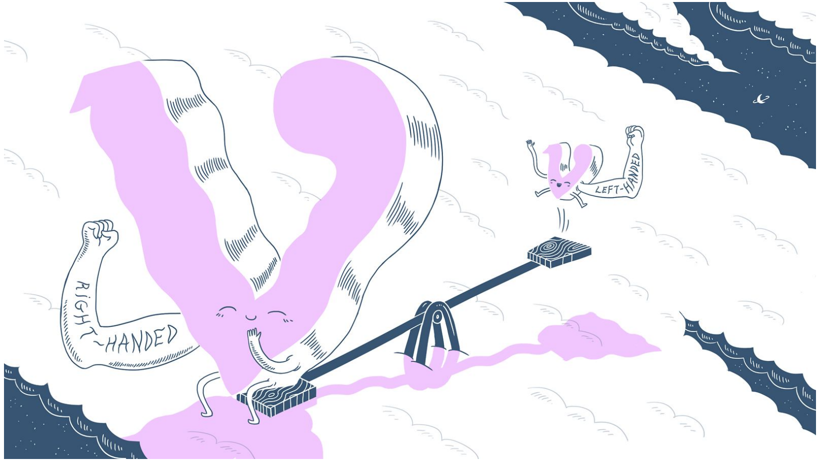
Searches for physics beyond the Standard Model at SBND

Jorge Romeo Araujo (CIEMAT)
on behalf of the SBND Collaboration

November 19, 2025
CPAN Days XVII, Valencia (Spain)



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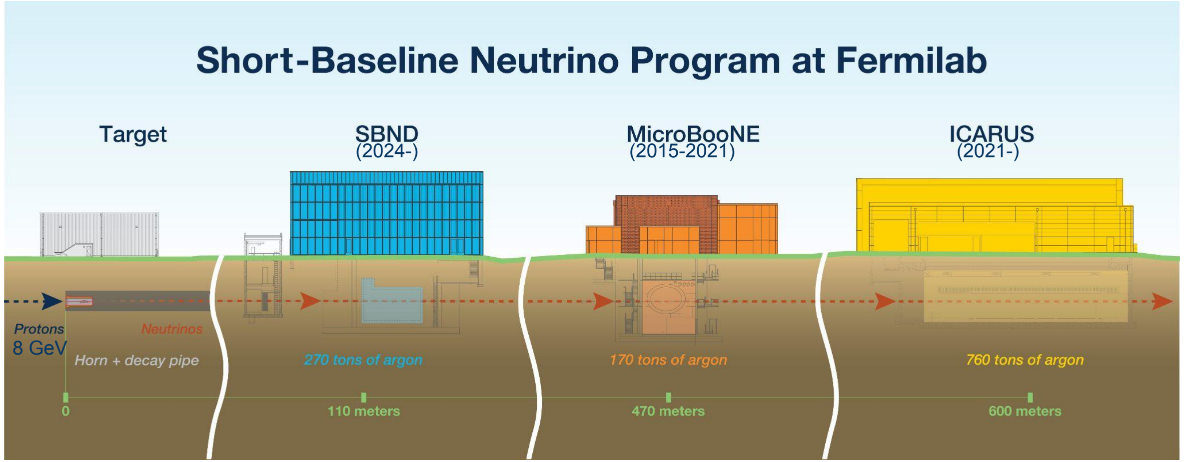
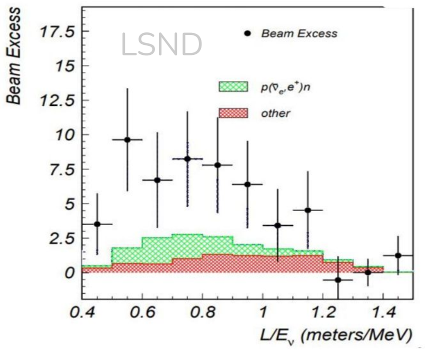
The Short-Baseline Neutrino Program (SBN)

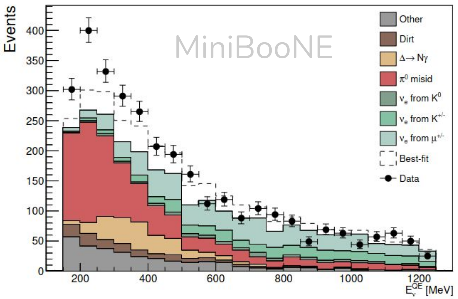




Program proposed to address the LSND and MiniBooNE excesses

Compatible with an extra sterile neutrino with mass splittings

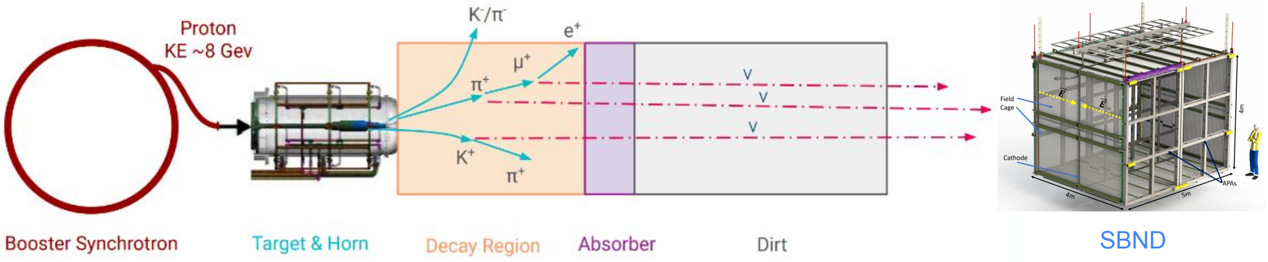
$$\Delta m^2_{43} \approx \Delta m^2_{42} \approx \Delta m^2_{41} \sim \mathcal{O}(1\,\mathrm{eV}^2)$$



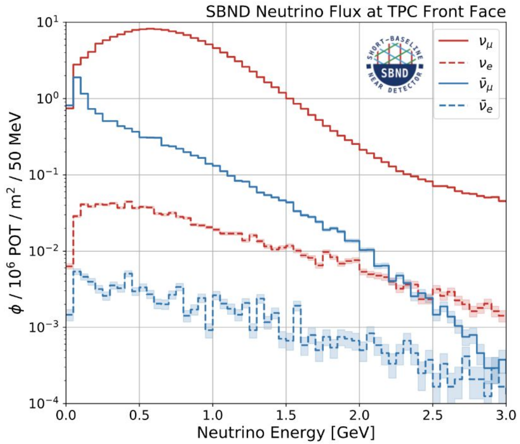
PhysRevD.64.112007

PhysRevD.103.052002

BNB Beam



- 8 GeV protons on Be target.
- BNB generates 1.6 μs proton spill with 81 Gaussian bunches 1.3 ns wide and period of 19 ns at a rate of 5 Hz.
- Beam composition: at SBND
  - ν_μ (93.6%)
  - $\bar{\nu}_\mu$ (5.9%)
  - $\nu_e+\bar{\nu}_e$ (0.5%)
- Mean ν_μ energy : ~0.7 GeV



The Short Baseline Near Detector (SBND)

SBND has 3 subsystems:

- Liquid Argon Time Projection Chamber (LArTPC)
- Photon Detection System (PDS)
- Cosmic Ray Tagger (CRT)

Run 1 (Dec 24 - July 25) with ~ 3 million neutrino interactions

Run 2 ongoing (Nov 25 -)

SBND Program goals

➔ **eV-scale sterile neutrino oscillations** by constraining the flux uncertainties.

➔ **Perform high-precision measurements of neutrino-argon interactions:** measurements of cross sections with already the largest neutrino-Ar sample in the world.

➔ **New physics:** searches for more Beyond Standard Model scenarios.

➔ **R&D in LArTPCs:** new scintillation detection technologies (X-ARAPUCAs, reflective TPB-coated foils, coated/uncoated devices…)

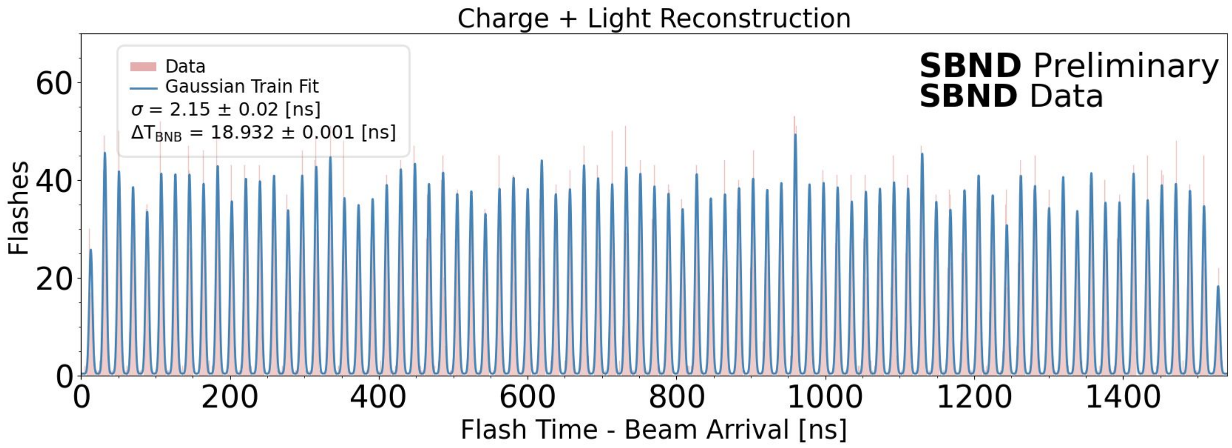
New Physics Searches in SBND

SBND has a unique sensitivity to various BSM scenarios in the MeV range thanks to:

- Proximity to the target (110 m)
- High intensity beam
- Great detector capabilities
- Late arrival due to heaviness

Main strategy for BSM searches is looking for an excess of events between bunches

Using the PDS the BNB bunch structure can be resolved with a resolution of ~ 2 ns.

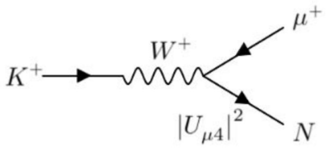


BSM Models

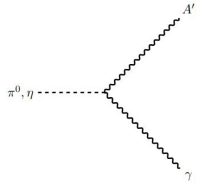
Several models can be tested in SBND using the BNB, the most studied so far:

Sterile Neutrinos

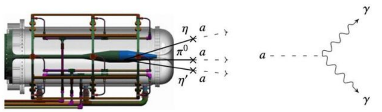
Heavy Neutral Leptons



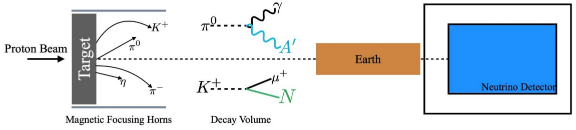
Dark Photons



Heavy QCD Axions



Generic Long-Lived Particles

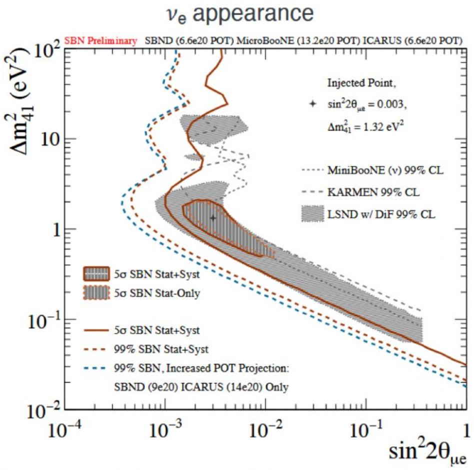


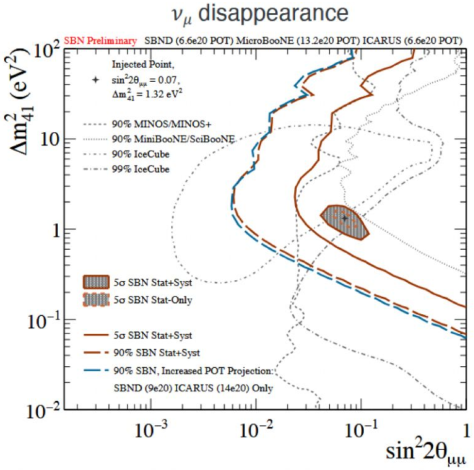
Sterile Neutrinos

SBND+ICARUS will be able to proof the sterile neutrino hypothesis compatible with the LSND and MiniBooNE excesses

SBND will measure the ν_μ and ν_e components of the BNB with large statistics

ICARUS will search for an excess of ν_e and a deficit of ν_μ using SBND's measurement as a reference

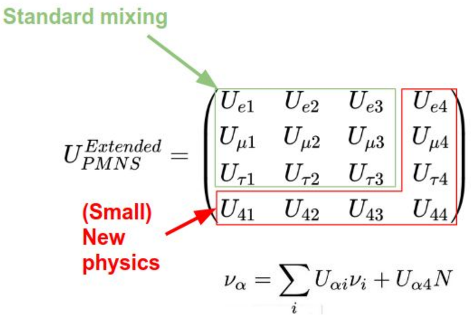




SBND+ICARUS covers almost the full allowed region with 5σ

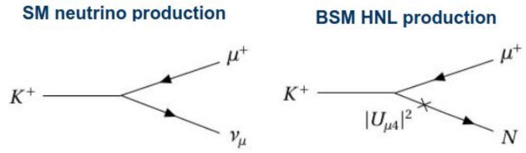
Only possible thanks to the reduction on the systematics uncertainty brought by SBND

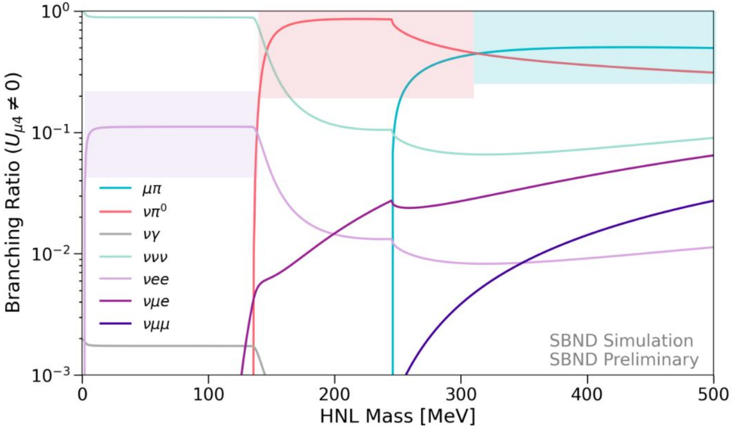
Heavy Neutral Leptons



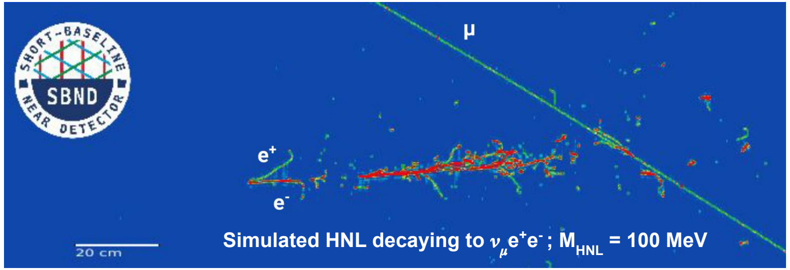
- Right-handed fermion addition to the 3-neutrino SM paradigm
- Can couple to all SM neutrinos by an extended PMNS matrix $U_{\alpha 4}$, $\alpha = \tau, \mu, e$
- Could be produced by mesons in the BNB, production implemented from $K^+ \rightarrow N\,\mu^+$ using the MeVPrtl generator, tool developed for SBN to simulate BSM scenarios

  Channels simulated:
  - $N \rightarrow \nu\, e^+ e^-$ (30 - 140 MeV)
  - $N \rightarrow \nu\, \pi^0$ (140 - 244 MeV)
  - $N \rightarrow \mu\, \pi$ (244 - 388 MeV)
- HNL can decay in flight into SM observables with event rate $\propto |U_{\alpha 4}|^4$





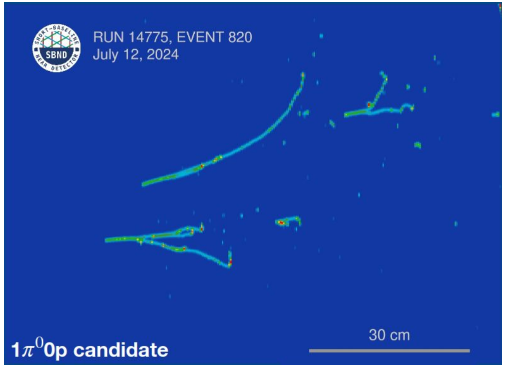
Branching ratios of probable decay channels of an HNL produced from the BNB for the muon-flavour coupling



Simulated HNL decaying to $\nu_\mu e^+e^-$; M_{HNL} = 100 MeV

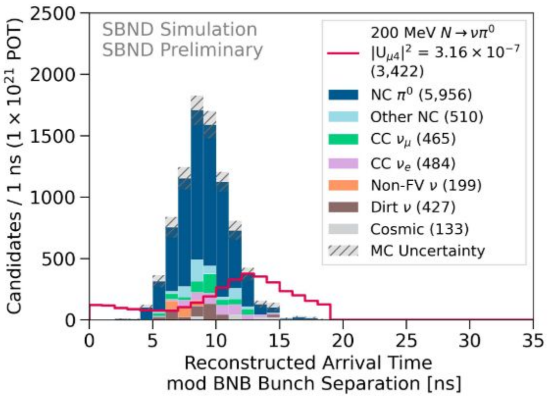
Heavy Neutral Leptons

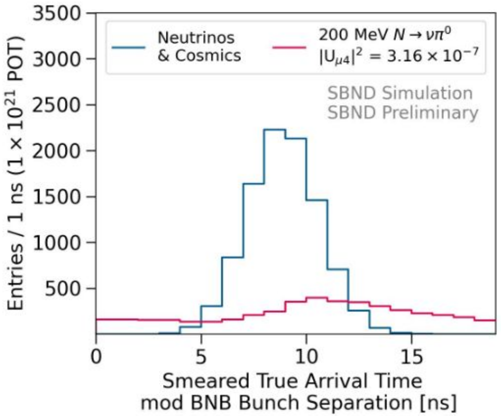
- Main backgrounds:
  - BNB NC π^0 events
  - BNB ν - electron scattering
- Leverage timing delay of HNLs for detection at SBND



Performed two MC studies:

1. Using the standard reconstruction workflow to evaluate the current reconstruction performance
2. Applying a smearing at truth level supposing an improved timing reconstruction to evaluate the impact on sensitivity

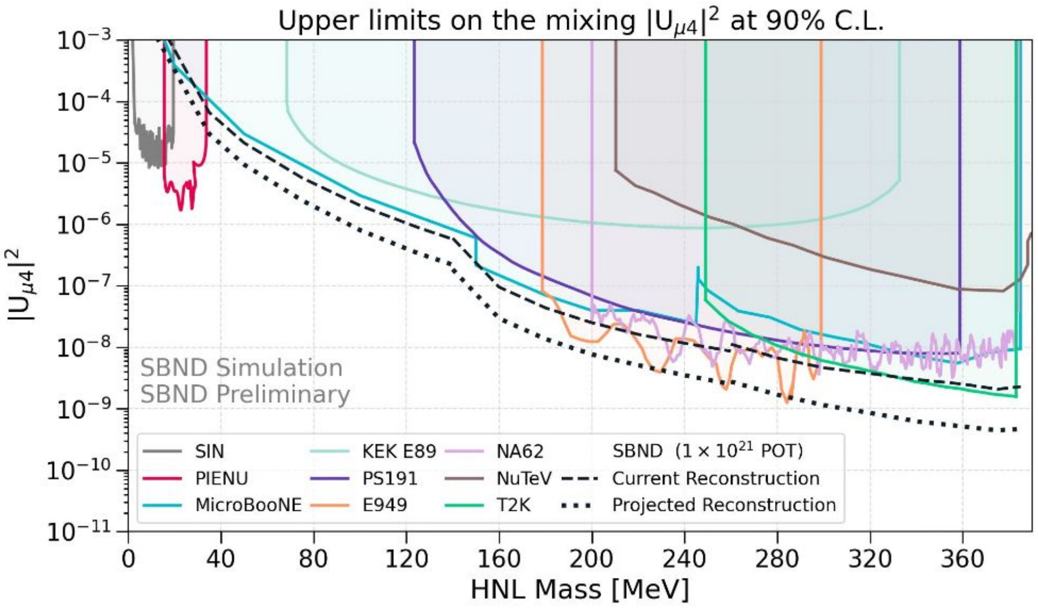




Heavy Neutral Leptons

CIEMAT leads this search where **Granada University** has also participated
Currently I'm working on the νe^+e^- channel

Mixing
$U_{\mu 4} \neq 0$
$U_{e4} = U_{\tau 4} = 0$



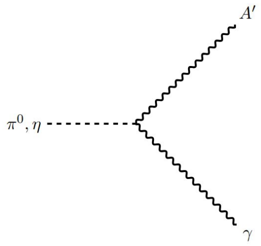
Mass limited by $m_K - m_\mu$

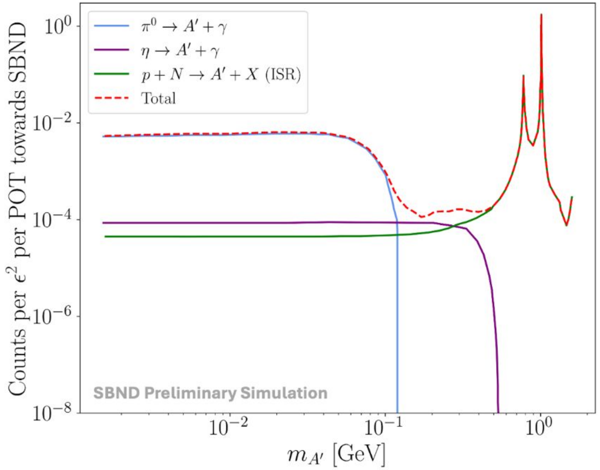
SBND has the potential to improve current sensitivity limits on HNLs !

Dark Photons

- U(1) gauge boson coupling to the SM via ϵ, kinetic mixing $\mathcal{L} \supset \frac{m_{A'}^2}{2} A'_\mu A'^\mu + e\epsilon \sum_f q_f \bar{f} \gamma^\mu f A'_\mu.$

- Two production modes:
  - 2-body neutral meson decay from π^0 and η
  - Proton bremsstrahlung from p-Be interaction



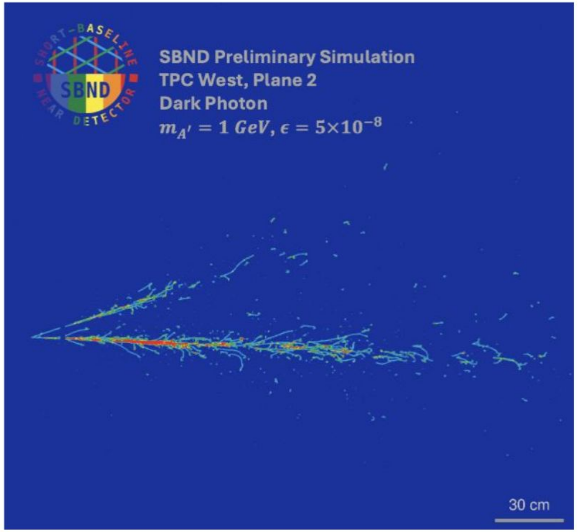


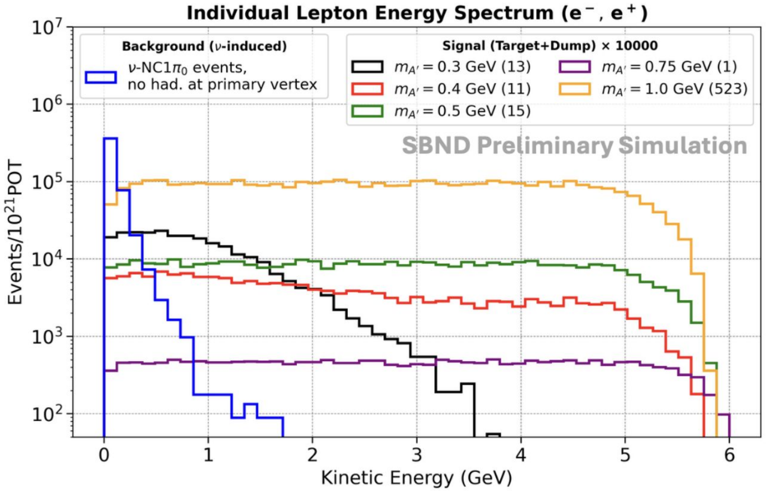
Probability of producing a dark photon via 2-body neutral meson decay and proton bremsstrahlung

- Decay channels:
  - Di-leptons ($e^+ e^-$ /$\mu^+ \mu^-$) currently exploring di-electrons channel
  - Other hadronic channels

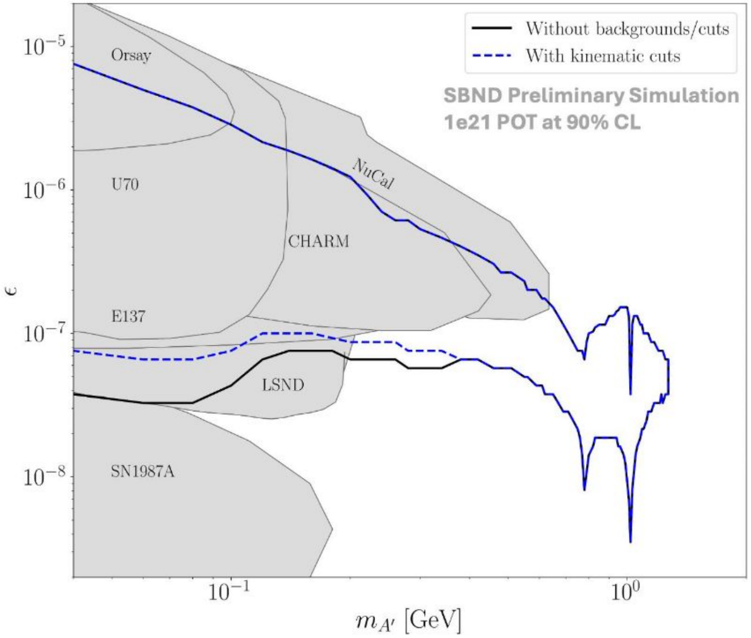
Dark Photons

- Main signal: highly forward-going electromagnetic showers without accompanying hadronic activity
- Main background: NC $\pi^0 \rightarrow \gamma\gamma$ and photons radiating to $e^+ e^-$
- Can leverage higher kinetic energy of Dark Photons to impose a 2 GeV cut





Dark Photons

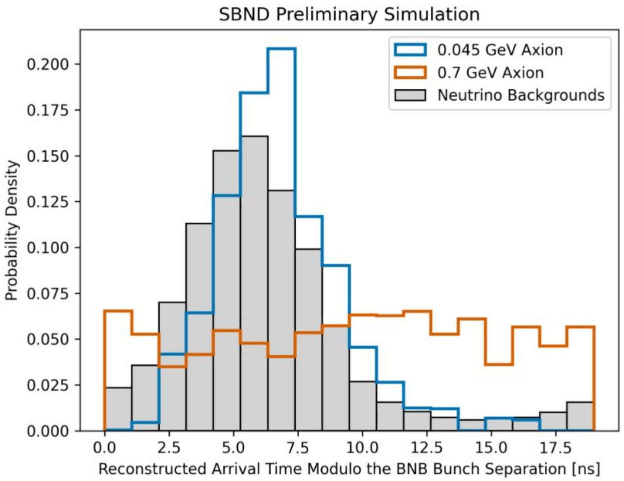


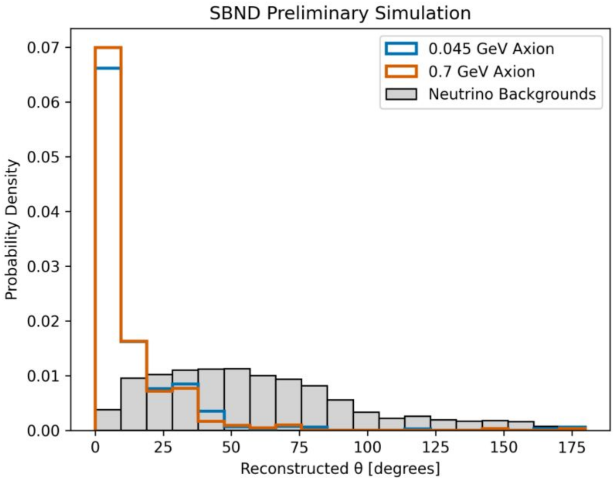
SBND has the potential to set world-leading limits on dark photons production!

Limits can be improved, as the simulation of neutral meson production in the BNB is currently being updated

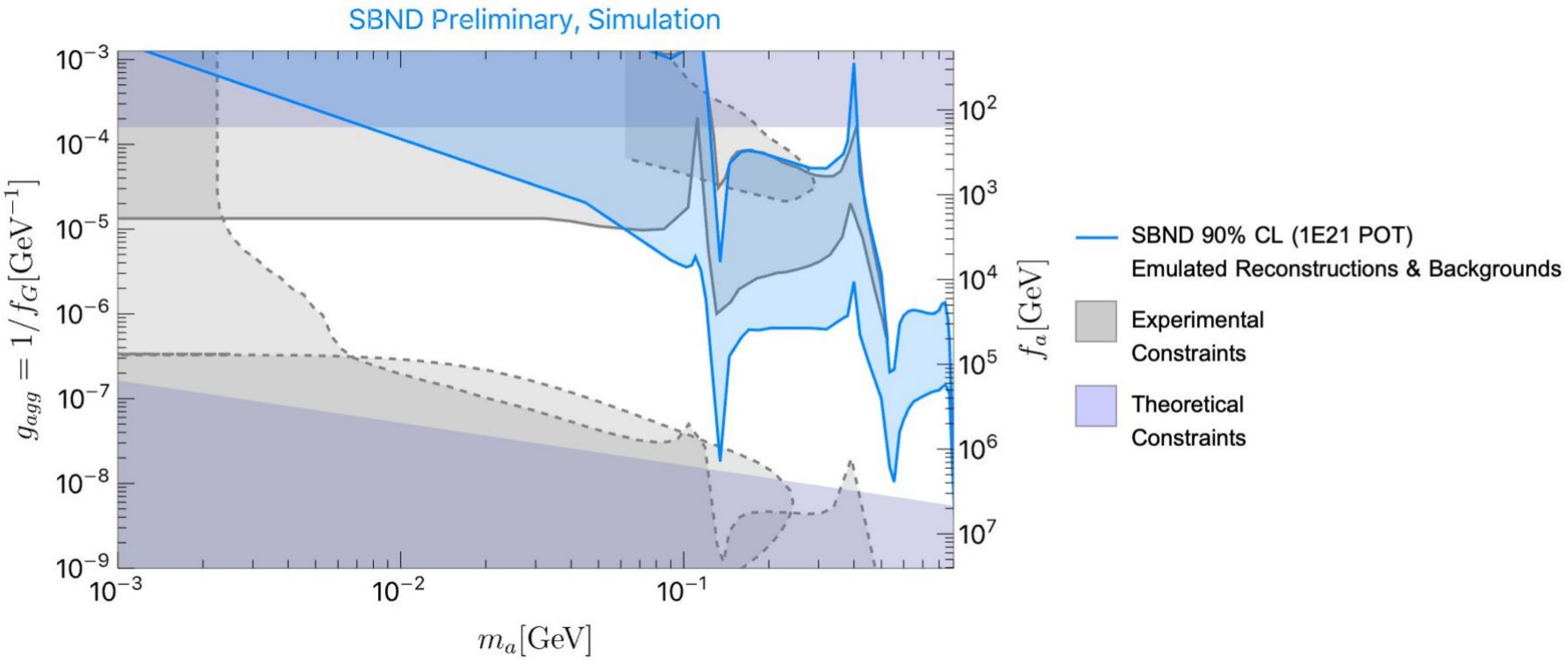
QCD Heavy Axions

- Proposed as a **solution to the strong CP Problem** $\mathcal{L}_{eff} = \frac{a}{8\pi f_a}(c_3\alpha_3 G\tilde{G} + c_2\alpha_2 W\tilde{W} + c_1\alpha_1 B\tilde{B})$
- Can be produced by mixing with BNB neutral mesons, same neutral meson flux as dark photons
- Signal: a $\rightarrow \gamma\gamma$
- Main background: NC π^0
- Strong signal-background discrimination power using time delay and angle with respect to beam distributions





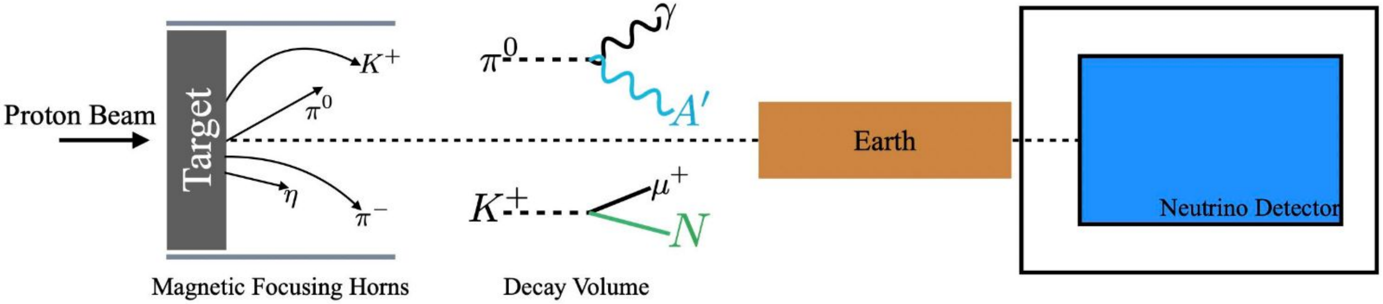
QCD Heavy Axions



Ability to place competitive, world-leading bounds on Heavy QCD axions parameter space!

Generic LLPs

- A model-independent search for various long-lived exotic particles that can be produced in the BNB and decaying inside SBND.
- For this analysis, we assumed:
  - LLP is produced via 2-body meson decay ($K^+ \rightarrow \pi^+ X$ and $K^+ \rightarrow \mu^+ X$)
  - Massive LLP m_X = 100, 250 MeV
  - LLP decays into a visible state inside SBND ($X \rightarrow e^+ e^-$)
  - Lifetime of $c\tau_X = 10, 10^6$ m



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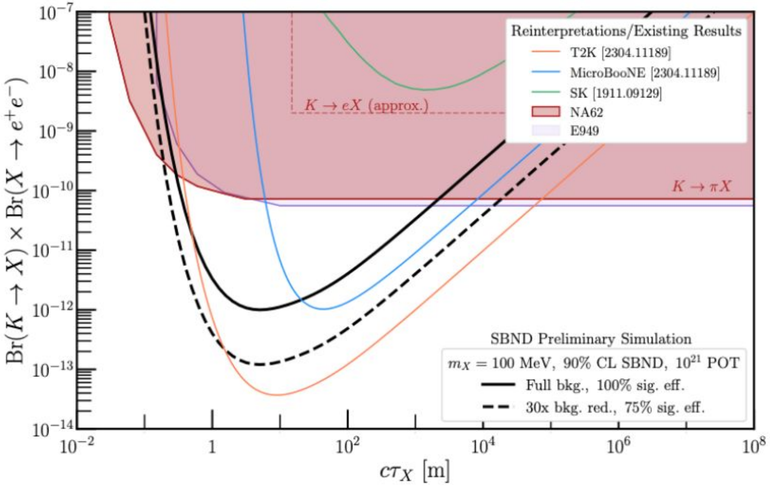
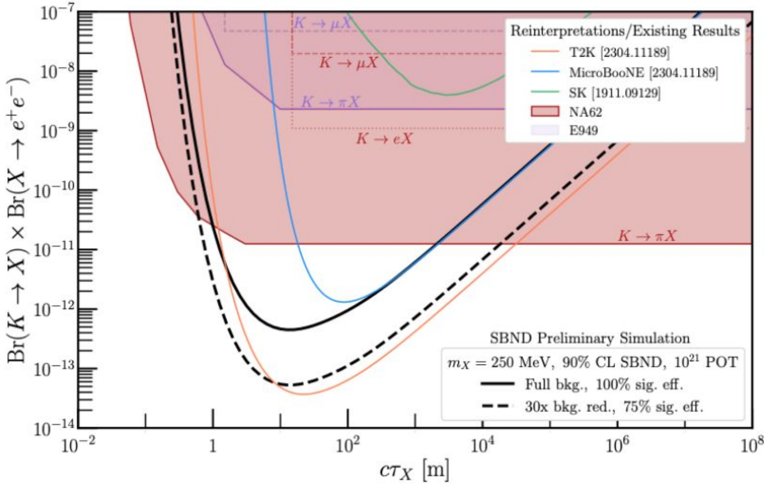




A model-independent search also has the potential to set world-leading limits!

Conclusions

- SBND is a **highly competitive experiment for performing BSM physics searches**, using its large statistics and timing/kinematic analyses to explore the parameter space of new-physics models never tested before

- The combination of its three detection systems — LArTPC, PDS, and CRT — provides **excellent spatial and timing resolution**

- A **BSM sensitivity publication led by Spanish groups is currently being prepared** to highlight the strengths and discovery potential of SBND. Stay tuned!

- Data taking is ongoing, expect **new SBND BSM results in the near future!**

SBND Collaboration Meeting at Sheffield University, UK June 2025

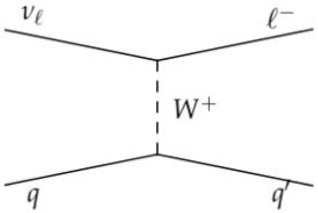
Thanks!

Backup

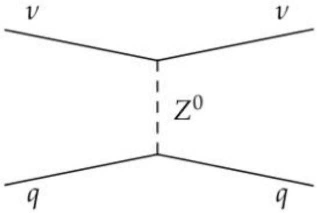
Neutrino physics

- **Neutrino interactions**

Small Cross section
↓
Difficult to detect

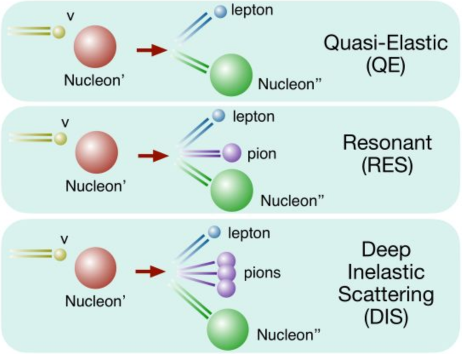


Charge Current (CC)



Neutral Current (NC)

Neutrino-nucleon interactions



- **Neutrino oscillations**

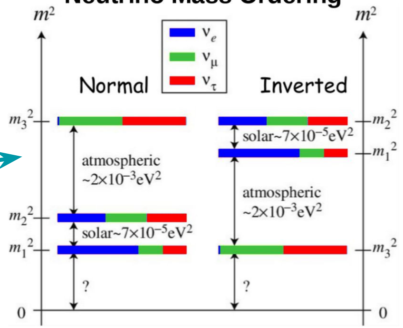
Flavor eigenstates — Mass eigenstates

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \underbrace{\begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix}}_{U_{\mathrm{PMNS}}} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

Oscillation probability depends on:

- 3 angles (Θ_{12}, Θ_{13}, Θ_{23}) → ¿octant?
- 2 squared mass differences (Δm^2_{21}, Δm^2_{32})
- 1 CP phase (δ_{CP}) → ¿value?

Neutrino Mass Ordering

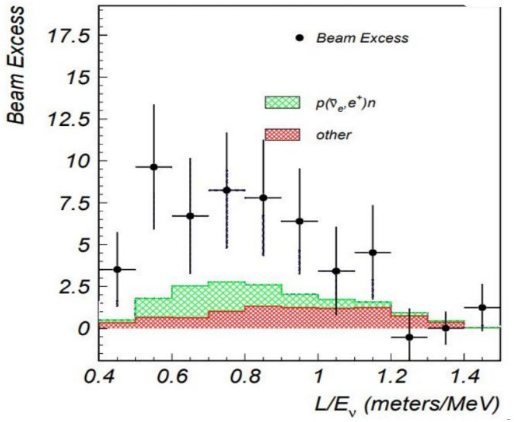


Future experiments: DUNE and Hyper-K

Short-baseline anomalies

LSND (liquid scintillator detector)
Using antineutrinos from pion decay-at-rest, observed 3.8σ excess in $\bar{\nu}_e$

MiniBooNE (mineral oil cherenkov detector)
Using neutrinos and antineutrinos from pion decay-in-flight beam, same L/E as LSND, observed 4.8σ excess in ν_e and $\bar{\nu}_e$.



PhysRevD.64.112007

Compatible with an extra sterile neutrino with mass splittings

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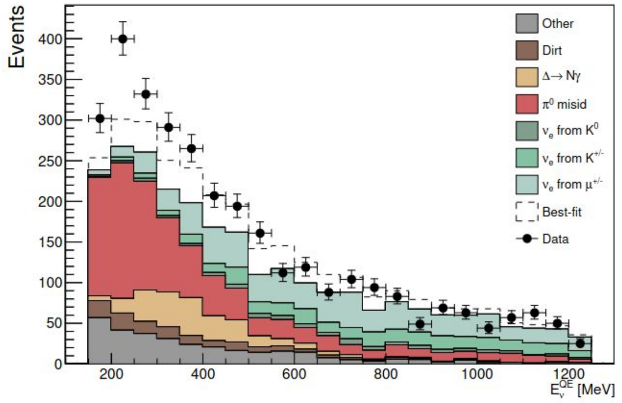
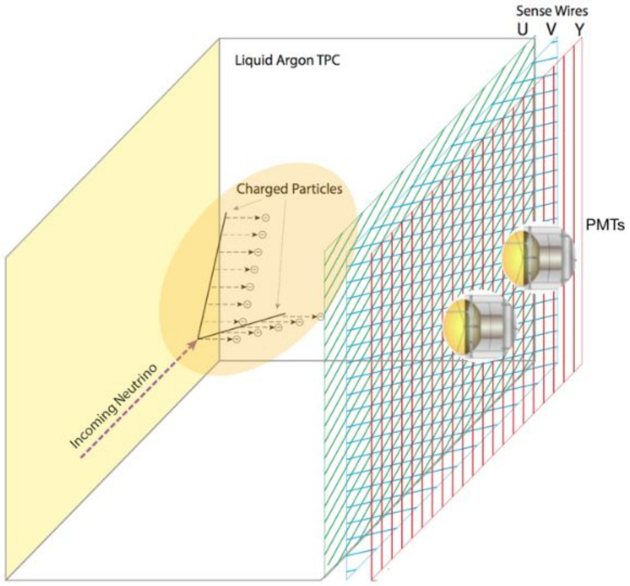


PhysRevD.103.052002

Detecting neutrino interactions with LArTPCs



Employs ionization charge and scintillation light (128 nm, VUV) produced in liquid argon (-186 °C)

Using ionization charge:

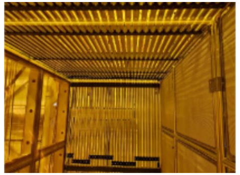
- Superb 3D reconstruction with mm-level resolution
- Excellent dE/dx and particle id
- Fine-granularity calorimetry
- Low energy threshold, sub-MeV to GeV

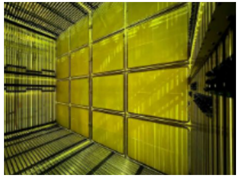
Using scintillation light:

- ns resolution for interaction timing
- Trigger capabilities
- Cosmic-rays rejection
- Complementary calorimetry

The SBND detector: LArTPC

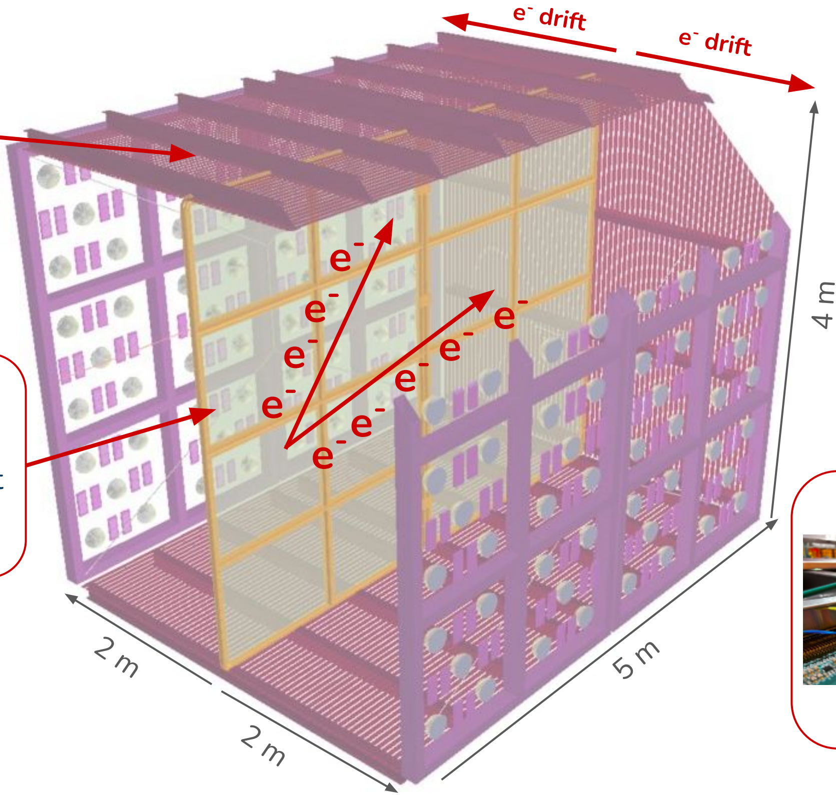
Field Cage
surrounds TPC, provides a uniform electric field



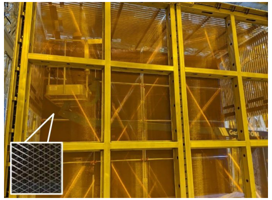


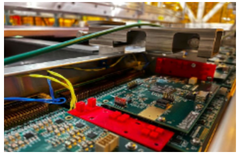
Cathode Plane
(-100kV) splits the detector into 2 drift volumes

SBND LArTPC Size
4 x 4 x 5 m^3
Active mass 112 t
2 drift volumes
Drift distance 2 m



Wire Planes
3 planes on each side of the detector
11,264 wires in total

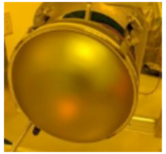


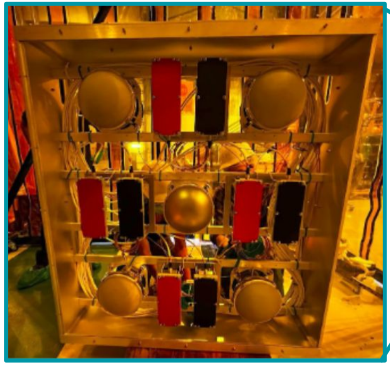


Cold electronics
at 89 K pre-amplifies and digitises wire signals with extremely low noise

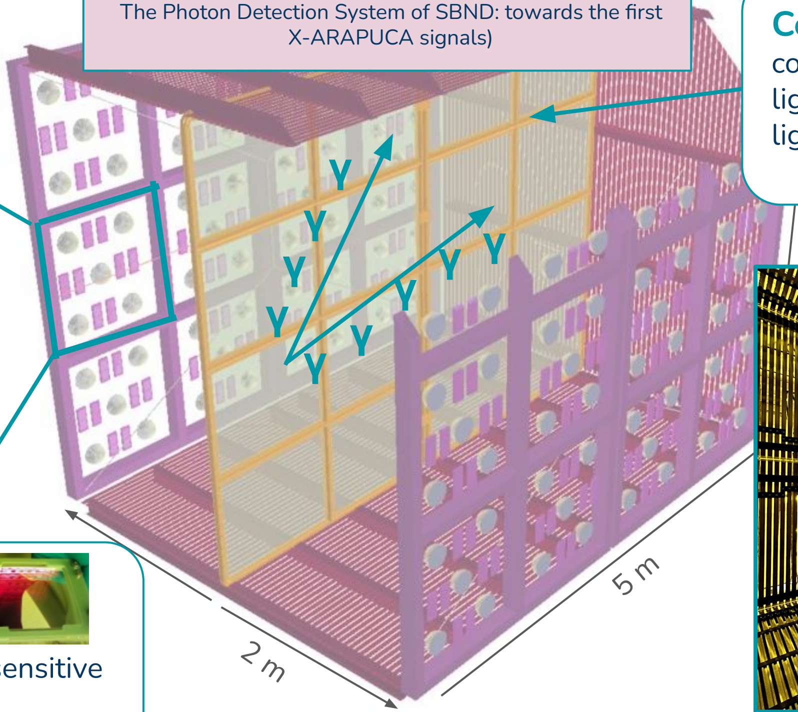
The SBND detector: Photon Detection System

PMT
96 PMTs (TPB-coated)
24 PMTs (uncoated)

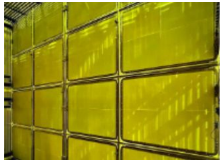




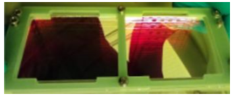
Check Alicia Vázquez Ramos' talk today
The Photon Detection System of SBND: towards the first X-ARAPUCA signals)



Coated Reflective Foil
converts VUV into visible light, enables uniform light collection

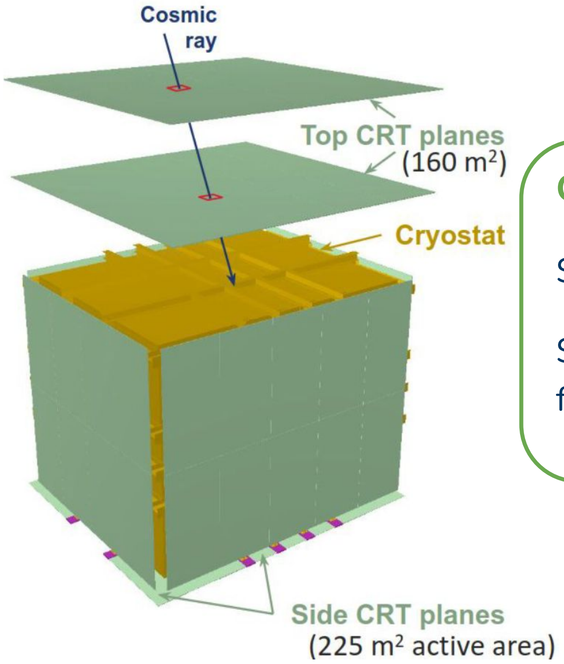


X-ARAPUCA
192 X-ARAPUCAs,
50% sensitive to VUV and 50% sensitive to visible light.
New technology for DUNE



Check out the recent SBND PDS paper!

The SBND detector: CRT



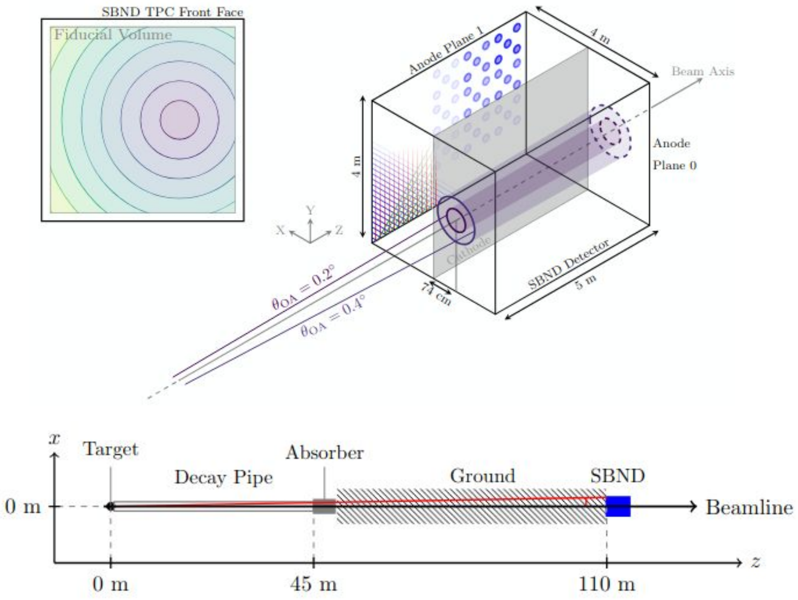
Cosmic Ray Tagger (CRT)

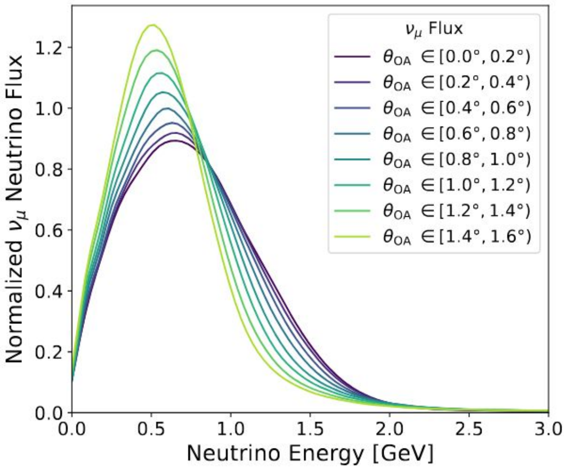
SBND is on the surface -> cosmic rays contamination

Surrounded by ~4π coverage of scintillator panels for cosmic tagging

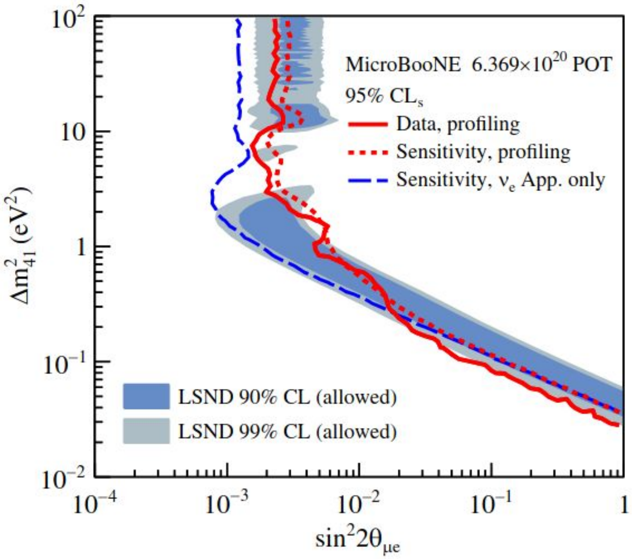
PRISM concept

SBND is sufficiently close to the beam target such that effects due to the beam angular spread are noticeable. Neutrino energy spectrum changes with angle.





New MicroBooNE oscillation analysis



PhysRevLett.130.011801

MicroBooNE's oscillation analysis excludes part of the LSND allowed region at 95% CL