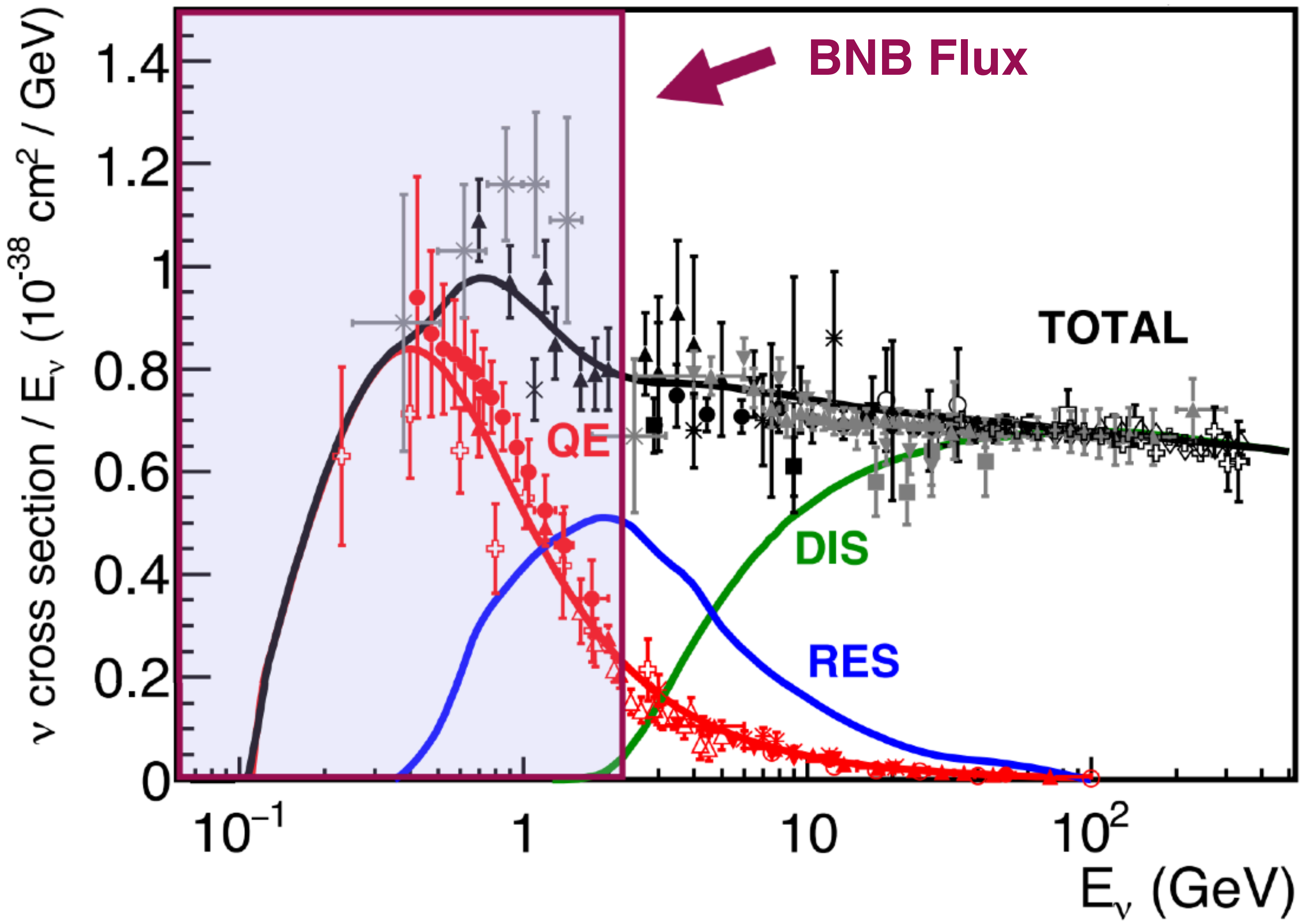

- The primary beam of interest at SBND is the Booster Neutrino Beam (BNB)
- The mean energy for muon neutrinos is about 0.8 GeV
- Beam composition by neutrino flavor:
  - 93.6% $\nu_\mu$
  - 5.9% $\overline{\nu}_\mu$
  - 0.5% $\nu_e$+$\overline{\nu}_e$
- Plan to collect data corresponding to 10e20–18e20 protons on target (POT) over the course of a 3–4 year run

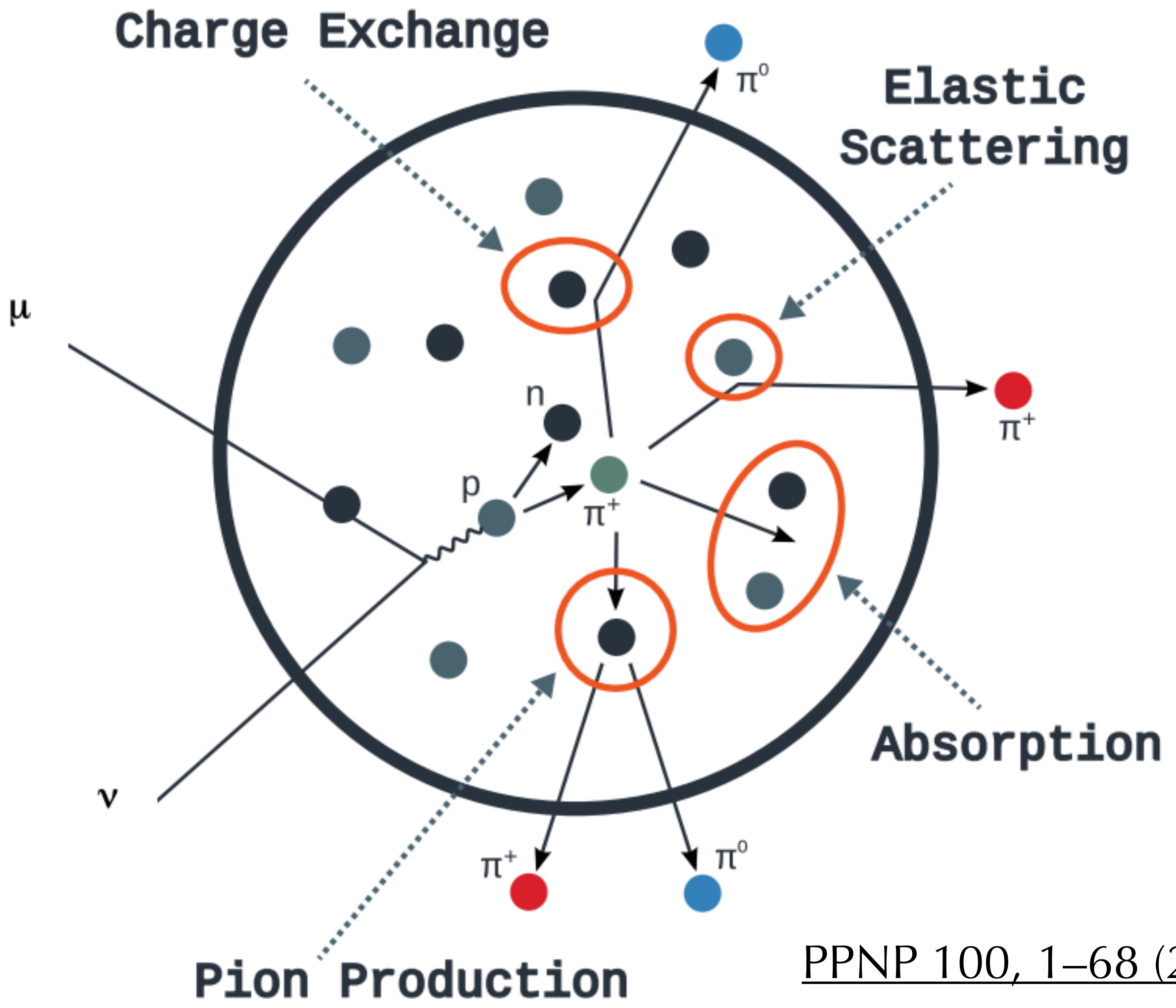
# Neutrino Interactions on Argon

- Understanding and modeling neutrino interactions is essential for interpreting final state particle content and kinematics to extract information about the initial state neutrino
- Theory of neutrino interactions on argon ($A$=40) is complex due to multiple processes, nuclear effects, and final-state interactions




Rev. Mod. Phys. 84, 1307 (2012)

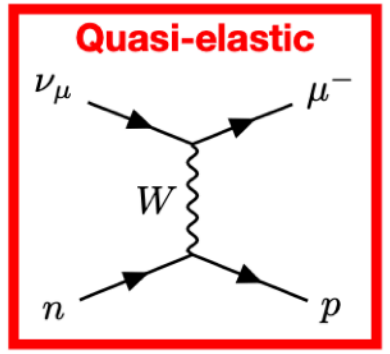


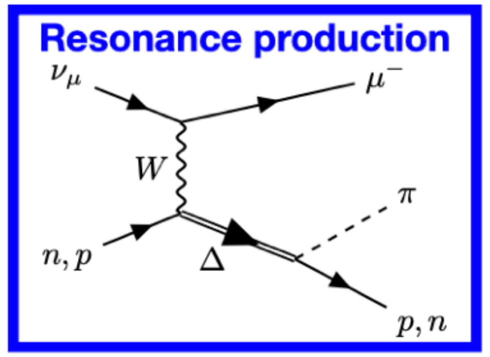



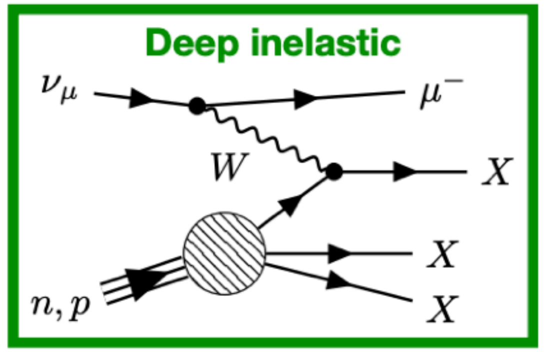

PPNP 100, 1–68 (2018)

# Neutrino Interactions on Argon

- A robust program of neutrino cross-section measurements is key to benchmarking models and improving them — and SBND expects to be a major contributor in the years ahead
- SBND is primarily using GENIE for simulating neutrino interactions, while also working to incorporate alternative generators such as GiBUU

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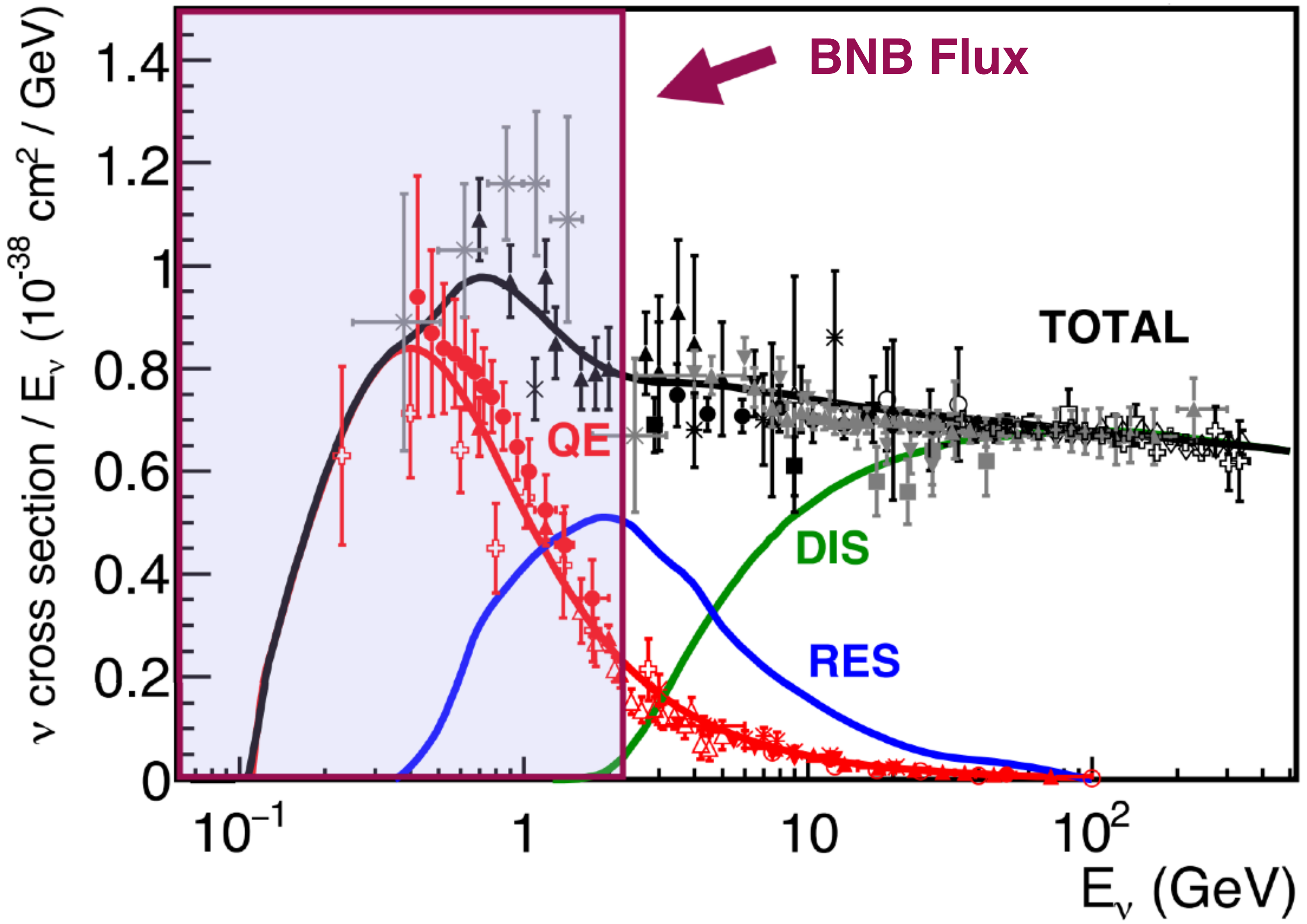
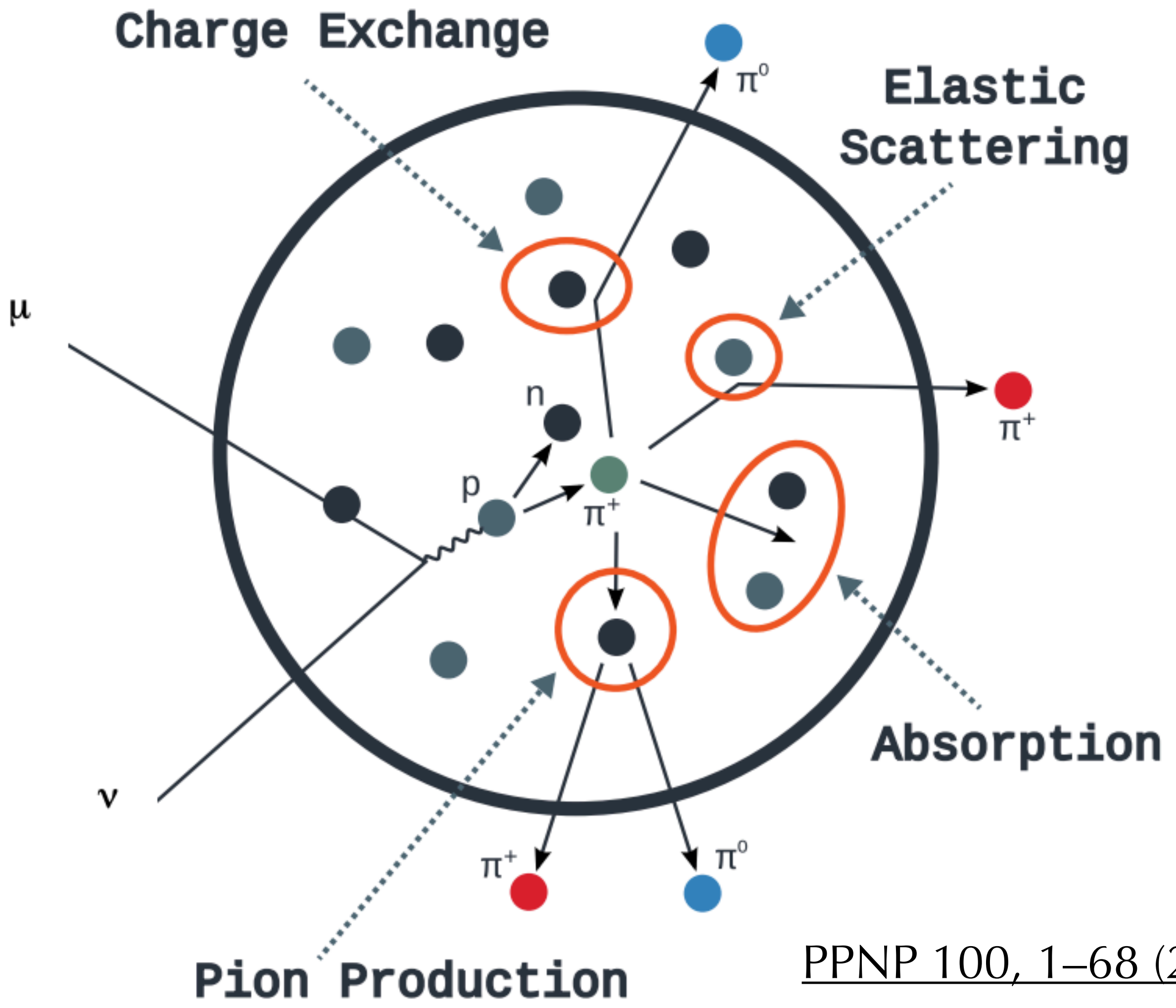
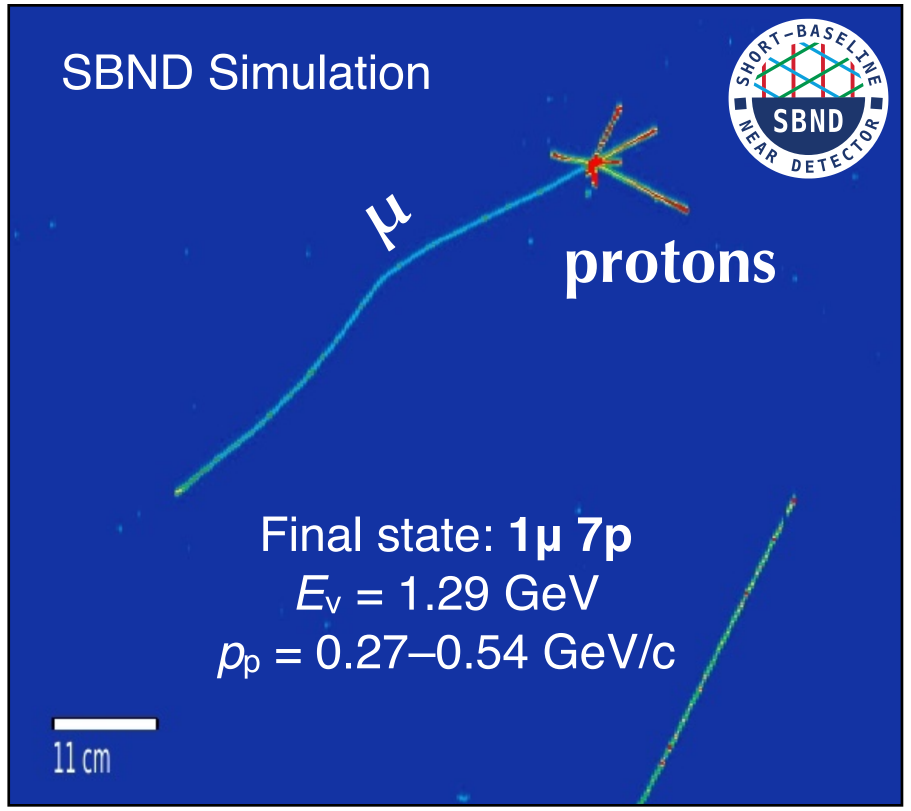


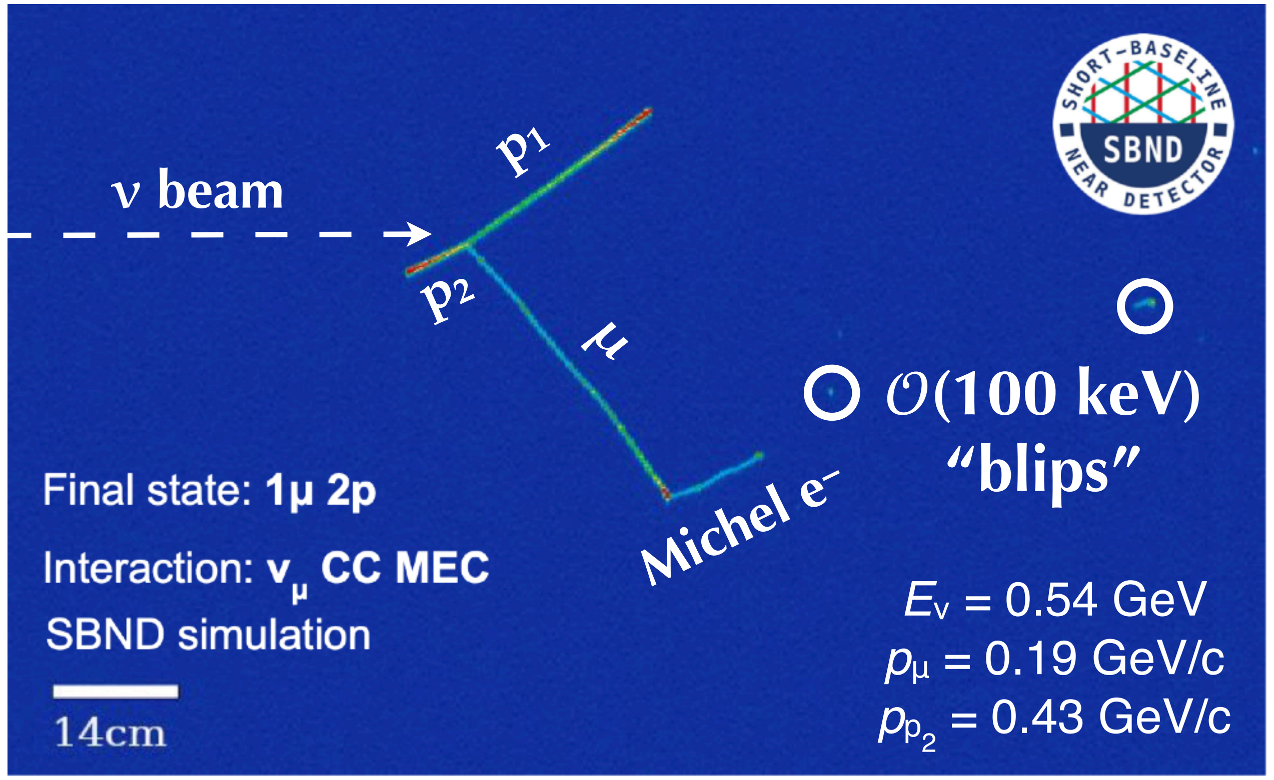



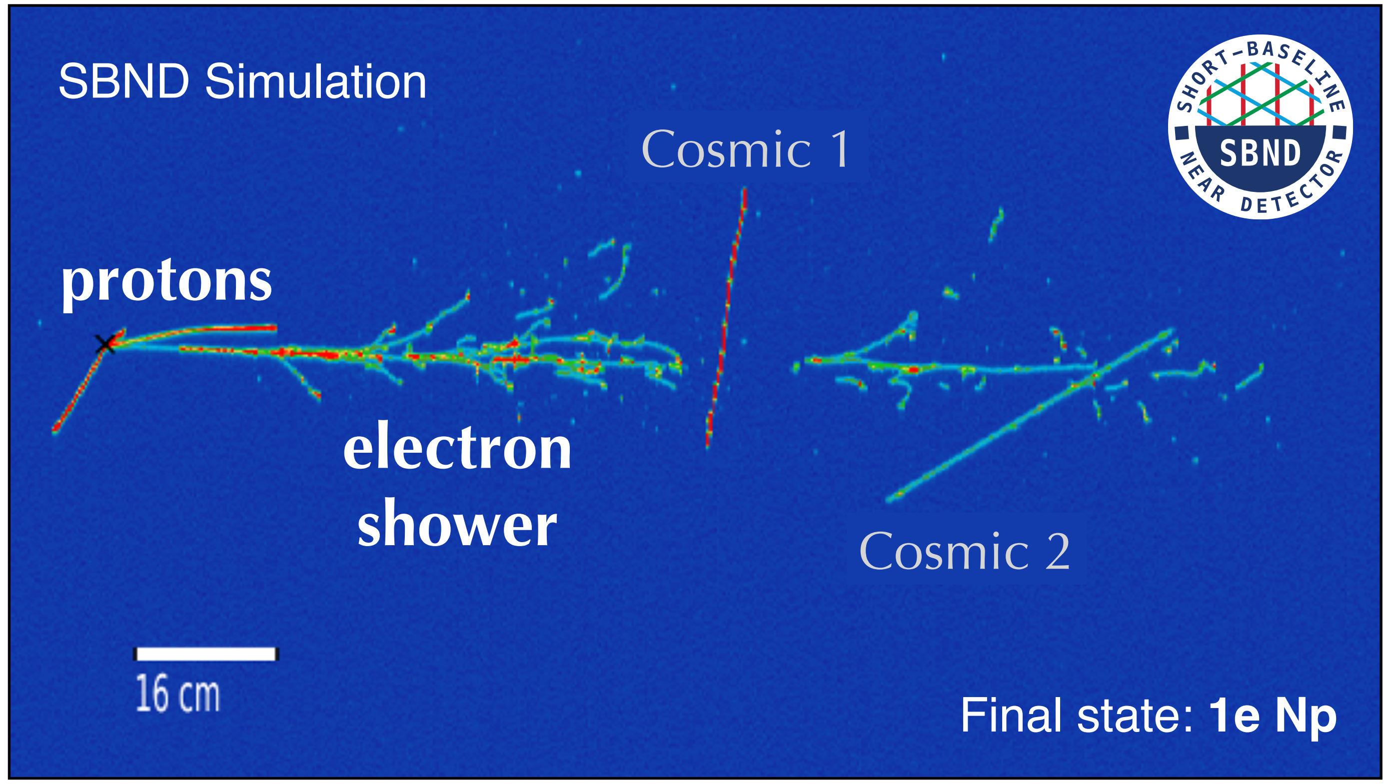

PPNP 100, 1–68 (2018)

# Detecting Neutrino Interactions with SBND

- LArTPC capabilities enable low reconstruction thresholds and excellent particle identification for interactions in SBND
- Fine resolution also enables disentangling complex final states
- In comparable LArTPC detectors, isolated energy deposits can be identified down to O(100) keV — expect similar from SBND
  - Opportunity to study MeV-scale activity, e.g. from neutron scatters

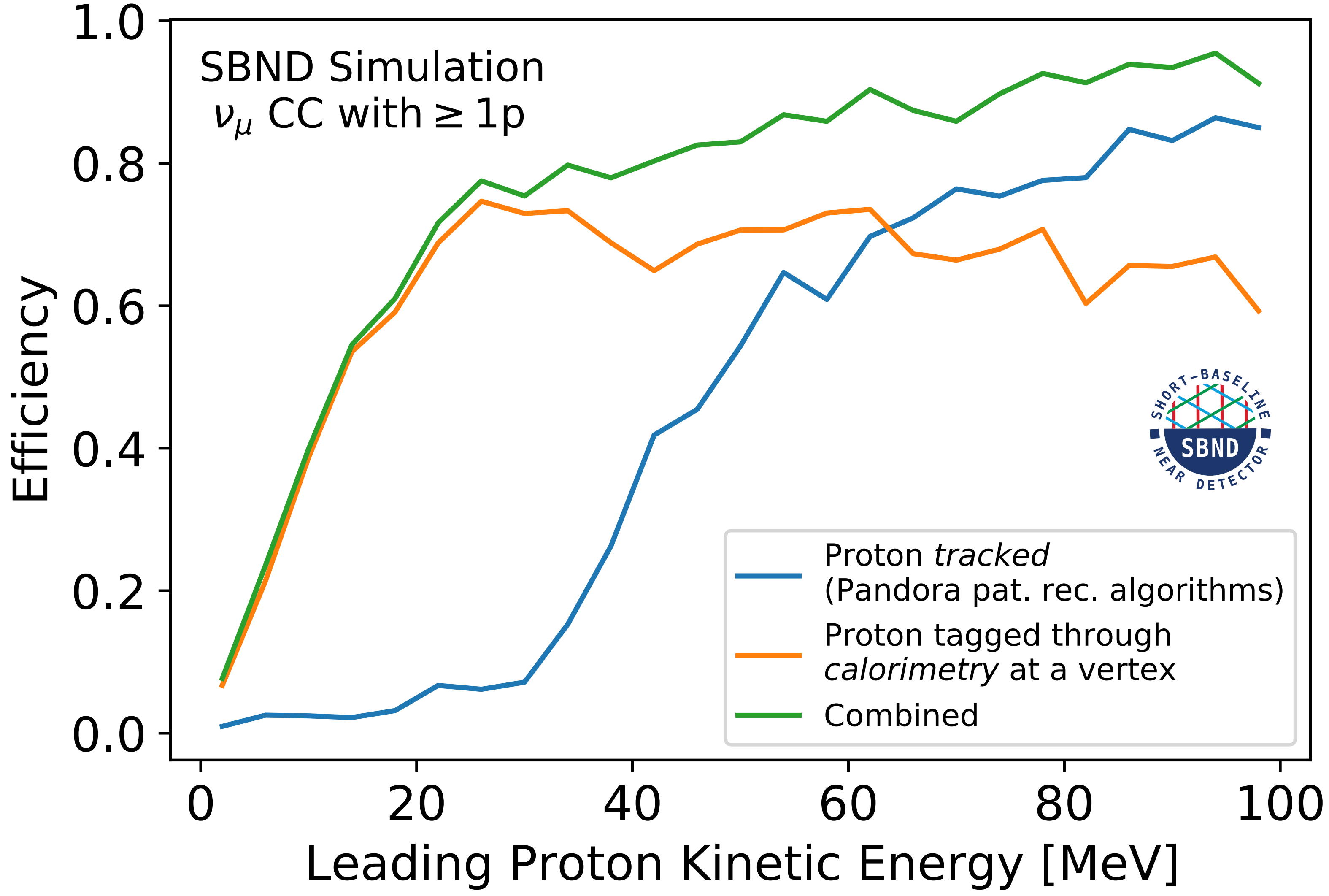


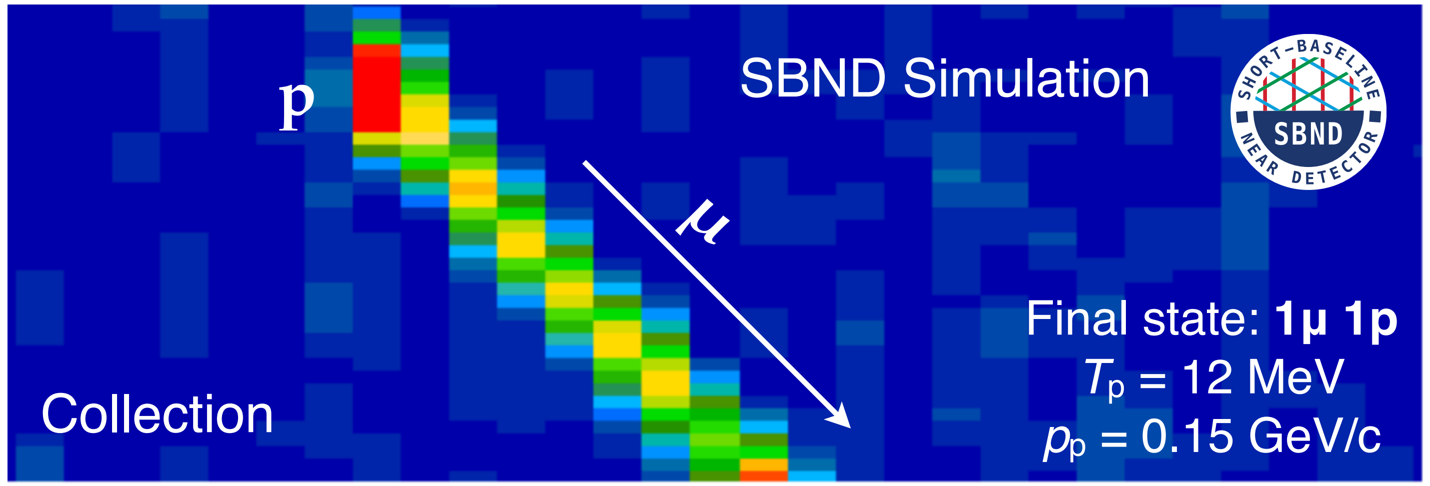



# Reconstructing Protons in SBND

- In SBND's simulation, Pandora reconstruction achieves a proton tracking threshold around 40 MeV (**blue** curve)
  - Pandora is a standard pattern recognition package, and is used in many LArTPC experiments
- In addition, we have developed a targeted algorithm to analyze heavy ionization deposits near the vertex to identify low energy protons (**orange** curve)
  - Works on top of existing Pandora reconstruction
- This pushes the proton identification threshold down below 15 MeV (**green** curve)



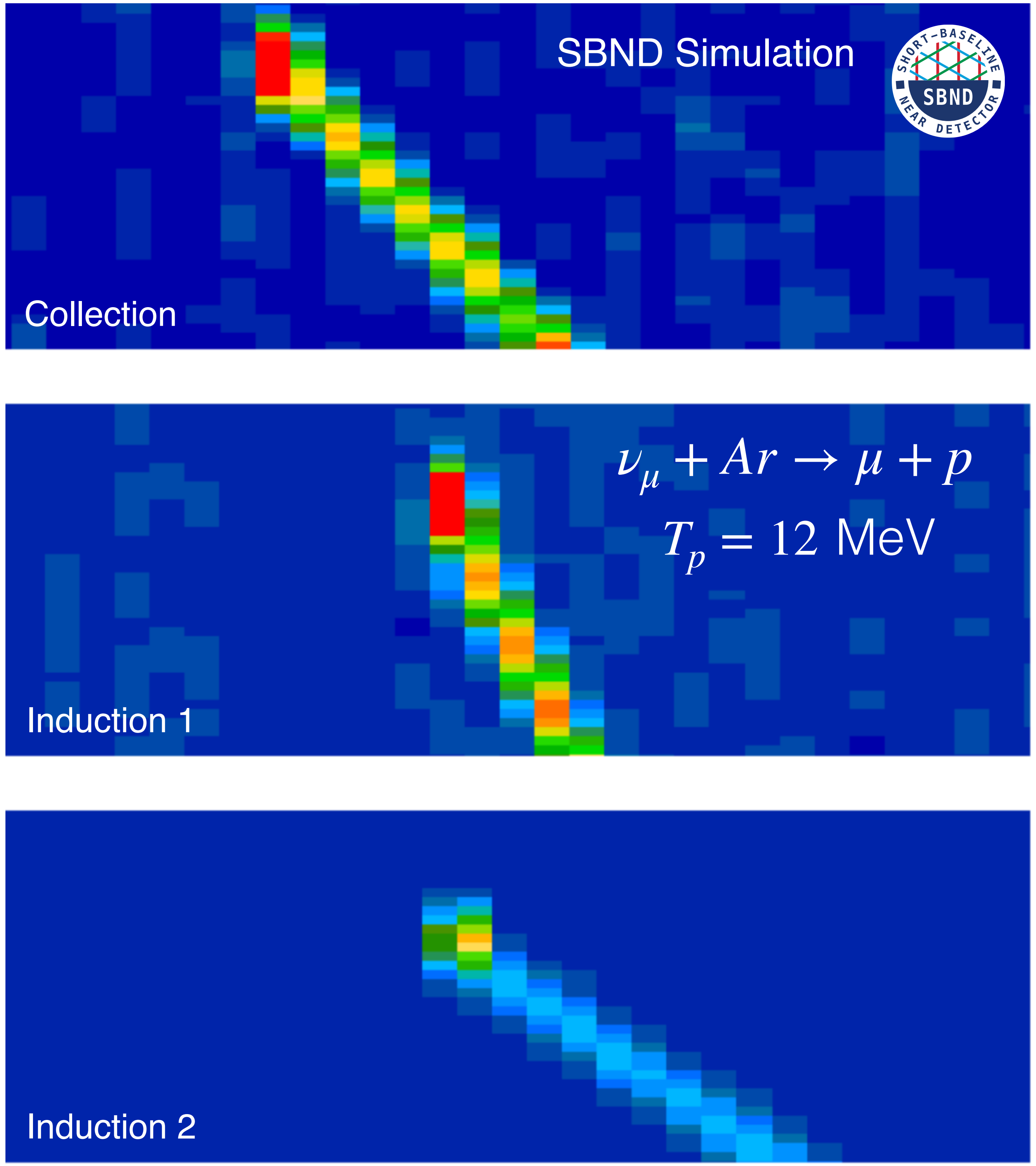




Pandora pattern recognition:
Eur. Phys. J. C 78, 82 (2018)

# Reconstructing Protons in SBND

- Below: table showing relationship between proton momentum, kinetic energy, and length in LAr
- Left: event display showing an interaction where there is a proton with kinetic energy of 12 MeV in the final state, which was tagged using calorimetry
  - Calorimetry able to identify the presence of a proton, but difficult to get any kinematic details

| $T_p$ (MeV) | $p_p$ (MeV/c) | Length (cm) |
|---|---|---|
| 20 | 195 | ~0.4 |
| 50 | 310 | ~2 |
| 100 | 445 | ~8 |
| 200 | 644 | ~26 |



# Neutrino Interactions by Event Topology in SBND

- High statistics in SBND will allow a wide variety of neutrino interaction measurements
  - For **more common channels**, SBND can make multi-dimensional differential measurements
  - For **rare channels**, SBND can make measurements that are not possible in other existing experiments
- Based on SBND simulations using GENIE v3.0.6 `G18_10a_02_11a` and 10e20 POT…
  - 6 million $\nu_\mu$ **CC inclusive** interactions
    - 4.3 million $\nu_\mu$ **CC Np0π**
      - 2.5 million $\nu_\mu$ **CC 1p0π**
      - 0.7 million $\nu_\mu$ **CC 2p0π**
    - 0.9 million $\nu_\mu$ **CC 1$\pi^\pm$ + X**
    - 0.5 million $\nu_\mu$ **CC 1$\pi^0$ + X**
    - 0.4 million $\nu_\mu$ **CC ≥2π + X**
  - ~600 $\nu_\mu$ **CC $K^+K^-$ + X**
  - ~700 $\nu_\mu$ **CC $K^0\bar{K}^0$ + X**
  - >1,000 $\nu_\mu$ **CC with charm baryons**
  - ~45,000 $\nu_e$ **CC inclusive** interactions
  - 2.5 million **NC inclusive** interactions
    - 1.7 million **NC 0π + X**
    - 0.5 million **NC 1$\pi^0$ + X**

R. Jones PhD thesis

# Neutrino Interaction Rates by Process in SBND

- Based on SBND simulations using GENIE v3.0.6 `G18_10a_02_11a` and 10e20 POT…

| CC Process | Number of Events |
|---|---|
| QE | 3.3 million |
| MEC | 0.7 million |
| RES | 1.8 million |
| DIS | 0.3 million |
| Coherent | ~11,000 |
| Other | ~3,600 |

| NC Process | Number of Events |
|---|---|
| QE | 1.3 million |
| MEC | 0.2 million |
| RES | 0.8 million |
| DIS | 0.2 million |
| Coherent | ~8,900 |
| Other | ~500 |

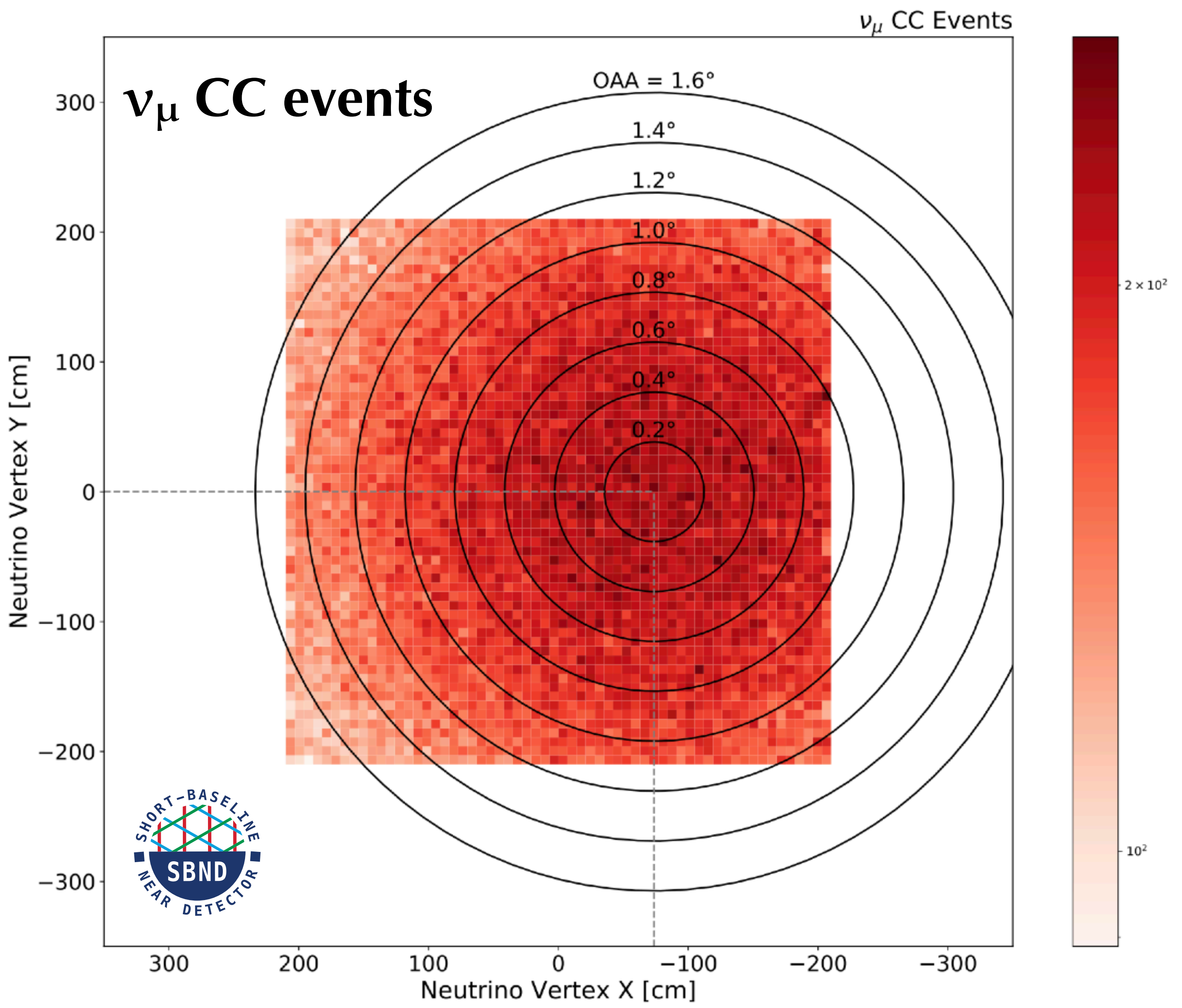
R. Jones PhD thesis

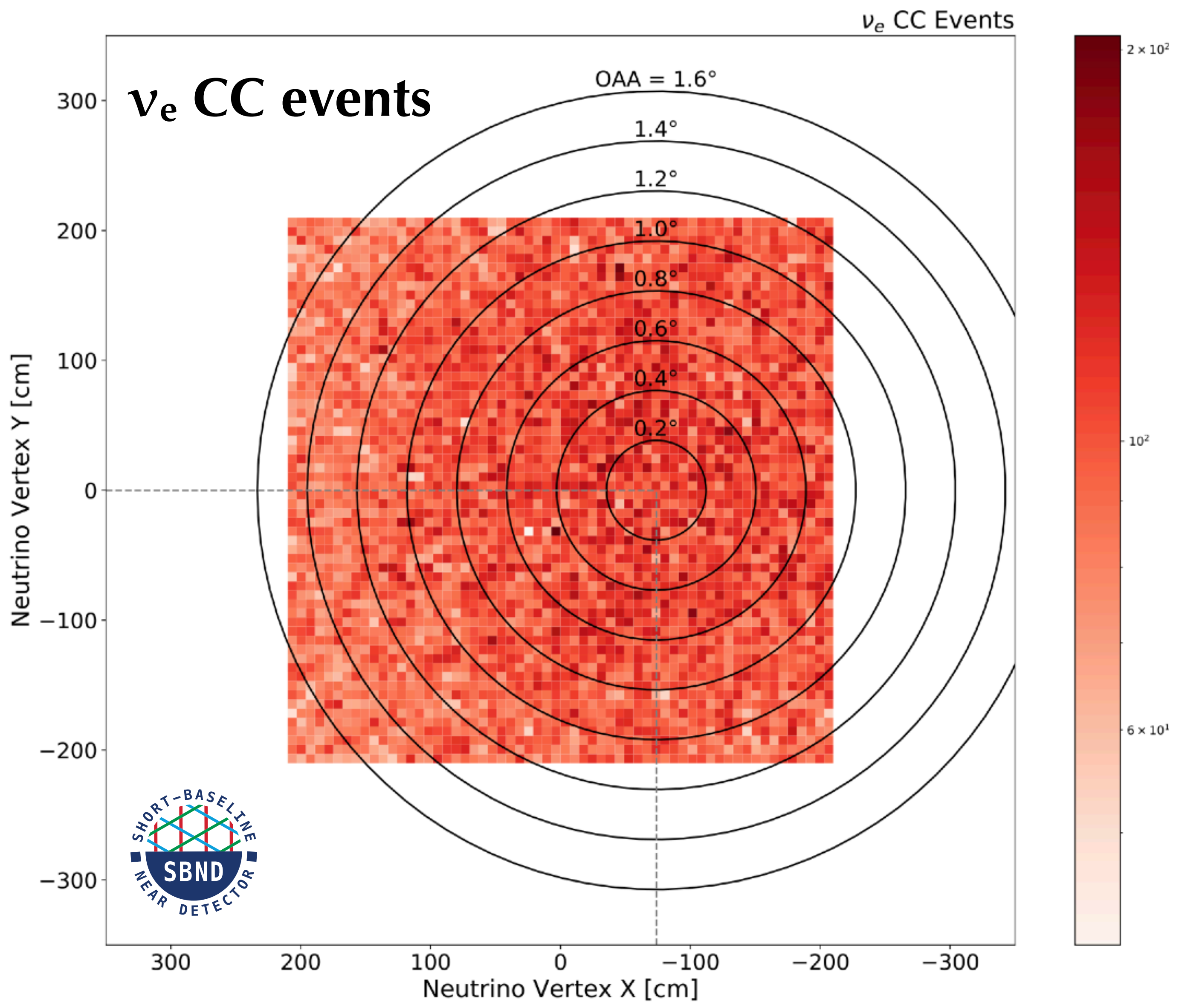
# What's In GENIE v3.0.6 `G18_10a_02_11a`?

- This is one of the comprehensive model configurations provided by GENIE v3
- The physics models include:
  - Local Fermi gas model for the initial nuclear state
  - Valencia model CC QE and 2p2h interactions, including the random phase approximation (RPA) description of long-range nucleon–nucleon correlations that suppresses CCQE at low $Q^2$
  - Berger Sehgal model of resonant and coherent pion production
  - Bodek–Yang model for deep inelastic scattering interactions
  - Semi-classical empirical model (`hA2018`) for final state interactions, including tuning of FSI parameters updated based on world data in 2018
- More information in Phys. Rev. D 104, 072009 (2021)

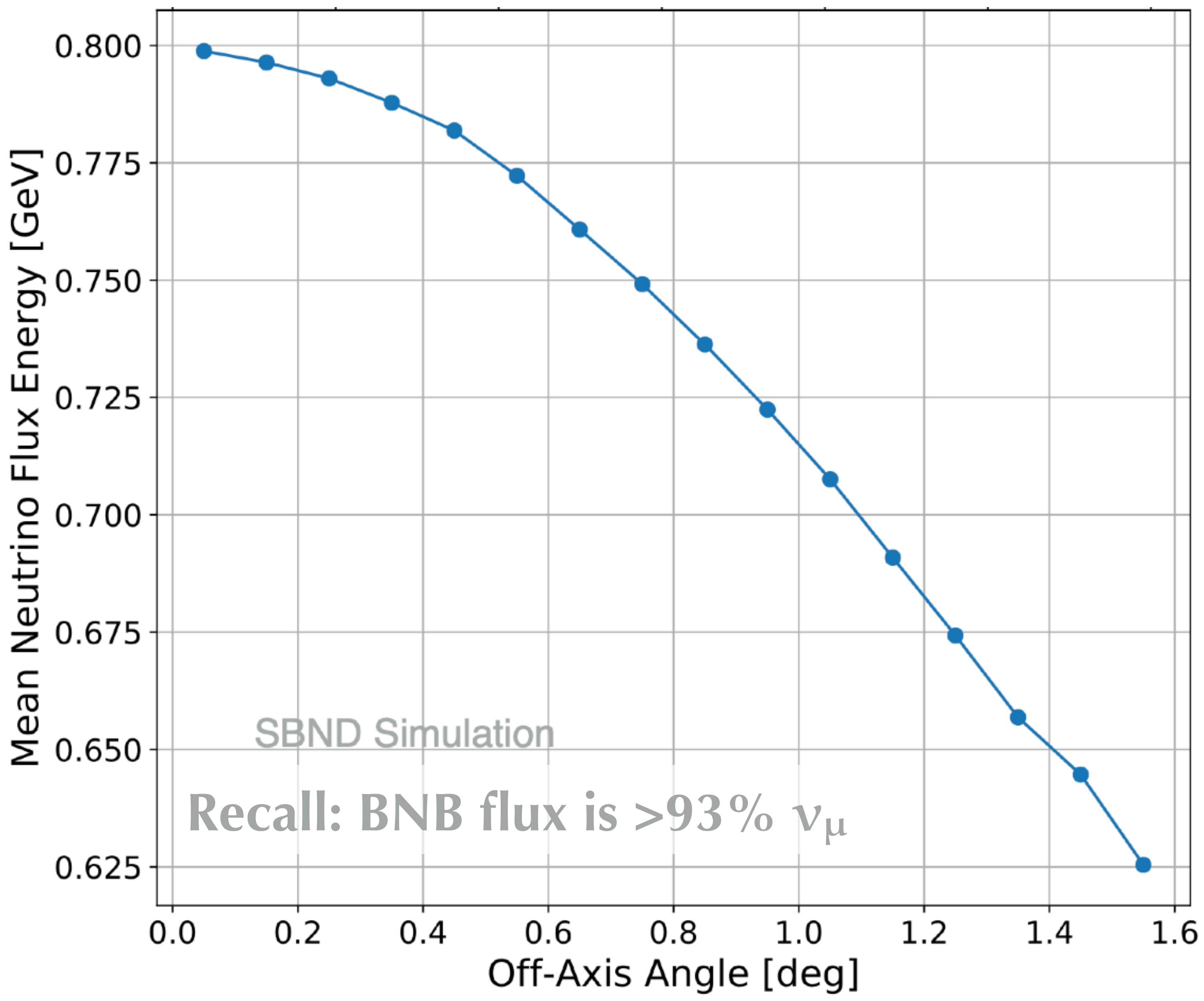
# SBND-PRISM for $\nu_\mu$ vs. $\nu_e$

- Due to meson decay kinematics, $\nu_e$ are distributed more evenly across the face of SBND
- The $\nu_\mu$ come from two-body decays, while $\nu_e$ generally come from three-body decays and thus have larger angular spread from the beam axis



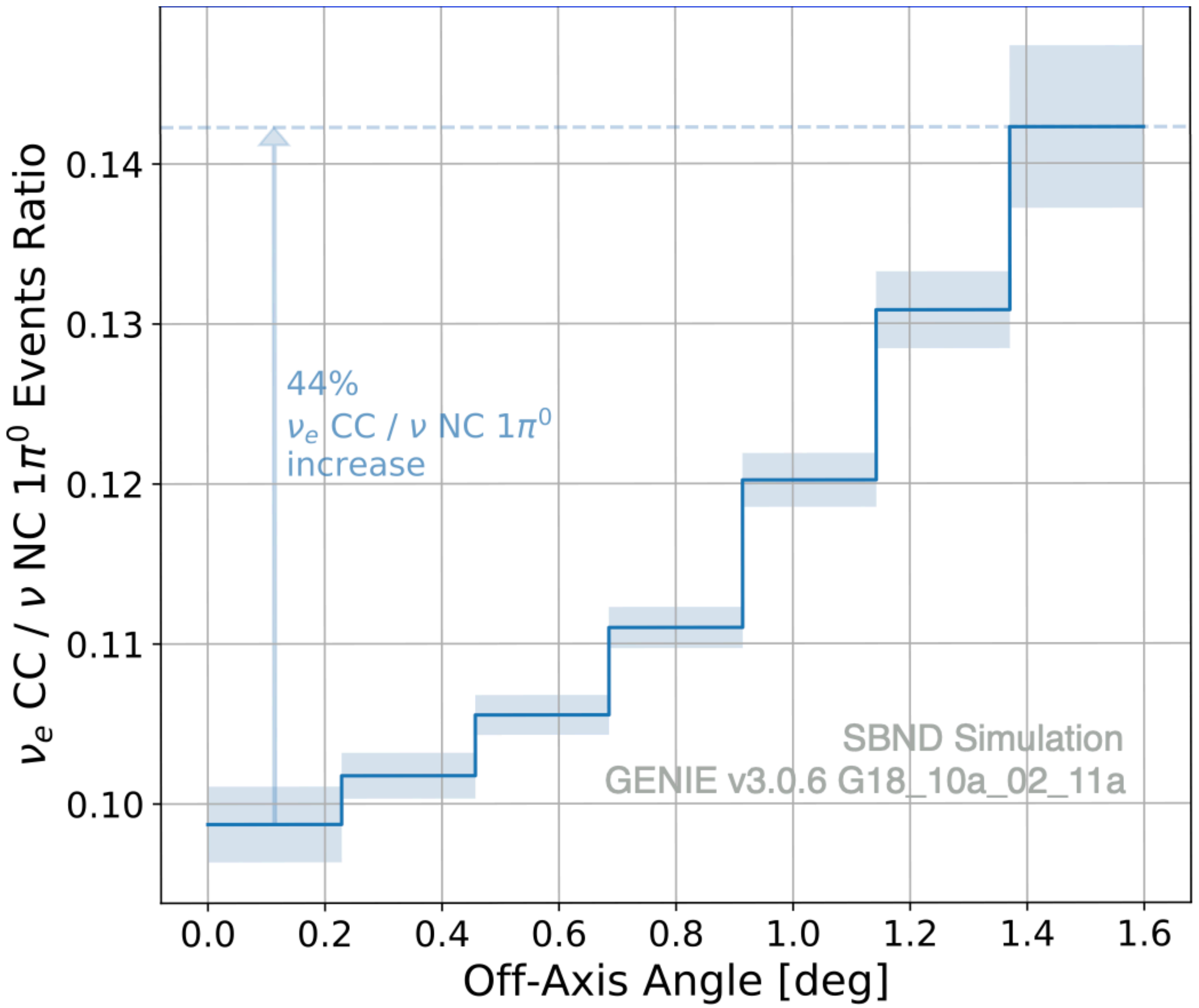



# SBND-PRISM for Interaction Measurements




- For $\nu_\mu$ measurements, looking at different slices of off-axis angle provides variations in mean energy of the neutrino flux of up to ~200 MeV
- Making simultaneous measurements across slices offers an opportunity to test energy dependence of the neutrino–argon interaction cross section
- Allows stringent tests of neutrino event generators and theoretical models

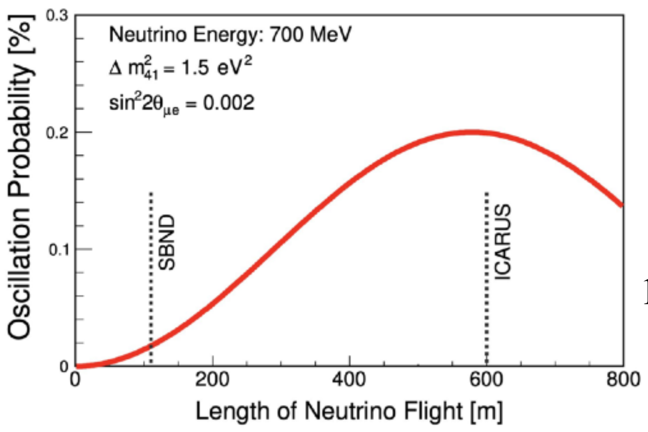
# SBND-PRISM for Interaction Measurements

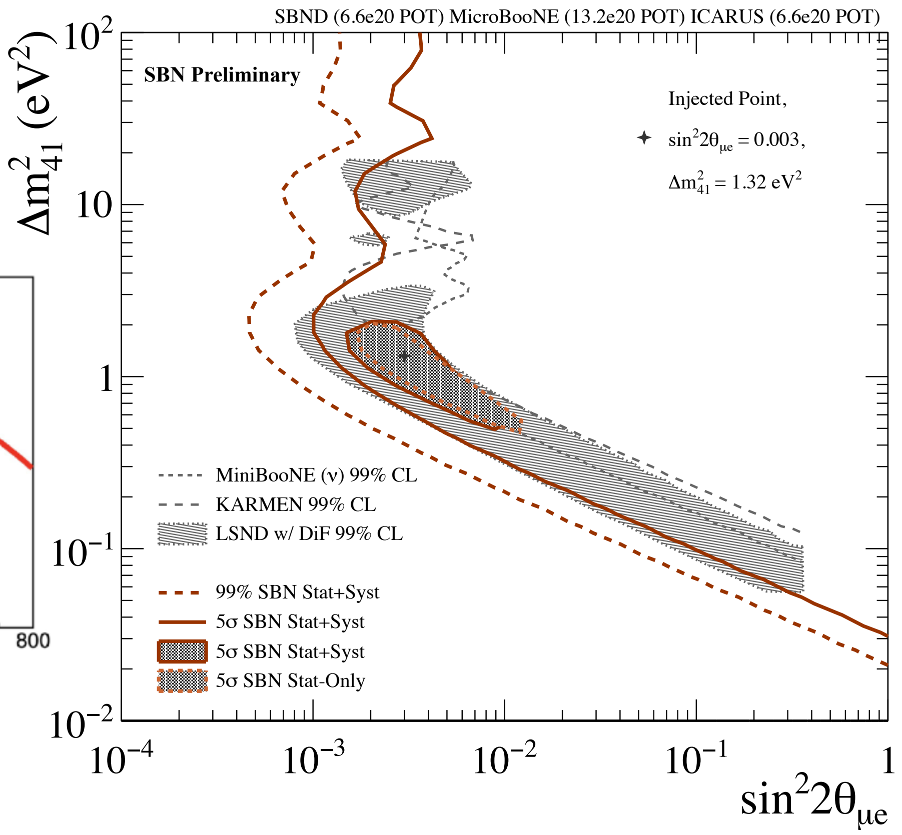


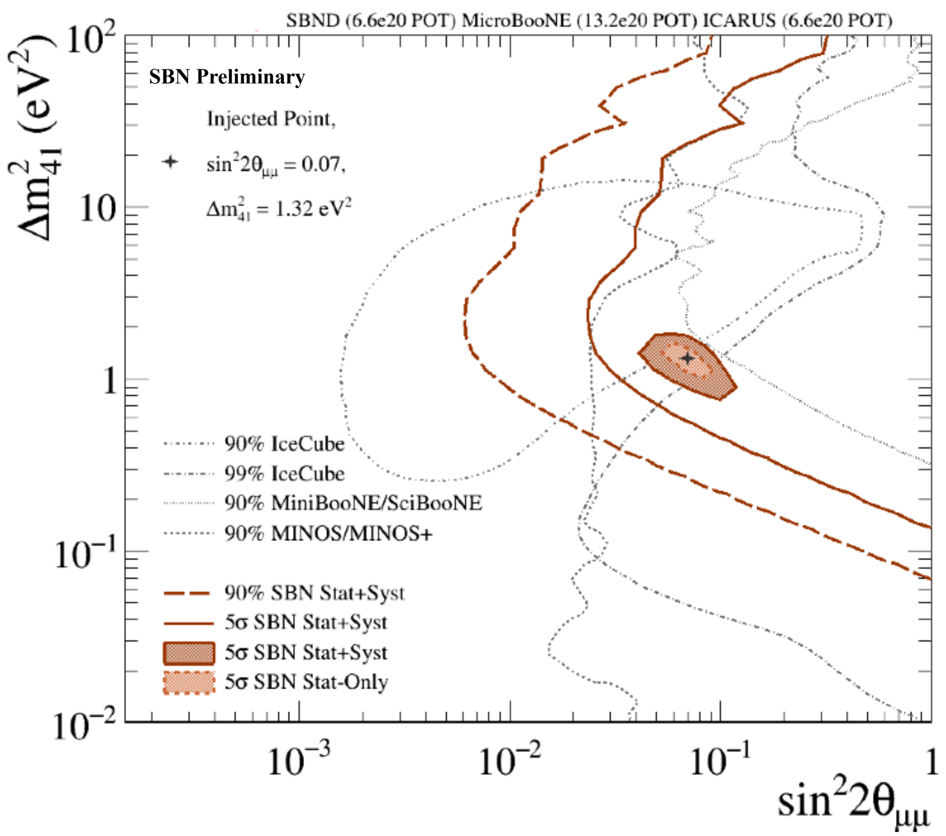

- For $\nu_e$ measurements in the BNB, $\nu_\mu$ backgrounds can be significant, e.g. from NC $1\pi^0$ events
- Due to meson decay kinematics, $\nu_e$ are distributed more evenly across the face of SBND than $\nu_\mu$
  - The $\nu_\mu$ come from two-body decays, while $\nu_e$ generally come from three-body decays and therefore have larger angular spread from the beam axis
- For $\nu_e$ analyses, further off-axis slices provide a reduction in $\nu_\mu$-induced backgrounds

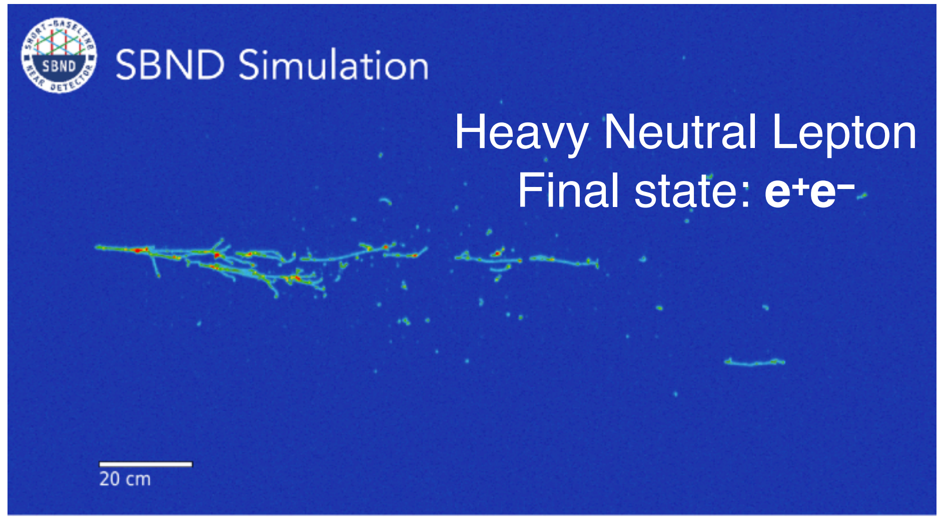
# Sterile Neutrinos and Other BSM Physics in SBND

- SBND contributes to the SBN Program as the near detector, characterizing the beam before eV-scale oscillations set in and thus addressing dominant systematic uncertainties
  - SBN has a unique chance to jointly study $\nu_e$ appearance, $\nu_\mu$ disappearance, and $\nu_e$ disappearance
- In addition, SBND will pursue other possible explanations for the MiniBooNE low-energy excess anomaly as well as other beyond Standard Model physics scenarios
  - Actively collaborating with theorists to explore possibilities for BSM searches with our detector



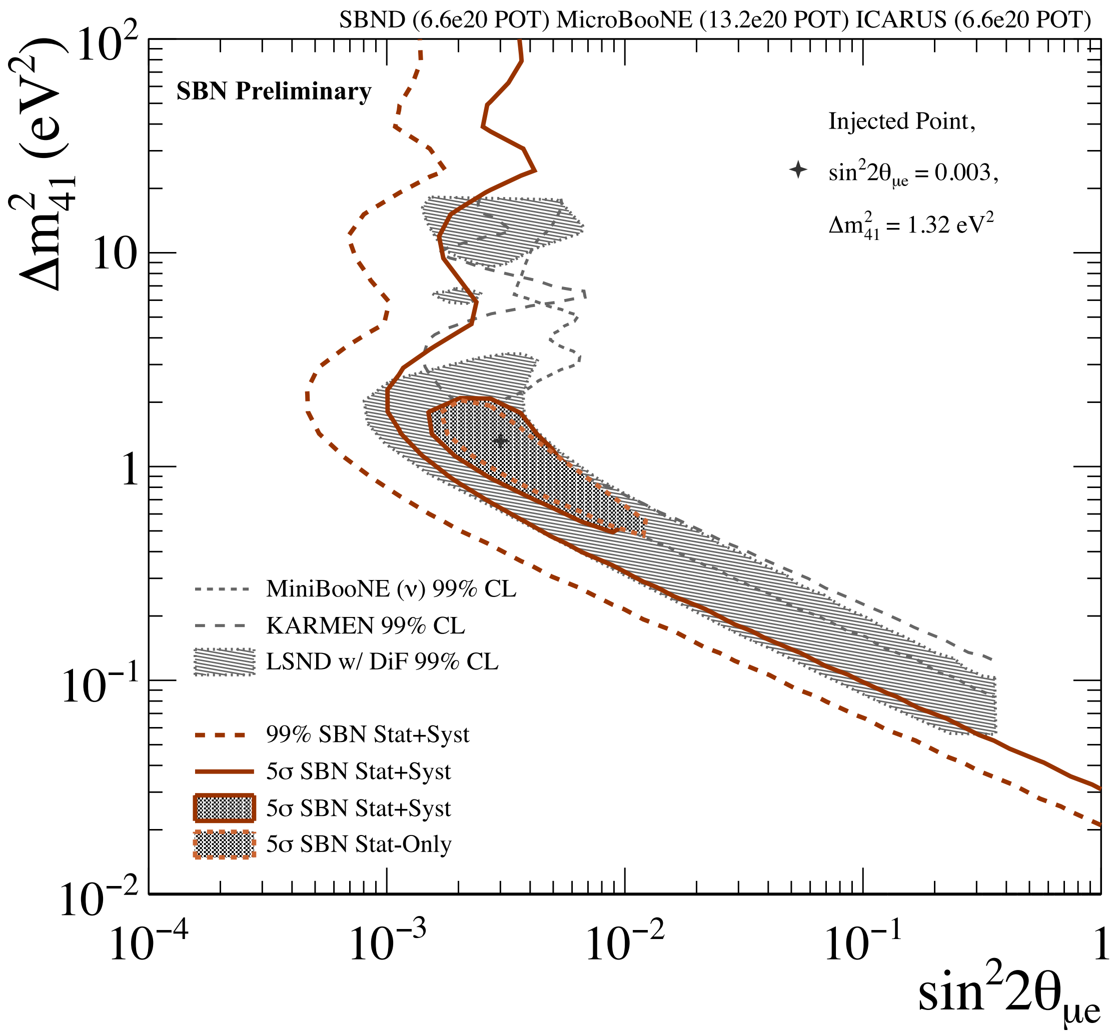



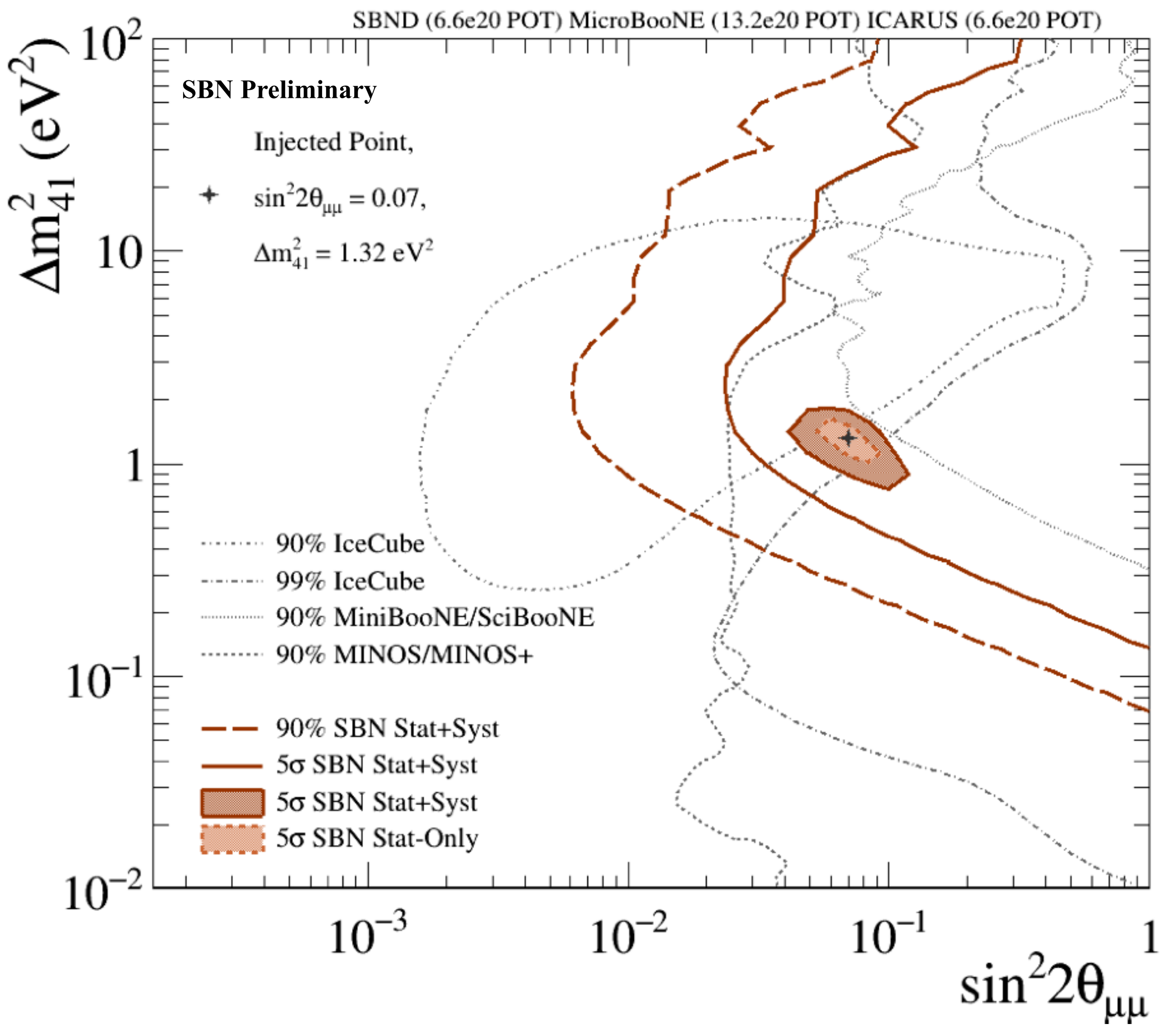



# SBN Oscillation Sensitivities

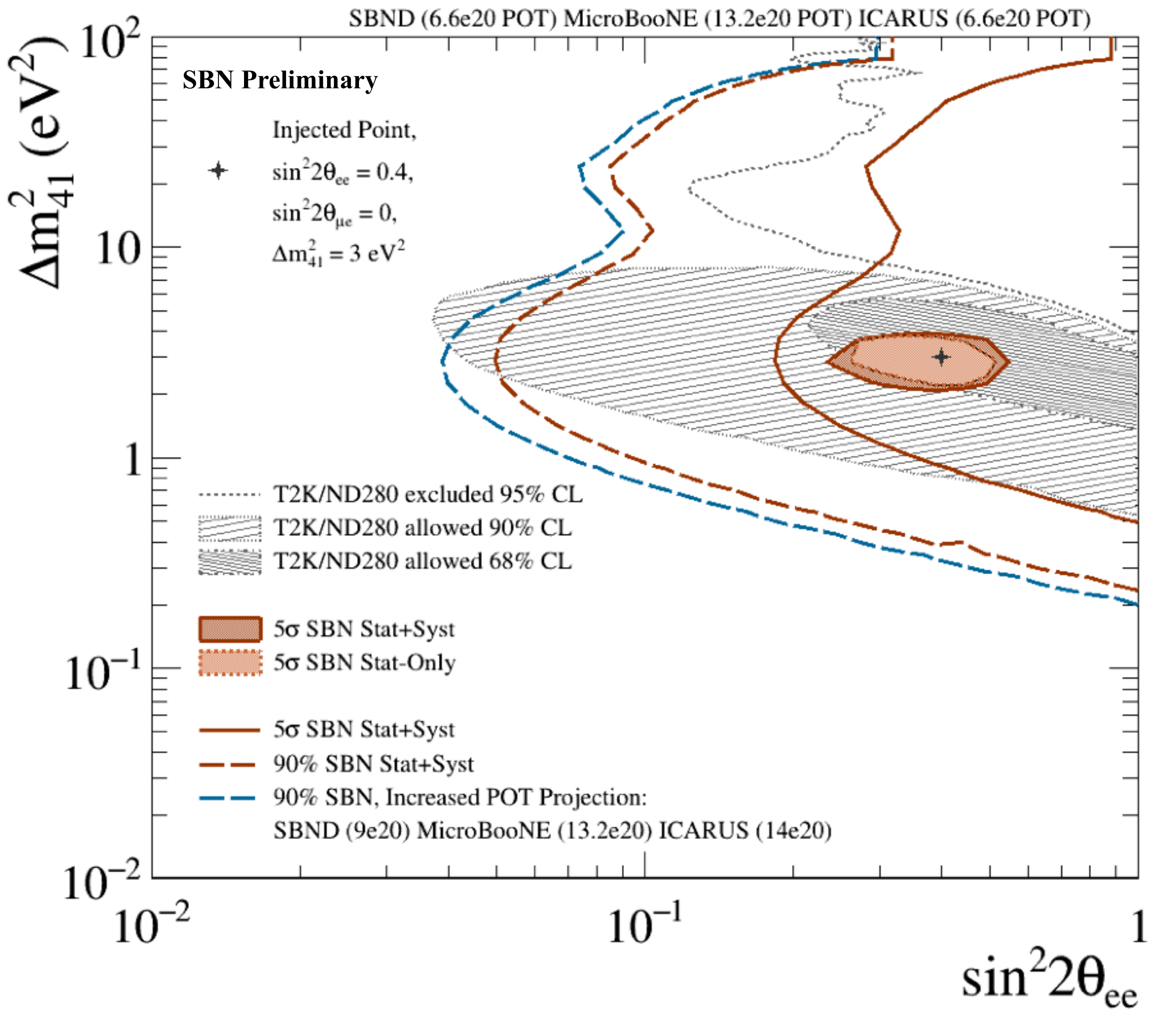
## $\nu_e$ Appearance




## $\nu_\mu$ Disappearance




## $\nu_e$ Disappearance



# Interaction Measurements and Other Physics Topics

- All of the information gained from measuring neutrino interactions in SBND will feed back into the overall SBND and SBN physics programs
- For SBN oscillation analyses, the constraints on the BNB neutrino interactions will be critical to reducing systematic uncertainties and reaching sensitivity targets
  - The SBND-PRISM effect offers the opportunity to put the PRISM concept into practice, using linear combinations of the fluxes at the near detector to compare to the oscillated flux at the far detector
- For new and rare physics searches, understanding of neutrino interactions is often critical to understanding and controlling neutrino-induced backgrounds