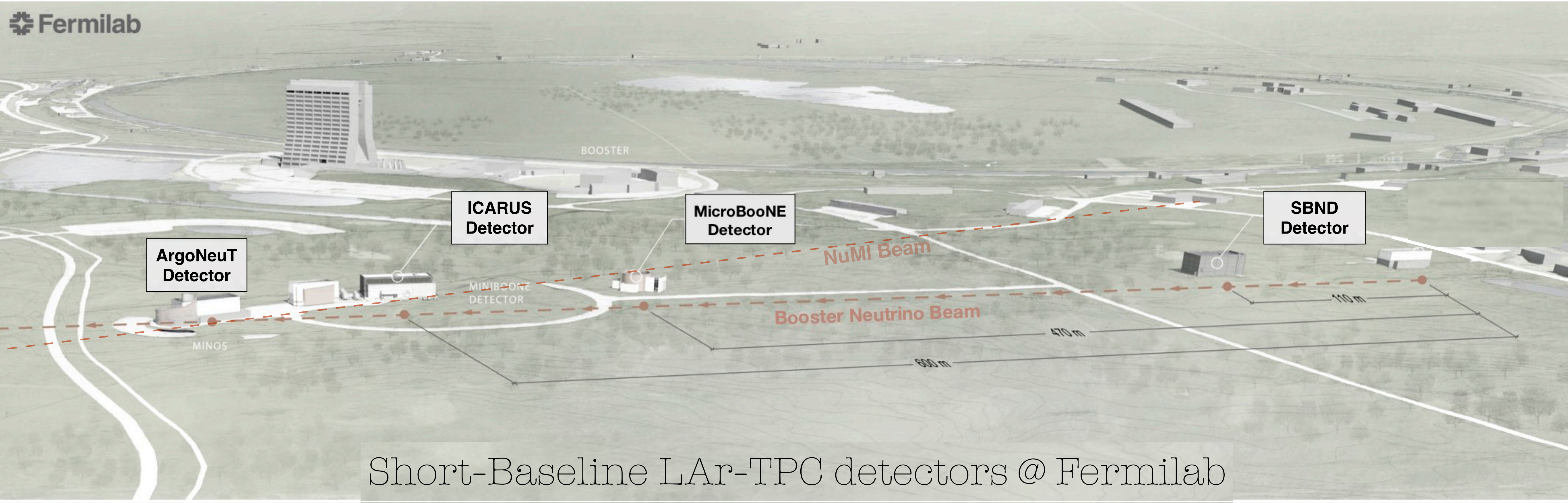


Short-Baseline Liquid Argon Neutrino Experiments

Interdisciplinary Developments in Neutrino Physics Conference
KITP, UC Santa Barbara
March 28th 2022

Ornella Palamara
Fermilab

Outline

Why Short-Baseline* (SBL) Neutrino Experiments?

Beyond three neutrino mixing & alternative physics scenarios.

Why Beyond Standard Model in SBL Liquid Argon Time Projection Chamber Neutrino Experiments?

MicroBooNE: first low energy excess result.

ArgoNeuT: constraints on new physics in unexplored parameter space regions.

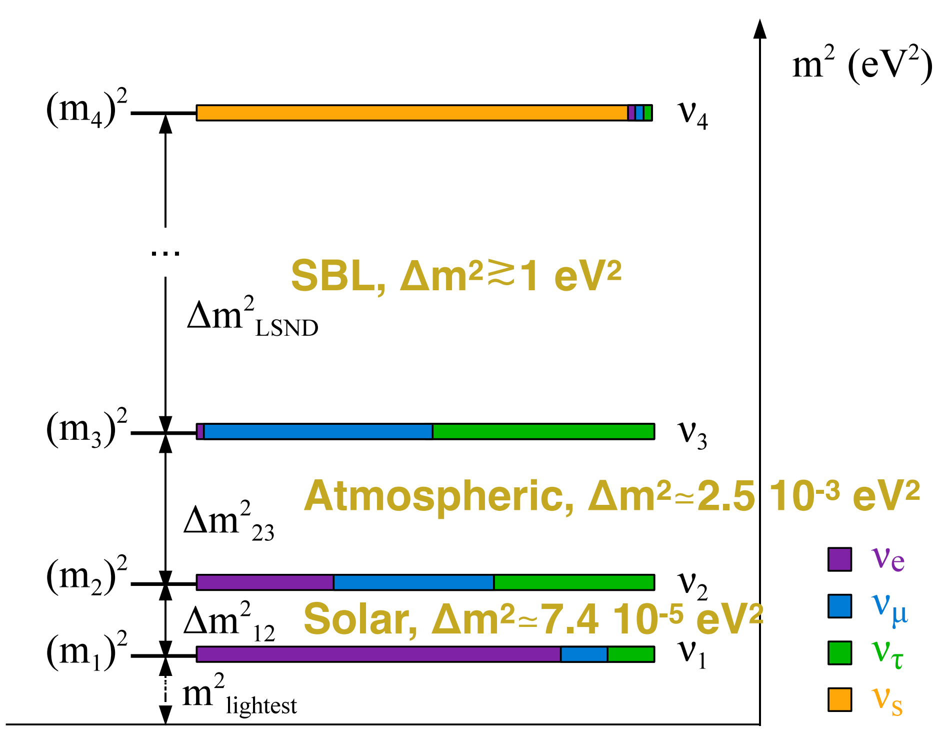
Short-Baseline Neutrino program: sterile neutrinos & other BSM explorations and neutrino interaction measurements.

* Short-Baseline: L ~ 100-1000 m, L/E ~ 1 eV^2, to be compared with Long-Baseline: L ~ 100-1000 Km, L/E ~ $10^{-3} eV^2$

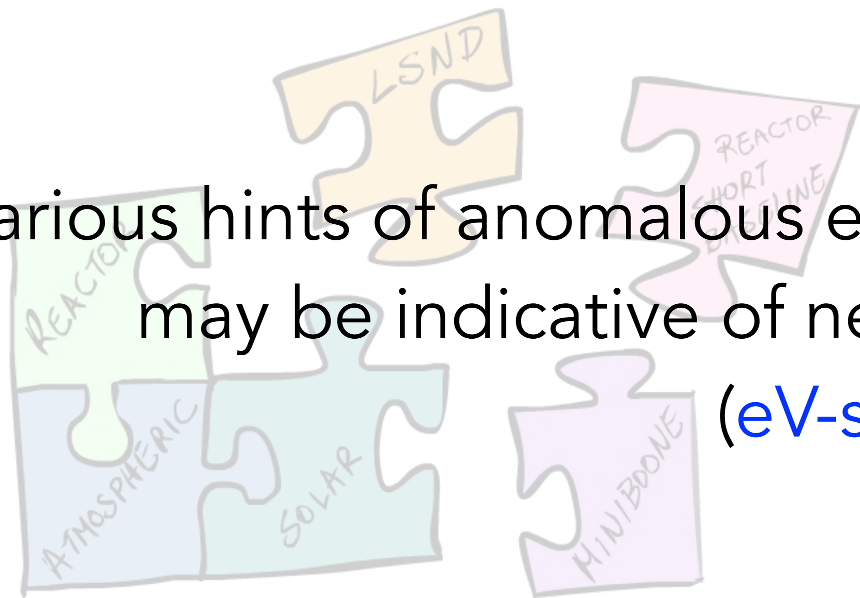
Short-Baseline Neutrino Anomalies

Accelerator "anomalies" (LNSD and MiniBooNE experiments) +
Reactor and Gallium "anomalies"

could be pointing at BSM physics in the neutrino sector:
additional "sterile" neutrino state(s) with
large mass-squared differences,
driving neutrino oscillation at small distances.



Why Short-Baseline Neutrino Experiments?



Mainly:

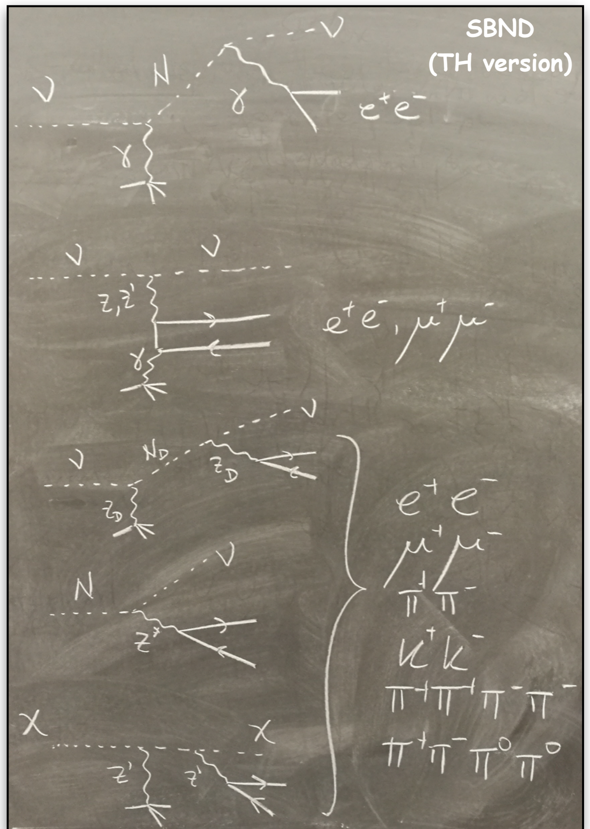
Various hints of anomalous electron-flavor appearance and disappearance may be indicative of new neutrinos participating in oscillations (eV-scale sterile neutrinos)

and also

Neutrino cross sections measurements for understanding neutrino interaction with matter and informing oscillation measurements.

But it is an evolving landscape

Alternative potential explanations from more recently emerging new physics scenarios from theory.



Courtesy of P. Machado

SBL Liquid Argon Experiments

- The parameter space of new oscillations/interactions continues to be explored with accelerator-based, including decay-in-flight and decay-at-rest, and reactor-based SBL experiments.*

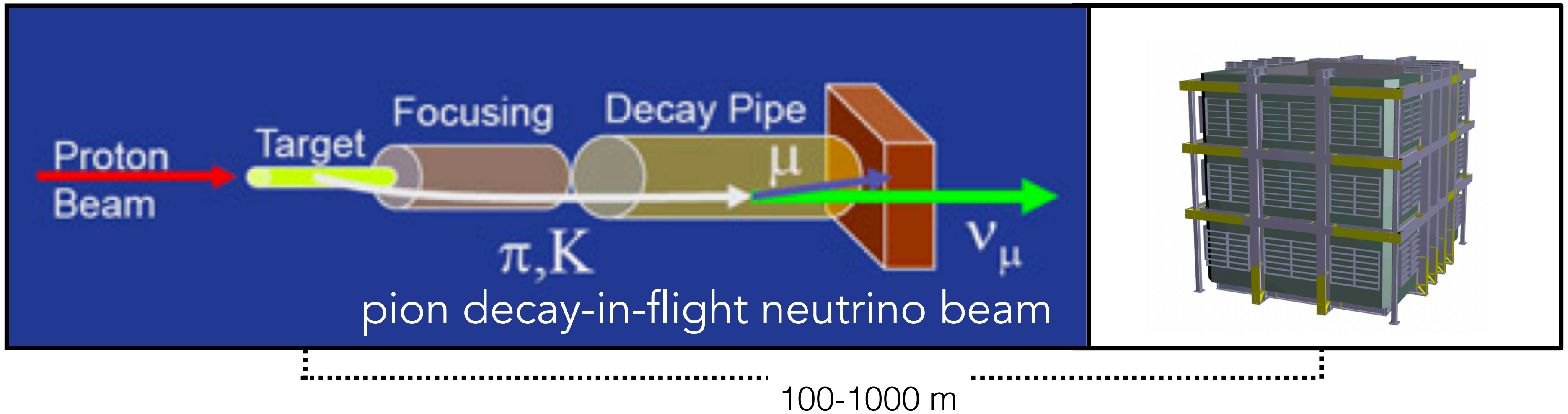
- Here will focus on recent results and status of accelerator-based (decay-in-flight) Liquid Argon Time Projection Chamber (LAr TPC) experiments:

  - Short-baseline Neutrino (SBN) program and ArgoNeuT experiment at Fermilab.

ArgoNeuT SBND µBooNE ICARUS @ Fermilab

*See C. Giunti, T. Lasserre, arXiv:1901.08330 for a review on eV-scale sterile neutrinos, including a complete list of current/future experiments (accelerator- and reactor-based experiments). See presentation from K. Heeger at this conference (on Wednesday), for a review of SBL reactor experiments.

Why BSM in SBL LAr TPC Neutrino Experiments?



The combination of

- **High-intensity proton beams (high intensity neutrino beams)** coupled with
- **Large mass LAr TPC detectors** close to the beam target, with
  - Event imaging
  - Fine granularity calorimetry and particle identification
  - Good timing resolution
  - Low energy threshold

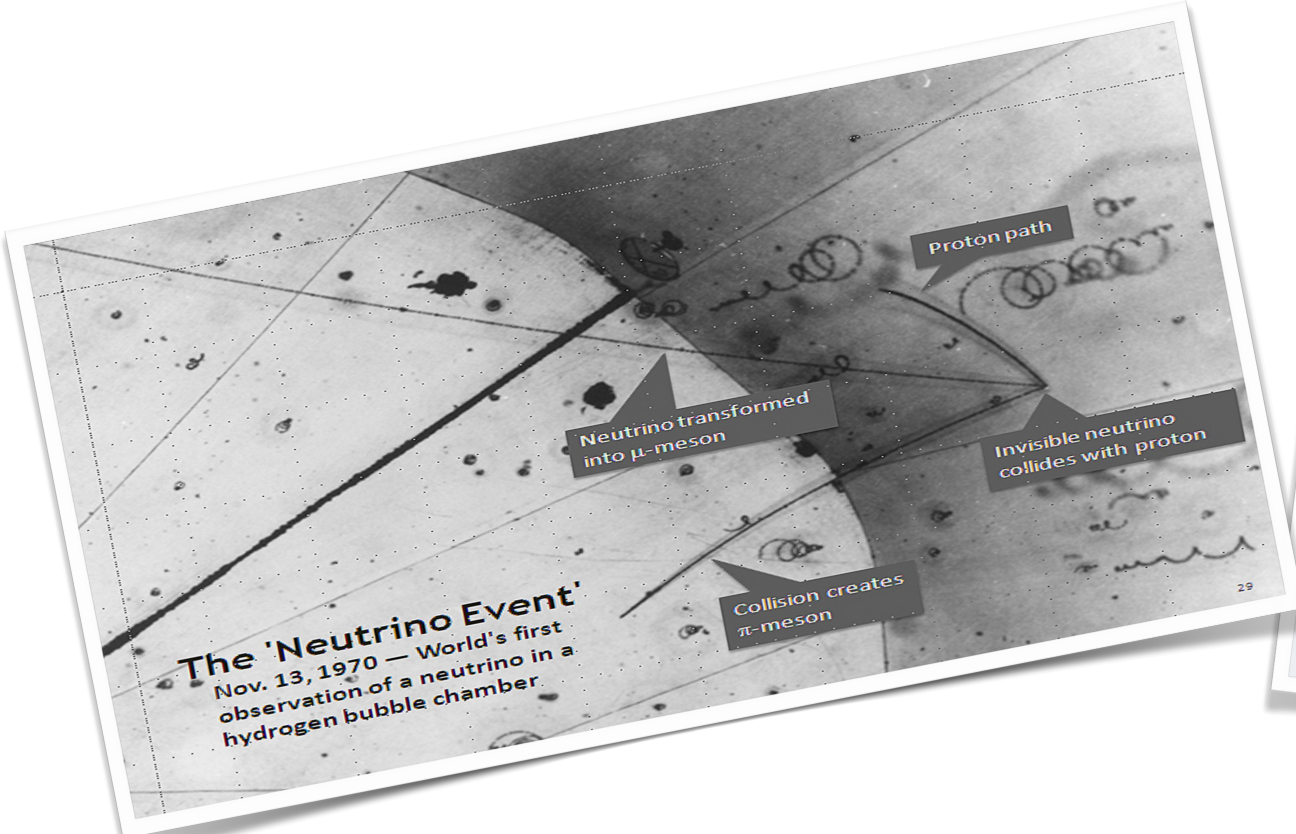
opens up unprecedented opportunities to probe signatures for

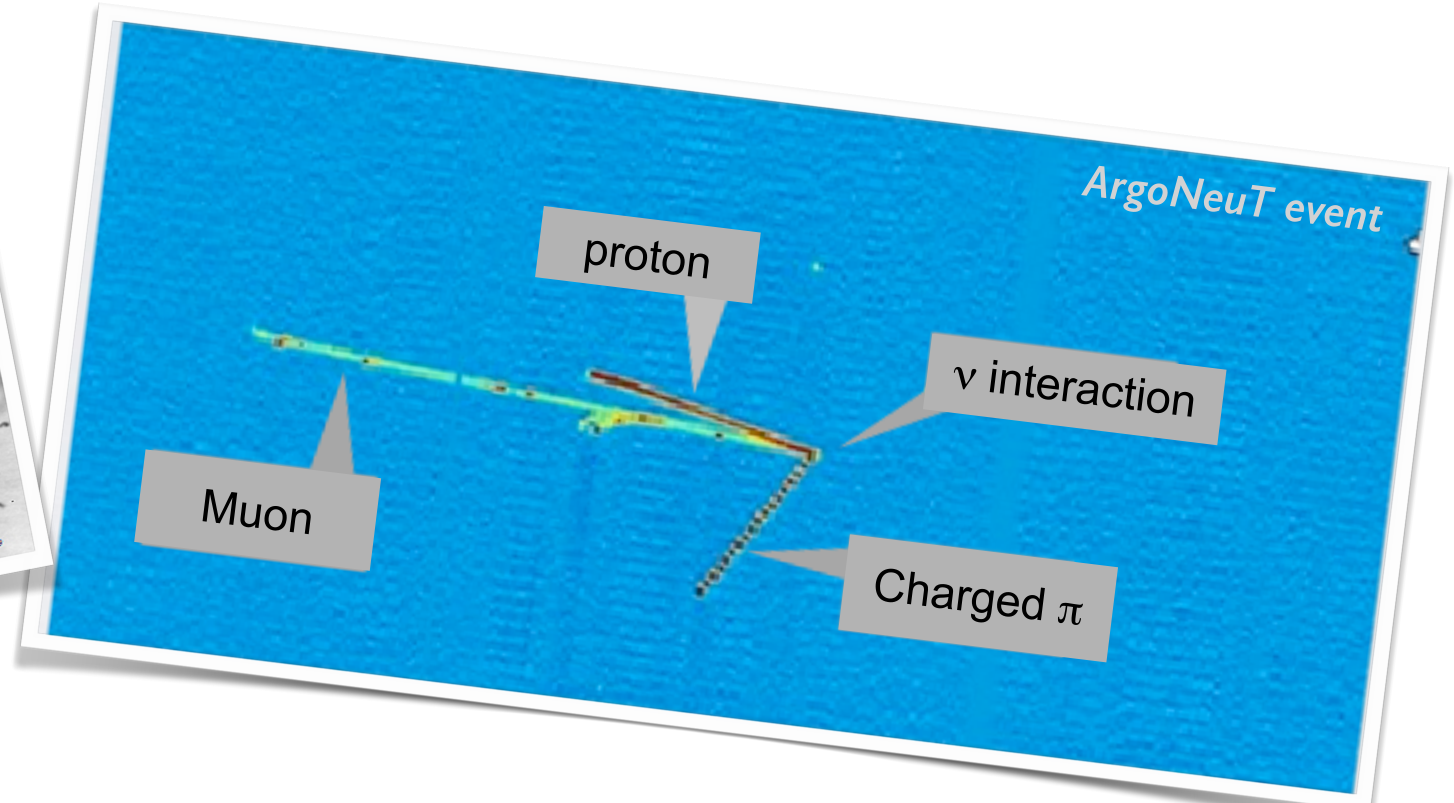
New Physics scenarios in the neutrino sector and beyond

Modifications to the neutrino oscillation paradigm
(effects of BSM physics on neutrino oscillation)

Novel experimental signatures
produced in the beam target

Why Liquid Argon Time Projection Chamber?





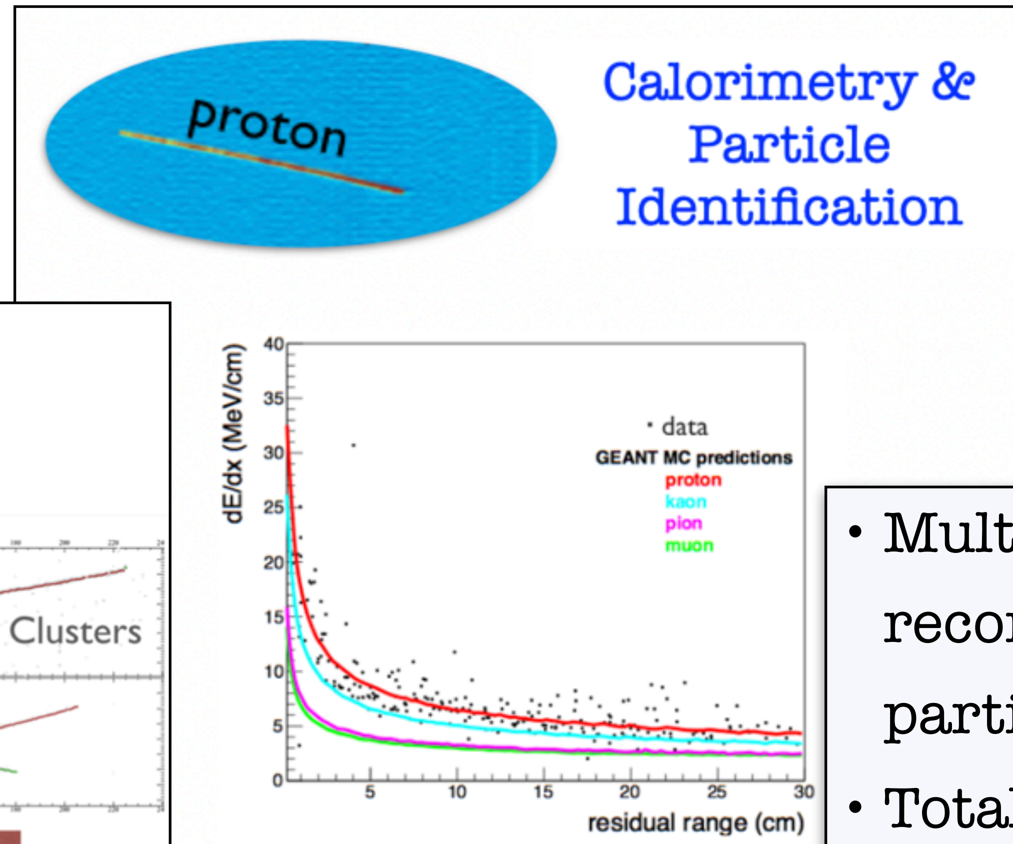
LAr TPC: Bubble chamber quality of data with added calorimetry

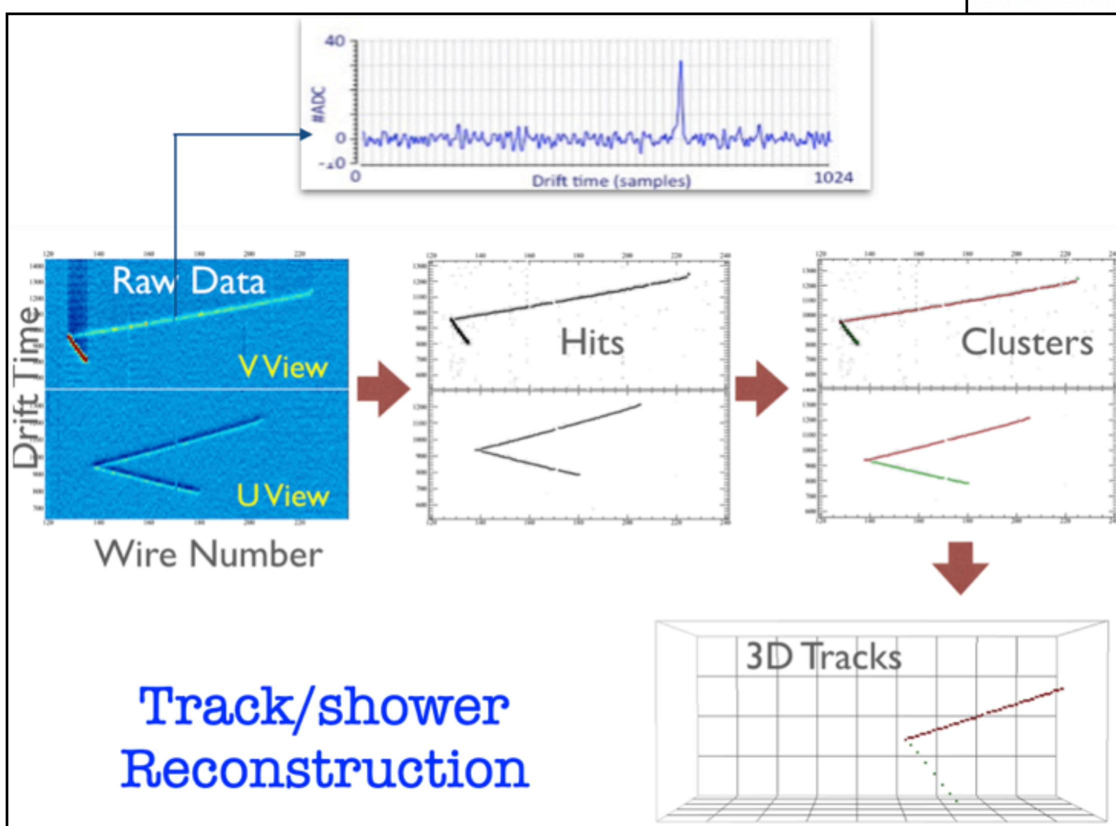
Liquid argon is the technology of choice for precision neutrino physics.

The LAr TPC Technology

Measure neutrino interactions **in real time with millimeter position resolution.**
Excellent capability for energy depositions **from sub-MeV to few GeV**,
far beyond that offered by any other neutrino detector.

LArTPC at work: imagining, energy and timing

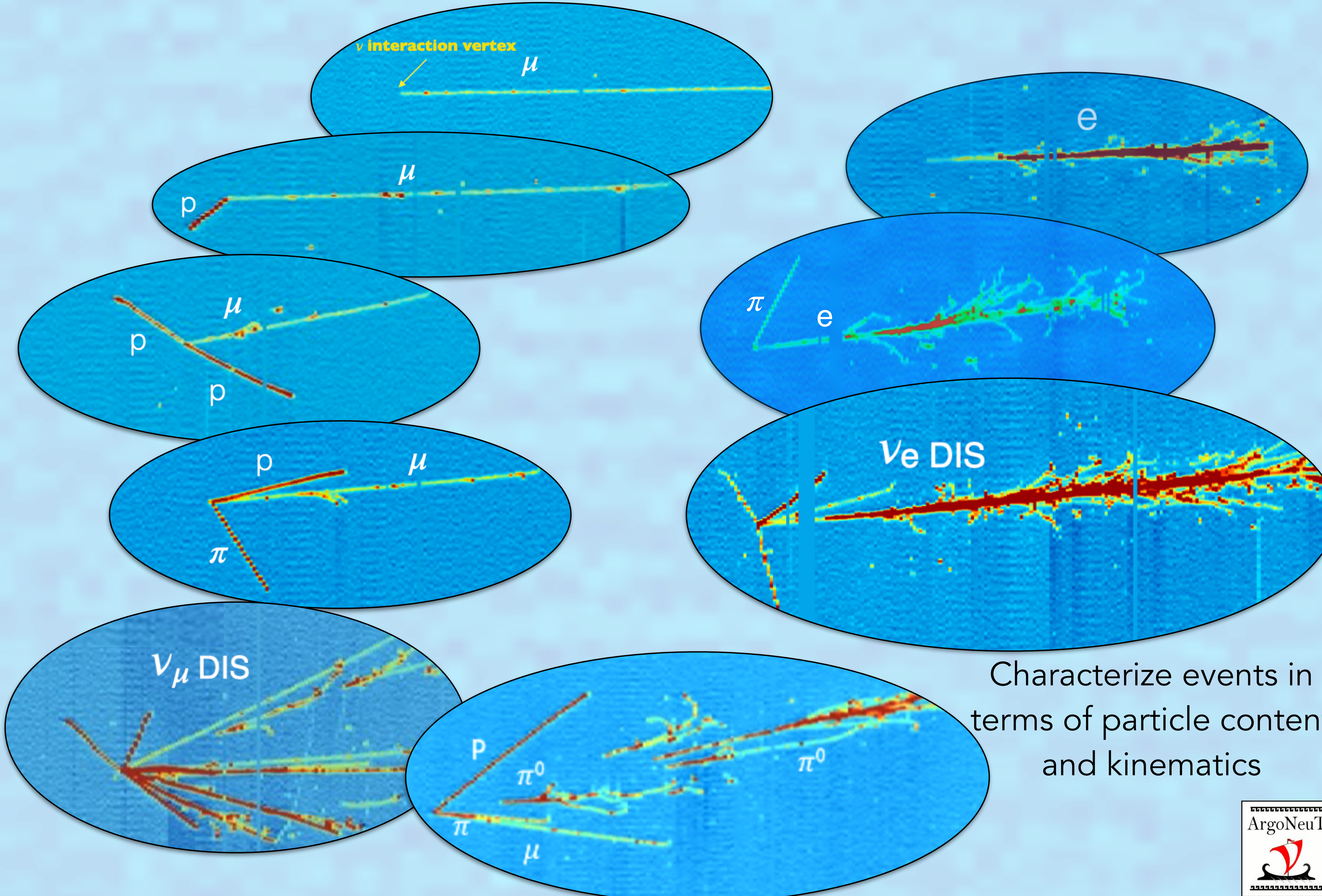




- Multiple 2D and the 3D reconstruction of charged particles ⇒ **Imaging**
- Total charge proportional to the deposited energy ⇒ **Calorimetry**
- dE/dx along the track ⇒ **Particle Identification**

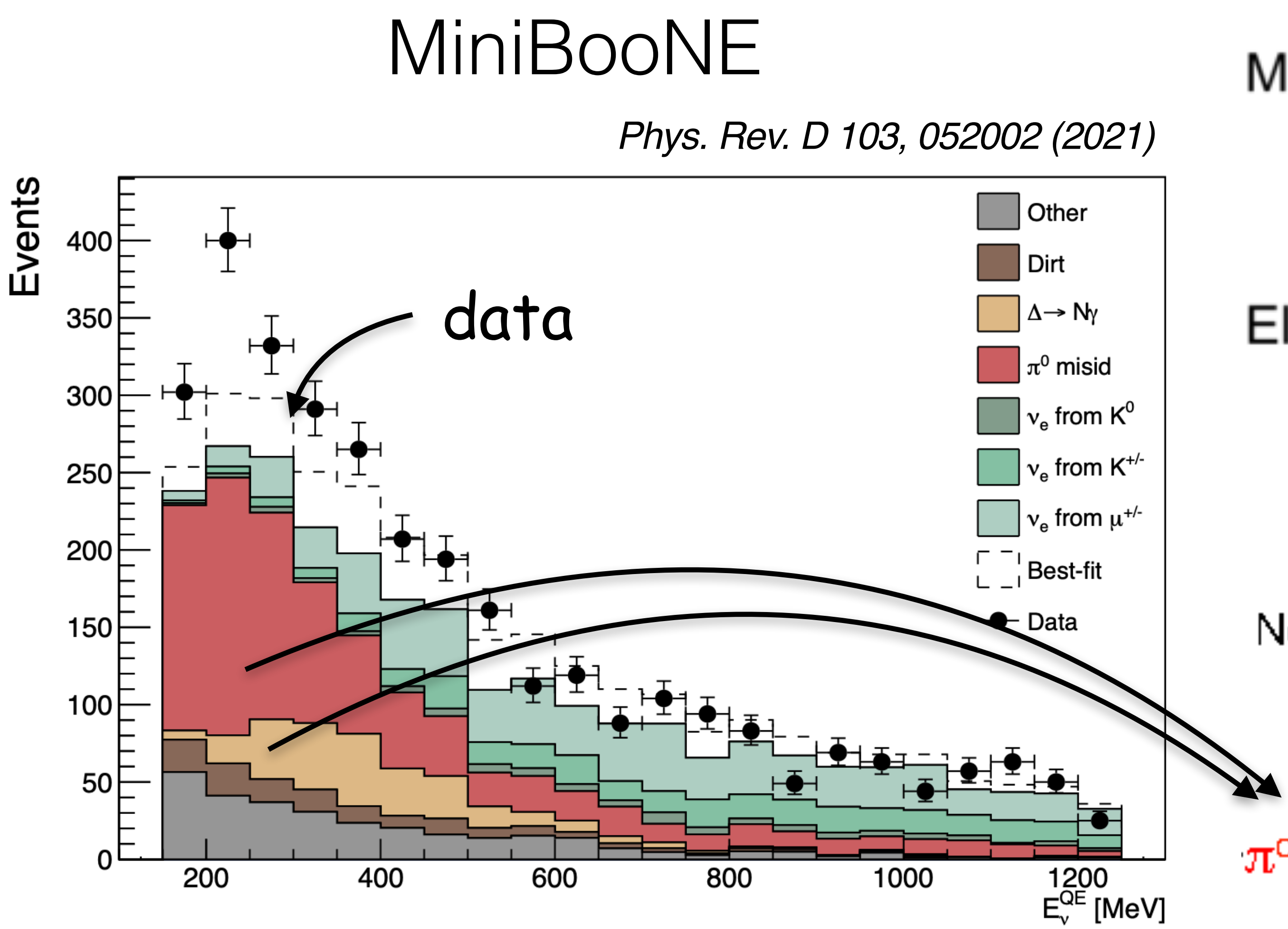
and few ns **timing** resolution from light detection system(s).

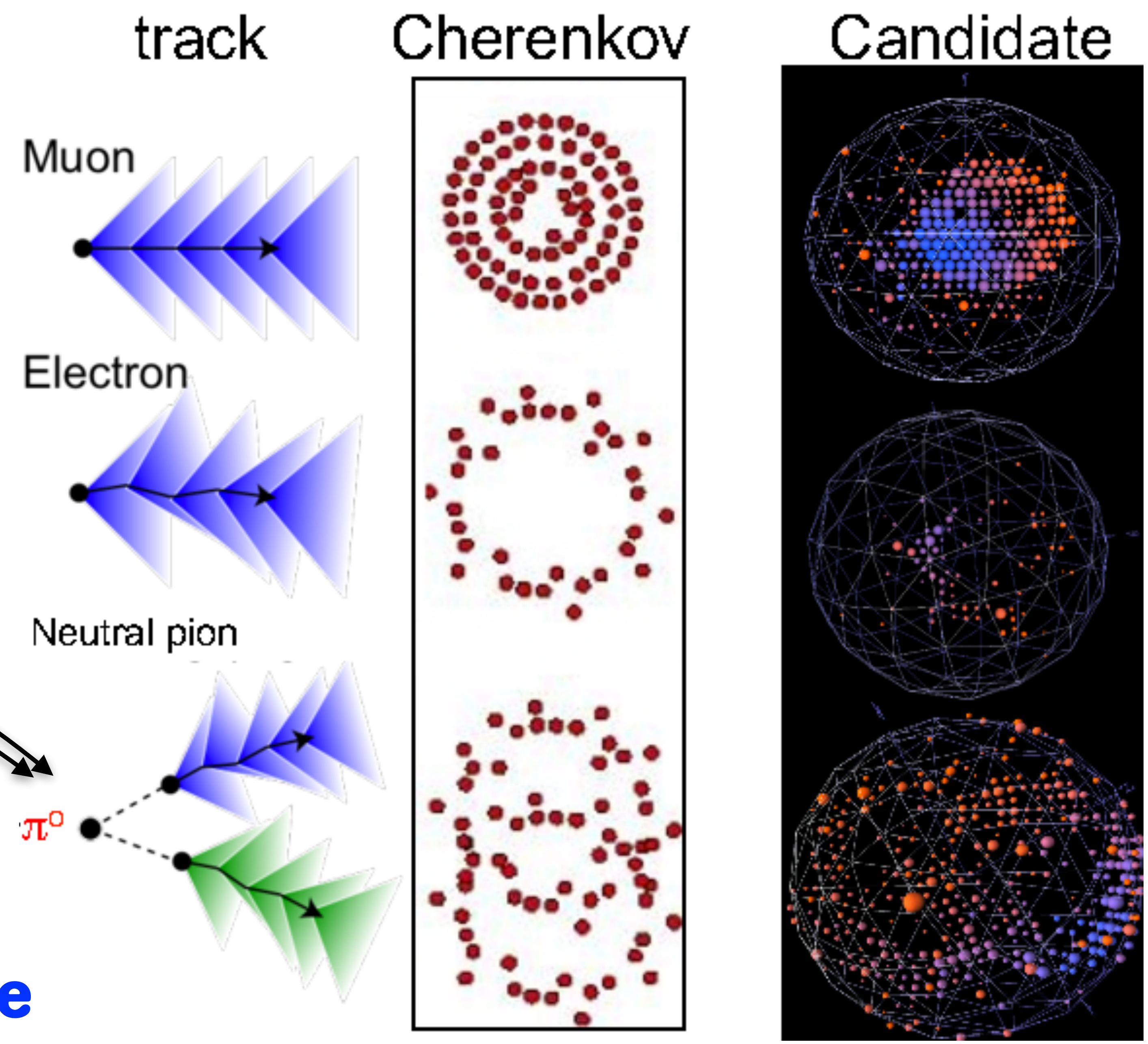
From "easy" to progressively more complicated topologies…



Characterize events in terms of particle content and kinematics

Electrons or photons?

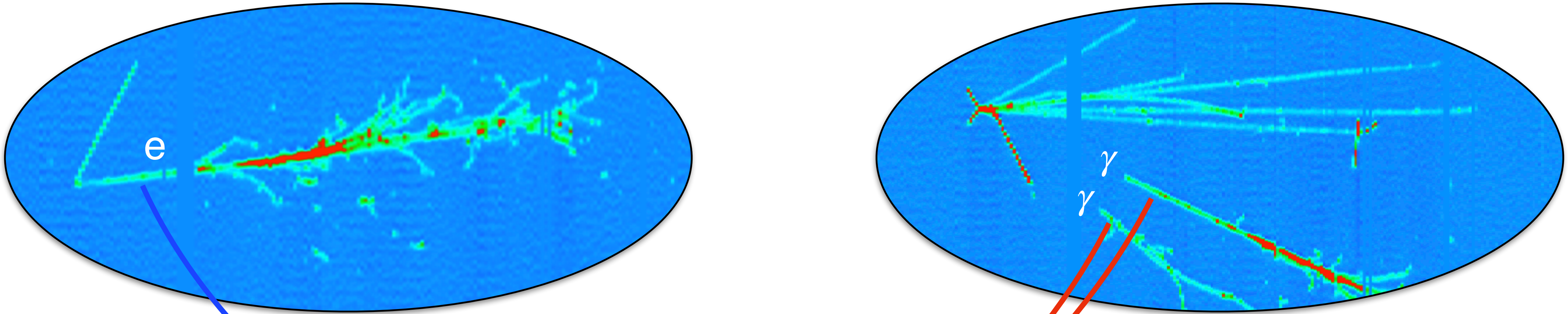


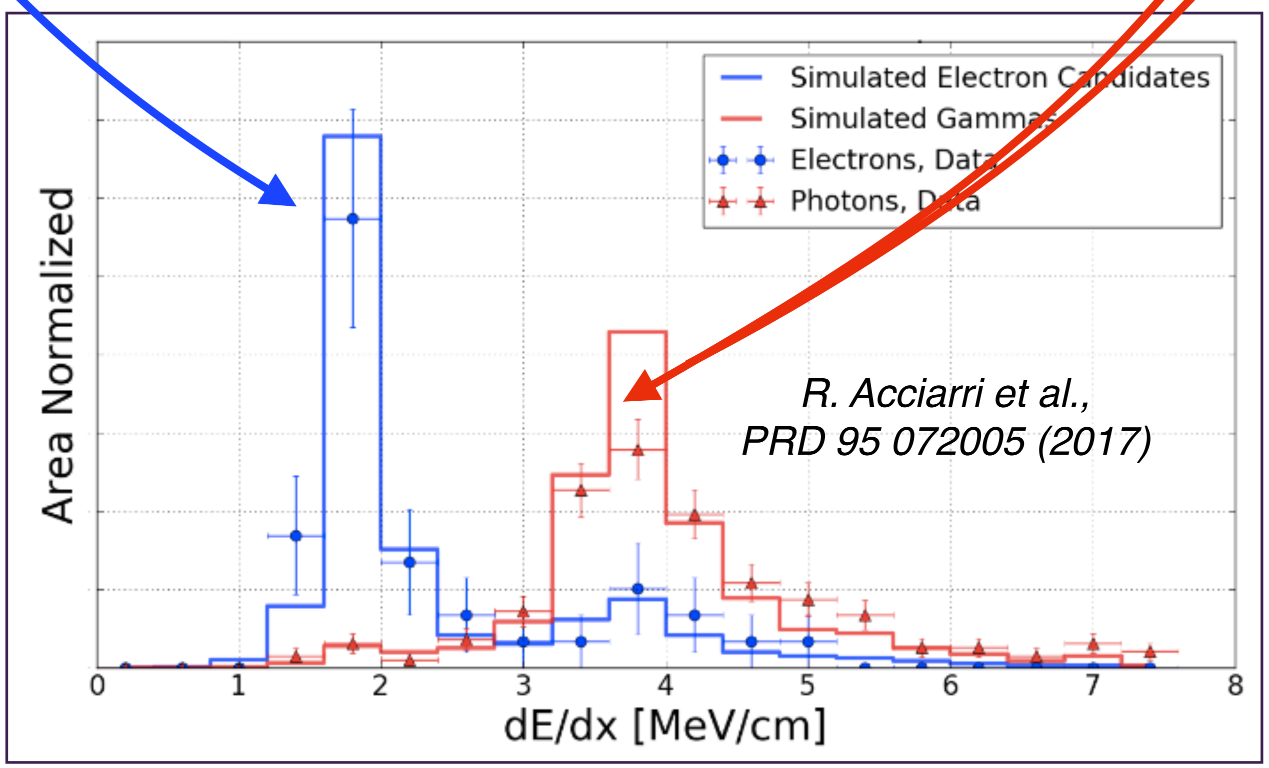


MiniBooNE electron-like "Low Energy excess"… Photons? Electrons?

LAr TPC!

Electron-γ discrimination in LAr TPC



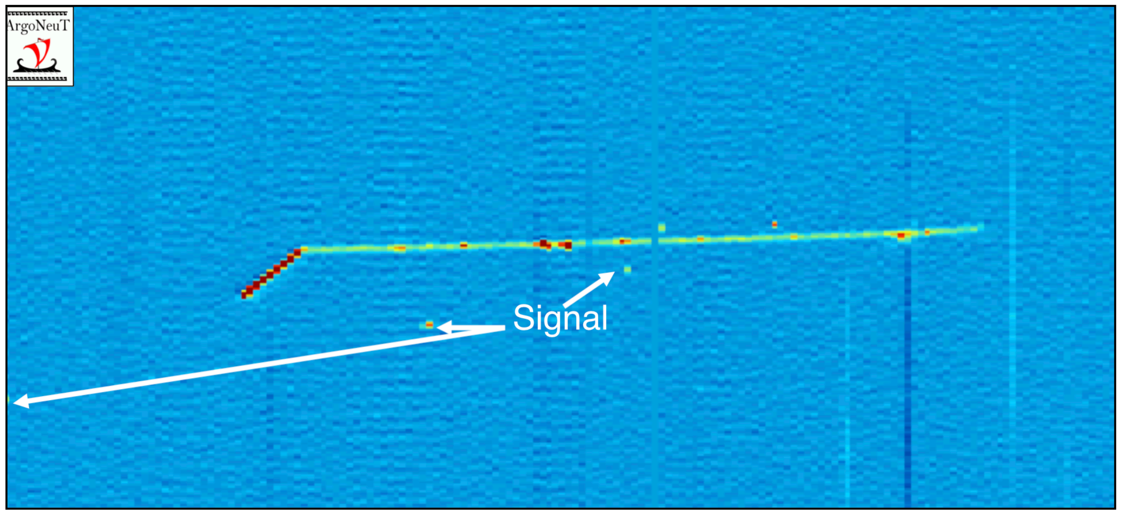


Analyzing topology (gap from the vertex) and dE/dx

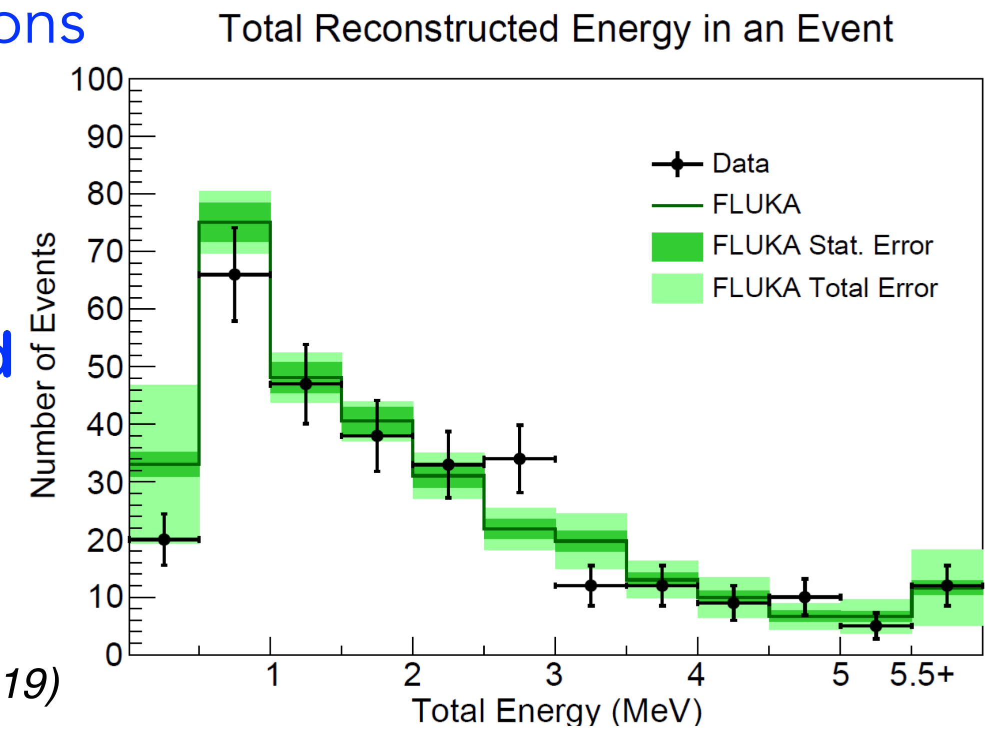
e-γ discrimination capability of LAr is crucial to disentangle the signal/background nature of the electron-like excess observed by MiniBooNE

The Low Energy Frontier

LAr TPC's have demonstrated to be able to detect and reconstruct (sub-)MeV energy depositions



300 KeV threshold
In ArgoNeuT



R. Acciarri et al., PRD 99, 012002 (2019)

Topologically separated low-energy depositions are identified as electrons produced by Compton scattering of

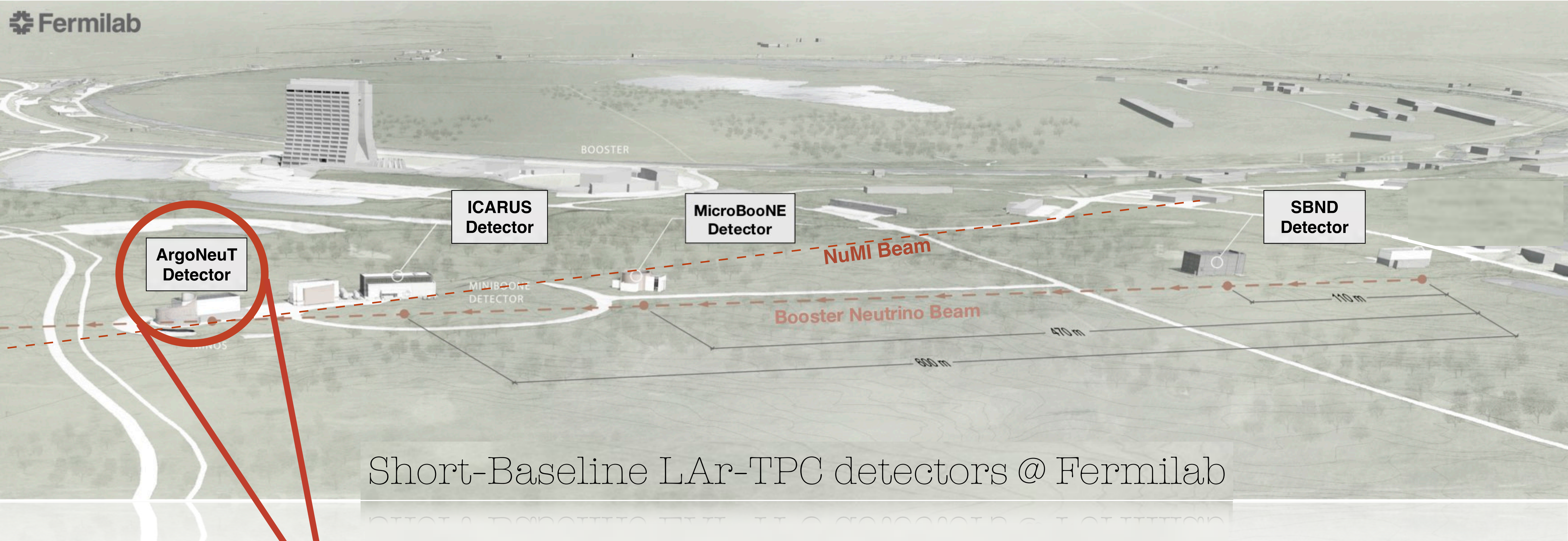
- de-excitation photons from the target nucleus and
- photon produced by neutron inelastic interactions

The capability to resolve individual collisions down to < MeV threshold is important for

- Neutrino Energy reconstruction [*A. Friedland and S. Weishi Li, PRD 99, 036009 (2019)*]
- Detection and reconstruction of supernova neutrino interactions in large LArTPCs (ex. DUNE)
- Study new physics scenarios

Fermilab - Neutrino beams

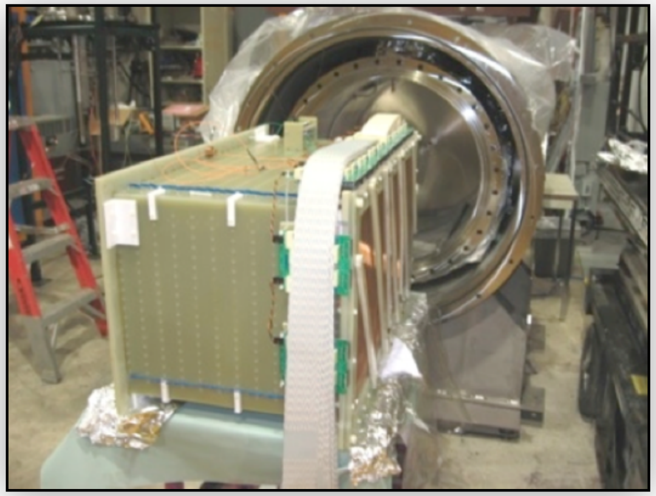
Short-Baseline LAr TPC detectors at Fermilab: ArgoNeuT



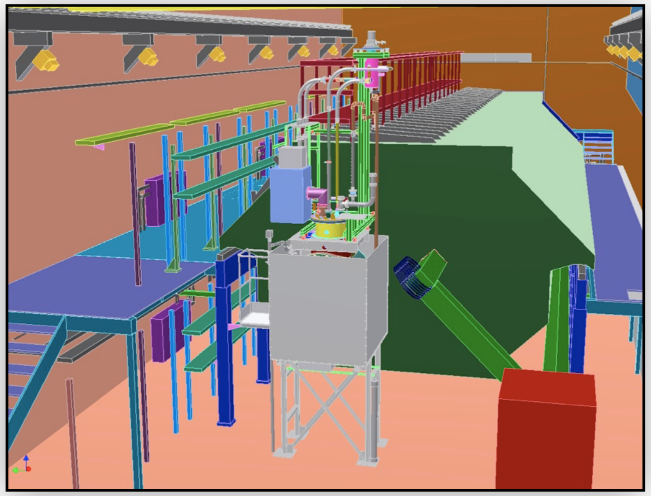
First LAr TPC detector at FNAL

5 months data collected in 2009-2010

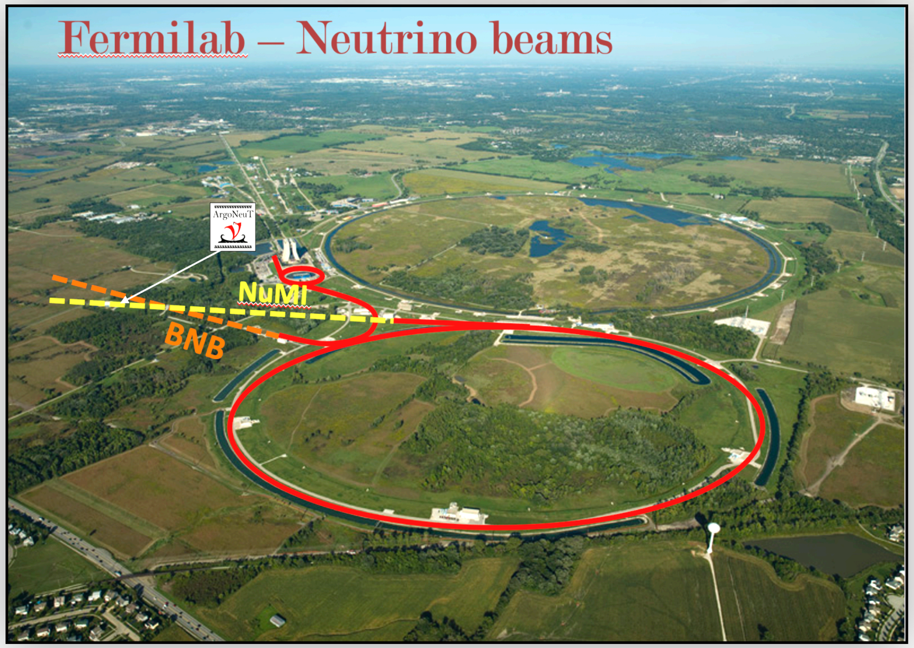
On-axis on NuMI $<E_{\nu}>\simeq 4$ GeV



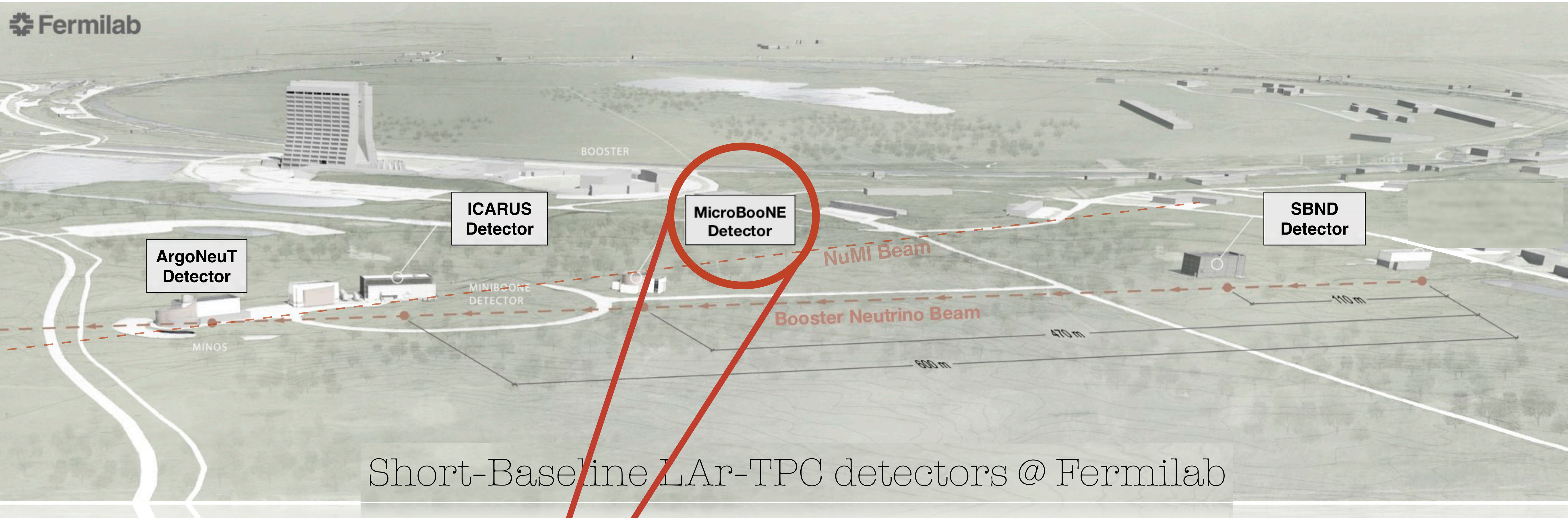
0.24 tons active volume LAr TPC



100 m underground, in front of the MINOS ND, ~ 1km from target

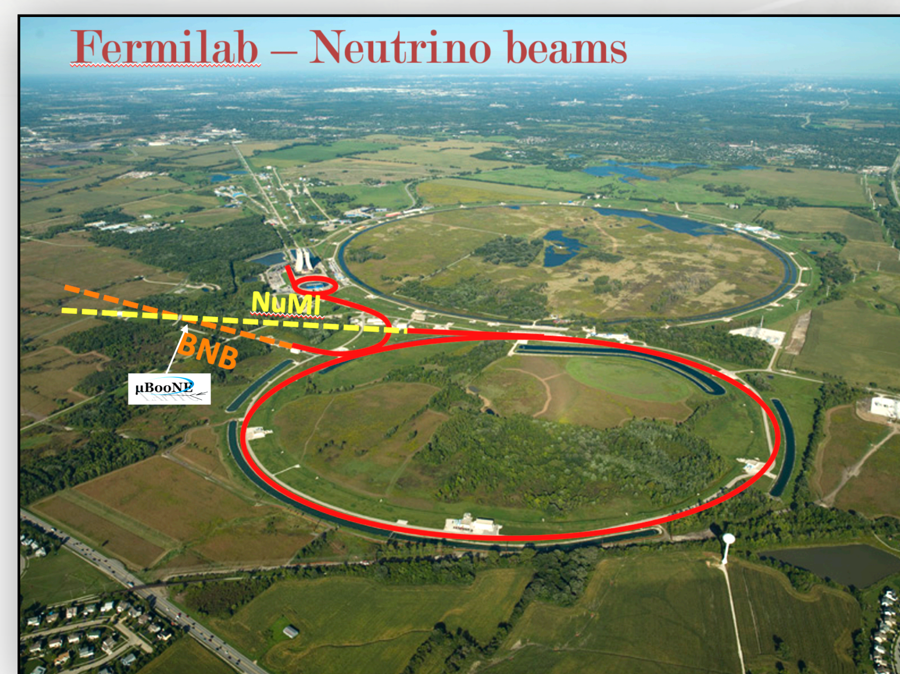


Short-Baseline LAr TPC detectors at Fermilab: MicroBooNE

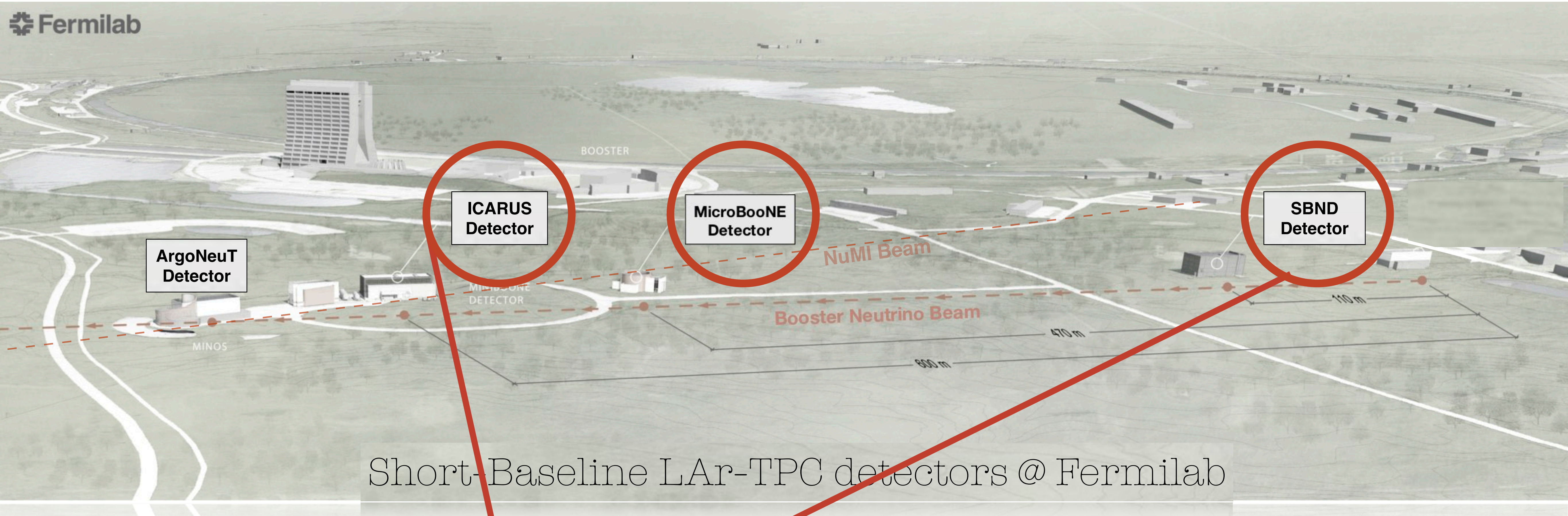


World's longest running LAr TPC (2015-2021)

On-axis on BNB (<E_ν>≃800 MeV) and off-axis on NuMI

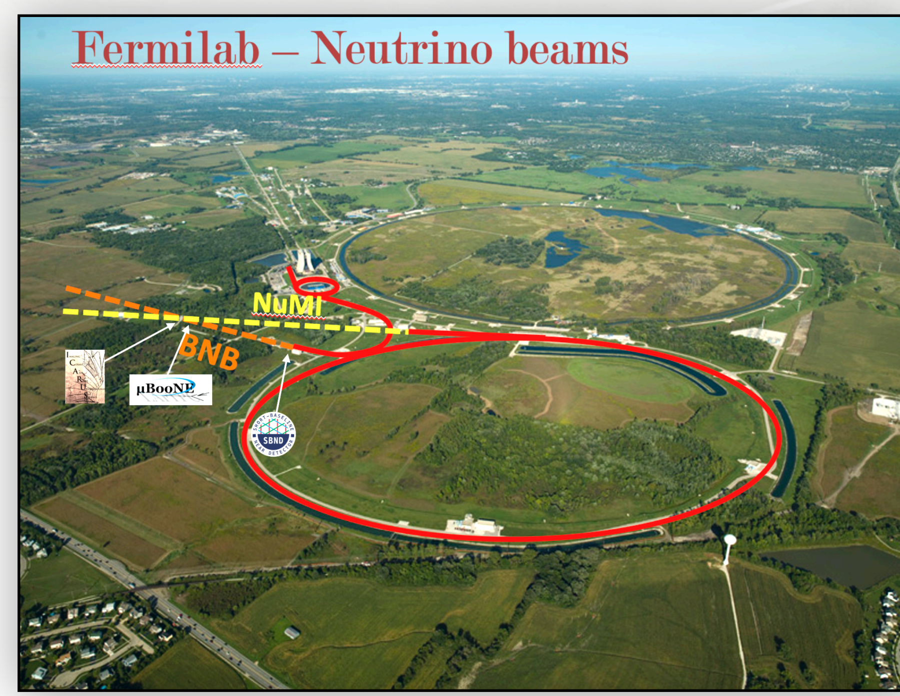


Short-Baseline LAr TPC detectors at Fermilab: SBN detectors

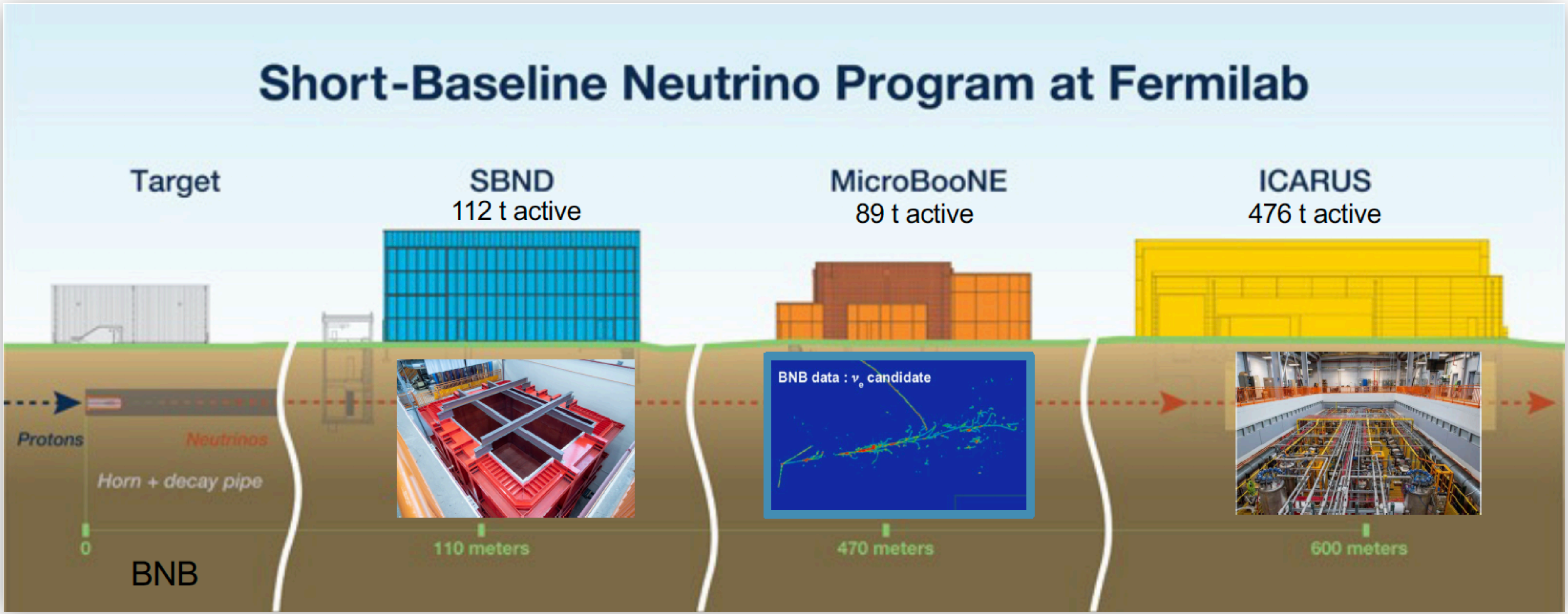


Two other detectors to form the Short-Baseline Neutrino (SBN) program

On-axis on BNB (SBND, MicroBooNE, ICARUS) and off-axis on NuMI (MicroBooNE, ICARUS)



Short Baseline Neutrino program



arXiv:1503.01520, January 2014
P.Machado, O.P., D. Schmitz, Annu. Rev. Nucl. Part. Sci. 69 363-387 (2019)

Designed for Sterile Neutrino searches

Same neutrino beam, nuclear target and detector technology: reducing systematic uncertainties to the % level

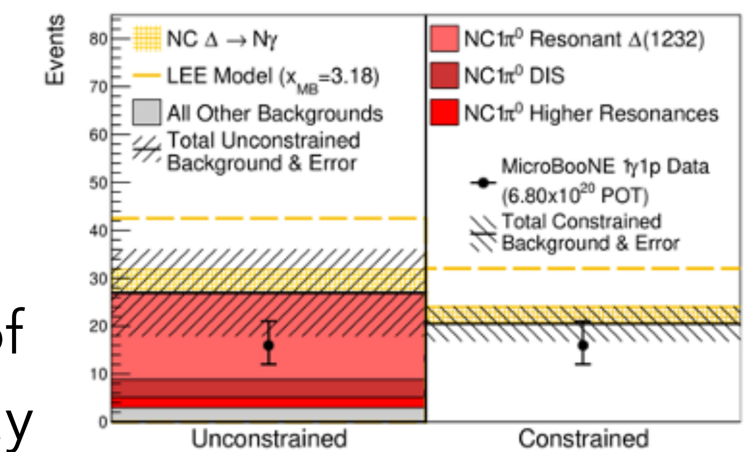
MicroBooNE experiment

- Designed to investigate the "low energy excess" observed by the MiniBooNE experiment.
- Physics run completed in 2021.
- First results on the "low energy excess" have been recently released (~1/2 of the full data sample). Four independent analyses, targeting different final states:
    - Single photon analysis
    - Search for a ν_e excess

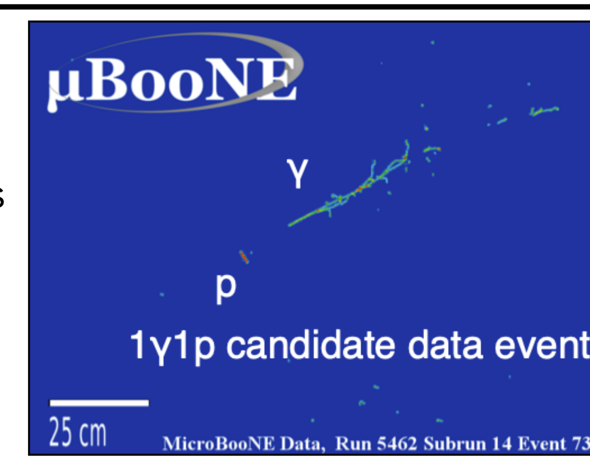
Single photon

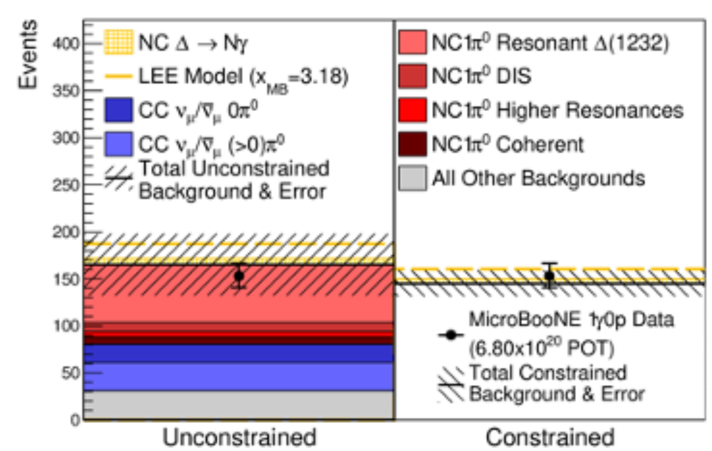
No evidence for an enhanced rate of single photons from NC $\Delta \rightarrow N\gamma$ decay above nominal GENIE expectations

P. Abratenko et al., PRL 111801 (2022)

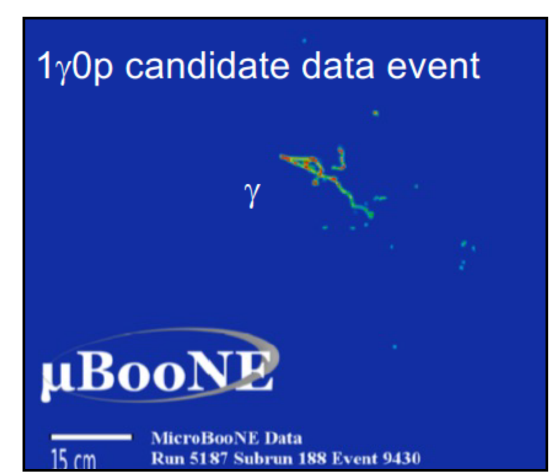


$1\gamma 1p$ events



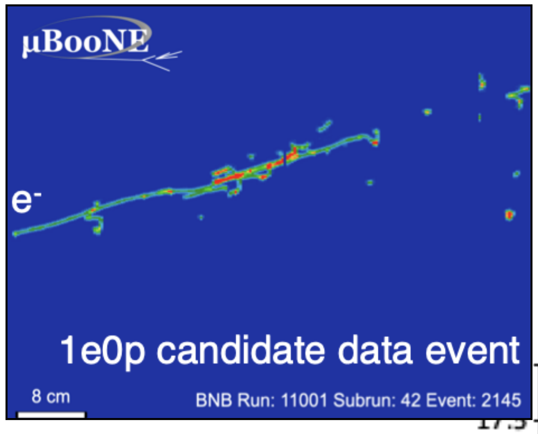


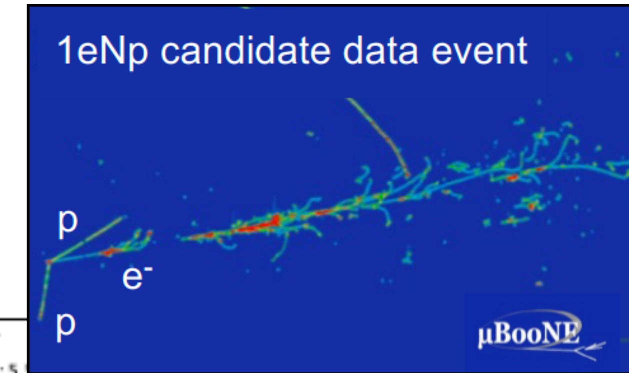
$1\gamma 0p$ events

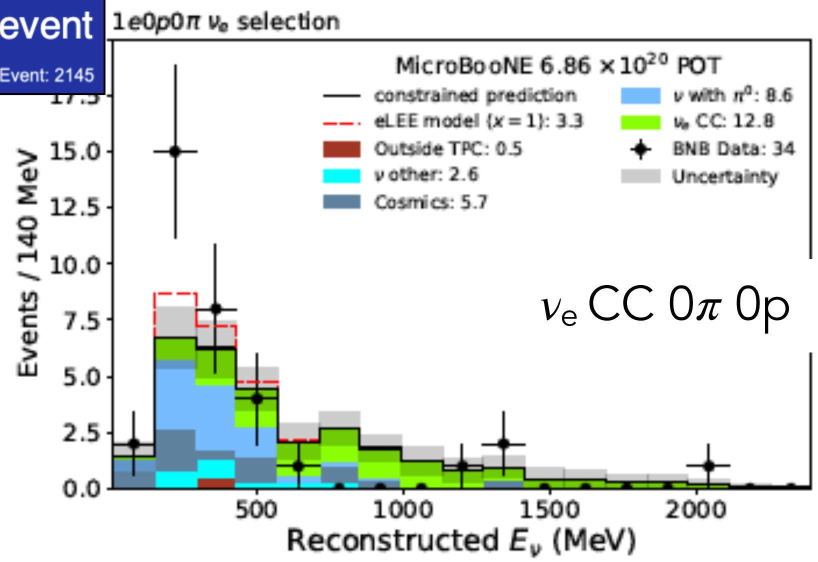


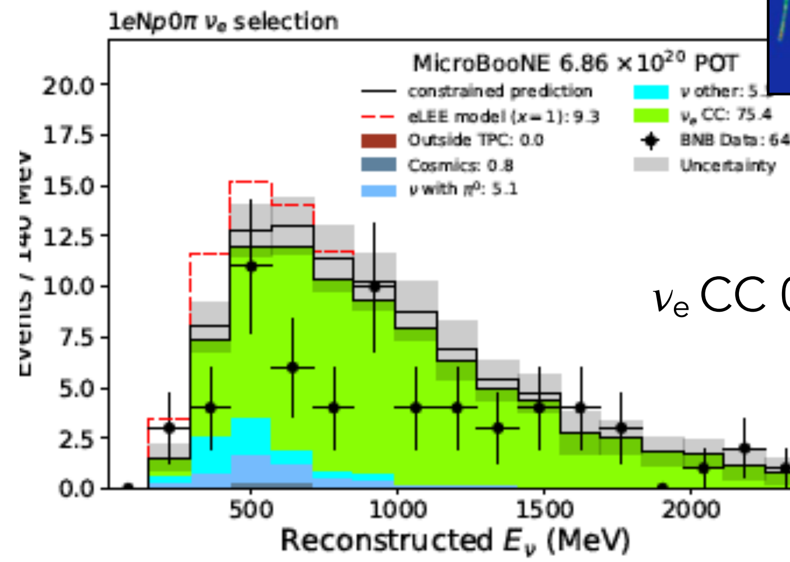
Search for a ν_e excess

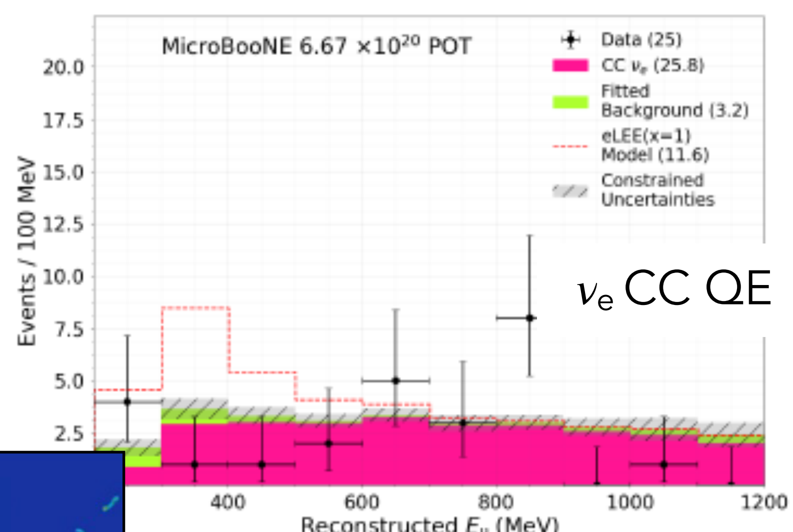
Three independent reconstruction frameworks.

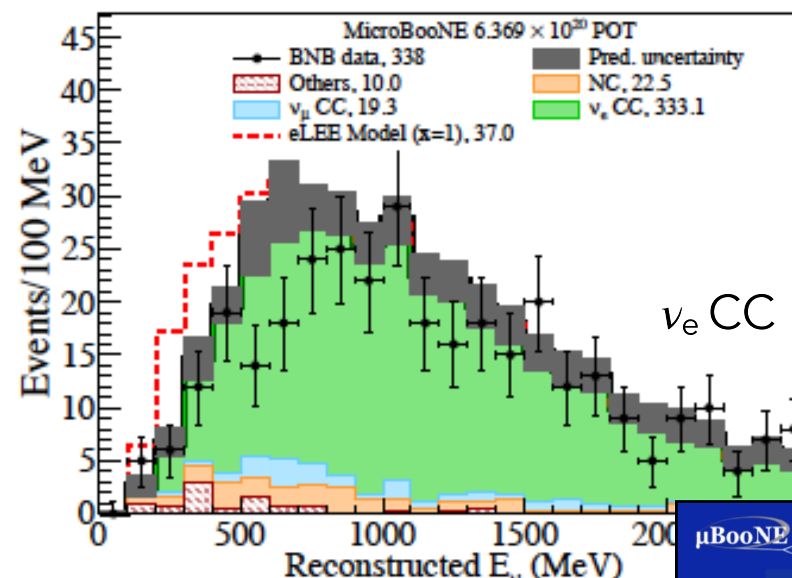


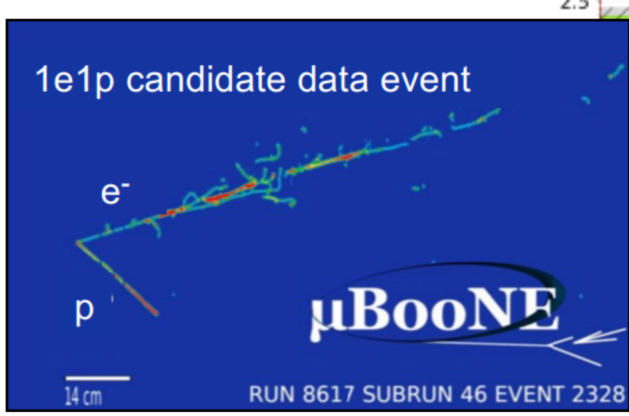


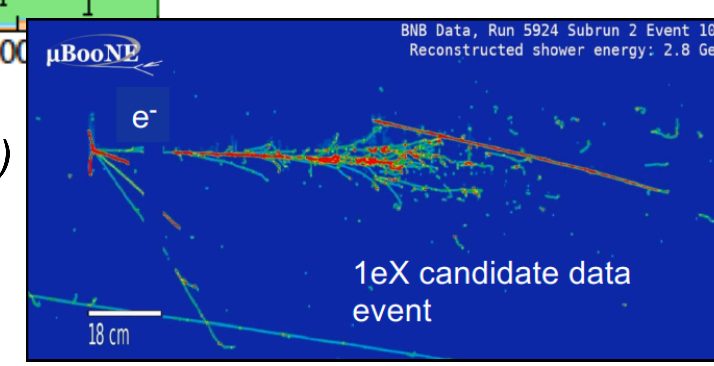






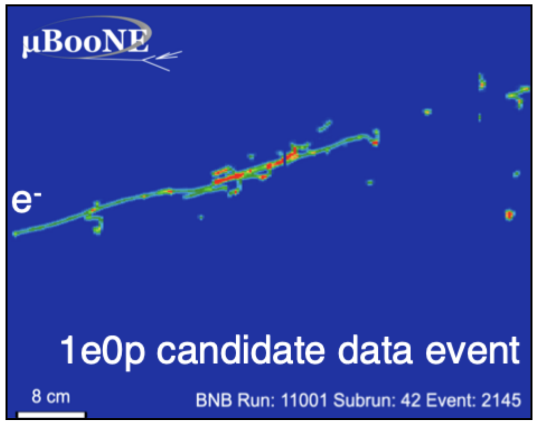


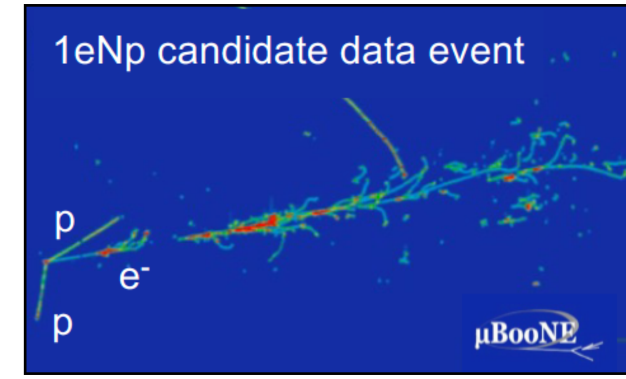




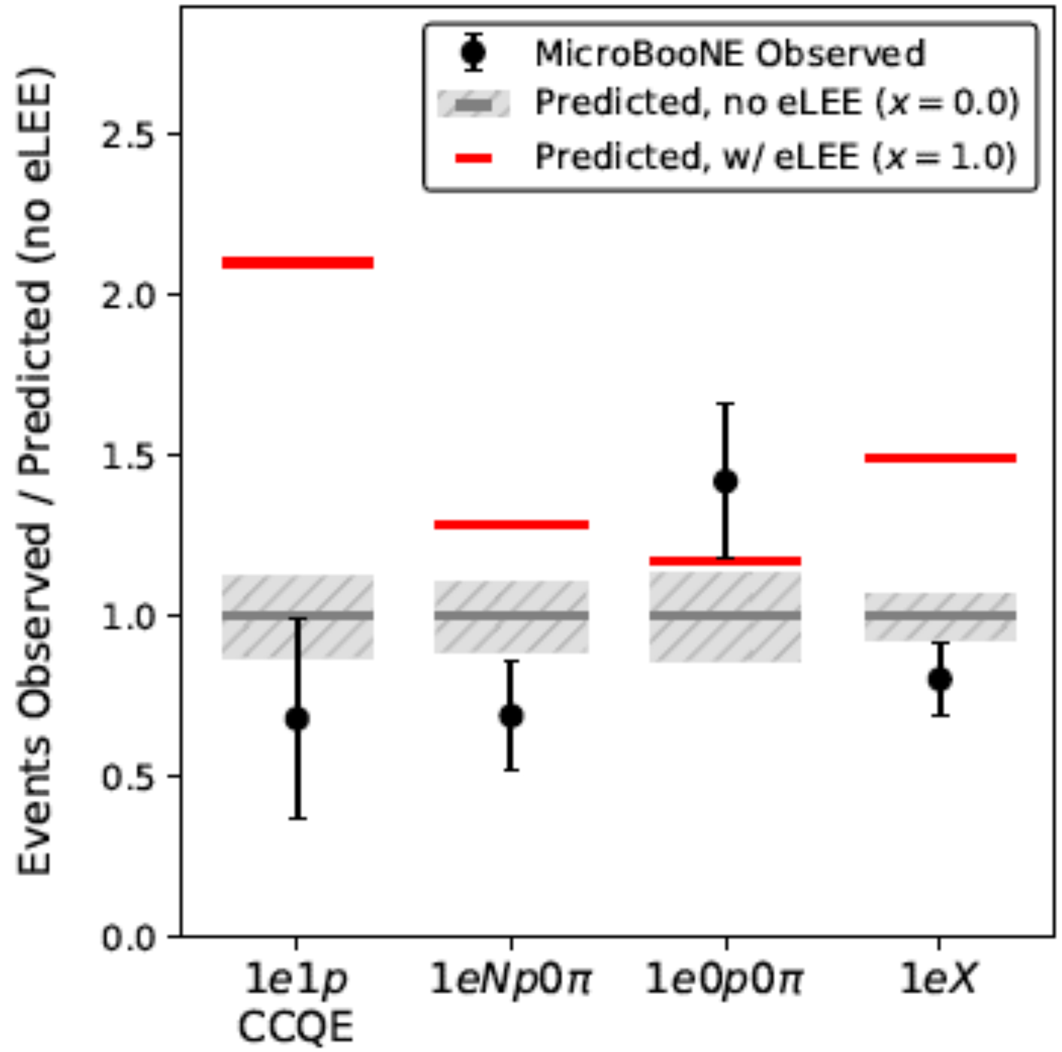
P. Abratenko et al., arxiv:2110.14054 (2021)

Search for a ν_e excess



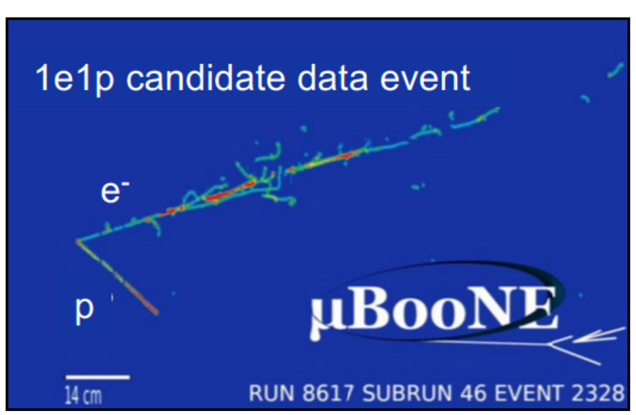


Observed ν_e candidate event rates in agreement with, or below, the predicted rates.

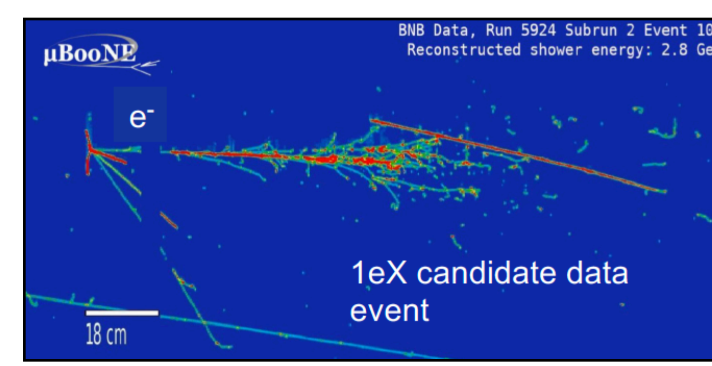


Reject the hypothesis that ν_e CC interactions are fully responsible for the MiniBooNE excess at >97% C.L. in all analyses.

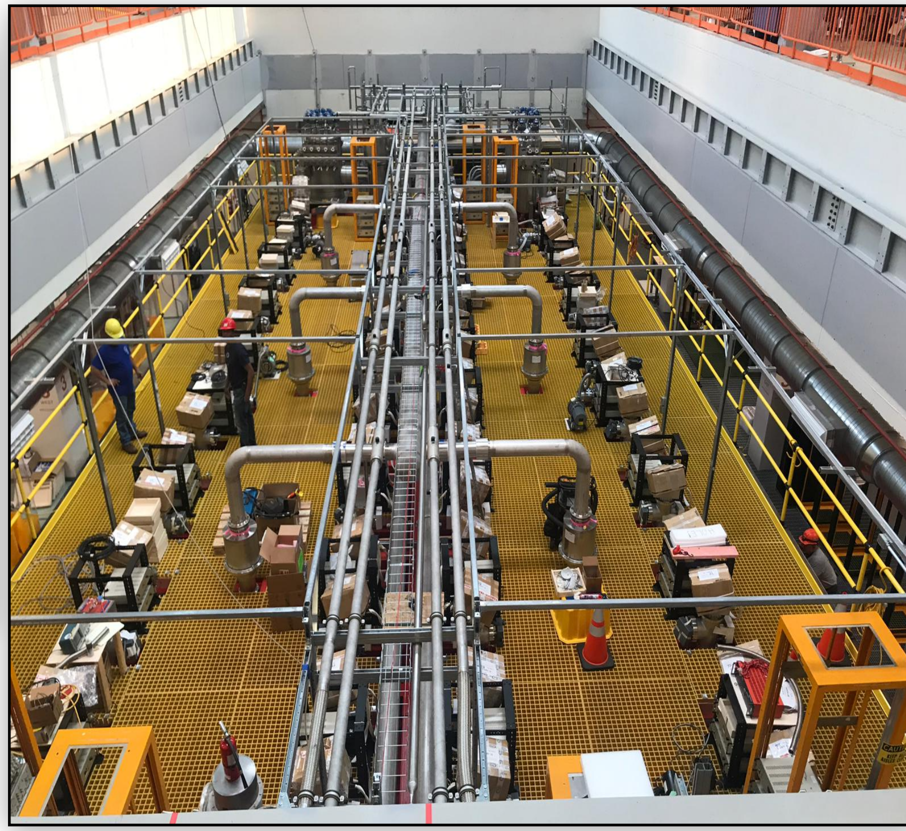
P. Abratenko et al., arxiv:2110.14054 (2021)



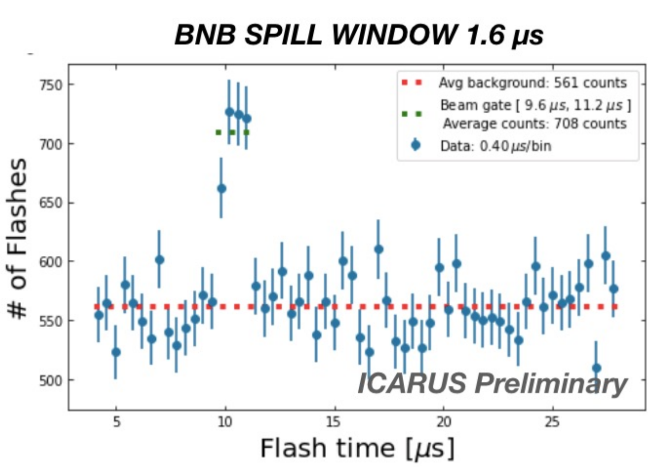
Currently planning the next phase of analyses.

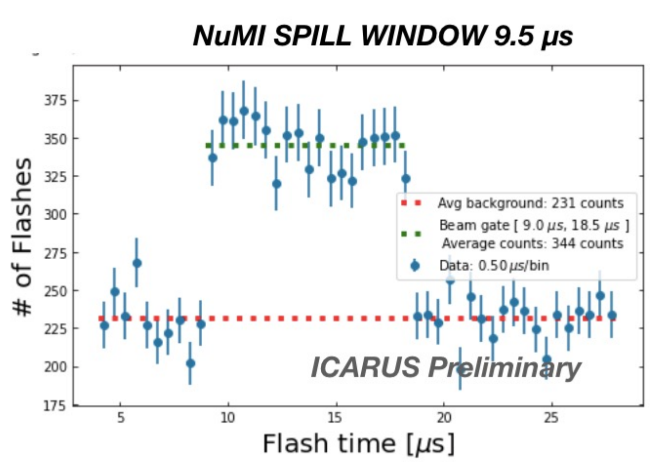


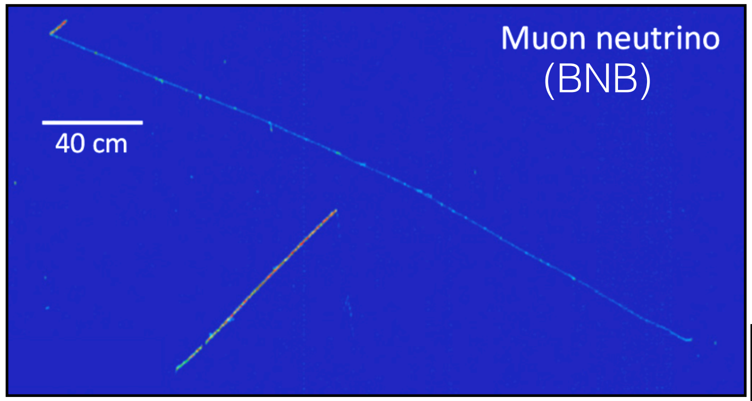
SBN Far detector: ICARUS

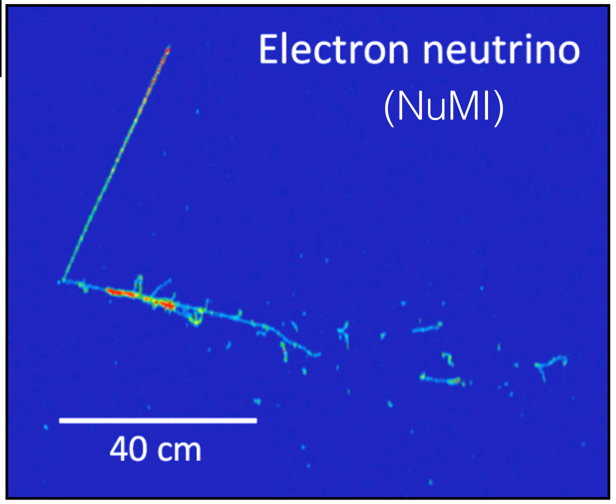


Neutrino data taking (BNB and NuMI) since October 2021





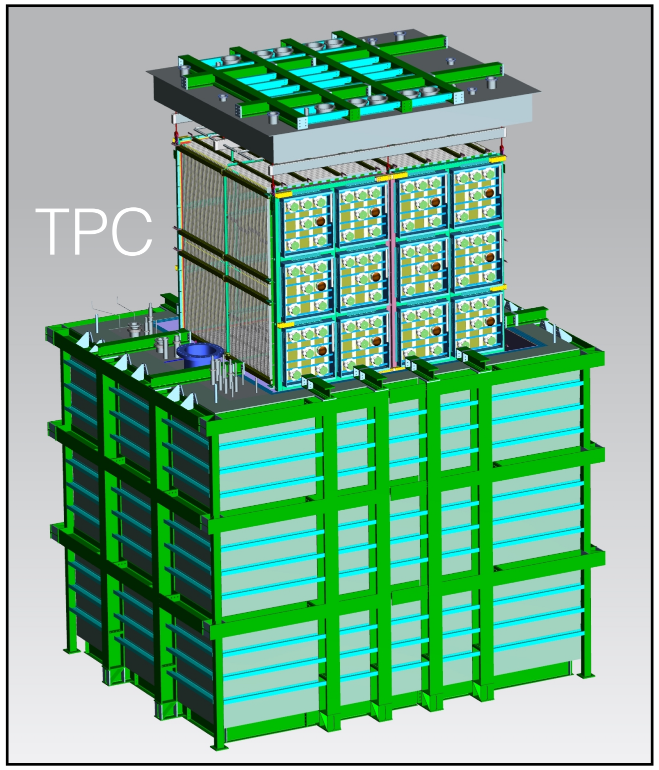


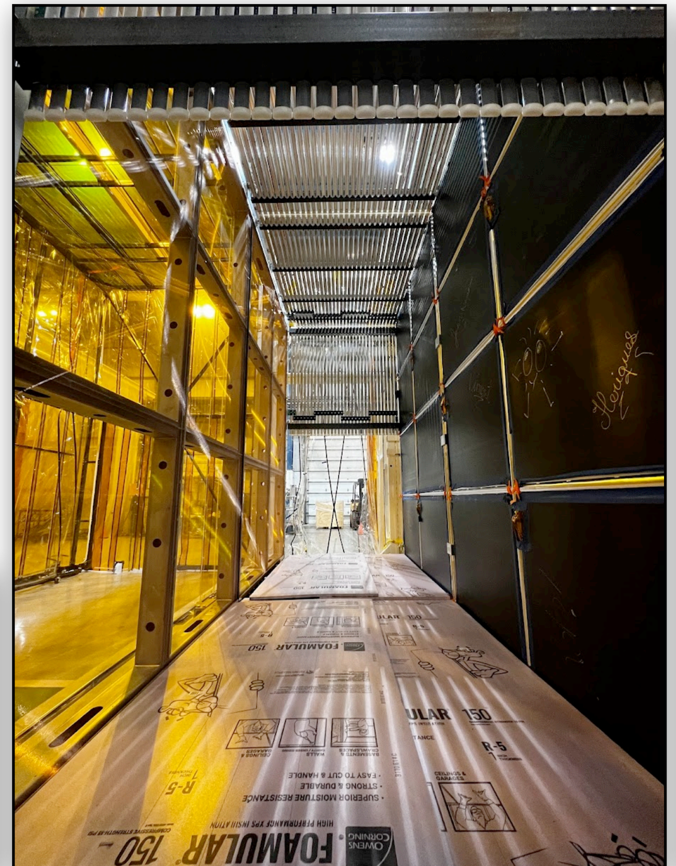


Commissioning of the full Cosmic Ray Tagger system and installation of a concrete overburden is ongoing.

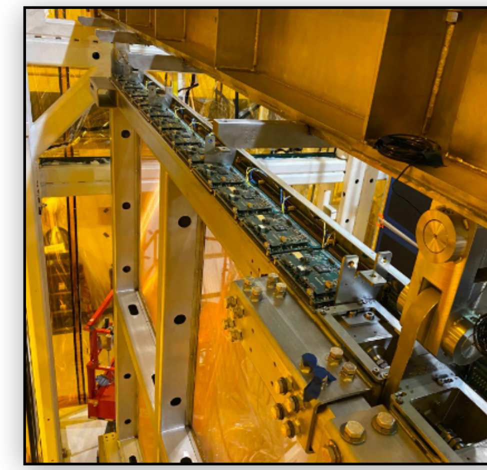
SBN Near detector: SBND

TPC assembly almost completed
Warm outer vessel installed in the building
Cryogenics/cryostat installation in progress
Ready for cold commissioning by Spring 2023

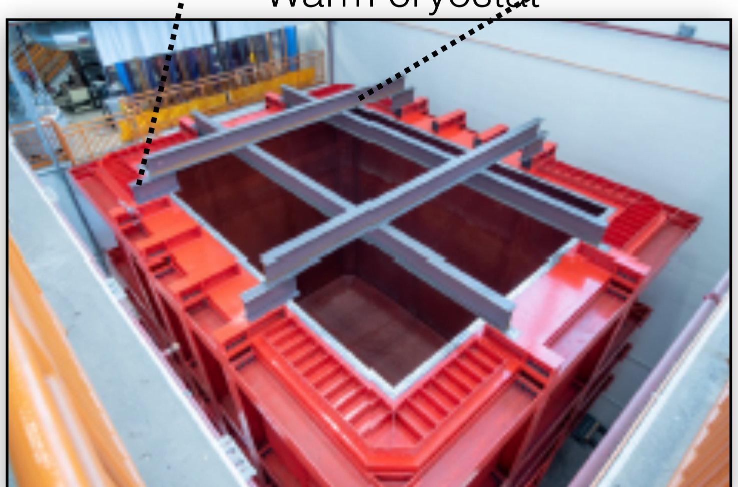




TPC Cold Electronics

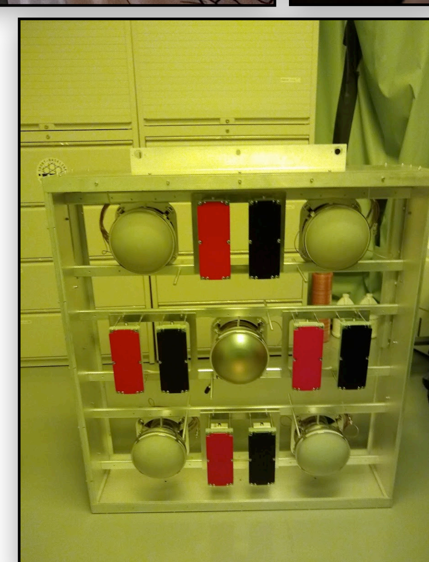


Warm cryostat

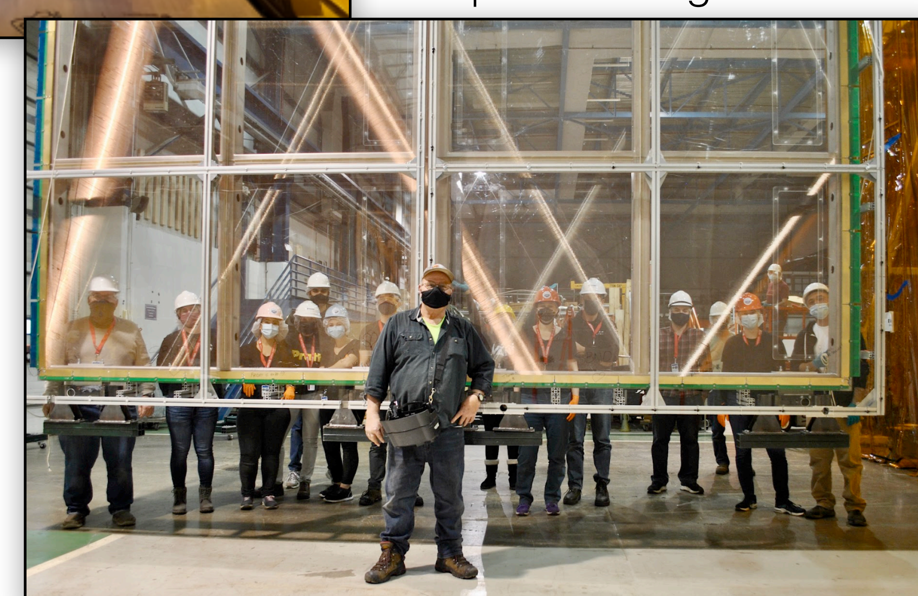


Photon Detector System module

PTMs and X-ARAPUCAs

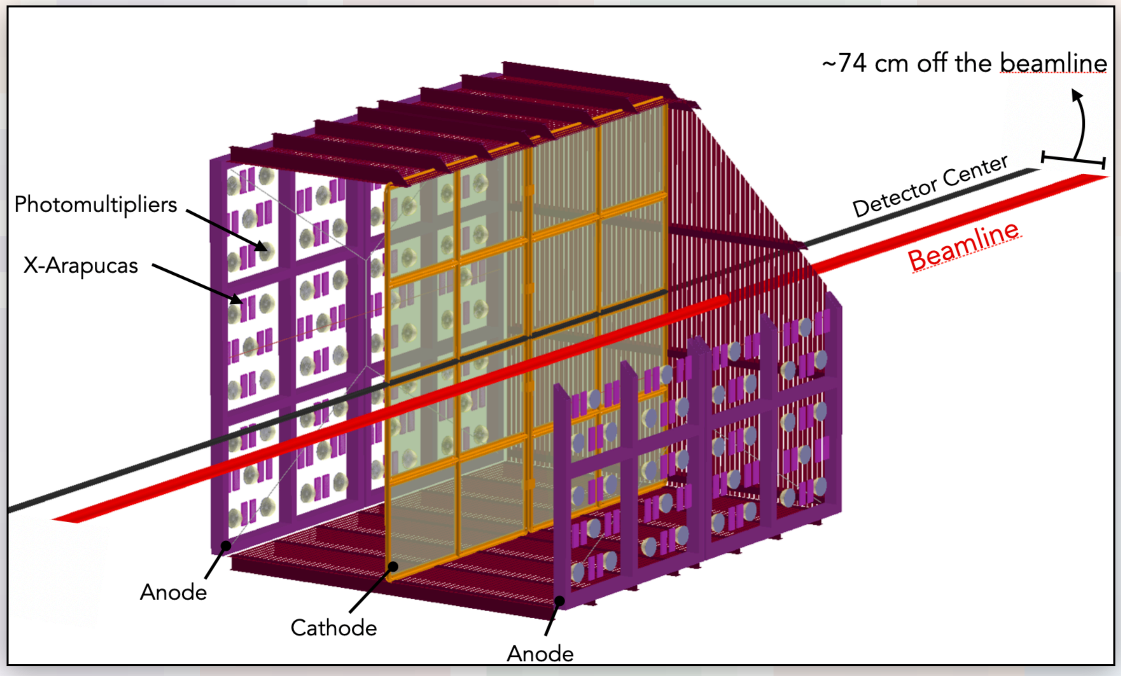


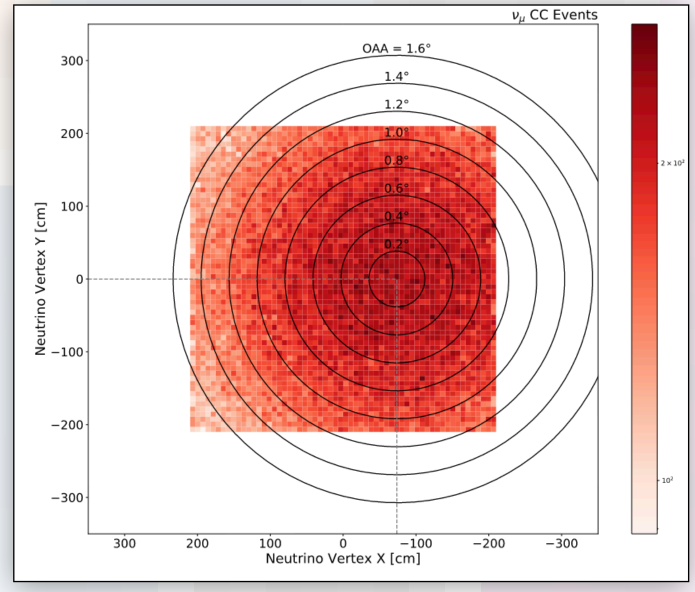
Wire plane during installation



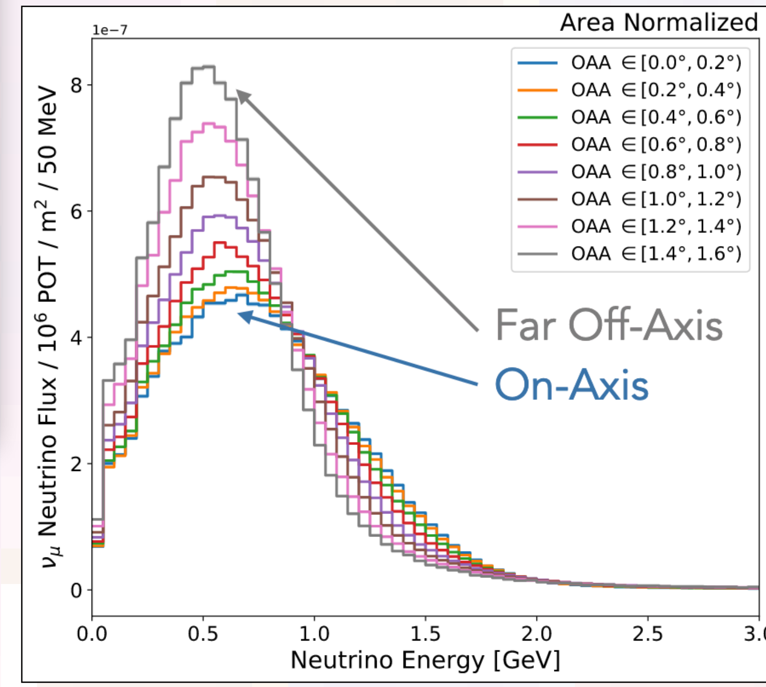
SBND-PRISM: Sampling Multiple Off-Axis Fluxes with the Same Detector

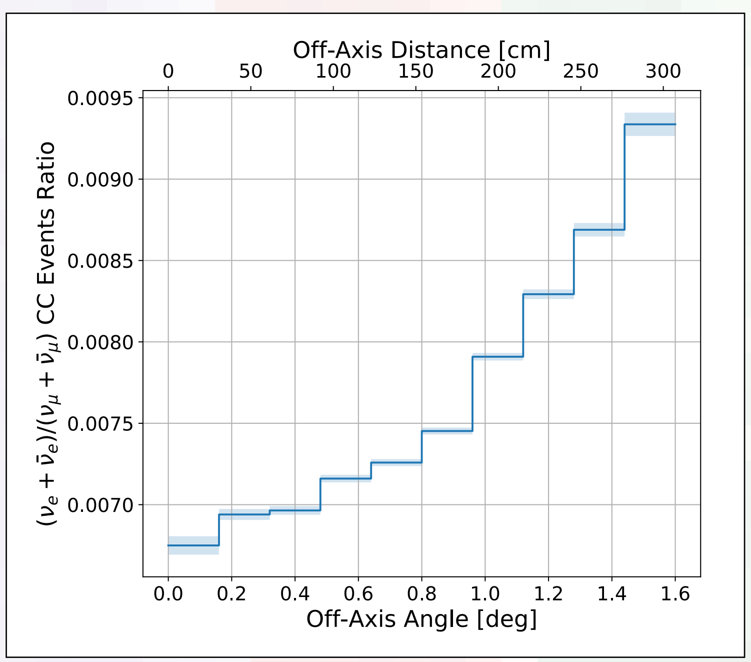
A Slightly Off-Axis Detector close to the neutrino source



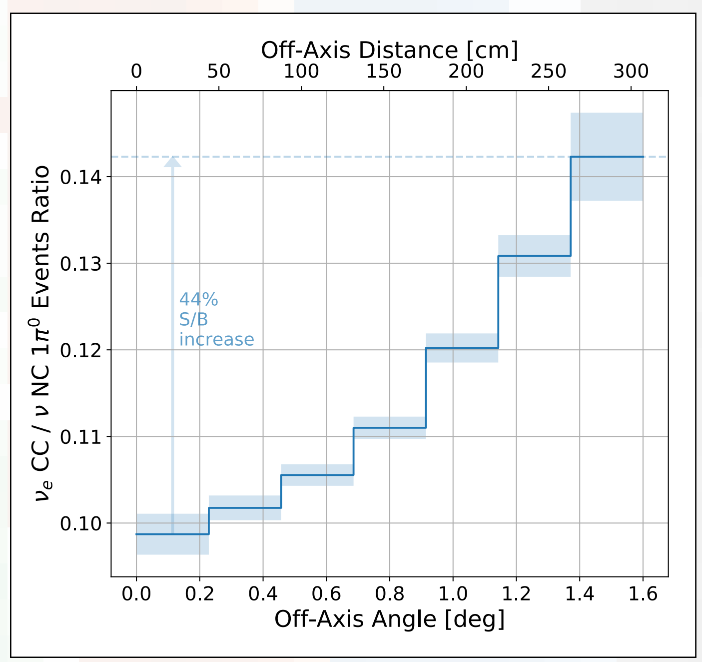


$\nu_\mu$flux





ν_e to ν_μ ratio changes moving off-axis



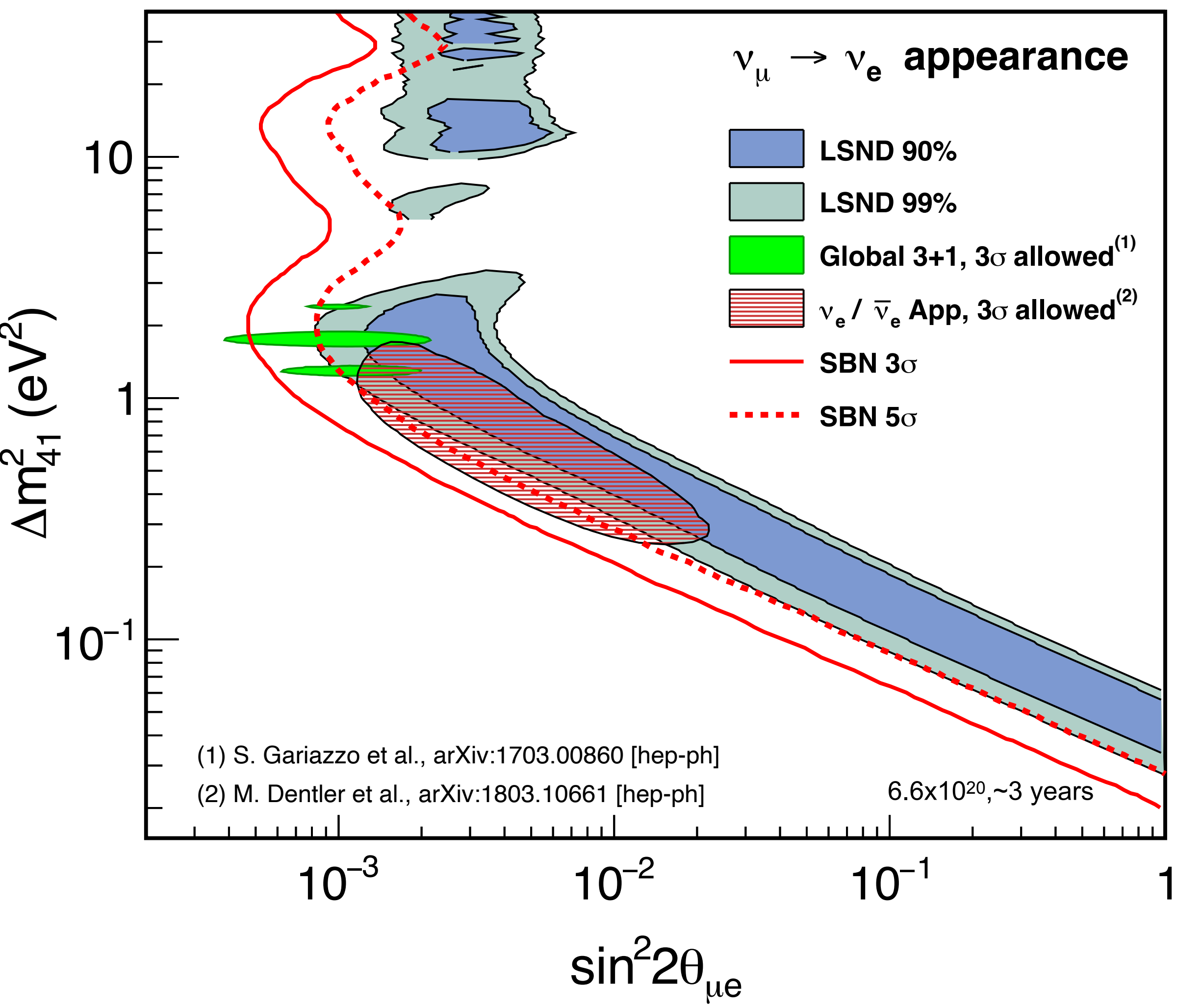
NC π^0 decreases moving off-axis

Additional physics potentials from SBND-PRISM

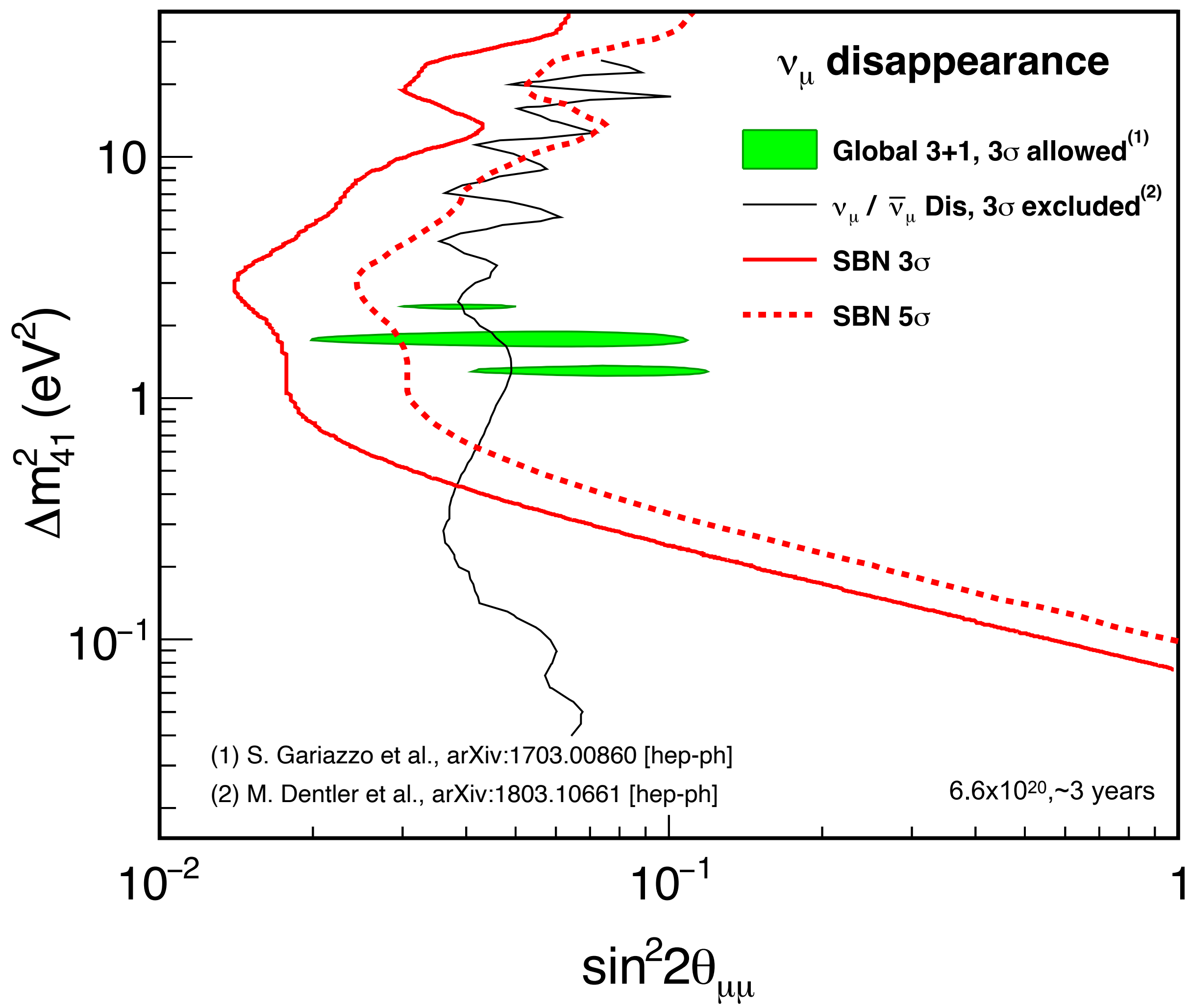
- Further constrain neutrino interactions in oscillation physics.
- Perform targeted neutrino interaction measurements and disentangle nuclear effects.
- Background reduction moving off-axis.

SBN Sterile Neutrino Sensitivity

$\nu_\mu \rightarrow \nu_e$ Appearance sensitivity



$\nu_\mu \rightarrow \nu_x$ Disappearance sensitivity



SBN can cover the parameters allowed by past anomalies at 5σ significance

SBN also has sensitivity to ν_μ disappearance

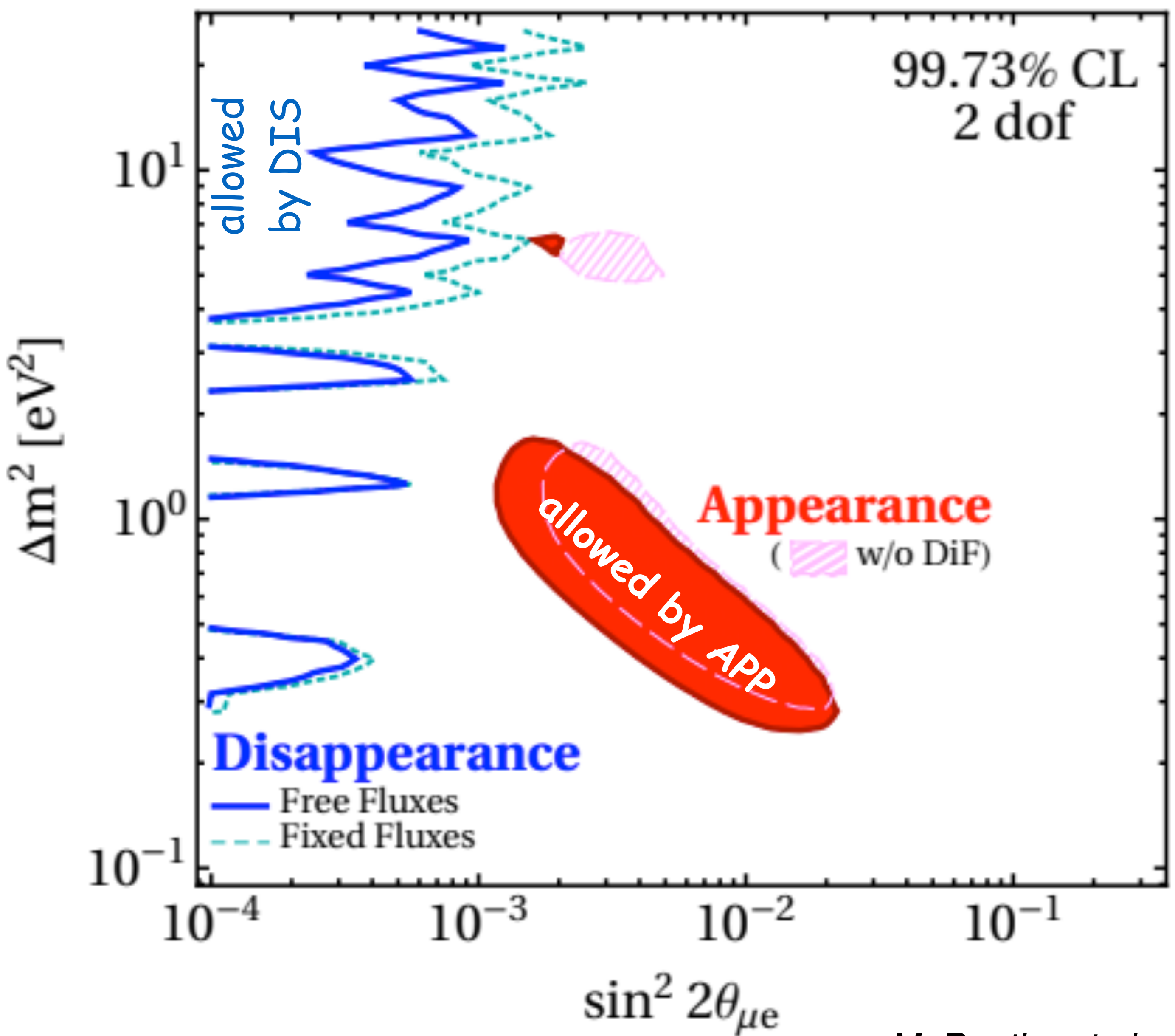
The observation of ν_μ disappearance would be essential to the interpretation of any electron neutrino excess as being due to the existence of sterile neutrinos

P. Machado, O.P., D. Schmitz: Annual Rev. Nucl. Part. Sci. 69 363-387 (2019)

Additional studies including constraints from SBND-PRISM are ongoing.

The Light Sterile Neutrino Experimental Landscape

Test of the sterile hypothesis



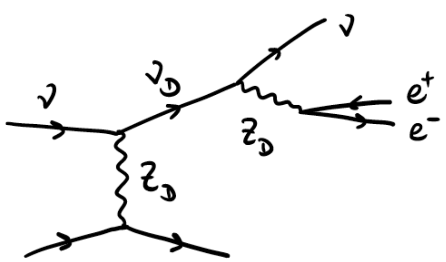
M. Dentler et al., JHEP 08:010 (2018)

4.7 σ tension arises when combining ν_e appearance and ν_μ disappearance data sets.

Evolving Landscape...

Several alternative explanation of the MiniBooNE excess (ν_e appearance) but not ν_μ disappearance have been proposed, together with other BSM scenarios at large.

Dark Neutrinos



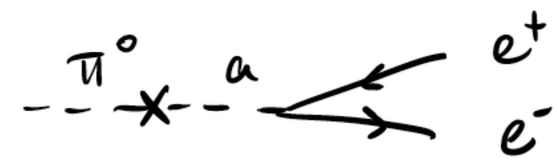
Light Z_D - *Bertuzzo Jana Machado Zukanovich PRL 2018*
Bertuzzo Jana Machado Zukanovich PLB 2019
Arguelles Hostert Tsai PRL 2019

Heavy Z_D - *Ballett Pascoli Ross-Lonergan PRD 2019*
Ballett Hostert Pascoli PRD 2020

Transition Magnetic Moment

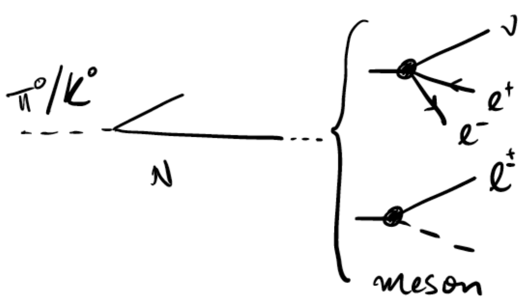
Gninenko PRL 2009
Coloma Machado Soler Shoemaker PRL 2017
Atkinson et al 2021
Vergani et al PRD 2021

Axion-like particles



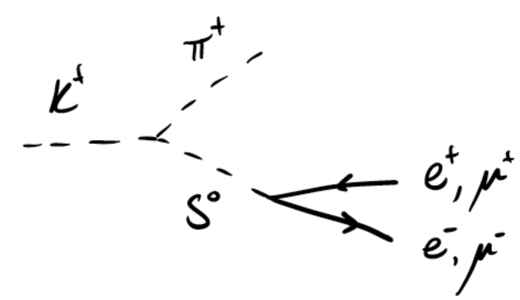
Kelly Kumar Liu PRD 2021
Brdar et al PRL 2021

Heavy Neutral Leptons



Long list, ex.
Ballett Pascoli Ross-Lonergan JHEP 2017
Kelly Machado PRD 2021

Higgs Portal Scalars



Pat Wilczek 2006
Batell Berger Ismail PRD 2019

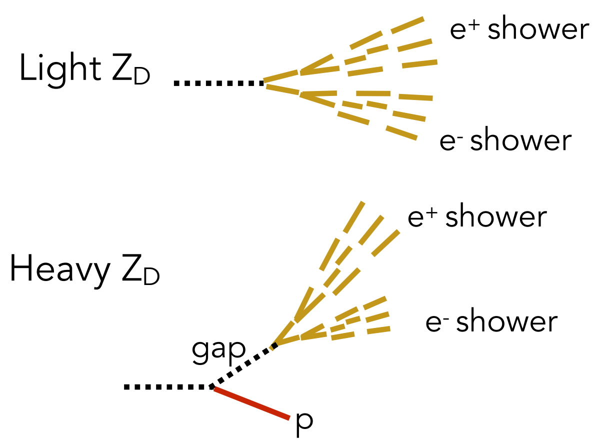
Courtesy of P. Machado

Note: not an exhaustive list!

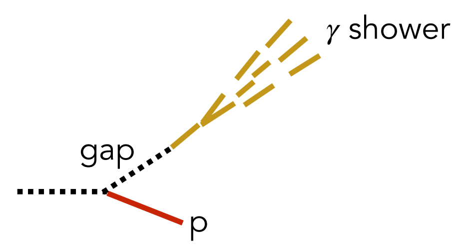
Evolving Landscape…

Final state experimental signature: single photon, single electron, "trident" with di-leptons - overlapping and/or highly asymmetric, with different levels of hadronic activity

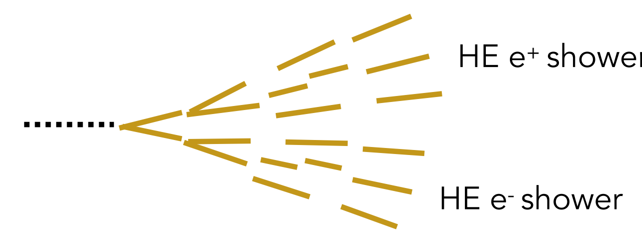
Dark Neutrinos



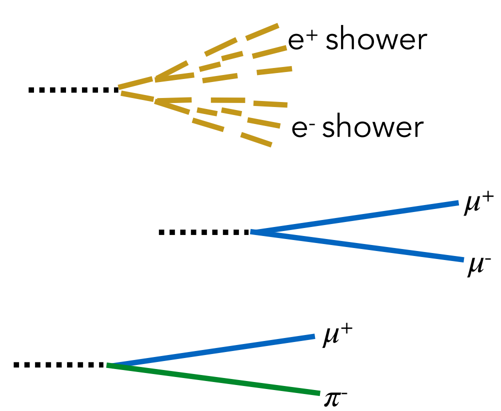
Transition Magnetic Moment



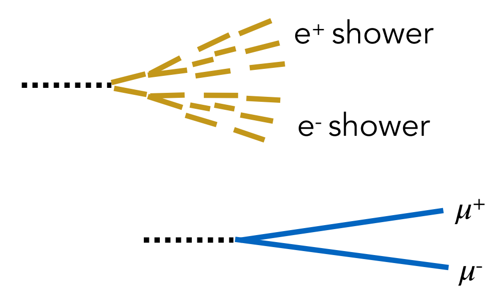
Axion-like particles



Heavy Neutral Leptons



Higgs Portal Scalars



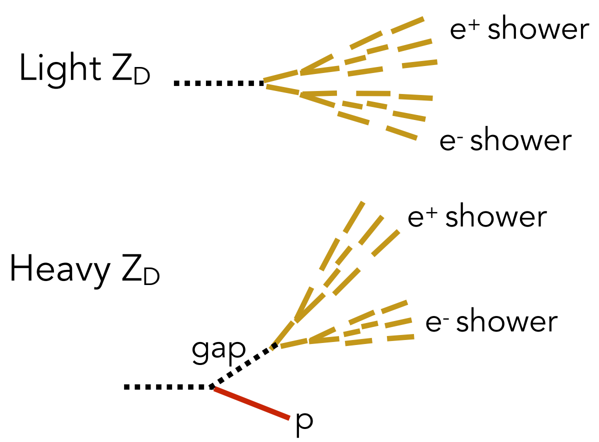
Note: not an exhaustive list!

Evolving Landscape…

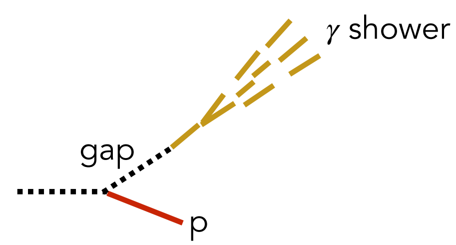
The unique capabilities of the LAr TPC technology open up more information than available in a Cherenkov detector (such as MiniBooNE)

- Characterize events in term of final state particle content and kinematics.
- Recognize the presence hadronic activity.

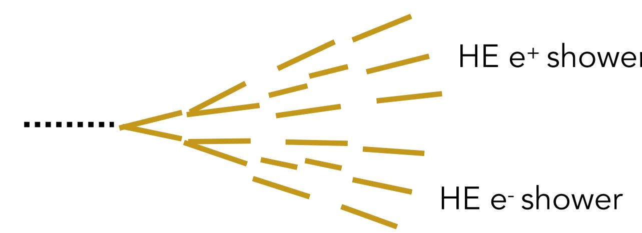
Dark Neutrinos



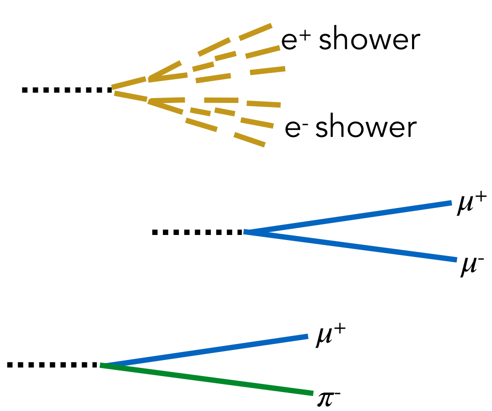
Transition Magnetic Moment



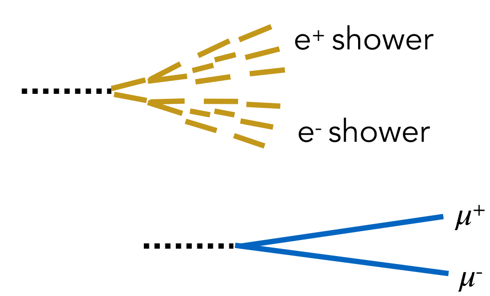
Axion-like particles



Heavy Neutral Leptons



Higgs Portal Scalars



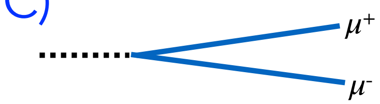
Collaboration between experimentalists and theorists is crucial for these searches!

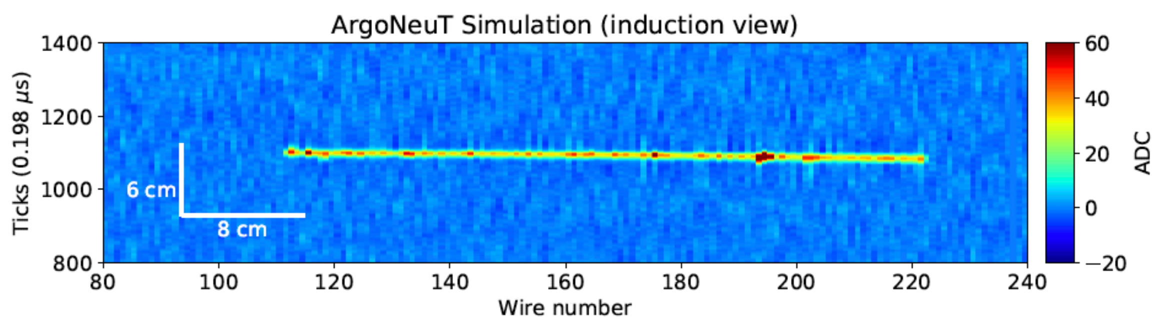
Searches for new physics in LAr TPC: ArgoNeuT

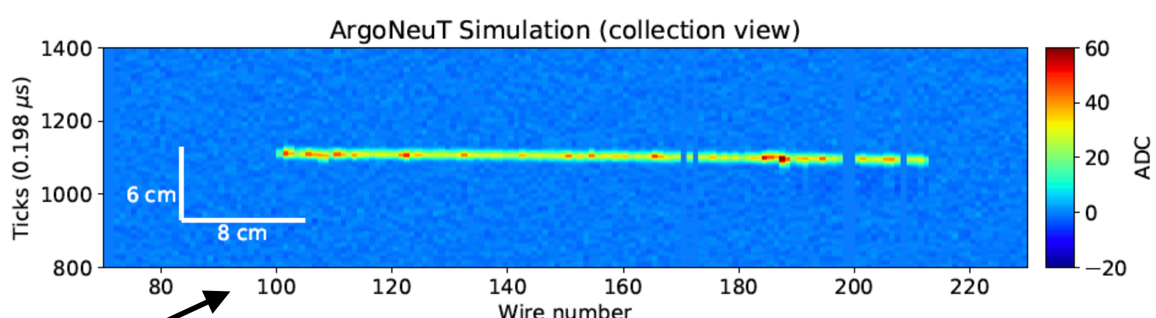
First search for Heavy Neutral Leptons N→$\nu\mu^+\mu^-$ in LAr TPC

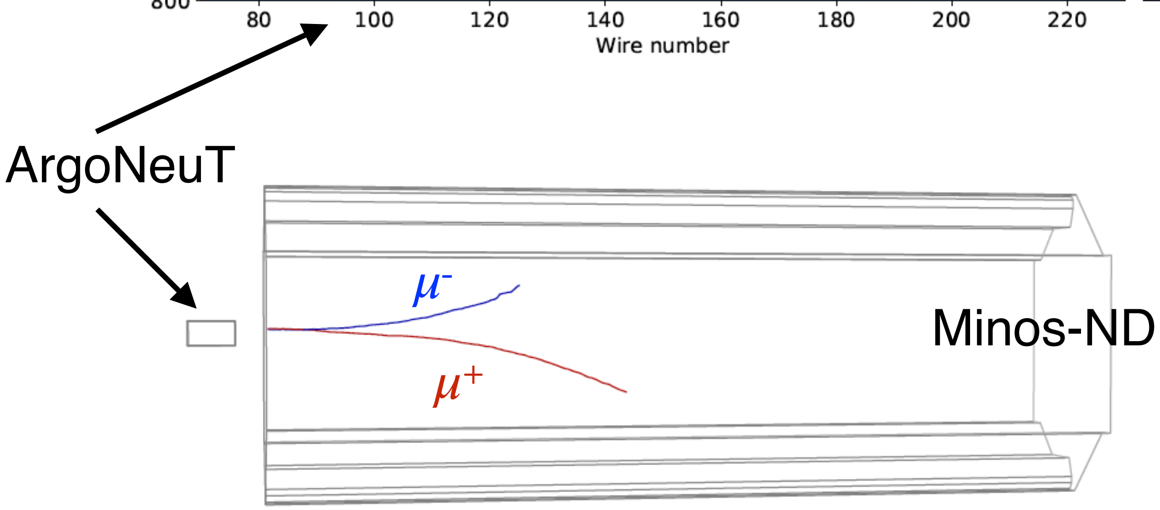
Assuming HNL production predominately from $\tau^\pm$ decay:
D/D_s decay to τ, that subsequently decay to HNLs
$\tau^\pm \rightarrow$N $X^\pm$ ($X^\pm$ is a SM particle e.g. $\pi^\pm$)

HNL decay (MC)
N→$\nu\mu^+\mu^-$



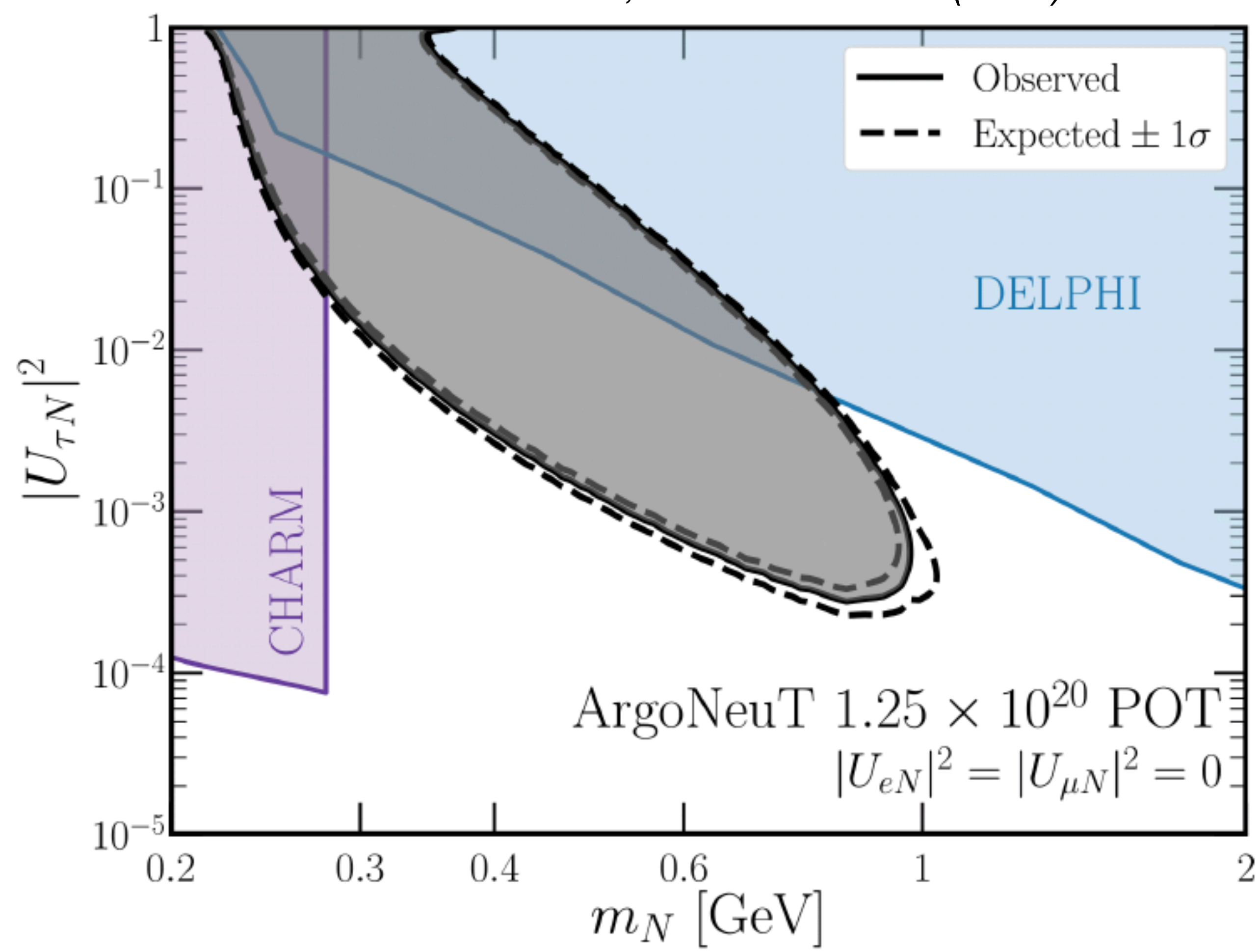






0 events observed in the data

R. Acciarri et al., PRL 127 121801 (2021)

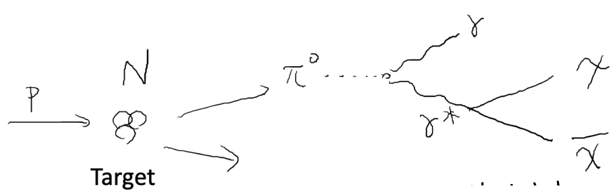


Significant increase in the parameter space exclusion region!

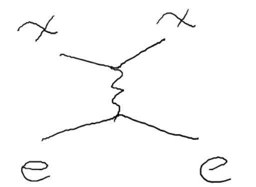
Searches for new physics in LAr TPC: ArgoNeuT

First search for Millicharged Particles in LAr TPC

mCP have an electric charge $Q=\epsilon \cdot e$ ($\epsilon \ll 1$)



- production: meson decays

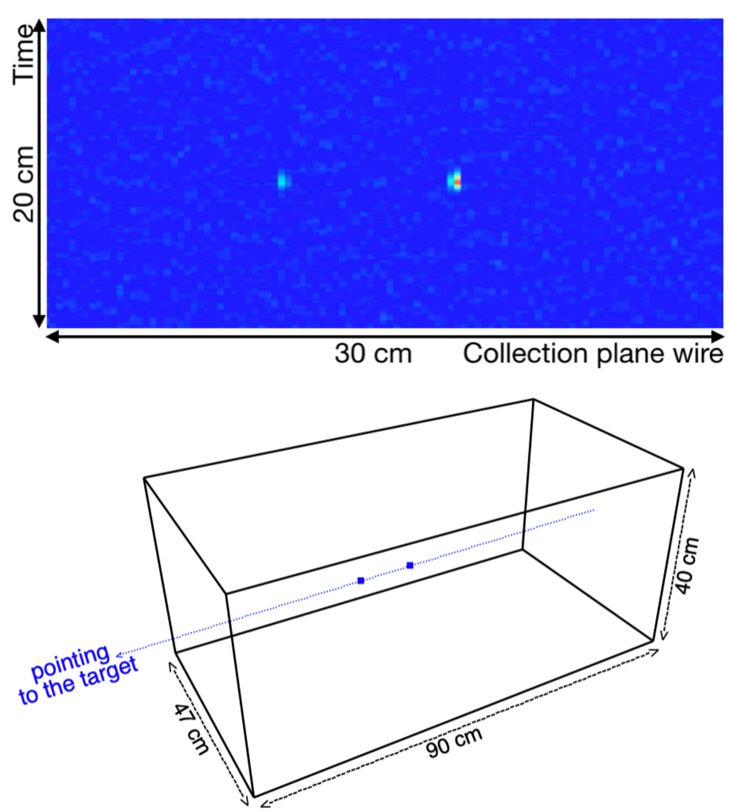


- detection: scattering electron

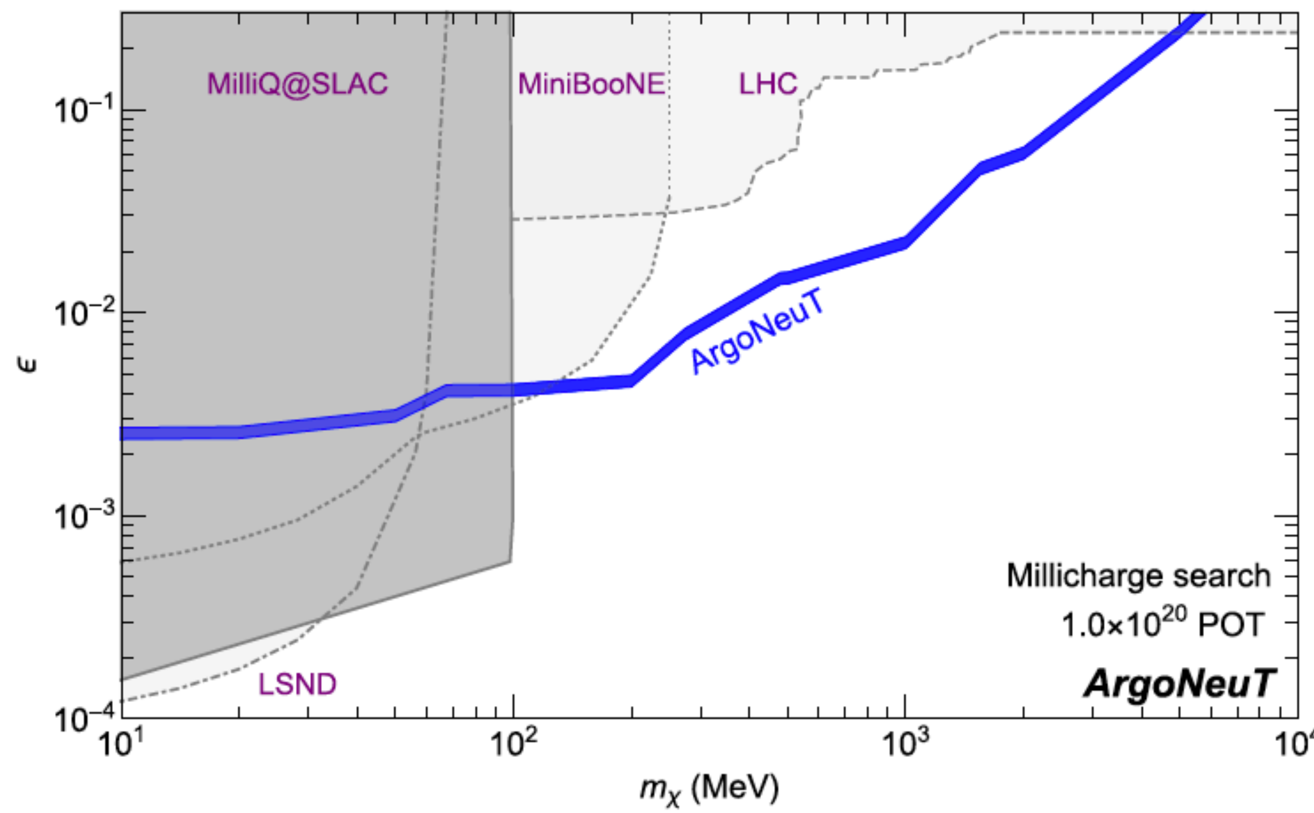
Low energy threshold (300 KeV) is the key!

one mCP Signal Candidate Event observed

[compatible with the expected background]



R. Acciarri et al., PRL124 131801 (2020)

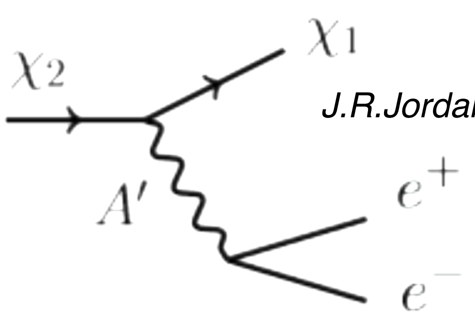


Leading constraints in unexplored parameter region!

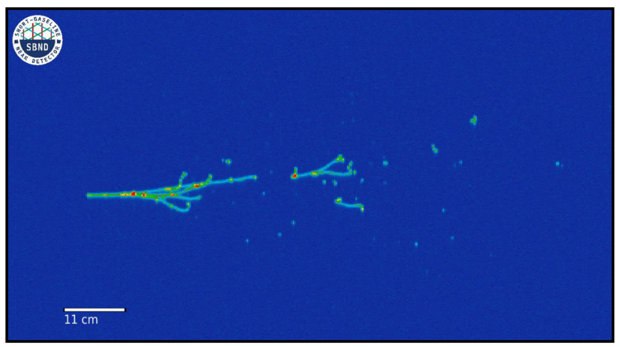
Signatures for new physics in LArTPC: SBND

Monte Carlo simulations

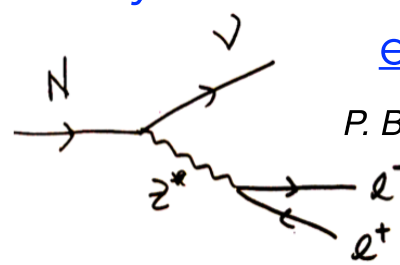
Dark Matter - electron-positron pair



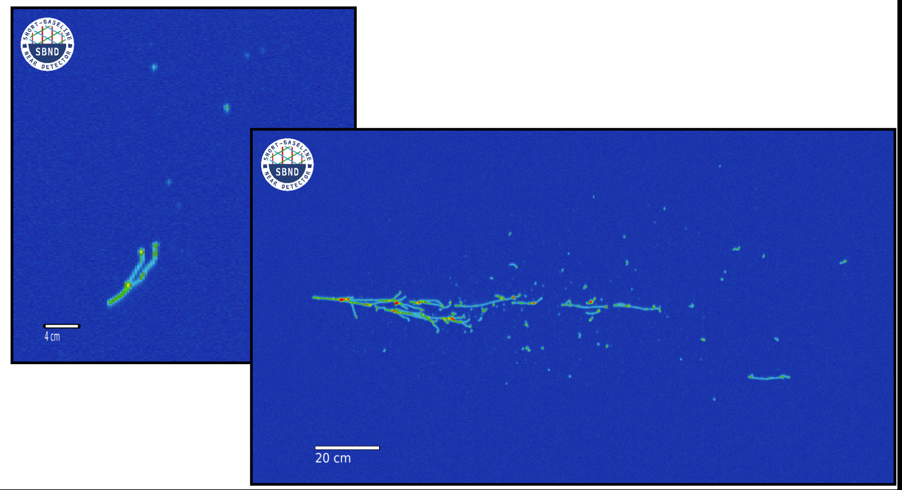
J.R.Jordan et al., arXiv:1806.05185



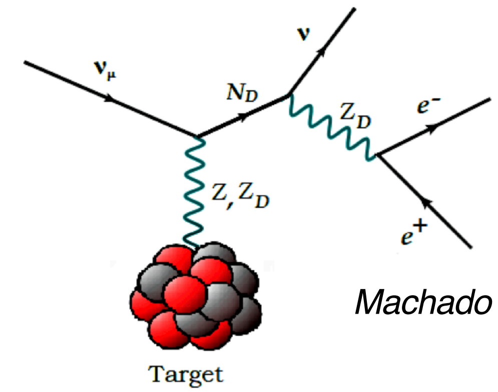
Heavy Neutral Leptons - electron-positron pair



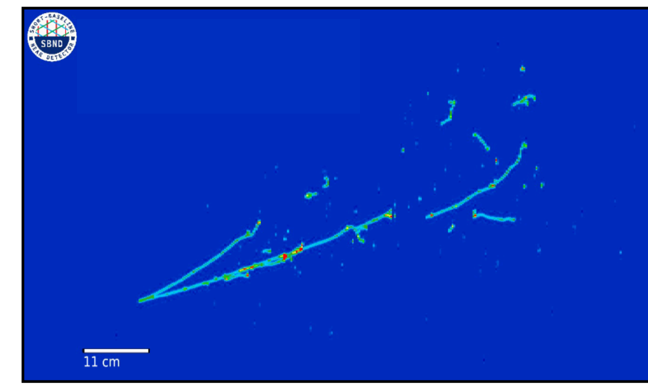
P. Ballet et al., JHEP 04 102 (2017)



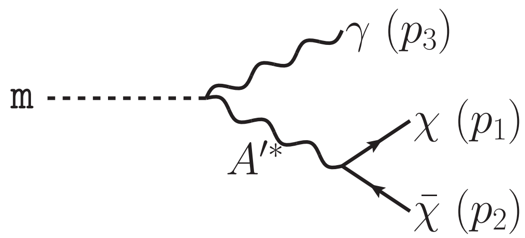
Dark Neutrino - electron-positron pair



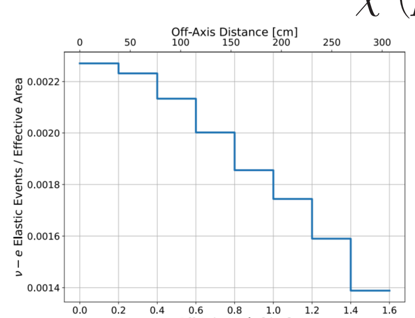
Machado et al., PRL 241801 (2018)



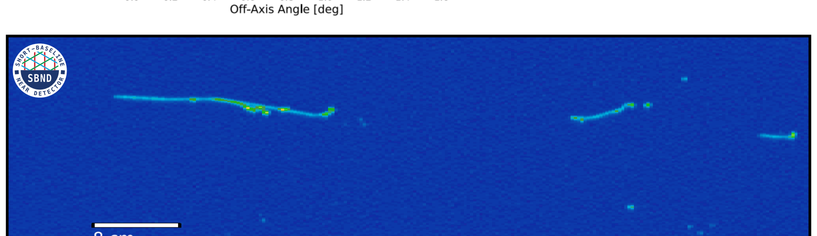
Dark Matter - forward electron



V. De Romeri et al., arXiv:1903.10505



SBND-PRISM: Signal is unfocused while background (ν-electron elastic scattering events) decrease with the off-axis angle



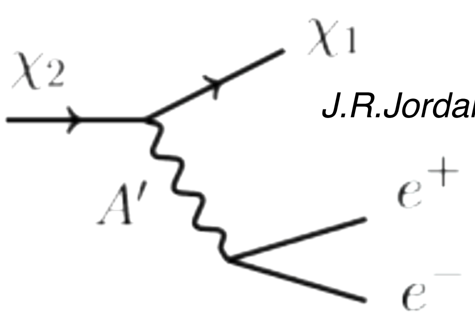
...several other studies and calculations of sensitivities ongoing

SBN(D) experiment(s) will explore the landscape and test **not only the sterile neutrino hypothesis**, but also other **new physics models.**

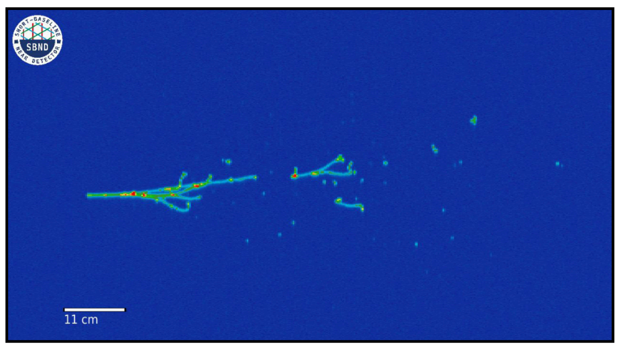
Signatures for new physics in LArTPC: SBND

Monte Carlo simulations

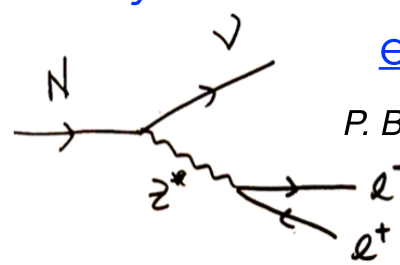
Dark Matter - electron-positron pair



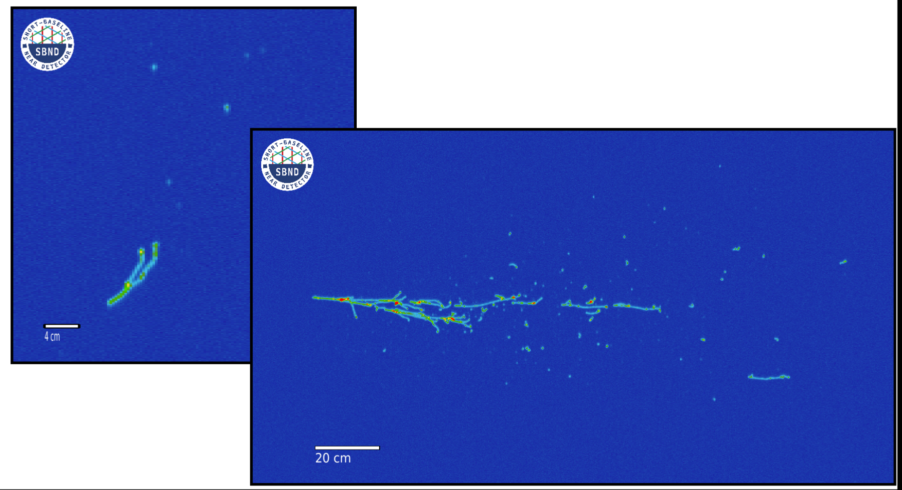
J.R.Jordan et al., arXiv:1806.05185



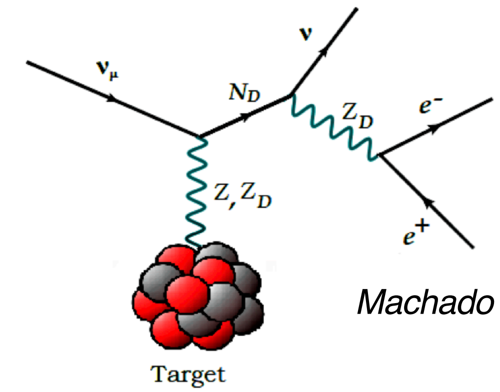
Heavy Neutral Leptons - electron-positron pair



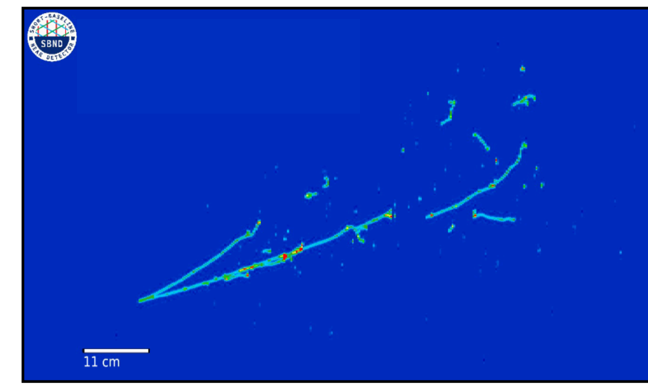
P. Ballet et al., JHEP 04 102 (2017)



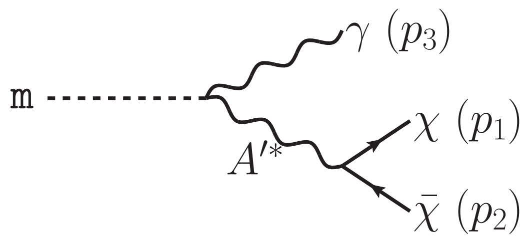
Dark Neutrino - electron-positron pair



Machado et al., PRL 241801 (2018)



Dark Matter - forward electron



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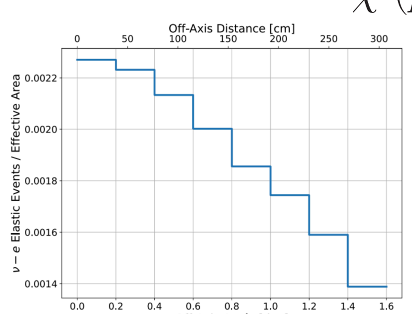

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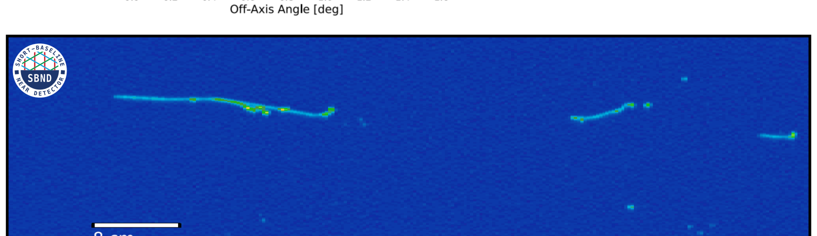


MicroBooNE has searched for

- Heavy Neutral leptons (N→$\mu^{\pm}\pi^{\mp}$ decay channel in a delayed time window)

  P. Abratenko et al., PRD 101 052001 (2020)

- Higgs scalar portal (e^+e^- final state from NuMi off-axis events)

  P. Abratenko et al., PRL 127 151803 (2021)

Results recasted to constraint Heavy Neutral Leptons

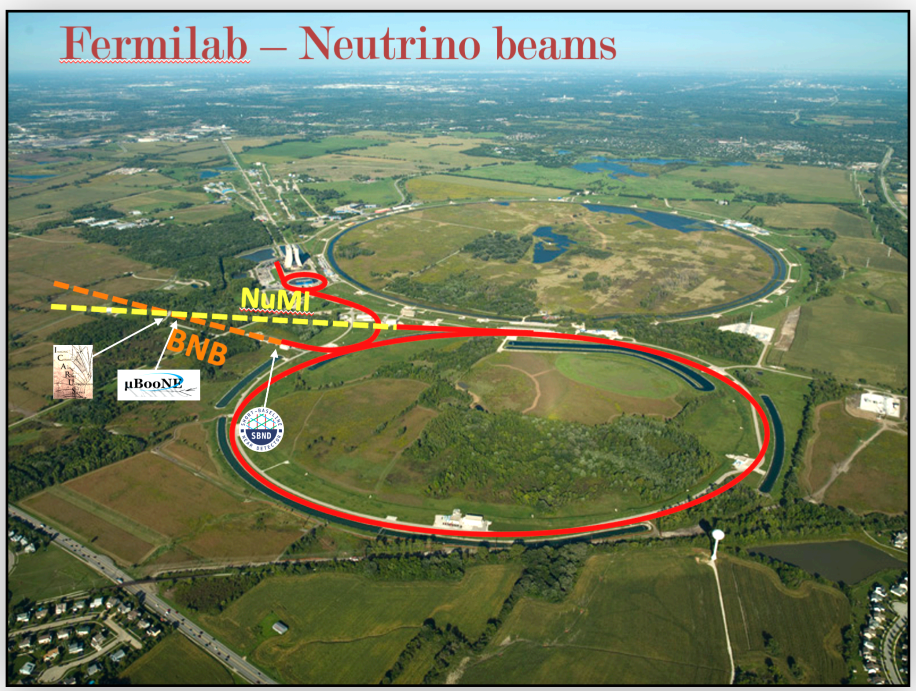
K. Kelly and P. Machado, arXiv:2106.06548

Not only BMS physics: Neutrino Cross Sections at SBN

A correct interpretation of the outcome of ν oscillation experiments and other BSM searches (standard neutrino interactions are background to BSM topologies) in LAr TPC require precise understanding of **neutrino-argon** interactions.

The ArgoNeuT experiment provided exploratory measurements of exclusive channels.

The SBN science program includes precision studies of neutrino-argon cross sections.



- MicroBooNE has provided several neutrino-argon cross section measurements.*
- ICARUS-T600 collects 100k neutrino events per year from NuMI off-axis.
- SBND will make the world's highest statistics cross section measurements by recording 2 million neutrino interactions per year from BNB.

A generational advance in neutrino-nucleus interaction studies!

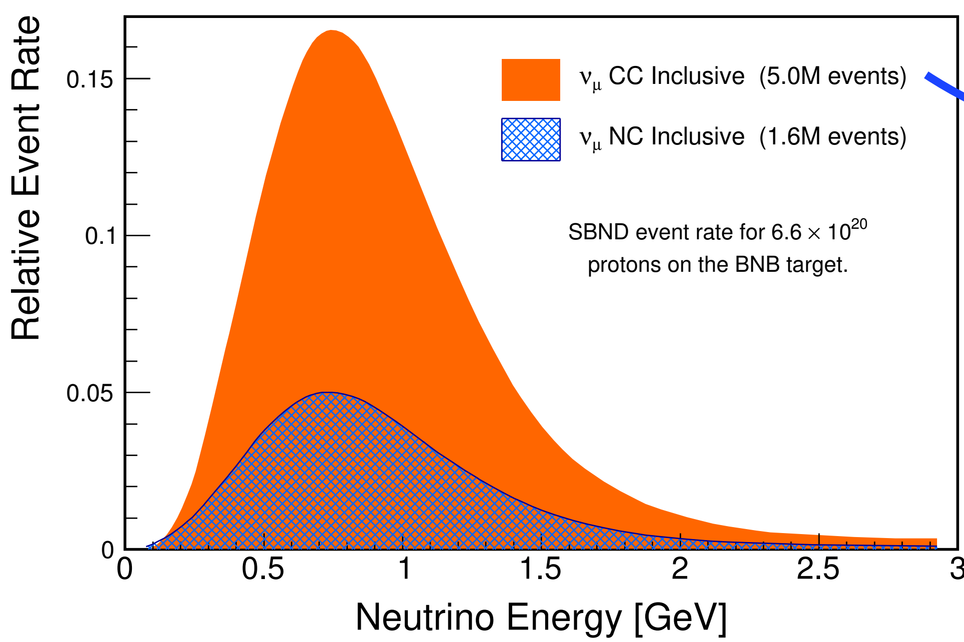
*See D. Caratelli at this conference (on Tuesday), for a review of MicroBooNE cross section measurements

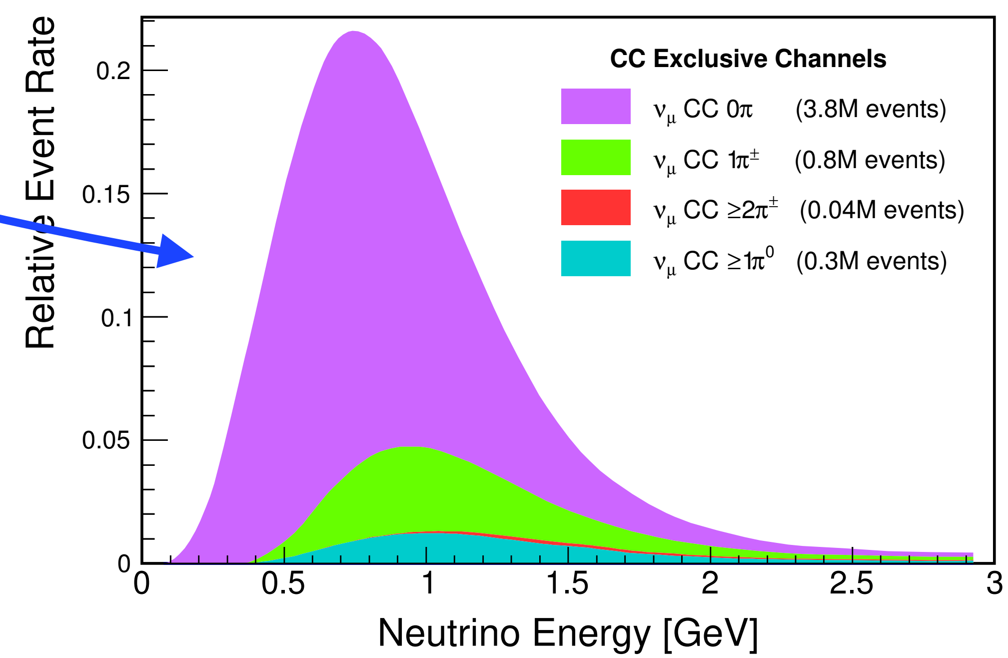
Precision Studies of Neutrino-argon Interactions in SBND

With its proximity to the neutrino source, SBND will compile neutrino data with unprecedented high event rate and provide precision studies of neutrino-argon interactions in the sub-GeV and GeV energy range.

~ 5000 ν events/per day!

In three months SBND will collects as much data as MicroBooNE has collected in five years.





1.5 million ν_μ Charged Current (CC) and 12,000 ν_e CC interactions per year.

Inclusive and exclusive measurements of different final states for ν_μ and ν_e, measure nuclear effects and rare processes

SBND-PRISM: perform targeted neutrino interaction measurements.

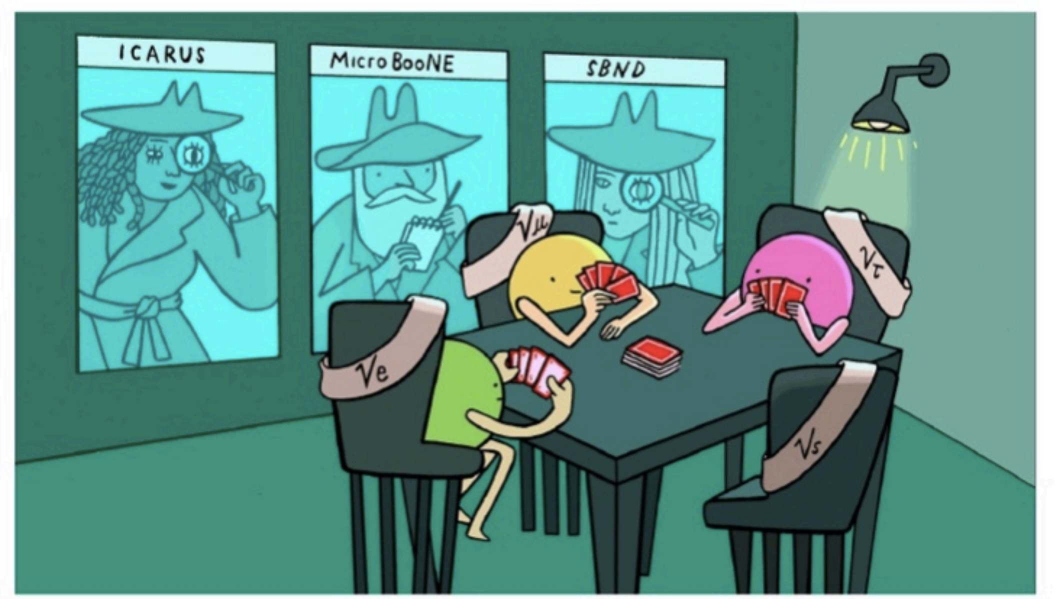
Summary

LAr TPC neutrino detectors at Short-Baseline are fantastic tools to look for new physics in the neutrino sector and beyond!

ArgoNeuT, a small LAr-TPC provided first neutrino cross sections and leading constraints on millicharged particles and heavy neutral leptons in unexplored parameter space regions.

MicroBooNE completed the first search for low energy excess, other BSM searches and several neutrino-argon cross section measurements.

The SBN detectors will perform a world-leading search for eV-scale sterile neutrinos.



Artwork by Sandbox Studio, Chicago with Corinne Mucha

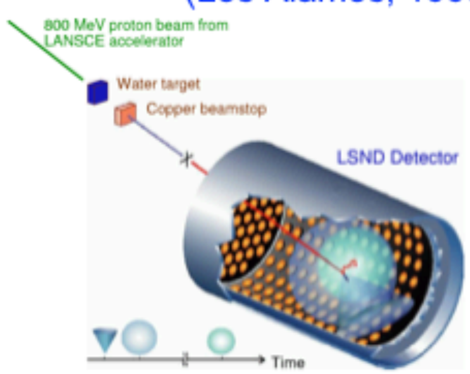
Beyond oscillation searches, the SBN program has a broad science goal, which addresses alternative explanations of the SBL anomalies, includes other BSM explorations and precision studies of neutrino-argon interactions.

OVERFLOW

Experimental Hints For Beyond Three Neutrino Mixing

Sterile Neutrinos?

Low energy $\bar{\nu}_\mu$ beam from a decay-at-rest pion beam (Los Alamos, 1993-1998)



LSND

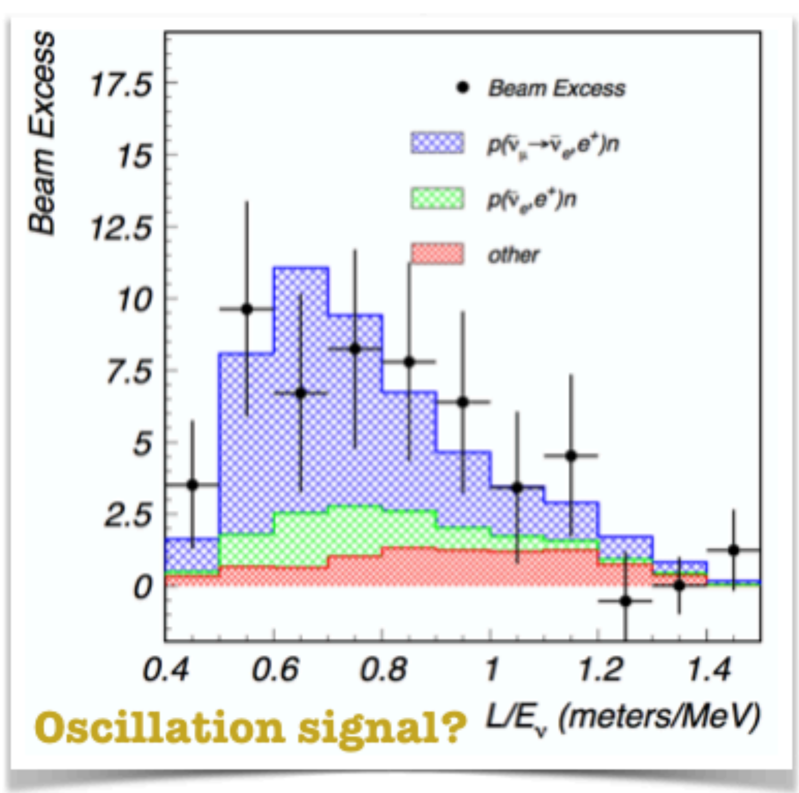
Baseline 30 m

E= [20 – 50] MeV

L/E ≈ 1 m/MeV

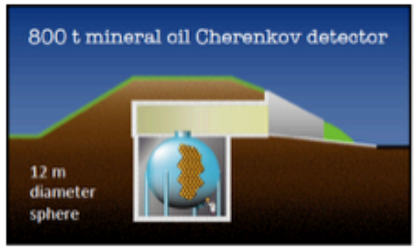
PRD 64 (2001) 112007

167 tons liquid scintillator



Decay in flight neutrino source (Booster Neutrino Beam - Fermilab)

L/E similar to LSND



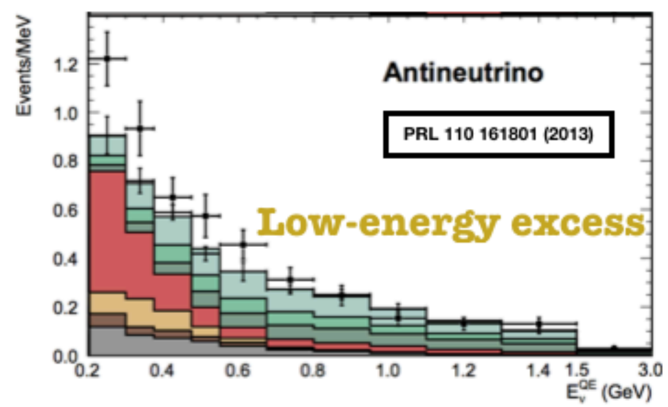
MiniBooNE

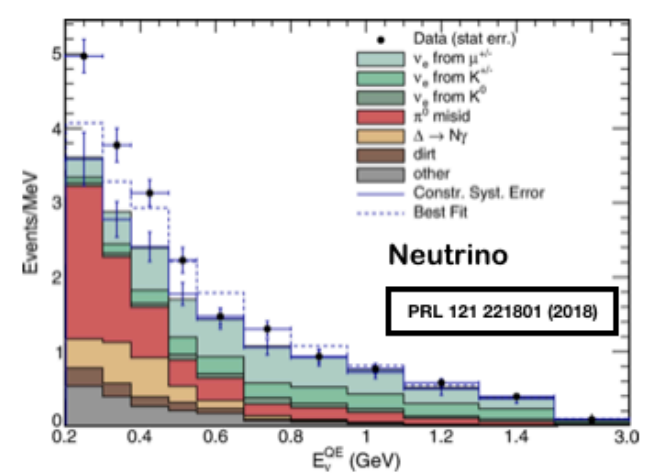
Baseline 540 m

E=[0 - 2] GeV

L/E ≈ 1 m/MeV

800 tons mineral oil

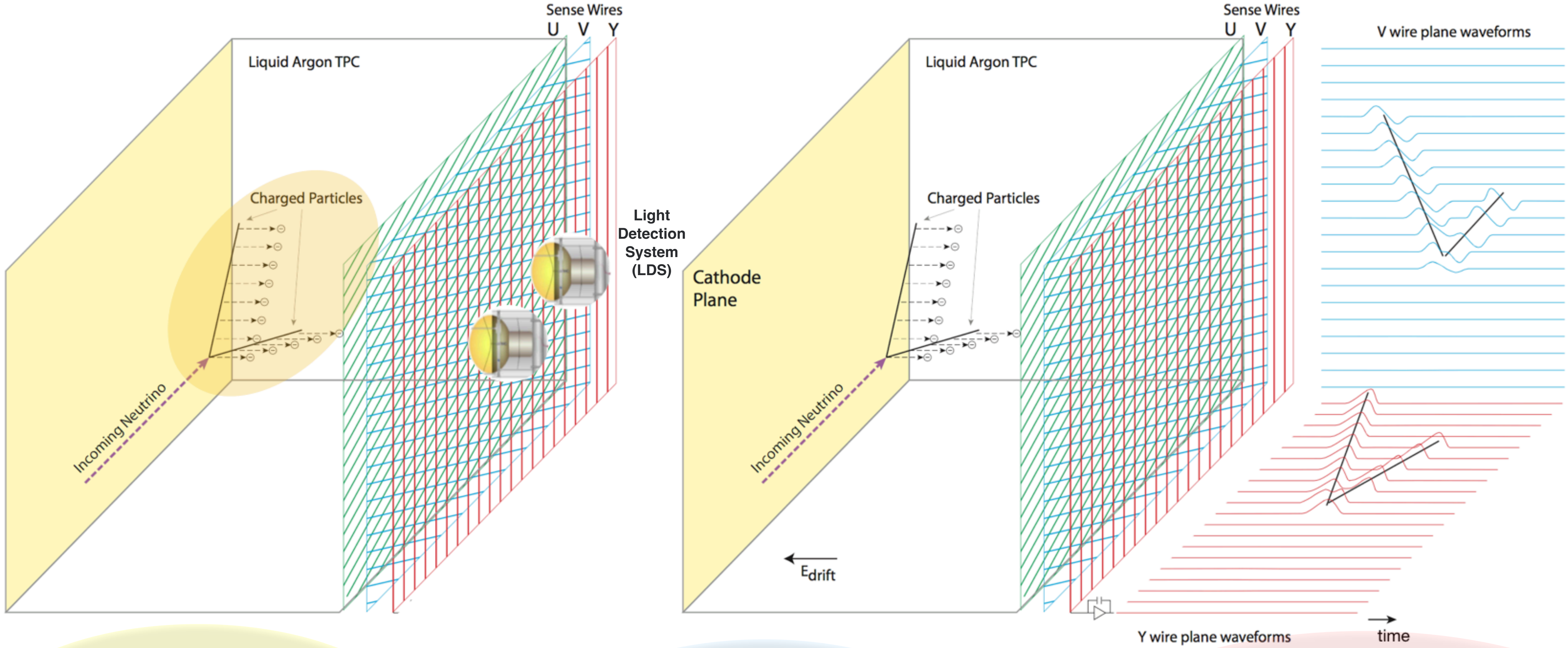




+

Reactor and Gallium "anomalies"

LArTPC at work



Charged particles in LAr produce free <u>ionization electrons</u> and <u>scintillation light</u>

Ionization charge <u>drifts in a uniform electric</u> field towards the readout wire-planes

Digitized signals from the wires are collected [*time of the wire pulses gives the drift coordinate of the track and amplitude gives the deposited charge*]

m.i.p. at 500 V/cm: ~ 60,000 e/cm
~ 50,000 photons/cm

Electron drift time ~ ms

<u>VUV photons</u> propagate and are <u>shifted into VIS</u> photons

Scintillation light fast signals from LDSs give event timing