Heavy Neutral Lepton Searches at the Short Baseline Near Detector

Nguyen Vu Chi Lan (she/her)

on behalf of the SBND Collaboration

New Perspectives Conference June 2023

FERMILAB-SLIDES-23-116-V

Heavy Neutral Leptons

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

Standard Model Mixing

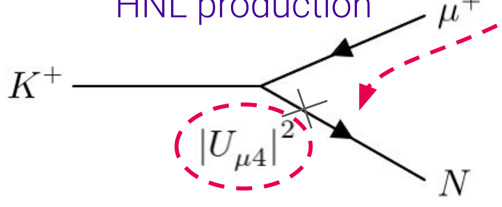
$$U^{Extended}_{PMNS} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} & U_{e4} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} & U_{\mu 4} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} & U_{\tau 4} \\ U_{41} & U_{42} & U_{43} & U_{44} \end{pmatrix}$$

New Physics

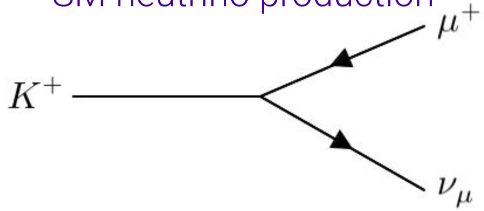
Beyond Standard Model (BSM) fermionic particles known as Heavy Neutral Leptons (HNL) (shown as N)

- An 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)
- **Right-handed mass term** → allows for possible mechanisms for neutrino masses
- HNL **mass is not constrained**
- **Both Majorana/Dirac** HNL are allowed
- **No oscillation** (MeV mass=loss of coherence)

HNL production

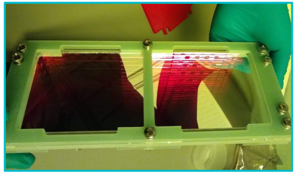


SM neutrino production

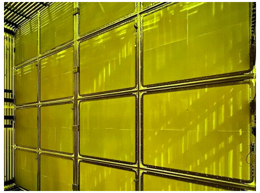


Short Baseline Near Detector

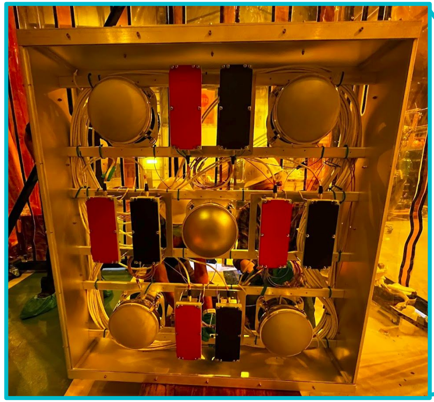
X-ARAPUCAS
192 X-ARAPUCAs, sensitive to VUV and visible light

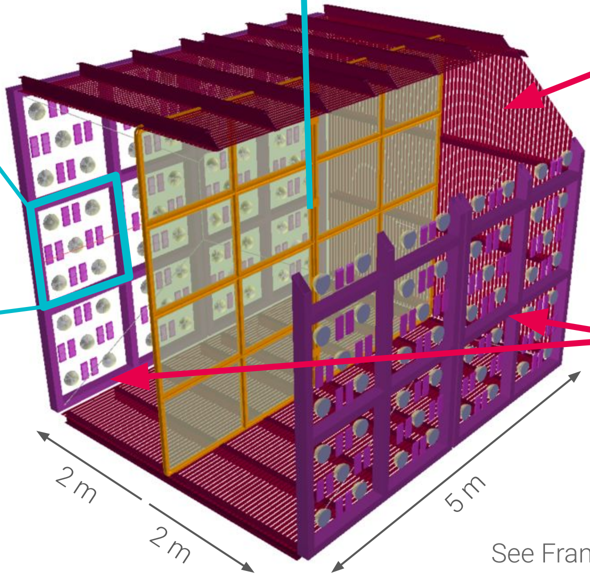


TPB-coated Reflective Foil
converts VUV into visible light, enables uniform light collection

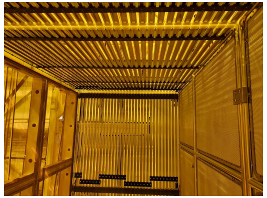


LAr Time Projection Chamber
$4 \times 4 \times 5\ m^3$
Active volume 112 t
2 drift volumes
Drift distance 2 m
Drift time 1.25 ms



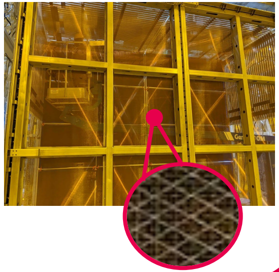


Field Cage
surrounds TPC, provides a uniform 500V/cm drift filed

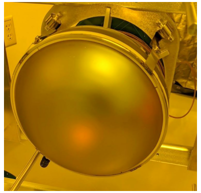


Two Anode Planes
on each side of the detector, made of 3 planes of wires with $\theta_{u,v,w} = \pm 60, 0^{o}$

11,264 wires in total

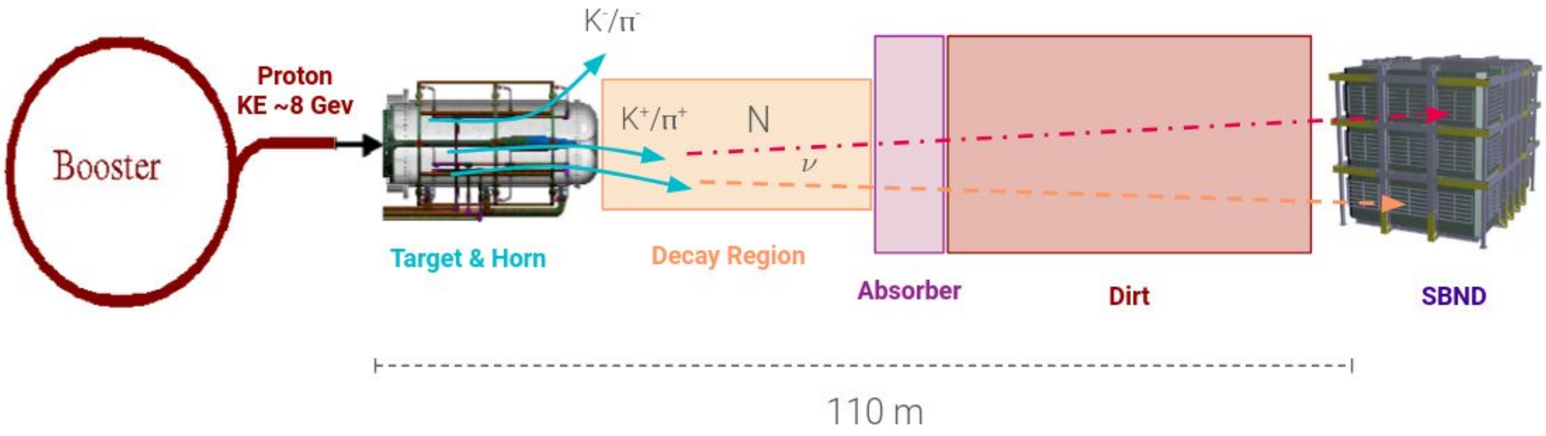


PMT
96 PMTs (TPB-coated)
24 PMTs (uncoated)



See Henry 's talk on SBND in 10 minutes
See Fran's talk on Tagging neutrino events with the SBND's PDS

HNL Production At The Booster Neutrino Beam



- Heaviest HNLs at BNB are produced from long lived meson **K^+**, constraining the HNL mass **< 495 MeV**
  - Production rate **$\propto |U_{\alpha 4}|^2$**
- HNL then **decay in flight** into observables
  - Decay rate **$\propto |U_{\alpha 4}|^2$**
- Fully simulate HNL flux from BNB flux, handled by **MeVPrtl generator** (More on next slide)

MeVPrtl Generator

MeVPrtl is an in-house generator developed by ICARUS and SBND collaborators for BSM physics purpose.

MesonGen:

- Sources the mesons that will decay into BSM particles, from extracting the BNB flux file in BooNE format

MeVPrtlFlux:

- Simulates the production of BSM particles from meson decay or mixing in a neutrino beam

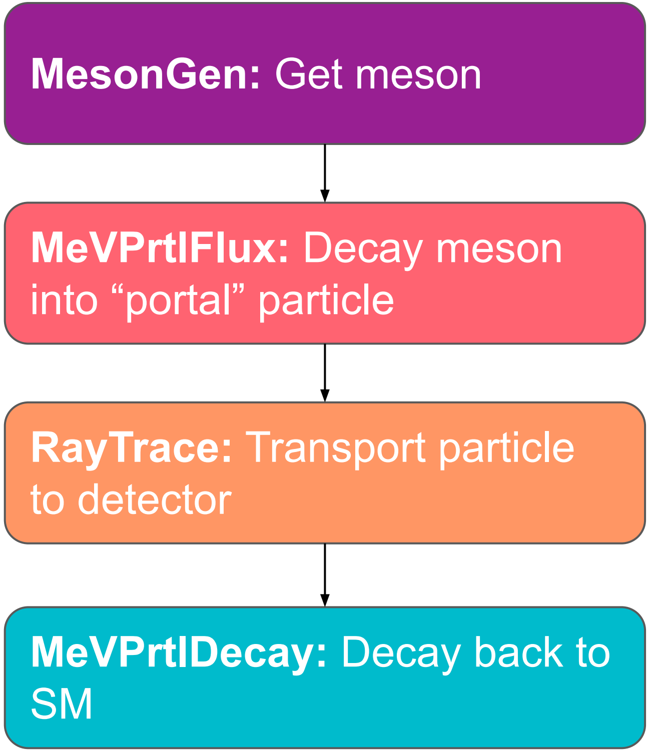
RayTrace:

- Forces the particle in a direction such that it impinges a specified detector volume

MeVPrtlDecay:

- Specify the decay information of the particle: 4-position and the list of particles it decays into

→ Output artroot files that can interface with LArsoft and be plugged into existing simulation chain on ICARUS and SBND.



Meson decay to HNL width is reference to arXiv:1912.07622
Meson decay to HNL polarization is reference to PhysRevD.105.015019
HNL decay width is reference to arXiv:0901.3589 and arXiv:1610.08512
HNL decay anisotropy is reference to PhysRevD.105.015019 and PhysRevD.104.015038

HNL$\rightarrow \nu + \pi^0, \pi^0 \rightarrow \gamma\gamma$

The $\boldsymbol{\nu\,\pi^0}$ channel is sensitive to intermediate masses **140 – 244 MeV**

Higher than 244 MeV: dominated by charged lepton + π channel ($\mu\,\pi$ for $|U_{\mu 4}|^2 \neq 0$ and e π for $|U_{e4}|^2 \neq 0$)

Lower than 140 MeV: dominated by $\boldsymbol{\nu}$ + ee

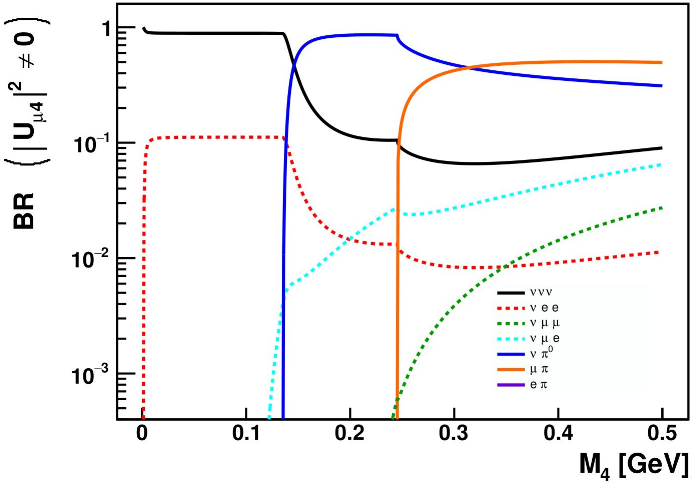
→ All the mass range is being studied by PhD students on SBND

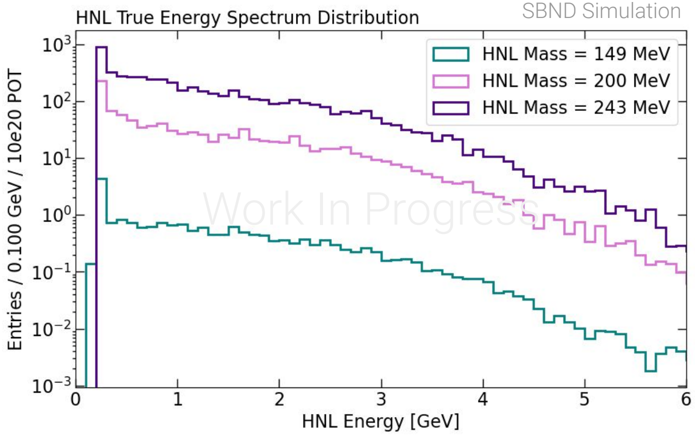
- Final event rate is **$\propto |U_{\alpha 4}|^4$**
- Expected event rate for 10e20 POT is $O(10^1\text{-}10^3)$.
- Rate is mass dependent

$\boldsymbol{\nu}$ escapes the detector while $\boldsymbol{\pi^0}$ decays into **a diphoton pair** (98.81%)

- 2-body decay topology
- Highly beam collimated: parallel to the beam axis
- Highly boosted showers: small opening angle between showers
- No hadronic activity at vertex

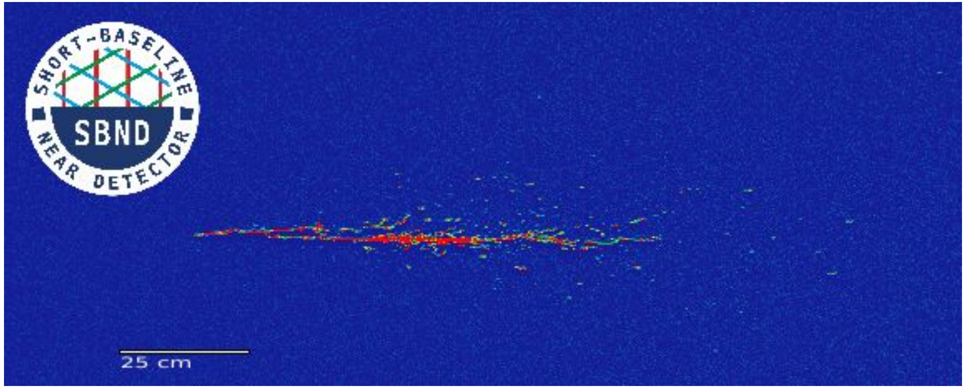
Branching ratio mixing with ν_μ



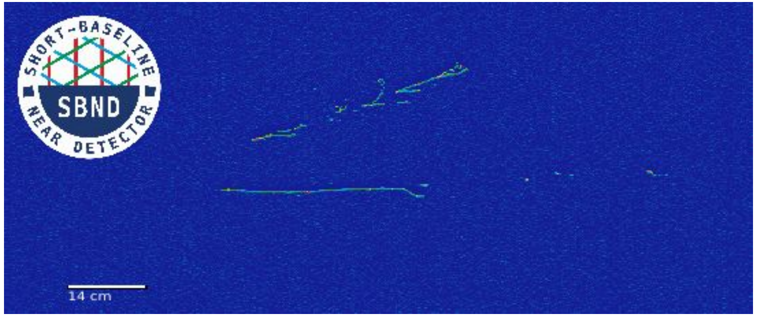


Examples: HNL$\rightarrow \nu + \pi^0 , \pi^0 \rightarrow \gamma\gamma$

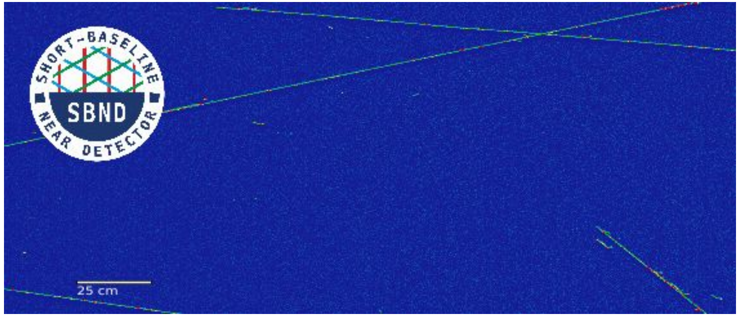
Signal: Simulated HNL$\rightarrow \nu + \pi^0$



Background: Simulated SM π^0



Background: Simulated Cosmics



Timing Selection

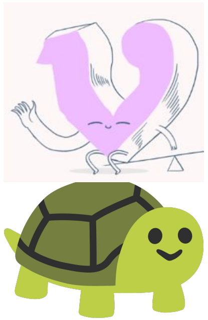
Neutrinos travel at the **~speed of light**.

HNL is heavier and hence travels at **a slower velocity** than neutrinos.

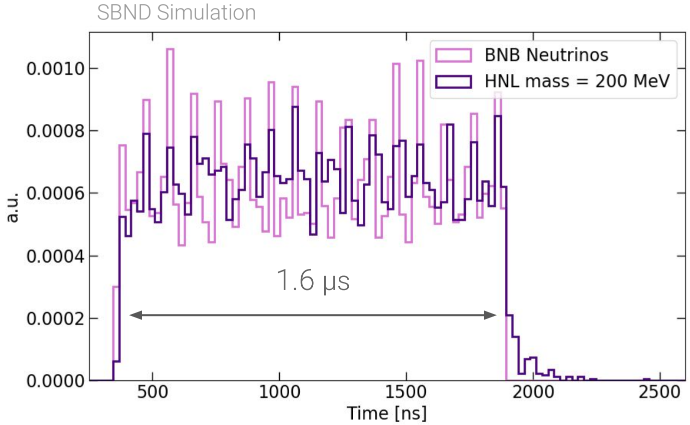
BNB beam spill lasts for 1.6 μs, with inner structure made up of 81 neutrino bucket of width 2 ns and period of 19 ns.

Can explore 2 possible timing selections for truth level study:

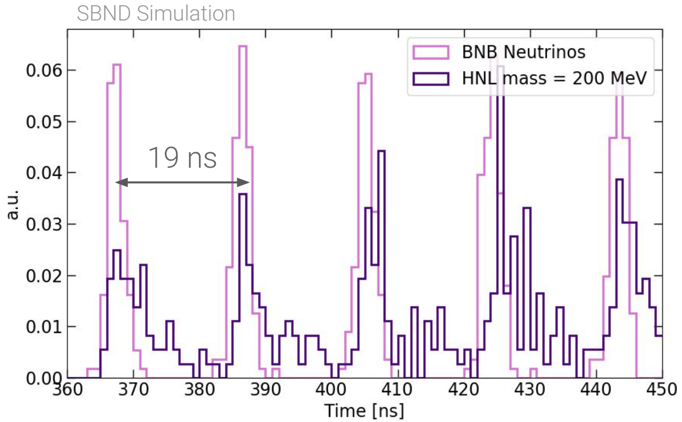
- **End of Spill:** HNL arrives late after the beam spill, require a delay hardware trigger
- **Between Buckets:** up to 80 pockets of HNL between the neutrino buckets, selection can be done offline without additional trigger



End of Spill Timing Distribution



Between Buckets Timing Distribution



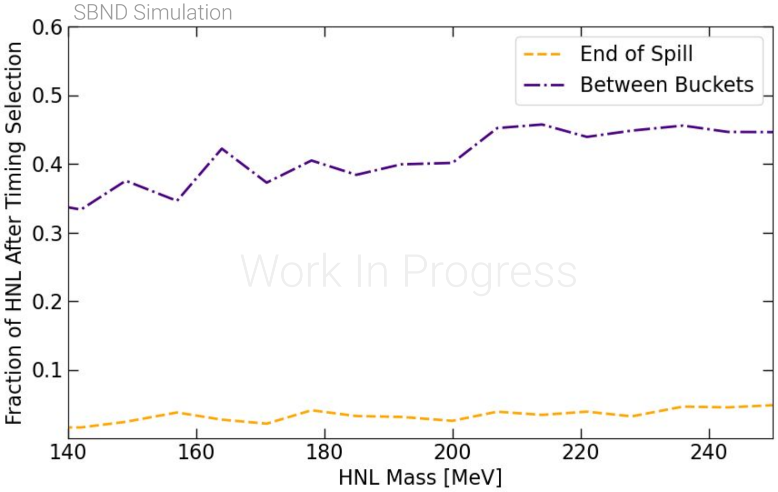
Timing Selection

End of Spill: 0.3 μs after the beam spill, HNL fraction ~4%

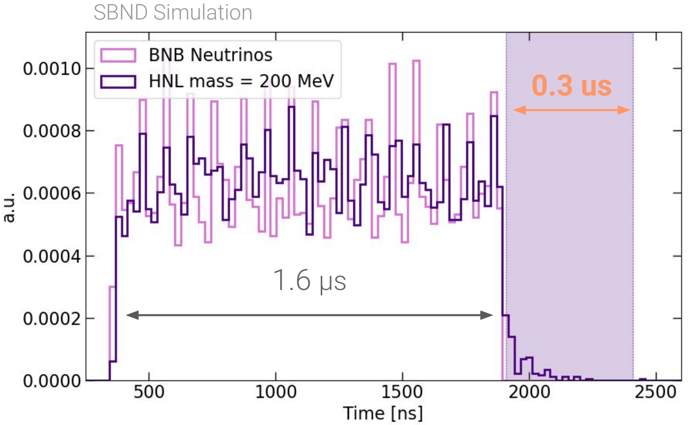
Between Buckets: 80 pockets of width 10 ns of HNL, HNL fraction ~40%

The $\nu\,\pi_0$ channel mass range of **140 – 244 MeV** can be searched using with the between buckets selection:

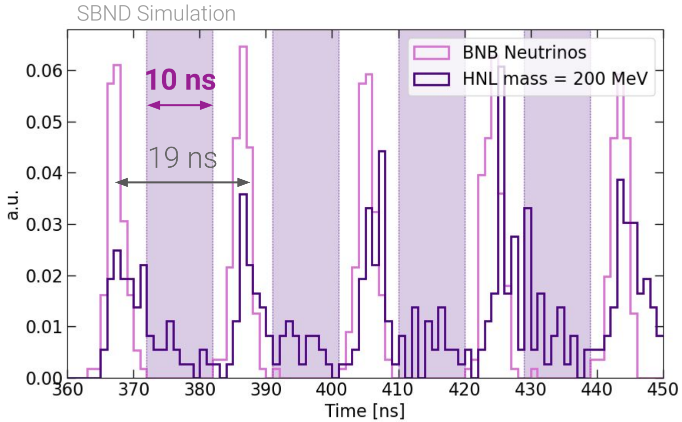
- Keep high HNL survival fraction after applying cut
- Can utilise BNB neutrino trigger, without additional trigger



End of Spill Timing Distribution



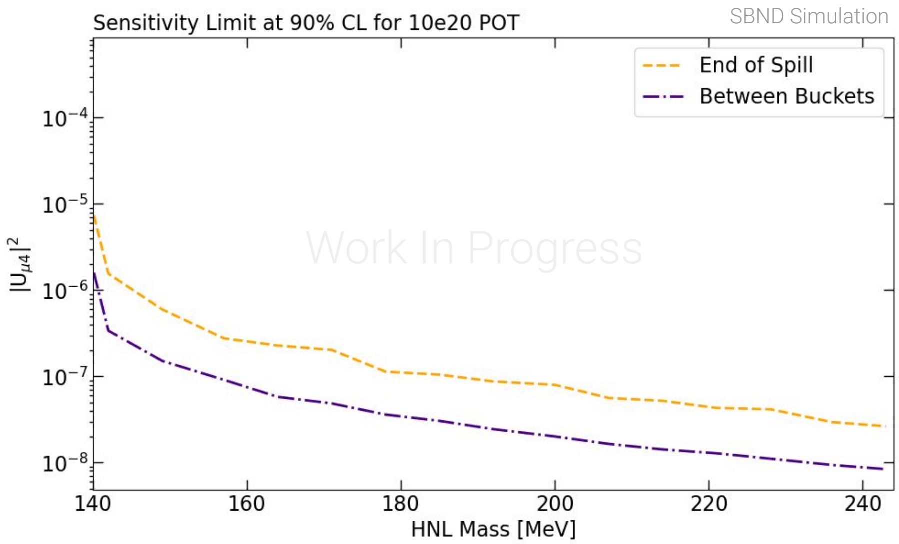
Between Buckets Timing Distribution



Preliminary Sensitivity Plot at Truth Level

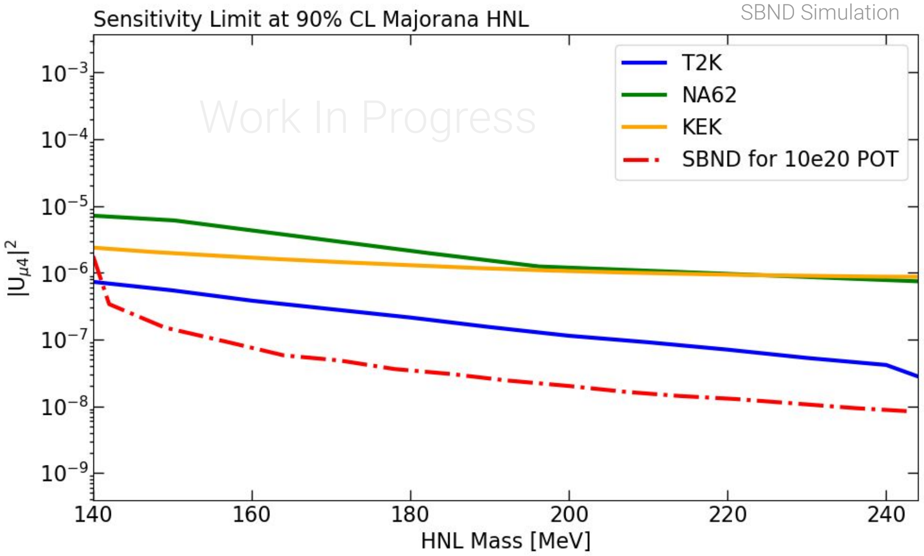
As a first pass, sensitivity study at truth level:

- Contained decay vertex inside TPC active volume
- Apply either End of Spill or Between Buckets timing selection
- Assume an additional efficiency of 15% (trigger, reconstruction, etc.)
- Scale to 10e20 POT
- Assume zero background and statistical errors only



Preliminary Sensitivity Plot at Truth Level

In context to published results, **SBND can be competitive** in the $\nu\,\pi_0$ channel mass range between **140 – 244 MeV for $|U_{\mu4}|^2 \neq 0$**, since this is not yet a well-explored channel



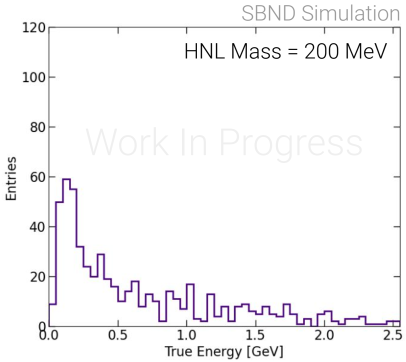
NA62 results: arXiv:1801.04207
KEK results: Phys. Rev. Lett. 49, 1305
T2K results: Phys. Rev. D 100, 052006

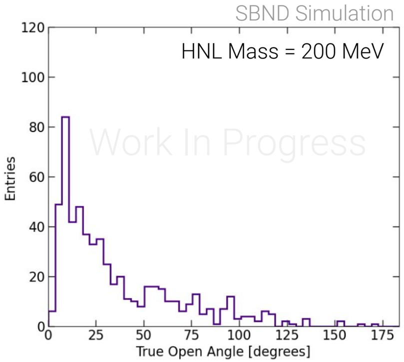
What About SM Neutrinos Background?

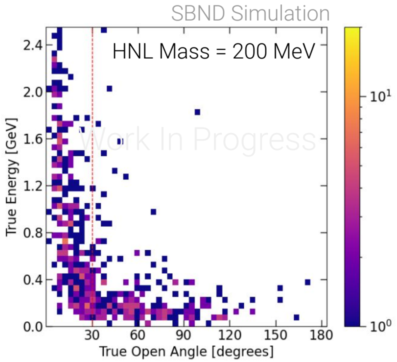
At truth level, clear distinction between **HNL π_0** and **SM neutrino π_0** : Opening angle between the diphoton showers

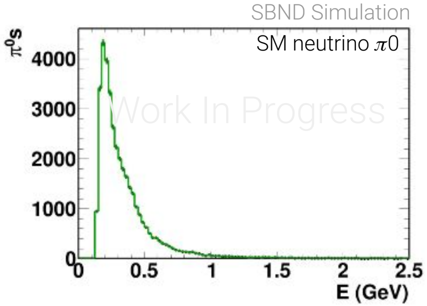
- **HNL:** is concentrated in the region < 30° → Highly collimated, boosted and likely overlapped showers
- **SM neutrino π_0:** is concentrated in the region > 30° → Likely to be reconstructed as 2 distinguishable showers

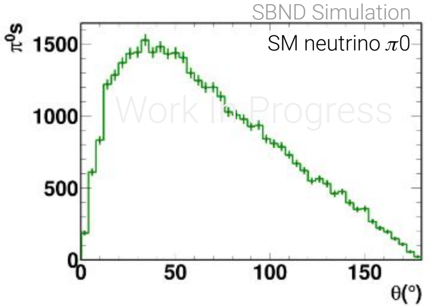
→ Work undergoing to exploit this topology for event selection study

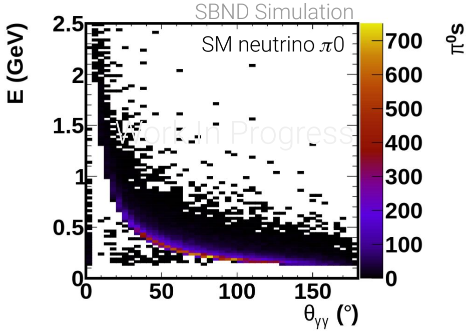








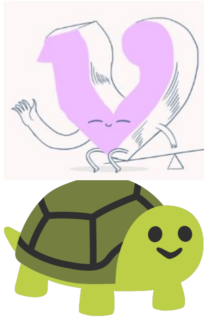


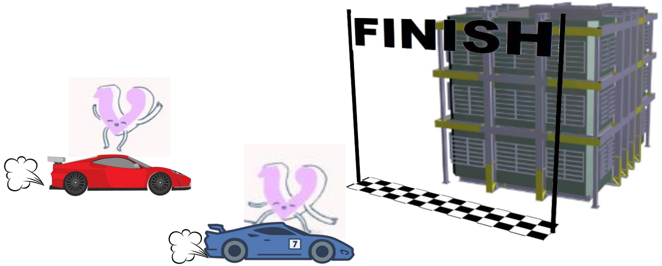


SM neutrino $\pi 0$
plots by Henry Lay

Conclusion

- A truth level study for timing selection of HNLs was undertaken.
- End of beam spill and between buckets were explored
- Between buckets selection keeps a large enough fraction and does not require additional delay trigger
- Preliminary sensitivity study for the $\nu\,\pi_0$ channel mass range between 140 – 244 MeV for $|U_{\mu4}|^2 \neq 0$ shows that SBND is competitive for POT = 10e20 – Promising!
- Stay tune for future BSM searches from SBND!





Thank you! Cảm ơn!
Questions and Comments are welcome

BACK-UP SLIDES

SBND Physics Program

Annu. Rev. Nucl. Part. Sci. 69:363-87

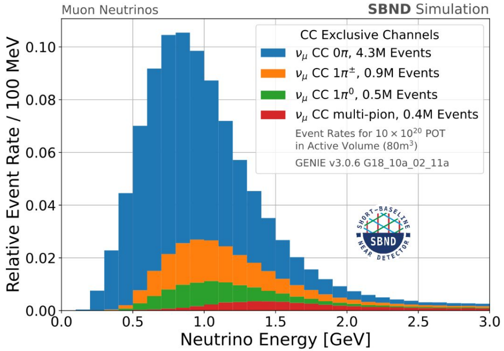
Only 110 m from the target means SBND is exposed to an intense beam of neutrinos. For 3 years run:

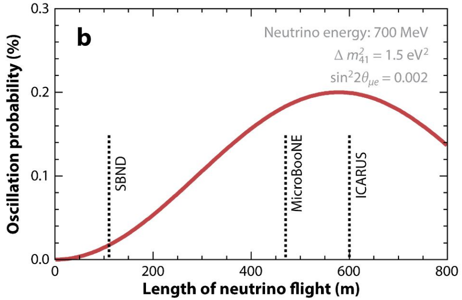
- 10×10^{20} POT from the BNB
- **10 million total** neutrino events (CC+NC)

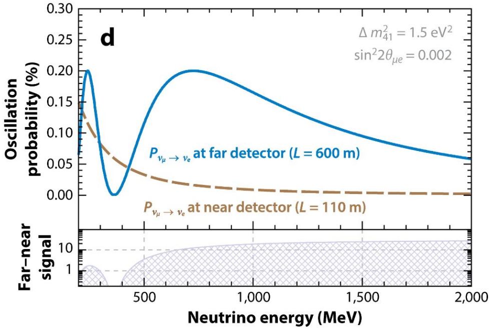
This opens up unique physics opportunities:

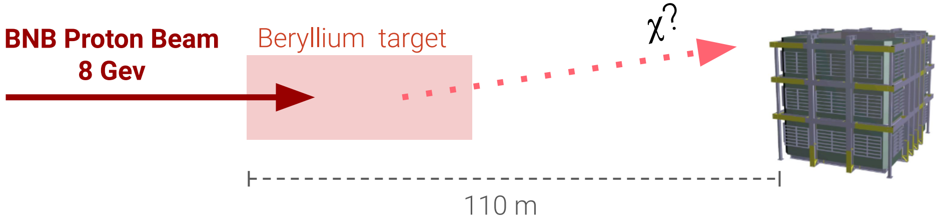
- **Cross sections measurements** of neutrino-argon interactions – Aiming to be world's largest statistics of such measurement!
- **SBN neutrino oscillation** – Testing the sterile neutrino hypothesis
- **Beyond Standard Model physics** searches – Probing new physics produced from BNB beam
- And so much more!

CC event rate for 10e20 POT: ~6M ν_μ CC



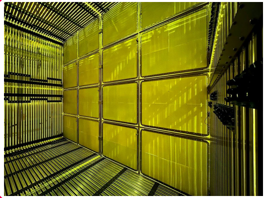




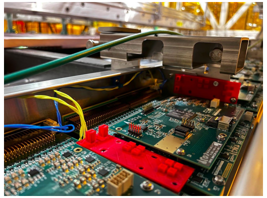


SBND Detector Systems: LArTPC

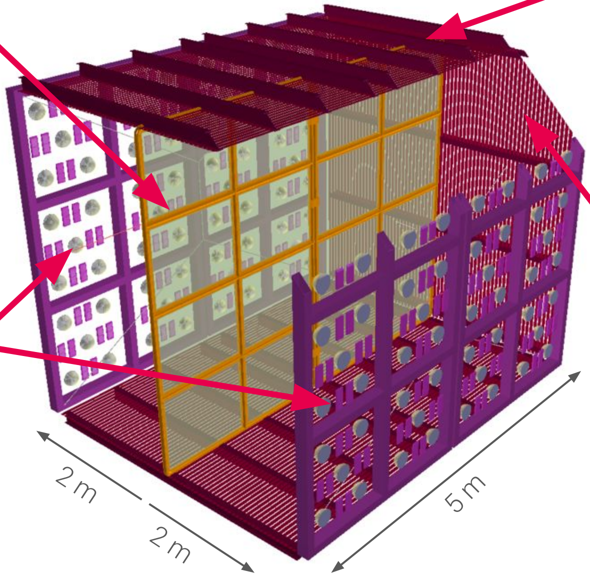
LAr Time Projection Chamber
4 ✕ 4 ✕ 5 m^3
Active volume 112 t
2 drift volumes
Drift distance 2 m
Drift time 1.25 ms



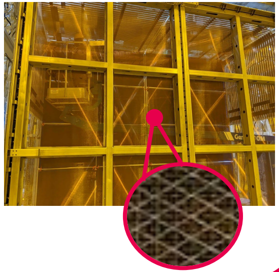
Cathode Plane
(-100 kV) splits the detector into 2



Cold Electronics
(89K) pre-amplifies and digitises wire signals

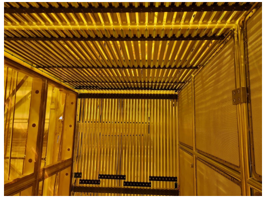


Two Anode Planes
on each side of the detector, made of 3 planes of wires with $\theta_{u,v,w} = \pm 60, 0^o$



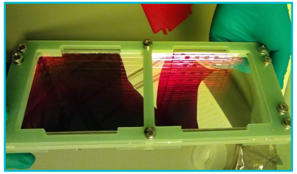
11,264 wires in total

Field Cage
surrounds TPC, provides a uniform 500V/cm drift filed

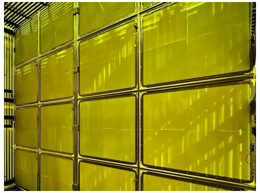


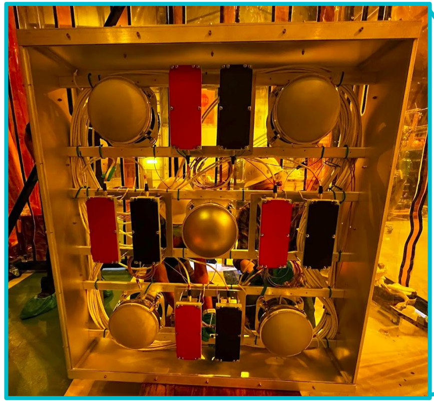
SBND Detector Systems: Photon Detection System

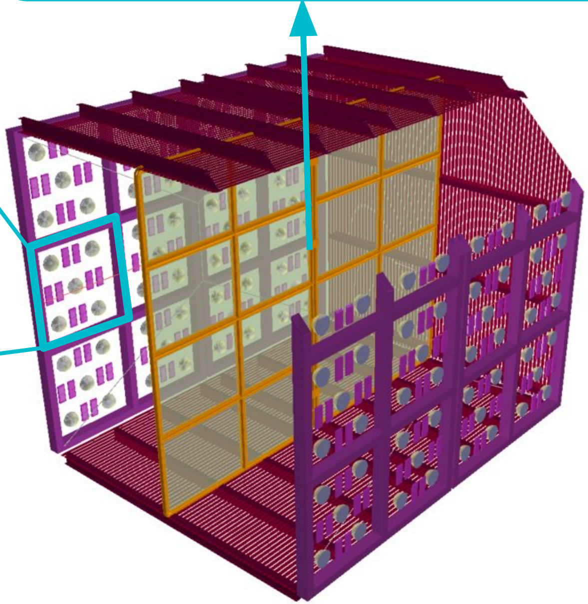
X-ARAPUCAS
192 X-ARAPUCAs, sensitive to VUV and visible light



TPB-coated Reflective Foil
converts VUV into visible light, enables uniform light collection

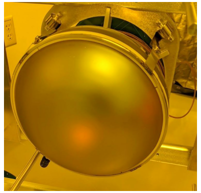






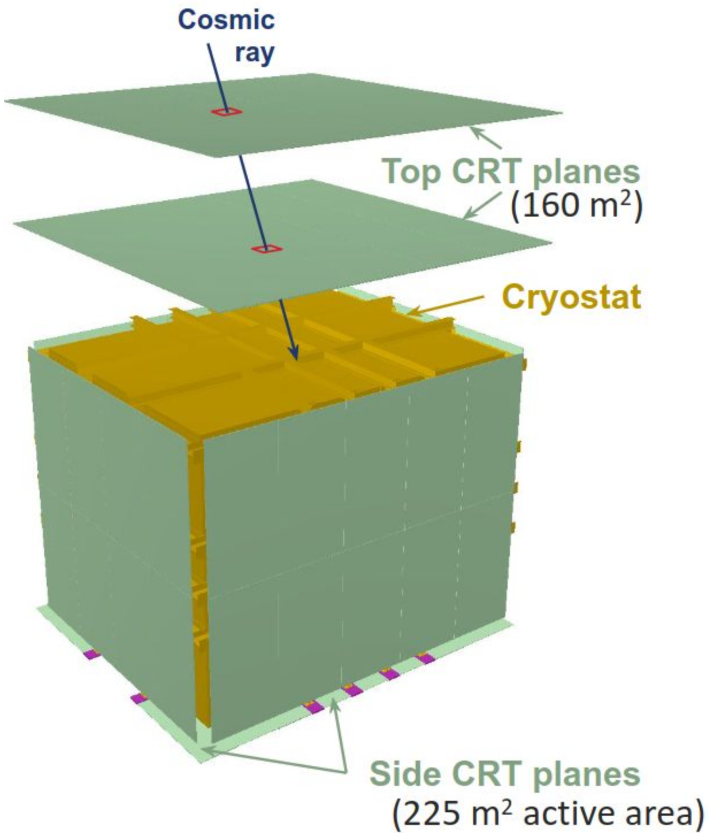
SBND PDS in it most glorious form!

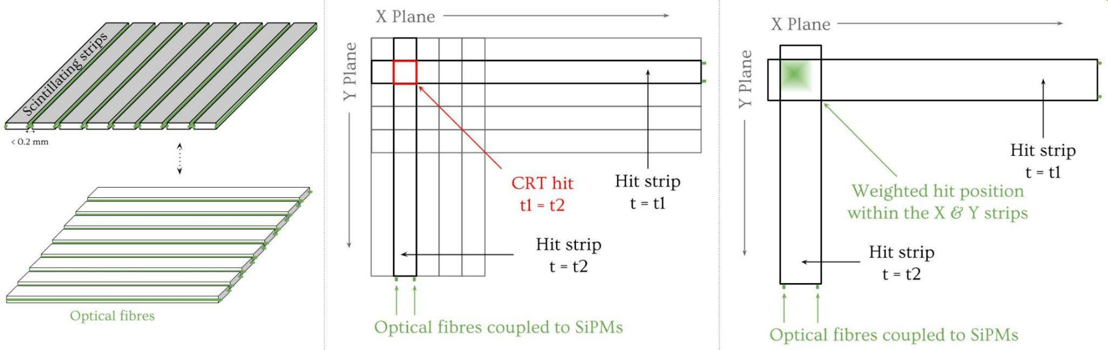
PMT
96 PMTs (TPB-coated)
24 PMTs (uncoated)



SBND Detector Systems: Cosmic Ray Tagger

Cosmic Ray Tagger
surrounds the entire SBND for 4π coverage. Two top panels for telescopic tagging.





CRT panel is made of scintillator strips in cross formation for precise hit reconstruction.

HNL Decay Branching Ratio