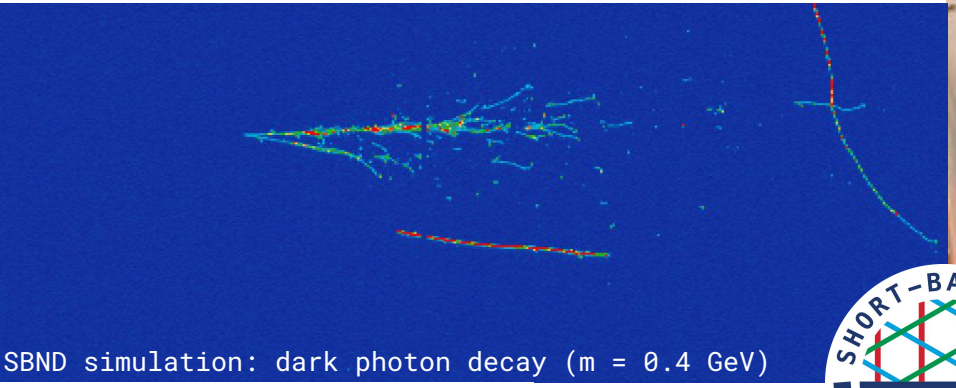
BSM New Physics Searches with SBND

Supraja Balasubramanian (FNAL)
José I. Crespo-Anadón (CIEMAT)

on behalf of the SBND collaboration

2nd SBN Exp-Theory Workshop | 04 April 2024



SBND simulation: dark photon decay (m = 0.4 GeV)

Fermilab

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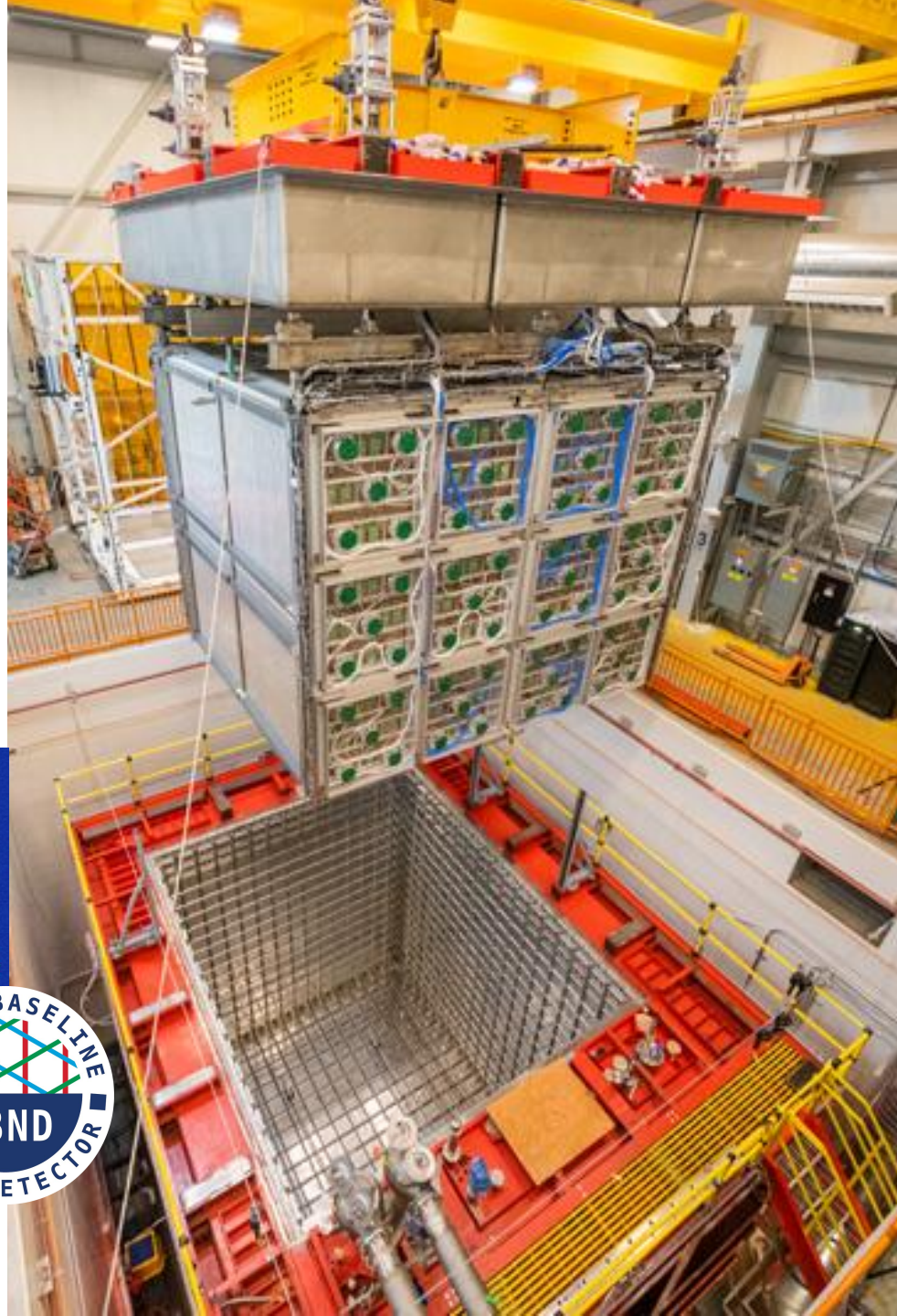


SBND & BSM Physics

Two large-mass LArTPCs:

- 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):

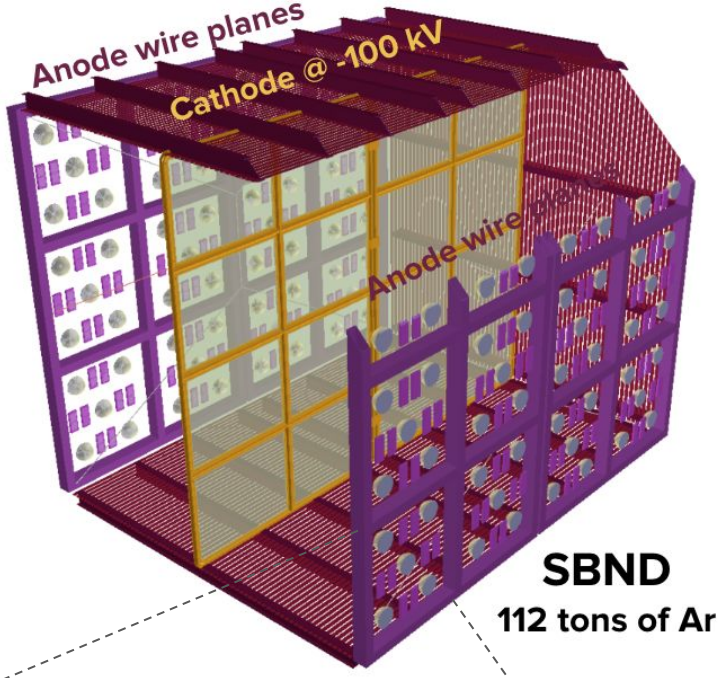
- Novel technology: **PMTs** and **X-ARAPUCAs**.
- Scintillation & reflected visible light => **high and uniform light yield** and **excellent timing resolution**.

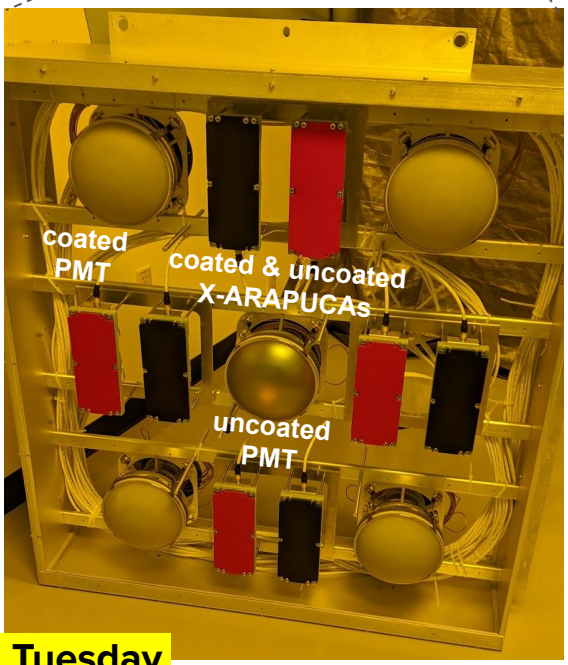
Cosmic Ray Tagger (CRT):

- 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





SBND's dual Photon Detection System:

96 TPB-coated + 24 uncoated PMTs

96 p-TP coated + 96 uncoated X-ARAPUCAs

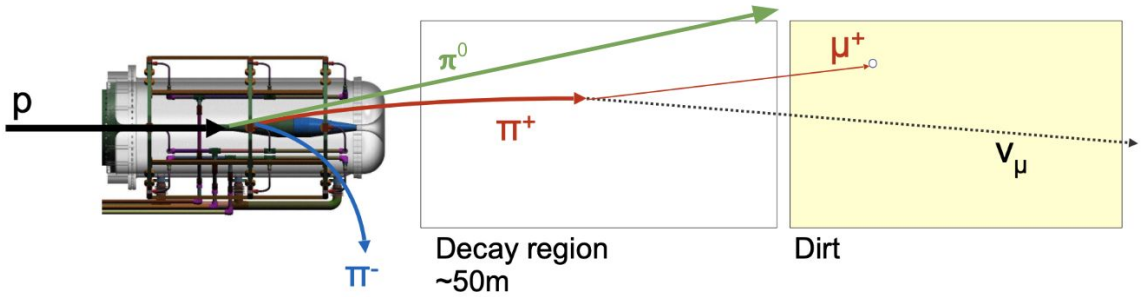
Learn more about SBND in Henry Lay's talk on Tuesday.

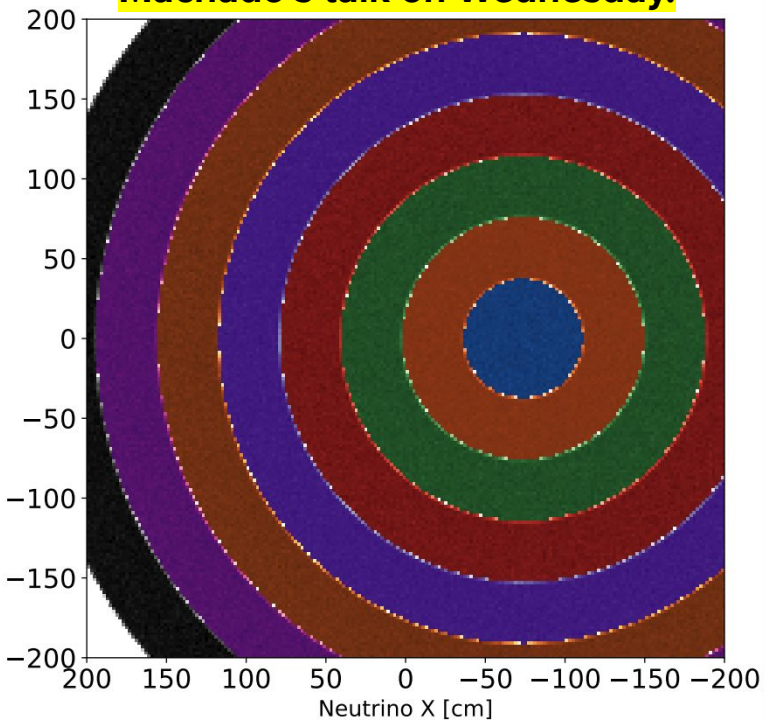
SBND PRISM

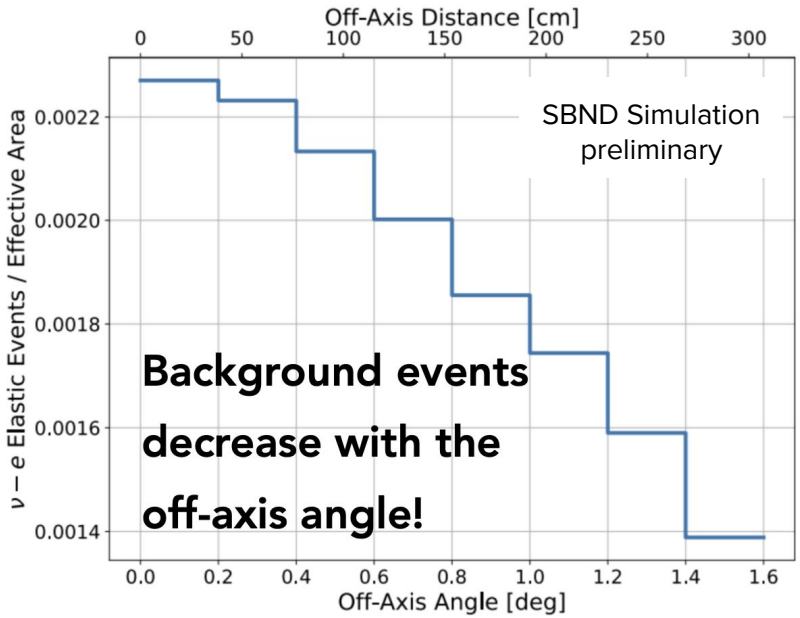
* nuPRISM

Find more details in Pedro Machado's talk on Wednesday.

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







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

Can sample **multiple off-axis fluxes** with the same detector, due to proximity of SBND to the beam source.

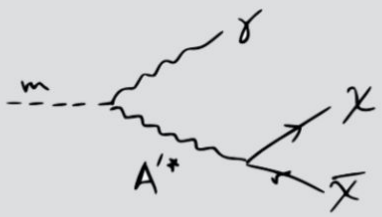
Neutral mesons in the BNB = less focused
can produce a variety of BSM: light DM, axion-like particles, millicharged particles.
Charged mesons in the BNB = more focused
produce SM neutrinos.

=> Background reduction of SM neutrinos at off-axis angles for BSM new physics searches.

BSM Production in the Booster Neutrino Beam

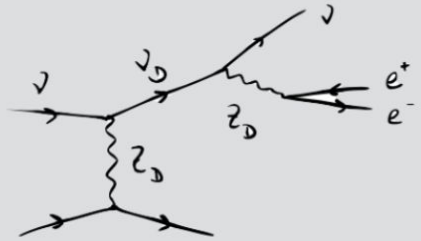
A non-exhaustive list of BSM new physics
that could be produced in the BNB.

Light Dark Matter



Romeri Kelley Machado PRD 2019

Dark Neutrinos

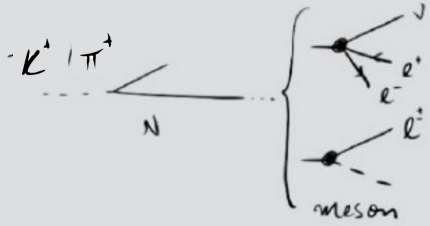


Bertuzzo Jana Machado Zukanovich PRL 2018, PLB 2019
Arguelles Hostert Tsai PRL 2019
Ballett Pascoli Ross-Lonergan PRD 2019
Ballett Hostert Pascoli PRD 2020

Millicharged Particles

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

Heavy Neutral Leptons

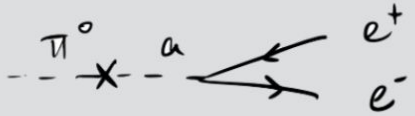


Ballett Pascoli Ross-Lonergan JHEP 2017
Kelly Machado PRD 2021

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: Pedro Machado, Marco Del Tutto

Theorist-SBND Collaborations

BSM physics in the BNB may happen **anywhere between the proton-target collision and the detector.**

We need BSM generators that can be interfaced with any of the simulation steps.

Access to ns **timing** requires BSM flux simulations with a **detailed propagation of the particles.**

de Niverville et al., arXiv:1609.01770v3
Dark matter production via vector portal

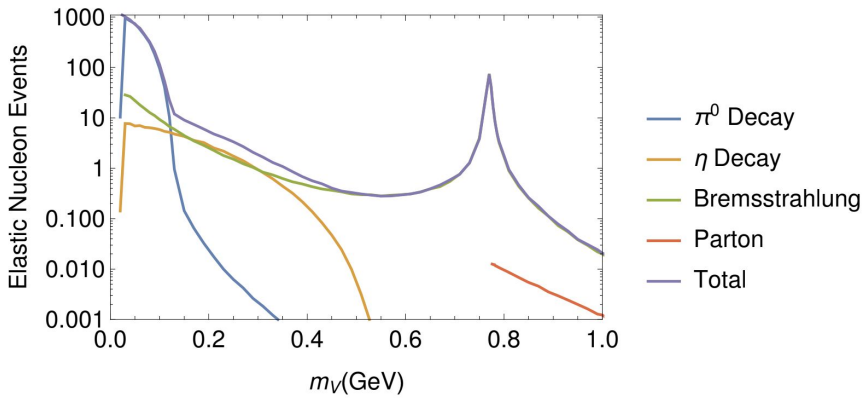
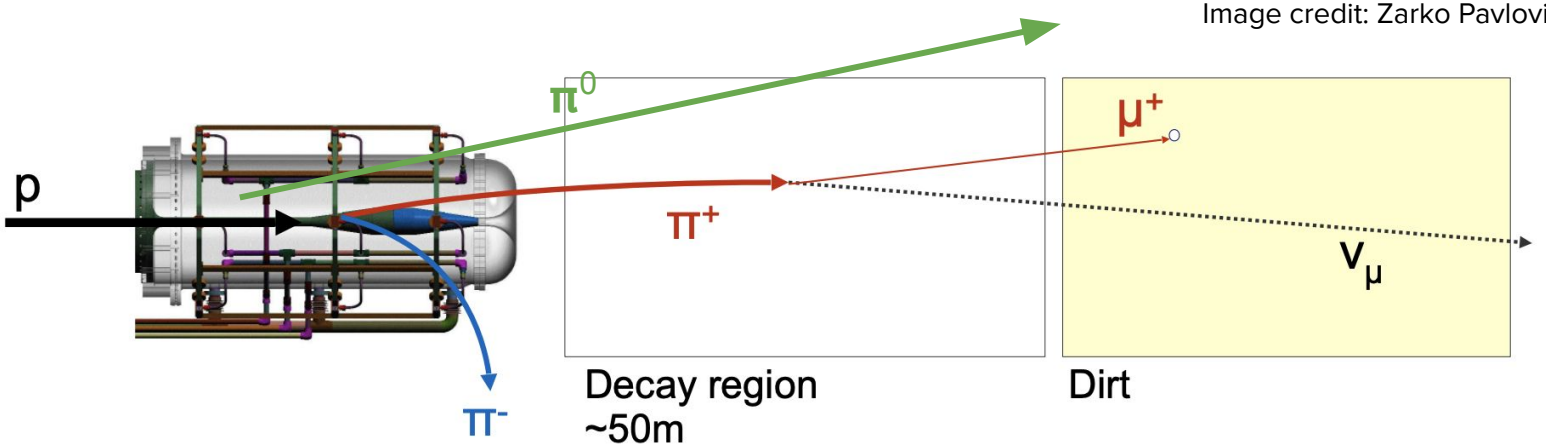


Image credit: Zarko Pavlovic



BSM Generators in SBND

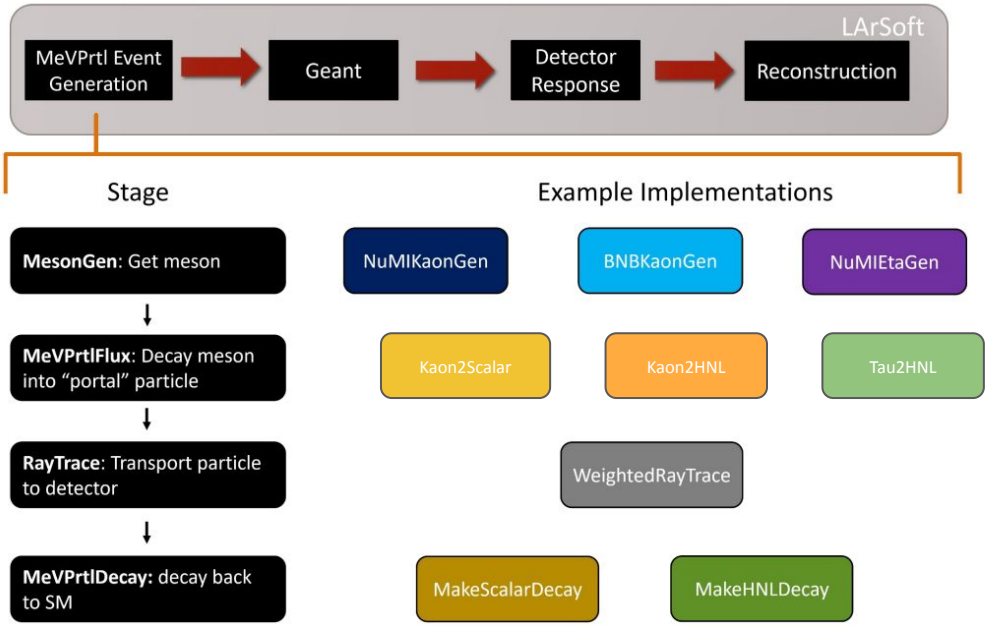
In the SBN Program we have developed **MeVPrtl: a BSM generator shared by SBND and ICARUS.**

- Interfaces with the BNB and NuMI meson beam simulation.
- Modular approach to new physics in beam.
- Ray tracing.
- Modular approach to new particles decaying in detector.
- Fully integrated with LArSoft:

  Carry time of flight and weights consistently.

  Optimized workflow for large sample generation

  Access to flux systematics evaluation



Used for HNL and model-independenent searches.

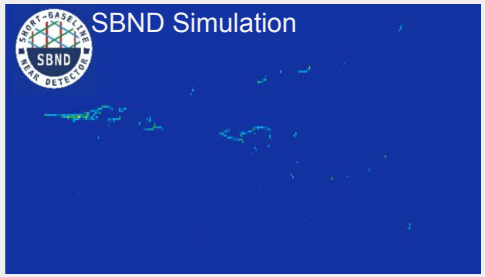
May expand to neutral mesons models in the future (currently using HEPEVT text files).

BSM Signatures in SBND

We introduce the model into our simulation & run reconstruction.

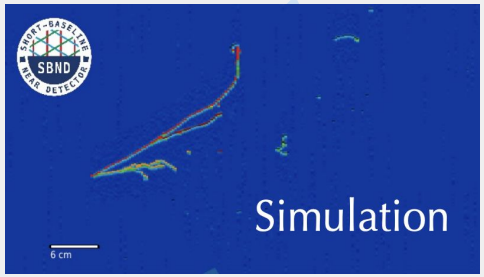
What SBND would see if these BSM phenomena interact inside SBND.

Light Dark Matter



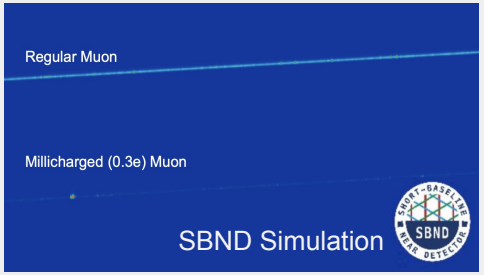
single e^- scattering or e^+e^- pair with no hadronic activity

Dark Neutrinos



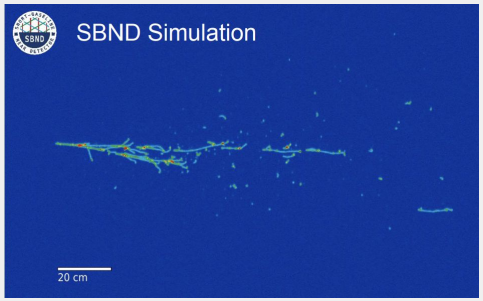
e^+e^- pair with or without hadronic activity

Millicharged Particles



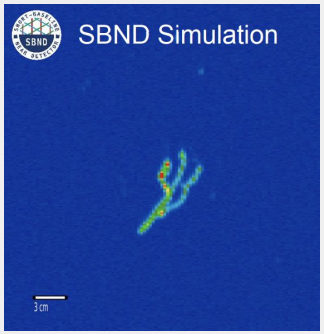
blips or faint tracks

Heavy Neutral Leptons



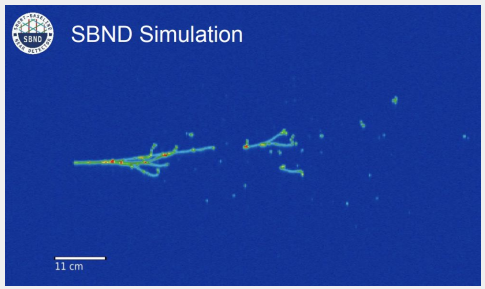
e^+e^-, $\mu^+\mu^-$, or $\mu^\pm\pi^\mp$ pair with no hadronic activity

Higgs Portal Scalar



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

Axion-Like Particles

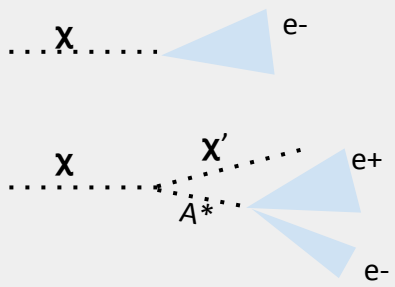


high-energy e^+e^- or $\mu^+\mu^-$ pair

BSM Signatures in SBND

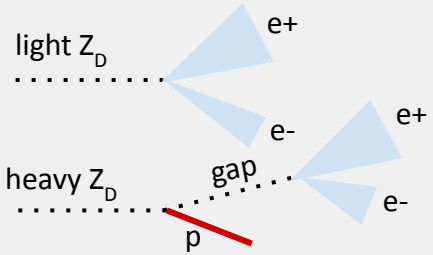
What SBND would see if these BSM phenomena interact inside SBND.

Light Dark Matter



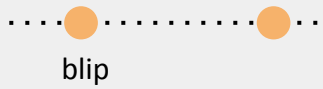
single e^- scattering or e^+e^- pair with no hadronic activity

Dark Neutrinos



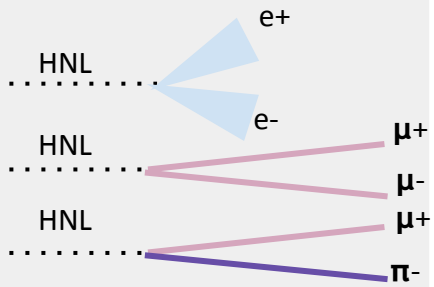
e^+e^- pair with or without hadronic activity

Millicharged Particles



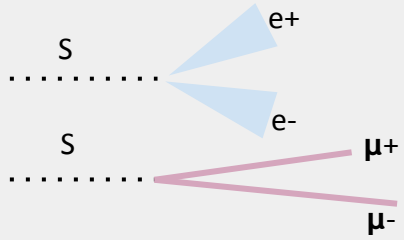
blips or faint tracks

Heavy Neutral Leptons



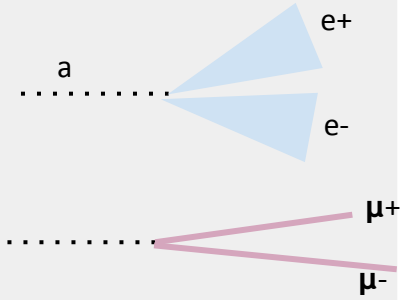
e^+e^-, $\mu^+\mu^-$, or $\mu^\pm\pi^\mp$ pair with no hadronic activity

Higgs Portal Scalar



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

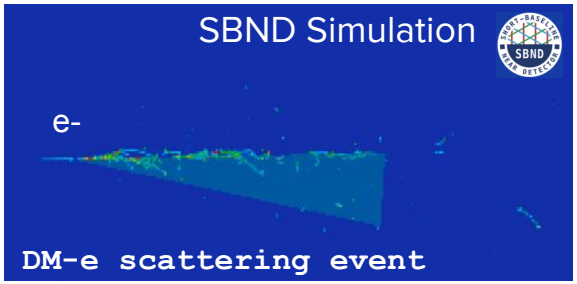
Axion-Like Particles



high-energy e^+e^- pair

Examples of Reconstruction Tools for BSM Physics*

*not exhaustive.



Electromagnetic Activity Reconstruction

Many BSM signatures produce **electromagnetic activity**.

E.g. the DM scatter electron is reconstructed ~91% of the time:

54% as a single shower,
10% as a shower+track,
8% as a single track,
8% as two showers,
and the rest as multiple tracks and/or showers.

Efforts to improve shower reconstruction completeness, purity and resolution are ongoing and will be shared across BSM searches.

Proton "Stub" Rejection

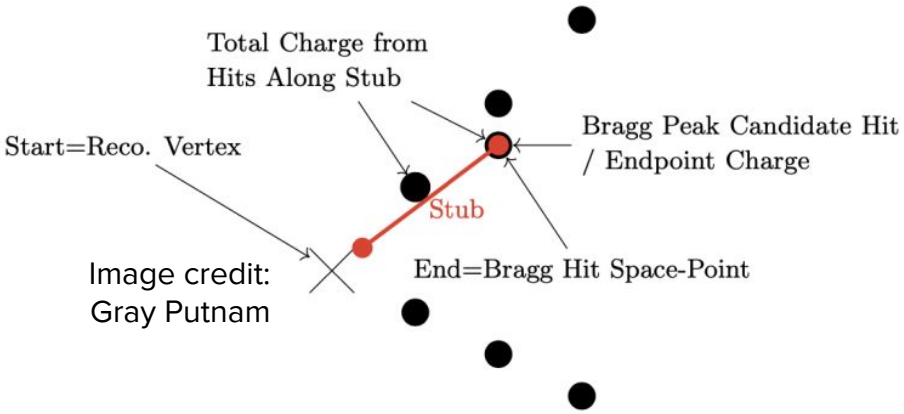
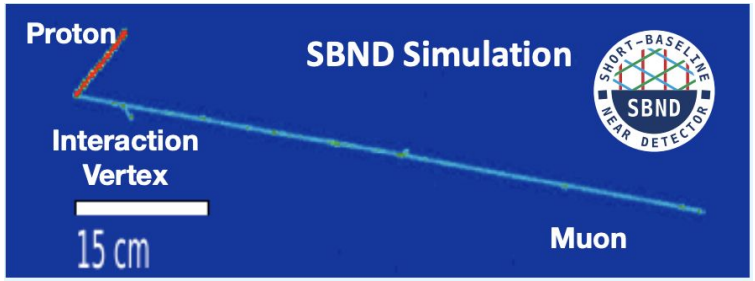
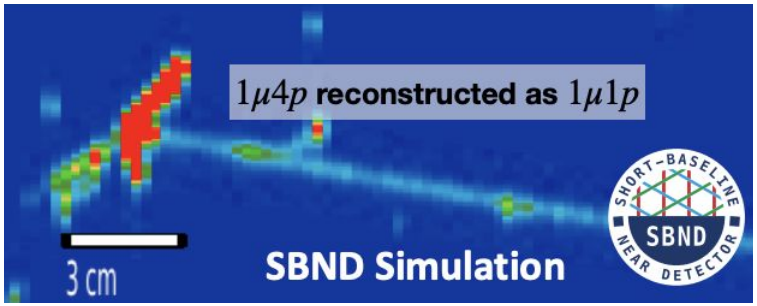


Image credit:
Gray Putnam

Tags and rejects low-energy stub-like charge depositions around a vertex that fail standard track reconstruction.





Heavy Neutral Leptons (HNLs)

Right-handed fermion **addition to the 3-neutrino SM paradigm**.

Can couple to SM neutrinos by extended PMNS matrix couplings $U_{\alpha 4}$, **α** = **e**, **μ**, **τ**.

Could be produced by mesons in the BNB.

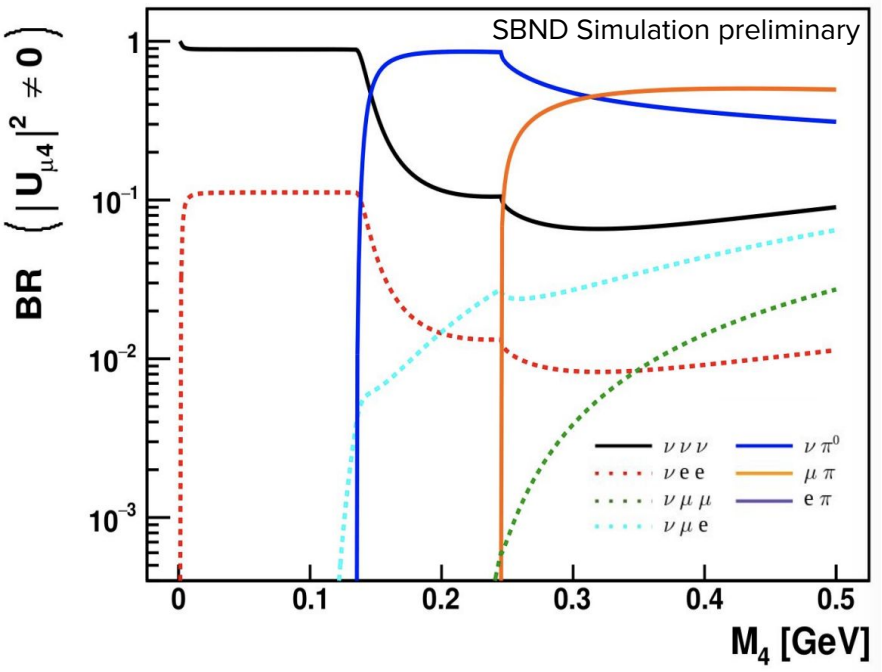
HNLs would decay in flight into SM observables with **event rate ∝ $|U_{\alpha 4}|^4$**.

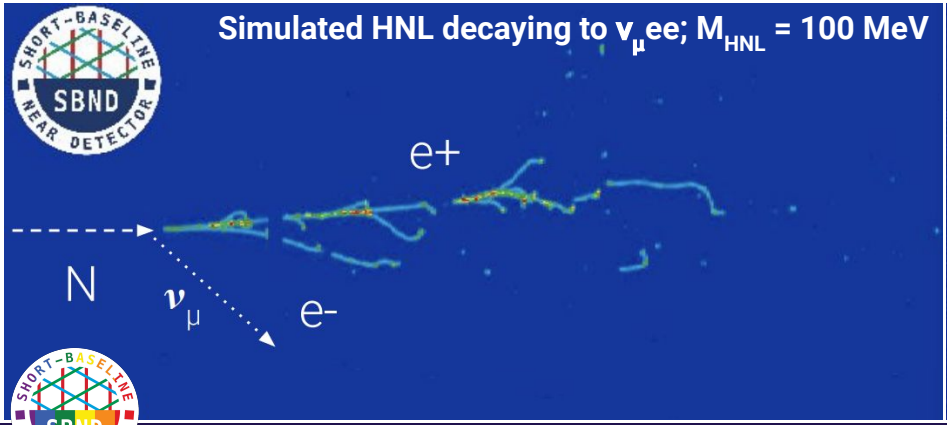
SBND is targeting several HNL decay channels:
HNL → **ν**ee (M_{HNL} 30–140 MeV)
HNL → **νπ**^{0} (M_{HNL} 140–244 MeV)
HNL → **μ**$^{\pm}$**π**$^{\mp}$ (M_{HNL} 244–388 MeV)

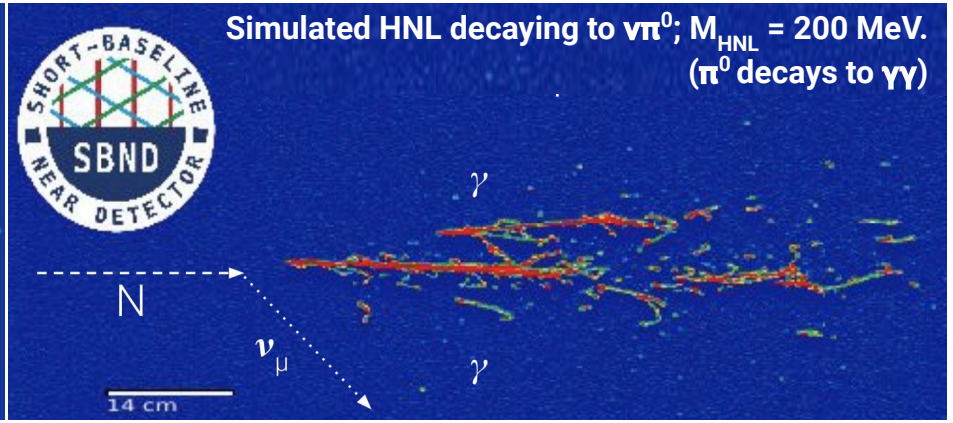
Main backgrounds:
BNB **ν** neutral current events producing **e** or **γ**.
BNB **ν** - electron scattering.

Decay modes of the HNL

Made with MeVPrtl





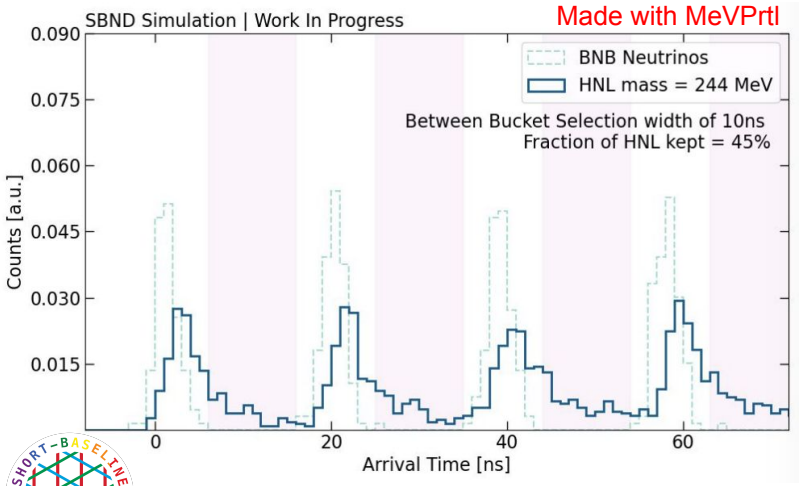


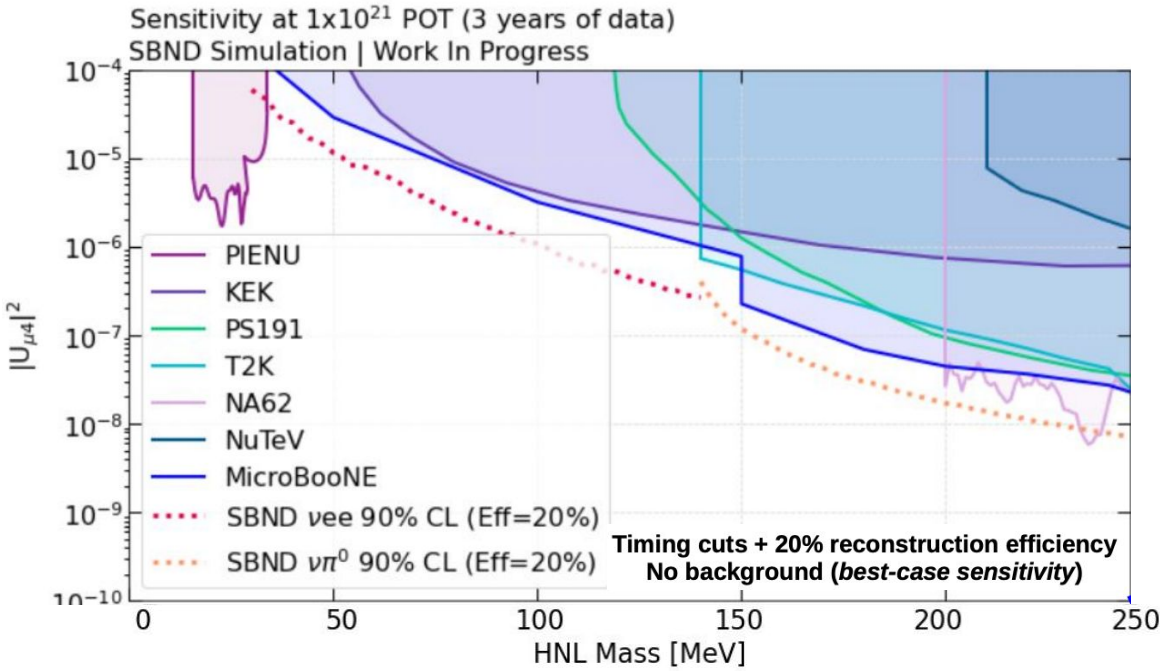
HNL Search in SBND

HNLs are heavier than neutrinos:

- Different arrival time profile.
- Can use a ***delayed selection*** to look ***in between neutrino buckets***.
- **Photon Detection System** has **ns timing resolution.**
- SBND has demonstrated **3D reconstruction with light information** to resolve the BNB structure.

Find more details in Rodrigo Álvarez-Garrote's talk today





Preliminary sensitivity shows SBND potential to lead searches for $U_{\mu 4}$-driven mixing below 250 MeV.

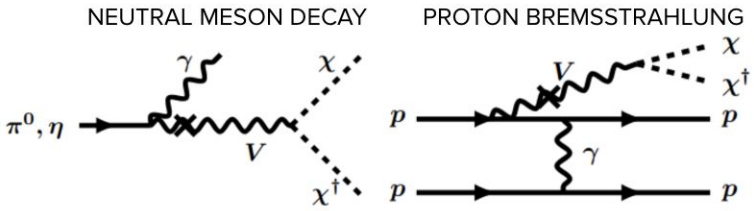
New end-to-end sensitivity in progress.

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

Light Dark Matter

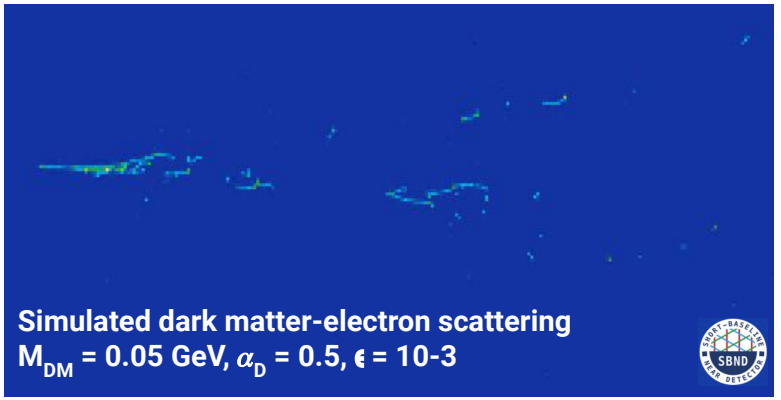
SBND can probe sub-GeV DM postulated by “thermal relic” models, compared to WIMP searches restricted to higher masses.

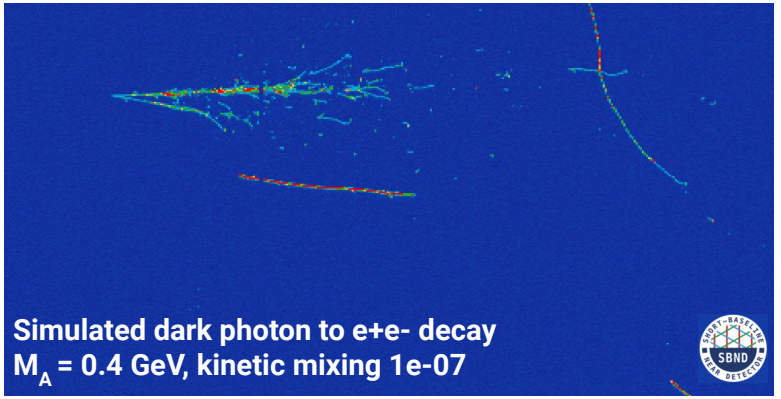
Vector portal DM models: light dark photon could be produced via meson decay or proton bremsstrahlung.



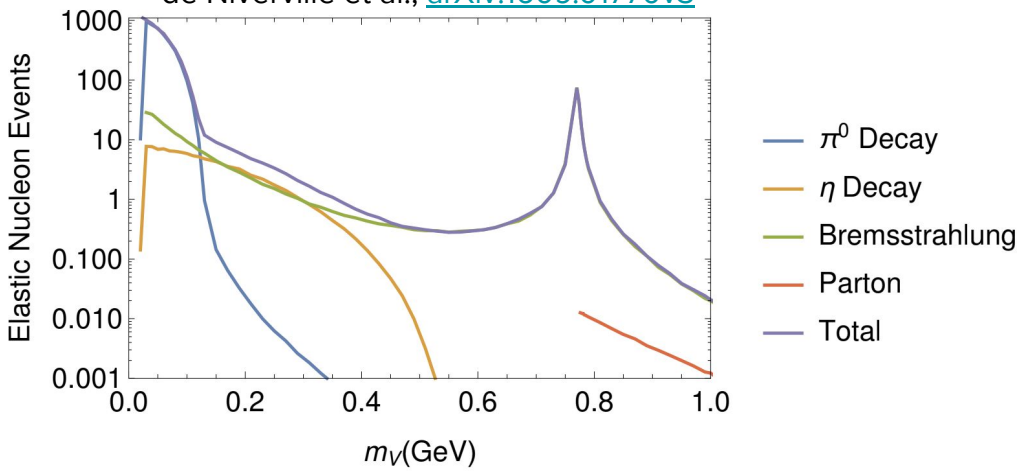
SBND is currently exploring **two models for DM production** in the BNB:

- Patrick de Niverville et al: production via **neutral meson decay + p brem**
- Bhaskar Dutta, Aparajitha Karthikeyan, Doojin Kim: production of long-lived dark photon via **charged meson decay** in addition to above modes.





de Niverville et al., arXiv:1609.01770v3



Light DM Search in SBND

SBND is looking for **2 types of DM interactions:**

- DM-electron scattering
- Dark photon ➡ e+e- decay

Main signature:

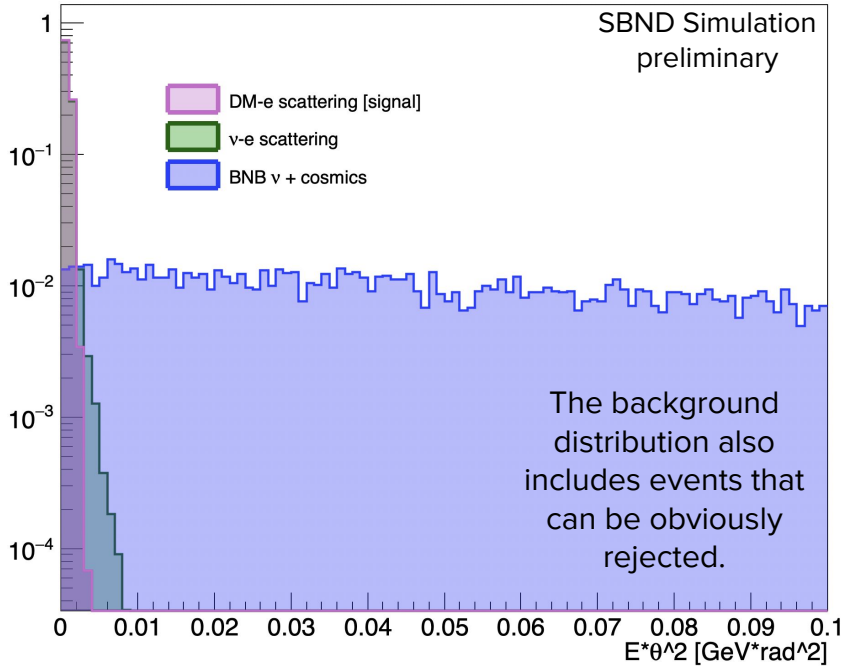
highly forward-going electromagnetic showers without accompanying hadronic activity.

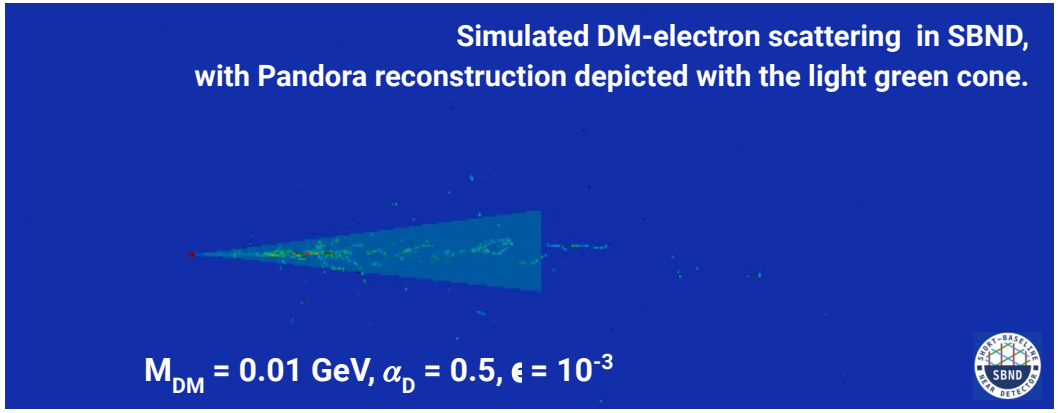
Main backgrounds:

BNB **ν** neutral current events producing e or **γ**.

BNB **ν** - electron scattering.

Synergistic search with HNLs!





Model-independent search

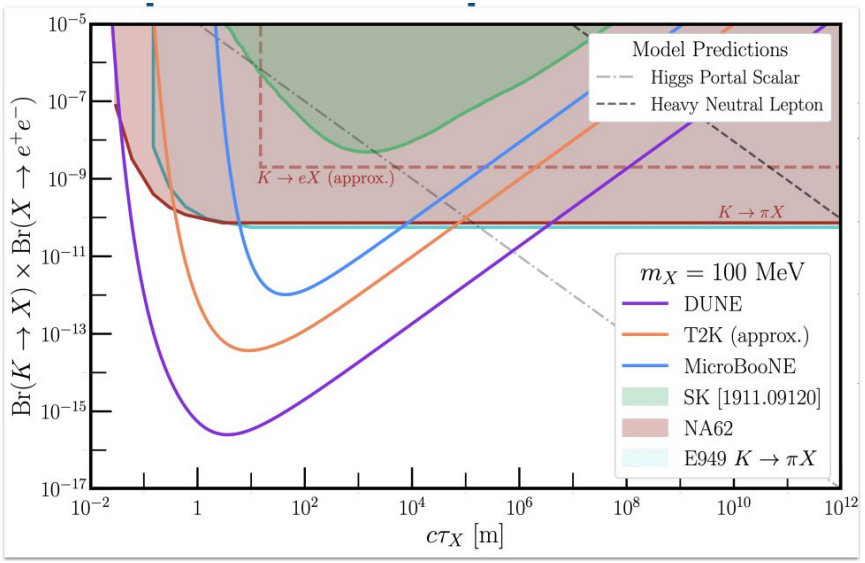
Explore sensitivity to a **generic long-lived massive particle** X produced in the BNB beam and decaying in the SBND detector.

Work in progress to **expand MeVPrtl generator** to produce samples with **minimal assumptions** in a phase space not constrained by specific BSM models.

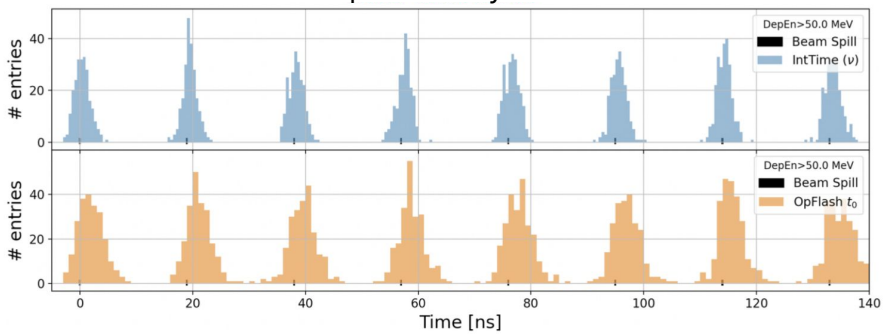
Synergistic with the reconstruction and analysis development for all the previous model-specific searches.

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

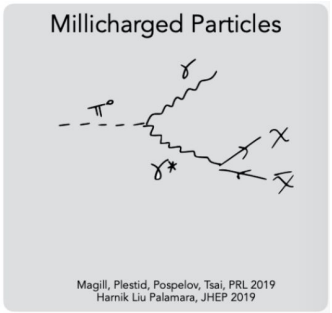


SBND Simulation preliminary



Simulated (top) and reconstructed (bottom) showing neutrino beam structure

Milicharged 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.

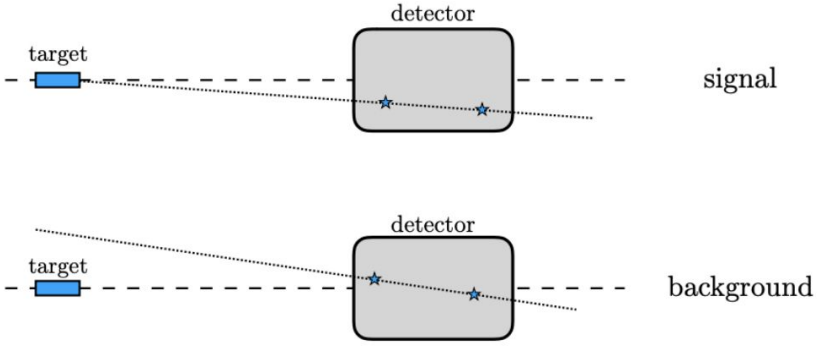
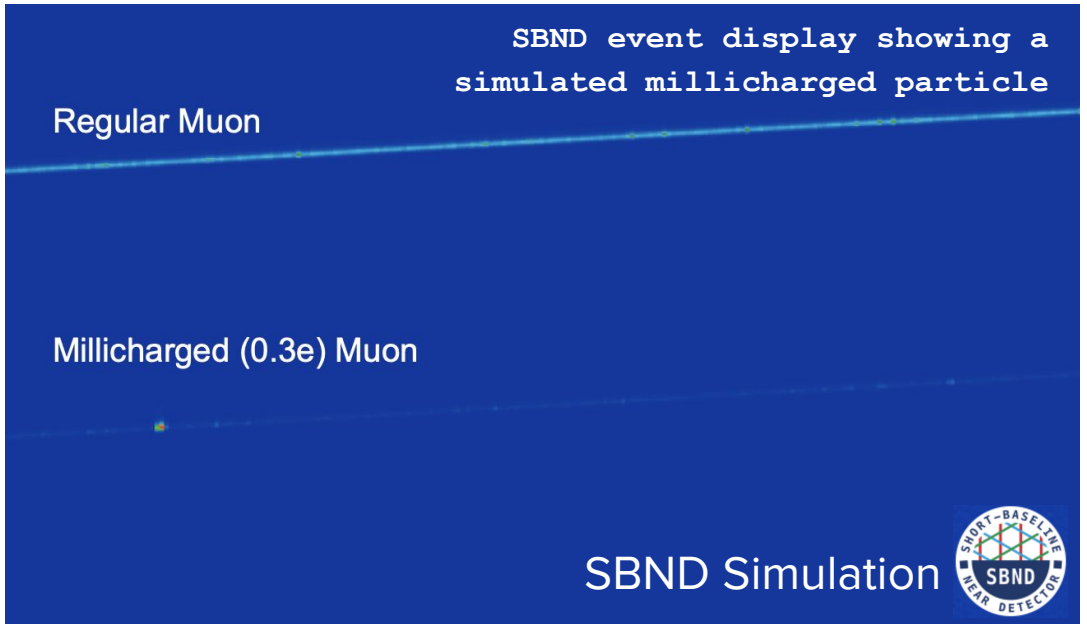
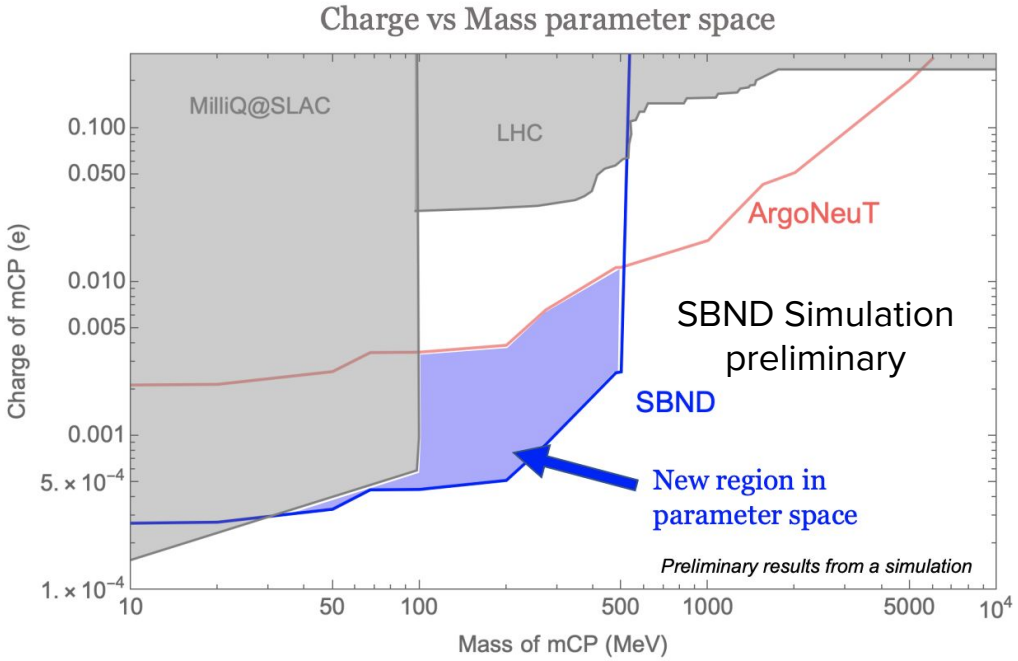


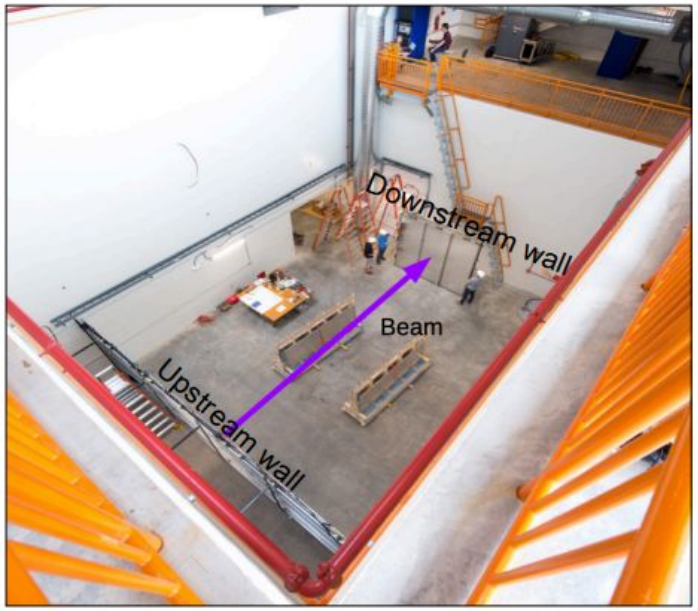
Image credit: ArgoNeuT, arXiv:1902.03246v2

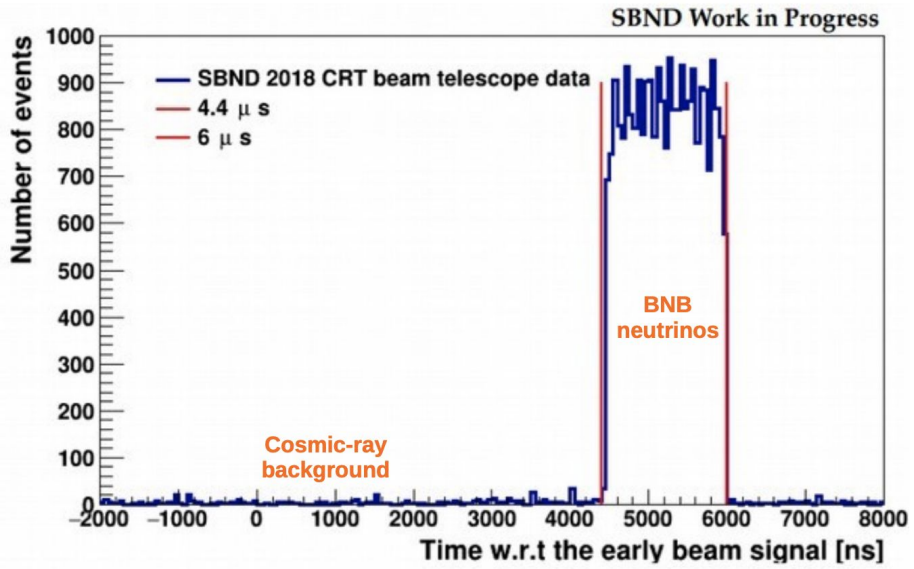


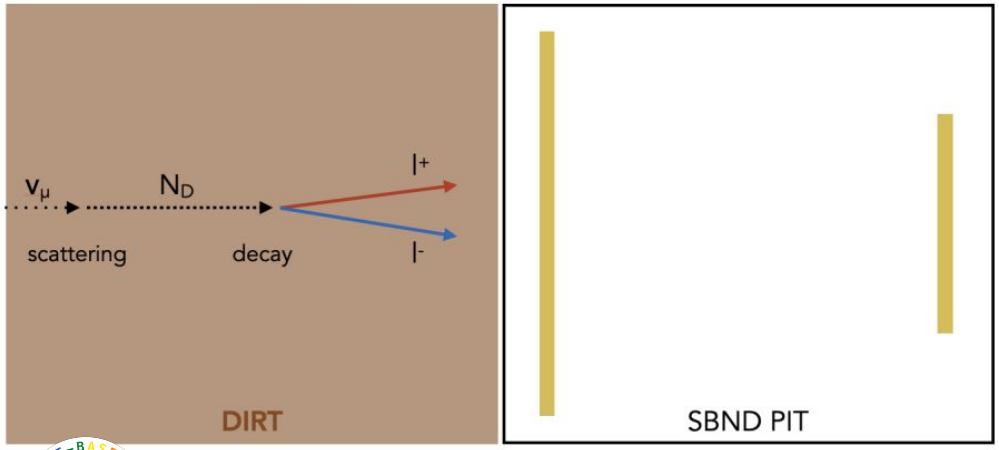


Preliminary SBND sensitivity projection from simulation

Dark Neutrino Search with SBND Cosmic Ray Tagger







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.

Outlook

- SBND is great 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
  - will collect 10×10^{20} POT of data over 3–4 years, **starting in 2024**.
- Diverse BSM program being pursued actively. More BSM searches being developed (heavy axions, dark neutrinos in TPC...)
- SBND has started several collaborations with theorists so that experimentalists and theorists can develop BSM searches together. Happy to look for more models!

  SBND BSM conveners: jcrespo@ciemat.es; xiaoluo@physics.ucsb.edu

Backup

Booster Neutrino Beam [BNB] & BSM Physics

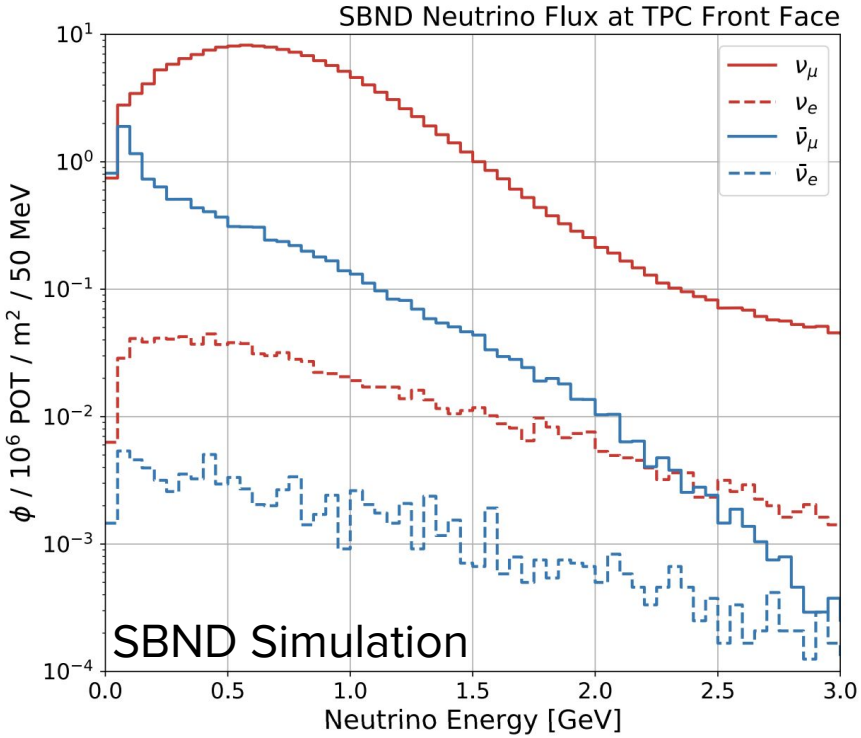
A **high-intensity 8-GeV proton beam** is focused on a Beryllium target, producing **charged and neutral mesons**, which decay to produce leptons, neutrinos, *and potentially a variety of BSM new physics*.

Neutrino composition of the beam: 93.6% ν_μ, 5.9% $\bar{\nu}_\mu$, 0.5% ν_e+$\bar{\nu}_e$

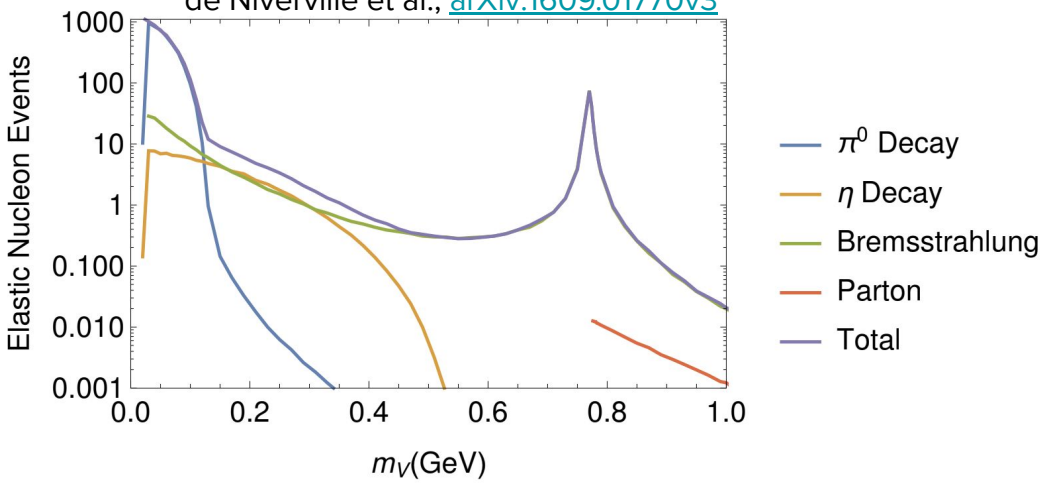
SBND is particularly **close to the beam target (110 m).**

BSM new physics opportunities with the BNB:

- **Modifications to the neutrino oscillation paradigm** to explain the short-baseline anomalies.
- **Novel physics produced in the beam** (dark matter, heavy neutral leptons, etc).



de Niverville et al., arXiv:1609.01770v3



Light Dark Matter production modes in the BNB. The x-axis shows the dark photon mass in this vector portal model.

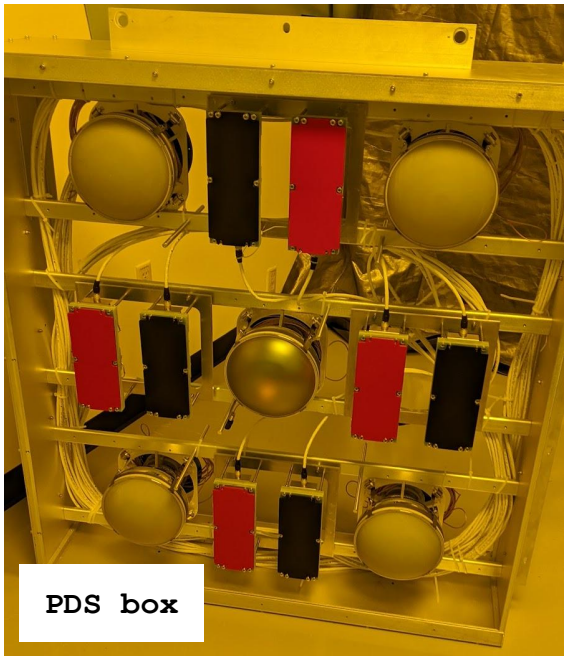
SBND Light Collection & Triggering

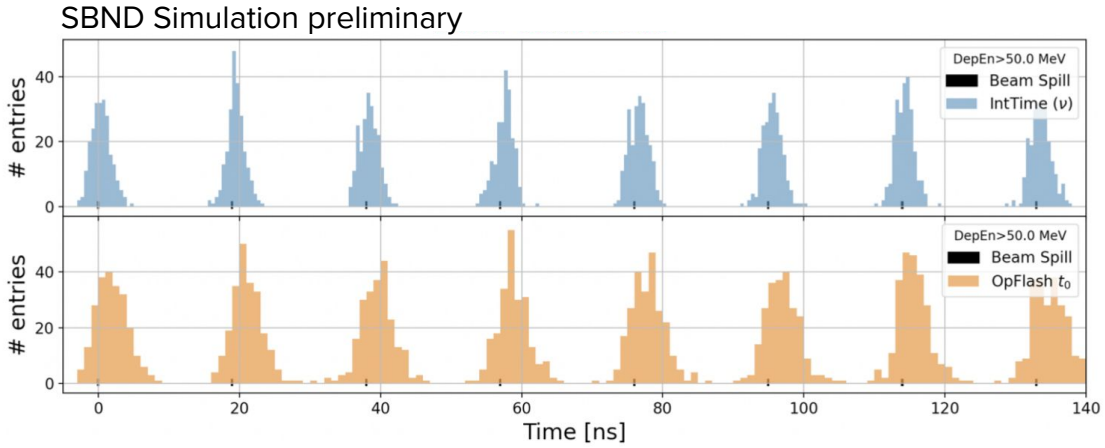
Three-part Photon Detection System (PDS):

- Photomultiplier tubes (coated + uncoated)
- X-Arapuca devices (sensitive to UV + visible)
- Cathode covered with wavelength-shifting reflective foils

Primary scintillation and reflected light: improved and more uniform total light yield.

Energy reconstruction: can supplement LArTPC charge information with light for calorimetry.

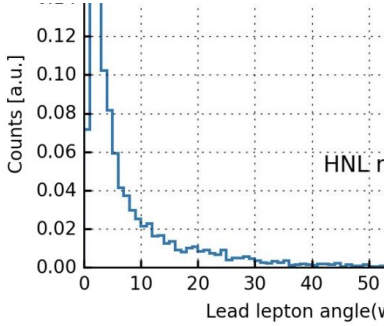




Simulated (top) and reconstructed (bottom) neutrino beam structure

HNLs

- Two channels are being explored:
  - **ν e e (30 – 140 MeV)**
  - **ν π^0 (140 – 244 MeV)**
- Challenging topology signatures:
  - **2 electromagnetic showers**
  - **Beam-collimated**
  - **Highly overlapping**
  - **No hadron activities**



- **Dominant background** comes **from SM neutrinos**:
  - ν – Argon neutral current interactions final states containing electrons/photons
  - ν – electron scattering
- **Efforts to improve reconstruction** completeness, purity and resolution are ongoing:
  - ML-techniques for cosmics ray rejections
  - Shower reconstruction
  - Proton identification for hadronic vertex veto
  - Muon/Pion identification for track-like veto
  - And others

- HNLs are **heavier** than neutrinos and hence travel at a **slower velocity**.
- BNB beam spill 1.6 μs long, made up of 81 buckets of 2 ns width separated by 19 ns.
- Can utilise the **high timing precision** from the **Photon Detection System**.
- SBND has demonstrated the capability to **3D reconstruct using only scintillation light signals** to retrieve the BNB bucket structure. (MicroBooNE first showed this reconstruction earlier this year)
- **Select HNL events between the buckets**, with efficiency ~40% depending on mass.
- Can **extend to other BSM heavy particles searches** such as Higgs Scalar Portal, Axion-like particles as well as model-independent searches.