



# Searches for Physics Beyond the Standard Model with the Short-Baseline Near Detector

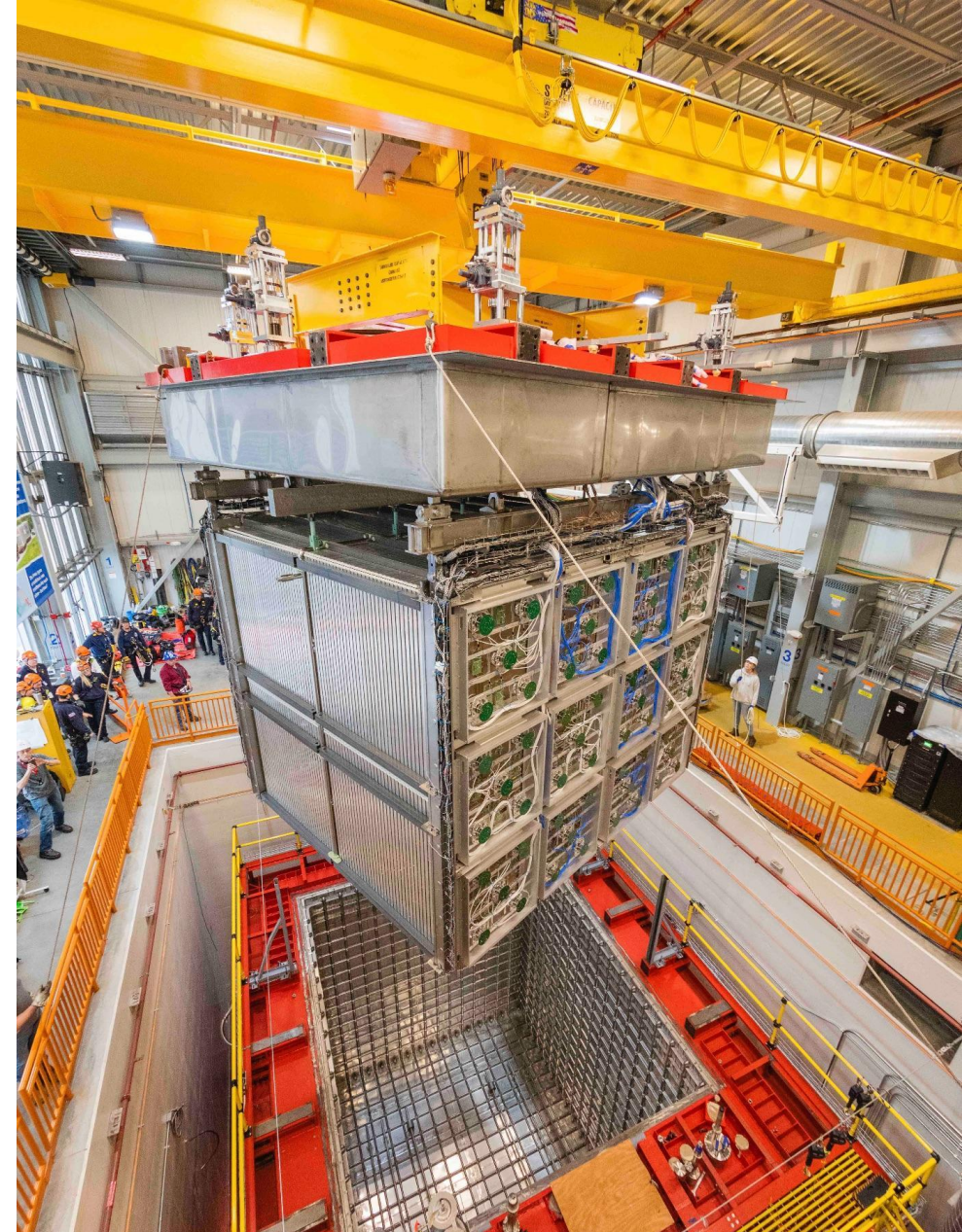
Rohan S. Rajagopalan

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*On Behalf of the SBND Collaboration*

26<sup>th</sup> International Workshop for Neutrinos from Accelerators

Sept. 2025



*SBND Time Projection Chamber being lowered into the Cryostat in April 2023*

# The Short Baseline Near Detector

- A 112-ton active volume **Liquid Argon Time Projection Chamber**
- Situated at the **Fermi National Accelerator Laboratory (Fermilab)**
- Sits 110 meters from **Booster Neutrino Beam (BNB) target hall**
  - 8 GeV proton beam incident on a 70 cm Beryllium Target

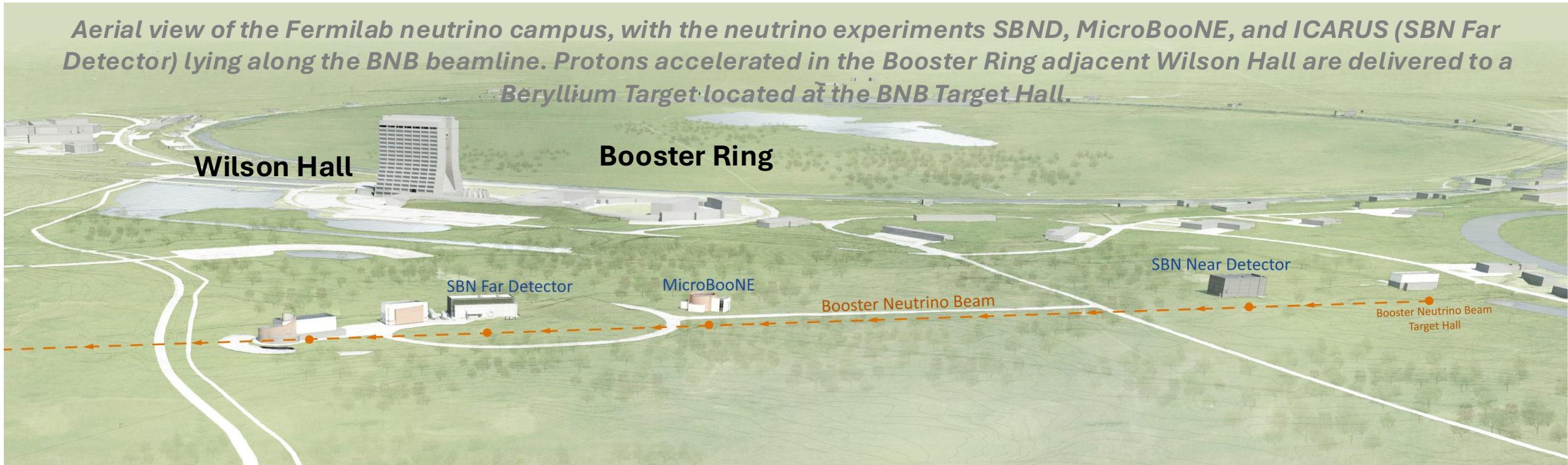


*SBND Time Projection Chamber being lowered into the Cryostat in April 2023*

# The Short Baseline Near Detector

➤ We study neutrinos delivered by the BNB!

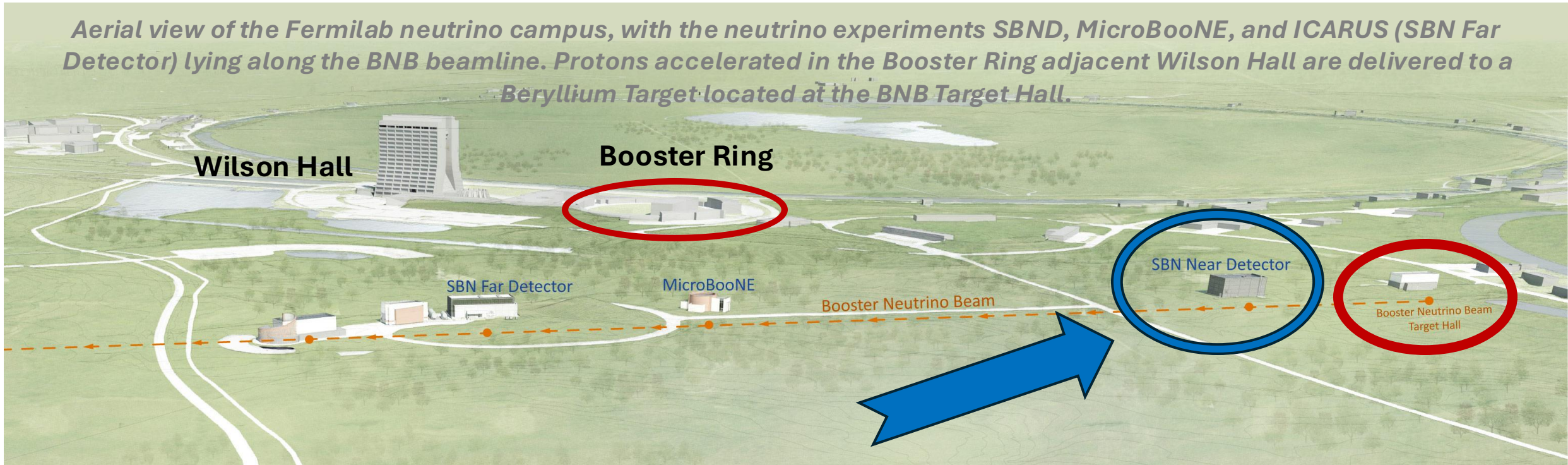
*Aerial view of the Fermilab neutrino campus, with the neutrino experiments SBND, MicroBooNE, and ICARUS (SBN Far Detector) lying along the BNB beamline. Protons accelerated in the Booster Ring adjacent Wilson Hall are delivered to a Beryllium Target located at the BNB Target Hall.*



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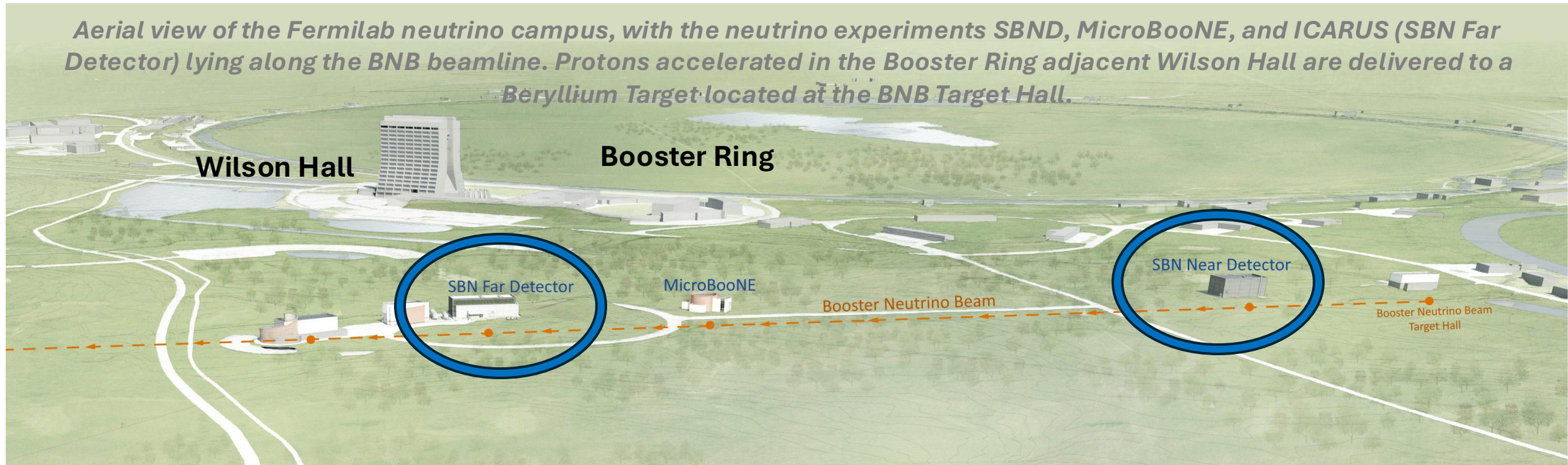
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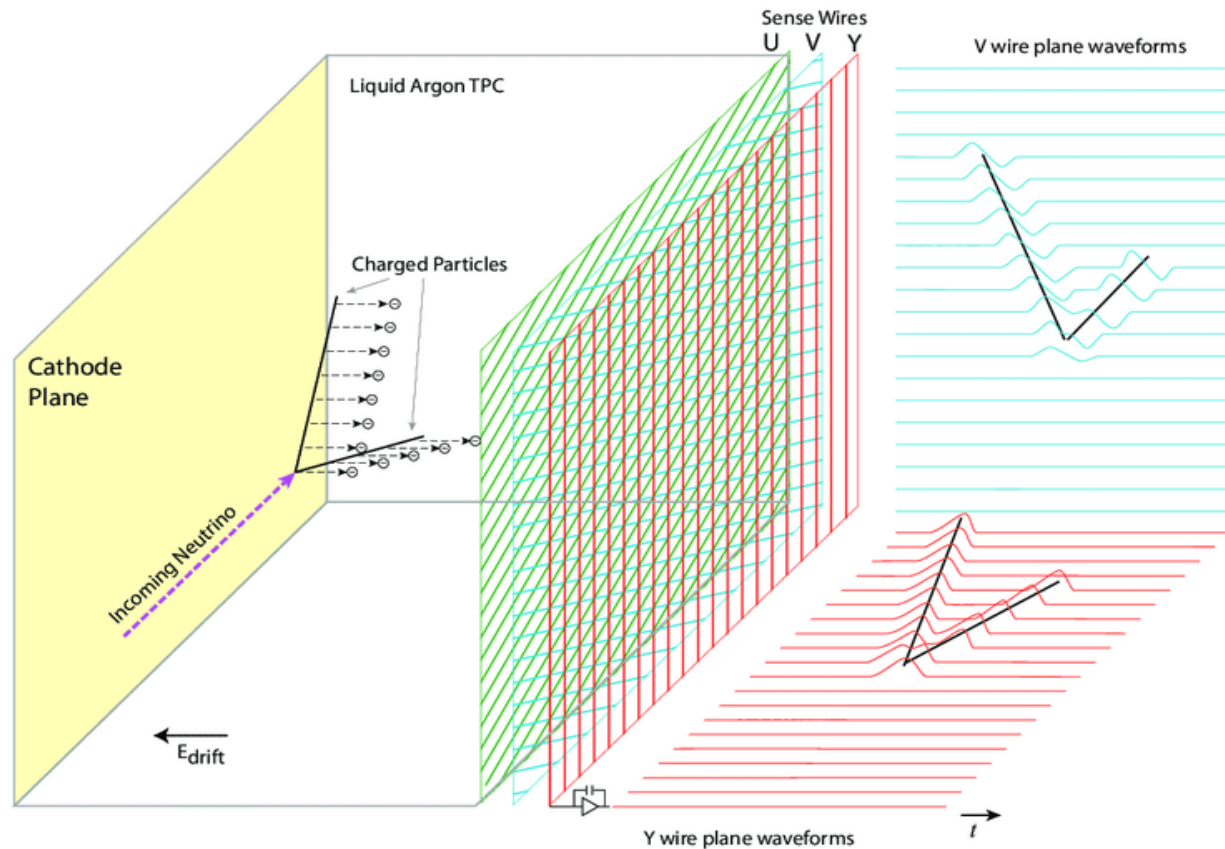
# Short Baseline Neutrino Program

- **SBND acts as the near detector for the SBN Program, with ICARUS as our far detector.**

*Aerial view of the Fermilab neutrino campus, with the neutrino experiments SBND, MicroBooNE, and ICARUS (SBN Far Detector) lying along the BNB beamline. Protons accelerated in the Booster Ring adjacent Wilson Hall are delivered to a Beryllium Target located at the BNB Target Hall.*



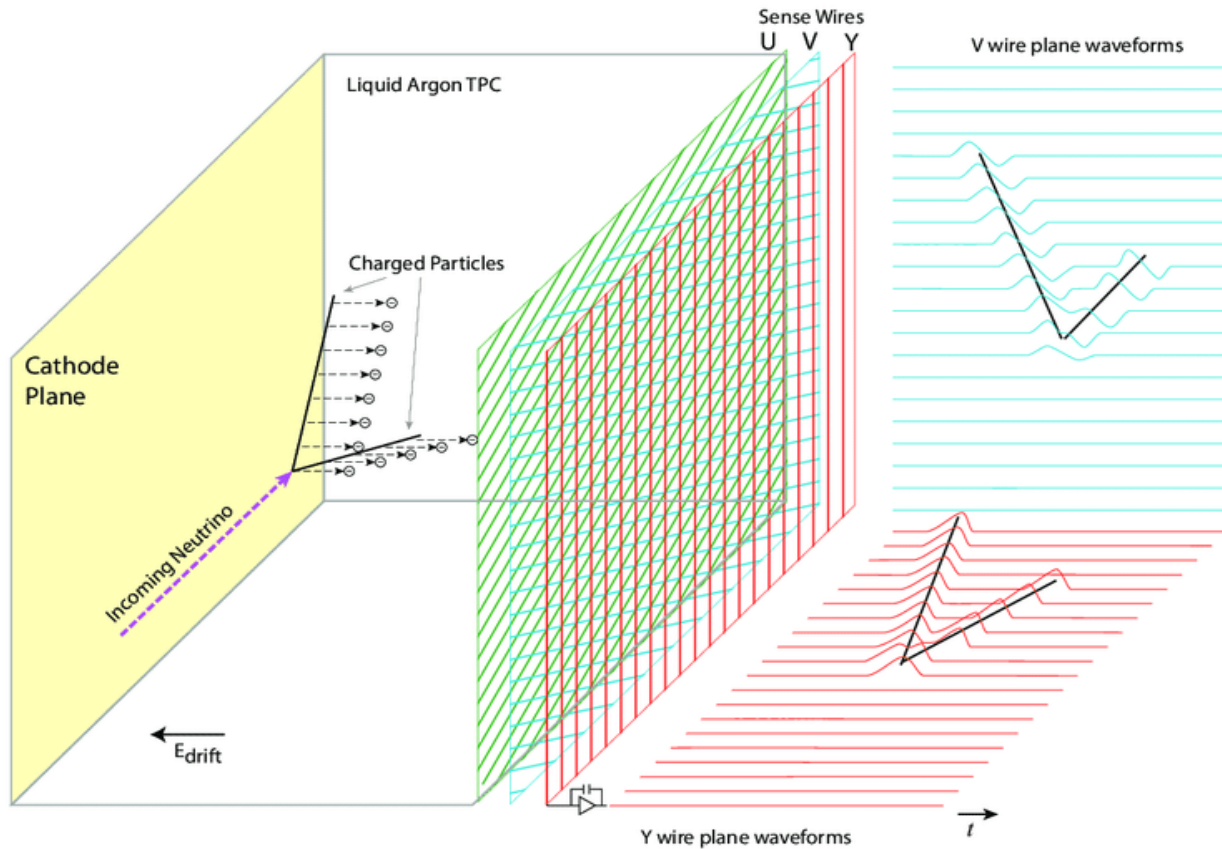
# The Ingredients of SBND



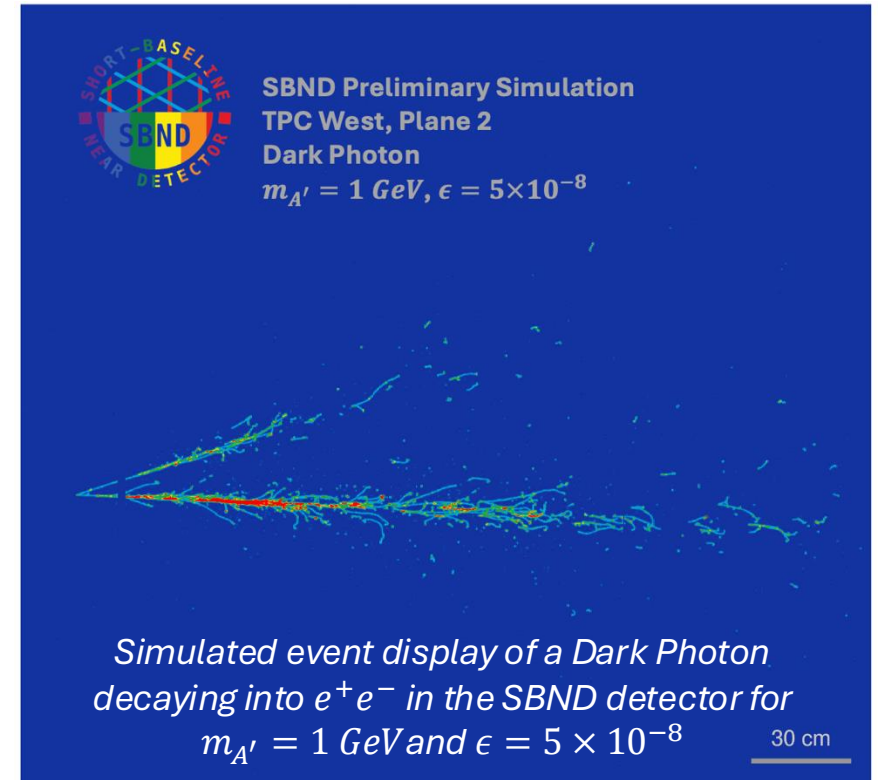
## ➤ Liquid Argon Time Projection Chamber (LArTPC)

- $4 \times 4 \times 5 \text{ m}^3$
- 112-ton active volume
- Two anode planes separated by one cathode, giving 2 drift volumes
  - 11,264 wires total
  - Uniform Drift Field of  $500 \text{ V/cm}$
  - Drift distance of 2 meters
  - Maximum drift time of 1.3 ns
- Use **scintillation light** generated inside the TPC for triggering on neutrino candidates and cosmic rays

# The Ingredients of SBND



- Fine spatial resolution of 3 mm
- Excellent Particle Identification
  - Electron/Photon Separation



# The Ingredients of SBND

## ➤ Cosmic Ray Tagger (CRT)

- Tags **cosmic rays** entering/exiting the detector
- Surrounds SBND giving  $4\pi$  angular coverage

## ➤ Photon Detection System (PDS)

- 120 PMTs + 192 X-ARAPUCAs
  - Critical for collecting scintillating light
- Excellent **nanosecond timing resolution**

SBND PDS Paper: [arXiv:2406.07514](https://arxiv.org/abs/2406.07514)



*The first wall of the Cosmic Ray Tagger (CRT), consisting of individual scintillating strip modules being installed on the downstream end of the cryostat.*

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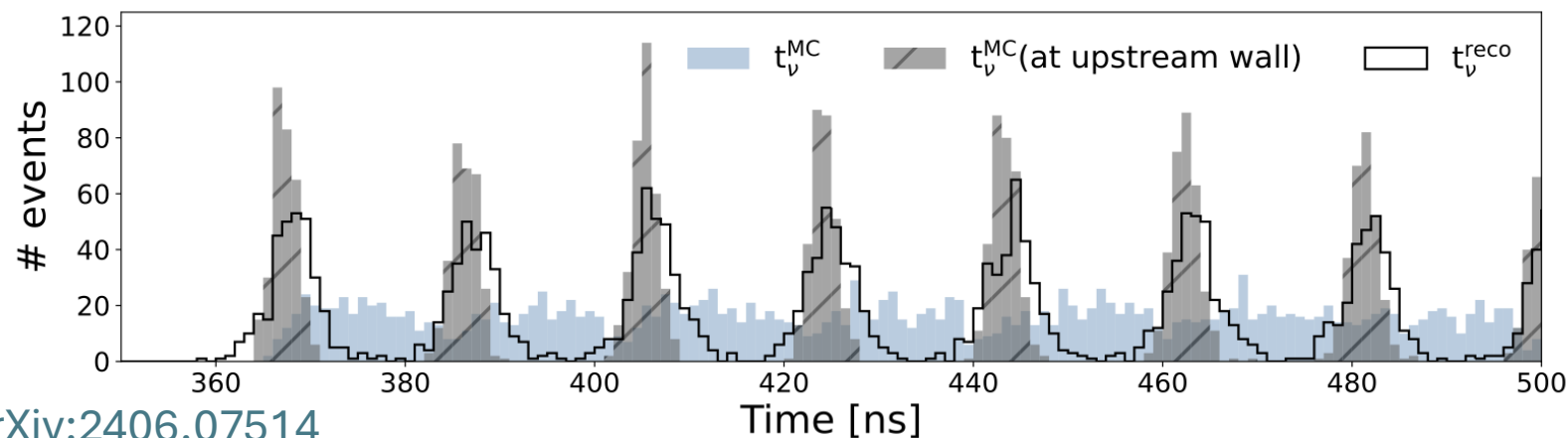


*Completed field cage and Anode Assembly Plane (APA) with twelve Photon Detection System (PDS) modules located behind the wire planes. Each PDS module contains five PMTs and eight X-ARAPUCA devices for light detection.*

SBND PDS Paper: [arXiv:2406.07514](https://arxiv.org/abs/2406.07514)

# The Ingredients of SBND

- Protons are delivered to BNB target in bunches ~2 ns wide and 19 ns apart
- Thanks to our PDS, we can achieve **nanosecond timing resolution**
- Allows us to examine the **neutrino bunch structure** in greater detail, and leverage timing as an analysis tool
  - Critical for accurately triggering on neutrino interactions
  - **Certain BSM signals may exist outside the neutrino bunch**

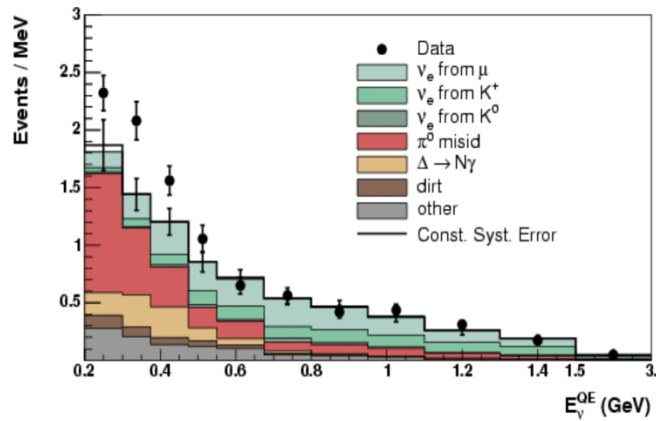


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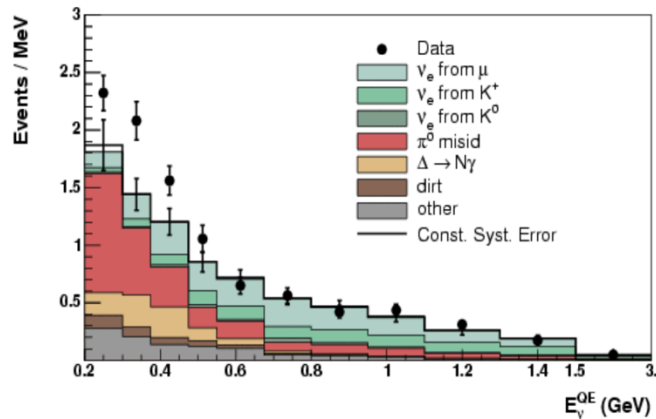
*SBND ramping up to full operating voltage on July 3<sup>rd</sup>, 2024*

# Our Physics Goals

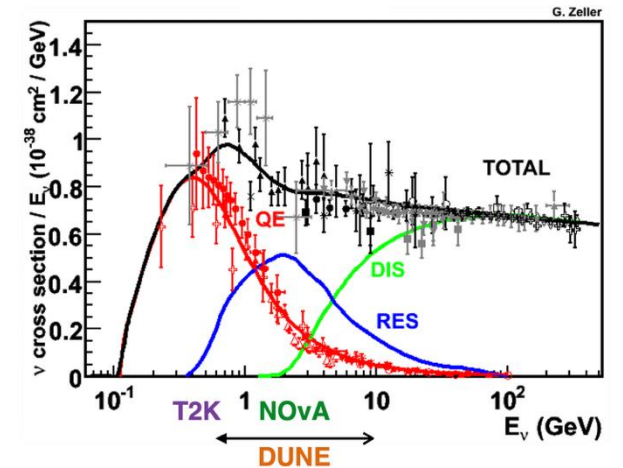


*Investigate Low Energy  
Excess observed at  
MiniBooNE*

# Our Physics Goals



**Investigate Low Energy  
Excess observed at  
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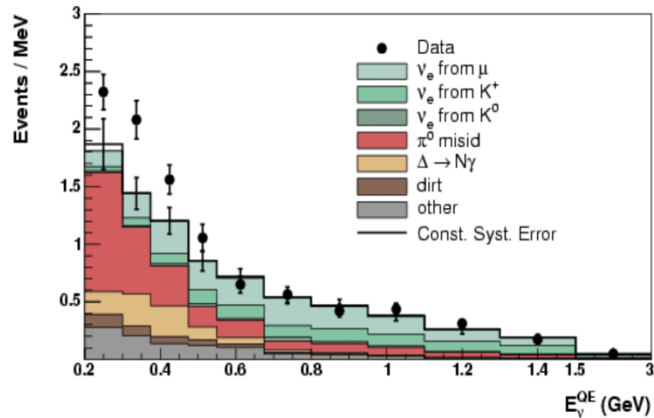


J.A. Formaggio, G. Zeller, Reviews of Modern Physics, 84 (2012)

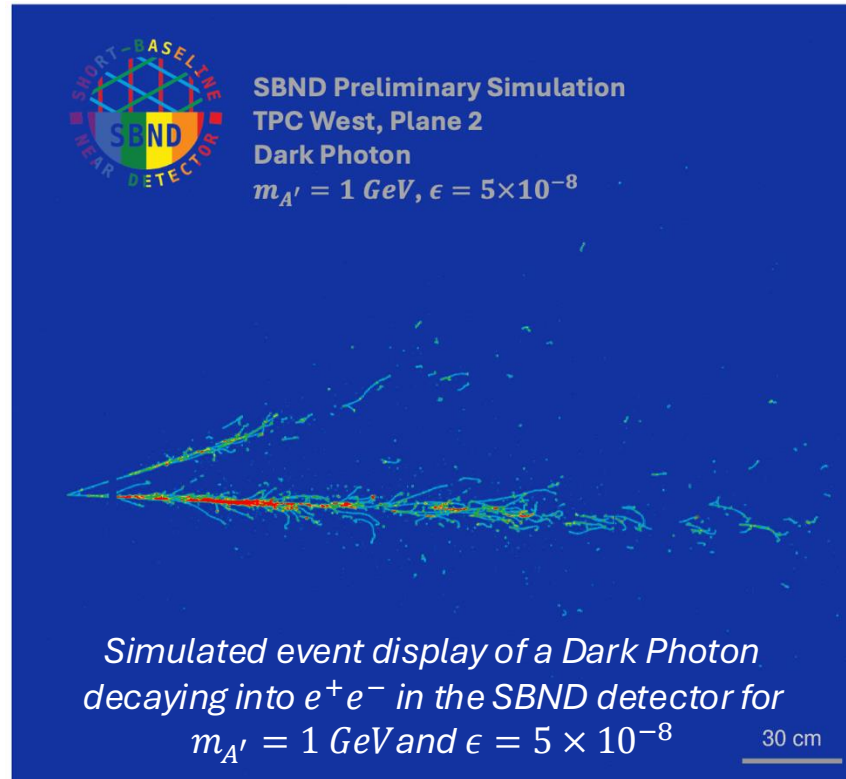
**Measure neutrino cross  
sections on LAr**

See Luis Pelegrina's talk

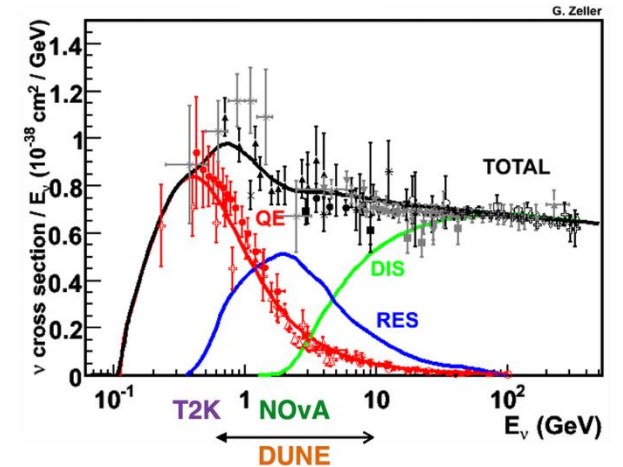
# Our Physics Goals



**Investigate Low Energy  
Excess observed at  
MiniBooNE**



**Probe Beyond the Standard  
Model Physics!**



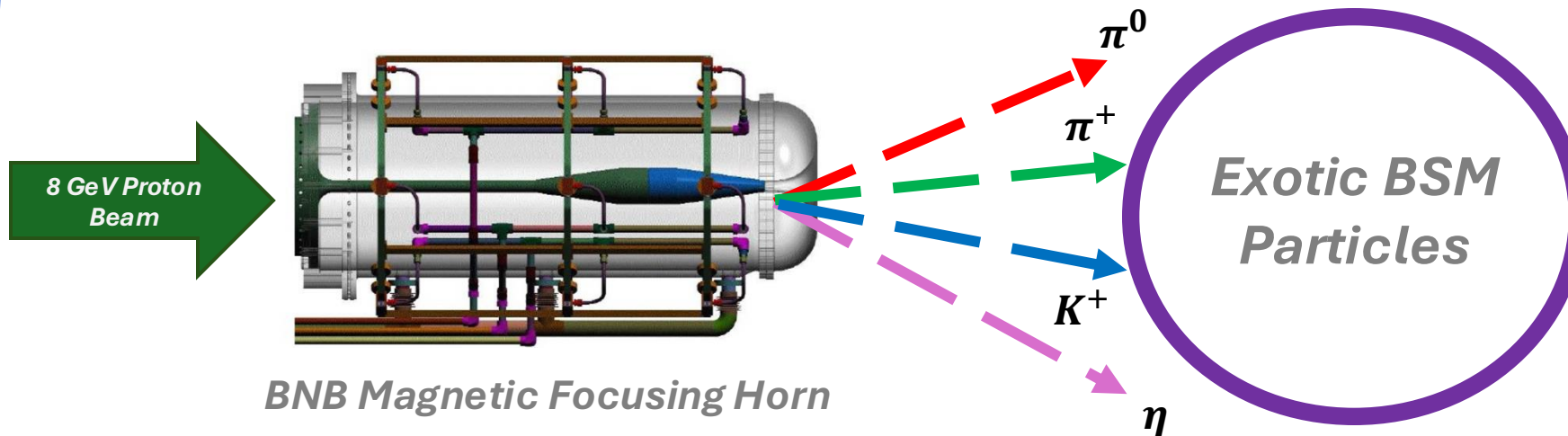
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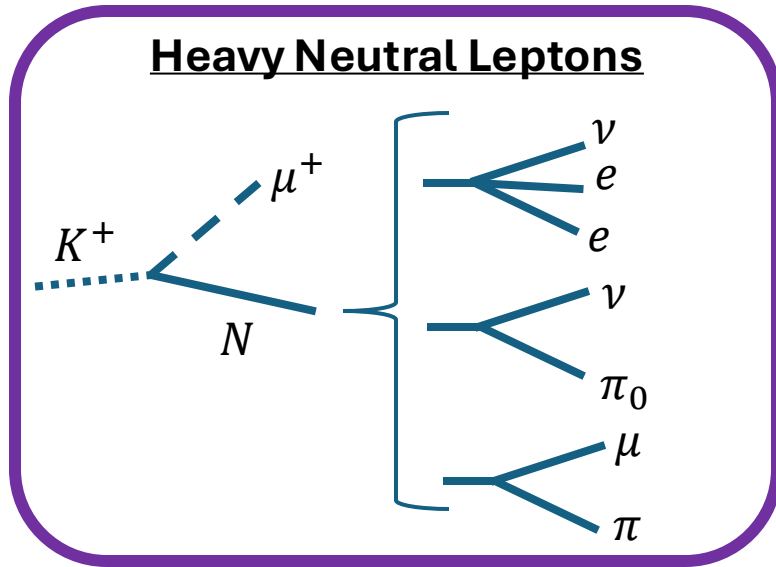
# Probing BSM Physics

- **Leverage proximity to the BNB Target**
  - Potential for high statistics measurements
  - Allows access to variety of signatures
    - Charged and neutral meson parents
  - Can probe low mass region for exotic particles



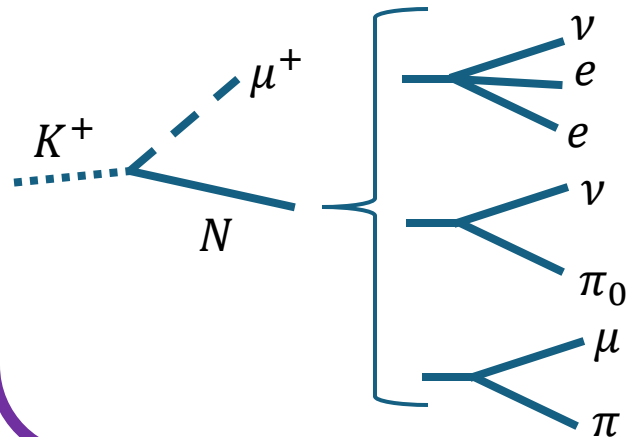


**BSM  
Searches  
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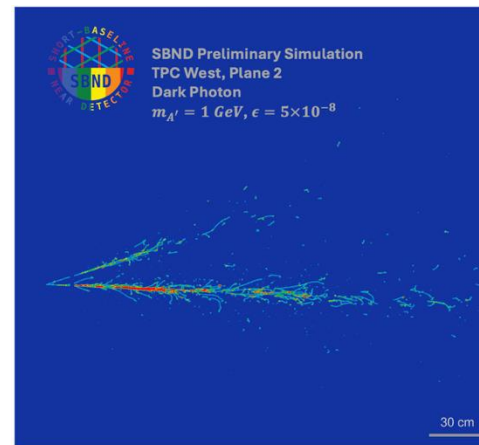


**BSM  
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## Heavy Neutral Leptons

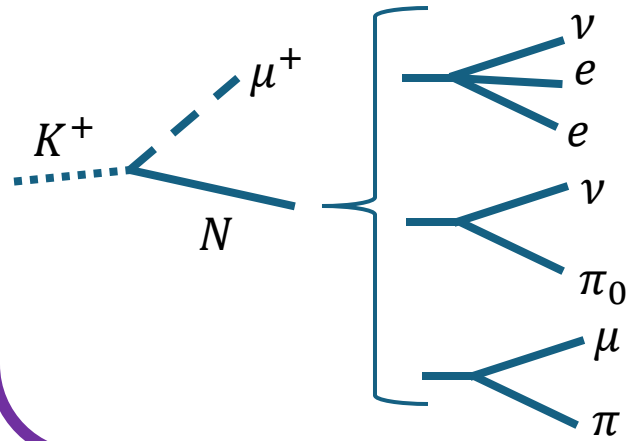


## Dark Photons

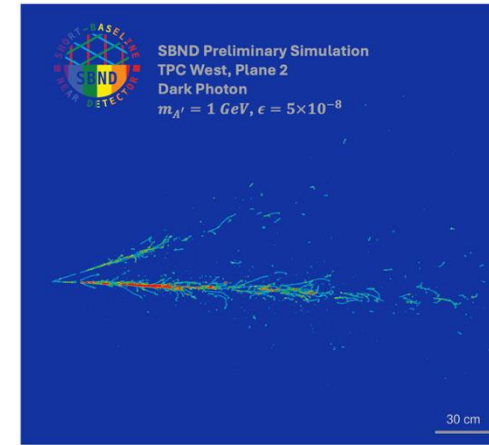


## BSM Searches at SBND

## Heavy Neutral Leptons

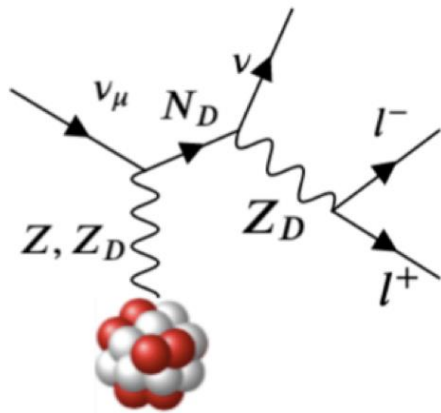


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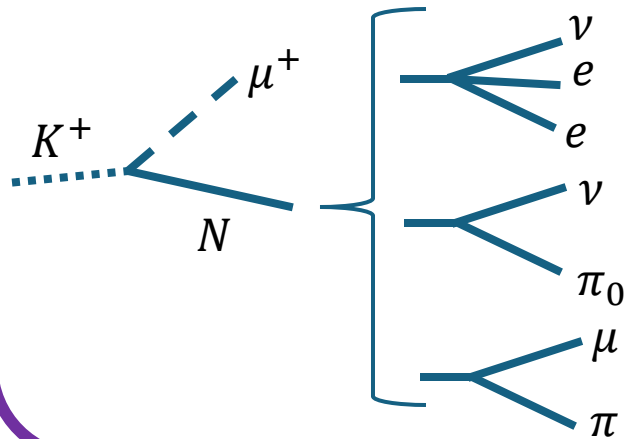


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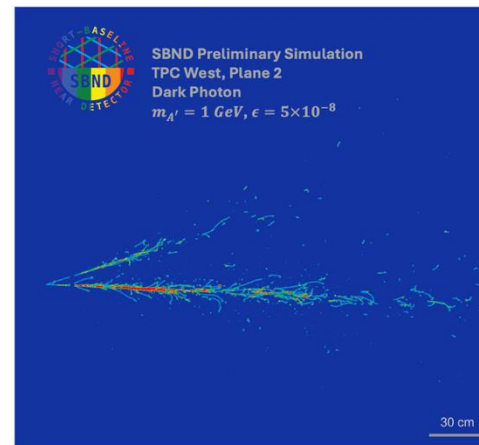
## Generic Long-Lived Particles



### Heavy Neutral Leptons

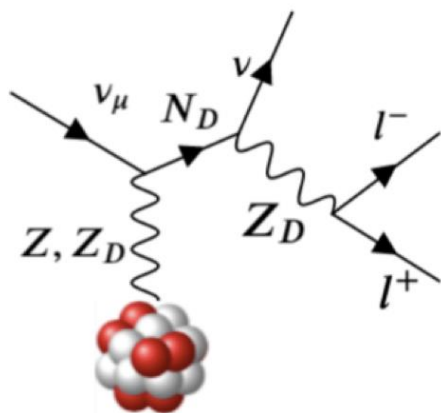


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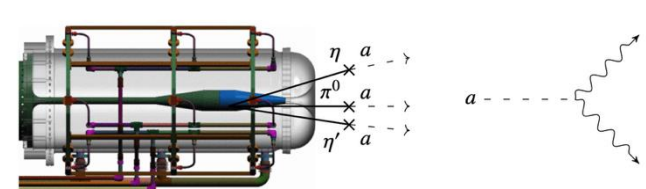


## BSM Searches at SBND

### Generic Long-Lived Particles



### Heavy QCD Axions



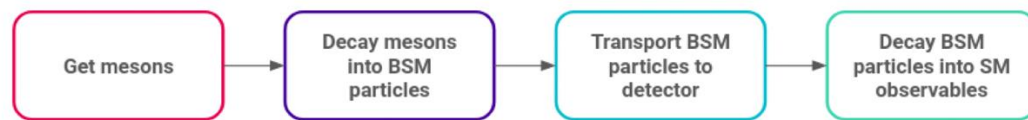
$$\mathcal{L}_{eff} = \frac{a}{8\pi f_a} (c_3 \alpha_3 G\tilde{G} + c_2 \alpha_2 W\tilde{W} + c_1 \alpha_1 B\tilde{B})$$

# Heavy Neutral Leptons

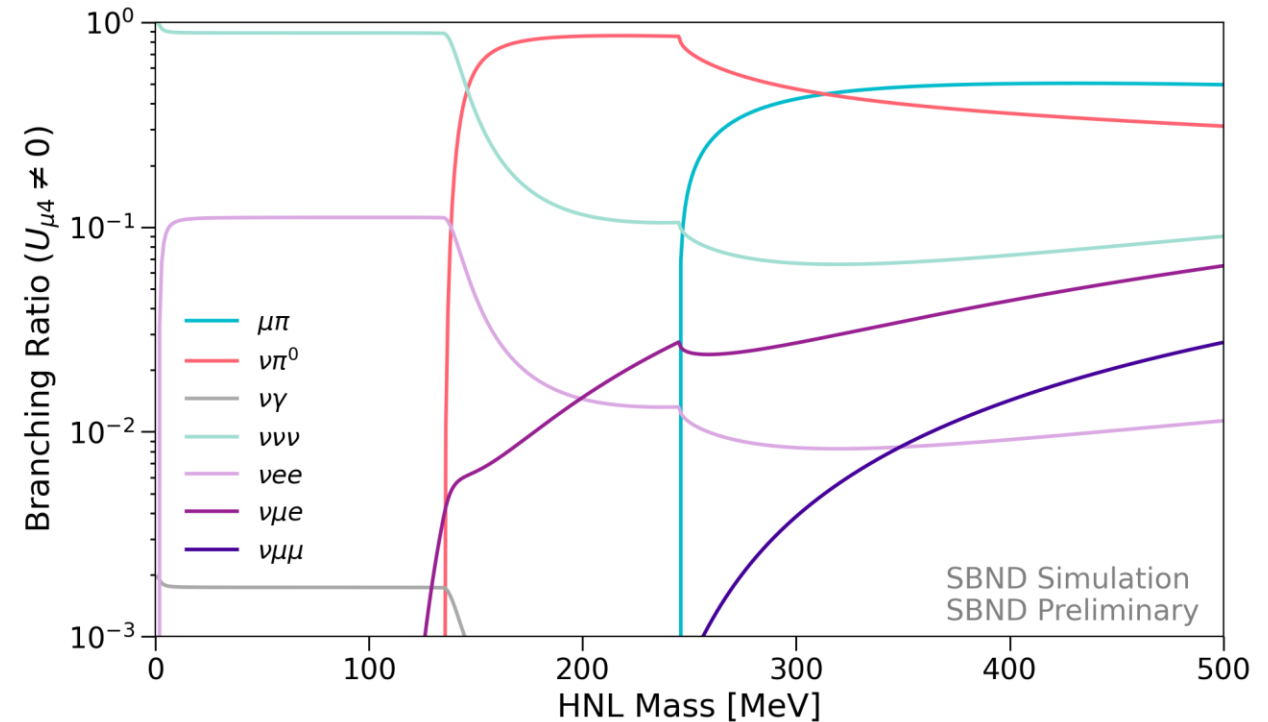
# Heavy Neutral Leptons



- Proposed **right-handed fermion** which couples to all neutrinos via an extended PMNS matrix
  - Assumed as Majorana for this analysis
- Makes use of the **MeVPrtl** simulation package, with various HNL decay channels for study
  - Note only the  $K^+ \rightarrow N$  production channel is available in MeVPrtl
  - Dedicated MeVPrtl paper underway!



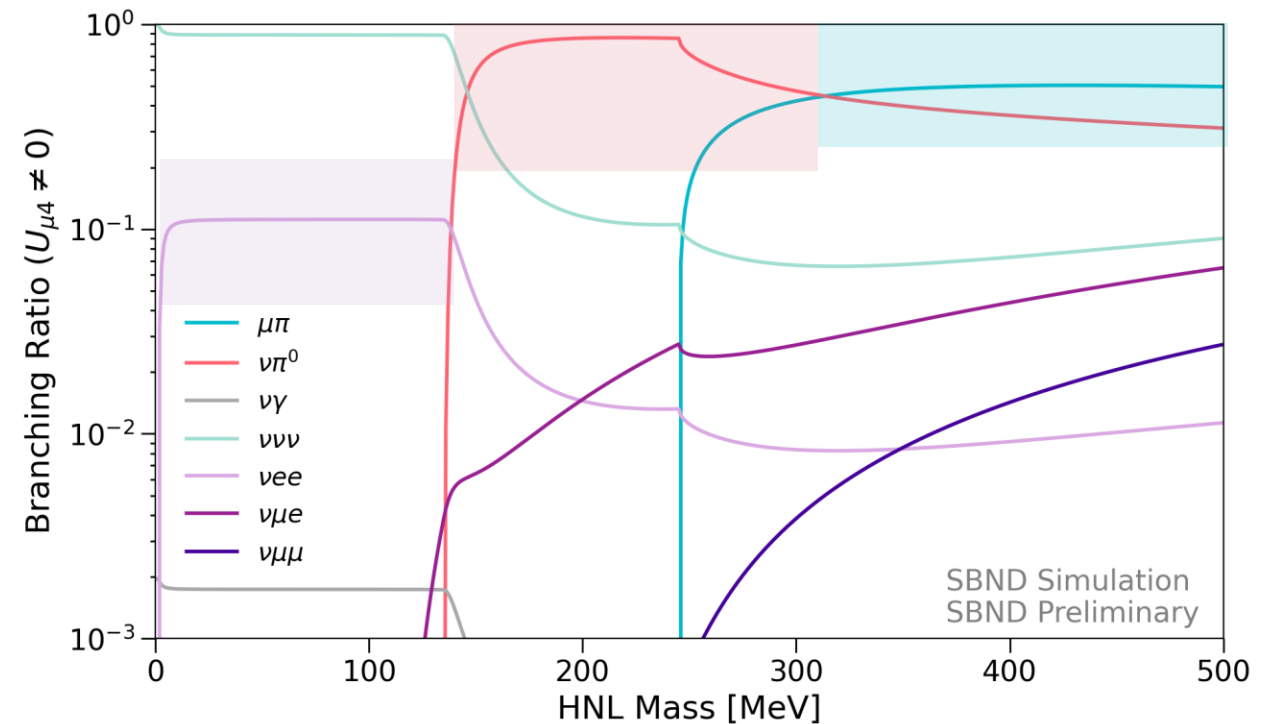
MeVPrtl Workflow for HNL Production



Branching ratios of probable decay channels of an HNL produced from the BNB for the muon-flavor coupling  $U_{\mu 4}$

# Heavy Neutral Leptons

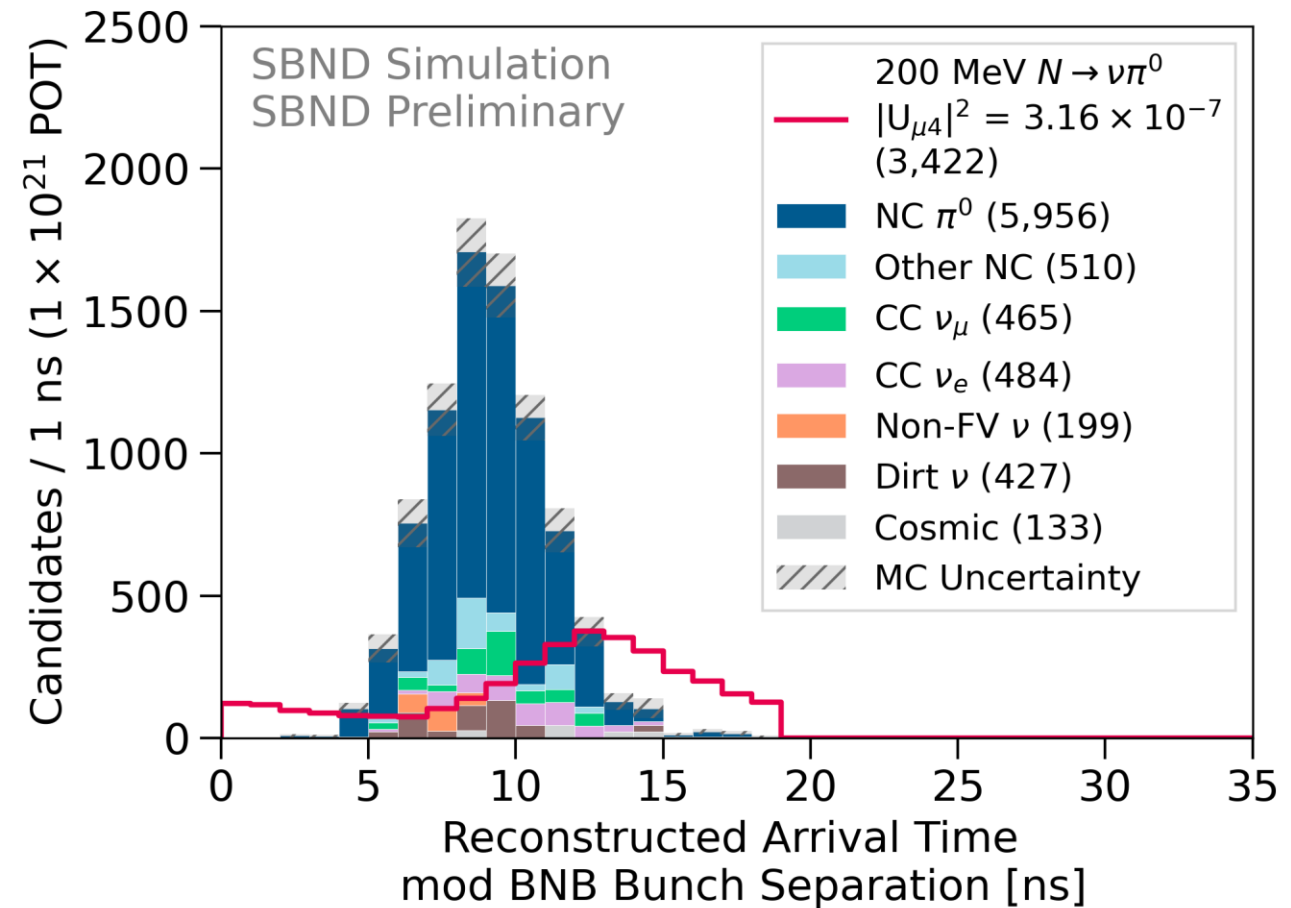
- Consider 3 HNL decay channels:
  - $N \rightarrow \nu ee$  covers sub 140 MeV mass region
  - $N \rightarrow \nu \pi_0$  probes intermediate mass range of  $140 < m_N < 260$  MeV
  - $N \rightarrow \mu \pi$  allows access to higher masses up to 388 MeV



*Branching ratios of probable decay channels of an HNL produced from the BNB for the muon-flavor coupling  $U_{\mu 4}$*

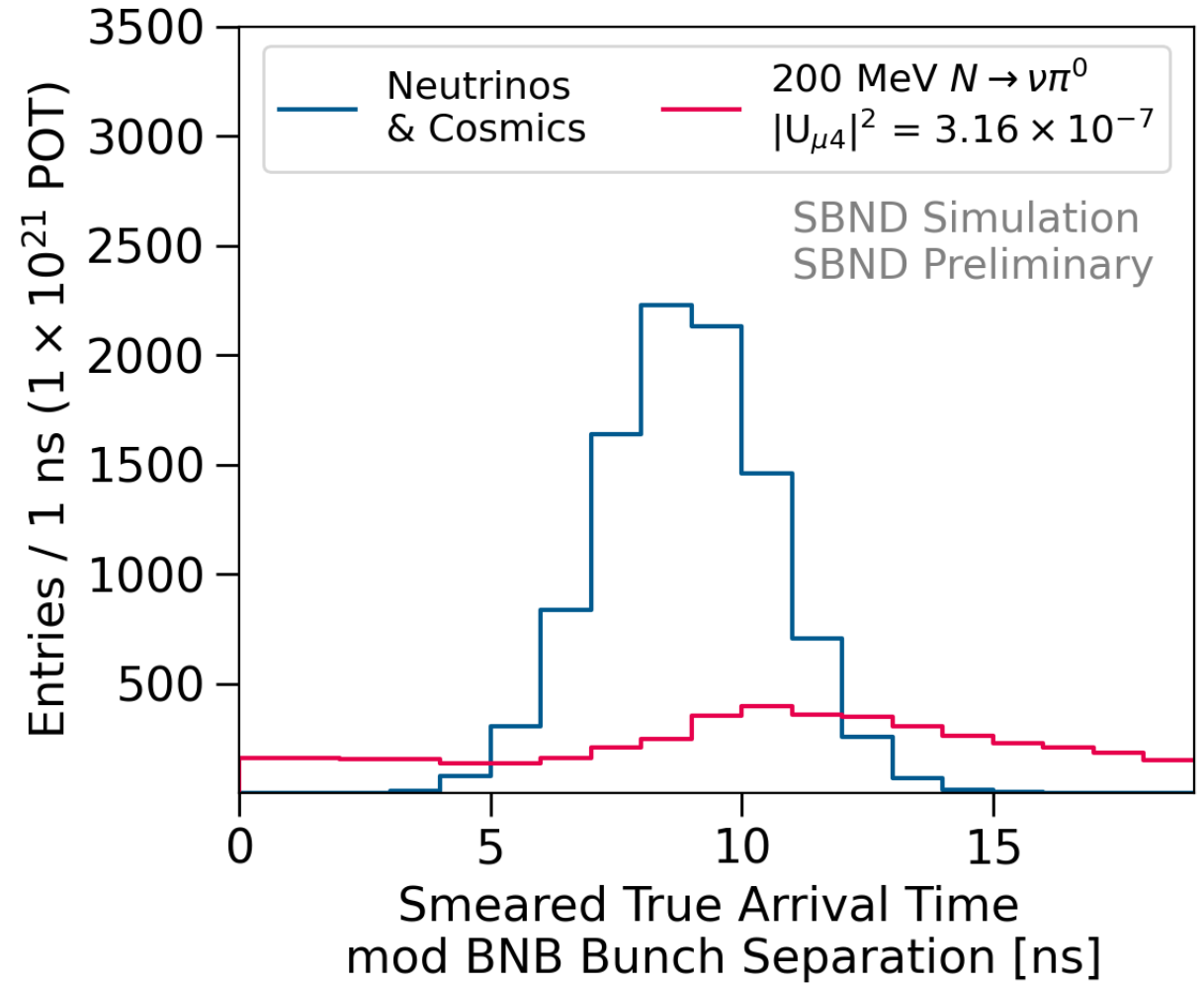
# Detector Signal

- Can leverage **timing delay** of HNLs for detection at SBND
  - HNL travel at slower speeds resulting in smearing of Gaussian distribution
- Perform two studies on the standard reconstruction workflow, and smearing applied at truth level
  - Both cases demonstrate power of HNL timing structure
- With both cases demonstrating this delayed timing feature, we gain more confidence in using timing in our analysis



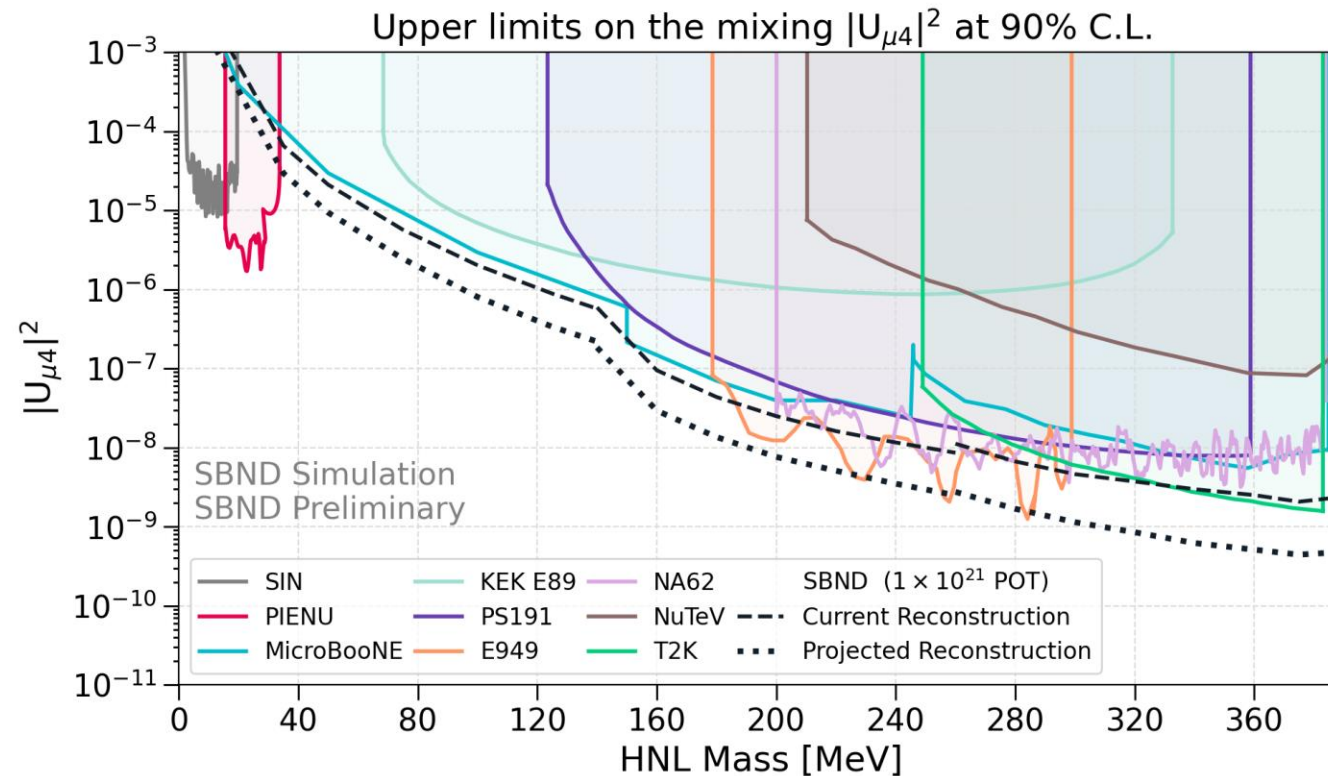
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# Sensitivity at SBND

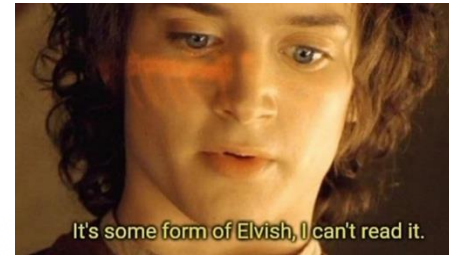
Potential to set world-leading limits on parameter space



# Dark Photons



# Dark Photons



➤ Proposed **gauge boson** that couples to SM photons

- $\epsilon$  is the kinetic mixing constant between Dark Photon  $A'$  and an SM photon

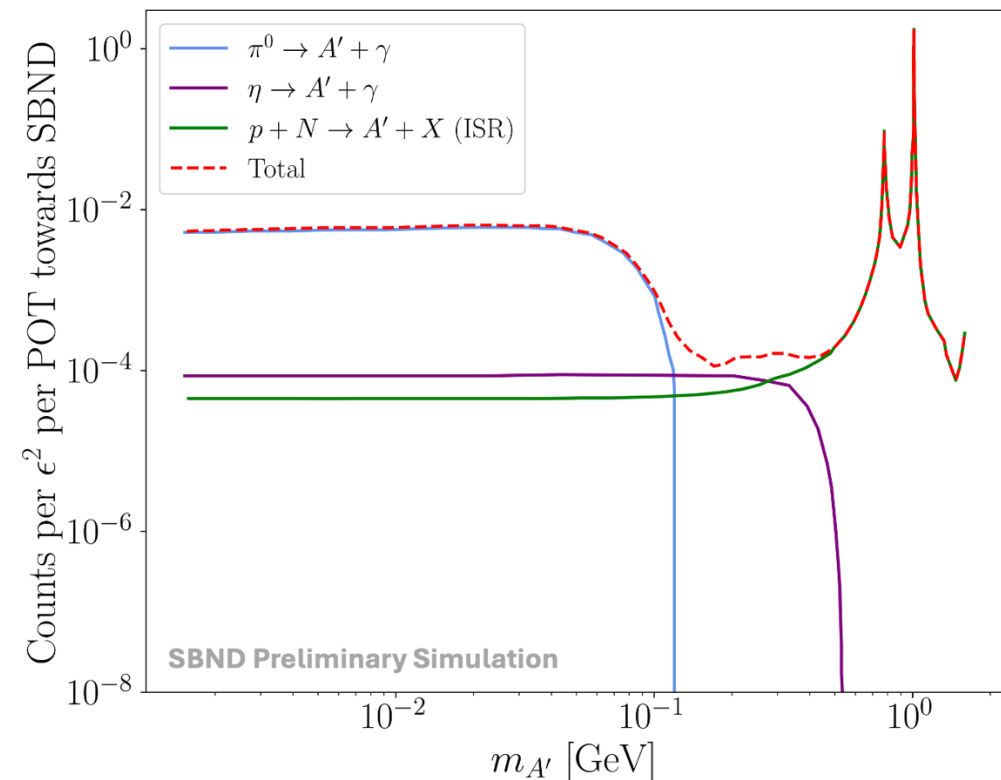
➤ **Production Channels:**

- 2-body neutral meson decay from  $\pi_0$  and  $\eta$
- Proton bremsstrahlung from p-Be interaction

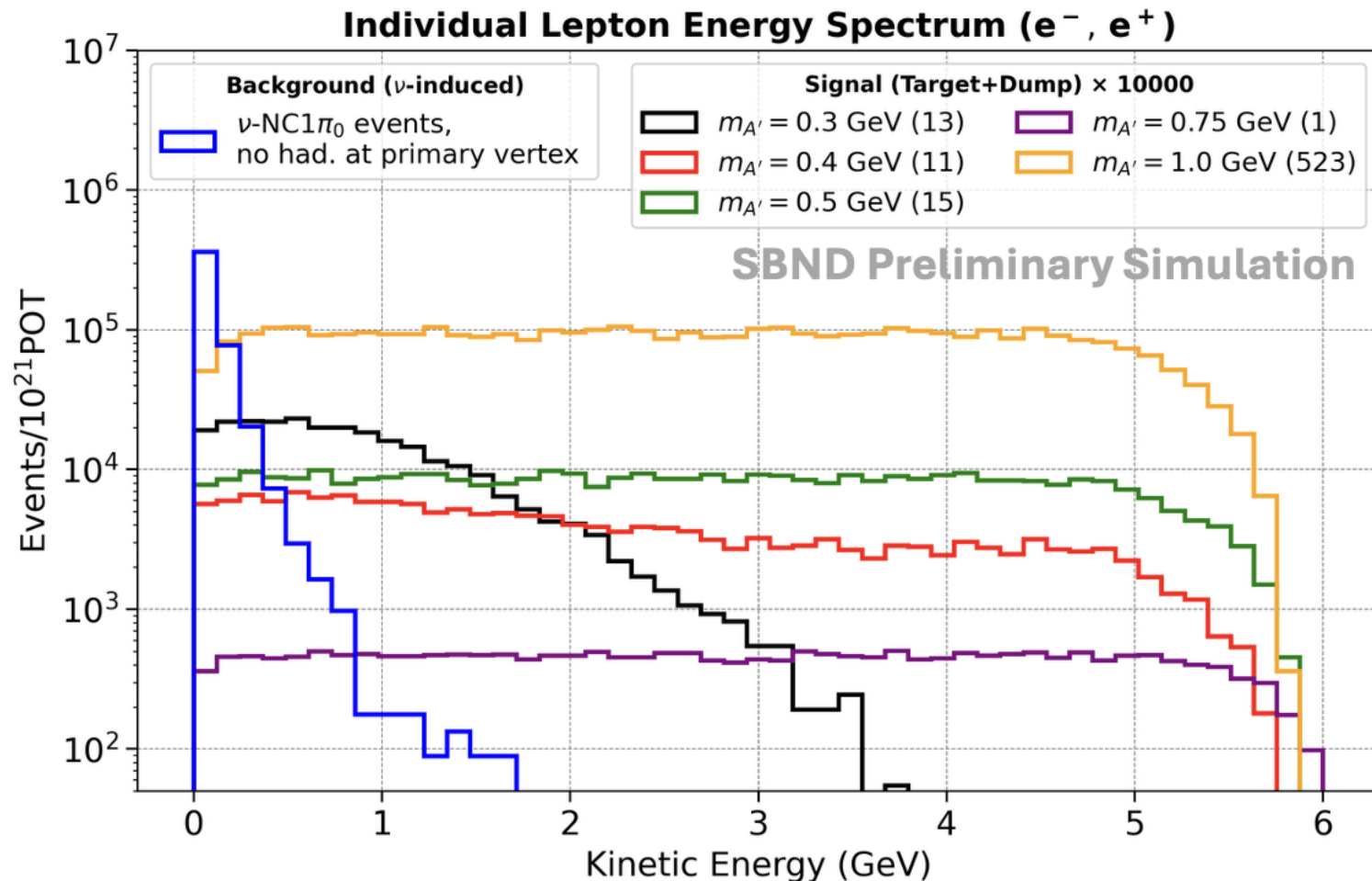
➤ **Decay Channels:**

- $e^+e^-$ 
  - Only channel being considered in current analysis
- $\mu^+\mu^-$
- Other hadronic channels

$$\mathcal{L} \supset \frac{m_{A'}^2}{2} A'_\mu A'^\mu + e\epsilon \sum_f q_f \bar{f} \gamma^\mu f A'_\mu.$$



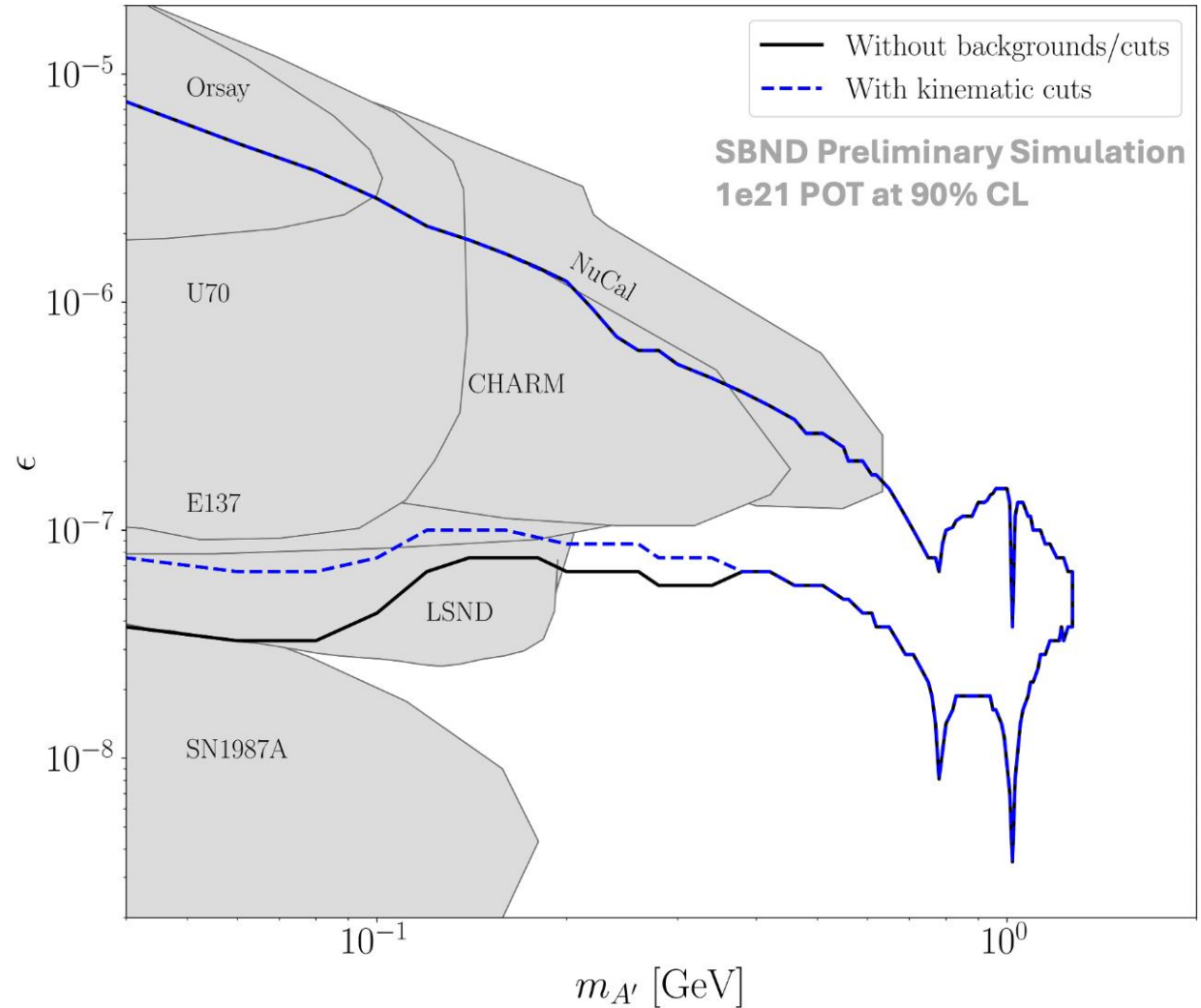
# Kinematic Analysis



- Primary background of  $NC\pi_0 \rightarrow \gamma\gamma$ 
  - Photons radiating to  $e^+e^-$  can be misreconstructed as Dark Photons
- Can leverage higher kinetic energy of Dark Photons to impose a  $2$  GeV cut

# Sensitivity

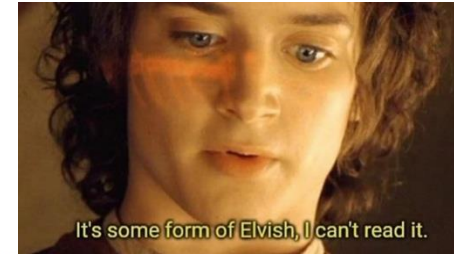
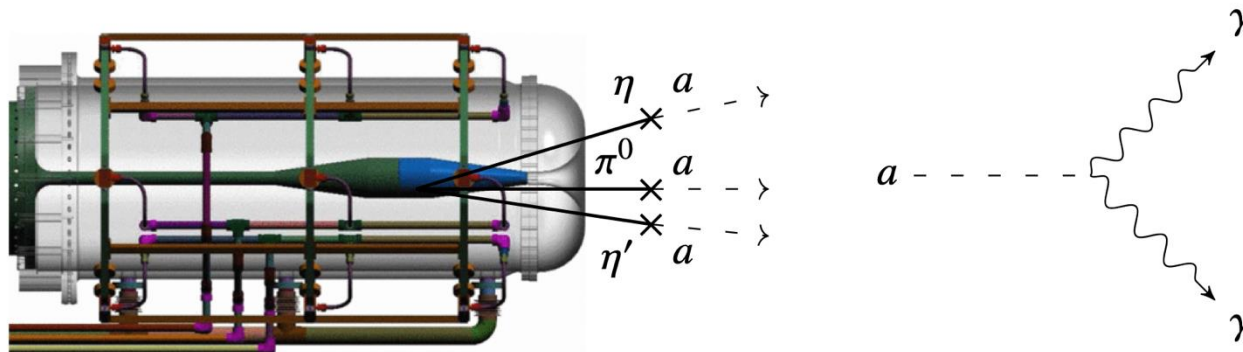
- Further improvements to neutral meson simulation also can improve both sensitivity and accuracy
- **Potential for setting world-leading limits on the Dark Photon**



# Heavy QCD Axions

# Heavy QCD Axions

- Proposed solution to the strong CP problem
- Specifically examine mixing with BNB produced neutral mesons
  - Same neutral meson simulation as Dark Photon team!

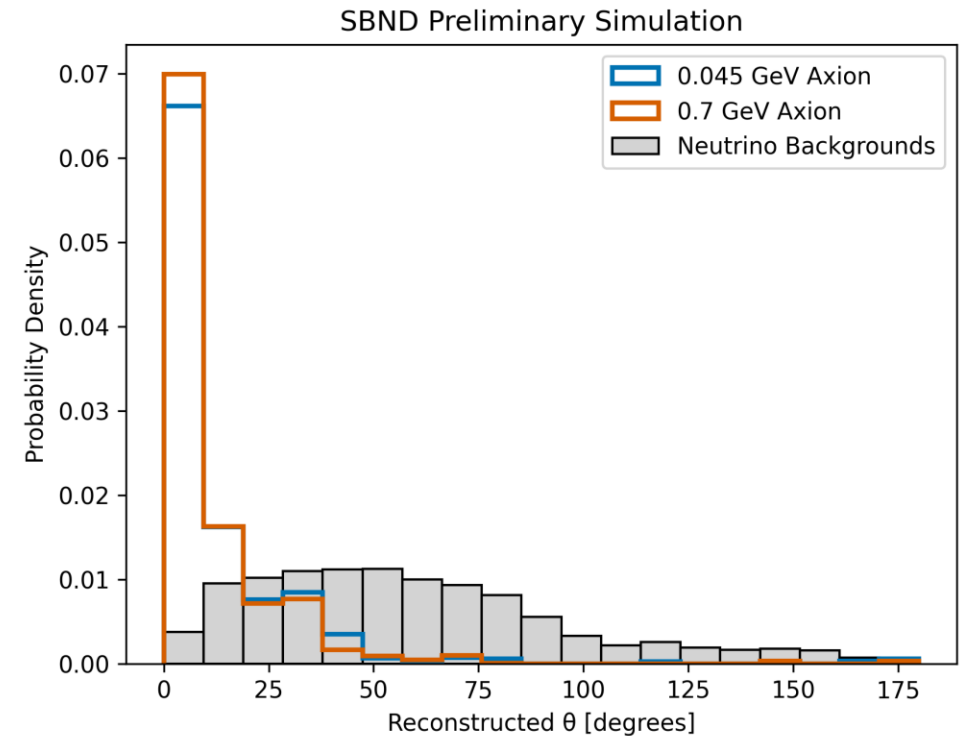
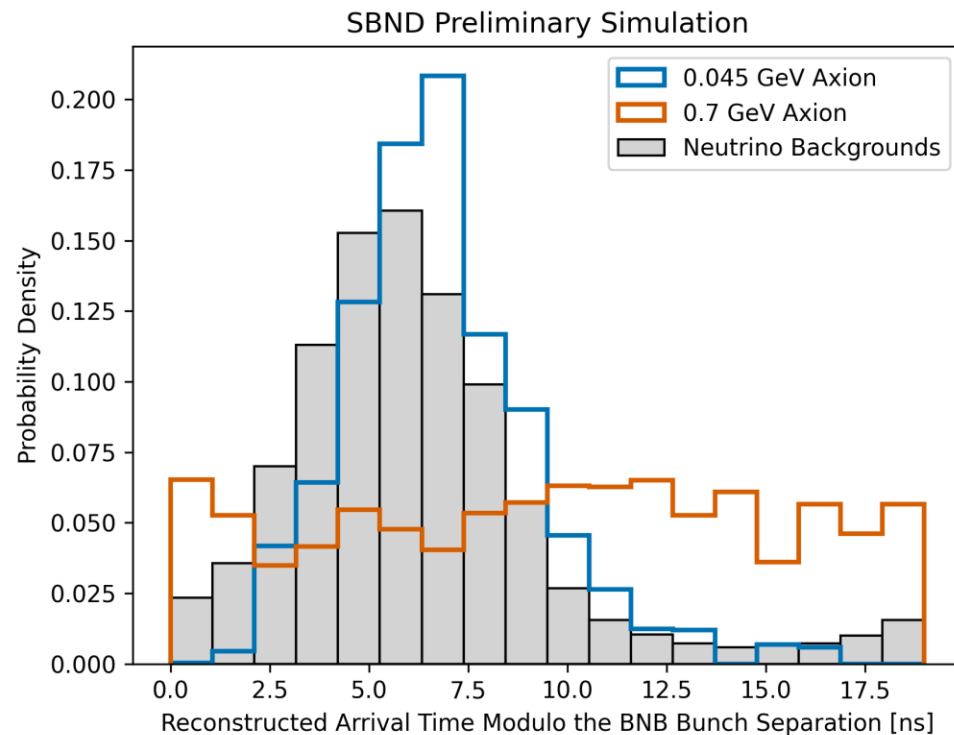


$$\mathcal{L}_{eff} = \frac{a}{8\pi f_a} (c_3 \alpha_3 G\tilde{G} + c_2 \alpha_2 W\tilde{W} + c_1 \alpha_1 B\tilde{B})$$

- $G, W, B$  are responsible to the coupling with gluons, leptons, and hadrons
- $\alpha_i$  represents the SM gauge coupling constants
- $c_i$  are the coefficients to be determined

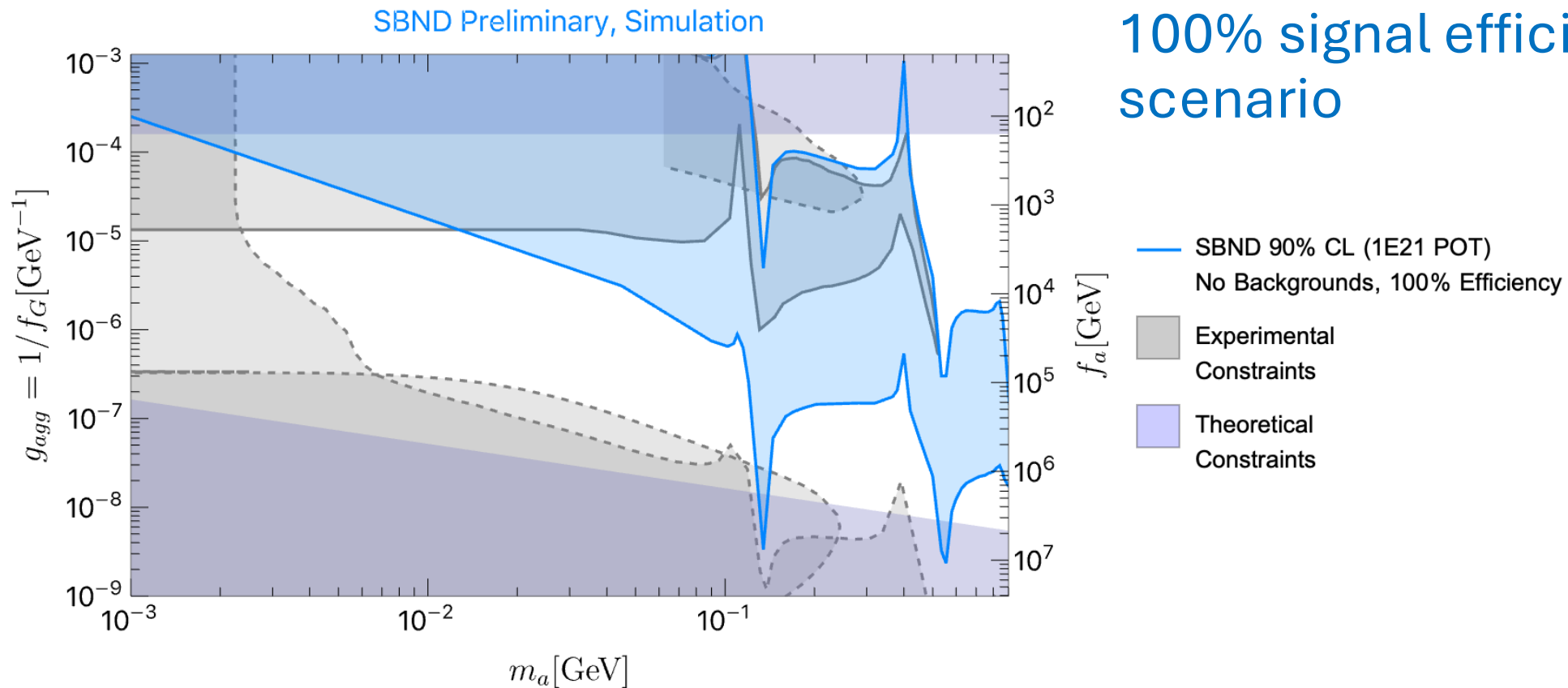
# Background Analysis

- Can leverage a combination of arrival time and angle for heavy axion detection!

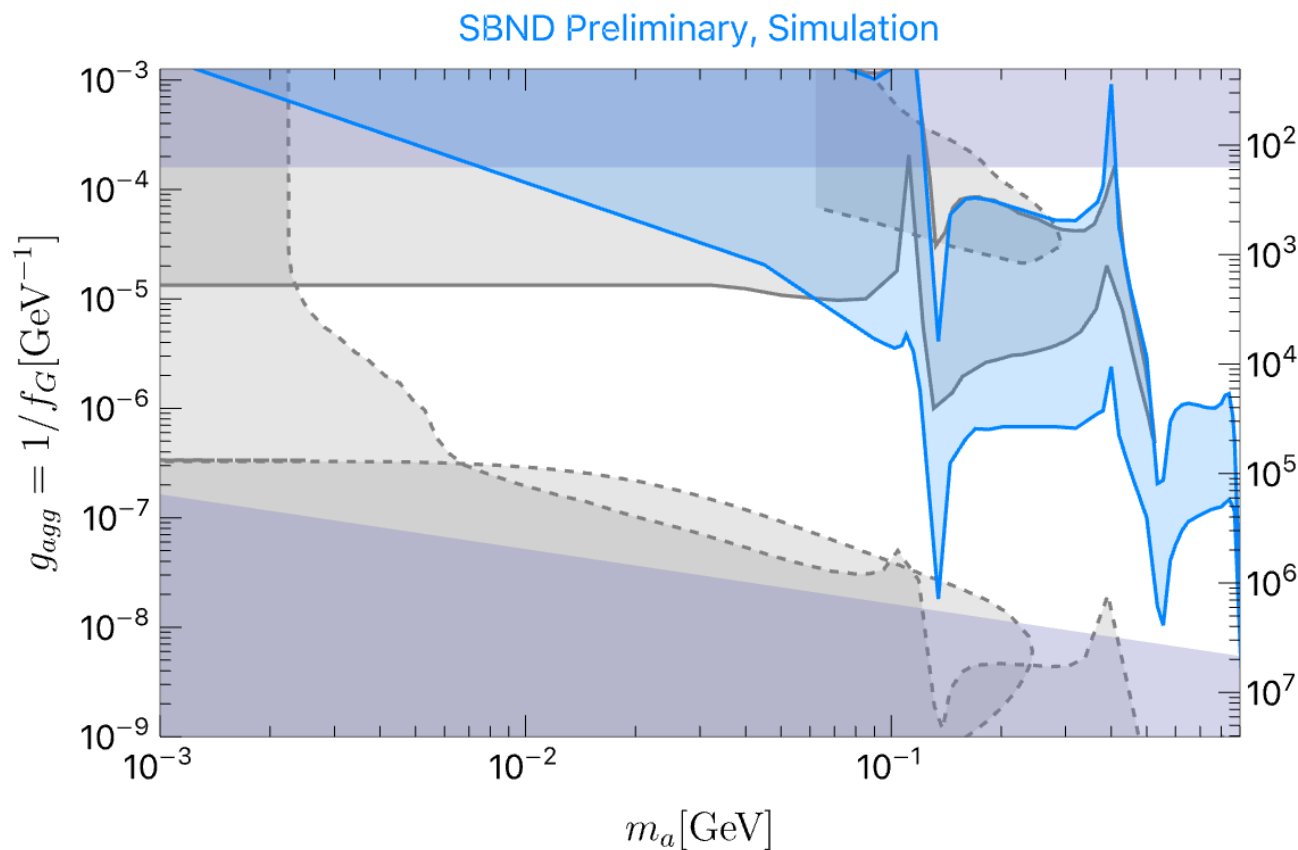


# Sensitivity – Theoretical Projection

➤ Ideal background free and 100% signal efficiency scenario



# Sensitivity – MC Estimation



➤ Estimates with more realistic signal/background efficiencies

➤ Focus on single shower topologies

- SBND 90% CL (1E21 POT)
- Emulated Reconstructions & Backgrounds
- Experimental Constraints
- Theoretical Constraints

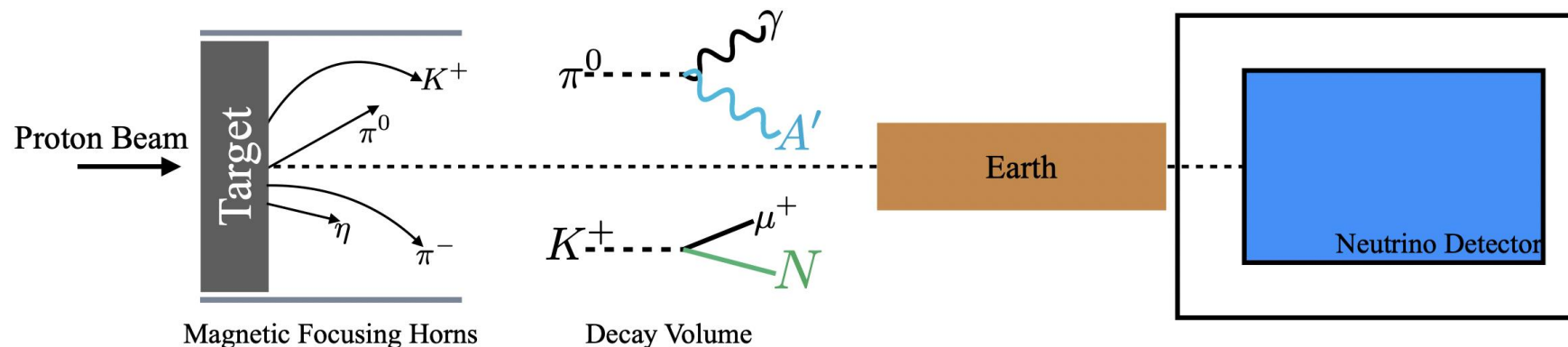
➤ In both scenarios, we have the potential to set world leading limits on Heavy Axions

# Generic Long-Lived Particles

See [\*Jiaoyang Li's talk!\*](#)

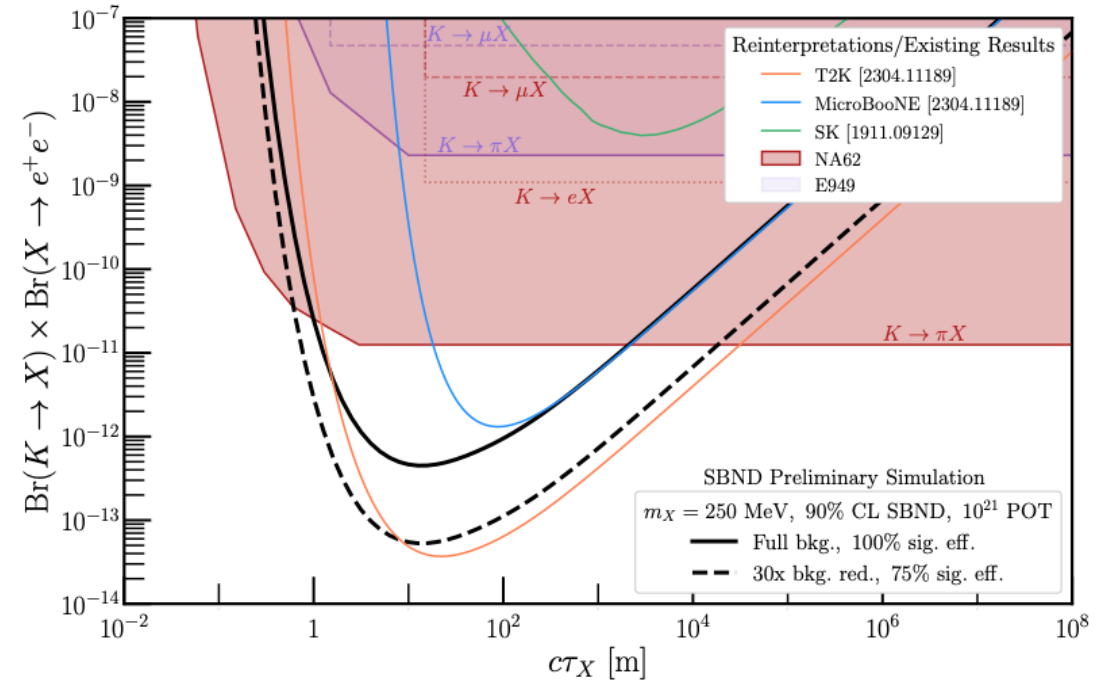
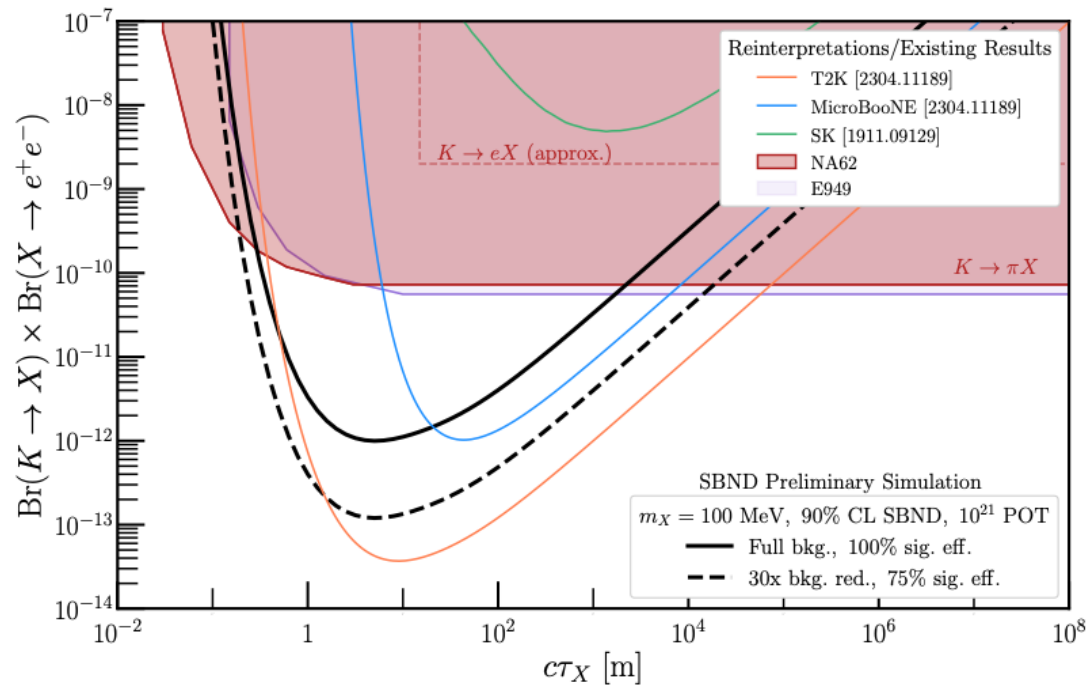
# Generic LLPs

- Generic model-independent search for various long lived exotic particles
- For this analysis, we consider 4 signal assumptions:
  - Produced via 2-body meson decay:  $K^+ \rightarrow \pi^+ X$  or  $K^+ \rightarrow \mu^+ X$
  - Massive LLP  $m_X = 100, 250 \text{ MeV}$
  - Final state is visible within SBND
  - Lifetime of  $c\tau_X = 10, 10^6 \text{ m}$



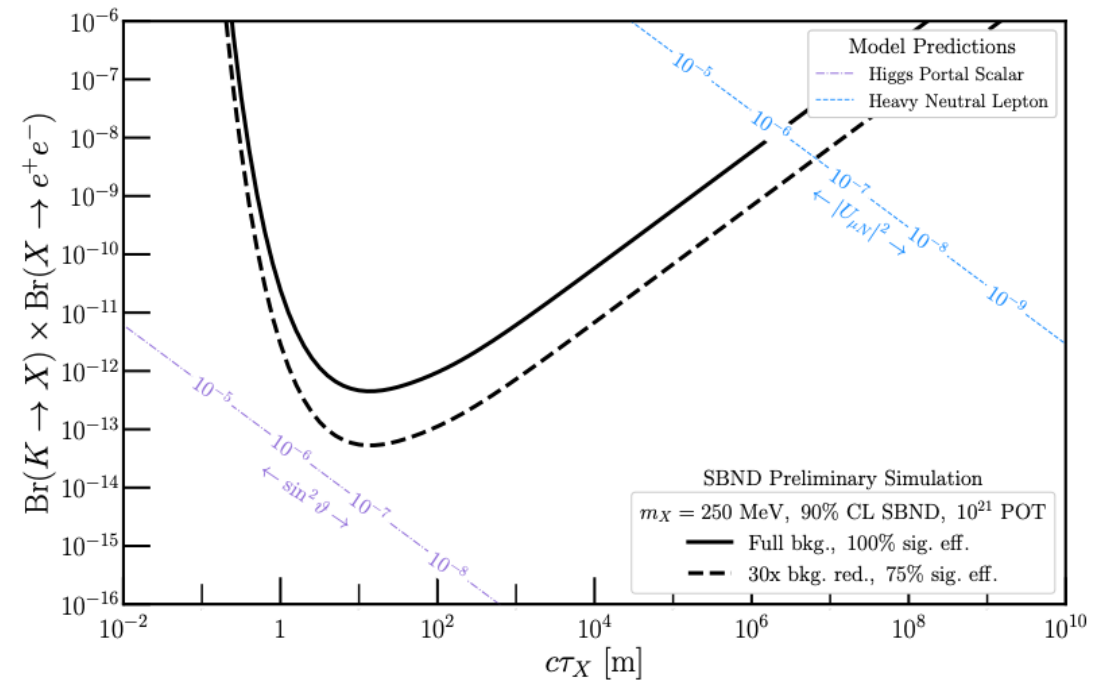
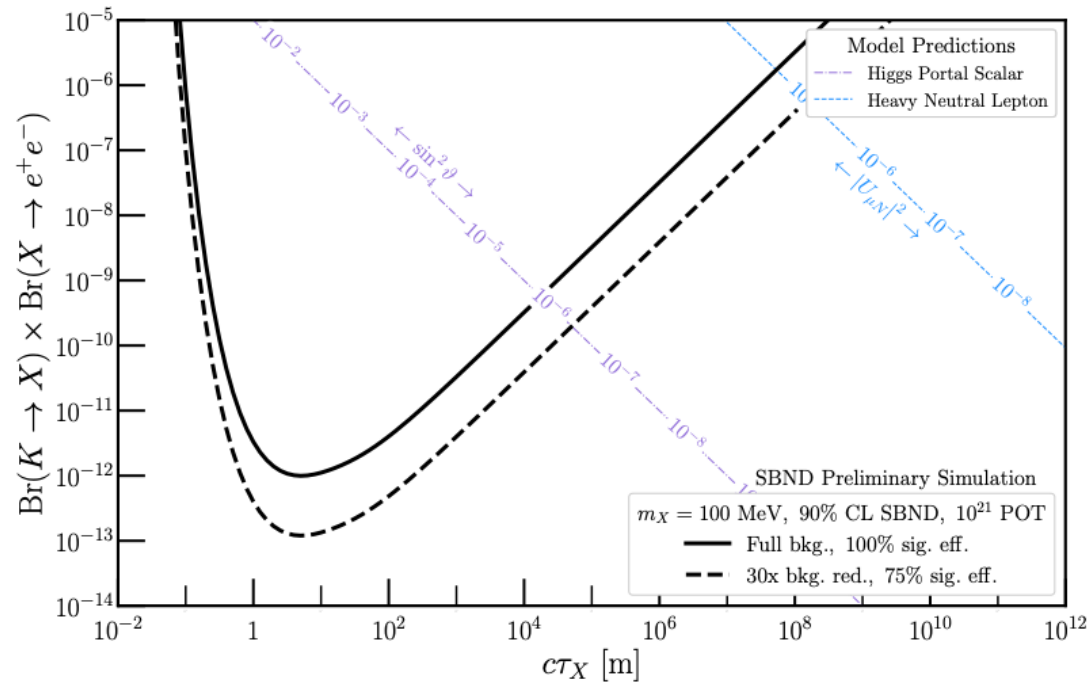
# Sensitivity – Existing Results

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



# Sensitivity – Model Predictions

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



# Conclusions

- **SBND** proves to be a competitive ground for probing BSM physics
  - **Large statistics** with diverse BSM signature pool
- **LArTPC, PDS, and CRT** technologies give us excellent **spatial** and **timing** resolution
- Using timing and kinematic analyses, we have the potential to set **world leading limits** on exotic searches
- Improvements to **neutral meson production** for Heavy Axion and Dark Photon teams are underway
- A **BSM Sensitivity Publication** is under development, highlighting the strengths of all searches ongoing at SBND
- **Data taking ongoing!**

*Detector hall for SBND, located 110 meter downstream of the Booster Neutrino Beam (BNB) Target on Fermilab's Neutrino Campus.*

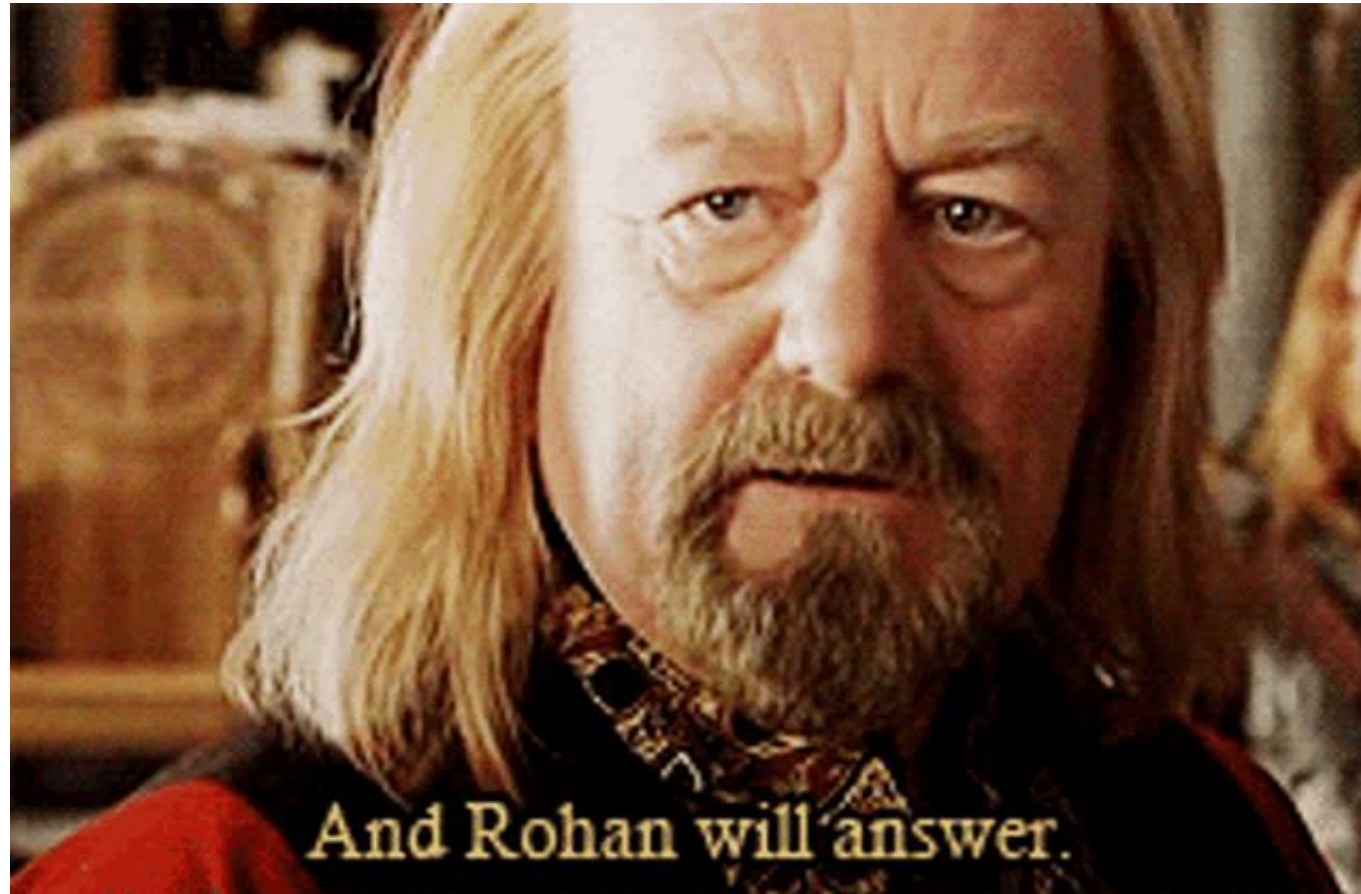


# Thank You!



*SBND Collaboration Meeting at Sheffield University, June 2025*

# Pose any questions...



# Backup Slides

# Short Baseline Neutrino Program

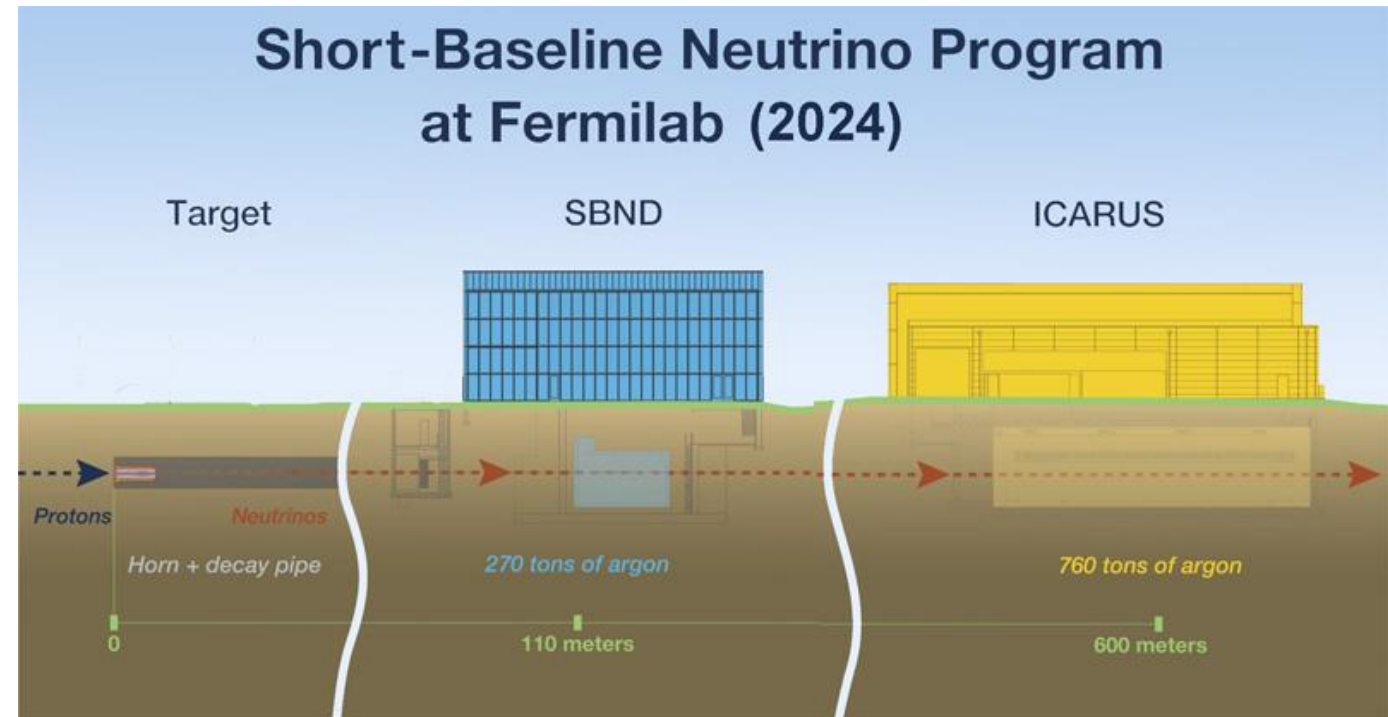
## SBND

Near Detector  
110 m from baseline  
112-ton active volume  
BNB only



## ICARUS

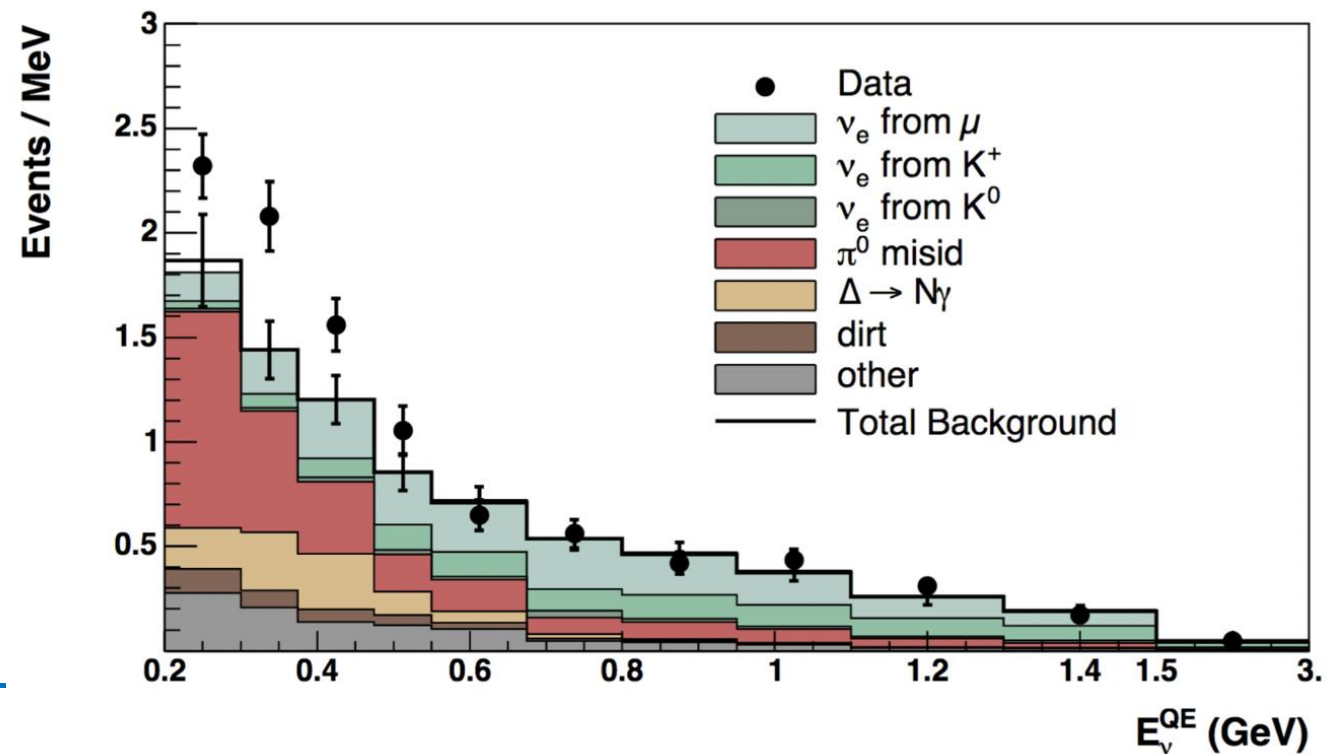
Far Detector  
600 m from baseline  
470-ton active volume  
BNB and NuMI



# Short Baseline Neutrino Program

## ➤ One of the core physics goals for the SBN program is to solve the Low Energy Excess

- 2001: The Liquid Scintillator Neutrino Detector (LSND) observes an excess in  $\bar{\nu}_e$  interactions above background
  - Uses a  $\bar{\nu}_\mu$  beam
- MiniBooNE experiment is designed to test the observed LSND excess
  - Cherenkov detector using mineral oil
- Running in both neutrino and anti-neutrino mode, MiniBooNE also observes an excess



# Short Baseline Neutrino Program

- Very prominent theory for explaining the excess involves **sterile neutrinos**
- However, it has been shown that many **BSM models** have the potential to also cause this excess, making BSM searches in SBN more attractive

