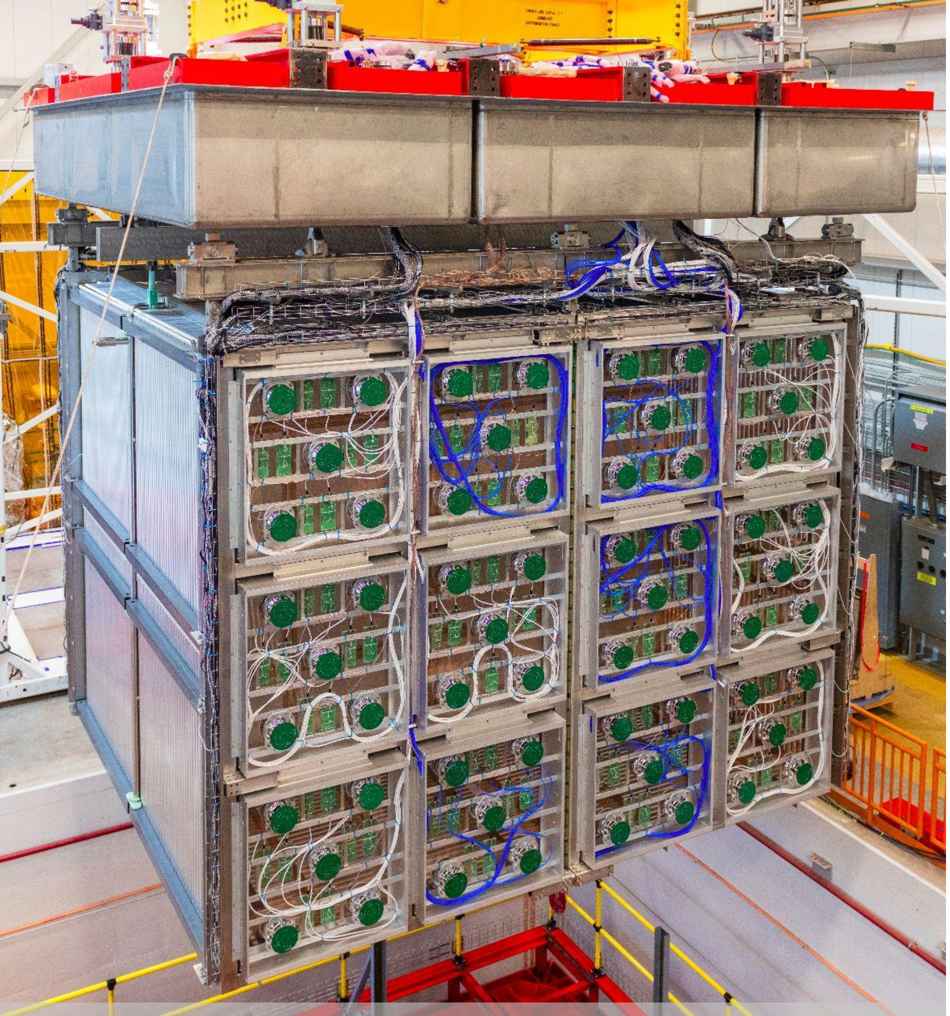


*The SBND detector being lifted into the cryostat (April 2023).*

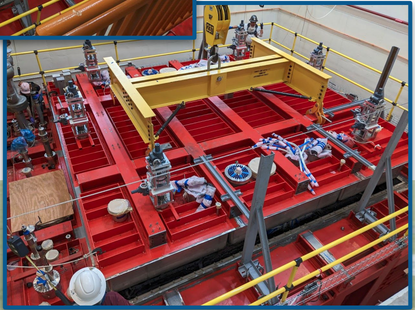
# Searches for physics beyond the Standard Model with the Short-Baseline Near Detector

**Nguyen Vu Chi Lan** (she/her)
on behalf of the SBND collaboration

vclnguyen@ucsb.edu

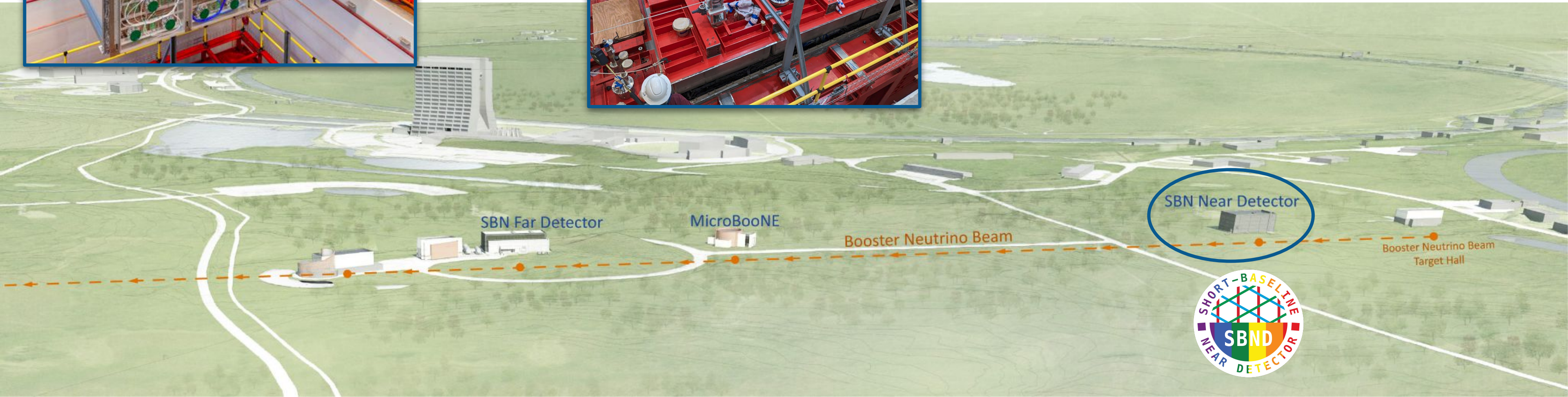
Brookhaven Forum 2025: 22 – 24 October 2025

# The Short-Baseline Near Detector



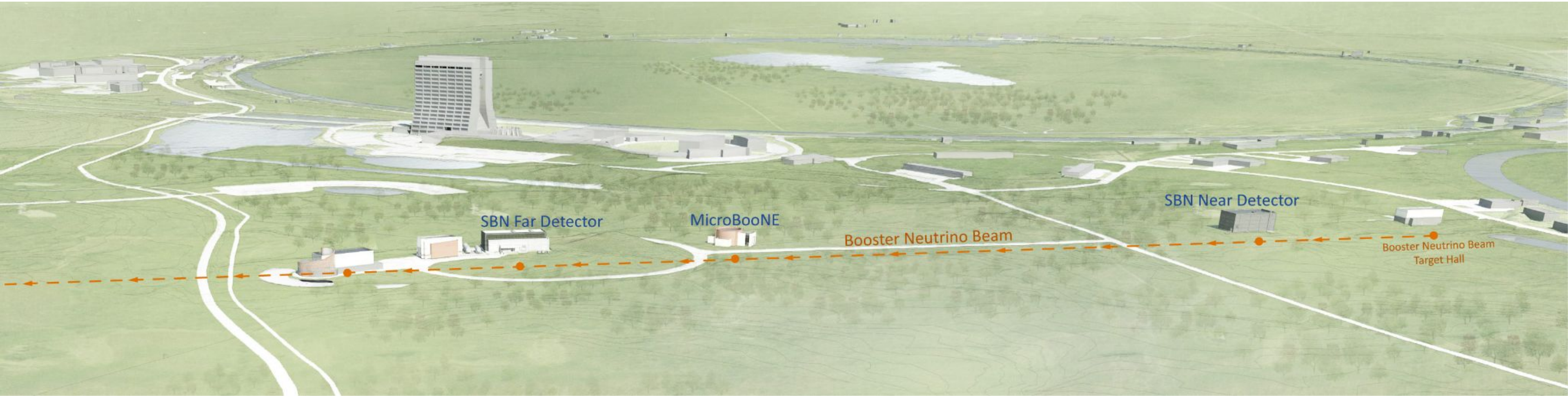
- A Liquid Argon Time Projection Chamber at 112 ton
- 110 m baseline on the Booster Neutrino Beam (BNB)
- **Run 1:** December 2024 – June 2025
- **Run 2:** Began in October 2025

**See Lynn Tung's previous talk on the status of SBND**



# The Short-Baseline Neutrino Program

- The Short-Baseline Neutrino (SBN) program was designed to be the world-leading short baseline experiment with the goal to investigate the low energy excess anomaly.
- Made up of two LArTPCs at different baselines along the BNB, SBND at 110 m and ICARUS at 600 m
- The same neutrino beam and detector technology aims to constrain systematic uncertainty to the %-level.

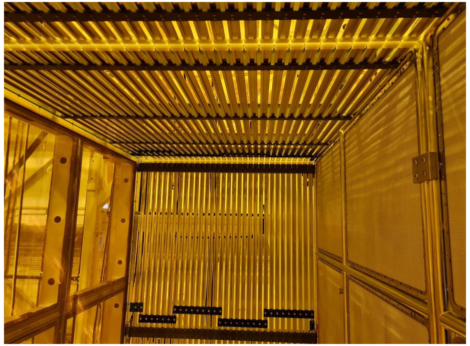


# Charge Detection System

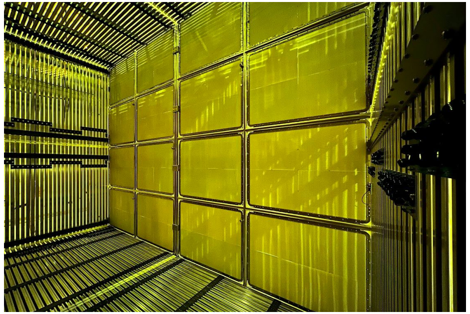
Ionisation electrons drift under an electric field.

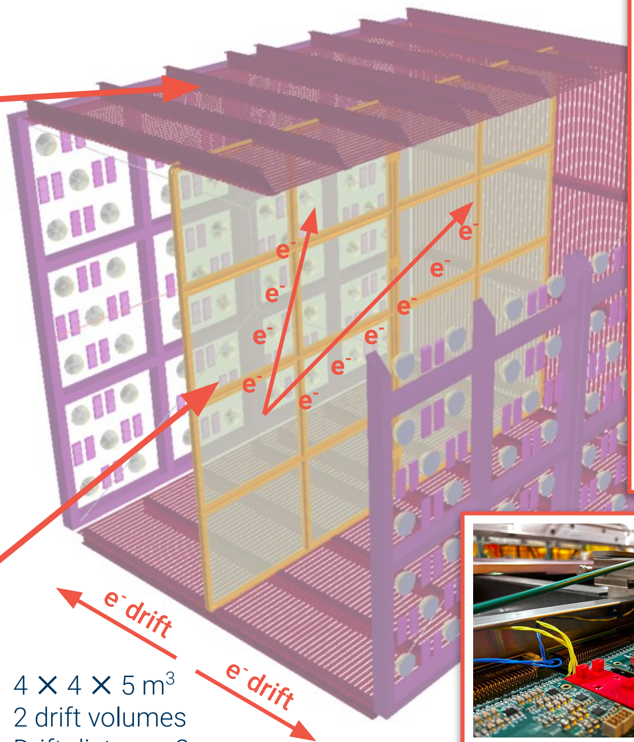
Once arrive at the anode, ionisation electrons induce current on the wire planes

**Field Cage** surrounds the TPC, aiming to provide uniform 500V/cm drift field.



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



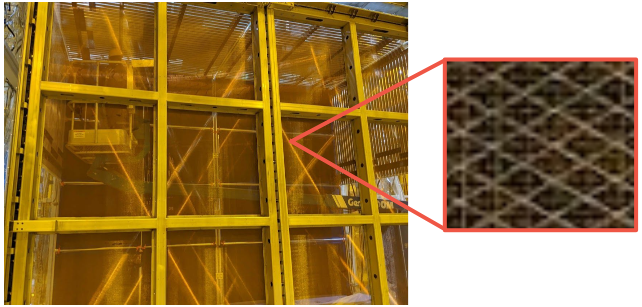


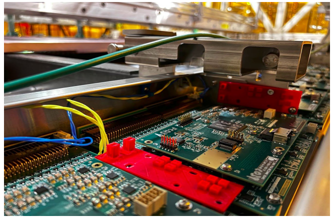

4 × 4 × 5 m$^3$
2 drift volumes
Drift distance 2 m

**Anode Plane Assembly** on east & west side.

- 3 wire planes, 11,264 wires in total
- $\theta_{u,v,w}$ = 0° and ± 60° from the vertical
- Wire pitch of 3 mm

JINST 15, P06033 (2020)





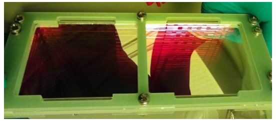
**Cold Electronics** (89K) pre-amplifies and digitises wire signals with extremely low noise.

# Photon Detection System

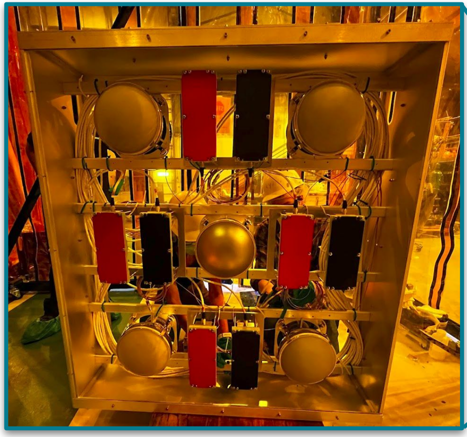
Scintillation photons are detected by active detection components located behind wire planes.

Additionally, scintillation photons are wavelength-shifted by passive components to improve light collection/reconstruction.

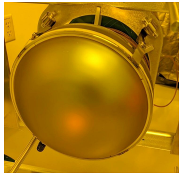
**X-ARAPUCA**
192 X-ARAPUCAs, sensitive to VUV and visible light

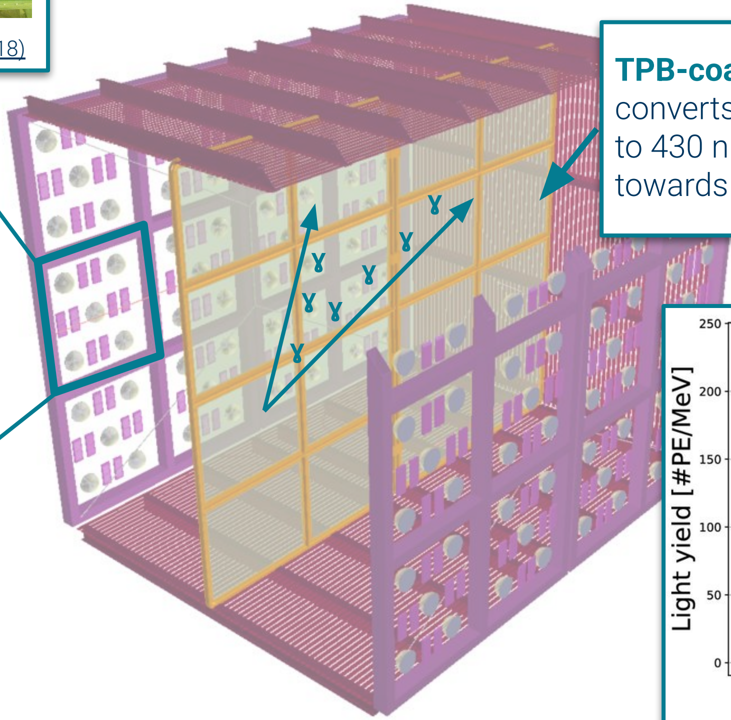


JINST 13, C04026 (2018)

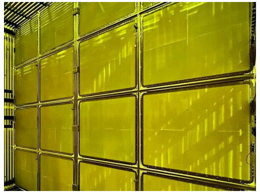


**PMT**
96 PMTs (TPB-coated)
24 PMTs (uncoated)

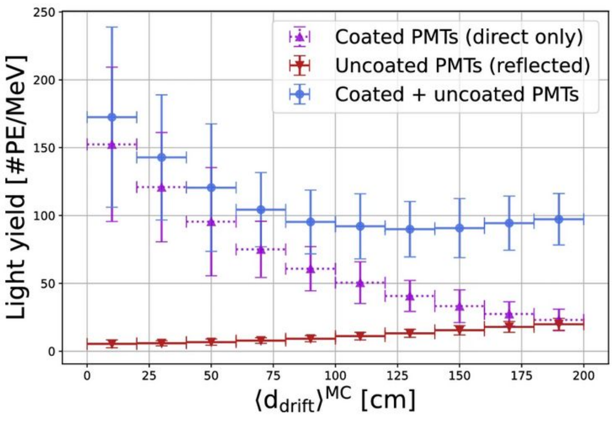




**TPB-coated Reflective Foils**
converts photons from 128 to 430 nm, and reflects back towards the anodes.

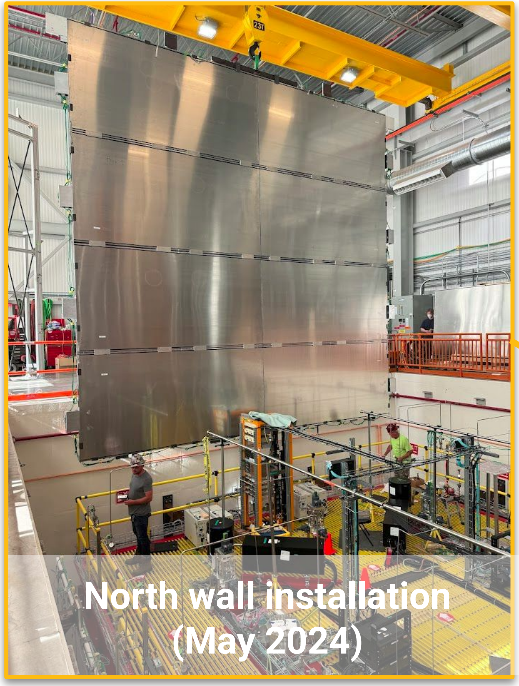


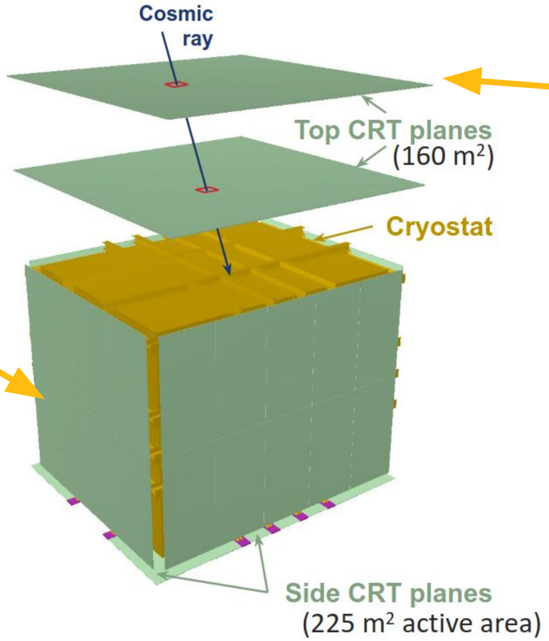
Eur. Phys. J. C 84, 1046 (2024)



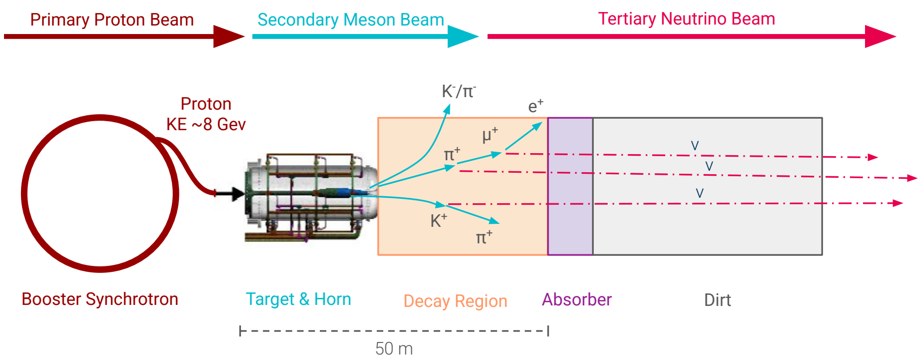
# Cosmic Ray Taggers

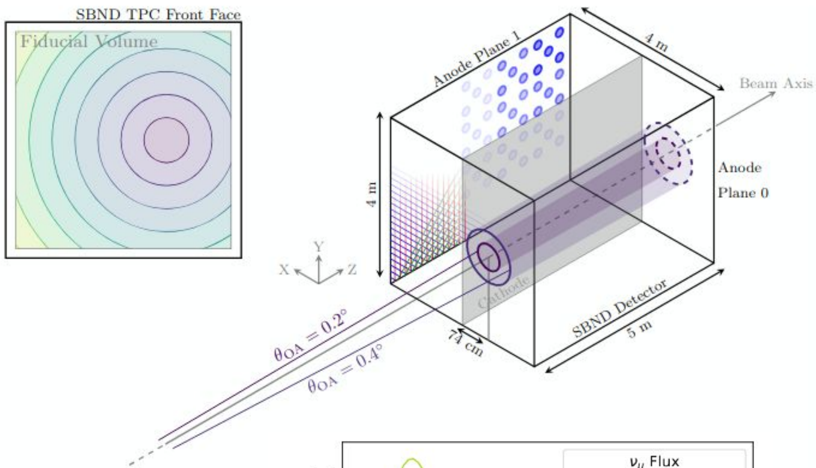
- The cryostat is surrounded by 7 walls of cosmic ray taggers
- 4π coverage for cosmic tagging
- 2360 optically isolated plastic scintillating strips read out by SiPMs.



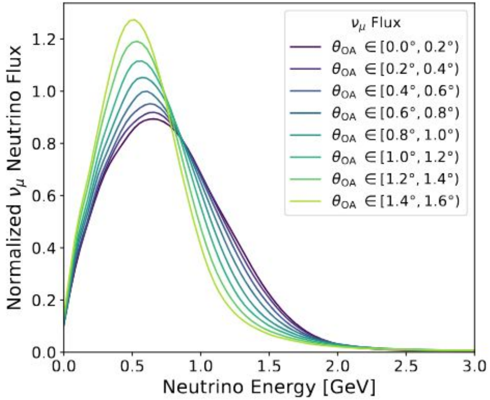




# The Booster Neutrino Beam




- A high-intensity 8 GeV proton beam is focused on Beryllium target producing charged and neutral mesons.
- SBND is close proximity and off-axis to the BNB
- Exploit the PRISM effect to sample fluxes at multiple off-axis angles (OAA)
  - Neutral mesons in the BNB = less focused
  - Charged mesons in the BNB = more focused
- Provide extra handles for systematic constraints



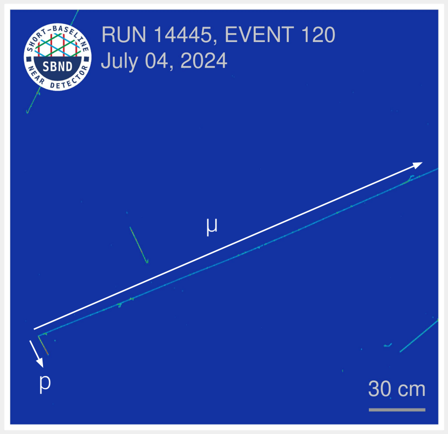

**$\nu_\mu$ flux at different off-axis angle**

arXiv:2508.20239

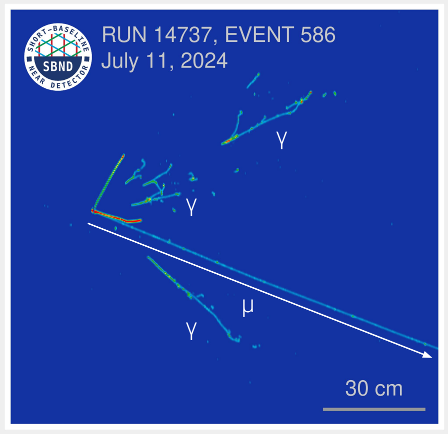
# Physics Program at SBND

- Only 110 m from the BNB target means 3 years of exposure results in 1 ⨉ 10^21 POT, equivalent to 10 million total neutrino events (CC+NC).
- Diverse physics program:
  - **Neutrino Oscillation** – characterising the unoscillated neutrino flux and simultaneously measuring $\nu_e$ (dis)appearance + $\nu_\mu$ disappearance
  - **Neutrino-Ar Cross Sections** – will collect the world's largest dataset of $\nu$-Ar interactions for high precision measurements
  - **PRISM** – extra handles for systematic constraints
- **Beyond Standard Models (BSM)** is also a big focus
- **Various beam production BSM models can potentially explain the Low Energy Excess** in $\nu_e$ appearance searches – an outstanding anomaly for 10+ years for short baseline neutrino experiments

Candidate: μ + p



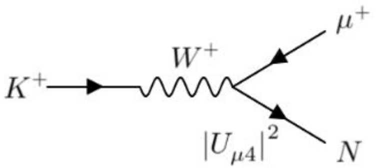

Candidate: $\mu + 2p + 2\pi^0$



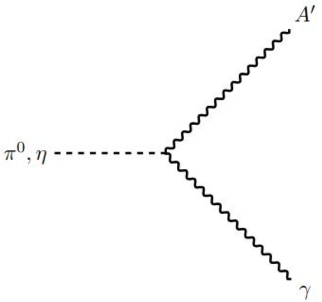
# BSM Production in the Booster Neutrino Beam

- 4 different BSM models that can be probed from the BNB
- These analyses more developed – but not the only ones being explored at SBND!

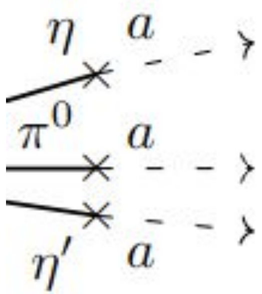
### Heavy Neutral Leptons



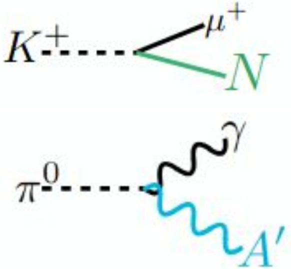

### Dark Photons




### Heavy QCD Axions

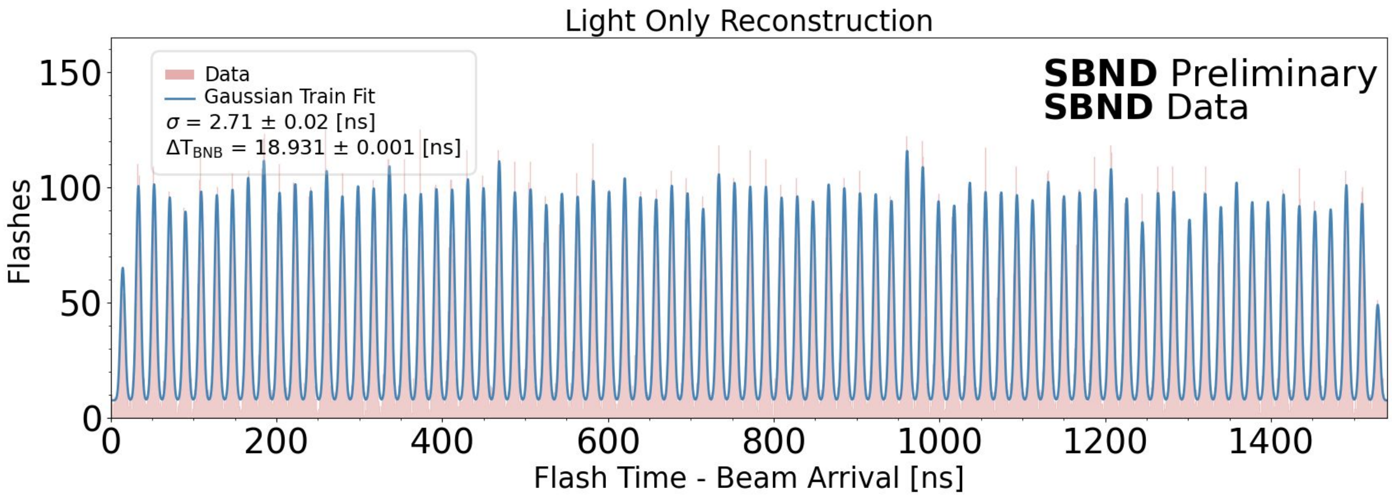



### Generic Long-Lived Particles



# Advantages of Beam Production BSM Signals

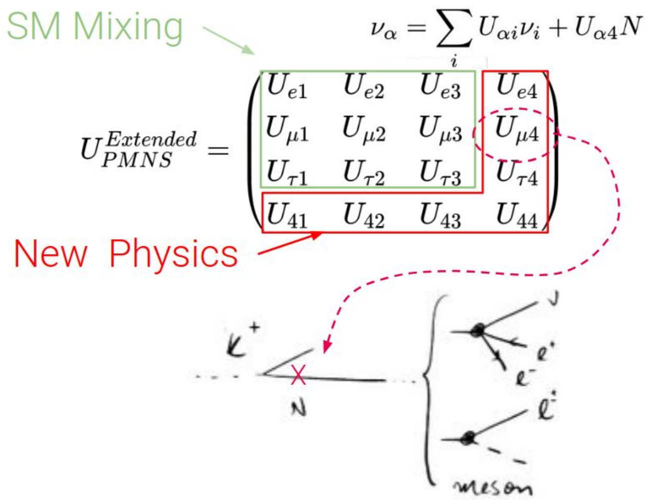
- Beam production BSM signals are typically theorised to be heavier than neutrinos – arriving at the detector later than neutrinos
- BNB has a bunch substructure: 81 Gaussian bunches with a sigma of ~2 ns and period of 19 ns
- At SBND, both the hardware and software were intentionally set up to achieve nanosecond resolution in timing reconstruction using the PMT signals
- This allows us to leverage timing as an analysis tools – search for BSM signals in-between the neutrino bunch



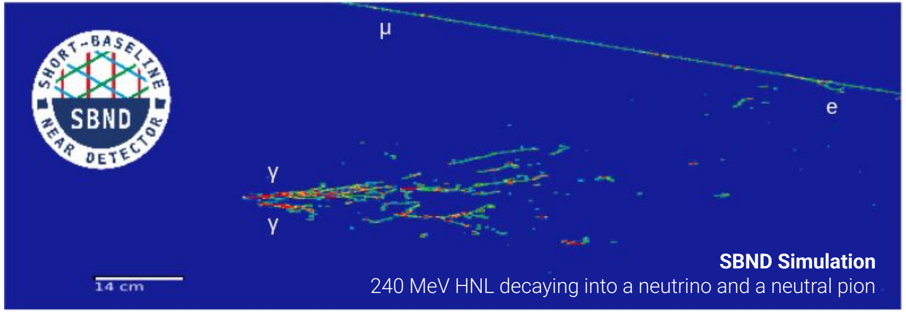
# Heavy Neutral Leptons

# Heavy Neutral Leptons

- Motivated by neutrino mass mechanism.
- Right-handed fermion addition to the 3-flavour paradigm.
- Can couple to all SM neutrinos by an extended PMNS matrix couplings $U_{\alpha 4}$, $\alpha = \tau, \mu, e$ (Need to be kinematically allowed).
- Produced by long lived meson $K^+$ from the BNB, constraining mass < 495 MeV.
- HNL then decay in flight into SM observables, with event rate $\propto |U_{\alpha 4}|$
- At SBND, the simulation of HNLs is via the MeVPrtl Generator – Dedicated paper underway!




Ballett Pascoli Ross-Lonergan JHEP 2017
Kelly Machado PRD 2021



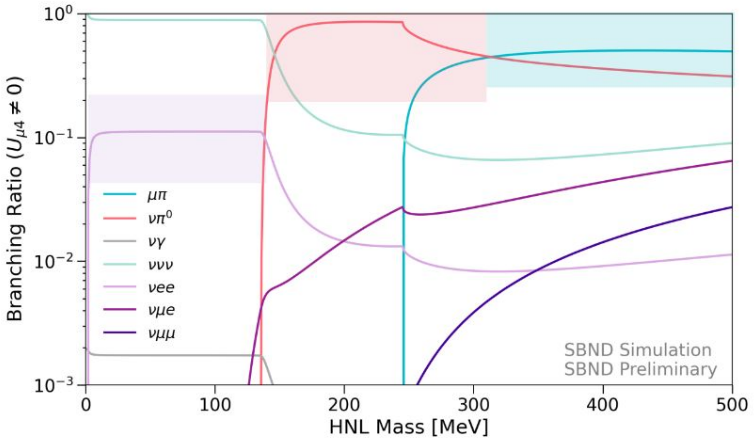

**SBND Simulation**
240 MeV HNL decaying into a neutrino and a neutral pion

# Heavy Neutral Leptons

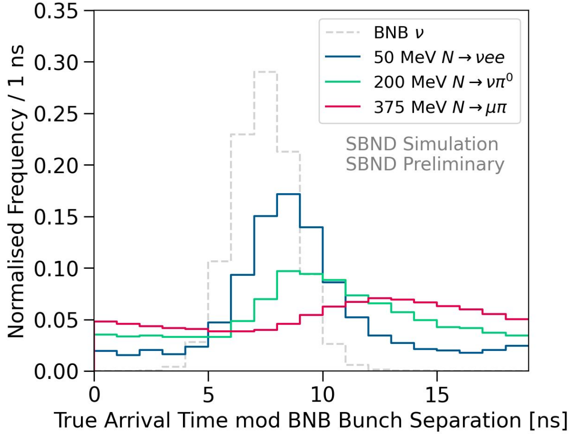
- Three channels are being explored:
  - $N \rightarrow \nu e e$ (30 – 140 MeV)
  - $N \rightarrow \nu \pi^0$ (140 – 244 MeV)
  - $N \rightarrow \mu \pi$ (244 – 388 MeV)
- Challenging topology signatures:
  - Beam-collimated
  - Boosted kinematics
  - No hadron activities

→ Leverage timing delay of HNLs for detection at SBND

→ HNLs are heavier and therefore travel at slower speed, smearing the Gaussian distribution



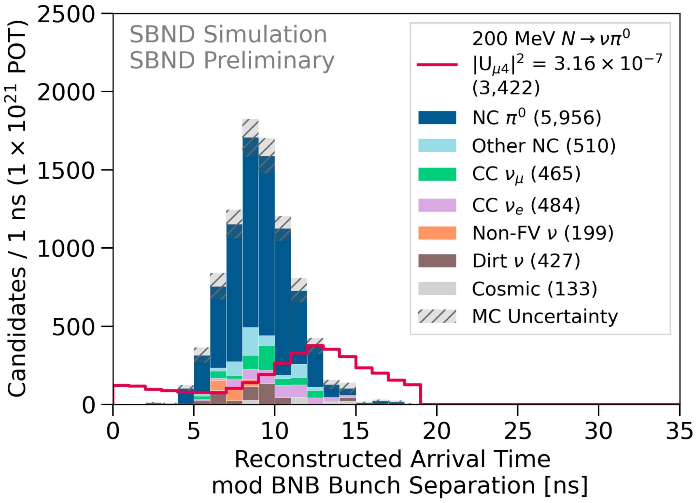

**Branching ratios of probable decay channels of an HNL produced from the BNB for the muon-flavour coupling**

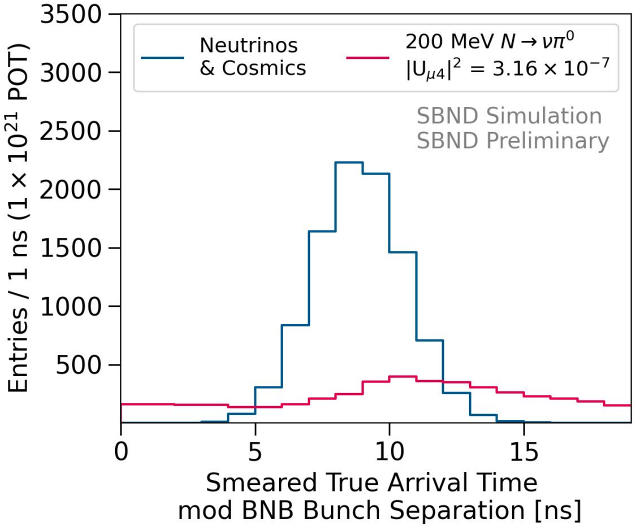


# Heavy Neutral Leptons Timing Studies

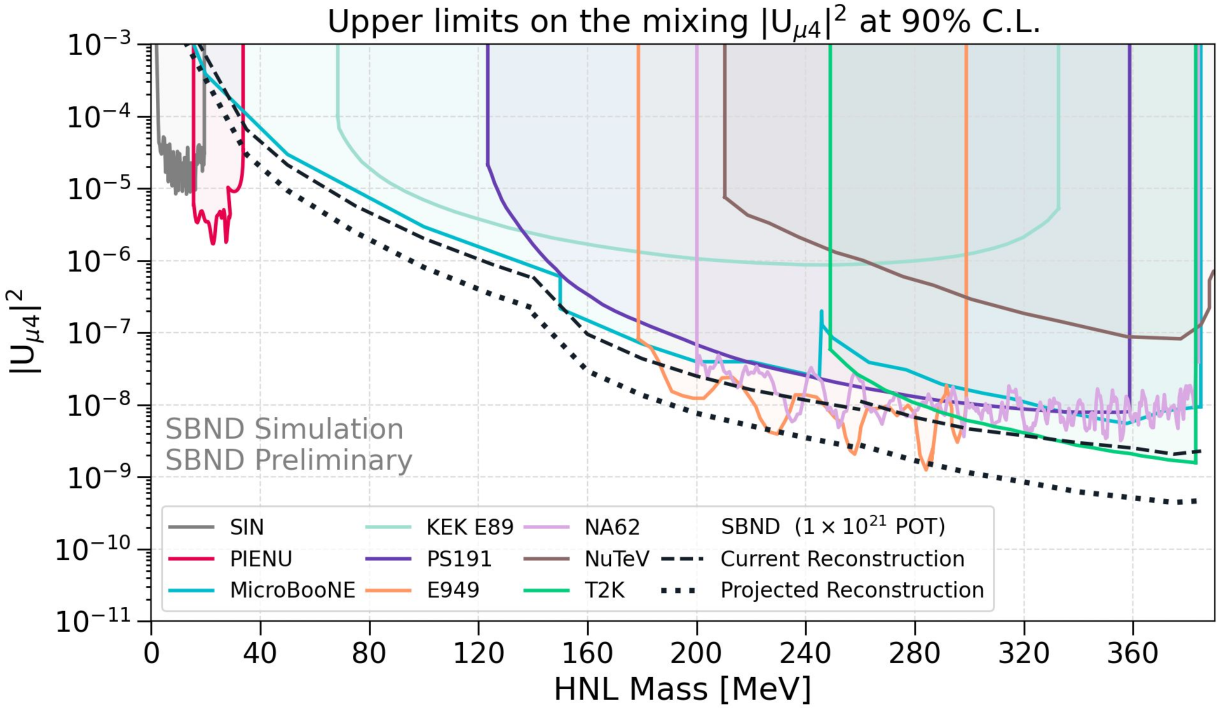
Performed two MC studies:

1. Using the standard reconstruction workflow to evaluate the current reconstruction performance
2. Applying a smearing at truth level under the assumption of an improved reconstruction to evaluate the impact on sensitivity gain



# Heavy Neutral Leptons Sensitivity

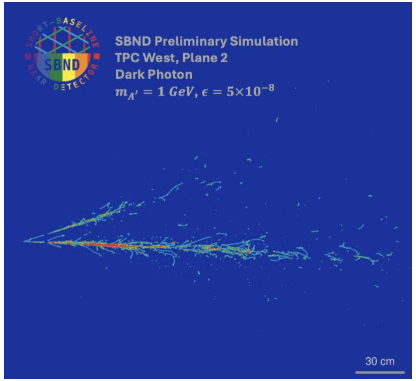


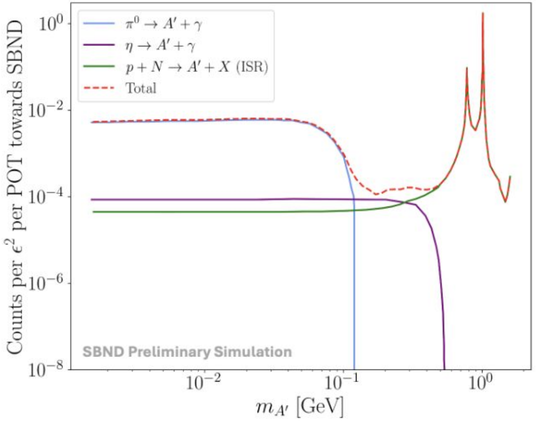

**SBND has the potential to improve current sensitivity limits on HNLs !**

# Dark Photons

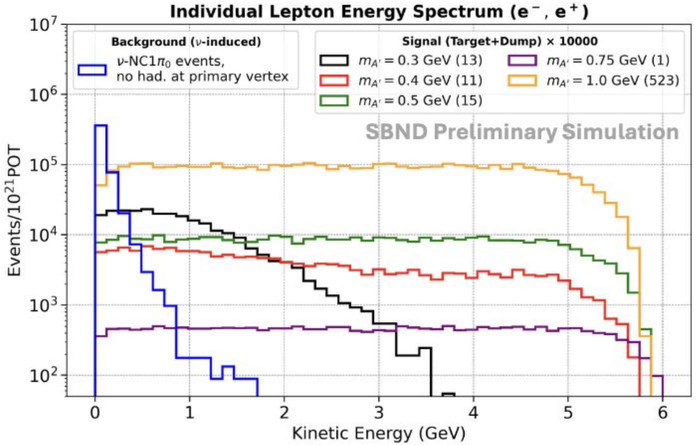
# Dark Photons

- Proposed gauge boson that can couple to SM photons
- Driven by the kinetic mixing constant $\varepsilon$ between the dark photon A' and an SM photon
- Two production channels from the BNB:
  - 2-body neutral meson decay from $\pi^0$ and η
  - Proton bremsstrahlung from p-Be interaction
- Decay channels:
  - Di-leptons → currently exploring di-electrons channel!
  - Other hadronic channels
- Exploit higher kinematics of dark photons to reject SM neutrino background at low energy

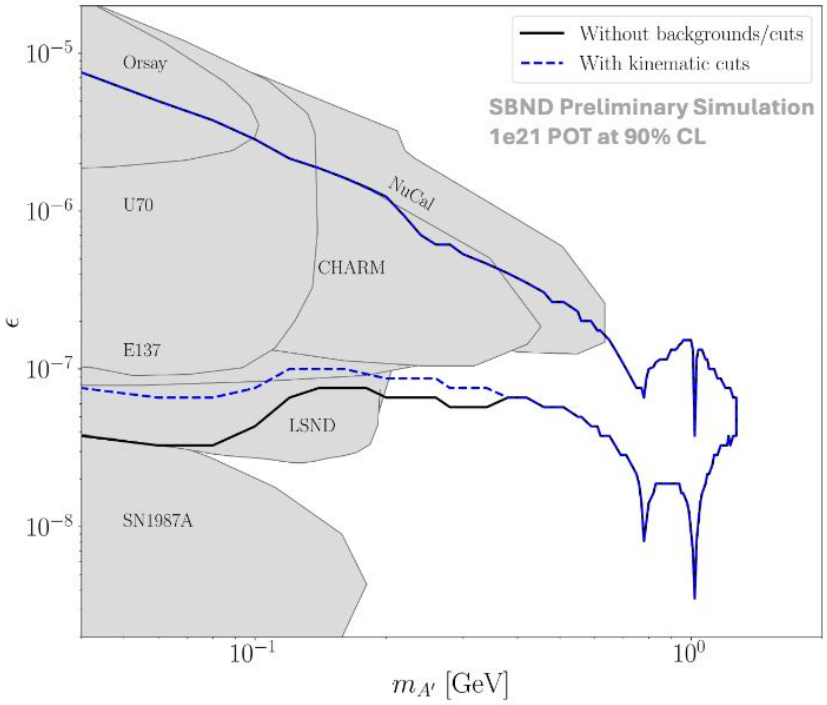



**Probability of producing a dark photon via 2-body neutral meson decay and proton bremsstrahlung**



# Dark Photons Sensitivity



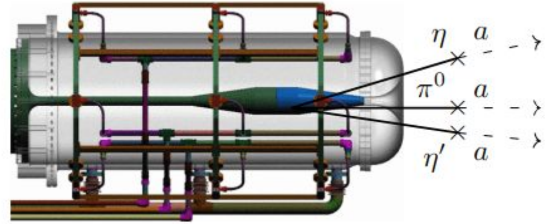

**SBND has the potential to set world-leading limits on dark photons sensitivity!**

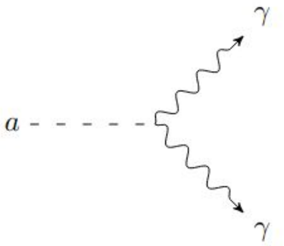
Still has room for improvement by currently updating the simulation of neutral meson production in the BNB

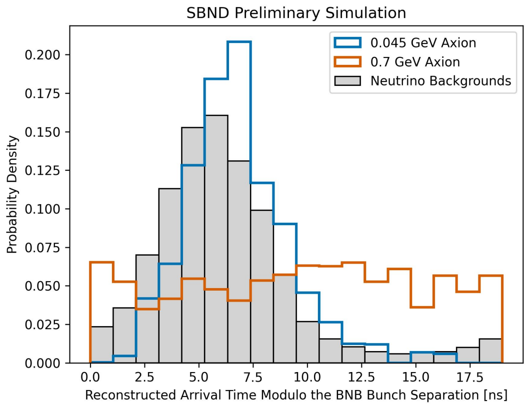
# Heavy QCD Axions

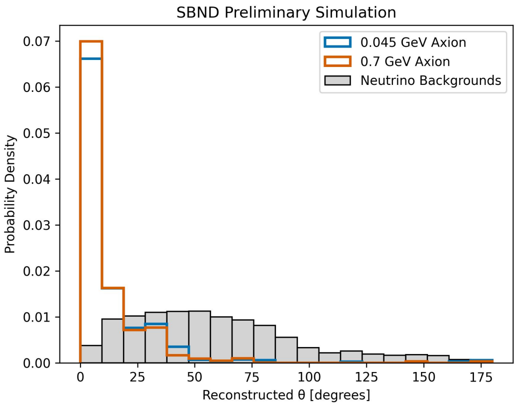
# Heavy QCD Axions

- Was proposed as a solution to the strong CP problem
- Can be produced by neutral mesons from the BNB via gluon-gluon fusion or meson mixing
- Decay channels: dileptons, diphotons or hadrons
- Share synergy with HNLs and dark photon analysis for collaborative efforts:
  - The same neutral meson simulation as dark photon
  - Similar boosted kinematics and timing delay as HNLs
- Currently exploring the sensitivity of the diphoton final state

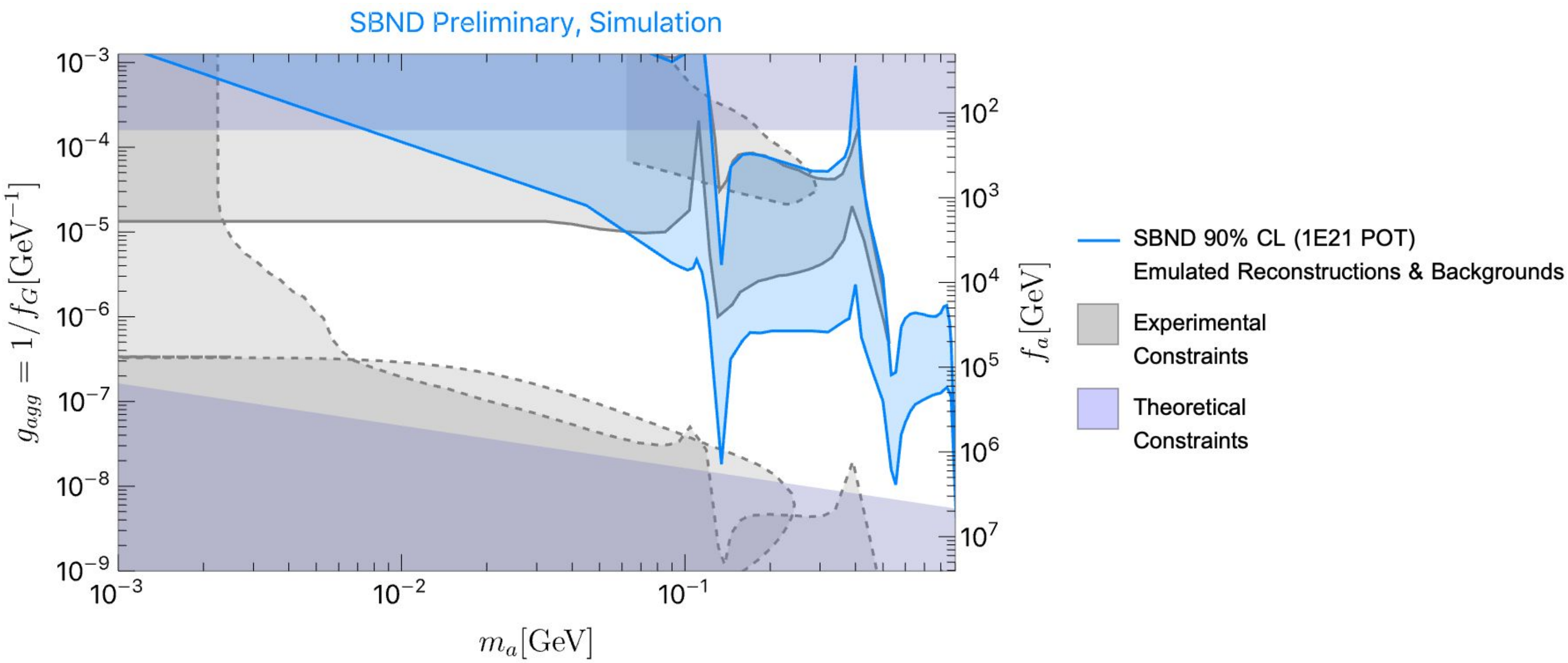


# Heavy QCD Axions Sensitivity

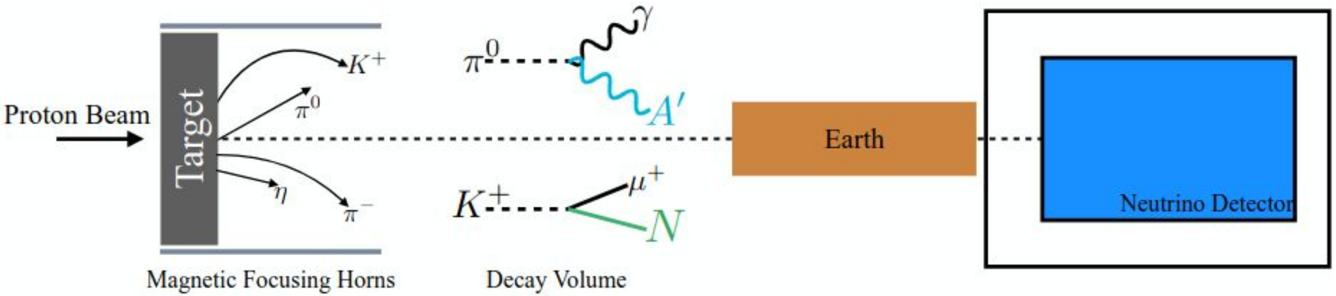



**SBND can further improve the sensitivity limits on Heavy QCD Axions!**

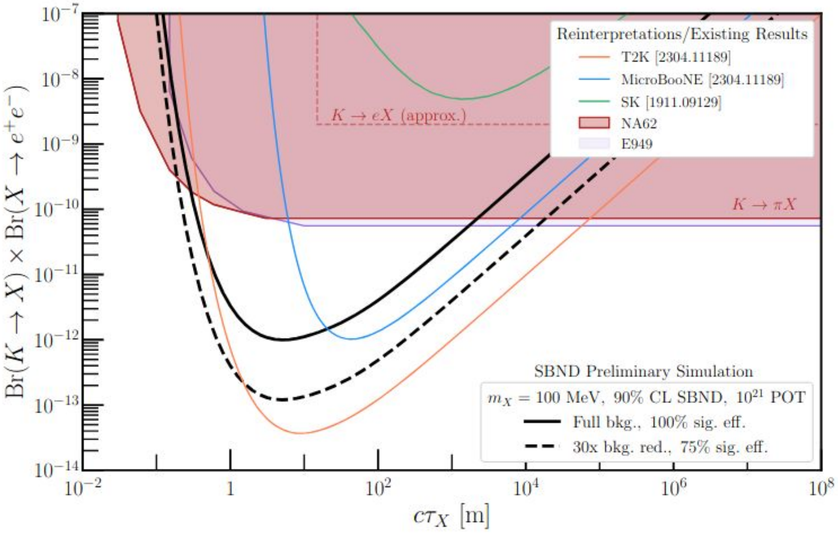
# Generic Long-Lived Particles

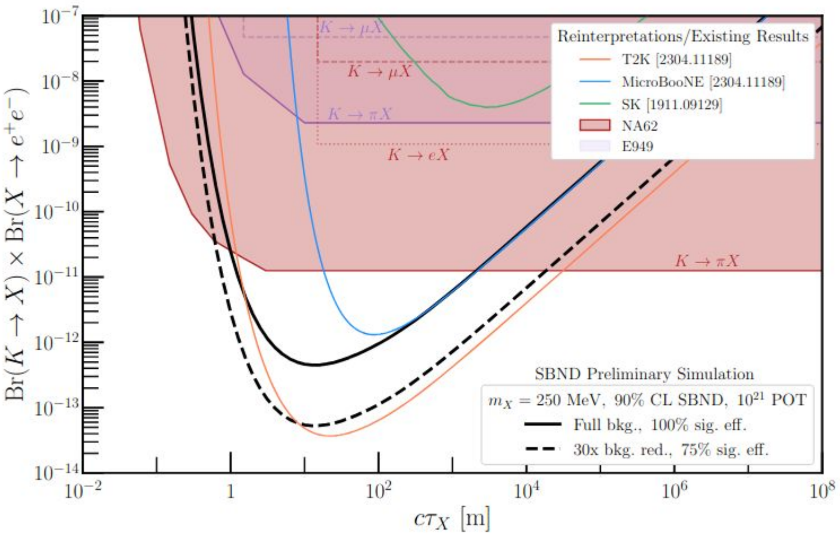
# Generic Long-Lived Particles

- Generic Long-Lived Particles (LLPs) is model-independent search for various long lived exotic particles that can be produced from the BNB
- Develop a simplified framework for LLP searches, with 4 key assumptions:
  1. Produced via 2-body meson decay: $K^+ \rightarrow \pi^+ X$ or $K^+ \rightarrow \mu^+ X$
  2. LLP mass $m_X$
  3. LLPs decay into visible states in inside SBND
  4. Lifetime of $c\tau_X$ = 10, $10^6$ m
- Currently exploring the sensitivity of the di-electron final state, $X \rightarrow \nu ee$, at truth level



# Generic Long-Lived Particles Sensitivity




**Preliminary performance indicates that a model independent search at SBND can set world-leading limits!**

# Outlooks

- SBND is a LArTPC with close proximity to the BNB → Can probe a variety of BSM models from BNB
- 3 detection systems combined: LArTPC + Photon Detection System + Cosmics Ray Tagger → Excellent spatial, timing and energy resolution
- Leverage the timing delay and kinematic analyses, SBND has the potential to set world leading limits on many exotic searches
- Work has begun for estimating sensitivities, developing event selections and reconstruction tools.


Thank You For Listening!