The Short-Baseline Near Detector: Neutrino Interactions Measurement Capabilities

Vishvas Pandey

for the SBND Collaboration

Neutrino Scattering at Low and Intermediate Energies, Mainz, Jun 26 – 30, 2023

Outline

- Short Baseline Neutrino (SBN) Program at Fermilab
  - Short-baseline anomalies, status
- Short Baseline Near Detector (SBND)
  - Installation status and timeline, key features
- Neutrino Interaction Physics at SBND
  - High statistics, detection capabilities, SBND-PRISM
- Broader Physics Program at SBND
  - Oscillations and BSM Physics

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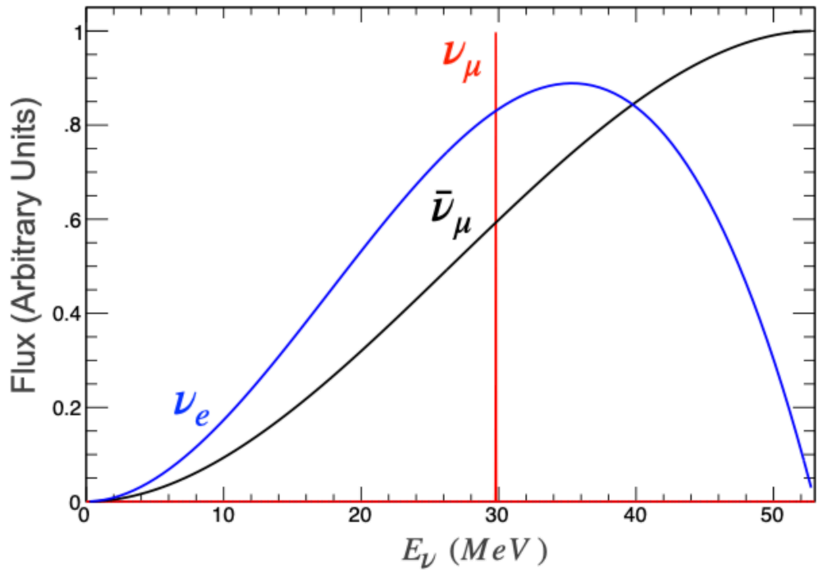
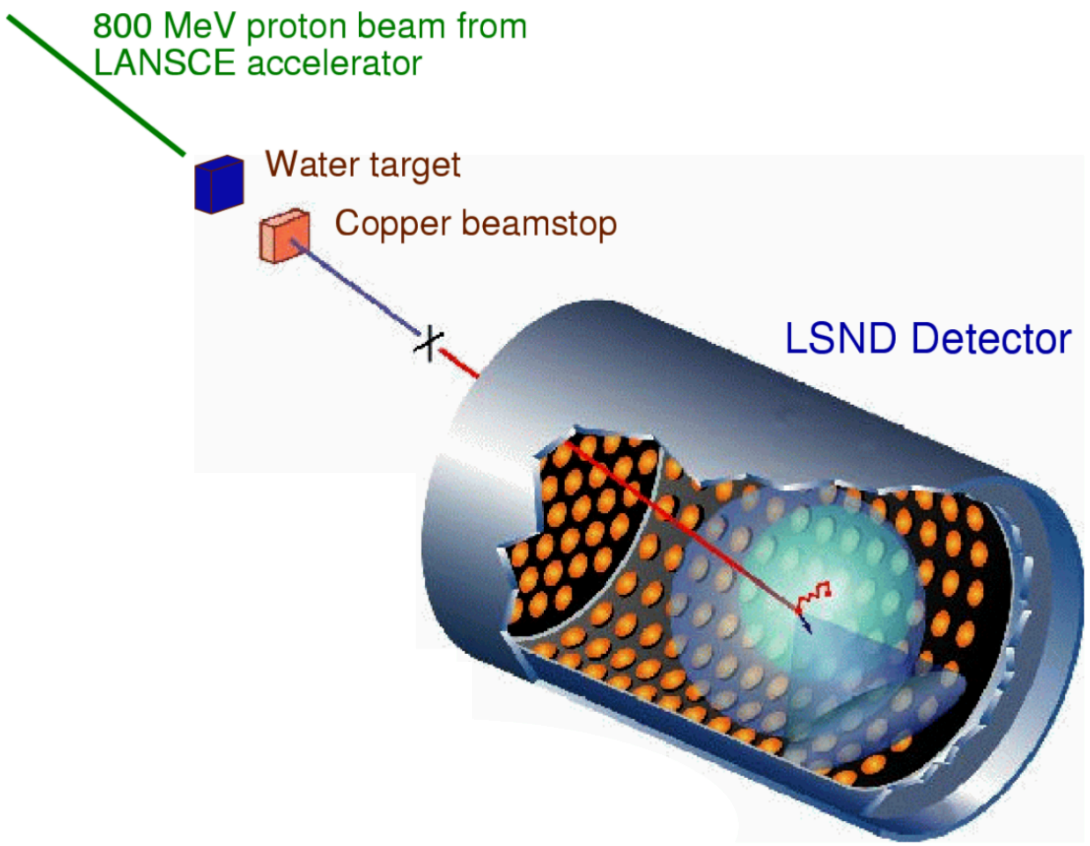
Liquid Scintillator Neutrino Detector (LSND) at LANL

- Well known decay-at-rest neutrinos:

$$\pi^+ \to \mu^+ + \nu_\mu$$

$$\mu^+ \to e^+ + \bar{\nu}_\mu + \nu_e$$





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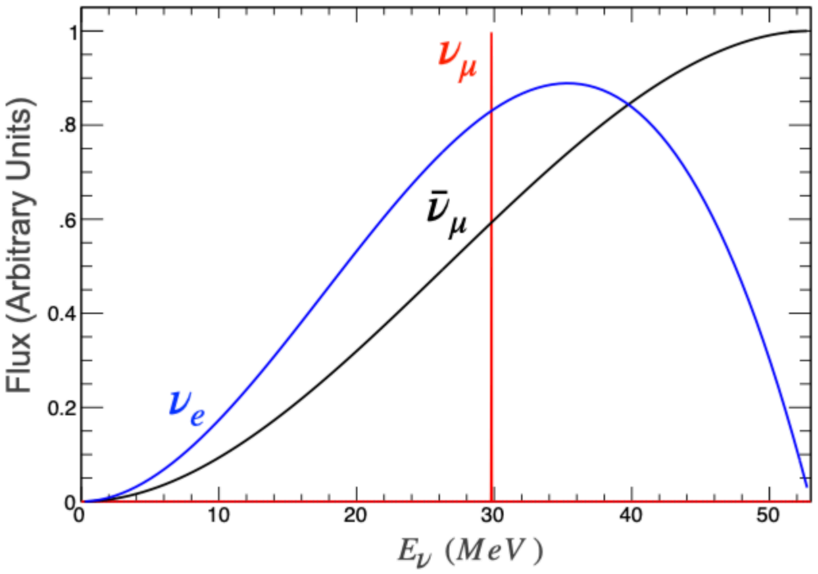
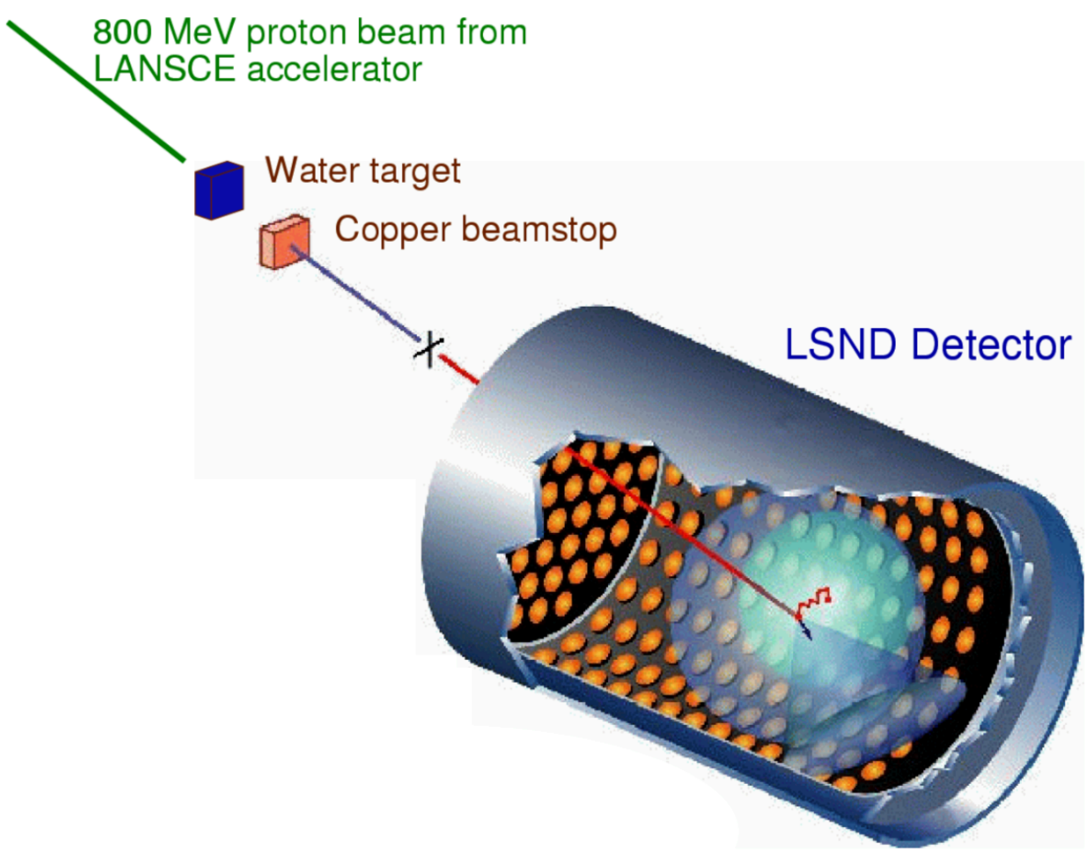
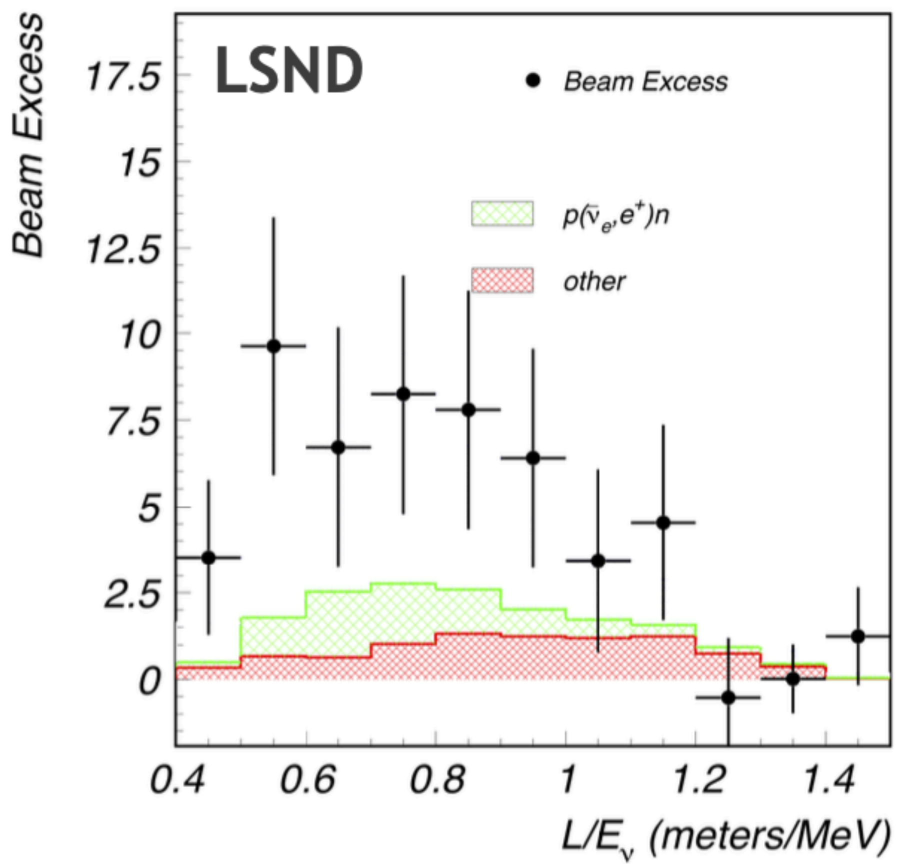




$$\boxed{\bar{\nu}_\mu \rightarrow \bar{\nu}_e ?}$$

Phys. Rev. D 64 112007, 2001



- A 3.8 σ excess of events over backgrounds was observed.
- Compatible with $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ oscillations with L/E ≈ 1 m/MeV

MiniBooNE at FNAL

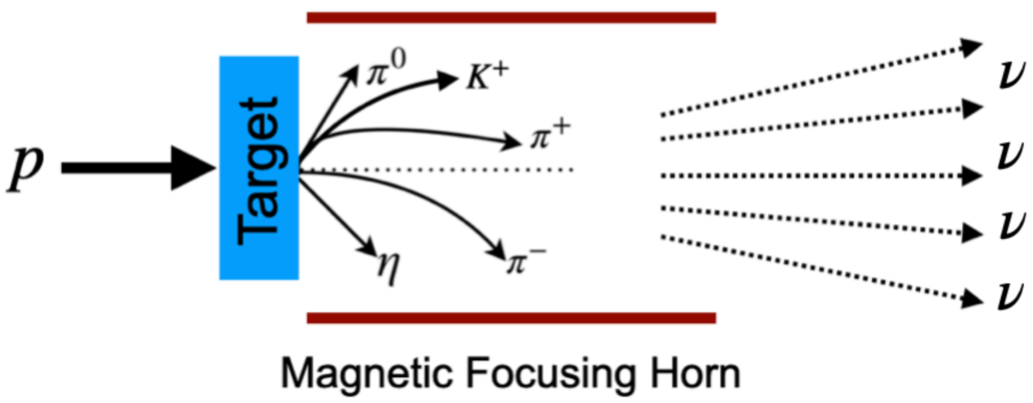
- Designed to test the LSND anomaly - very different L, E, but similar L/E
- Decay in flight neutrinos

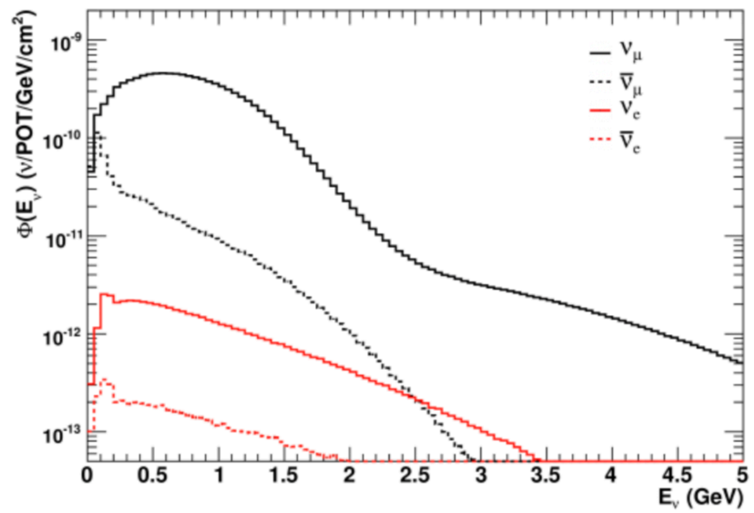
$$\pi^+ \rightarrow \nu_\mu + \mu^+ \qquad \mu^+ \rightarrow \nu_e + \bar{\nu}_\mu + e^+$$

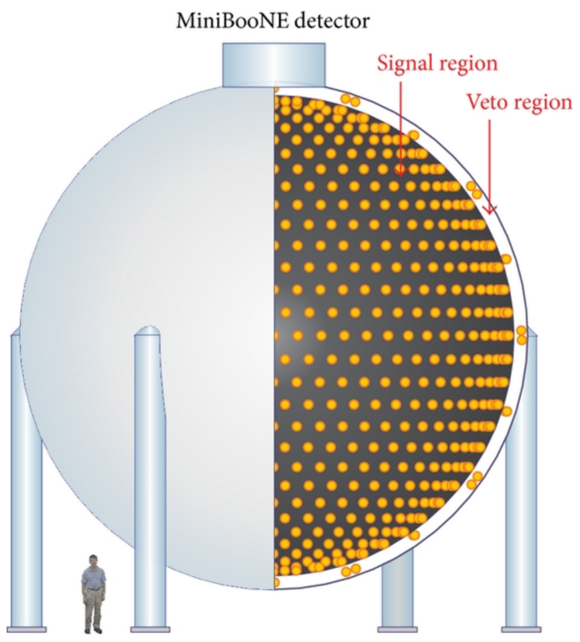
$$K^+ \rightarrow \nu_\mu + \mu^+ \qquad K^+ \rightarrow \nu_e + e^+ + \pi^0$$

$$K_L^0 \rightarrow \nu_e + e^+ + \pi^-$$

ν_μ *(93.6%),* $\bar{\nu}_\mu$ *(5.9%),* $\nu_e + \bar{\nu}_e$ *(0.5%)*







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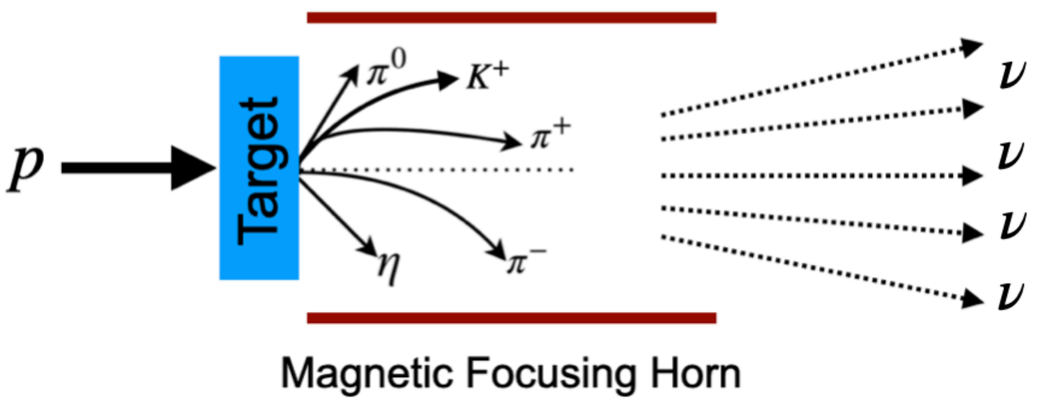
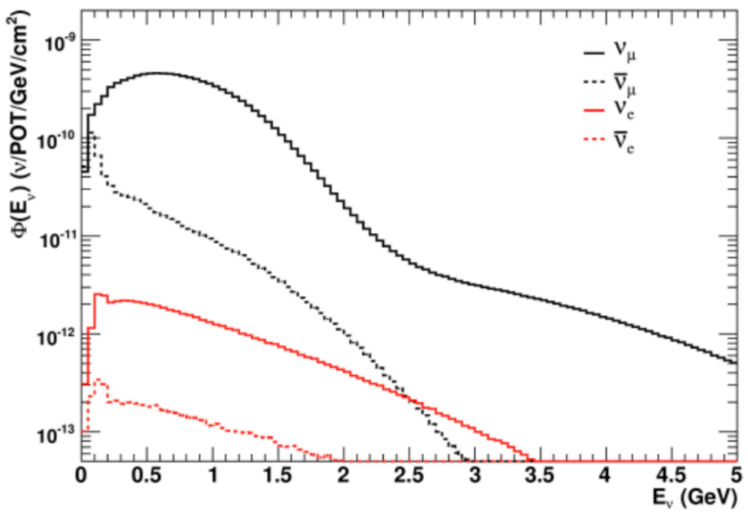
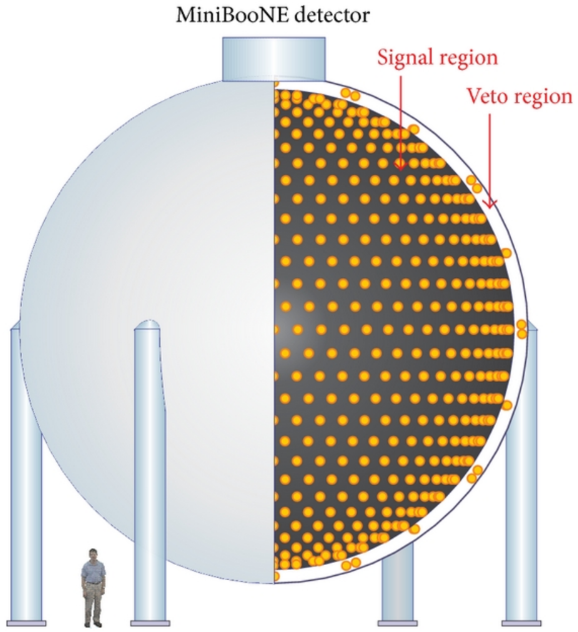
$$K^+ \to \nu_\mu + \mu^+ \qquad K^+ \to \nu_e + e^+ + \pi^0$$
$$K^0_L \to \nu_e + e^+ + \pi^-$$

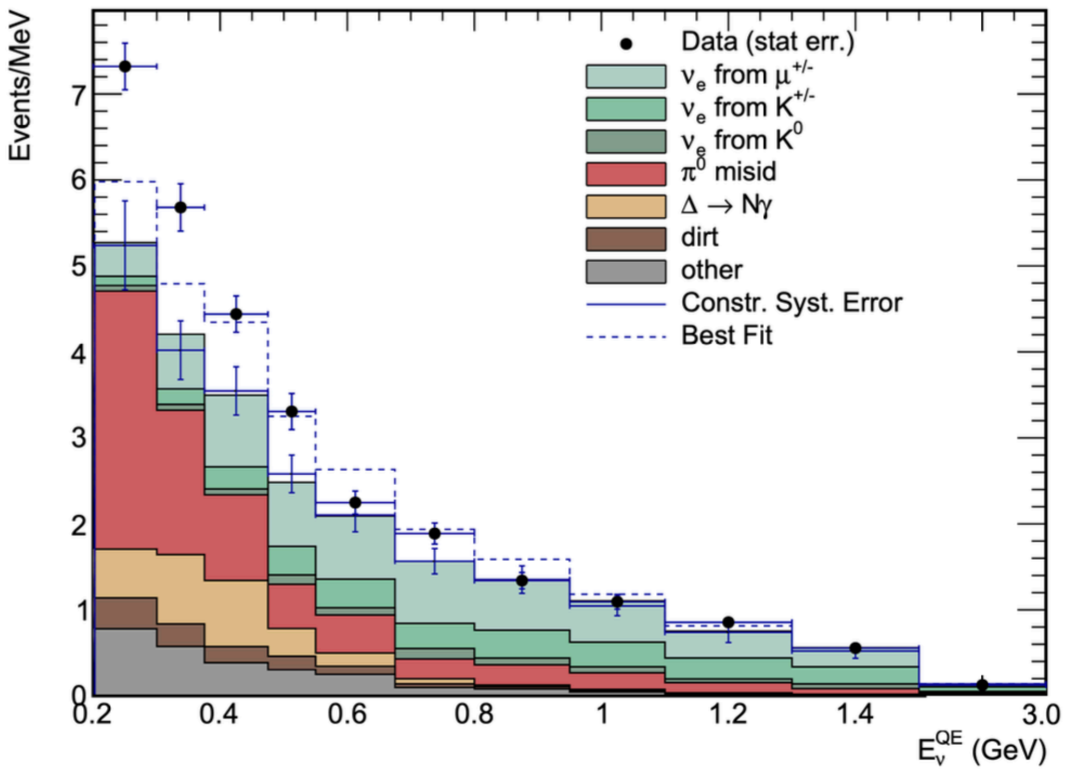
$$\nu_\mu \to \nu_e \; AND \; \bar{\nu}_\mu \to \bar{\nu}_e ?$$

ν_μ (93.6%), $\bar{\nu}_\mu$ (5.9%), $\nu_e + \bar{\nu}_e$ (0.5%)









MiniBooNE Collaboration, Phys. Rev. D 103, 052002 (2021)

- A 4.5 (2.8) σ excess of events observed with same L/E as LSND;
- Excess compatible with LSND within a sterile neutrino framework

Short-Baseline Anomaly: Sterile Neutrino?

- Similar observation by reactor experiments (reactor anomaly, $\bar{\nu}_e$ disappearance) and Source experiments (Gallium anomaly, ν_e disappearance)
- If coming from oscillations, all these results require a new mass eigenstate around the eV scale
- A new heavier mass state with mass-splitting $\Delta m^2_{41} \sim \mathcal{O}\left(1eV^2\right)$ that can generate neutrino oscillations at short-distances

$$\boxed{P\left(\nu_\mu \rightarrow \nu_e\right) = \sin^2\left(2\theta_{\mu e}\right)\sin^2\left(\frac{\Delta m^2_{41} L}{4E_\nu}\right)}$$

$$\boxed{\sin^2\left(2\theta_{\mu e}\right) \equiv 4\left|U_{e4}\right|^2\left|U_{\mu 4}\right|^2}$$

Short-Baseline Anomaly: Caveats?

- **Electron/photon separation**

- **Appearance/disappearance tension**

Short-Baseline Anomaly: Caveats?

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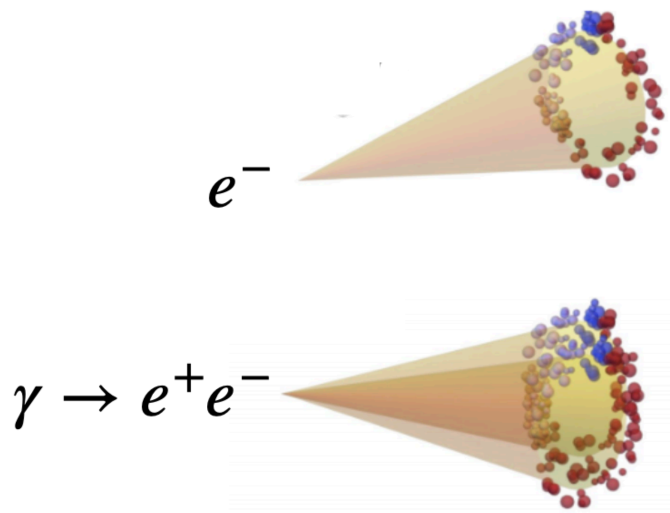
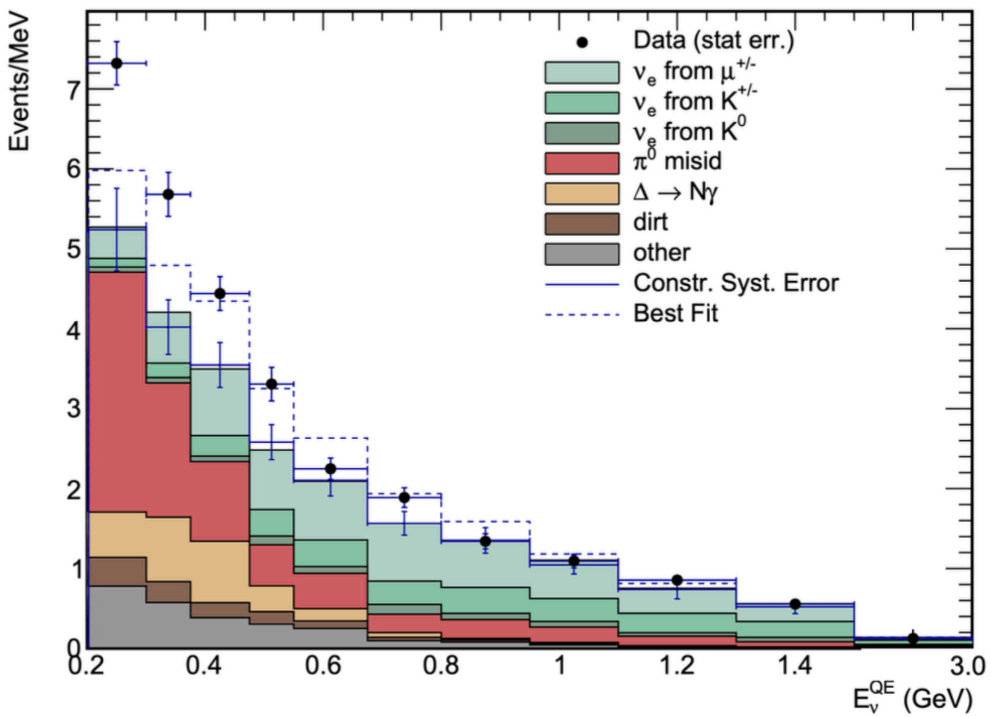
  - Cherenkov signatures in MiniBooNE are unable to distinguish between photons and electrons





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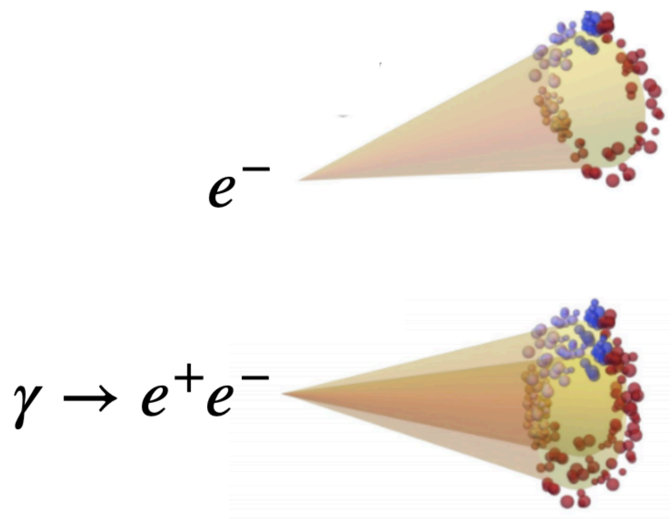
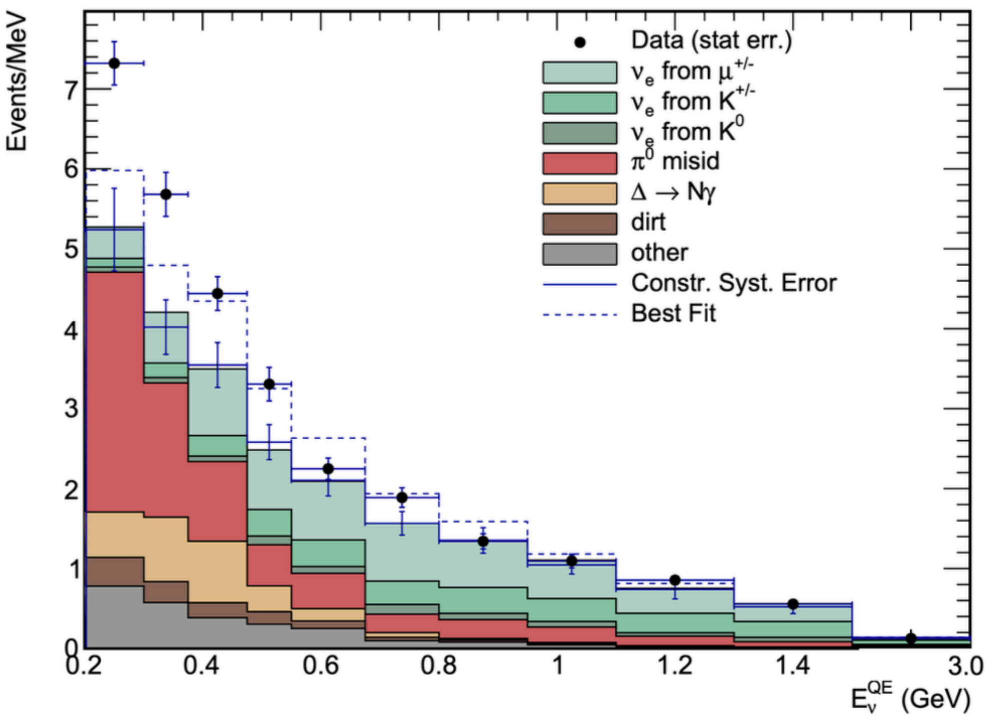


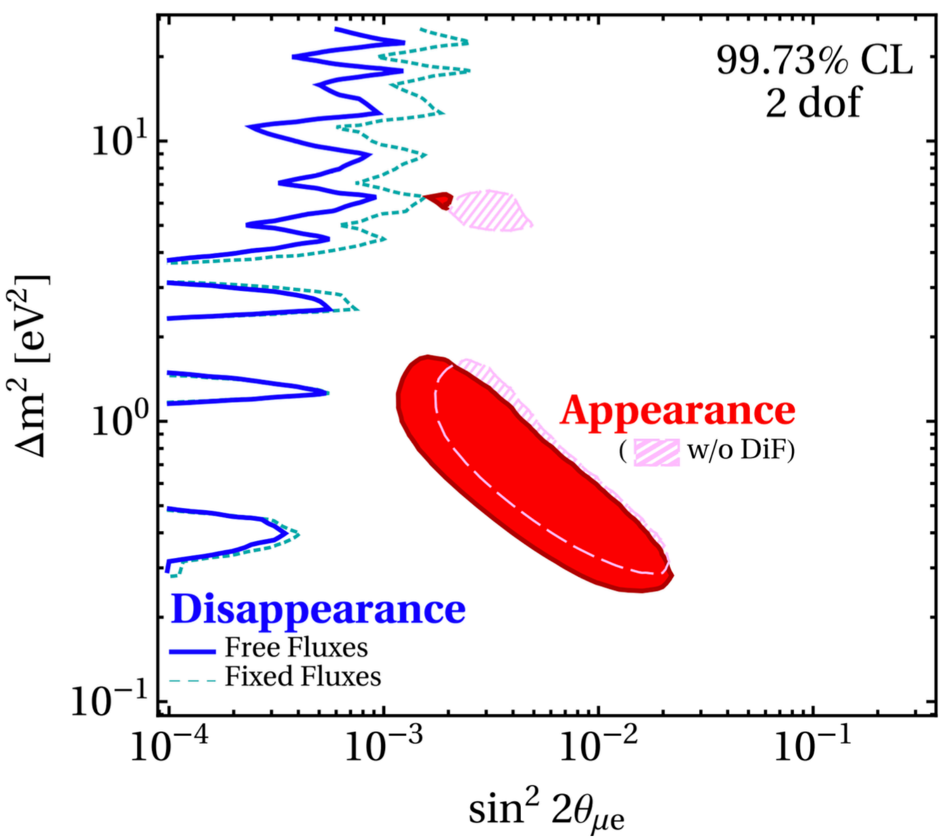


MiniBooNE Collaboration, Phys. Rev. D 103, 052002 (2021)

Appearance/disappearance tension

- When combining appearance and disappearance data, a 4.7 σ tension arises.
- A lack of overlap between the parameter region favored by appearance data (driven by LSND and MiniBooNE) and the strong exclusion limits from disappearance data.

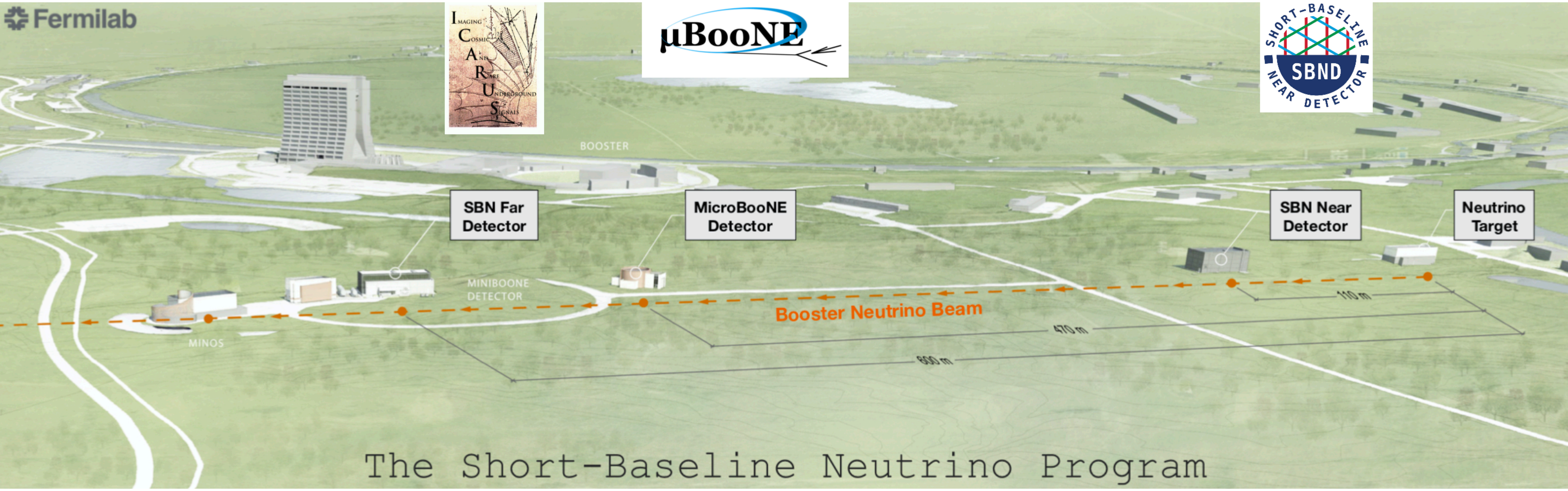
Sterile Neutrino Global Fits ca 2019



M. Dentler et al., JHEP 08, 010 (2018)

Short-Baseline Neutrino (SBN) Program at Fermilab

- Three functionally identical Liquid Argon Time Projection Chamber (LArTPC) detectors located along the Booster Neutrino Beamline (BNB) at Fermilab
  - Introducing a new detector technology to this endeavor - LArTPC
- Same neutrino beam, nuclear target and detector technology to reduce systematic uncertainties to the % level.
- Large LArTPC detector masses and proximity to intense beams enables a broad physics program, including BSM searches & high statistics cross section measurements.
- SBN is also a ground for the LArTPC technology development that will be used in DUNE.

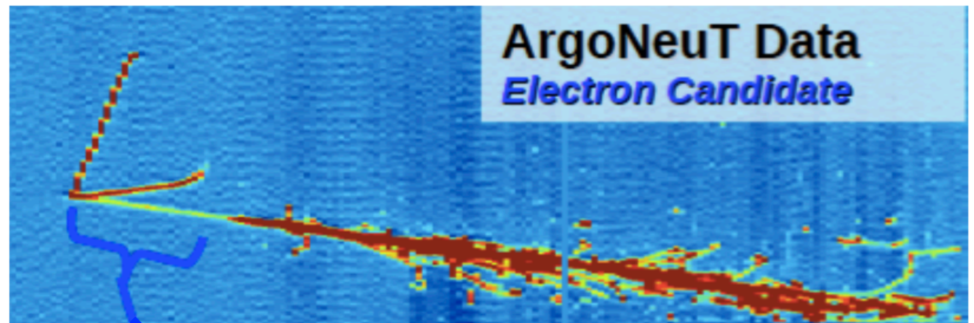


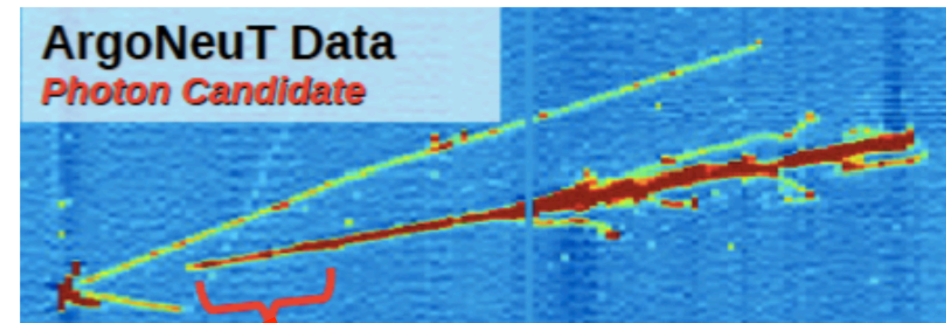
Short-Baseline Neutrino (SBN) Program at Fermilab

■ Electron/photon separation

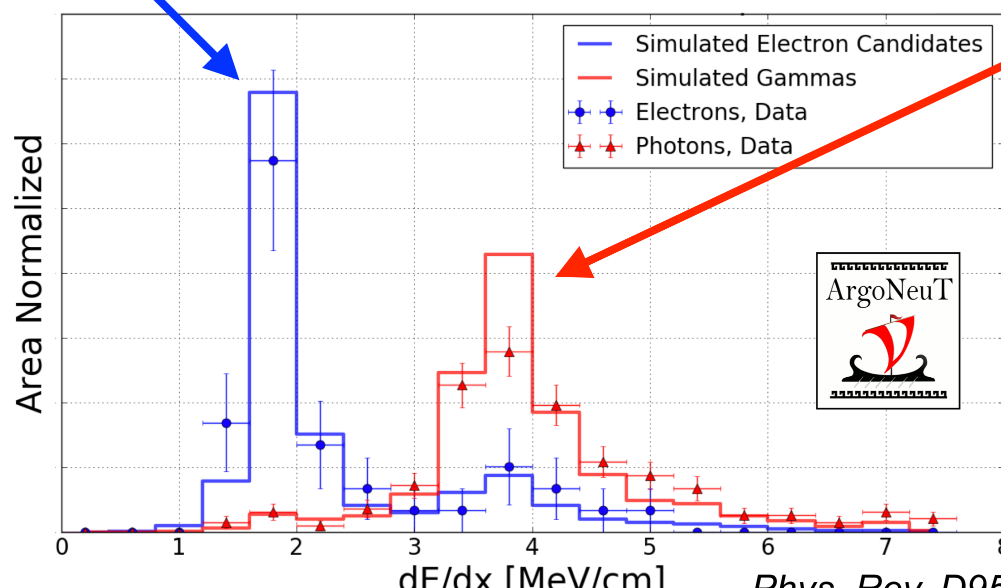
- Liquid Argon Time Projection Chamber (LArTPC)
  Fully active calorimeter and high resolution tracking - allows strong electron-photon separation

- Analyzing topology:
  gap between vertex and shower





- Analyzing dE/dx:
  Ionization in the first segment of showers



Phys. Rev. D95, 072005 (2017)

***Electrons** are one minimally ionizing particle (MIP) ~ 2 MeV/cm*

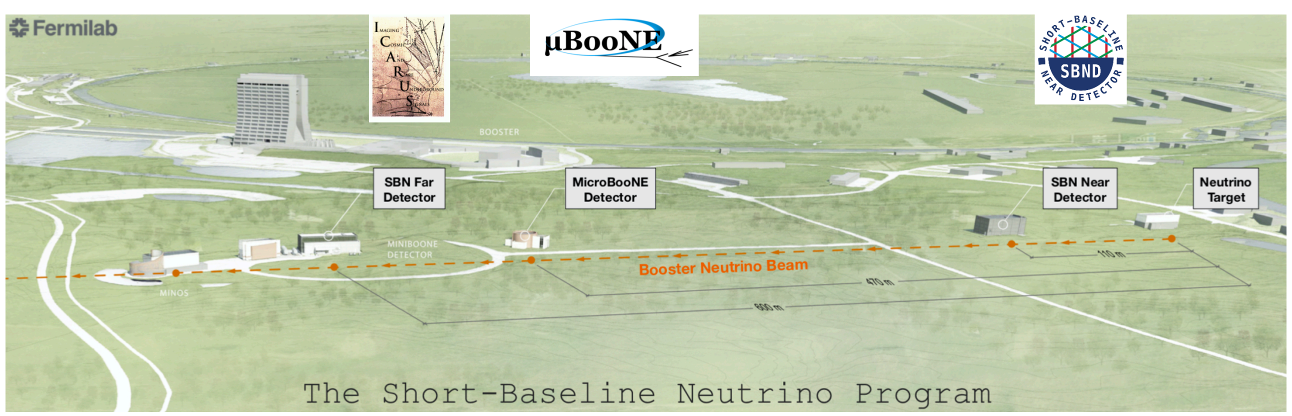
***Photons** pair convert to produce an aligned e^+e^- pair, which are two MIPs: ~4 MeV/cm*

■ Appearance/disappearance tension

- Three functionally identical detectors along the same beam line will allow studying ν_e appearance, ν_μ disappearance and ν_e disappearance oscillation channels in the same program, and help resolve the appearance-disappearance tension.

Short-Baseline Anomaly: Evolving Landscape

- The landscape of SBN anomalies have evolved in recent years.
- Many alternative explanations.
- SBN program can directly test a vast array of these interpretations, ranging from conventional origins, to flavor transformation, and to new particle production in the beam or in neutrino scattering.



New physics explanations of the short-baseline anomalies categorized by their signature.

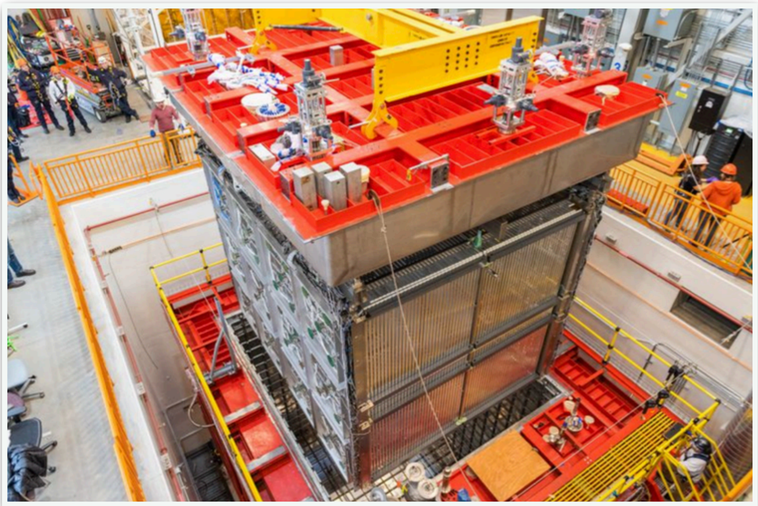
Category	Model	Signature	Anomalies: LSND	MiniBooNE	Reactor	Gallium
Flavor Conversion: Transitions	3+N oscillations	oscillations	✓	✓	✓	✓
	3+N w/ invisible sterile decay	oscillations w/ ν_4 invisible decay	✓	✓	✓	✓
	3+N w/ sterile decay	$\nu_4 \to \phi\nu_e$	✓	✓	✓	✓
Flavor Conversion: Matter Effects	3+N w/ anomalous matter effects	$\nu_\mu \to \nu_e$ via matter effects	✓	✓	✗	✗
	3+N w/ quasi-sterile neutrinos	$\nu_\mu \to \nu_e$ w/ resonant ν_s matter effects	✓	✓	✓	✓
Flavor Conversion: Flavor Violation	lepton-flavor-violating μ decays	$\mu^+ \to e^+\nu_\alpha\bar{\nu}_e$	✓	✗	✗	✗
	neutrino-flavor-changing bremsstrahlung	$\nu_\mu A \to e\phi A$	✓	✓	✗	✗
Dark Sector: Decays in Flight	transition magnetic mom., heavy ν decay	$N \to \nu\gamma$	✗	✓	✗	✗
	dark sector heavy neutrino decay	$N \to \nu(X \to e^+e^-)$ or $N \to \nu(X \to \gamma\gamma)$	✗	✓	✗	✗
Dark Sector: Neutrino Scattering	neutrino-induced up-scattering	$\nu A \to NA$, $N \to \nu e^+e^-$ or $N \to \nu\gamma\gamma$	✓	✓	✗	✗
	neutrino dipole up-scattering	$\nu A \to NA$, $N \to \nu\gamma$	✓	✓	✗	✗
Dark Sector: Dark Matter Scattering	dark particle-induced up-scattering	γ or e^+e^-	✗	✓	✗	✗
	dark particle-induced inverse Primakoff	γ	✓	✓	✗	✗

✓– the model can naturally explain the anomaly, ✓– the model can partially explain the anomaly, ✗– the model cannot explain the anomaly.

Snowmass NF02 White Paper: https://arxiv.org/abs/2203.07323

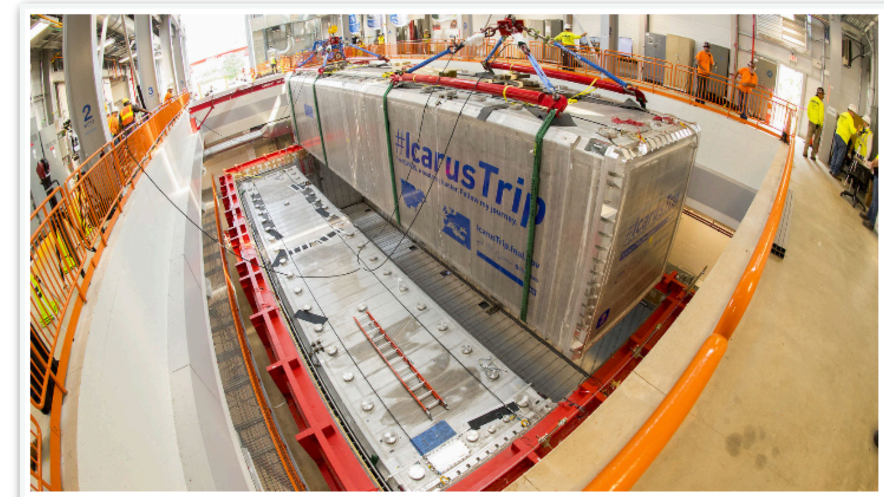
- Three functionally identical Liquid Argon Time Projection Chamber (LArTPC) detectors located along the Booster Neutrino Beamline (BNB) at Fermilab

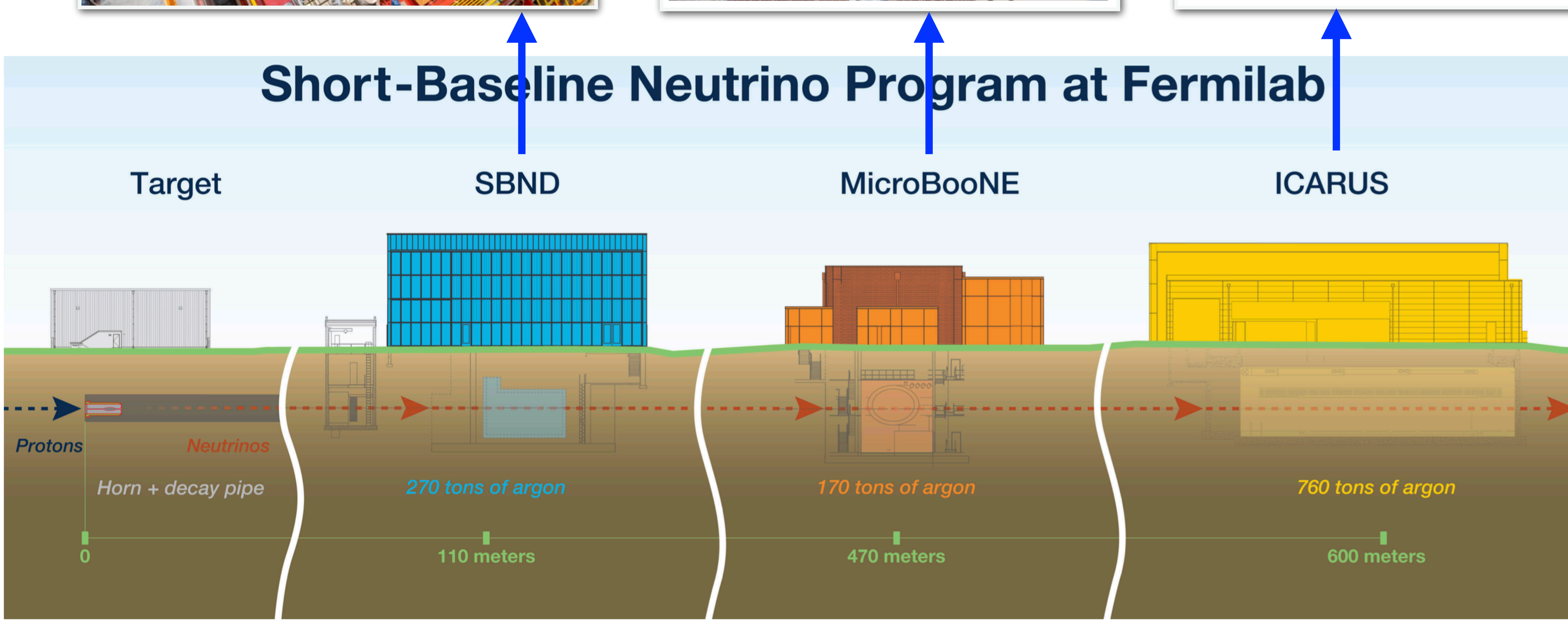
Commissioning expected late in 2023



Took data from 2015 to 2021

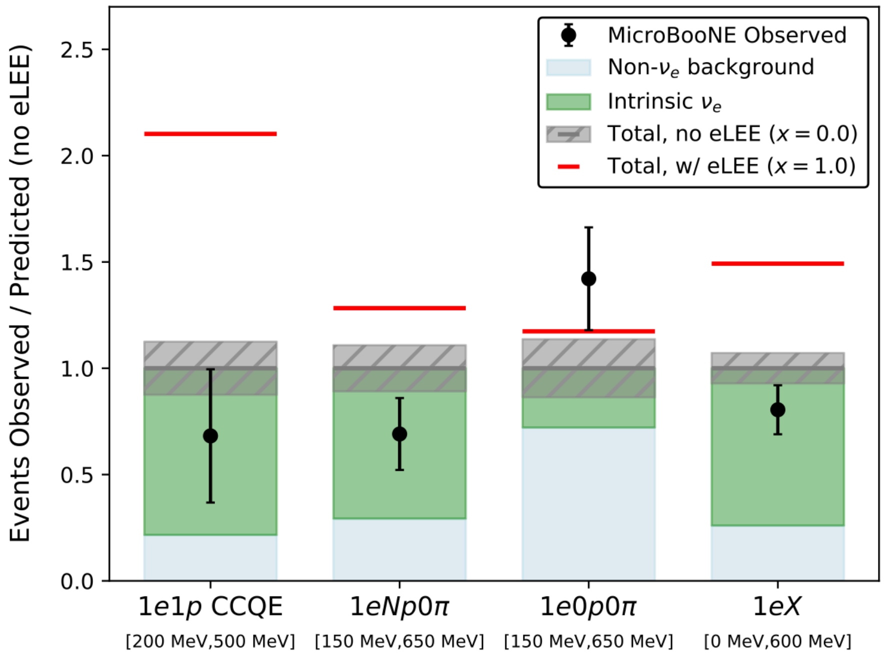
Steady data taking since March 2021





SBN Program Status

- **MicroBooNE:** First detector to operate. Took data from 2015 to 2021, now producing large numbers of scientific publications

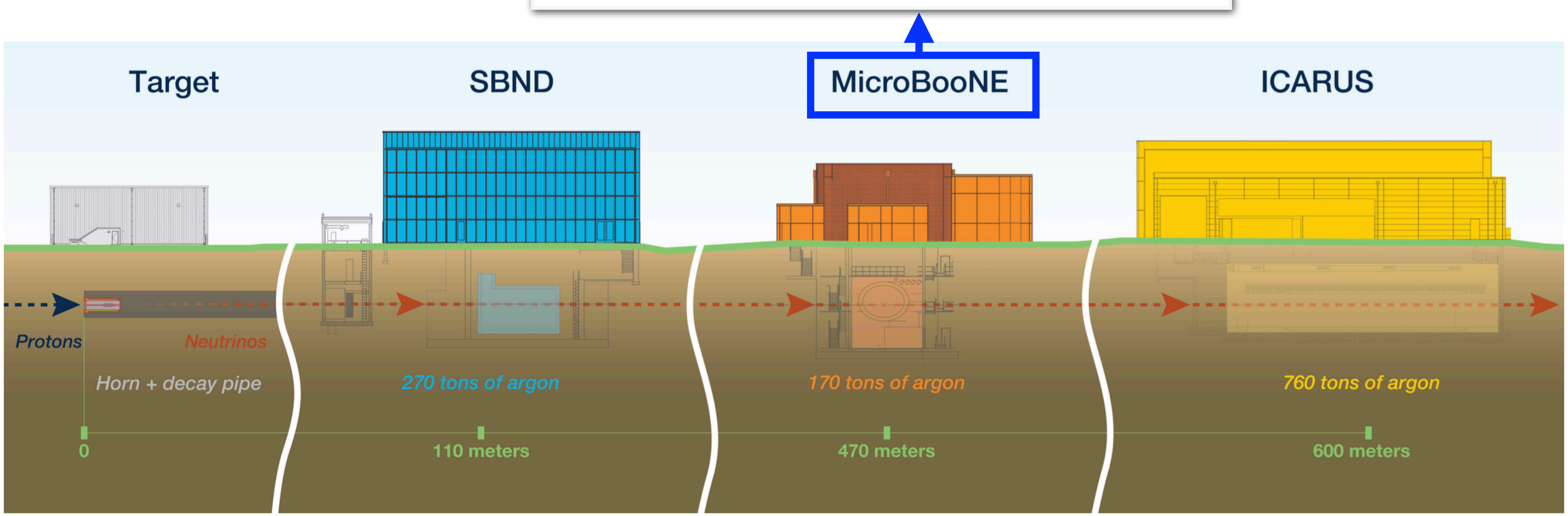


Phys. Rev. Lett. 128, 241801 (2022)

- Recently presented the results of first analyses searching for an excess of low-energy electromagnetic events:

  no hints of an electromagnetic event excess, but results do not rule out existence of sterile neutrinos.

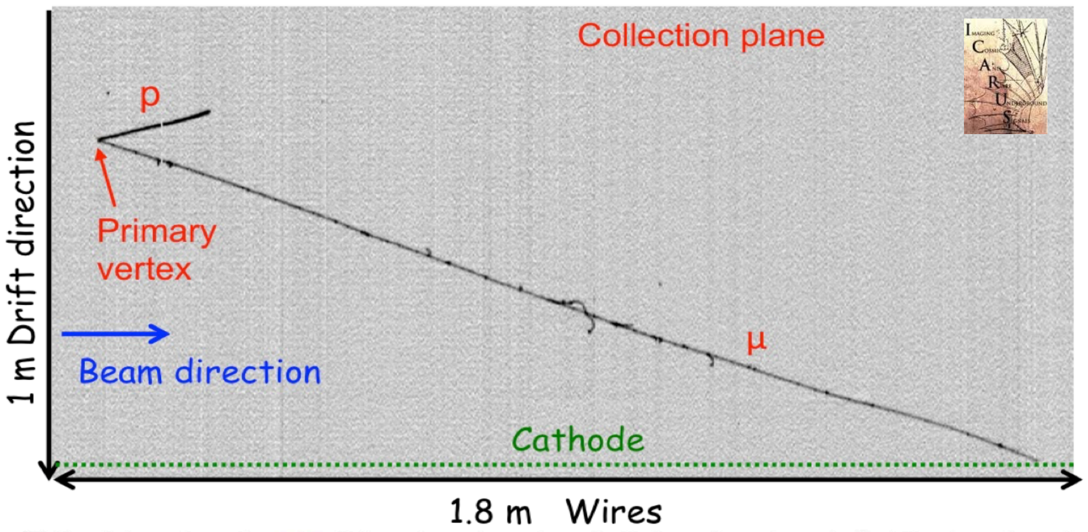
More in Afroditi's talk

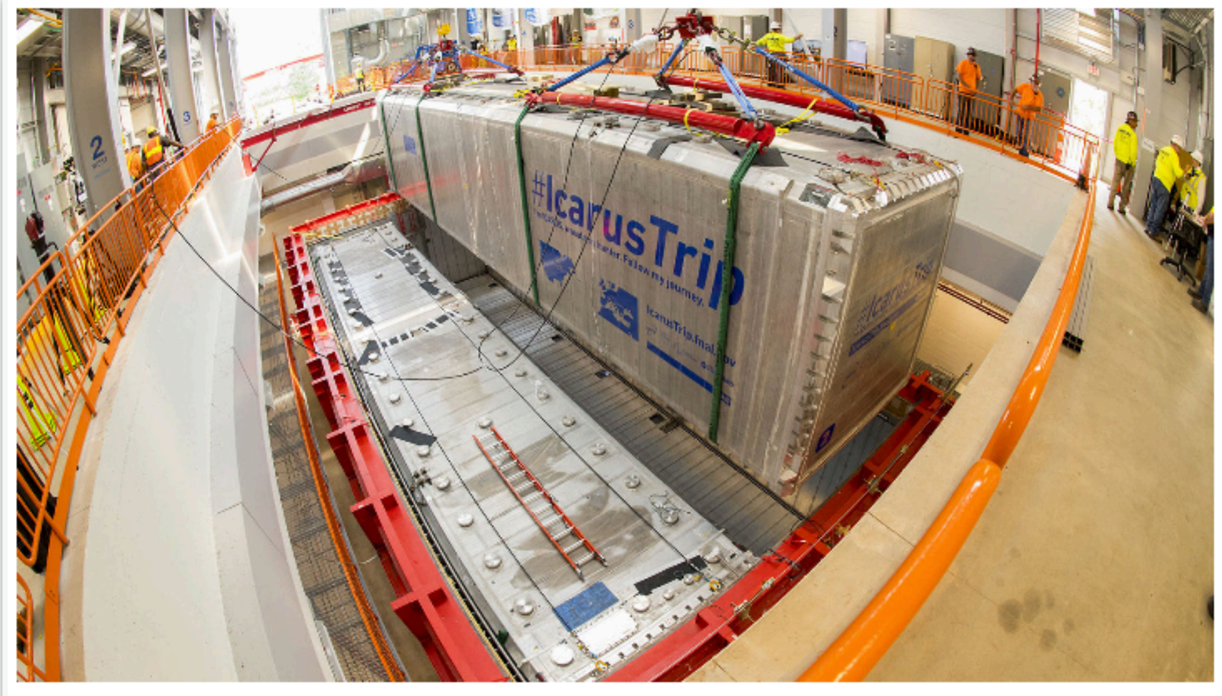


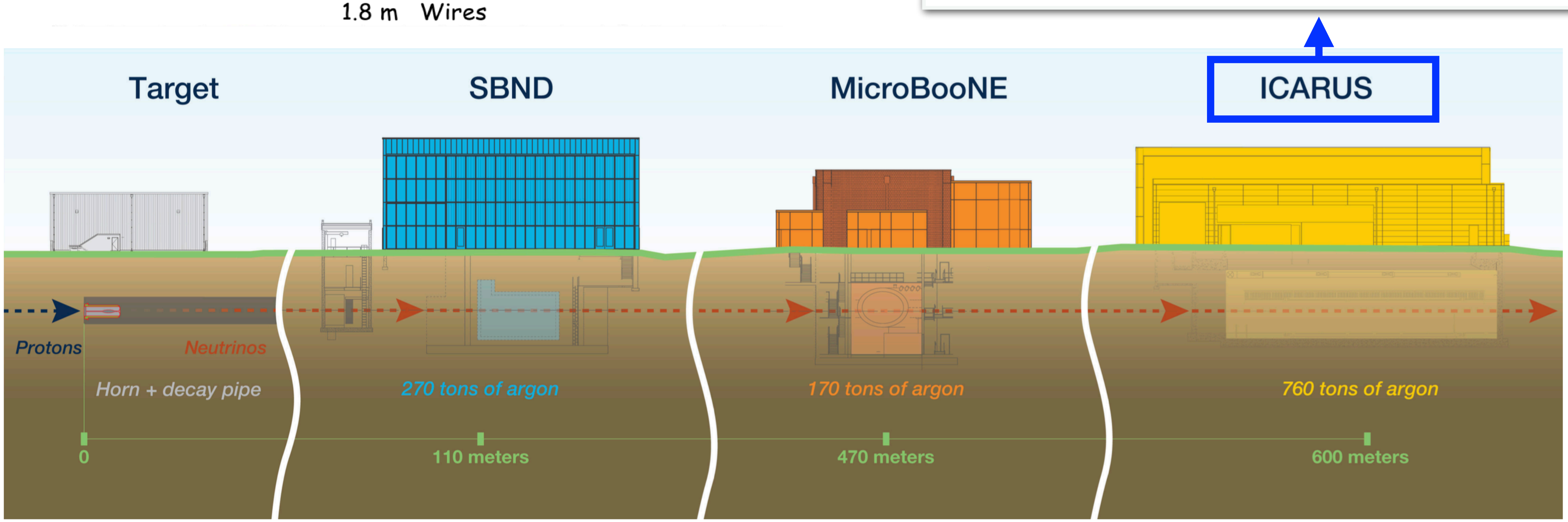
SBN Program Status

- **ICARUS:** First LArTPC experiment in the world. Refurbished and transported from the Gran Sasso Lab to Fermilab via CERN. Steady data taking since March 2021 .

- Commissioning and physics data have been used to perform the calibration and event reconstruction. First analyses with neutrino data are underway.

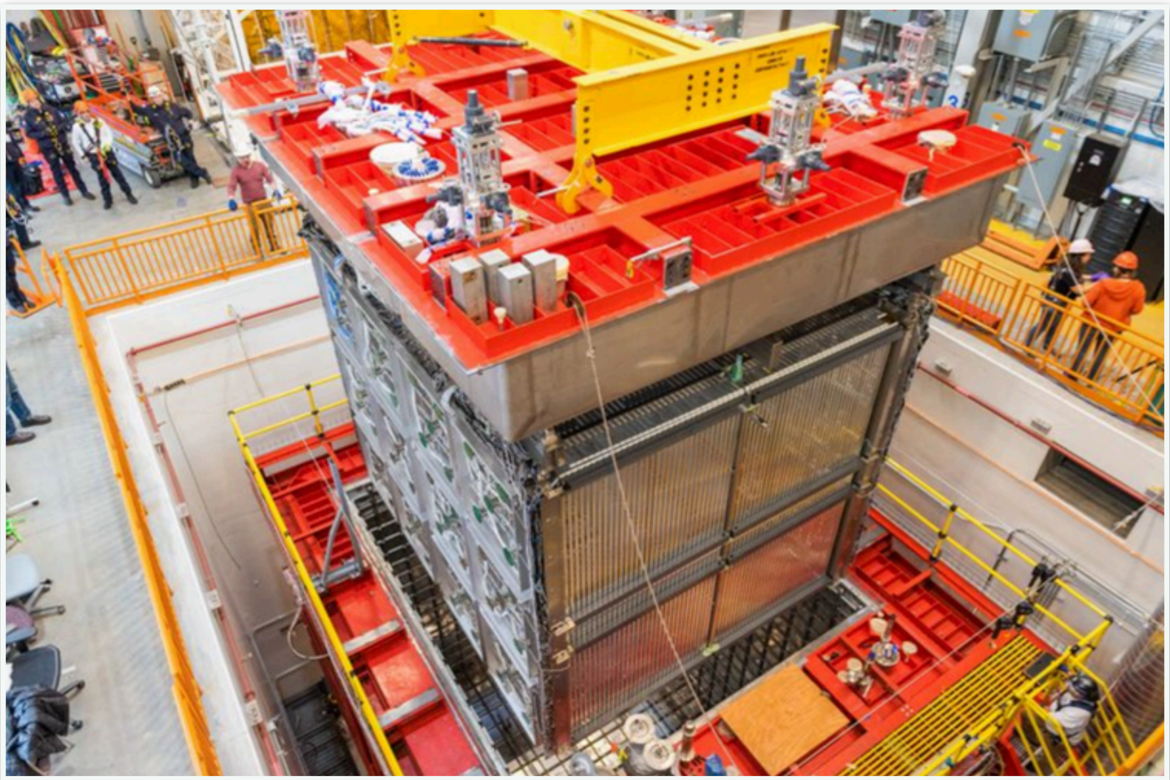




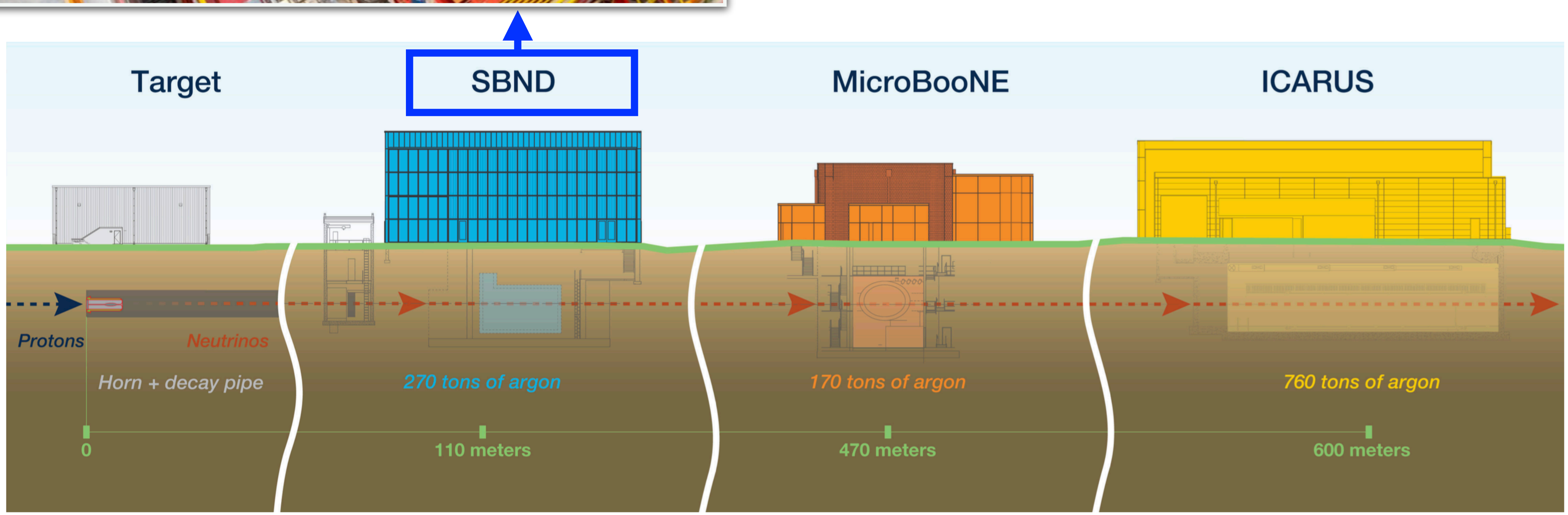


SBN Program Status

- **SBND:** Installation recently completed. Commissioning expected late in 2023.



Focus of this talk!



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- **Short Baseline Near Detector (SBND)**
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- Neutrino Interaction Physics at SBND
  - High statistics, detection capabilities, SBND-PRISM
- Broader Physics Program at SBND
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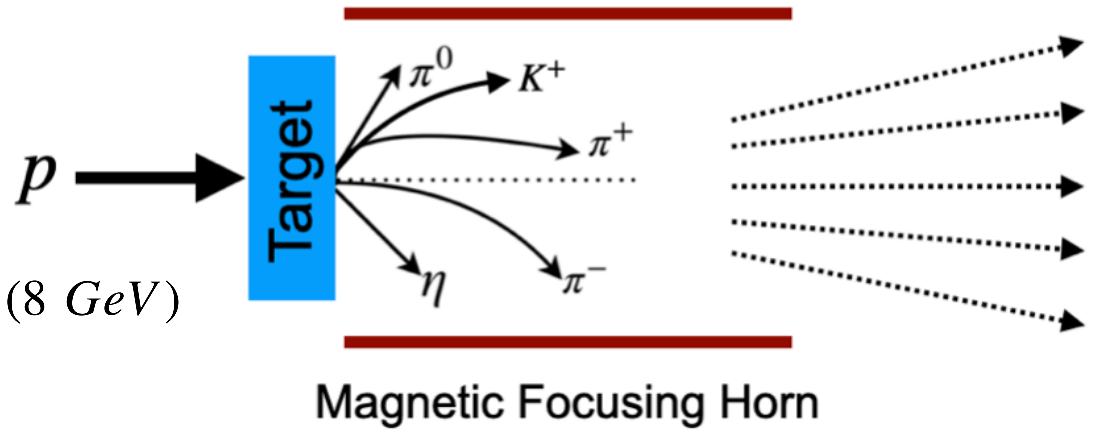
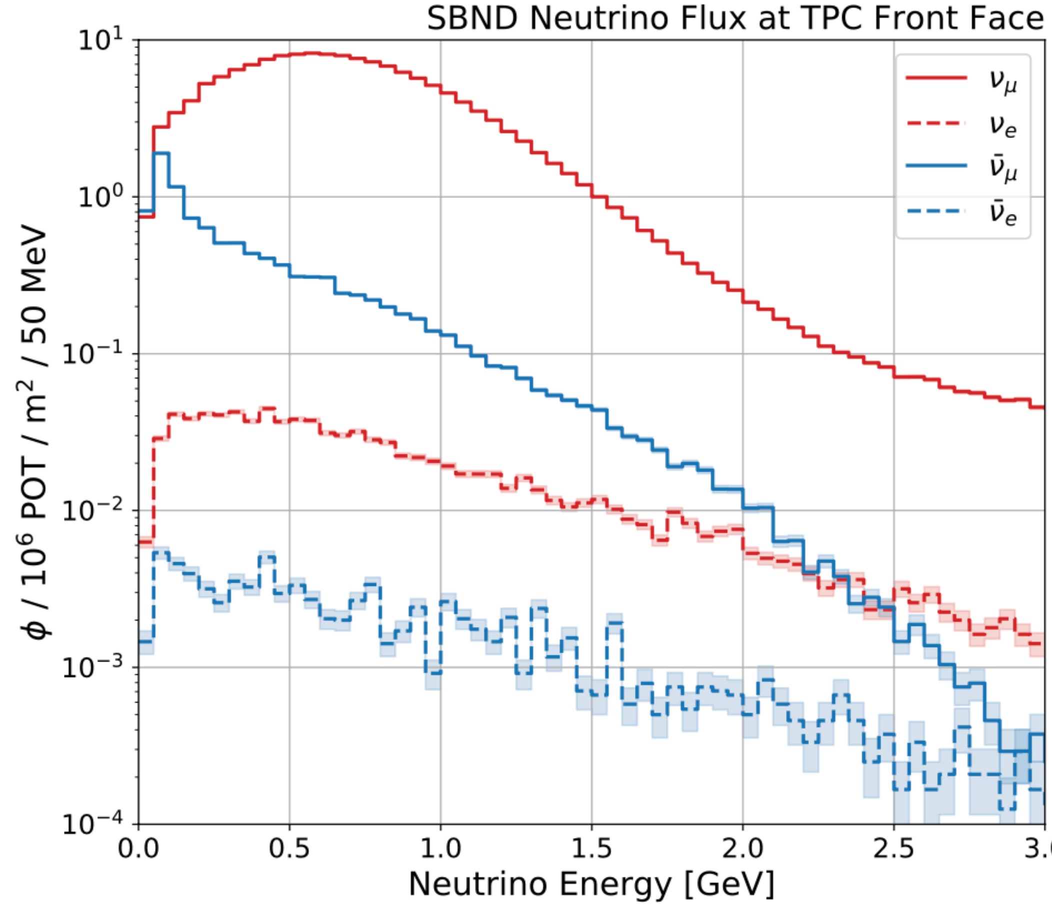
The SBND Experiment

- **Neutrino Flux**

  Neutrino flux at the SBND front face

  ν_μ (93.6%), $\bar{\nu}_\mu$ (5.9%), $\nu_e + \bar{\nu}_e$ (0.5%)



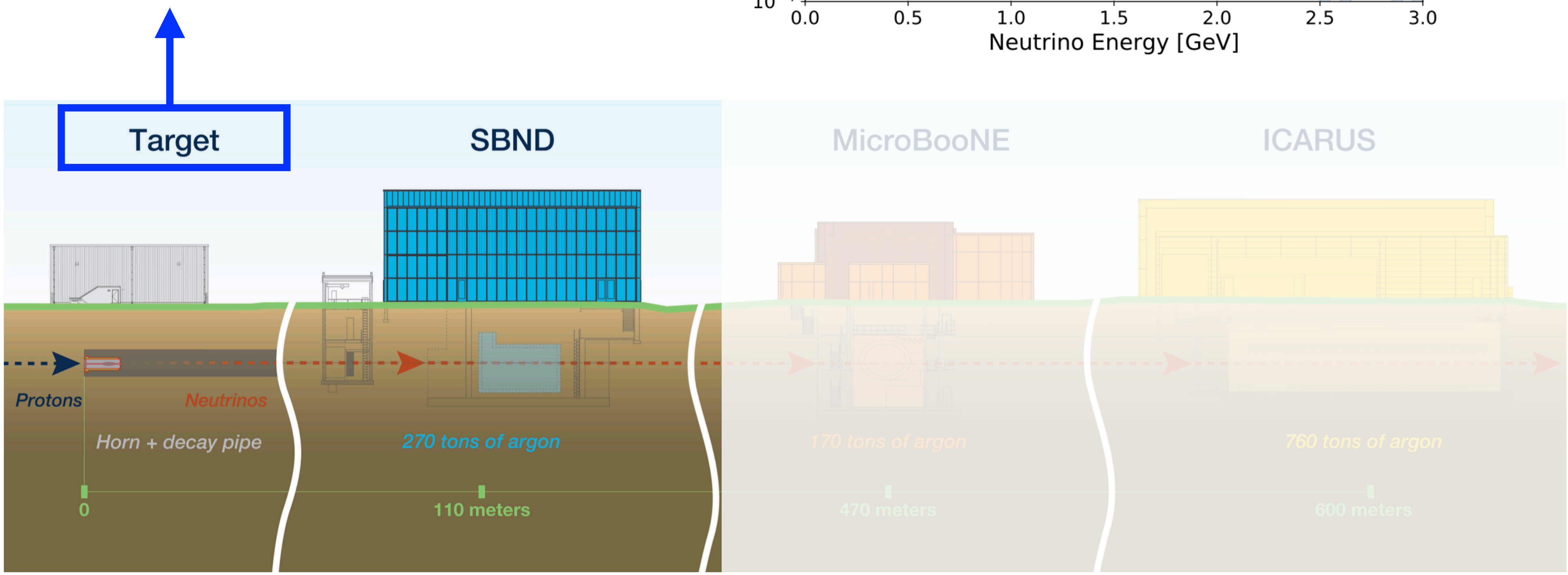


ν_μ from 2-body decay

$$\pi^+ \rightarrow \nu_\mu + \mu^+$$
$$K^+ \rightarrow \nu_\mu + \mu^+$$

ν_e from 3-body decay

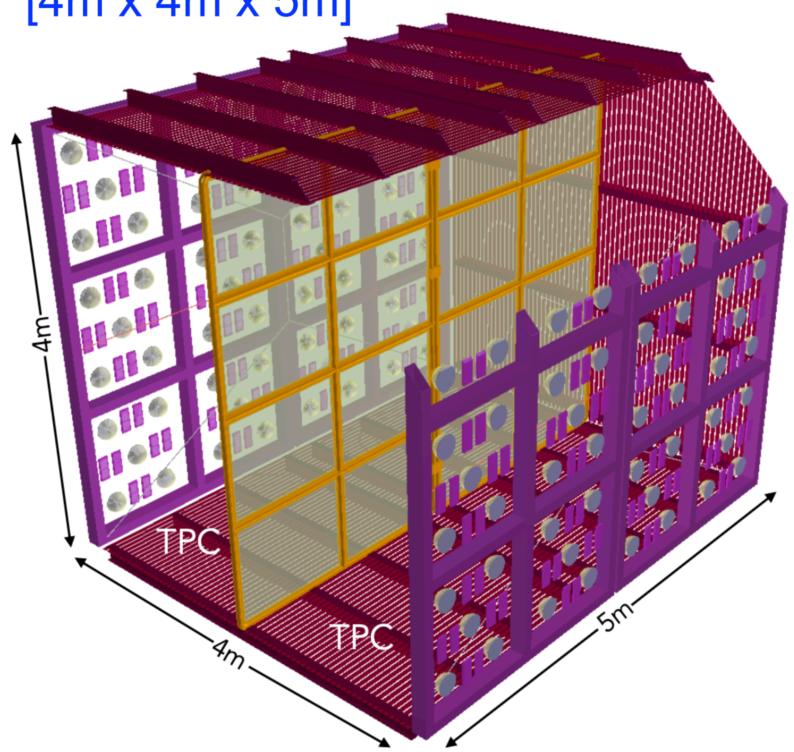
$$\mu^+ \rightarrow \nu_e + \bar{\nu}_\mu + e^+$$
$$K^+ \rightarrow \nu_e + e^+ + \pi^0$$
$$K_L^0 \rightarrow \nu_e + e^+ + \pi^-$$



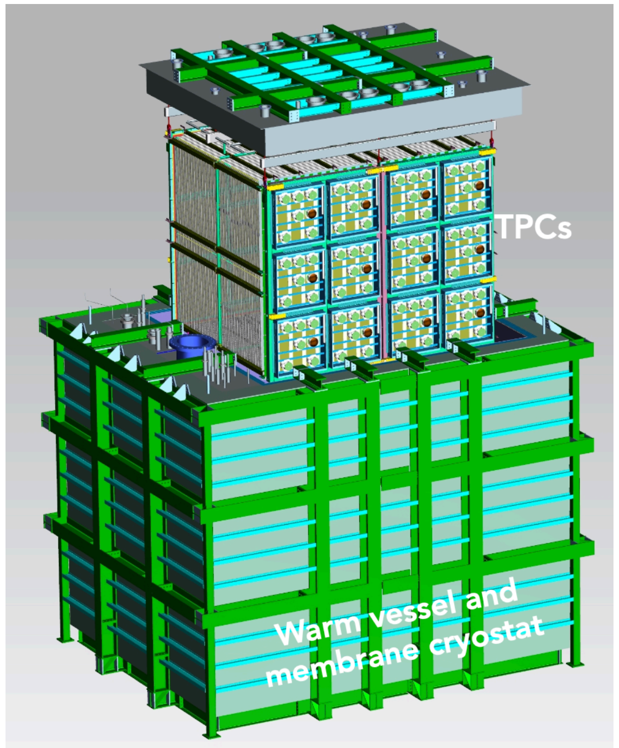
The SBND Experiment

- **SBND Design Overview**

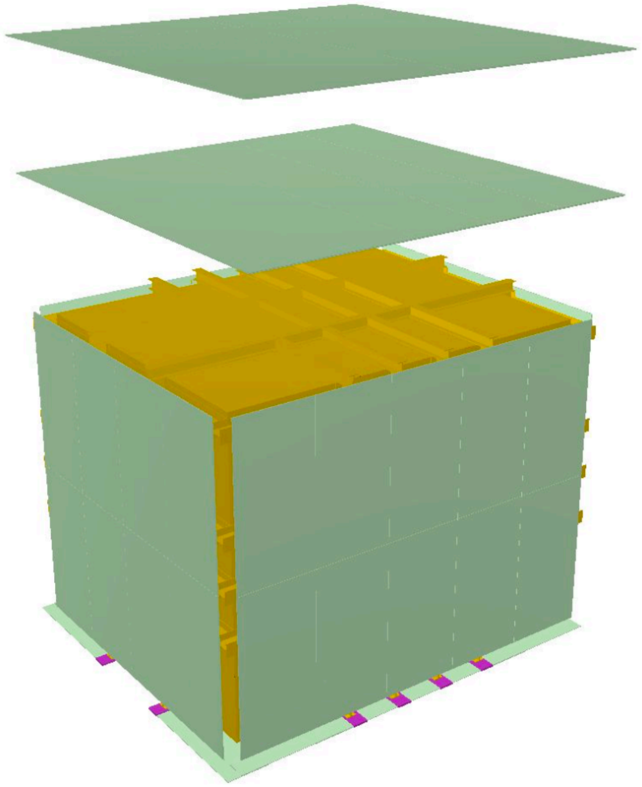
2 Time Projection Chambers along with photon detector systems [4m x 4m x 5m]

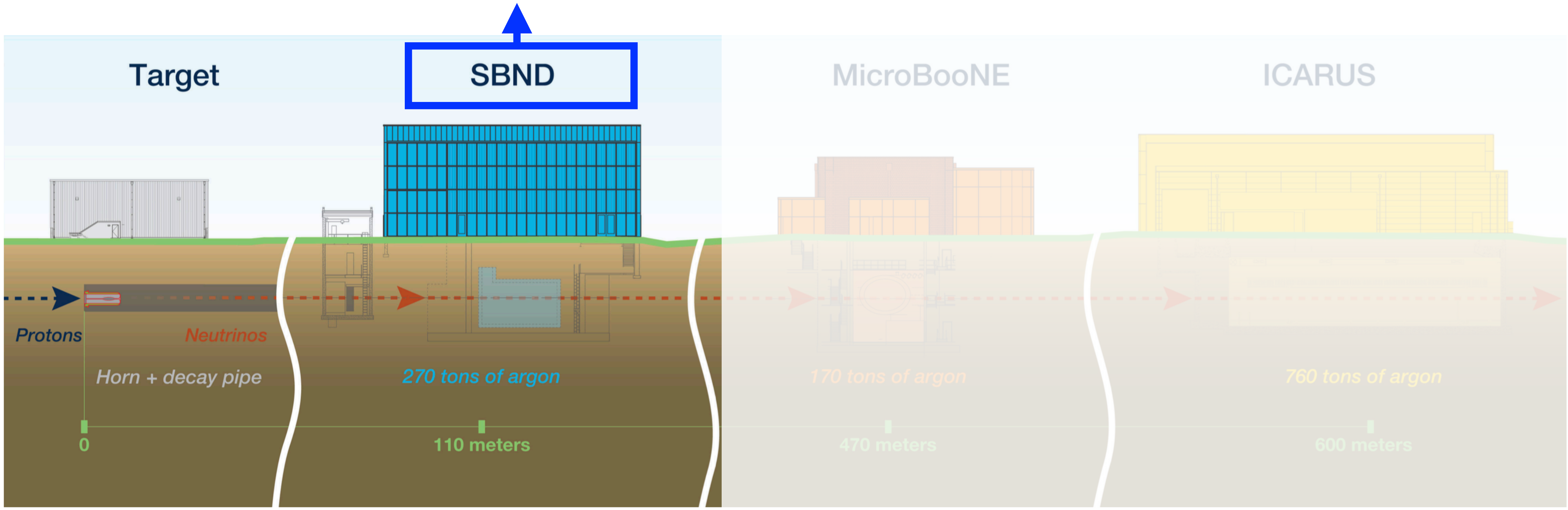


Warm vessel and membrane cryostat

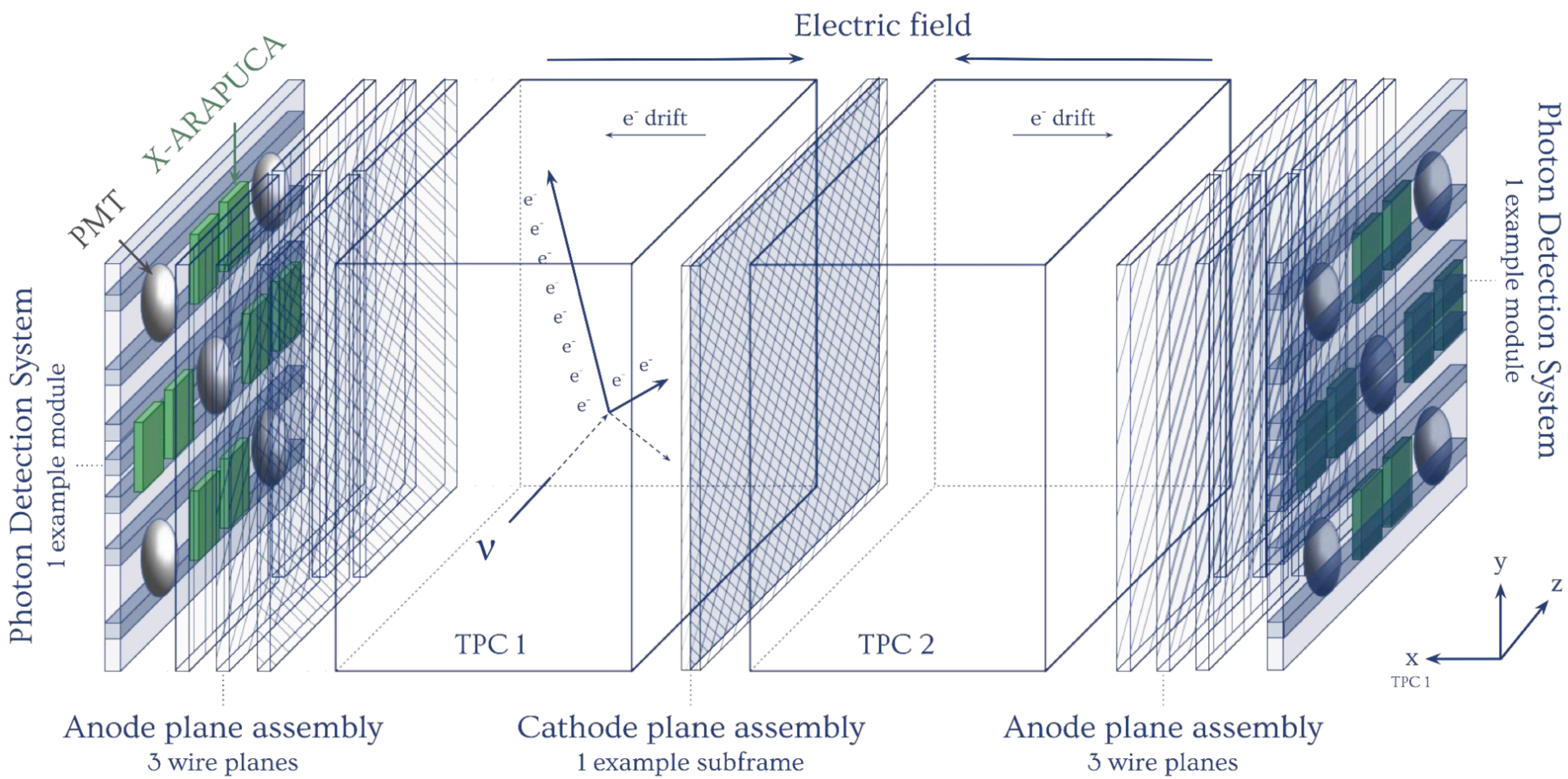


Cryostat surrounded by a Cosmic Ray Tagger system



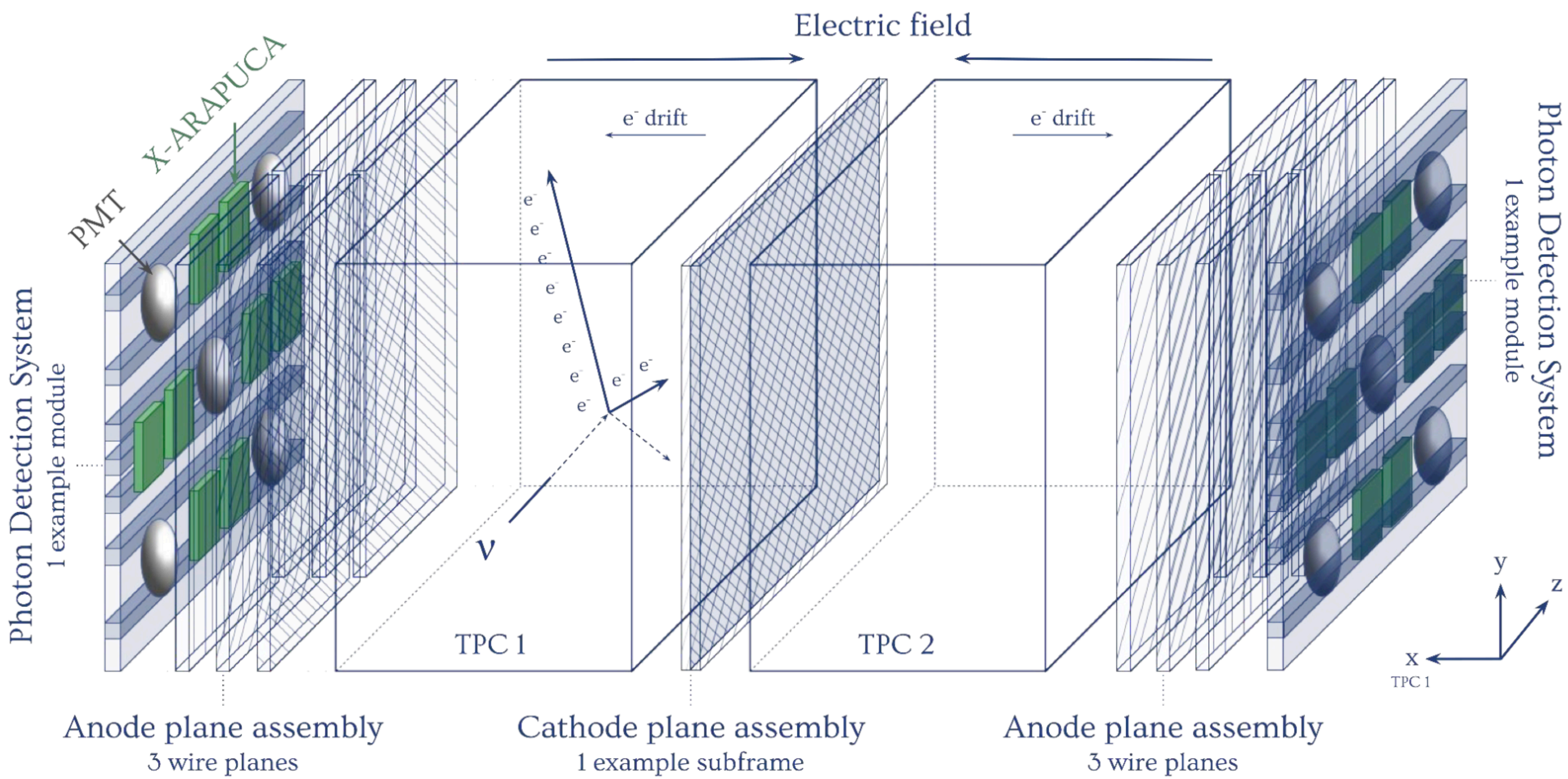


LArTPC Operating Principle

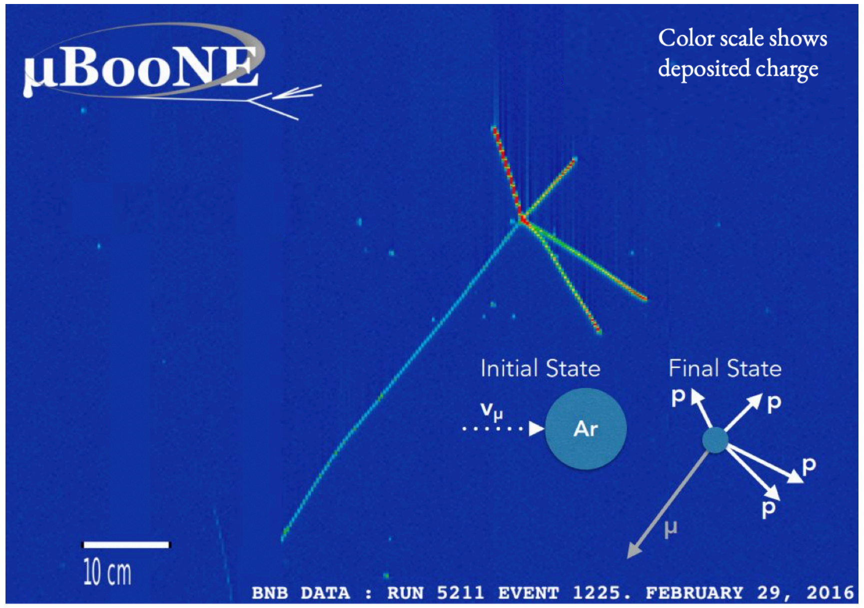


- A neutrino enters the detector, interacts within the argon to produce final state particles.
- Charged particles ionise and excite the argon atom as they propagate through the detector. Creating ionization electron and scintillation photons.
- Ionized electrons drift (~ms) under uniform electric field & deposit charge on the anode wire readout planes. Digitized signals from the wires are collected. Time of the wire pulses gives the drift coordinate and amplitude gives the deposited charge.
- Scintillation light (~ns) collected by the photon detection system provides timing information (and additional light calorimetry).

LArTPC Operating Principle

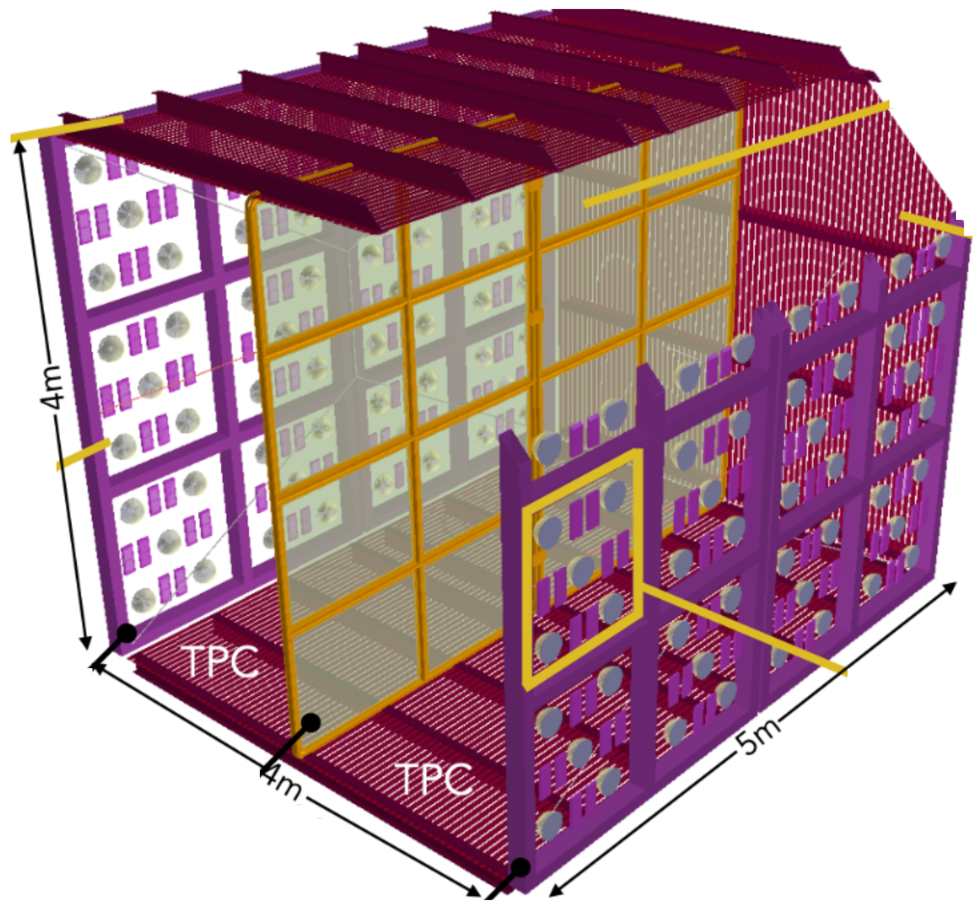


- The neutrino interaction is reconstructed in 3D using geometry, charge and timing information
- Event imaging with fine granularity calorimetry and particle identification and calorimetry information



The SBND Detector

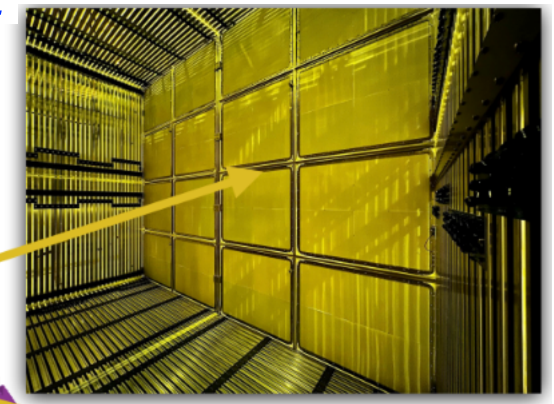
2 Time Projection Chambers
Total Dimension: 4m x 4m x 5m



The SBND Detector

CPA: *The cathode plane (at - 100 kV) assembly (CPA) splits the detector into two TPCs. Drift distance is 2 m, drift time is 1.25 ms*

TPB-coated reflective foils to convert VUV into visible light for the PDS.



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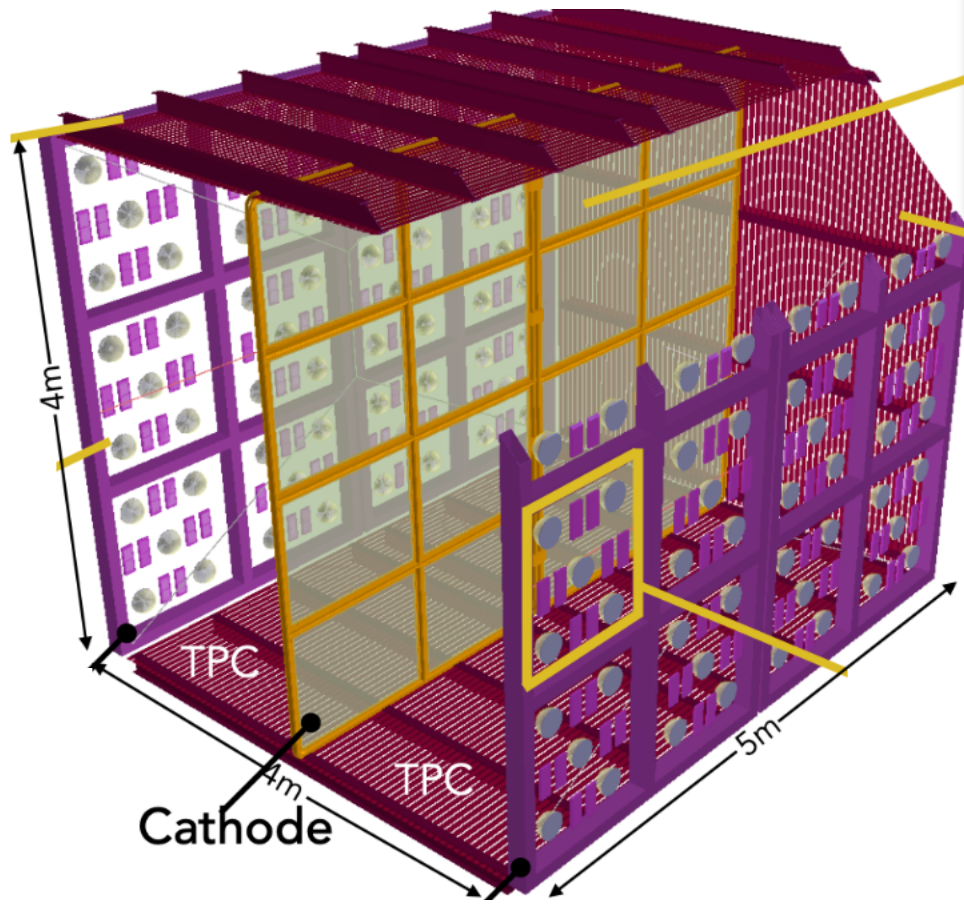

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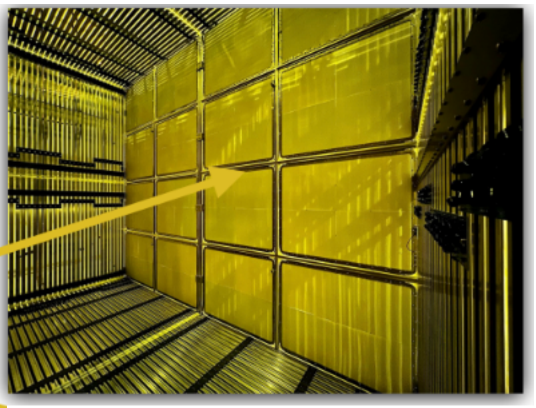
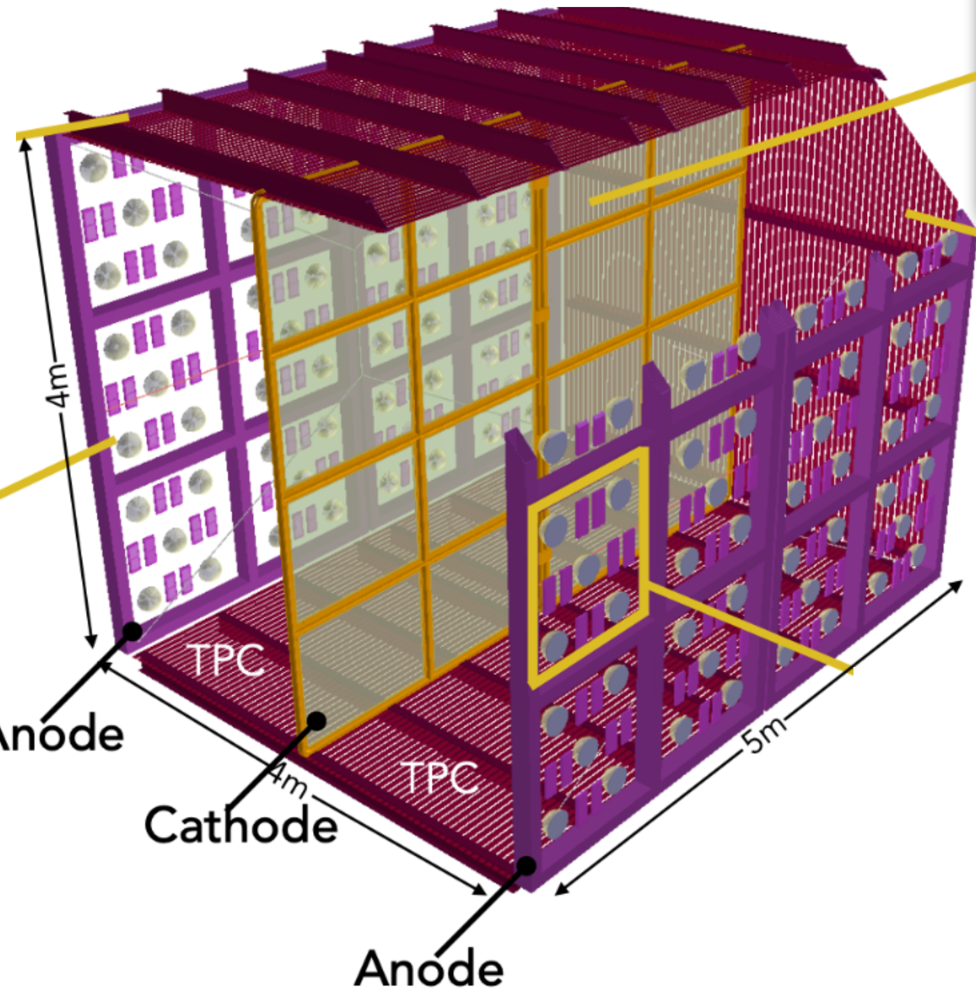
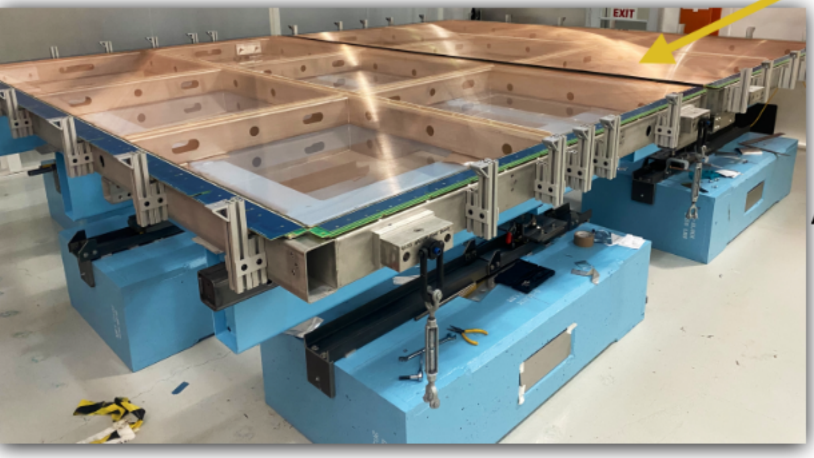
TPB-coated reflective foils to convert VUV into visible light for the PDS.



2 Time Projection Chambers
Total Dimension: 4m x 4m x 5m





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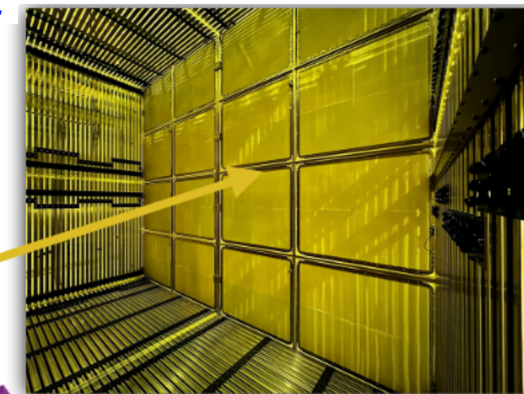

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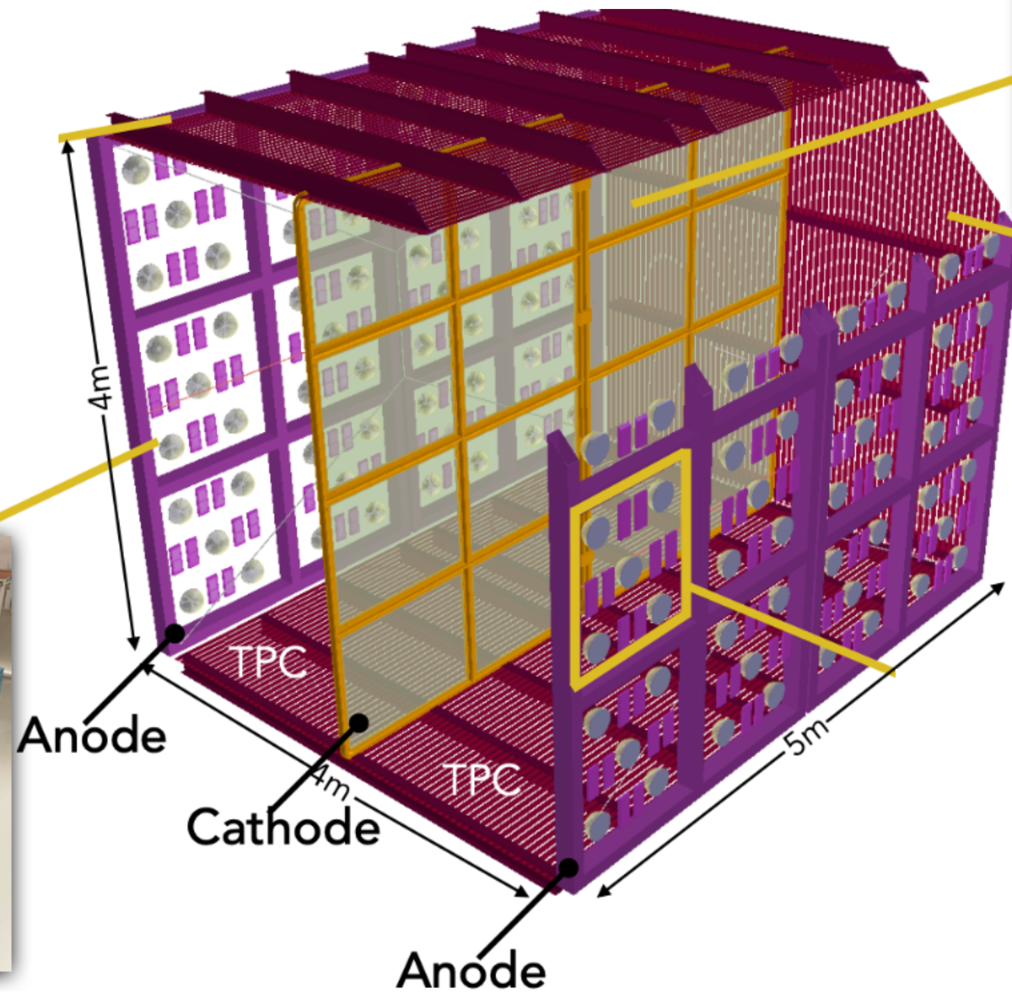

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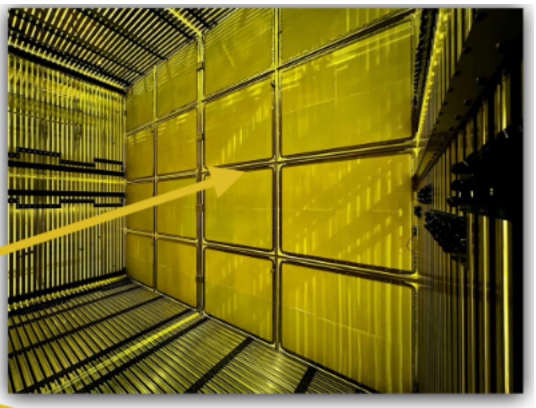

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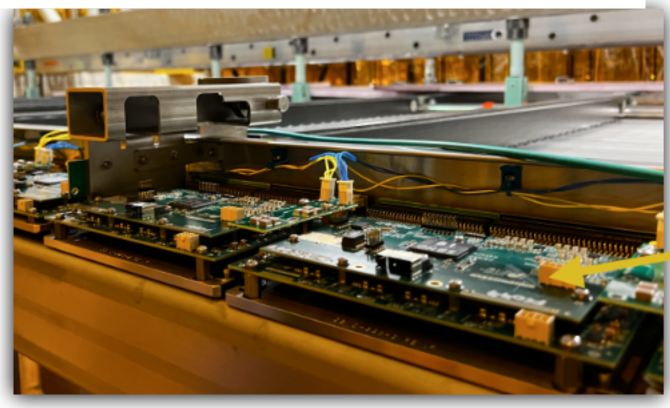

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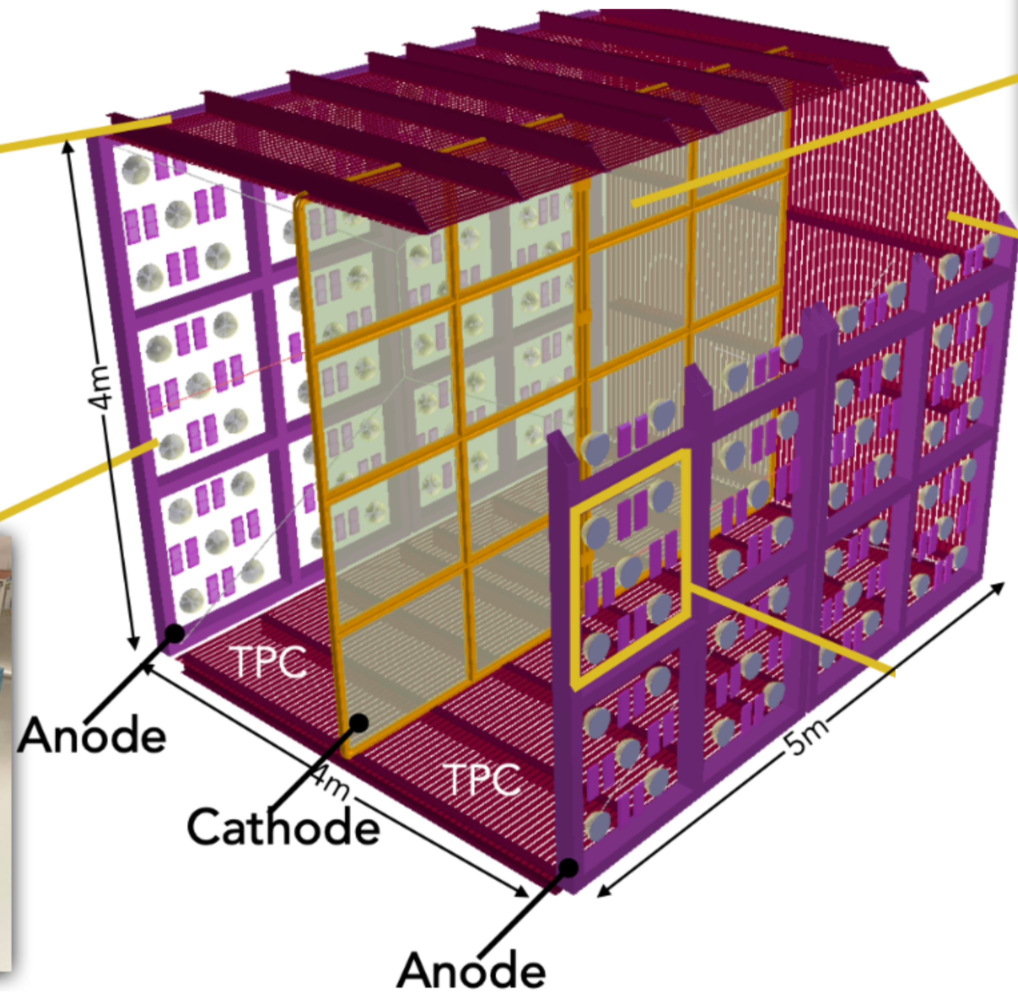

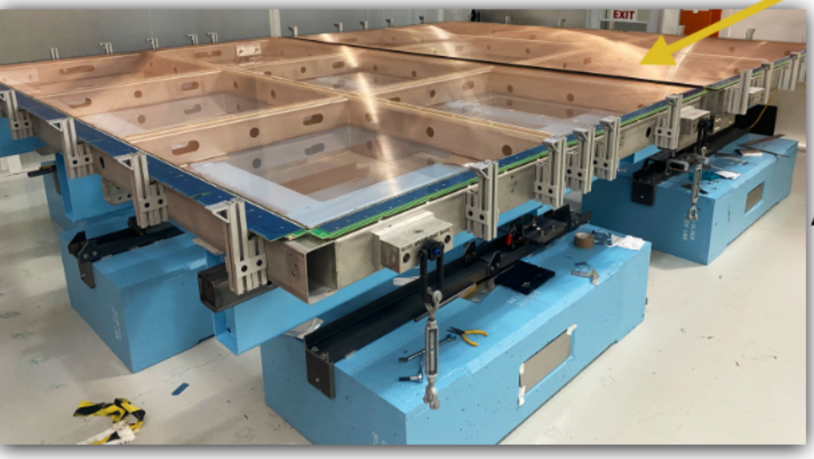

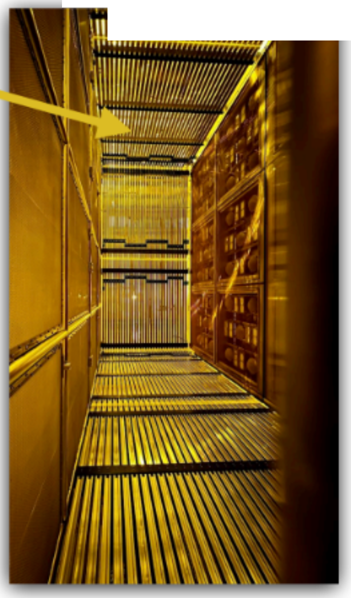

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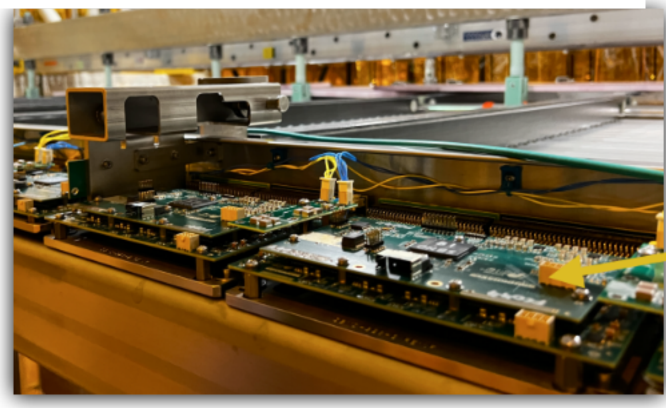

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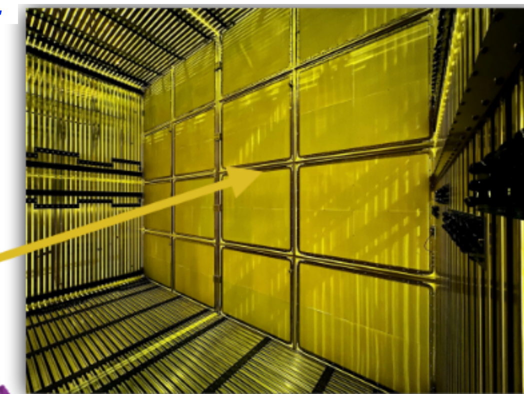

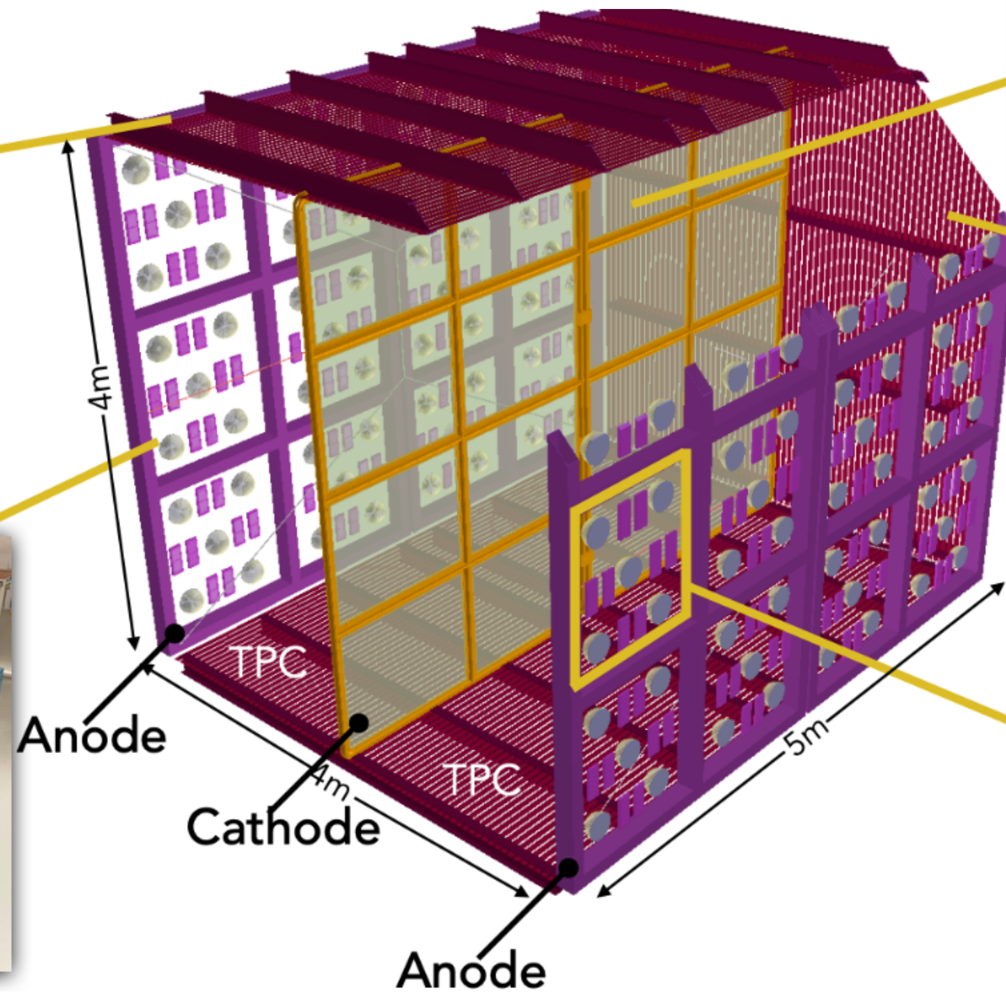

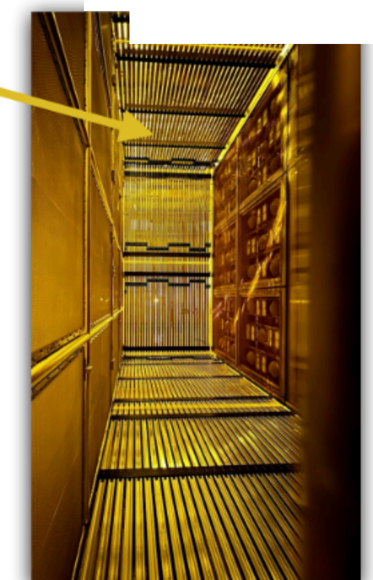

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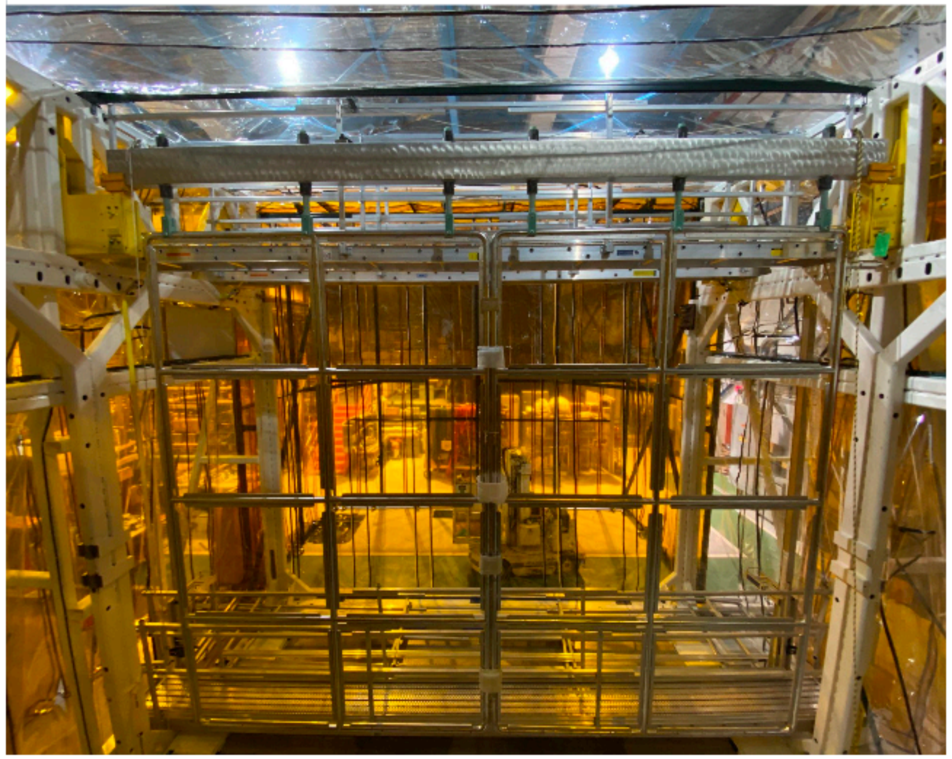
Photon Detection System:
120 8” PMTs (96 coated with TPB)
192 X-ARAPUCA modules
together with TPB-coated reflector foils on the cathode, sensitive to both VIS and VUV light

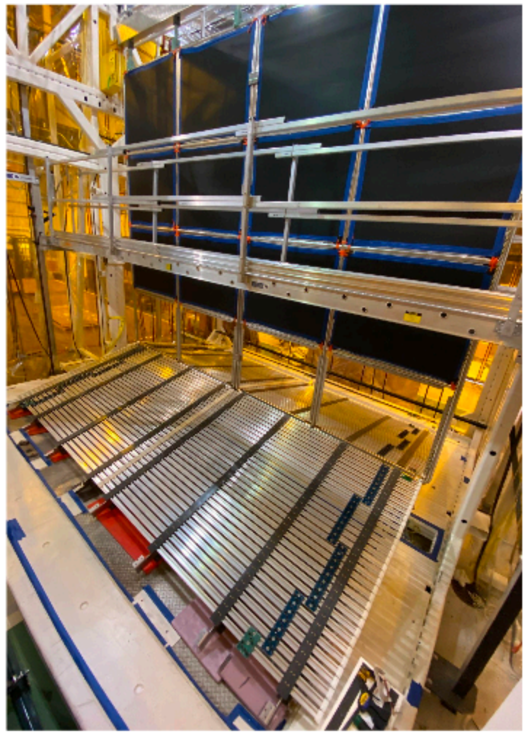
The SBND Detector: Installation Timeline

Fall 2019 *- Assembly Transport Frame Construction*

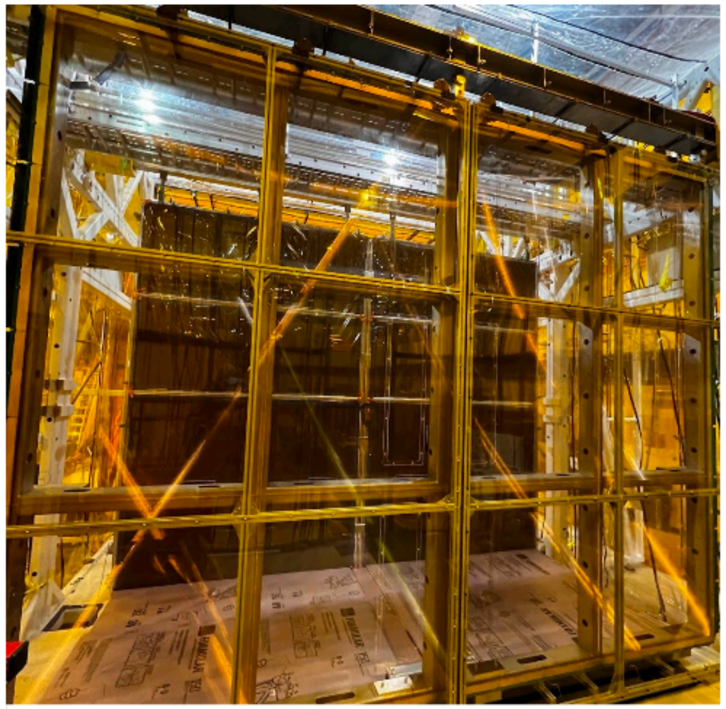
Jul 2021 *- CPA Installation*



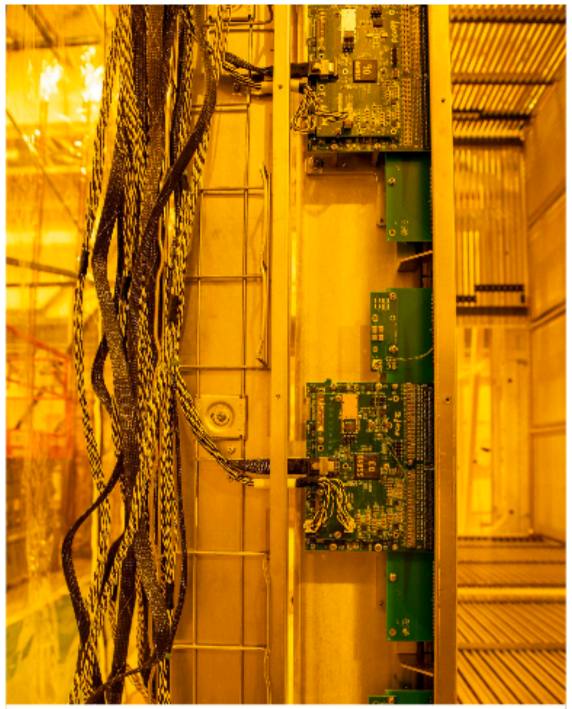
Aug 2021 *- CPA refl. window & bottom FC Installation*



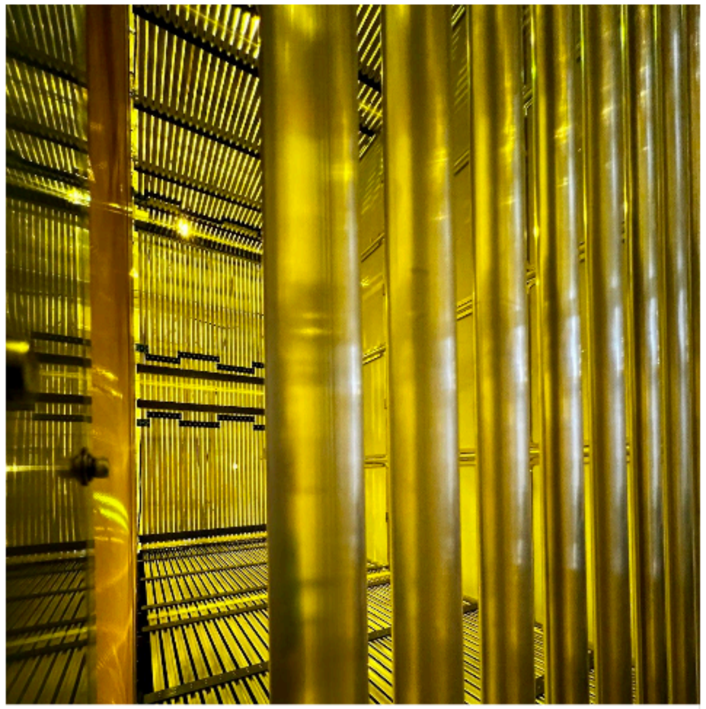
Oct & Dec 2021 *- APA Installation*



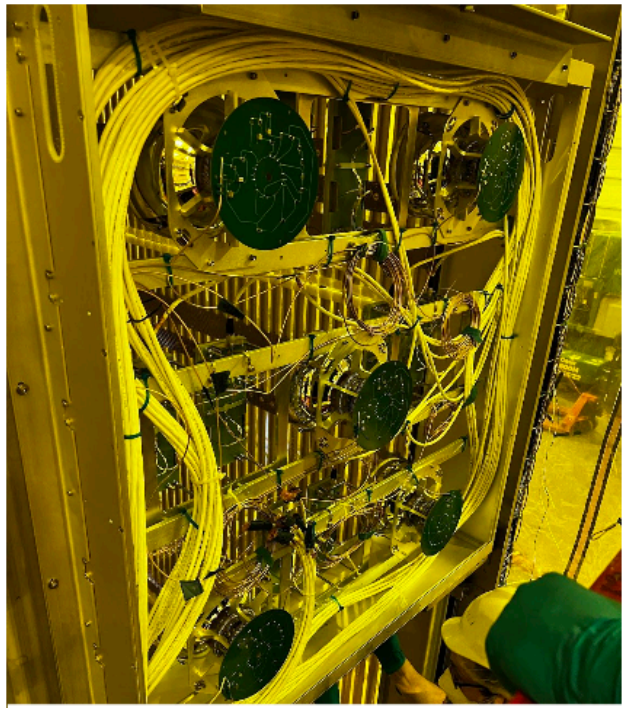
Jan 2022 *- CPA, both APAs and ground meshes installed*



Feb & May 2022 *- Cold Electronics Installation*



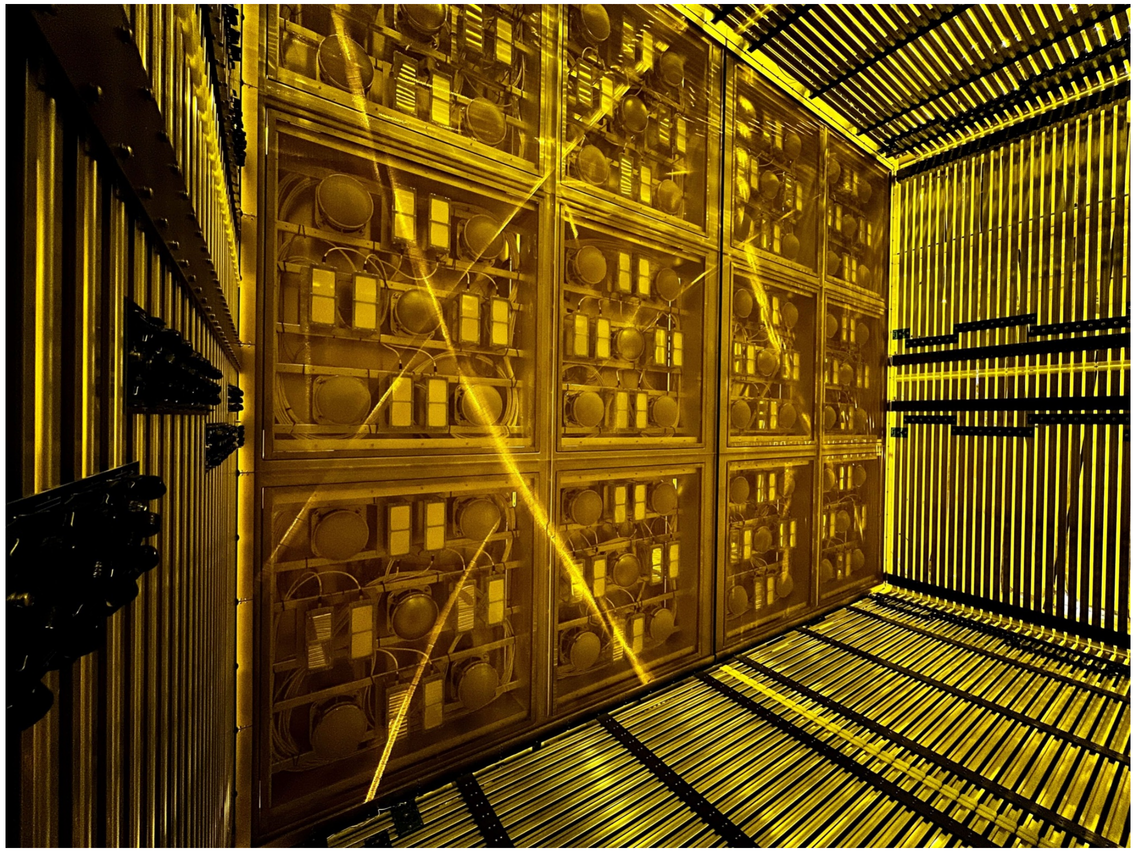
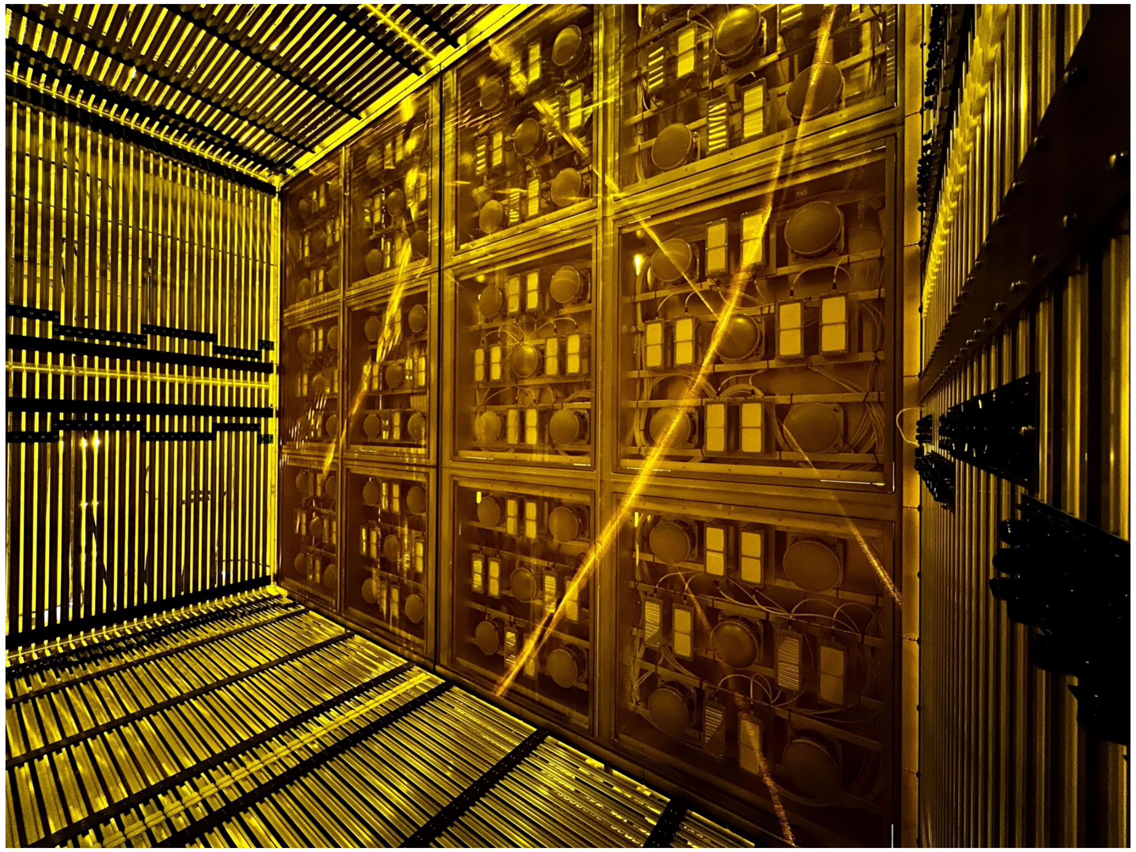
Jun 2022 *- Field Cage Closing*



Sep 2022 *- PDS Installation*

The SBND Detector: Installation Timeline

- The SBND Detector Assembly was completed in October 2022.

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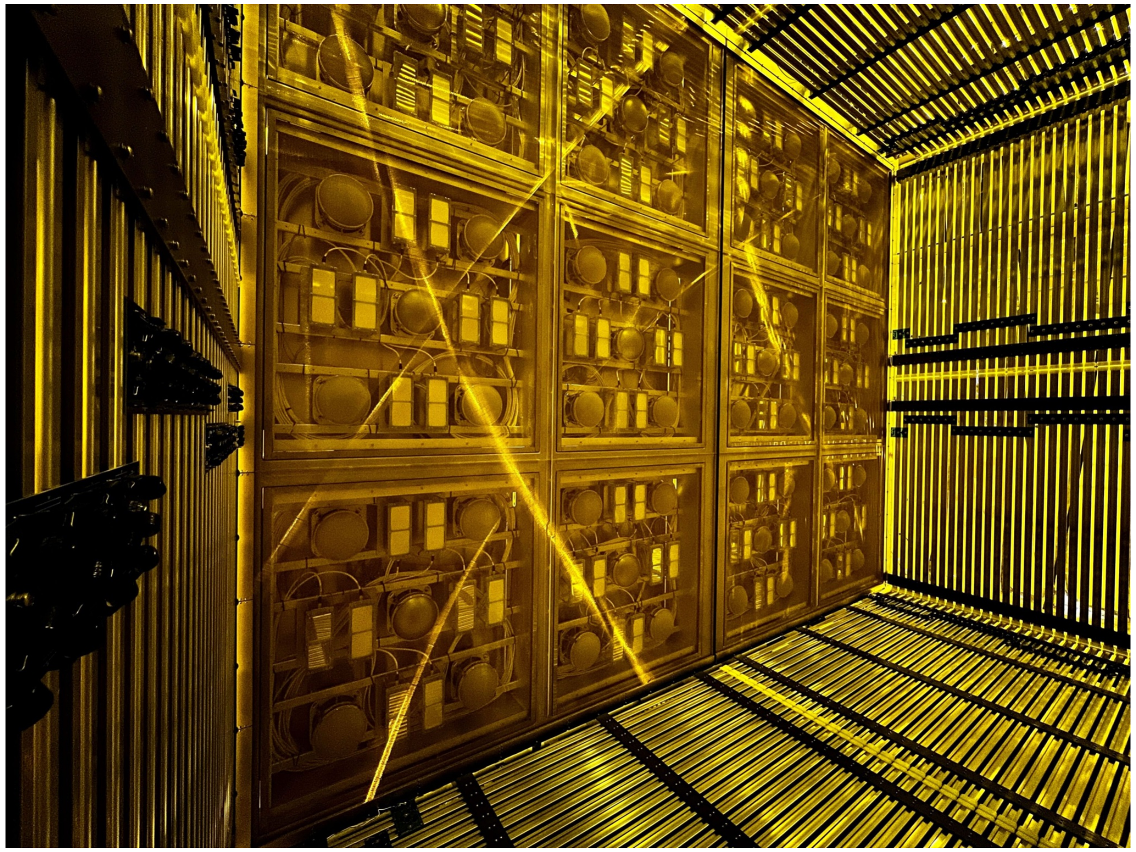
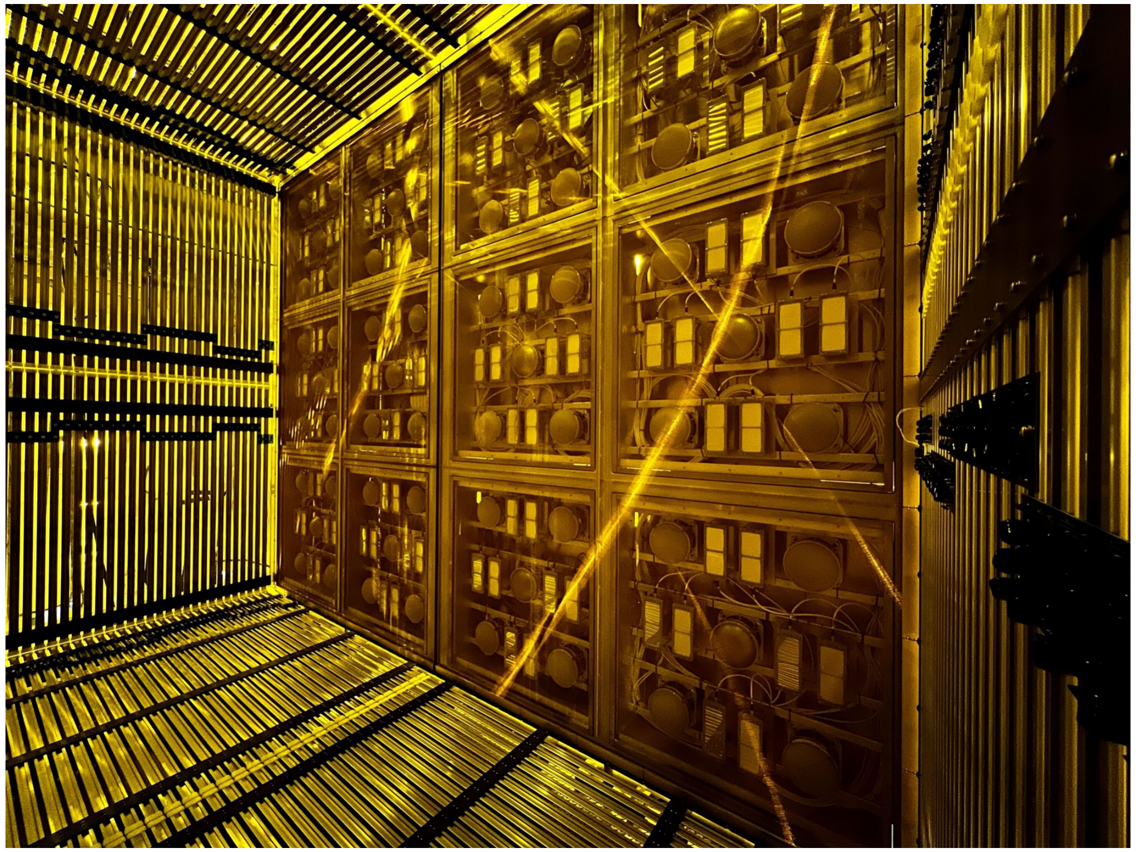
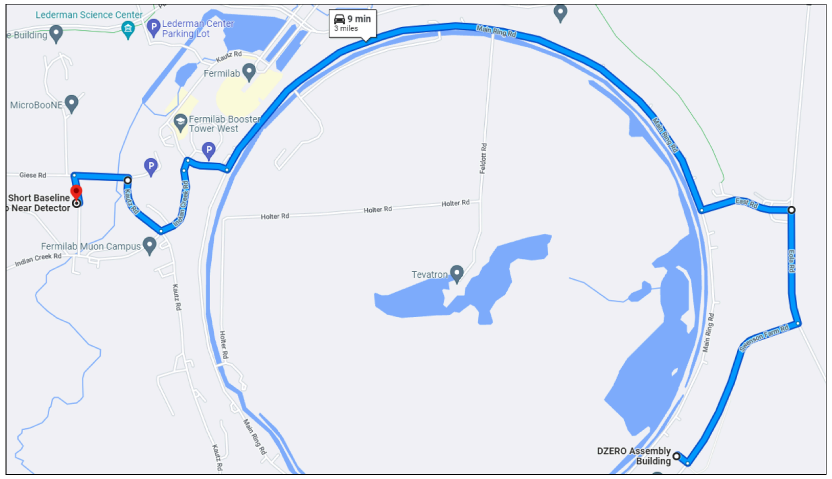
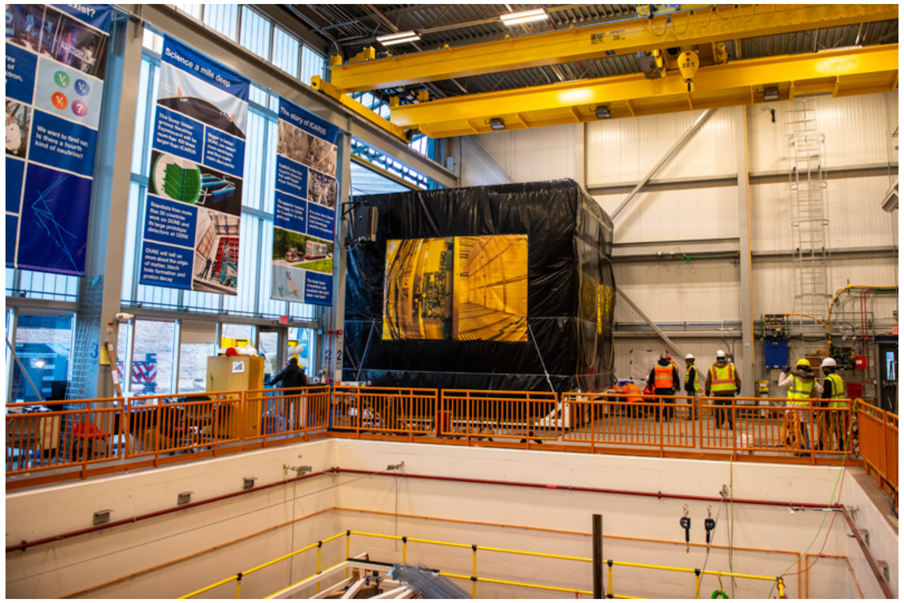




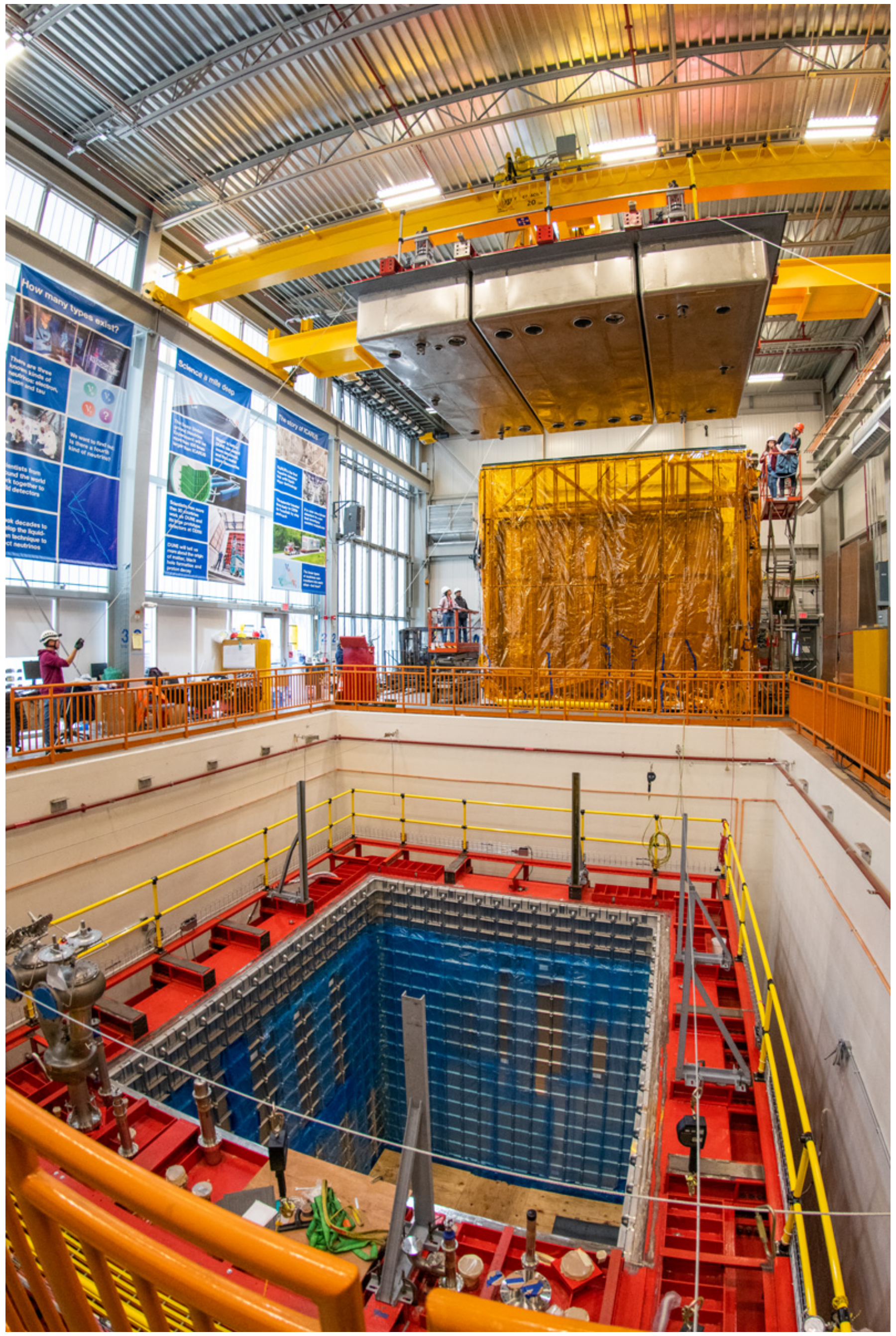
- The Detector was transported from D0 Assembly Building to the SBN-ND building in December 2022.





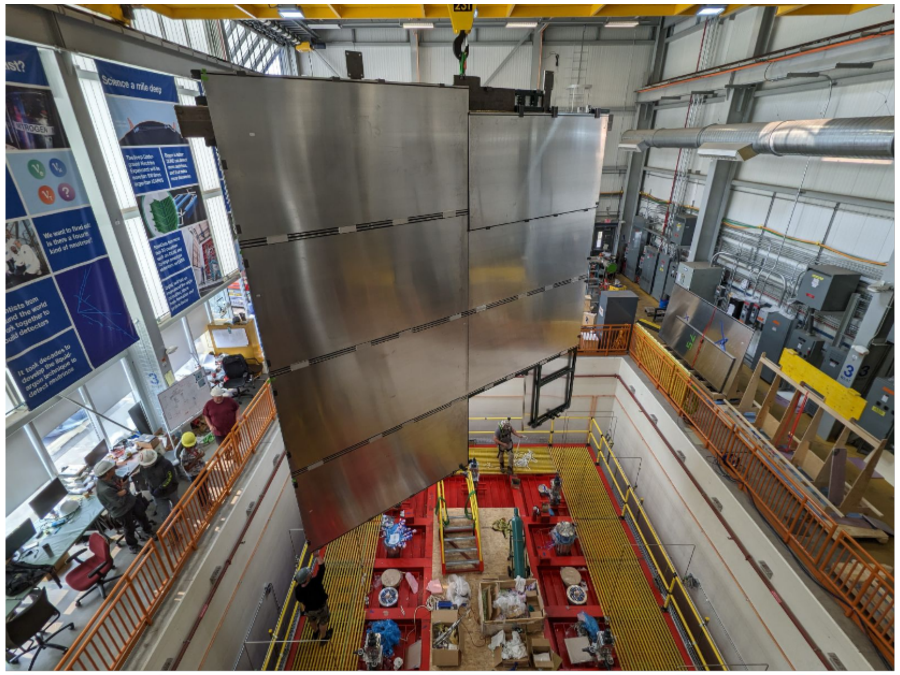
The SBND Detector: Installation Timeline

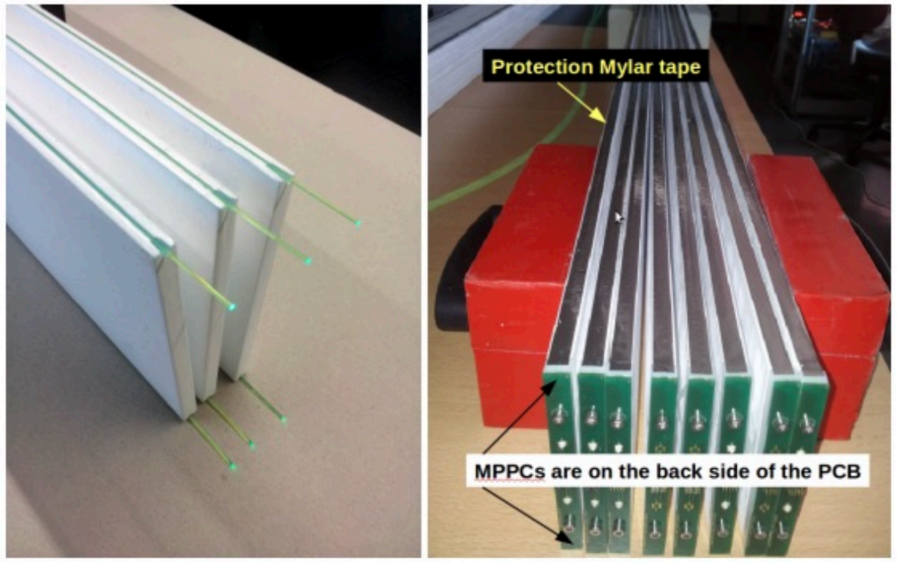
Detector Top cap was installed in Feb 2023



Detector was rigged inside the cryostat in April 2023

CRT North wall was installed in May 2023





***CRT:** plastic scintillator panels coupled to SiMPs to tag cosmic rays*

- **Commissioning activities are currently going on. Cold commissioning expected to start later this year.**

Outline

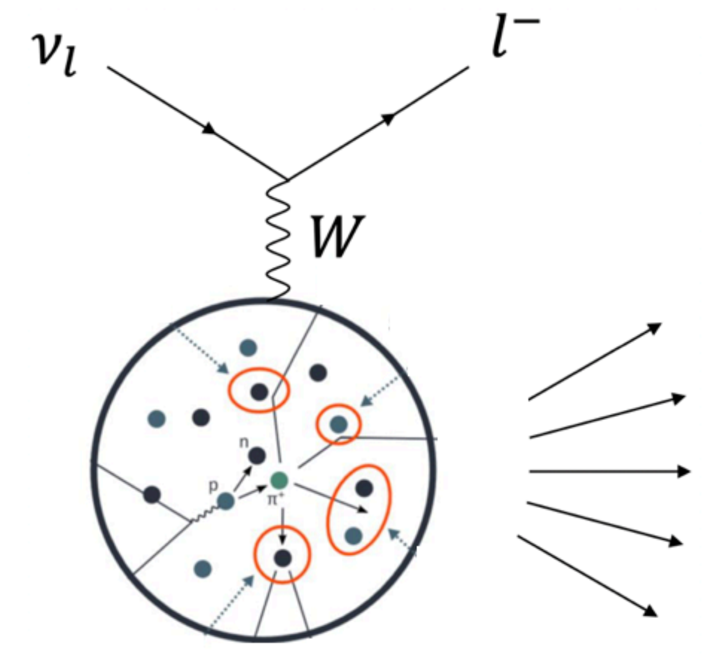
- Short Baseline Neutrino (SBN) Program at Fermilab
  - Short-baseline anomalies, status
- Short Baseline Near Detector (SBND)
  - Installation status and timeline, key features
- **Neutrino Interaction Physics at SBND**
  - **High statistics, detection capabilities, SBND-PRISM**
- Broader Physics Program at SBND
  - Oscillations and BSM Physics

Neutrino-Nucleus Interactions

- Neutrino-Nucleus interactions constitutes one of the biggest systematics uncertainty in neutrino experiments.

- Nucleus is a complex many-body quantum mechanical system
  - Nucleons bound in the nucleus subject to various nuclear effects
  - Multi-body nucleon correlation, Pauli blocking

- Hadrons re-interact inside the nuclear medium before exiting: **Final State Interaction (FSI)**
  - FSI can cause different interaction modes to have the same final state



(adapted from T. Golan)

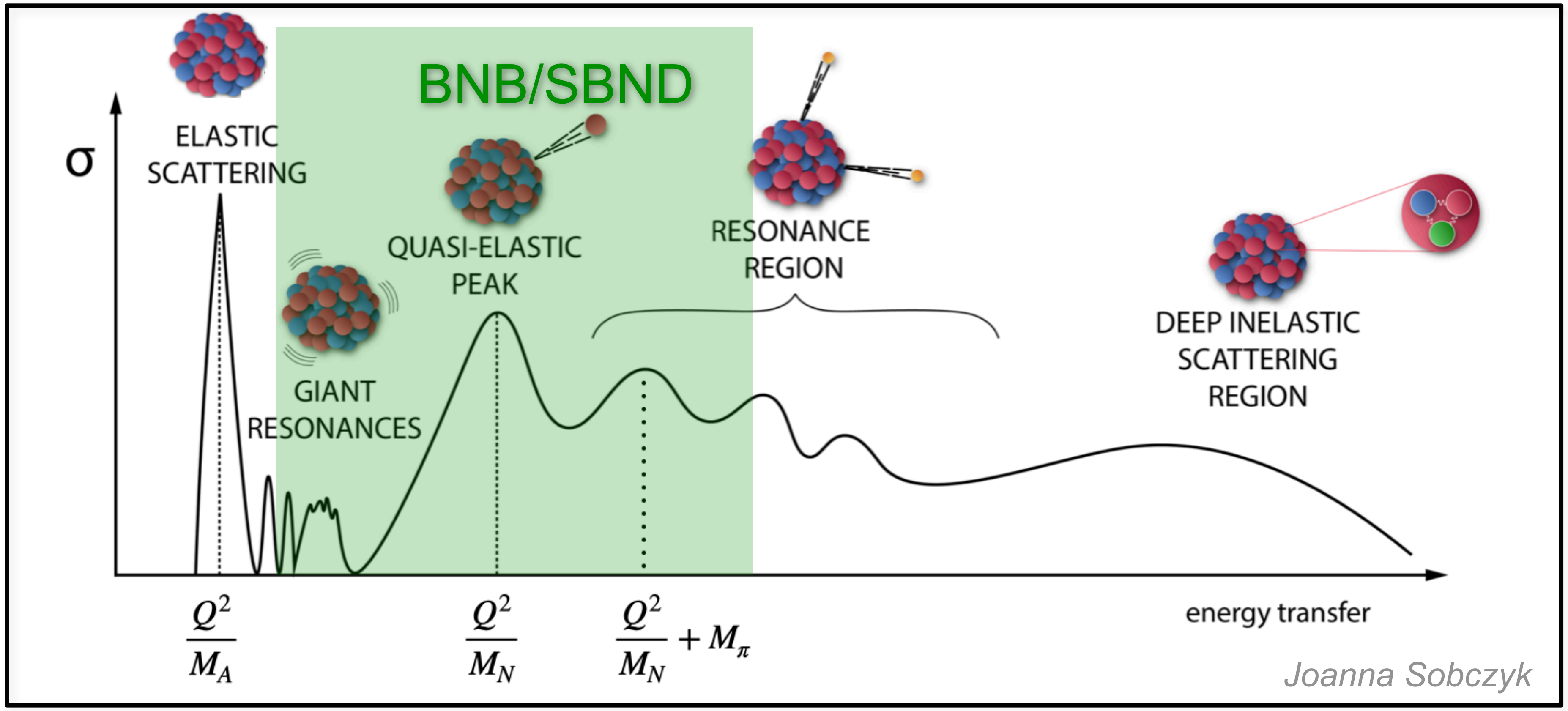
Any discovery in the neutrino sector requires detailed understanding of neutrino interactions with the target material in the detector.

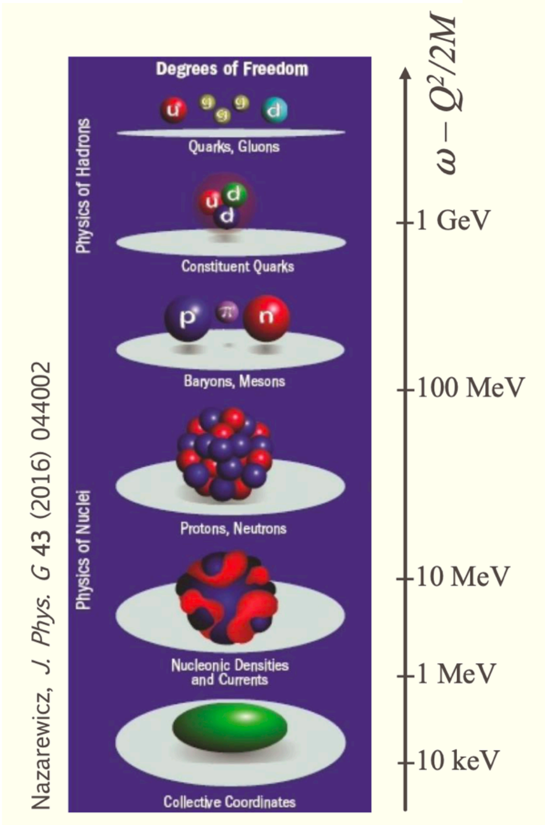
- Neutrino interactions on argon, an isospin asymmetric nucleus, is complex due to multiple nuclear effects and interaction processes relevant for SBN and DUNE.

A substantial neutrino-argon cross-section physics program is critical!

Neutrino-Nucleus Interactions

- MicroBooNE is already making several interesting measurements - see Afroditi's talk
- SBND will enable a generational advance in the study of neutrino-argon interactions in the GeV energy range
  - Unprecedented statistics
  - Unique detector capabilities (large photon detector coverage, low thresholds, ns timing, ...)
  - Multiple correlated fluxes (PRISM)
- Huge Statistics combined with LArTPC detector's capabilities - low thresholds and 4pi acceptance, imaging, high-resolution tracking, calorimetry and excellent particle identification - will allow distinguishing various exclusive final-state particles including rare channel (e.g. production of hyperons).





Neutrino Interactions in SBND: High Statistics

- SBND expects approximately 2 million ν_μ CC and 15 thousand ν_e CC interactions per year, with around **7,000 total neutrino interactions observed per day**
  - Every ~3 months, SBND will collect a dataset equivalent to the full MicroBooNE BNB five-year run
- SBND will record ~20–30x more neutrino–argon interactions than is currently available
- Large statistics will allow us to study different variables and exclusive and rare channels

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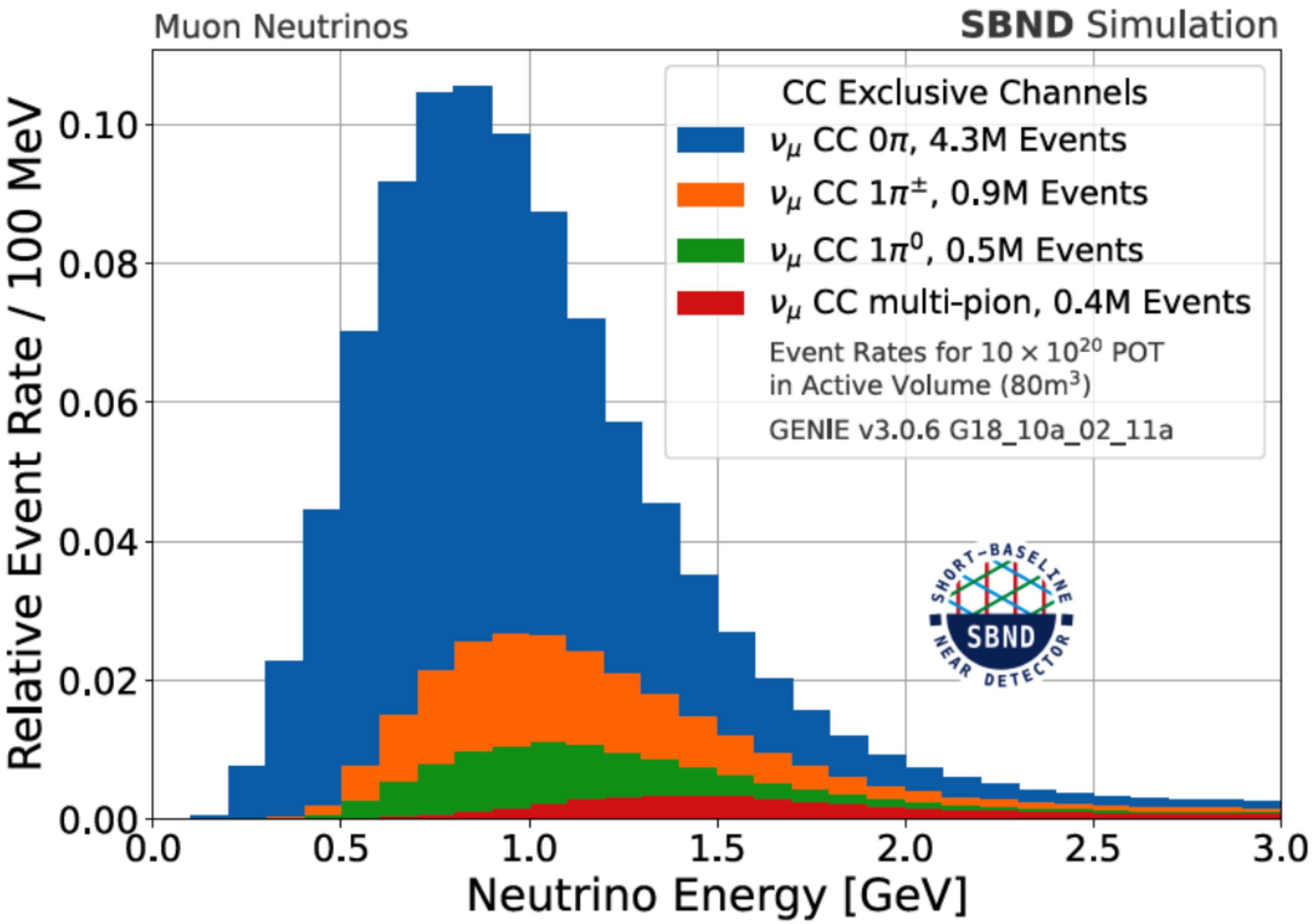
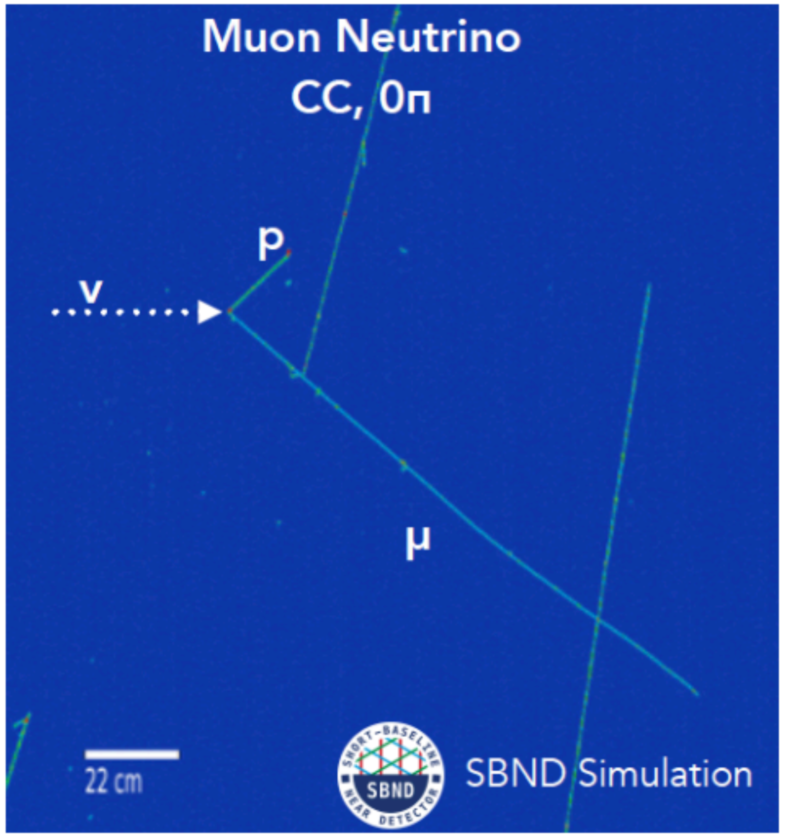
$\nu_\mu - ^{40}Ar$

2M ν_μ CC events in 1 year





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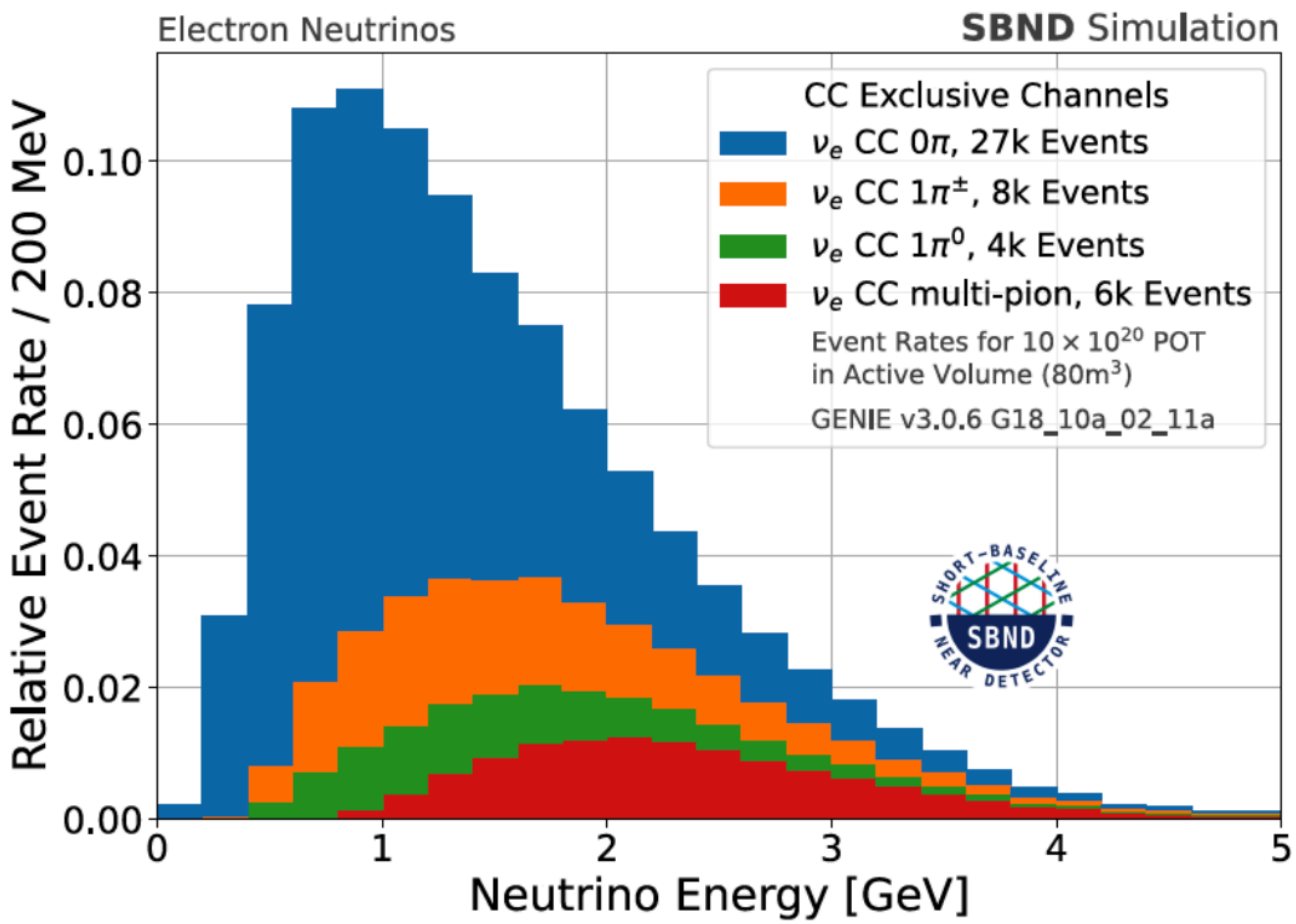
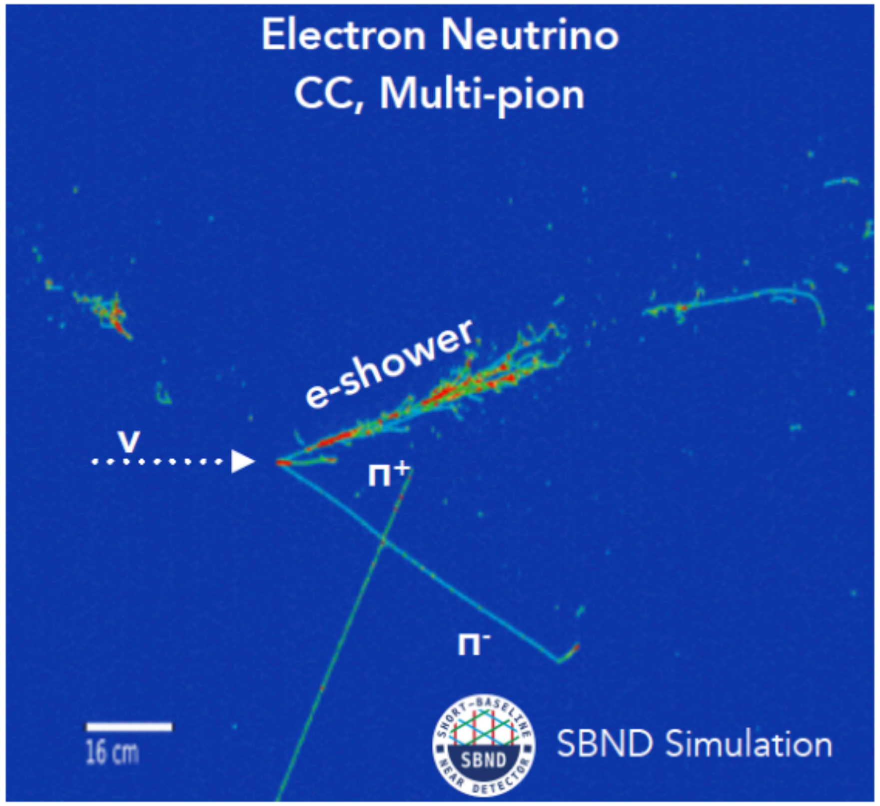
$\nu_e - ^{40}Ar$

15k ν_e CC events in 1 year





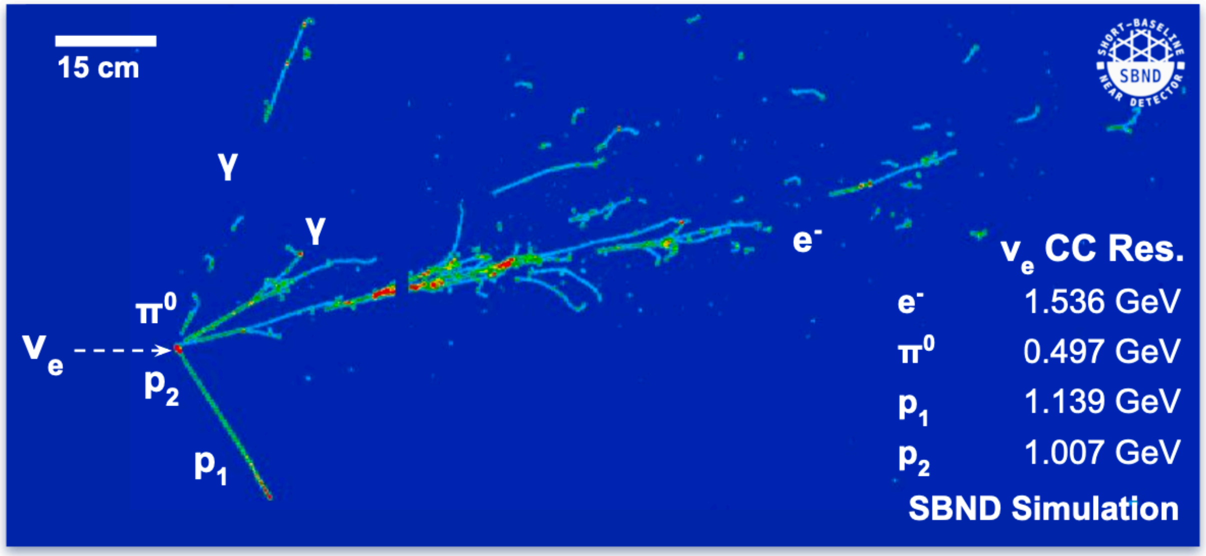
Neutrino Interactions in SBND: LArTPC Capabilities

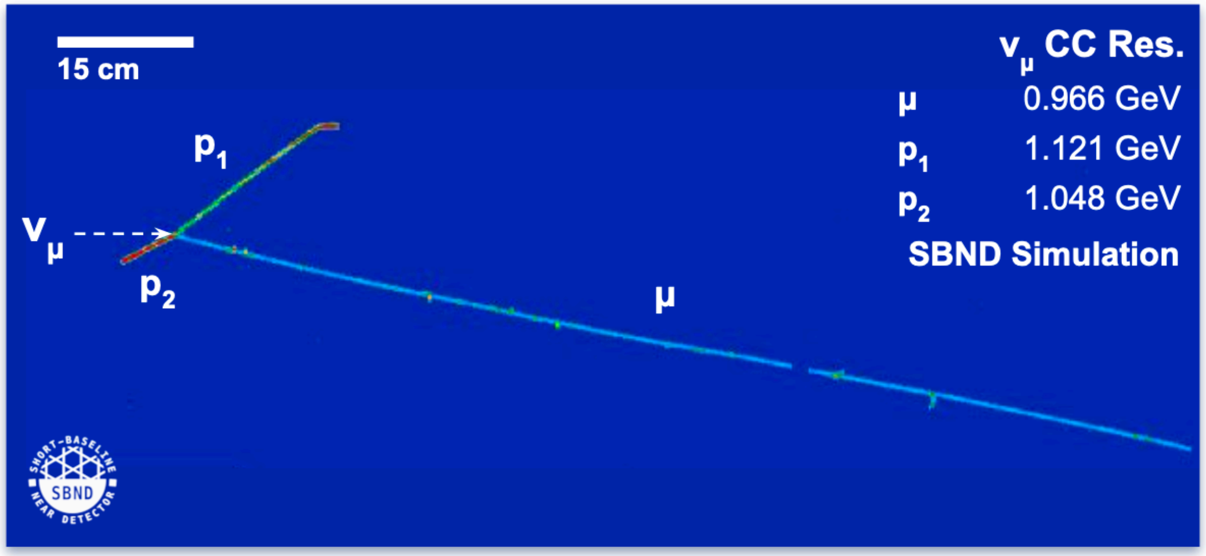
- SBND has 3mm wire spacing

  - Images of interaction final states recorded with bubble chamber resolution & detail

  - Complex final states can be disentangled

  - Isolated energy deposits may be identified down to O(100) keV
    Opportunity to study MeV-scale activity





- Highly-capable, fully-active tracking calorimeters

  - Low reconstruction thresholds

  - Excellent particle identification

- Capable of ns timing resolution, facilitates:

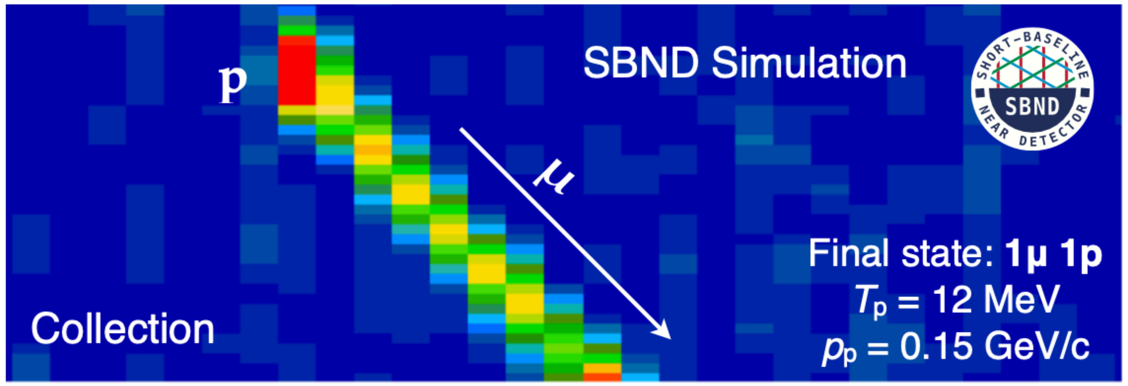
  - Cosmic rejection in neutrino beam searches

  - Beam rejection in rare and exotic searches

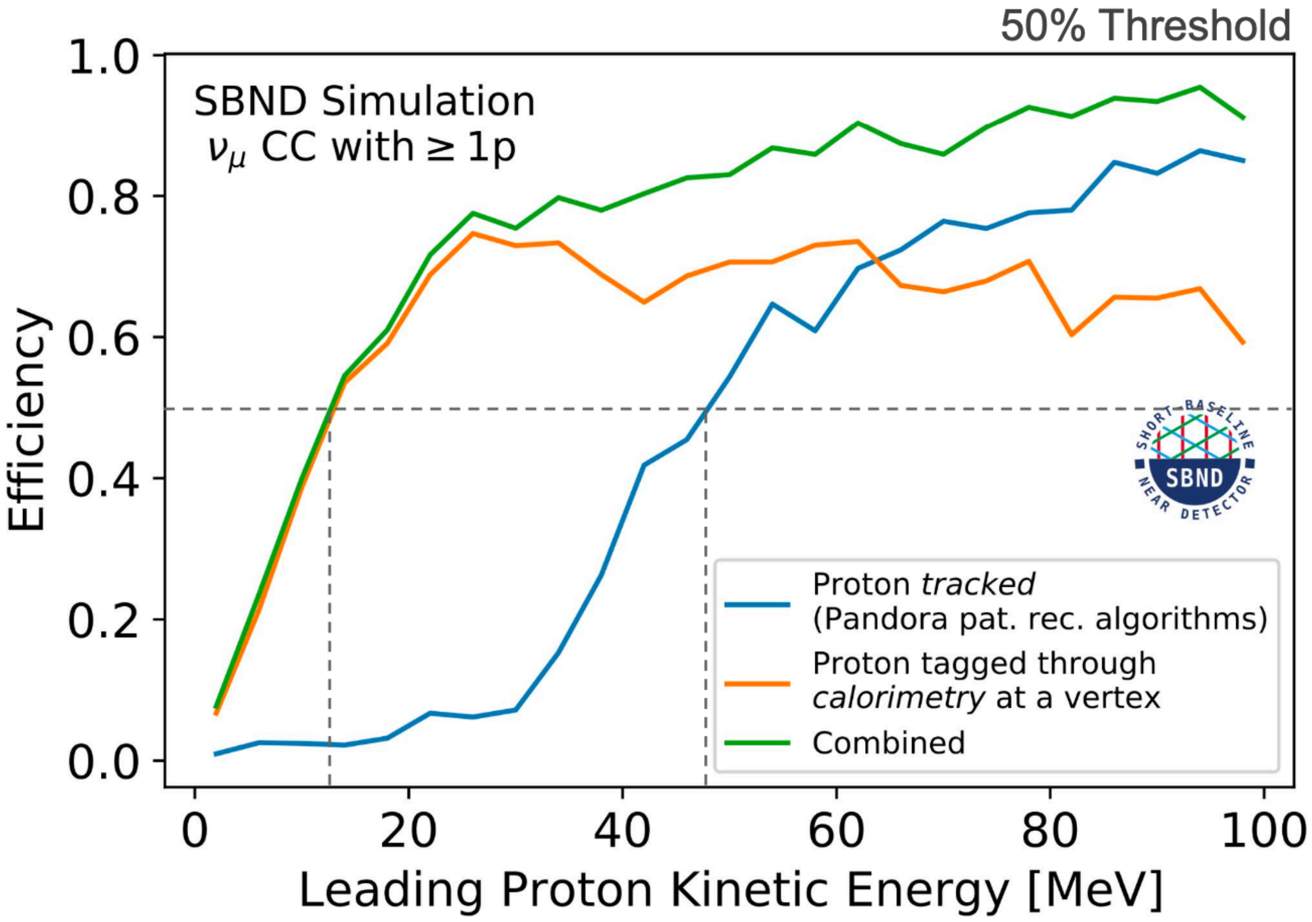
Large volumes of LAr data will enable further developments of powerful reconstruction and analysis techniques.

Proton Reconstruction

- A key challenge in reconstructing LArTPC neutrino interactions lies in the proton reconstruction.
- As highly-ionising particles (HIPs), protons quickly deposit large amounts of energy.



- In SBND's simulation, the geometry-driven Pandora* reconstruction achieves a proton tracking threshold around 40 MeV (**blue** curve)
- Calorimetry has been incorporated into the reconstruction to identity heavy ionization deposits near the vertex for low-energy proton reconstruction (**orange** curve)
- When combined, the proton identification threshold can be pushed below 15 MeV (**green** curve)



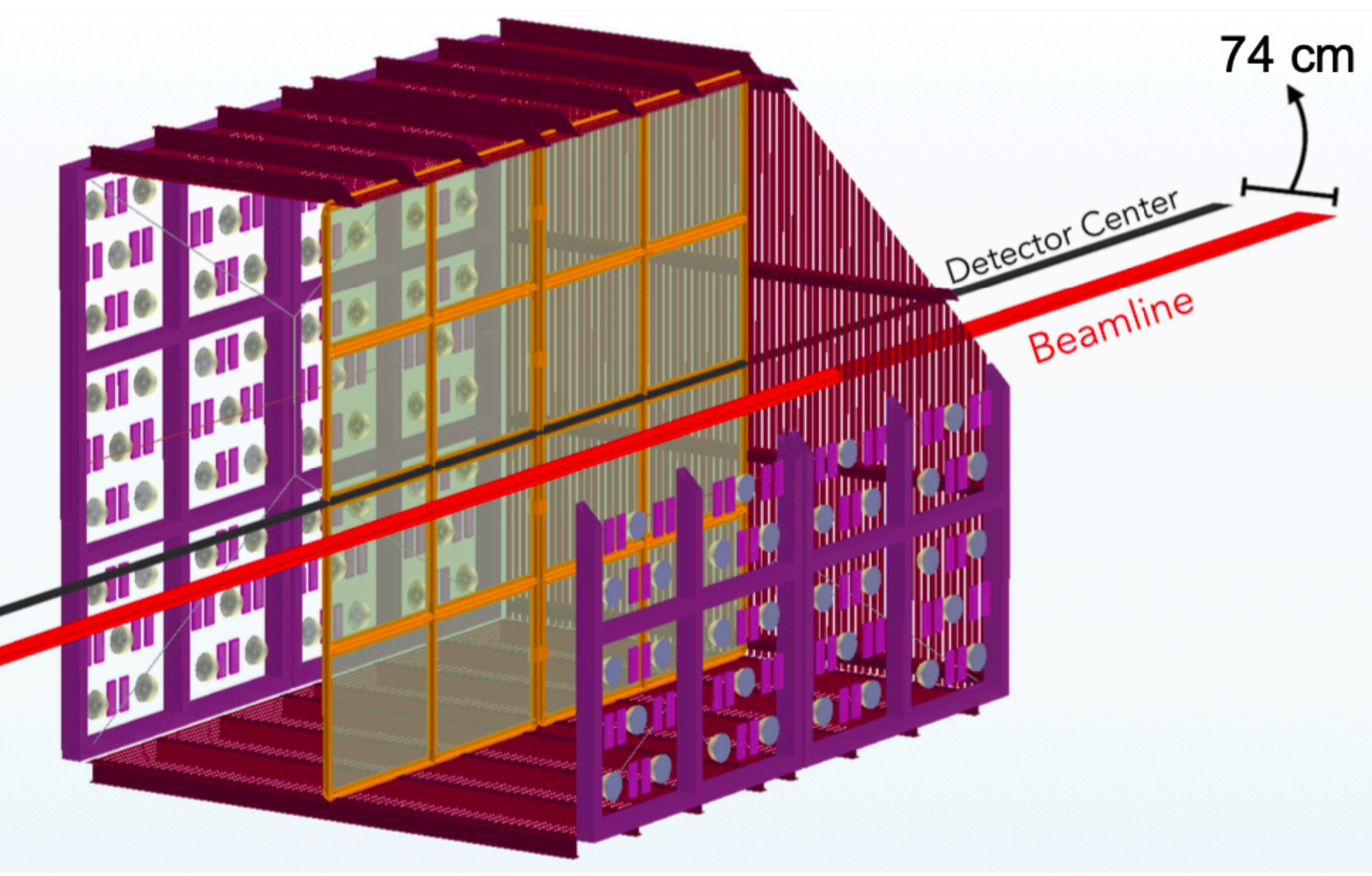
Pandora is a standard pattern recognition package, and is used in many LArTPC experiments: Eur. Phys. J. C 78, 82 (2018)

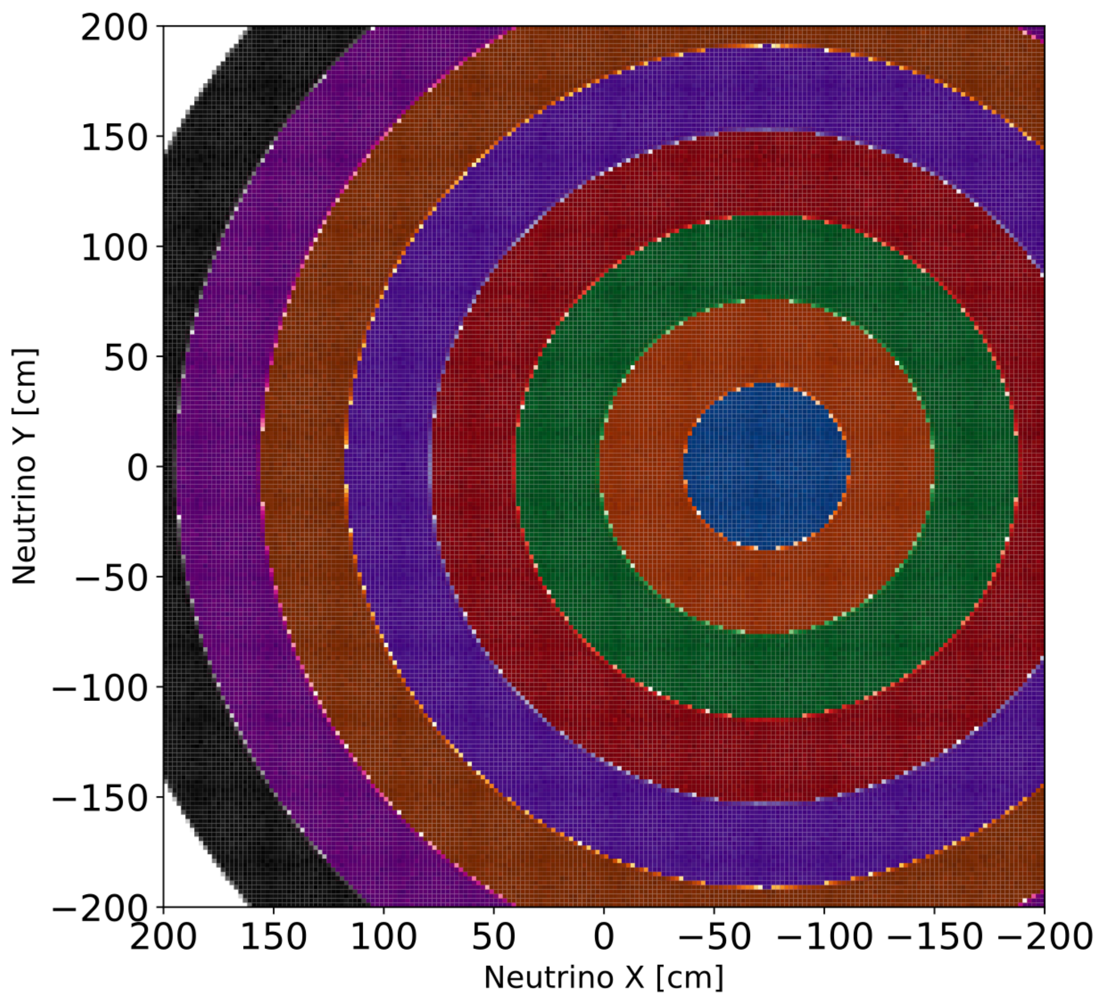
A Slightly Off-Axis Detector: SBND-PRISM

SBND-PRISM:

- Being close (110 m) to the neutrino source
- Positioned offset relative to the beam center

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





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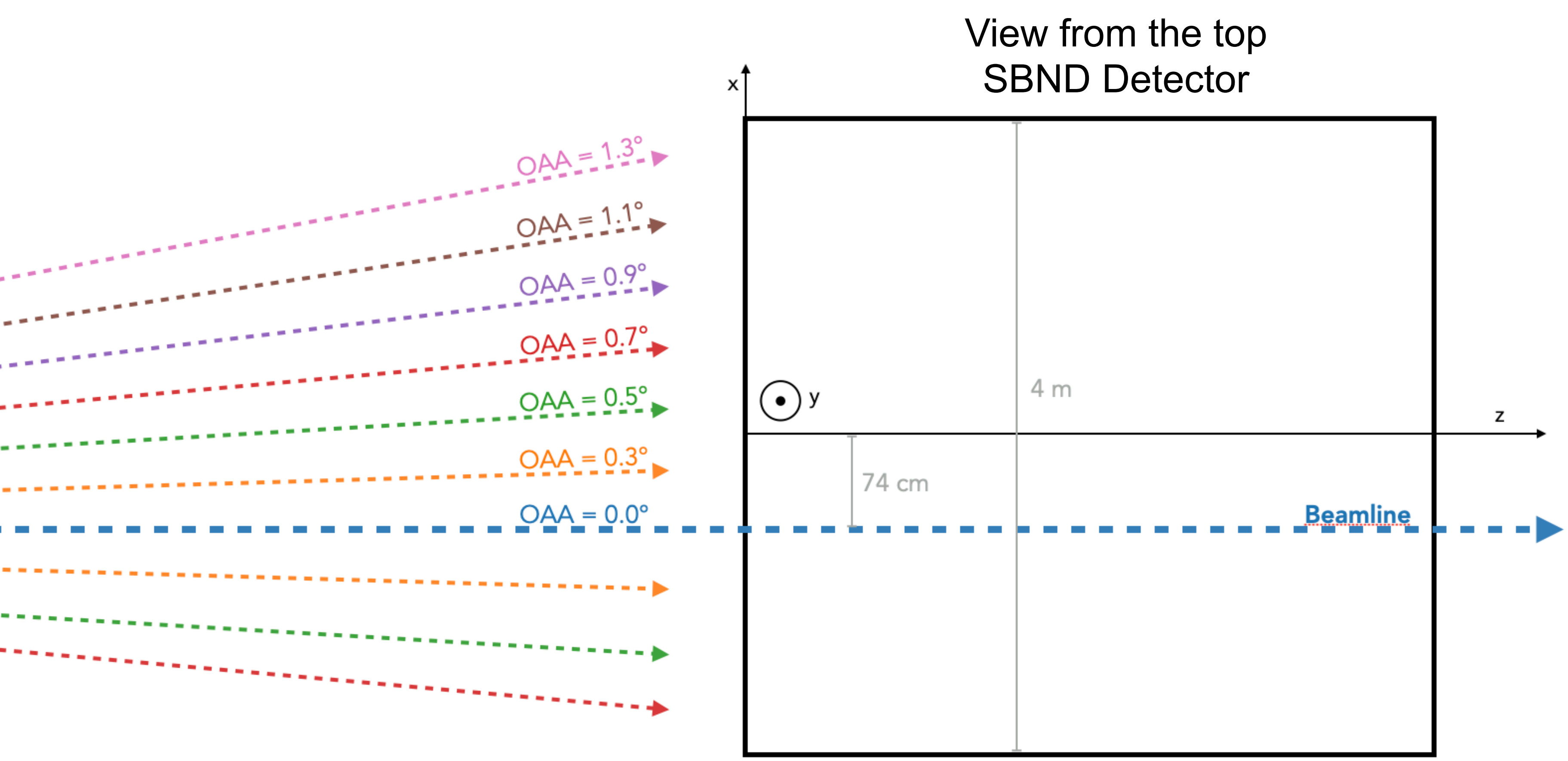
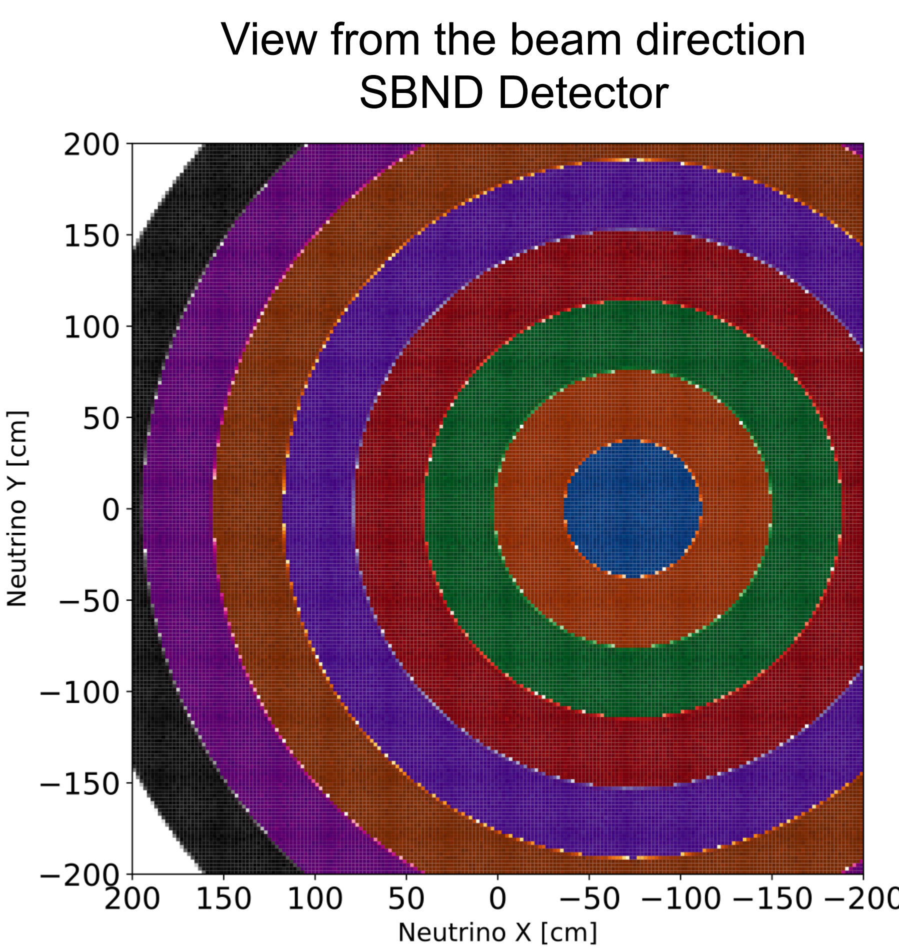
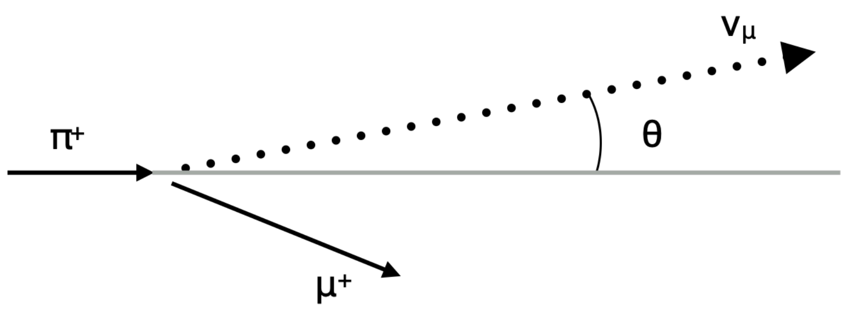




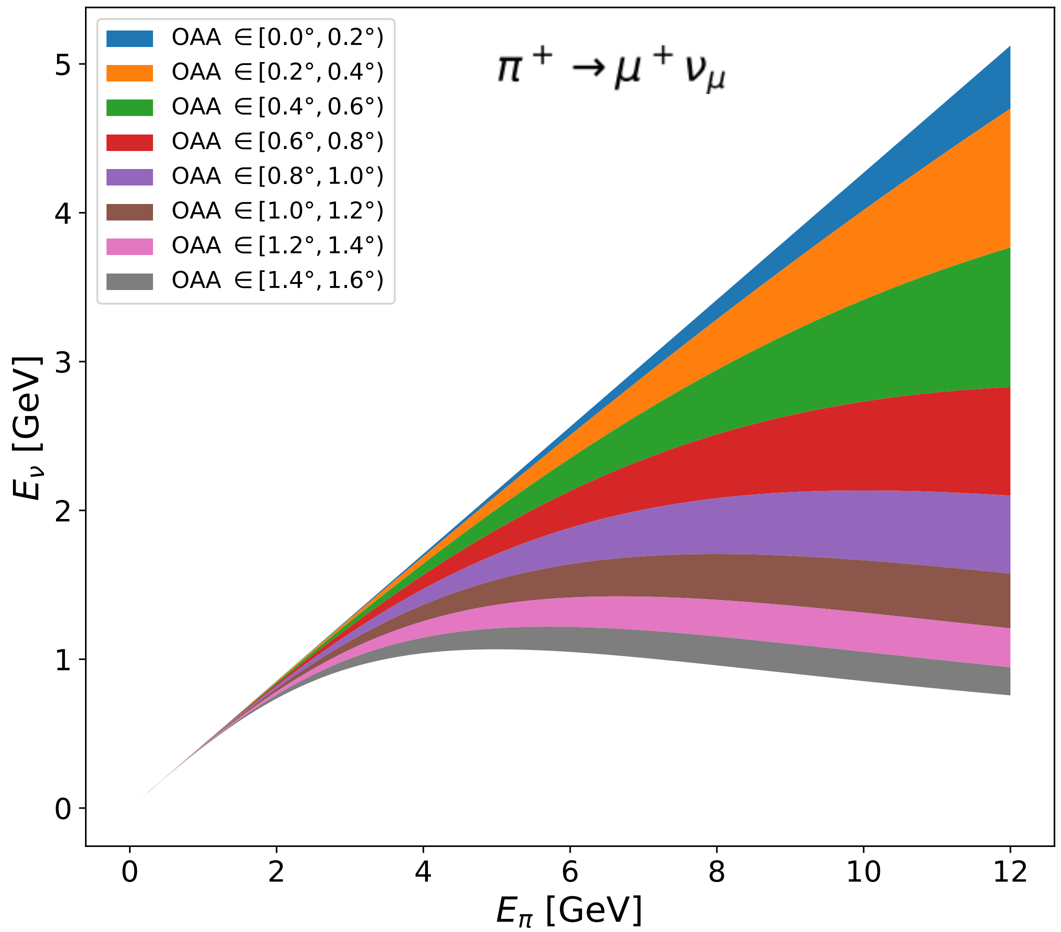
SBND-PRISM: ν_μ Energy Distribution

- ν_μ come predominately from the two-body decay, less angular spread, flux changes rapidly with respect to the beam axis.
- With the OAA, the observed neutrino energy spectrum narrows and peaks at a lower energy.

$$\pi^+ \rightarrow \nu_\mu + \mu^+$$
$$K^+ \rightarrow \nu_\mu + \mu^+$$

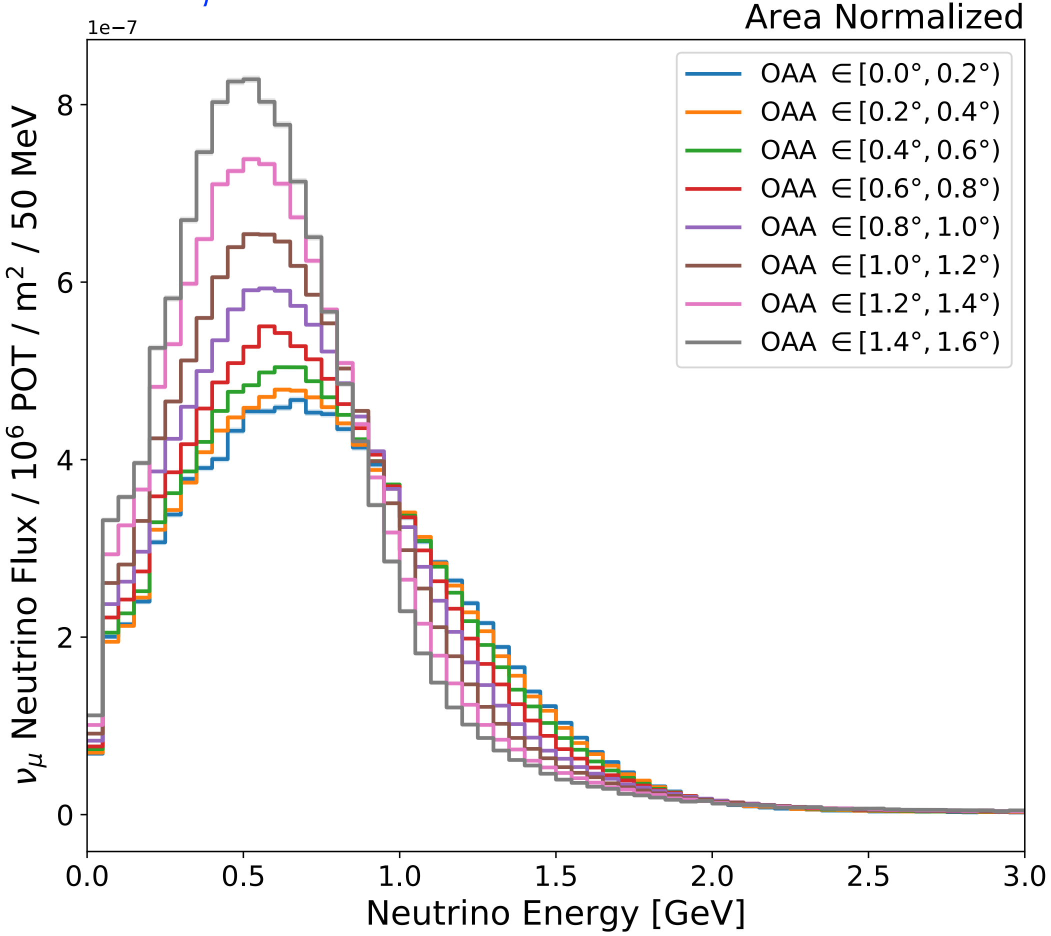


Neutrino Energy vs Pion Energy for different decay angles



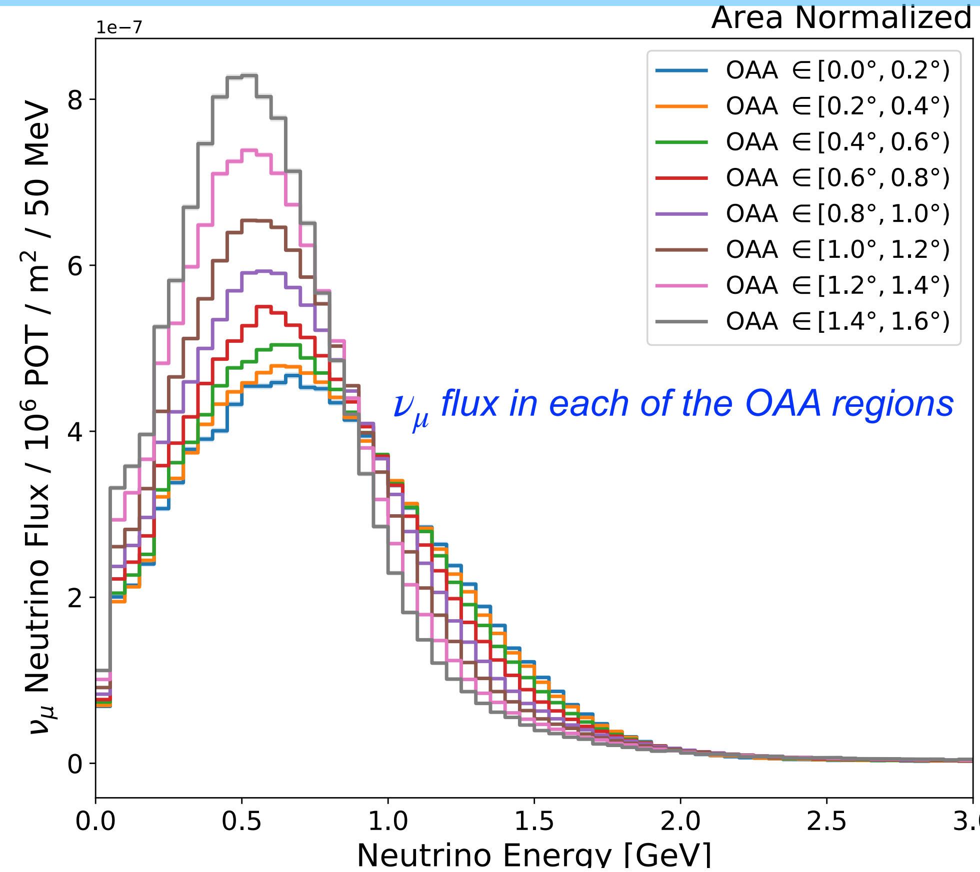
(assuming the pion is perfectly collinear with the beamline)

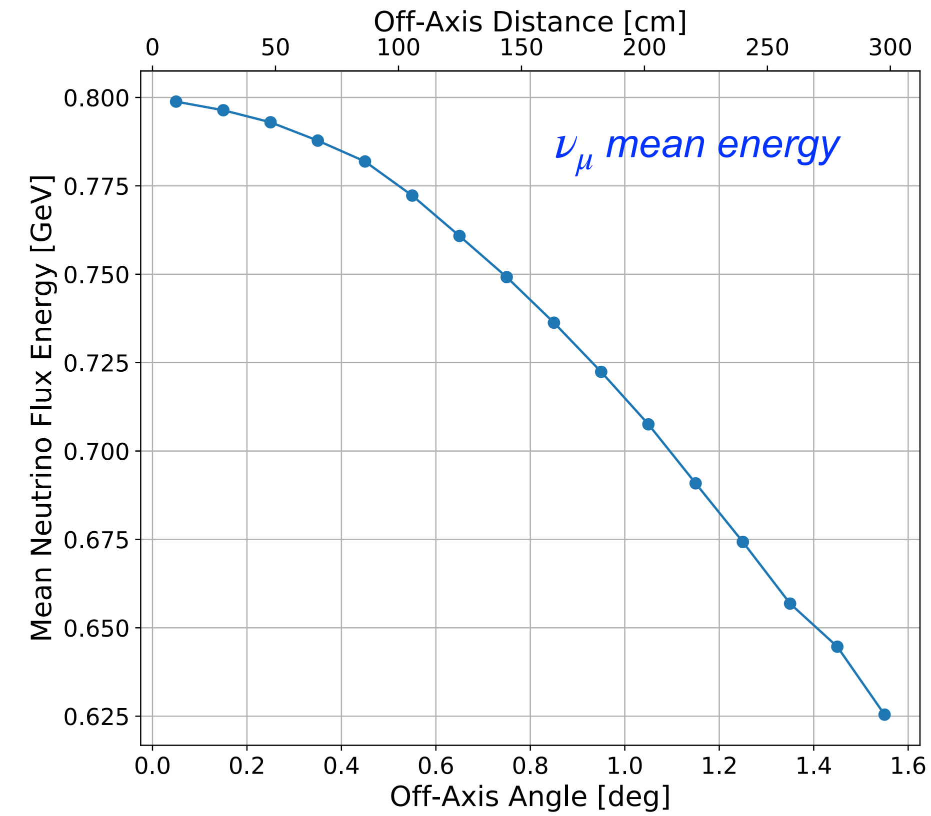
ν_μ flux in each of the OAA regions



SBND-PRISM: ν_μ Energy Distribution

- **Energy dependence:**
  - Up to ~200 MeV difference in ν_μ mean energy
  - By measuring neutrino interactions at different OAA, we can infer the energy dependence of the cross section (and various nuclear effects) spanning over nearly 200 MeV energy difference.
  - Study the relationship between neutrino energy, and lepton (and hadron) kinematics, done by measuring differential cross-section in lepton (and hadron) kinematics at different OAA.





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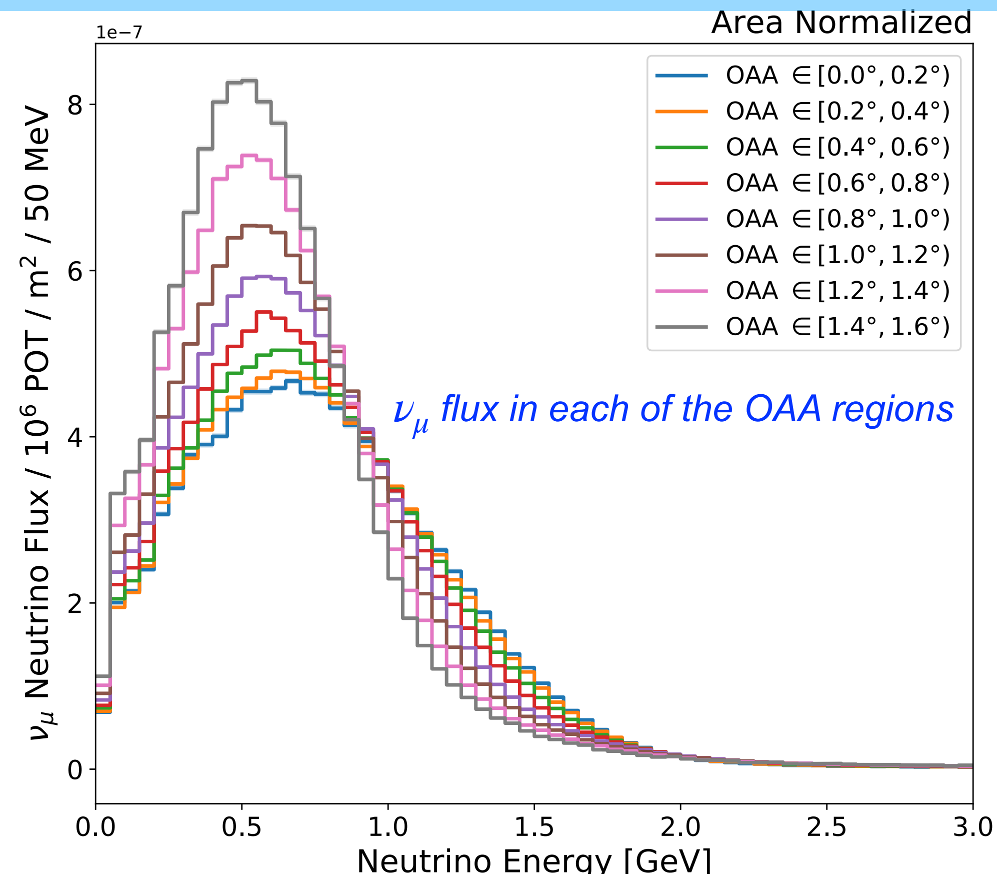
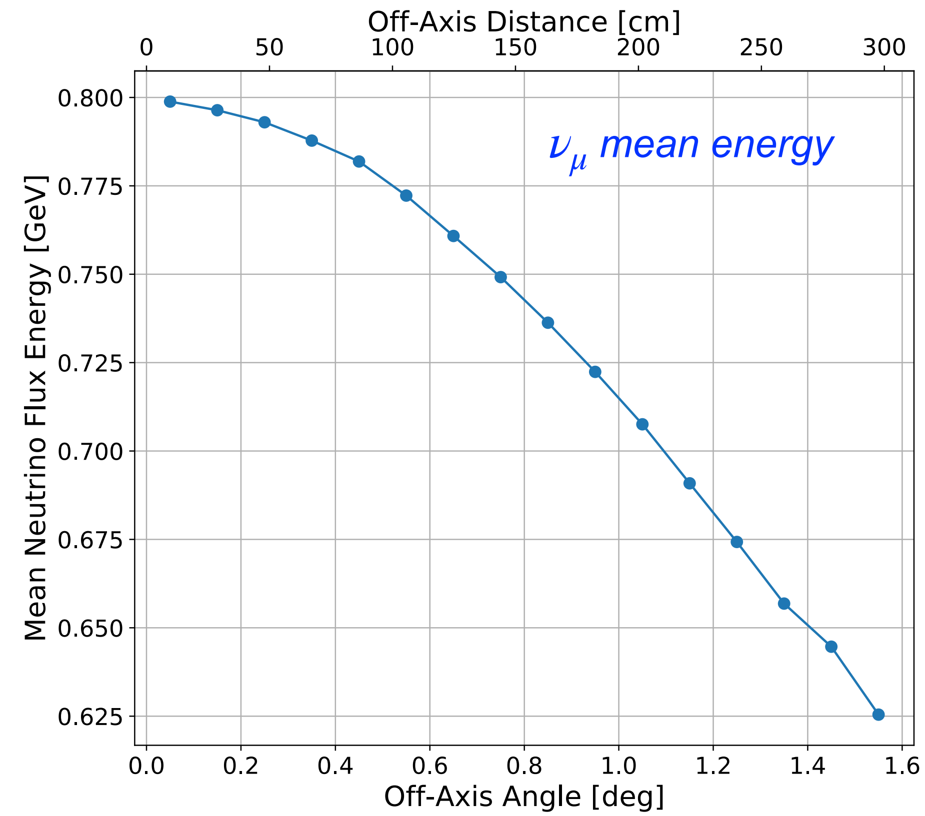


- **Disentangling nuclear physics at the "higher-energy" tail:**
  - The "higher energy" tail of the ν_μ flux shrinks as a function of the OAA.
  - This would potentially allow us to disentangle nuclear effects that start to dominate at ~1 GeV energy, e.g. non-QE contributions (2p-2h contribution, etc.).

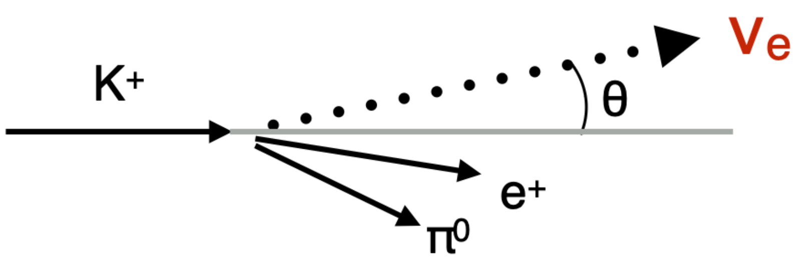


Allows stringent tests of theoretical models and event generators

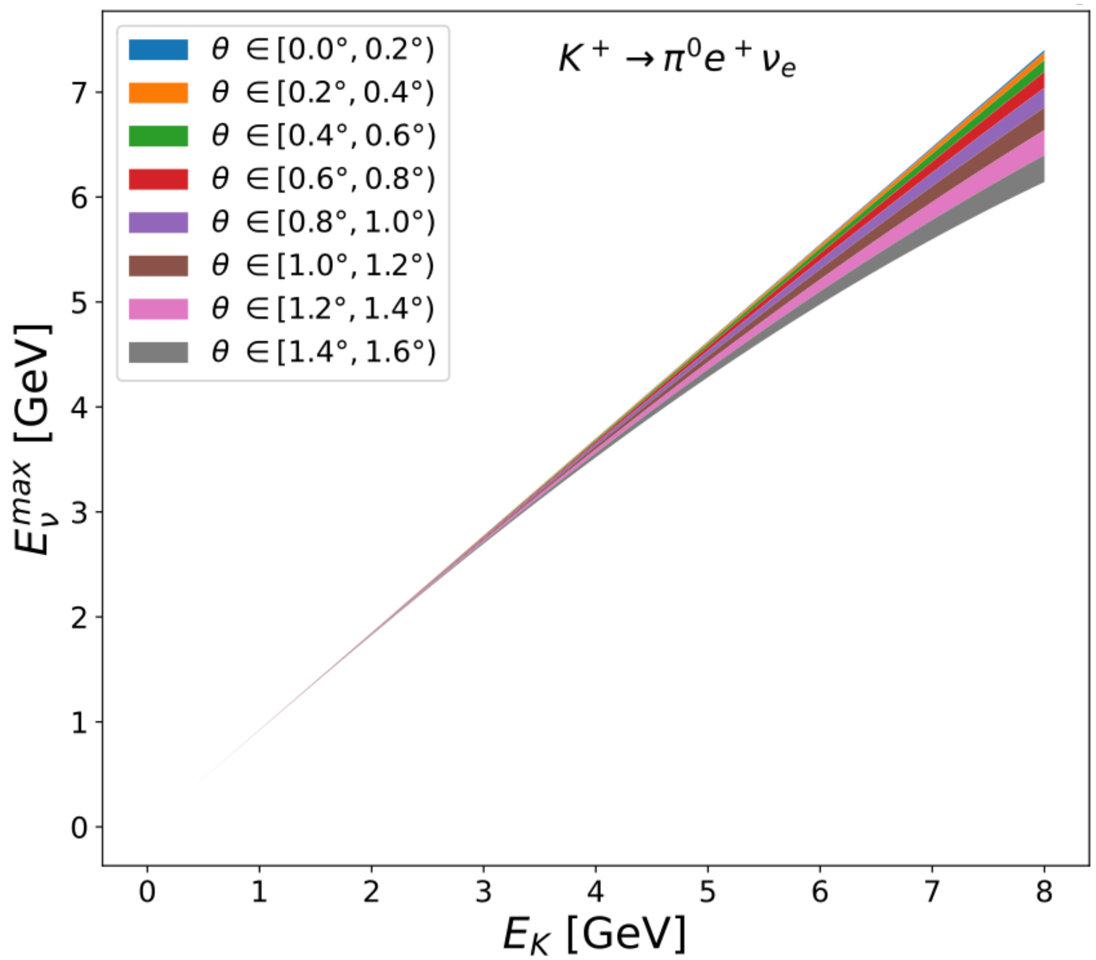
SBND-PRISM: ν_e Energy Distribution

- Unlike ν_μ, ν_e come predominately from the three-body decay. For the same parent energy, the ν_e flux has a larger angular spread than that of ν_μ, and does not follow the same "off-axis" effect as ν_μ.

$$\mu^+ \to \nu_e + \bar{\nu}_\mu + e^+$$
$$K^+ \to \nu_e + e^+ + \pi^0$$
$$K_L^0 \to \nu_e + e^+ + \pi^-$$

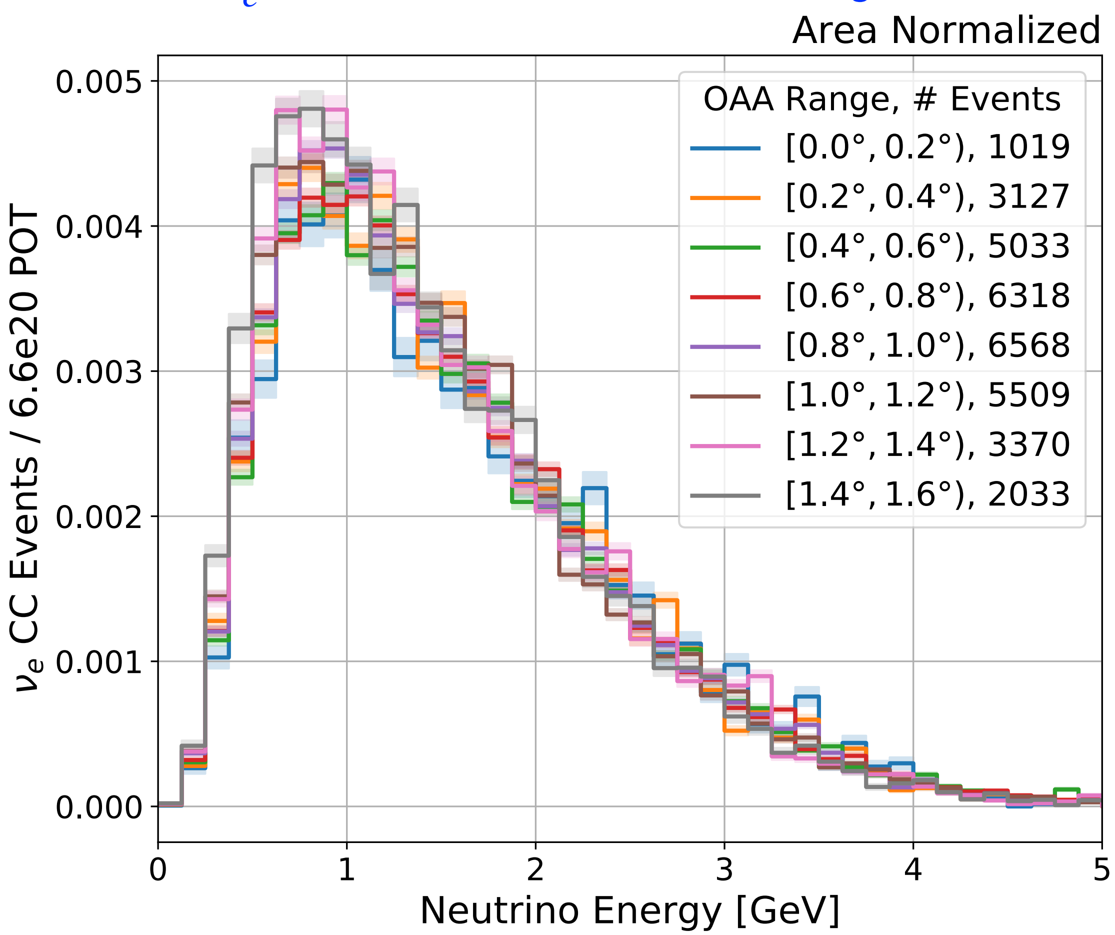


Neutrino Energy vs Kaon Energy for different decay angles



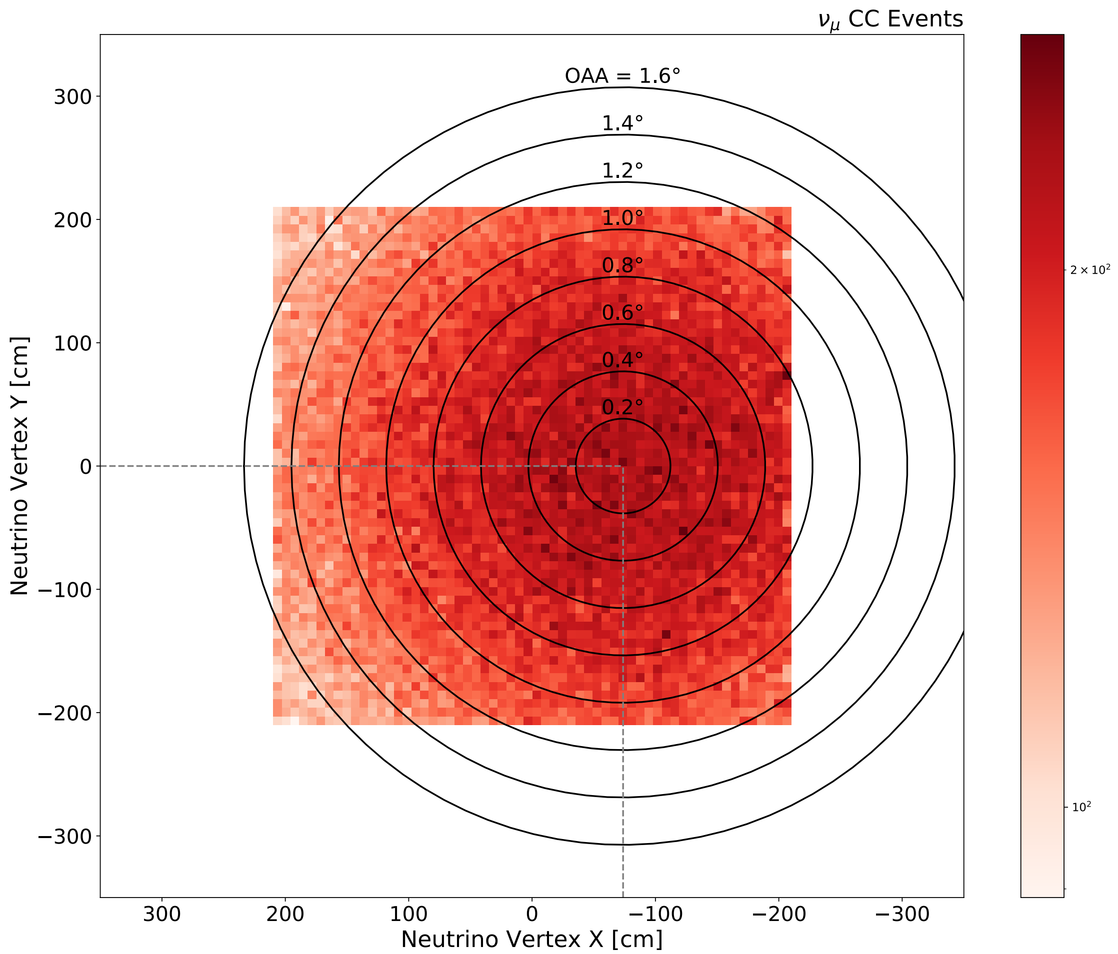
(assuming the kaon is perfectly collinear with the beamline)

ν_e events in each of the OAA regions

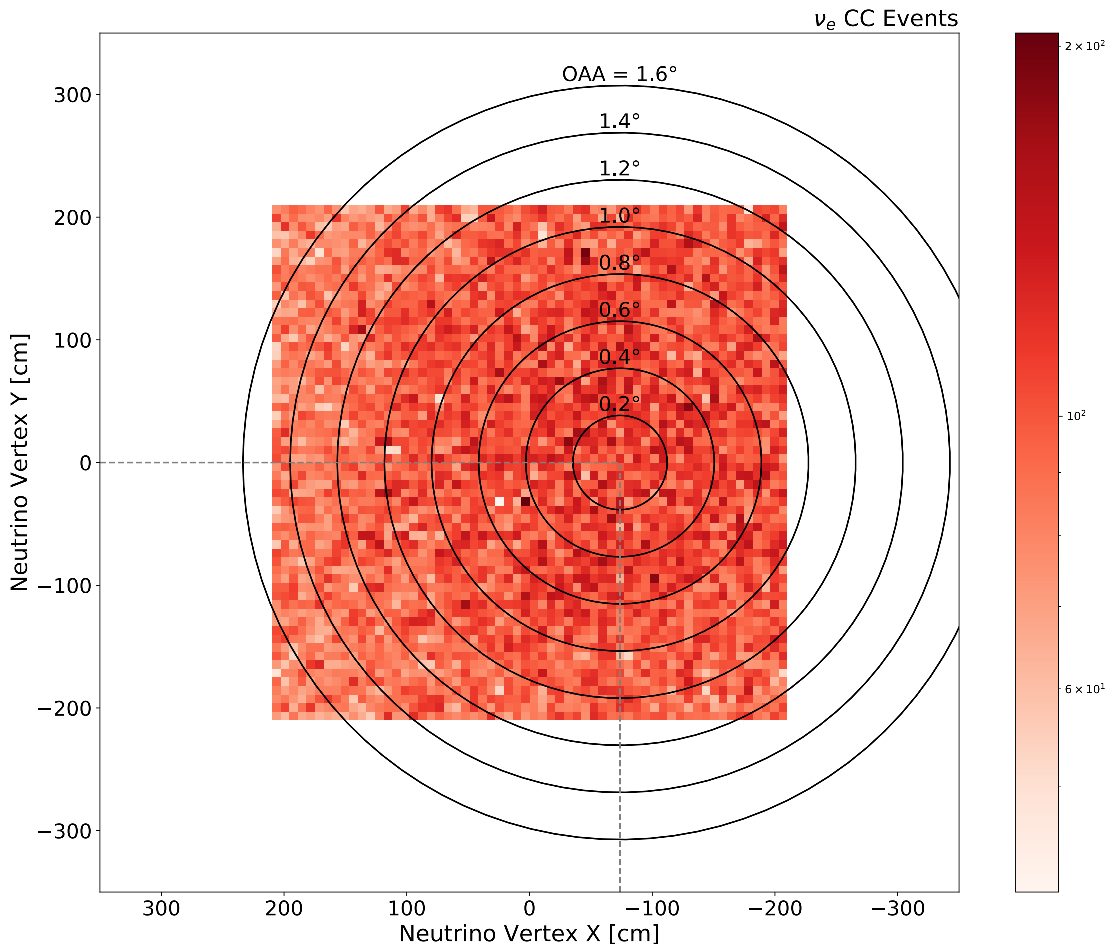


SBND-PRISM: ν_μ and ν_e Event Distributions

ν_μ CC Events
peak coincides with the on-axis position



ν_e CC Events
distribution is almost constant

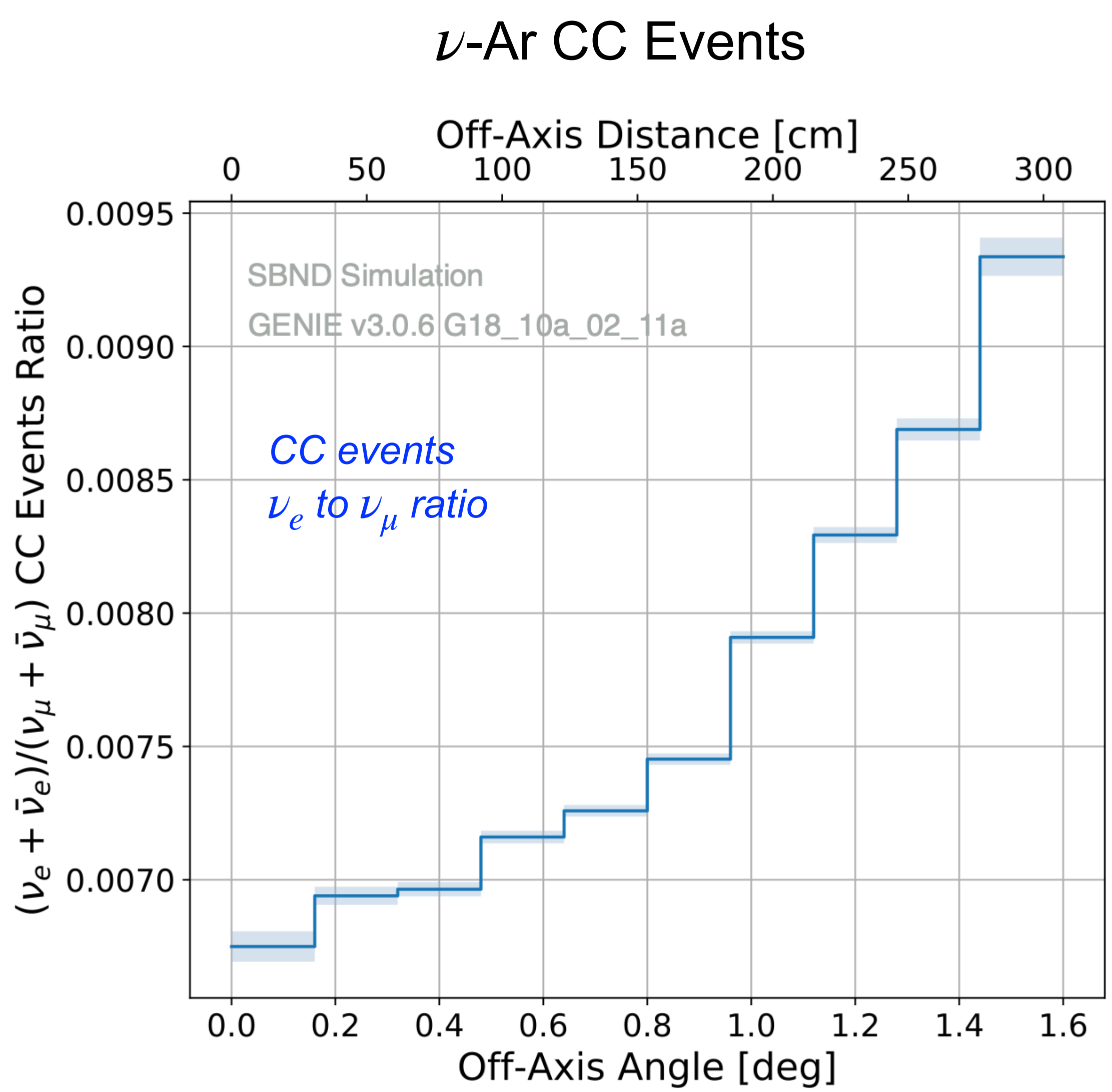


- Note high event statistics in all off-axis regions

SBND-PRISM: ν_μ and ν_e Event Distributions

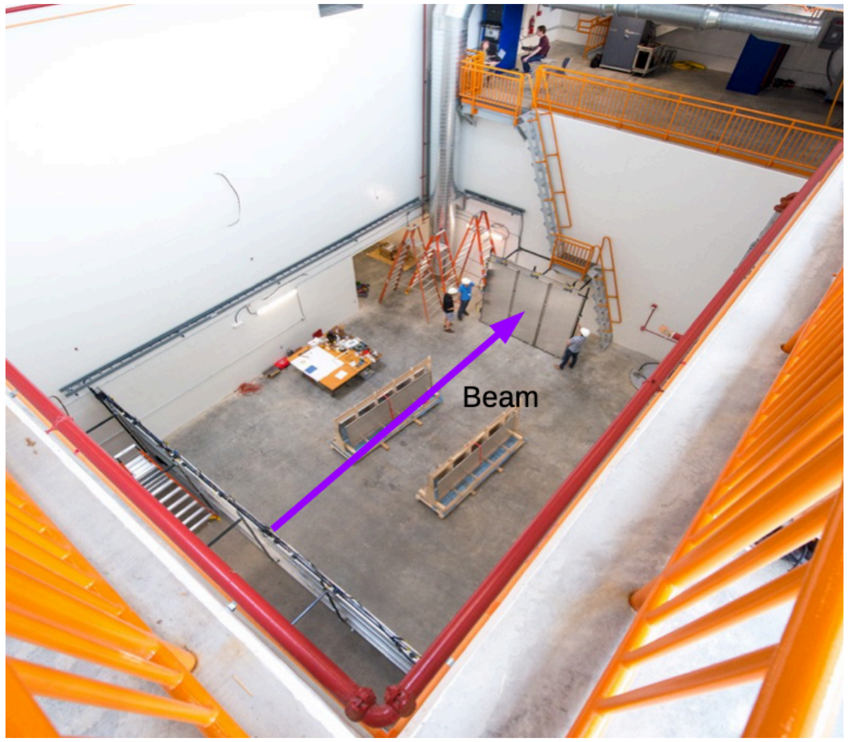
- **ν_μ to ν_e cross sections:**

  - Going off-axis, the increase in ν_e to ν_μ flux ratio combined with a choice of kinematics where ν_e to ν_μ differences are expected to be prominent should allow us to measure the ν_e/ν_μ cross section.
  - This would allow us to study lepton mass effects, and test Lepton Flavor Universality.
  - Note that we expect high event statistics in all off-axis regions.



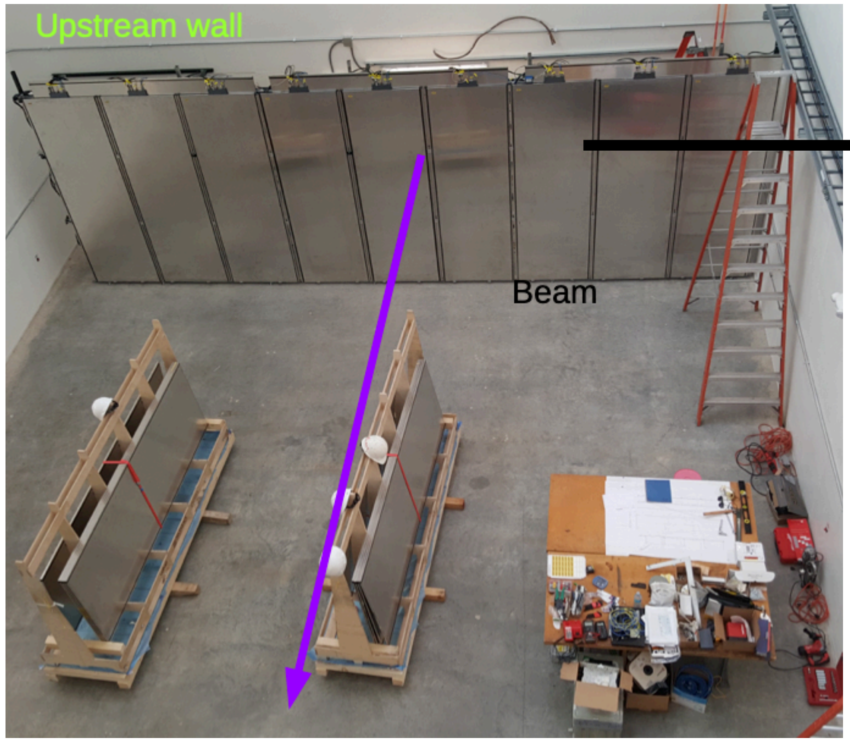
SBND-PRISM: CRT Data

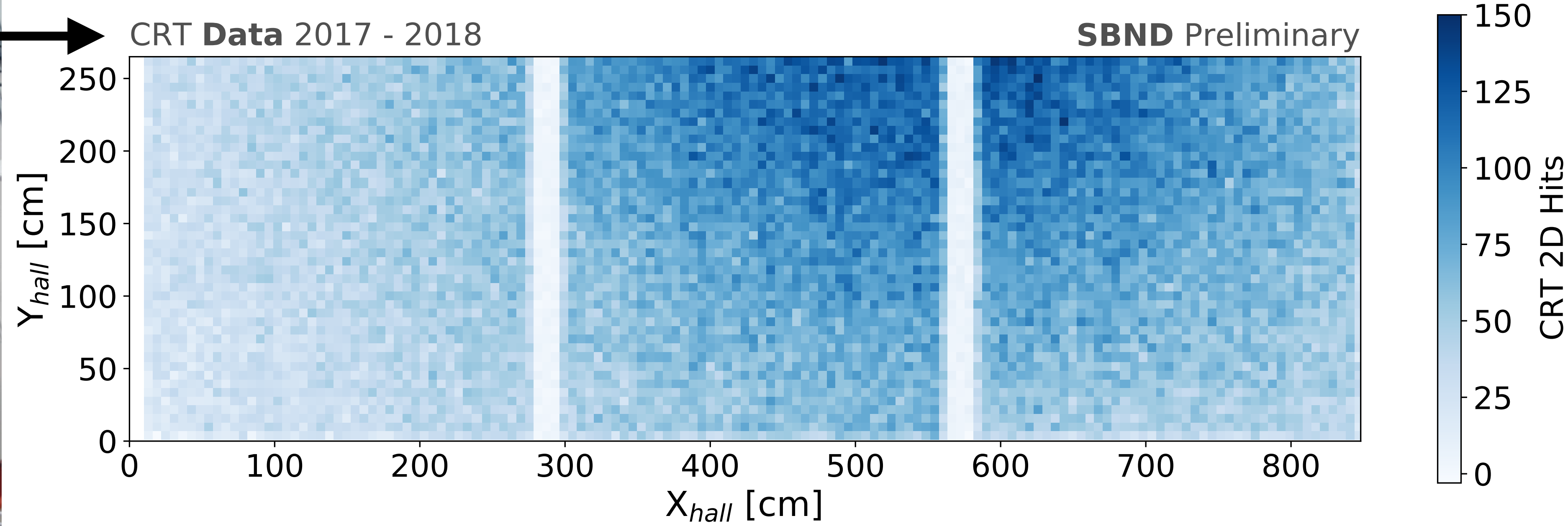
- SBND sees neutrinos from several off-axis angles (OAAs)
  (Off-axis angle is calculated w.r.t. target position)



▪ CRT Data

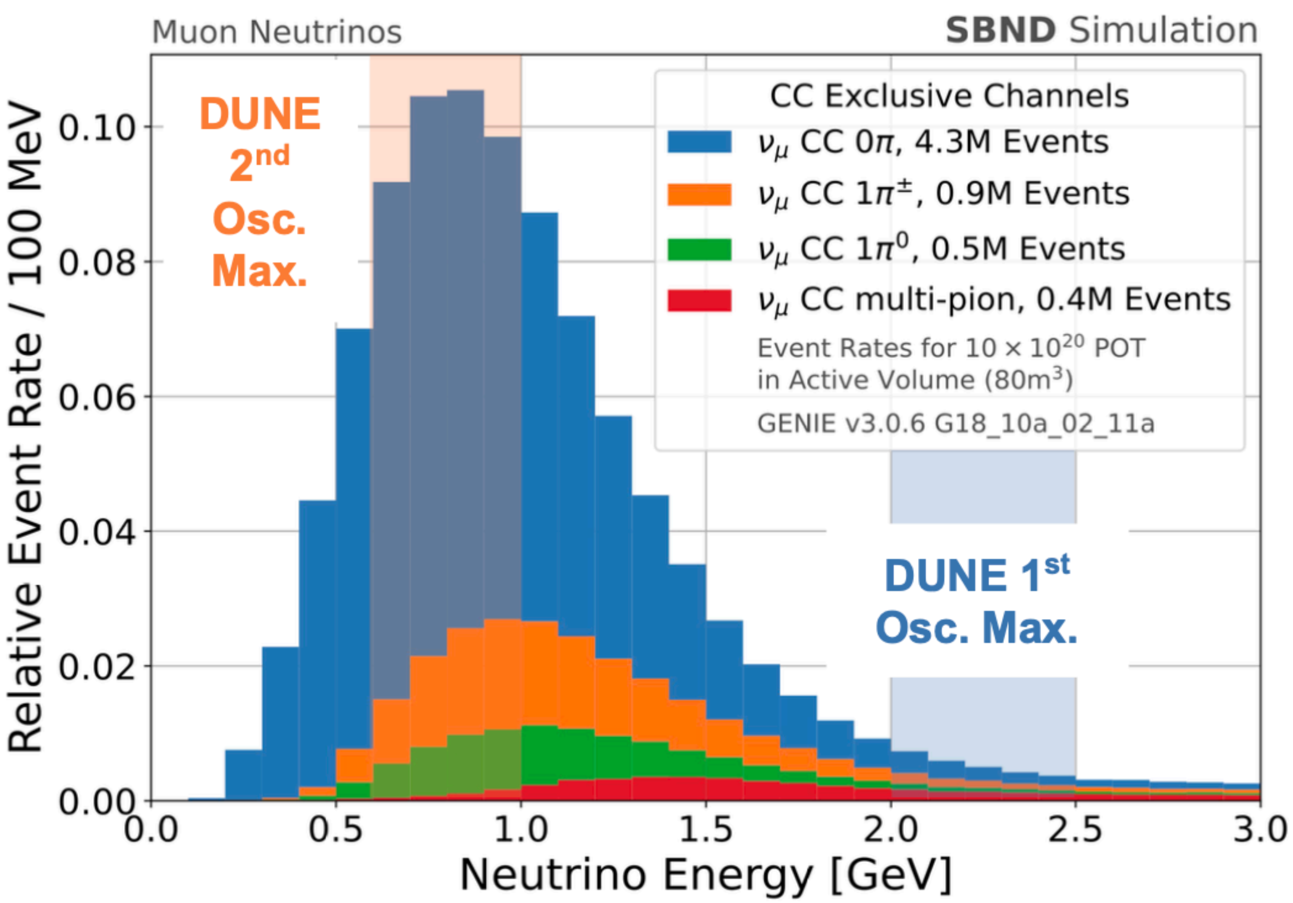
- Part of the SBND cosmic ray tagger system was temporary installed in the detector hall.
- Below is a real data plot of **muons from neutrinos** interacting in the material upstream of the SBND detector hall (cosmic background subtracted).
- Data taken with the CRT shows the number of beam-induced muons decreases moving away from the beam center.

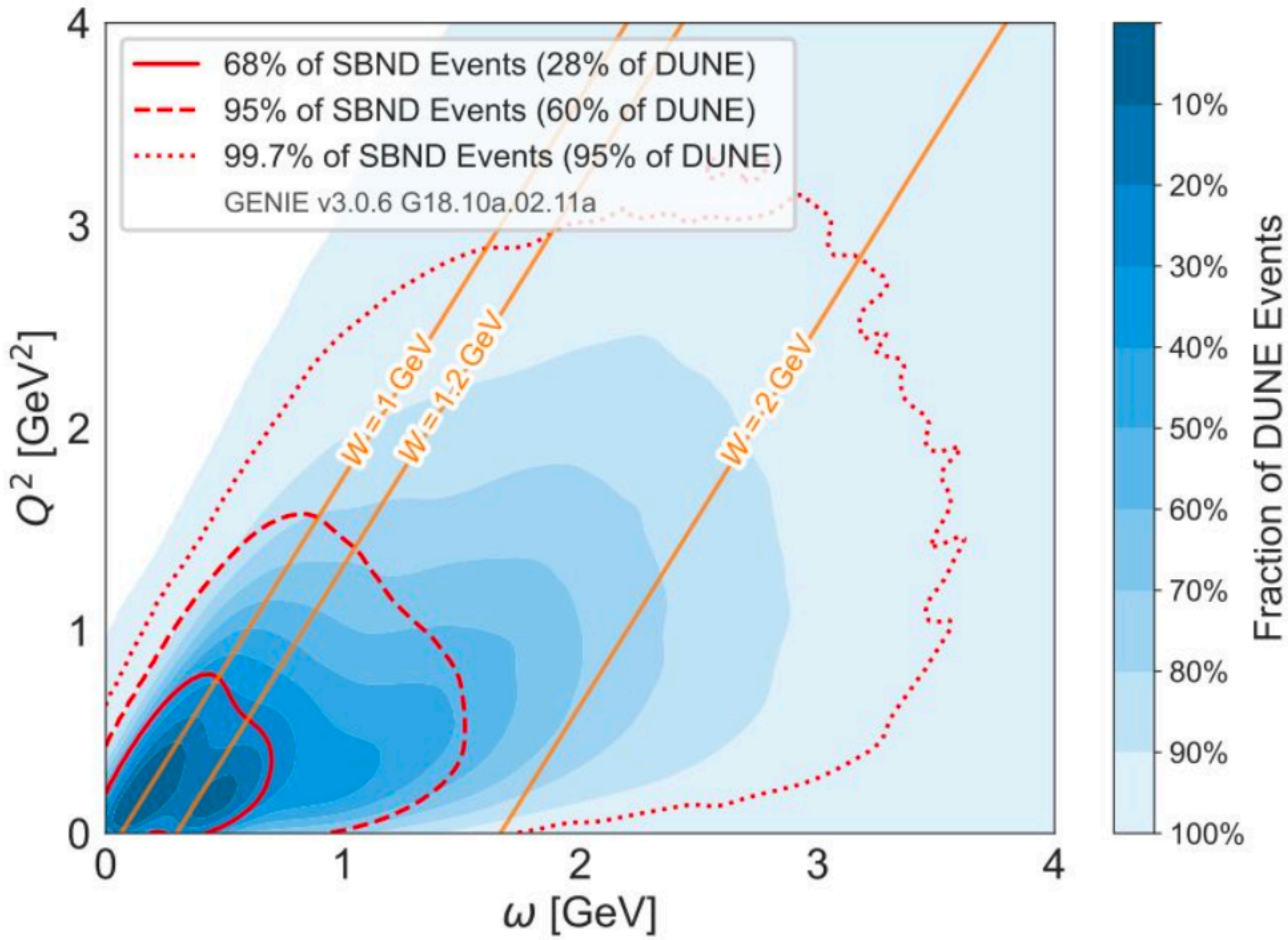




SBND and DUNE

- SBND interactions will cover significant parts of kinematic phase space relevant for DUNE, including energy range spanning first and second oscillation maxima
- SBND has a **significant phase space overlap with DUNE** → SBND measurements can be used to constrain the same physics DUNE needs to know.



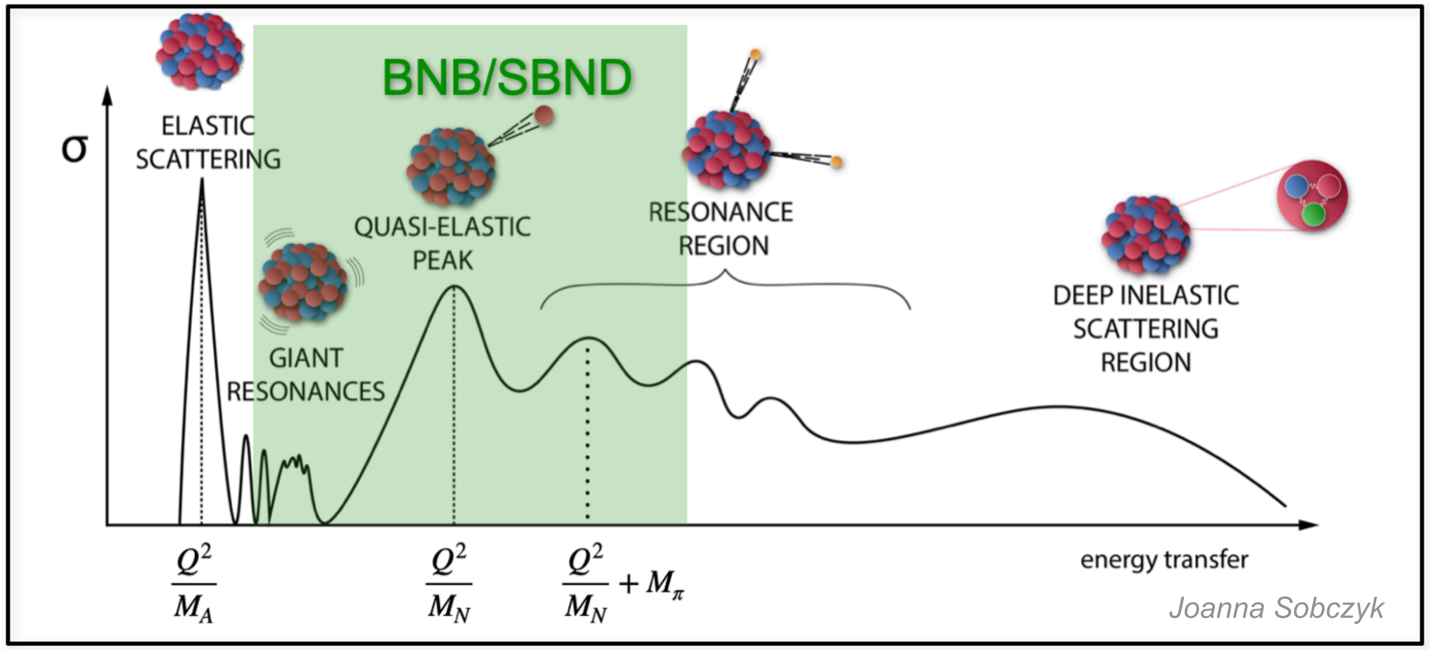


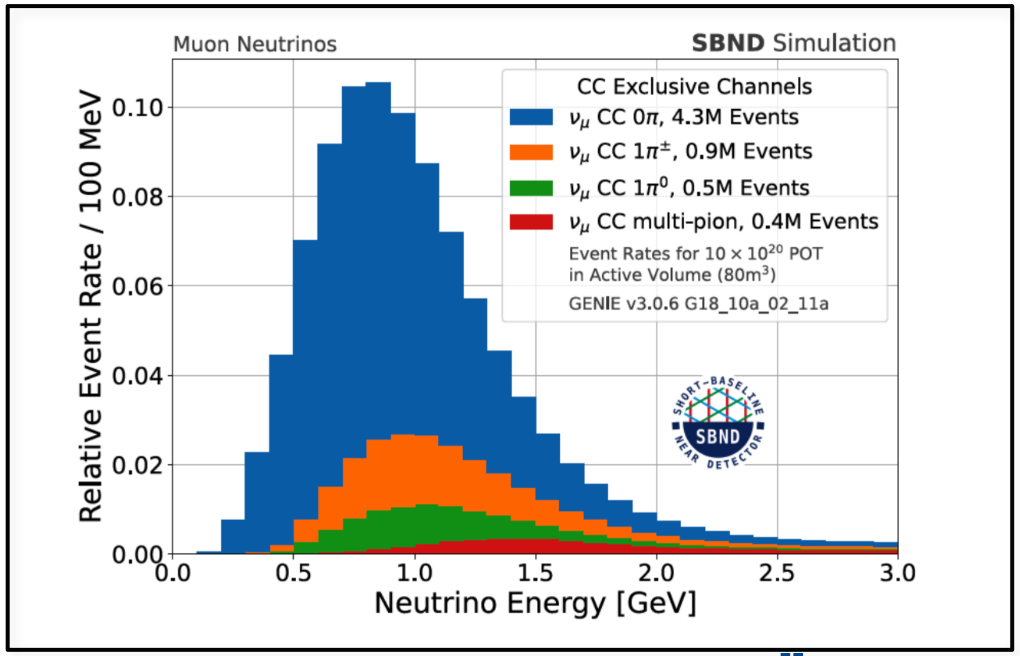
DUNE kinematic coverage is represented with the blue 2D histogram

SBND kinematic coverage is shown with 3 contours, representing 68%, 95%, and 99.7% of all SBND data.

Neutrino Interactions in SBND

- The capabilities of SBND described so far provide ample opportunities
  - High-statistics searches in high-multiplicity neutrino interaction channels
  - Utilizing the calorimetric and low threshold particle ID capabilities of LArTPC's one can select and study precise various baryonic final states in details
  - Searches for higher order resonance and rare channels with sensitivities beyond what has been possible before
  - Design analyses to be capable of probing regions of greatest model discrimination power
- These capabilities will allow the study of nuclear effects in neutrino interactions in argon nuclei with unprecedented high precision, providing the testbed to assess and validate nuclear models and generator, and hopefully pave the way for precision neutrino-argon scattering physics.
- Engagement from the theory community is highly encouraged to fully exploit SBND xsec physics program!

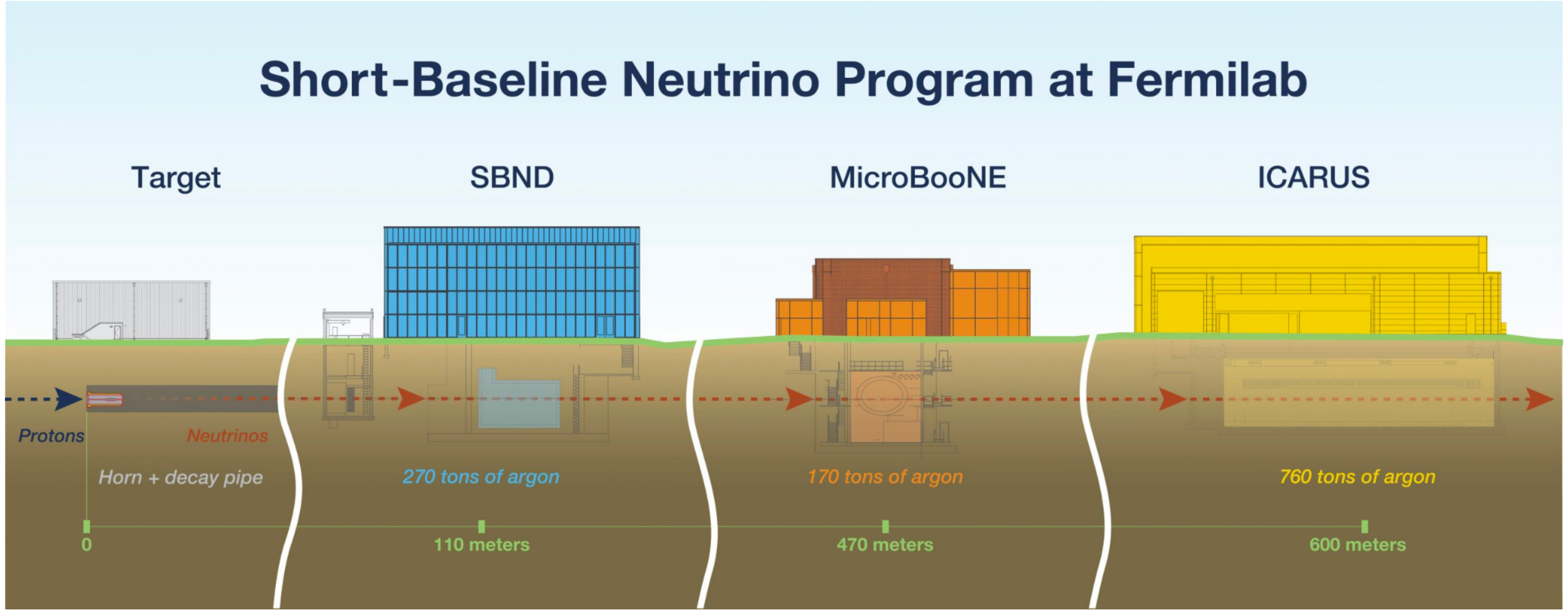


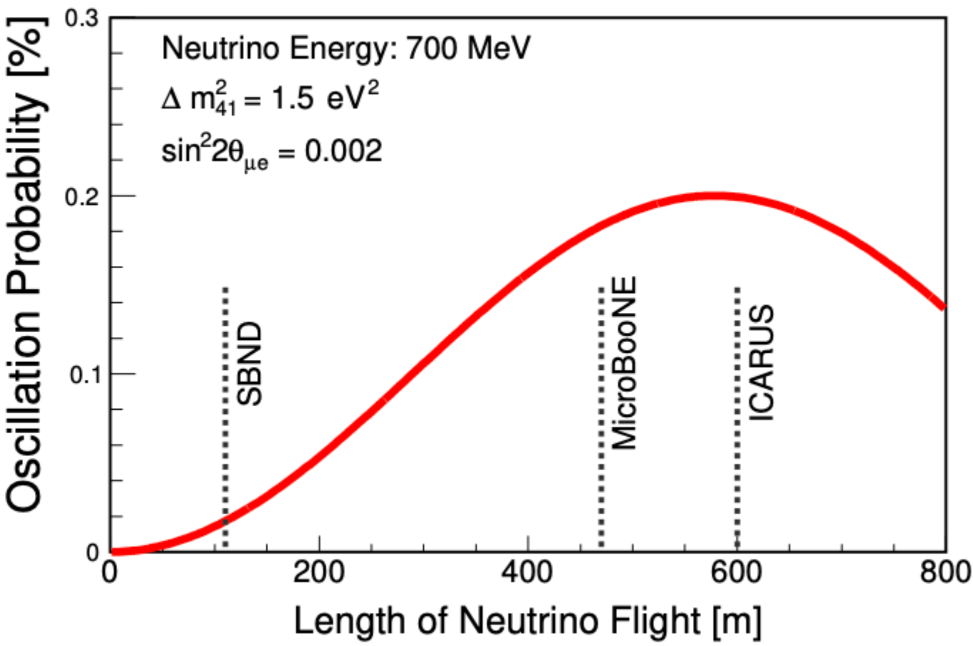


Outline

- Short Baseline Neutrino (SBN) Program at Fermilab
  - Short-baseline anomalies, status
- Short Baseline Near Detector (SBND)
  - Installation status and timeline, key features
- Neutrino Interaction Physics at SBND
  - High statistics, detection capabilities, SBND-PRISM
- **Broader Physics Program at SBND**
  - **Oscillations and BSM Physics**

SBN Oscillations Sensitivities





P. Machado, O. Palamara, D. Schmitz, Annu. Rev. Nucl. Part. Sci. 69 363-387 (2019)

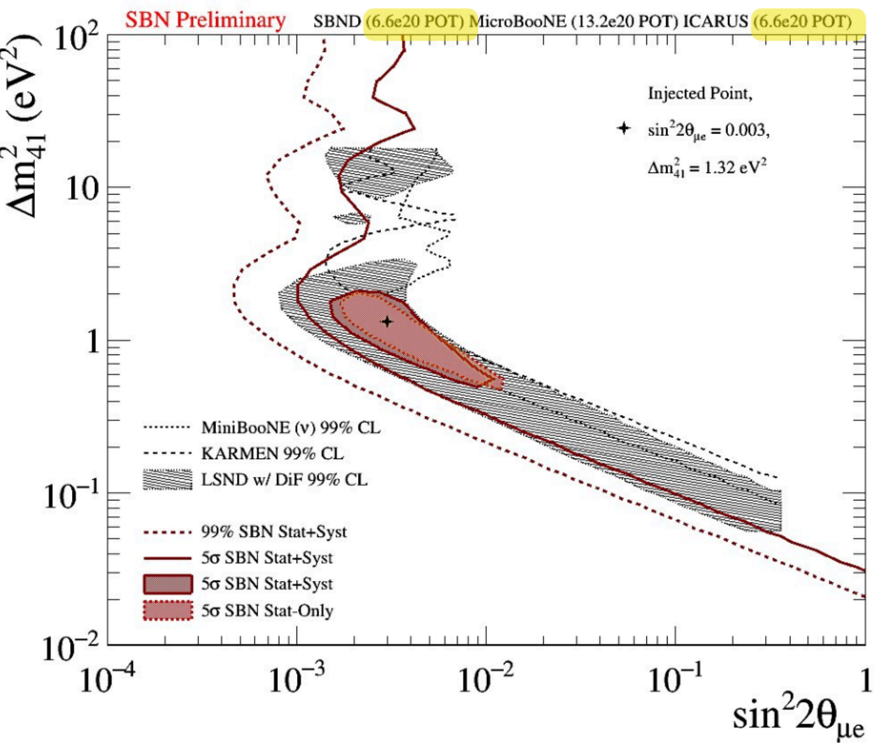
- SBND, as the near detector, is crucial for oscillation searches.

  - It sits before oscillations turn on @eV-scale → it characterizes the beam and addresses the dominant systematic uncertainties

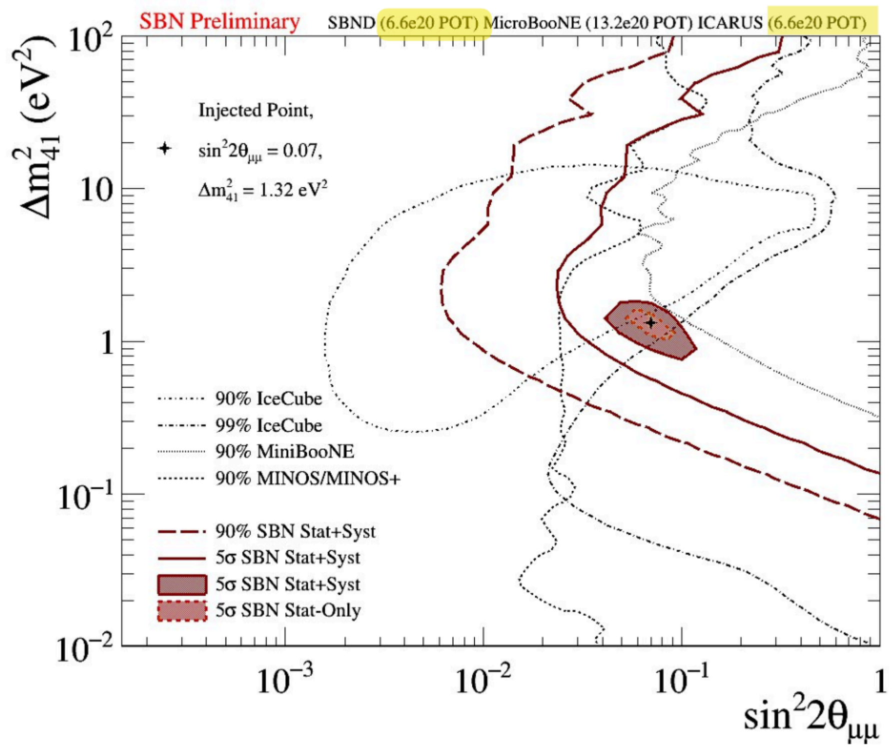
- The PRISM feature of SBND can potentially improve the SBN sensitivities to sterile neutrino oscillations.

SBN Oscillations Sensitivities

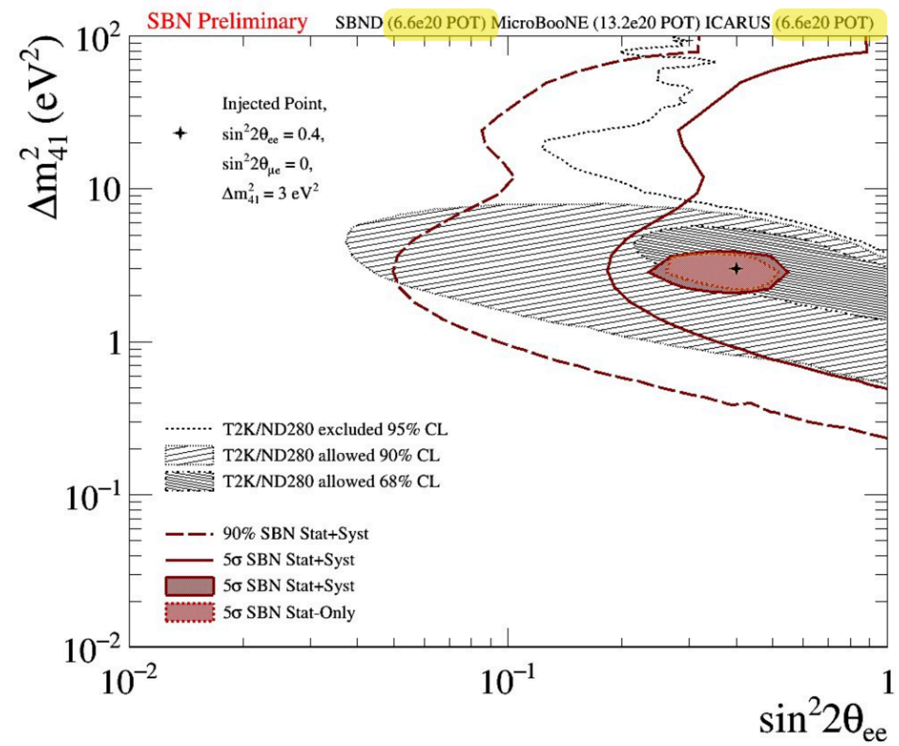
ν_e Appearance



ν_μ Disappearance



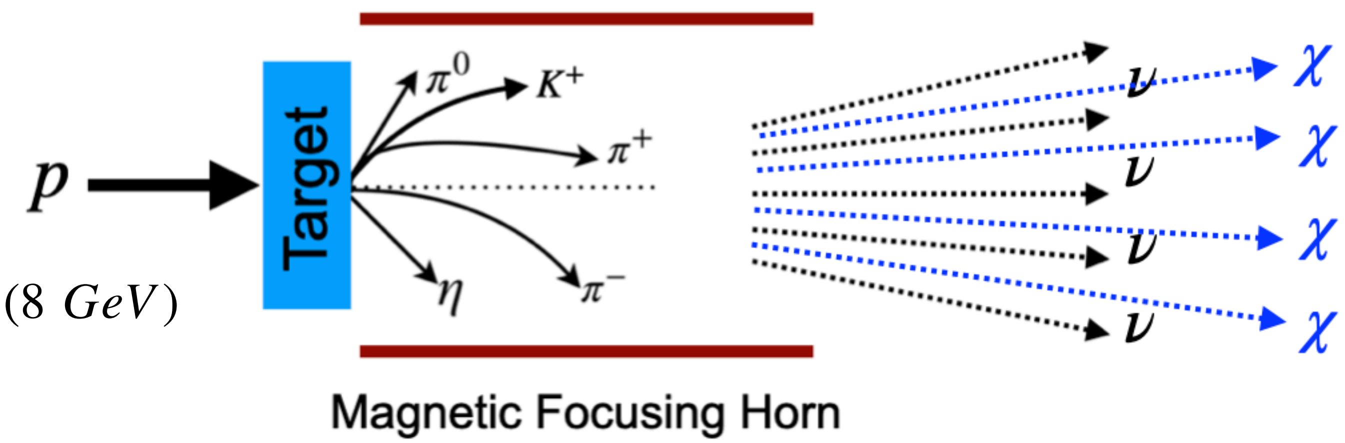
ν_e Disappearance



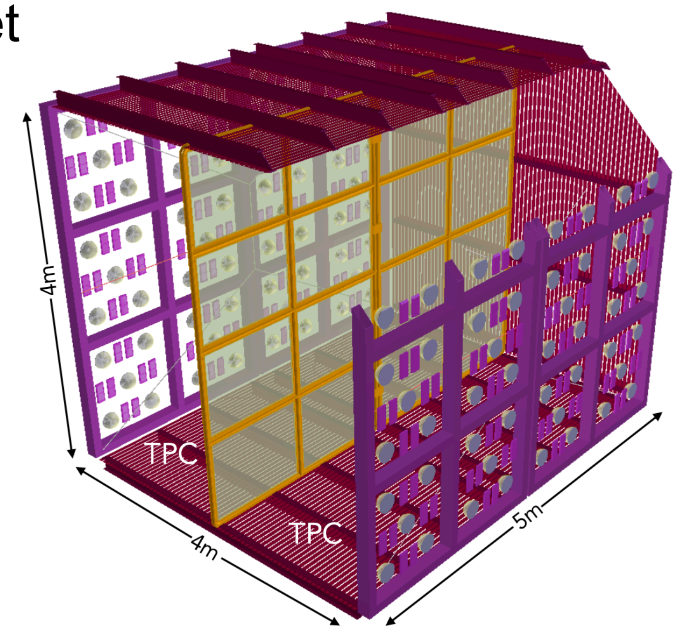
- Current sensitivity plots from SBN using up-to-date models, systematics and geometries
- In **two/three sterile oscillation channels**, SBN will be sensitive to the parameter space favored by previous measurements at the **5σ confidence level**
- Directly address existing tensions observed in the combined appearance and disappearance data.

Beyond the Standard Model Searches at SBND

- High-intensity proton beams (high-intensity neutrino beams)



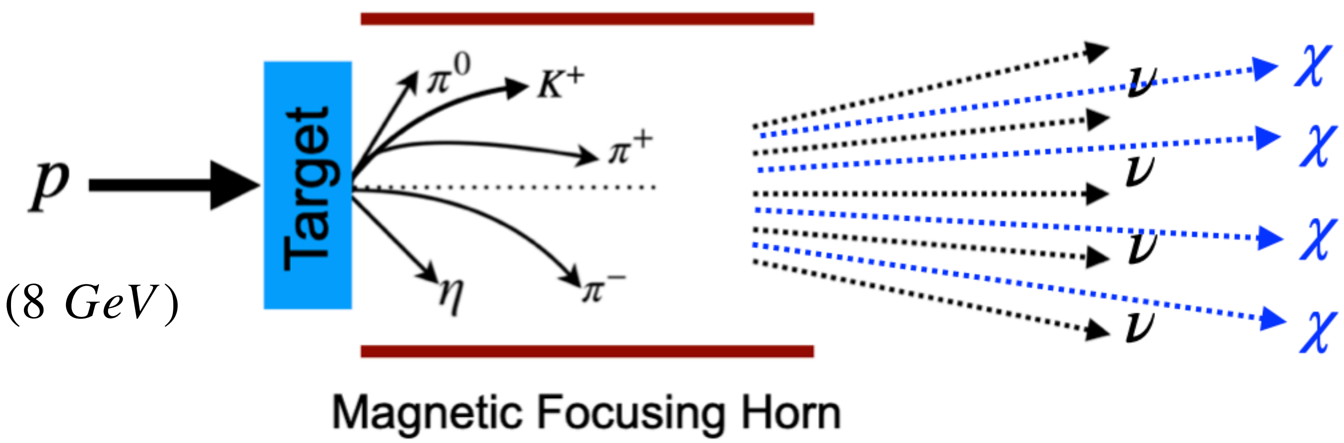
- SBND's proximity to the target



- Large mass LArTPC detectors
  - Event imaging
  - Fine granularity calorimetry and particle identification
  - Good timing resolution
  - Low energy threshold

Beyond the Standard Model Searches at SBND

- High-intensity proton beams (high-intensity neutrino beams)



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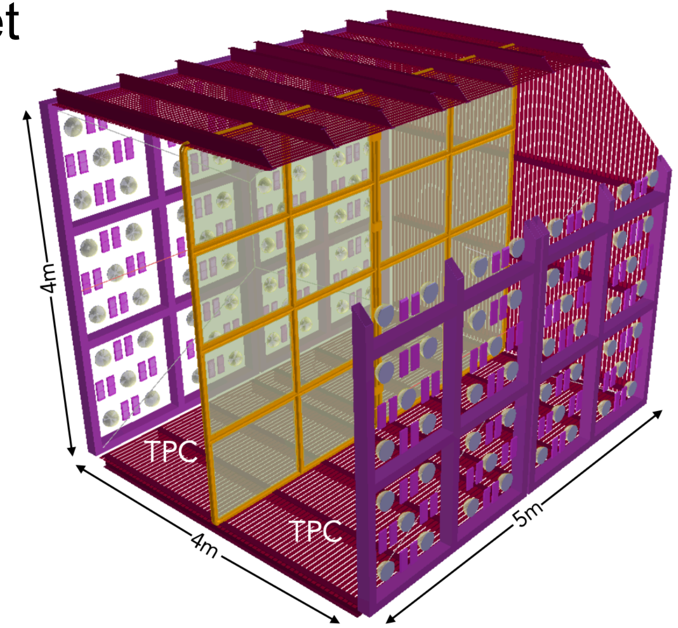
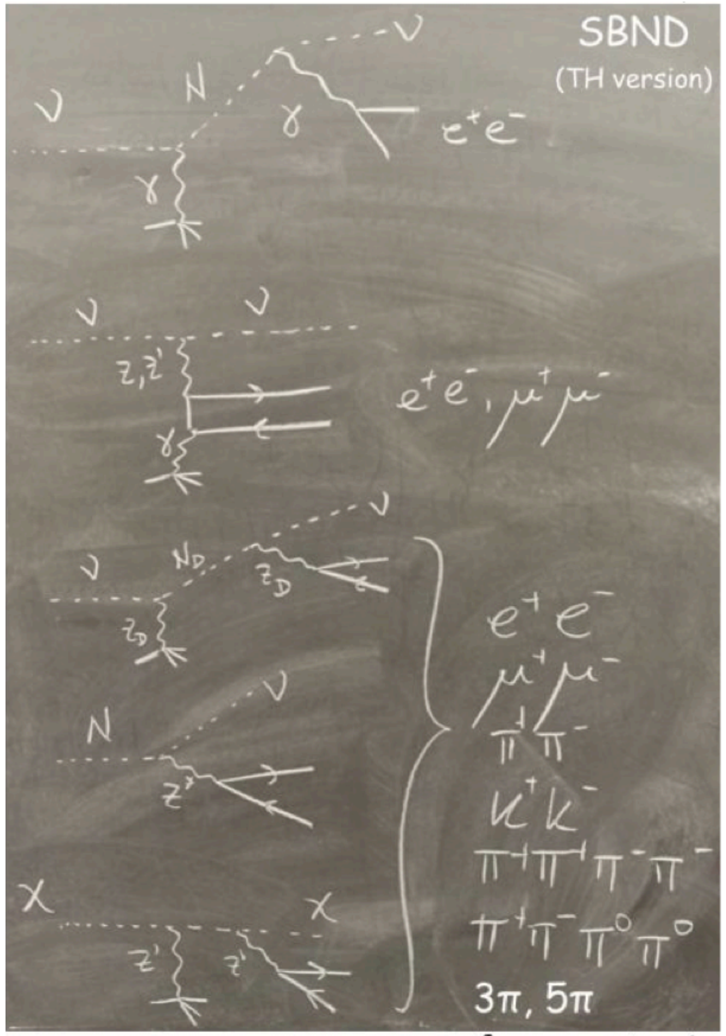




Courtesy of P. Machado

- Large mass LArTPC detectors
  - Event imaging
  - Fine granularity calorimetry and particle identification
  - Good timing resolution
  - Low energy threshold

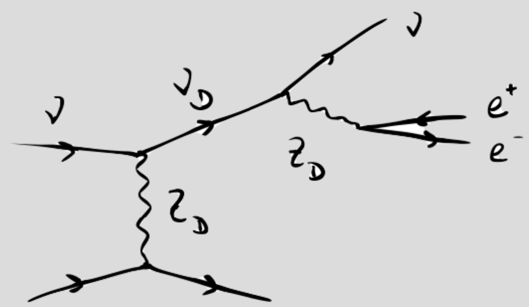
- Unprecedented opportunities to probe signatures for new physics scenarios in the neutrino sector and beyond
- Many ideas for new searches emerging from collaboration with theory colleagues

Beyond the Standard Model Searches at SBND

- Alternative explanations to the MiniBooNE excess and other BSM scenarios.
- Many ideas for new searches emerging from close collaboration with theory colleagues

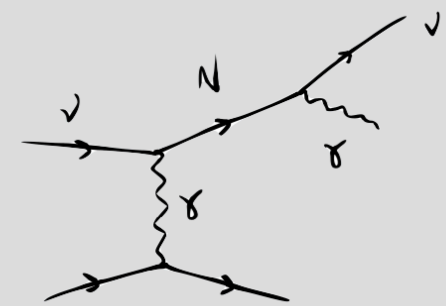
- Collaboration with theory colleagues is crucial for these searches.
- Several models already implemented in our simulation and reco

Dark Neutrinos



Bertuzzo Jana Machado Zukanovich PRL 2018, PLB 2019
Arguelles Hostert Tsai PRL 2019
Ballett Pascoli Ross-Lonergan PRD 2019
Ballett Hostert Pascoli PRD 2020

Transition Magnetic Moment

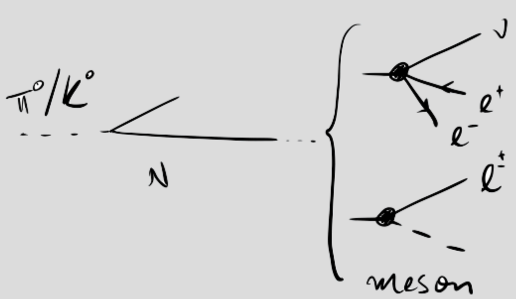


Gninenko PRL 2009
Coloma Machado Soler Shoemaker PRL 2017
Atkinson et al 2021 Vergani et al 2021

Axion-like Particles

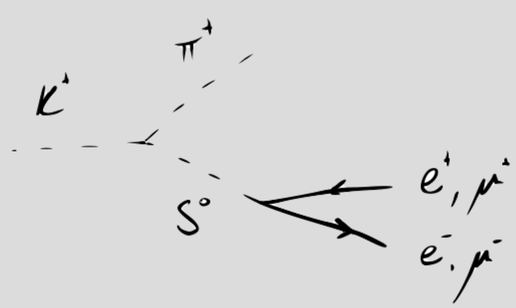
Kelly Kumar Liu PRD 2021
Brdar et al PRL 2021

Heavy Neutral Leptons



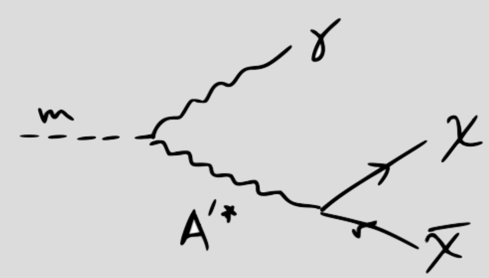
Ballett Pascoli Ross-Lonergan JHEP 2017
Kelly Machado PRD 2021

Higgs Portal Scalar



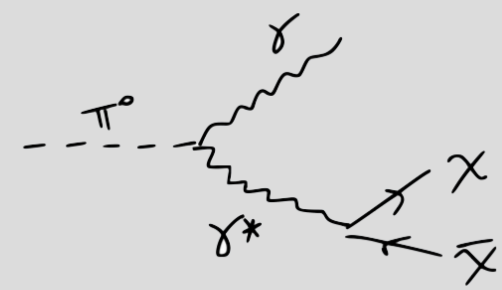
Pat Wilczek 2006
Batell Berger Ismail PRD 2019
MicroBooNE 2021

Light Dark Matter



Romeri Kelly Machado PRD 2019

Millicharged Particles



Magill, Plestid, Pospelov, Tsai, PRL 2019
Harnik Liu Palamara, JHEP 2019

*(*Not an exhaustive list)*

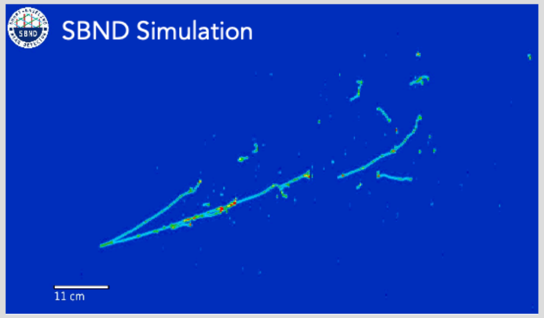
Beyond the Standard Model Searches at SBND

- Alternative explanations to the MiniBooNE excess and other BSM scenarios.
- Many ideas for new searches emerging from close collaboration with theory colleagues

Example signatures and event displays for various BSM scenarios

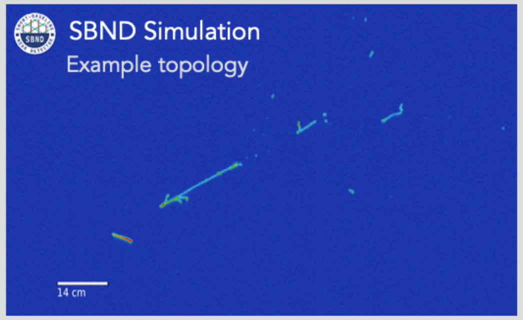
- Collaboration with theory colleagues is crucial for these searches.
- Several models already implemented in our simulation and reco

Dark Neutrinos



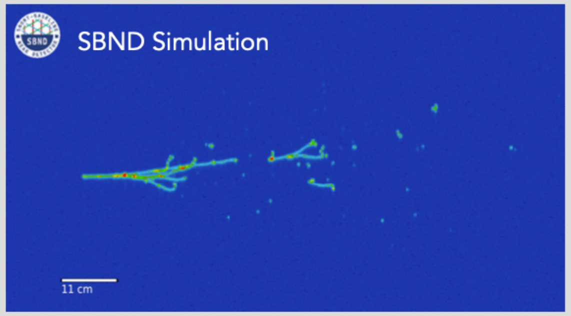
e+e- pair w/ or w/o hadronic activity

Transition Magnetic Moment



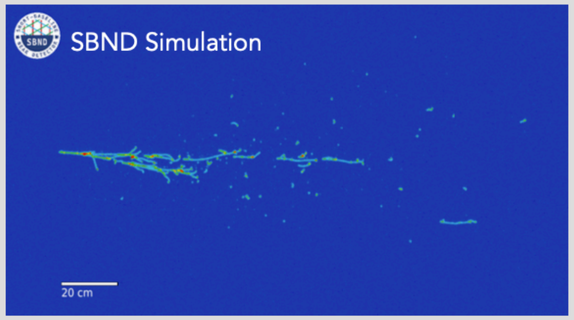
photon shower and hadronic activity

Axion-like Particles



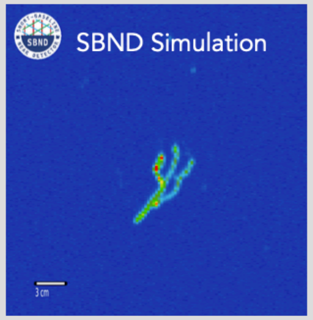
high-energy e^+e^-, $\mu^+\mu^-$

Heavy Neutral Leptons



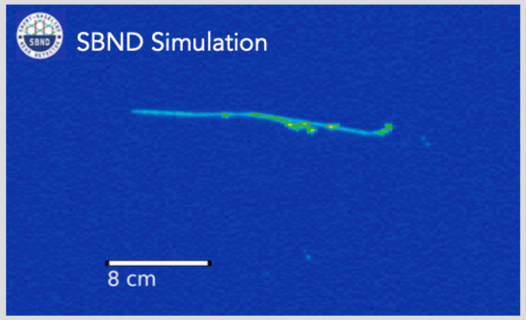
e^+e^-, $\mu^+\mu^-$, $\mu\pi$

Higgs Portal Scalar



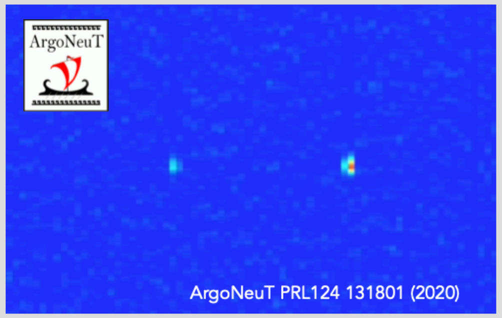
e^+e^-, $\mu^+\mu^-$, no hadronic activity

Light Dark Matter



electron scattering

Millicharged Particles



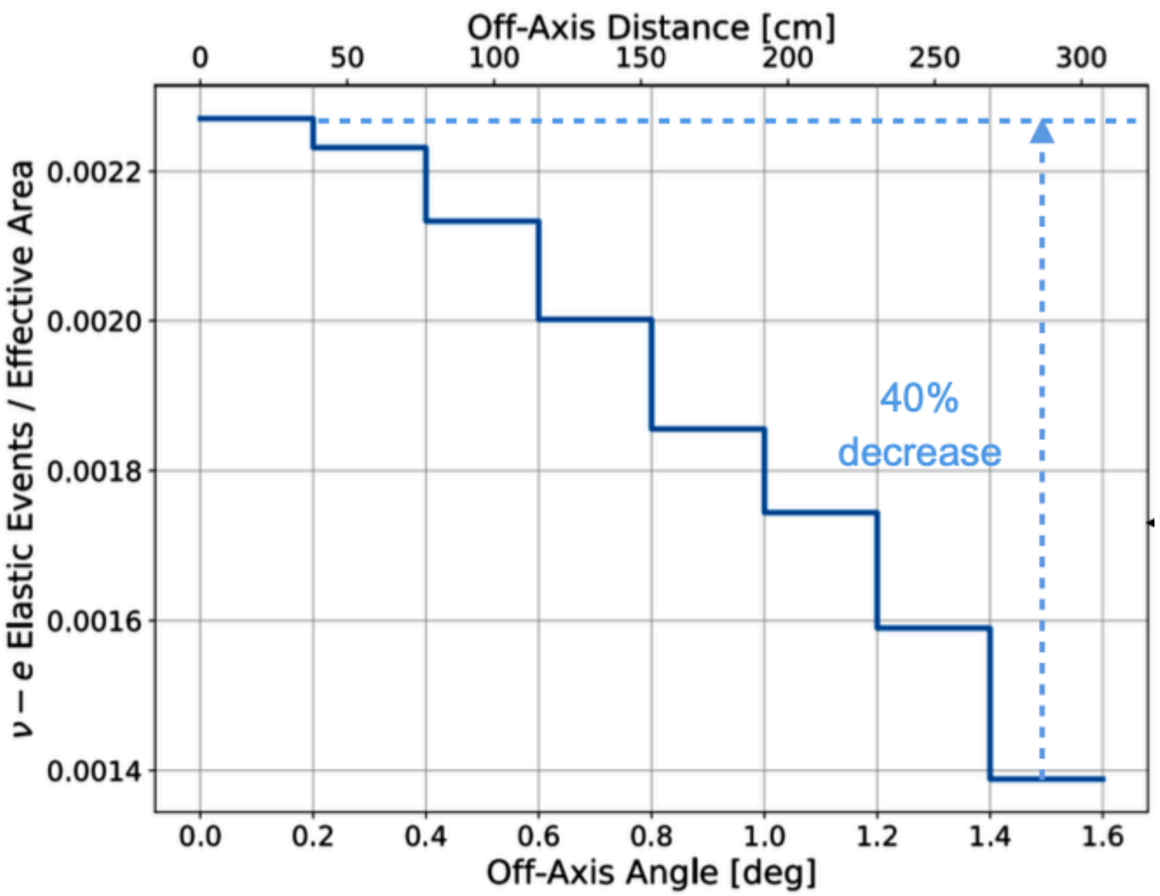
blips/faint tracks

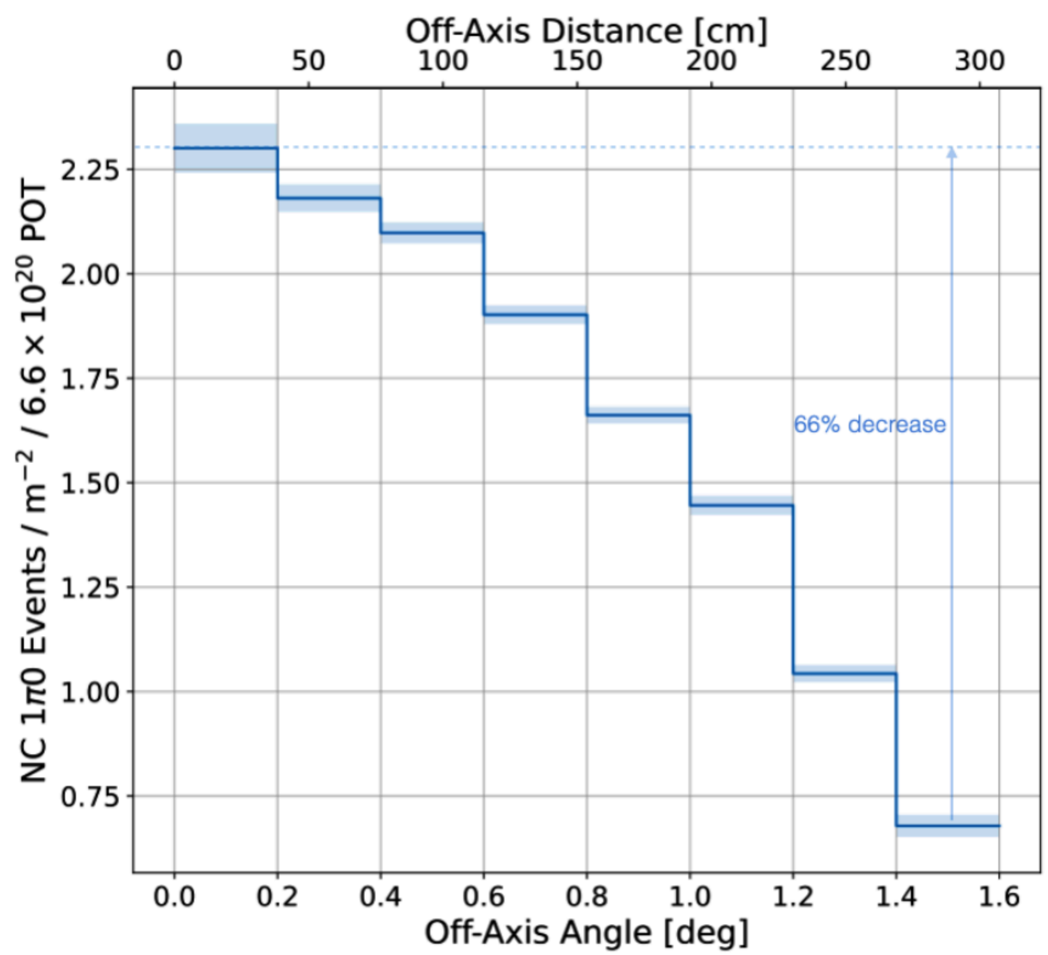
Final state signatures: single photon, single electron, electron-positron pairs, "trident" with di-leptons and different levels of hadronic activity

■ SBND-PRISM provides a natural way to mitigate neutrino induced background

- For the (vector portal, sub-GeV, light) dark matter-electron scattering signal, ν - e elastic scattering is one of the primary background.
- The neutrino induced background decreases as a function of OAA, while the DM induced signal (produced via neutral meson) is isotopic.

- NC π^0 elastic scattering is one of the primary background for many BSM e^+e^- pair signatures.
- Neutrino induced NC π^0 background significantly decreases as a function of OAA. While the BSM signal, if produced via neutral meson, will be isotopic.





Summary

- SBND experiment is wrapping up installation, preparing for commissioning, and is on-track to start operations early in 2024!

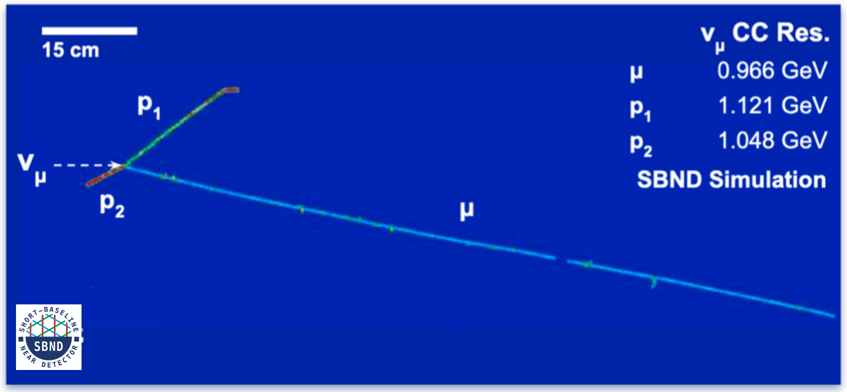
- SBND has a broad science goal as part of SBN program and on its own, addressing alternative explanations of the Short-Baseline anomalies, BSM searches and precision studies of neutrino-argon interactions.

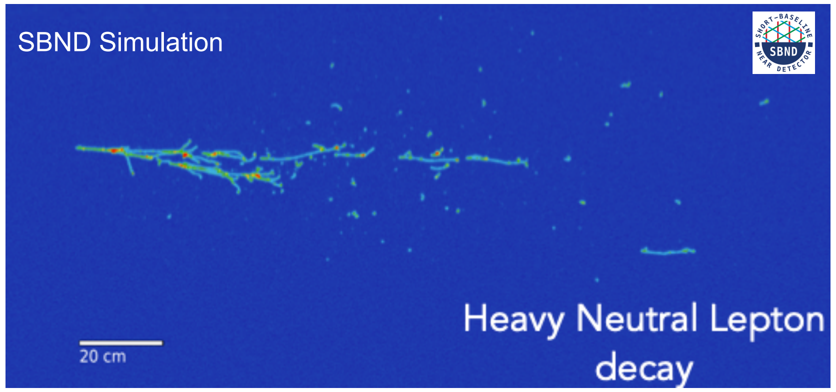
- Neutrino interaction measurements are a key part of SBND's physics program, and will benefit other physics goals of the SBN program and beyond.

- 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.

- SBND data will provide the testbed to assess and validate nuclear models and generator, and hopefully pave the way for precision neutrino-argon scattering physics.

- SBND-PRISM enhances physics potential on SBND.





Thank you!

262 Total Collaborators

210 Scientific Collaborators
(faculty/scientists, postdocs, PhD students)

40 Institutions

5 Brazilian Universities
CERN
1 Spanish University, 1 National Laboratory
1 Swiss University
8 UK Universities, 1 National Laboratory
18 US Universities, 4 National Laboratories

Fermilab