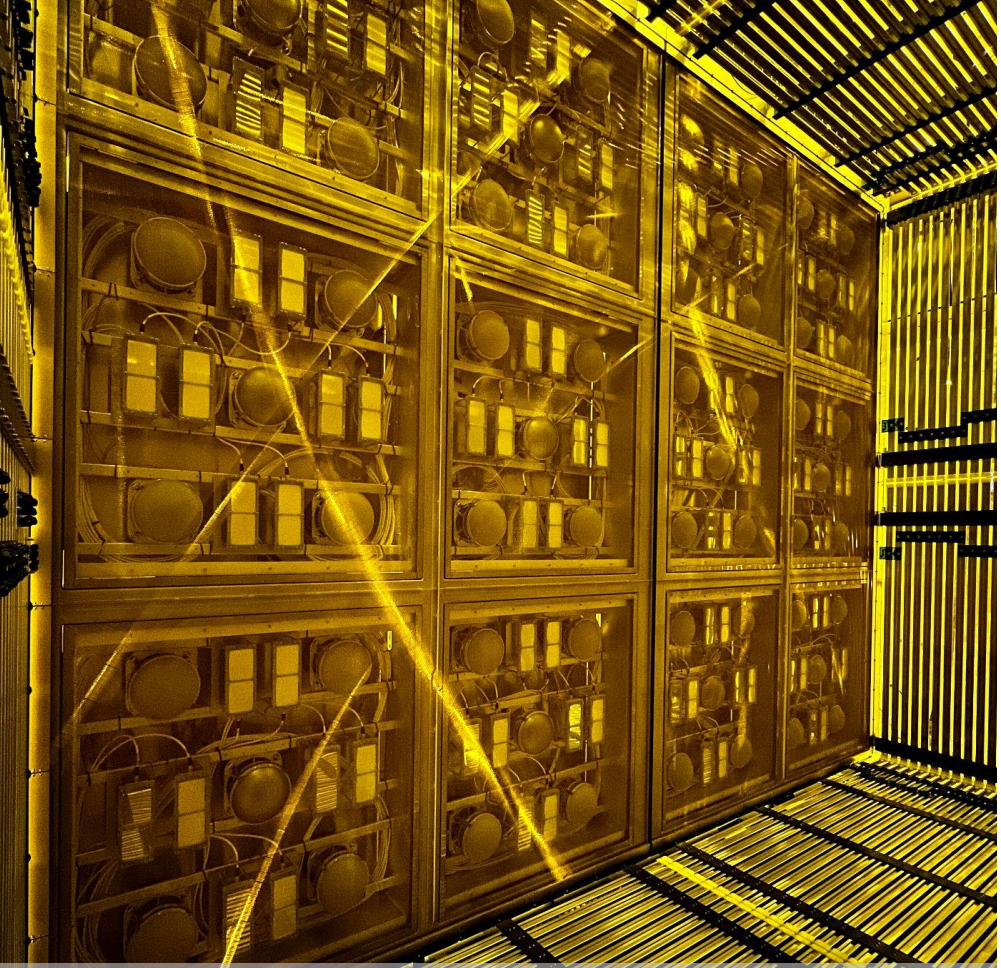


SBND time projection chamber completed with the Photon Detection System, wire planes and field cage.

University of Sheffield

Beyond Standard Model Searches with the Short-Baseline Near Detector

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

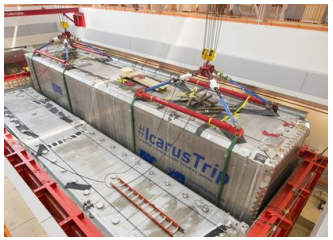
European Physical Society Conference on High Energy Physics

21– 25 August 2023

The Short-Baseline Neutrino Program

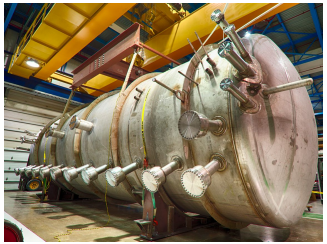
ICARUS

600 m baseline
470 t active volume
Operating



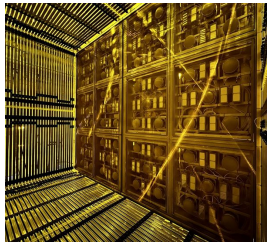
MicroBooNE

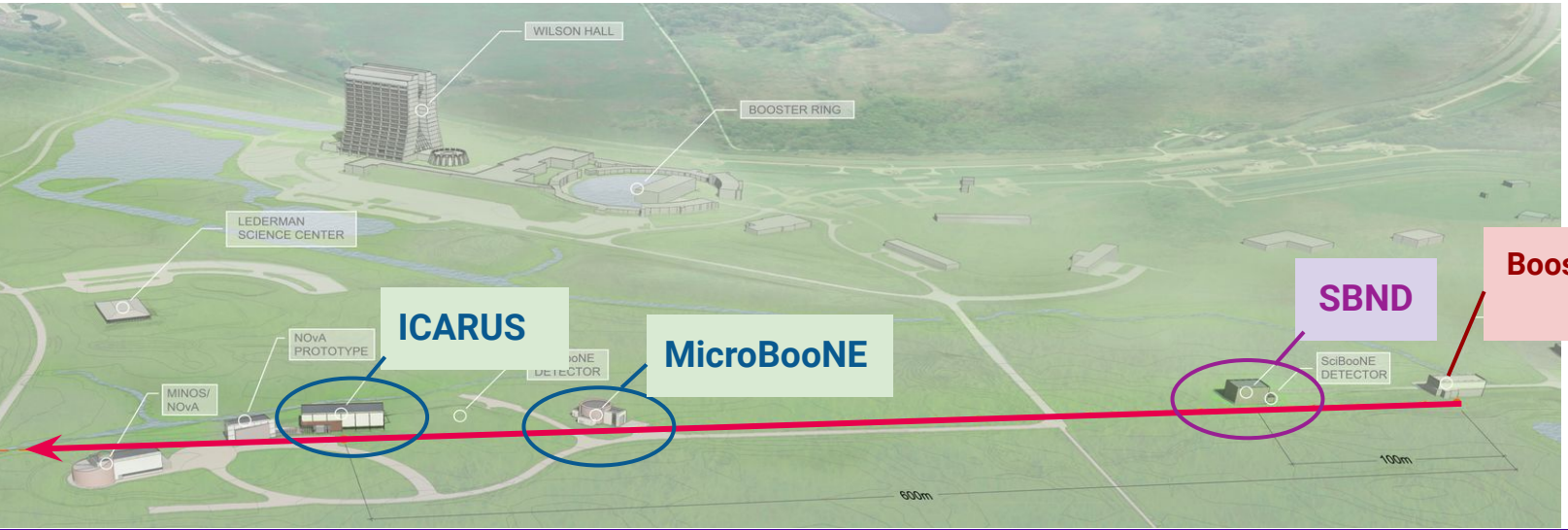
470 m baseline
87 t active volume
2015 – 2021



SBND

110 m baseline
112 t active volume
Commissioning

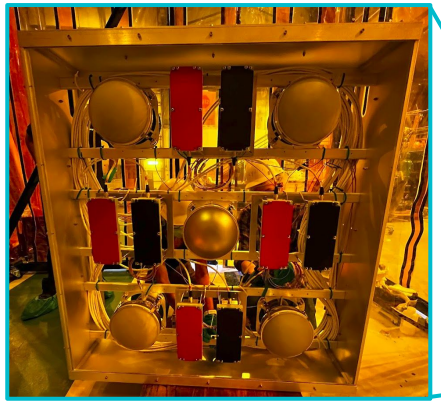




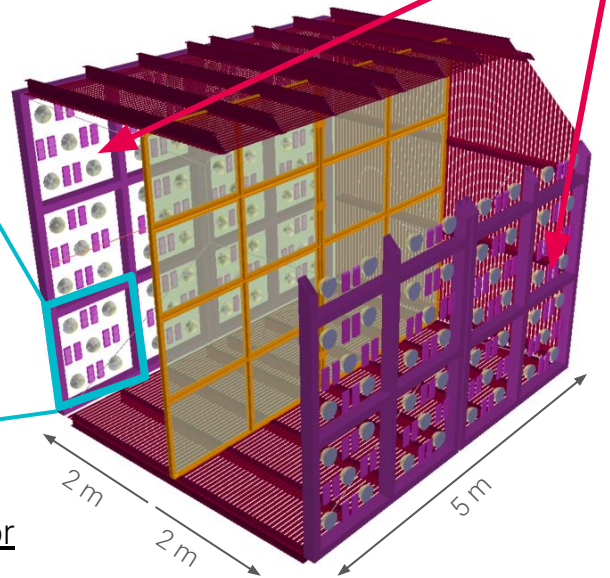
Booster Neutrino Beam
8 GeV

Short-Baseline Near Detector

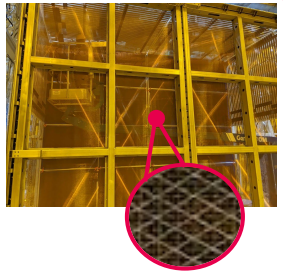
Photon Detection System
96 PMTs (TPB-coated)
24 PMTs (uncoated)
192 X-ARAPUCAs
TPB-reflective foils
- Sensitive to VUV and visible light
- High and uniform light yield
- Excellent timing resolution



LAr Time Projection Chamber
$4 \times 4 \times 5\ m^3$
Active volume 112 t
2 drift volumes
Drift distance 2 m
Drift time 1.25 ms



Anode Plane Assembly
on each side of the detector, made of 3 planes of wires with $\theta_{u,v,w} = \pm 60, 0^o$
11,264 wires in total
Uniform 500V/cm drift filed

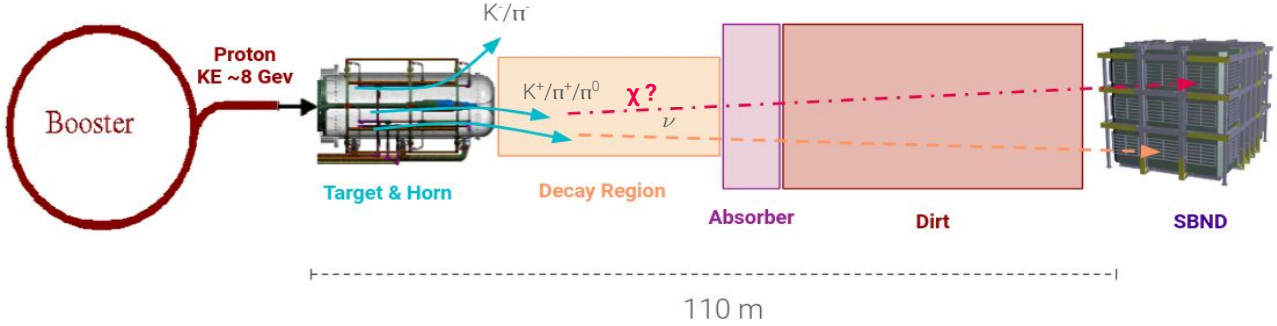


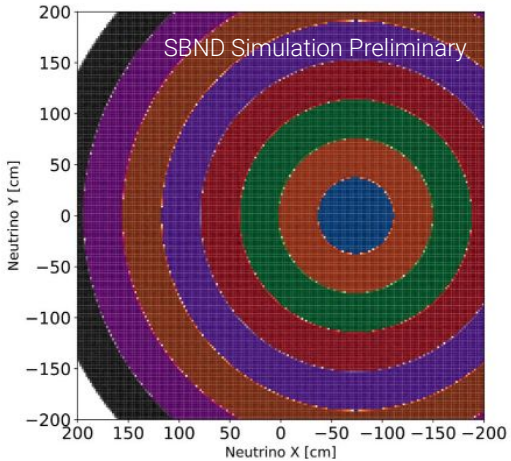
- Fine spatial resolution of 3 mm
- Fine-granularity calorimetry
- Excellent particle identification

Cosmic Ray Tagger
completely surrounds the entire SBND for 4π coverage.
- Excellent spatial and timing resolution
- Tag cosmics + entering/exiting particles

See Leonidas Aliaga 's talk on
Status of the Short-Baseline Near Detector at Fermilab

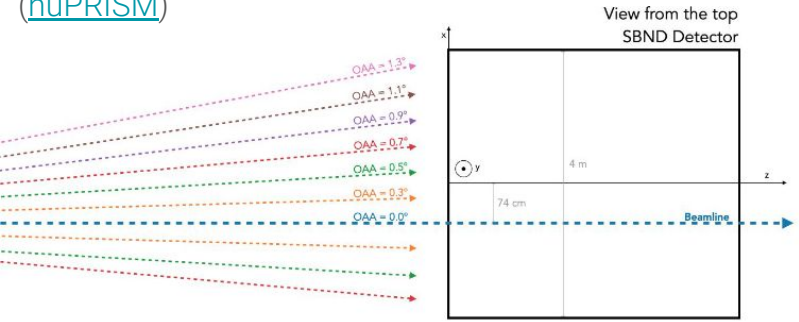
Booster Neutrino Beam





BNB flux at the front face of SBND detector, sampling at off-axis angles between 0-1.6°

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

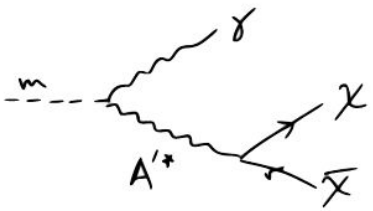


- A high-intensity **8-GeV proton beam** is focused on **a Beryllium target**, producing **charged and neutral mesons**.
- The mesons **potentially decay to a variety of BSM physics**, which are **observables at SBND**.
- SBND is close proximity and off-axis to the BNB → exploit PRISM effect to **sample fluxes at multiple off-axis angles** (OAA)
  - Neutral mesons in the BNB = less focused
  - Charged mesons in the BNB = more focused

→ **Background reduction of SM neutrinos at off-axis**

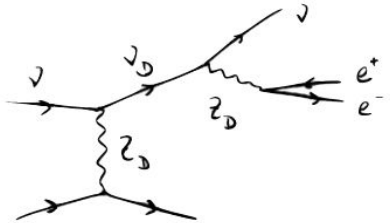
BSM Production in the Booster Neutrino Beam

Light Dark Matter



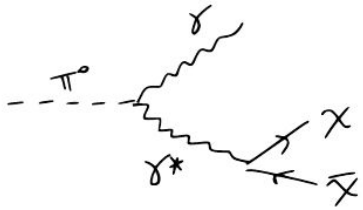
Romeri Kelley Machado PRD 2019

Dark Neutrinos



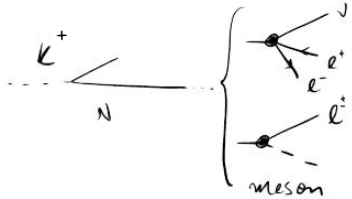
Bertuzzo Jana Machado Zukanovich PRL 2018, PLB 2019
Arguelles Hostert Tsai PRL 2019
Ballett Pascoli Ross-Lonergan PRD 2019
Ballett Hostert Pascoli PRD 2020

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 Scalar Portal

Pat Wilczek 2006
Batell Berger Ismail PRD 2019
MicroBooNE 2021

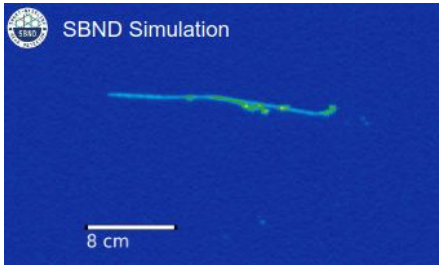
Axion-like Particles

Kelly Kumar Liu PRD 2021
Brdar et al PRL 2021

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

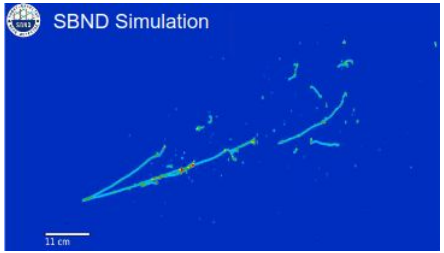
BSM Signatures at SBND

Light Dark Matter



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

Dark Neutrinos

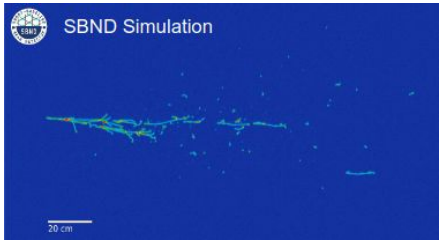


Pair of e+e- and μ+μ-
With or without hadronic activity

Millicharged Particles

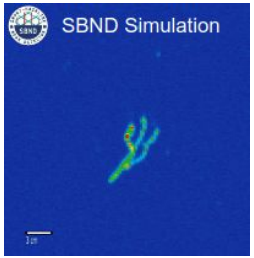
Blip or faint tracks

Heavy Neutral Leptons



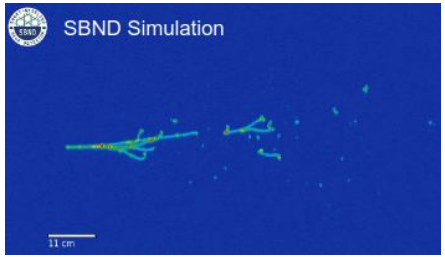
Single lepton + π
High energy pair of e+e-, μ+μ- and γγ
No hadronic activity

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

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

Heavy Neutral Leptons

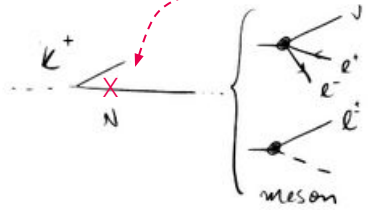
- **Right-handed fermion addition** to the 3-flavour paradigm.
- Motivated by neutrino mass mechanism.
- Can **couple to all SM neutrinos** by an extended PMNS matrix couplings $U_{\alpha 4}$, $\alpha = \tau, \mu, e$ (Need to be kinematically allowed).
- Produced by **long lived meson K+**, constraining mass **< 495 MeV**.
- HNL then **decay in flight** into SM observables, with event rate **∝ $|U_{\alpha 4}|^4$**

SM Mixing

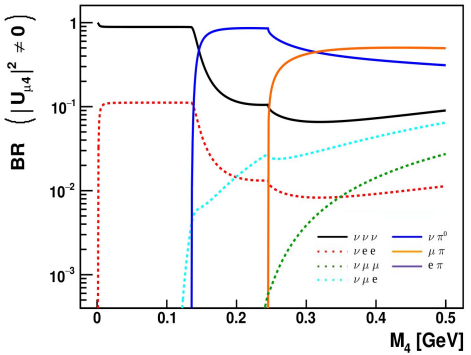
$$\nu_\alpha = \sum_i U_{\alpha i}\nu_i + U_{\alpha 4}N$$

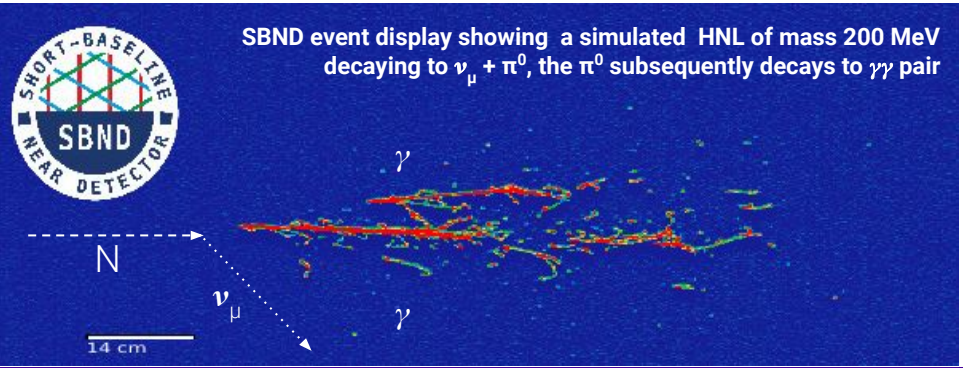
$$U_{PMNS}^{Extended} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} & U_{e4} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} & U_{\mu 4} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} & U_{\tau 4} \\ U_{41} & U_{42} & U_{43} & U_{44} \end{pmatrix}$$

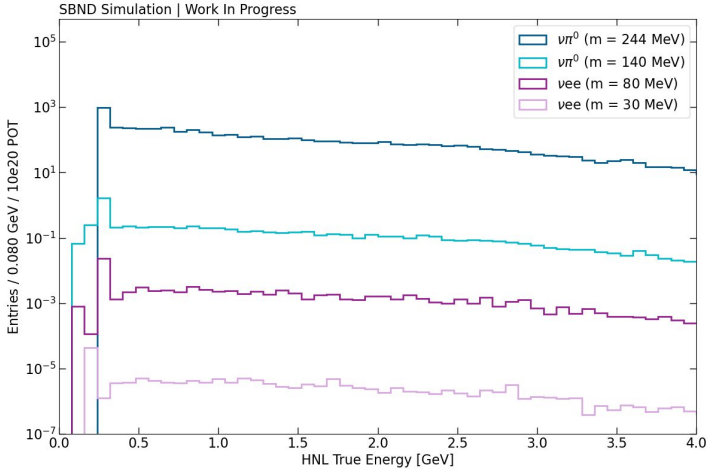
New Physics



Ballett Pascoli Ross-Lonergan JHEP 2017
Kelly Machado PRD 2021



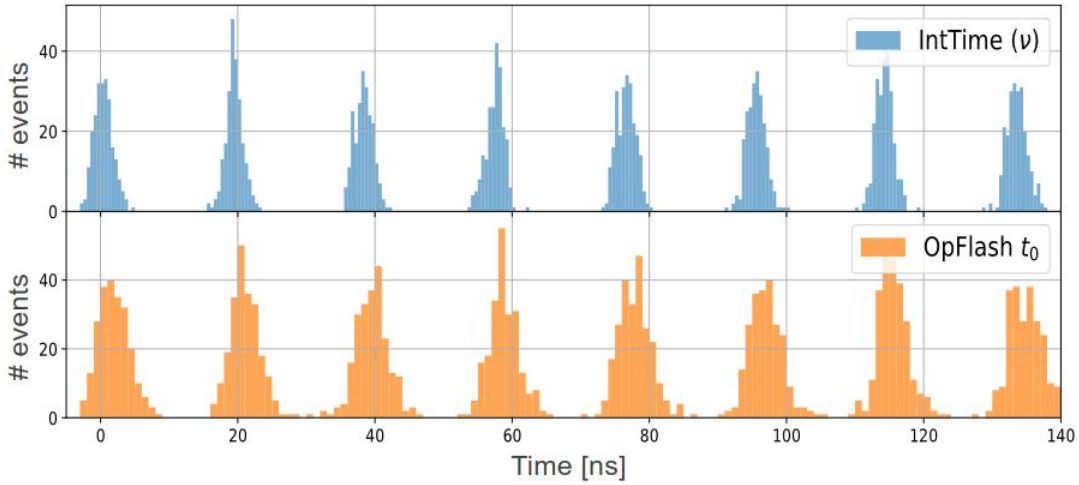


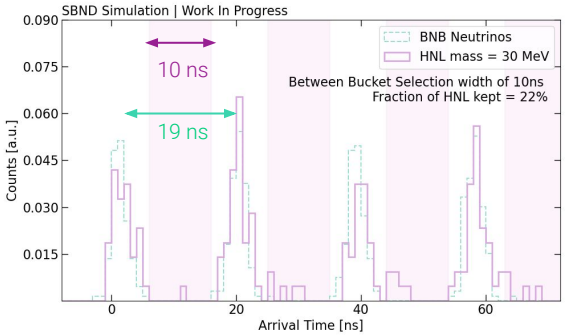


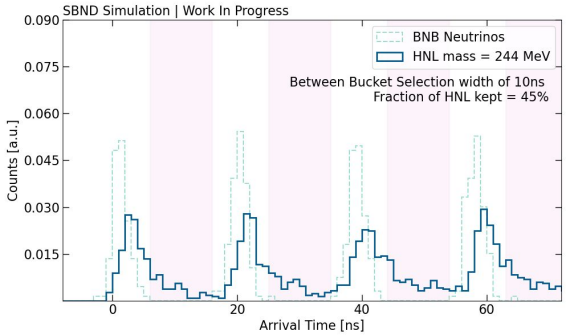
Heavy Neutral Leptons

- 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.

Top: Simulated neutrino arrival time distribution at SBND
Bottom: Reconstructed neutrino arrival time from light signals



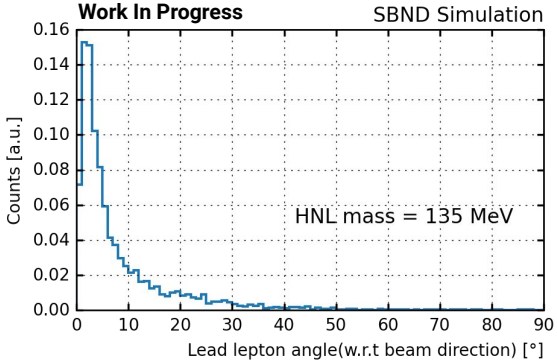


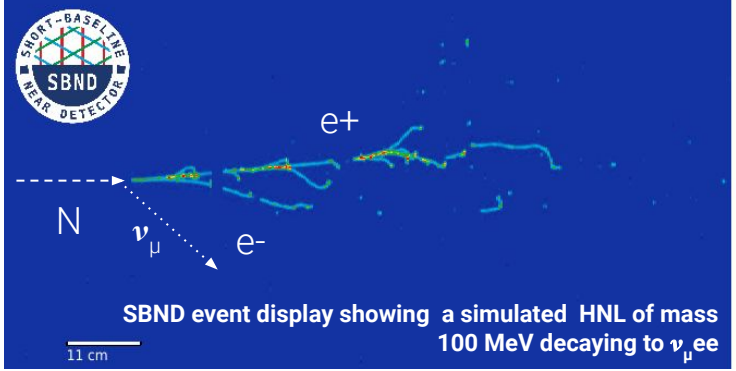


The plots above are area normalised and do not have smearing due to reconstruction.

Heavy Neutral Leptons

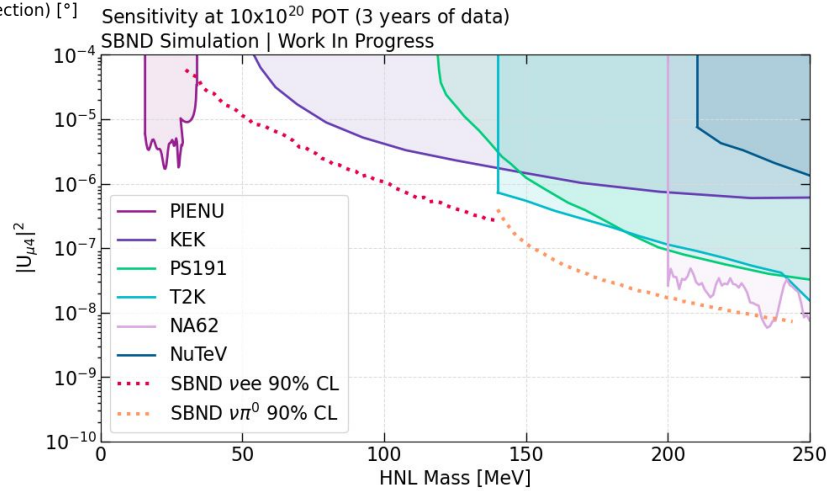
- Two channels are being explored:
  - **ν e e (30 – 140 MeV)**
  - **ν π^0 (140 – 244 MeV)**
- Challenging topology signatures:
  - **2 electromagnetic showers**
  - **Beam-collimated**
  - **Highly overlapping**
  - **No hadron activities**





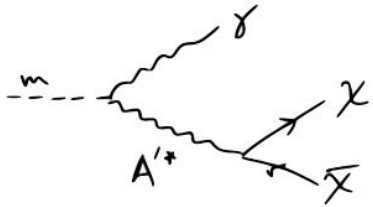
SBND event display showing a simulated HNL of mass 100 MeV decaying to $\nu_\mu$ee

- **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



The plot above assumes no background and applies between bucket event selection and reconstruction efficiency of 20%.

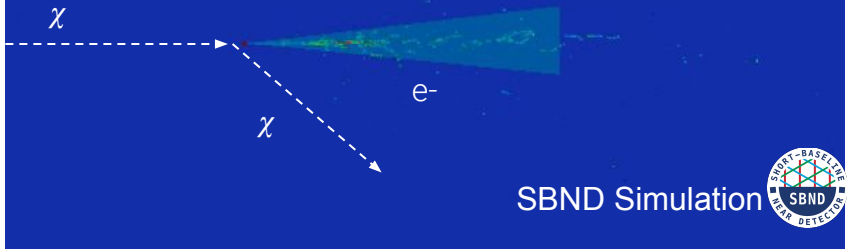
Light Dark Matter



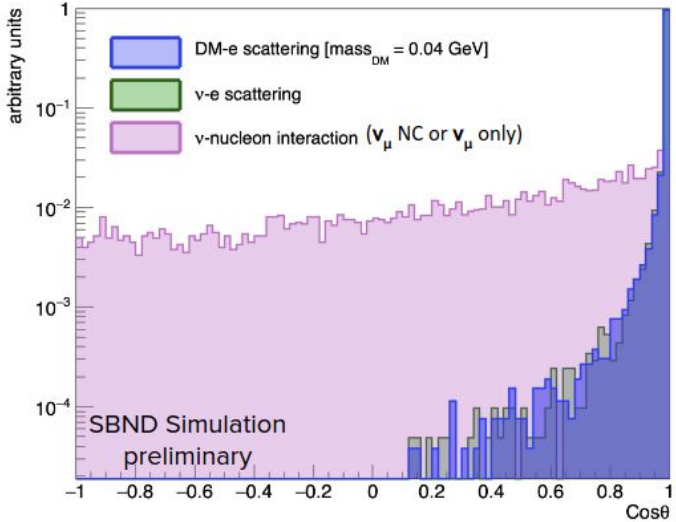
Romeri Kelley Machado PRD 2019

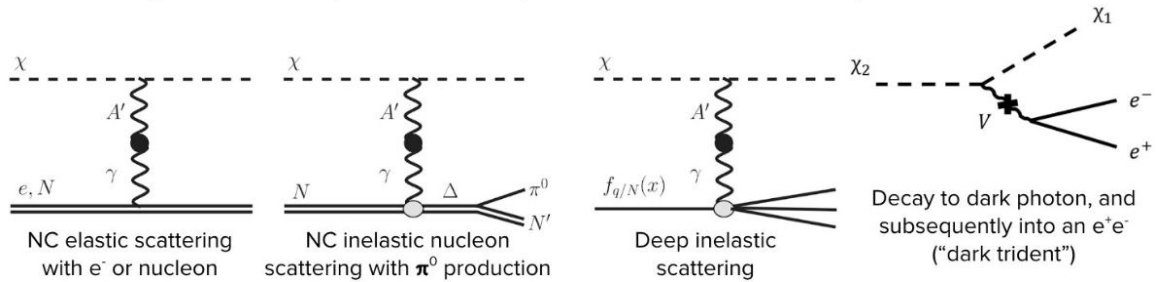
- SBND can probe **sub-GeV DM** postulated by "thermal relic" models, compared to WIMP searches restricted to higher mass.
- Vector portal DM models: produced by **neutral meson decay** or **proton bremsstrahlung** in the BNB.
- The light DM **scatter** or **decay** inside SBND.
- Two channels are being explored:
  - **Scattering with e-**
  - **Dark photon decay ("dark trident")**
- Produce **electromagnetic showers** and **no hadronic activity**.

SBND event display showing a simulated light DM-electron scattering event, where the reconstructed shower is depicted in the green cone (M_{dm} = 0.01 GeV, α_D = 0.5, $\epsilon = 10^{-3}$)



Distribution of events w.r.t. the beam direction (area-normalised)

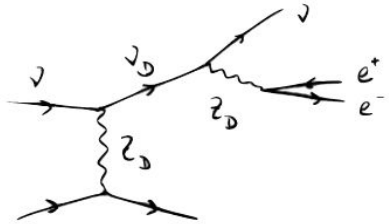




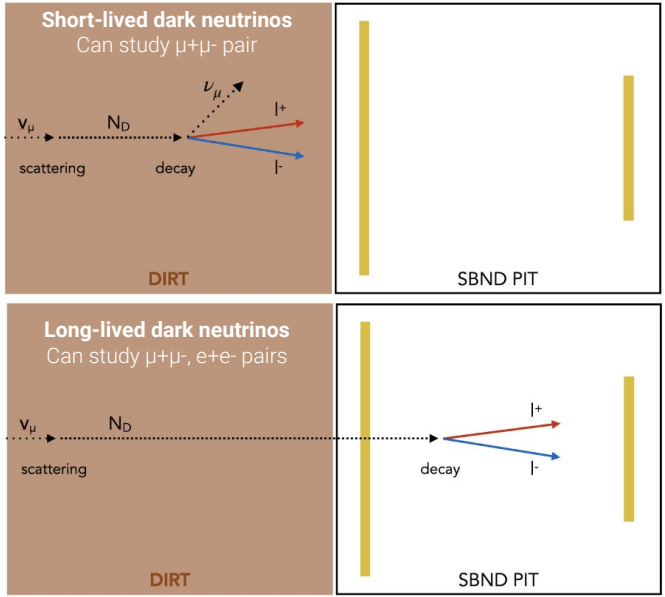
Light Dark Matter interaction modes in SBND

Dark Neutrinos

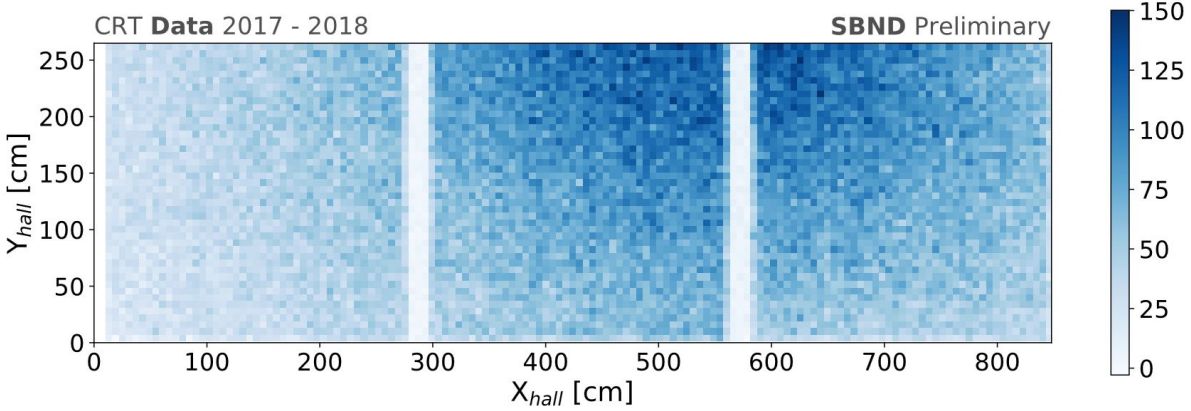
- Produced via **neutrino-nucleus scattering**, followed by their decay to a **dark gauge boson**, which then **decay to dilepton pairs**.
- Motivated by MiniBooNE electron-like excess.
- Can be tagged by the **CRT upstream** and/or **downstream** panels.
- In **2017-2018**, **took data with BNB** in the SBND detector hall using this setup, which can be searched for dark neutrinos.

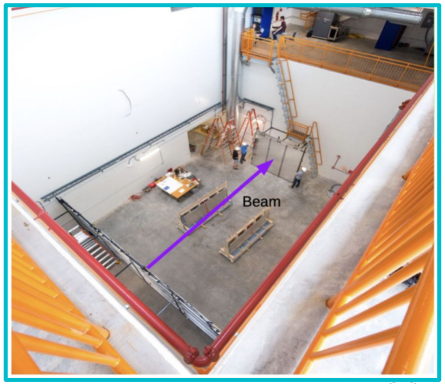


Bertuzzo Jana Machado Zukanovich PRL 2018, PLB 2019
Arguelles Hostert Tsai PRL 2019
Ballett Pascoli Ross-Lonergan PRD 2019
Ballett Hostert Pascoli PRD 2020



Spatial distribution of the CRT 2D hits in the upstream panels, showing the centre of the BNB





SBND detector hall photo taken in 2017-2018, with the CRT panels inside the pit located up/downstream to the BNB.

The rigging of the detector attached to the cryostat top cap into the cryostat, on April 25th, 2023.

Conclusions

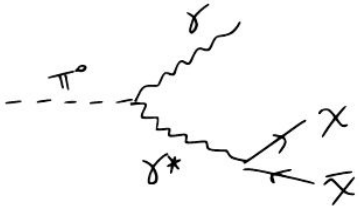
- SBND is a LArTPC with close proximity to the 8 GeV Booster Neutrino Beam
  → **High statistics** and **off-axis angle fluxes**
- 3 detection systems combined: LArTPC + Photon Detection System + Cosmics Ray Tagger
  → **Excellent spatial**, **timing** and **energy resolution**
- New physics opportunities at SBND
  → Probe **a variety of BSM models from Booster Neutrino Beam**
- Work has begun for estimating sensitivities, developing event selections and reconstruction tools: **heavy neutral leptons**, **light dark matter**, **dark neutrinos**
- SBND is scheduled to start data-taking in **2024**.

Thank you! Cảm ơn!
Questions and Comments are welcome

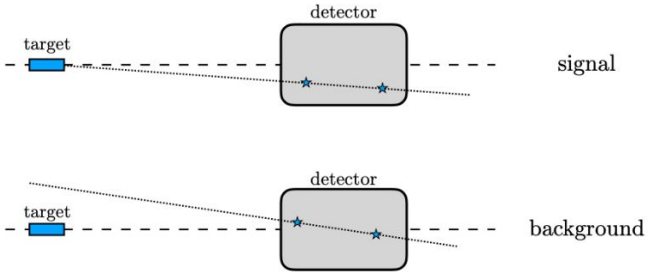
Photo taken at SBND Collaboration Meeting at Arlington, June 2023

Back-up

Millicharged Particles

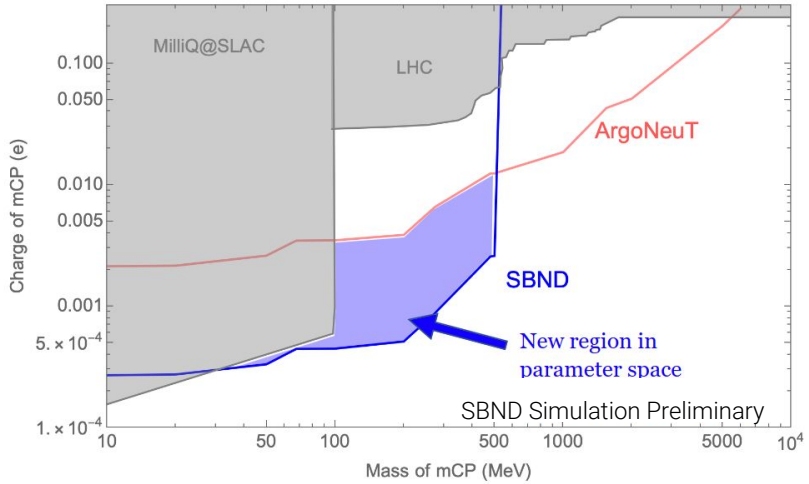


- A hypothetical new type of particle with a **fractional charge compared to the electron**.
- Motivated by a cosmological anomaly (EDGES) and a potential candidate for dark matter.
- Produced by **neutral mesons decay** in the BNB.
- Appear as **blips** or **faint tracks** in SBND, pointing back to the target in BNB.
- SBND threshold is projected to be 50 keV.

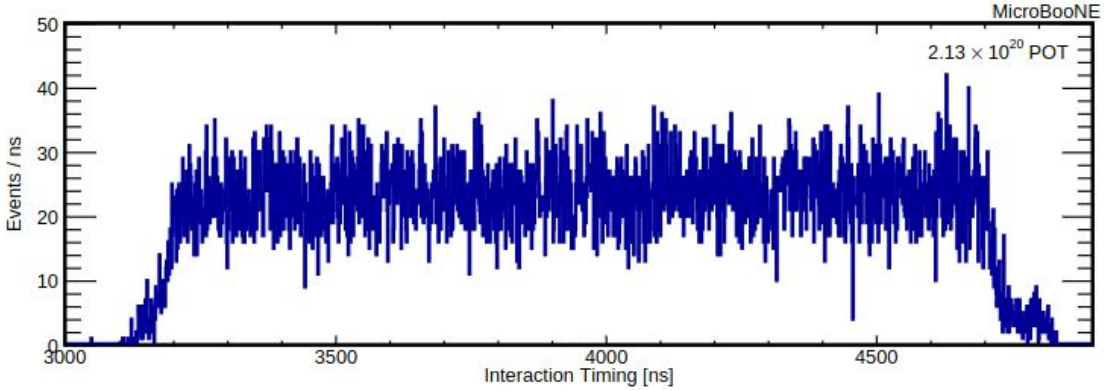


Credit: ArgoNeuT (arXiv:1902.03246)

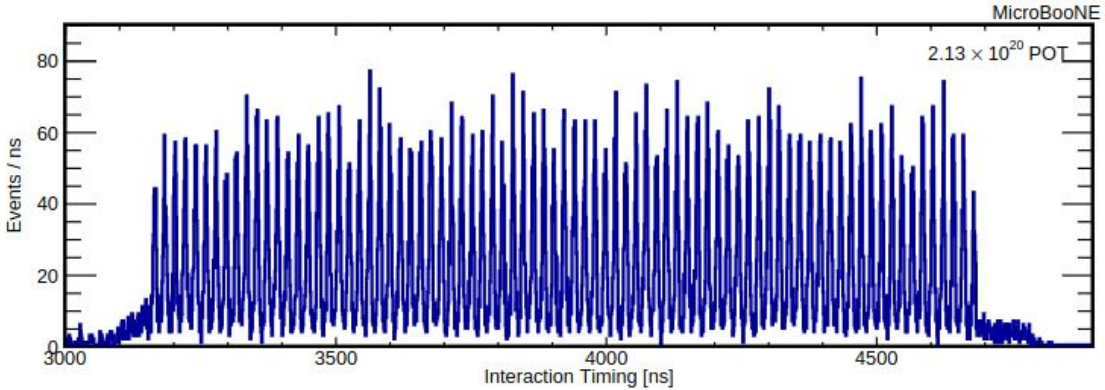
Preliminary SBND Sensitivity from Simulation



MicroBooNE nanosecond timing



(a) Interaction timing distribution before the propagation reconstruction.



(b) Interaction timing distribution after the propagation reconstruction.

https://arxiv.org/pdf/2304.02076.pdf