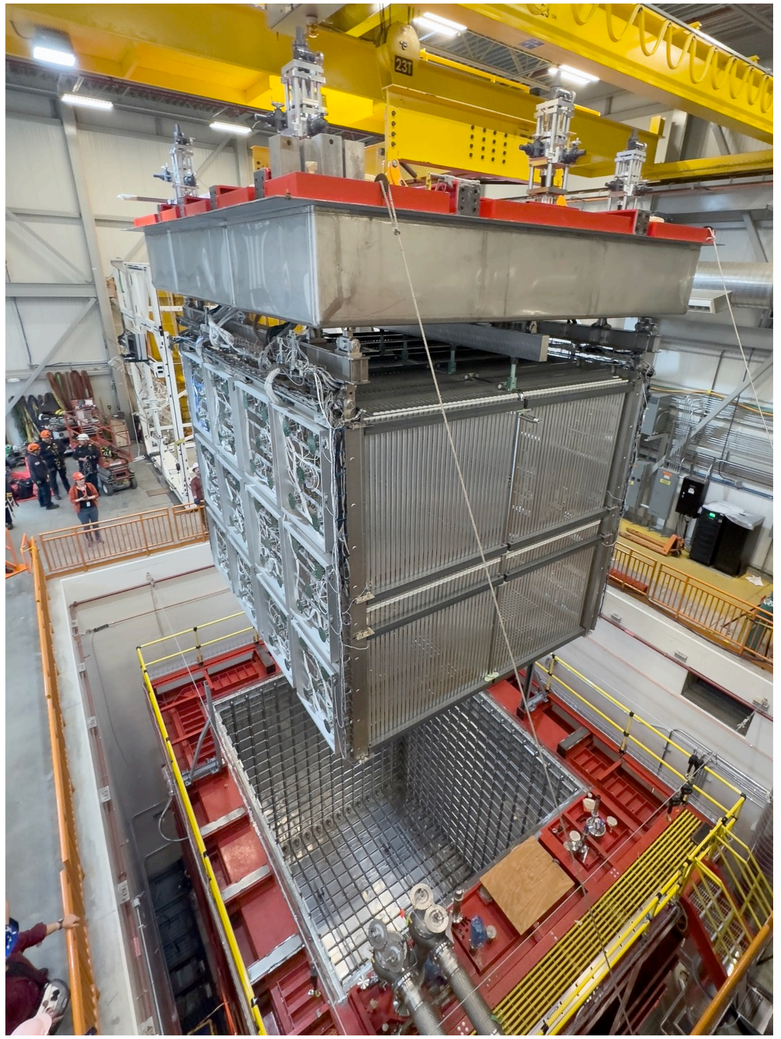
Status of the Short-Baseline Near Detector at Fermilab

Inés Gil Botella (CIEMAT)

on behalf of the SBND collaboration

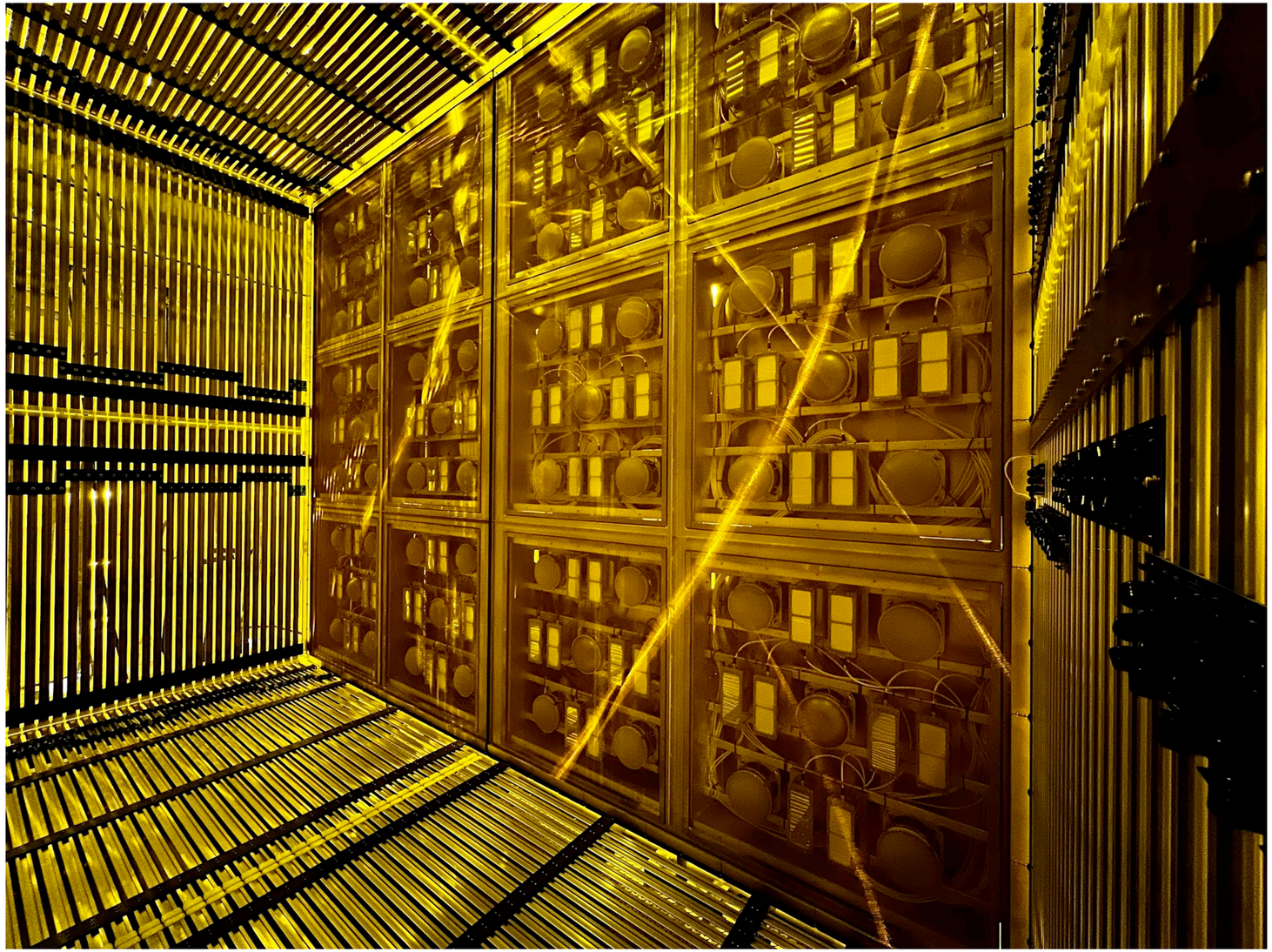


SUSY 2024
Theory meets Experiment

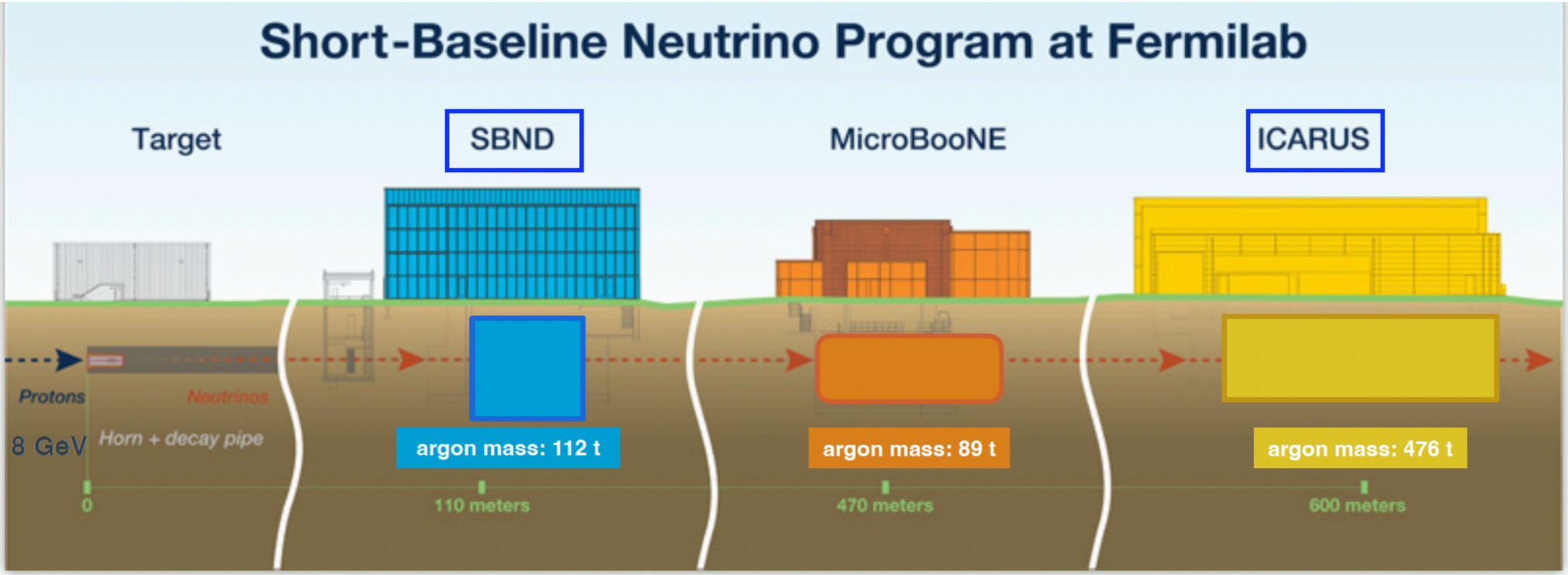
The 31st International Conference on Supersymmetry and Unification of Fundamental Interactions
10-14 June 2024
IFT (Madrid, Spain)

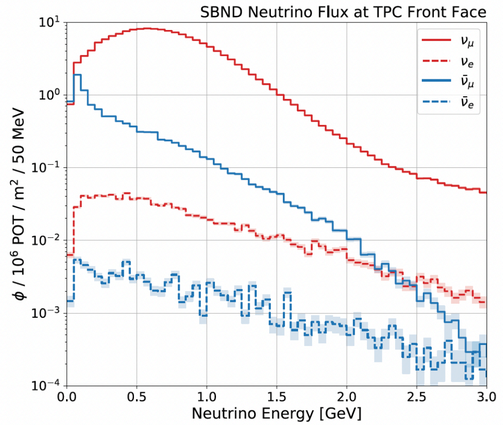
Outline

- SBN Program at Fermilab
- SBN Physics
- SBND LAr TPC Detector
- BSM in the Booster Neutrino Beam
  - Heavy Neutral Leptons
  - Light Dark Matter
  - Model independent searches
  - Millicharged particles
  - Dark neutrino with cosmic tagger
- Summary



Short-Baseline Neutrino Program @FNAL





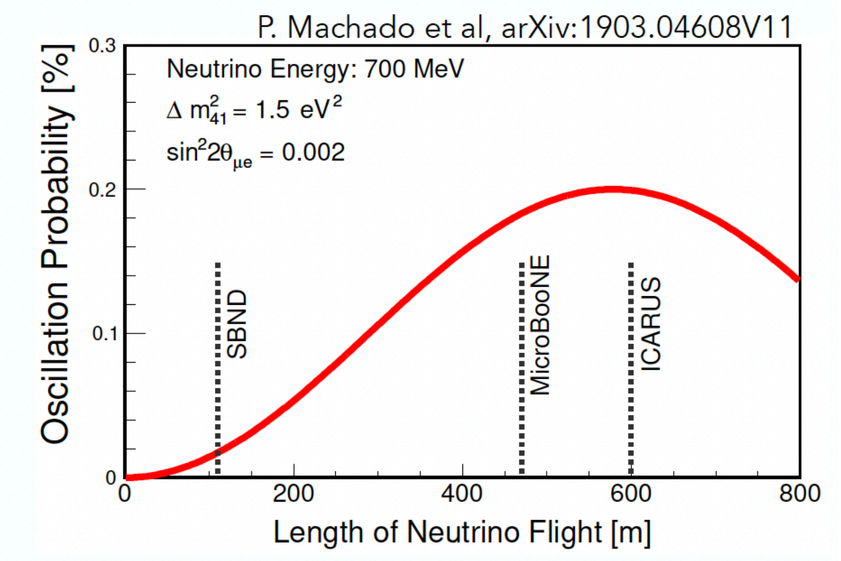
2015-2021
Large production of scientific results

Beam composition:
ν_μ (93.6%)
$\bar{\nu}_\mu$ (5.9%)
ν_e+$\bar{\nu}_e$ (0.5%)

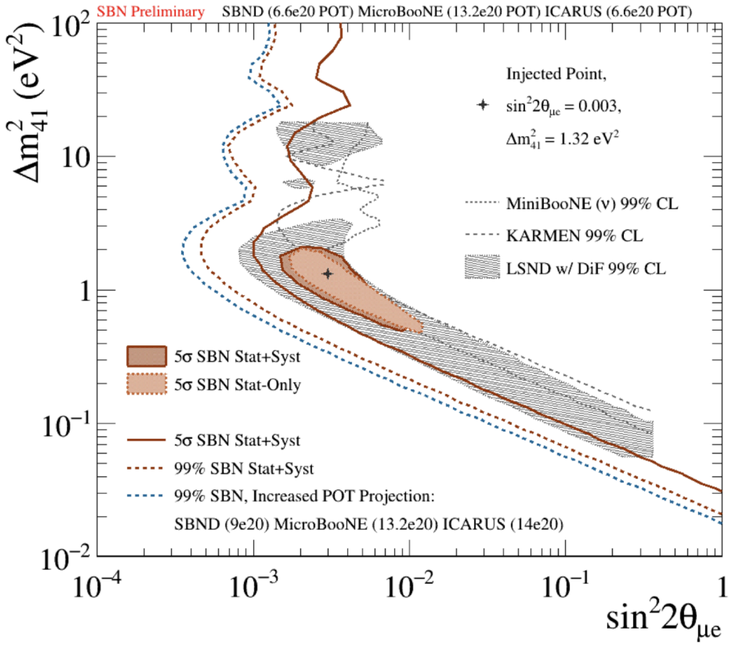
Mean ν_μ energy: ~0.8 GeV

SBN physics program

- **eV-scale sterile neutrinos**: searches for physics beyond the three-neutrino mixing with multiple-detectors at different baselines
- **Neutrino-argon interactions**: with an order of magnitude more data than is currently available
- **New physics scenarios**: study alternative explanations of the short-baseline anomalies and other Beyond Standard Model scenarios
  - Many ideas for new searches emerging from collaboration with theory colleagues - *P. Machado, O. Palamara, D. Schmitz, Annu. Rev. Nucl. Part. Sci. 69 363-387 (2019)*



ν_e appearance



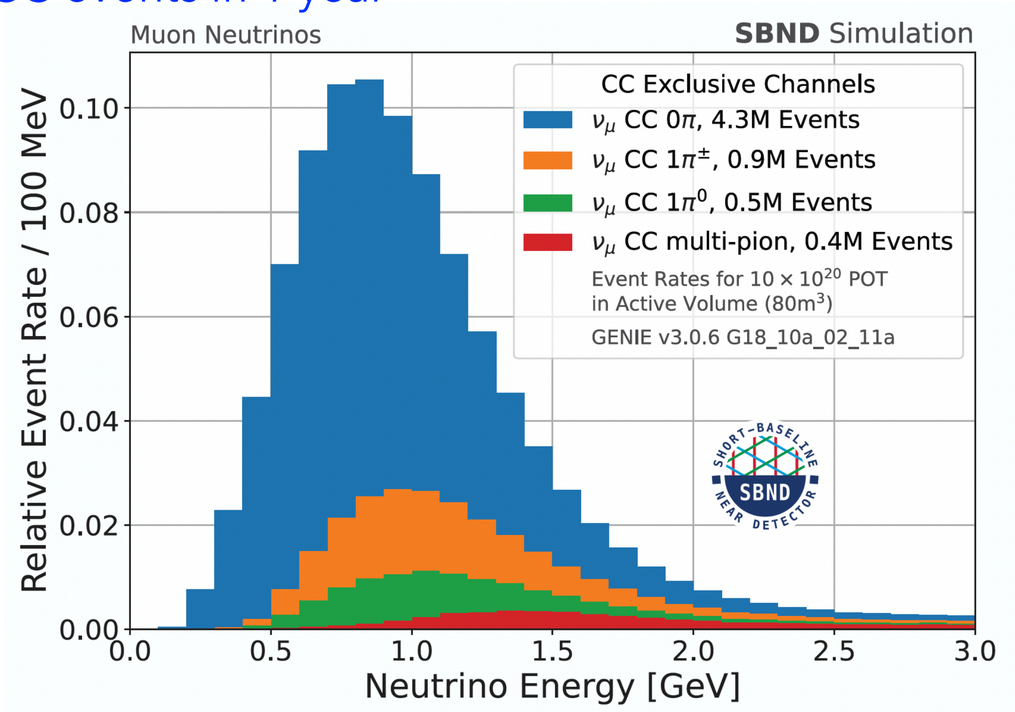
Cross-section measurements

- SBND data will enable a generational advance in the study of **neutrino-argon interactions in the GeV energy range**, with low thresholds for particle tracking and calorimetry and enormous statistics.
- SBND will have the **largest dataset of ν-Ar interactions** and will do high-statistics measurements of many signatures and can observe rare channels.

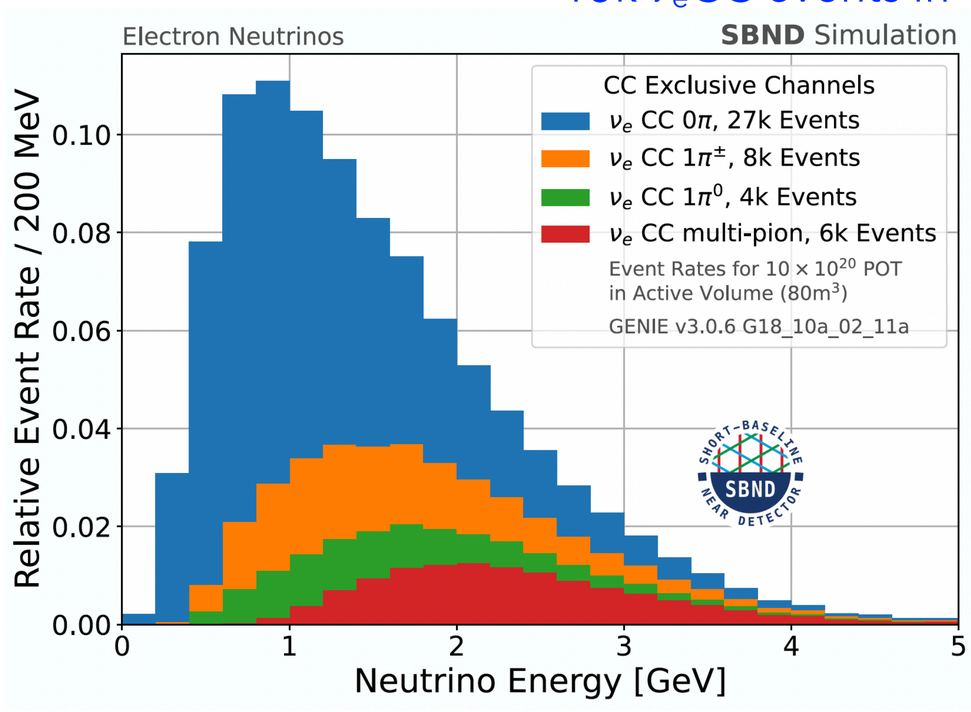
SBND will record **20-30x more neutrino-argon interactions than is currently available**

SBND will observe up to 7000 ν-events/day!

2M ν_μCC events in 1 year

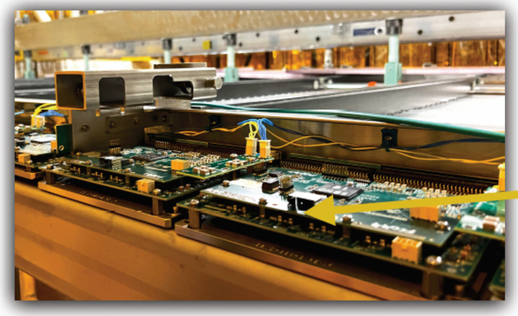


15k ν_eCC events in 1 year

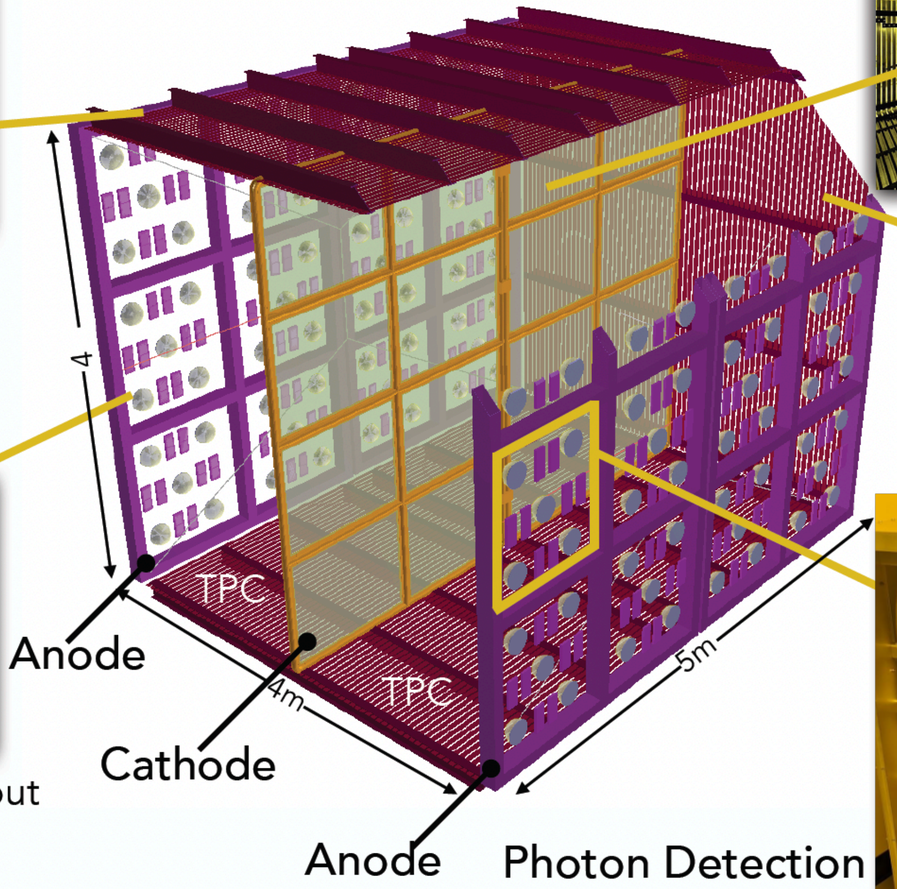


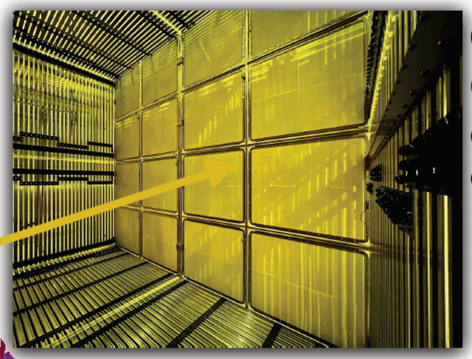
The Short-Baseline Near Detector

TPC Cold electronics



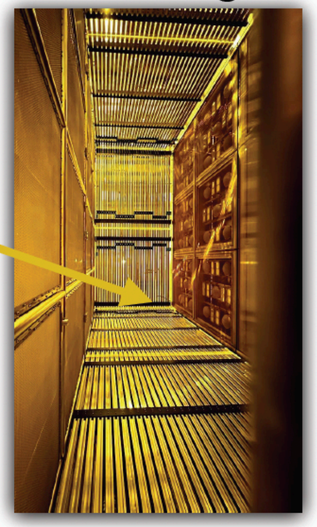
Two Time Projection Chambers
Total dimension: 4m x 4m x 5m

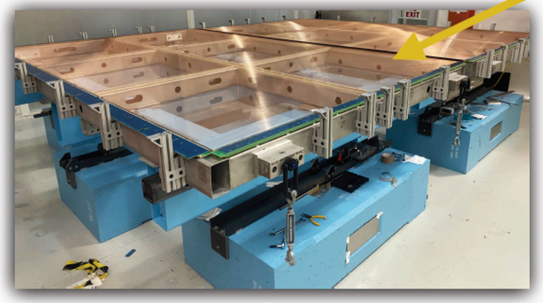




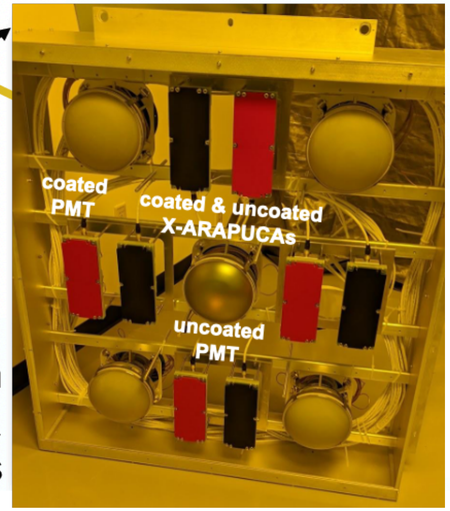
CPA - Cathode covered with TPB coated reflectors

Field Cage





APA - wire planes - 3 readout planes, ~11000 wires



Photon Detection Systems: 120 PMTs, 192 X-Arapucas

SBND's dual Photon Detection System:

96 TPB-coated + 24 uncoated PMTs

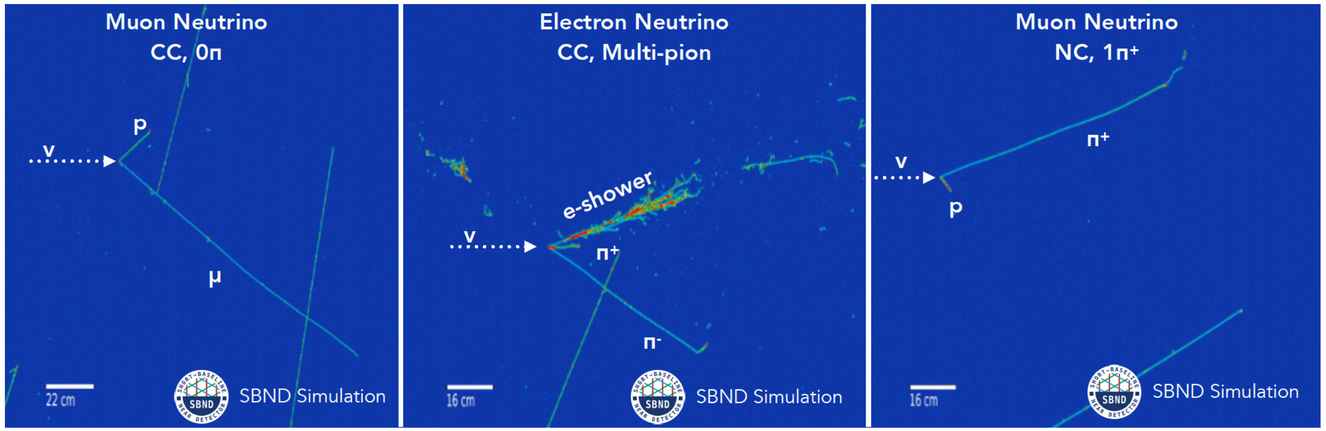
96 p-TP coated + 96 uncoated X-ARAPUCAs

SBND LAr TPC capabilities and status

- **Large mass LArTPC:**
  - 3D reconstruction with **mm-level resolution**
  - Fine-granularity **calorimetry**
  - **Excellent particle identification** with dE/dx information
  - Low energy thresholds, **sub-MeV to GeV**
- **Photon Detection System (PDS):**
  - Scintillation & reflected visible light => **high and uniform light yield** and **excellent timing resolution**
- **Cosmic Ray Tagger (CRT):**
  - Timing and position resolution allows for **triggering** on entering/ exiting particles

All of these features make SBND a multi-purpose detector that can look for **Beyond the Standard Model new physics**:

- Rare processes
- Low-energy signatures
- Challenging topologies



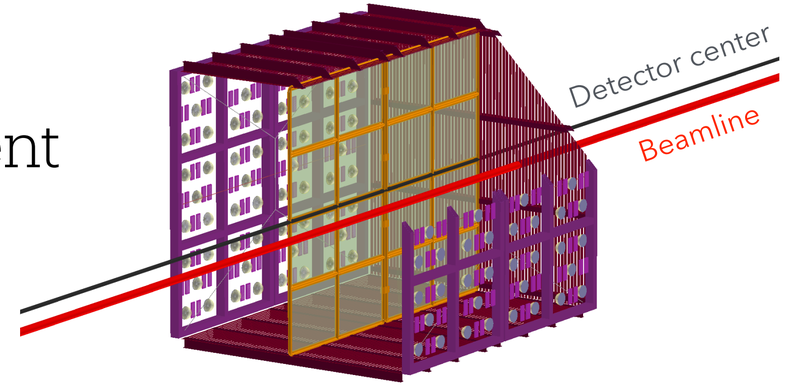
Status

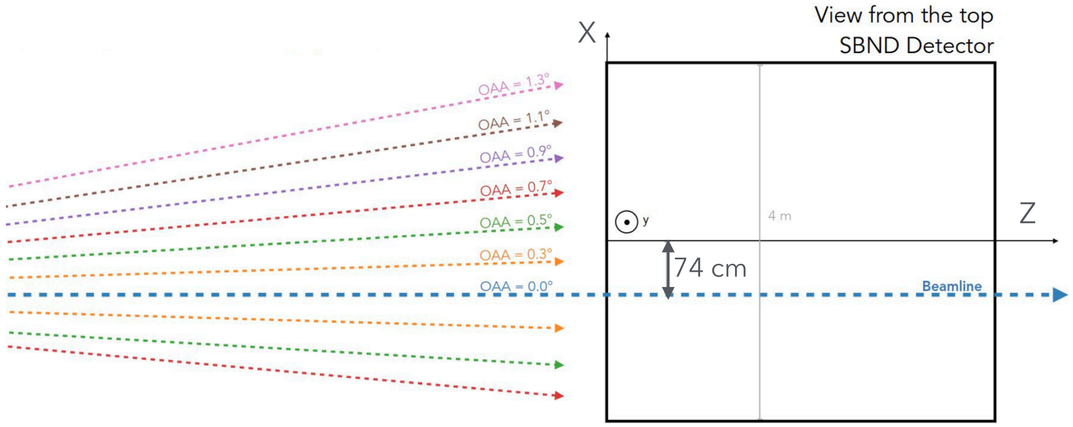
- Detector completed in **Sept 2022**
- Detector installation in **April 2023**
- Detector filled with LAr in **March 2024**
- Detector **being commissioned & calibrated**

SBND-PRISM

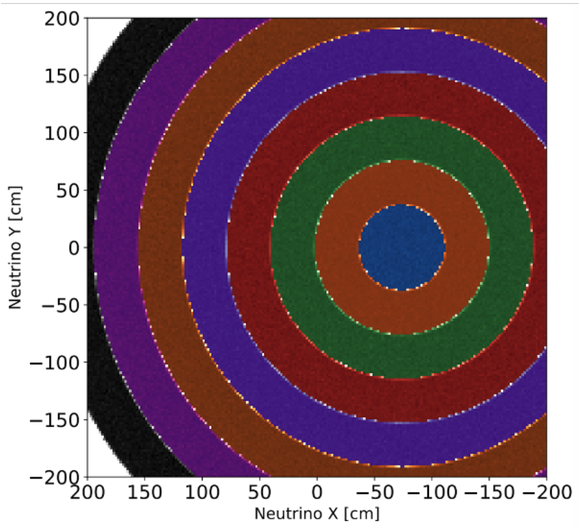
Precision **R**eaction **I**ndependent **S**pectrum **M**easurement

- SBND is very close (110 m) to the neutrino source and not perfectly aligned with the neutrino beamline (~74 cm off)
- SBND can sample multiple off-axis fluxes with the same detector

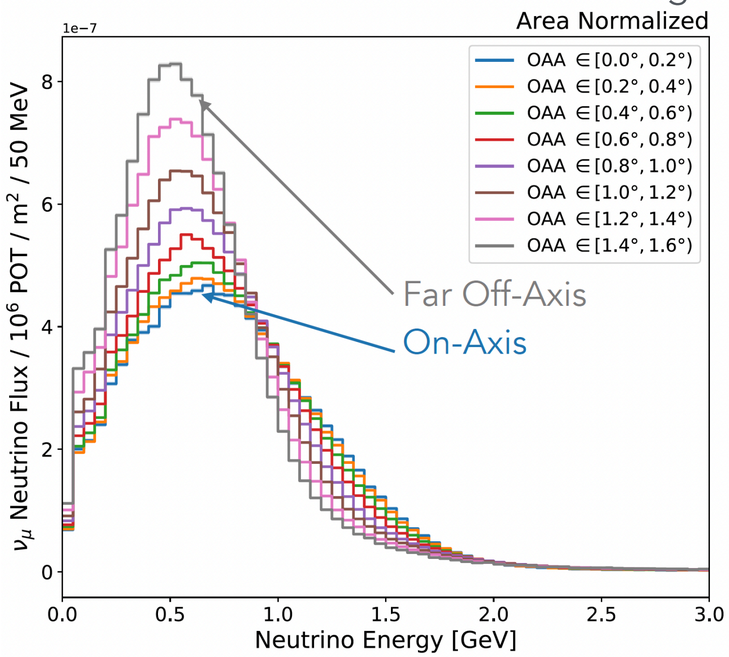




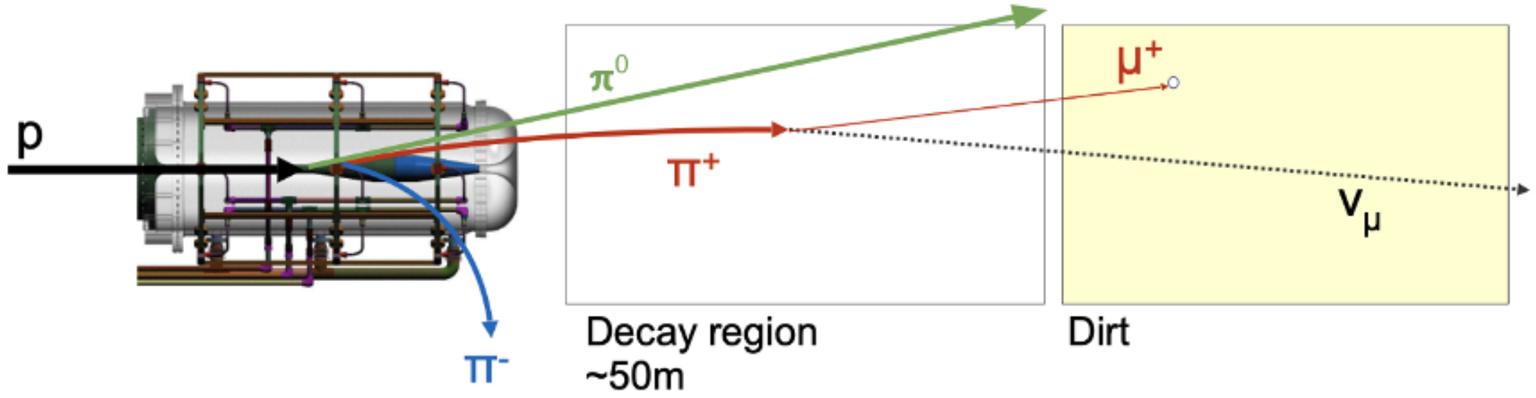
View of the SBND front



Muon neutrino flux in each of the OAA regions



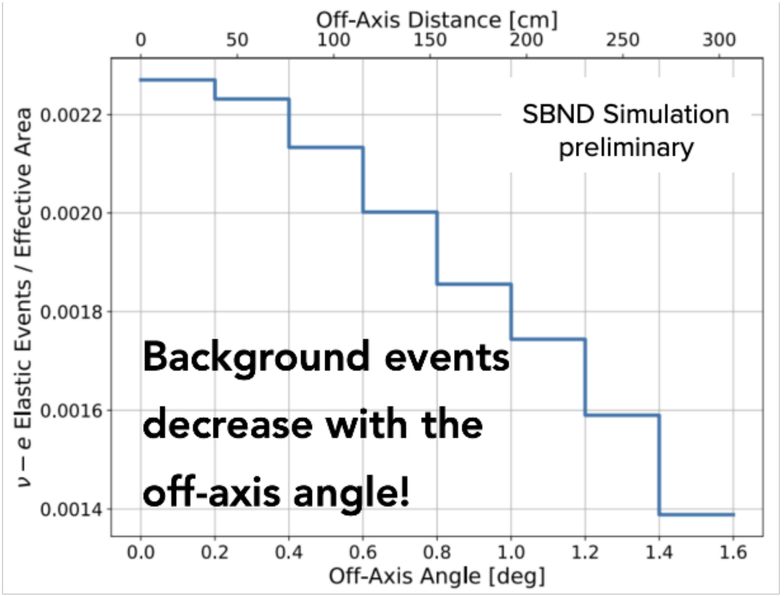
SBND-PRISM



- **BSM** particles from neutral mesons in the BNB are less focused while **SM neutrino** background from charged mesons in BNB are more focused

→ **Background reduction** of SM neutrinos at off-axis angles for BSM new physics searches

SBND-PRISM provides a natural way to reduce backgrounds by looking off-axis

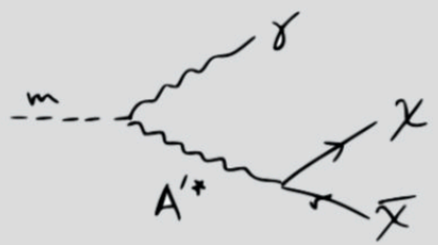


ν-e scattering event rate as a function of off-axis angle (background for DM-e scattering)

New Physics Searches in SBND

A non-exhaustive list of BSM new physics that could be produced in the BNB

Light Dark Matter



Romeri Kelley Machado PRD 2019

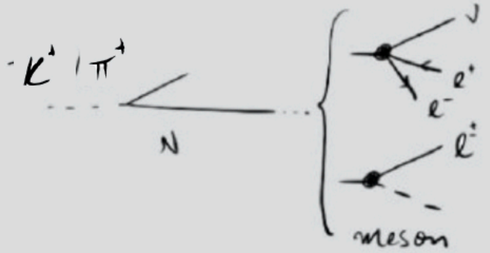
Dark Neutrinos

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

Millicharged Particles

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

Heavy Neutral Leptons

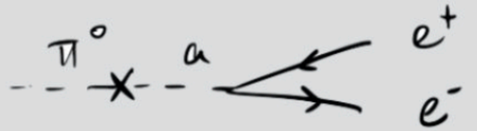


Ballett Pascoli Ross-Lonergan JHEP 2017
Kelly Machado PRD 2021

Higgs Portal Scalar

Pat Wilczek 2006
Batell Berger Ismail PRD 2019
MicroBooNE 2021

Axion-like Particles

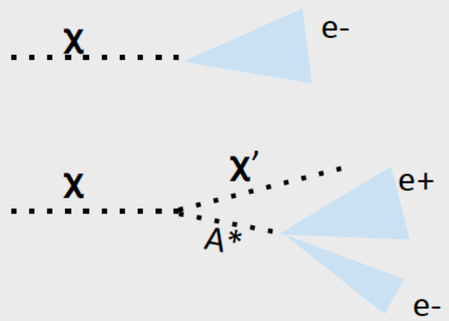


Kelly Kumar Liu PRD 2021
Brdar et al PRL 2021

Image credits P. Machado & M. Del Tutto

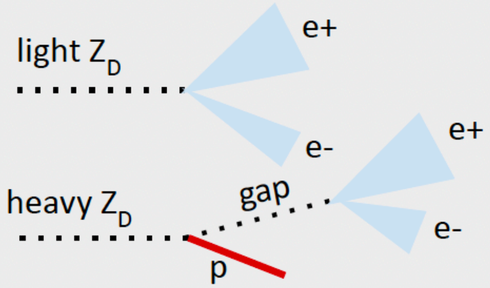
BSM signatures in SBND

Light Dark Matter



single e^- scattering or e^+e^- pair with no hadronic activity

Dark Neutrinos

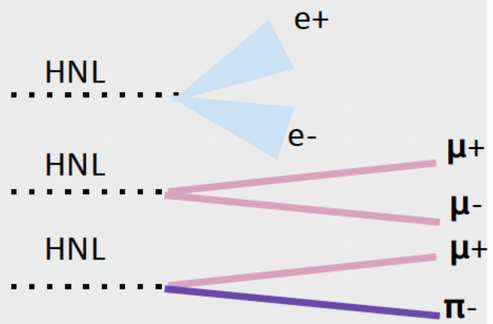


e^+e^- pair with or without hadronic activity

Millicharged Particles

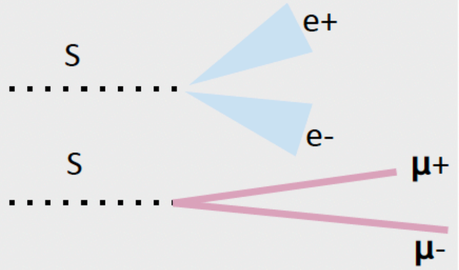
blips or faint tracks

Heavy Neutral Leptons



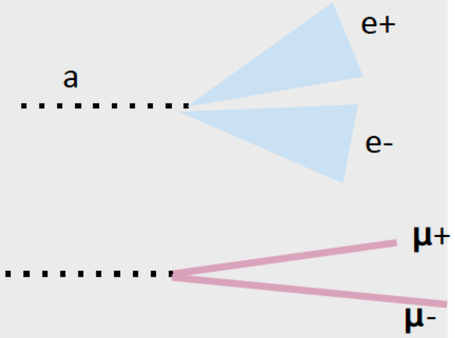
e^+e^-, $\mu^+\mu^-$, or $\mu^\pm\pi^\mp$ pair with no hadronic activity

Higgs Portal Scalar



e^+e^- or $\mu^+\mu^-$ pair with no hadronic activity

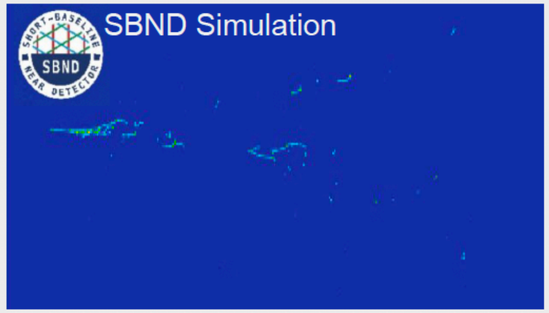
Axion-Like Particles



high-energy e^+e^- pair

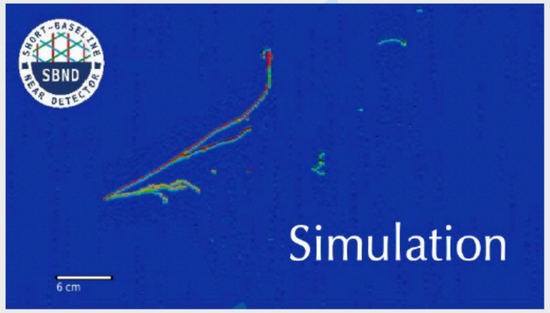
BSM signatures in SBND

Light Dark Matter



single e^- scattering or e^+e^- pair with no hadronic activity

Dark Neutrinos

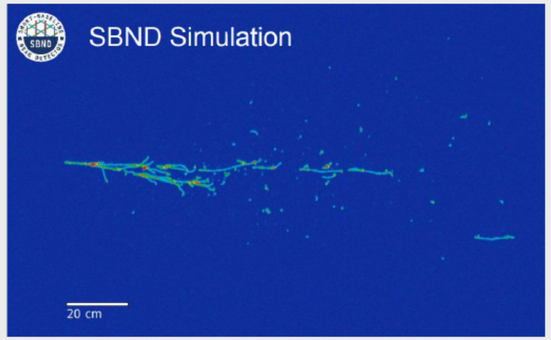


e^+e^- pair with or without hadronic activity

Millicharged Particles

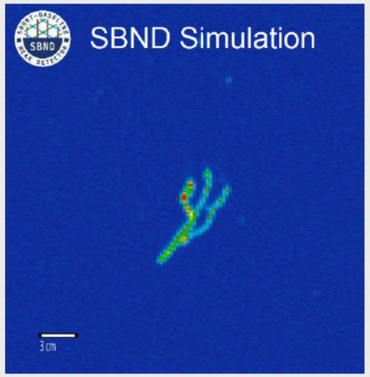
blips or faint tracks

Heavy Neutral Leptons



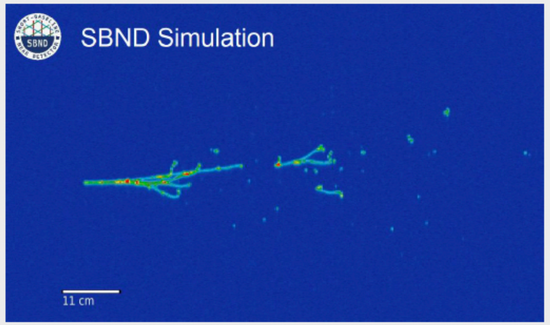
e^+e^-, $\mu^+\mu^-$, or $\mu^\pm\pi^\mp$ pair with no hadronic activity

Higgs Portal Scalar



e^+e^- or $\mu^+\mu^-$ pair with no hadronic activity

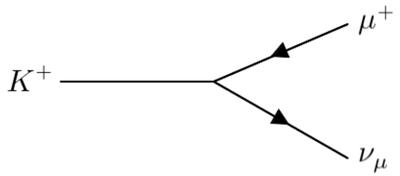
Axion-Like Particles



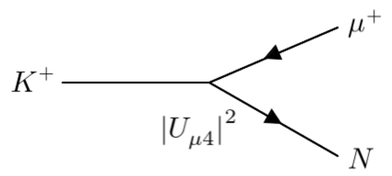
high-energy e^+e^- or $\mu^+\mu^-$ pair

Heavy Neutral Leptons

SM neutrino production

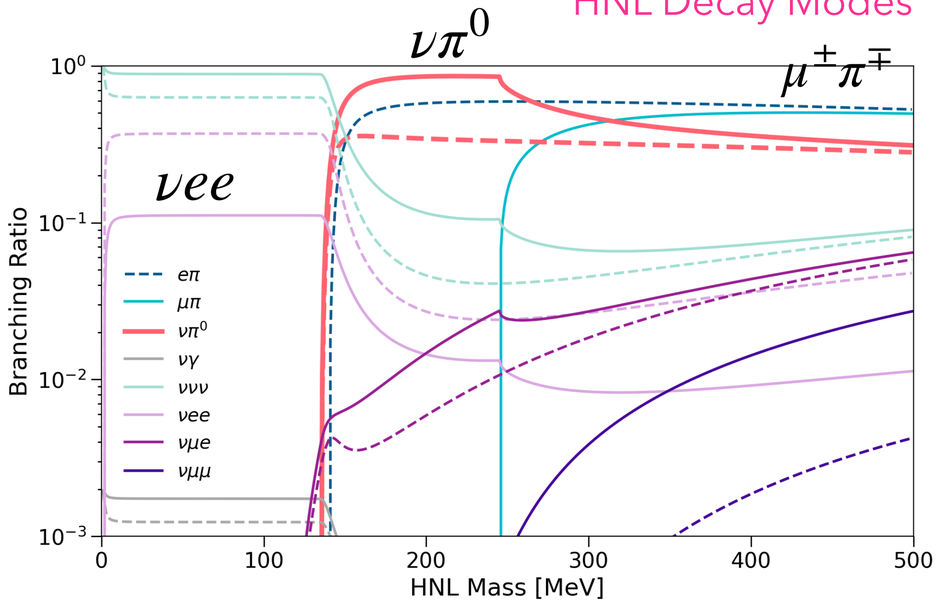


HNL production



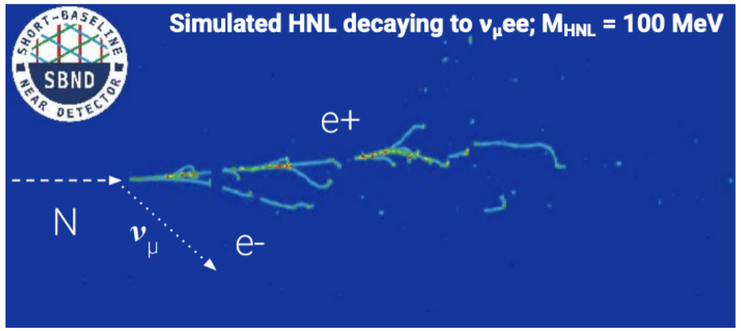
- **Right-handed fermion addition to the 3-neutrino SM paradigm**. Can couple to SM neutrinos by extended PMNS matrix couplings.
- HNLs can be produced by mesons in the BNB and decay in flight into SM observables with event rate $\propto |U_{\alpha 4}|^4$
- Developed a BSM generator shared by SBND and ICARUS (MeVPrtl)

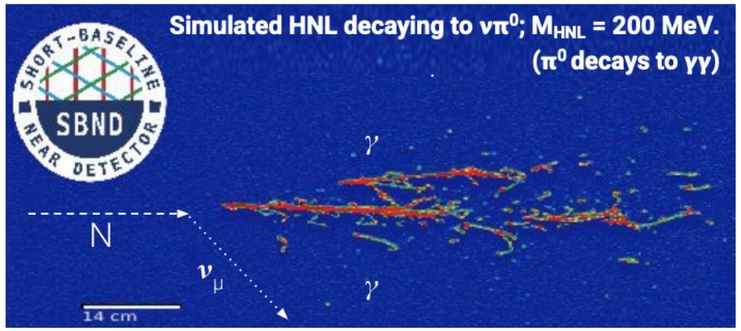
HNL Decay Modes



- SBND is targeting several **decay channels**:
  - HNL → νee (M_{HNL} 30–140 MeV)
  - HNL → $\nu\pi^0$ (M_{HNL} 140–244 MeV)
  - HNL → $\mu^\pm\pi^\mp$(M_{HNL} 244–388 MeV)

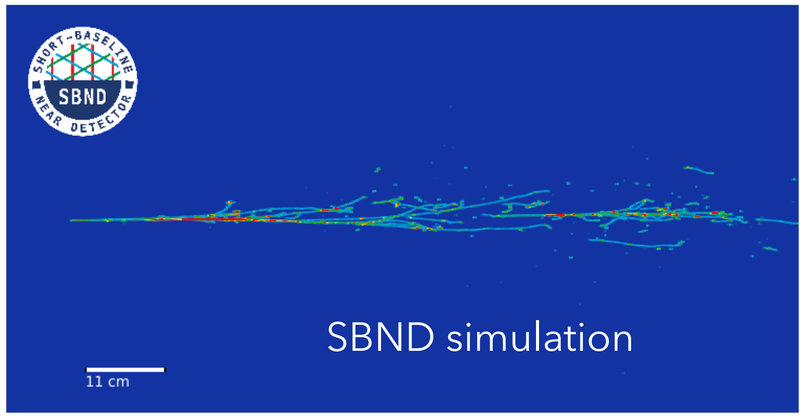
- Main **backgrounds**:
  - BNB ν - electron scattering (single showers)
  - BNB ν neutral current events producing e or γ



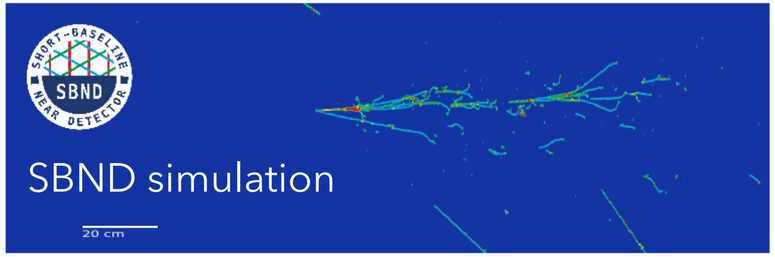


Examples of reconstruction challenges

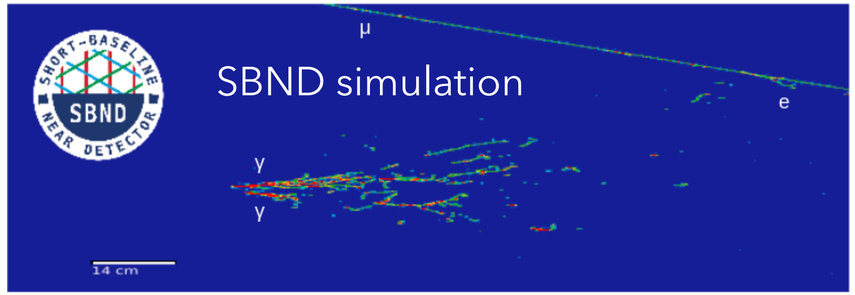
HNL νee: 2 showers look like one single shower



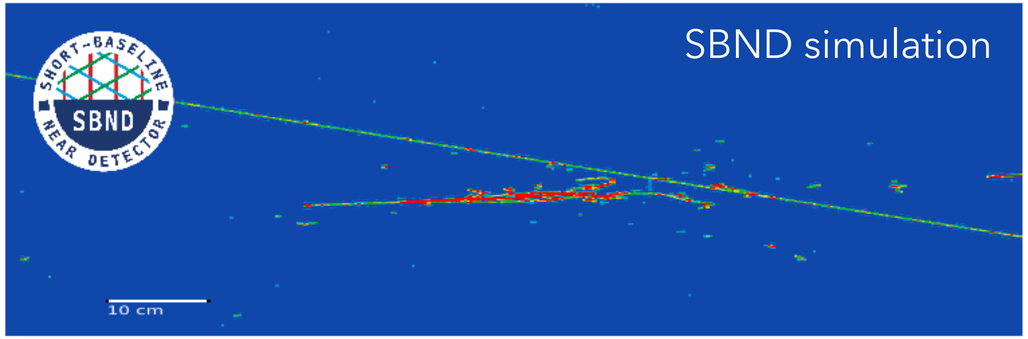
HNL νee:
2 showers look like one single shower + ?



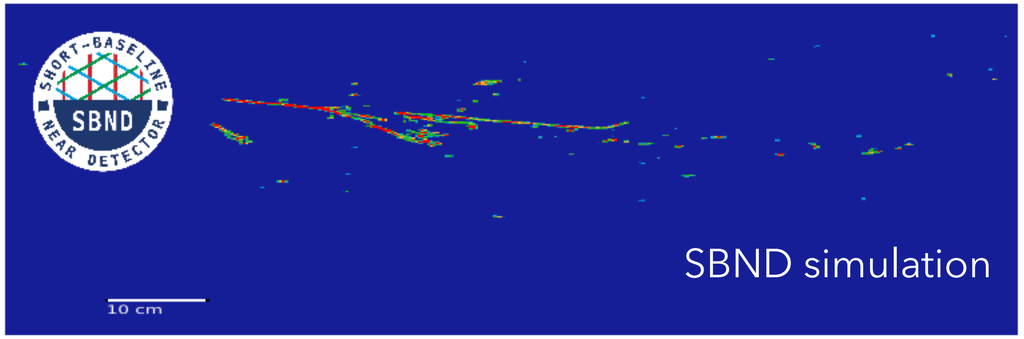
HNL $\nu\pi^0$: 2 gammas look like 2 showers from same vertex



SM Backgrounds: ν_eCC



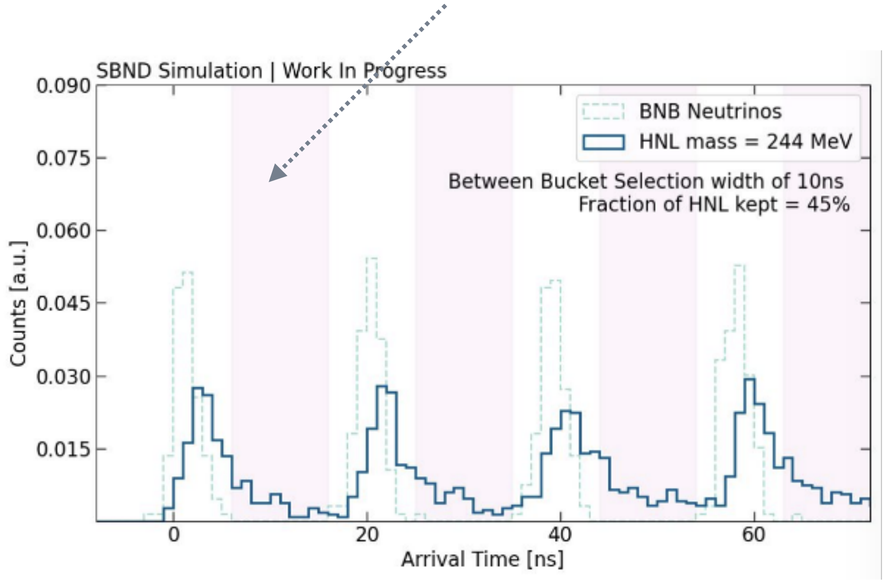
SM Backgrounds: NCπ^0

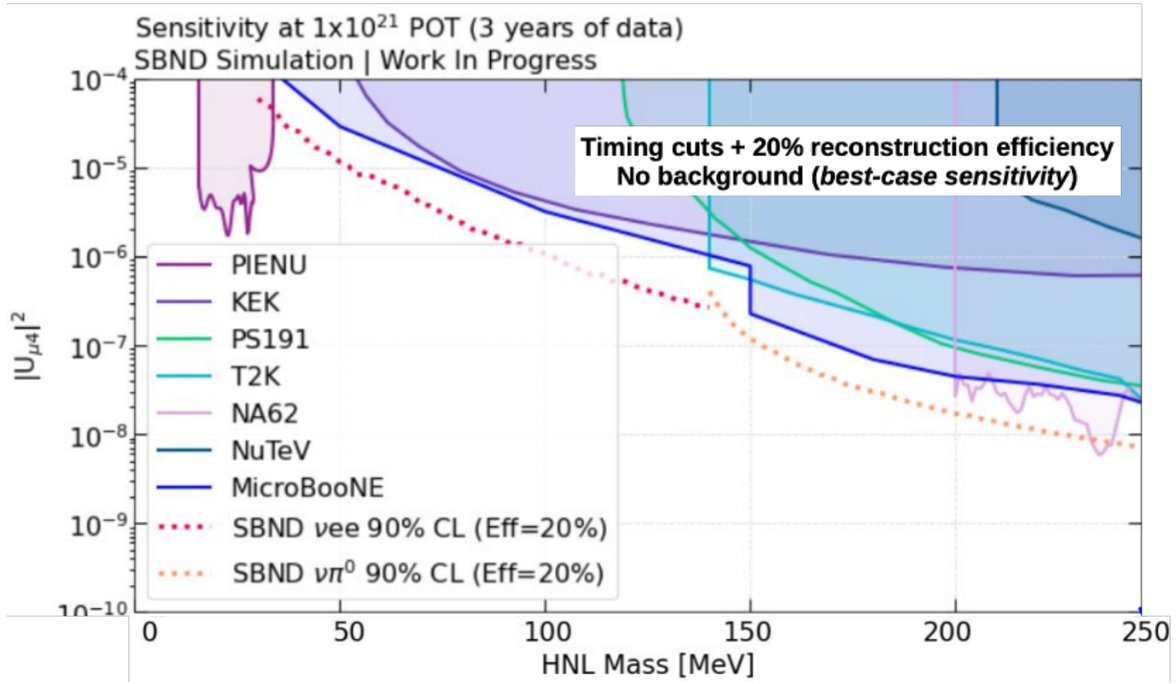


HNL searches in SBND

- HNLs are heavier than neutrinos:
  - More **boosted** decay products
  - Different arrival **time profile**
  - Can use a **delayed selection** to look in between neutrino buckets
- Photon Detection System has **ns timing resolution** (arXiv:2406.07514)
- SBND has demonstrated 3D reconstruction with light information to resolve the BNB structure

Almost backg free regions





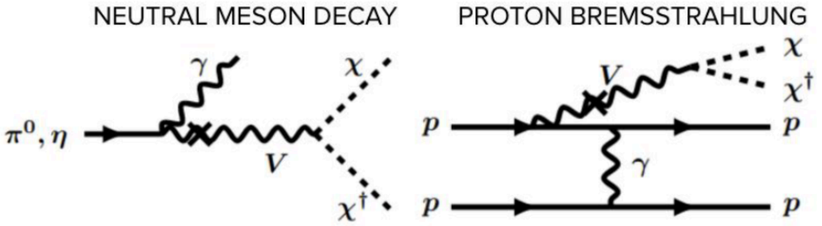
Preliminary sensitivity shows SBND potential to lead searches for Uμ4-driven mixing below 250 MeV

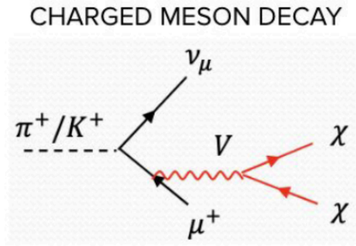
New end-to-end sensitivity in progress

- Machine learning tools for cosmic rejection using TPC, PDS and Cosmic Ray Tagger
- Electromagnetic shower reconstruction
- Low-energy hadron background tagging

Light Dark Matter searches

- SBND can probe **sub-GeV DM** postulated by "thermal relic" models, compared to WIMP searches restricted to higher masses
- **Vector portal DM models**: light dark photon could be produced via meson decay or proton bremsstrahlung

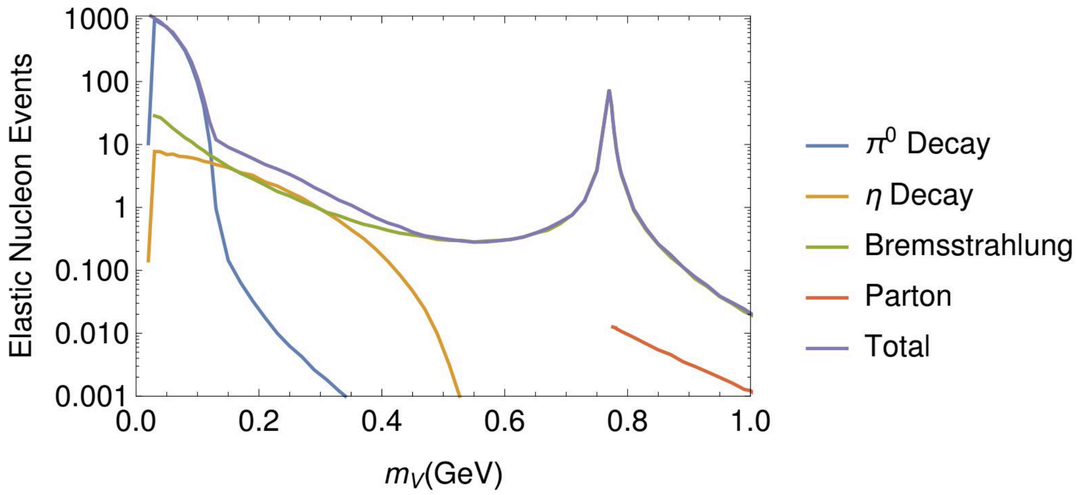




SBND is exploring **two models for DM production** in the BNB:

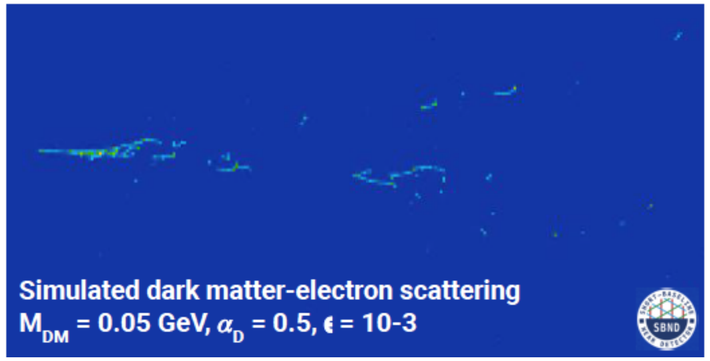
- **Production via neutral meson decay + p brem** (*Patrick de Niverville et al, Phys. Rev. D 95, 035006 (2017)*)
- **Production of long-lived dark photon via charged meson decay** in addition to above modes (*B. Dutta, D. Kim, A. Thompson, R.T. Thornton, R.G. Van de Water, PRL 129, 111803*)

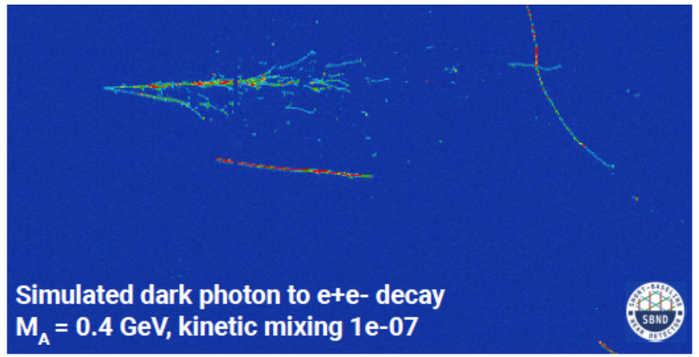
De Niverville et al., arXiv:1609.017703



Light Dark Matter search in SBND

- SBND is looking for **2 types of DM interactions**:
  - DM-electron scattering
  - Dark photon → e+e- decay

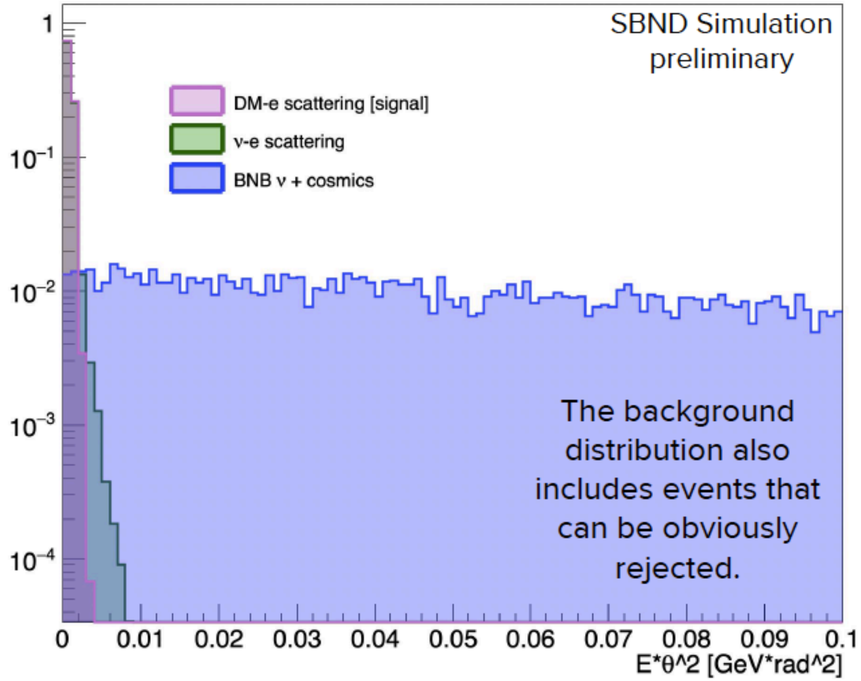




- Main **signature**:
  - Highly forward-going electromagnetic showers without accompanying hadronic activity

- Main **backgrounds**:
  - BNB ν neutral current events producing e or γ
  - BNB ν - electron scattering

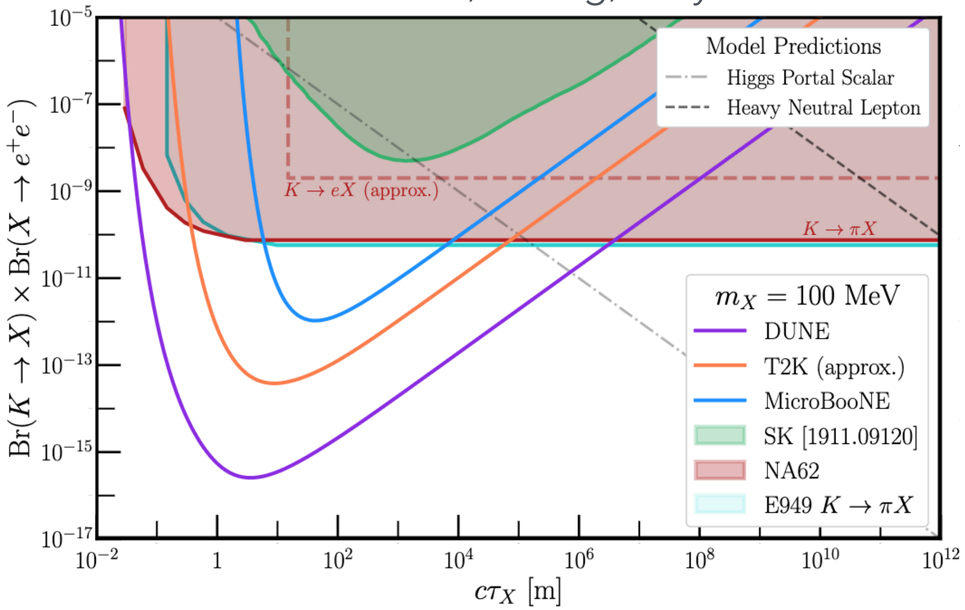
- **Synergistic search with HNLs!**



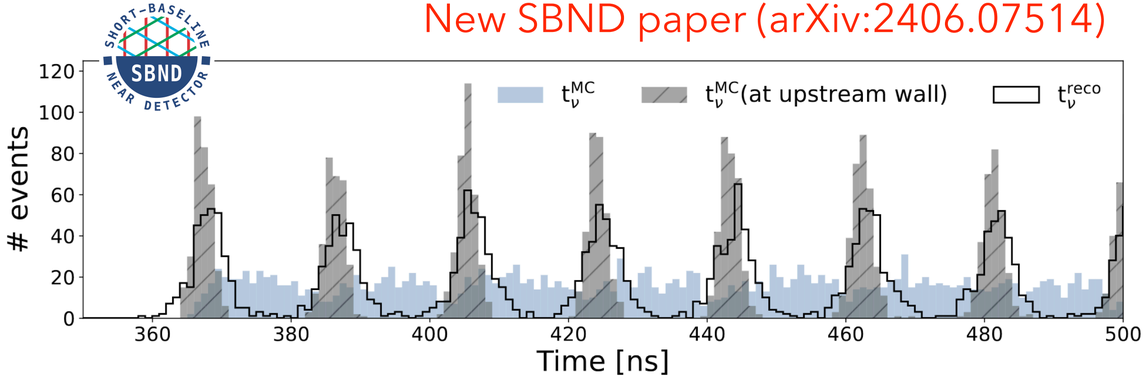
Model independent long-lived particle search

- Explore sensitivity to a **generic long-lived massive particle** X produced in the BNB beam and decaying in the SBND detector.
- Work in progress to **expand MeVPrtl generator** to produce samples with minimal assumptions in a phase space not constrained by specific BSM models.
- **Synergistic with the reconstruction and analysis development** for all the previous model-specific searches.
- SBND's **ns timing resolution** with light information alone provides a topology-agnostic handle to search for any long-lived massive particle.

Batell, Huang, Kelly 2304.11189



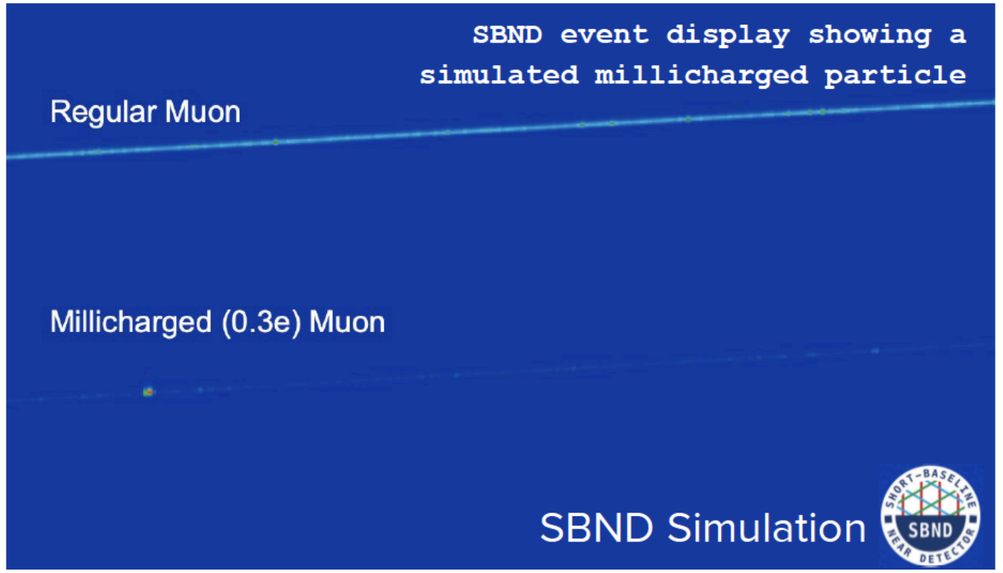
New SBND paper (arXiv:2406.07514)

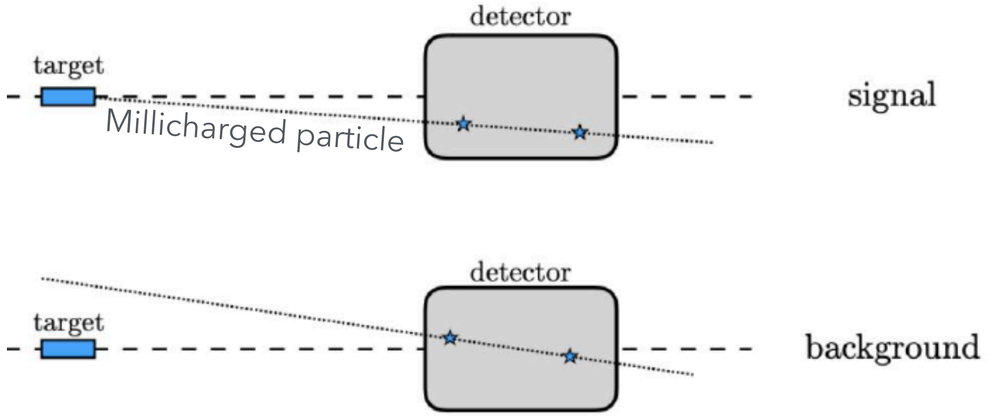


True ν time arrival at upstream wall and inside the active volume (colored regions) vs reconstructed ν interaction time after ToF correction

Millicharged Particles

- Hypothesized particles with **fractional electronic charge**, motivated by a cosmological anomaly (EDGES)
- Could be a constituent of **dark matter**
- Produced by **neutral meson decay** in the BNB
- They would appear as **blips** or **faint tracks** pointing back to the target in SBND

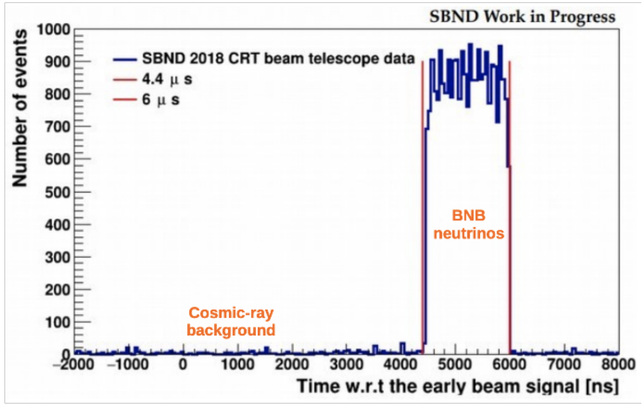




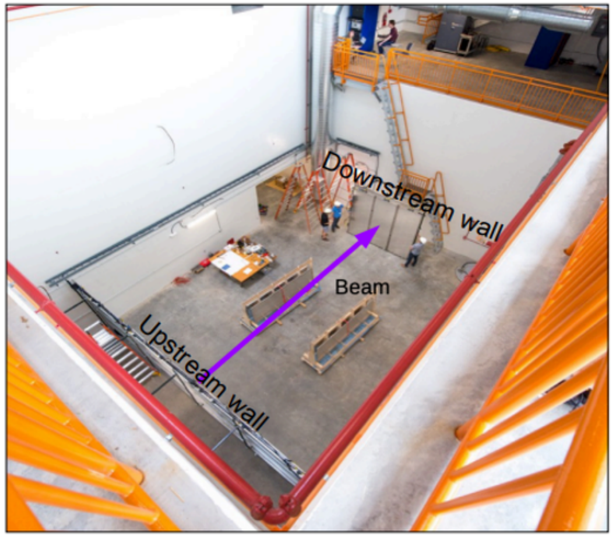
ArgoNeuT *arXiv:1902.03246v2*

Dark Neutrino search with SBND CRT

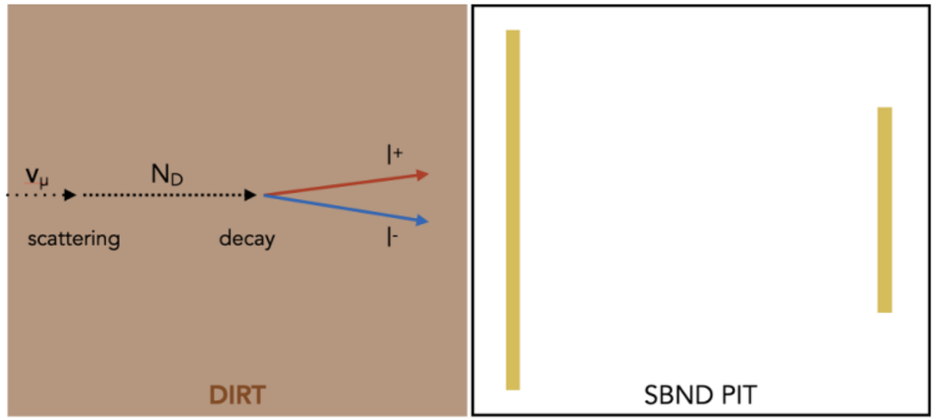
- The SBND cosmic-ray tagger test **data from 2017–2018** can be used to search for BSM new physics particles that would **decay in the dirt around SBND or in the cavern**



- **Dark neutrinos**:
  - A possible BSM explanation for the MiniBooNE low-energy excess
  - Produced via upscattering of SM neutrinos in the dirt
  - Decays to dilepton pairs
  - These can be tagged by the CRT upstream or downstream panels



SBND has an ongoing search for $N_D \rightarrow l^+l^-$ decay using CRT information



Summary

- The Short-Baseline Near Detector in the SBN Program at Fermilab will test the **sterile neutrino** hypothesis, conduct world-leading neutrino **cross-section measurements** on argon, and perform **BSM physics searches**

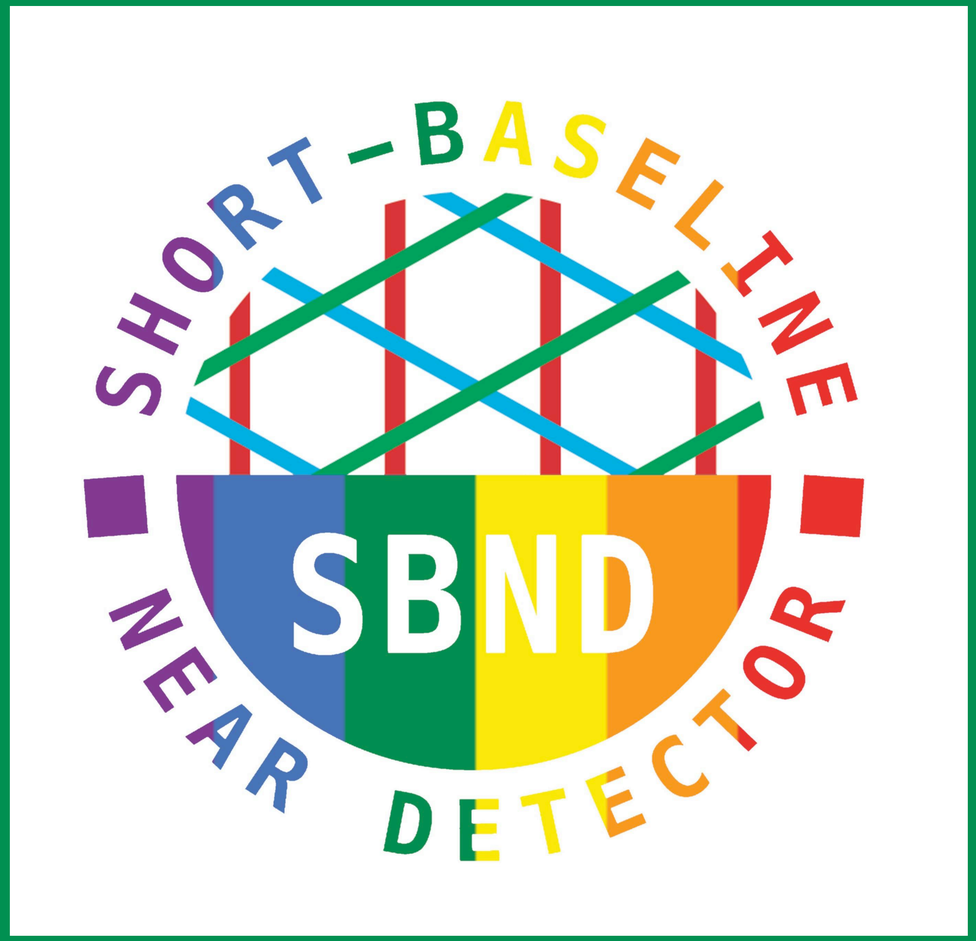
SBND collaboration meeting at FNAL - June 2024

- SBND has great **capabilities for BSM searches**:
  - close proximity to a high-intensity neutrino beam target
  - off-axis fluxes
  - mm-scale spatial resolution and sub-MeV detection thresholds
  - nanosecond timing resolution

- **Diverse BSM program** being pursued actively (HNL, LDM,..) and starting to be developed (heavy axions, dark neutrinos in TPC...) including full detector simulation and reconstruction

- SBND has started several **collaborations with theorists** (even members of SBND collaboration) so that experimentalists and theorists can develop BSM searches together. Happy to look for more models!

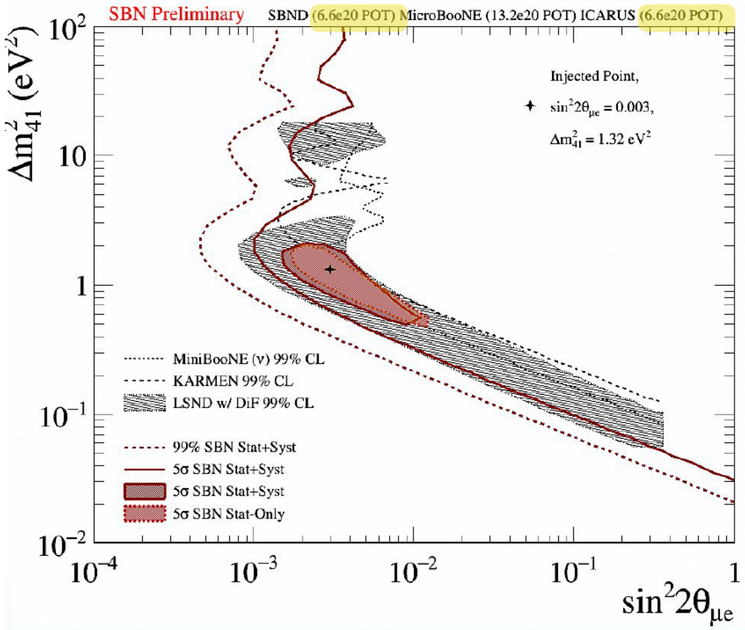
Progress is being made **commissioning** the various SBND components: SBND will start **data taking soon**!



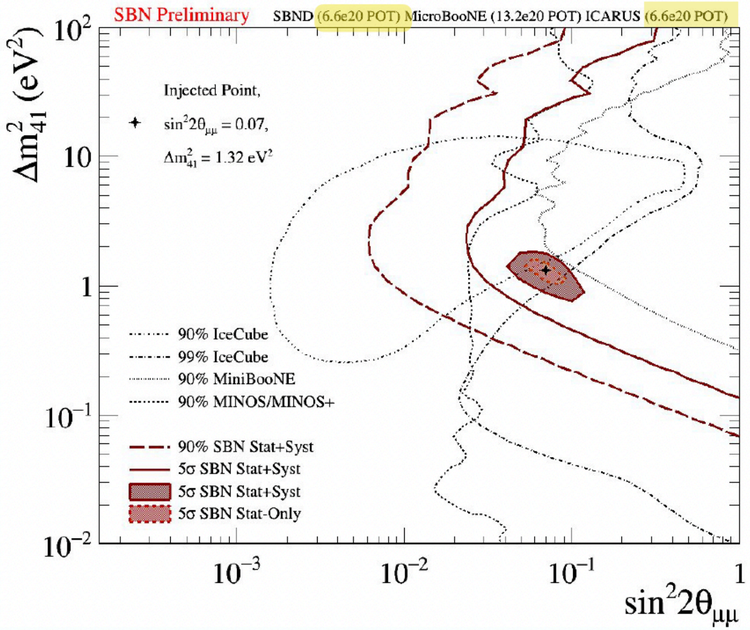
Gracias

SBN sterile neutrino sensitivities

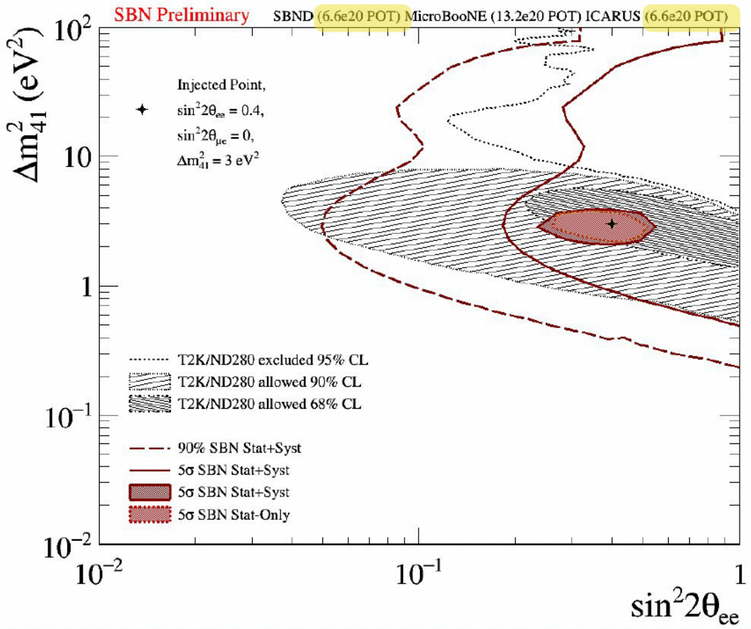
ν_e Appearance



ν_μ Disappearance



ν_e Disappearance



The SBN program tests the sterile neutrino hypothesis by covering the parameter regions allowed by past anomalies at **5σ significance**.

Complementary measurements in different modes:
important for interpretation in terms of **sterile neutrino oscillation**.