Neutrino Interaction Measurement Capabilities of the SBND Experiment

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On Behalf of the SBND Collaboration

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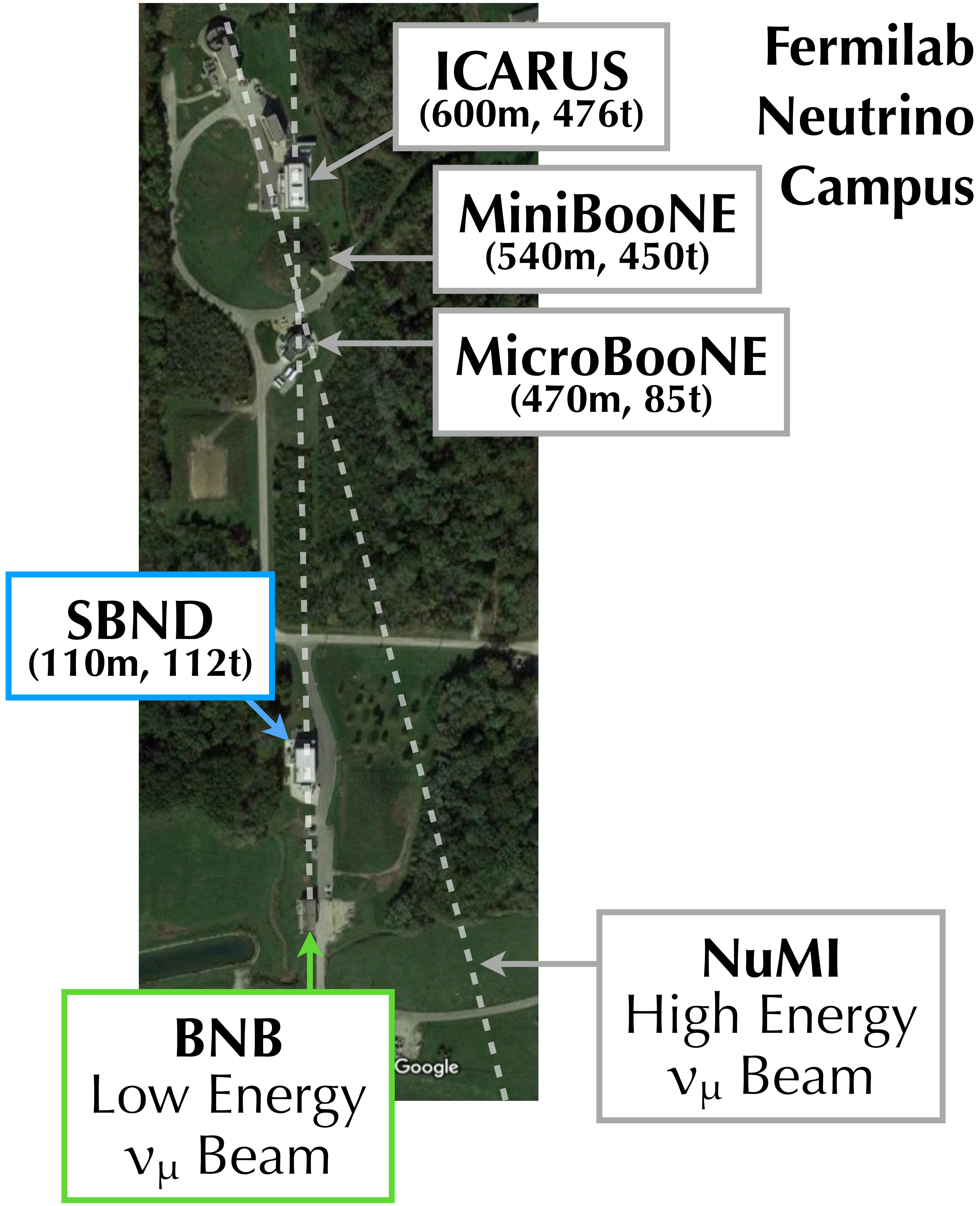
Neutrino Interactions and the SBND Physics Program

- As you heard in Supraja's talk, SBND is part of Fermilab's Short Baseline Neutrino (SBN) program
- The main physics goals of SBND include:
  - Serving as the near detector for the SBN oscillation analyses searching for eV-scale sterile neutrinos
  - Studying neutrino–argon cross sections at the GeV scale
  - Searching for new and rare physics processes in the neutrino sector and beyond
- Neutrino interaction physics is important for all of this
  - For precise oscillation and BSM measurements, interactions must be well-understood and well-modeled
- Information learned about neutrino–argon interactions will inform theory & generator work, and lay important groundwork for future experiments such as DUNE



Fermilab Neutrino Campus

ICARUS (600m, 476t)

MiniBooNE (540m, 450t)

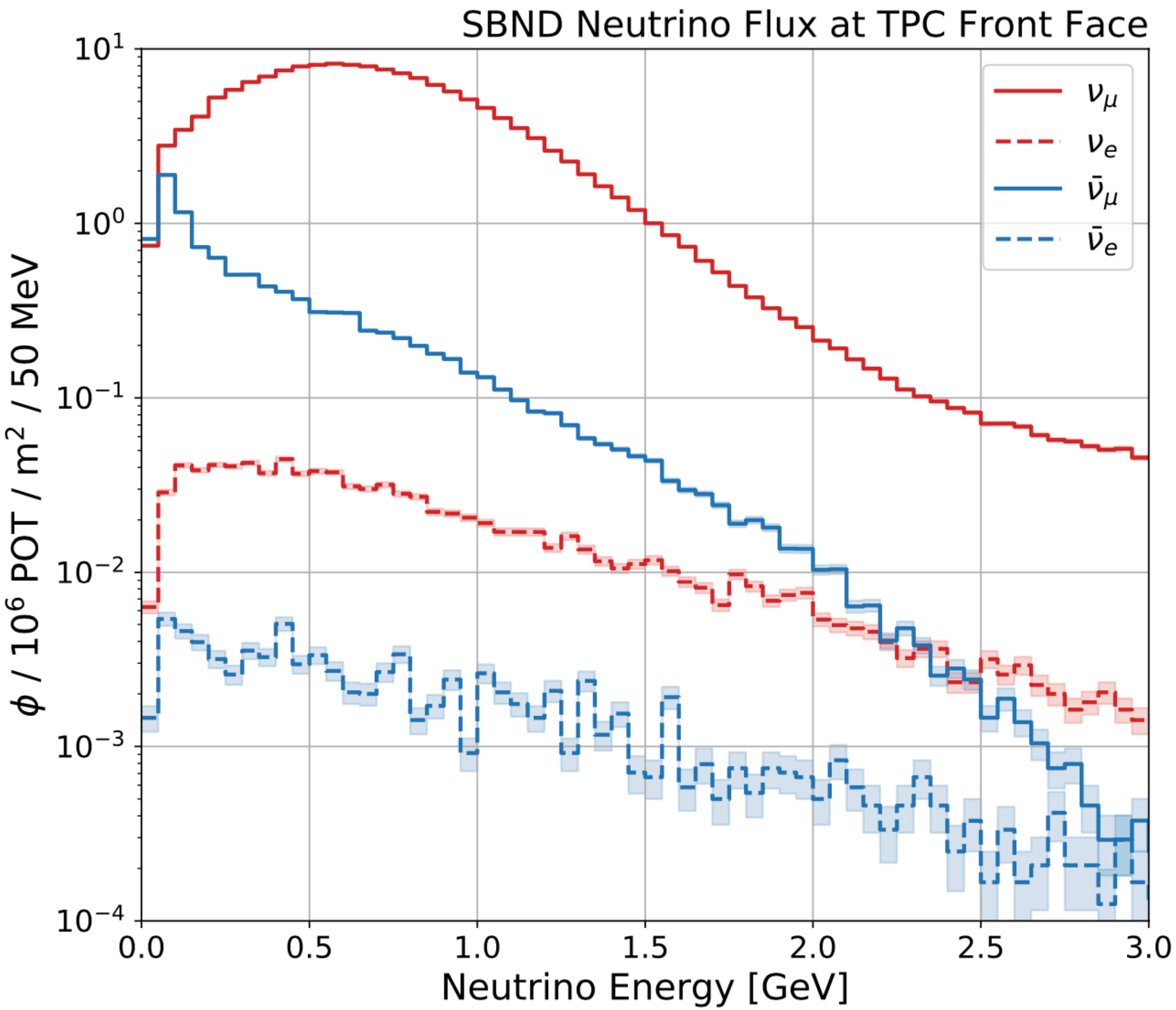
MicroBooNE (470m, 85t)

SBND (110m, 112t)

BNB Low Energy ν_μ Beam

NuMI High Energy ν_μ Beam

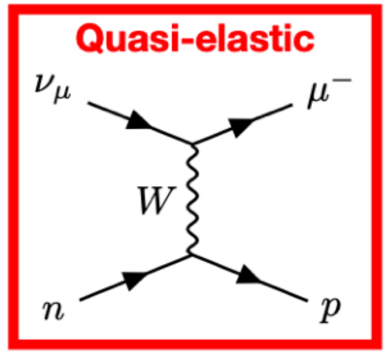
Booster Neutrino Beam Flux at SBND

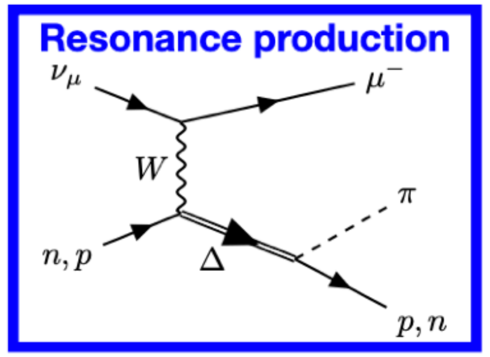


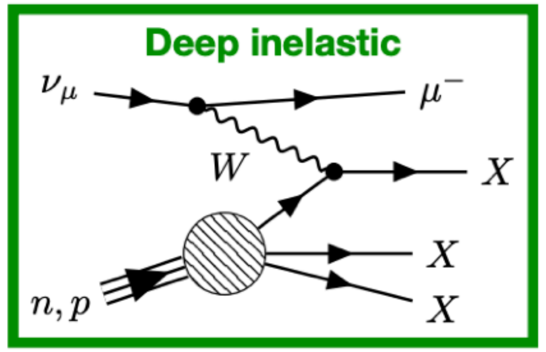
- The primary beam of interest at SBND is the Booster Neutrino Beam (BNB)
- The mean energy for muon neutrinos is about 0.8 GeV
- Beam composition by neutrino flavor:
  - 93.6% ν_μ
  - 5.9% $\overline{\nu}_\mu$
  - 0.5% ν_e+$\overline{\nu}_e$
- Plan to collect data corresponding to 10e20–18e20 protons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

Neutrino Interactions on Argon

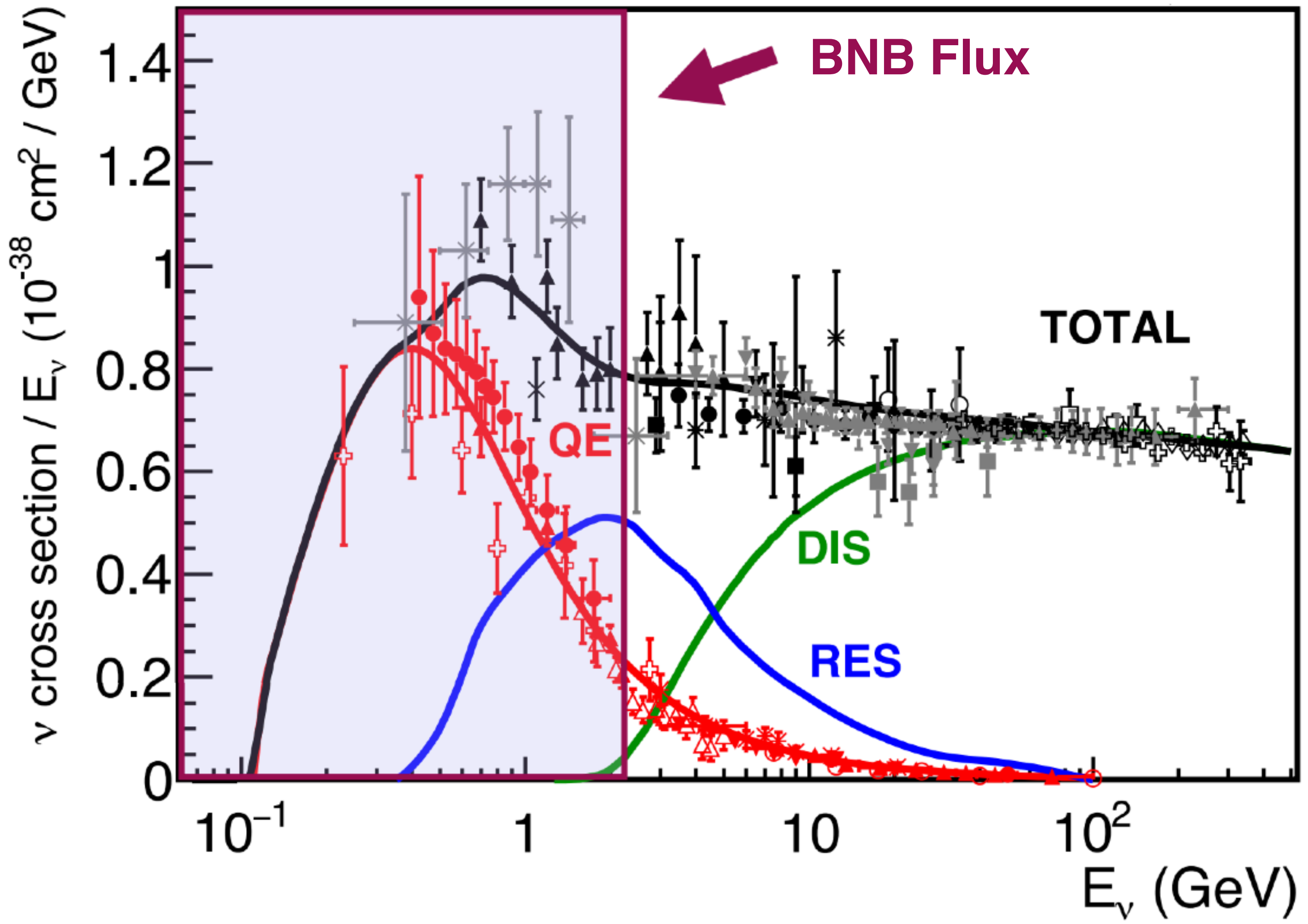
- Understanding and modeling neutrino interactions is essential for interpreting final state particle content and kinematics to extract information about the initial state neutrino
- Theory of neutrino interactions on argon (A=40) is complex due to multiple processes, nuclear effects, and final-state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

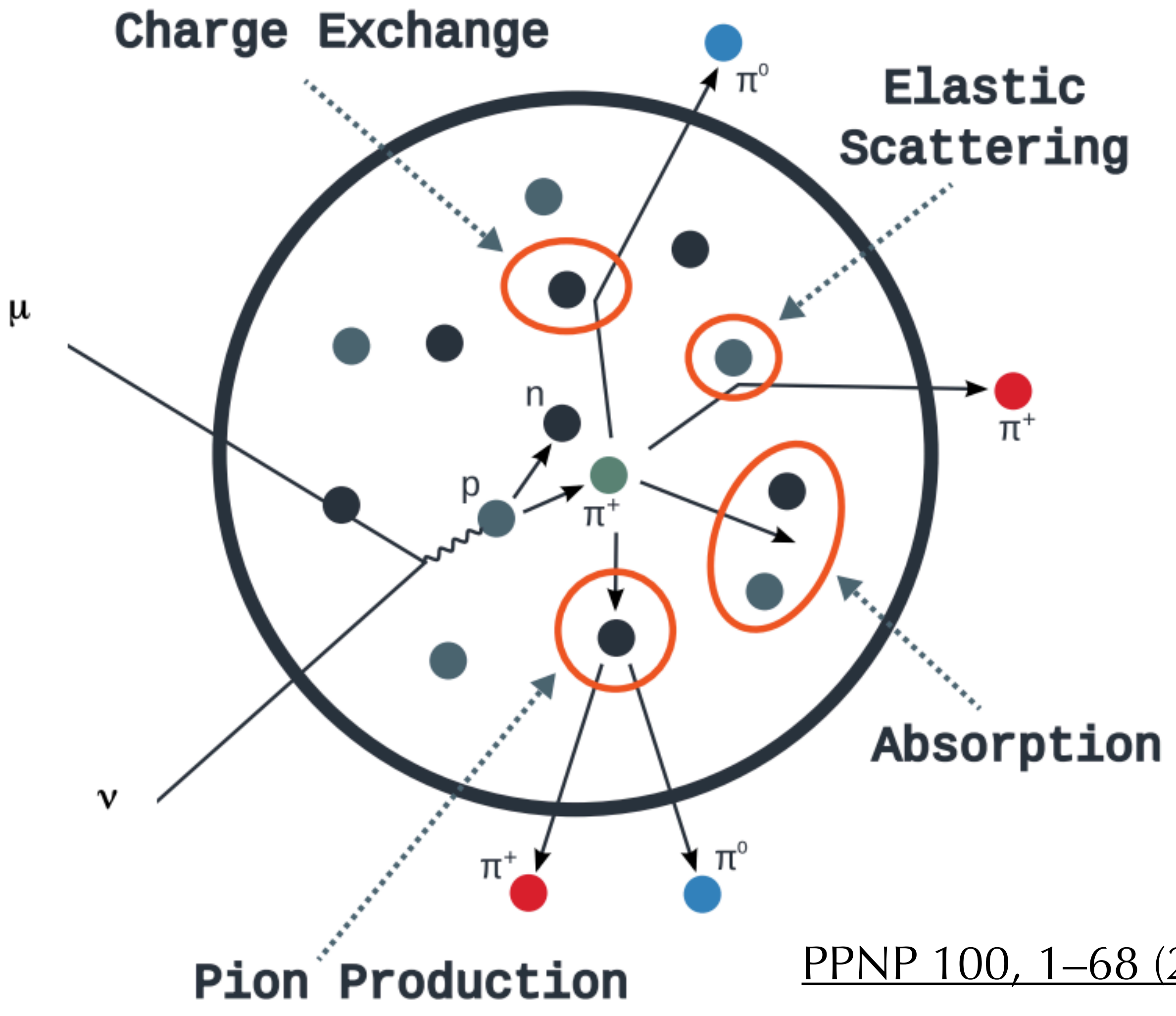






Rev. Mod. Phys. 84, 1307 (2012)

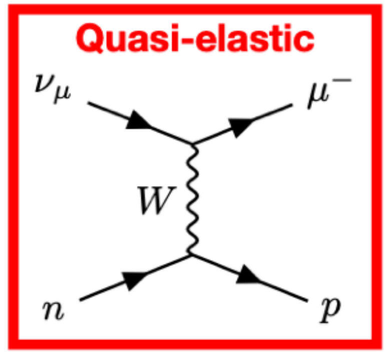


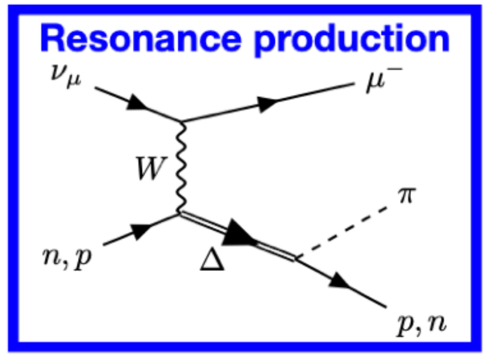


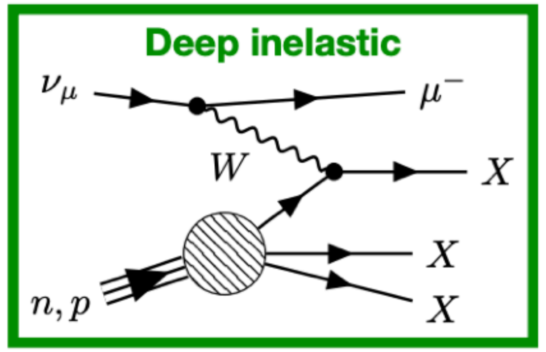
PPNP 100, 1–68 (2018)

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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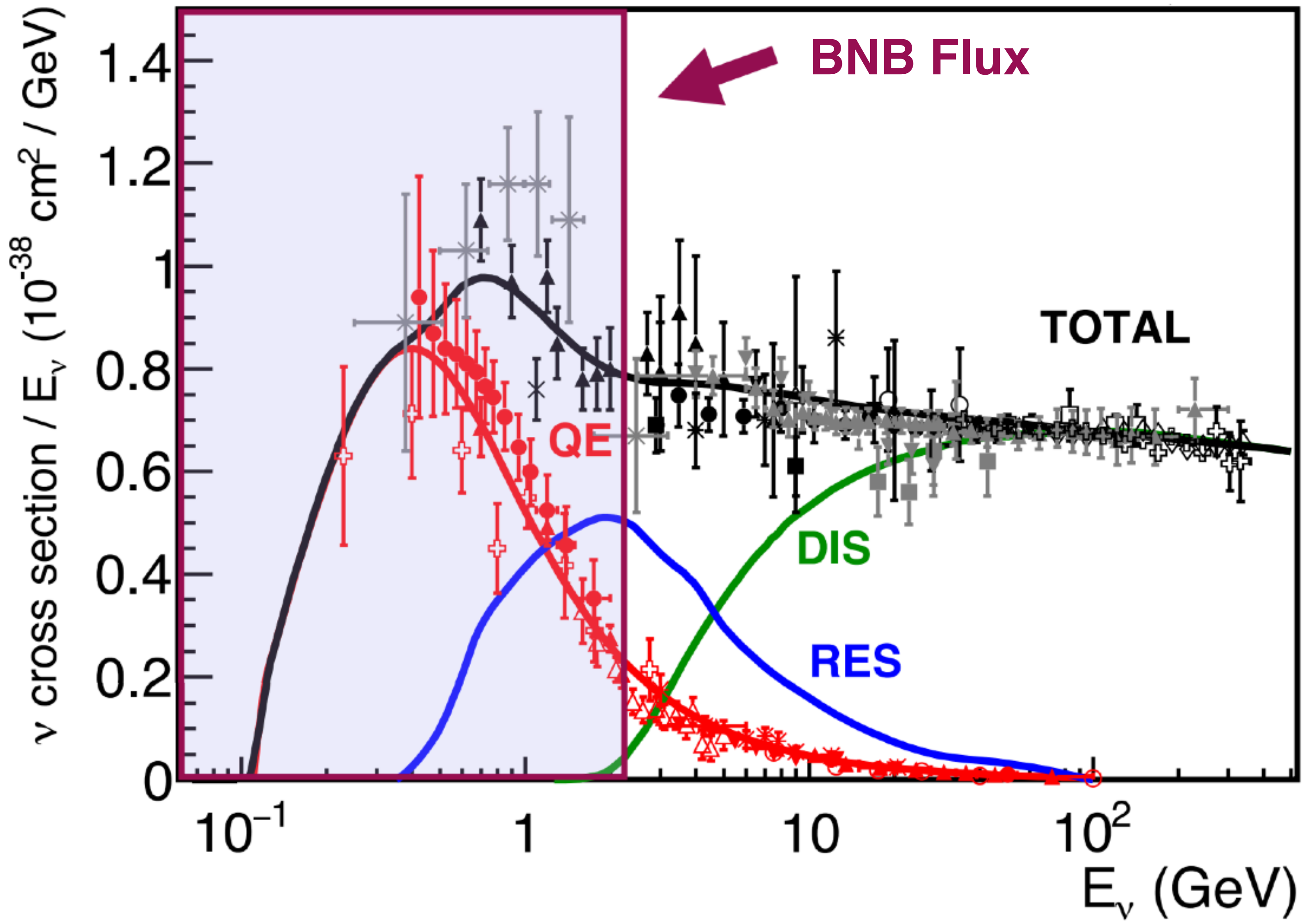
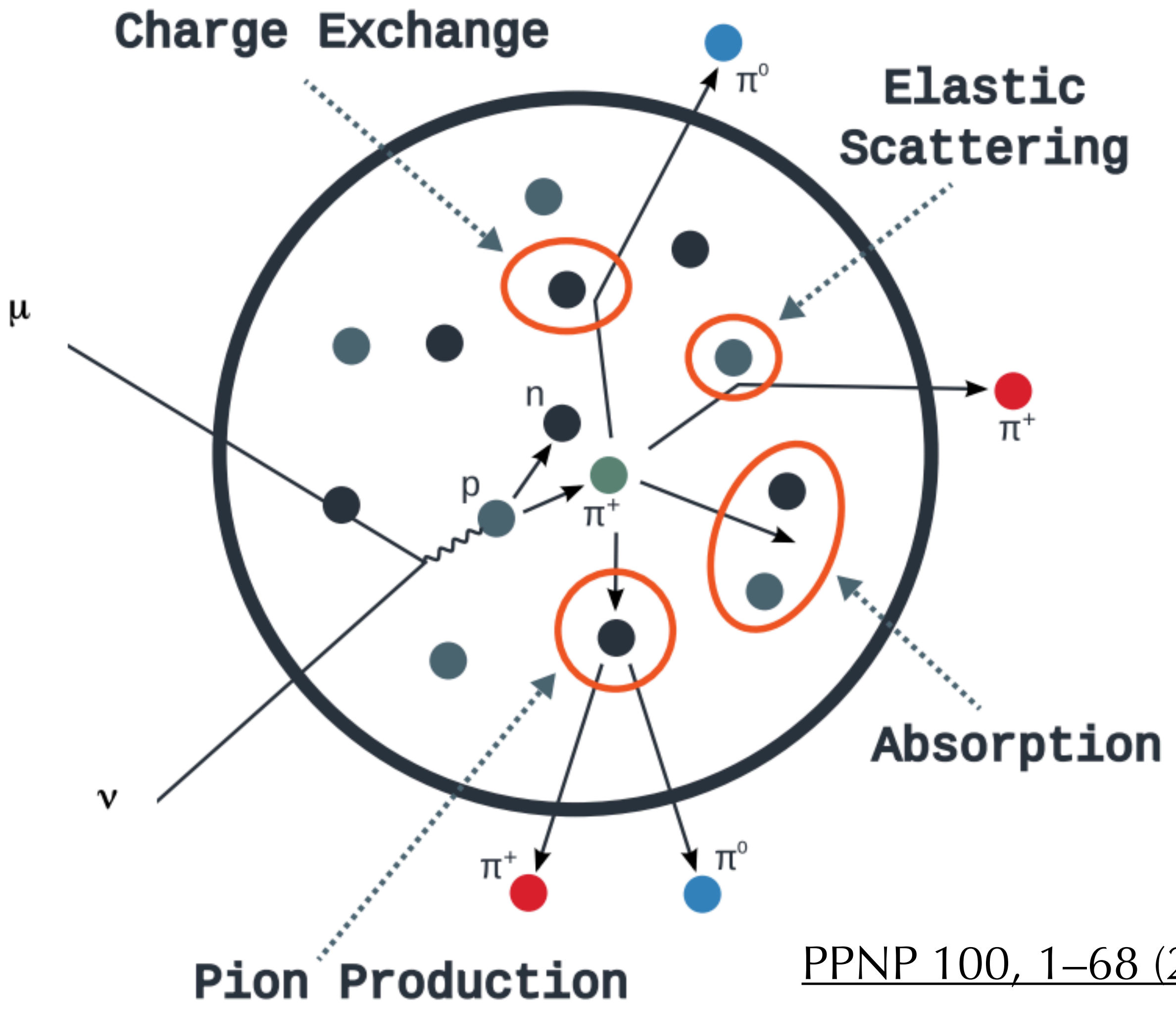
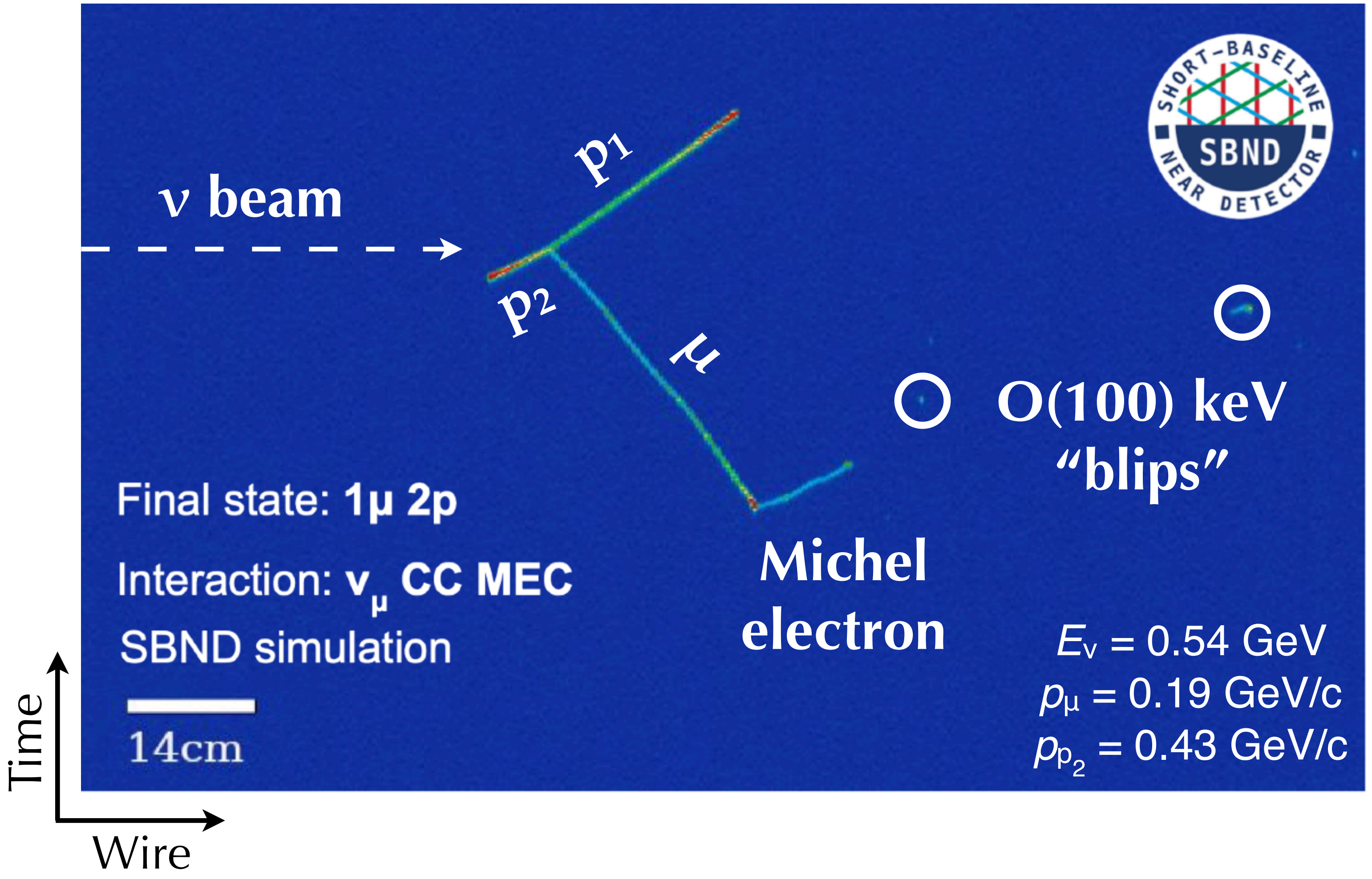


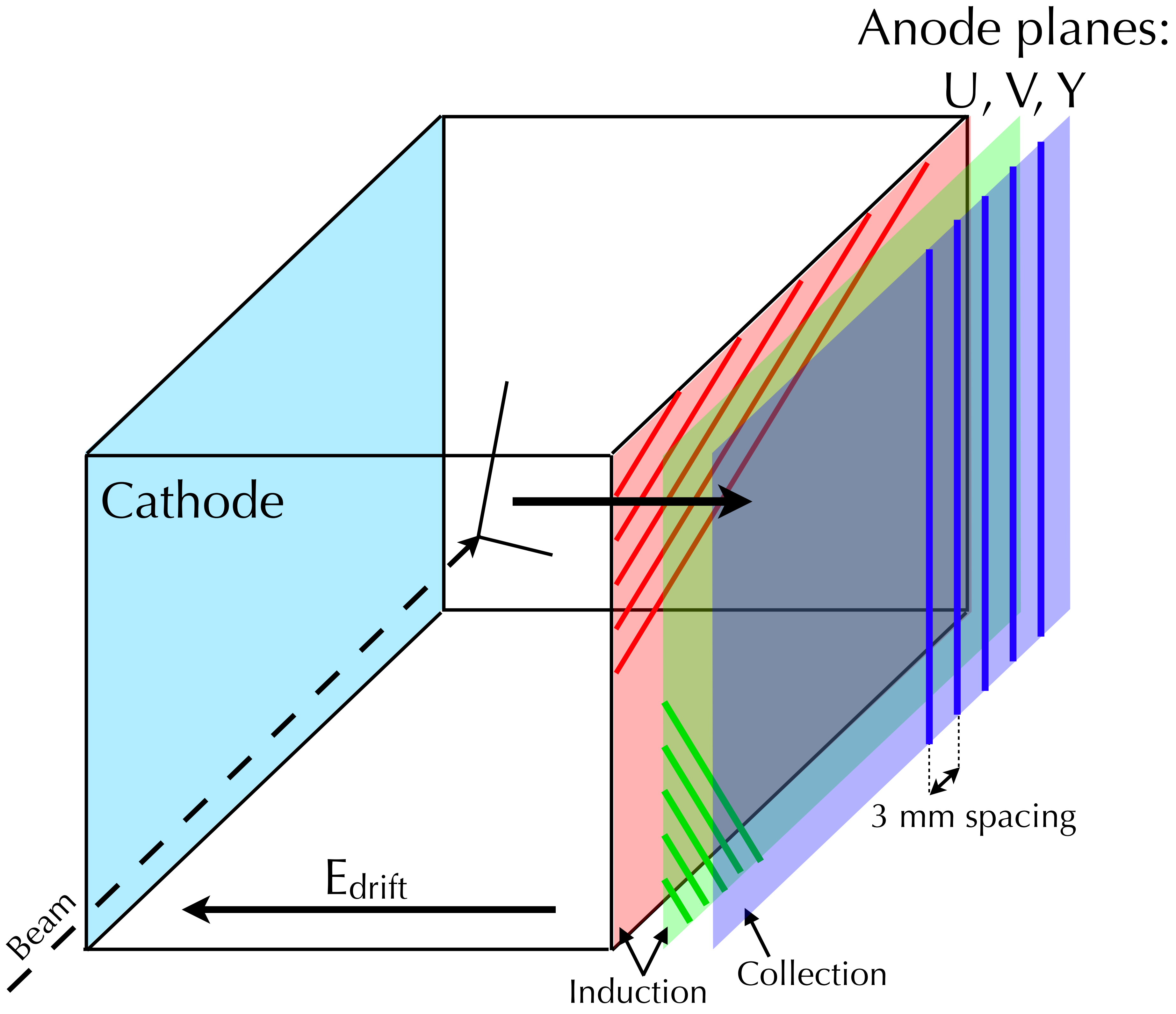


PPNP 100, 1–68 (2018)

Detecting Neutrino Interactions with SBND

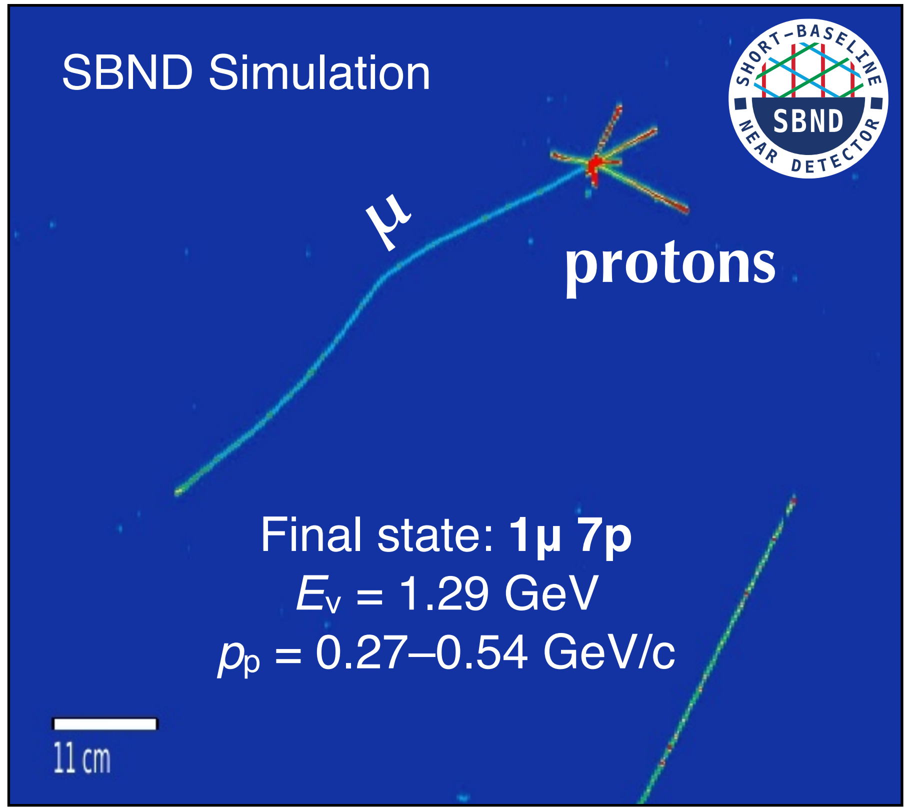
- LArTPCs are highly-capable, fully-active tracking calorimeters
- Detailed images of neutrino interactions enable low reconstruction thresholds and excellent particle identification



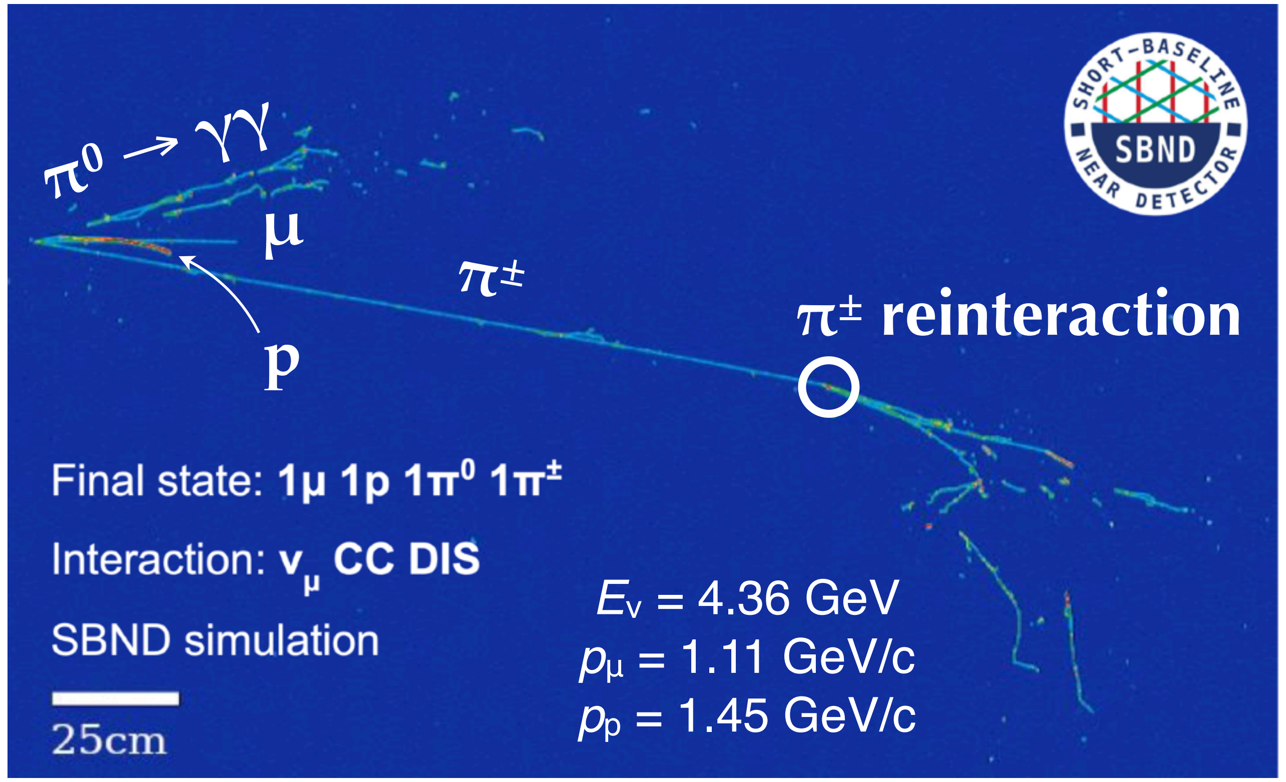


Detecting Neutrino Interactions with SBND

- SBND's wires are spaced 3mm apart, similar to MicroBooNE and ICARUS (and closer than ArgoNeuT and DUNE)
- High 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

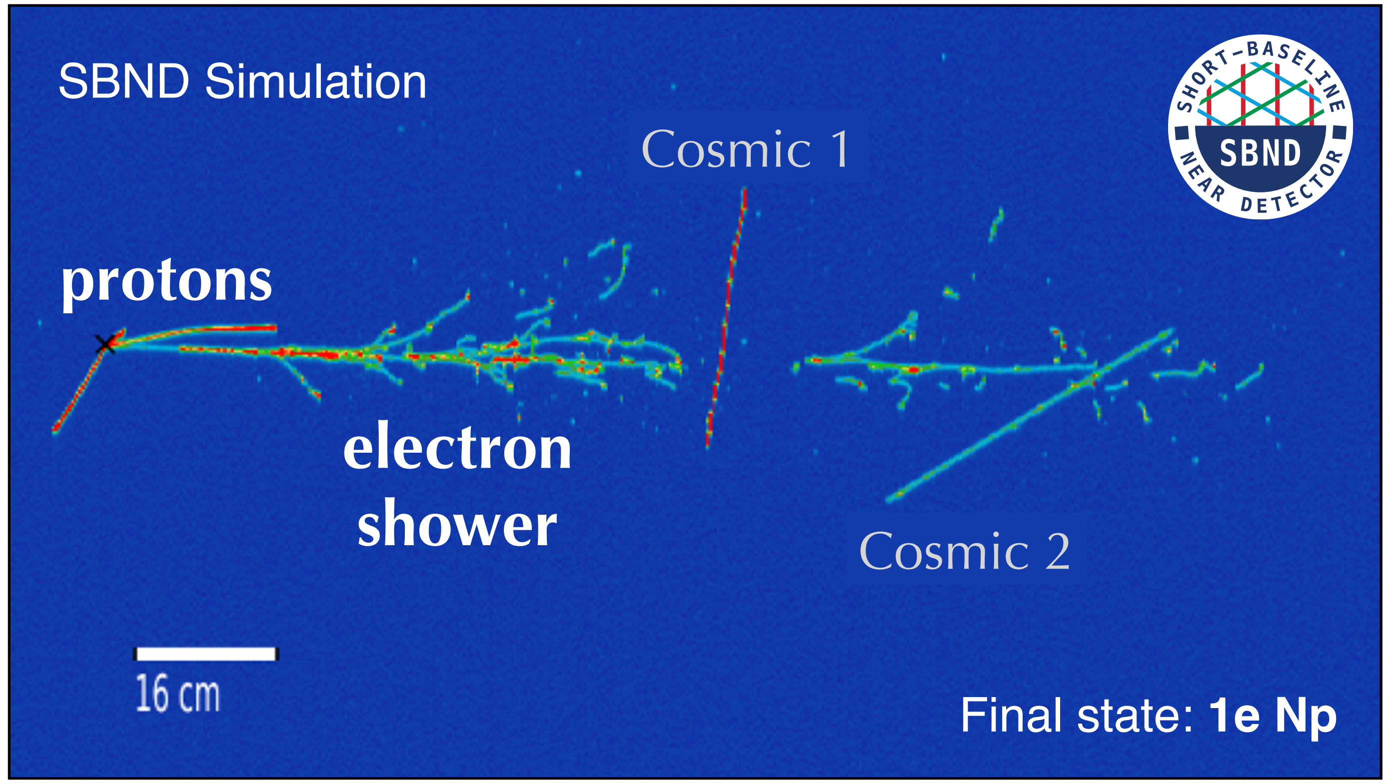


Final state: **1μ 7p**
E_ν = 1.29 GeV
p_p = 0.27–0.54 GeV/c



Final state: **1μ 1p 1π^0 1$\pi^\pm$**
Interaction: **ν_μ CC DIS**
SBND simulation

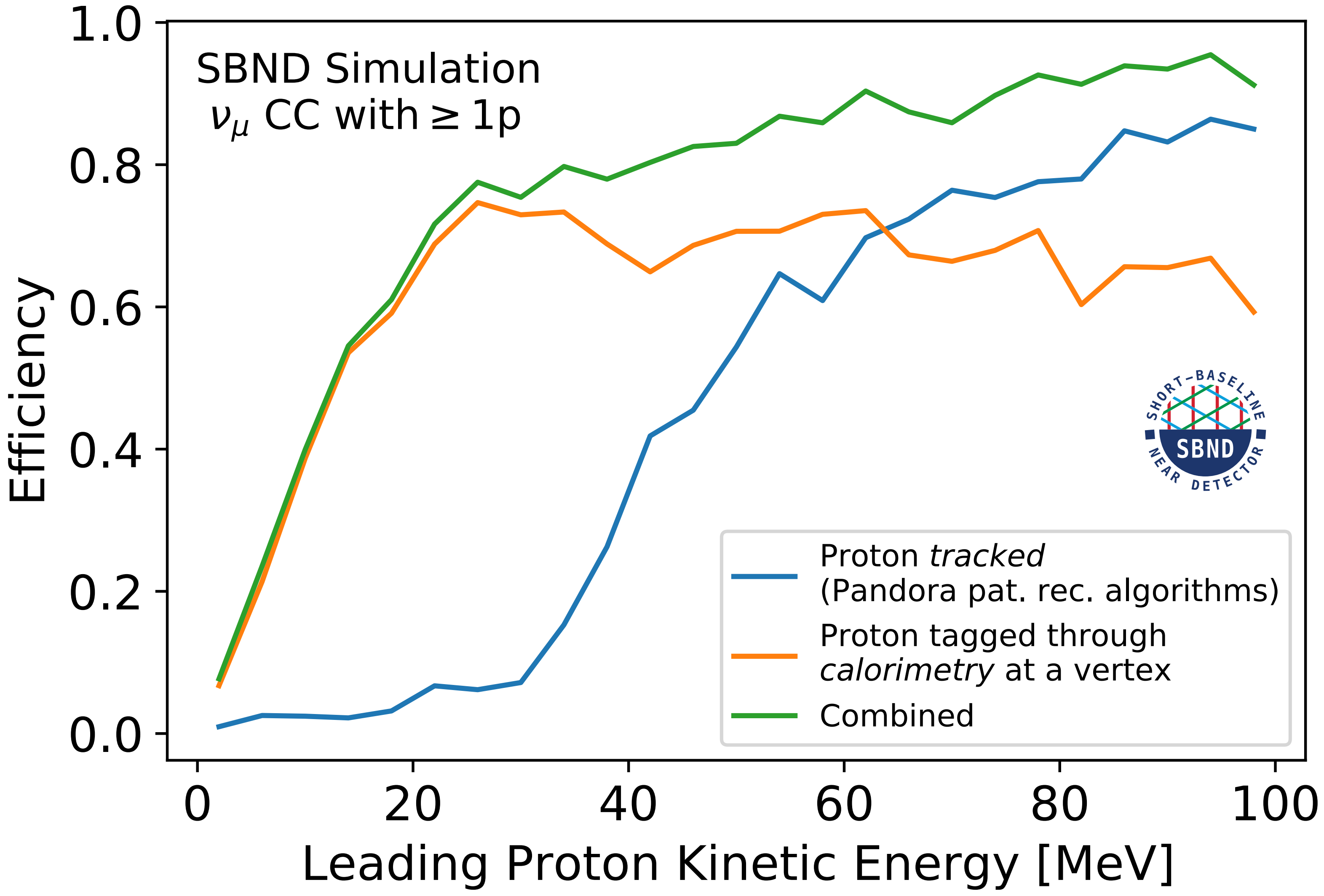
E_ν = 4.36 GeV
p_μ = 1.11 GeV/c
p_p = 1.45 GeV/c

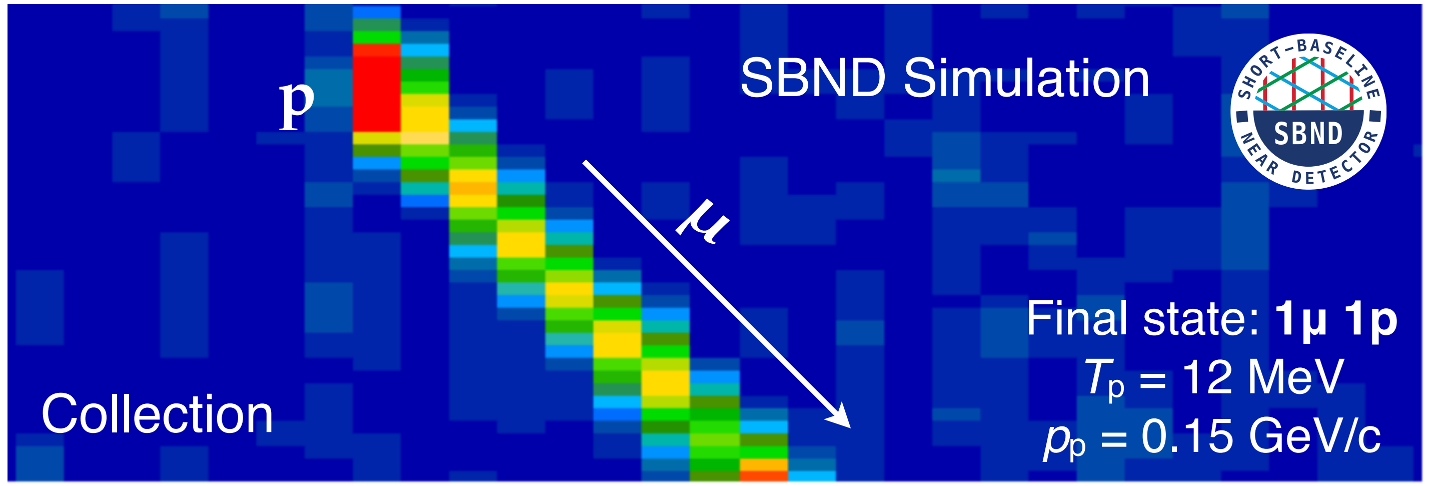


Final state: **1e Np**

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)

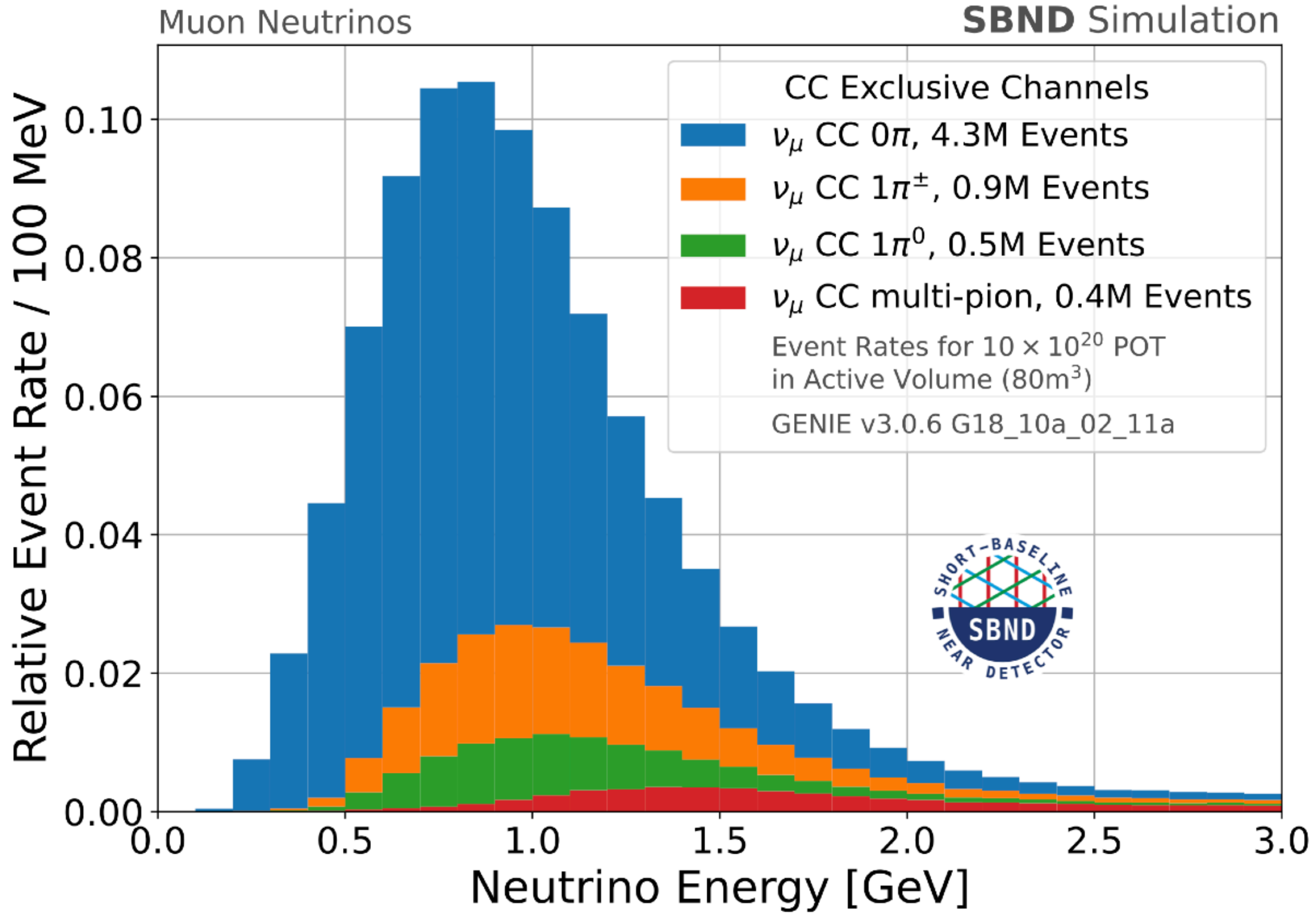


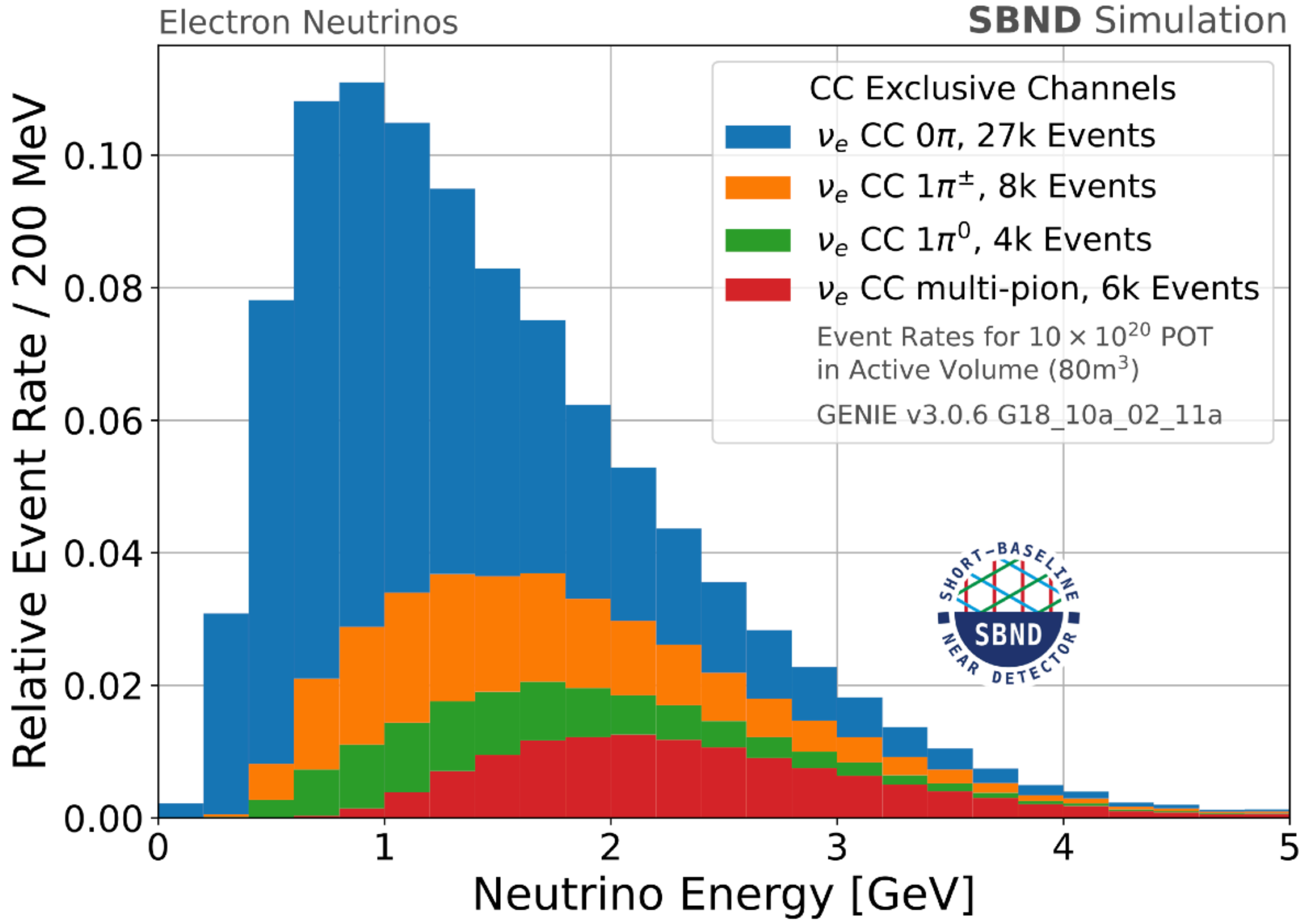


Pandora pattern recognition:
Eur. Phys. J. C 78, 82 (2018)

Neutrino Interaction Rates in SBND

- SBND expects approximately 2 million ν_μ CC and 15,000 ν_e CC interactions per year, with around 5,000 total neutrino interactions observed per day
  - Every ~3 months, SBND will collect a dataset equivalent to the full MicroBooNE BNB five-year run
- Will record ~20–30x more neutrino–argon interactions than is currently available





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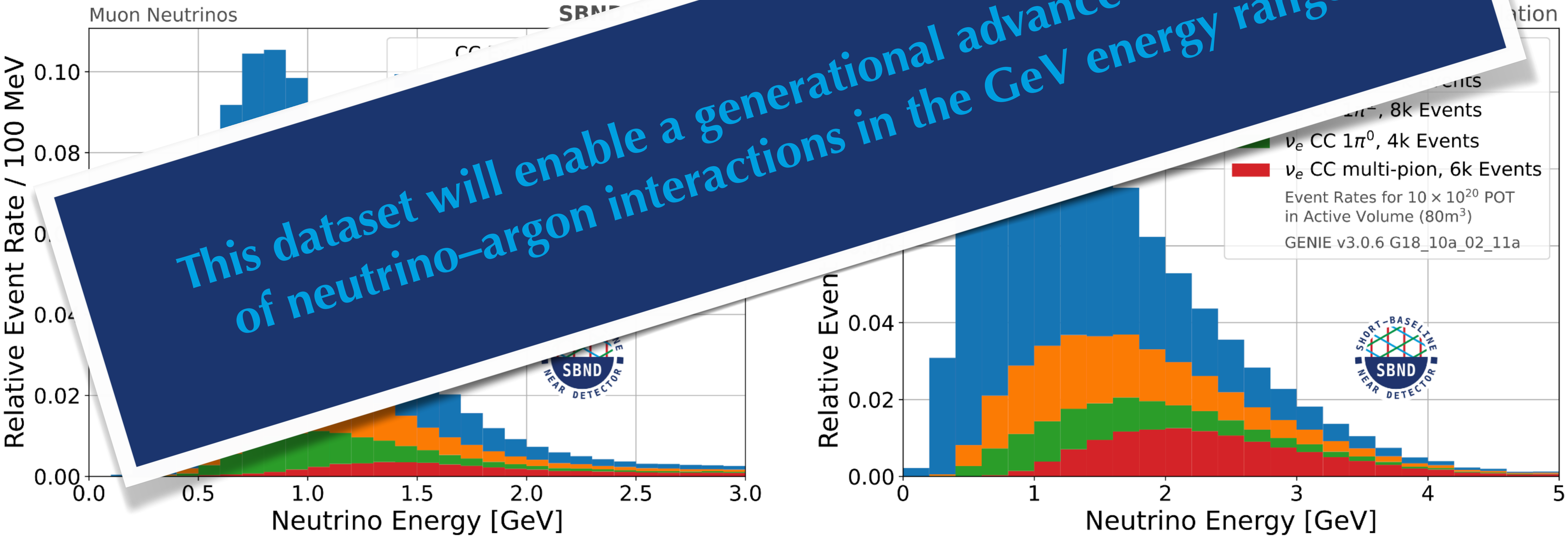


This dataset will enable a generational advance in the study of neutrino–argon interactions in the GeV energy range

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 **ν_μ CC inclusive** interactions
    - 4.3 million **ν_μ CC Np0π**
      - 2.5 million **ν_μ CC 1p0π**
      - 0.7 million **ν_μ CC 2p0π**
    - 0.9 million **ν_μ CC 1$\pi^\pm$ + X**
    - 0.5 million **ν_μ CC 1π^0 + X**
    - 0.4 million **ν_μ CC $\geq$2π + X**
  - ~600 **ν_μ CC K^+K^- + X**
  - ~700 **ν_μ CC $K^0\overline{K}^0$ + X**
  - >1,000 **ν_μ CC with charm baryons**
  - ~45,000 **ν_e CC inclusive** interactions
  - 2.5 million **NC inclusive** interactions
    - 1.7 million **NC 0π + X**
    - 0.5 million **NC 1π^0 + X**

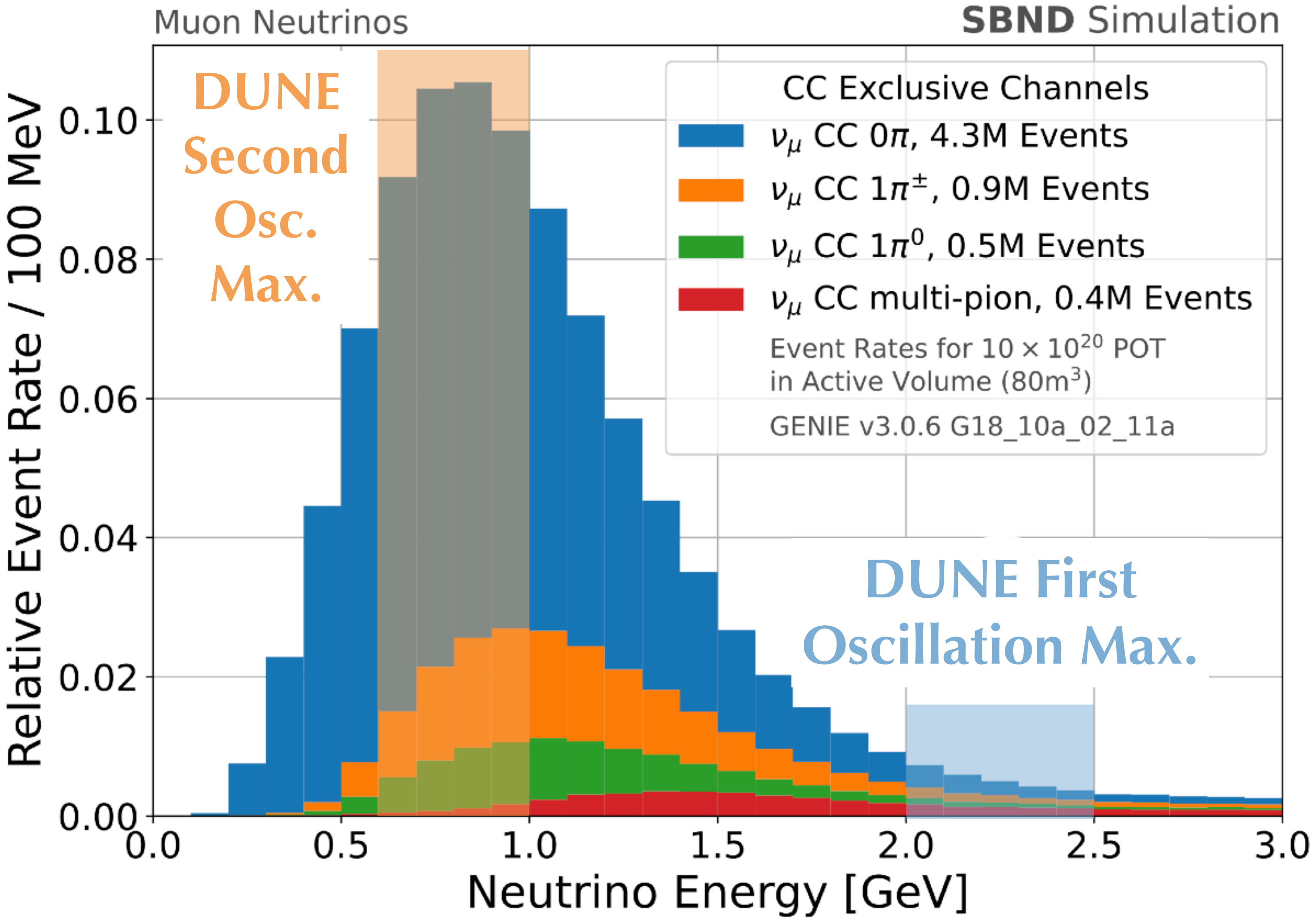
R. Jones PhD thesis

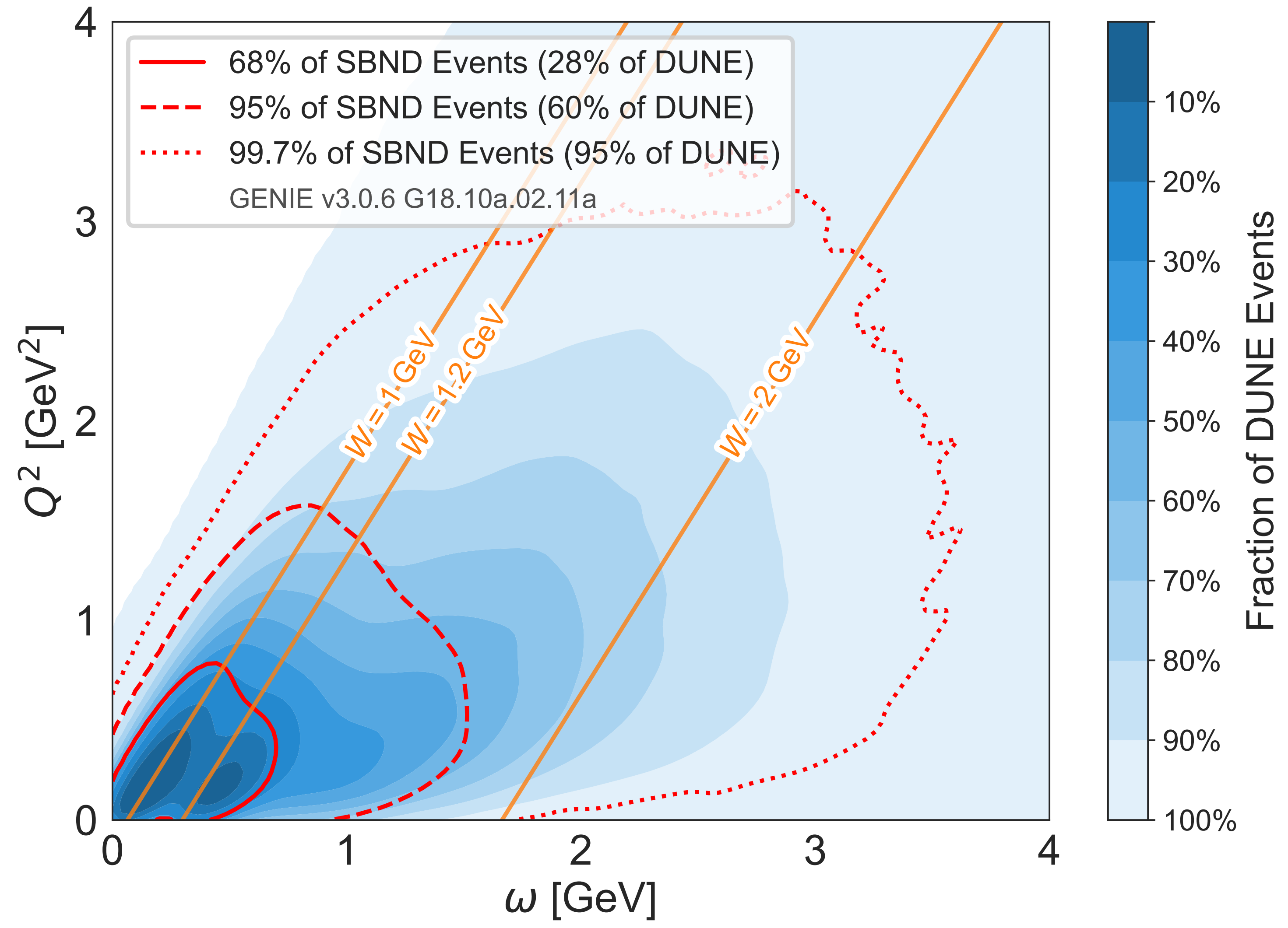
Neutrino Interaction Measurements in SBND

- 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…
  - **ν_μ CC inclusive**
  - **ν_μ CC Np 0π**
  - **ν_μ CC Np 1π^0**
  - **ν_μ CC Np 1$\pi^\pm$**
  - **$\bar{\nu}_\mu$ CC quasielastic hyperon production (Λ^0, Σ^0, Σ^-)**
  - **ν_μ CC inelastic kaon production ($K^+ + \Lambda^0$)**
  - **ν_e CC inclusive**
  - **NC Np 0π**
  - **NC Np 1π^0**
  - **NC Np 1γ**
  - **Neutrino–electron elastic scattering**
  - … more to come!

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





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

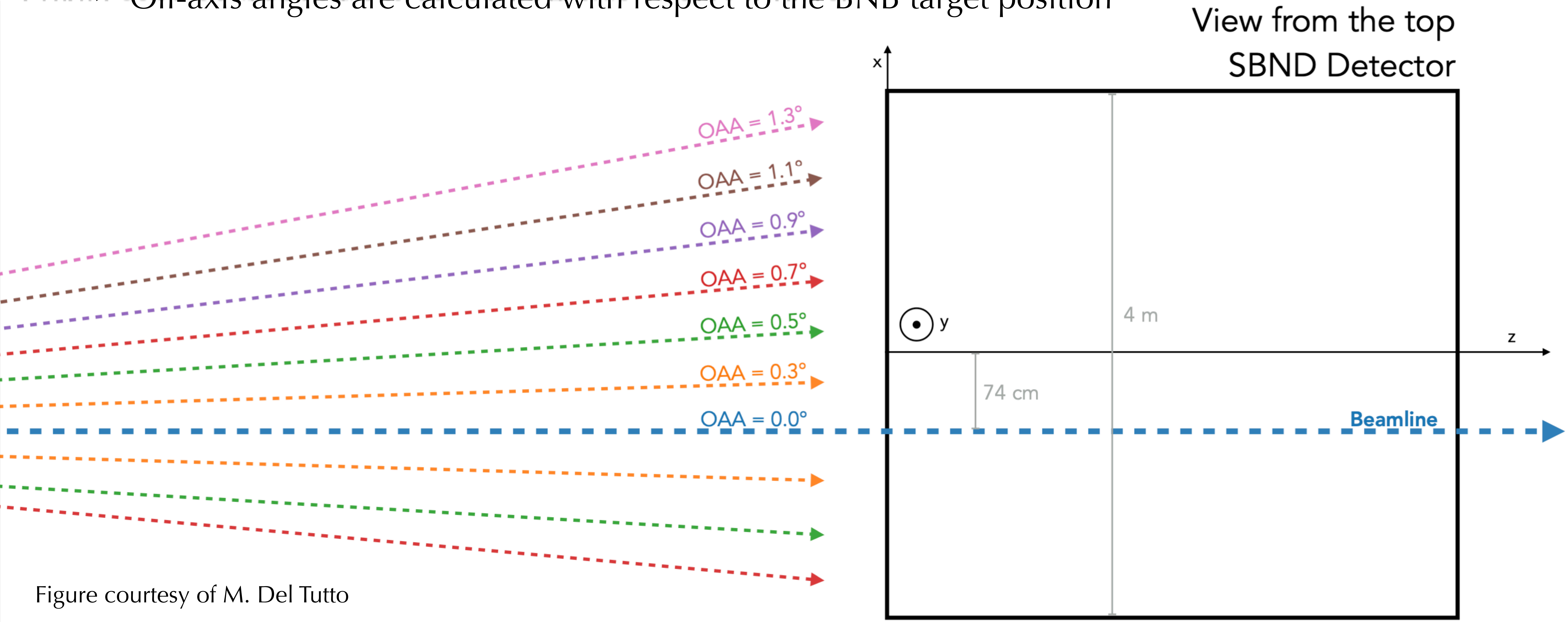
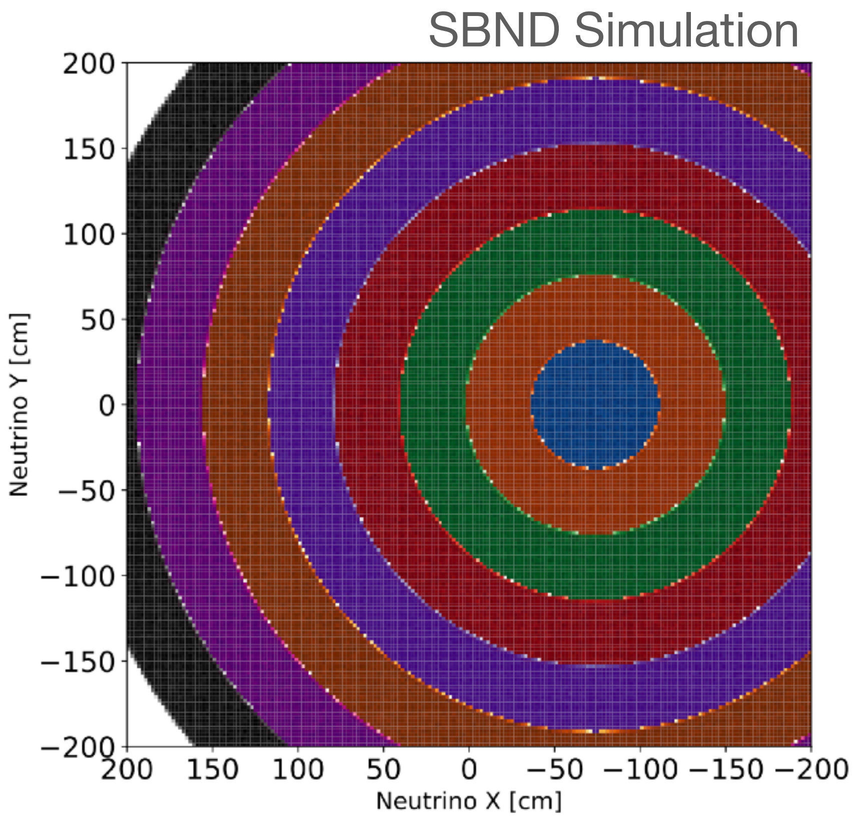


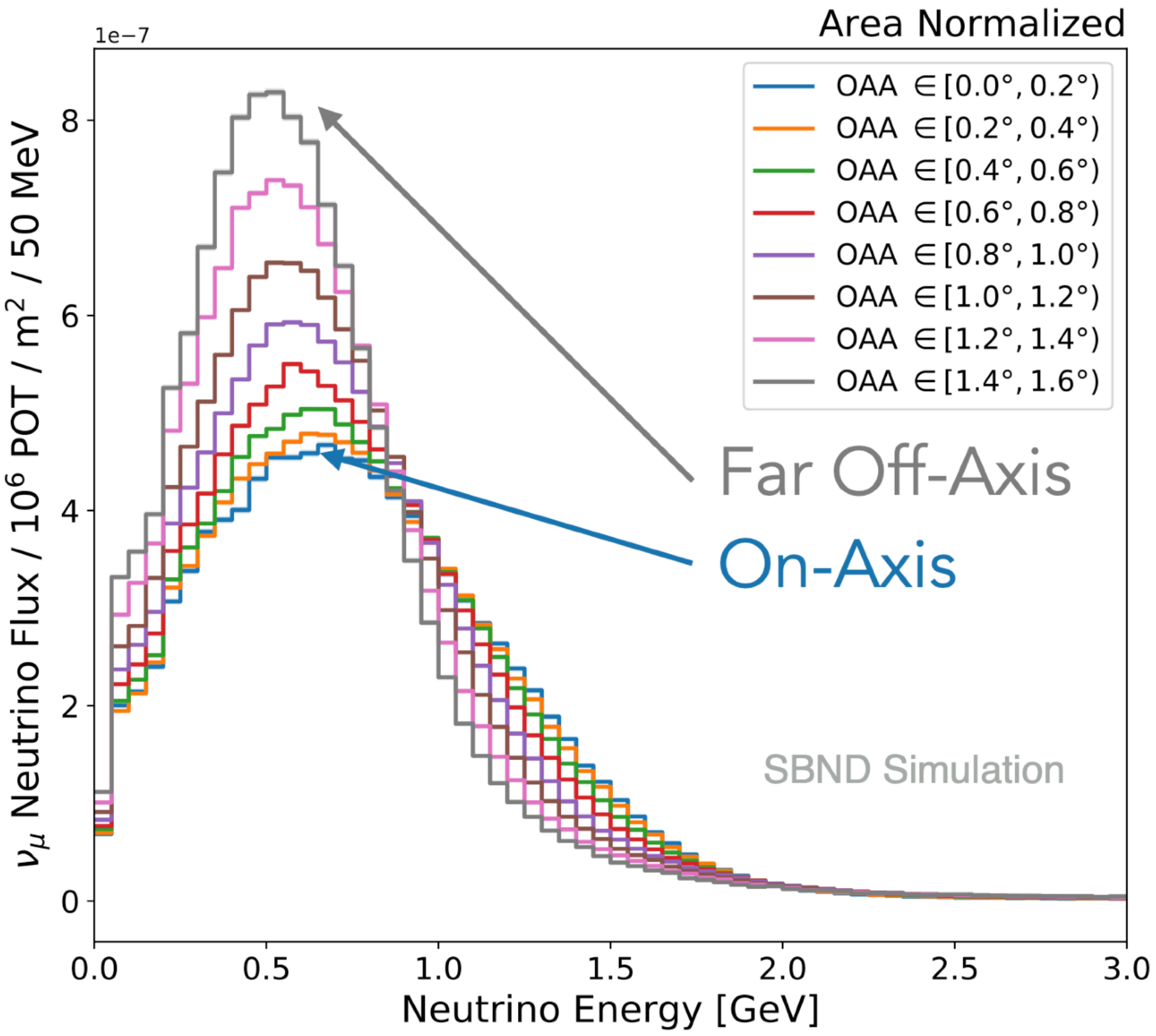
Figure courtesy of M. Del Tutto

SBND-PRISM

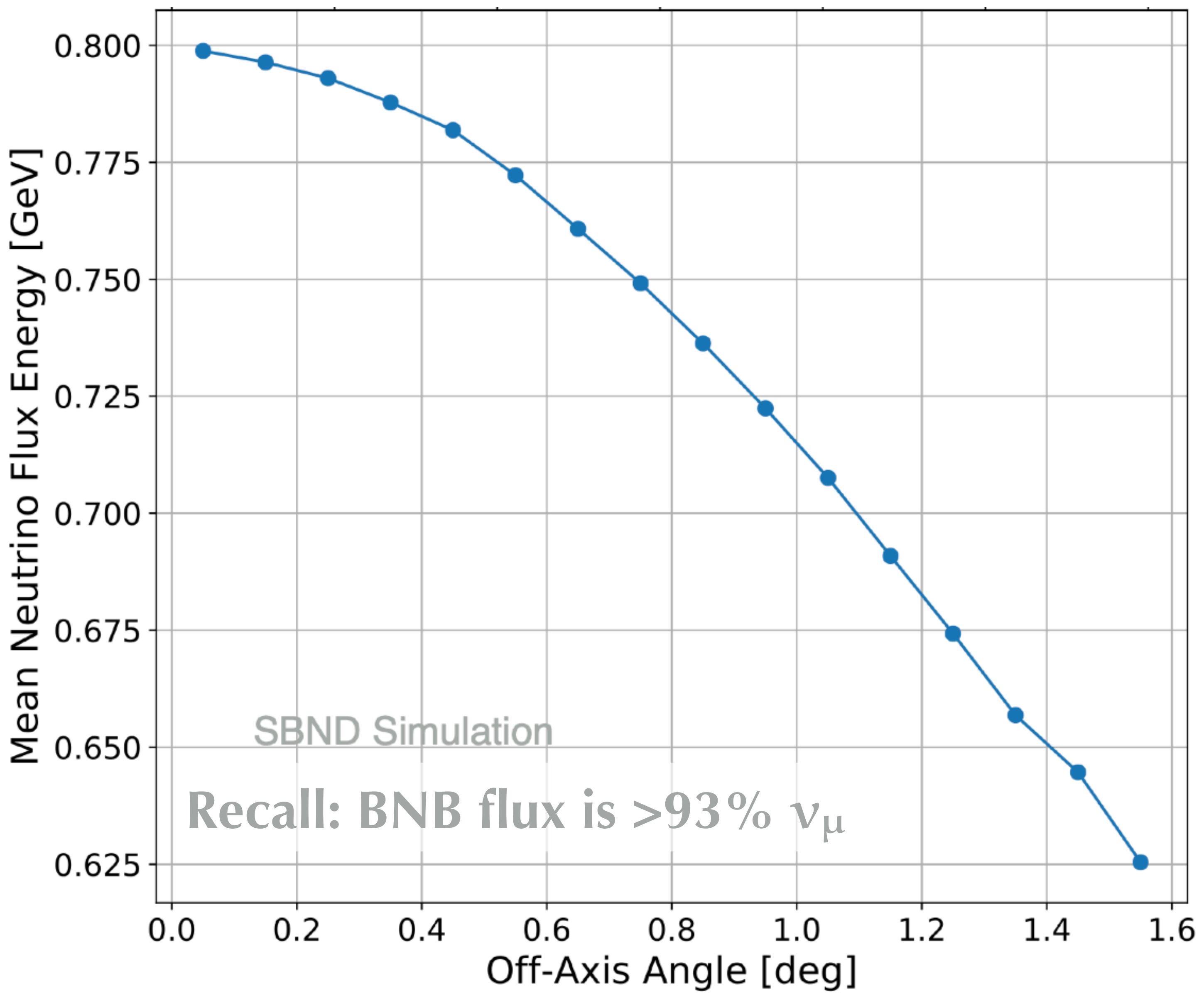
nuPRISM proposal:
arXiv:1412.3086

- Off-axis angle directly corresponds to the neutrino interaction vertex position
- The flux spectrum evolves as a function of the off-axis angle
  - Further off-axis fluxes peak lower and tighter
- Allows SBND to leverage PRISM concept





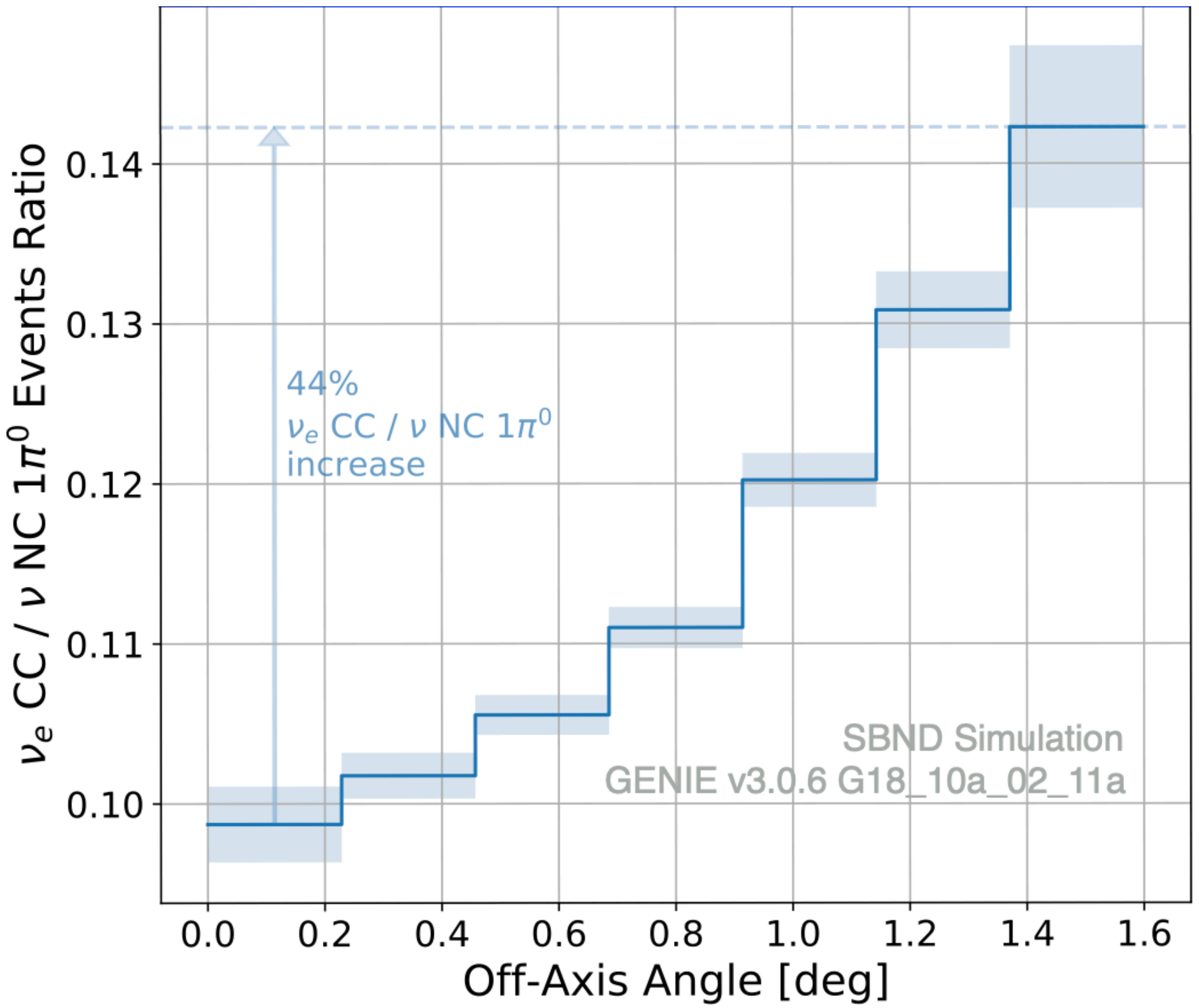
SBND-PRISM for Interaction Measurements



Recall: BNB flux is >93% ν_μ

- For ν_μ 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

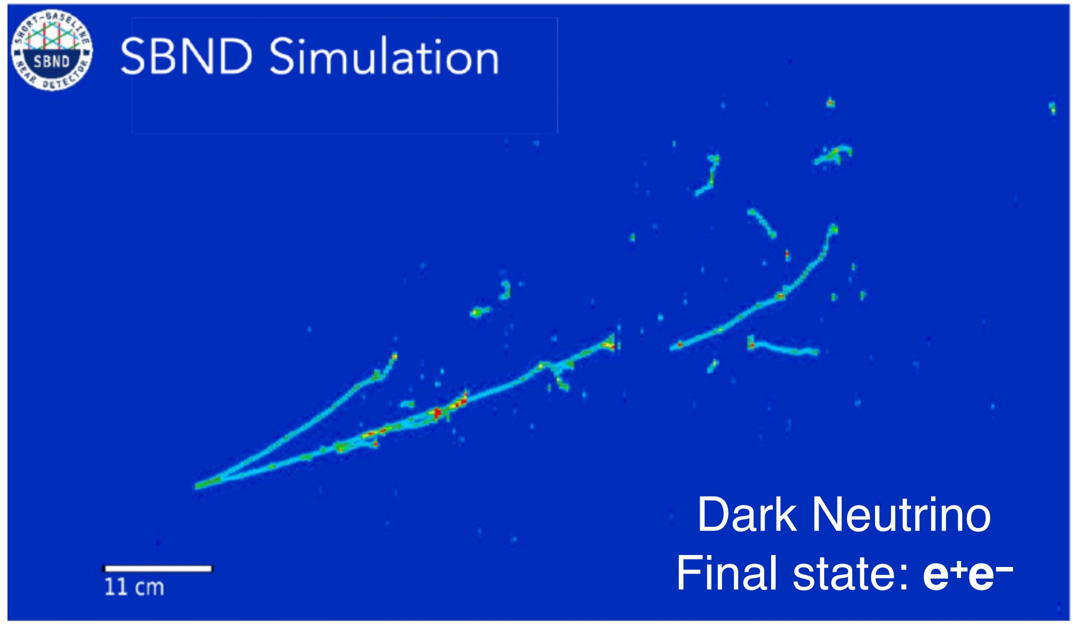
SBND-PRISM for Interaction Measurements

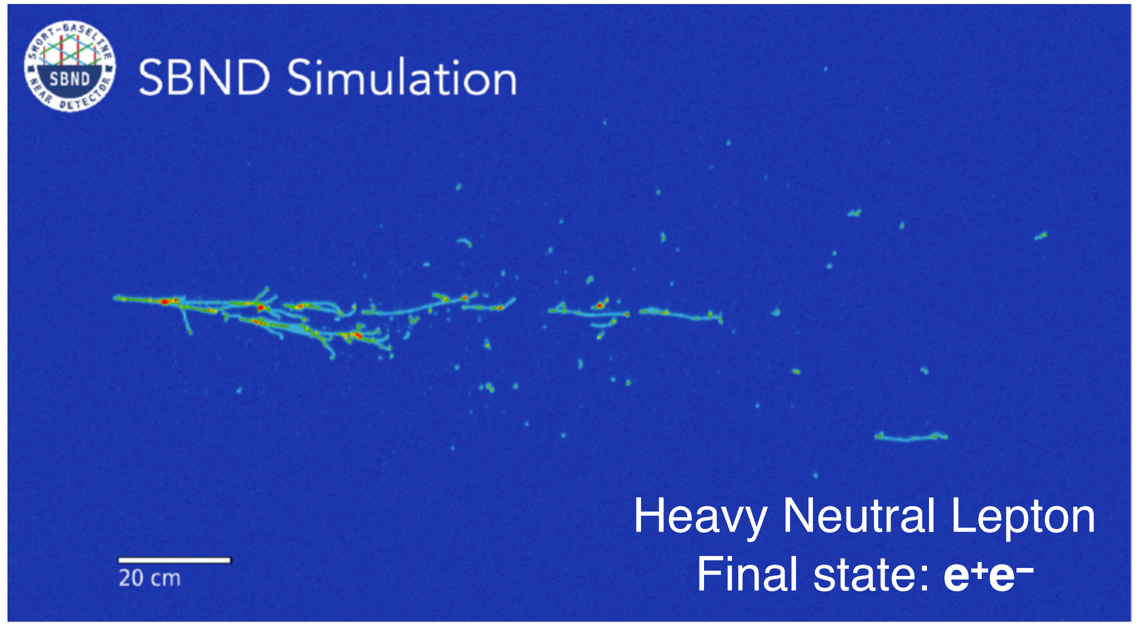


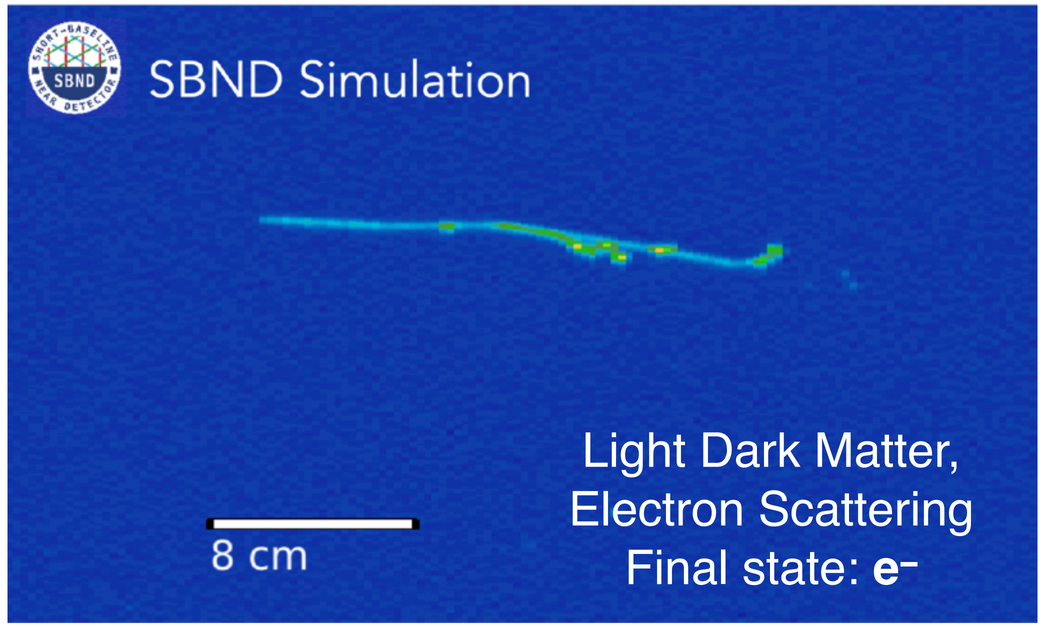
- For ν_e measurements in the BNB, ν_μ backgrounds can be significant, e.g. from NC $1\pi^0$ events
- Due to meson decay kinematics, ν_e are distributed more evenly across the face of SBND than ν_μ
  - The ν_μ come from two-body decays, while ν_e generally come from three-body decays and therefore have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

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







Summary

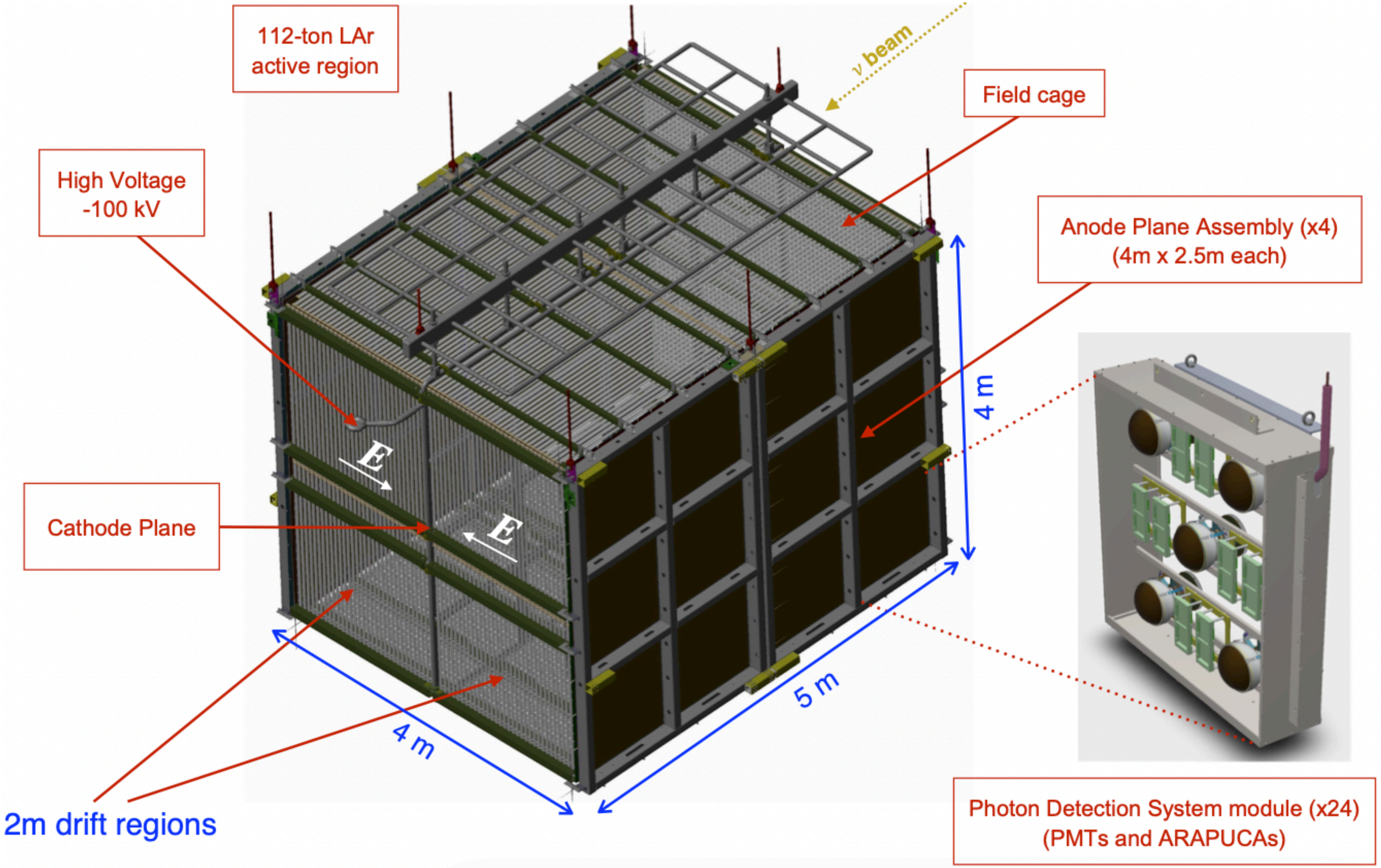
- SBND experiment is wrapping up assembly and installation, preparing for commissioning, and is on-track to start operations in 2023
- Neutrino interaction measurements are a key part of SBND's physics program, and will benefit other physics aims in the SBN program and beyond
- The highly-capable LArTPC detector technology combined with SBND's high statistics will enable a wide variety of neutrino–argon interaction measurements at the GeV scale
    - Expect to collect about 2 million ν_μ CC interactions per year, over the course of a 3–4 year run
    - This represents ~20–30x more neutrino–argon interaction data statistics than is currently available
- SBND-PRISM provides a unique opportunity to probe different neutrino fluxes within the same stationary detector

Thank You!

SBND Collaboration Meeting
Fermilab, June 2022

Additional Slides

The SBND Detector



112-ton LAr active region

High Voltage -100 kV

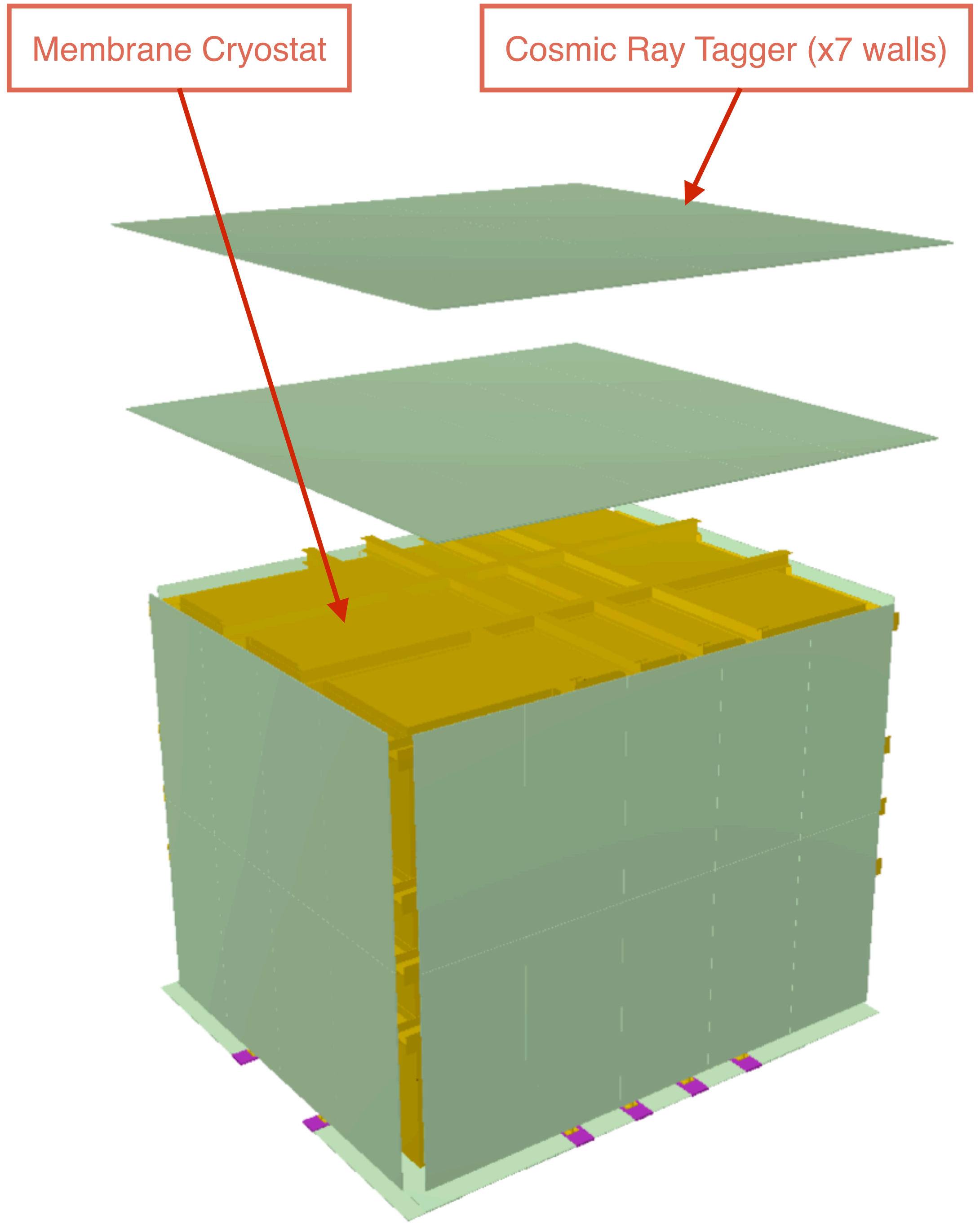
Field cage

Anode Plane Assembly (x4) (4m x 2.5m each)

Cathode Plane

2m drift regions

Photon Detection System module (x24) (PMTs and ARAPUCAs)



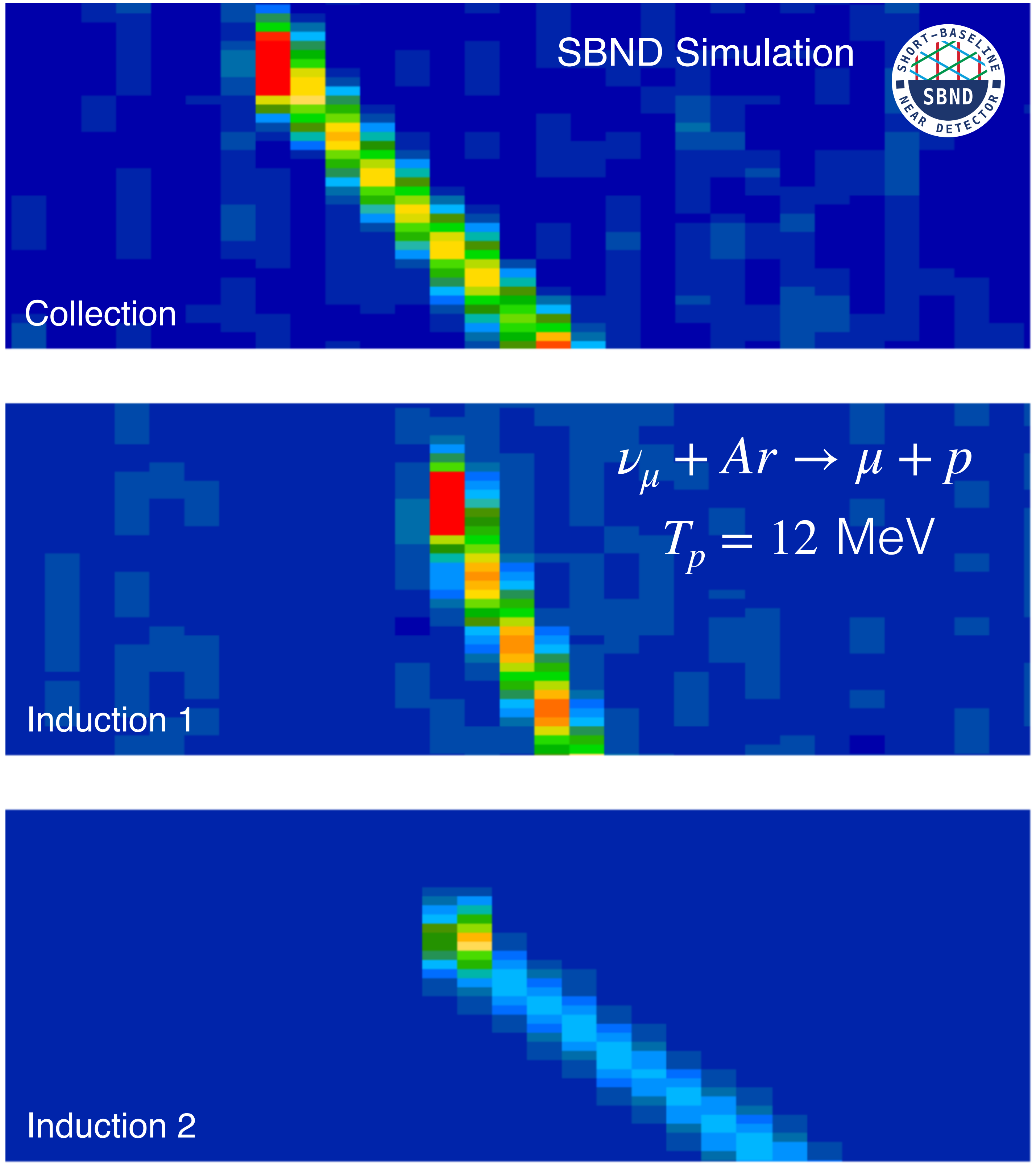
Membrane Cryostat

Cosmic Ray Tagger (x7 walls)

Proton Reconstruction

- 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



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)

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

SBND-PRISM for ν_μ vs. ν_e

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