TAUP VIENNA 2023

# Searches for Beyond Standard Model Physics in the SBND neutrino experiment

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CIEMAT

for the SBND Collaboration

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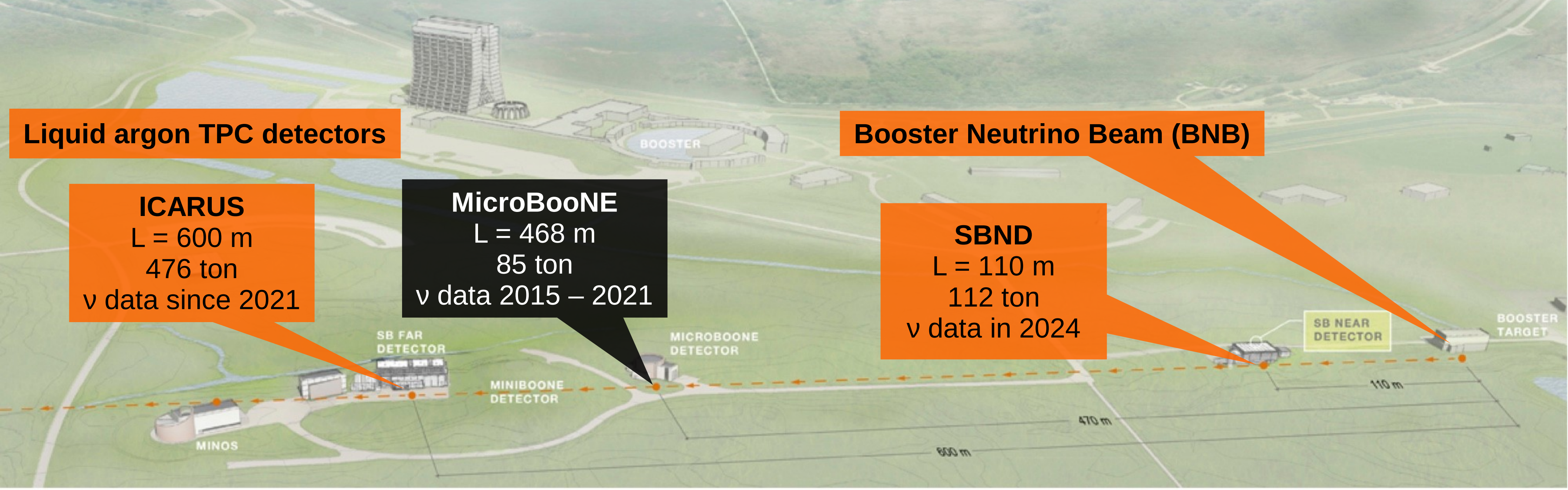
# SBND @ The Short-Baseline Neutrino Program at Fermilab




**The Short-Baseline Near Detector (SBND) physics program:**

1) **Perform a high-precision measurement of the BNB flux × ν-Ar cross-section before oscillation.**

   High correlation between near and far detectors → Reduction on the systematic uncertainties → Boost in the sensitivity for oscillations at $\Delta m^2 \sim 1$ eV$^2$ to conclusively address the short-baseline neutrino oscillation anomalies.

2) **Perform high-precision measurements of cross-sections of $\nu_\mu$ and $\nu_e$ on Ar.**

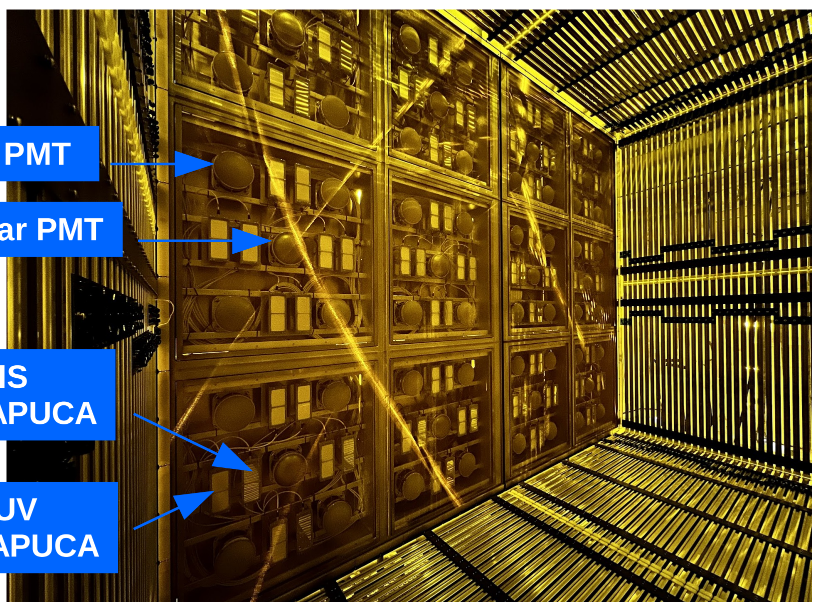
   Improve our knowledge of neutrino-nucleus interactions and reduce systematic uncertainties on oscillation searches, for both short and long baselines.

3) **Search for Beyond Standard Model physics.**

4) **Advance further the LArTPC detector technology.**

**Lauren Yates' talk in the Neutrino physics and astrophysics session on Aug 28th:**
**Status of the Short-Baseline Near Detector at Fermilab**

# SBND detector


**Liquid Argon Time Projection Chamber (LArTPC)**

Cathode Plane in the middle of the TPC at -100 kV. 2 drift volumes. 2m drift.

Both sides with 3 wire planes to reconstruct 3D interaction. 3 mm wire pitch.

**Most-advanced Photon Detection System (PDS) in a LArTPC:**

120 8” Hamamatsu R5912 Cryogenic PMTs mounted behind the wire planes.

192 X-ARAPUCAs (light traps). Same photodetector technology to be used in DUNE.

Wavelength-shifting (TPB) reflector foils on the Cathode Plane Assembly.

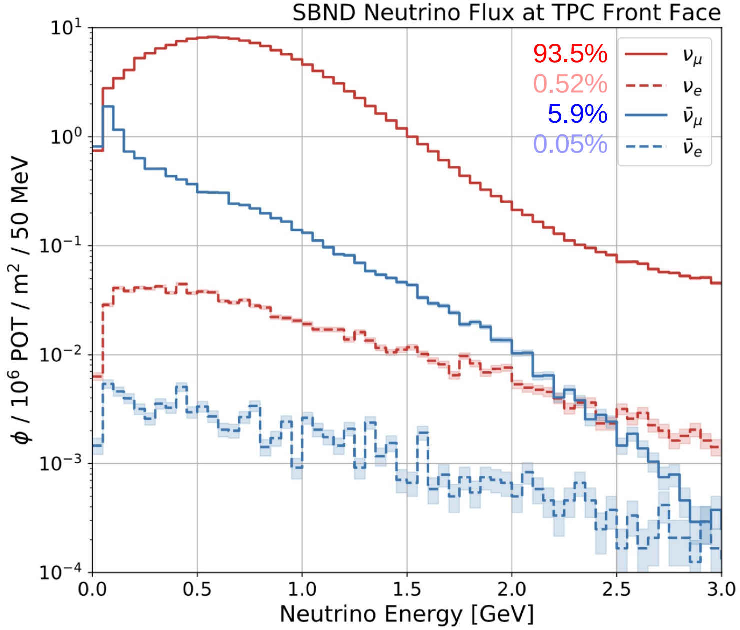
20% of PMTs and 50% of X-ARAPUCAs dedicated to visible light.

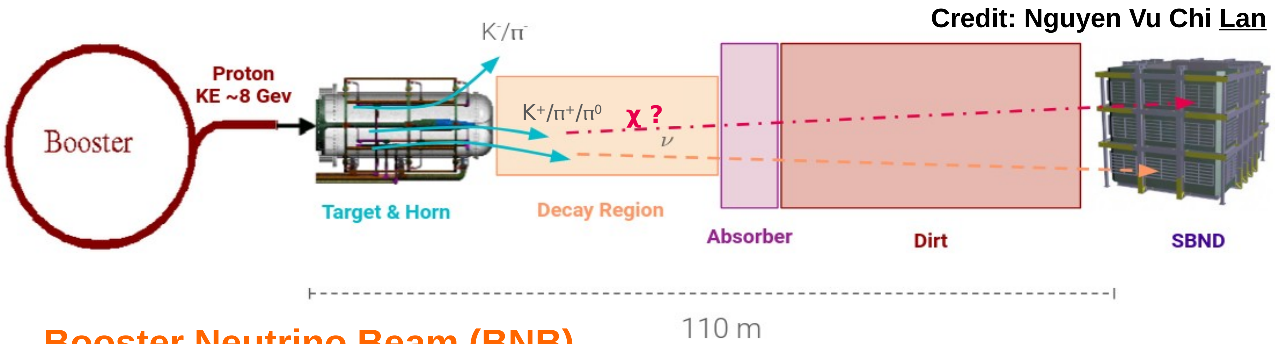
**Cosmic-Ray Tagger (CRT):**

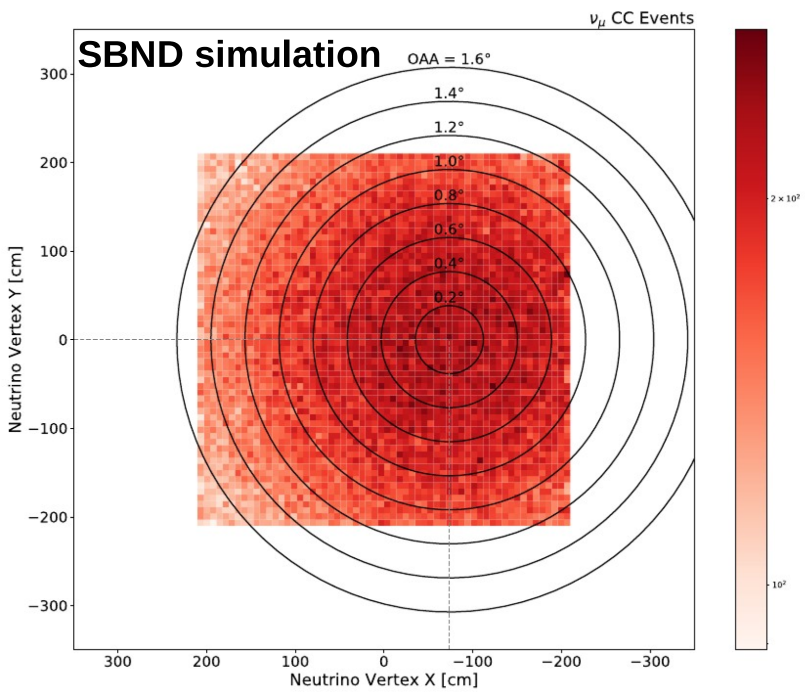
Aprox. 4π coverage with plastic scintillator strips (2D location).

**Tereza Kroupova's talk in the Neutrino physics and astrophysics session on Aug 29th: SBND Hardware Trigger System**

# The Booster Neutrino Beam




**Booster Neutrino Beam (BNB)**

8 GeV protons on Be target. p + Be → mesons + X

$\langle E_\nu \rangle$ ~ 0.7 GeV. Mostly from pion decay-in-flight (plus kaon and muon decay contributions).

Well-understood beam, same as MiniBooNE **[PRD 79, 072002 (2009)]**.

**PRISM concept**: SBND is so close to the beam origin that can measure the off-axis flux dependence (without moving!).

$\nu_\mu$ flux arises mainly from pion decays → decreases with off-axis angle.

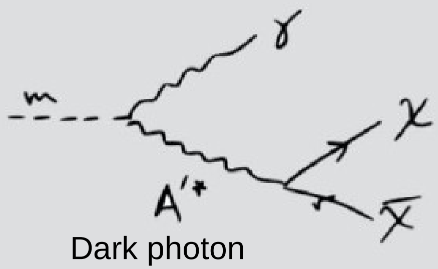
$\nu_e$ flux arises mainly from kaon 3-body decays → uniform.

Additional handles for background rejection, interaction model constraints, and flux systematic uncertainty reduction.

# Beyond oscillations: beyond Standard Model searches

Any new physics in the BNB will show up with the highest statistics at SBND thanks to the close location to the beam origin.

## Light Dark Matter

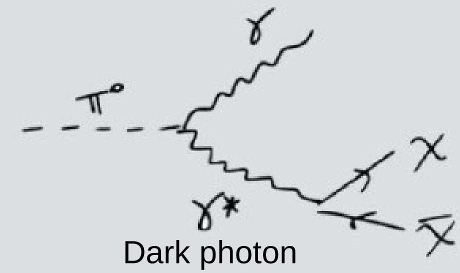



Romeri Kelley Machado PRD 2019

## Dark Neutrinos

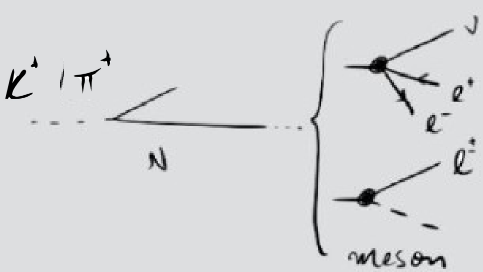

Bertuzzo Jana Machado Zukanovich PRL 2018, PLB 2019
Arguelles Hostert Tsai PRL 2019
Ballett Pascoli Ross-Lonergan PRD 2019
Ballett Hostert Pascoli PRD 2020

## 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

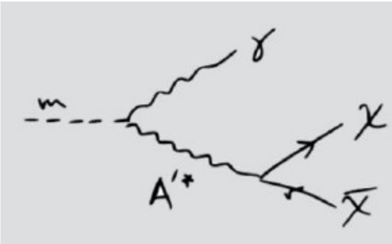
Pat Wilczek 2006
Batell Berger Ismail PRD 2019
MicroBooNE 2021

## Axion-like Particles

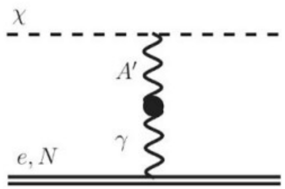
Kelly Kumar Liu PRD 2021
Brdar et al PRL 2021

Image credits: Pedro Machado, Marco Del Tutto

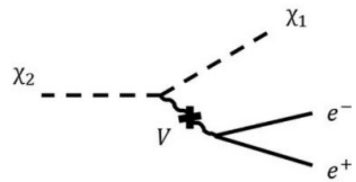
# Light dark matter



Production

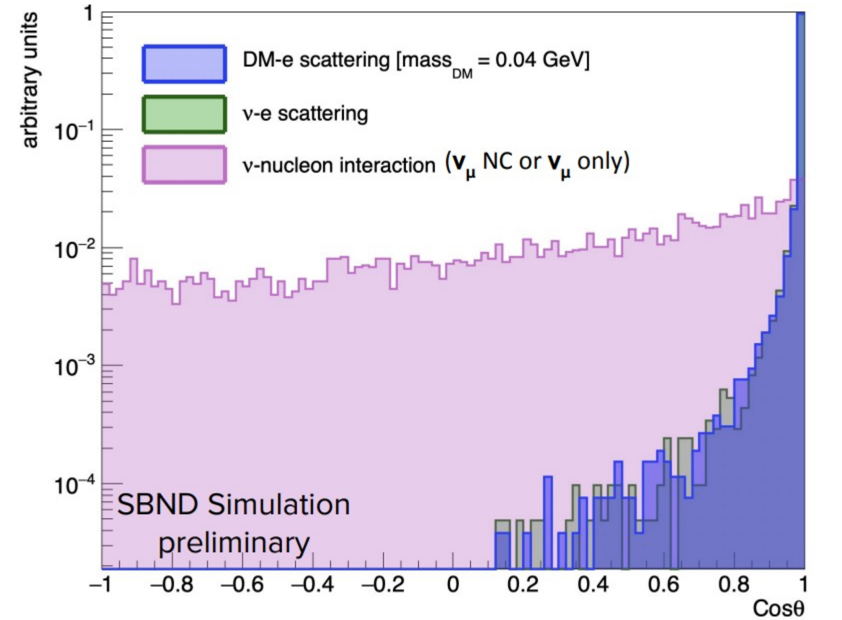


NC elastic scattering with $e^-$ or nucleon



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

**[PRD 95, 035006 (2017)]**



Distribution of events with respect to the beam direction

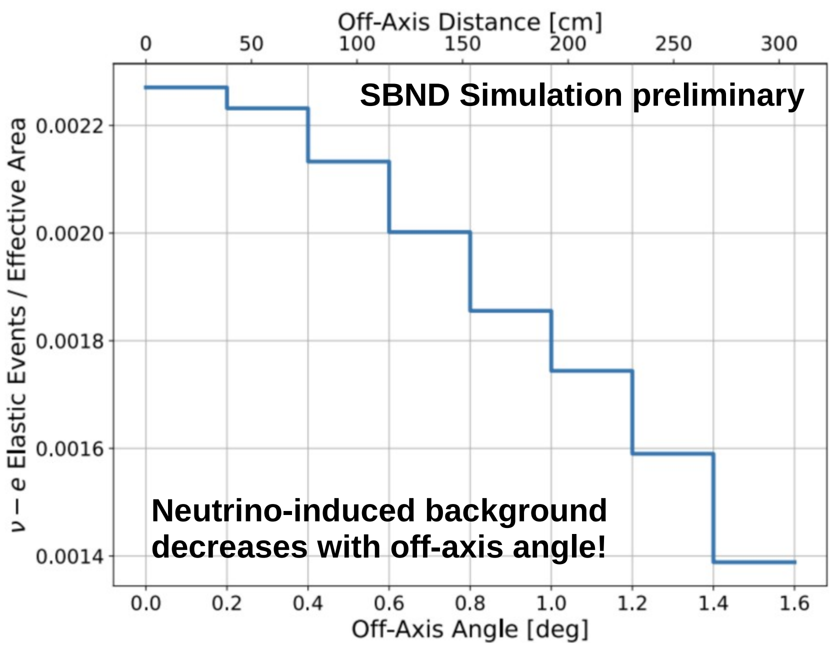
SBND can **search for sub-GeV dark matter**, complementary to WIMP searches at higher masses.

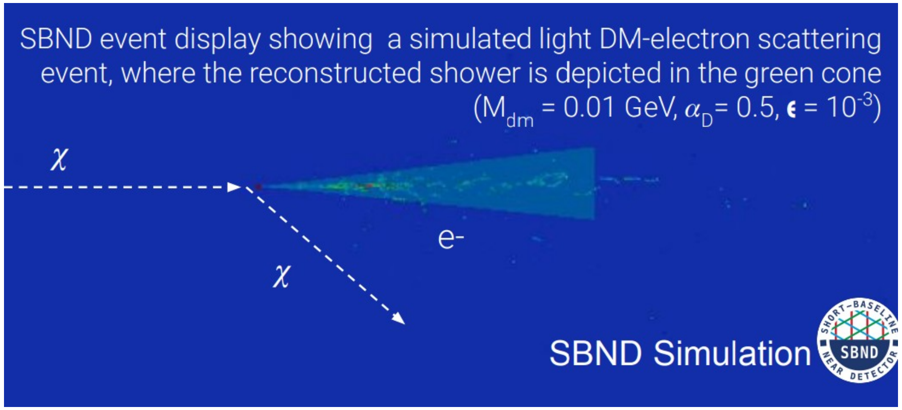
**Vector portal: Light dark photon mediator.**

Production in neutral meson decays or proton bremsstrahlung in the BNB target.

Scattering or decay inside SBND.

Focus on EM-shower final states with no hadronic activity.



# Dark neutrinos

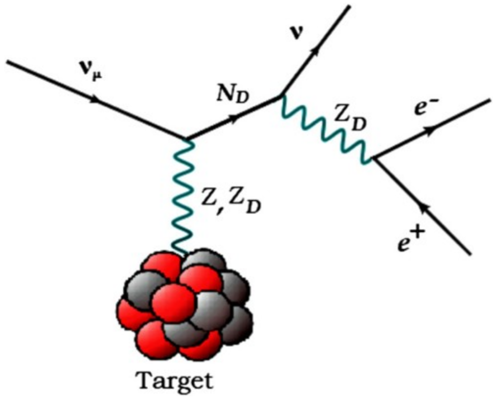
Model proposed as source of the **MiniBooNE anomalous excess**.

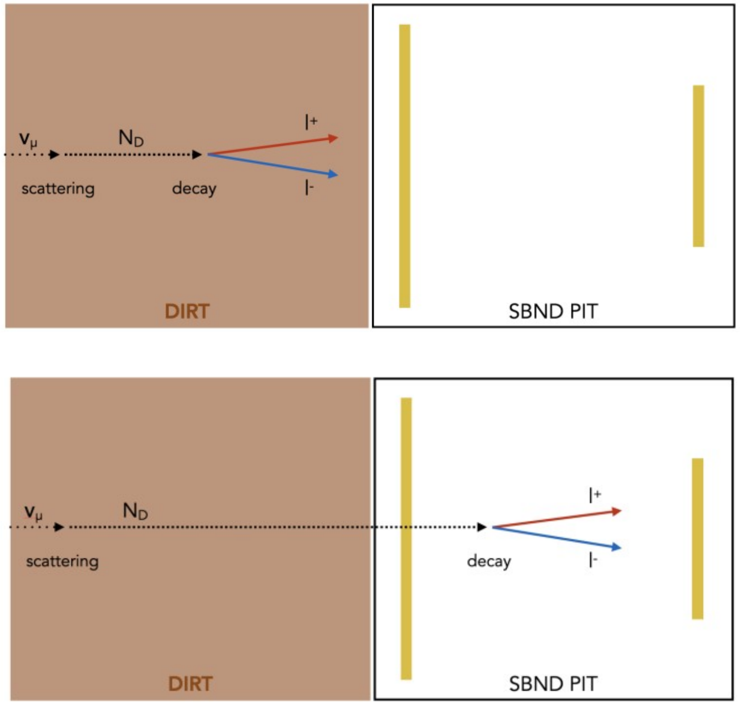
SM neutrinos up-scatter to dark neutrinos via Z' (dark boson) exchange, and then decay into collimated $e^+e^-$ pairs.

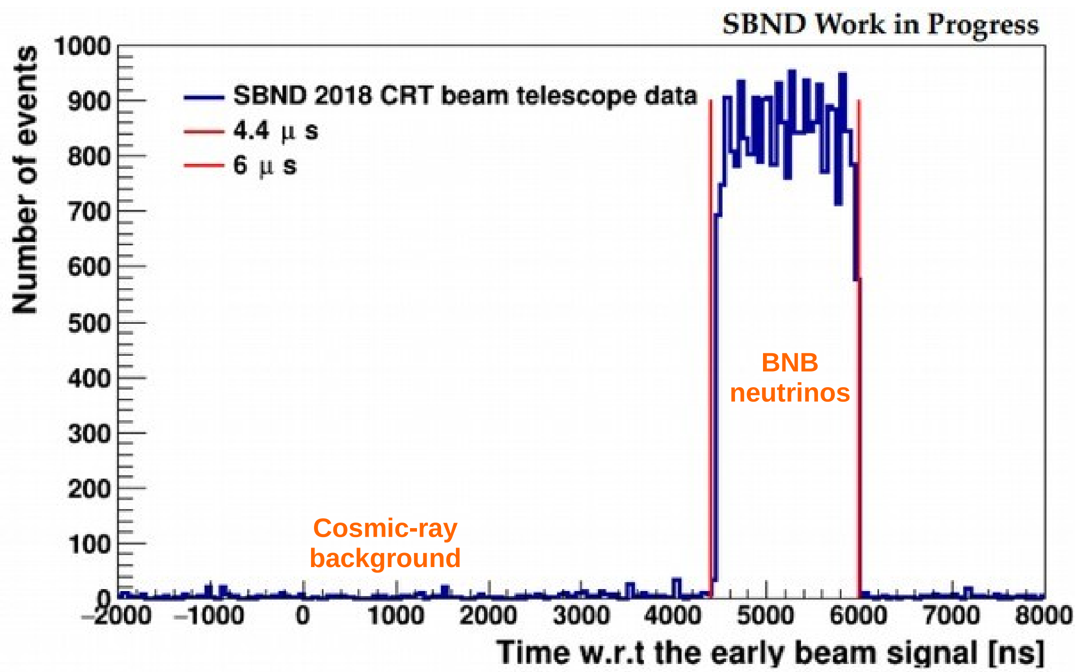
Before the SBND cryostat was installed, Cosmic-Ray Tagger panels took data in a beam telescope configuration.

**Data analysis in progress.**

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



# Heavy neutral leptons (HNLs)

Extension of SM: **right-handed** counterparts to left-handed neutrinos.

Can have both **Dirac** (Yukawa) and **Majorana** masses. **Mass scale unconstrained.**

**See-saw mechanism** explains SM neutrino mass scale.

Provide dark matter candidate, baryon asymmetry mechanism (νMSM).

Production in BNB meson decays through mixing with SM neutrinos via extended PMNS mixing matrix elements: $U_{e4}$, $U_{\mu4}$ (no τ production in BNB).

HNL mass range limited by kaon mass.

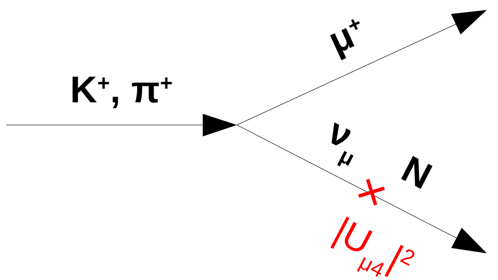
No oscillation due to large mass. HNL decays in flight via extended PMNS mixing again.

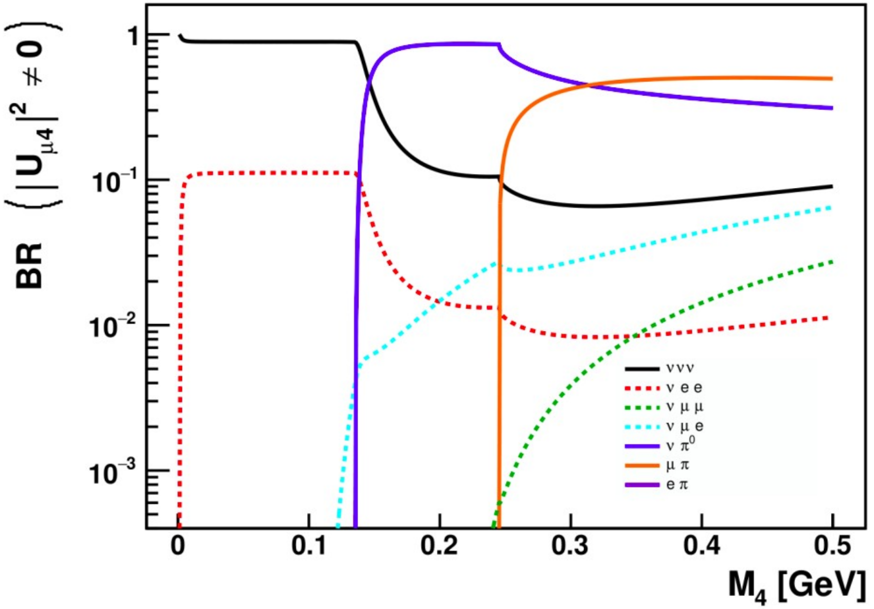
No interaction with Ar nucleus.

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

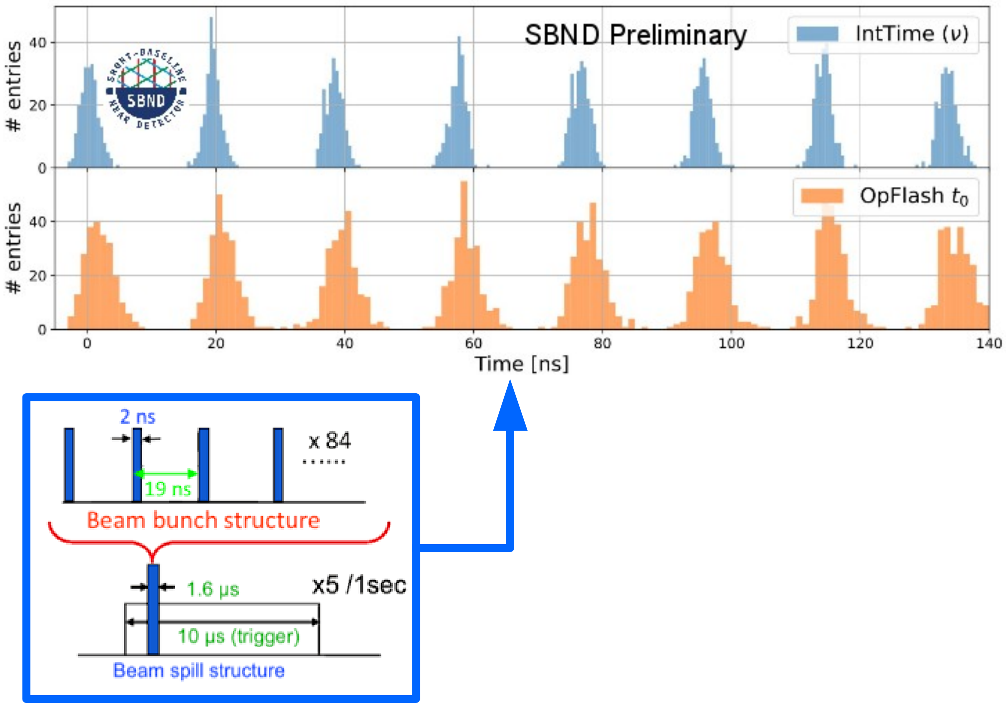
**Extended PMNS matrix**

$$\begin{bmatrix} U_{e1} & U_{e2} & U_{e3} & U_{e4} \\ \vdots & & \vdots & U_{\mu4} \\ \vdots & & \vdots & U_{\tau4} \\ U_{s1} & U_{s2} & U_{s3} & U_{s4} \end{bmatrix}$$



# Photon-detection system nanosecond timing

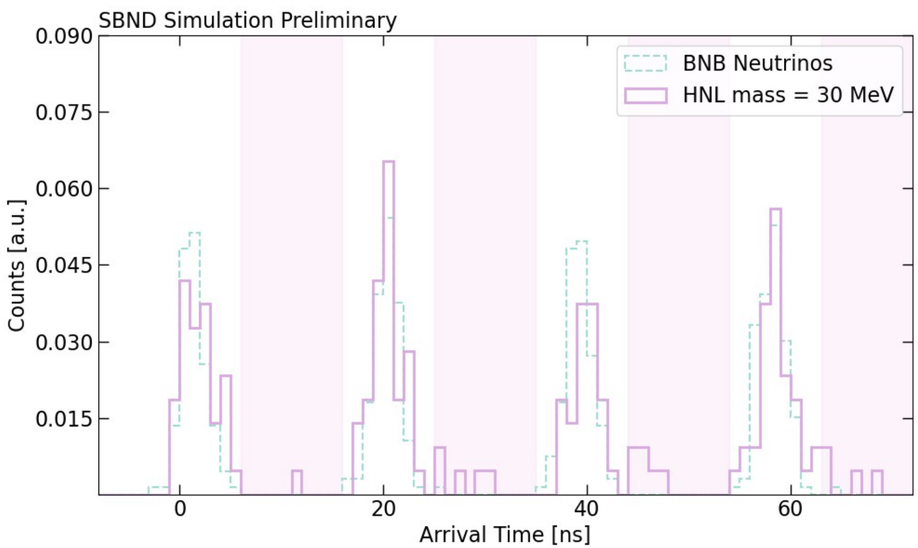


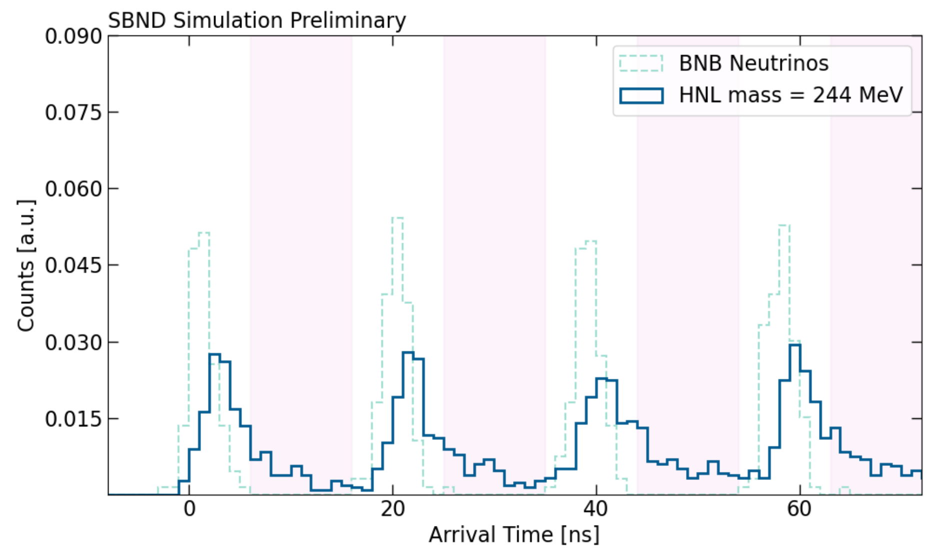

SBND has developed a full beam simulation for SM neutrinos and HNLs, including time of flight.

The PDS is capable of achieving **timing resolution at the nanosecond level.**

Enough to resolve the RF frequency of the BNB beam and observe the bunch structure.

**Possibility to search for any massive long-lived particle (not just HNLs) between the SM neutrino bunches.**



# HNL sensitivity

First SBND sensitivity to HNLs using the full beam simulation, including mass effects:

- Helicity enhancement in 2-body meson decays.
- Flux forward-focusing
- Time of flight

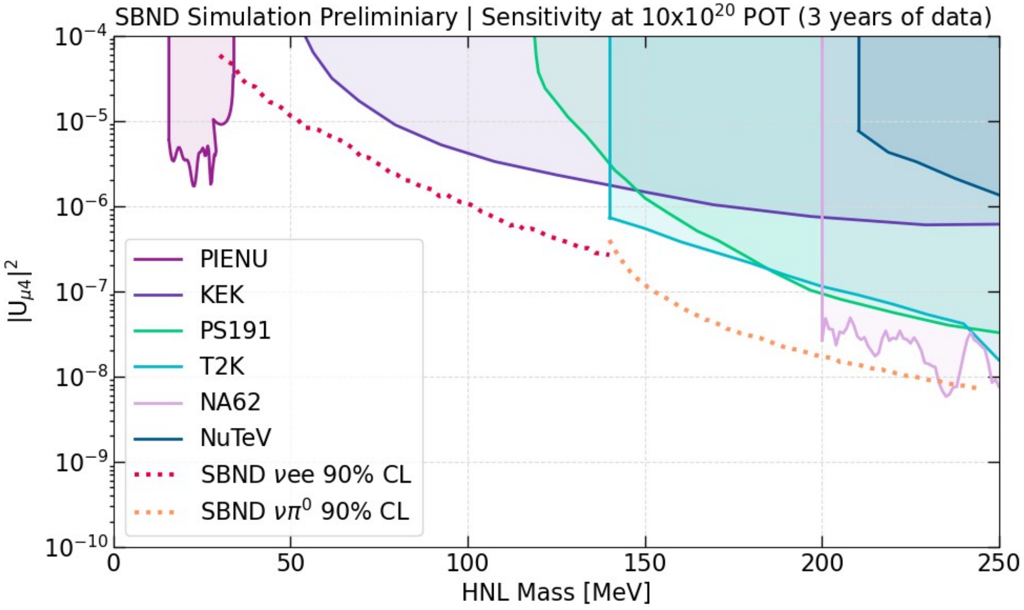
**SBND is competitive in $U_{\mu 4}$-driven mixing in the HNL mass region below 250 MeV.**

Main decay channels:

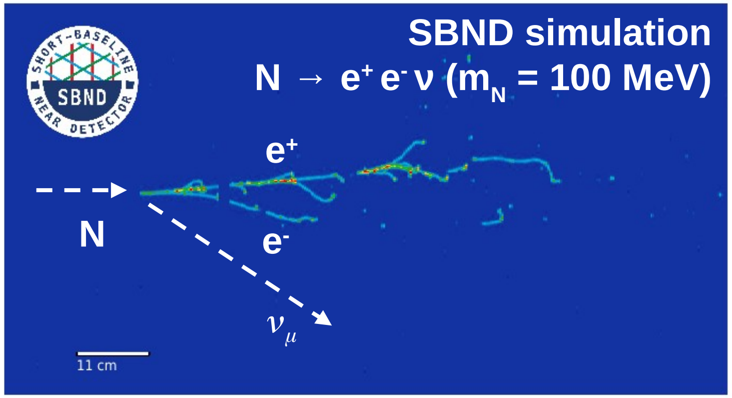
N → $e^+ e^- \nu$ ($m_N$ < 135 MeV)

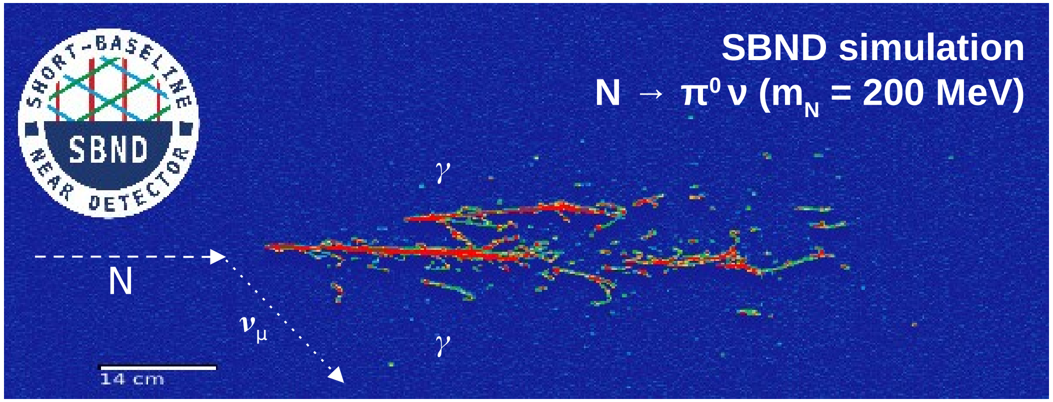
N → $\pi^0 \nu$ ($m_N$ > 135 MeV)

On-going effort on developing the event reconstruction.




**Timing cuts + 20% reconstruction efficiency**
**No background (*best-case sensitivity*)**



# Conclusions

- In addition to conclusively address anomalies potentially caused by sterile neutrinos at $\Delta m^2 \sim 1\ eV^2$, SBND will perform **multiple searches for Beyond Standard Model physics taking advantage of the close location to the beam origin and the liquid argon TPC capabilities.**

- **Nanosecond-level precision in the photon detection system** can be used to search for massive long-lived particles in a model-independent way.

- Possibility to search for **sub-GeV dark matter from neutral mesons and proton beam bremsstrahlung.**

- **On-going analysis using SBND Cosmic-Ray Tagger panels data in a telescope configuration to search for dark neutrinos** proposed as an explanation of the MiniBooNE anomaly.

- SBND has the potential to reach **leading sensitivity to heavy neutral leptons produced through $|U_{\mu 4}|$ mixing for masses below 250 MeV**.

- Work in progress to **include more new physics models**.

- SBND **installation is almost complete**. Ready for beam in 2024.

# Backup

# SBND collaboration

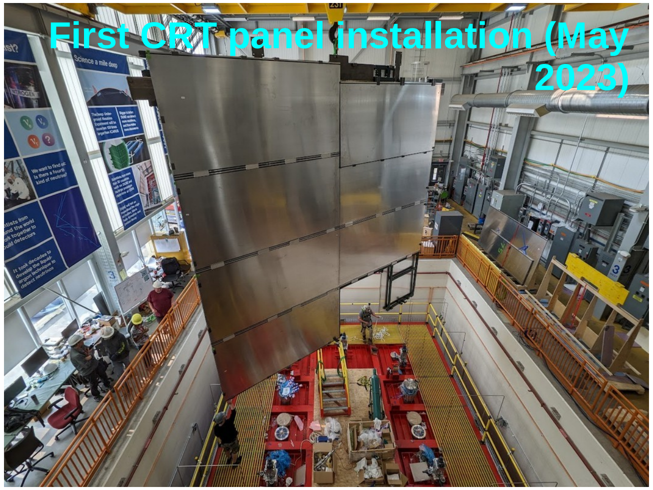
262 total collaborators

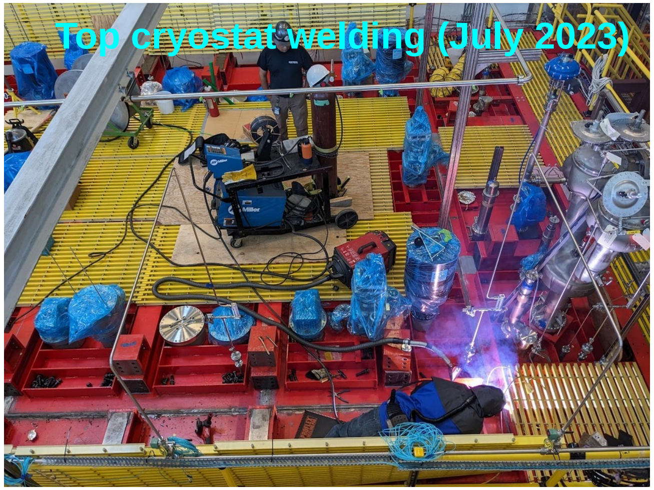
40 institutions

- 4 US DOE national laboratories, 20 US universities
- 5 Brazilian universities
- 1 Spanish university, 1 Spanish national laboratory
- 1 Swiss university
- 8 UK universities, 1 national laboratory
- CERN

# Detector status





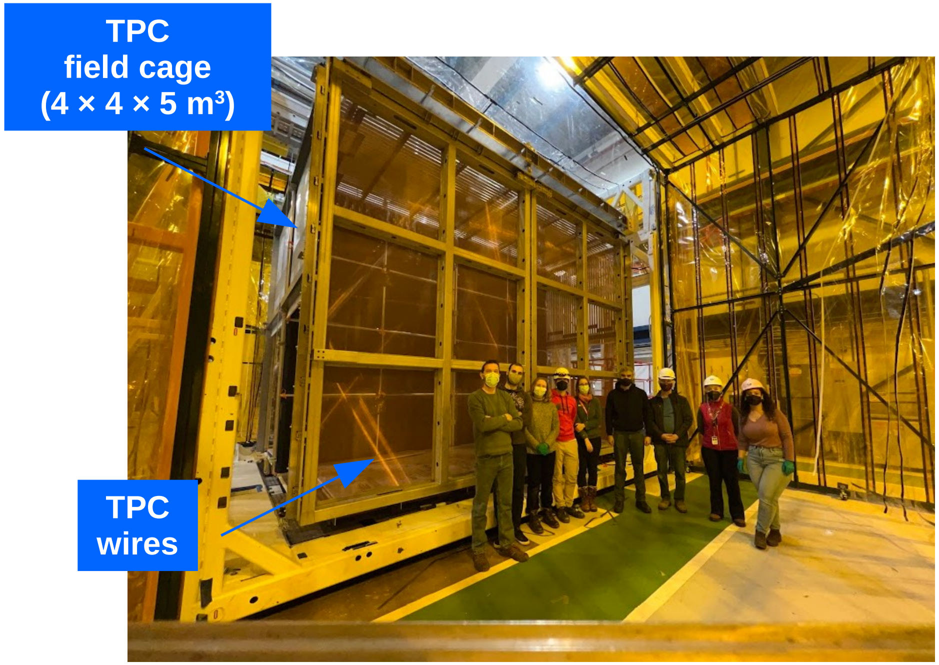



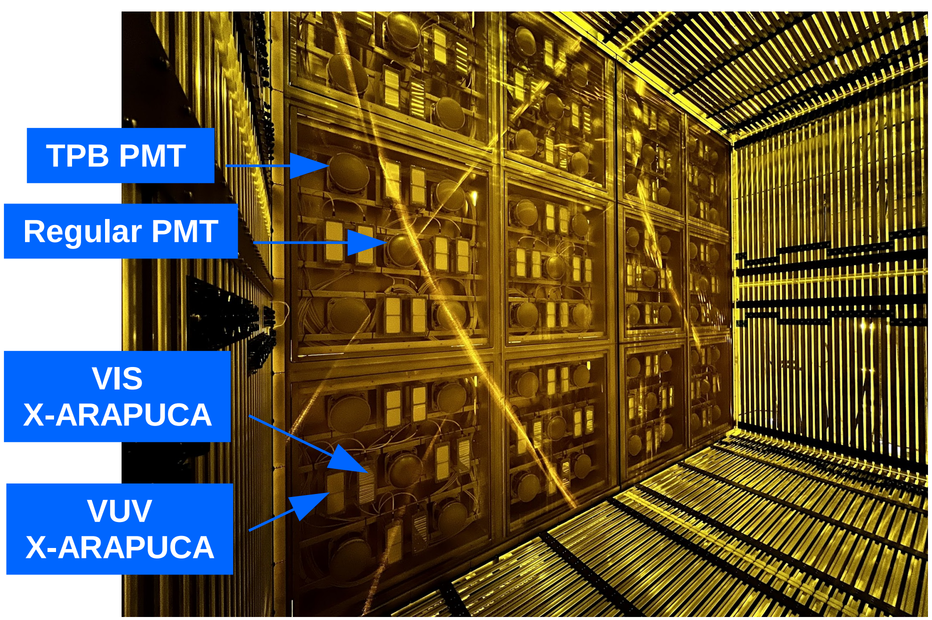

**Final installation happening now.**

**Detector filling with liquid argon in Fall 2023.**

**Commissioning in early 2024.**

# SBND detector details




### Liquid Argon Time Projection Chamber (LArTPC)

Cathode Plane in the middle of the TPC at -100 kV.

2 drift volumes. 2m drift. Maximum drift time: 1.28 ms.

Anode Plane Assemblies on both sides with 3 wire planes to reconstruct 3D interaction.

3 mm wire pitch. 11264 channels.

TPC cold electronics (same model as ProtoDUNE Single Phase).

### Most-advanced Photon Detection System (PDS) in a LArTPC:

120 8” Hamamatsu R5912 Cryogenic PMTs mounted behind the wire planes.

192 X-ARAPUCAs (light traps). Same photodetector technology to be used in DUNE.

Wavelength-shifting (TPB) reflector foils on the Cathode Plane Assembly.

20% of PMTs and 50% of X-ARAPUCAs dedicated to visible light.

### Cosmic-Ray Tagger (CRT):

Aprox. $4\pi$ coverage with plastic scintillator strips (2D location).

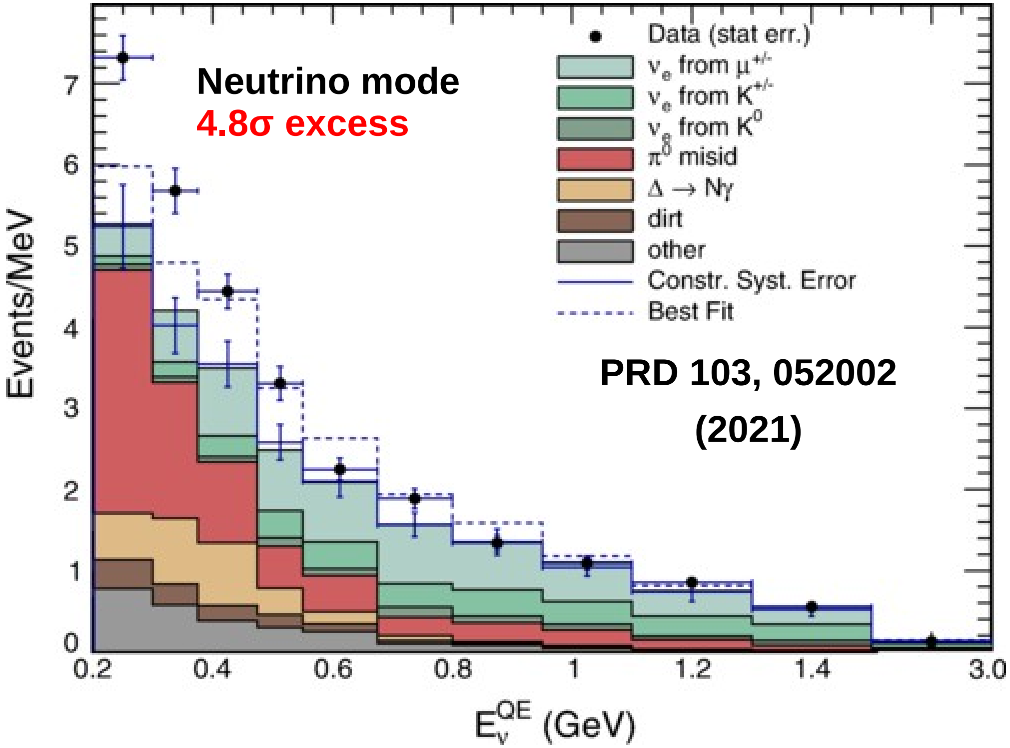
# Final MiniBooNE results

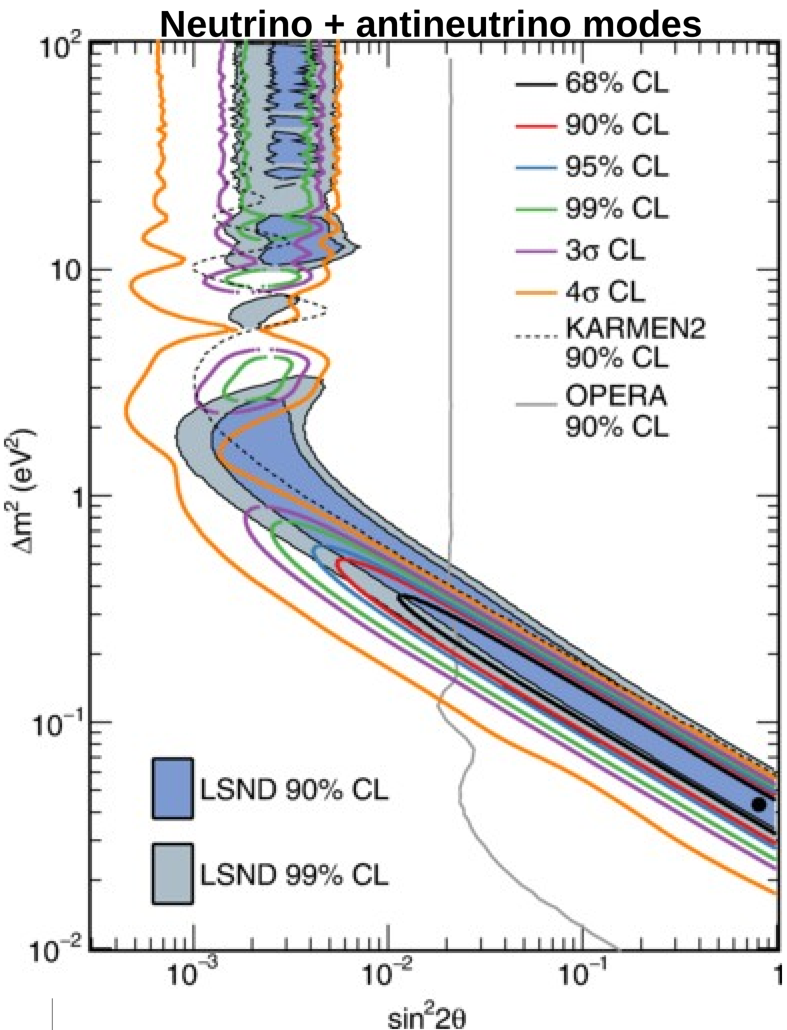
Latest MiniBooNE results (2018, 2021) more than **doubled statistics** in neutrino mode.

Old and new datasets are **consistent** with each other.

Same analysis. Improved background constrains with the additional statistics.

Consistent results with **LSND**.




**SM neutrinos have $\Delta m^2$ of $O(10^{-3})$ and $O(10^{-5})$ eV².**