The Status and Latest Results from SBND & ICARUS (SBN Program)

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Fermilab

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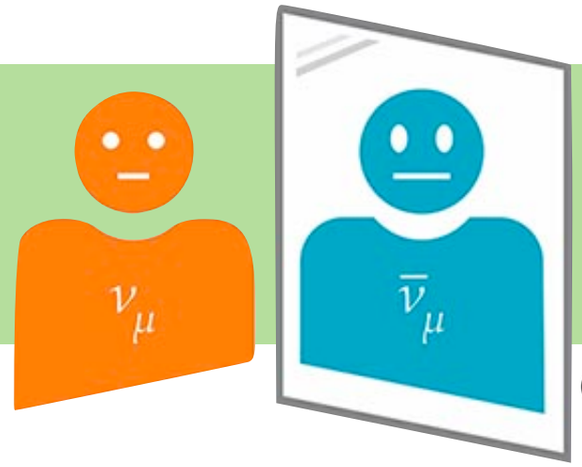
Neutrino Questions

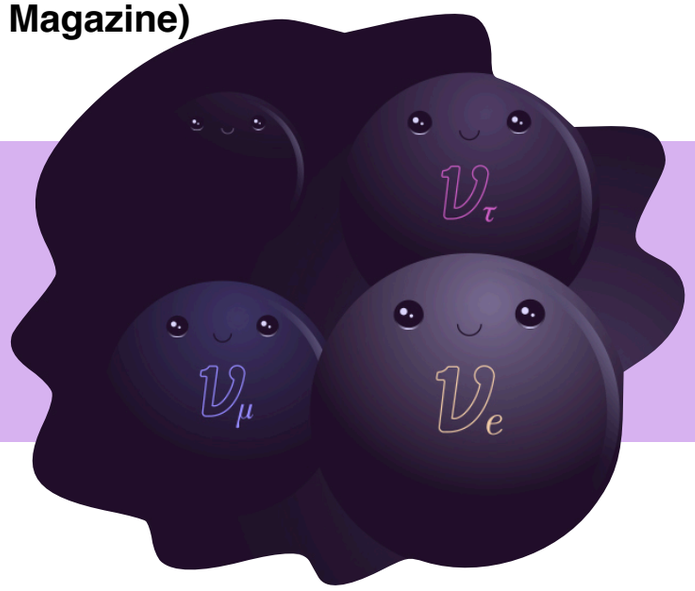
Several tantalizing questions can be explored thanks to the phenomenon of neutrino oscillations:

Do neutrinos and anti-neutrinos oscillate differently?



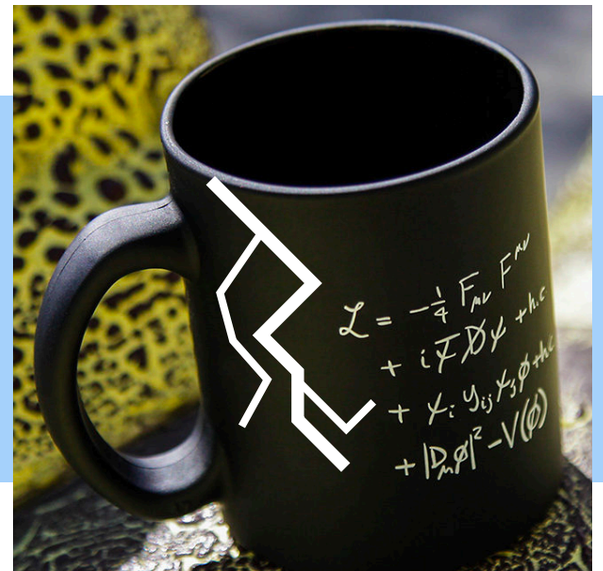
(Donna Padian)

(Symmetry Magazine)



Are there more than the 3 neutrinos that interact with matter?

Can we use intense neutrino sources and sophisticated detectors to search for new physics?



Neutrino Questions

Several tantalizing questions can be explored thanks to the phenomenon of neutrino oscillations:

Do neutrinos and anti-neutrinos oscillate differently?

Long-baseline experiments are very sensitive to ν-A interaction uncertainties

Use large, short-baseline detectors exposed to two beams to study ν-Ar with unprecedented precision

Past experimental anomalies have hinted at the presence of additional sterile neutrino states

The SBN Program was designed to **definitively** cover this phase space

Are there more than the 3 neutrinos that interact with matter?

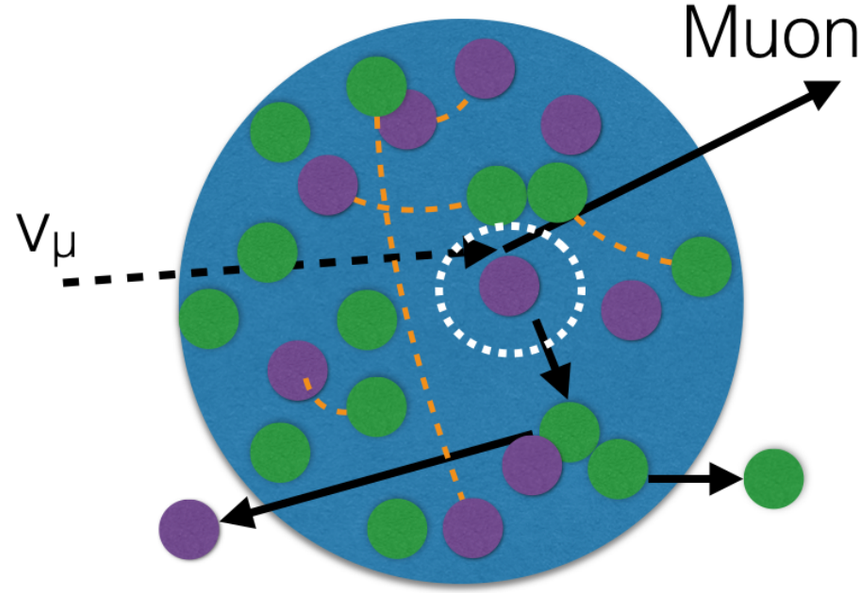
Can we use intense neutrino sources and sophisticated detectors to search for new physics?

Other BSM processes could explain these anomalous results

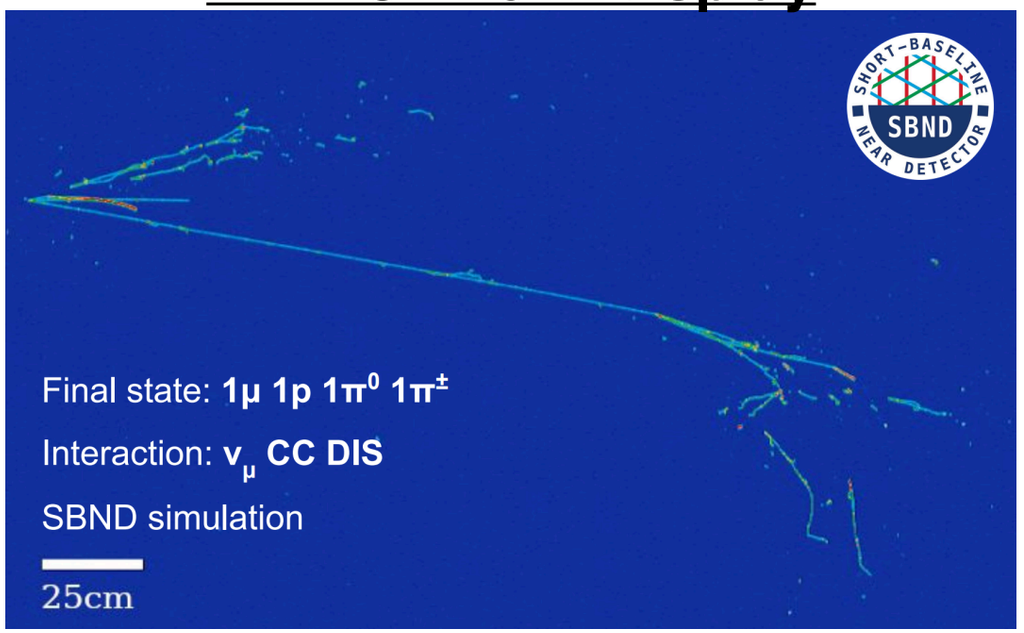
The intense environment of neutrino beams provides an opportunity to search for this new physics

Neutrino Interactions

- Studying neutrino oscillations requires an understanding of neutrino interactions with matter
- Neutrino energy inferred from final state particles and their kinematics
- These can be influenced by several nuclear effects, including:
  - The initial nucleon momentum, nucleon form factors, nuclear binding energies, multi-nucleon correlations, and final state interactions
- LArTPCs, with their low thresholds & excellent detection capabilities can help to probe many of these effects



LATPC Event Display

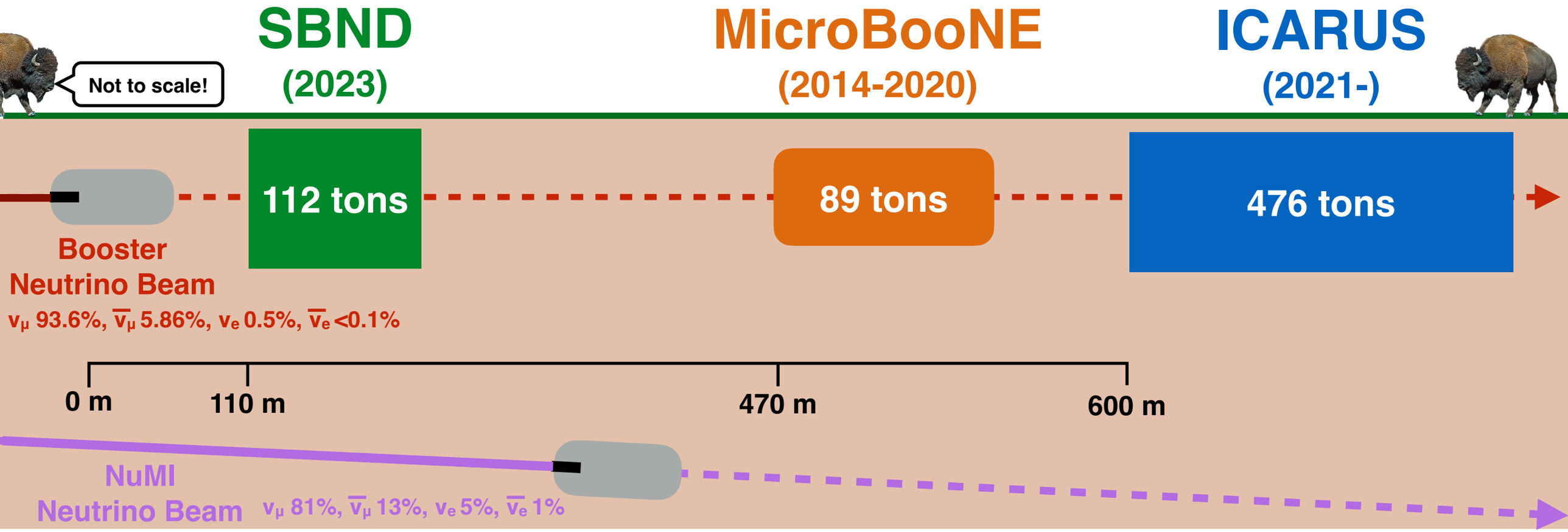


Short-Baseline Neutrino Program at Fermilab

The SBN Program is three LArTPC on a shared beam

Common beam, detector, and target offer **systematic constraints**

Other power features: short baseline, a second (very off-axis) neutrino beam, and detectors with low thresholds



Graphic inspired by Marco Del Tutto

Short-Baseline Neutrino Program at Fermilab

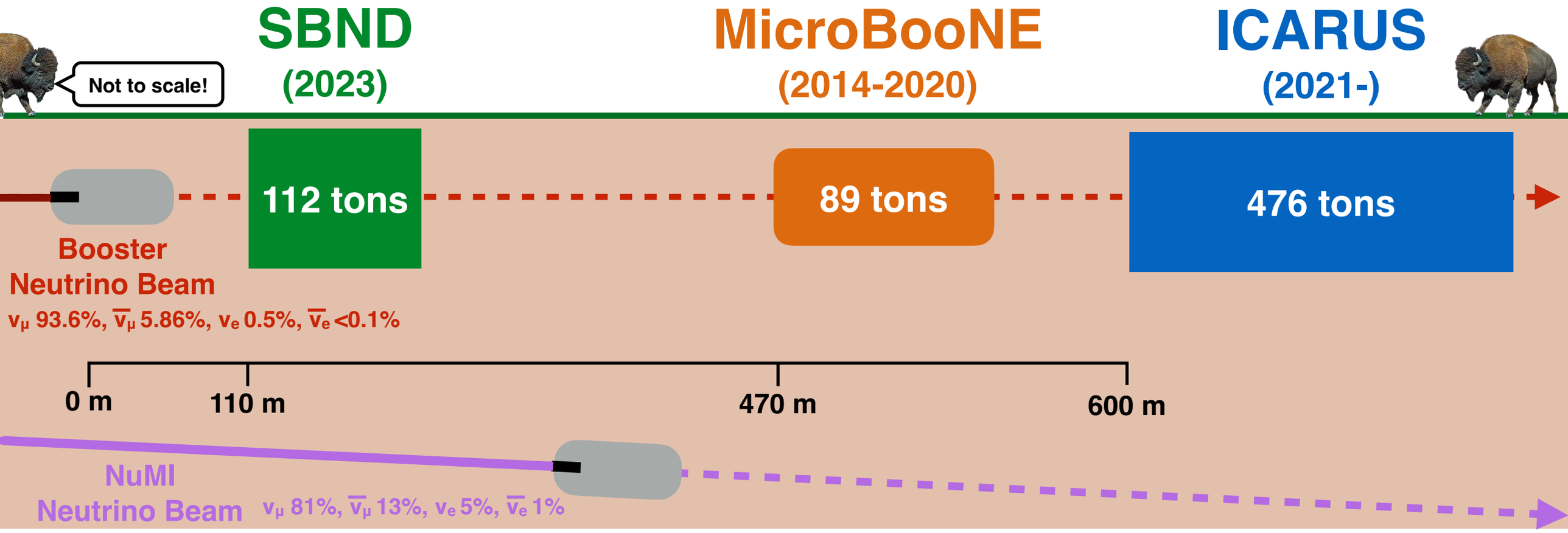
MicroBooNE was designed to test the MiniBooNE low energy excess and has recently released its first results!

See Josh Barrow's Talk Thursday

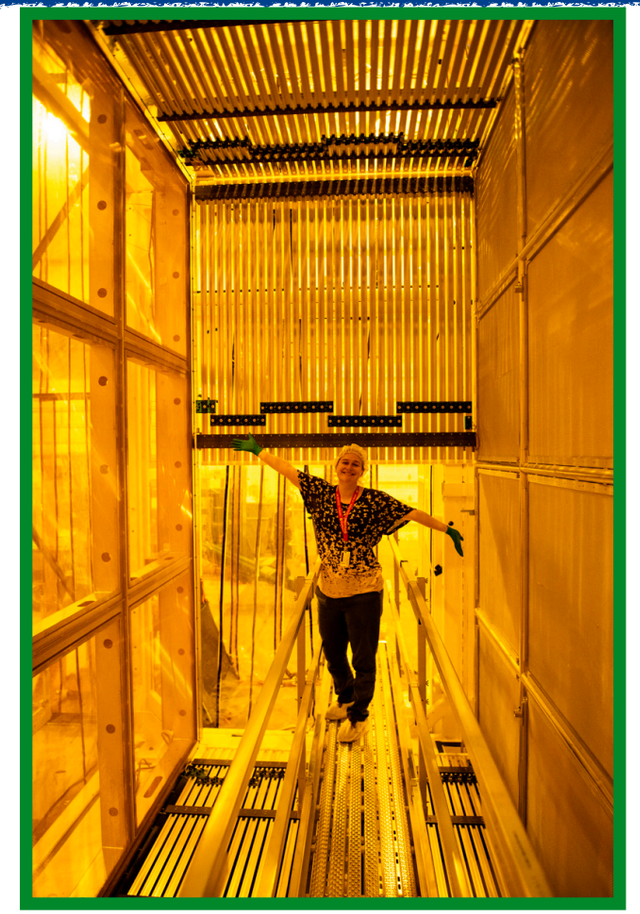
Entering the next phase…

Close location to the beam providing a high statistics constraint of systematic uncertainties before neutrinos have an opportunity to oscillate

The large mass of a very well-understood detector at a far distance offers such a high statistics test of oscillations



Short-Baseline Neutrino Program at Fermilab



SBND
(2023)

ICARUS
(2021-)

112 tons

89 tons

476 tons

Booster Neutrino Beam

ν_μ 93.6%, $\bar{\nu}_\mu$ 5.86%, ν_e 0.5%, $\bar{\nu}_e$ <0.1%

0 m

110 m

470 m

600 m

NuMI Neutrino Beam

ν_μ 81%, $\bar{\nu}_\mu$ 13%, ν_e 5%, $\bar{\nu}_e$ 1%

Graphic inspired by Marco Del Tutto

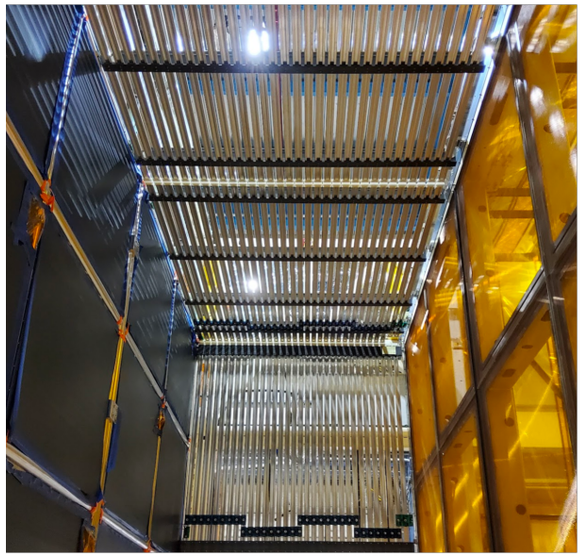
Near Detector: SBND

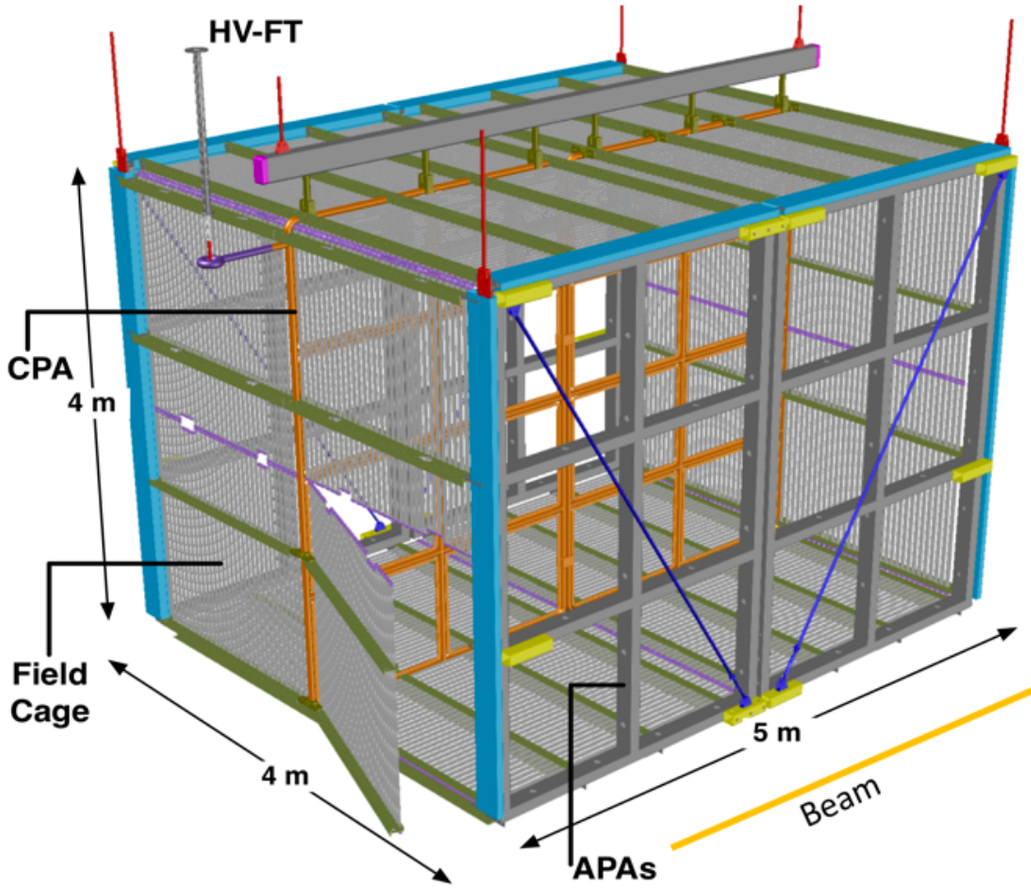
Short-Baseline Near Detector being assembled at Fermilab

Two TPCs ***112 tons of LAr***

HV feedthrough

16 field shaping panels

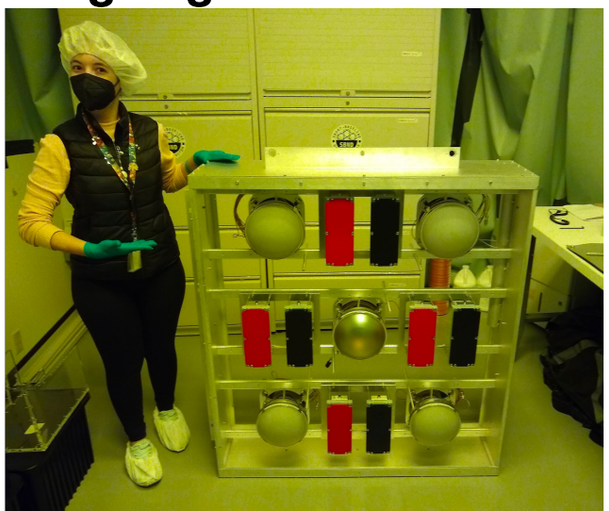




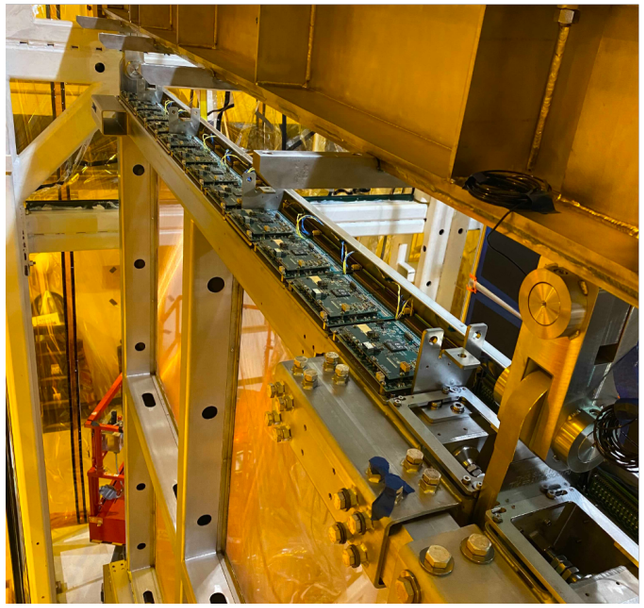
11k wires across two planes

Cathode fitted w/ reflectors

High light collection eff



Cold electronics reduce noise



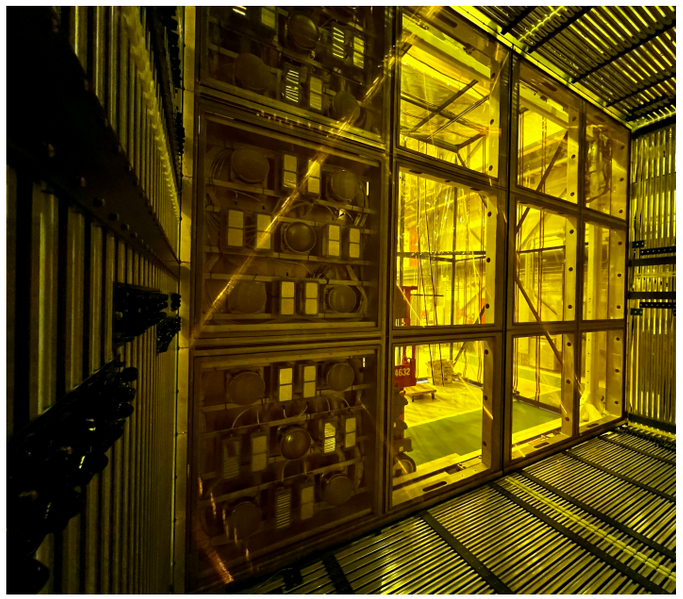
Assembly Progress

- ***SBND TPC assembly was completed this summer!***
- ***The cryostat has completed its assembly and is being leak checked***
- The installation of the photon detector system is underway
- Expect commissioning to begin next year

TPC Assembly Complete!

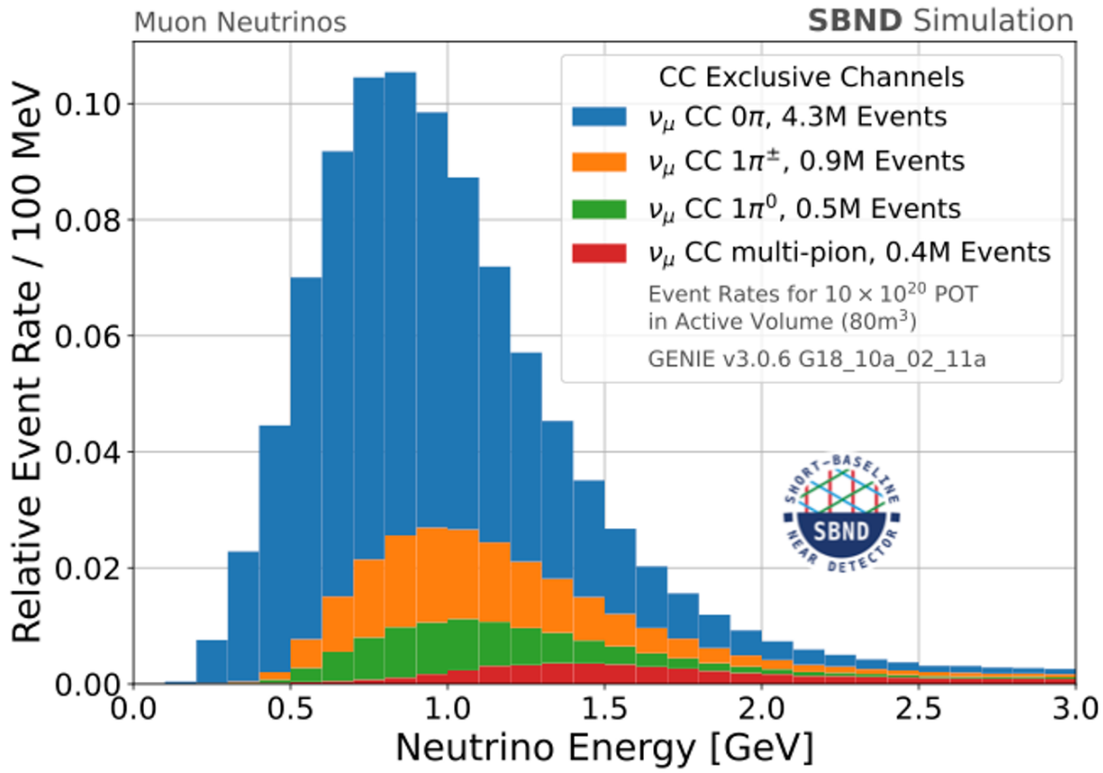
Cryostat Installation

Photon Detector System Installation

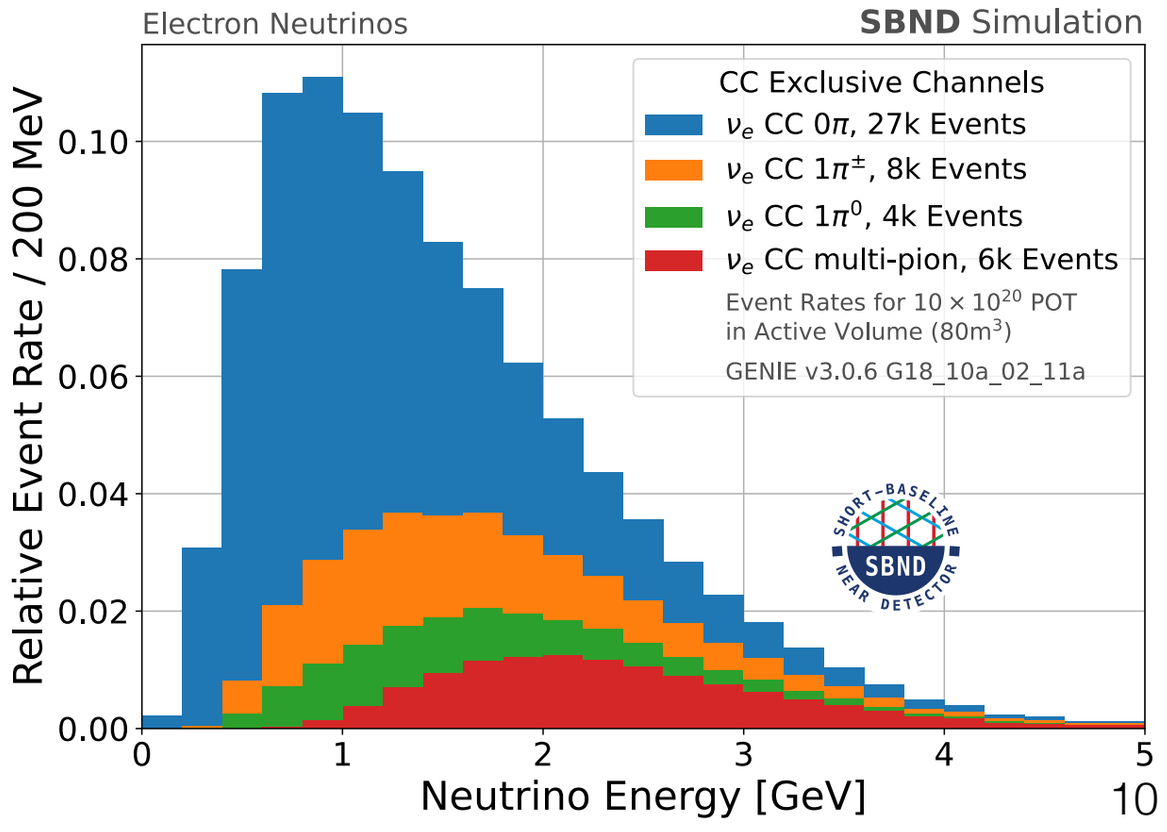


BNB Cross Section Program

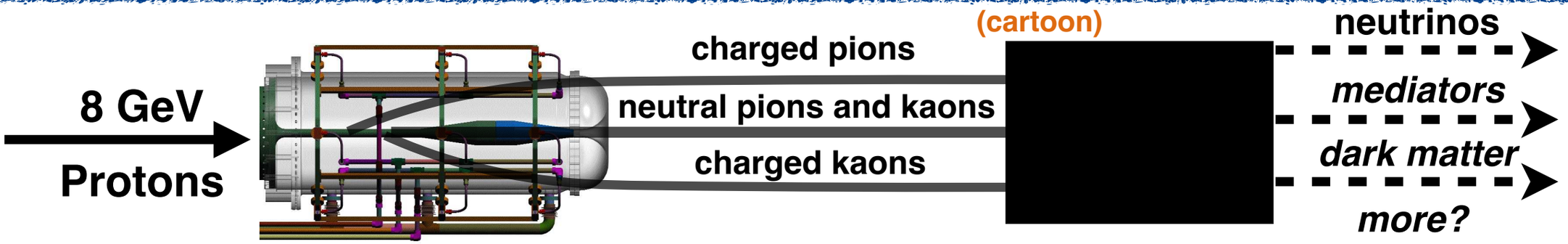
- SBND sits very close (110m) to the BNB target providing a high rate of neutrino interactions
  - ***Over 5000 interactions per day!***
- This will enable it to collect the world's largest sample of v-Ar interactions before DUNE



- High-statistics measurements of exclusive final states, rare processes, and tests of v-Ar models
- Aim to reduce uncertainties for SBN searches and the future CP violation searches at DUNE



Searching for New Physics in the BNB

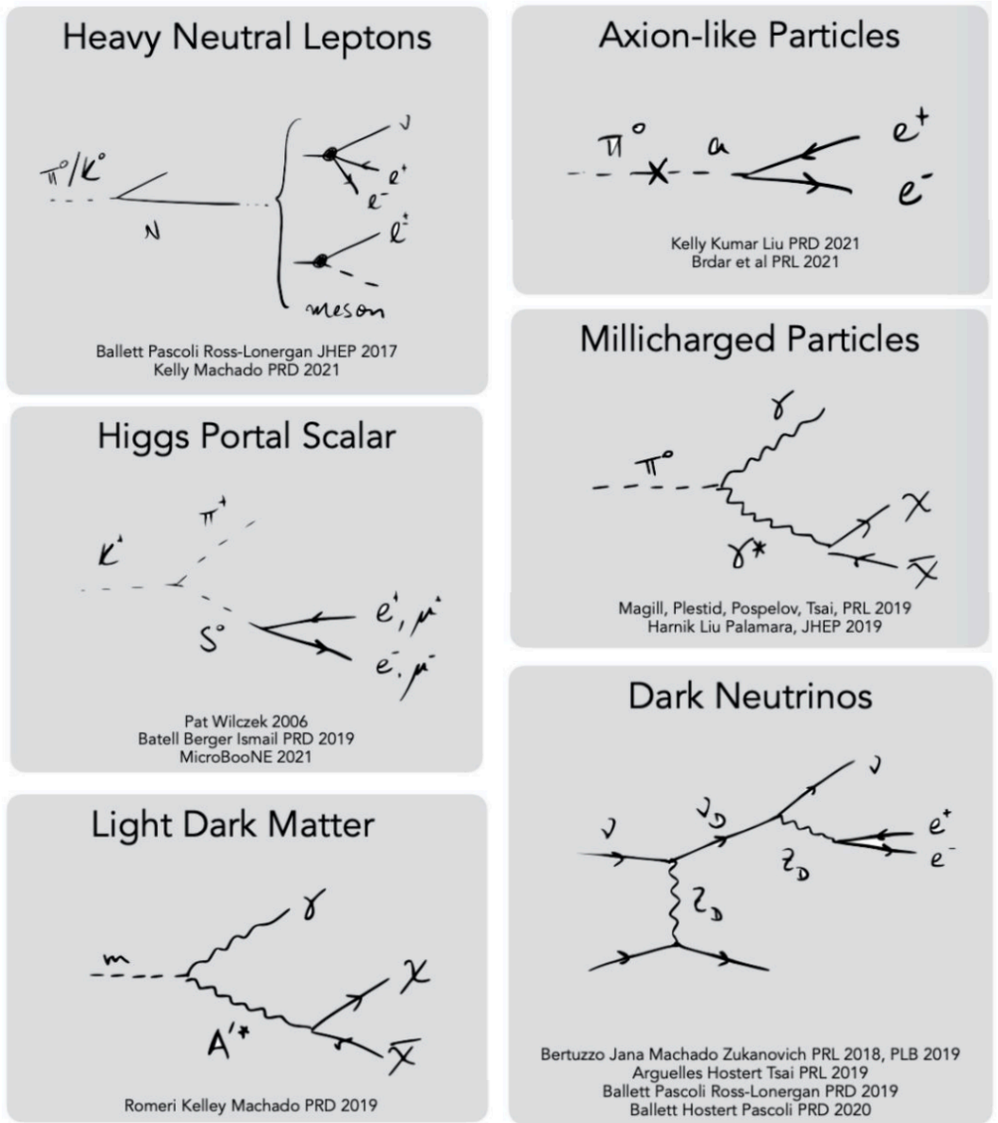


- A rich theory landscape has developed around describing the neutrino anomalies

- Even though we're in a low-energy beam, the high-intensity SBND observes provides unique phase space coverage across many BSM channels

SBND will observe
O(10^{21}) protons hit the target!

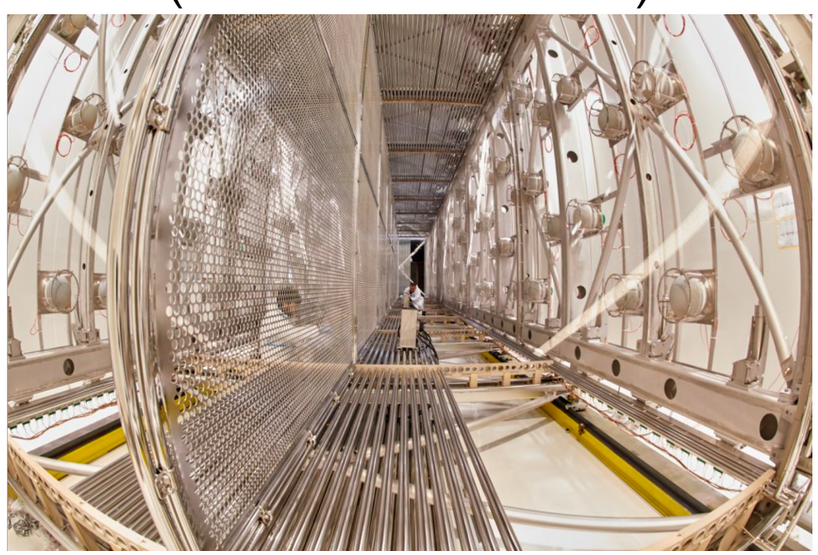
Signatures of a Rich Program!



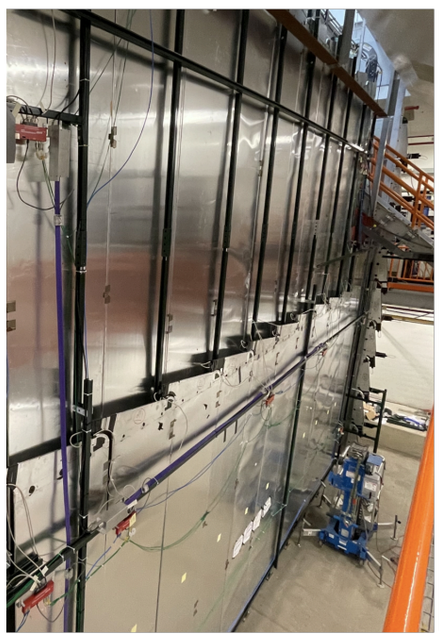
Schematics of final states in backups

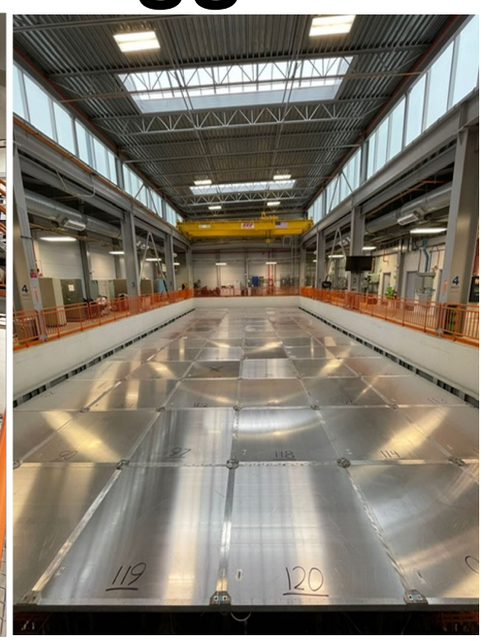
Far Detector: ICARUS

TPC and PMTs
(2 out of 4 TPCs)



Cosmic Taggers





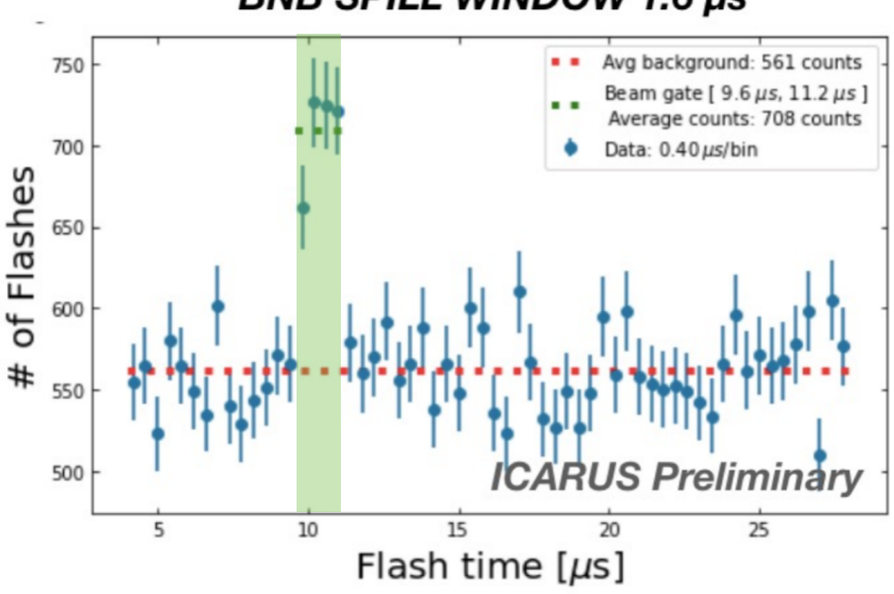
3 m Overburden

- ICARUS was originally deployed in Gran Sasso and exposed to the LNGS beam before moving to CERN to be refurbished for its run at Fermilab
- Four TPCs split between two cryostats, 470 tons of active LAr, observed by 360 8” PMTs, 54000 wires, a cosmic ray tagger system, and a 3 m concrete overburden to reduce soft cosmic backgrounds
- Data taking started fall 2020, with stable noise & electron lifetime (>3 ms)

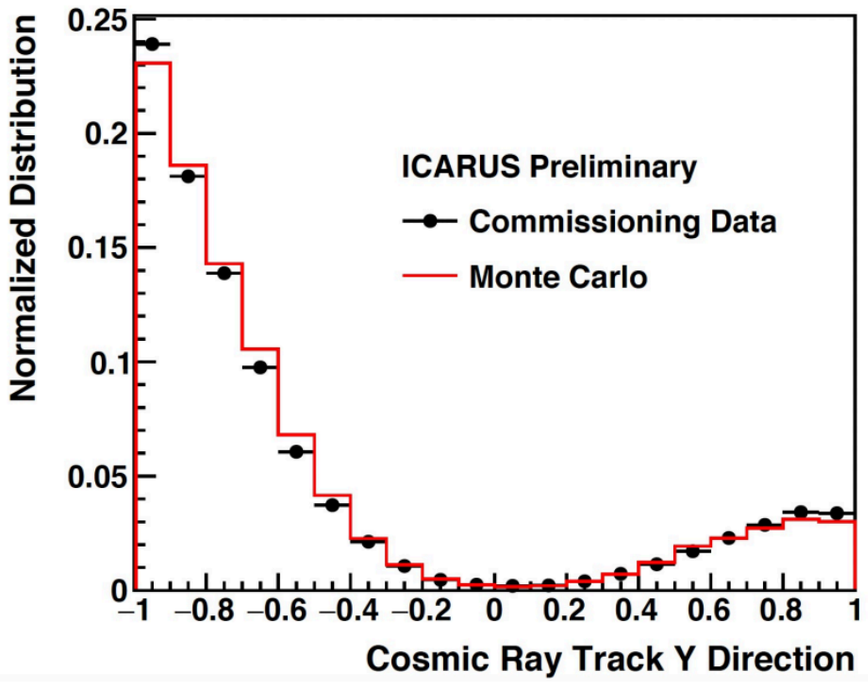
Started Physics Running

- Started collecting neutrino beam for commissioning in June 2021
- ***Commissioning finished and the physics run started June 2022!***

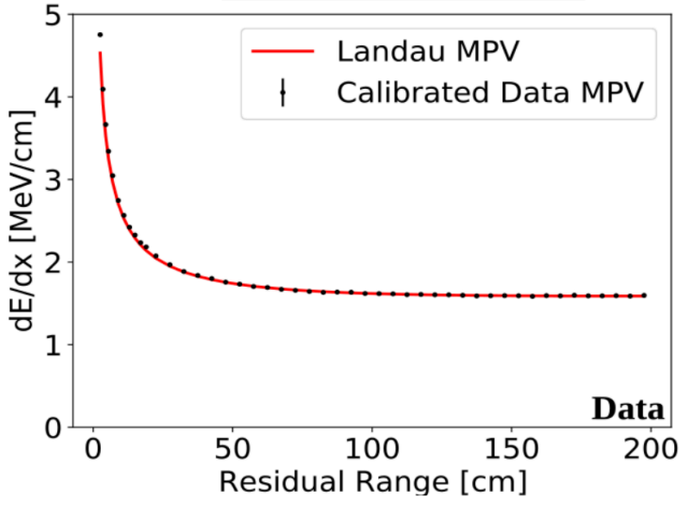
Commissioning



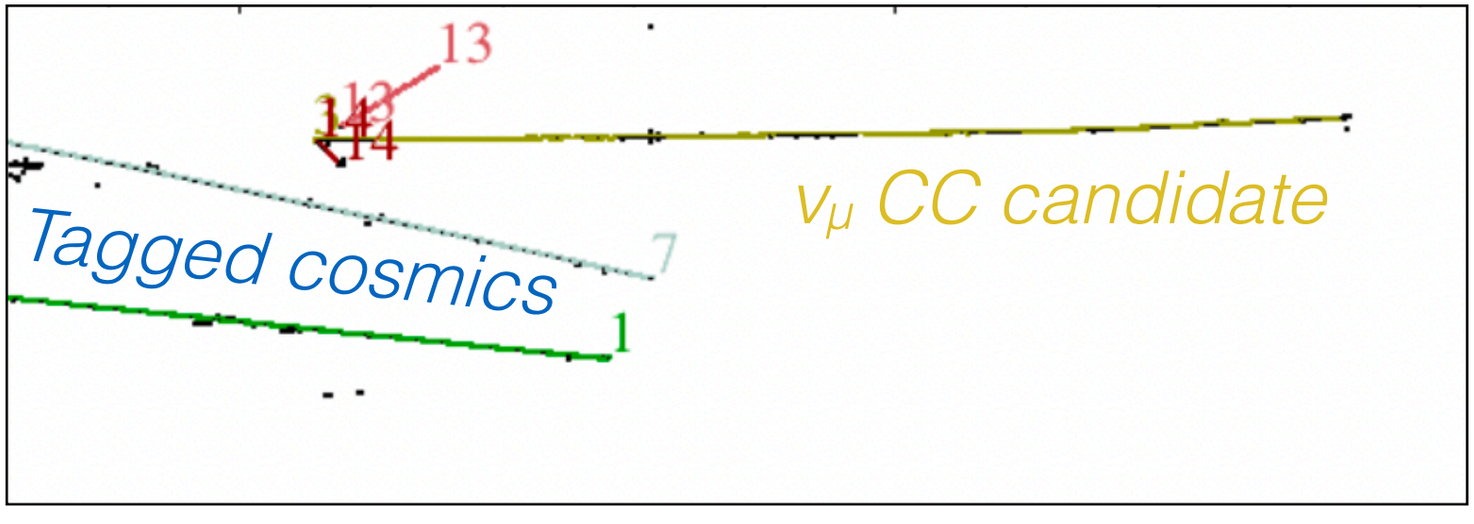
Data-to-MC Comparisons



Calibrations



Reconstructed neutrino interactions

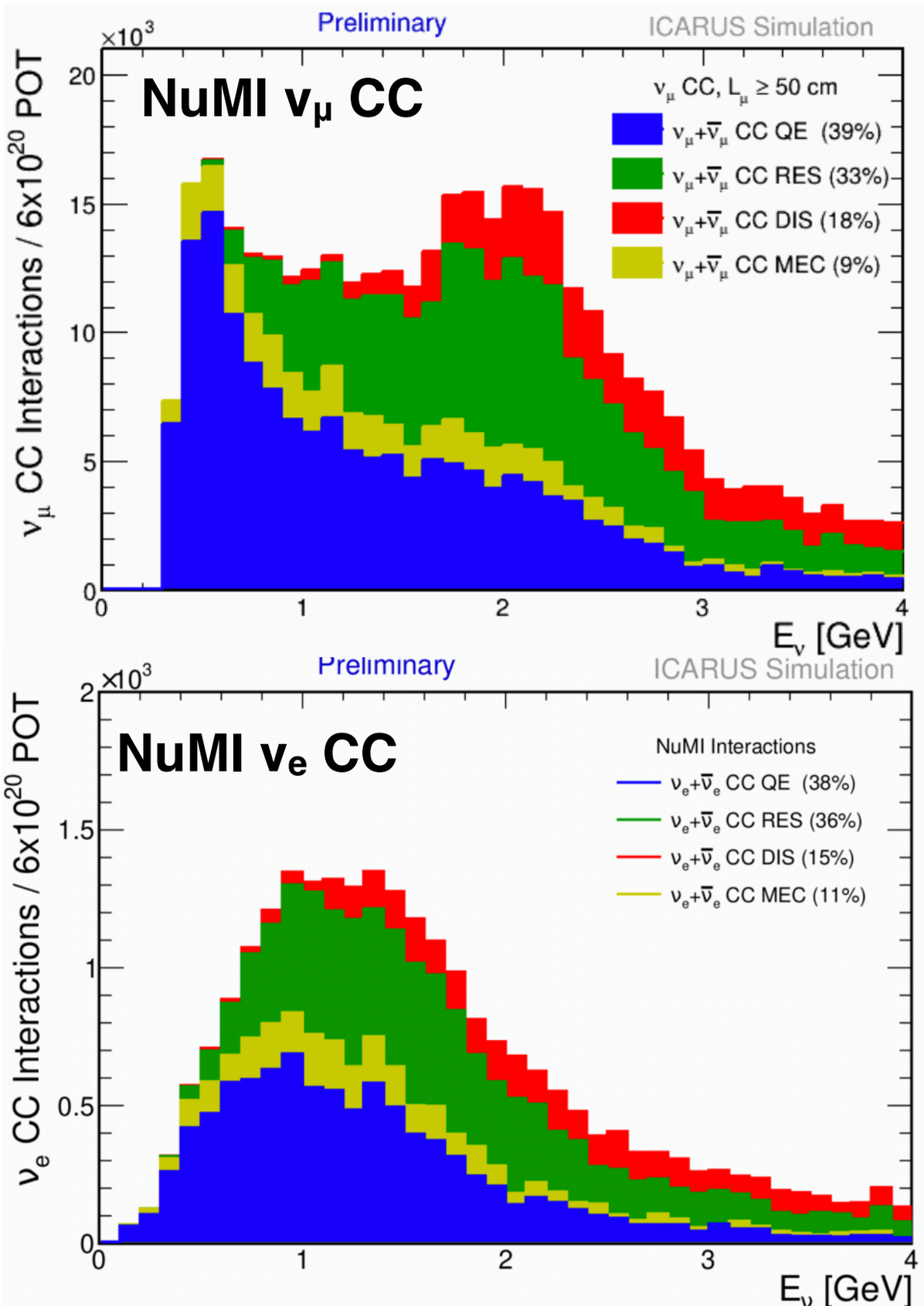


NuMI Cross Section Program

- ICARUS is exposed to the off-axis (6°) NuMI neutrino beam
  - This leads to a strong enhancement in the ve content of the beam
  - 5% in NuMI vs. 0.5% in BNB

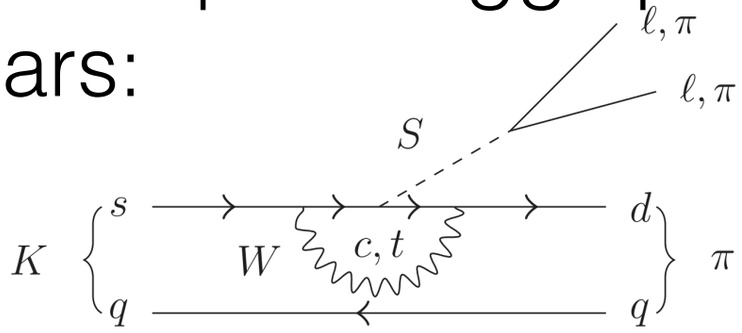
- The higher proton energy of NuMI (120 GeV) leads to higher neutrino energies

- This provides ICARUS a complementary sample to study neutrino interactions for DUNE



Highly Off-axis BSM Searches

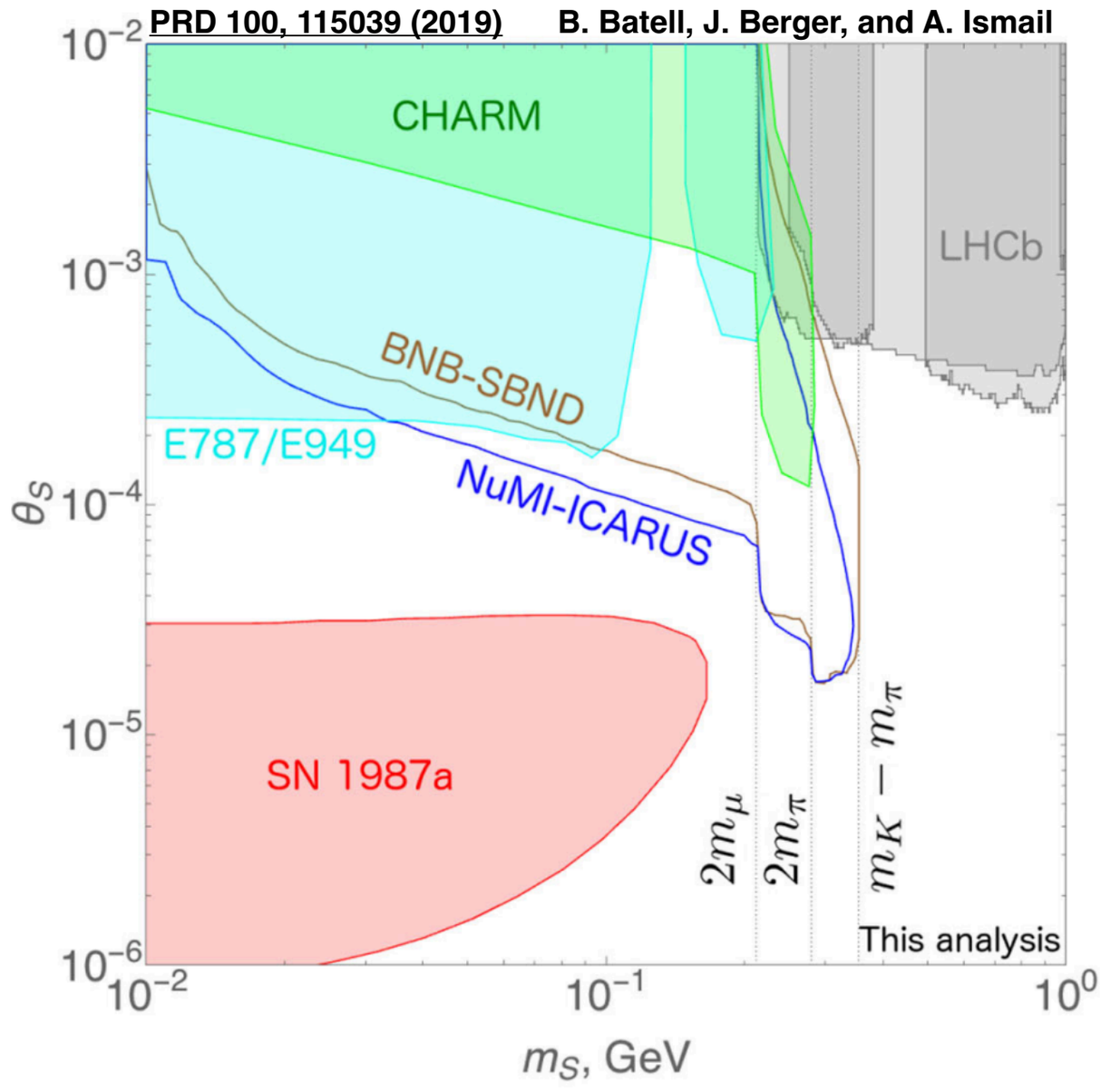
- Certain BSM searches benefit from sitting off-axis such as kaon coupled Higgs portal scalars:



- Phenomenological studies have shown great promise for a search like this
  - Analyses exploring this are ongoing!

- Other searches include low mass dark matter, Higgs portals, heavy neutral lepton decays

Phenomenological study

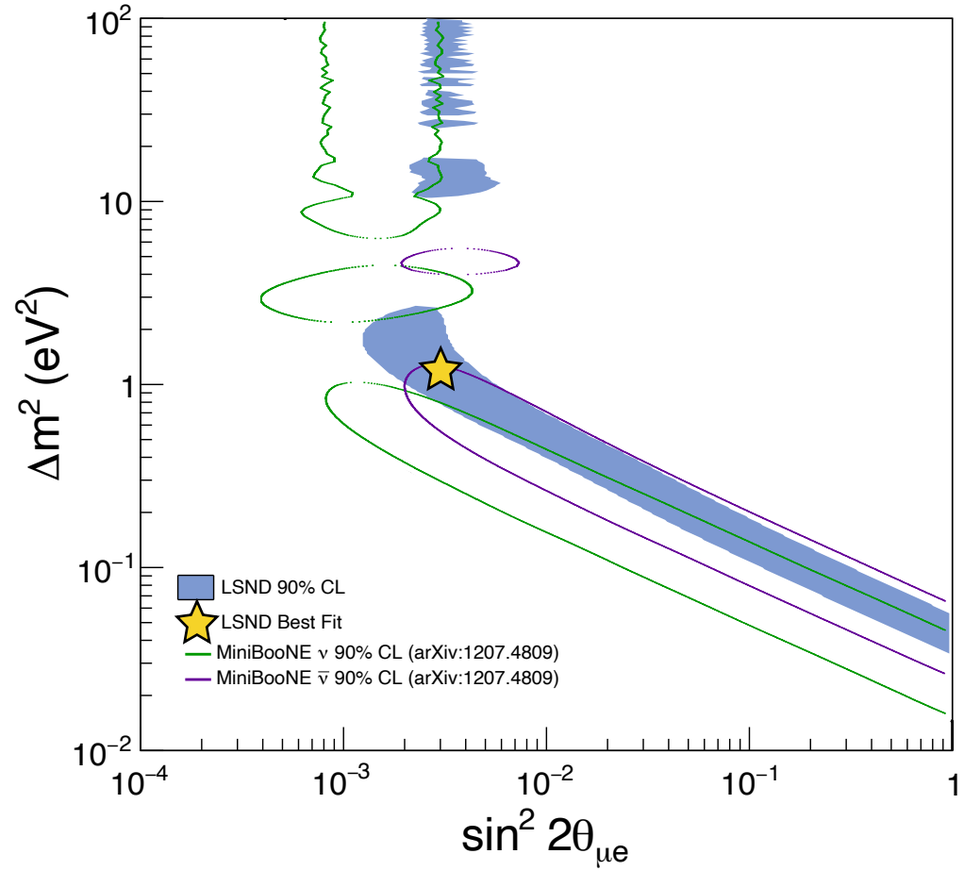


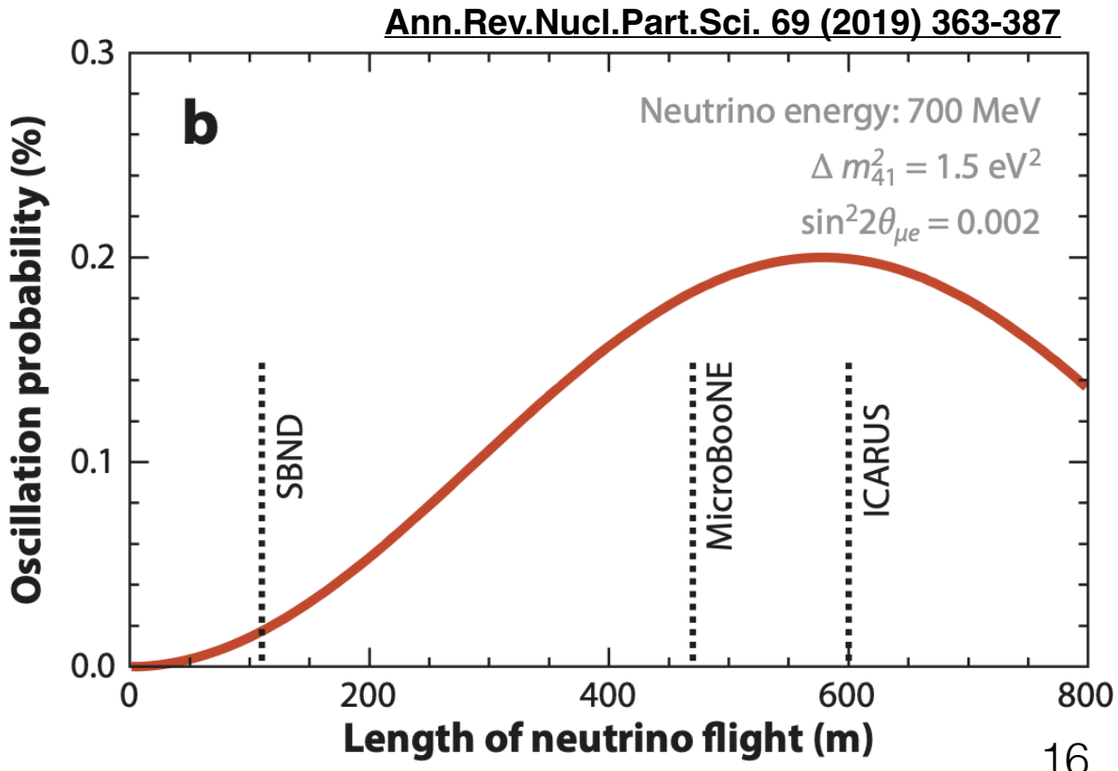
SBN Program: Bringing Them Together

- Designed to **definitively** cover the ν_s oscillation parameters that cover the LSND results

- SBN does this by leveraging the shared target, beam, and detector technology to reduce systematics
  - Must be sensitive to sub-percent oscillation probabilities

- SBN is unique that it can search for oscillations via ν_μ disappearance and ν_e appearance & disappearance, simultaneously
  - **Can directly test the sterile neutrino oscillation hypothesis!**

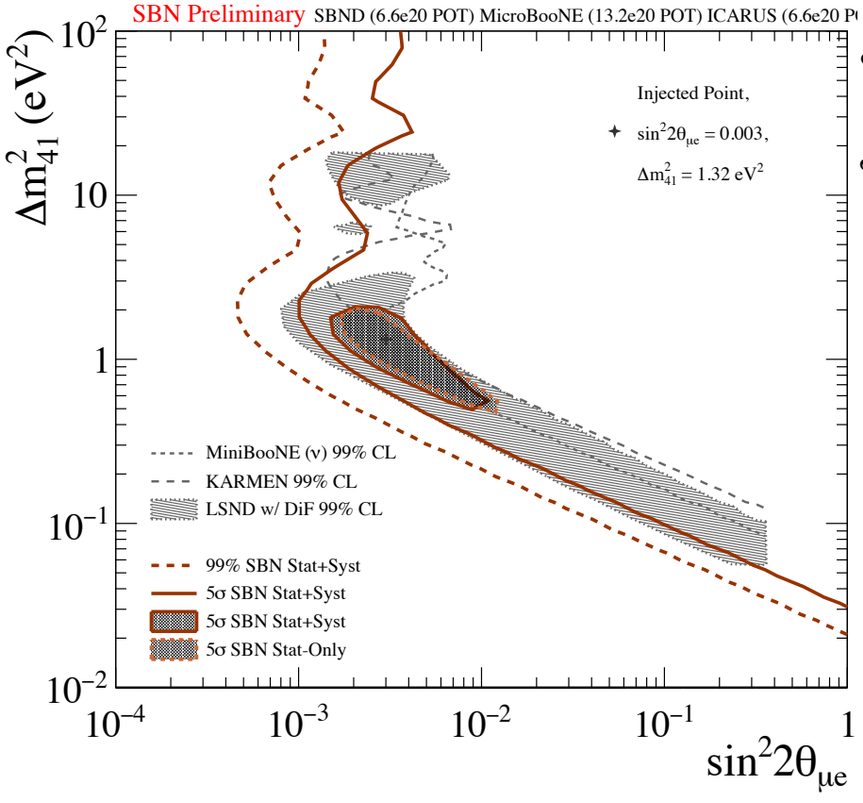




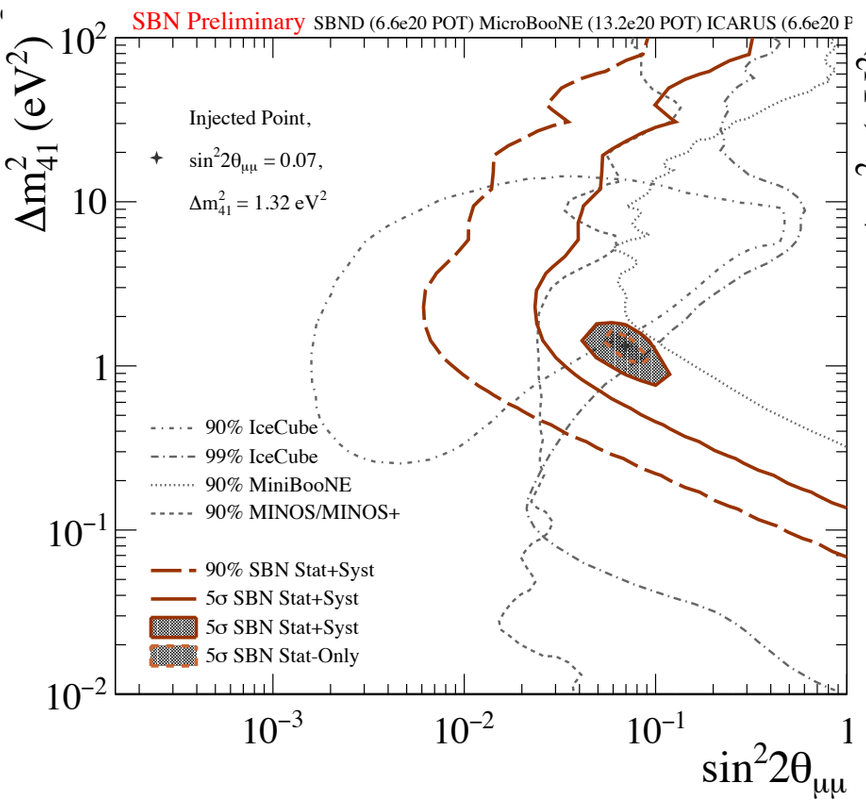
Searches for Sterile Neutrinos

Searches for sterile neutrinos with the SBN Program will definitively cover the LSND allowed region and stringently test the global allowed regions in three channels!

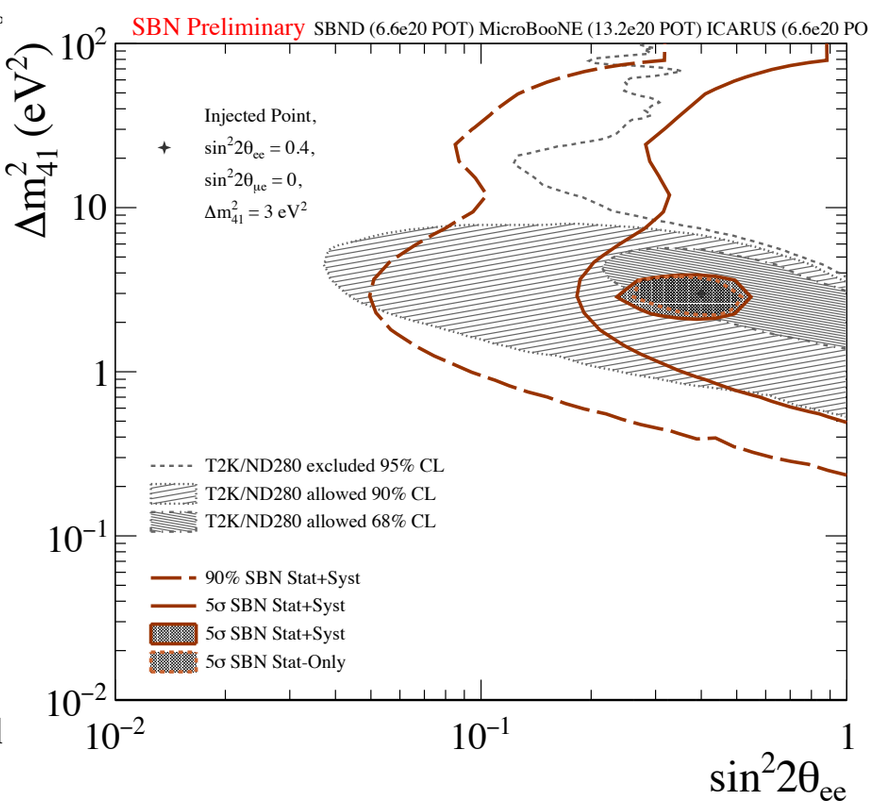
ν_e appearance



ν_μ disappearance



ν_e disappearance

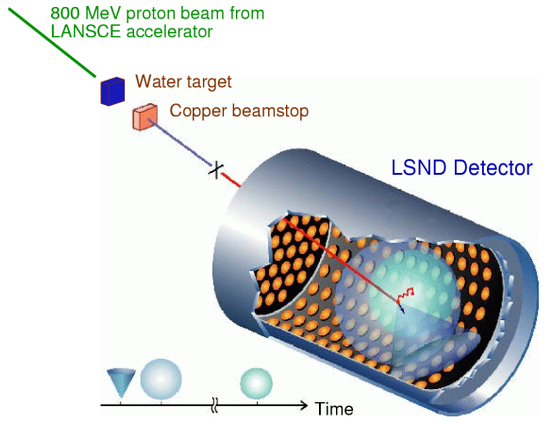


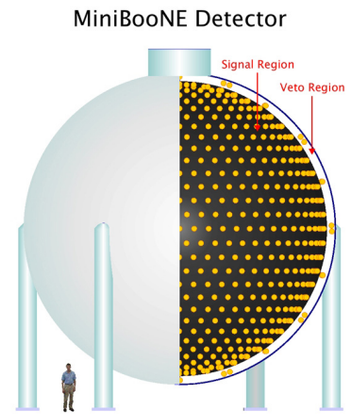
Conclusions

- SBND is finishing detector assembly, and ICARUS has started its physics running
- Stay tuned as the SBN Program launches itself toward an exciting physics program!
  - Including world-leading v-Ar cross section measurements, definitive searches for eV-scale sterile neutrino oscillations, and other BSM physics

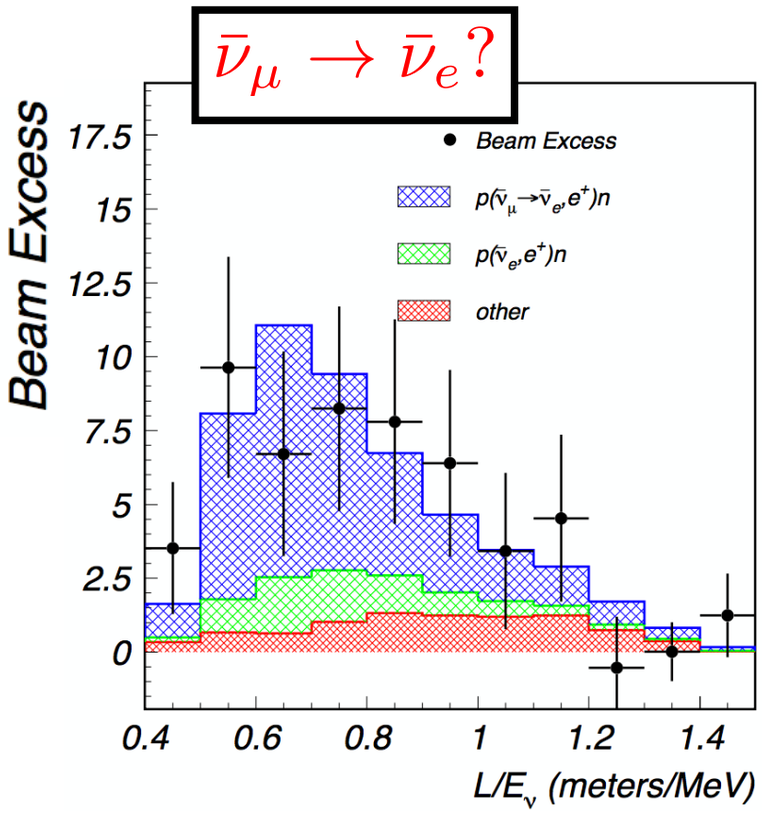
Neutrino Anomalies

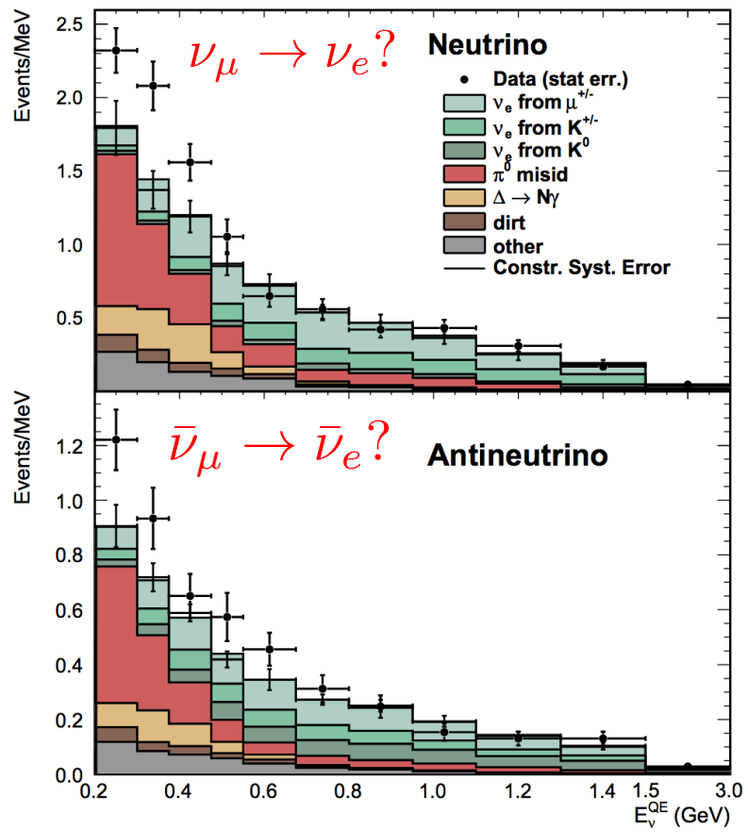
- Experiments have explored this region by searching for ν_μ to convert into ν_e along short-baselines
  - The most significant of these come from LSND
  - MiniBooNE followed up with additional anomalous results
- These two experiments can be interpreted in a similar way





$$\frac{L}{E} \approx 0.001 \frac{\text{km}}{\text{MeV}}$$

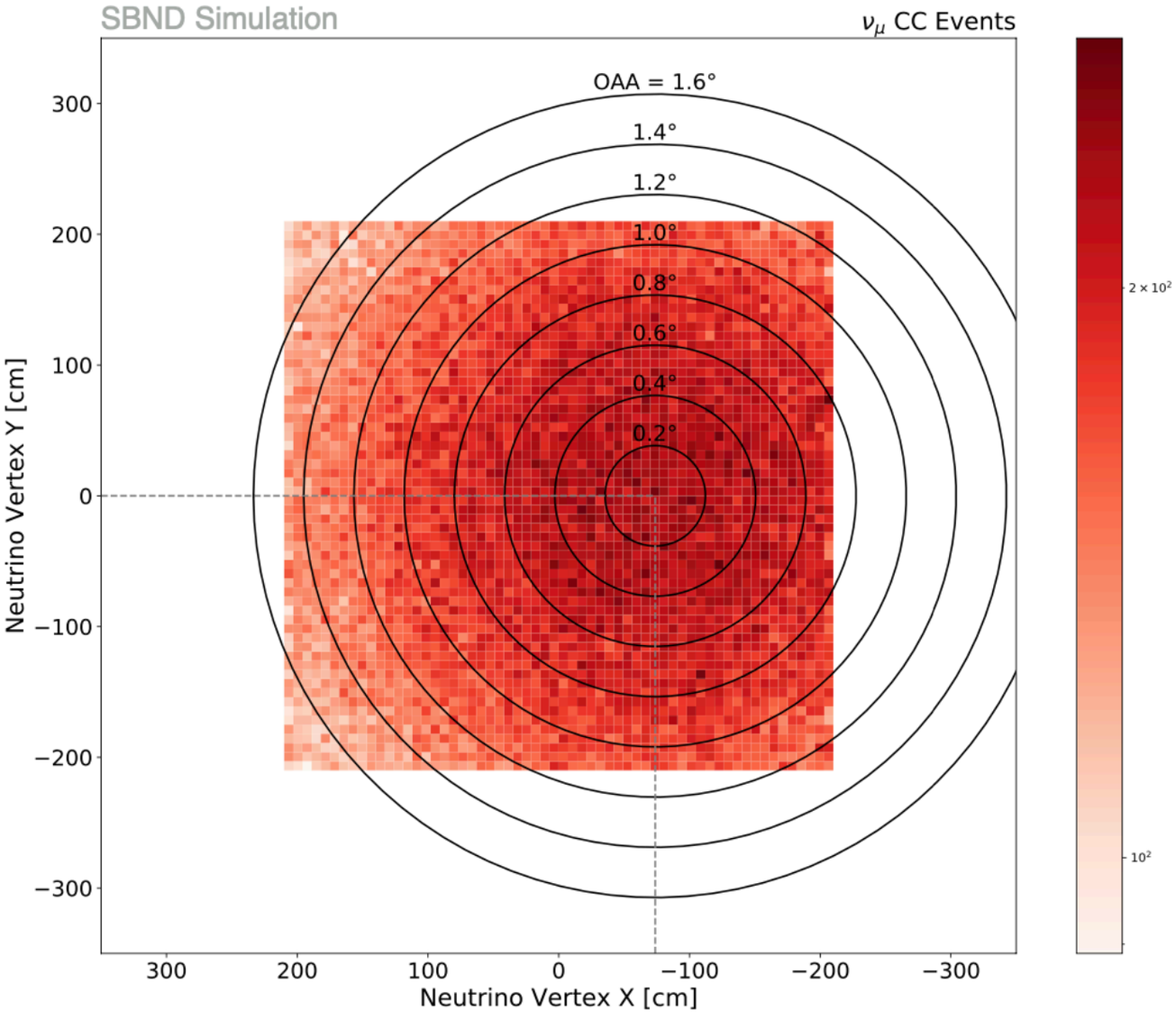


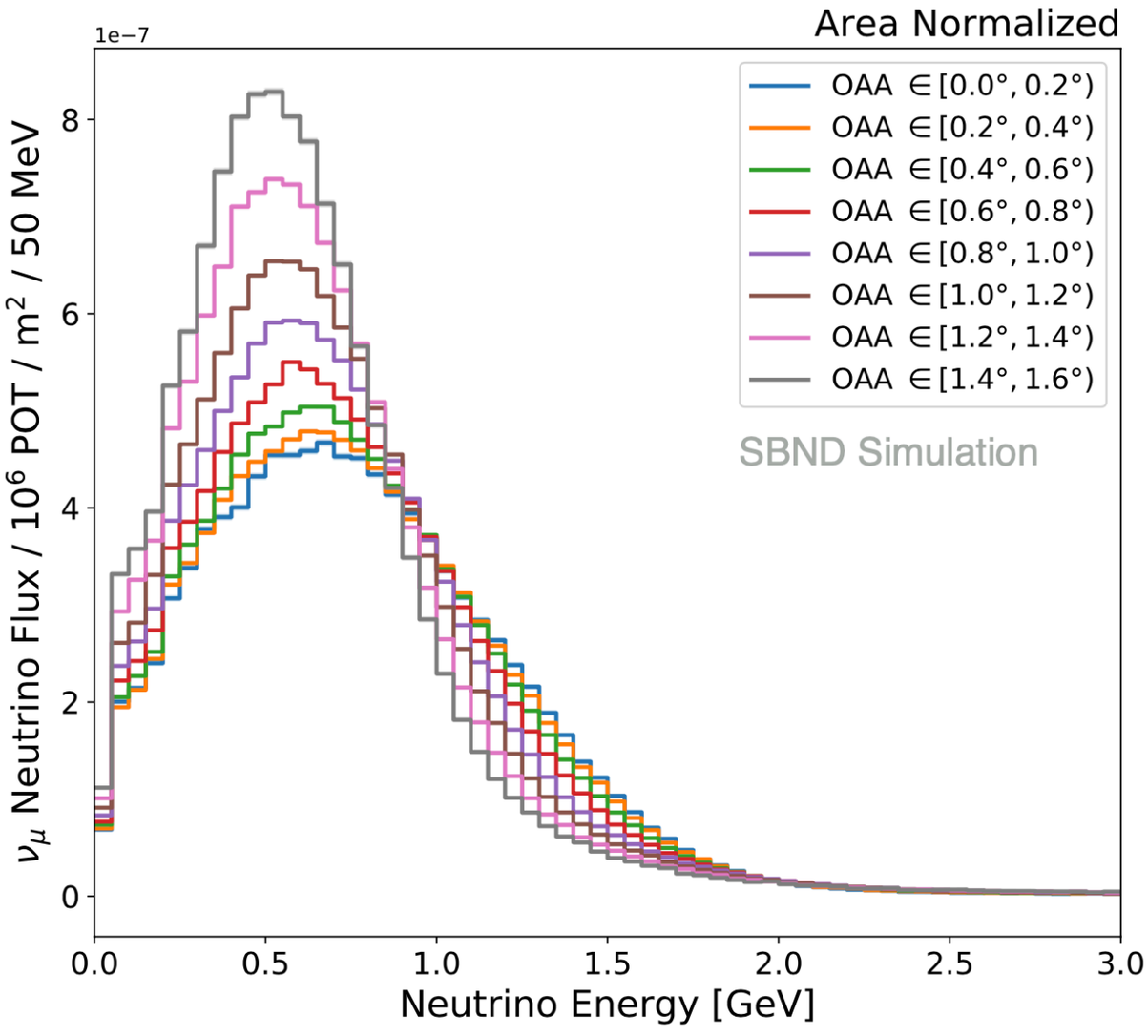


SBND Prism

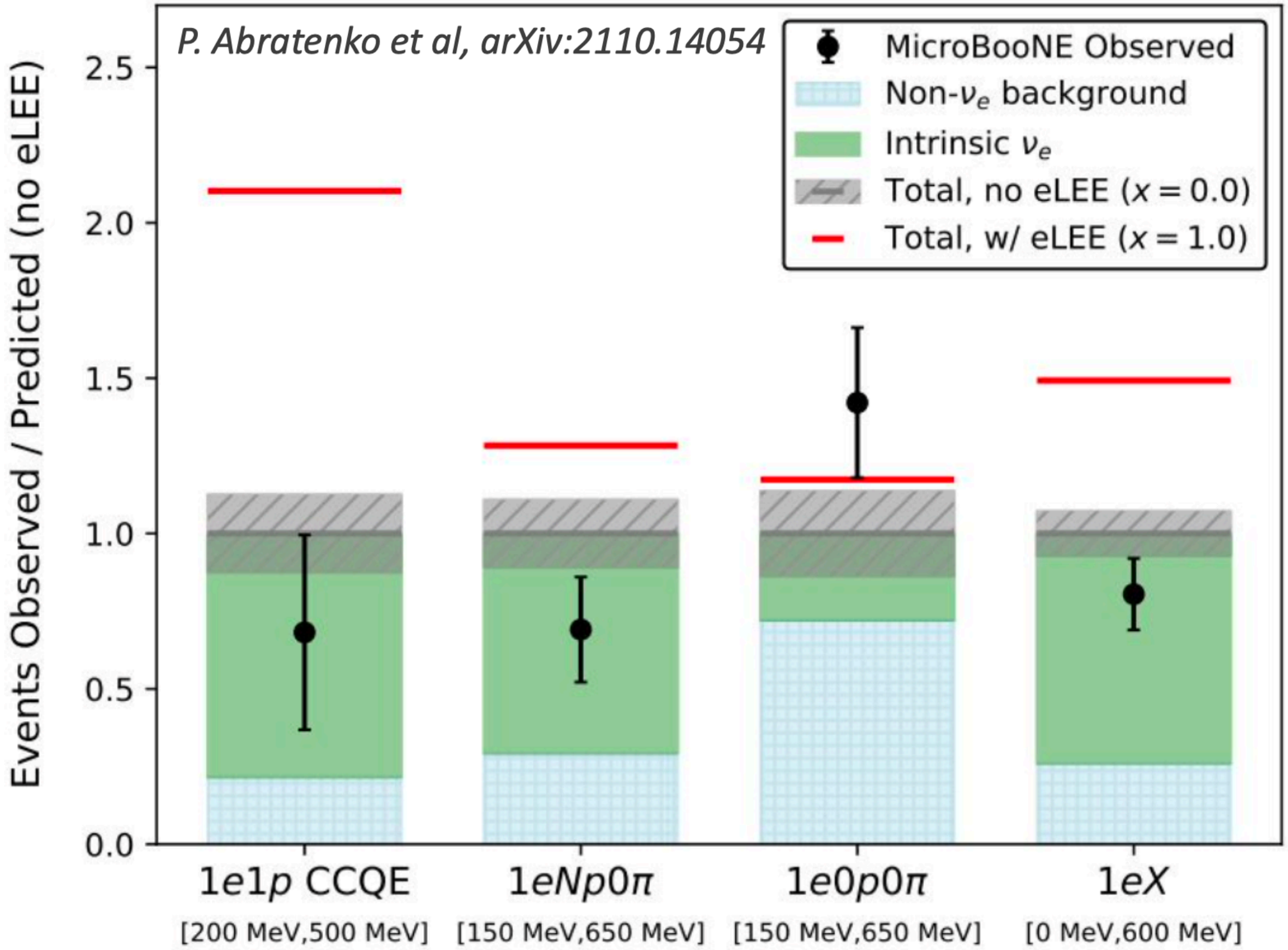
Muon-neutrinos CC Events

peak coincident with the on-axis position





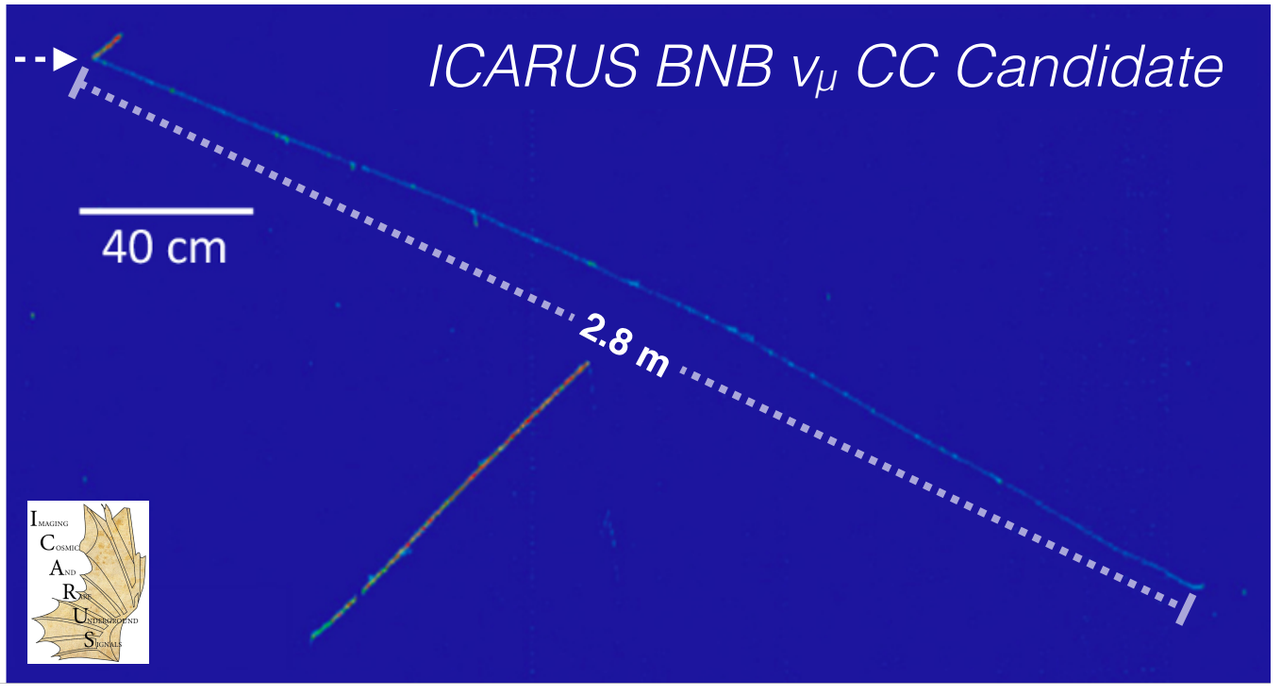
MicroBooNE Results

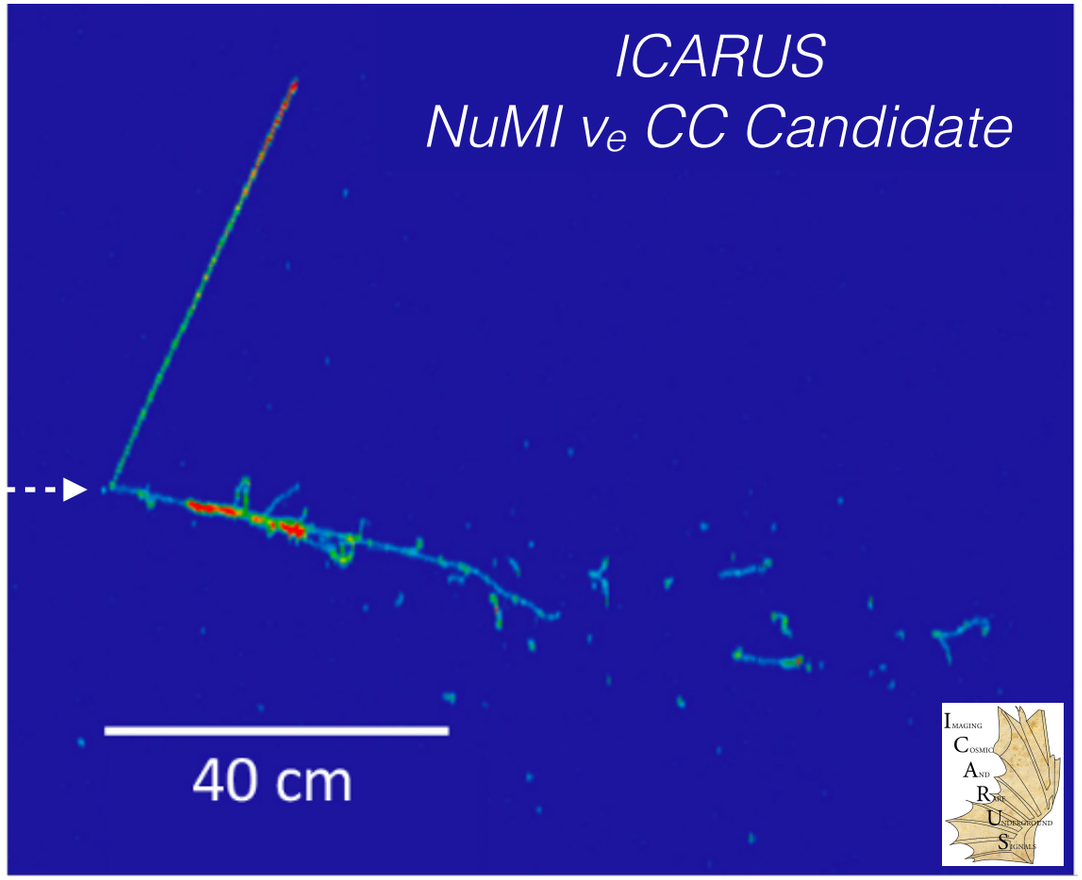


See Josh Barrow's Talk Thursday

Liquid Argon TPCs

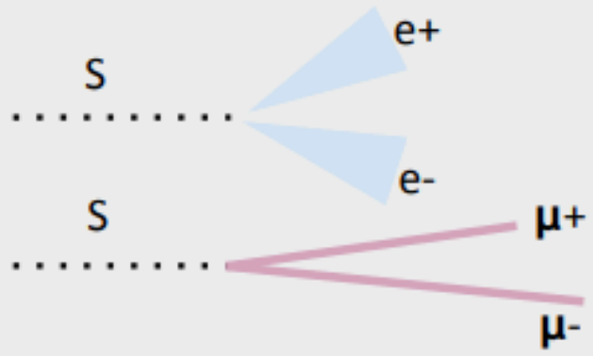
- LArTPCs work by drifting ionization electrons through monolithic volumes of LAr to sensitive readout planes and offer:
  - **Low Thresholds** – important for detecting low-energy particles
  - **Excellent Calorimetry** – important for precise estimation of neutrino energy and identifying particles
  - **High Spatial Resolution** – allows for background rejection and particle ID
  - **Scalability** – large detectors yielding high event rates for precision physics
- Using these detectors we study electron and muon neutrinos with high precision





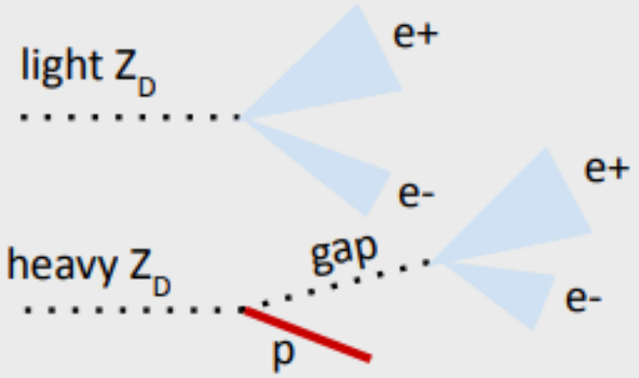
Searching for New Physics in the BNB

Higgs Portal Scalar



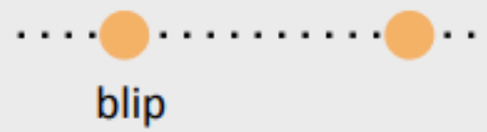
e^+e^- or $\mu^+\mu^-$ pair with no hadronic activity

Dark Neutrinos



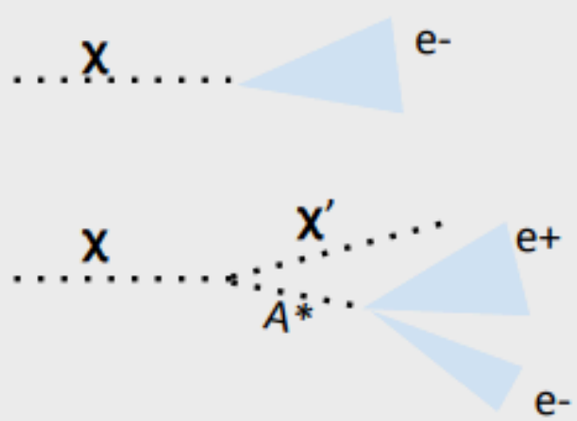
e^+e^- pair with or without hadronic activity

Millicharged Particles



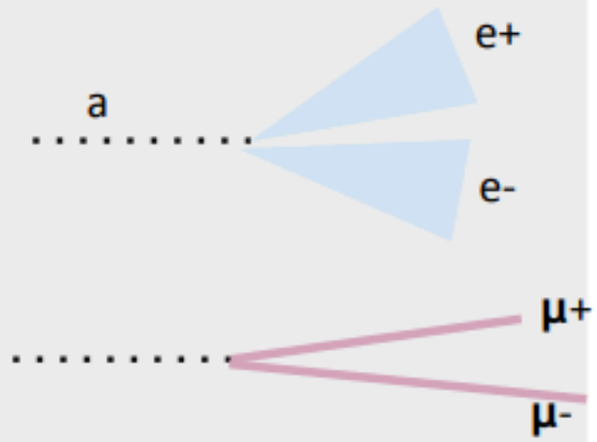
blips or faint tracks

Light Dark Matter



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

Axion-Like Particles



high-energy e^+e^- pair

Heavy Neutral Leptons

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

Images from Supraja Balasubramanian