Status of the Short Baseline Near Detector at Fermilab

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On Behalf of the SBND Collaboration

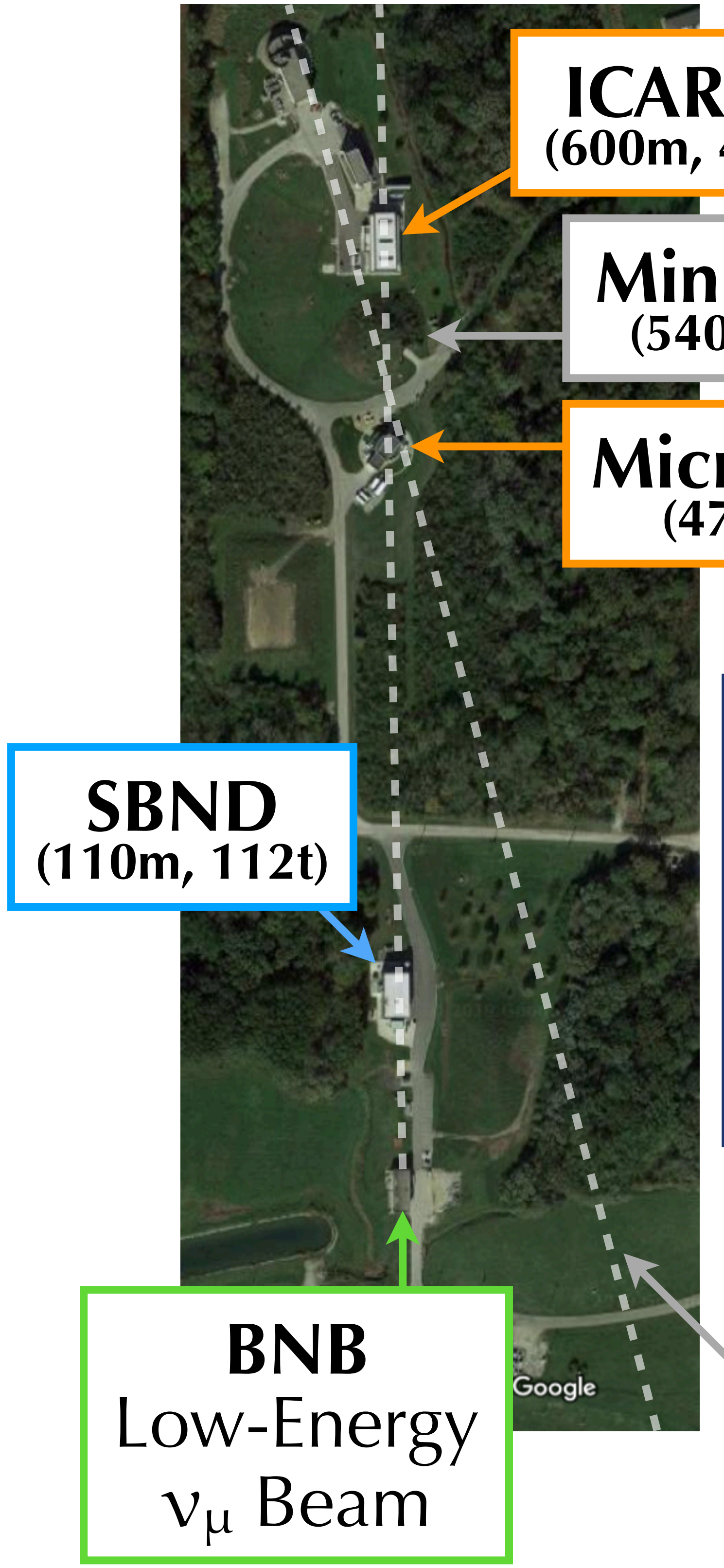
TAUP 2023 — University of Vienna
August 28, 2023

FERMILAB-SLIDES-23-271-ND

The Short Baseline Neutrino Program at Fermilab

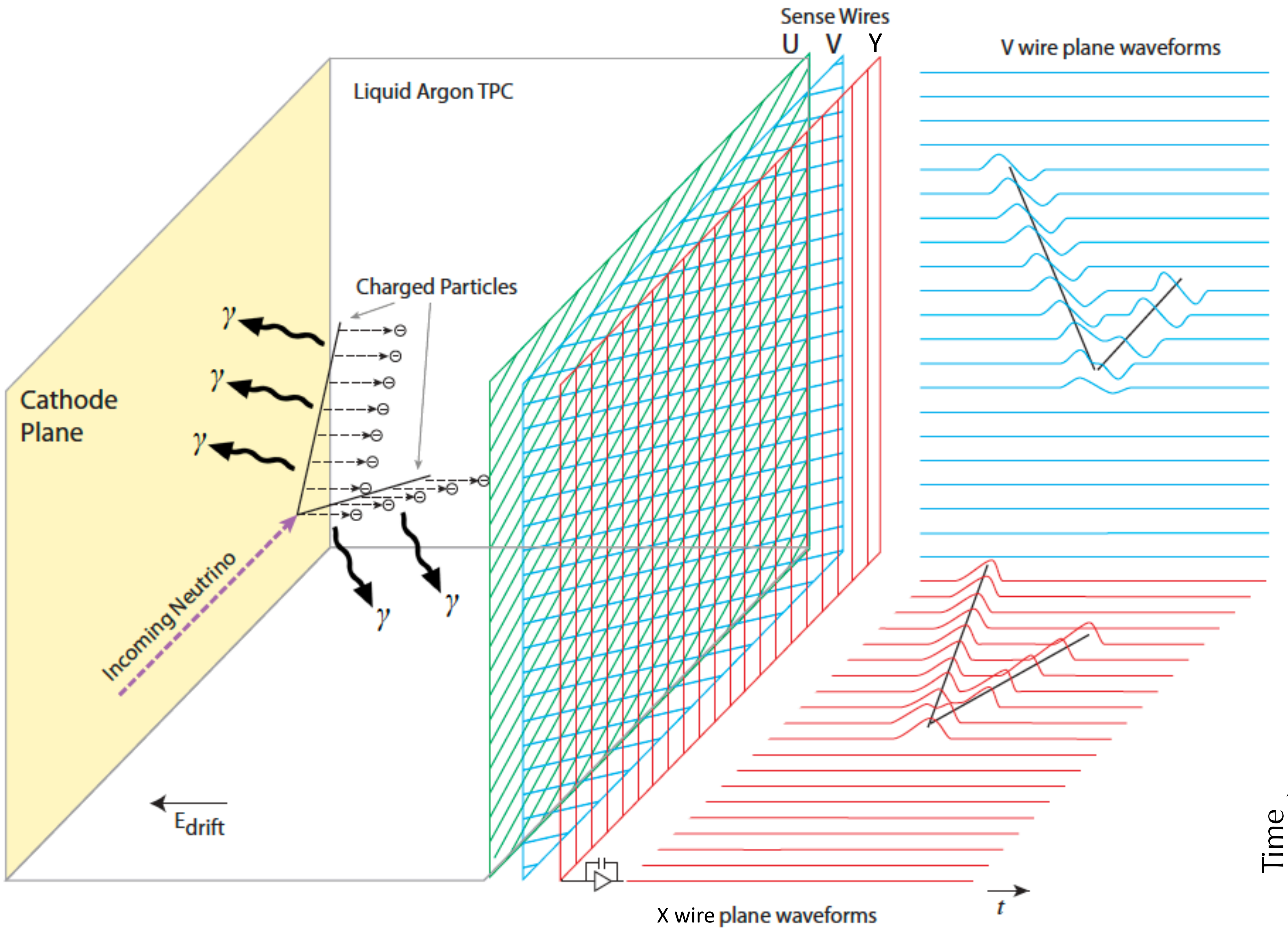
- The Short Baseline Neutrino (SBN) Program at Fermilab consists of three LArTPC detectors, all in Fermilab's Booster Neutrino Beam (BNB) but at different baselines
- BNB is a primarily muon neutrino beam, with a mean ν_μ energy of ~0.8 GeV and ν_μ purity of ~94%
  - ~6% contamination from $\bar{\nu}_\mu$, ~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 sections measurements and new and rare physics searches
- Will lay important groundwork for future experiments using LArTPC detectors, such as DUNE

Fermilab Neutrino Campus

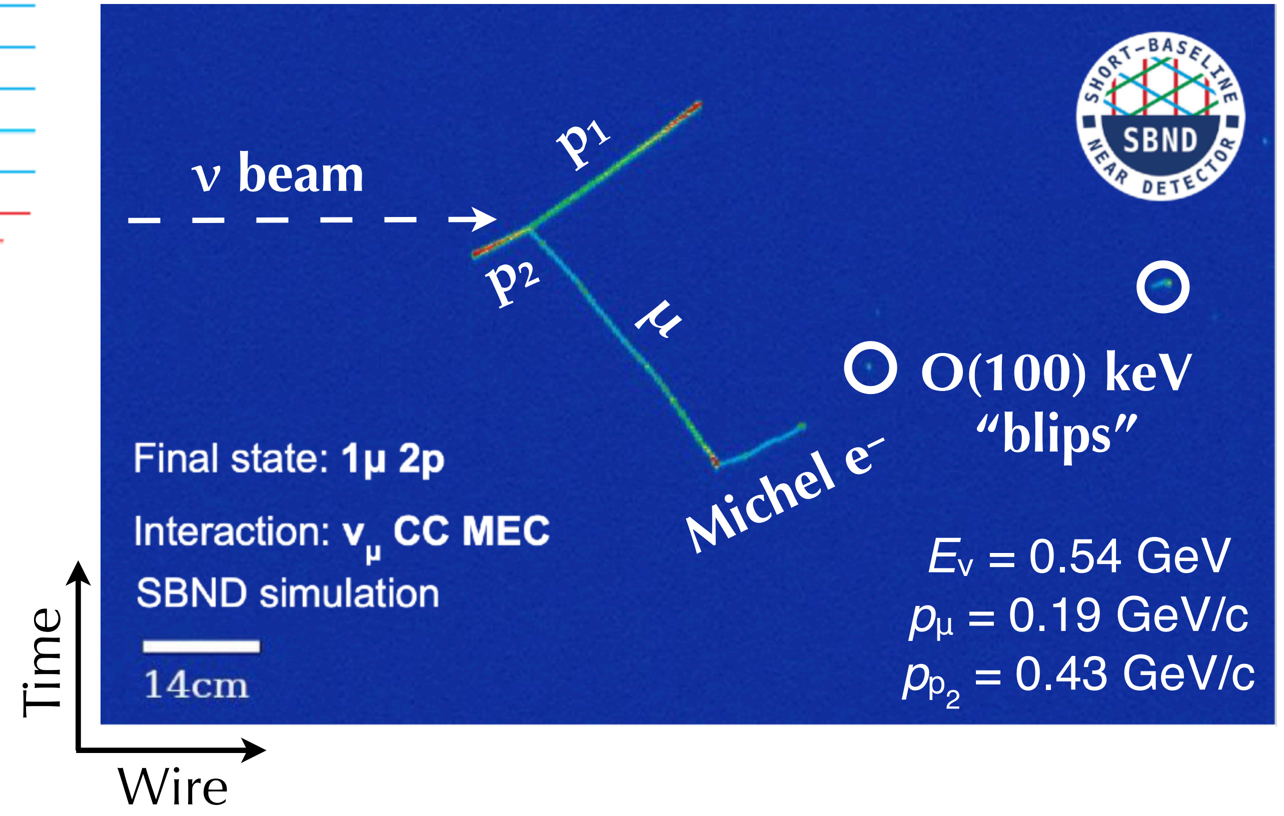


J. Micallef: Sterile Neutrino Searches at MicroBooNE
D. Mendez: ICARUS Status & Perspectives
Tuesday at 2pm
in Hörsaal 21

Detecting Neutrino Interactions with a LArTPC



- LArTPCs are highly-capable, fully-active tracking calorimeters
- Precise timing information also available via scintillation light

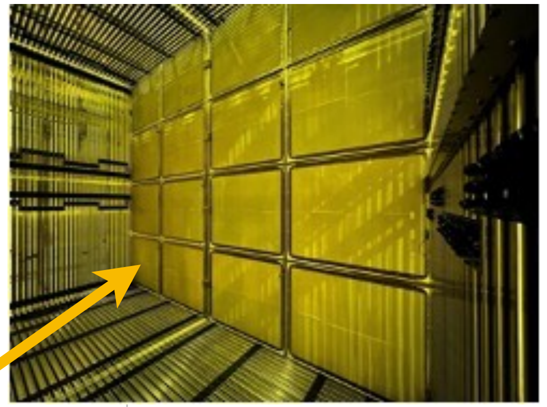


The SBND Detector

LArTPC

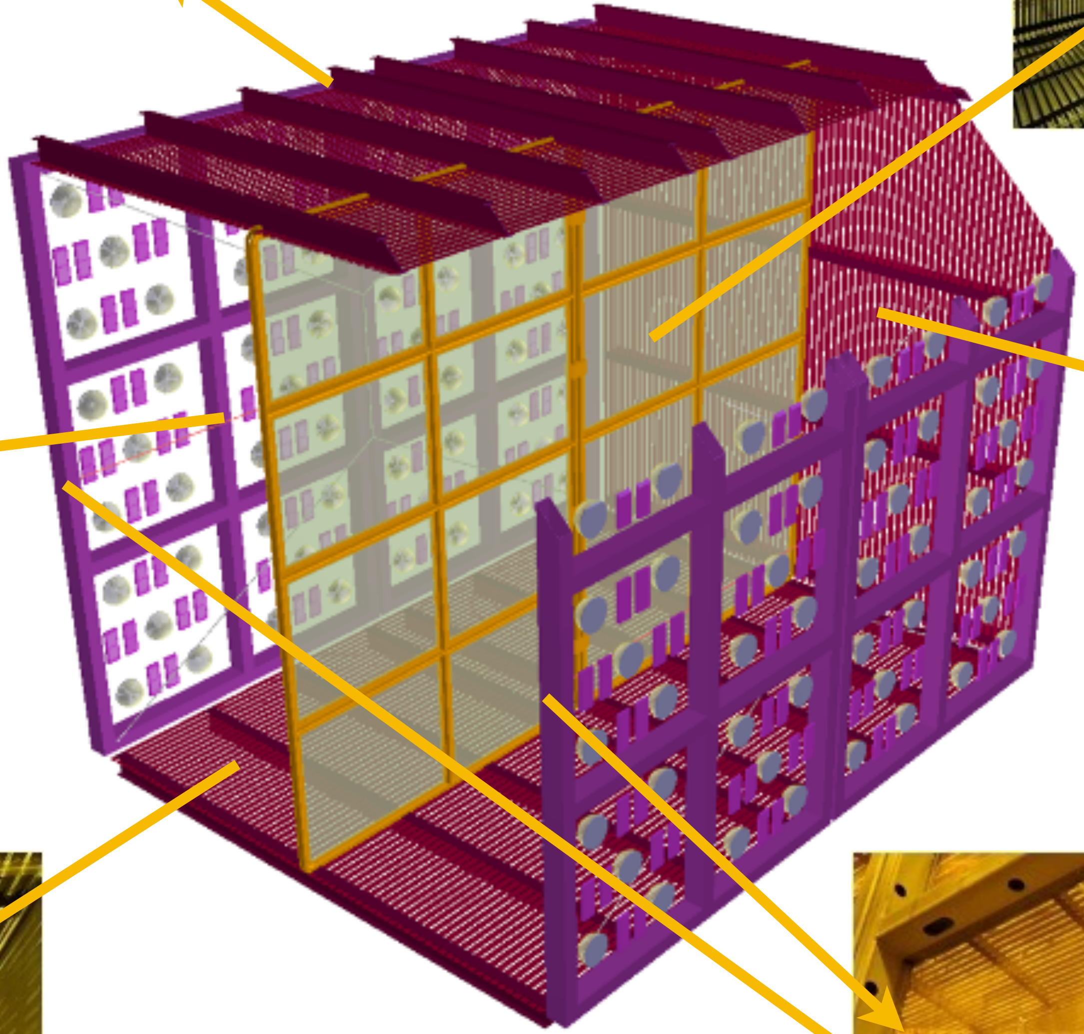
Active mass is 112 t
Active volume is 4×4×5 m^3

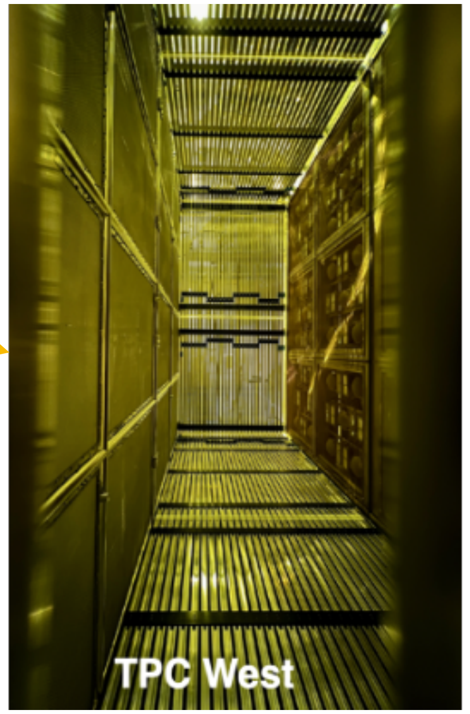
Cold Electronics (in LAr)
pre-amplify and digitize
TPC wire signals



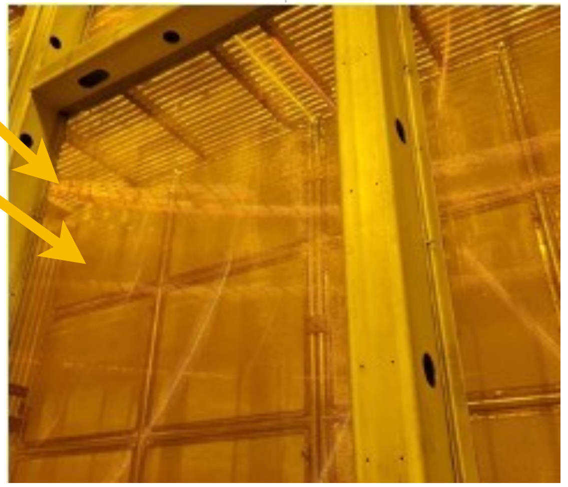
Cathode Plane at –100 kV
divides the detector into two
drift volumes

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





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

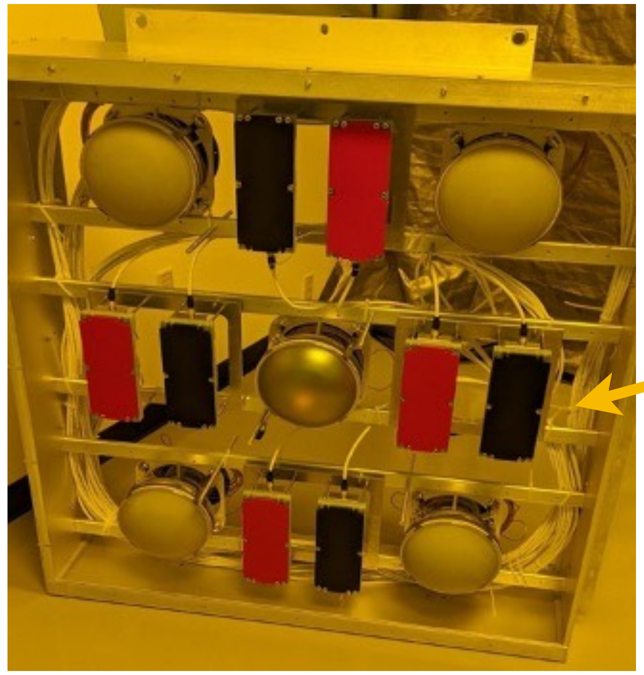


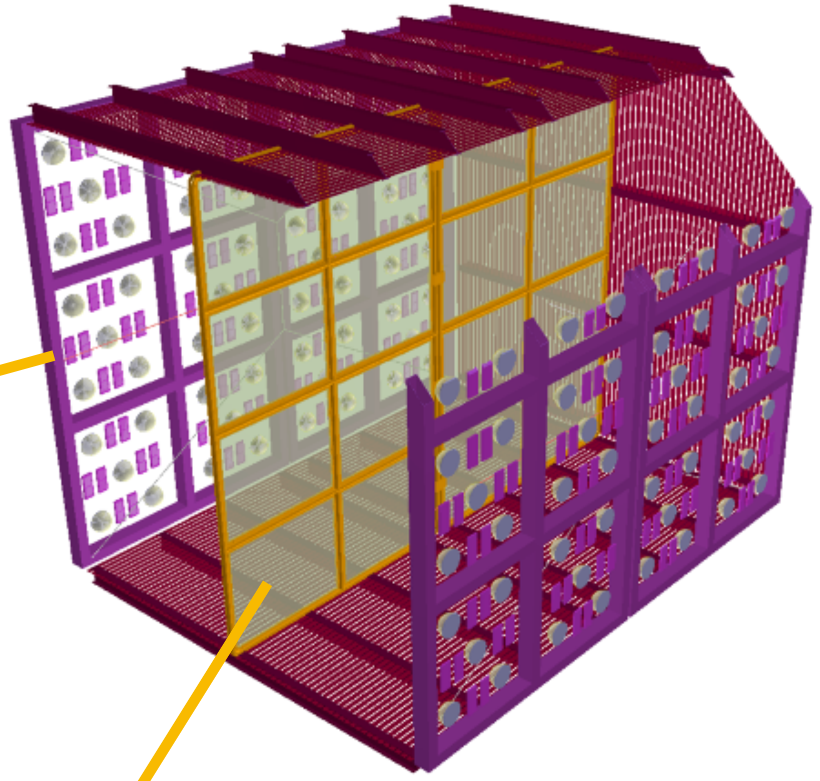
Anode Plane on either side,
each with three wire planes
with 3 mm wire spacing and
different orientation per plane

Total of 11,260 wires

The SBND Detector

Photon Detection System





24 PDS Boxes
behind the anode wire planes

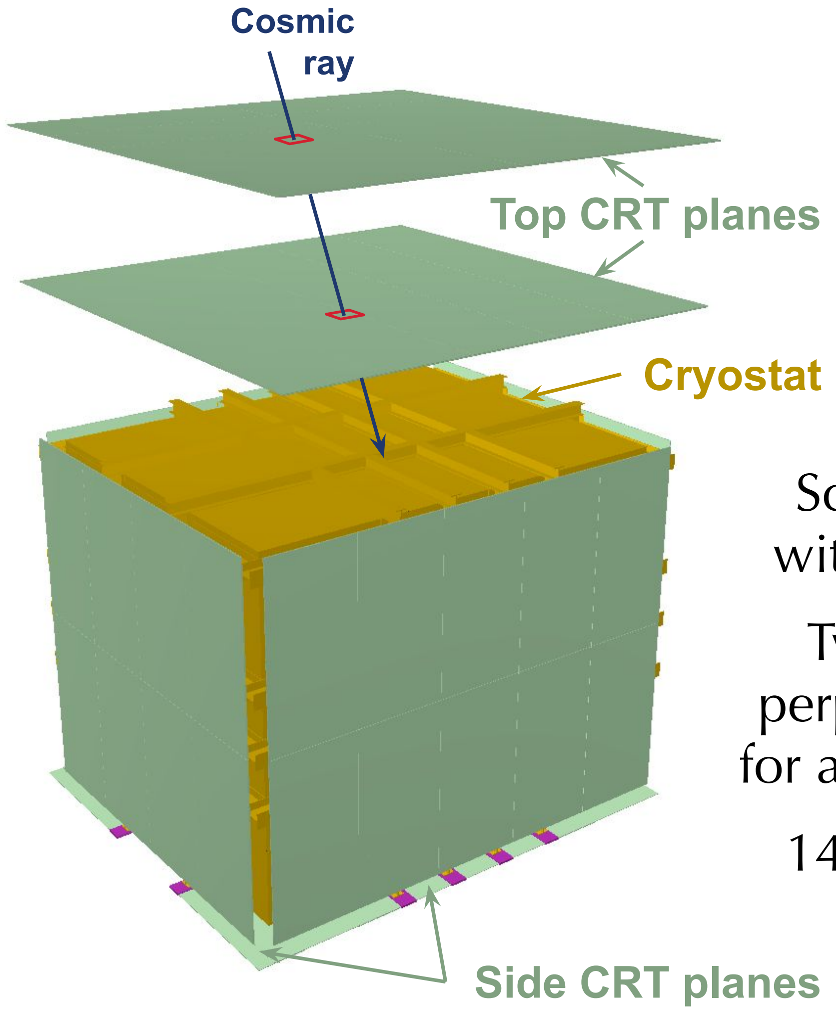
5×24 = **120 8″ PMTs**
80% TPB-coated,
20% uncoated

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

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

Trigger System

T. Kroupová
SBND Hardware Trigger System
Tuesday at 3pm in Hörsaal 21



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)

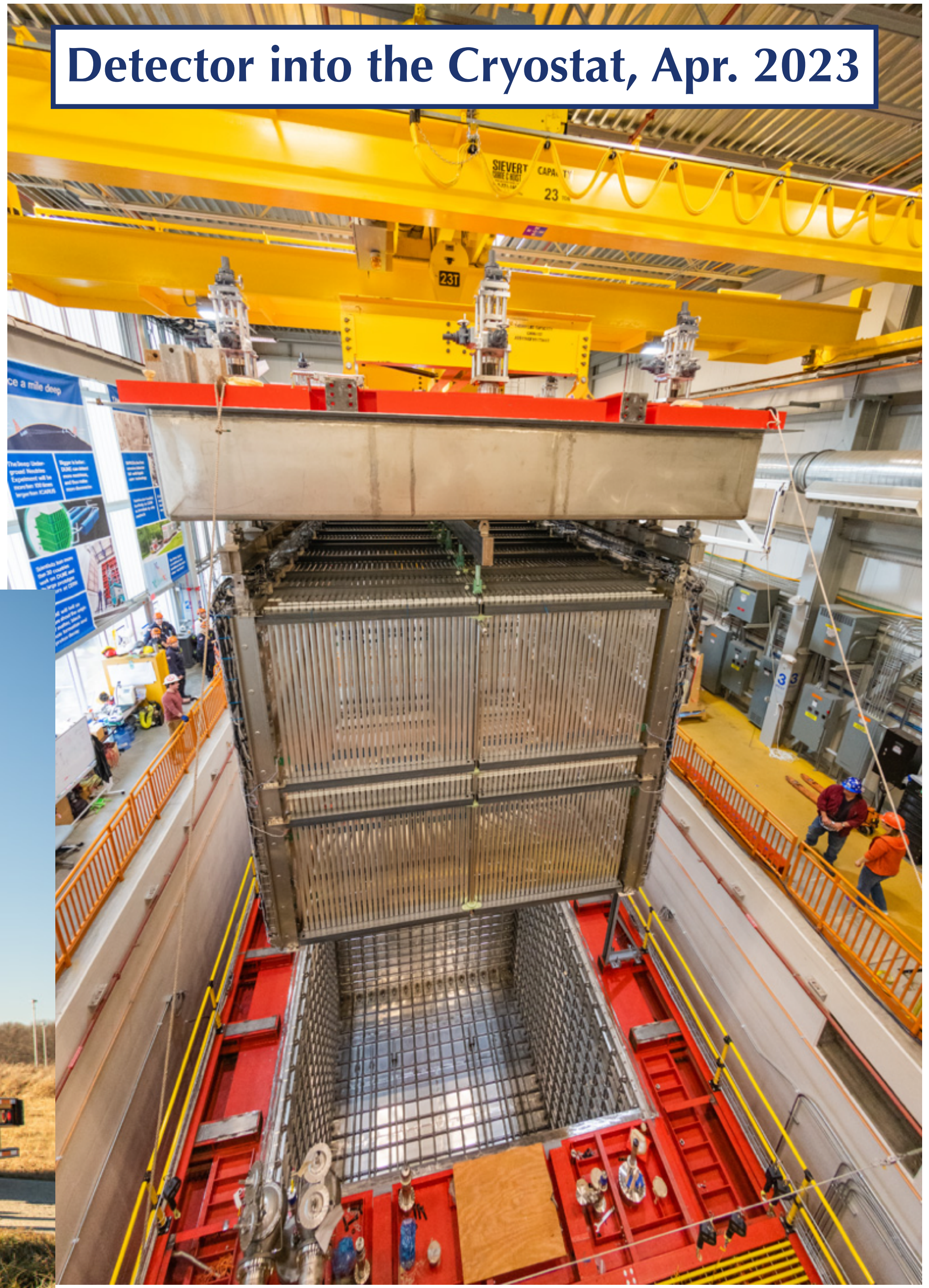
Cosmic Ray Tagger

SBND Assembly & Installation

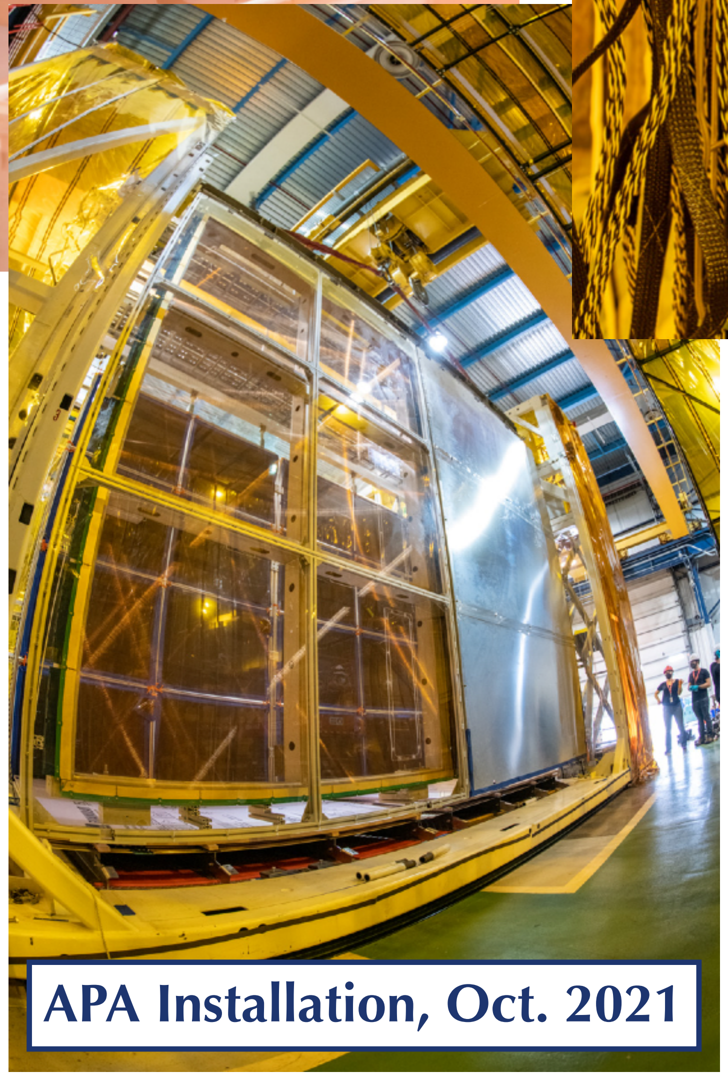
APA Assembly, Dec. 2018

CE Installation, May 2022

PDS Box Installation, Sep. 2022



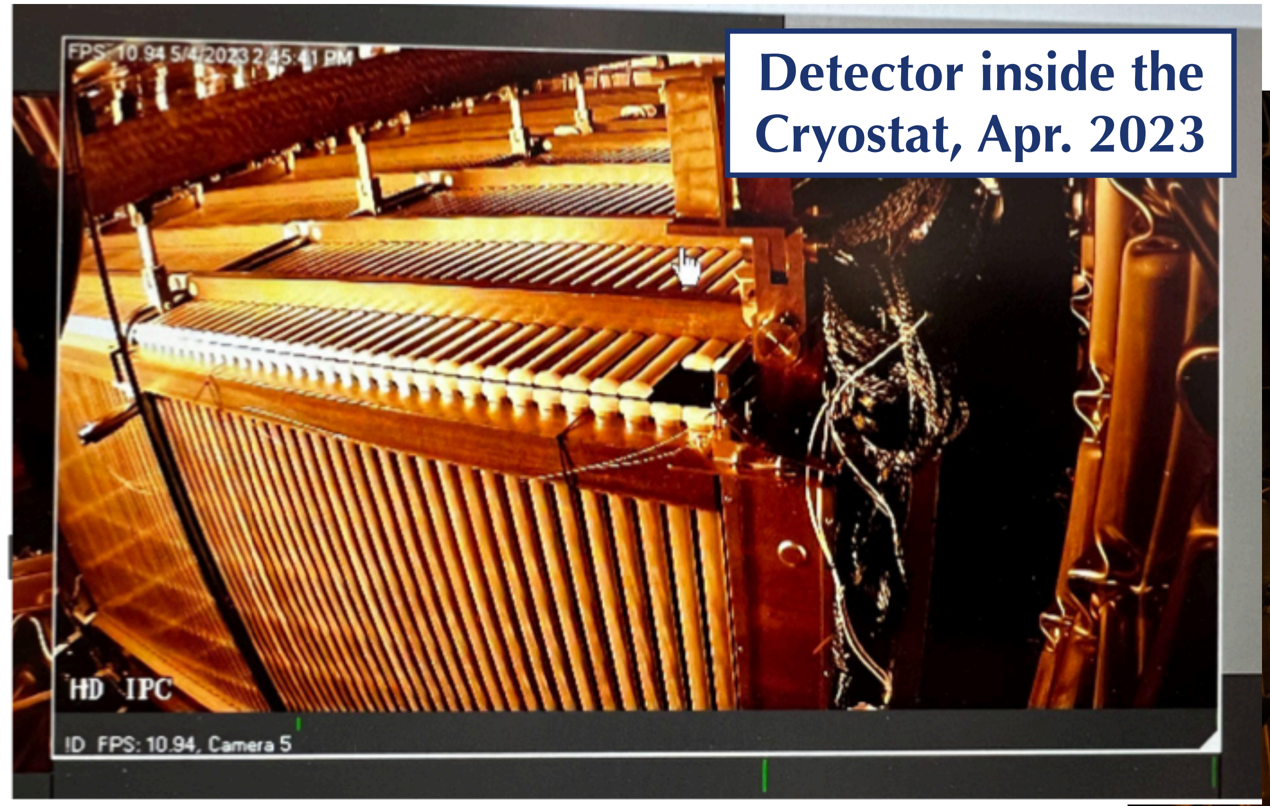
Detector into the Cryostat, Apr. 2023



APA Installation, Oct. 2021

Detector to SBND, Dec. 2022

SBND Assembly & Installation


Detector inside the Cryostat, Apr. 2023

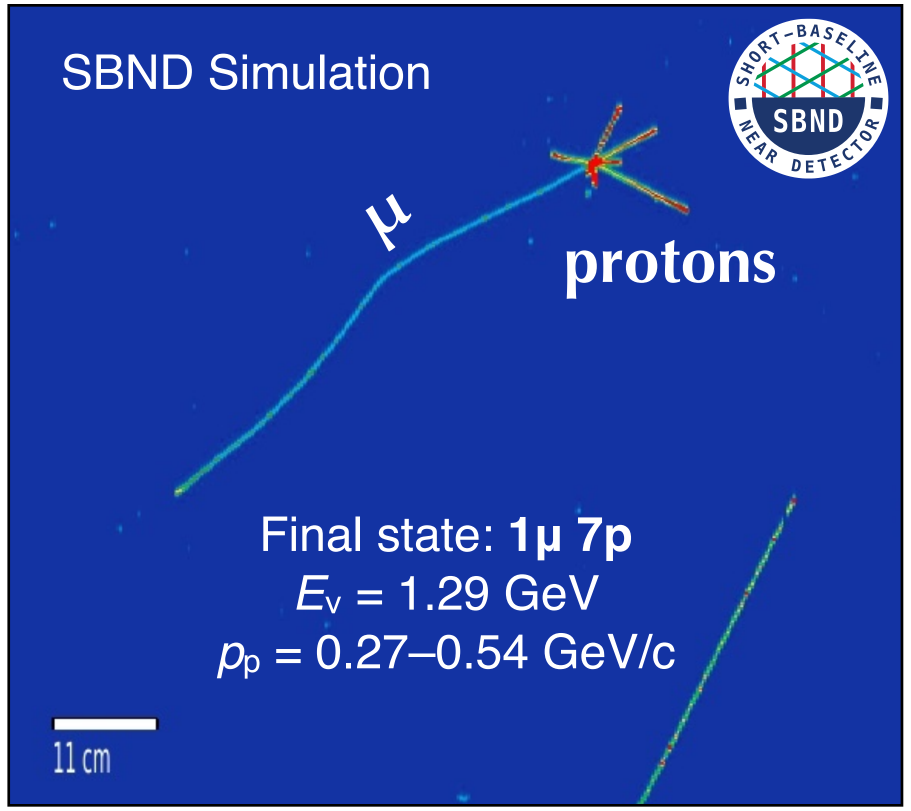

Cathode HV Feedthrough Installation, Jul. 2023

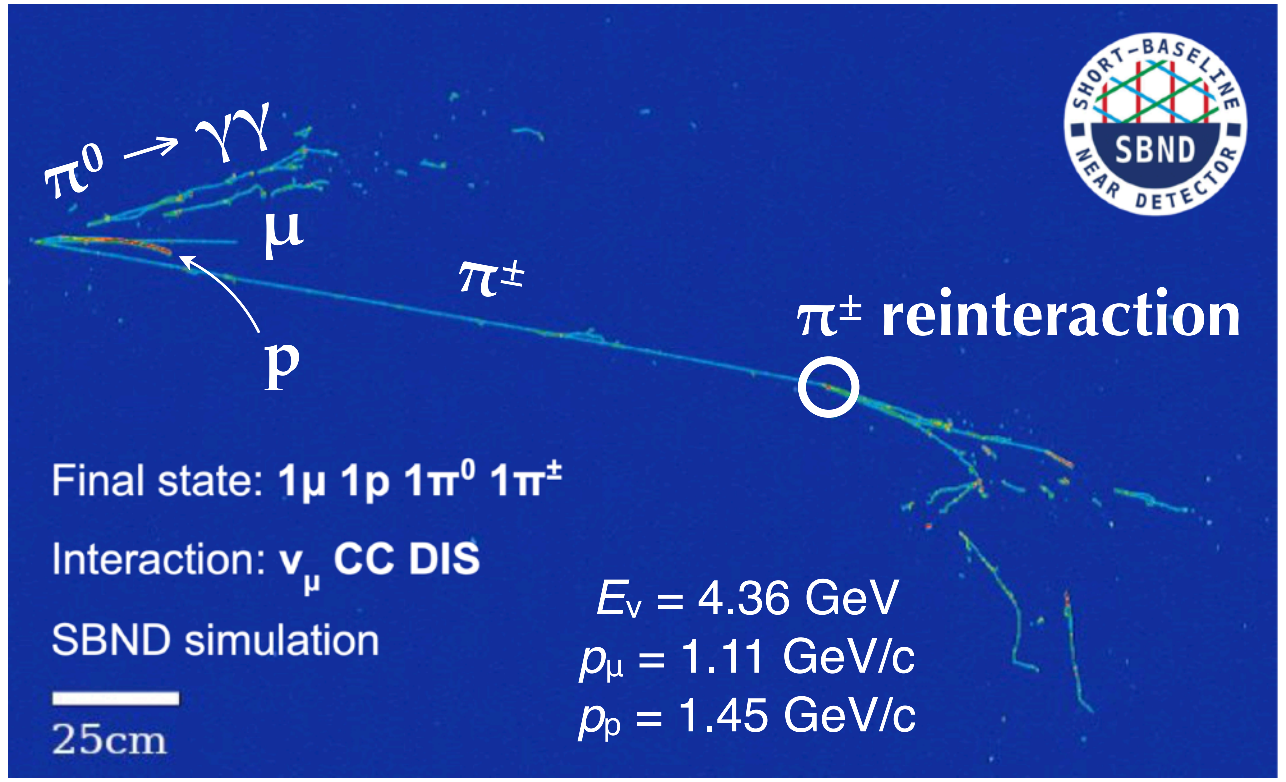

North CRT Wall Installation, May 2023

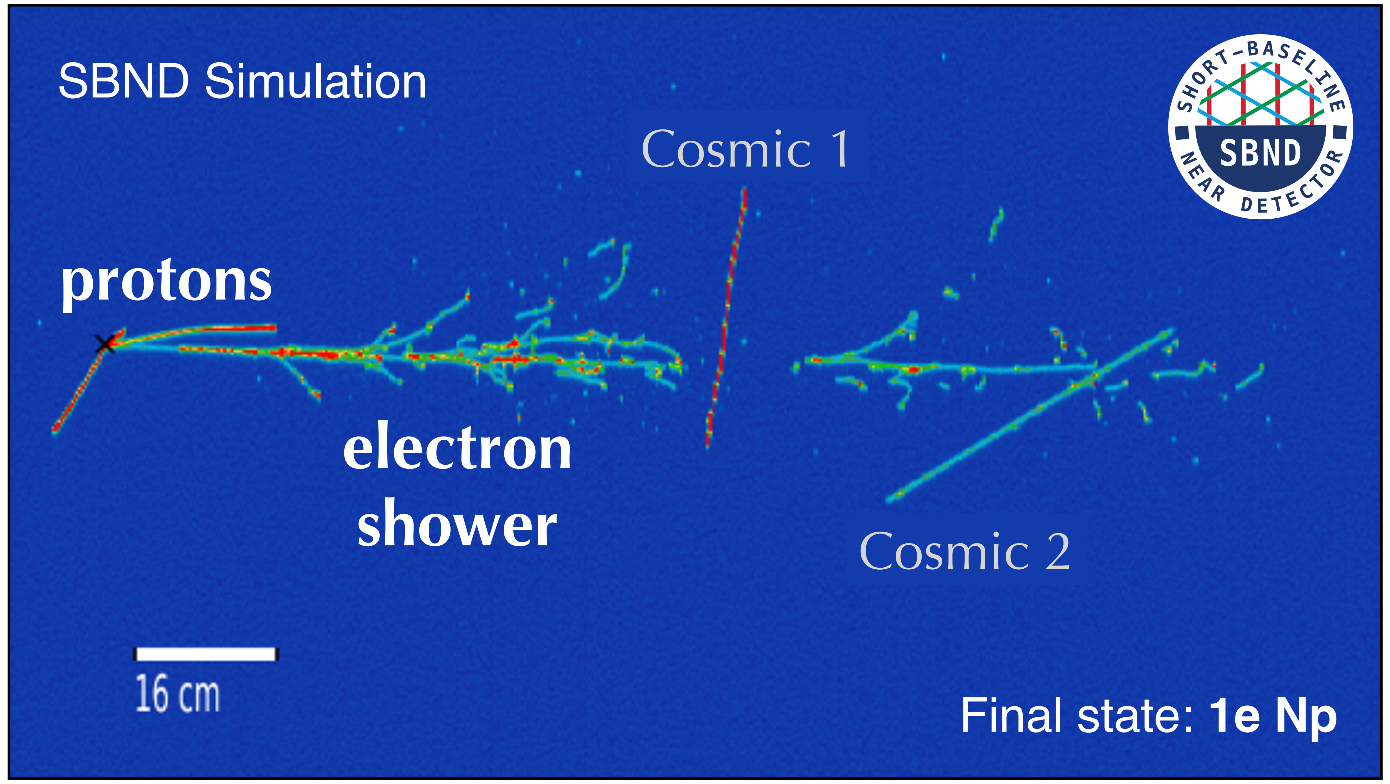
- Detector assembly and installation for all components inside the cryostat is complete, and bottom and north CRT walls are already in place
- Currently working on cabling all systems from cryostat flanges to readout electronics racks, and in parallel with that on the final parts of cryogenics installation
- Expect to fill the cryostat with liquid argon later this year

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

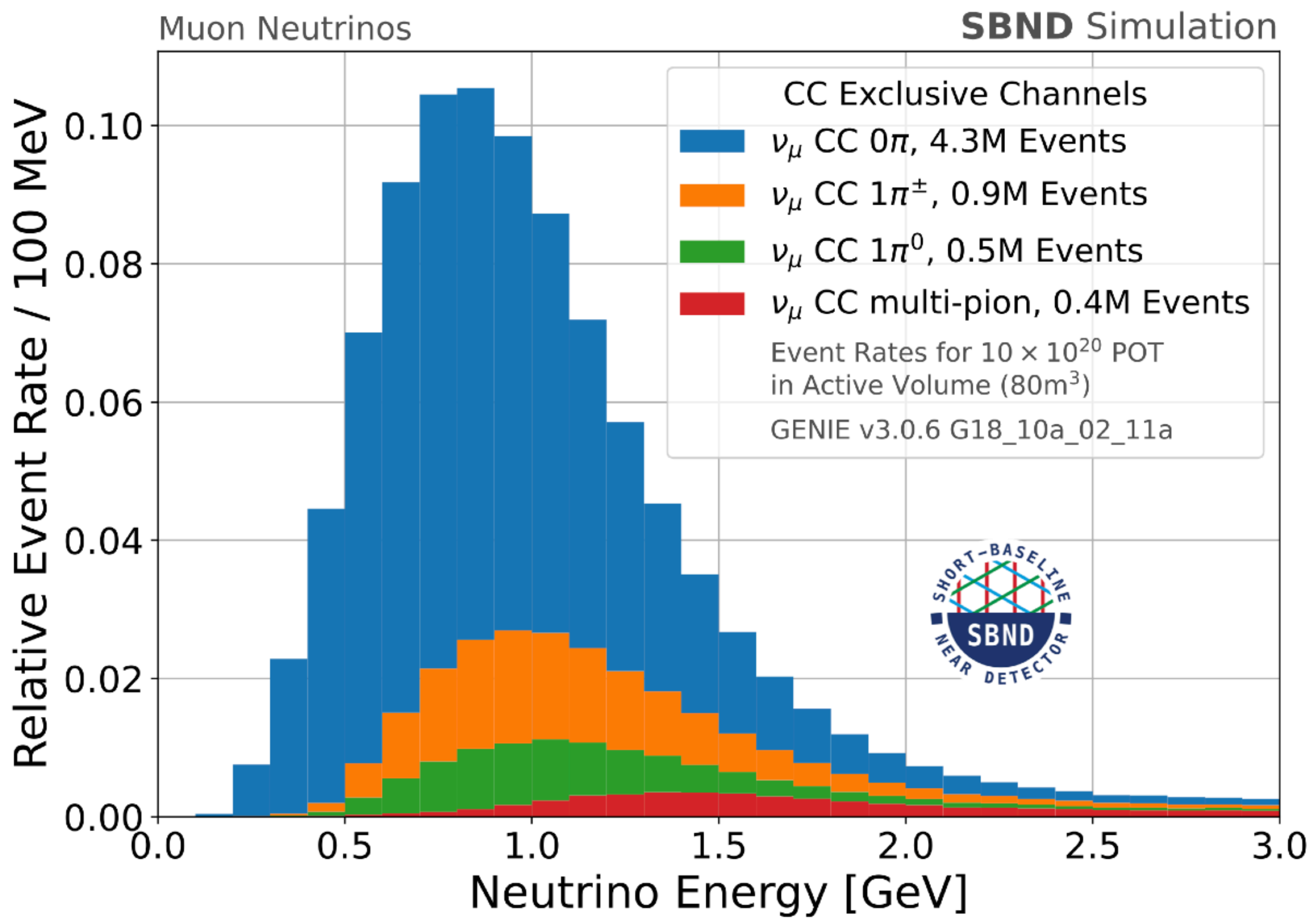


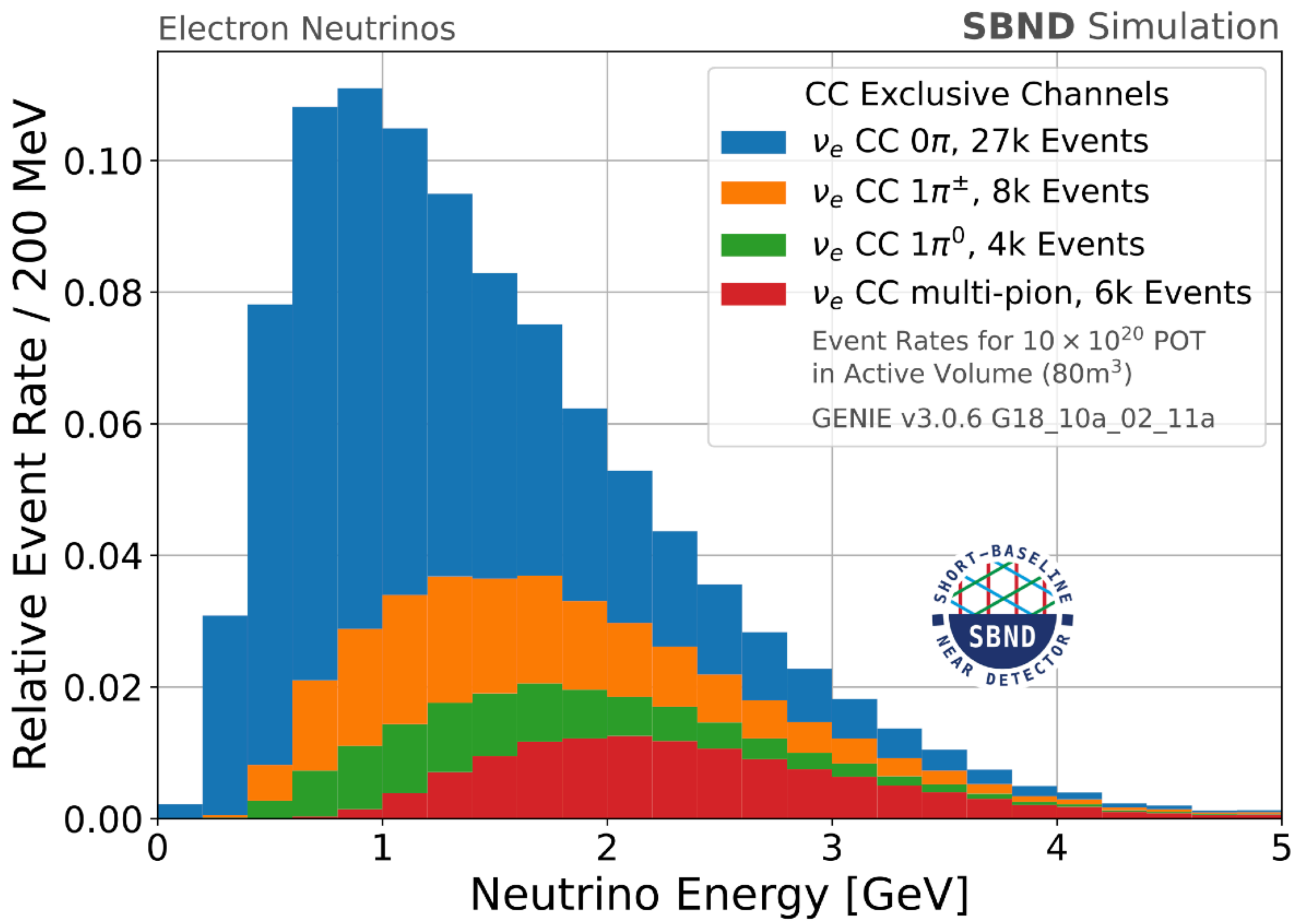




Neutrino Interaction Rates in SBND

- SBND expects approximately 2 million ν_μ CC and 15,000 ν_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



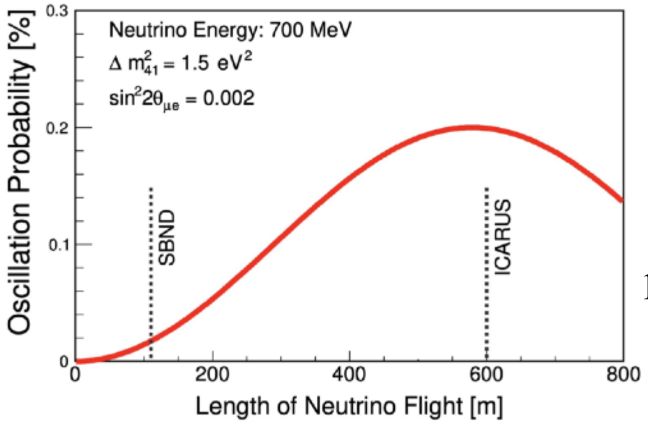


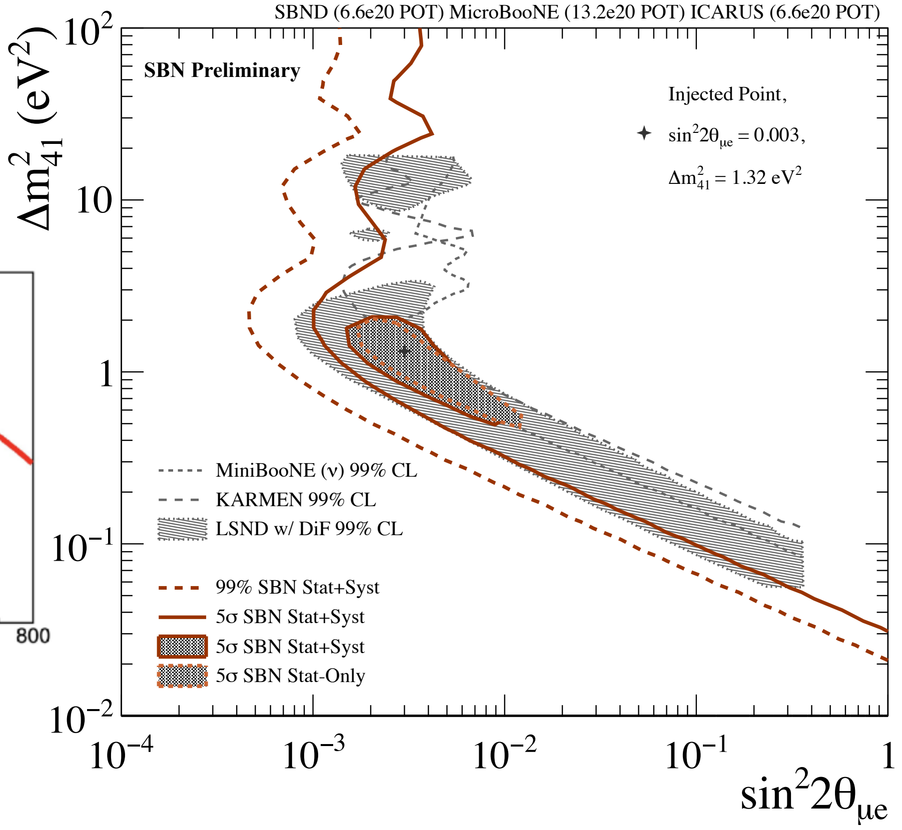
Neutrino Interaction Measurements in SBND

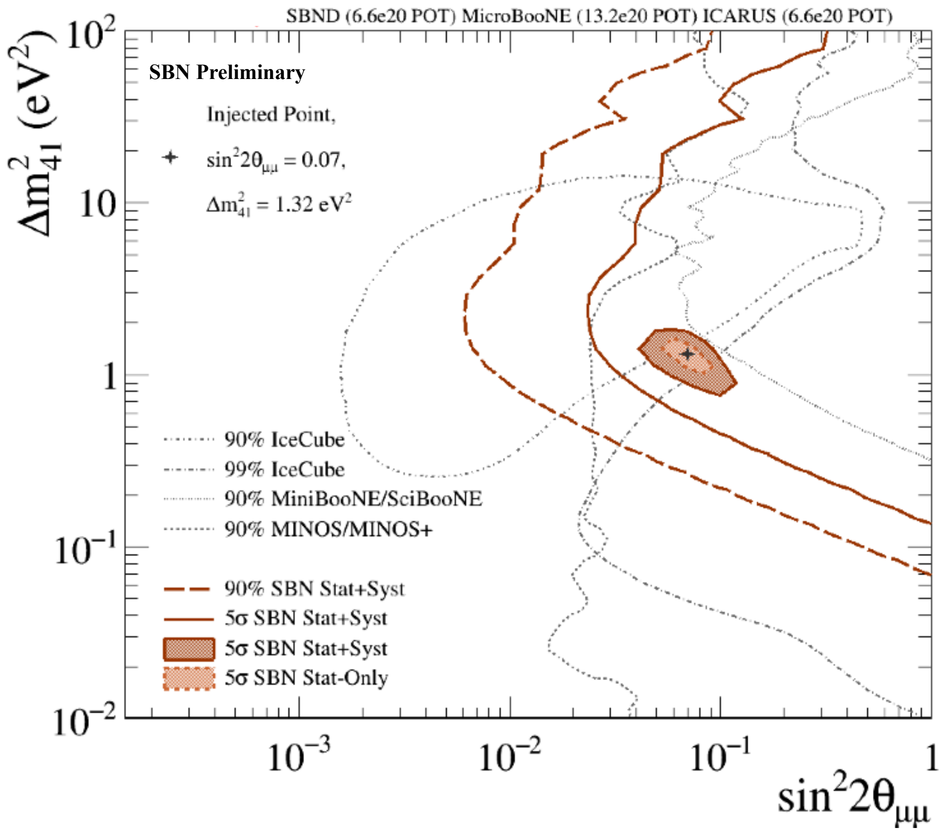
- High statistics in SBND will allow a wide variety of neutrino interaction measurements
  - For **more common channels**, SBND can make multi-dimensional differential measurements
  - For **rare channels**, SBND can make measurements that are not possible in other existing experiments
- A quick sampler of measurement channels that are being worked on…
  - **ν_μ CC inclusive**
  - **ν_μ CC Np 0π**
  - **ν_μ CC Np $1\pi^0$**
  - **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 $1\pi^0$**
  - **NC Np 1γ**
  - **Neutrino–electron elastic scattering**
  - … more to come!

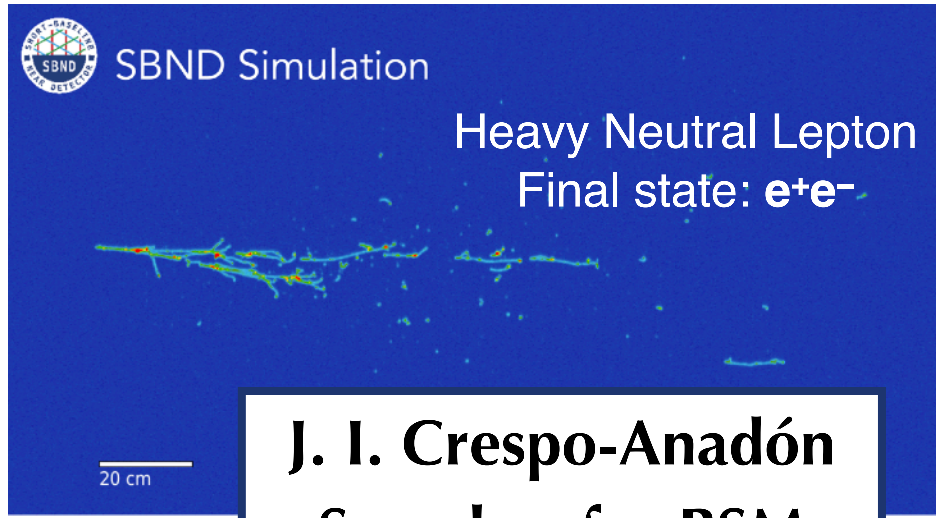
Sterile Neutrinos and Other BSM Physics in SBND

- 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 ν_e appearance, ν_μ disappearance, and ν_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









J. I. Crespo-Anadón
Searches for BSM Physics in SBND
Thursday at 2:15pm in Hörsaal 7

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

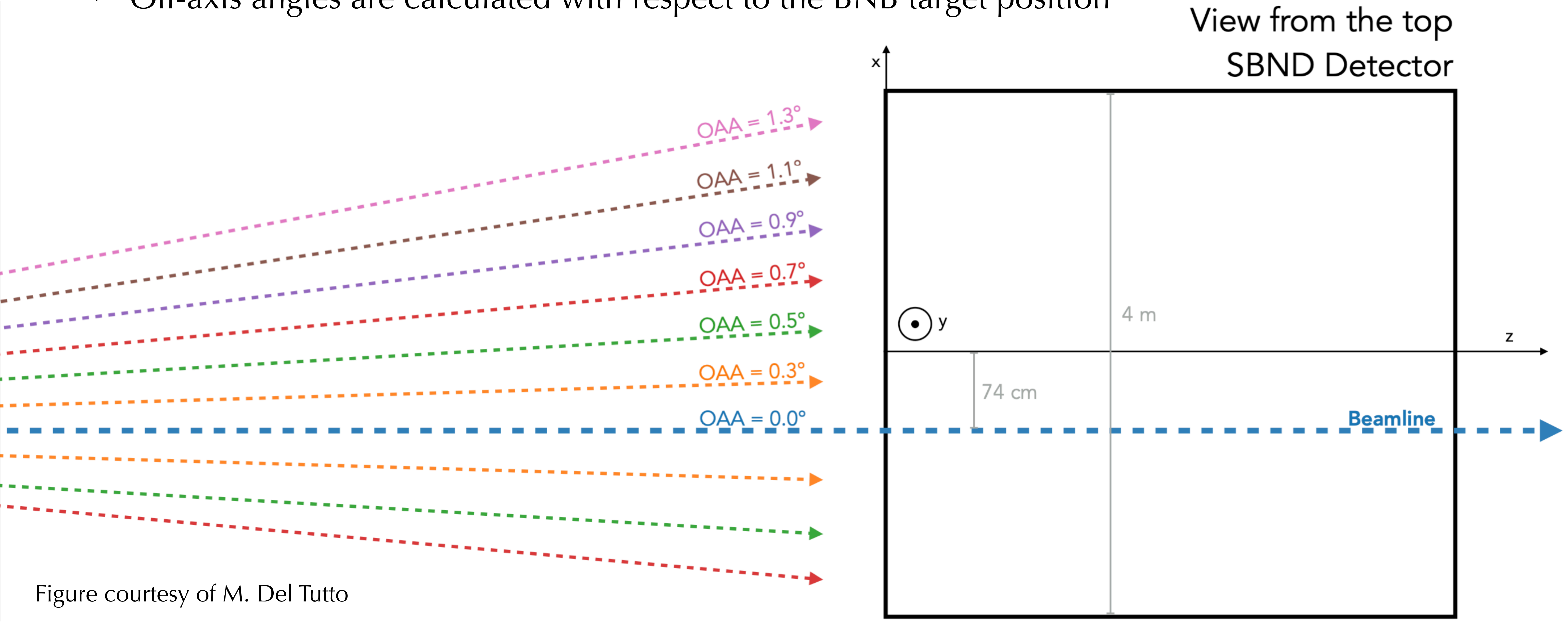
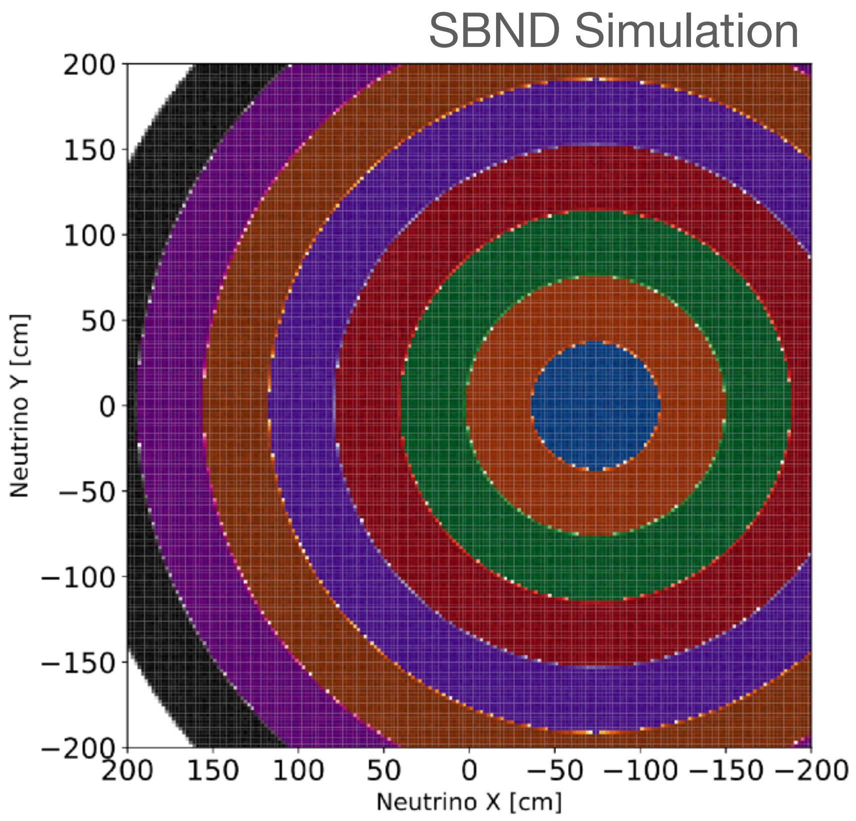


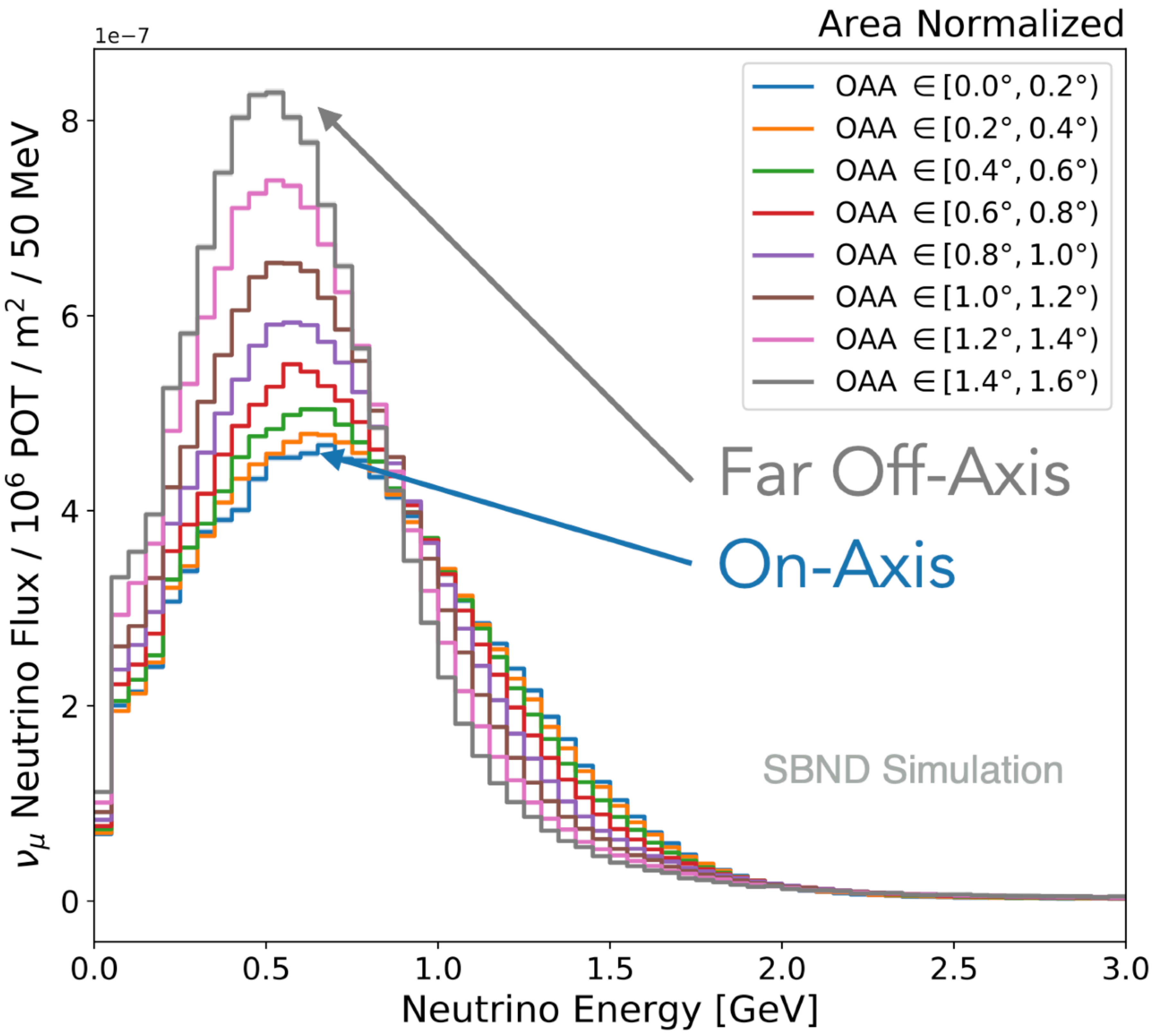
Figure courtesy of M. Del Tutto

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





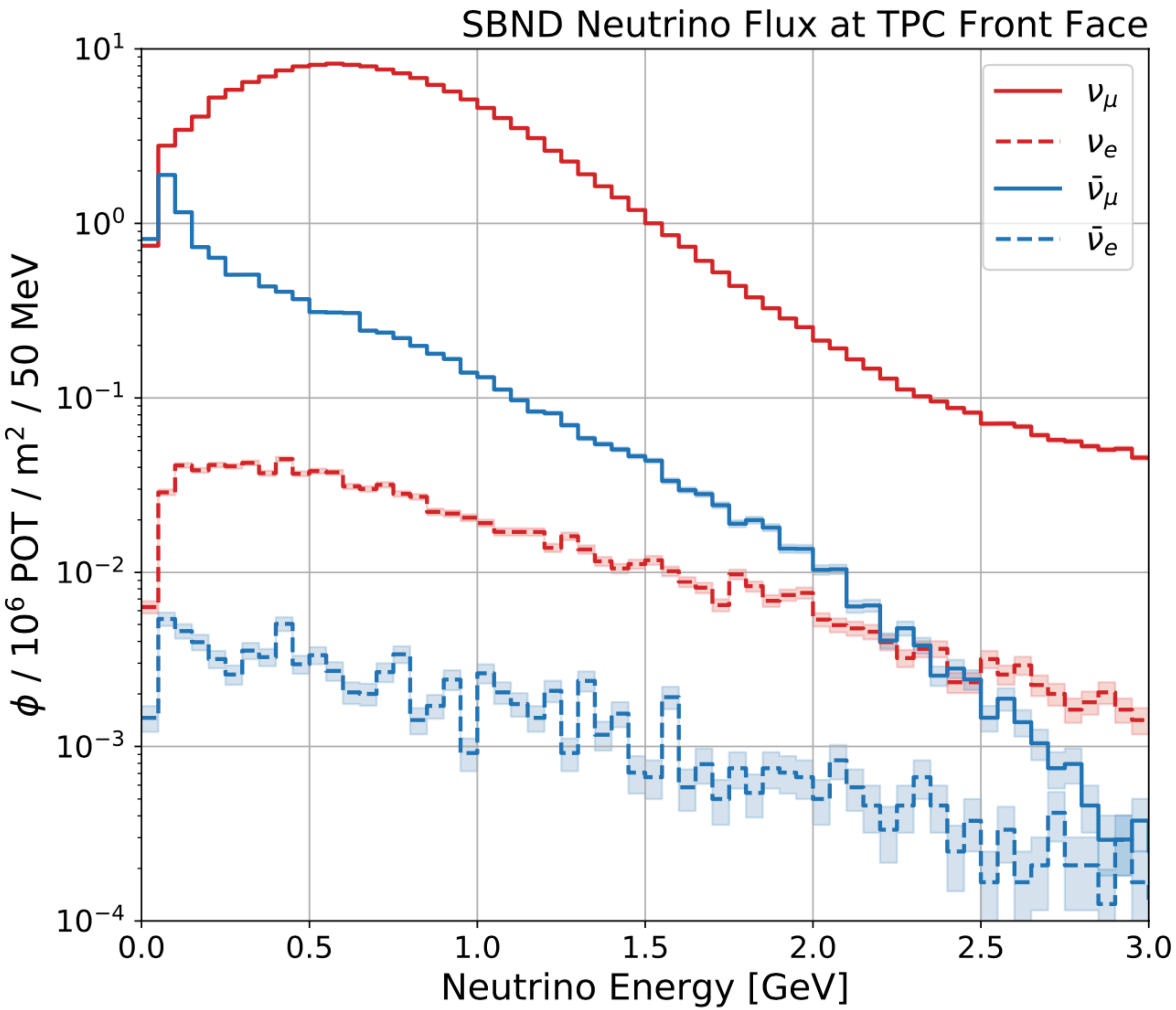
Summary & Outlook

- SBND experiment is in the final stages of installation, preparing for commissioning, and is on-track to start operations in 2024
- 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's physics program includes:
    - 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
- SBND-PRISM provides a unique opportunity to probe different neutrino fluxes within the same stationary detector

Thank you! Danke!

Additional Slides

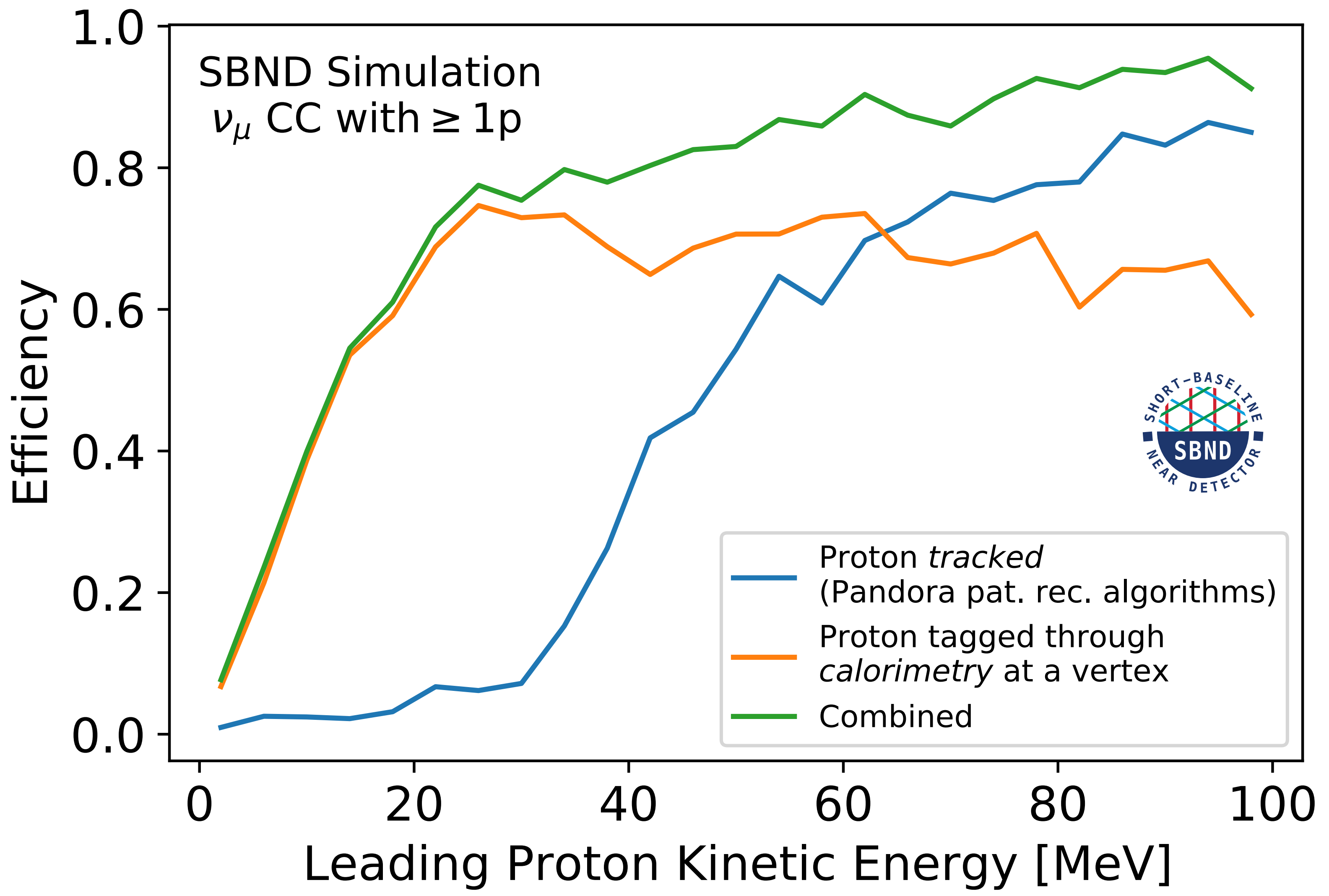
Booster Neutrino Beam Flux at SBND

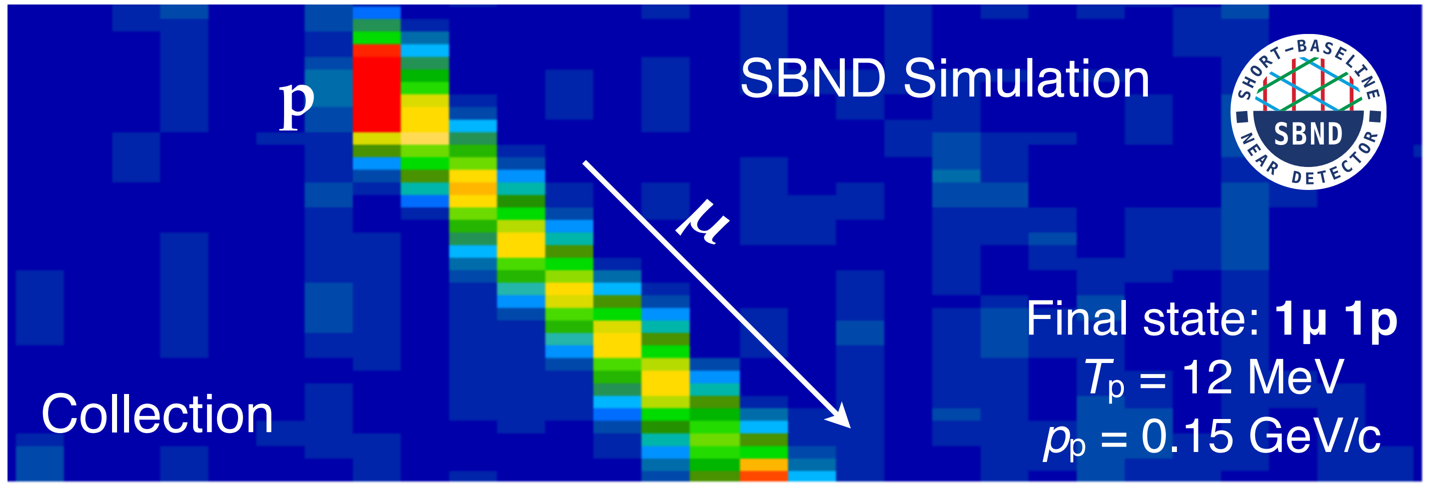


- The primary beam of interest at SBND is the Booster Neutrino Beam (BNB)
- The mean energy for muon neutrinos is about 0.8 GeV
- Beam composition by neutrino flavor:
  - 93.6% ν_μ
  - 5.9% $\overline{\nu}_\mu$
  - 0.5% $\nu_e+\overline{\nu}_e$
- Plan to collect data corresponding to 10e20–18e20 protons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

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)



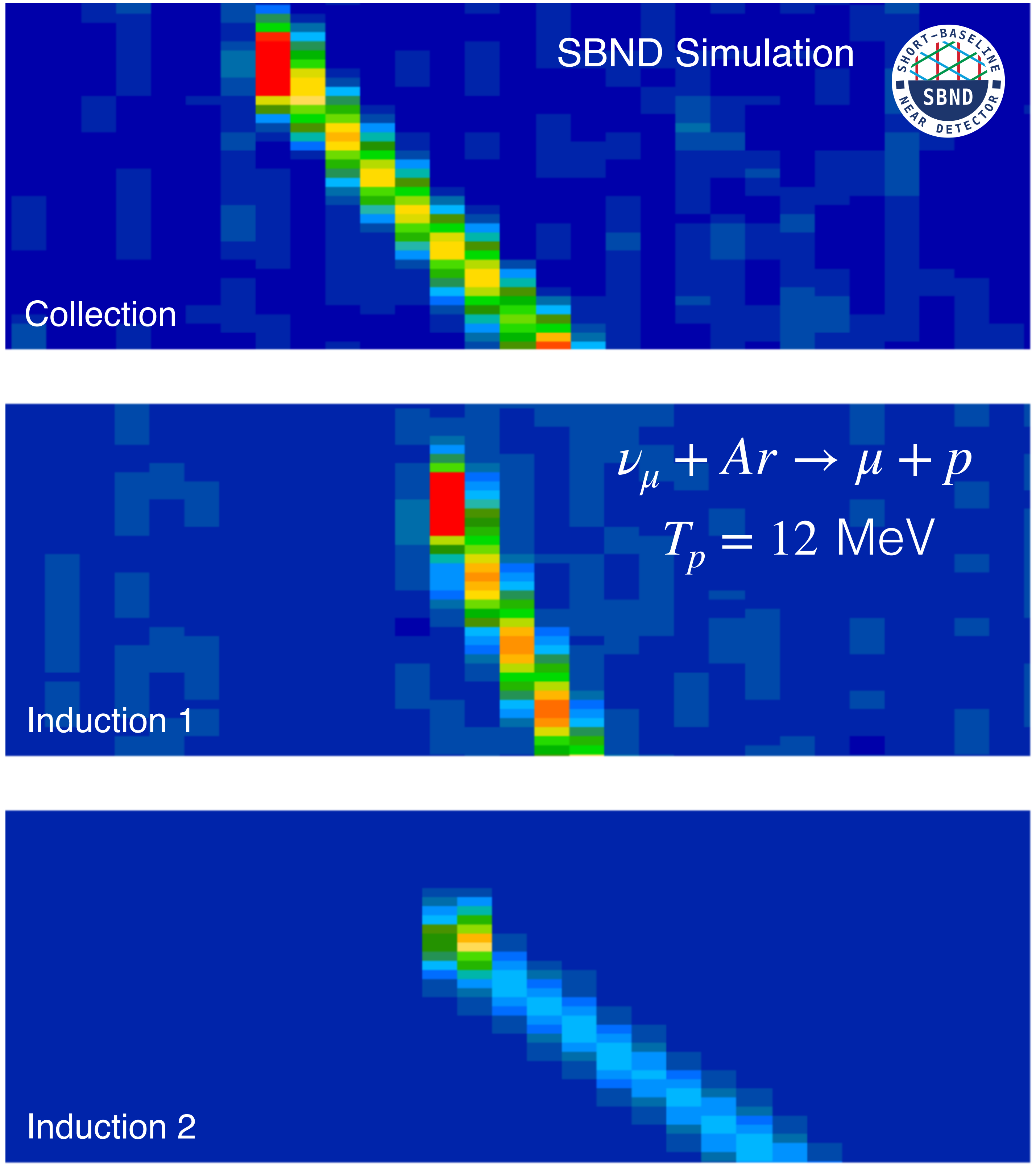


Pandora pattern recognition:
Eur. Phys. J. C 78, 82 (2018)

Reconstructing Protons in SBND

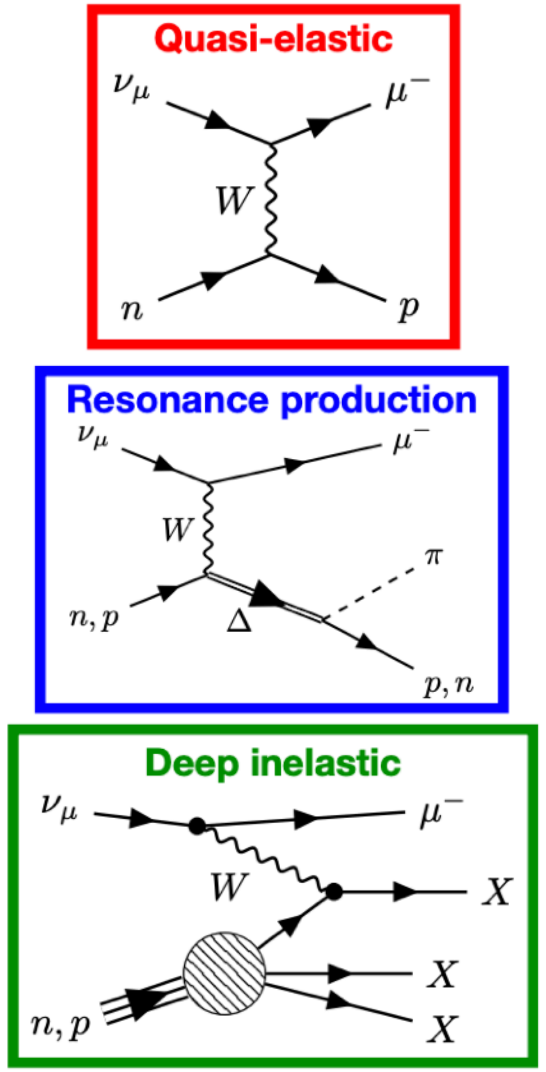
- Below: table showing relationship between proton momentum, kinetic energy, and length in LAr
- Left: event display showing an interaction where there is a proton with kinetic energy of 12 MeV in the final state, which was tagged using calorimetry
  - Calorimetry able to identify the presence of a proton,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

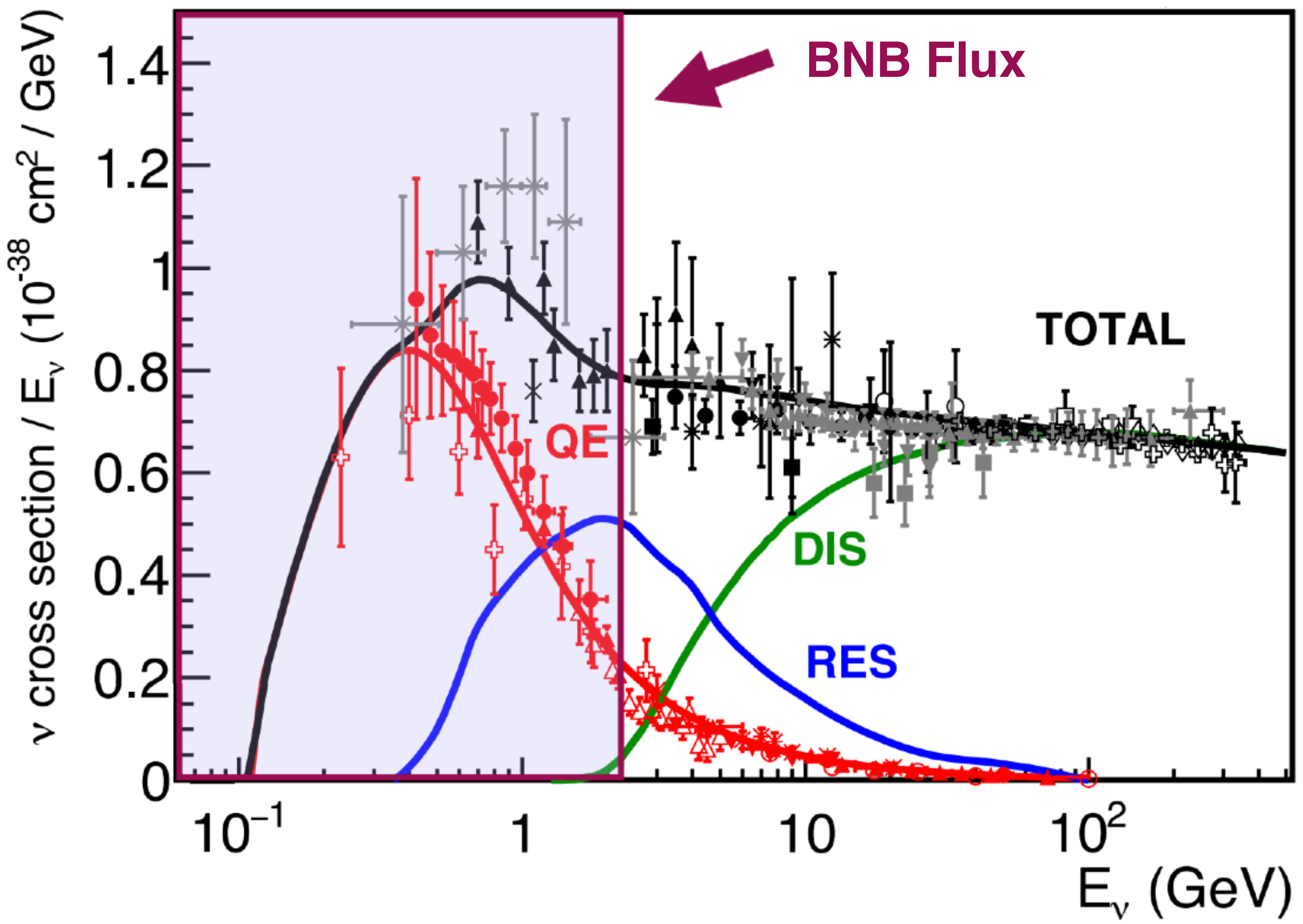


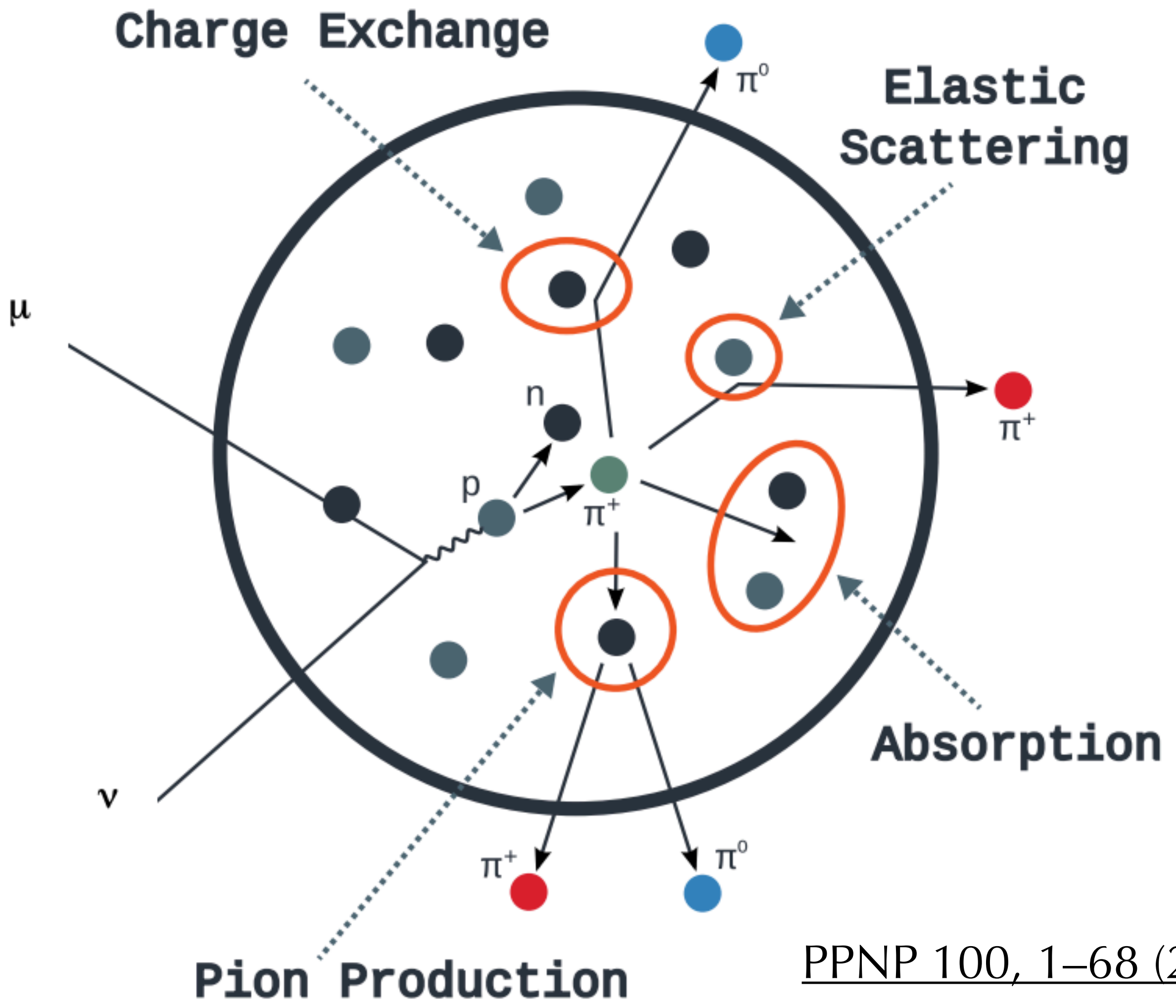
Neutrino Interactions on Argon

- 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)

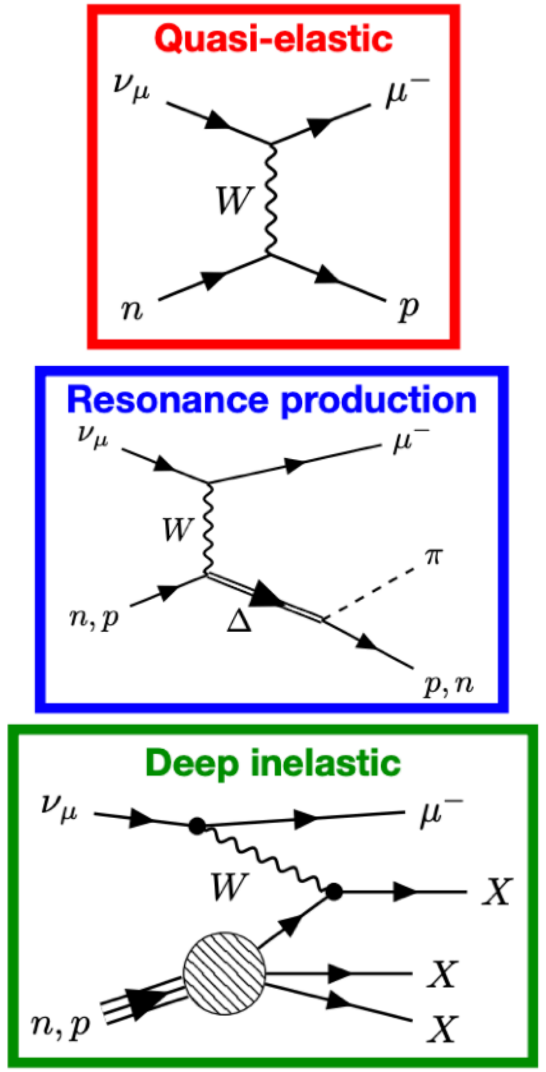




PPNP 100, 1–68 (2018)

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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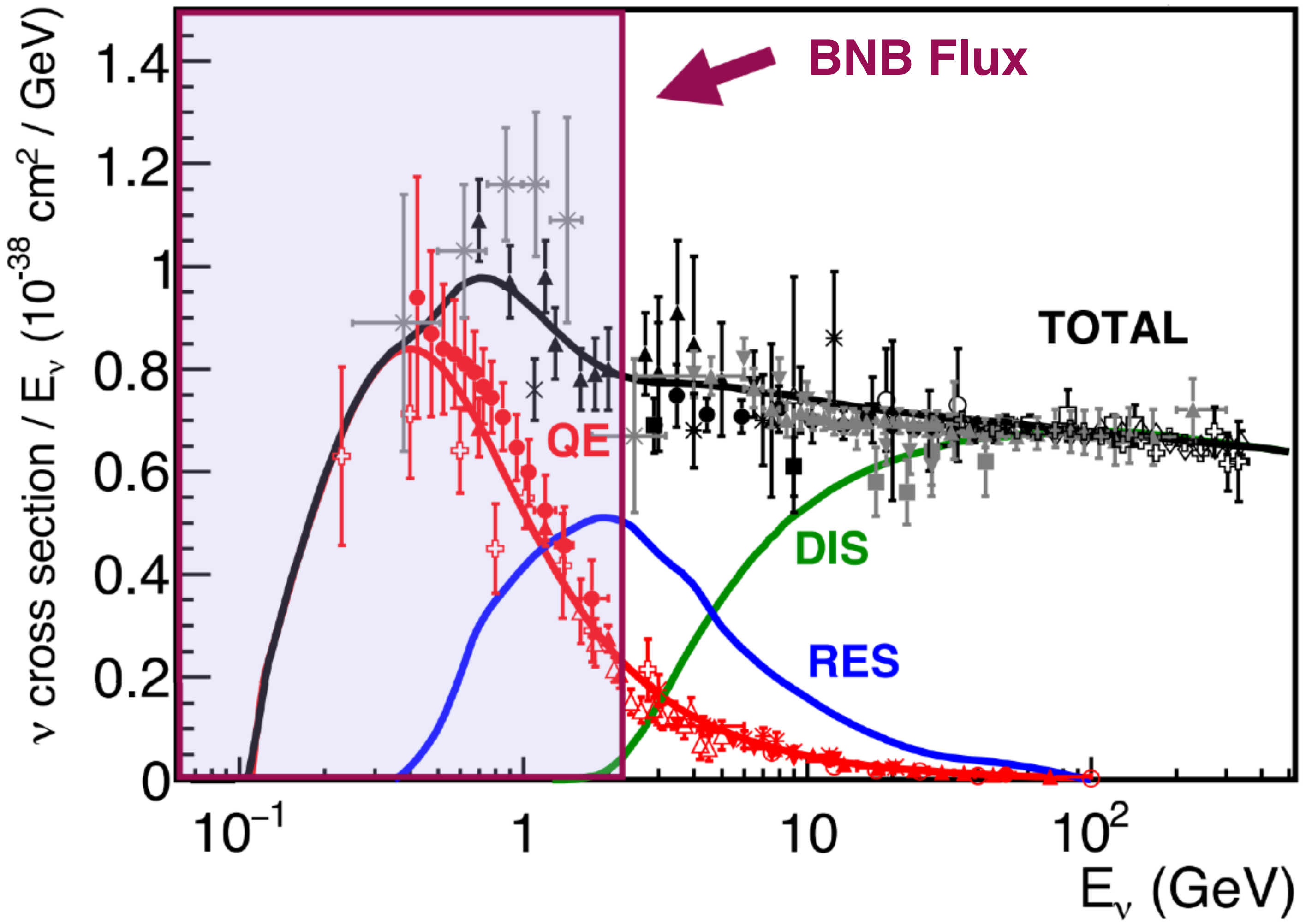
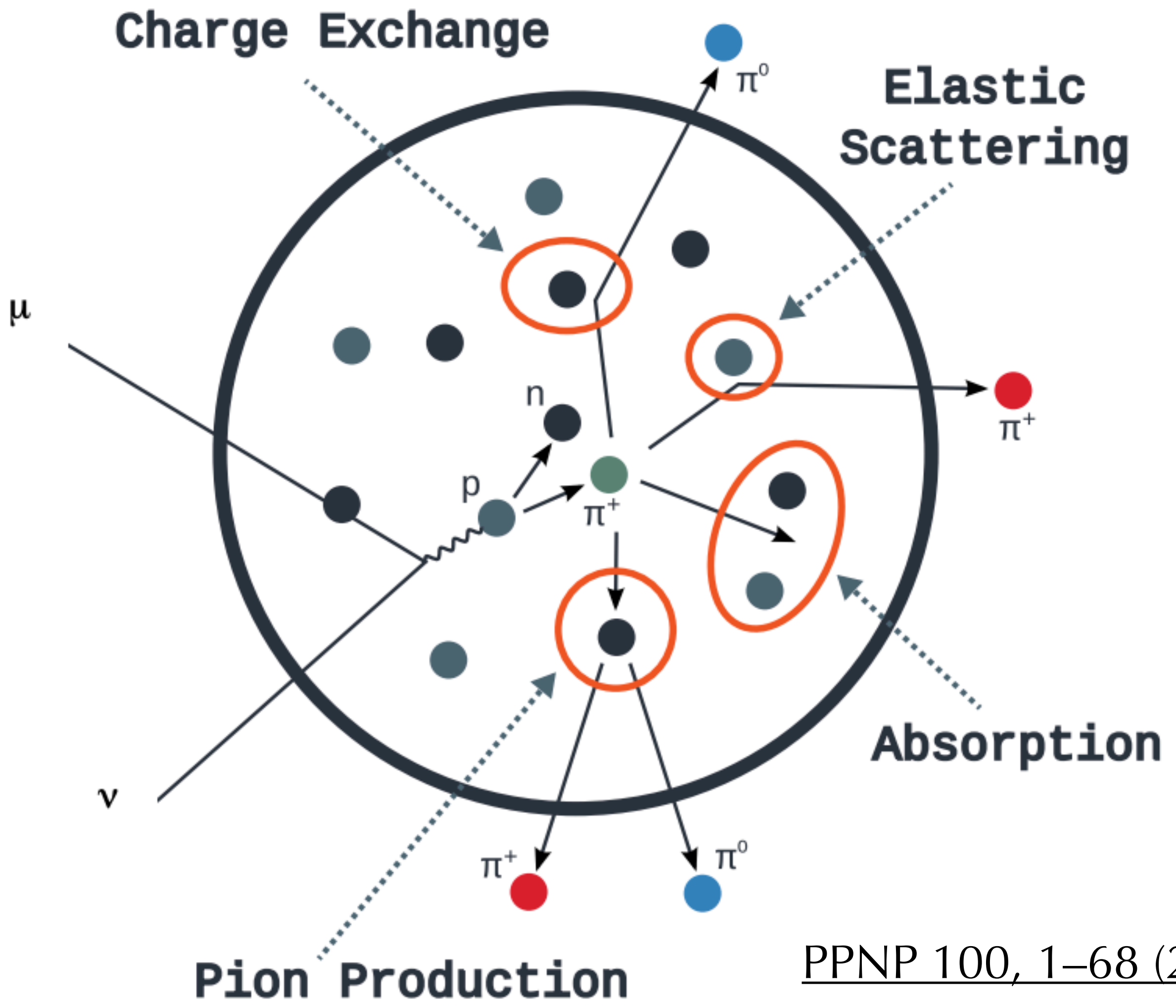




PPNP 100, 1–68 (2018)

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 ≥2π + X**
  - ~600 ν_μ **CC K^+K^- + X**
  - ~700 ν_μ **CC $K^0\bar{K}^0$ + 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 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

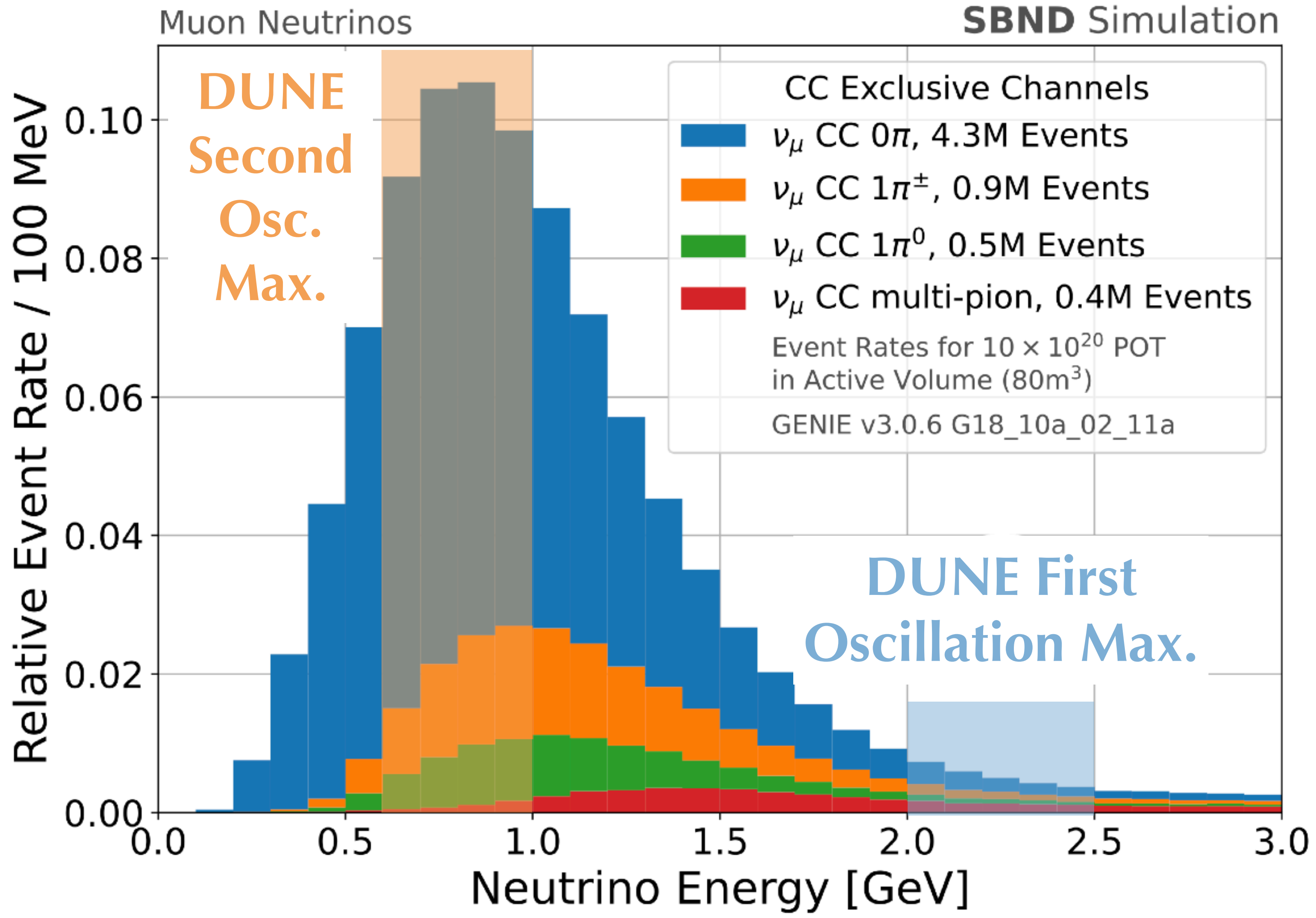
R. Jones PhD thesis

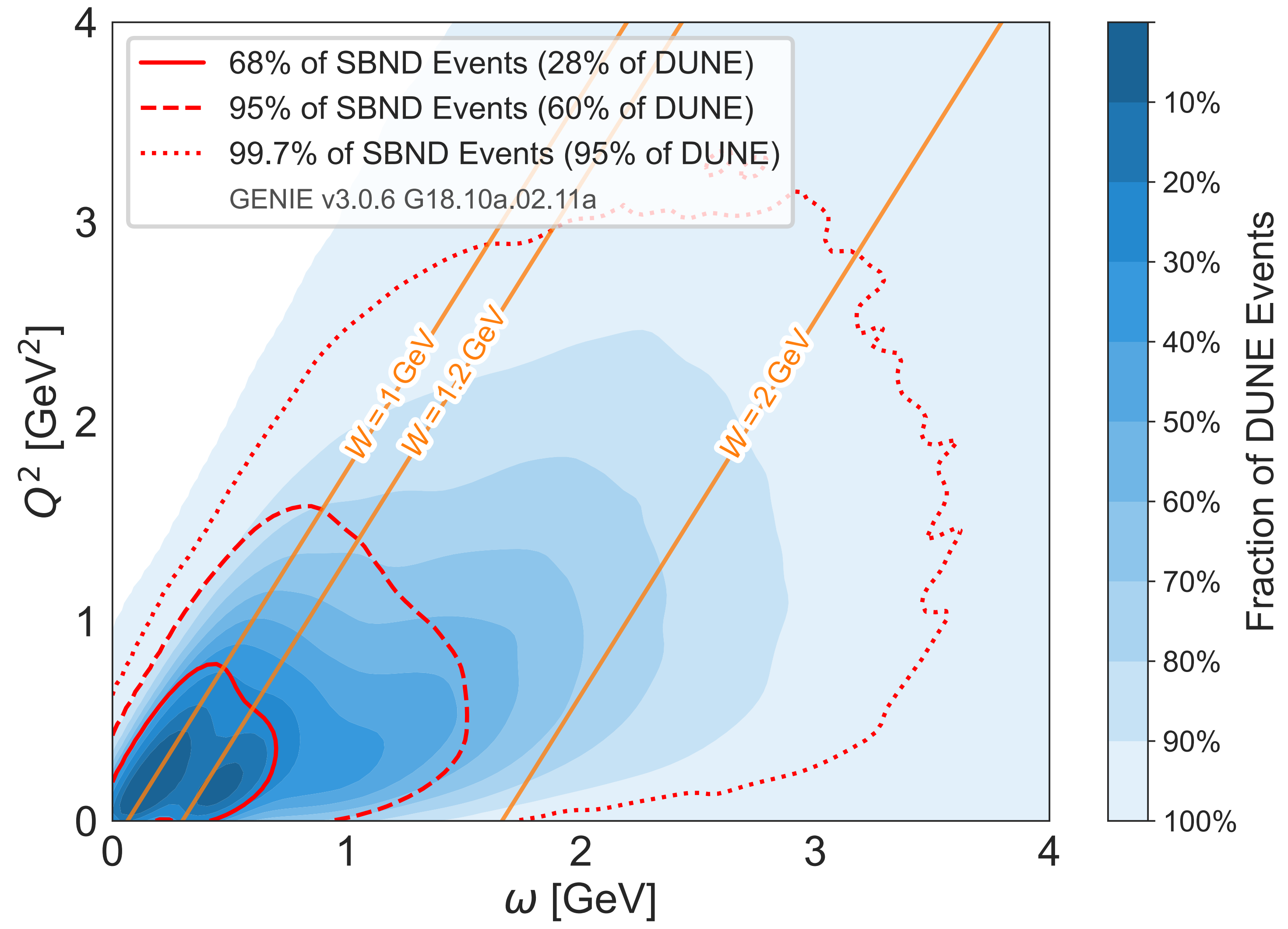
What's In GENIE v3.0.6 `G18_10a_02_11a`?

- 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 Interactions vs. the DUNE Phase Space

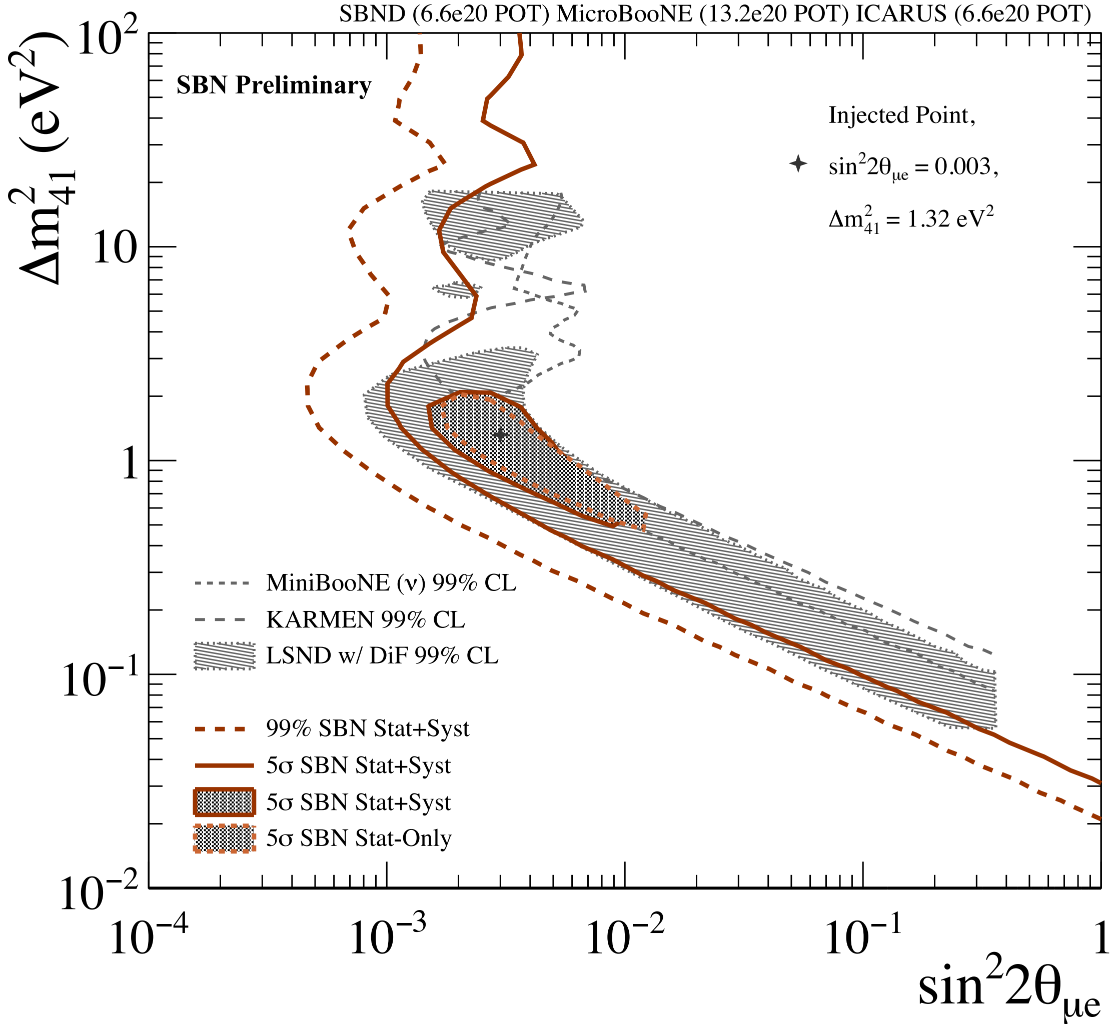
- SBND interactions will cover significant parts of kinematic phase space relevant for DUNE, including energy range spanning first and second oscillation maxima
- Have the opportunity to map out the argon nuclear response to neutrino probes from the quasielastic region to the resonance region and beyond



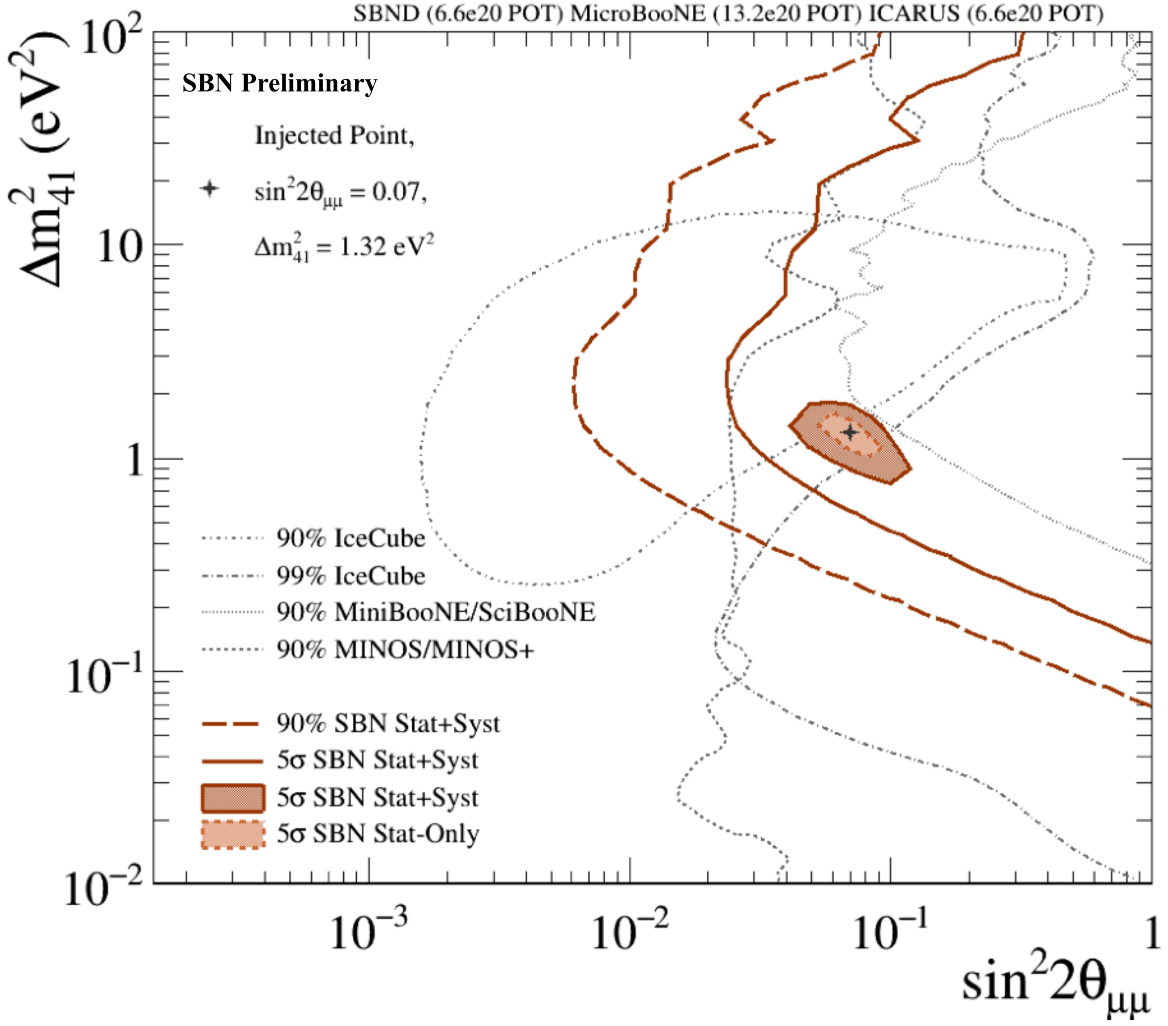


SBN Oscillation Sensitivities

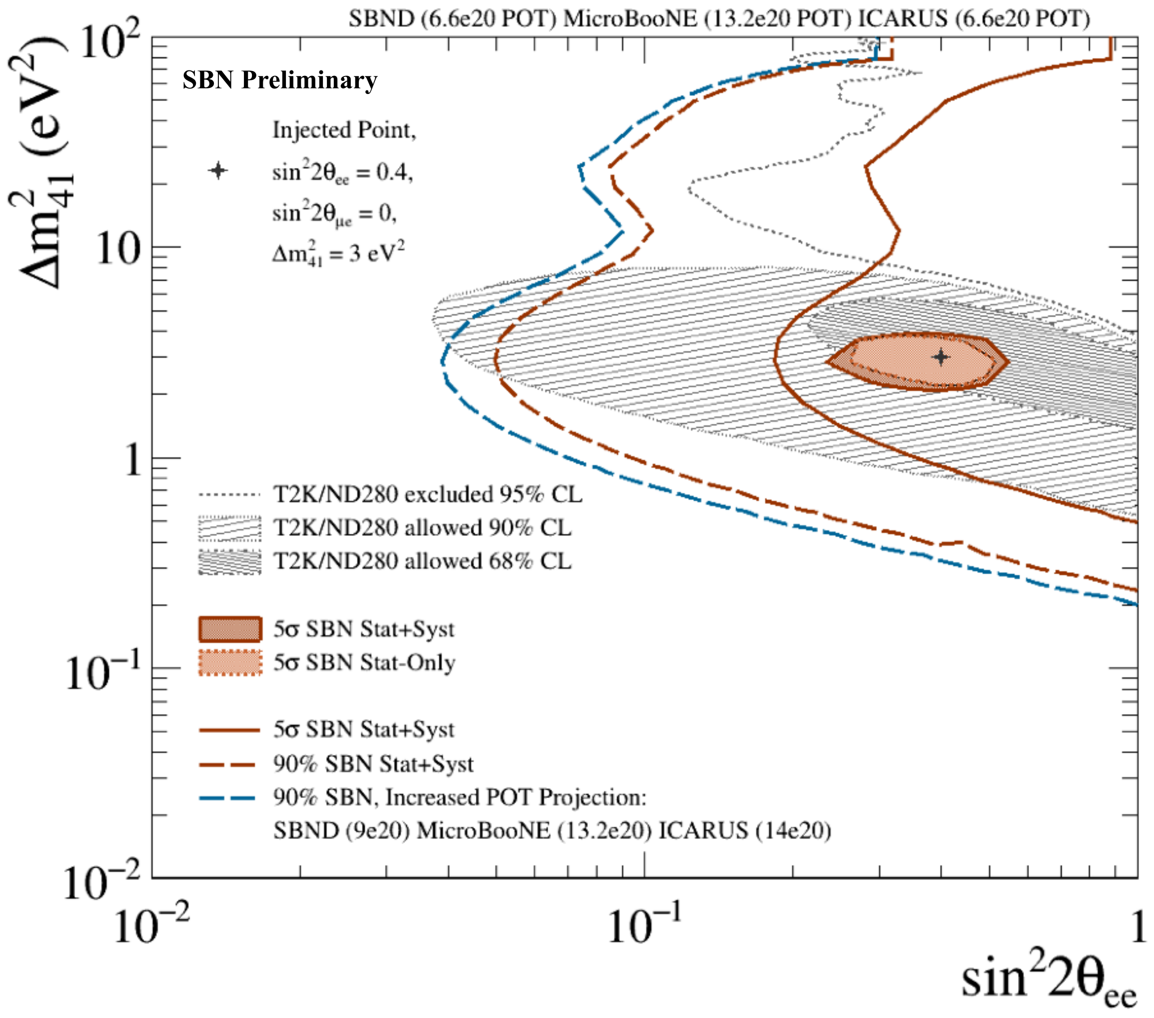
ν_e Appearance



ν_μ Disappearance



ν_e Disappearance



ν_e Appearance vs. ν_μ Disappearance in Short Baseline Anomalies

- Some experiments studying ν_μ beams at short baselines (≲0.01 km/MeV) have observed anomalous appearance of ν_e that could indicate sterile-induced oscillations
- However, other experiments looking for the same signatures or for ν_μ and ν_e disappearance don't see anomalies — conflicting results create tension when performing global fits
- The simple case of one sterile neutrino (3+1) seems unlikely but other new physics involving sterile neutrinos is still plausible

	$\nu_\mu \to \nu_e$	$\nu_\mu \to \nu_\mu$	$\nu_e \to \nu_e$
Neutrino	MiniBooNE (BNB) * MiniBooNE (NuMI) NOMAD	SciBooNE/MiniBooNE CCFR CDHS MINOS	KARMEN/LSND cross section SAGE/GALLEX *
Antineutrino	LSND * KARMEN MiniBooNE (BNB) *	SciBooNE/MiniBooNE CCFR MINOS	Bugey NEOS DANSS * PROSPECT STEREO Neutrino-4 *

Experiments denoted with * have a >2σ signal

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