Neutrino interaction physics at SBND

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University of Sheffield, UK

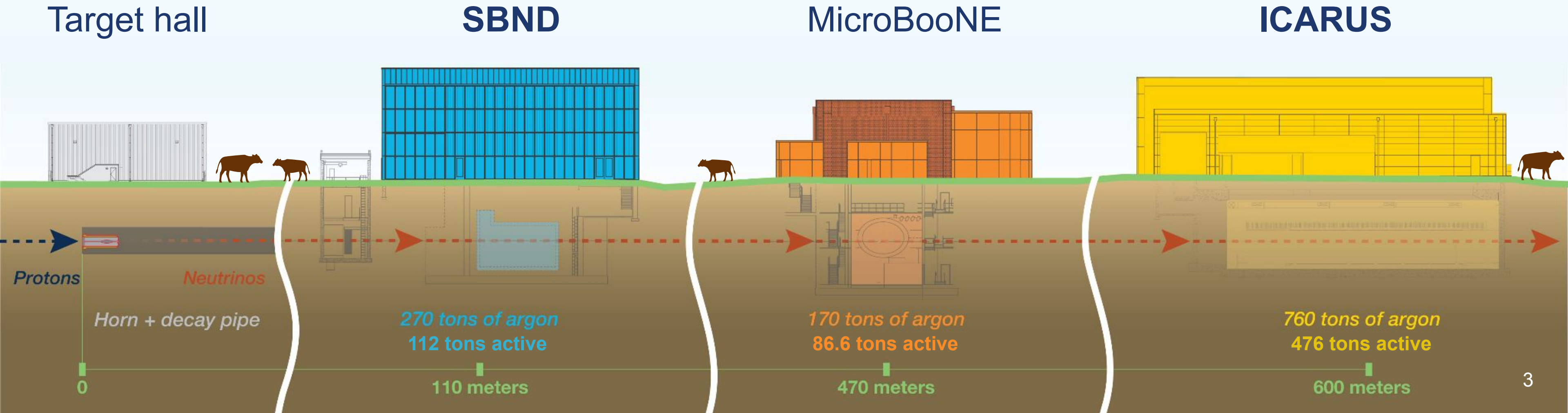
nuSTORM 2023
Exploring the Physics Opportunities of nuSTORM
6th April 2023

Overview

1. Introduction to the Short Baseline Near Detector (SBND) within the Short Baseline Neutrino (SBN) program
2. Key features of the SBND systems
3. SBND status
4. **Neutrino-argon interactions in SBND**
5. Wider SBND physics program

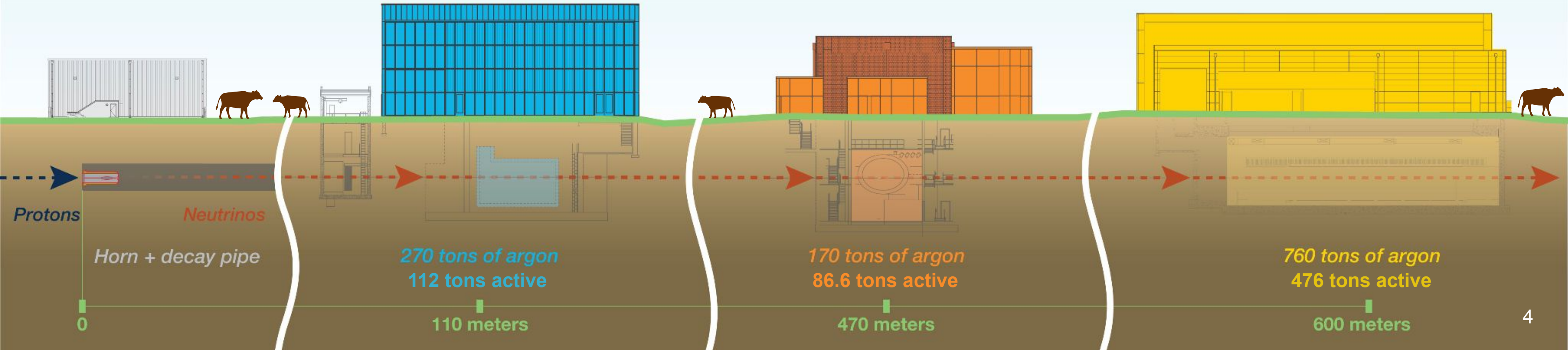

SBND detector systems, September 2022

The Short Baseline Neutrino (SBN) program



The Short Baseline Neutrino (SBN) program

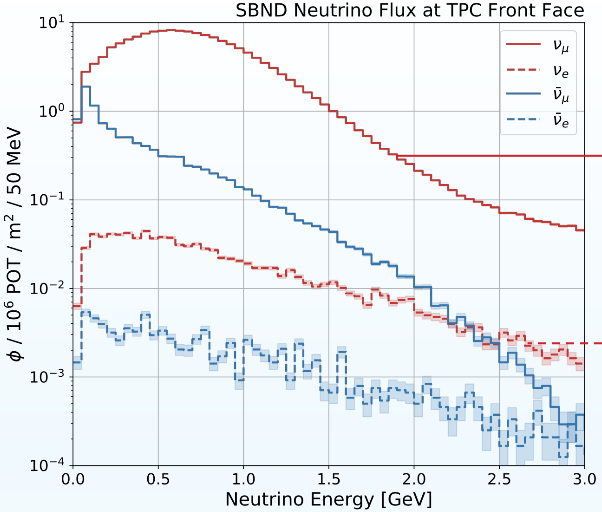
- The SBN program consists of three liquid argon time projection chamber (LArTPC) detectors in the Booster neutrino beamline (BNB) at Fermilab
- Designed to resolve experimental anomalies in the search for sterile neutrinos
- All detectors will make high-precision neutrino-Argon cross-section measurements
- Each detector will give valuable LArTPC operational experience for DUNE



The Booster Neutrino Beam (BNB)

- BNB flux primarily composed of ν_μ **(93.6%)**
  - Intrinsic contributions from $\bar{\nu}_\mu$ (5.9%), ν_e / $\bar{\nu}_e$ (0.5)
- Well known beam, used by MiniBooNE
- Mean ν_μ energy ~0.8 GeV
- Projected to take a total of 10-13 x 10^{20} POT

  ⇒ Huge flux of neutrinos at the near detector
- The ν_μ and ν_e fluxes are primarily produced via two and three-body decays respectively



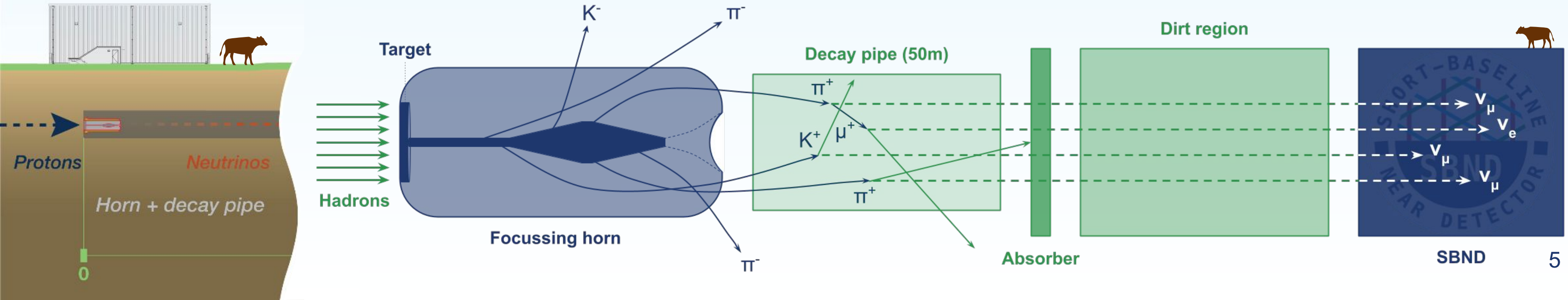
$\pi^+ \rightarrow \nu_\mu + \mu^+$

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

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

$K^+ \rightarrow \nu_e + e^+ + \pi^0$

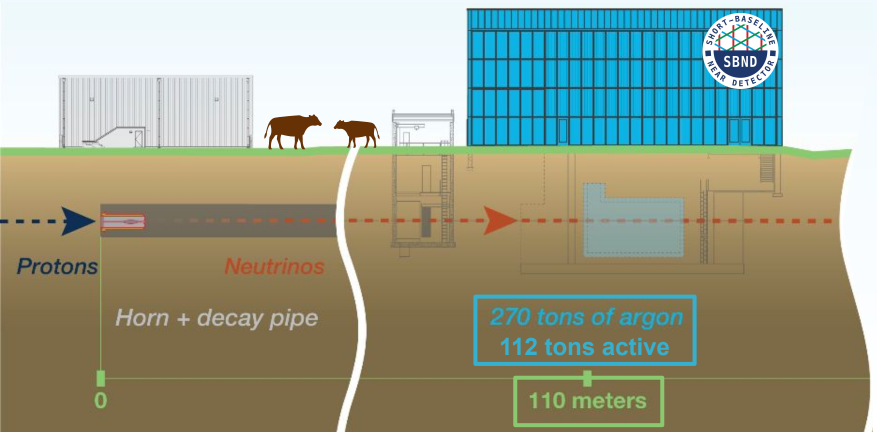
$K^0 \rightarrow \nu_e + e^+ + \pi^-$

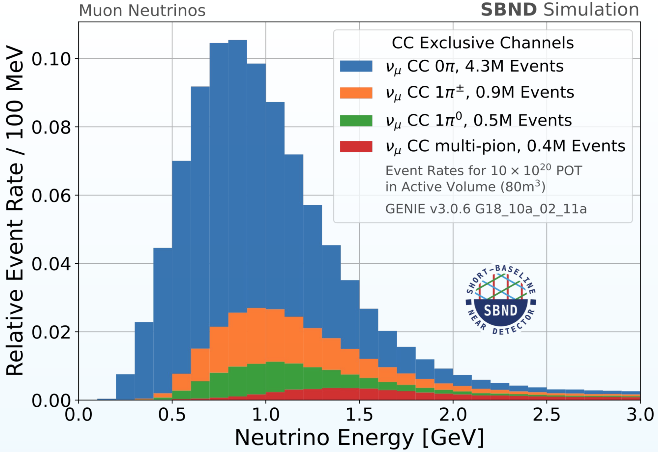


The Short Baseline Near Detector (SBND)

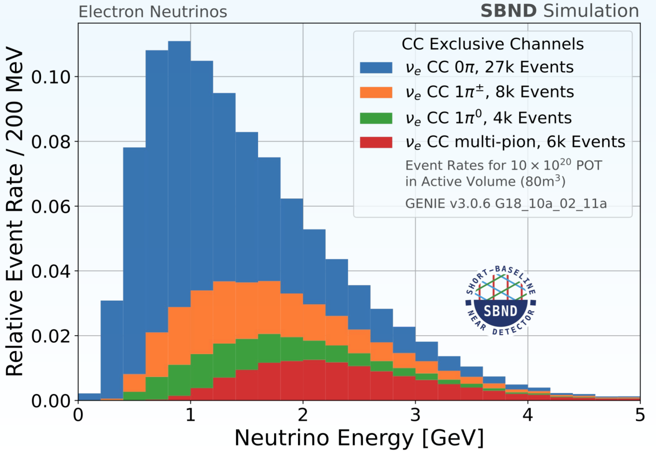
- SBND is the near detector in the SBN program
- 112 tons of argon in its active volume
- 110m away from the target

~2 million neutrinos from the BNB will interact within SBND per year





~6M ν_μ CC



~45k ν_e CC

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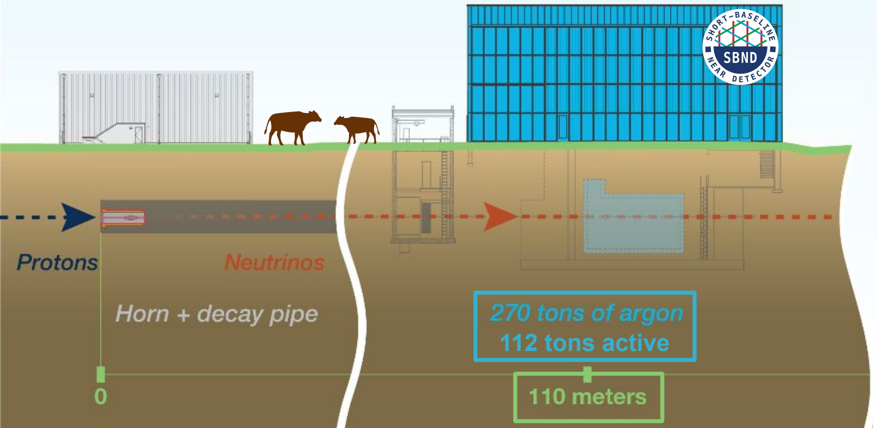
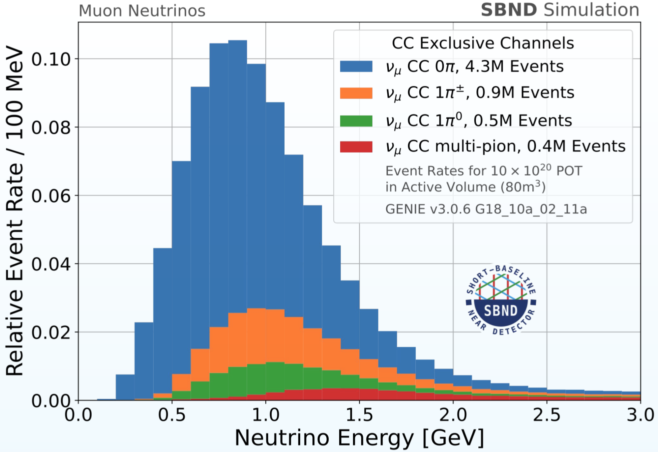
~20 – 30x more neutrino-argon interactions than currently available





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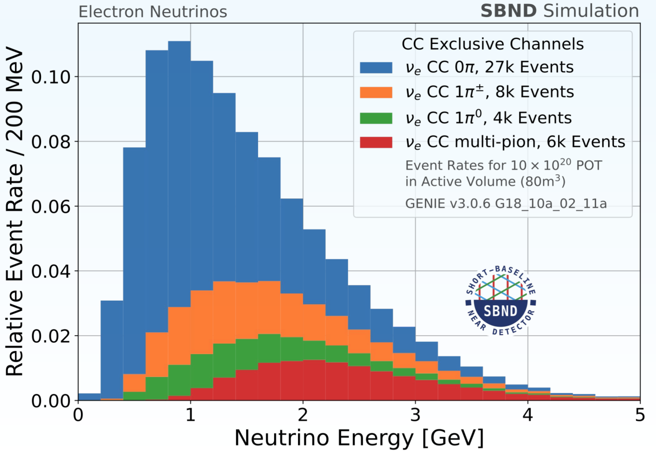
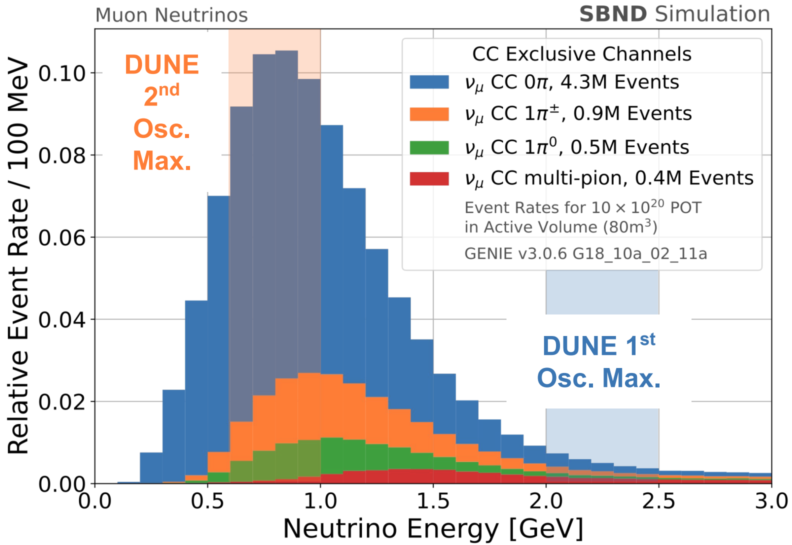
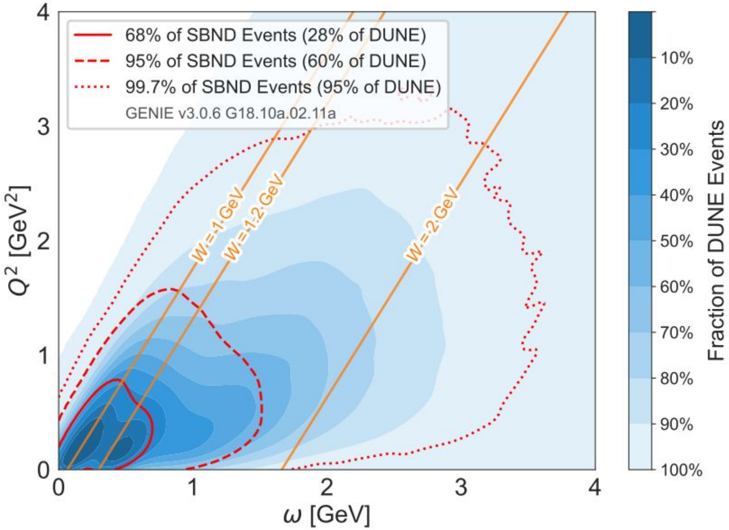


~45k ν_e CC

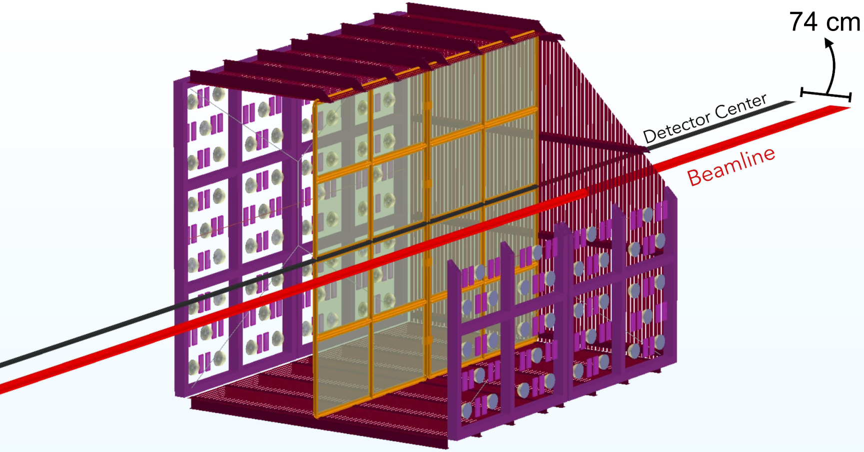
DUNE phase-space coverage

- The kinematics of SBND neutrino interactions will cover significant parts of the DUNE kinematic phase space, including the first and second DUNE oscillation maxima
- SBND neutrino interaction measurements will therefore directly impact the physics output of DUNE through interaction generator and modelling optimisation in key kinematic regions & topologies

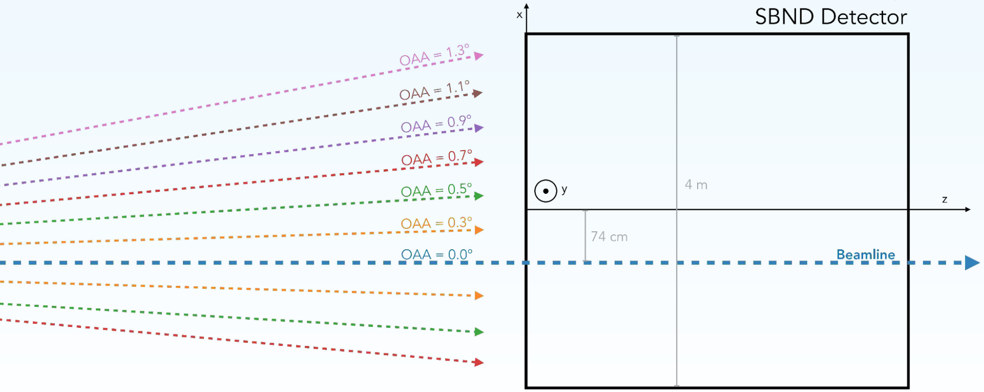




SBND PRISM



- SBND is positioned ~74 cm off the beamline
  - Neutrinos enter the detector from numerous off-axis angles (OAA)



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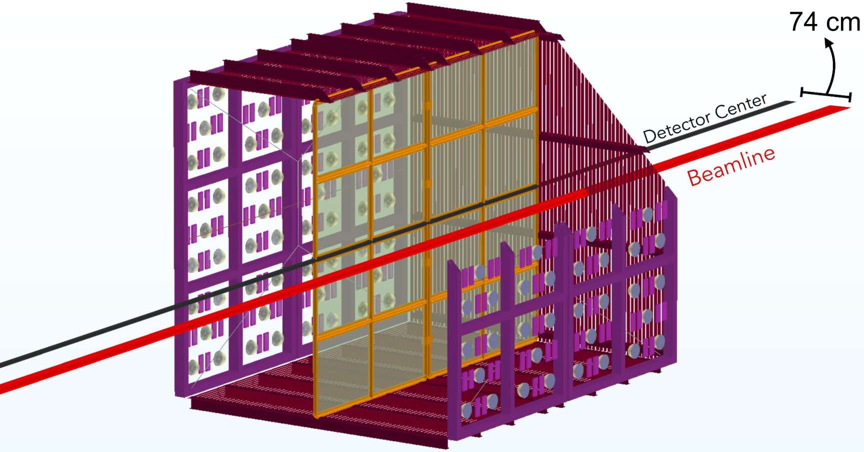

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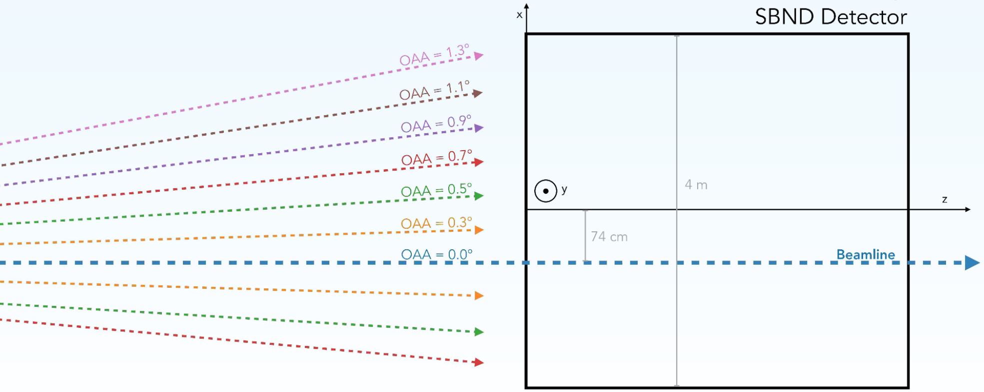
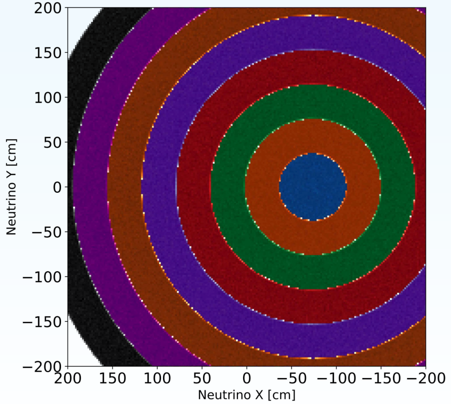
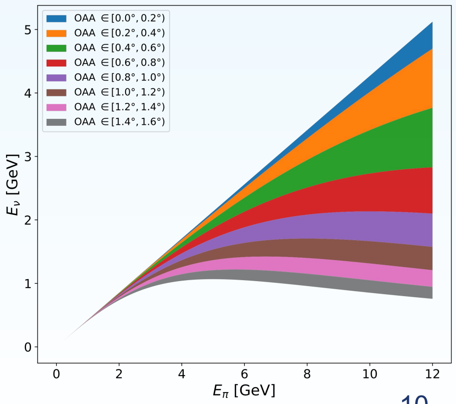
  - Neutrinos enter the detector from numerous off-axis angles (OAA)
- The detector can be separated into OAA segments
  - Each segment will see > 10,000 ν_μ for 10 x10^{20} POT
  - A 1^o OAA corresponds to ≈ 2 m at the front face
  - In DUNE PRISM 1^o ≈ 10 m at the front face



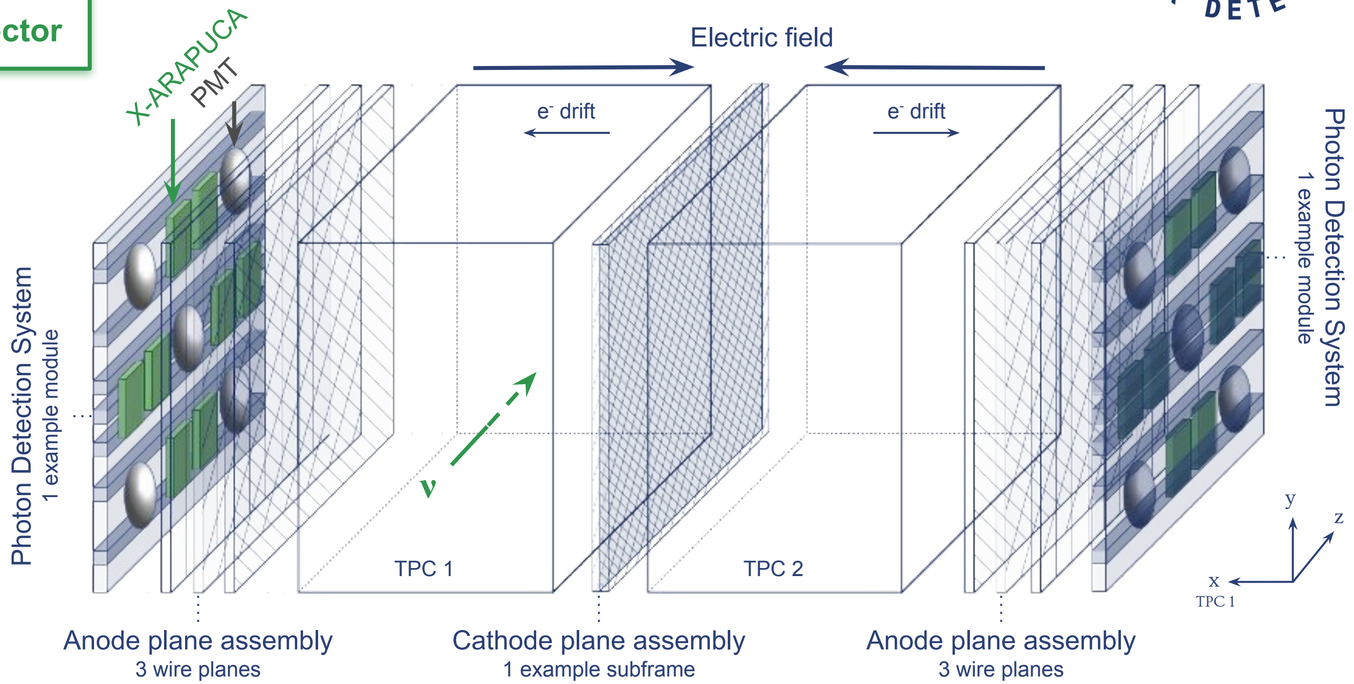




The SBND Detector Systems

Liquid argon time projection chambers

A neutrino from the BNB enters through the front face of the detector



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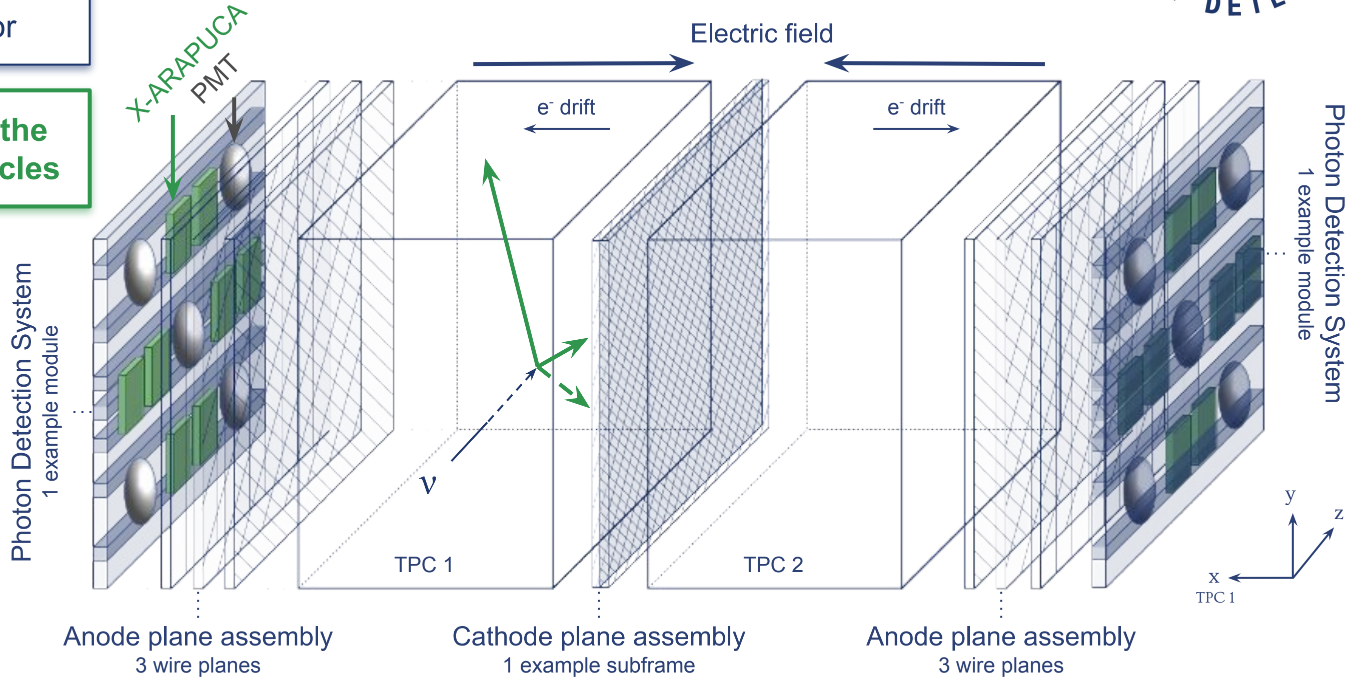

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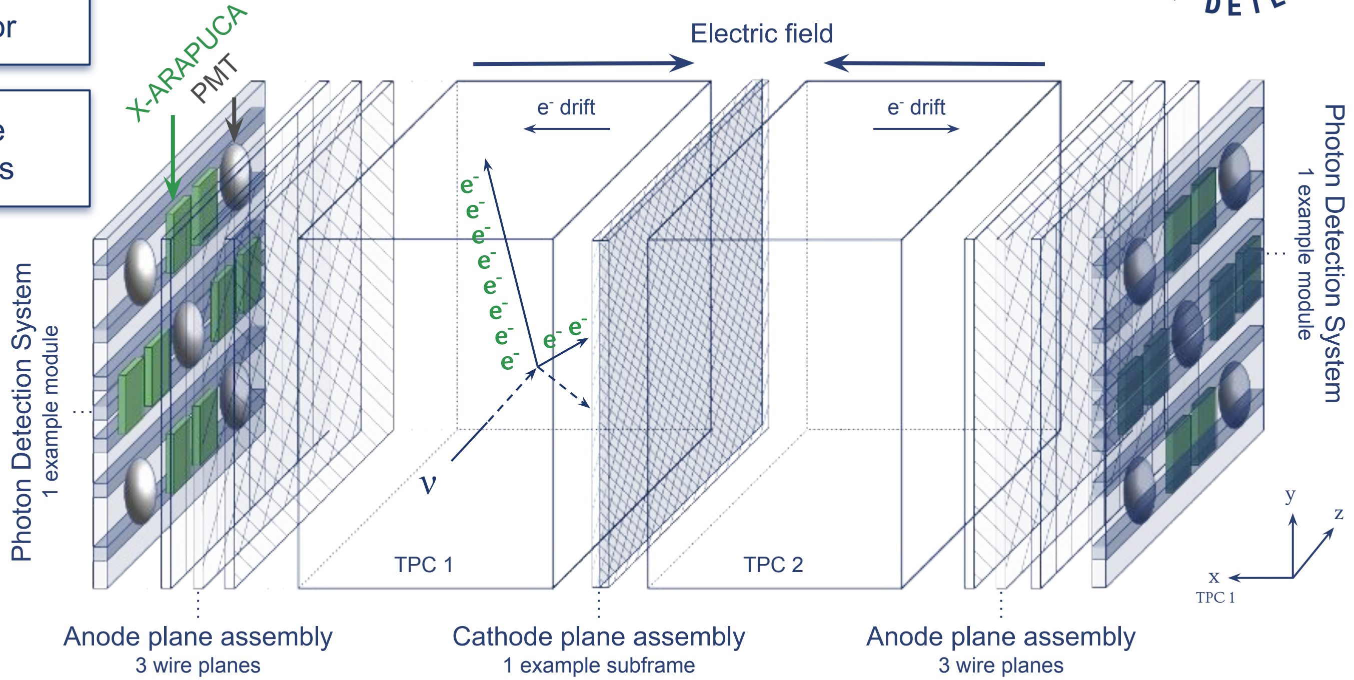

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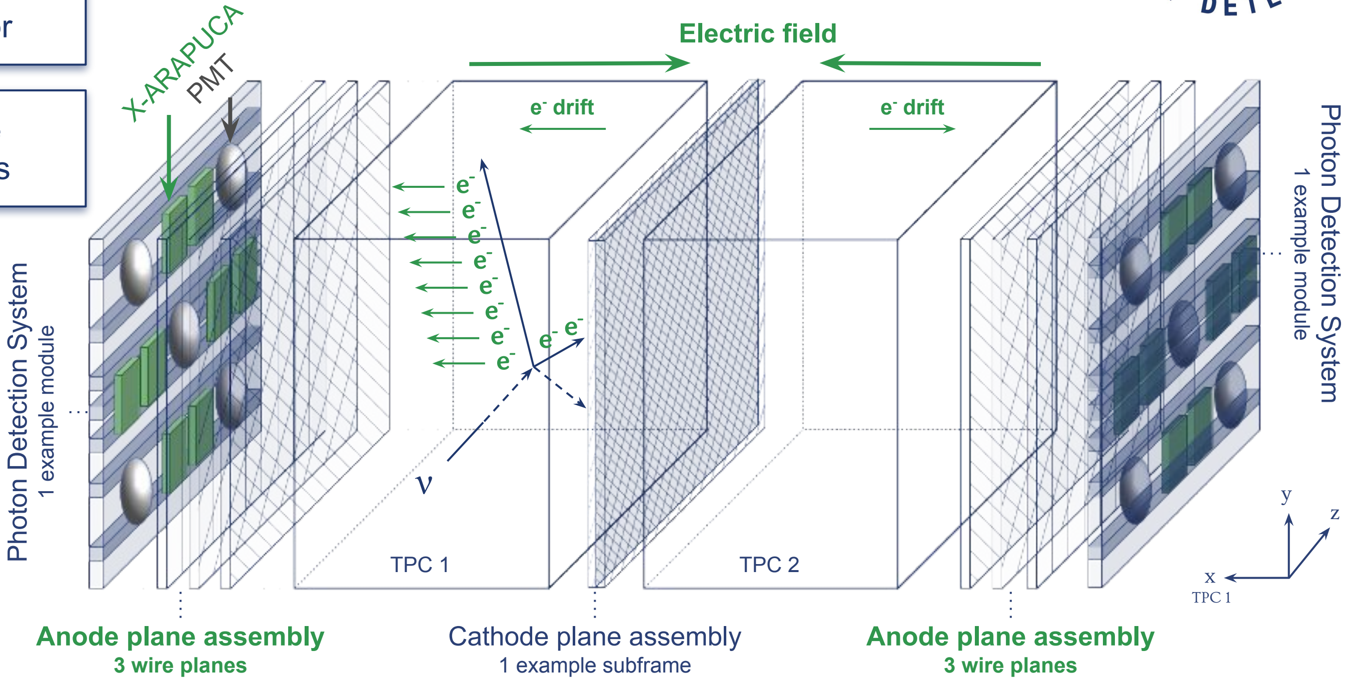

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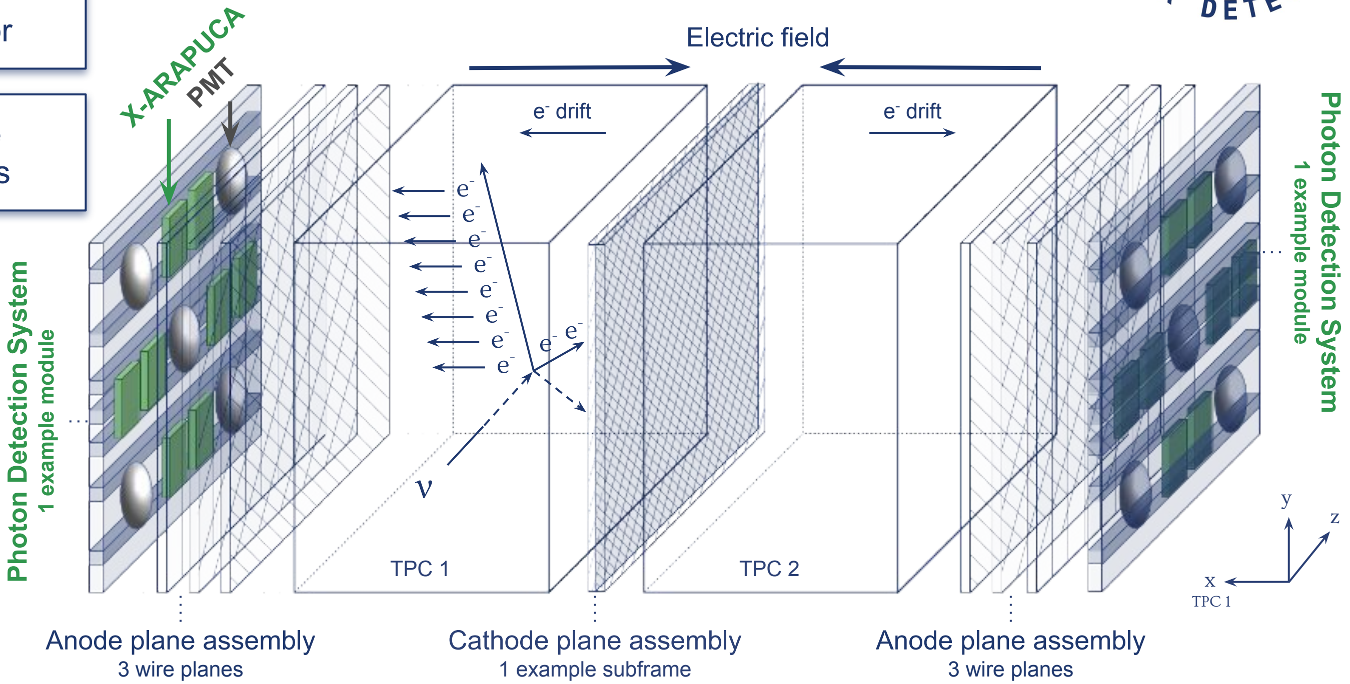

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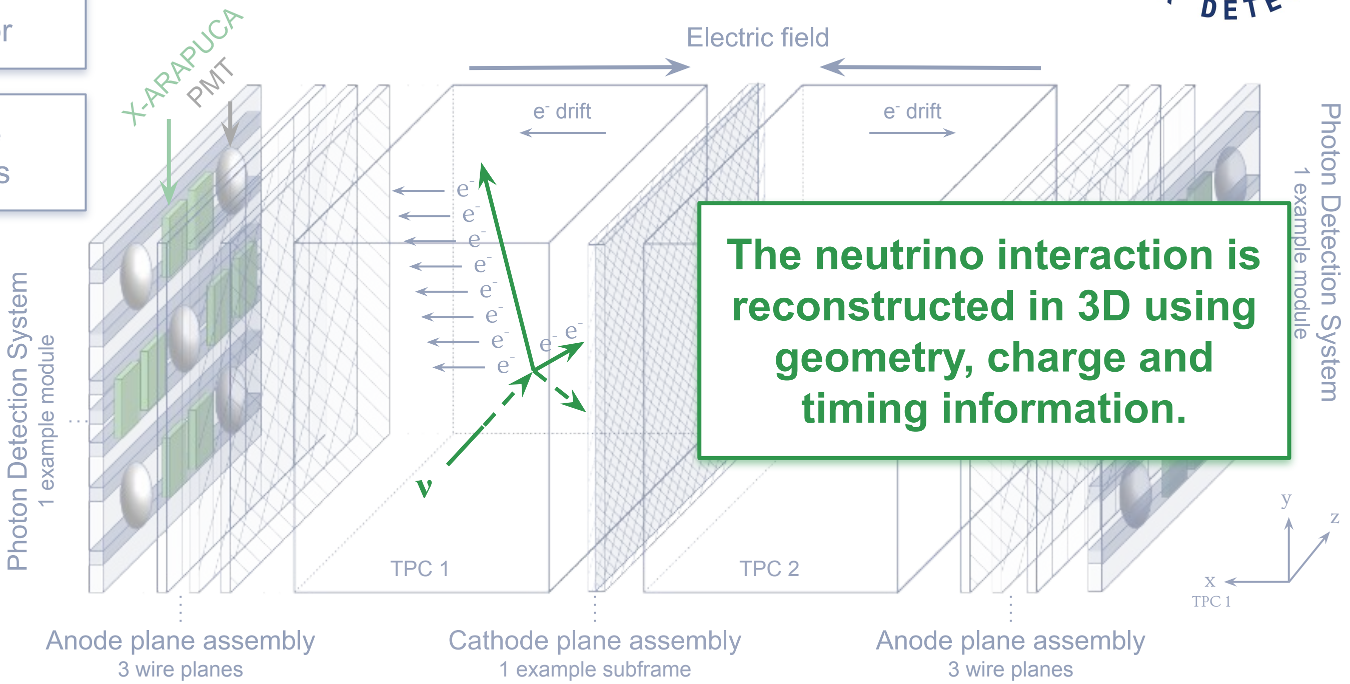
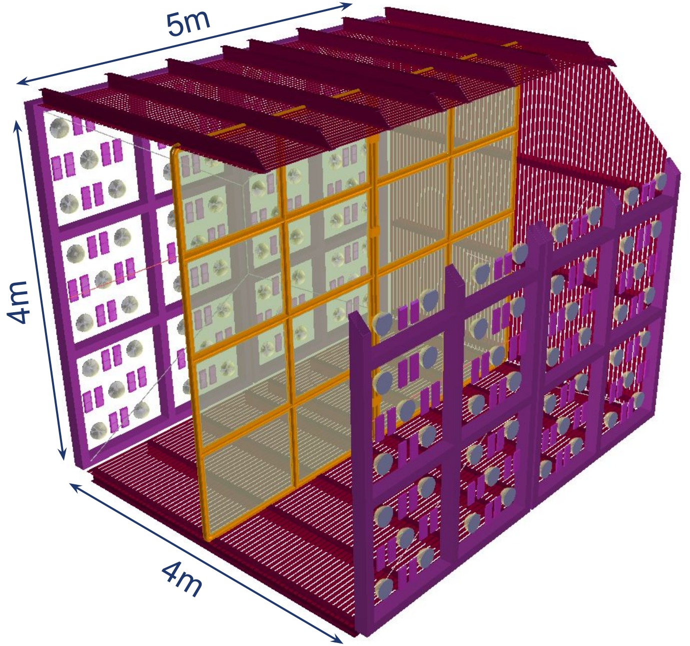


The neutrino interaction is reconstructed in 3D using geometry, charge and timing information.

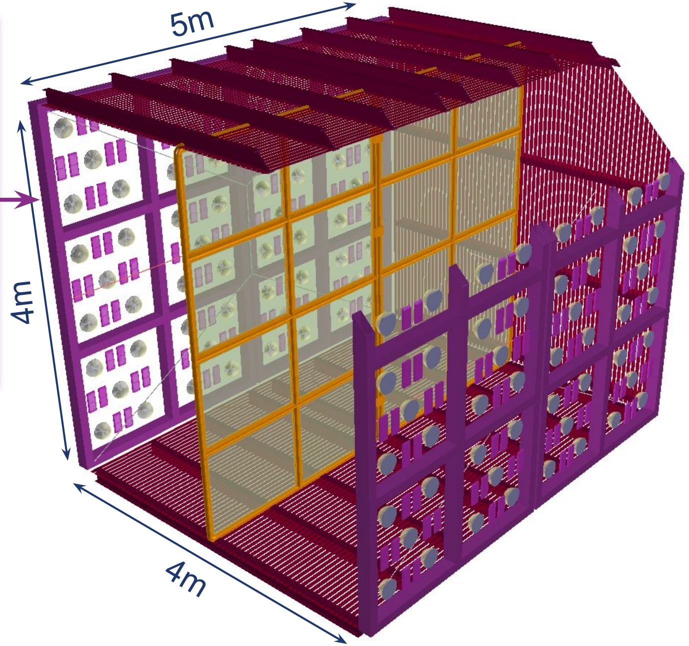
The SBND detector systems: LArTPC & PDS



The SBND detector systems: LArTPC & PDS

Novel photon detection system (**PDS**). Testing components which will be used in **DUNE.**

120 PMTs
192 X-Arapucas



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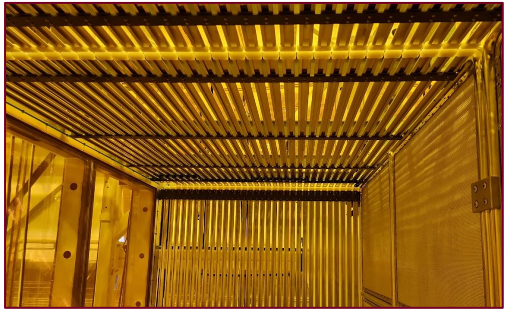

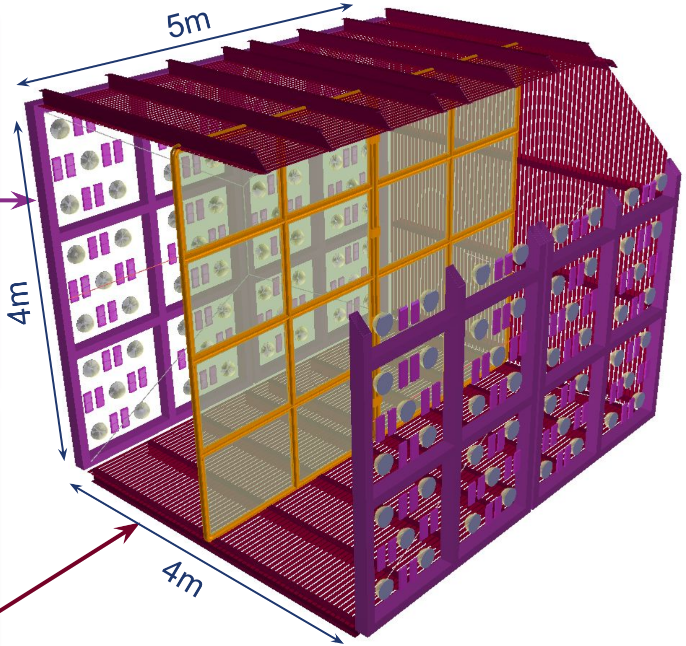

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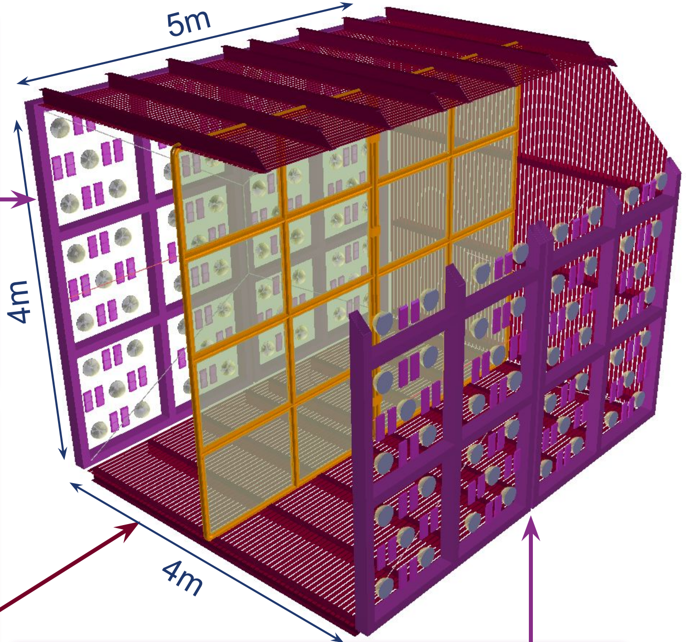

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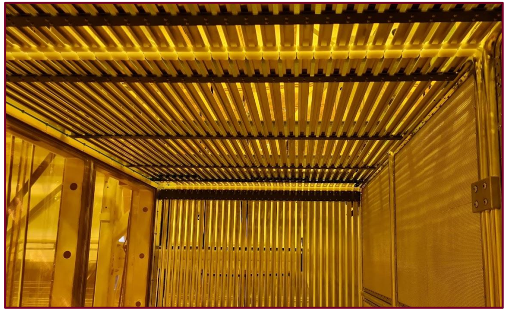

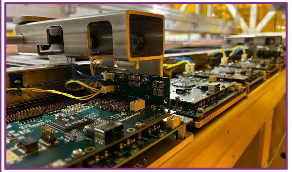

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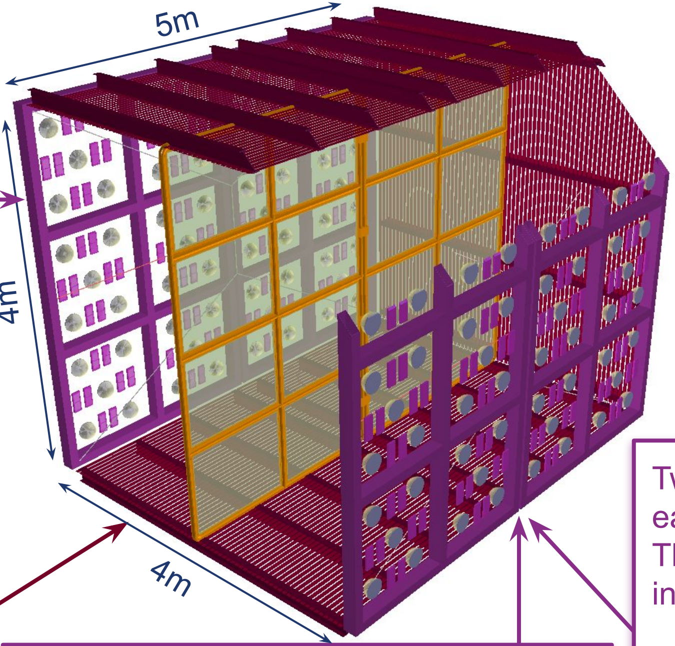

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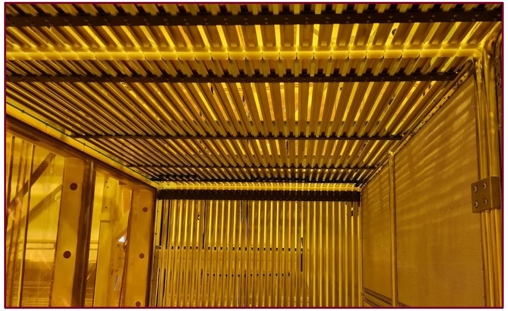

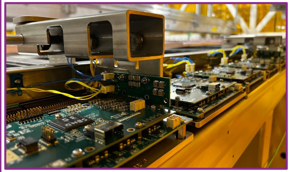

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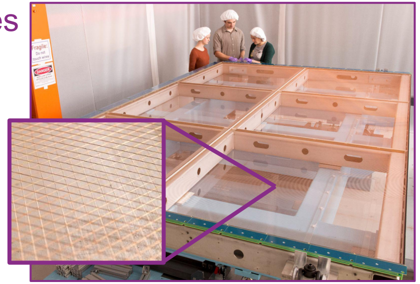
Two anode plane assemblies (**APAs**) on each side of the detector in front of the PDS. Three wire planes in each APA.

Wire θ_Y: **0, ± 60°**

Wire & plane spacing: **3 mm**



JINST 15, P06033 (2020)

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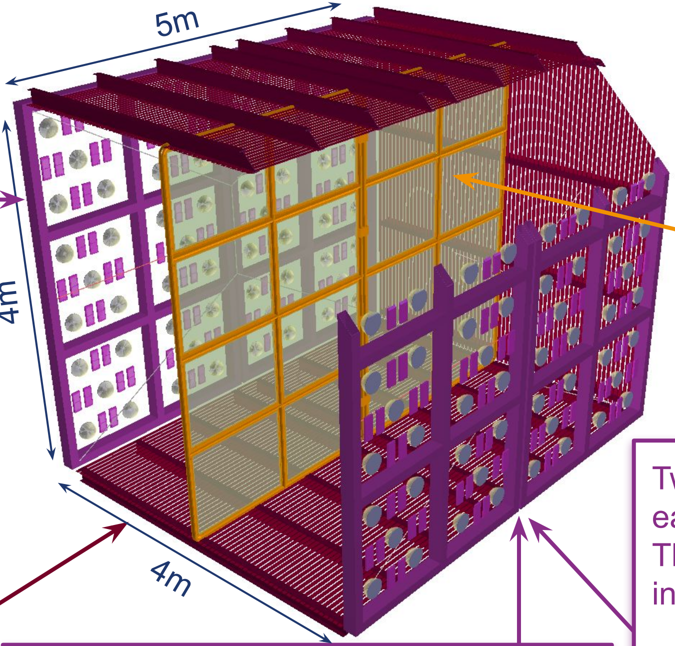
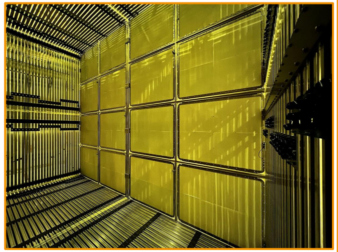


The cathode plane assembly (**CPA**) splits the detector into **two TPCs.**

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



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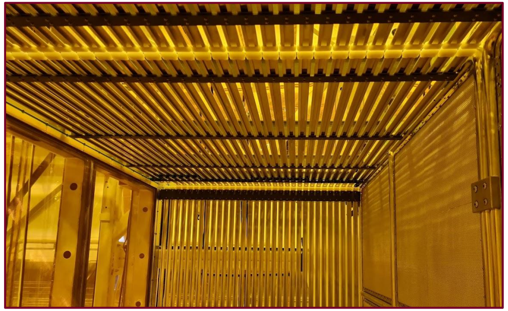

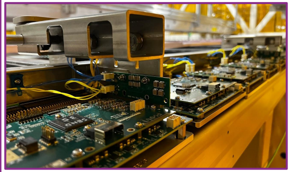

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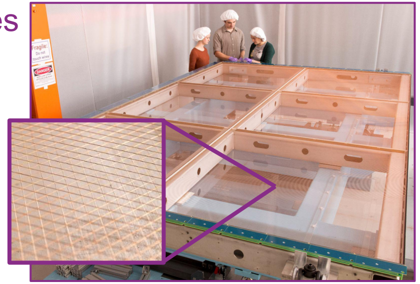
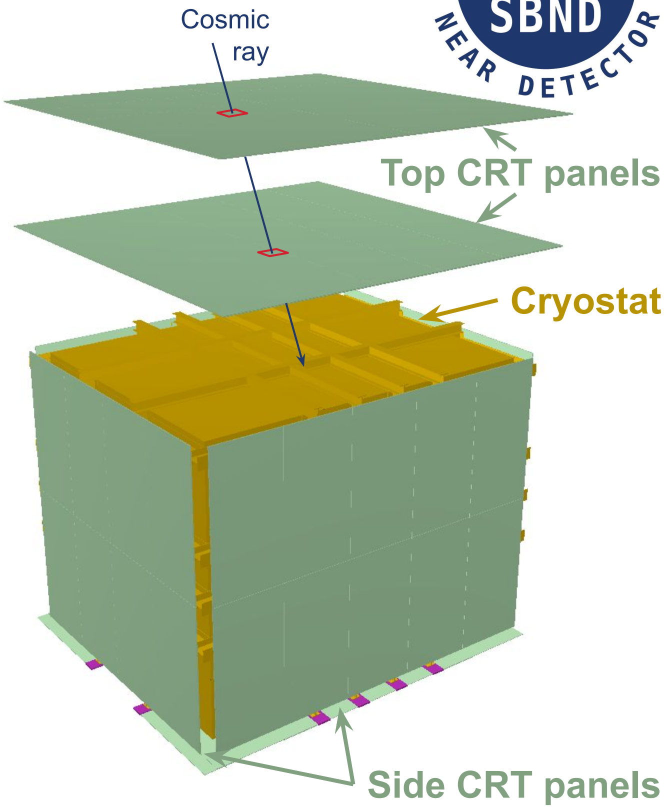
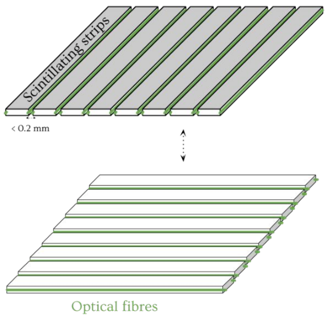


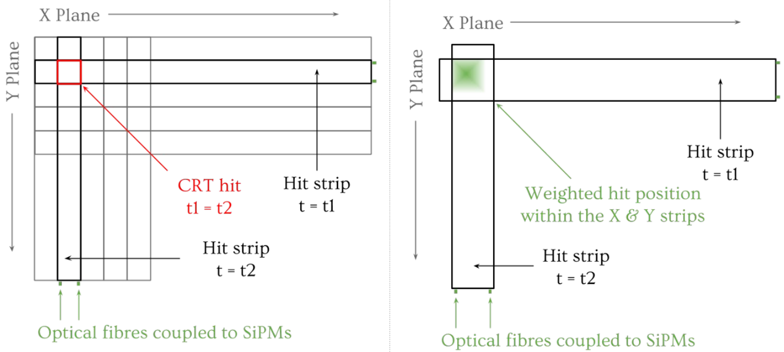
The SBND detector systems: CRT

- The SBND will be entirely surrounded by planes of cosmic ray taggers (**CRTs**)
  - 4π coverage important for surface detectors
  - Two panels on top for telescopic tagging



Each CRT plane comprises panels of scintillator strips in a cross formation for precise hit reconstruction

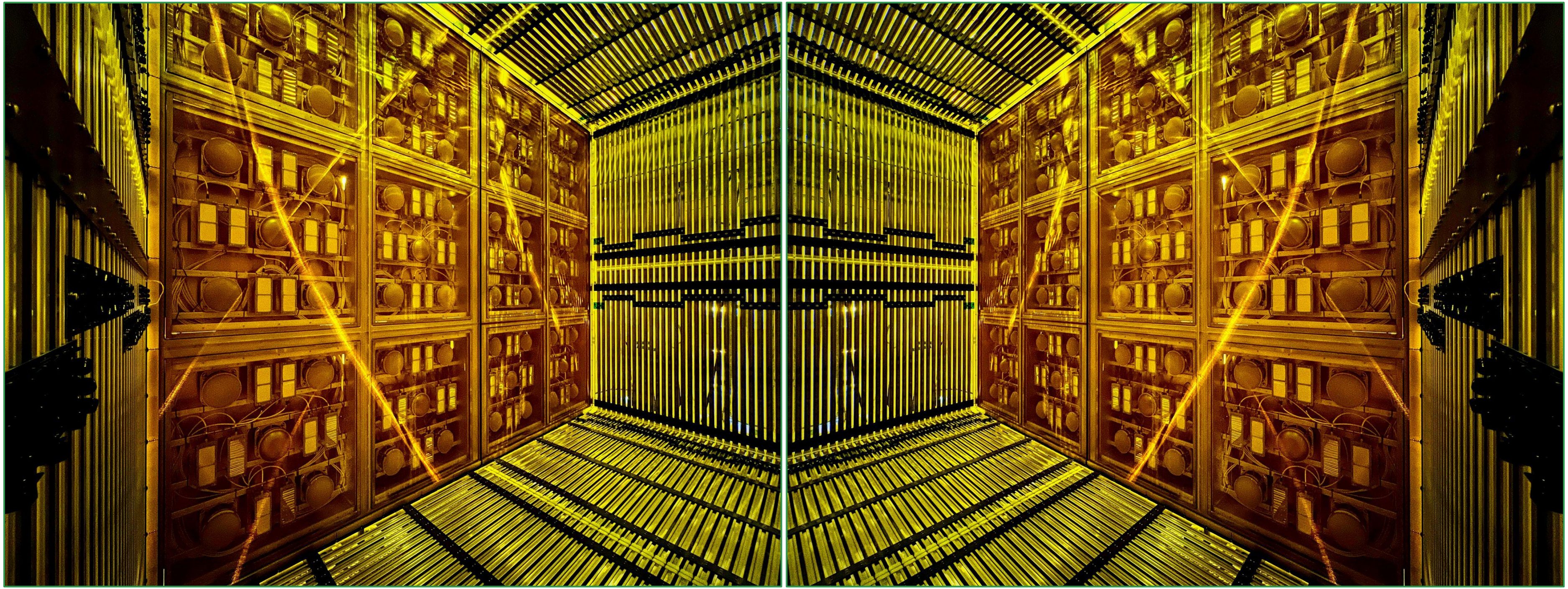




SBND Status

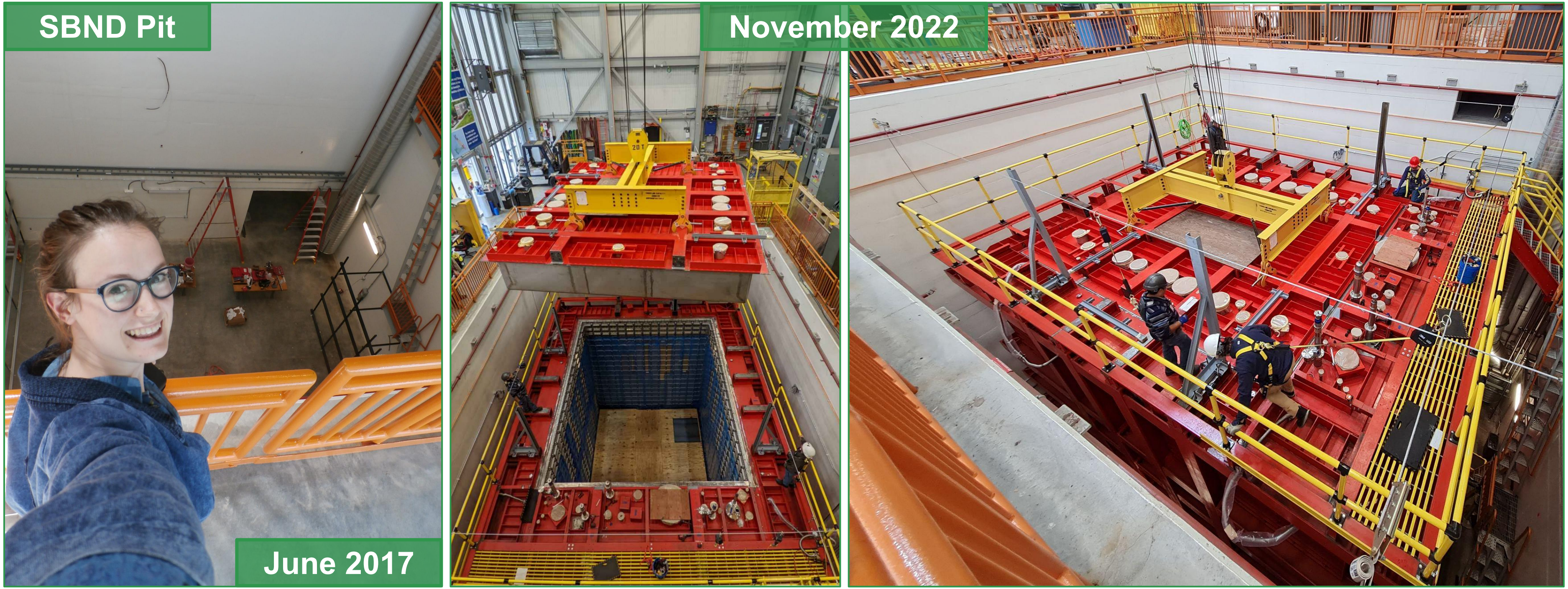
TPC & PDS

September 2022: **Completed the SBND TPC & PDS**



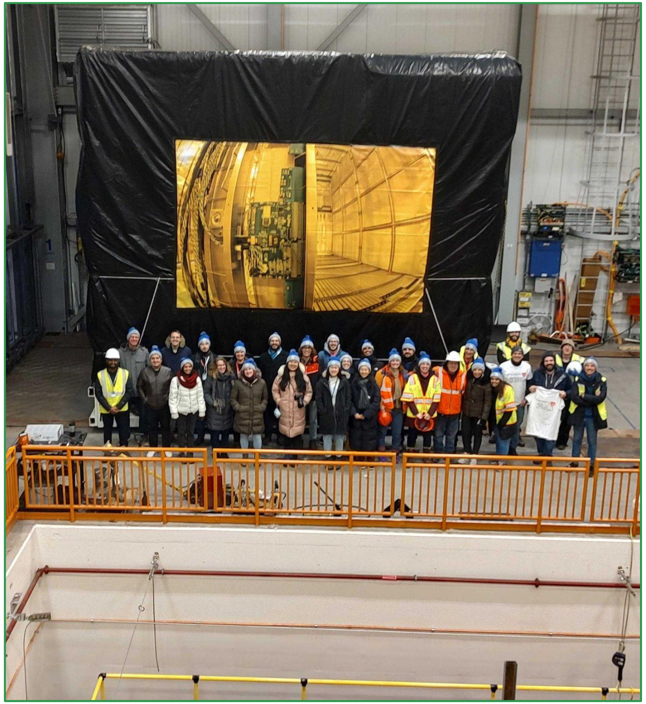
Cryostat

October 2022: **Completed the SBND cryostat**



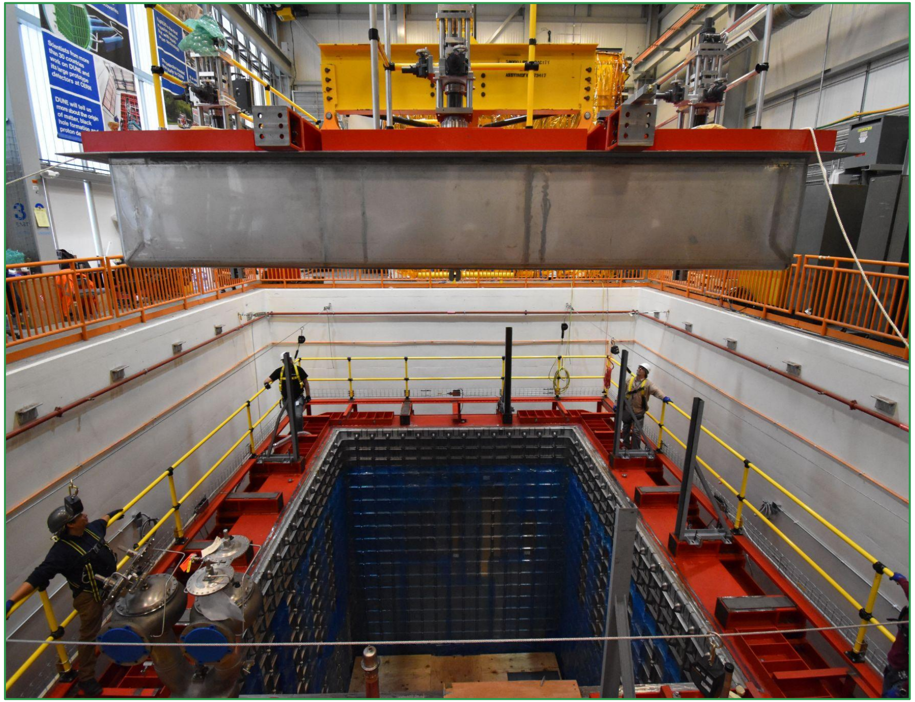
Detector transport

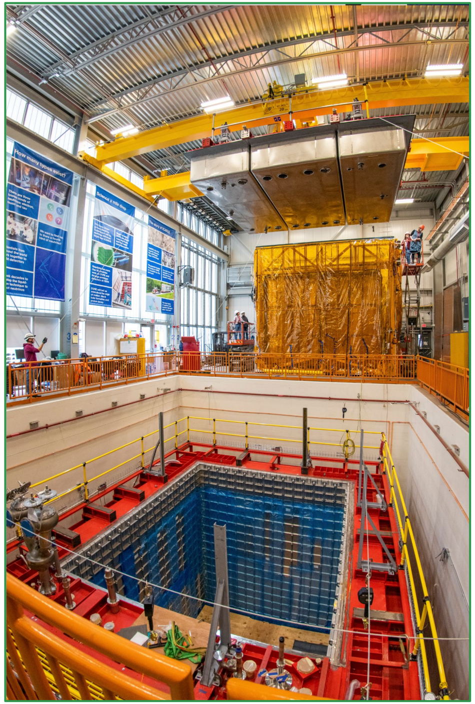
December 2022: **Transported the TPC across Fermilab**



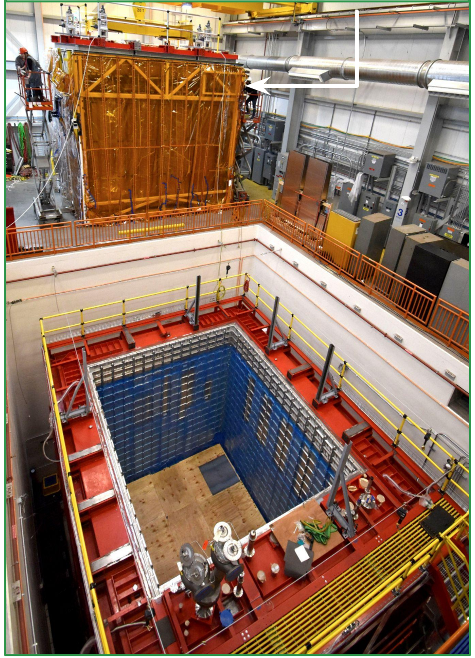
Top-cap installation

March 2023: **Top-cap installed on the ATF***

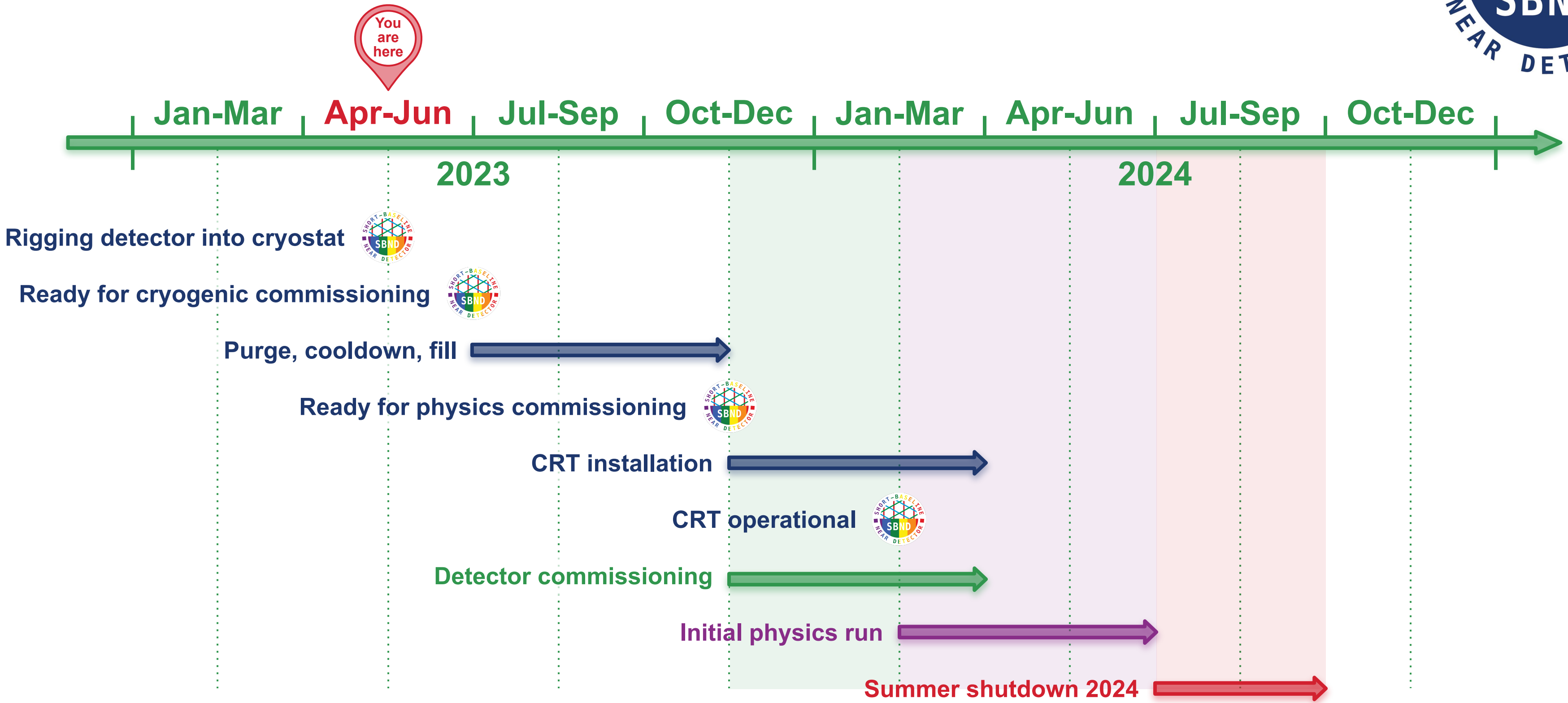




*Assembly & Transport Fixture



SBND timeline



Neutrino interactions in SBND

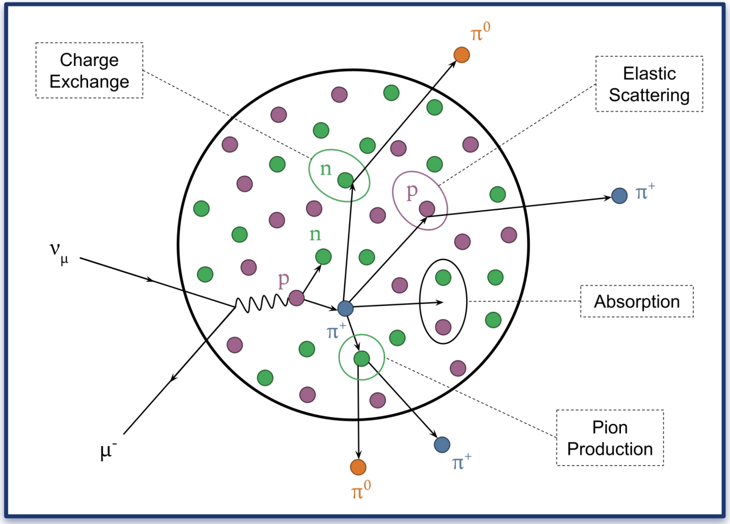
Physics with the near detector

- SBND will provide the largest dataset of neutrino-Argon cross-section measurements in the few-GeV energy range to date

Neutrino interactions on argon

Argon has a **heavy nucleus** (40 p+n) which enables final state interactions (**FSI**) to occur following the initial neutrino interaction

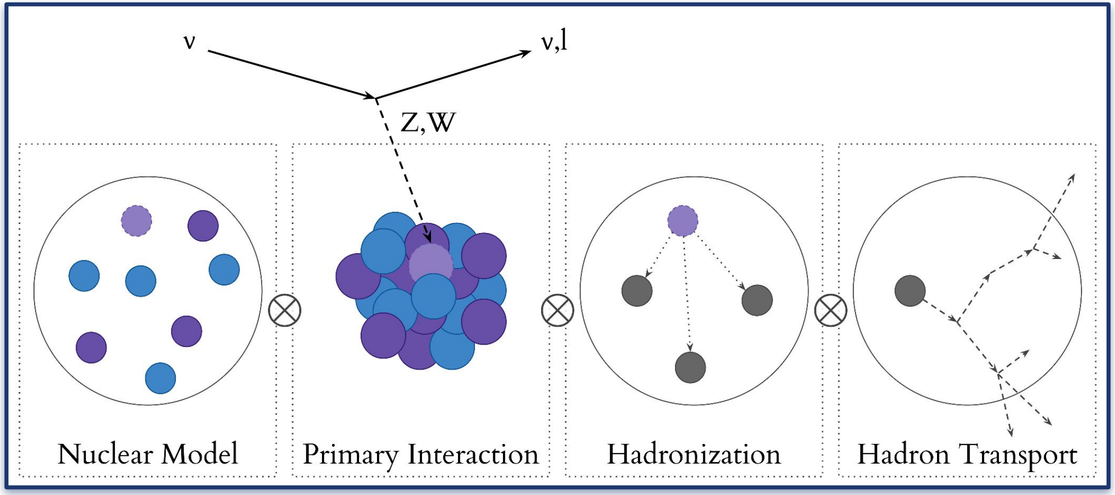
- These FSIs may modify the observed topological and kinematic final state of a given neutrino interaction
- This makes reconstructing the initial neutrino interaction extremely challenging



Neutrino interactions on argon

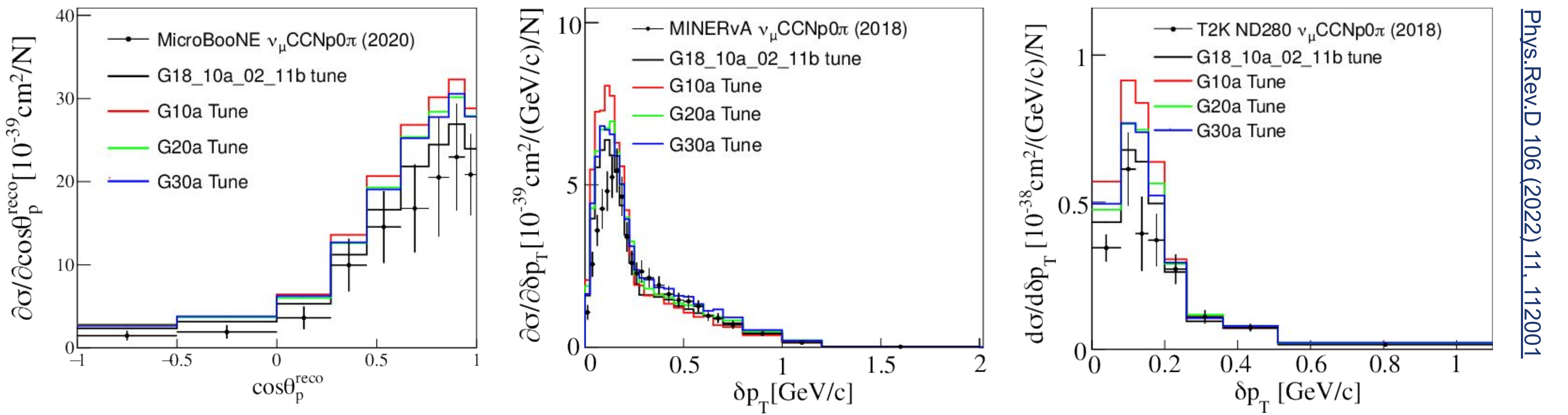
We need to extract as much information as possible about the neutrino and the initial interaction from the observed final states

- Interaction, nuclear, FSI/hadron transport and hadronization models must be well-established and understood to achieve our physics goals



Neutrino interactions on argon

- Comparisons between MicroBooNE (^{40}Ar), MINERvA (^{12}C) and T2K (^{12}C) datasets and multiple GENIE tunes to neutrino-nuclear interaction data demonstrate a single example of the difficulties in modelling heavy-nuclear environments
  - For instance, here there is tension between ν_μ CC 0π data and ν_μ CC 0π **Np** data (N ≥ 1)
- Possible contributions to the tension which are currently under investigation include,
  - Nuclear modelling variations, final state interaction modelling variations, energy or *A*-dependence



Partial tunes of the GENIE G18_10a_02_11b model configuration using MiniBooNE ν_μ CC 0π, T2K ND280 ν_μ CC 0p 0π and MINERvA ν_μ CC 0π data

Neutrino interactions by topology

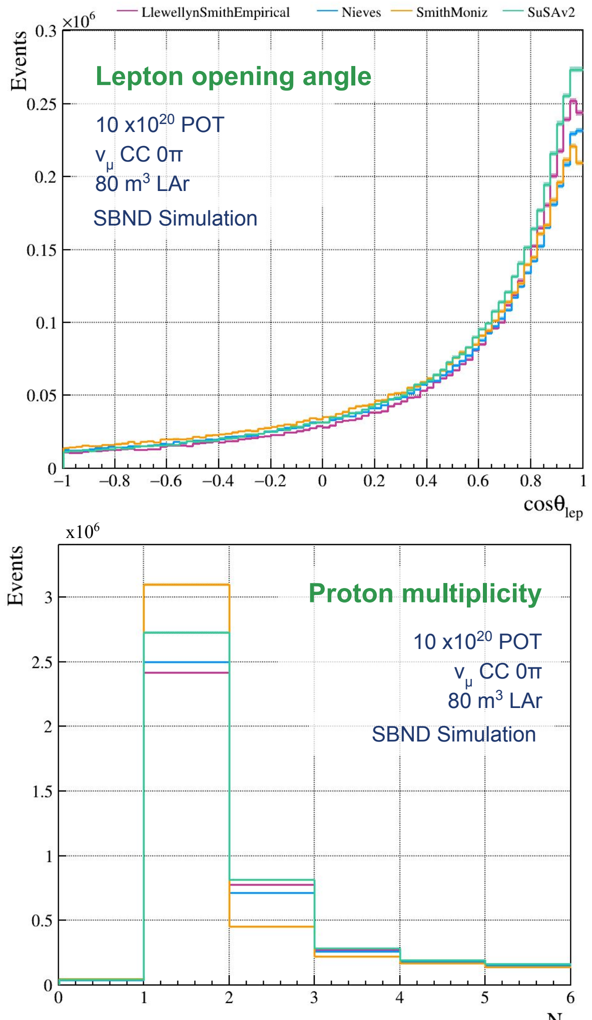
- Statistical significance (< 0.5% statistical uncertainty) in charged current ν_μ channels with high proton and pion multiplicities
- < 5% uncertainty in channels which produce Kaons, hyperons or charmed Sigma/Lambda baryons
- Statistical significance (< 0.5% stat. uncertainty) in all dominant neutral current ν_μ channels
- ν_e statistical significance (< 0.5% stat. uncertainty)

Event rates generated with GENIE v3.0.6 (G18_10a_02_11a) for the full 112 active volume of SBND and a projected 10 $\times 10^{20}$ POT.

Hadronic Final State	G18_10a_02_11a Num. Events	Stat. Err.
ν_μ *Charged Current*		
Inclusive	6,057,919	0.04%
0π + X	4,419,116	0.05%
0π 0p	56,139	0.42%
0π 1p	2,506,924	0.06%
0π 2p	713,315	0.12%
0π 3p	263,577	0.19%
0π > 3p	879,160	0.11%
$1\pi^+$ + X	807,849	0.11%
$1\pi^-$ + X	54,499	0.43%
$1\pi^0$ + X	460,337	0.15%
2π + X	238,034	0.20%
$\geqslant 3\pi$ + X	78,082	0.36%
$> 1\mu$ + X	13	27.74%
$K^\pm, K^0$ (+ X)	11,118	0.95%
$K^+K^-, K^0\bar{K}^0$ (+ X)	1279	2.80%
$\Sigma^\pm, \Sigma^0, \Lambda^0$ (+ X)	6065	1.28%
$\Sigma_c^{++}, \Sigma_c^+, \Lambda_c^+$ (+ X)	1346	2.73%
ν_μ *Neutral Current*		
Inclusive	2,459,237	0.06%
0π	1,686,863	0.08%
$1\pi^\pm$ + X	307,011	0.18%
$\geqslant 2\pi^\pm$ + X	103,279	0.31%
$\geqslant 1\pi^0$ + X	362,083	0.17%
ν_e		
Inclusive	62,258	0.40%

SBND ν interaction modelling

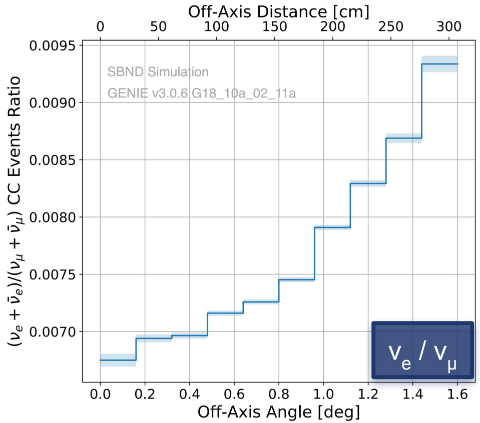
- SBND has the potential for disentangling between neutrino interaction models
  - Utilise high statistics in exclusive final state topologies
- RH plots demonstrate this capability for the expected true ν_μ CC 0π event rate as a function of two observable quantities, lepton opening angle and proton multiplicity
  - Variations of **only** the CC QE & CC 2p2h models
  - No detector effects or reconstruction inefficiencies
  - No systematics considered
- Emphasises the importance of
  - Constraining systematic uncertainties
  - Developing powerful reconstruction tools to minimise efficiency losses and background contamination
- SBND data will be critical for tuning generators for the next generation of LAr physics

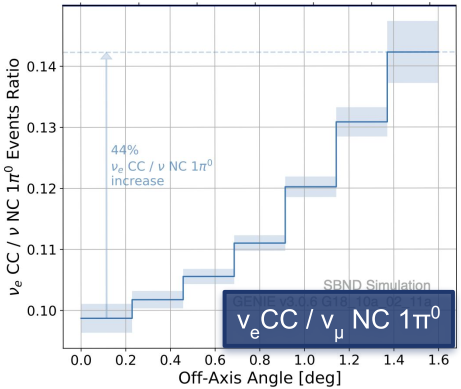


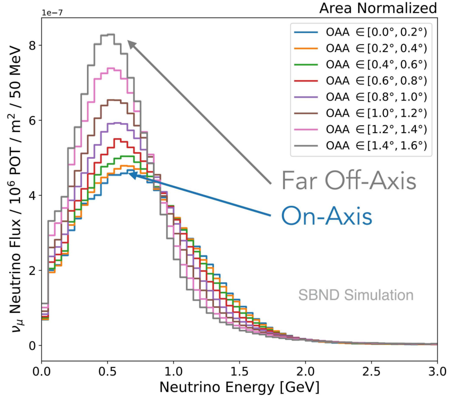
RSJONES FERMILAB-THESIS-2021-40

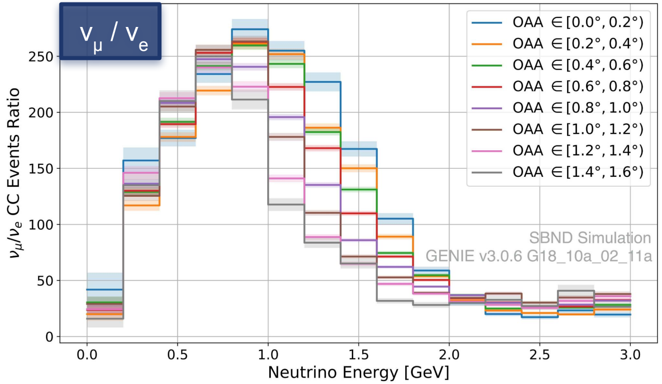
SBND PRISM capabilities

- Due to the difference in production mechanisms, the ν_e flux has a larger angular spread for a given parent energy than ν_μ
- The PRISM concept can exploit this to,
  - Better understand ν_μ & ν_e cross-section differences
  - Reduce ν_μ NC π^0 backgrounds to ν_e interactions
  - Stringent tests of neutrino event generators and theoretical models
  - Improve systematic constraints in oscillation analyses



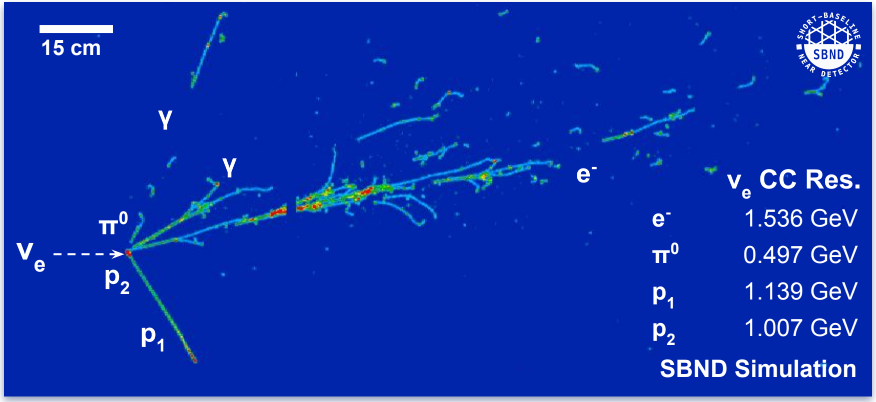


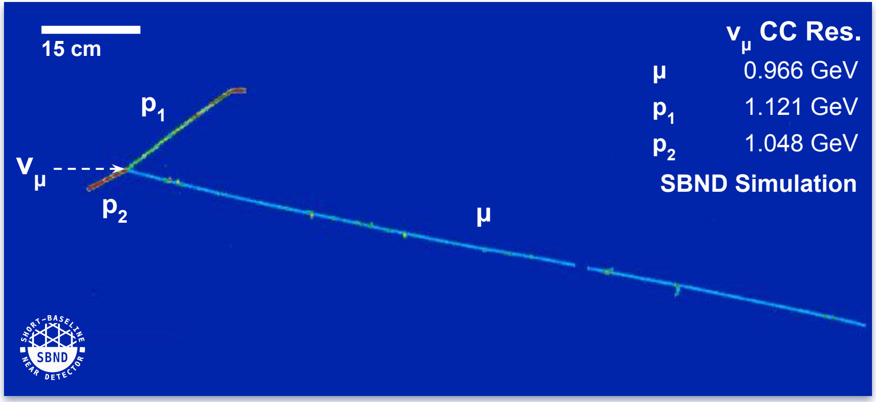




Reconstruction in LArTPCs

Key features of LArTPC neutrino detection





SBND has 3mm wire spacing

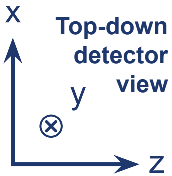
- Images of interaction final states recorded with bubble chamber resolution & detail
- Complex final states can be disentangled
- Isolated energy deposits may be identified down to O(100) keV
  - Opportunities to study MeV-scale activity

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



Top-down detector view

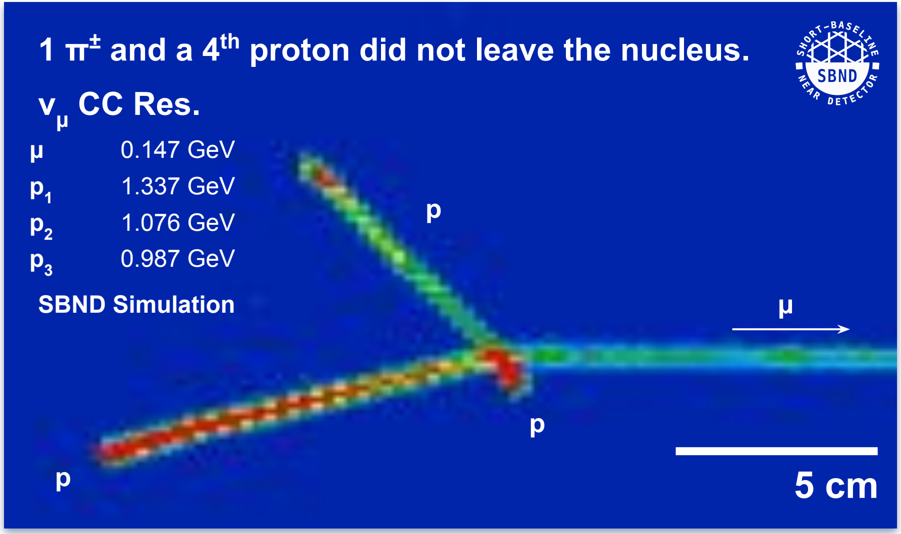
Proton (HIP) reconstruction

A key challenge in reconstructing LArTPC neutrino interactions lies in the proton reconstruction.

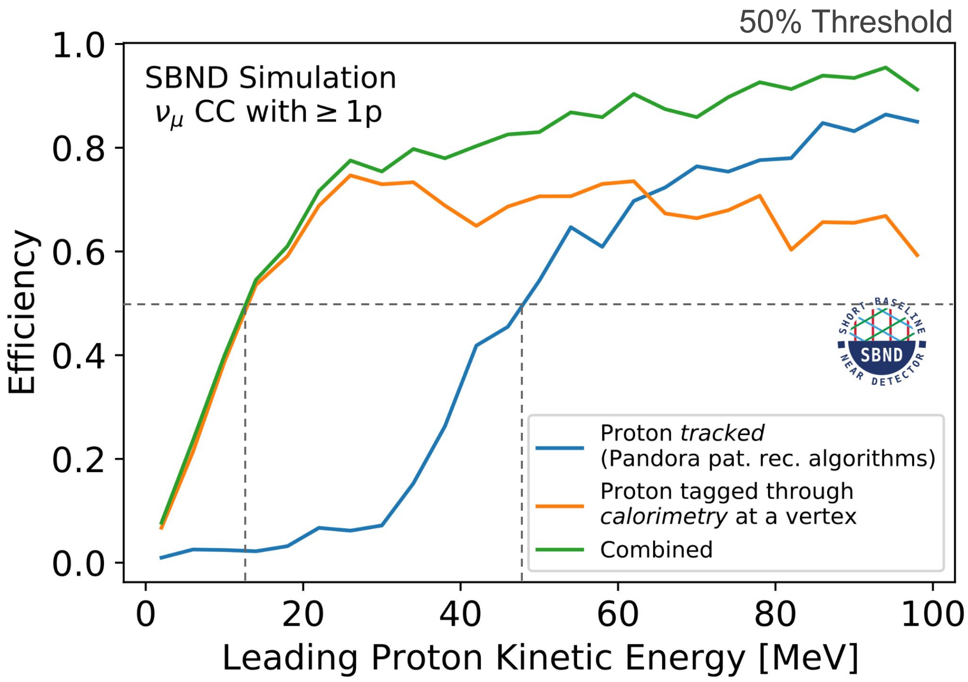
As highly-ionising particles (HIPs), protons quickly deposit large amounts of energy.

Fully and correctly reconstructing visible proton depositions is critical to,

- Neutrino energy reconstruction
  - It is not possible to directly measure neutron energy depositions
  - Some particles may not leave the nucleus
  - ⇒ Some energy is already missing
- Correctly identifying final state topologies
  - Understand the impact of physics & modelling variations on the final state
  - Ultimately, determine how the neutrino interacted



Proton (HIP) reconstruction



- In SBND, 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 pattern recognition: Eur. Phys. J. C 78, 82 (2018)

Current scope

- The capabilities of SBND described so far provide ample opportunities
  - High-statistics searches in high-multiplicity neutrino interaction channels
  - Searches for rare channels with sensitivities beyond what has been possible before
- Channels currently being studied by members of the SBND collaboration:

ν_μ CC Inclusive	ν_e CC Inclusive
ν_μ CC Np 0π	NC Np 0π
ν_μ CC Np $1\pi^\pm$	NC Np $1\pi^0$
ν_μ CC Np $1\pi^0$	
ν_μ CC hyperon prod. (Λ^0, Σ^0, Σ^-)	NC Np 1γ
ν_μ CC kaon production	ν-e elastic scattering

More to come!

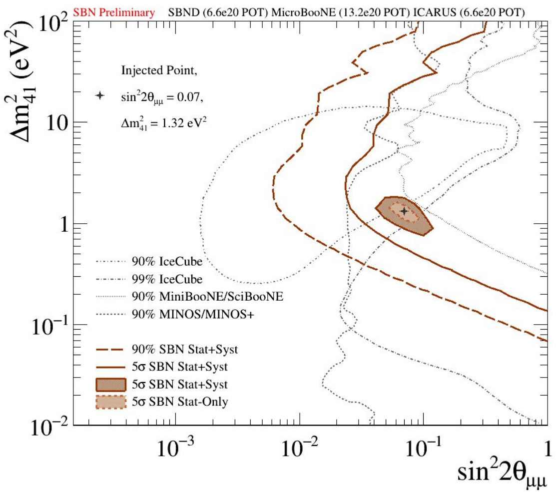
SBND physics program

Physics with the near detector

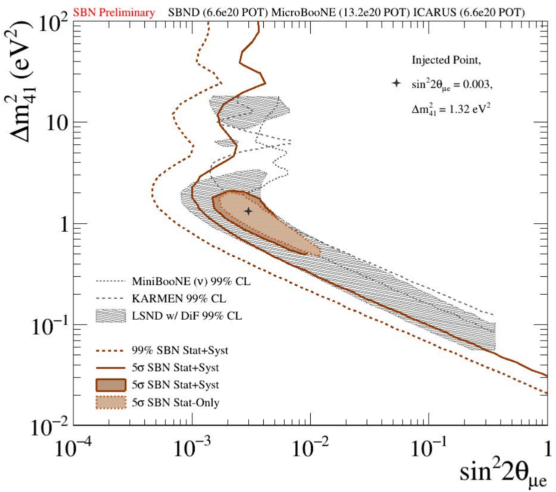
- SBND will provide the largest dataset of neutrino-Argon cross-section measurements in the few-GeV energy range to date
- As the near detector in the SBN program, SBND will constrain the unoscillated component of the neutrino flux in the search for sterile neutrinos

SBN oscillations: Sensitivities

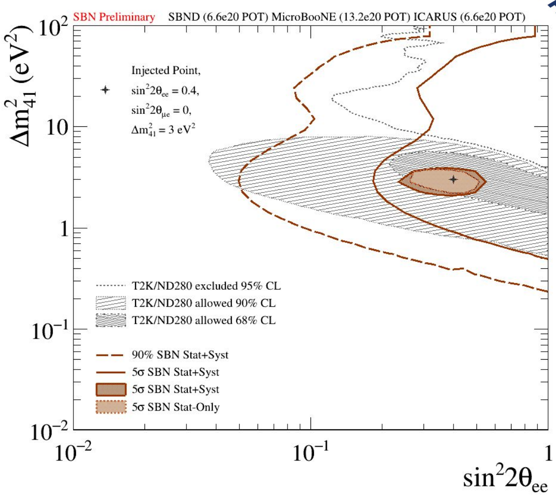
ν_μ disappearance



ν_e appearance



ν_e disappearance



External data:

IceCube ν_μ 2020
MiniBooNE ν_μ 2011
MINOS/MINOS+ ν_μ 2017

MiniBooNE ν_e 2013
KARMEN ν_e 2002
LSND ν_e 2001

T2K ν_e 2014

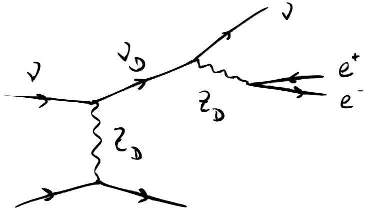
- New sensitivity plots from SBN using up-to-date models, systematics and geometries with respect to the SBN proposal (2015)
- **As the near detector, SBND will carefully constrain the interaction and flux systematics**
- In **two/three sterile oscillation channels**, SBN will be sensitive to the parameter space favoured by previous measurements at the **5σ confidence level**
- Directly address existing tensions observed in the combined appearance and disappearance data

Physics with the near detector

- SBND will provide the largest dataset of neutrino-Argon cross-section measurements in the few-GeV energy range to date
- As the near detector in the SBN program, SBND will constrain the unoscillated component of the neutrino flux in the search for sterile neutrinos
- Some statistical significance in rare and exotic interaction channels for probing beyond the Standard Model (**BSM**) physics searches

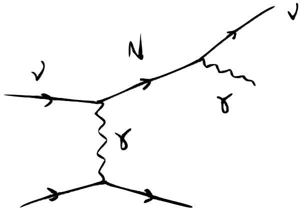
Beyond the Standard Model

Dark Neutrinos



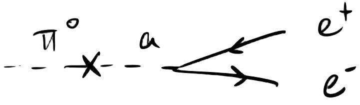
Bertuzzo, Jana, Machado, Zukanovich, PRL 2018, PLB 2019
Arguelles, Hostert, Tsai PRL 2019
Ballett, Pascoli, Ross-Lonergan PRD 2019
Ballett, Hostert, Pascoli PRD 2020

Transition Magnetic Moment



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

Axion-like Particles



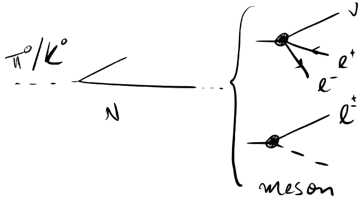
Kelly, Kumar, Liu PRD 2021
Brdar et al PRL 2021

Alternative explanations to the MiniBooNE excess and other BSM scenarios

Not an exhaustive list

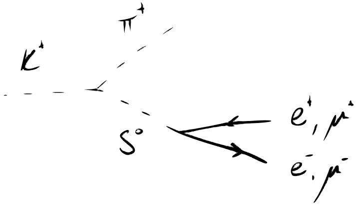
Some diagrams credit: Pedro Machado
Slide credit: Marco Del Tutto

Heavy Neutral Leptons



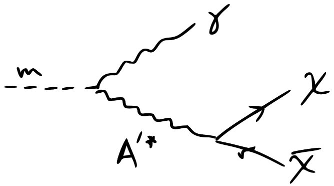
Ballett, Pascoli, Ross-Lonergan JHEP 2017
Kelly, Machado PRD 2021

Higgs Portal Scalar



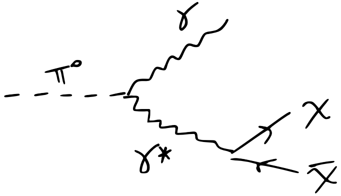
Patt, Wilczek 2006
Batell, Berger, Ismail PRD 2019
MicroBooNE 2021

Light Dark Matter



Romeri, Kelly, Machado PRD 2019

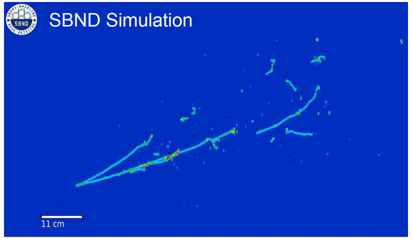
Millicharged Particles



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

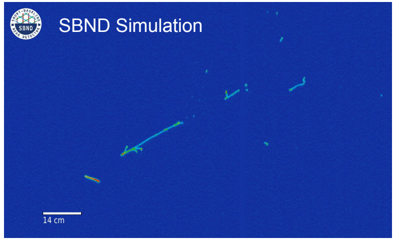
BSM signatures in SBND

Dark Neutrinos



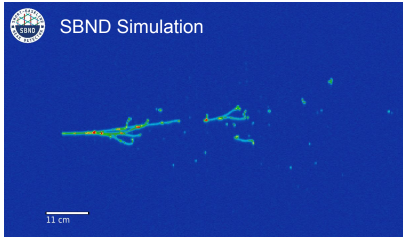
e^+e^- pair with or w/o hadronic activity

Transition Magnetic Moment



Photon shower and hadronic activity

Axion-like Particles



High-energy e^+e^- or $\mu^+\mu^-$

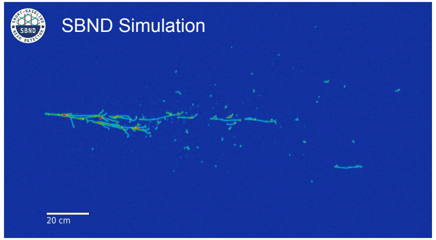
Example signatures and event displays for various BSM scenarios

Not an exhaustive list

Some diagrams credit: Pedro Machado

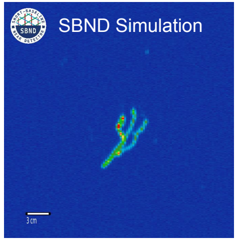
Slide credit: Marco Del Tutto

Heavy Neutral Leptons



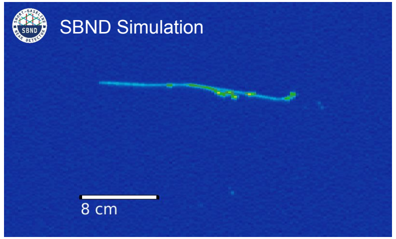
e^+e^-, $\mu^+\mu^-$ or $\mu\pi$

Higgs Portal Scalar



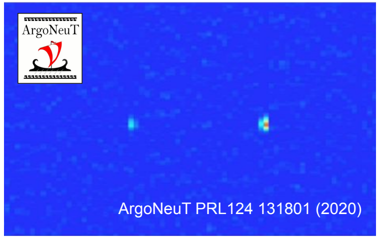
e^+e^- or $\mu^+\mu^-$, no hadronic activity

Light Dark Matter



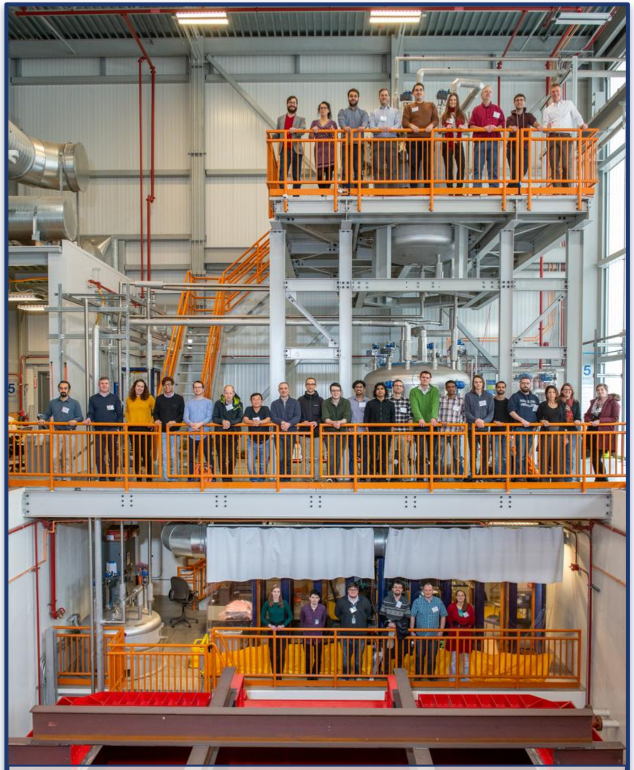
Electron scattering

Millicharged Particles



Blips/faint tracks

Summary and conclusions



SBND collaboration, SBN-ND building, December 2019

SBND is almost ready for data

- Detector operations will commence this year
- The SBND physics program boasts a wide variety of exciting opportunities
  - Multi-channel search for eV-scale sterile neutrinos
  - Searches for rare and exotic **BSM** physics

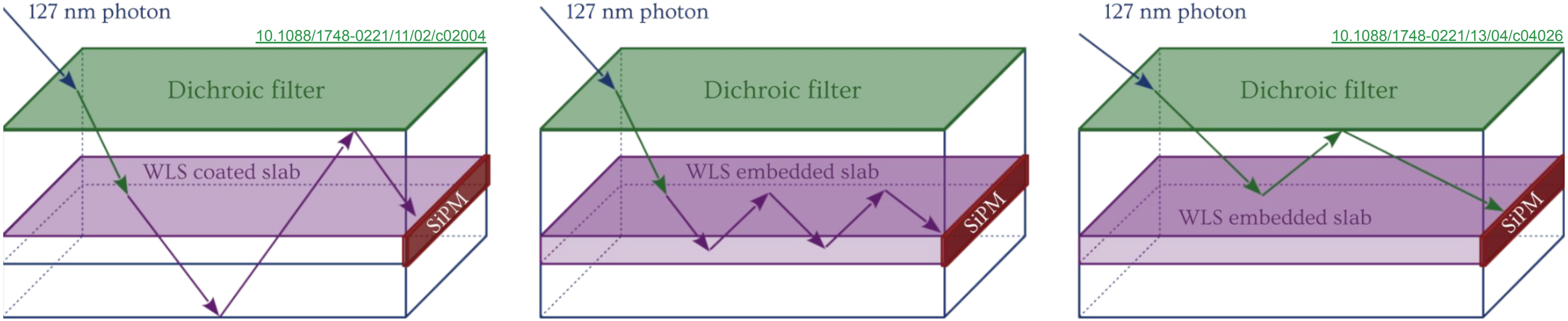
The SBND neutrino interaction physics program has **huge** potential and will pave the way for the next generation of LArTPC measurements and beyond

Thank you!

SBND collaboration, SBN-ND building, June 2022

X-Arapuca operation principles

The ARAPUCA concept aims to record scintillation photons with extremely high efficiency by trapping them within a box that has highly reflective internal surfaces without the need for a large active photon detection system.



Original ARAPUCA | X-ARAPUCA: Total internal reflection | X-ARAPUCA: High incident angles

Photons enter the light box, are wavelength shifted when travelling through the coated slab and are then reflected internally until they reach and are detected by the SiPM.

The main idea behind the X-ARAPUCA, in which the photons are totally internally reflected inside the wavelength shifting slab until they reach the SiPM.

Photons with high incident angles will be reflected by the slab. These photons remain trapped in the upper part of the ARAPUCA and are reflected internally until they reach the SiPM

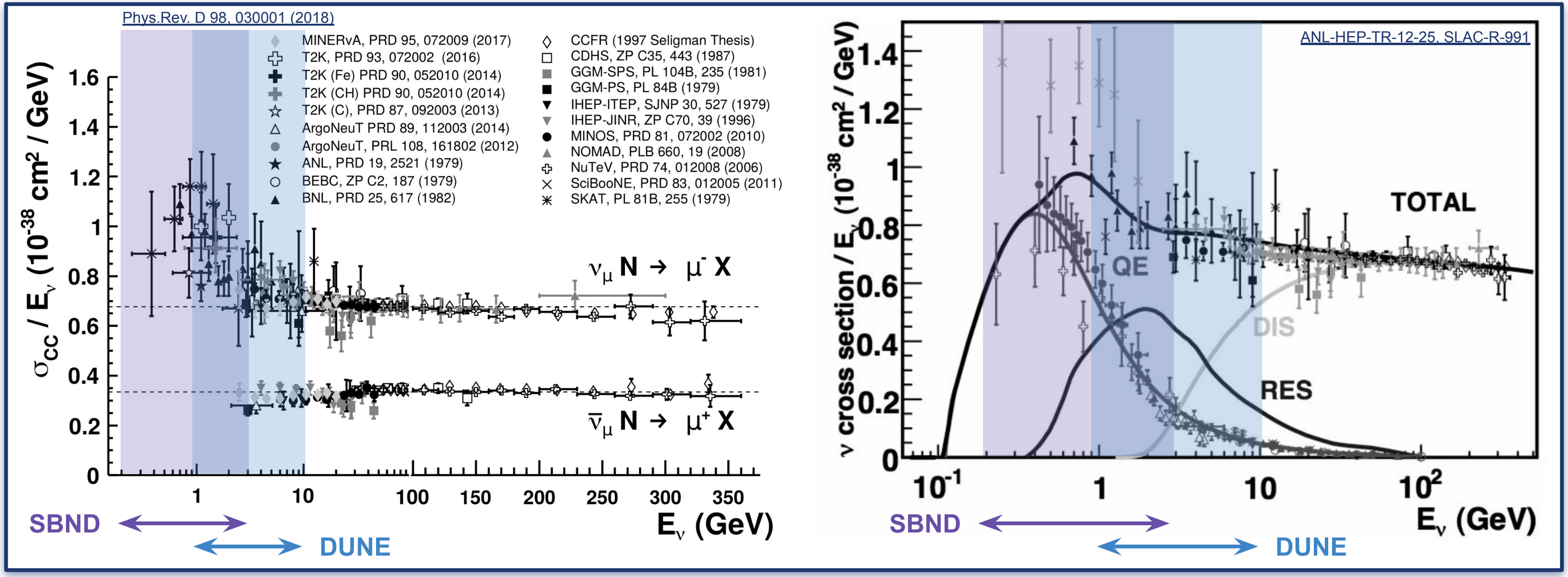
Neutrino interactions on argon

Neutrino cross-section data in the 0.1-10 GeV energy range is quite limited

- Has seen substantial improvements in recent years thanks to the likes of T2K and Minerva

Neutrino-argon cross-section data remains scarce

- A substantial cross-section physics programme is critical
- All aspects of the physics modelling must be benchmarked and improved to update generators



BNB flux prediction

		ν_μ		$\overline{\nu}_\mu$
Flux (ν/ cm^2/POT)		5.19×10^{-10}		3.26×10^{-11}
Frac. of Total		93.6%		5.86%
Composition	π^+:	96.72%	π^-:	89.74%
	K^+:	2.65%	$\pi^+ \to \mu^+$:	4.54%
	$K^+ \to \pi^+$:	0.26%	K^-:	0.51%
	$K^0 \to \pi^+$:	0.04%	K^0:	0.44%
	K^0:	0.03%	$K^0 \to \pi^-$:	0.24%
	$\pi^- \to \mu^-$:	0.01%	$K^+ \to \mu^+$:	0.06%
	Other:	0.30%	$K^- \to \pi^-$:	0.03%
			Other:	4.43%

		ν_e		$\overline{\nu}_e$
Flux (ν/ cm^2/POT)		2.87×10^{-12}		3.00×10^{-13}
Frac. of Total		0.52%		0.05%
Composition	$\pi^+ \to \mu^+$:	51.64%	K^0_L:	70.65%
	K^+:	37.28%	$\pi^- \to \mu^-$	19.33%
	K^0_L:	7.39%	K^-:	4.07%
	π^+:	2.16%	π^-:	1.26%
	$K^+ \to \mu^+$:	0.69%	$K^- \to \mu^-$:	0.07%
	Other:	0.84%	Other:	4.62%

GEANT4-based Monte Carlo (MC) simulation in which hadron production cross-sections are tuned to external data, primarily via:

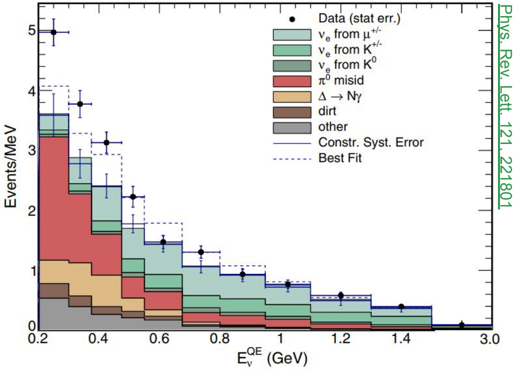
- $\pi^\pm$ neutrino production mechanism [1]:
  - The Sanford and Wang (SW) parameterization of the differential cross-section as a function of meson kinematics, p, θ, and incident proton momentum, p_B
  - Tuned to HARP p-Be data at 8.89 GeV/c, > 80% coverage [2]
- K^+ neutrino production mechanism [1]:
  - Feynman scaling of global K^+ production data to 8.89 GeV from various proton energies
- K^0_L neutrino production mechanism
  - Tuned SW parameterization
- K^- neutrino production mechanism
  - Tuned MC simulation of p-Be interactions

[1] Phys. Rev D79, 072002 (2009)

[2] D. Schmitz, FERMILAB-THESIS-2008-26

SBN oscillations: Motivation

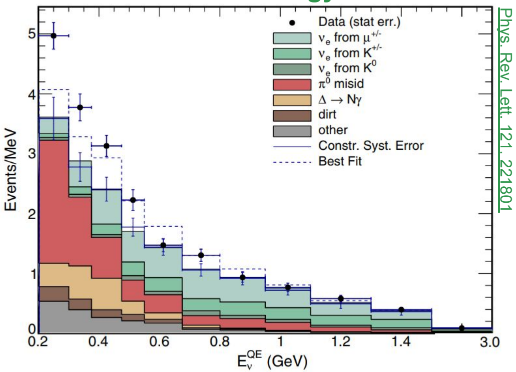
MiniBooNE Low Energy Excess



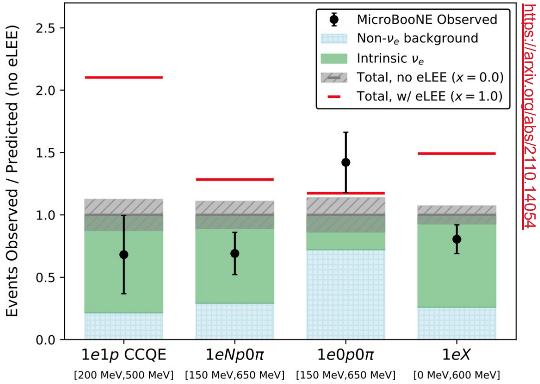
- Gallium, reactor and accelerator neutrino experiments have all reported anomalous results in some of their oscillation data
- LSND & MiniBooNE observed an excess of low-energy electron-like signals
  - Known as the 'Low Energy Excess' (**LEE**) anomaly
  - **Is this caused by sterile neutrinos oscillating into active neutrinos?**
- MicroBooNE was built in order to better-characterise this excess
  - LArTPCs have a greater ability to differentiate between e^- and γ signals

SBN oscillations: Motivation

MiniBooNE Low Energy Excess



MicroBooNE Low Energy Excess



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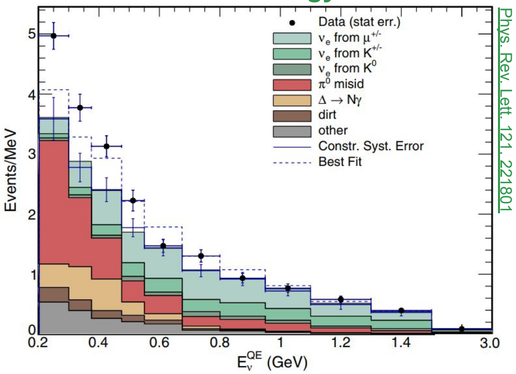
  - LArTPCs have a greater ability to differentiate between e^- and γ signals
- MicroBooNE **did not observe the same LEE signal**
  - This result alone doesn't rule out the existence of sterile neutrinos

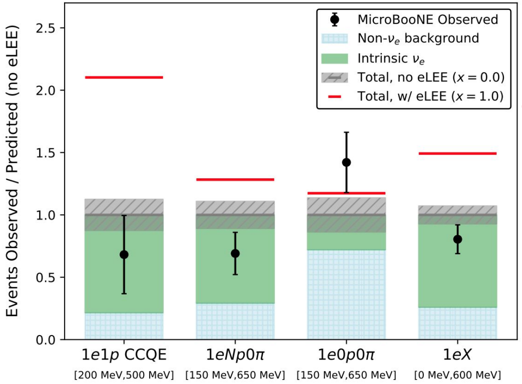
SBN oscillations: Motivation

MiniBooNE Low Energy Excess



Phys. Rev. Lett. 121, 221801

MicroBooNE Low Energy Excess



https://arxiv.org/abs/2110.14054

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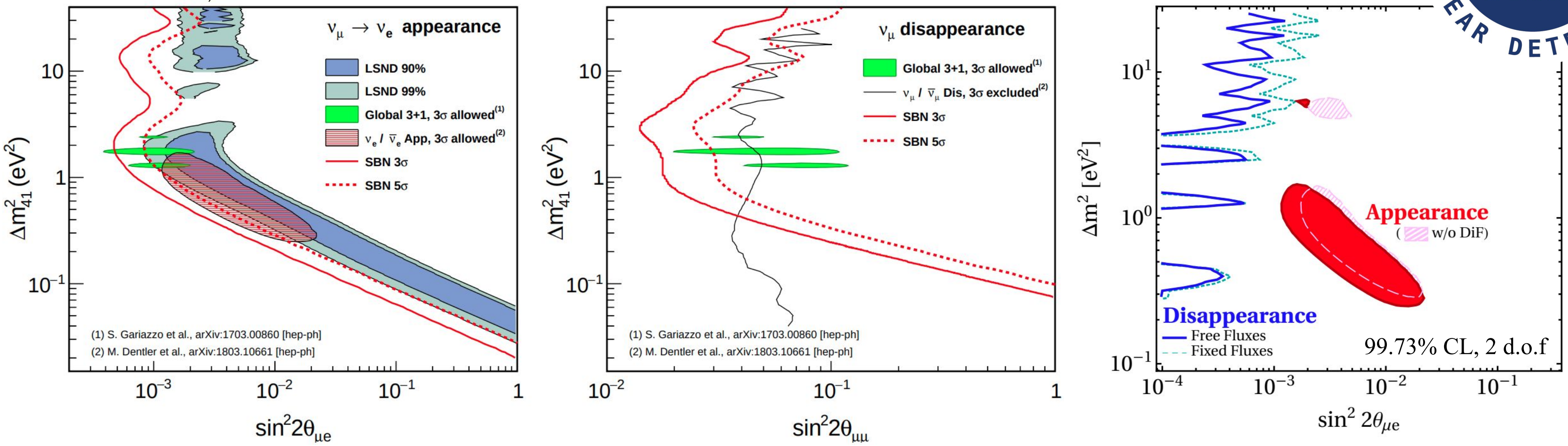
  - LArTPCs have a greater ability to differentiate between e^- and γ signals
- MicroBooNE **did not observe the same LEE signal**
  - This result alone doesn't rule out the existence of sterile neutrinos
- The SBN program will probe all three sterile neutrino oscillation channels

ν_e appearance and ν_μ & ν_e disappearance

The multi-detector SBN oscillation analysis will substantially improve the global dataset and our confidence in whether sterile neutrinos exist

SBN oscillations: Sensitivities

P. Machado et al, arXiv:1903.04608V11



- The SBN program will search for sterile neutrinos with three detectors utilising the same technology in the same beamline
- **As the near detector, SBND will carefully constrain the interaction and flux systematics**
- In **two of the sterile oscillation channels**, SBN will be sensitive to the parameter space favoured by previous measurements at the **5σ confidence level**
- Directly address **existing tensions** observed in the combined appearance and disappearance data