# Deciphering the complex nature of neutrinos with SBND

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University of Sheffield

**RAL PPD Seminar**

22nd April 2026

# Overview

- Short-baseline experimental neutrino physics landscape.
- Liquid argon-based neutrino detection.
- The Short Baseline Near Detector (SBND).
- The SBND physics programme.
- The road to SBND.
- Current status and future results.

# Short-baseline experimental neutrino physics landscape

# Neutrino oscillations

The groundbreaking discovery of neutrino flavour oscillations at the turn of the century by the Super-K and SNO experiments was awarded the Nobel Prize in Physics in 2015.

Super-Kamiokande (1998)

SNO (2001)

Nobel Prize in Physics (2015)

Some of the major developments in HEP during this century so far have consequently involved improving the limits on the parameters which govern neutrino flavour oscillations.

# Neutrino oscillations

$$P_{\alpha\to\beta}(t) = \sum_{k,j=1}^{3} U^*_{\alpha k} U_{\beta k} U_{\alpha j} U^*_{\beta j} \exp\left(-i\frac{\Delta m^2_{kj} L}{2E}\right)$$

$$\Delta m^2_{kj} = m^2_k - m^2_j$$

$$U_{\alpha k} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

$c_{ij} = \cos\theta_{ij}$ and $s_{ij} = \sin\theta_{ij}$

JHEP 12 (2024) 216

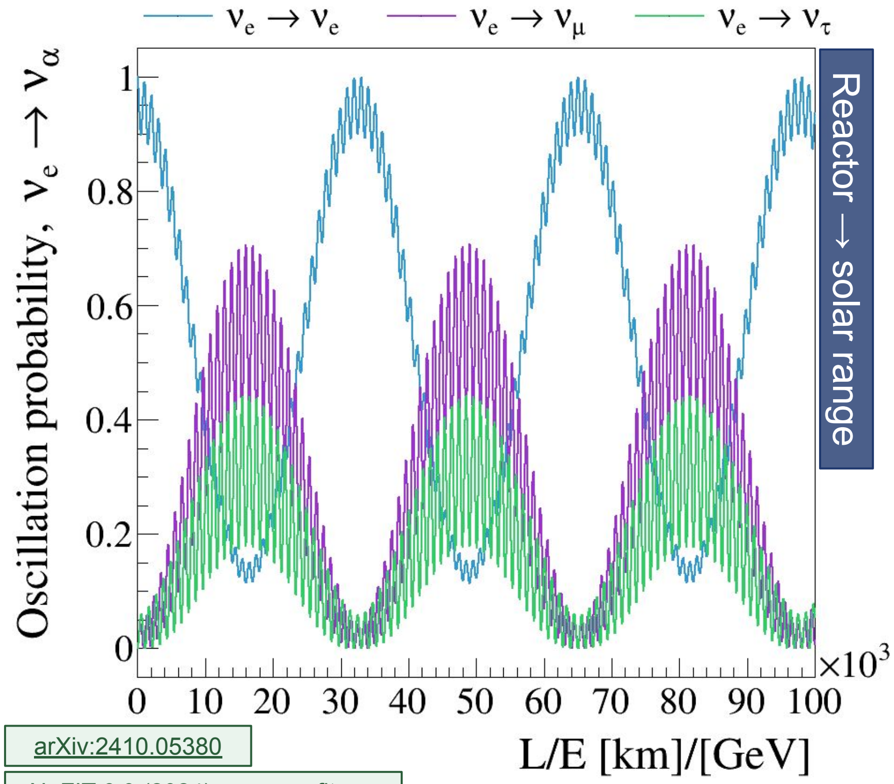
NuFIT 6.1 (2025), www.nu-fit.org

| Parameter | Limit | |
|---|---|---|
| $\theta_{12}$ /° | 33.76 | + 0.42 / - 0.41 |
| $\theta_{23}$ /° | 43.29 | + 0.96 / - 0.79 |
| $\theta_{13}$ /° | 8.62 | + 0.11 / - 0.11 |
| $\delta_{CP}$ /° | 212 | + 26 / - 36 |
| $\Delta m^2_{21}$ /$10^{-5}$ eV$^2$ | 7.537 | + 0.094 / - 0.100 |
| $\lvert\Delta m^2_{3l}\rvert$ /$10^{-3}$ eV$^2$ | 2.511 | + 0.021 / - 0.020 |

*Assumed NO with SK atmospheric data.*

# Neutrino oscillations

$$|\Delta m^2| \sim \frac{E}{L}$$




arXiv:2410.05380

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The existing measurements of these parameter limits have had to come from numerous experiments.

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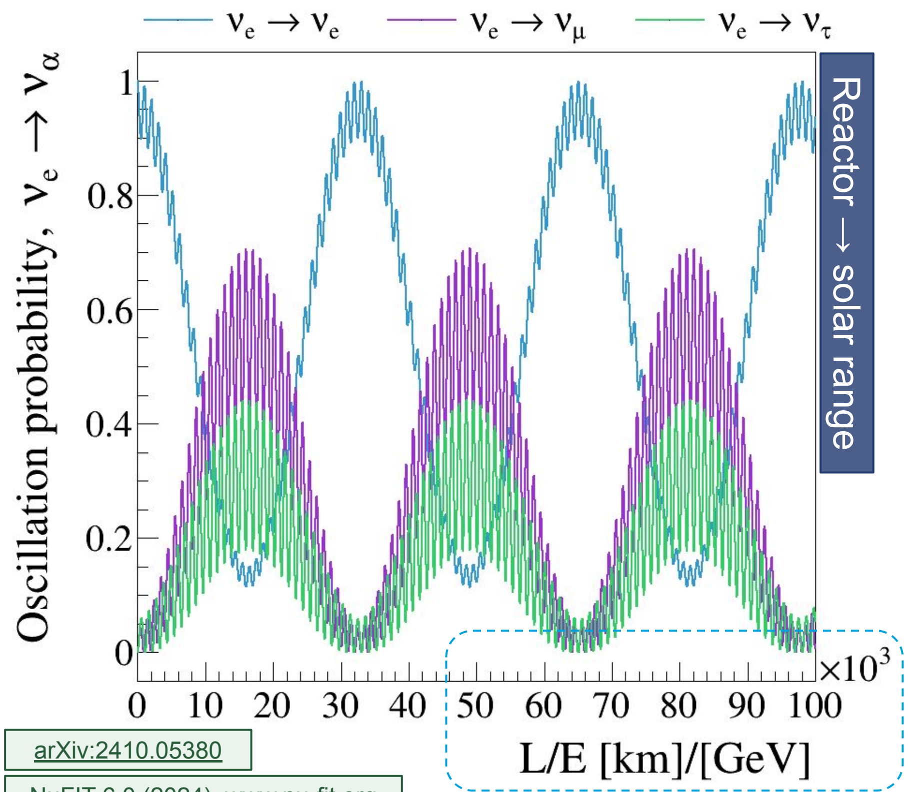


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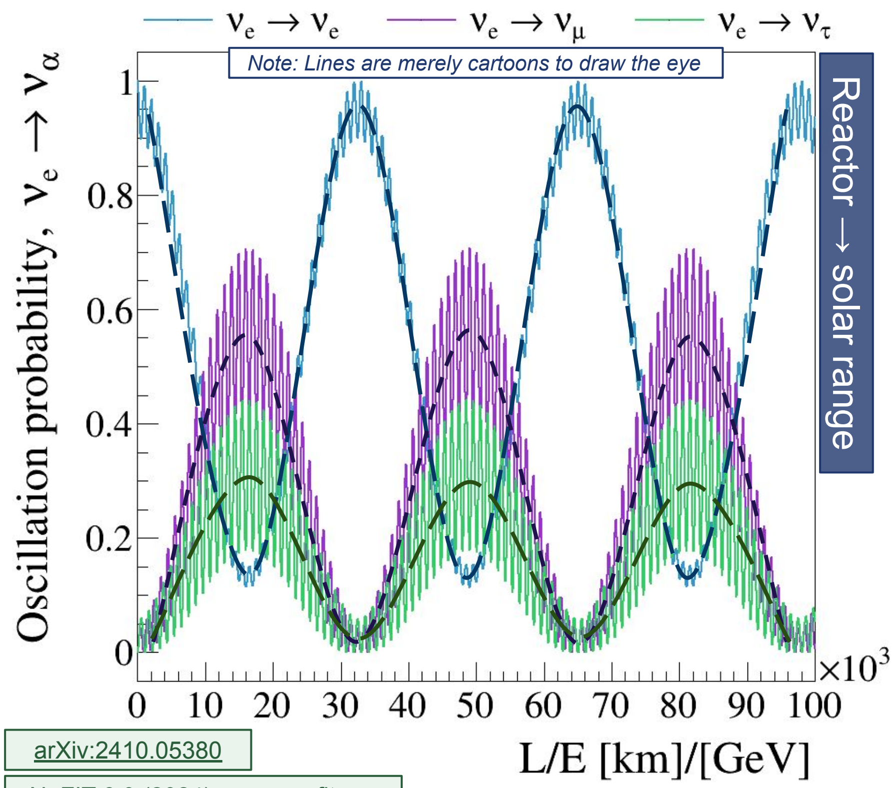


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$$\Delta m^2 \sim 10^{-5}\ eV^2 \sim \mathbf{\Delta m^2_{21}}$$

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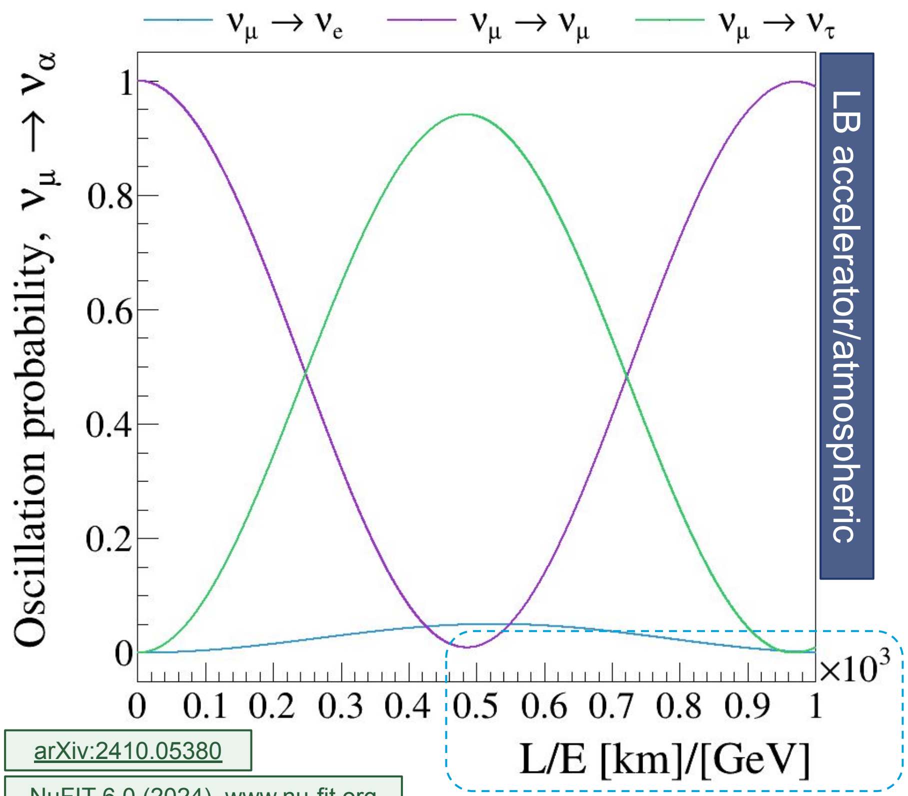


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NuFIT 6.0 (2024), www.nu-fit.org

The existing measurements of these parameter limits have had to come from numerous experiments.

→ Long-baseline accelerator & atmospheric experiments are sensitive to

$\Delta m^2 \sim 10^{-3}\ \mathrm{eV}^2 \sim \boldsymbol{\Delta m^2_{31}} \sim \boldsymbol{\Delta m^2_{32}}$

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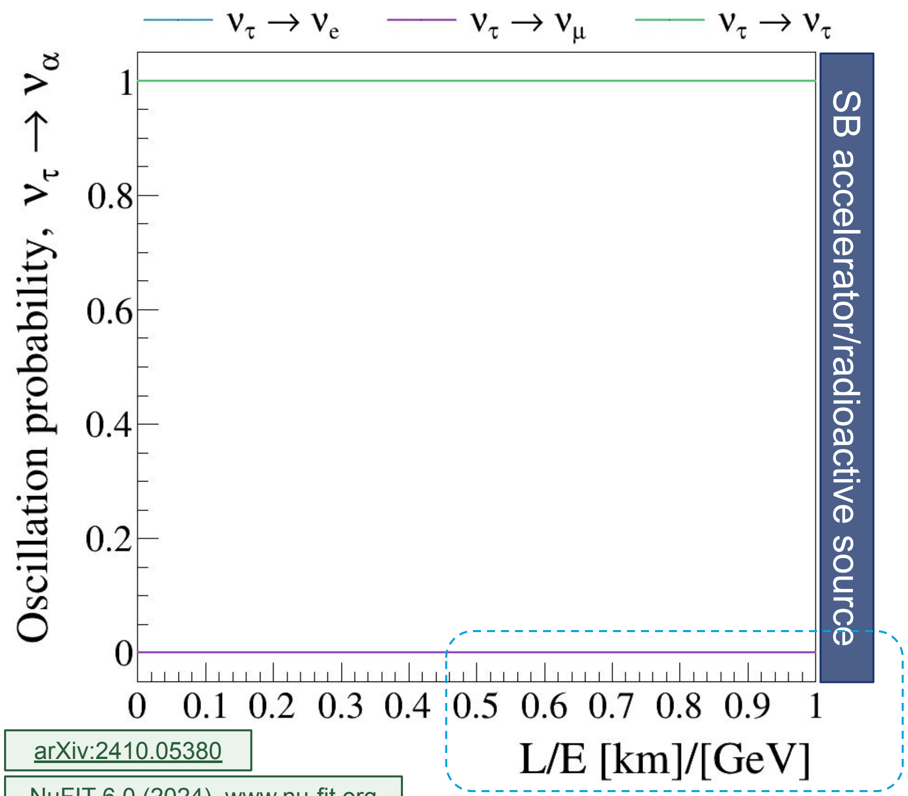


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NuFIT 6.0 (2024), www.nu-fit.org

The existing measurements of these parameter limits have had to come from numerous experiments.

→ Short-baseline accelerator experiments are sensitive to

**none of these mass-splittings**

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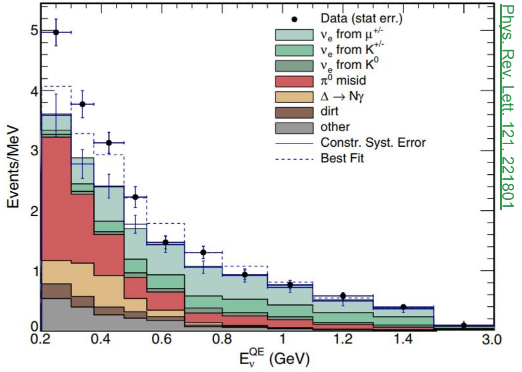
# Short-baseline experimental landscape

MiniBooNE Low Energy Excess




- Gallium, reactor and accelerator neutrino experiments have reported anomalous results in some of their data.
- LSND & MiniBooNE observed an excess of low-energy electron-like signals,
  - Above the expected active neutrino oscillation 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.

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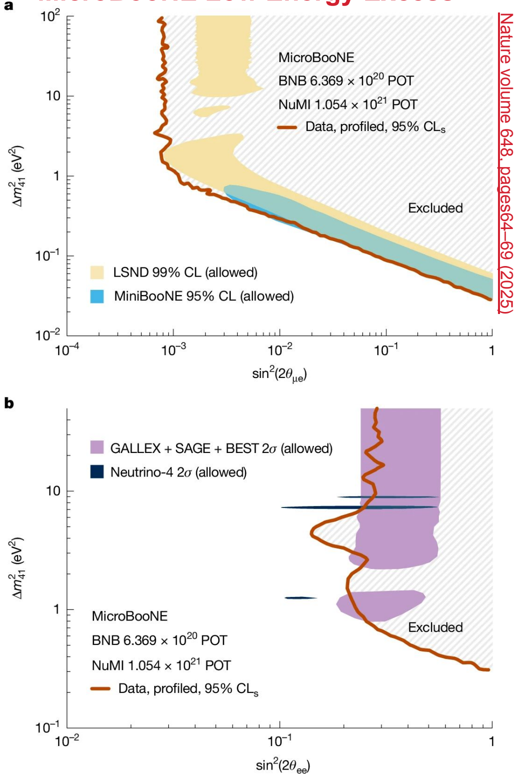


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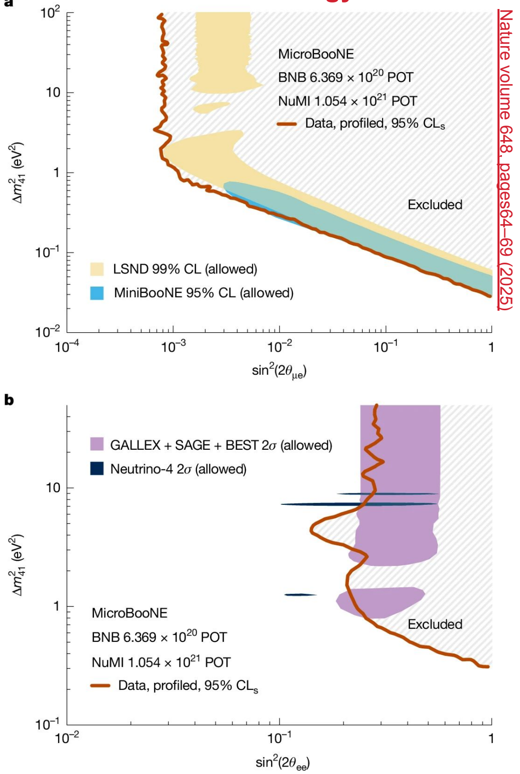


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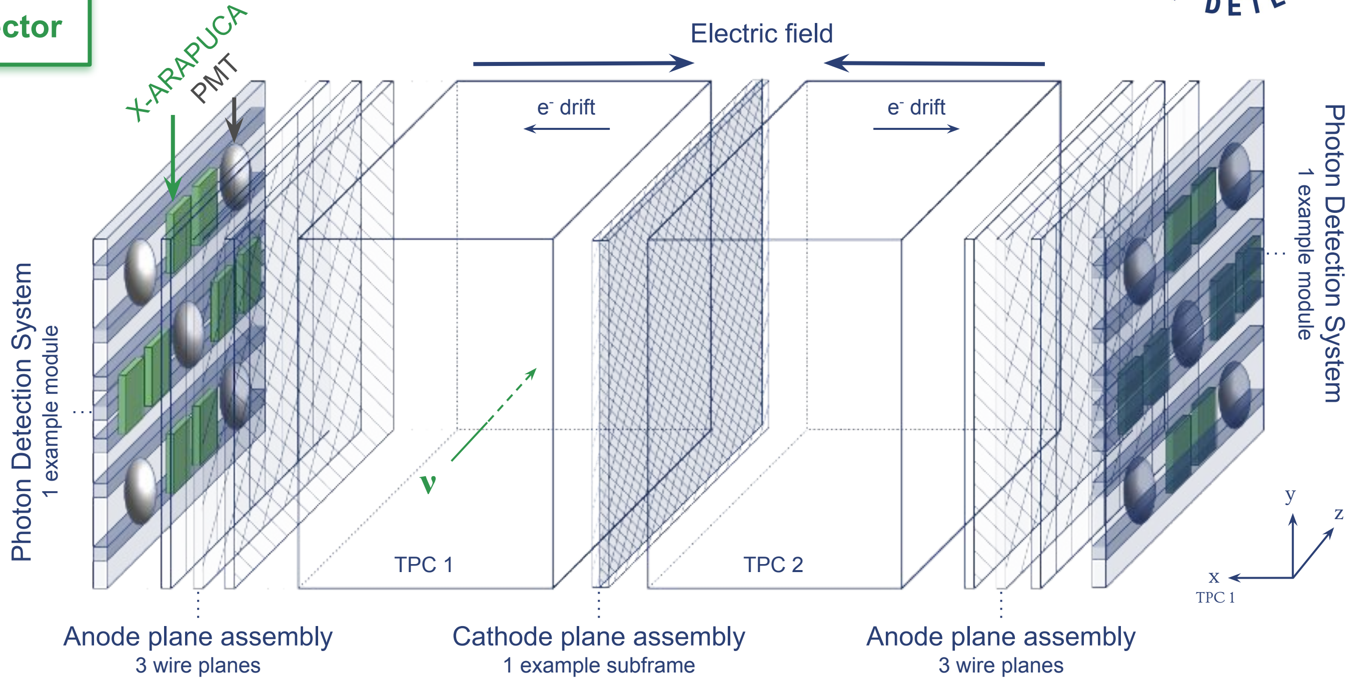
The SBN program will probe all three sterile neutrino oscillation channels.

**$\nu_e$ appearance and $\nu_\mu$ & $\nu_e$ disappearance.**

# Liquid argon-based neutrino detection

# Liquid argon time projection chambers

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



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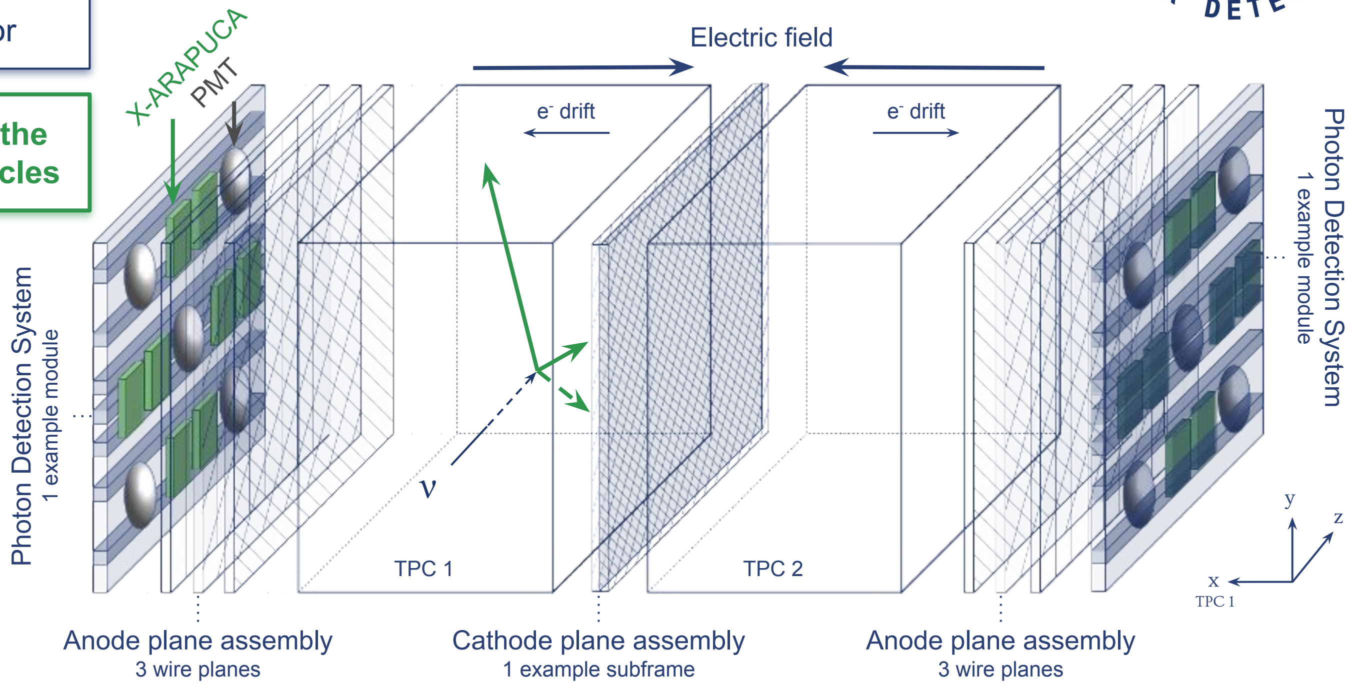
**The neutrino may interact within the argon to produce final state particles**



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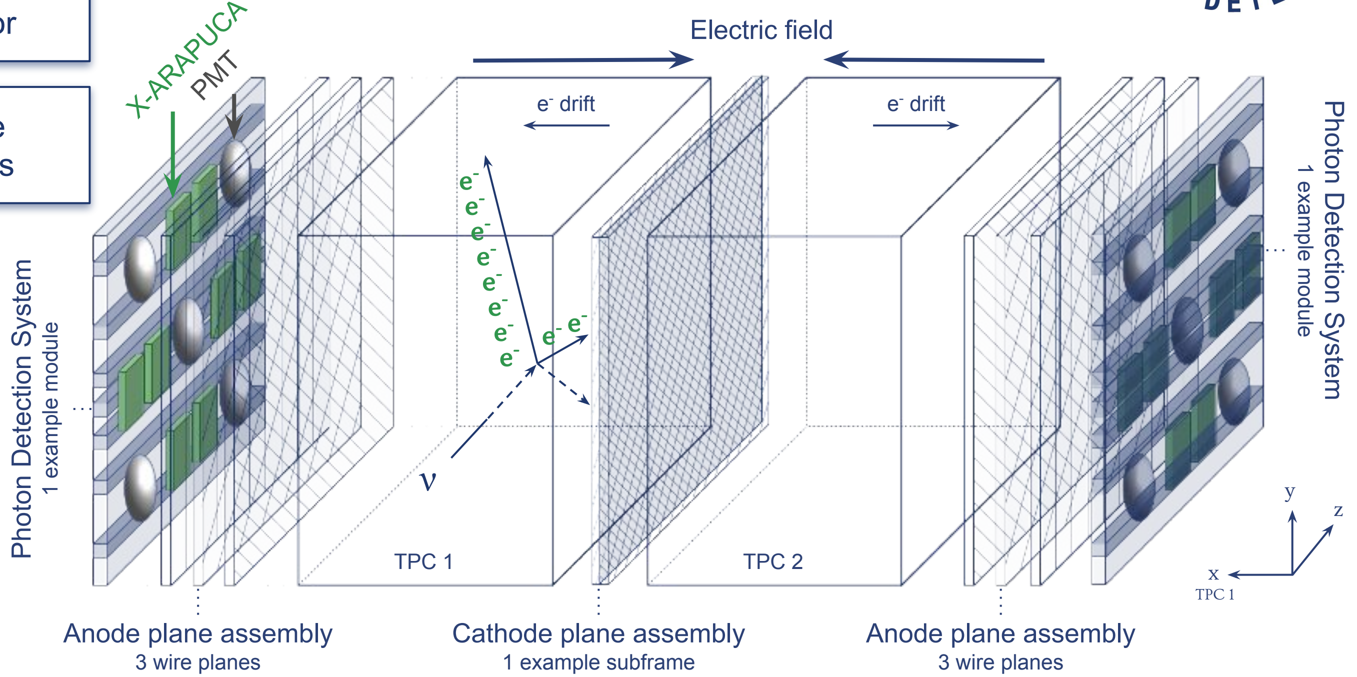



University of Sheffield

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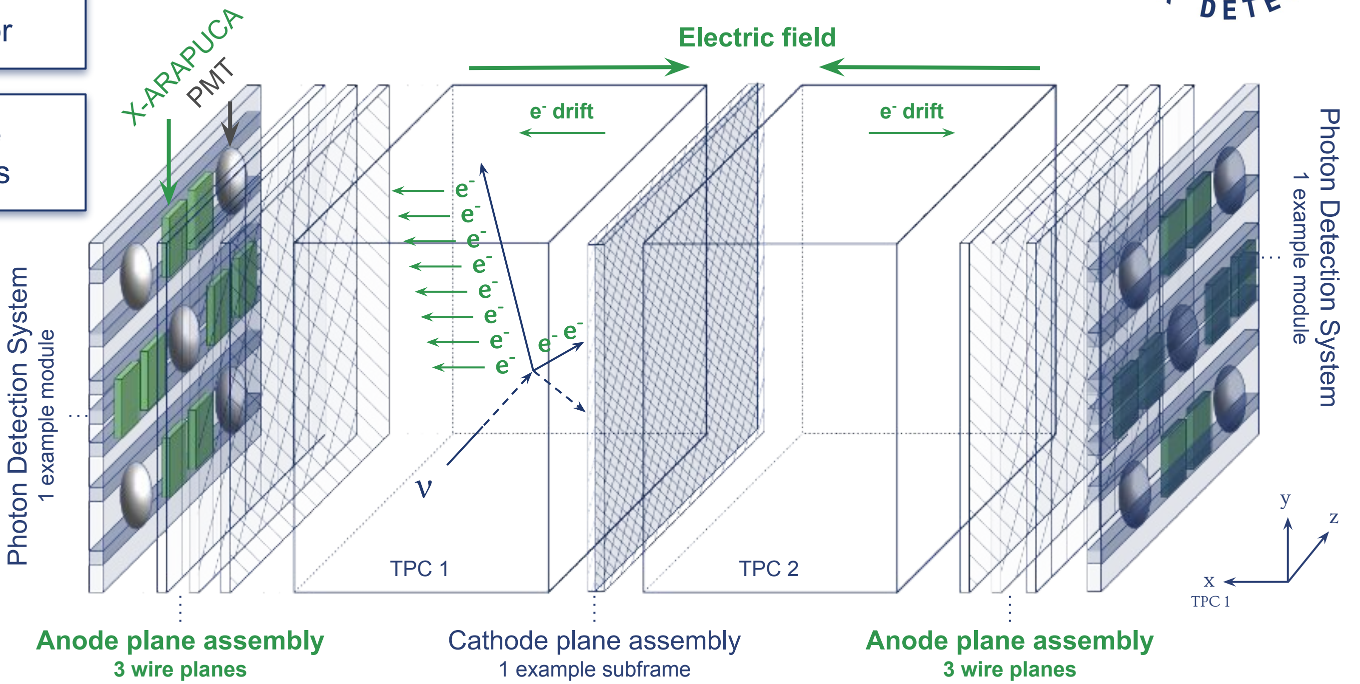

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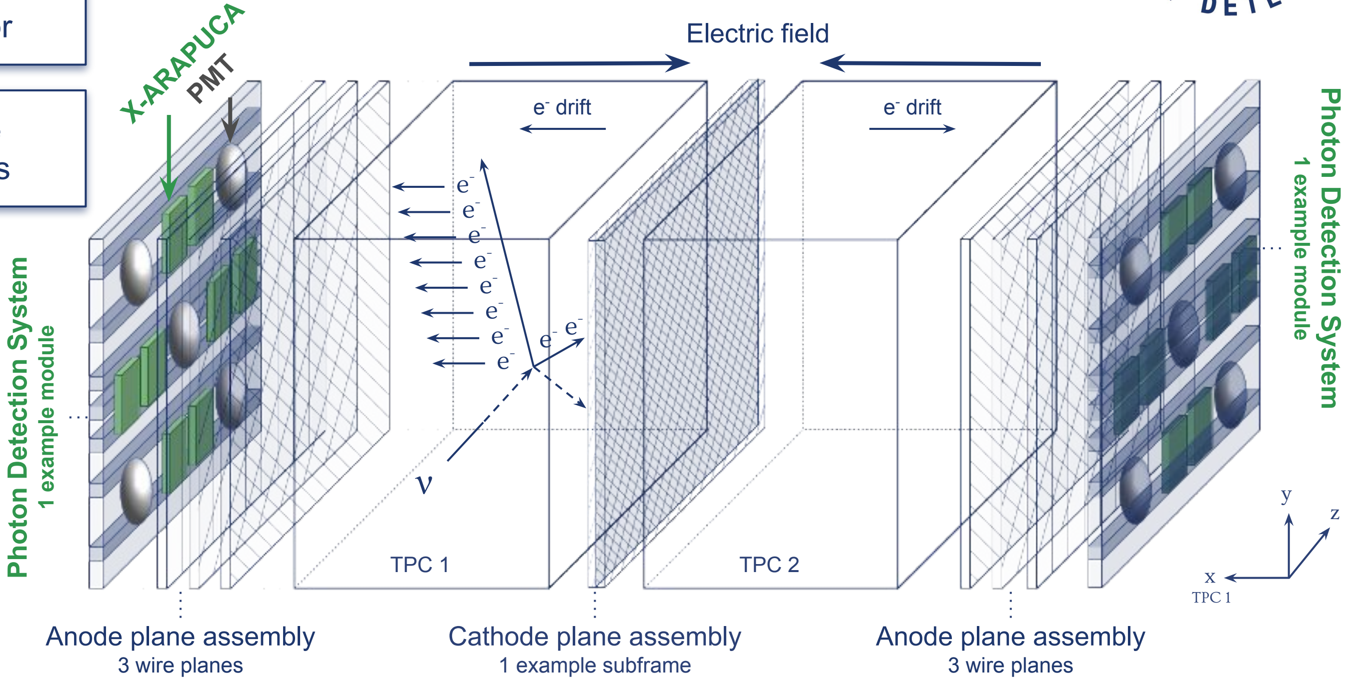

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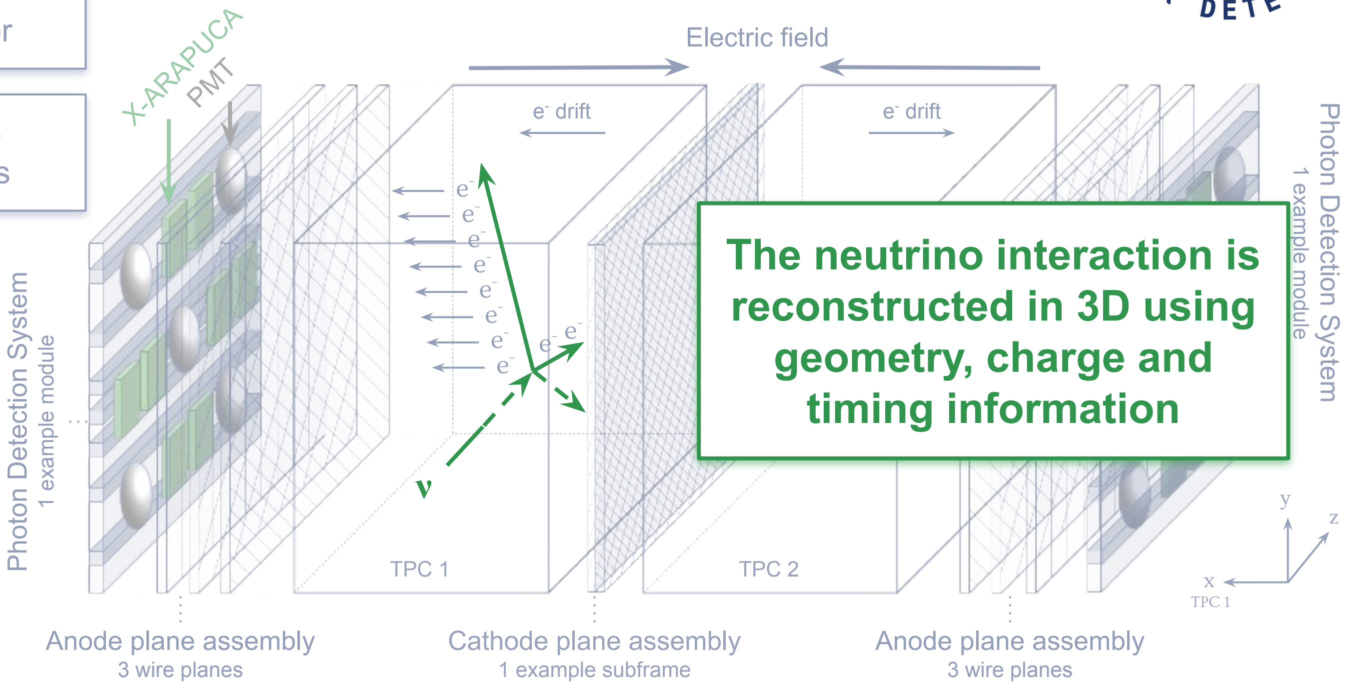
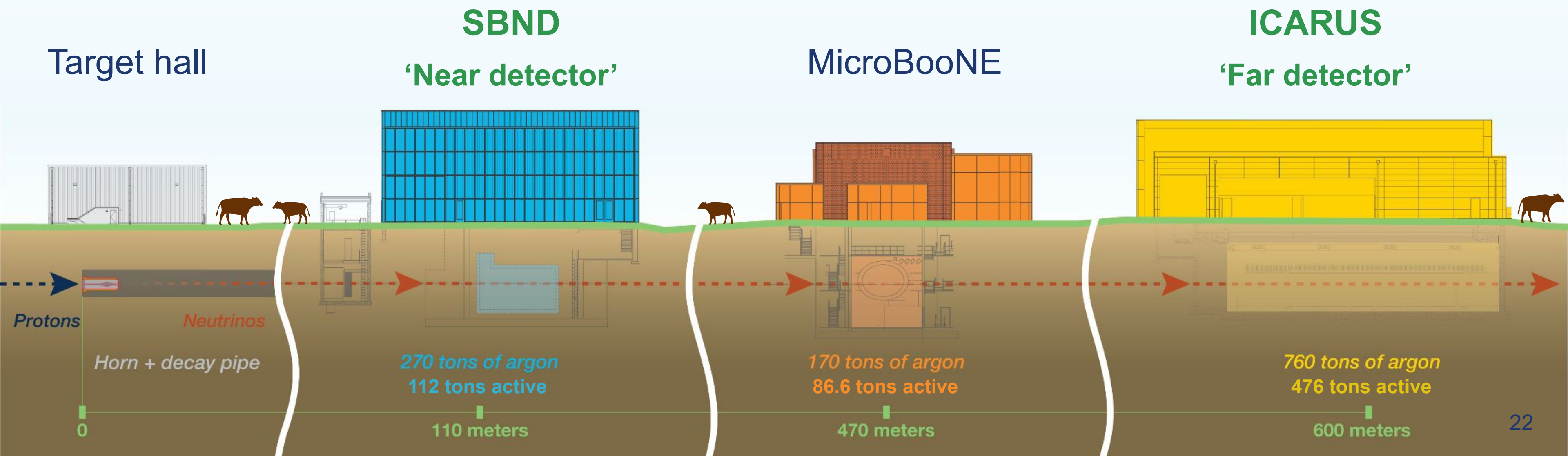



**The neutrino interaction is reconstructed in 3D using geometry, charge and timing information**

# The Short Baseline Near Detector (SBND)

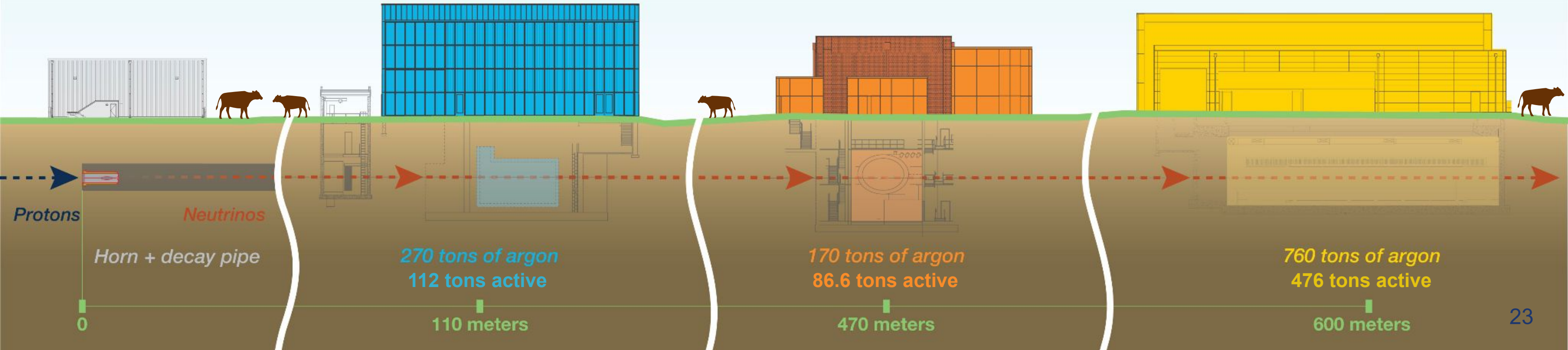
Paper in review!

# The Short Baseline Neutrino (SBN) program



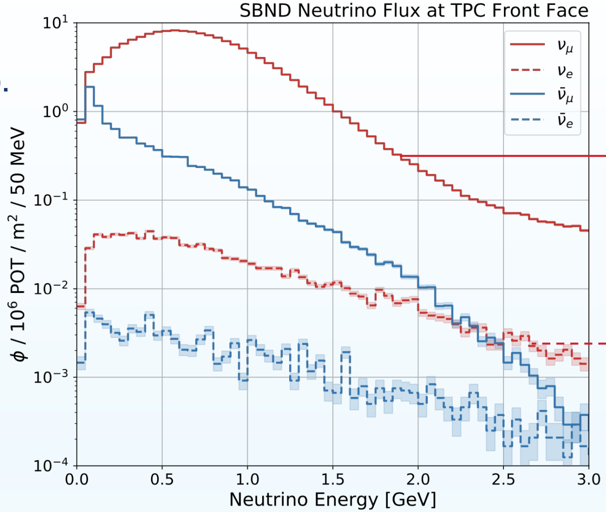
# The Short Baseline Neutrino (SBN) program

- The SBN program consists of two 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 $\nu_\mu$ **(93.6%),**
  - Intrinsic contributions from $\bar{\nu}_\mu$ (5.9%), $\nu_e$ / $\bar{\nu}_e$ (0.5%).
- Well known beam, used by MiniBooNE.
- Mean $\nu_\mu$ energy ~0.8 GeV.
- SBND projected to record 10-13 x $10^{20}$ POT,
  - ⇒ Huge flux of neutrinos at the near detector.
- The $\nu_\mu$ and $\nu_e$ fluxes are primarily produced via two and three-body decays respectively.



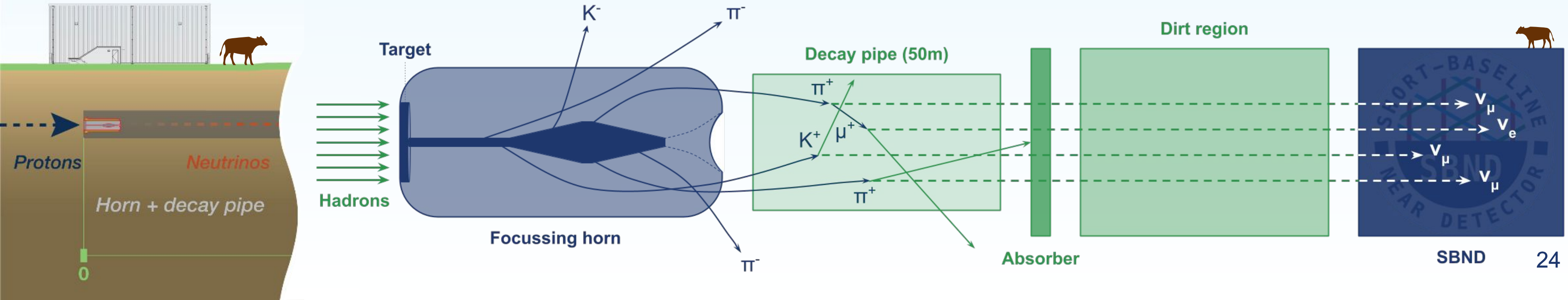

$\pi^+ \rightarrow \nu_\mu + \mu^+$

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

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

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

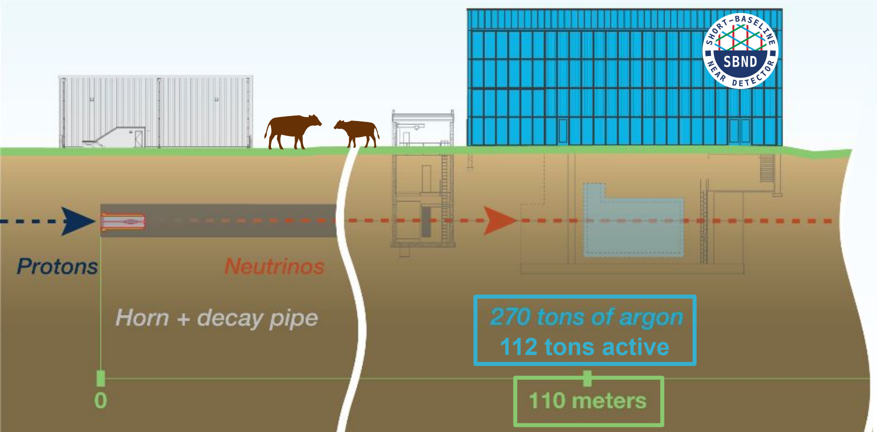
$K^0 \rightarrow \nu_e + e^+ + \pi^-$

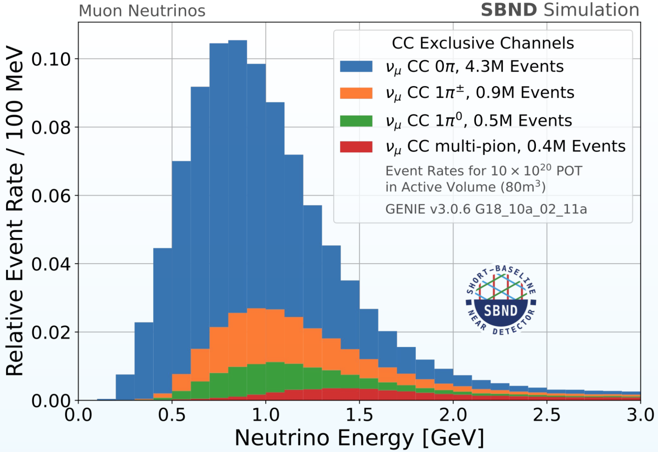


# The Short Baseline Near Detector (SBND)

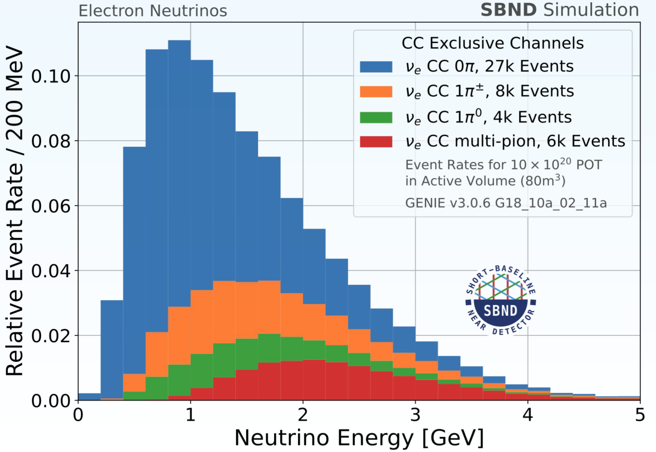
- SBND is the near detector in the SBN program.
- 112 tons of argon in its active volume.
- 110m away from the target.

**>2 million BNB neutrinos** interacted within SBND in its first year of running.




~6M $\nu_\mu$ CC




~45k $\nu_e$ CC

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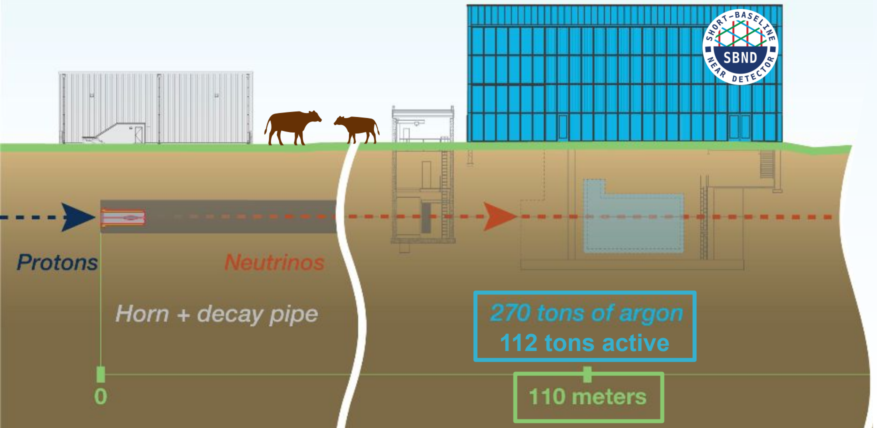
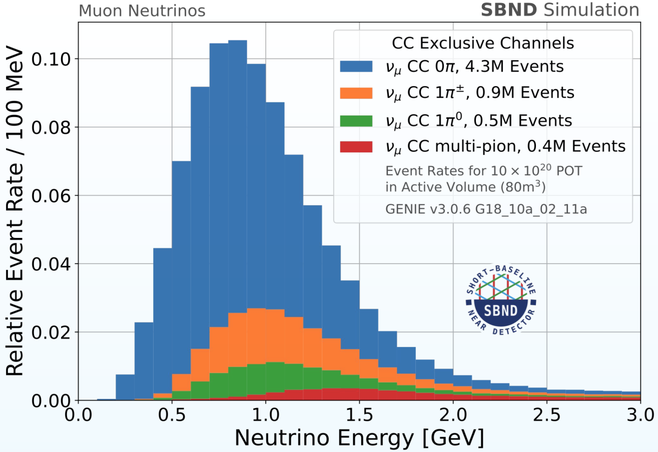
Will record **~20 – 30x more** ν-Ar interactions than currently available.

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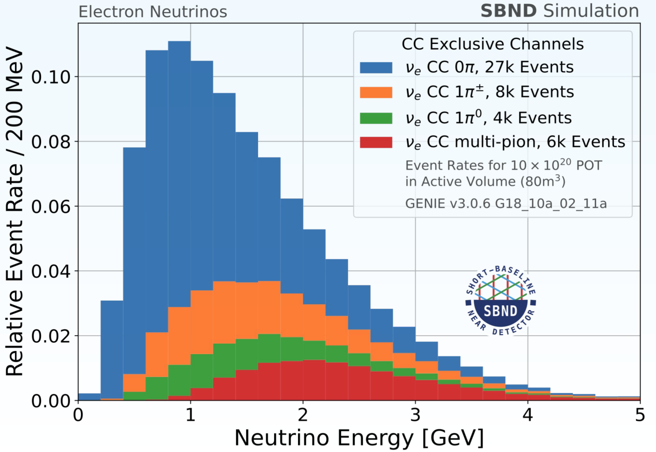


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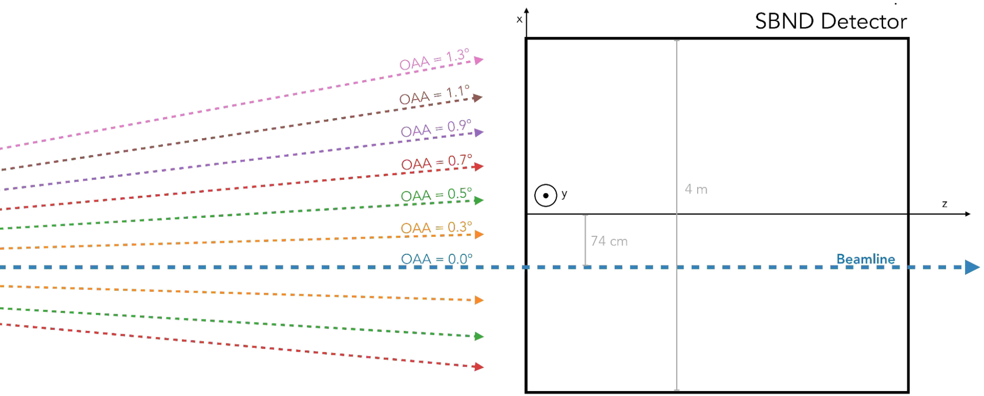
# SBND PRISM

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



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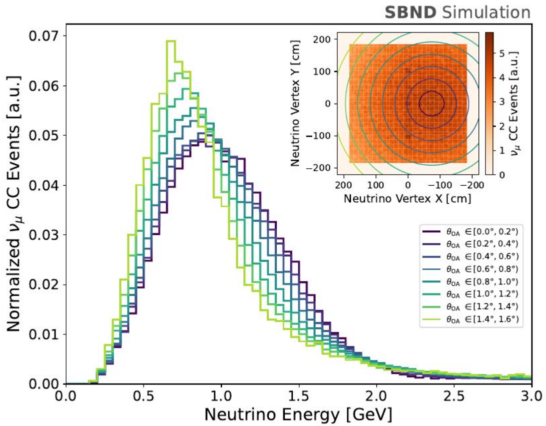


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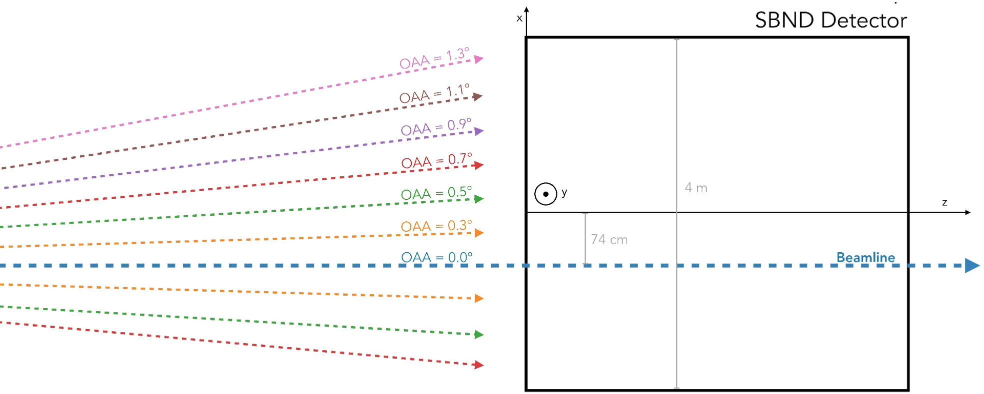
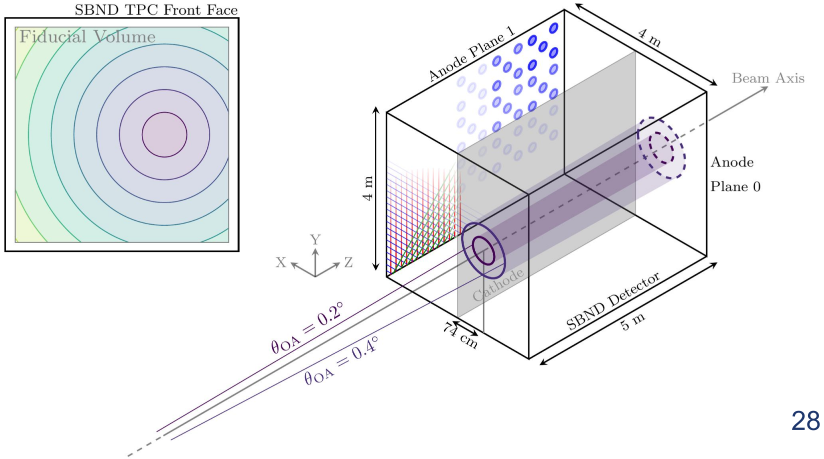
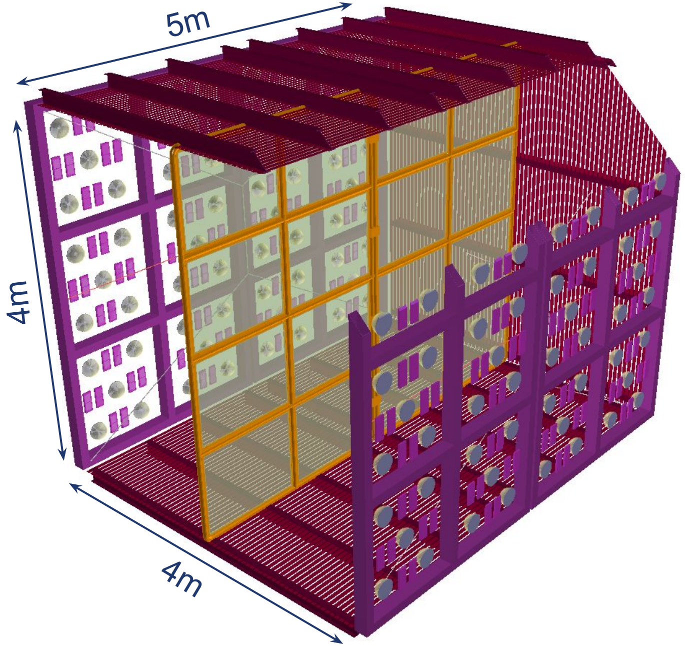
  - Neutrinos enter the detector from numerous off-axis angles (OAA).
- The detector can be separated into OAA segments,
  - Each segment will see > 10,000 $\nu_\mu$ for 10 x$10^{20}$ POT,
  - A 1° OAA corresponds to ≈ 2 m at the front face,
  - In DUNE PRISM 1° ≈ 10 m at the front face.



# The SBND detector systems: LArTPC & PDS



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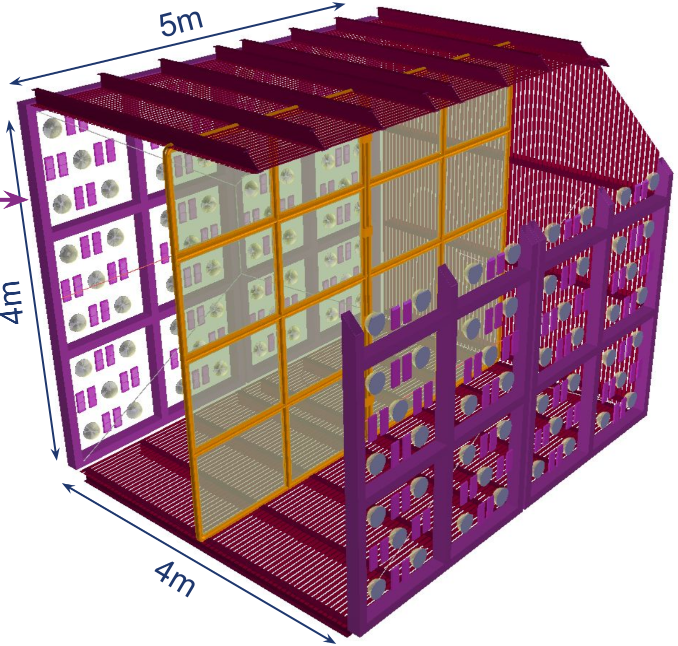
**Novel** photon detection system (**PDS**). Testing components which will be used in **DUNE.**

**120 PMTs**
**192 X-Arapucas**



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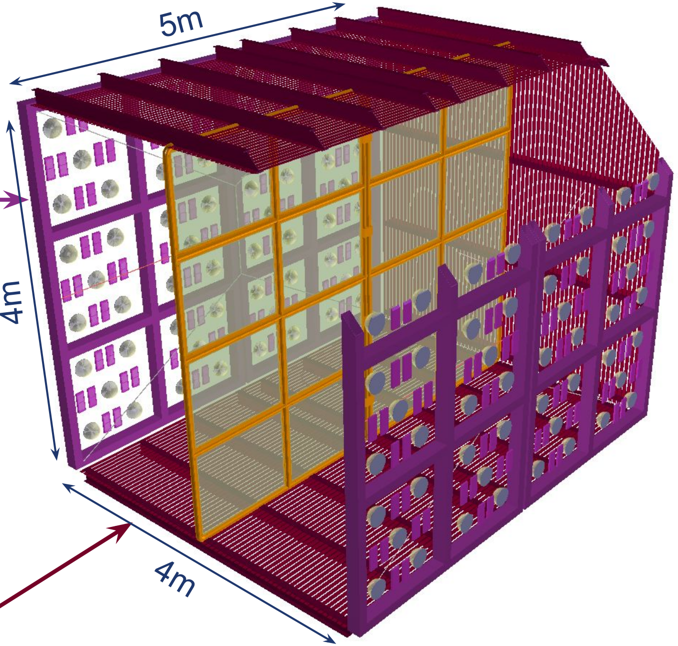
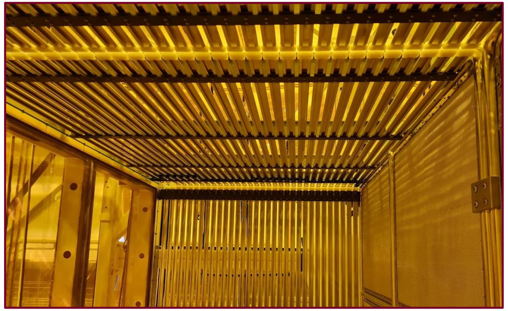



Field cage (**FC**) surrounds the TPC. Aims to maintain 500 V/cm drift field.



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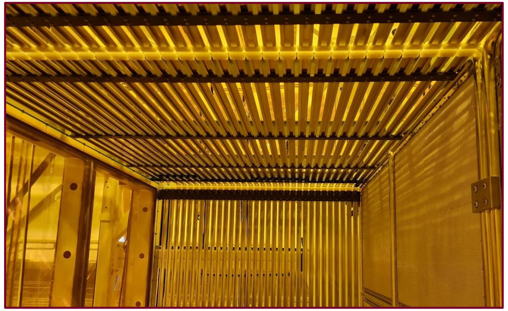

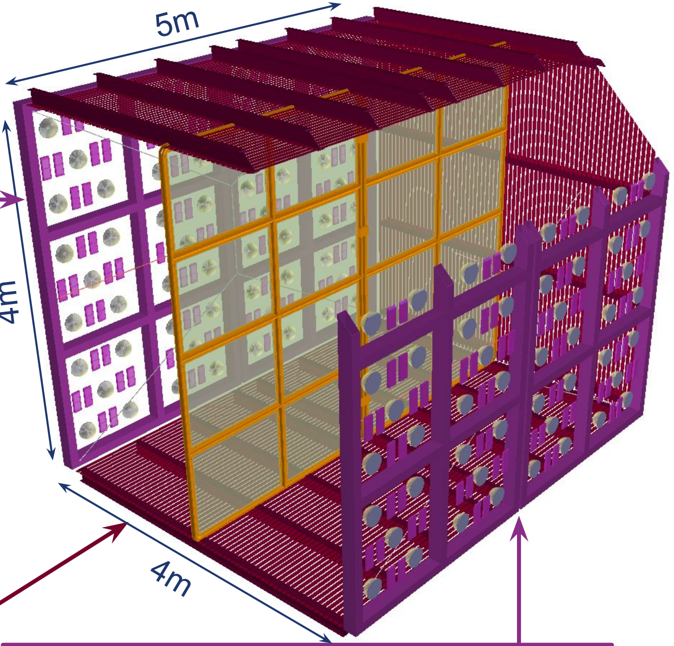


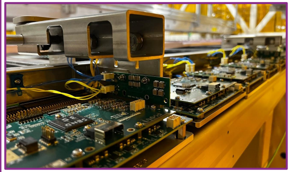

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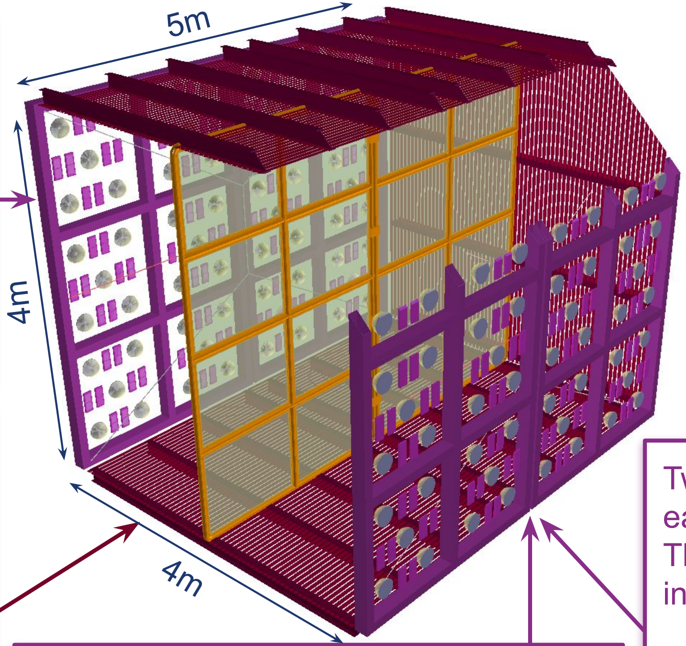


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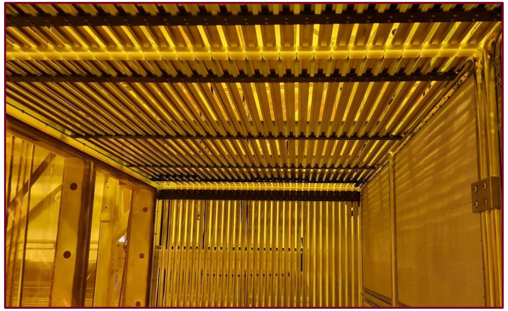

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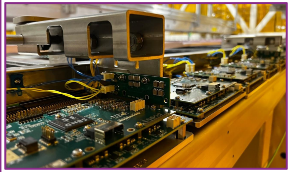
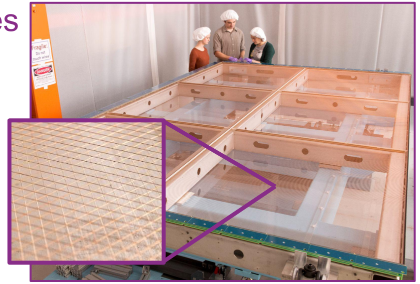


Two anode plane assemblies (**APAs**) on each side of the detector in front of the PDS. Three wire planes in each APA.

Wire $\theta_Y$: **0, ± 60°**

Wire & plane spacing: **3 mm**

JINST 15, P06033 (2020)



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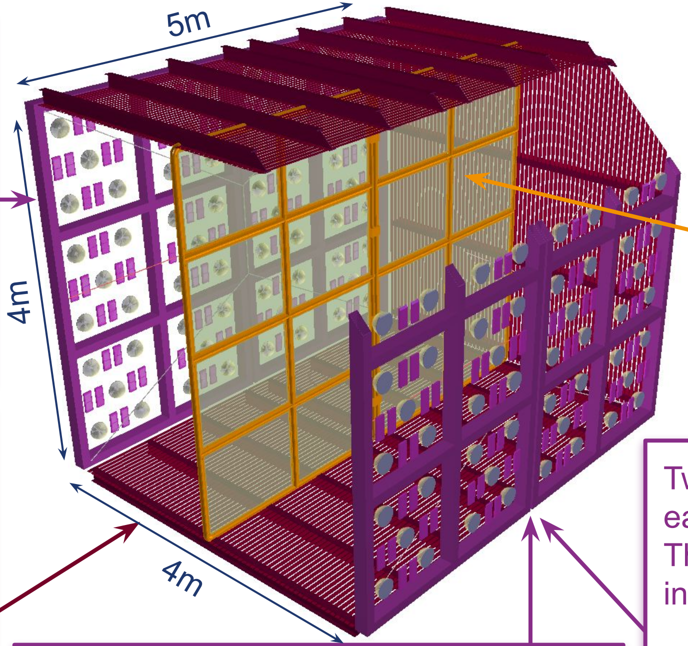
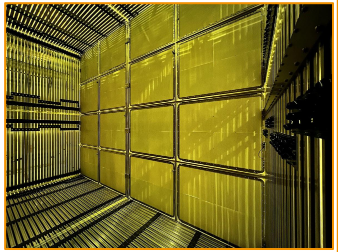
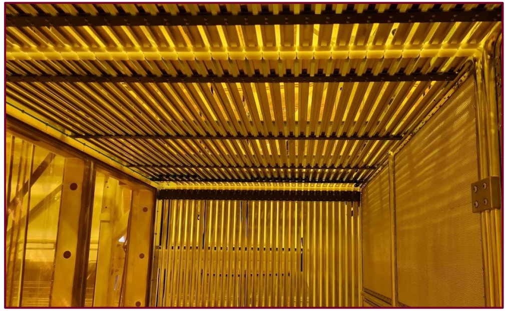


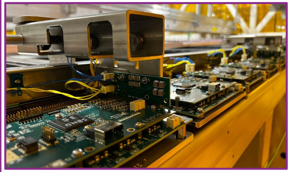

The cathode plane assembly (**CPA**) splits the detector into **two TPCs.**

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



Field cage (**FC**) surrounds the TPC. Aims to maintain 500 V/cm drift field.





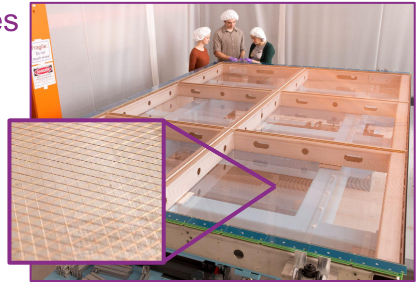
**Cold electronics** installed to optimise noise reduction in the readout.

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

Wire $\theta_Y$: **0, ± 60°**

Wire & plane spacing: **3 mm**

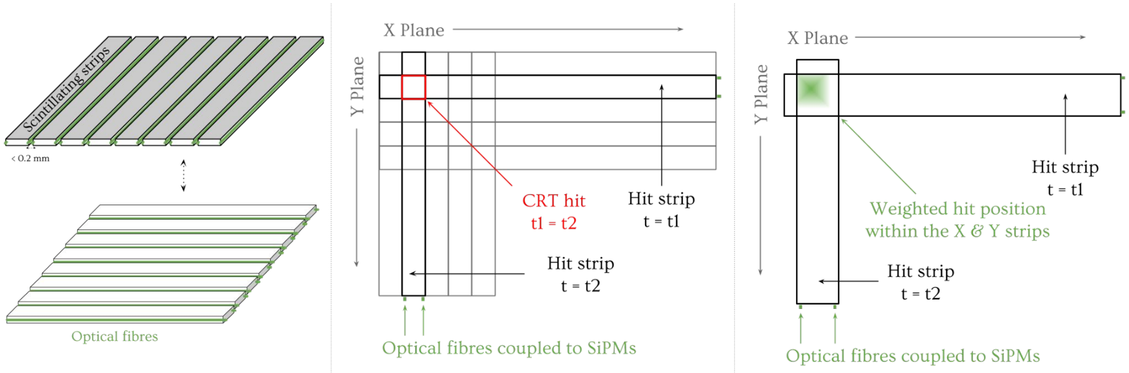
JINST 15, P06033 (2020)

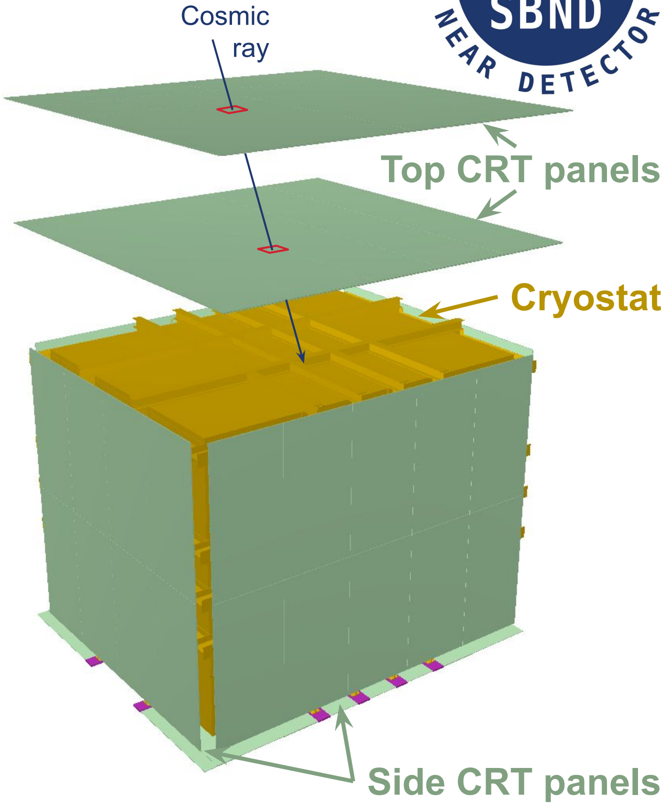


# The SBND detector systems: CRT

- The SBND is 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 physics programme

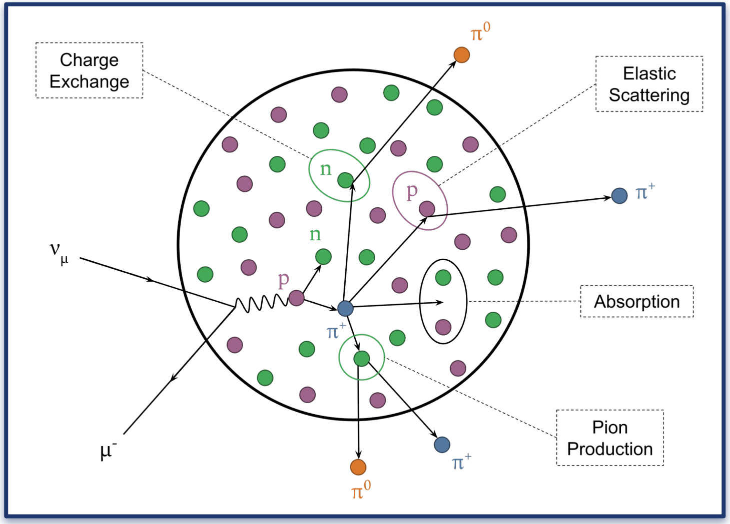
# Physics with the near detector

- 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.

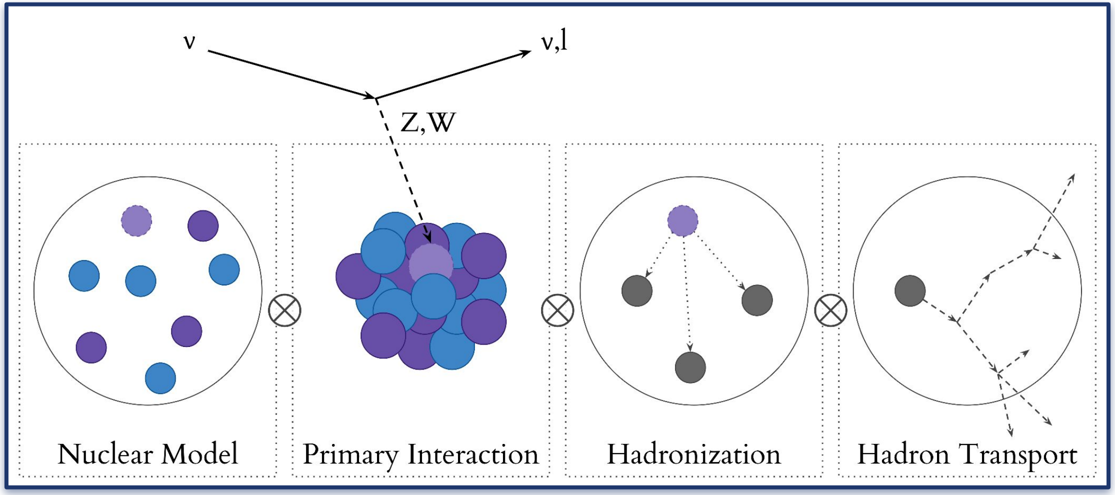
- These FSIs may modify the observed topological and kinematic final state of a given neutrino interaction.
- This makes reconstructing the initial neutrino interaction extremely challenging.



# 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.



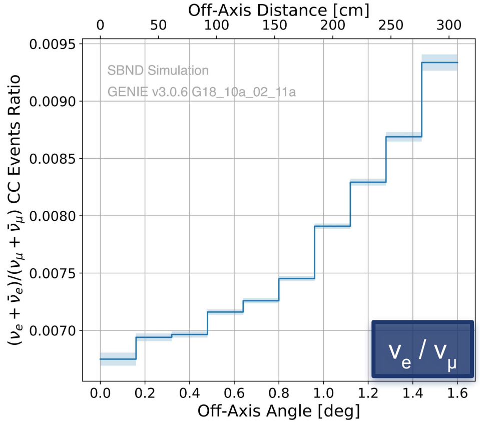
# Neutrino interactions by topology

- Statistical significance (< 0.5% statistical uncertainty) in charged current $\nu_\mu$ 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 dominant neutral current channels.
- $\nu_e$ 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 x10[20] POT.*

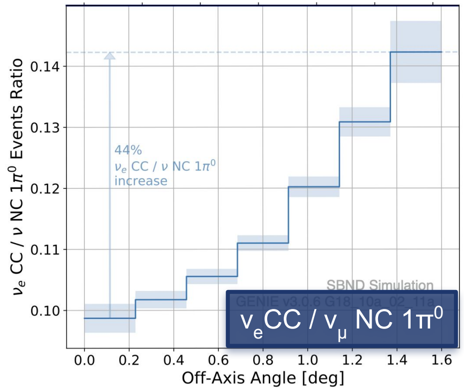
| Hadronic Final State | G18_10a_02_11a Num. Events | Stat. Err. |
|---|---|---|
| | $\nu_\mu$ *Charged Current* | |
| Inclusive | 6,057,919 | 0.04% |
| $0\pi$ + X | 4,419,116 | 0.05% |
| $0\pi$ 0p | 56,139 | 0.42% |
| $0\pi$ 1p | 2,506,924 | 0.06% |
| $0\pi$ 2p | 713,315 | 0.12% |
| $0\pi$ 3p | 263,577 | 0.19% |
| $0\pi > 3$p | 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% |
| $2\pi$ + 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% |
| | $\nu_\mu$ *Neutral Current* | |
| Inclusive | 2,459,237 | 0.06% |
| $0\pi$ | 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% |
| | $\nu_e$ | |
| Inclusive | 62,258 | 0.40% |

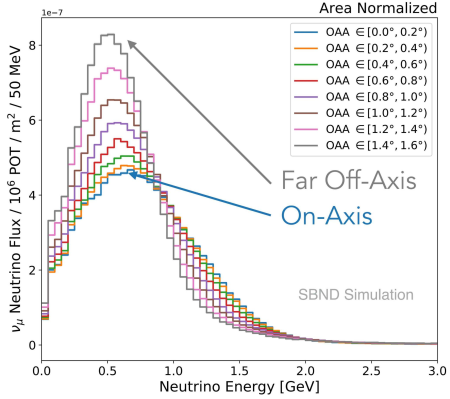
# SBND PRISM capabilities

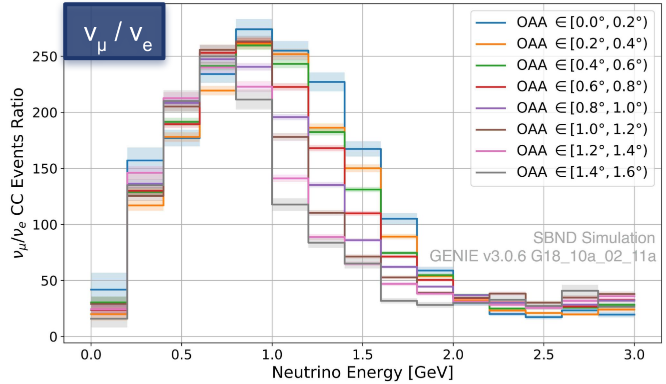



- Due to the difference in production mechanisms, the $\nu_e$ flux has a larger angular spread for a given parent energy than $\nu_\mu$.
- The PRISM concept can exploit this to,
  - Better understand $\nu_\mu$ & $\nu_e$ cross-section differences,
  - Reduce $\nu_\mu$ NC $\pi^0$ backgrounds to $\nu_e$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

Paper accepted in PRD!

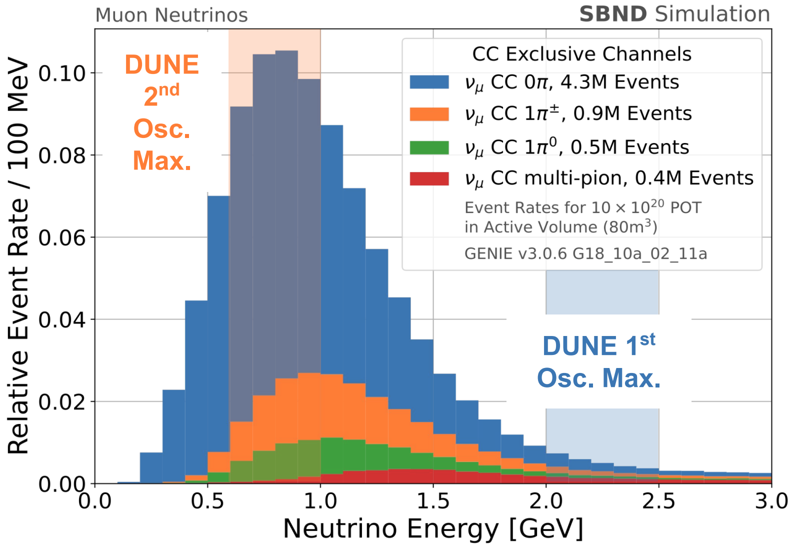


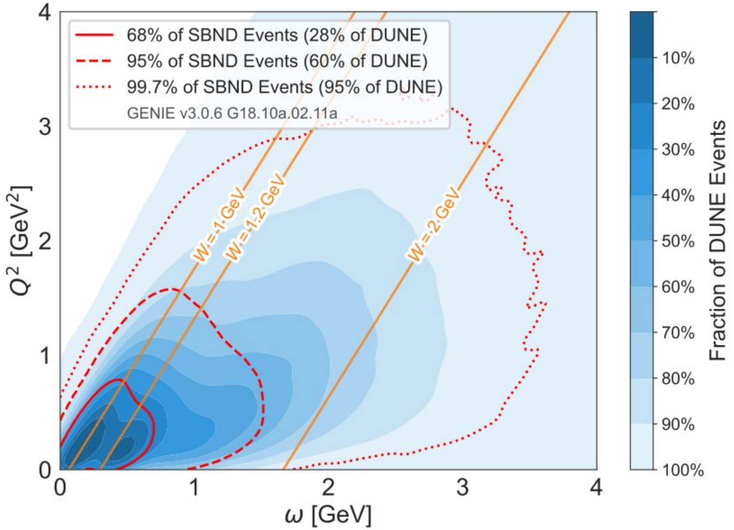



# DUNE phase-space coverage

- 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.



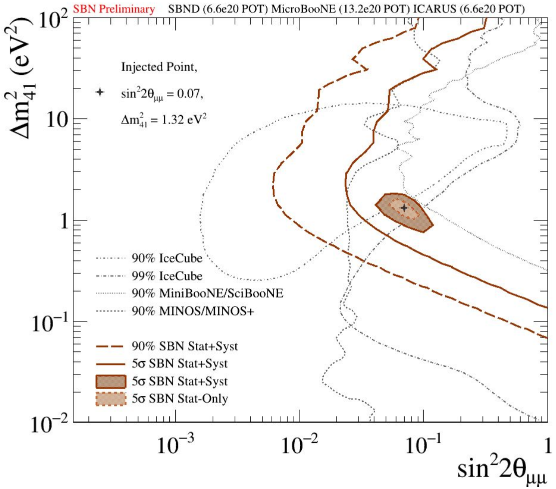



# Physics with the near detector

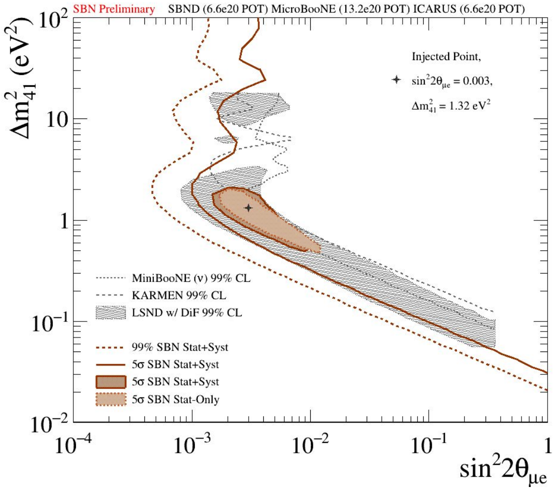
- SBND will provide the largest dataset of neutrino-Argon cross-section measurements in the few-GeV energy range to date.
- As the near detector in the SBN program, SBND will constrain the unoscillated component of the neutrino flux in the search for sterile neutrinos.

# SBN oscillations: Sensitivities

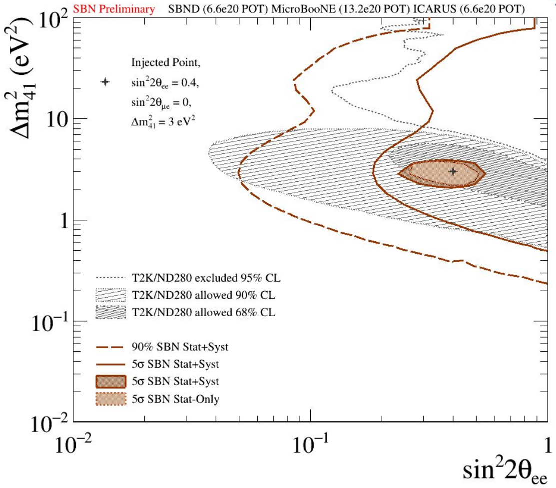
## $\nu_\mu$ disappearance




## $\nu_e$ appearance




## $\nu_e$ disappearance




**External datasets**

$\nu_\mu$ disappearance
IceCube $\nu_\mu$ 2020
MiniBooNE $\nu_\mu$ 2011
MINOS/MINOS+ $\nu_\mu$ 2017

$\nu_e$ appearance
MiniBooNE $\nu_e$ 2013
KARMEN $\nu_e$ 2002
LSND $\nu_e$ 2001

$\nu_e$ disappearance
T2K $\nu_e$ 2014

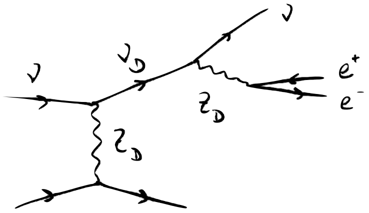
- As the near detector, SBND will **carefully constrain the interaction and flux systematics.**
- In **2/3 sterile oscillation channels**, SBN will be sensitive to the parameter space favoured by previous measurements at the **5σ confidence level.**
- Directly address existing tensions observed in the combined appearance and disappearance data.
- SBN will soon make the most-confident statement to date regarding the existence of sterile neutrinos.

# 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.

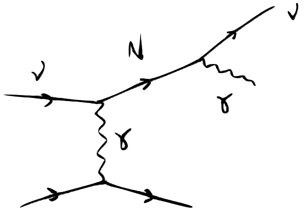
# Beyond the Standard Model

### Dark Neutrinos



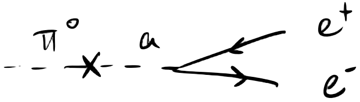
Bertuzzo, Jana, Machado, Zukanovich, PRL 2018, PLB 2019
Arguelles, Hostert, Tsai PRL 2019
Ballett, Pascoli, Ross-Lonergan PRD 2019
Ballett, Hostert, Pascoli PRD 2020

### Transition Magnetic Moment




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

### Axion-like Particles

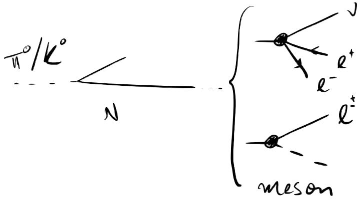


Kelly, Kumar, Liu PRD 2021
Brdar et al PRL 2021

Alternative explanations to the MiniBooNE excess
and other BSM scenarios

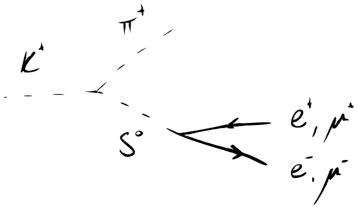
Not an exhaustive list
Some diagrams credit: Pedro Machado
Slide credit: Marco Del Tutto

### Heavy Neutral Leptons



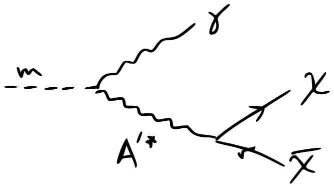

Ballett, Pascoli, Ross-Lonergan JHEP 2017
Kelly, Machado PRD 2021

### Higgs Portal Scalar



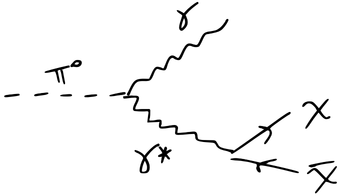
Patt, Wilczek 2006
Batell, Berger, Ismail PRD 2019
MicroBooNE 2021

### Light Dark Matter



Romeri, Kelly, Machado PRD 2019

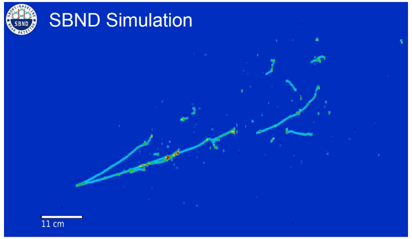
### Millicharged Particles



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

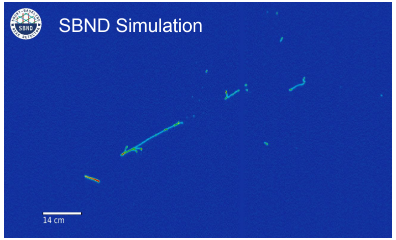
# BSM signatures in SBND

## Dark Neutrinos



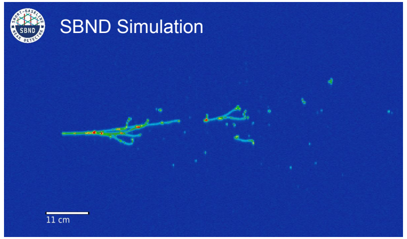

$e^+e^-$ pair with or w/o hadronic activity

## Transition Magnetic Moment




Photon shower and hadronic activity

## Axion-like Particles




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

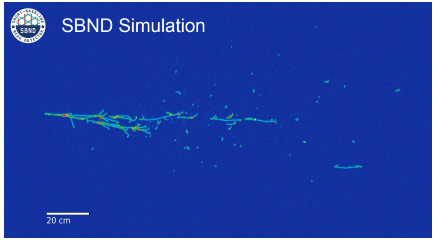
Example signatures and event displays for various BSM scenarios

Not an exhaustive list

Some diagrams credit: Pedro Machado

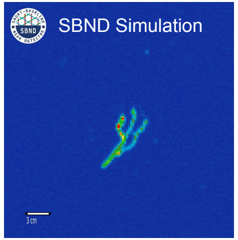
Slide credit: Marco Del Tutto

## Heavy Neutral Leptons



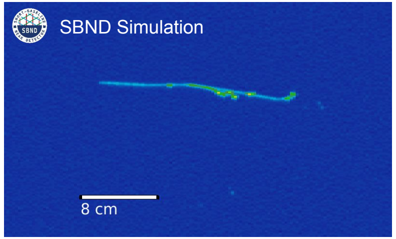

$e^+e^-$, $\mu^+\mu^-$ or $\mu\pi$

## Higgs Portal Scalar



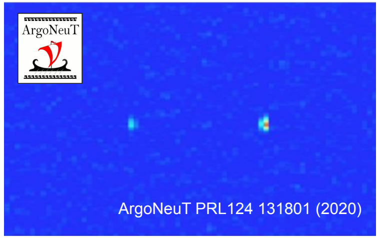

$e^+e^-$ or $\mu^+\mu^-$, no hadronic activity

## Light Dark Matter




Electron scattering

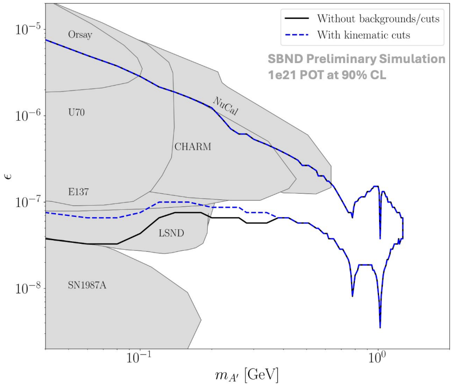
## Millicharged Particles



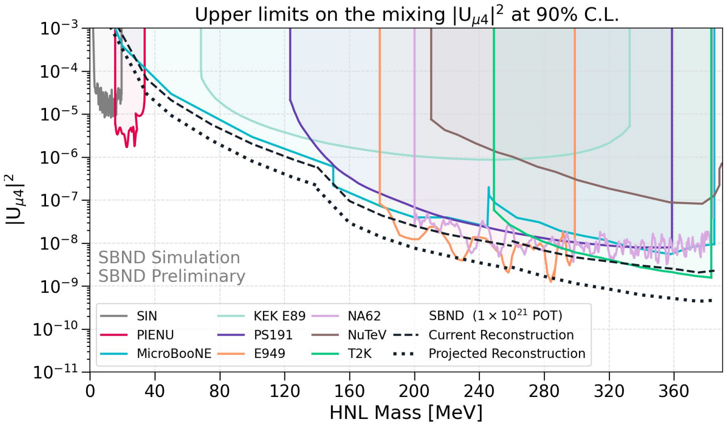

Blips/faint tracks

# BSM sensitivities in SBND

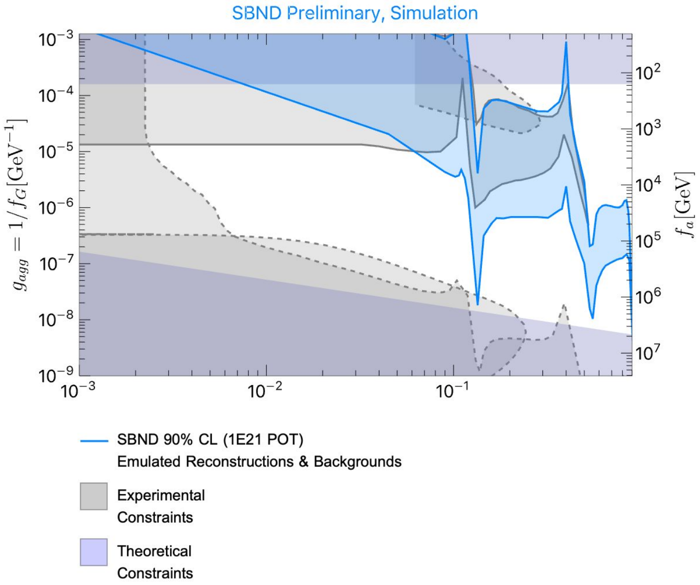
## Dark photons




## HNLs




## Axion-like particles

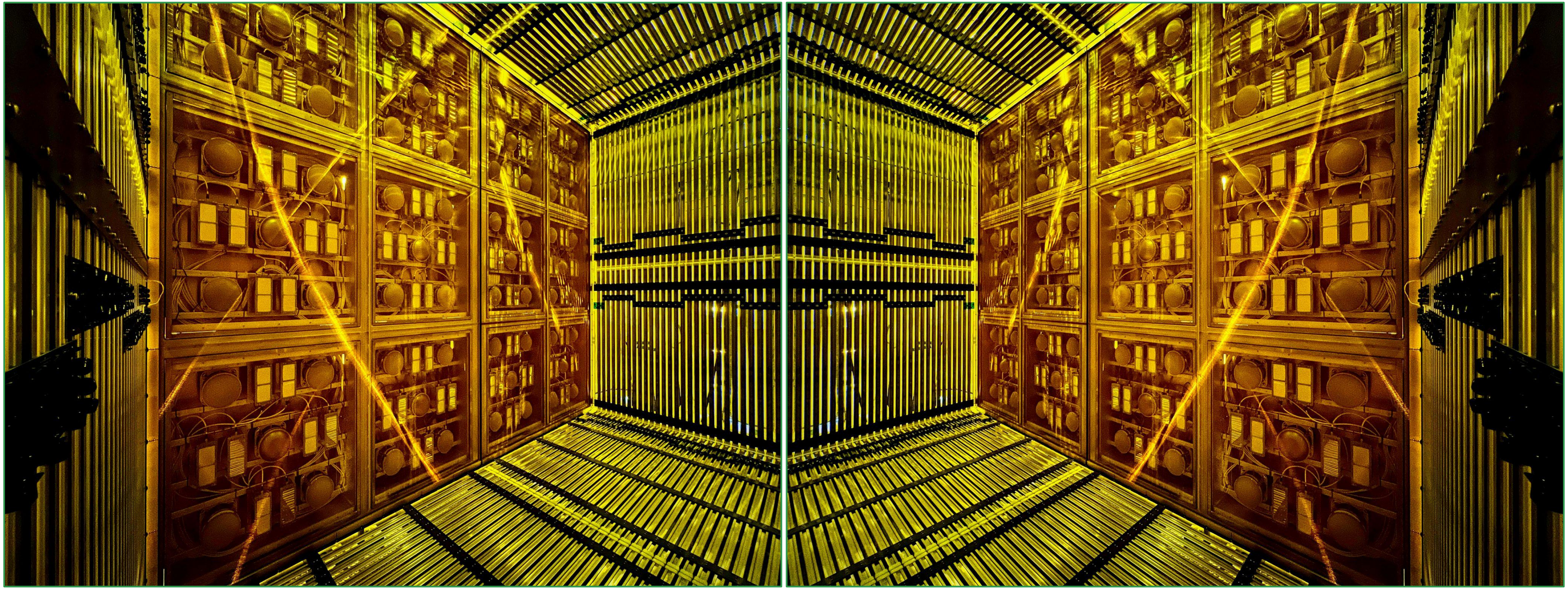



Paper in review!

# The road to SBND

# TPC & PDS

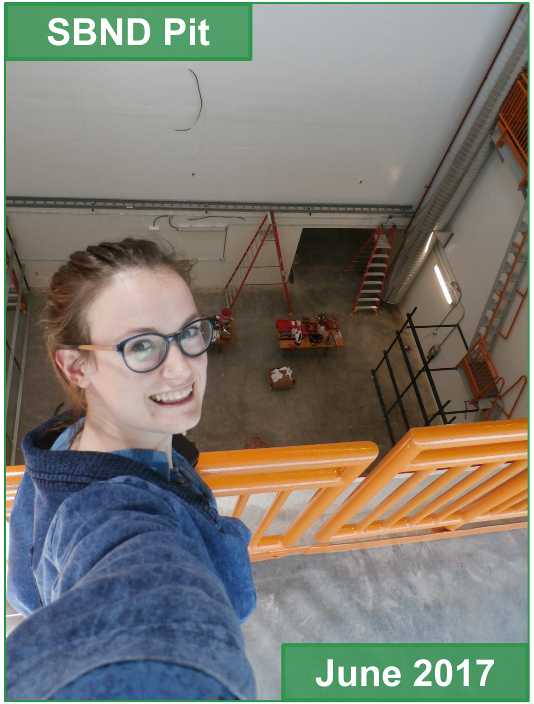
September 2022: **Completed the SBND TPC & PDS**



# Cryostat

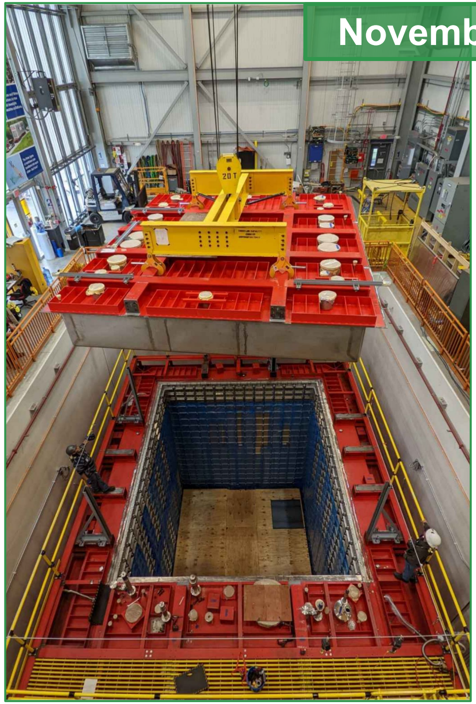
## October 2022: **Completed the SBND cryostat**

SBND Pit



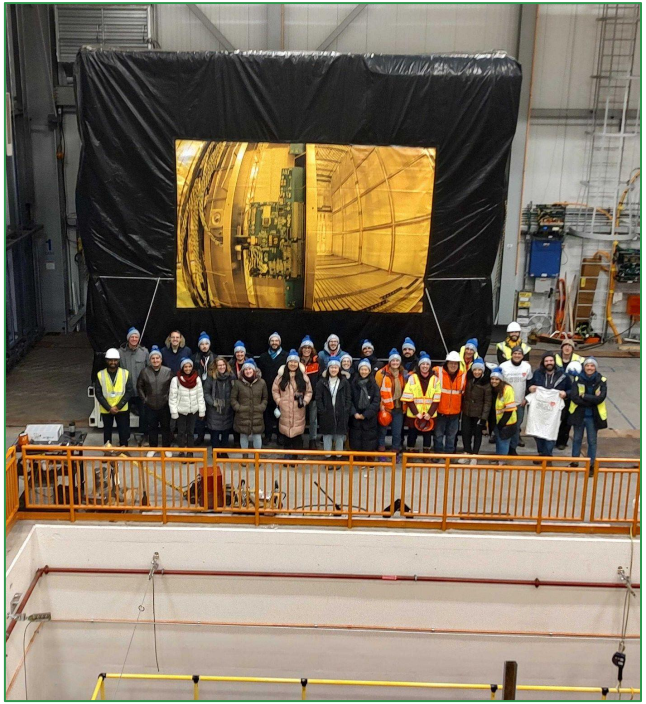
June 2017

November 2022



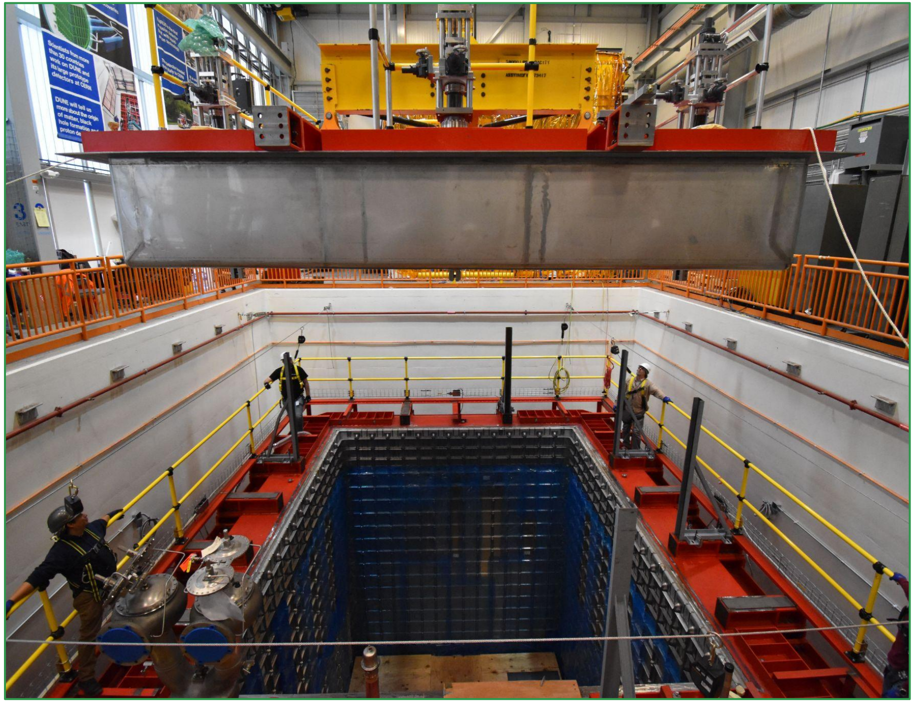
# Detector transport

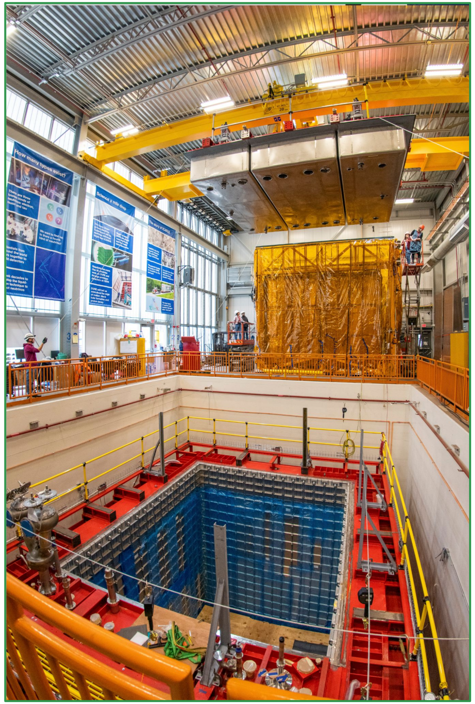
## December 2022: **Transported the TPC across Fermilab**



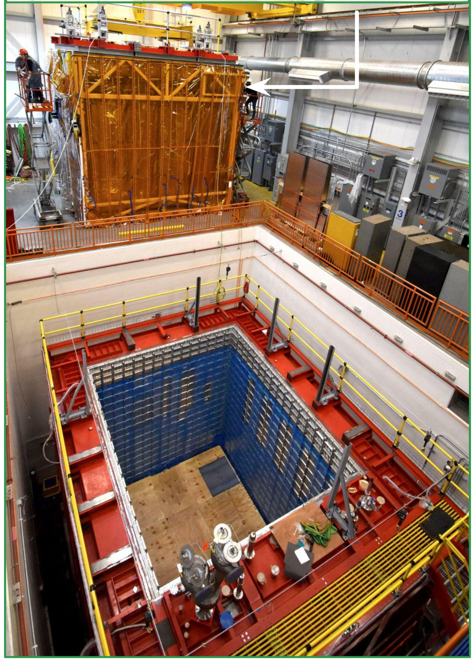
# Top-cap installation

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



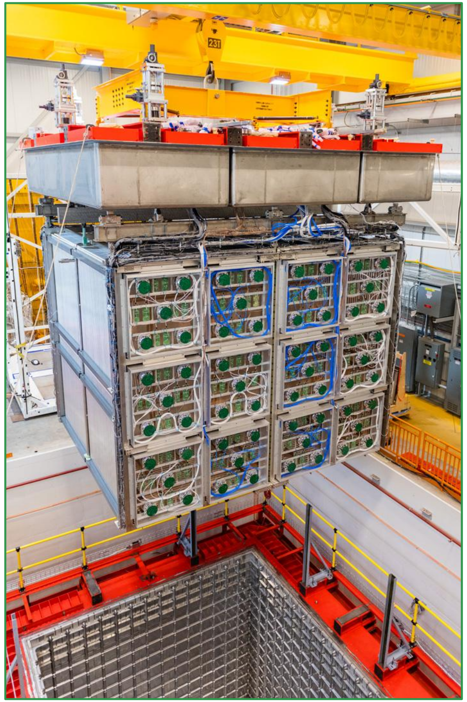


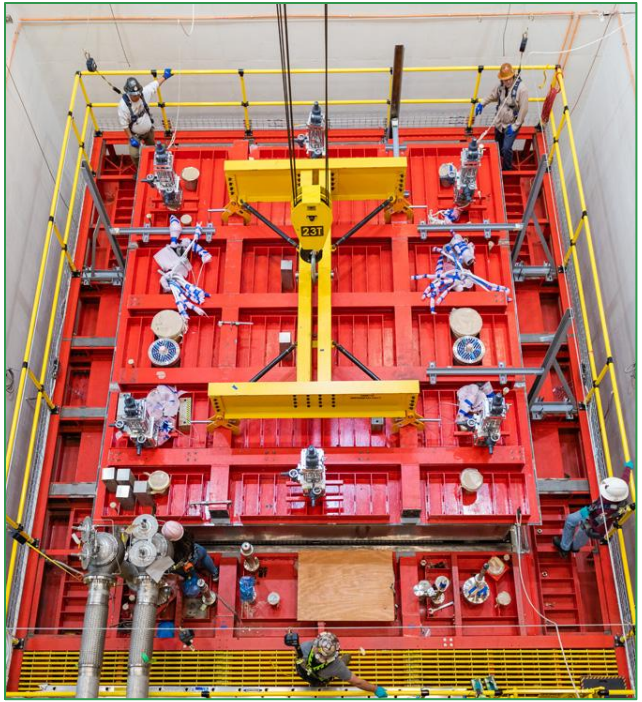
*Assembly & Transport Fixture



# Detector lowered into cryostat

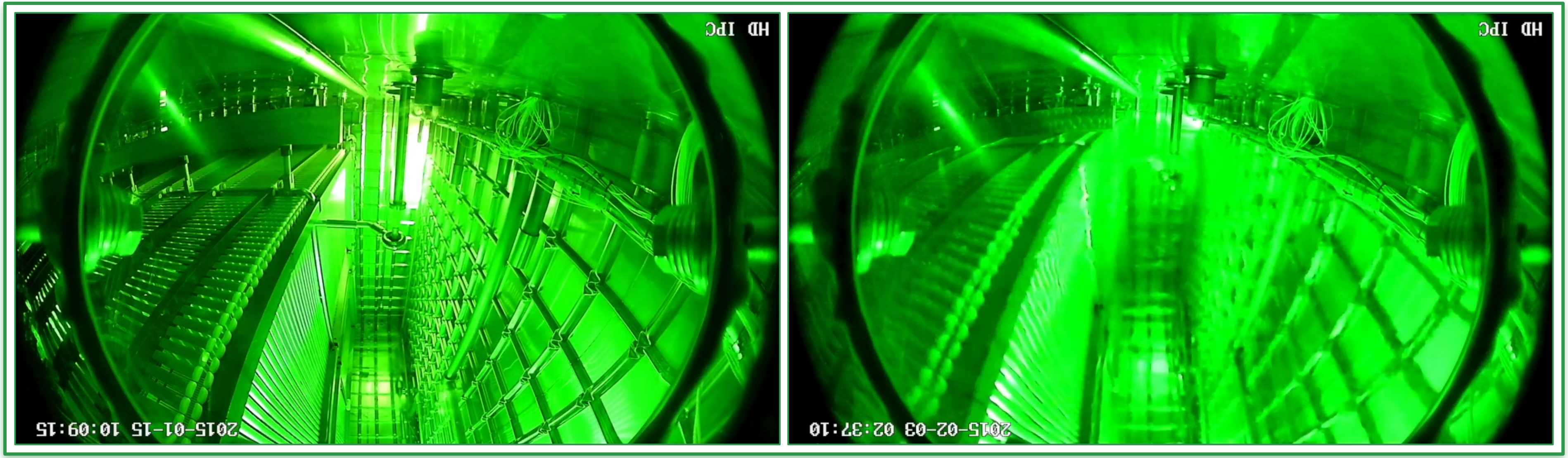
April 2023: **Detector lowered into the cryostat**





# Liquid argon filling

March 2024: **Detector filled with liquid argon**

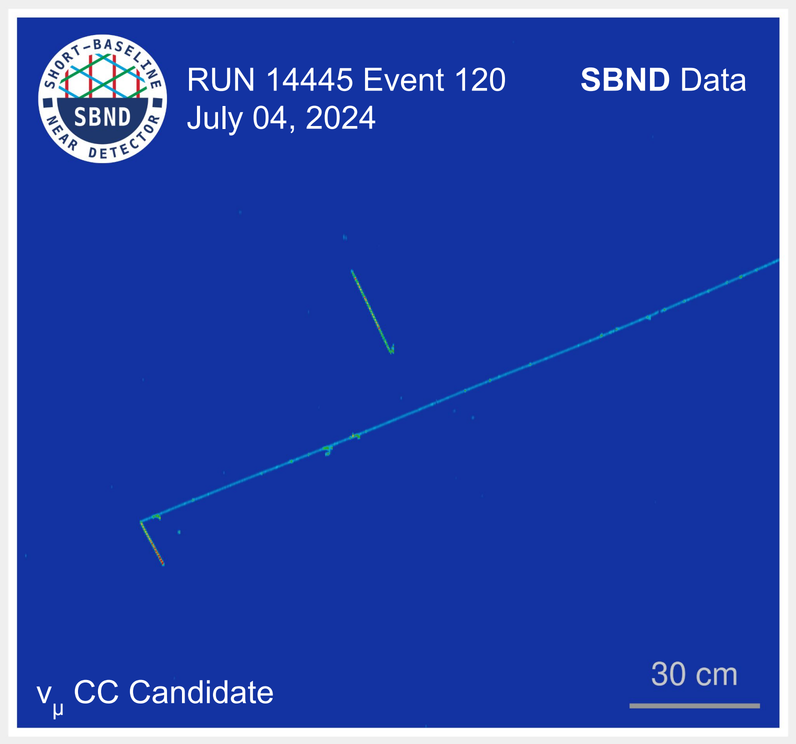


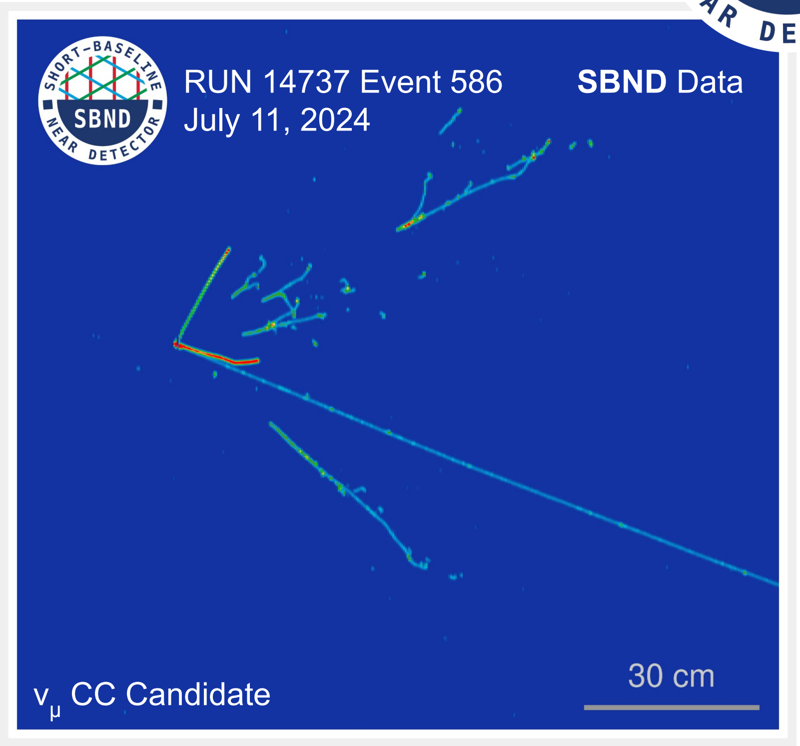
# TPC high voltage ramped up successfully

## July 2024: **Ramped high voltage up to 500 V/cm successfully!**

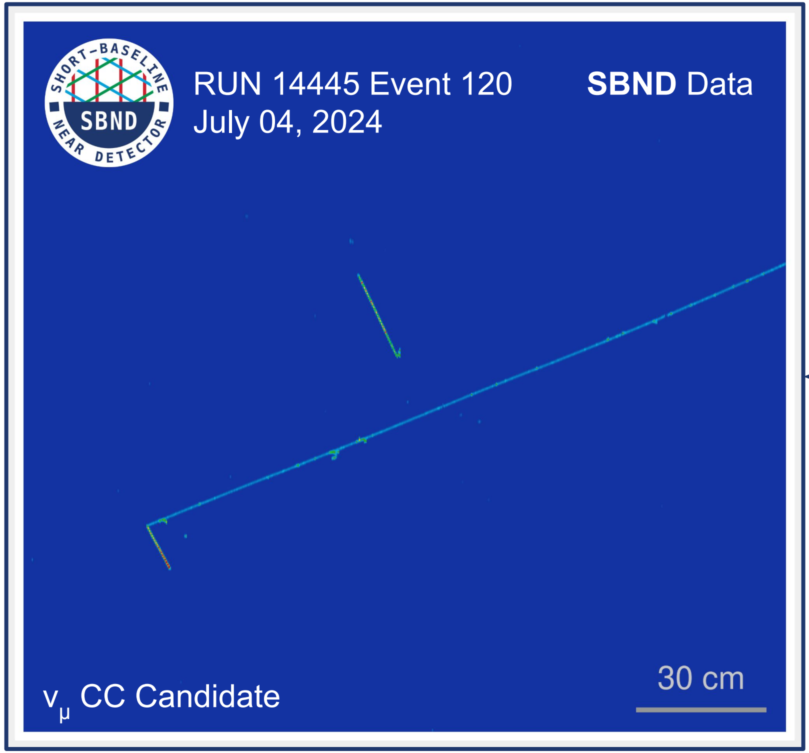
# Neutrinos!

# REAL Neutrinos interacting in the TPC



# REAL Neutrinos interacting in the TPC





Nice and clean, simple to interpret

Long track: **Muon**

Short track: **Proton**

Angular separation: **Almost 90º**

*(energy shared almost equally between muon and proton)*

Most-likely interaction: **CC QE**

*(charged-current quasielastic scattering)*

# REAL Neutrinos interacting in the TPC


More complex and difficult to interpret

Long track: **Muon**

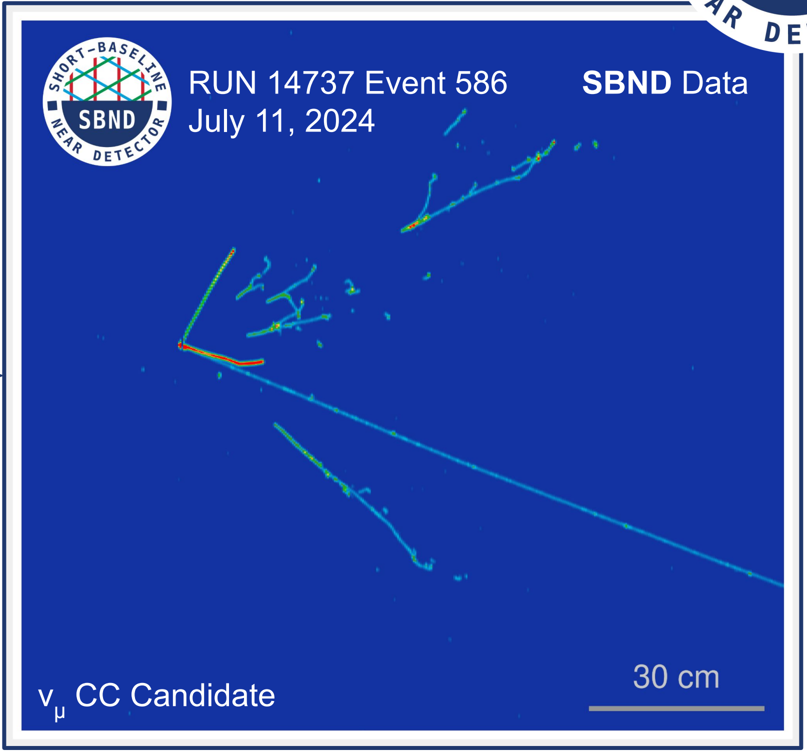
Short tracks: **Protons/charged pions**

EM showers: **Neutral pions**

*($\pi^0 \rightarrow \gamma\gamma$)*

Most-likely interaction: **CC Res**

*(charged-current resonant pion production)*



# REAL Neutrinos interacting in the TPC



In short:

**Neutrino interactions on argon are pretty, but they’re *tricky.***

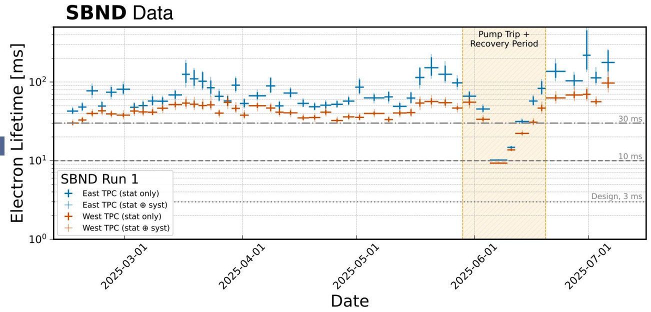
But that’s half the fun.

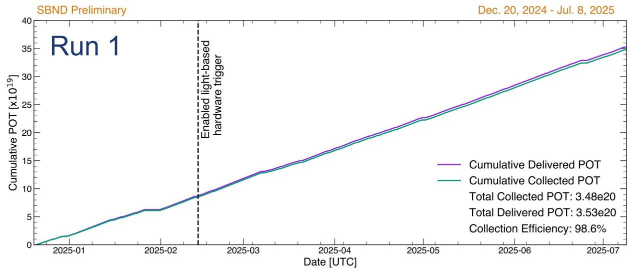
# Current status & near future

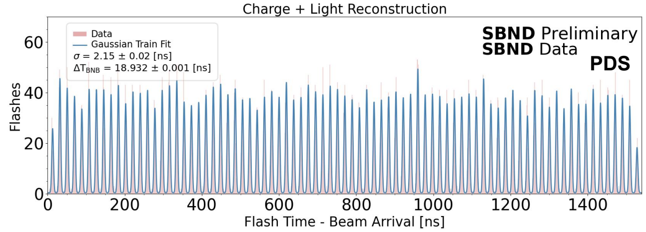
# Detector performance

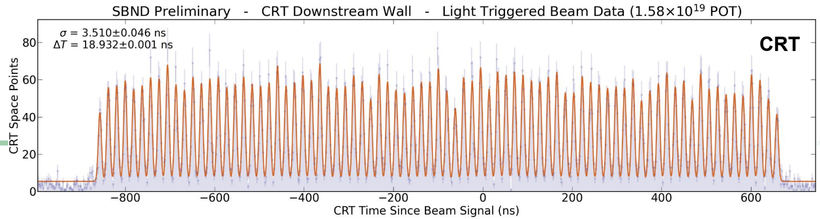
- The electron lifetime is consistently **well-above nominal**,
  - This indicates high argon purity.
- POT collection efficiency is **> 98%**,
  - A testament to the dedication of our shifters.
- **Nanosecond** timing resolution from both the PDS and the CRT systems,
  - Crucial for background rejection & exotic/BSM searches.

Papers in review!



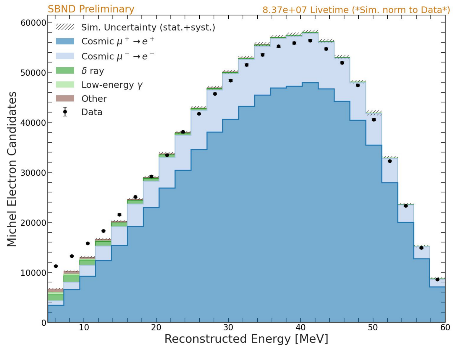



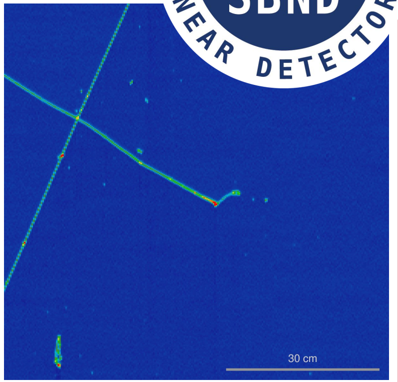



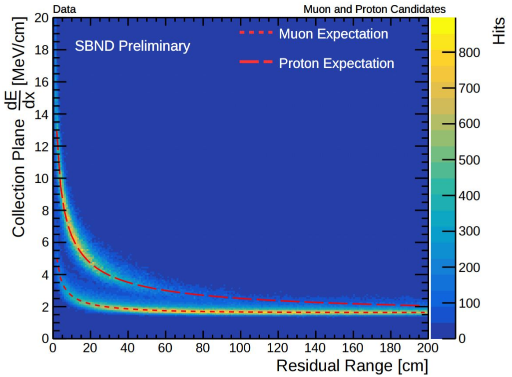



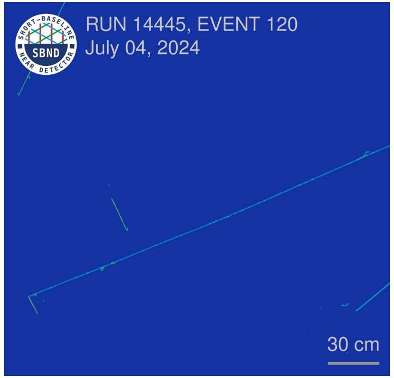
# Detector performance

- Sensitive to low energy activity,
  - Michel electron reconstruction.
- Excellent charge calorimetry,
  - Muon-proton separation.
- Consequently, we are able to record **high-resolution images** of complex neutrino interactions as planned,
  - Giving our reconstruction algorithms high-quality input data,
  - Crucial for **precision** physics.





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# Near(ish)-term upcoming measurements

**Cross-sections**

- **$\nu_\mu$ CC.**
  - $\nu_\mu$ CC **Inclusive.**
  - $\nu_\mu$ CC **$0\pi$ 1p.**
  - $\nu_\mu$ CC **$0\pi$ 2p.**
  - $\nu_\mu$ CC **$1\pi^{\pm}$.**
  - $\nu_\mu$ CC **$1\pi^{0}$.**
  - $\nu_\mu$ CC **1η.**
  - $\nu_\mu$ CC **COH.**
- **$\nu_\mu$ NC.**
  - $\nu_\mu$ NC **$0\pi$ 1p.**
  - $\nu_\mu$ NC **$1\pi^{0}$.**
- **$\nu_e$ CC** Inclusive.
  - $\nu_e$ CC **$1\pi^{\pm}$.**

**Oscillations**

- **$\nu_\mu$ disappearance** with **CC inclusive.**
- **$\nu_\mu$ disappearance** with **exclusive CC.**
- **$\nu_e$ appearance** with **CC inclusive.**
- Joint **$\nu_\mu$ disappearance & $\nu_e$ appearance.**
- **Neutral current** oscillation searches.

**Many** papers in the works!

**BSM**

- **Dark photons.**
- **Axion-like particles.**
- **Heavy Neutral Leptons.**
- **Higgs Portal Scalars.**

# Summary

- An extremely exciting time for SBND,
  - The physics programme is vast,
  - First neutrino data in July 2024 and it looks **excellent,**
  - SBND measurements will ultimately pave the way for **DUNE**.
- Exciting measurements coming up,
  - First-data **cross-section** results,
  - First-data **BSM** limits,
  - First-data **sterile** searches,
  - **Many papers** currently in review.

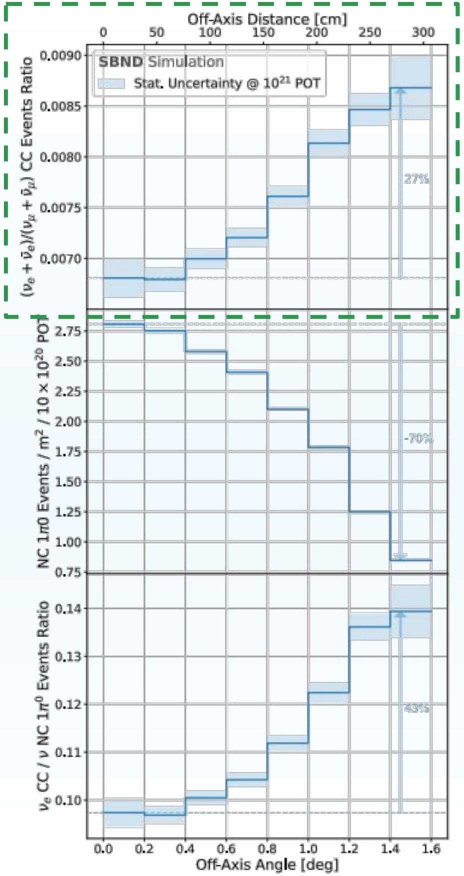

Sheffield, June 2025

# Thank you for listening!

# SBND PRISM

Ratio of muon-to-electron-neutrino CC events in SBND as a function of the off-axis angle.

$\nu_e/\nu_\mu$ asymmetry provides an extra handle for cross-section measurements and oscillation analyses.



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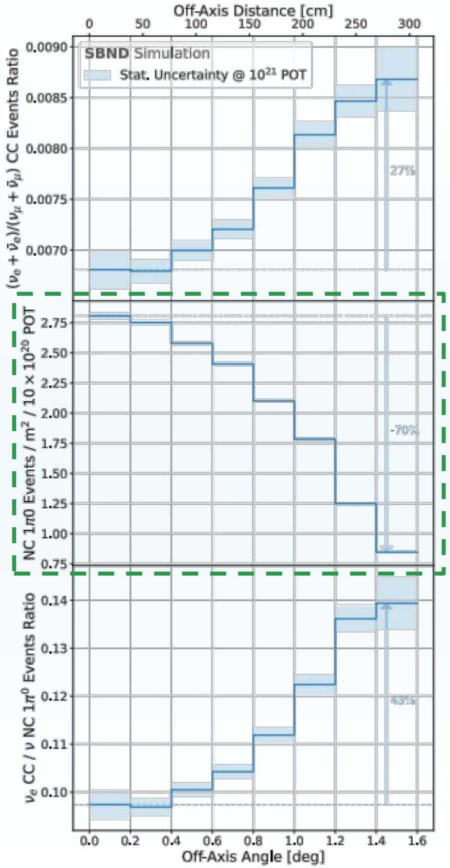



Number of NC $\pi^0$ neutrino events per square meter decrease rapidly moving from on-axis to off-axis.

This happens because NC $\pi^0$ require a higher-energy neutrino to be produced, but the high-energy tail of the neutrino flux reduces quickly with off-axis angle.

Major background mitigation tool.

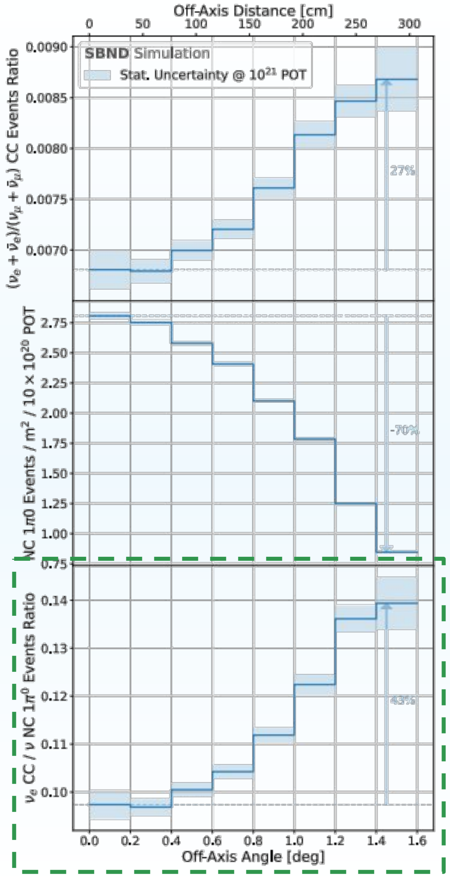
# SBND PRISM

Ratio of muon-to-electron-neutrino CC events in SBND as a function of the off-axis angle.

$\nu_e/\nu_\mu$ asymmetry provides an extra handle for cross-section measurements and oscillation analyses.

The number NC $\pi^0$ events drops more rapidly with the off-axis angle compared to the number of $\nu_e$ CC.

This can be used to characterize or mitigate backgrounds to $\nu_e$ events - an important SBND signal.

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