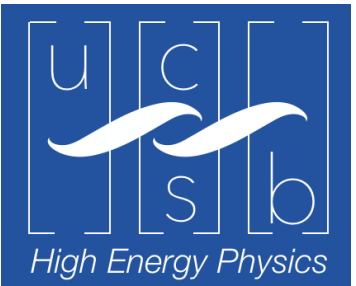
Searches for Beyond Standard Model Physics in the SBND experiment

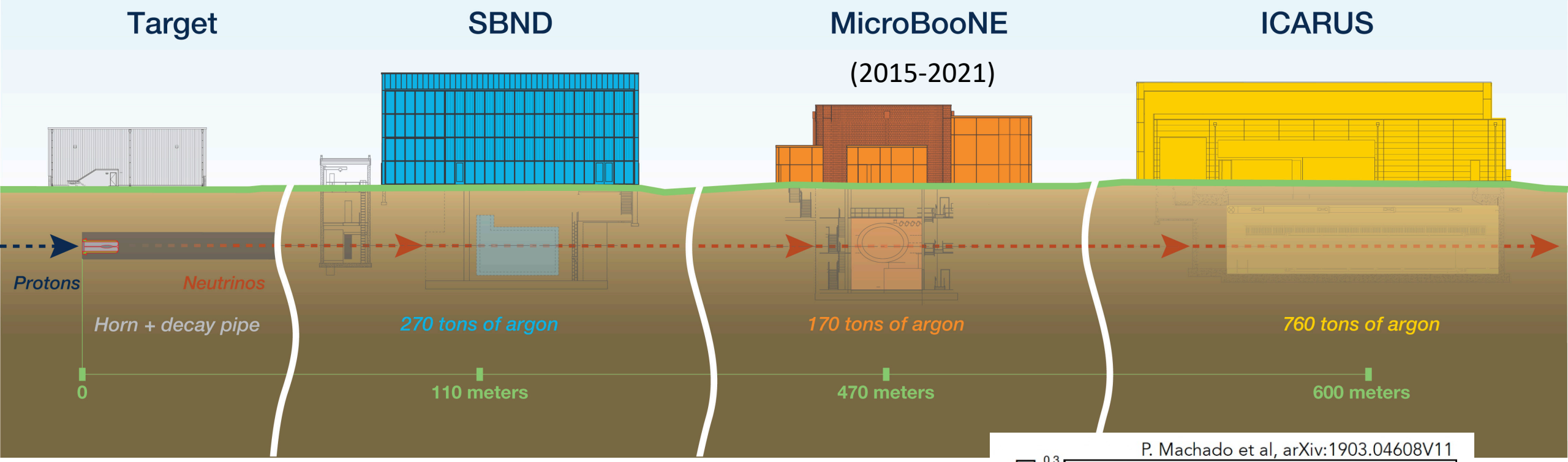
IDM 2024, L'Aquila, Italy

Xiao Luo, University of California Santa Barbara

on behalf of SBND collaboration

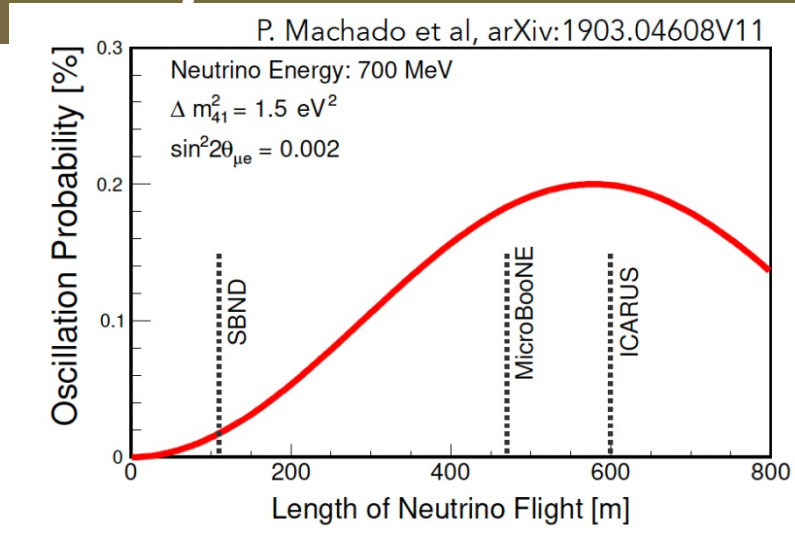


Short-Baseline Neutrino Program at Fermilab

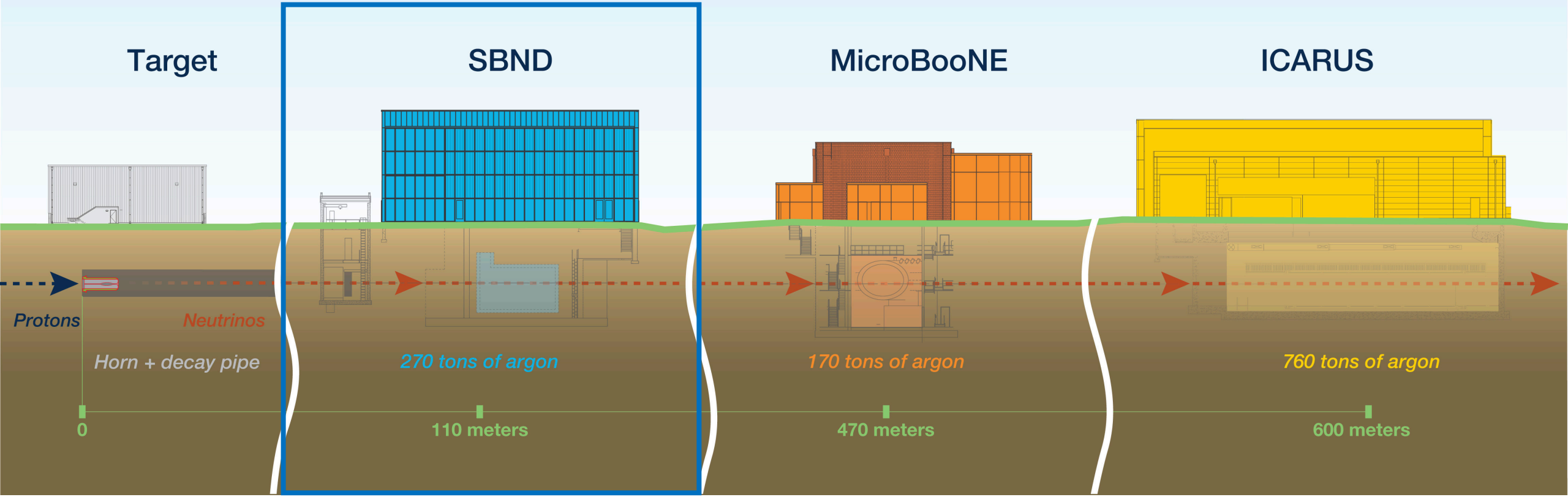


- Consists of 3 Liquid Argon TPC neutrino detectors
- On-axis of intensive GeV neutrino beamline
- Short baseline neutrino oscillation experiments with L/E ~ 1km/GeV

Search for eV sterile neutrino with 5σ sensitivity



Short-Baseline Neutrino Program at Fermilab



- Consists of 3 Liquid Argon TPC neutrino detectors
- On-axis of intensive GeV neutrino beamline
- O(100) m baseline

But there is more sub-GeV scale BSM physics than just sterile neutrino

Short Baseline Near Detector (SBND) offers unique opportunity for BSM searches

SBND – BSM production

Neutrino experiments
energy landscape

PTOLEMY

Solar ν

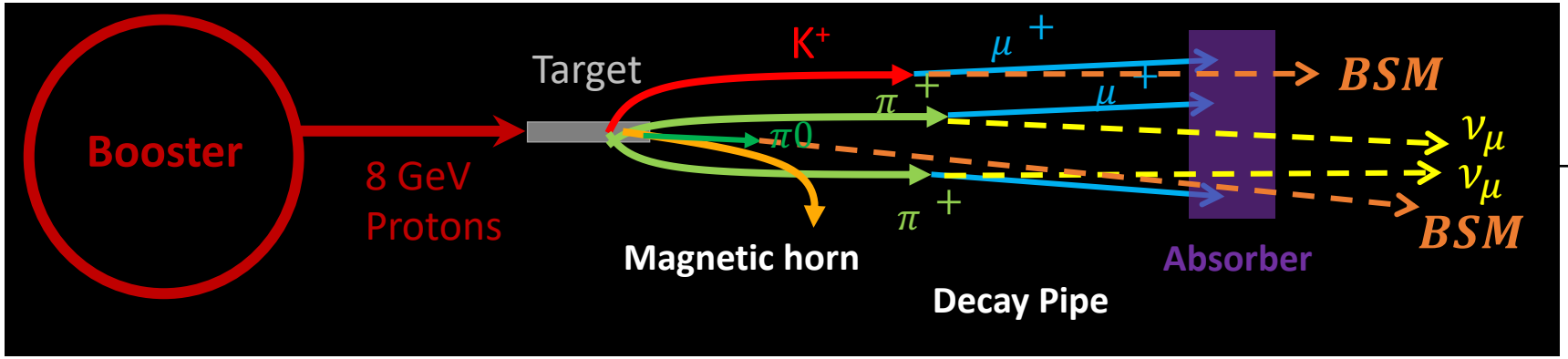
Accelerator ν

Sub-GeV scale BSM in the intense neutrino beamline

Collider

ICECUBE

...meV | eV | keV | MeV | GeV | TeV | PeV



110 m

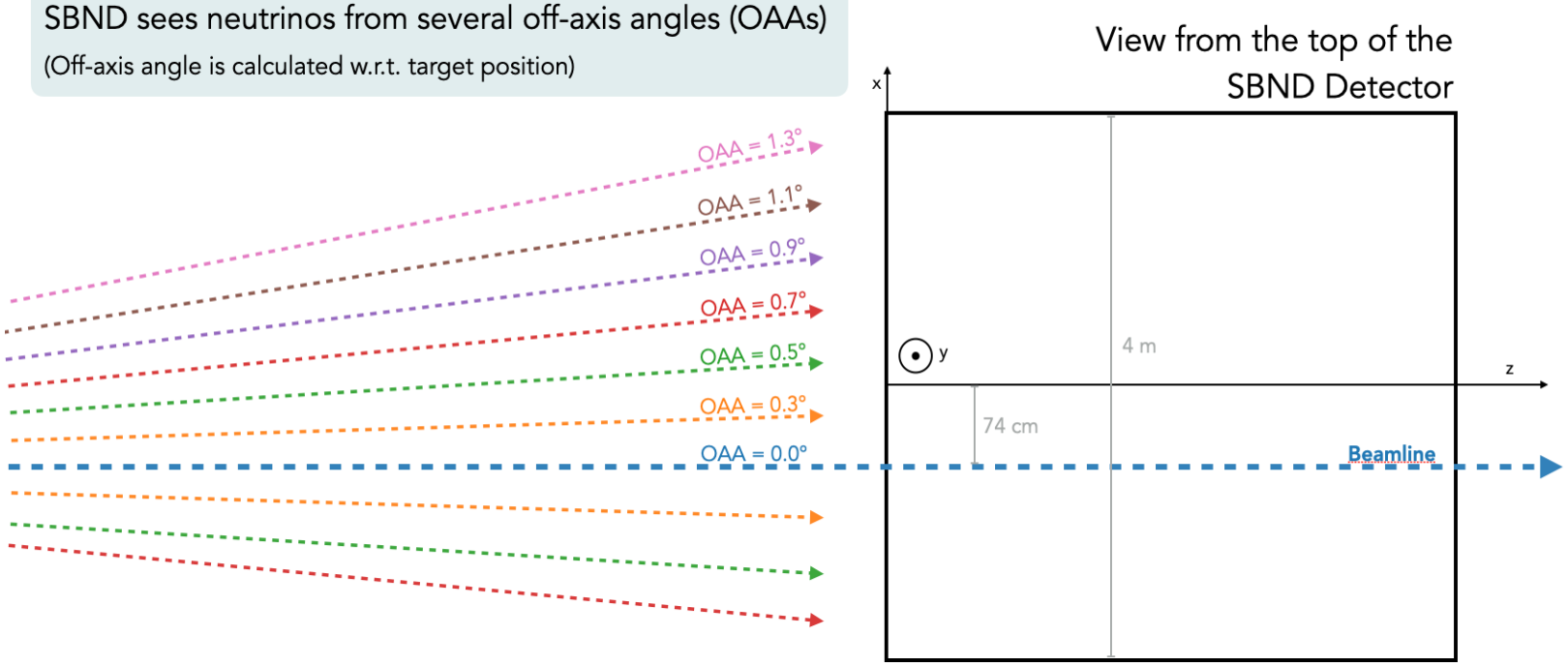
SBND

Closest to the beam, high BSM production rate, better for heavier shorter lived BSM particles comparing to the other two SBN experiments.

SBND-PRISM

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

SBND sees neutrinos from several off-axis angles (OAAs)
(Off-axis angle is calculated w.r.t. target position)

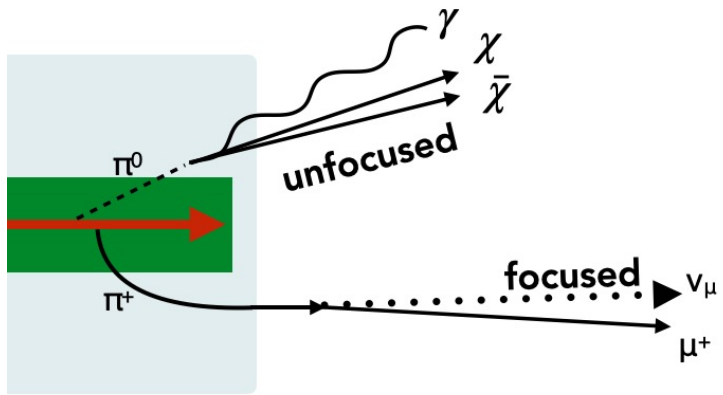


Close proximity to target -> larger solid angle coverage

Off-axis-angle range [0, 1.6°]

Application of SBND-PRISM:

- Constrain flux/xsec systematic uncertainty for SM neutrino background
- Higher BSM Signal / ν bckg. ratio with large off-axis-angle selection.



SIGNAL

Dark matter (signal) events come from **unfocused** neutral mesons

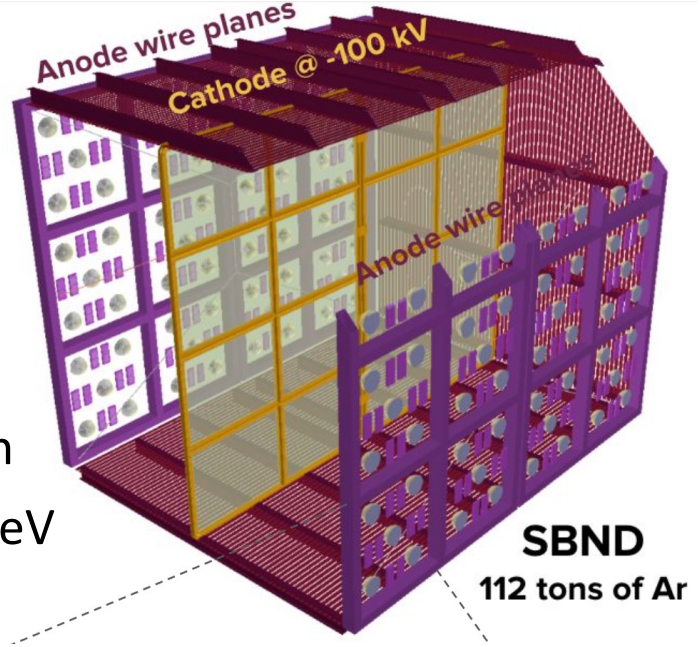
BACKGROUND

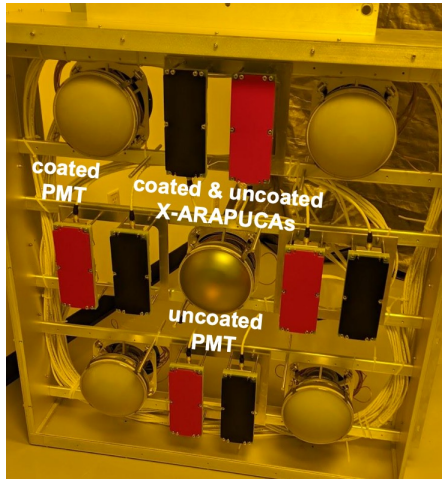
SBND-PRISM: Neutrinos (background events) **decrease** with the off axis angle

SBND detector and status

Two large mass LArTPCs

- 112 tons of LAr
- mm spatial resolution
- Fine-granularity calorimetry
- Excellent particle identification
- Low energy thresholds, sub-MeV





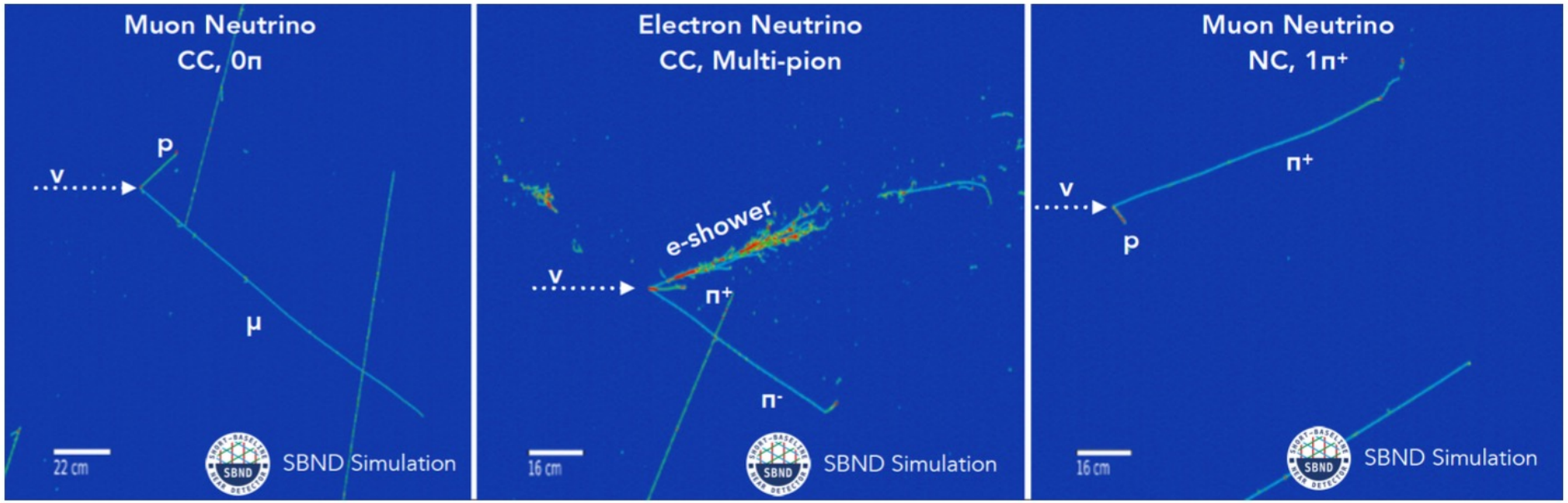
Photon Detection System

- PMTs: 96 + 24 wi/wo TPB
- X-ARAPUCAs: 96+96 wi/wo p-TP coating
- reflective cathode for high and uniform light yield and excellent timing resolution

Cosmic Ray Taggers

- Timing and position resolutions allows for triggering on entering/existing particles

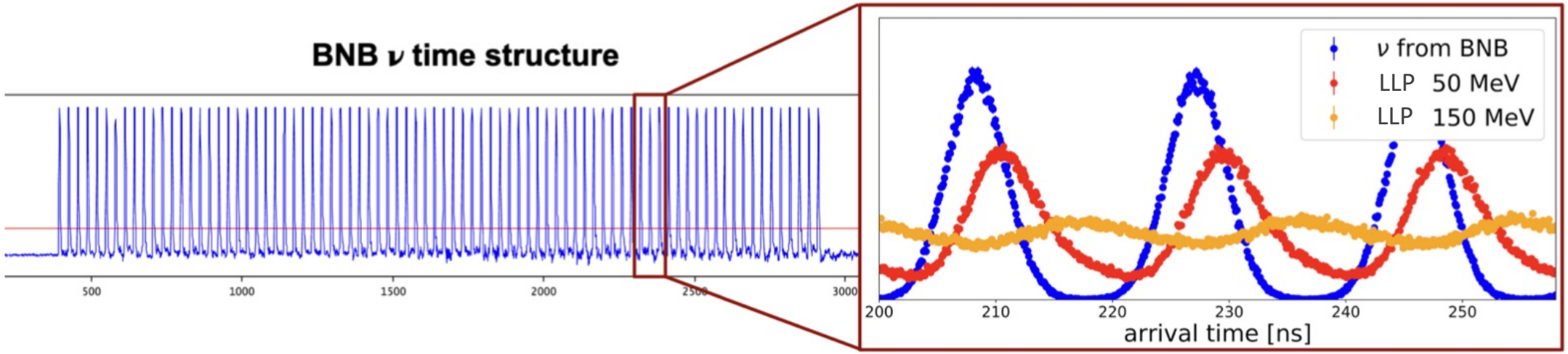
HD camara for 3D images of the particle interactions



SBND – Precise Timing

Bunched structure of ν beamlines
2ns ν bucket separate by ~18 ns gaps

Heavier BSM particles arrived at detector later than ν



Time-of-Flight measurement with nanosecond precision offers a unique **model-independent** handle for any massive Long-Lived Particle

O(1) ns timing was first achieved in MicroBooNE's LArTPC detector with real data (PRD.108.052010)

SBND – Precise Timing

Bunched structure of ν beamlines
2ns ν bucket separate by ~18 ns gaps

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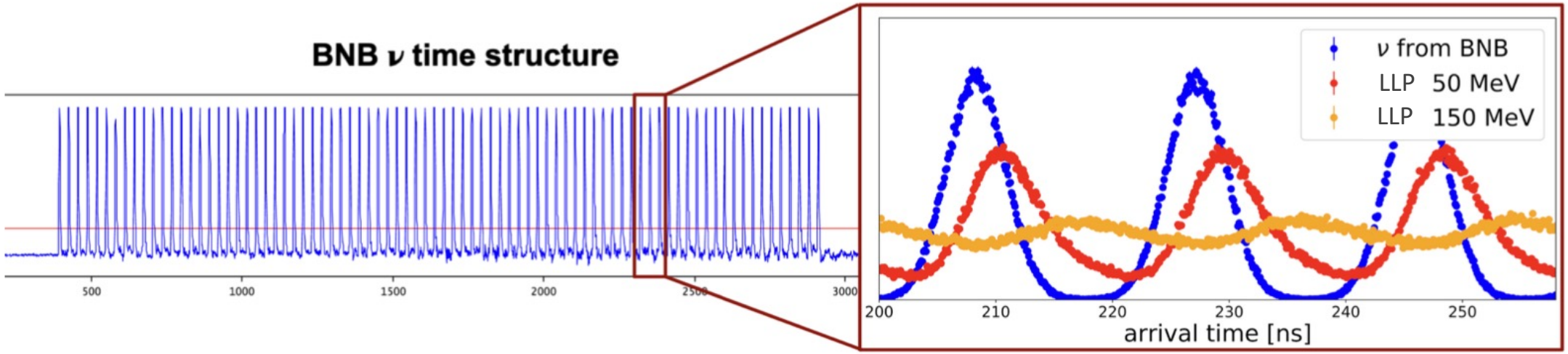
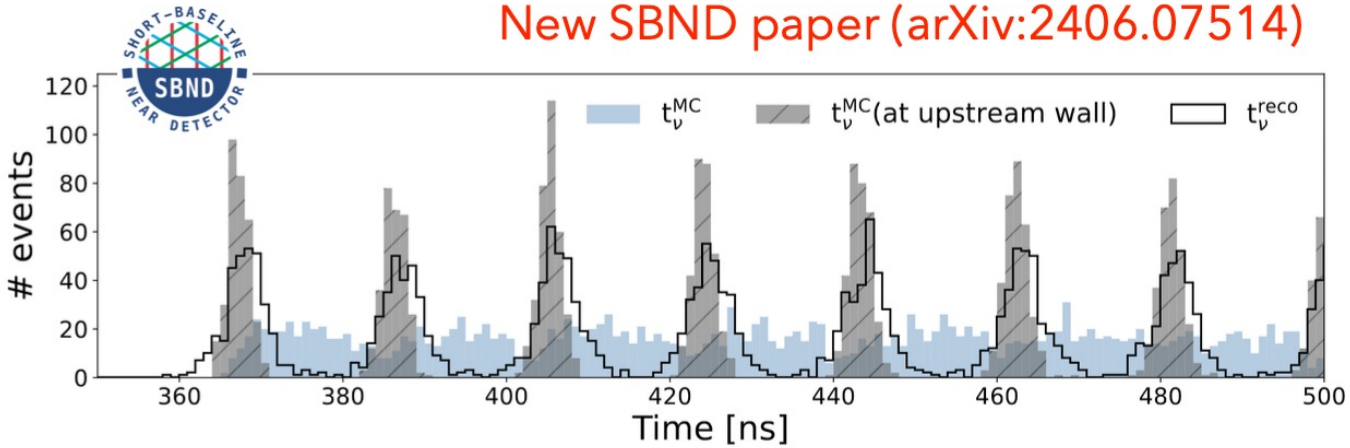
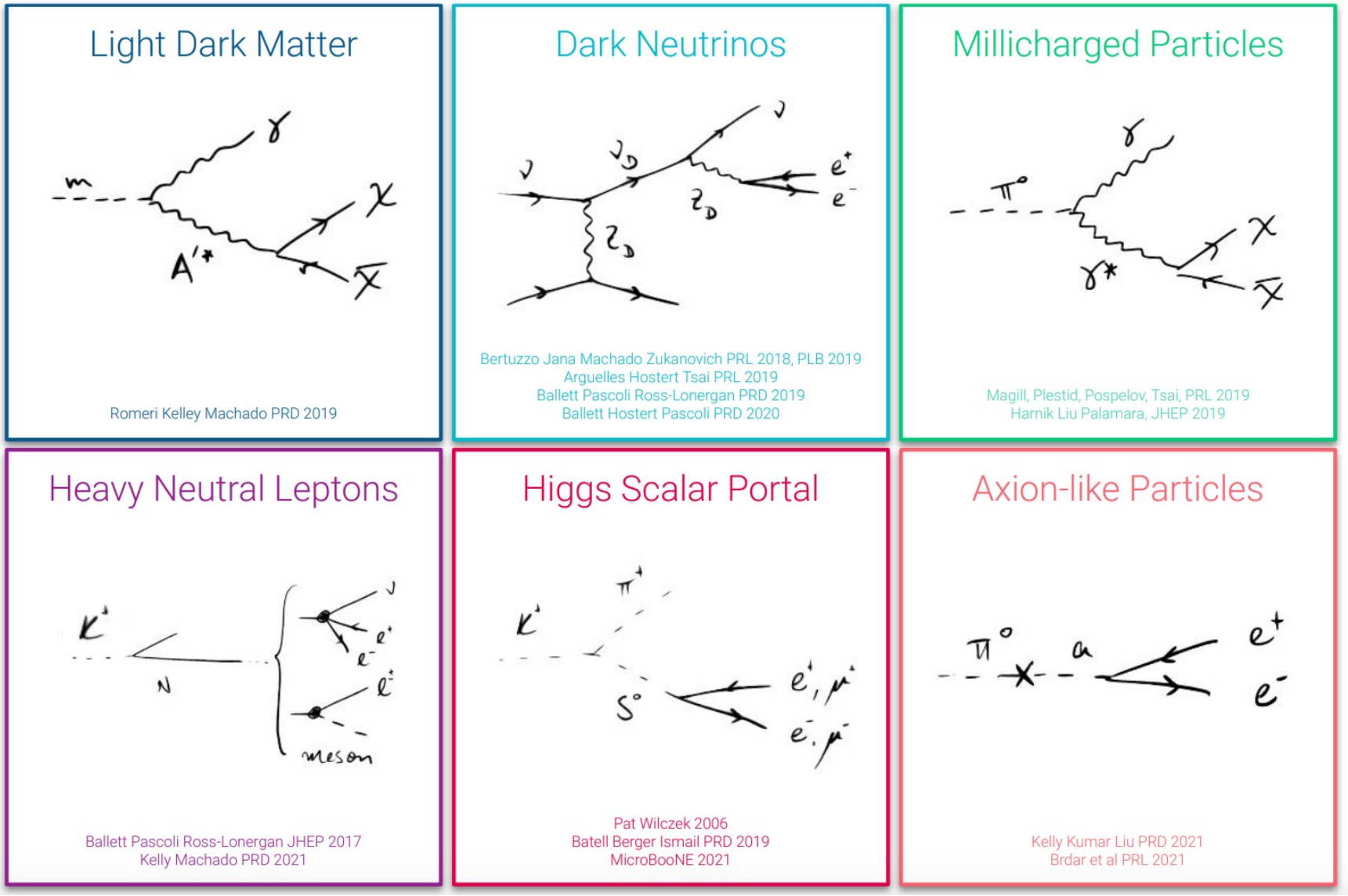


New SBND paper (arXiv:2406.07514)



SBND is capable of reconstructing Booster Neutrino Beam bunch structure demonstrated with simulation.

What BSM physics?

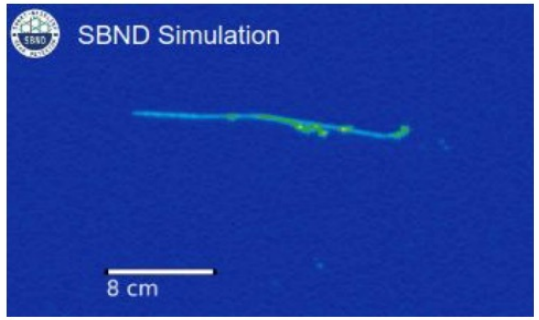


A non-exhaustive list of BSM particles produced at the Booster Neutrino Beam

Image credit: Pedro Machado, Marco Del Tutto

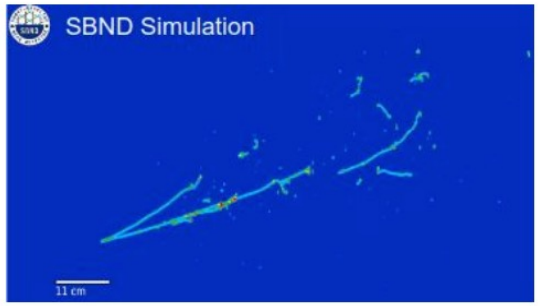
BSM events @ SBND

Light Dark Matter



Single e- scattering
Pair of e+e- and γγ
No hadronic activity

Dark Neutrinos

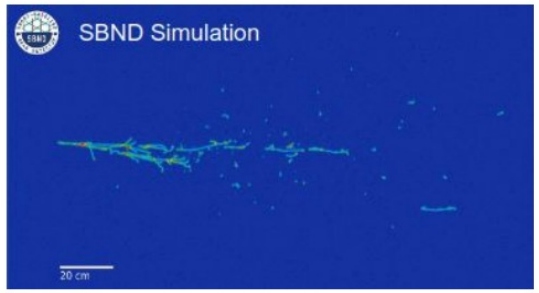


Pair of e+e- and μ+μ-
With or without hadronic activity

Millicharged Particles

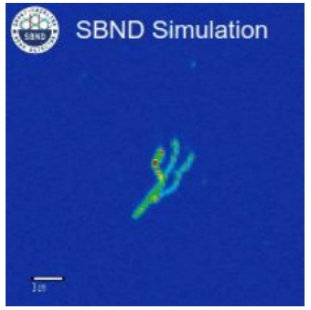
Blip or faint tracks

Heavy Neutral Leptons



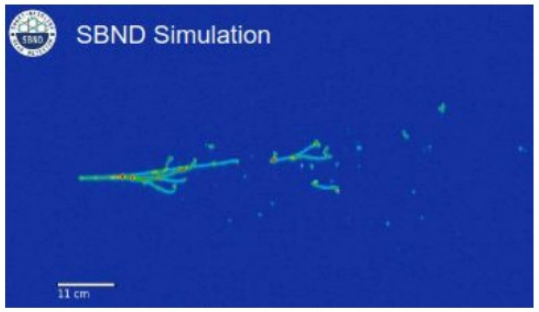
Single lepton + π
High energy pair of e+e-, μ+μ- and γγ
No hadronic activity

Higgs Scalar Portal



Pair e+e- and μ+μ-
No hadronic activity

Axion-like Particles



High energy pair of e+e- , μ+μ- and γγ
No hadronic activity

Long-Lived-Particle decay:
- Final states with lepton pairs or photon(s) without hadronic activity

BSM particle scattering:
- Electron or nuclear recoil

LArTPC's powerful particle identification capability is ideal for observing these similar final states with different kinematics, and differentiate among the BSM models

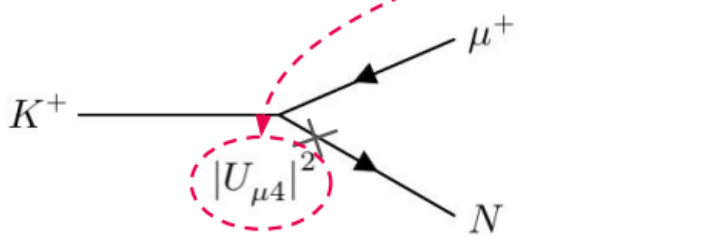
Heavy Neutral Lepton

JHEP 04 (2017) 102
JHEP 02 (2020) 174
EPJC 81 (2021) 1, 78
PRD 104, 015038 (2021)

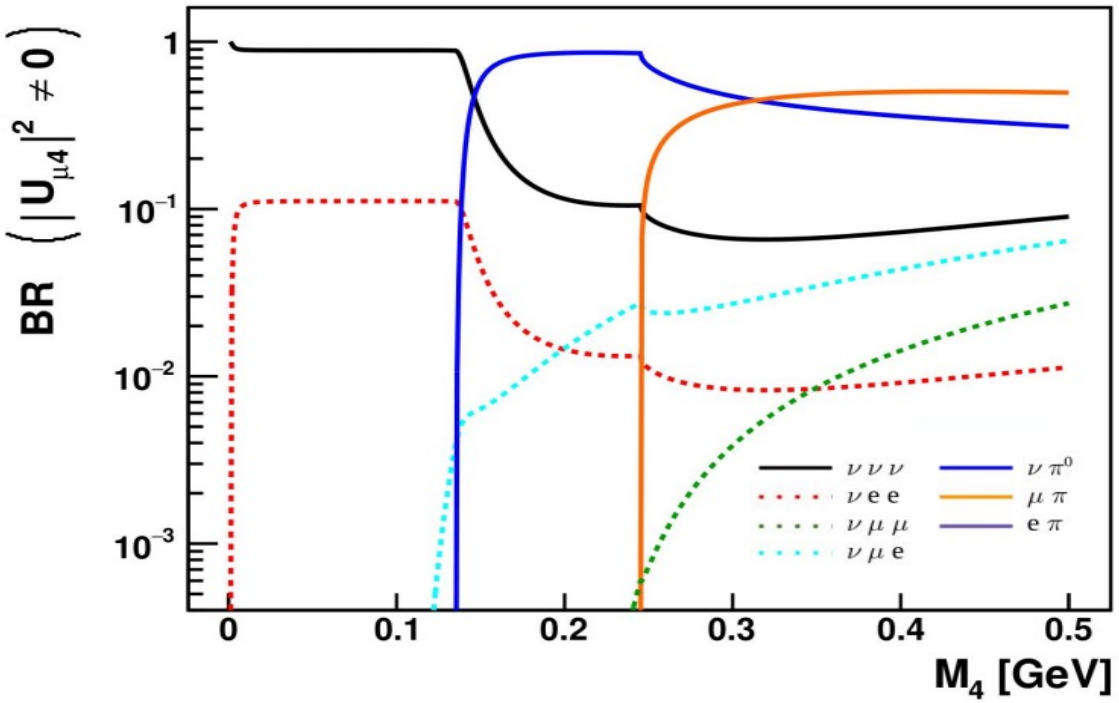
Production

$$U_{PMNS}^{Extended} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} & U_{e4} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} & U_{\mu 4} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} & U_{\tau 4} \\ U_{41} & U_{42} & U_{43} & U_{44} \end{pmatrix}$$

New Physics



Decay

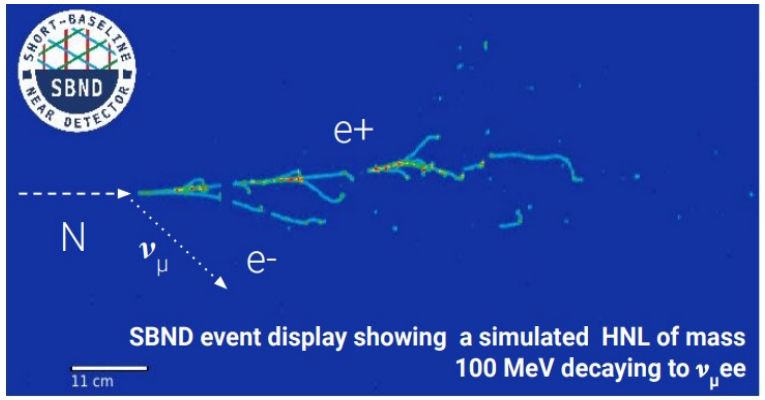


At Booster Neutrino Beamline, HNL can be produced from K+ decay up to ~500 MeV

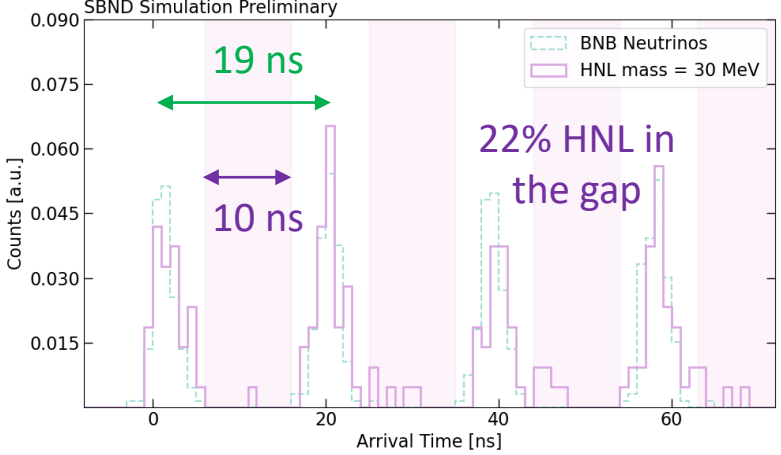
HNL then decays to SM particles with rate $\propto |U_{\alpha 4}|^4$

Heavy Neutral Lepton continued

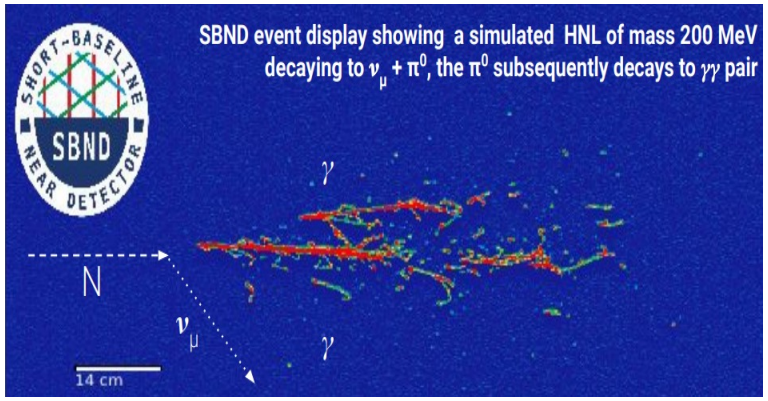
$\mathrm{HNL} \rightarrow \nu ee$



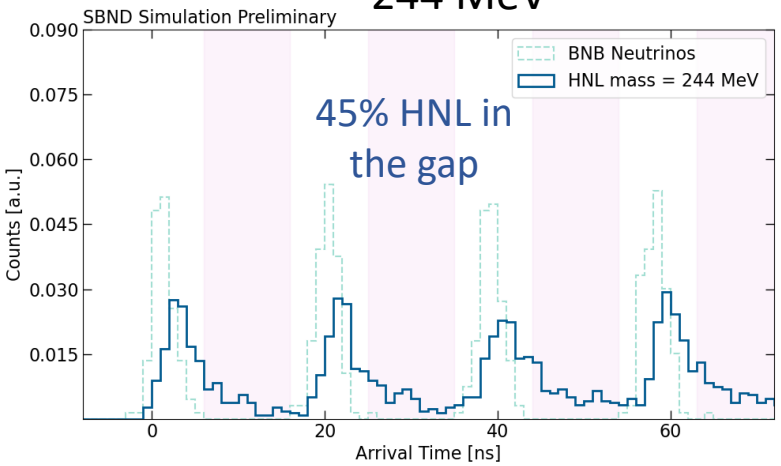
30 MeV



$\mathrm{HNL} \rightarrow \nu\pi^0$



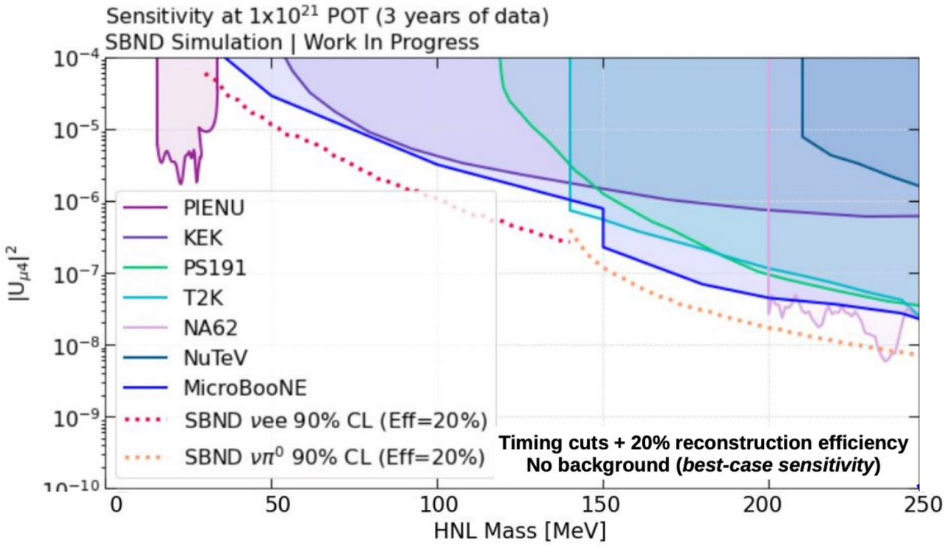
244 MeV



Two final states channels are under investigation

Use ToF to find HNL in between neutrino beam bucket

Preliminary truth-based sensitivity competitive up to 250 MeV



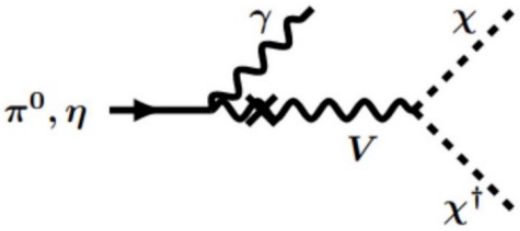
New end-to-end sensitivity

- with reconstruction & ML-based event selection
- realistic background consideration
- in three decay channels
  - $HNL \rightarrow \nu ee$ ($\mathrm{M_{HNL}}$ 30 – 140 MeV)
  - $HNL \rightarrow \nu\pi^0$ ($\mathrm{M_{HNL}}$ 140 – 244 MeV)
  - $HNL \rightarrow \mu\pi$ ($\mathrm{M_{HNL}}$ 244 – 388 MeV)

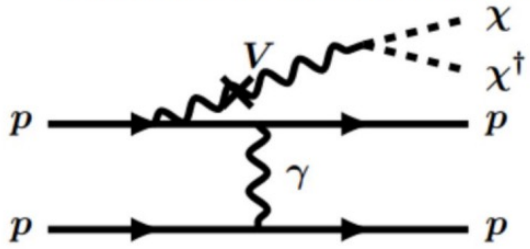
Light Dark Matter

[PRD 95, 035006 (2017)]

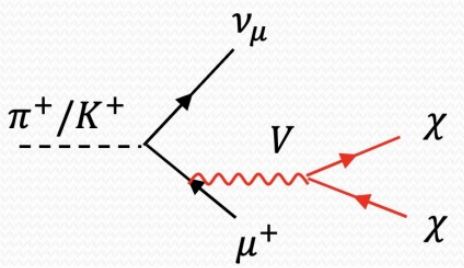
NEUTRAL MESON DECAY



PROTON BREMSSTRAHLUNG

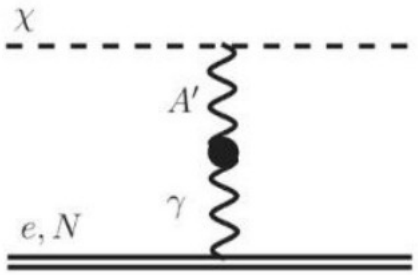


CHARGED MESON DECAY

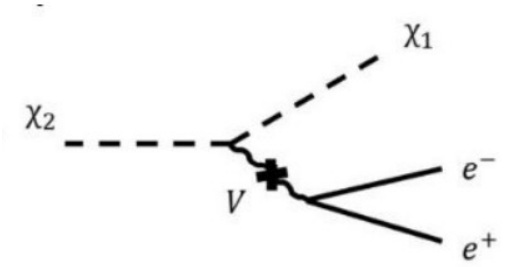


In the Booster neutrino beamline, Sub-GeV Dark Matter can be produced from neutral/charge meson decay and proton Bremsstrahlung

Light DM can scatter or decay inside SBND

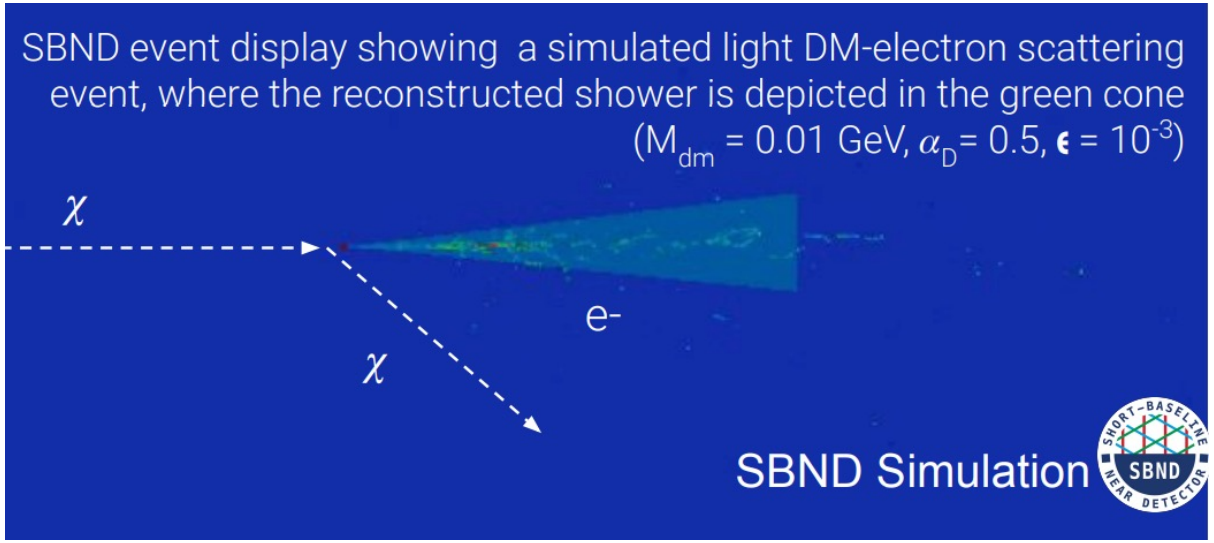


NC elastic scattering with e^- or nucleon



Decay to dark photon, and subsequently into an e^+e^- ("dark trident")

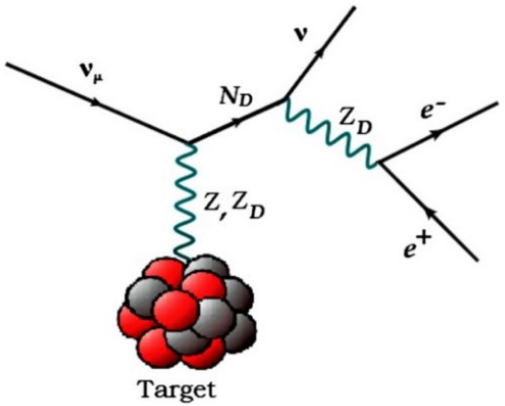
Both channels are being explored in SBND, search for signature with EM showers without hadronic activity



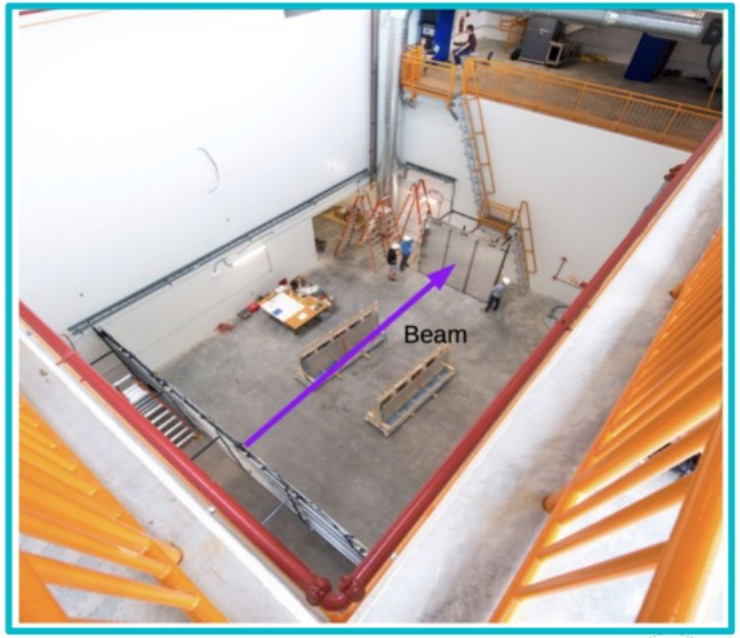
Dark Neutrino

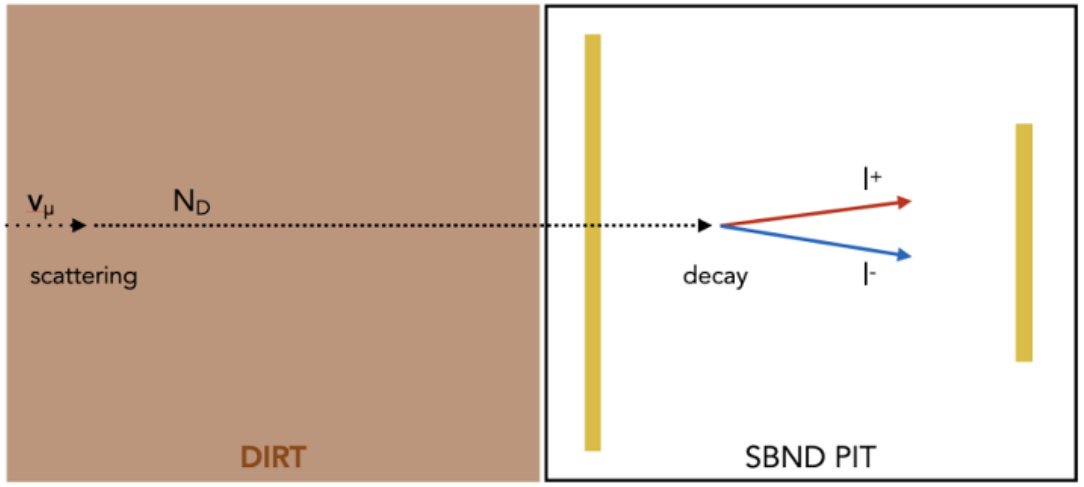
- A possible BSM explanation of the MiniBooNE anomaly
- Produced via ν-nucleon scattering, then decay to dark gauge boson, which decays to dilepton

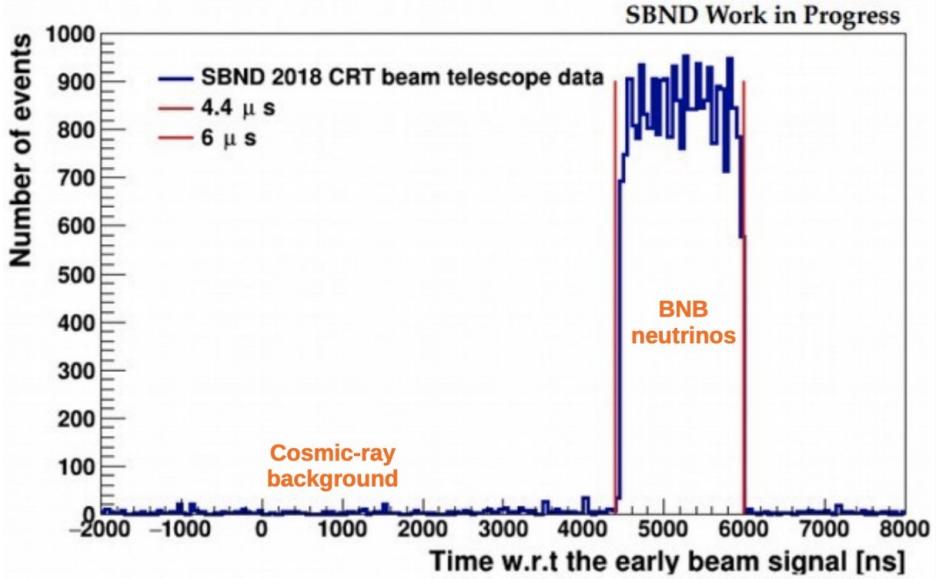
Dark neutrino portal
[PRL 121, 241801 (2019); PRD 99, 071701 (2019)]



SBND installed Cosmic Ray Tagger panels at up & downstream of the detector. Lepton pairs from the dark neutrinos can be tagged by these CRT detector







Dark neutrinos searching using real data collected by CRT from 2017-18 data is currently ongoing.

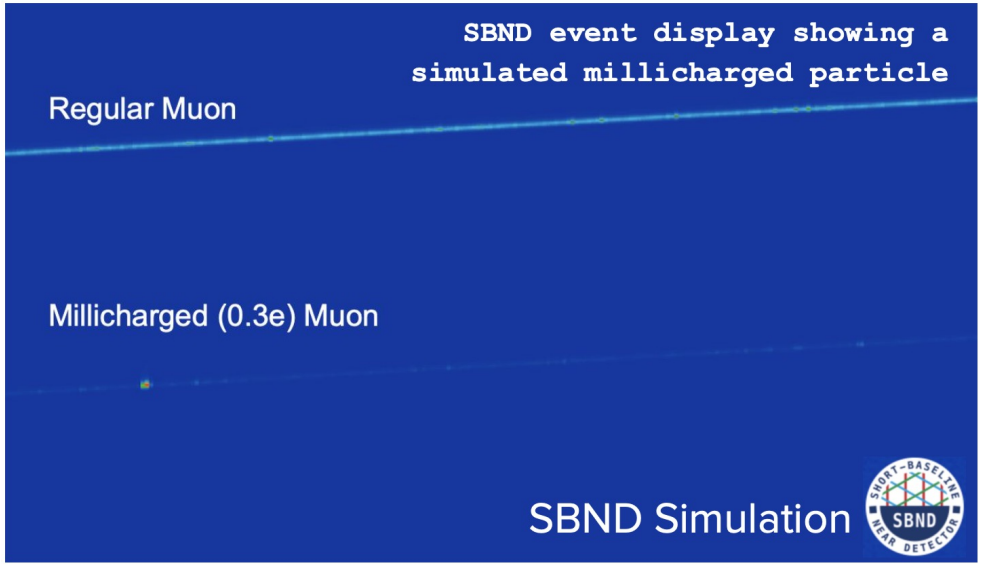
Millicharged particle

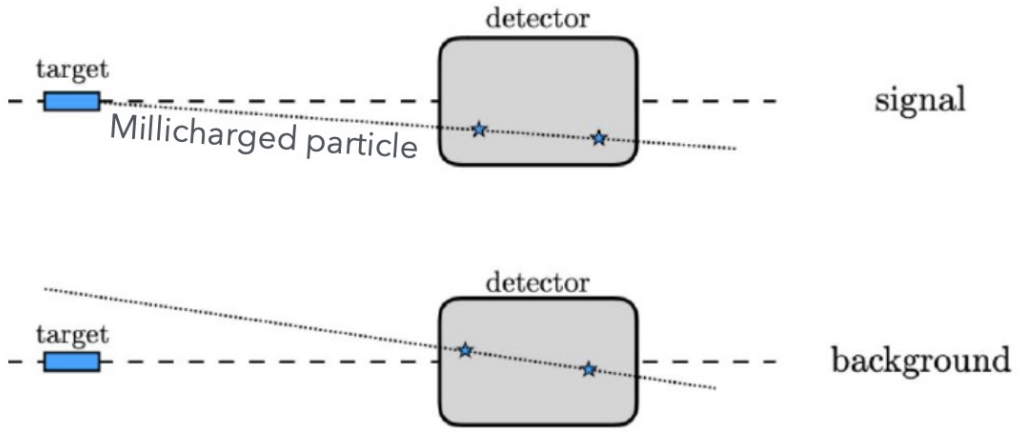
- Hypothesized particles with fractional electronic charge

- 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 beam target from SBND





ArgoNeuT *arXiv:1902.03246v2*

- Blip analysis is under development in SBND (1-3 hits pointing back to the BNB target)

- SBND is also the testbed to develop new machine-learning based TPC trigger for low energy (blip) activity. This will be very useful for future BSM searches in SBN program and DUNE

Model independent BSM search

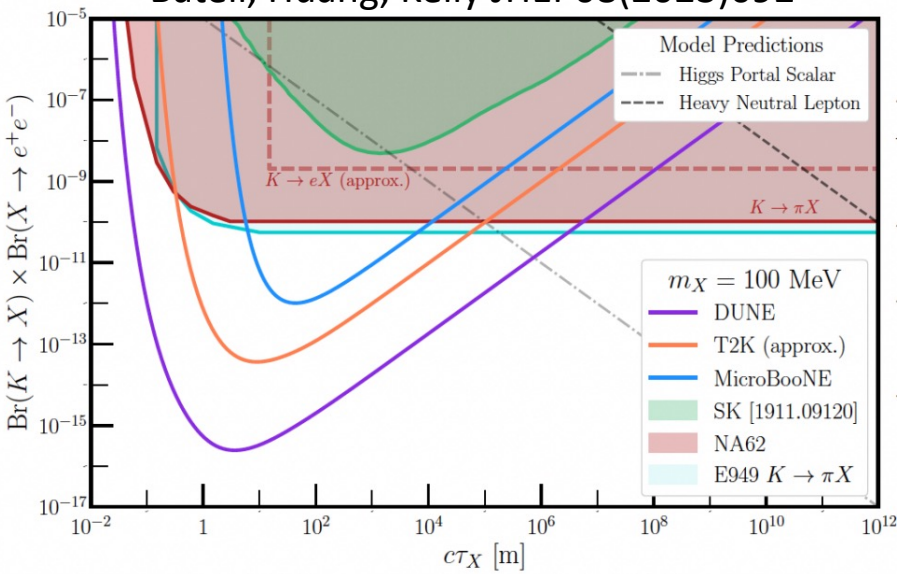
Search driven by experimental observables

BSM models	Dark ν light Z_d	Dark ν heavy Z_d	QCD Axion	HNL	Dark matter
Delayed timing	no	no	yes	yes	maybe
Final states	e+e-	e+e-	γγ, ee, μμ	e+e-, μπ	e, ee, γγ
Opening angle	small	small	tiny	large	?
Proton	no	yes	no	no	no

Advantage

- Maximize discovery potential, needed for BSM field
- Simplified, unified sensitivity defined by experimental observables
- Easy to translate to any specific model

Batell, Huang, Kelly JHEP08(2023)092



New analysis in the SBND BSM program

Stay tuned for the SBND curve!

Summary

- Short Baseline Neutrino Detector (SBND) is in a unique position to search for **sub-GeV BSM** physics
  - High BSM production rate
  - SBND – PRISM for systematic constraints and S/B optimization
  - **Bunched nu beam + O(1) ns ToF** for low background
- Vibrant BSM search program
  - Model specific: HNL, Light Dark Matter, Dark ν, Millicharge
  - Model-independent to maximize discovery potential, enable comparisons across experiments
- SBND detector is fully installed and commissioned (TPC HV raised to 100kV last week!!), and will start data taking in 2024.
- BSM sensitivity paper is in-progress to guide searches and inform the community, stay tuned!

Thank you


Photo taken at SBND Collaboration Meeting at Arlington, June 2023

Backup

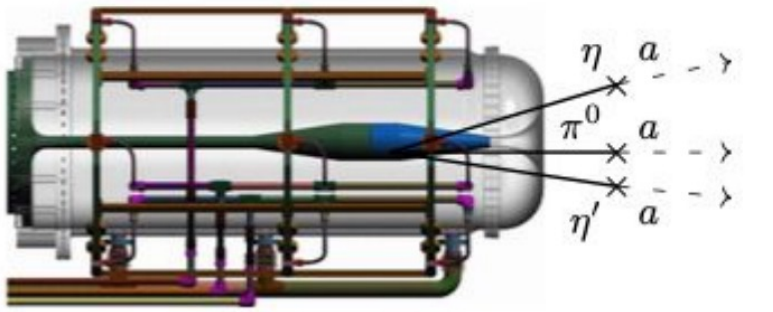
Heavy QCD Axion

R.T. Co, S. Kumar, Z.Liu JHEP02(2023)111

- Well motivated theory model to address the strong CP problem
- Model characterized by the lifetime and axion mass
- DUNE ND and SBN detectors can be ideal places to search for **sub-GeV QCD axion**

Production

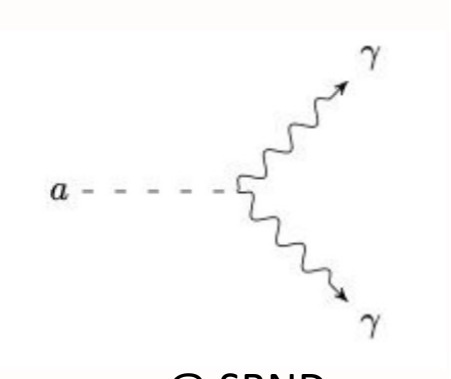
(meson mixing, gluon-gluon fusion)



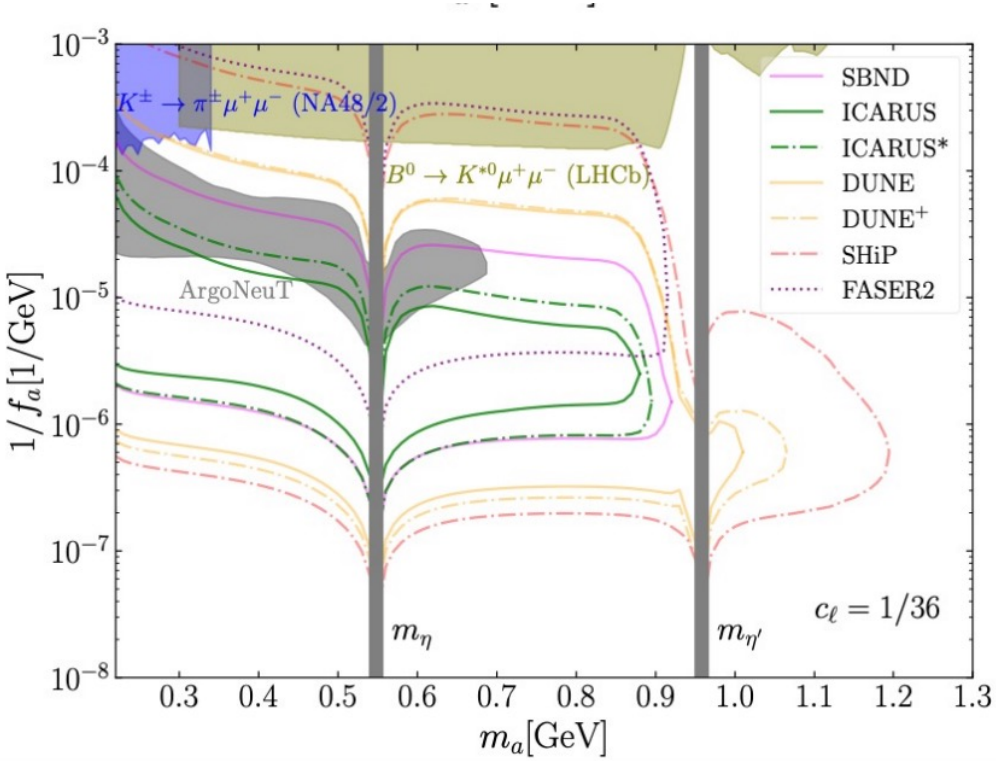
BNB Target

Decay

(photon pairs, di-muons, hadrons)



@ SBND



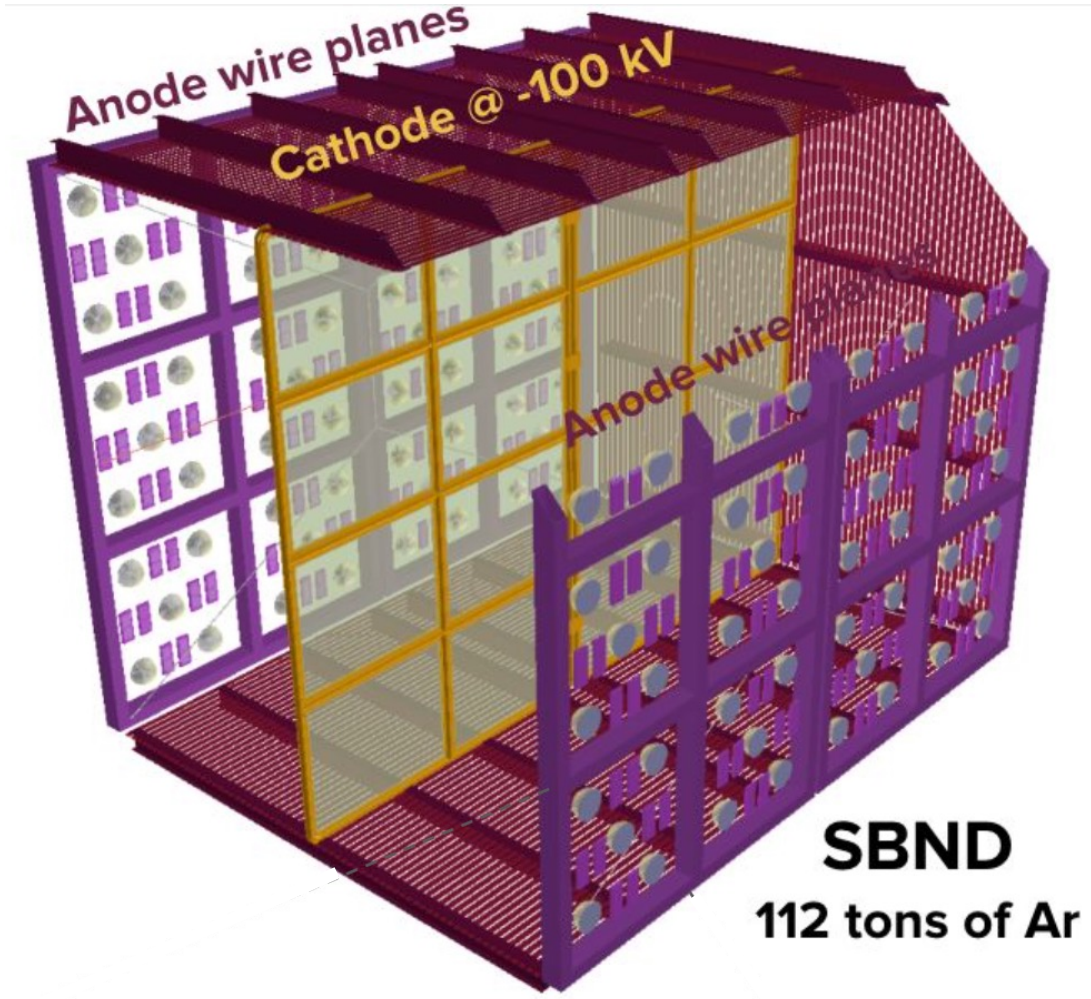
Work ongoing in SBND to search for Heavy QCD axion in the diphoton channel

Stay tuned!

K.Kelly, S. Kumar, Z. Liu, Phys. Rev. D. 103.095002

SBND detector status

- 112 tons of LAr
- mm spatial resolution
- Fine-granularity calorimetry
- Excellent particle identification
- Low energy thresholds, sub-MeV



Detector Status

- Construction completed in Sep. 2022
- Installation at Fermilab in Dec. 2023
- Detector filled with LAr in Mar. 2024
- Detector is fully Commissioned (HV raised to 100kV last week!)
- Data taking for detector calibration