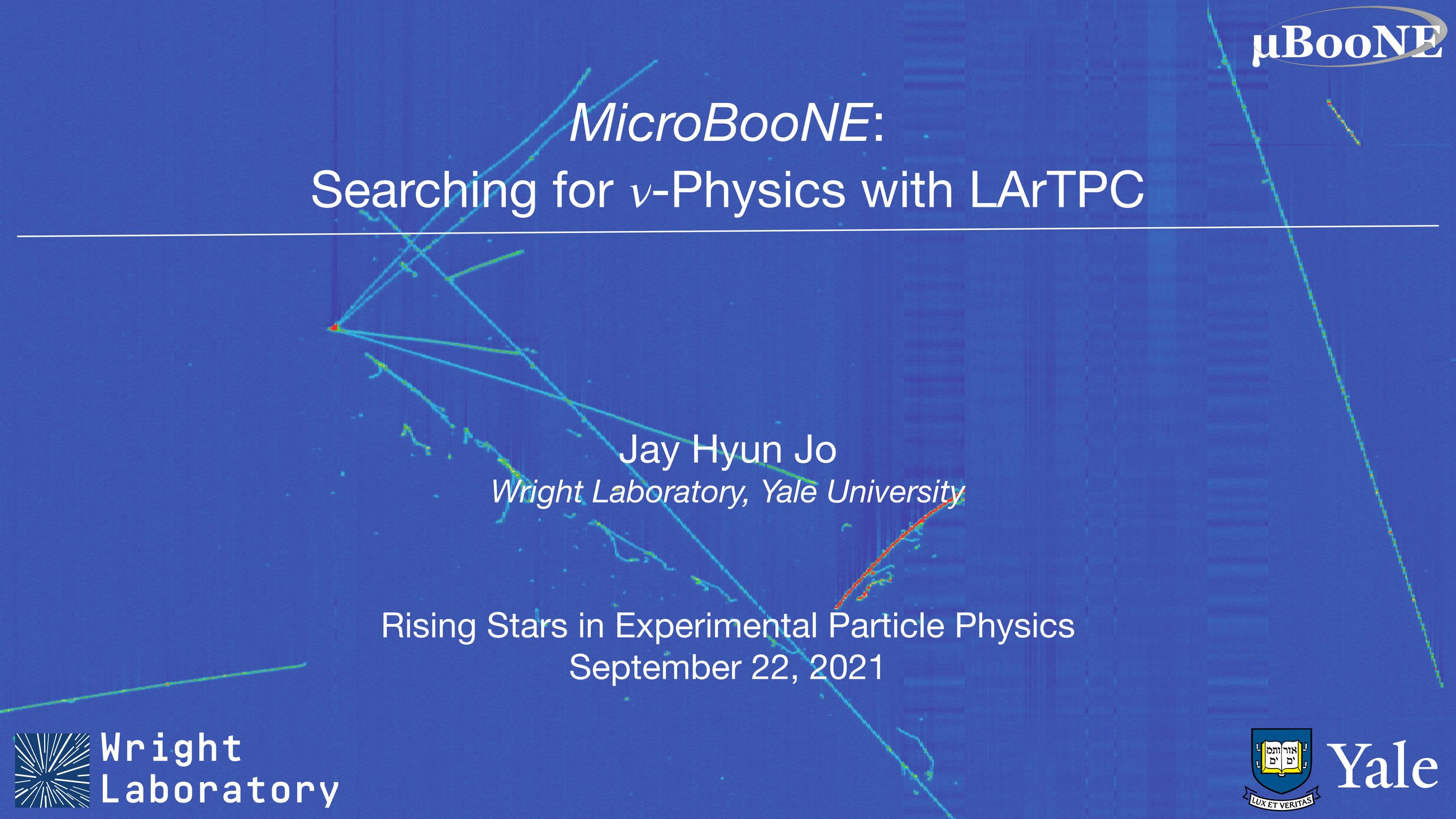


MicroBooNE: Searching for ν-Physics with LArTPC

Jay Hyun Jo

Wright Laboratory, Yale University

Rising Stars in Experimental Particle Physics

September 22, 2021

μBooNE

Wright Laboratory

Yale

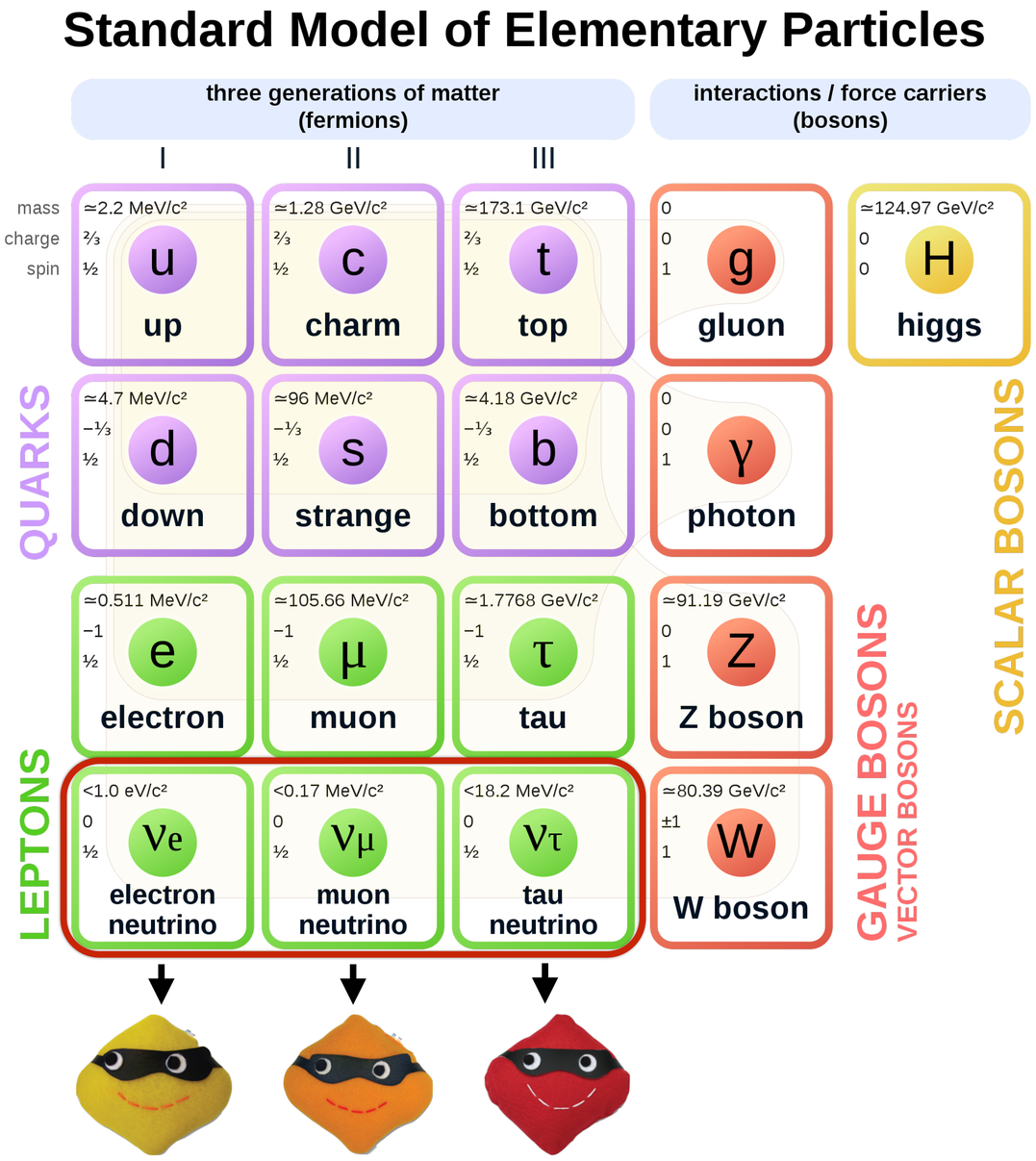
content

- neutrinos in SM and BSM
- LSND/MiniBooNE anomaly: Low Energy Excess (LEE)
- LArTPC and MicroBooNE to the rescue!
- MicroBooNE’s LEE searches and beyond

neutrinos in SM and BSM

standard model of particle physics

- standard model that describes the elementary particles has been very successful so far
- however, there are still unsolved questions in SM, especially in neutrino sector
  - neutrino oscillation observation implies neutrino has non-zero mass
  - but we still do not know neutrino masses, mass ordering, precise value of δ_{CP} values, …



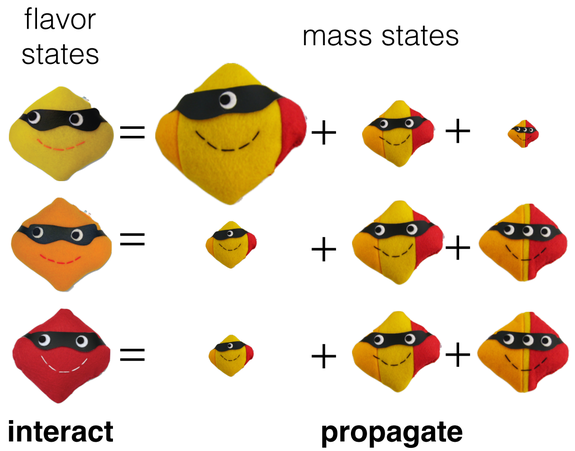
neutrino oscillation

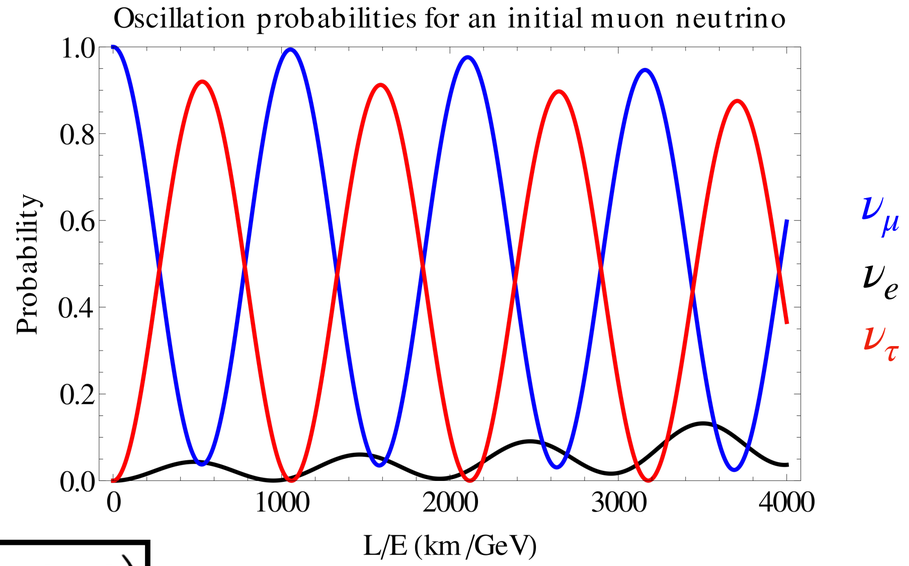
Mixing matrix

$$|\nu_\alpha\rangle = \sum_i U^*_{\alpha i} |\nu_i\rangle$$

Flavor eigenstates participating in weak interactions

Mass eigenstates ν_1, ν_2, ν_3





two-neutrino model

$$P(\nu_\alpha \to \nu_\alpha) = 1 - \sin^2 2\theta \sin^2\left(1.27 \frac{\Delta m^2\ [\mathrm{eV}]^2 \cdot L\ [\mathrm{km}]}{E_\nu\ [\mathrm{GeV}]}\right)$$

- neutrino flavor eigenstates are not the same as the mass eigenstates
- neutrinos generally are produced in a *flavor* eigenstate, which is a superposition of three *mass* eigenstates
- these mass eigenstates change phase over time at different rates, leads to **neutrino oscillations** when viewed in the flavor basis

remaining questions in ν-physics

standard model

could **CP violation** in neutrino interactions explain the matter/antimatter asymmetry?

what is the **ordering of the neutrino mass**?

beyond the standard model

are there **new interactions** we could discover via neutrino?

are there **additional neutrinos** beyond known three types?

what is neutrino mass?

is the neutrino its own anti particle?

remaining questions in ν-physics

standard model

could **CP violation** in neutrino interactions explain the matter/antimatter asymmetry?

what is the **ordering of the neutrino mass**?

what is neutrino mass?

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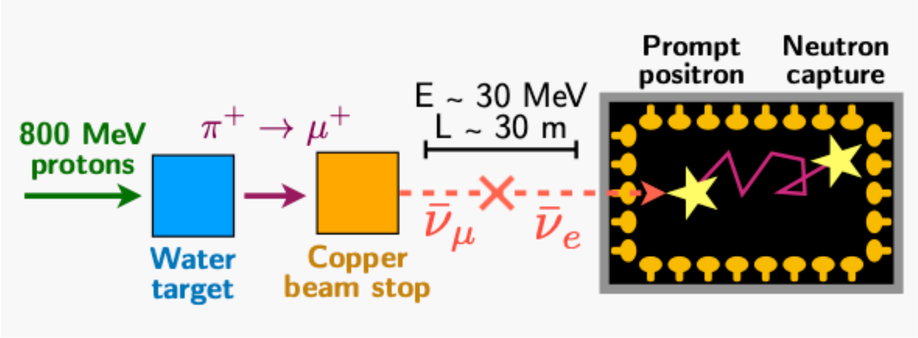
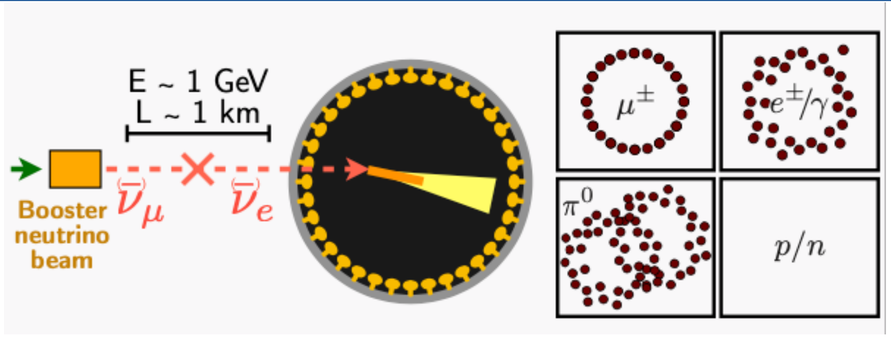
are there **new interactions** we could discover via neutrino?

are there **additional neutrinos** beyond known three types?

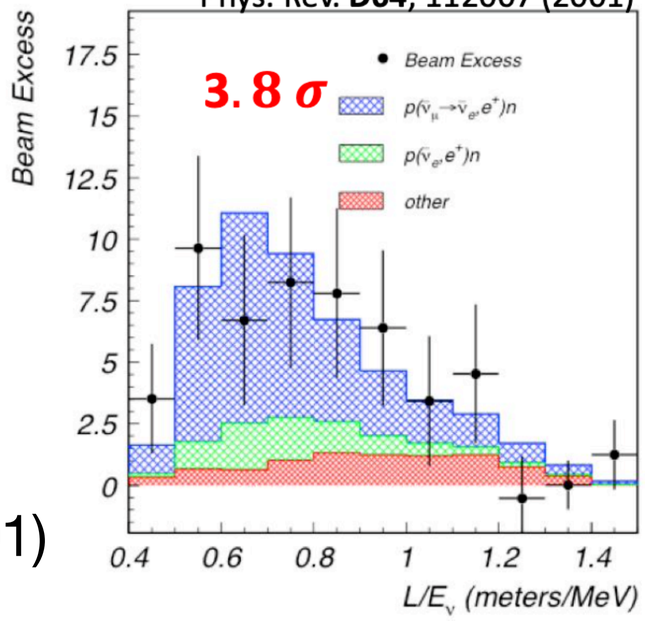
LSND & MiniBooNE anomaly: Low Energy Excess

LSND & MiniBooNE anomaly

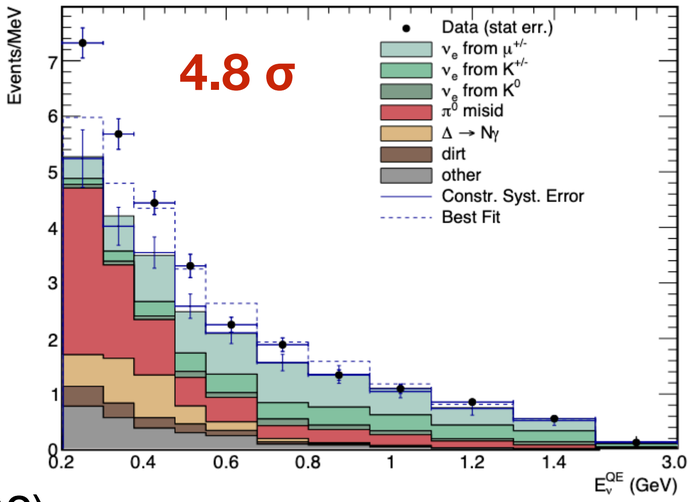




Phys. Rev. **D64**, 112007 (2001)



arxiv:2006.16883



- **LSND** (1990-2001)
- $\bar{\nu}_\mu$ -> $\bar{\nu}_e$ excess over background suggests evidence for oscillation at $\Delta m^2 \sim 1eV^2$

- **MiniBooNE** (1998-2020)
- measured ν_μ-> ν_e and $\bar{\nu}_\mu$-> ν_e appearance
- the excess of events at low energy

extra neutrinos?

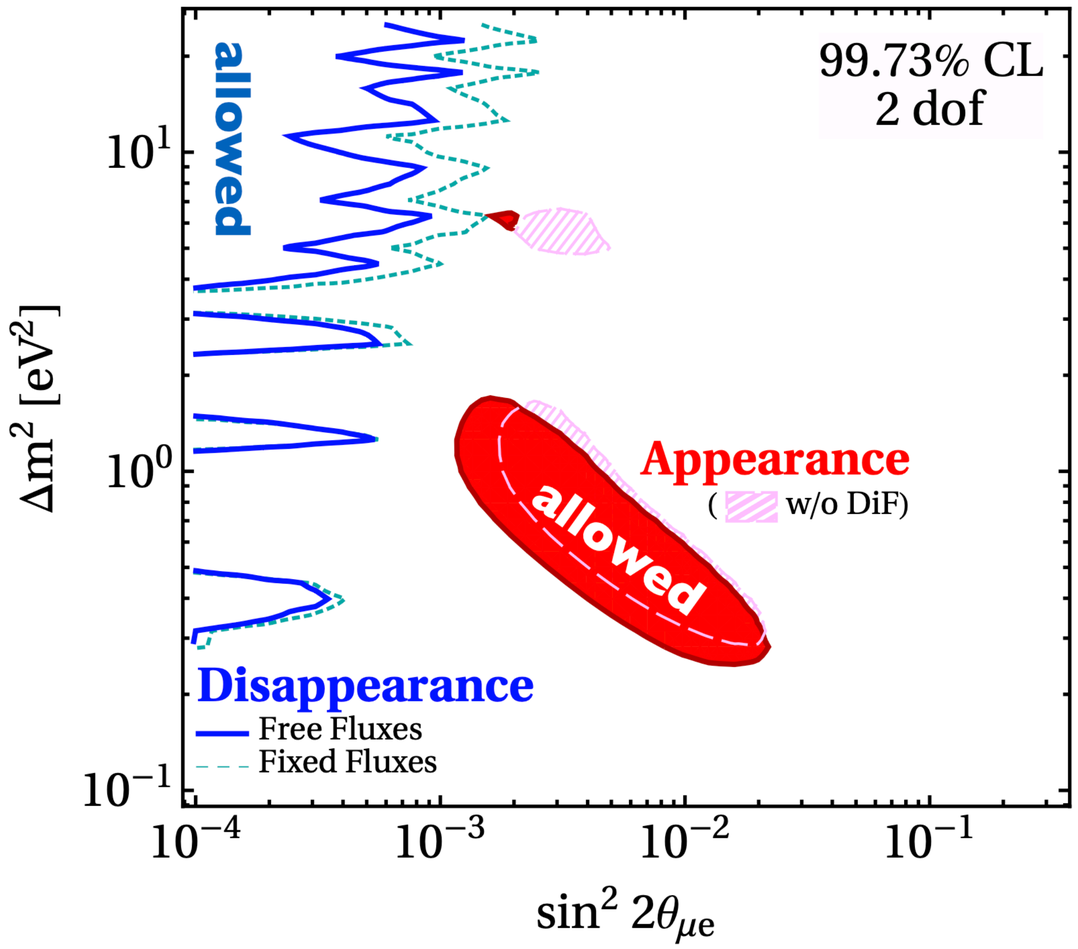
- the number of *weekly interacting* "**active**" neutrino flavors is fixed to three, by the *Z* width measurements (LEP)
- but additional, *non-interacting* "**sterile**" neutrino states could still exist
- potentially detectable through impact on neutrino oscillations
- *can this new type of neutrino be solution to the anomaly?*

$$U = \begin{array}{c} \\ \nu_e \\ \nu_\mu \\ \nu_\tau \\ \nu_s \end{array} \begin{array}{c} \begin{array}{cccc} \nu_1 & \nu_2 & \nu_3 & \nu_4 \end{array} \\ \begin{bmatrix} \blacksquare & \blacksquare & \blacksquare & ? \\ \blacksquare & \blacksquare & \blacksquare & ? \\ \blacksquare & \blacksquare & \blacksquare & ? \\ ? & ? & ? & ? \end{bmatrix} \end{array}$$

Flavor transitions via this new mixing:

$$P_{\alpha\beta} = 4|U_{\alpha 4}|^2|U_{\beta 4}|^2 \sin^2\left(1.27\frac{\Delta m^2_{41} L}{E}\right)$$

tension in global picture



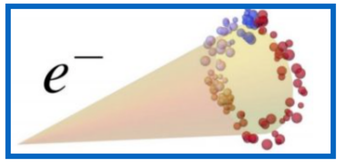
From Pedro Machado's Neutrino 2020 talk: Sterile Neutrino Global Picture

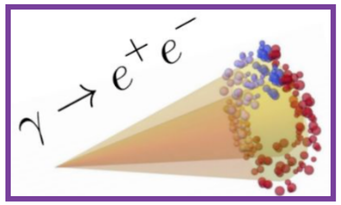
- *unfortunately, it's more complicated than that…*
- significant tension between
  ν_e appearance and
  ν_e and ν_μ disappearance
- lots of different independent observations currently unexplained
- *we need to understand the anomalies better!*

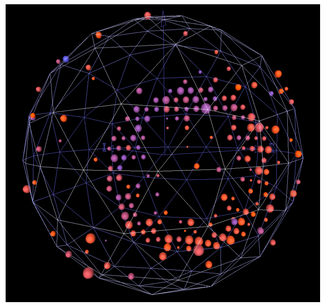
MiniBooNE low energy excess

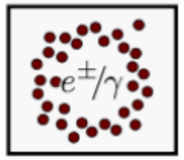
PRD 103 (2021) 052002

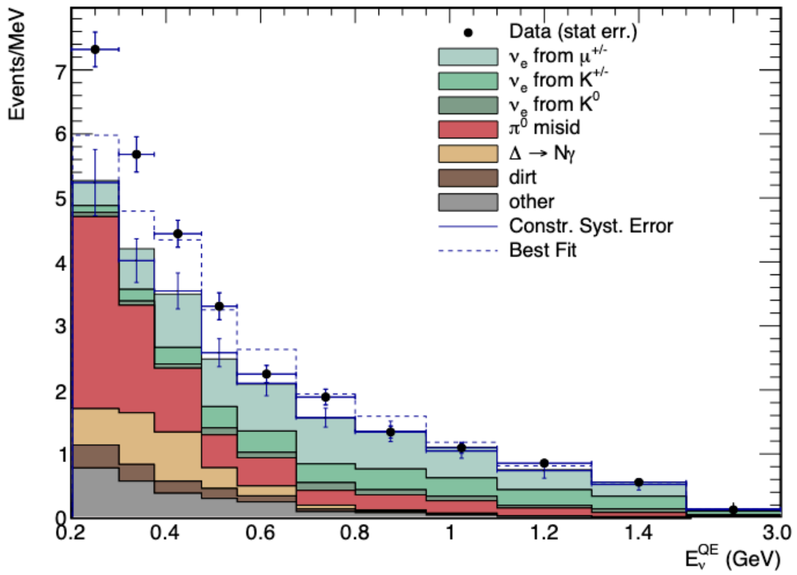
- nature of the excess could be “electron-like” (eLEE) or “photon-like” (*γ*LEE)
  - at low energy, largest background in MiniBooNE is misidentified photon events from NCπ^0 decay
  - MiniBooNE struggled distinguish between electrons and photons, also does not have hadron information
- *can we separate electrons and photons? can we understand the excess with enough event topology information such as hadronic activities?*

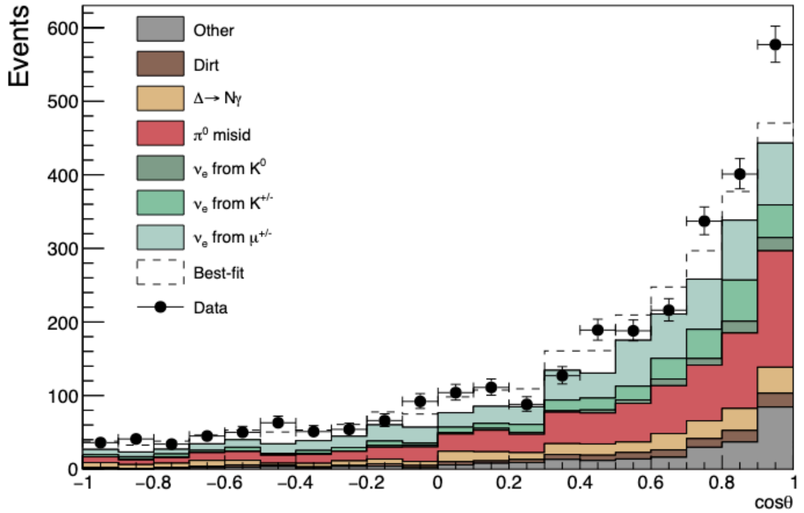












LArTPC and MicroBooNE to the rescue!

LArTPC: Liquid Argon Time Projection Chamber

- **LAr** as total absorption calorimeter
  - denser than water, leads to more interactions
  - abundant and cheap
  - easy ionization and high scintillation light
- **TPC** as 4π charged particle detector
  - 3D reconstruction with fully active volume
- **LAr+TPC** to obtain fine-grained 3D tracking with local dE/dx information and fully active target medium

NUCLEAR INSTRUMENTS AND METHODS 120 (1974) 221–236; © NORTH-HOLLAND PUBLISHING CO.

LIQUID-ARGON IONIZATION CHAMBERS AS TOTAL-ABSORPTION DETECTORS*

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Instrumentation Division, Brookhaven National Laboratory, Upton, New York 11973, U.S.A.

Received 14 May 1974

1974

The Time-Projection Chamber
- A new 4π detector for charged particles

David R. Nygren

Lawrence Berkeley Laboratory
Berkeley, California 97420

1976

THE LIQUID-ARGON TIME PROJECTION CHAMBER:

A NEW CONCEPT FOR NEUTRINO DETECTORS

C. Rubbia

1977

LArTPC: Liquid Argon Time Projection Chamber

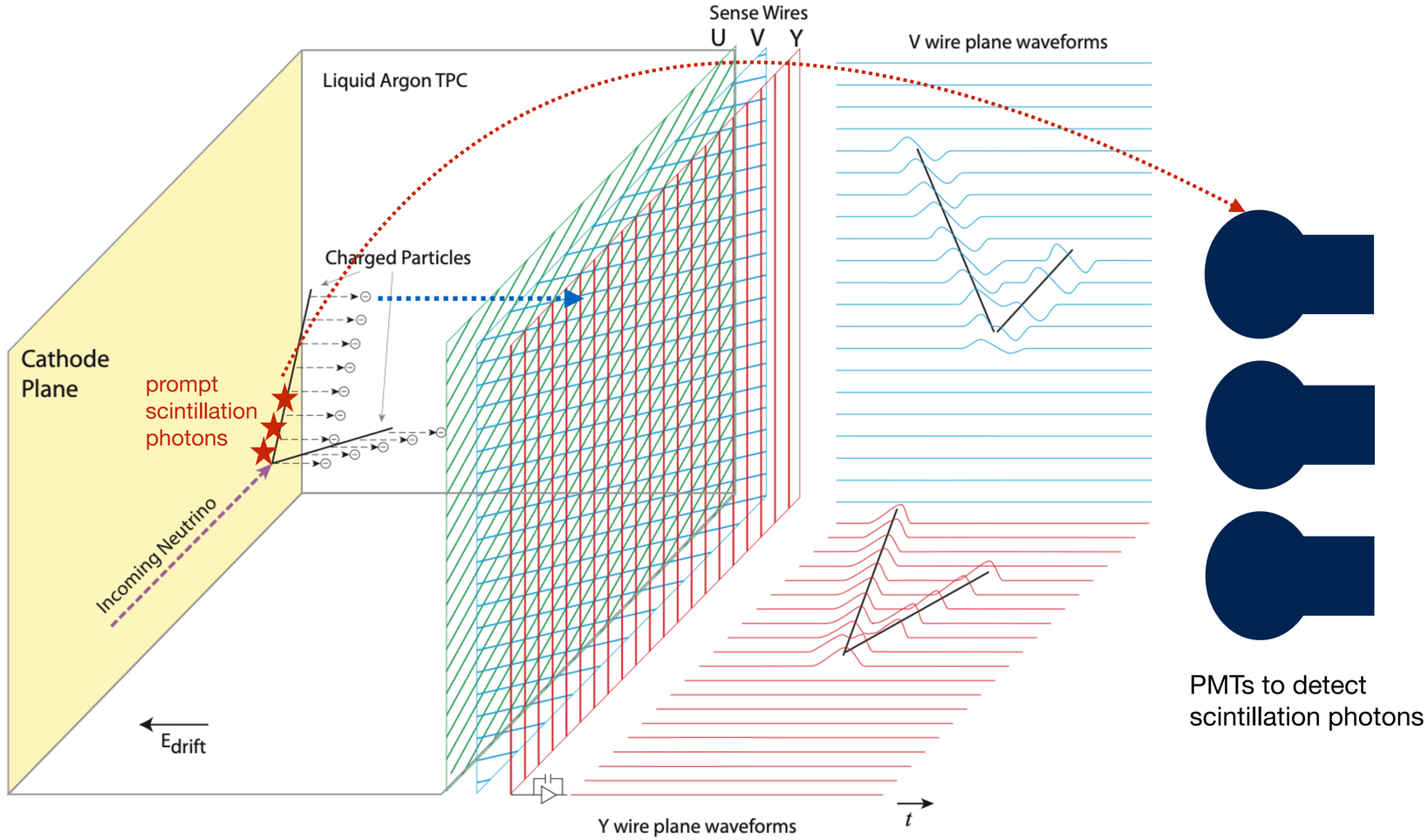
charged particle enters detector

⬇

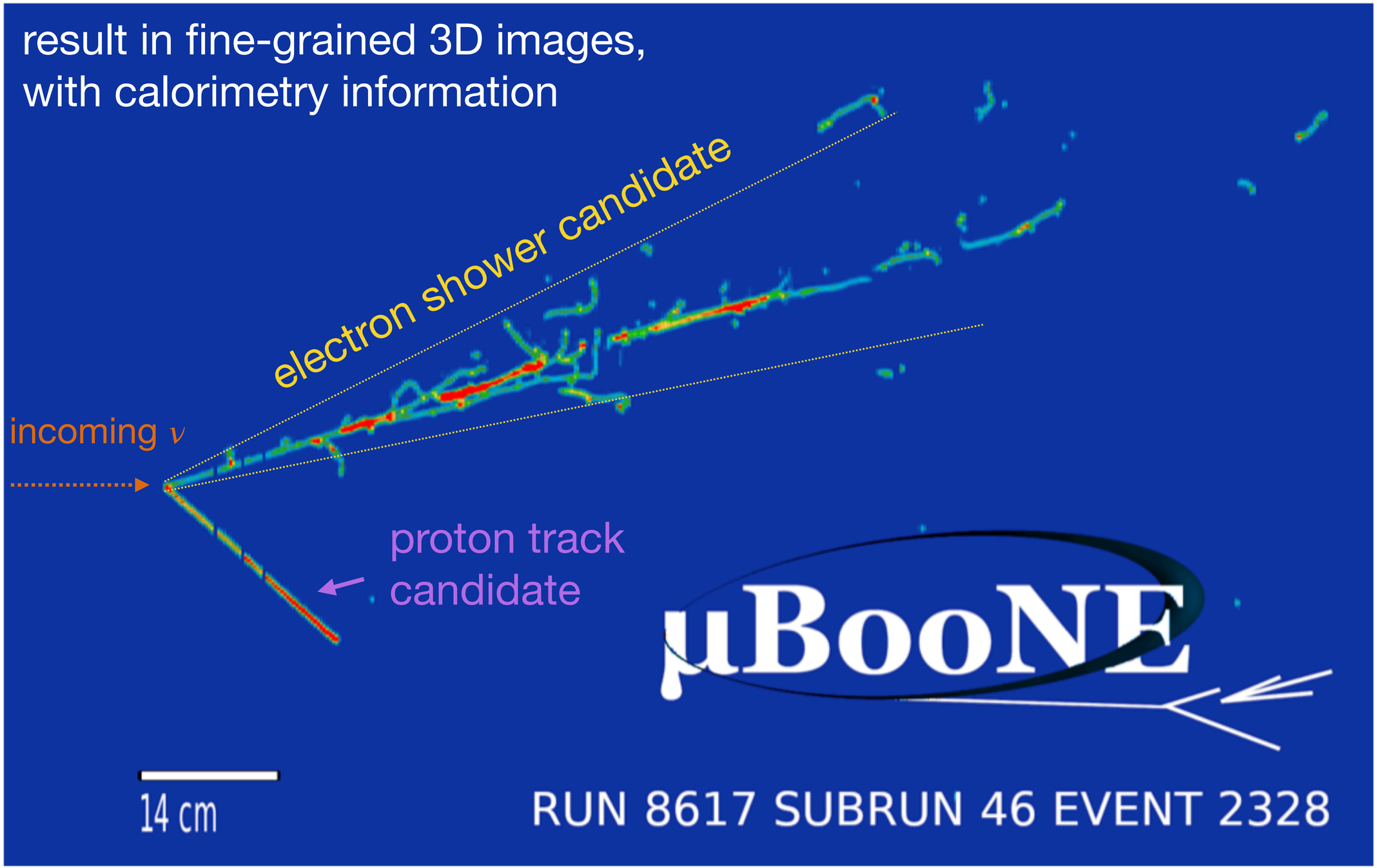
scintillation light emitted by excited Ar, detected by PMTs

⬇

ionization electrons drift to anode plane, detected by sense wires

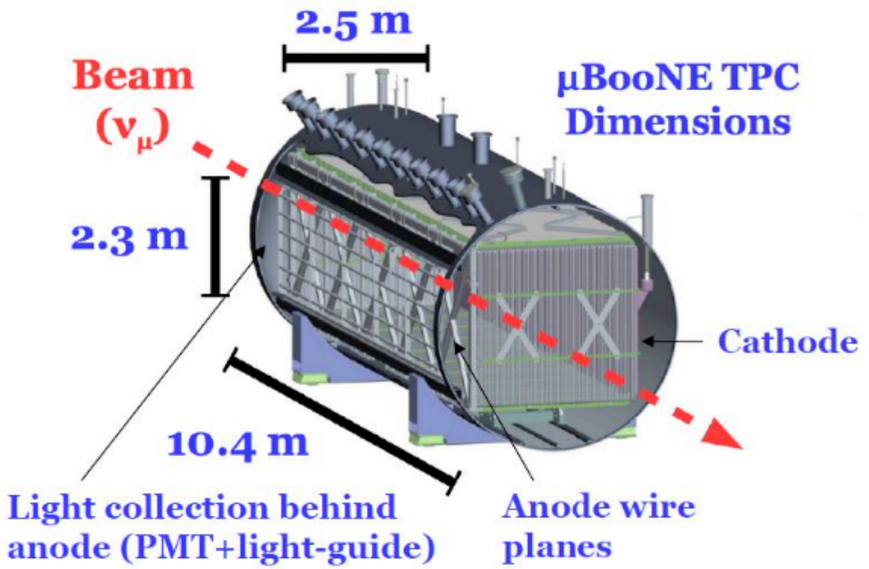


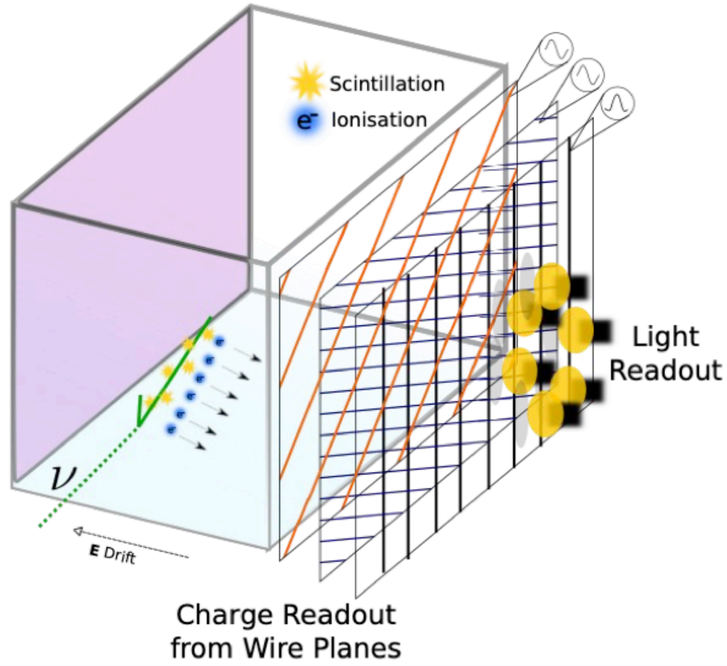
result in fine-grained 3D images,
with calorimetry information



MicroBooNE experiment

- **LArTPC Detector**
  - 85 tons of LAr active volume
  - TPC: 8256 anode sense wires in 3 planes
    PMT: 32 8-inch PMTs
  - located at BNB beamline in Fermilab, started taking data since Oct. 2015
- **physics goal**
  - strong understanding of the detector and highly developed event reconstruction, paving the way to future LAr detectors (SBN & DUNE)
  - neutrino interaction measurements
  - towards low-energy excess: definitively address the MiniBooNE anomaly

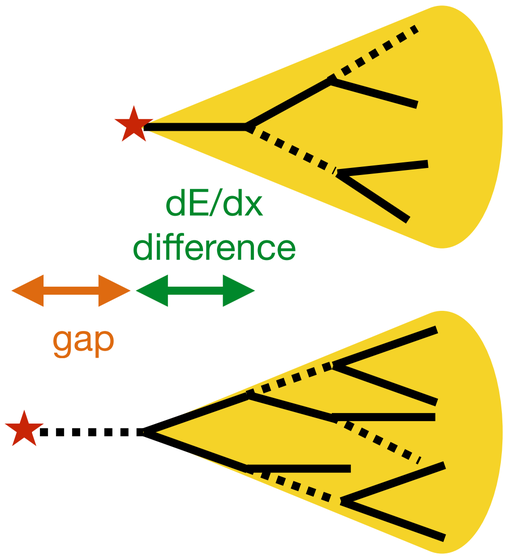




testing eLEE vs. γLEE hypotheses with MicroBooNE

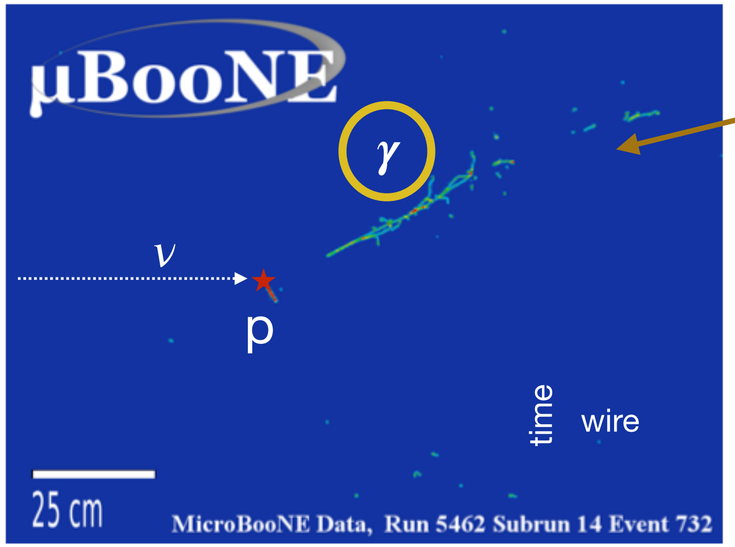
vertex
e^-/e^+
γ

electron shower

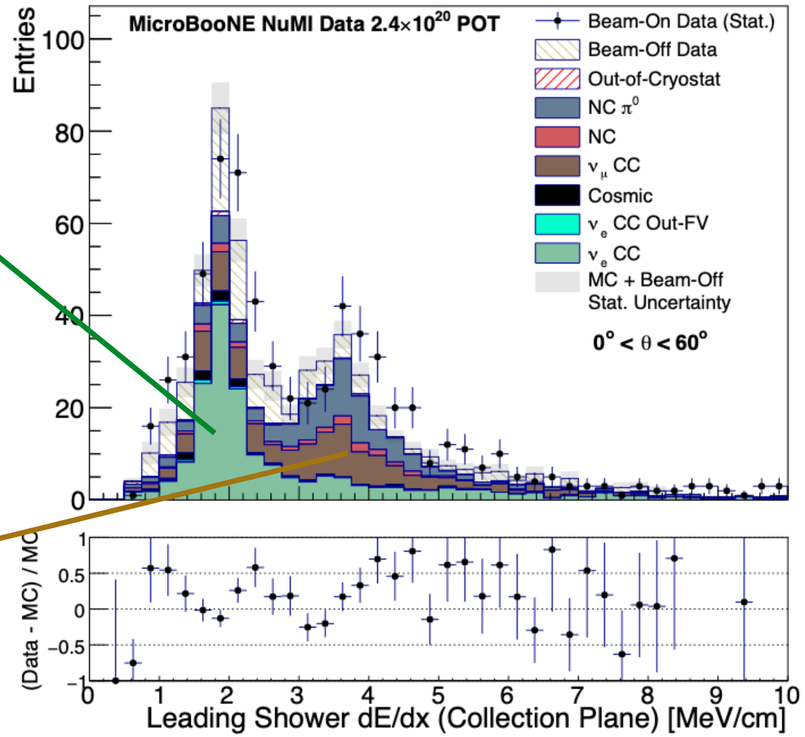


photon shower

topology information



arxiv:2101.04228



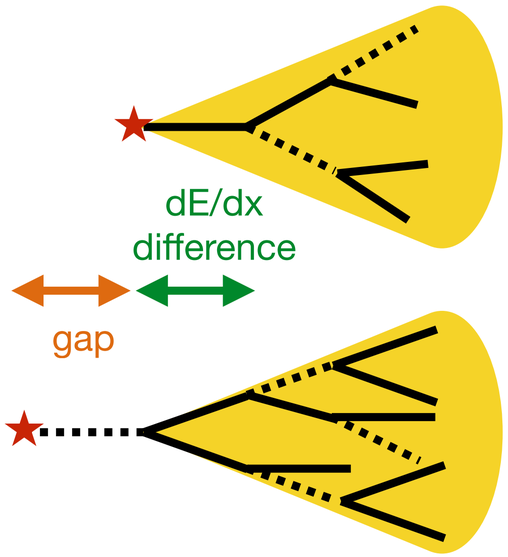
ionization dE/dx

MicroBooNE uses the excellent properties and resolution of its LArTPC to select both eLEE and γLEE signals with high purity

testing eLEE vs. γLEE hypotheses with MicroBooNE

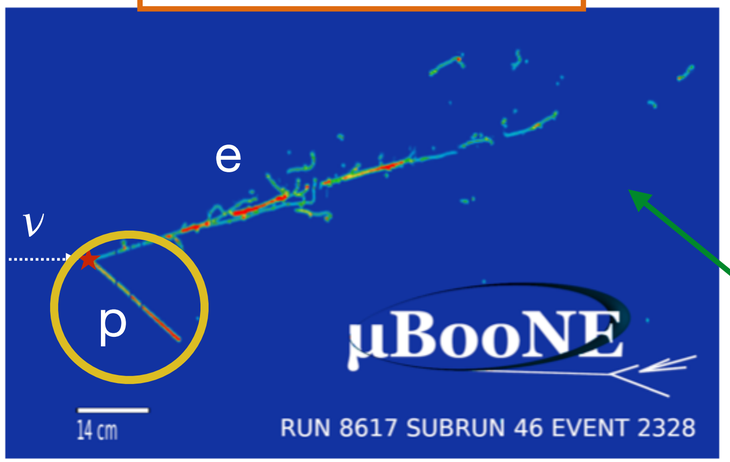
vertex
e^-/e^+
γ

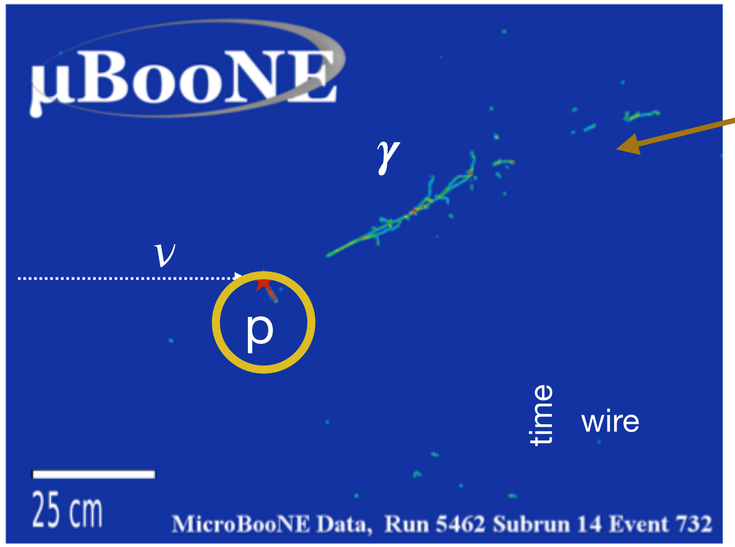
electron shower



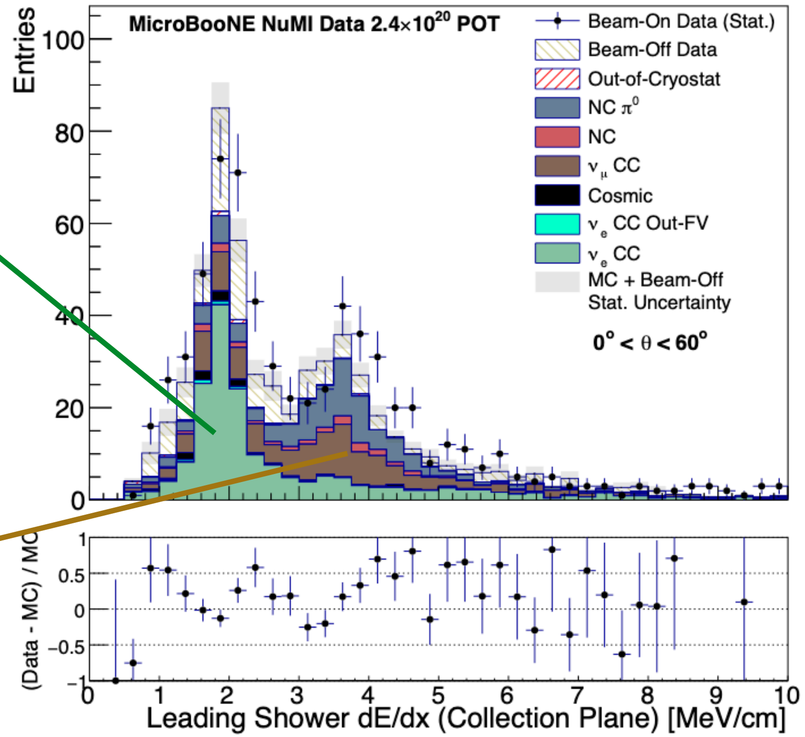
photon shower

topology information





arxiv:2101.04228



ionization dE/dx

…also to identify hadronic final states to provide more information of different interactions

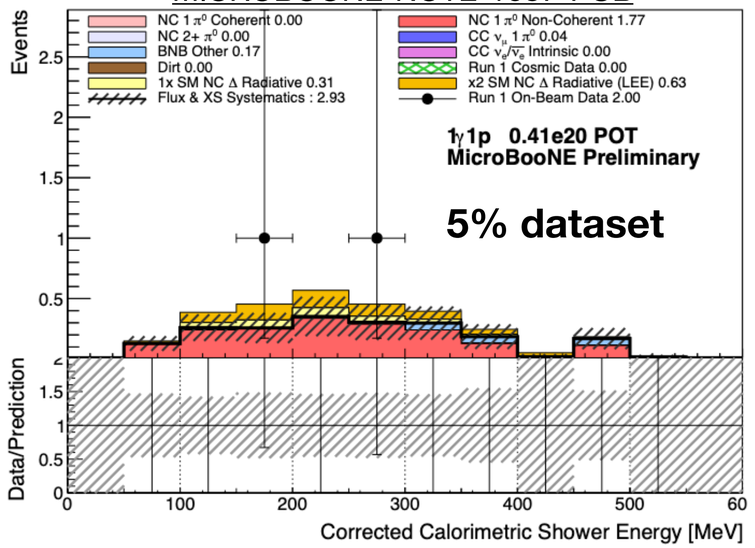
MicroBooNE’s LEE searches and beyond

γLEE search

- targets 1γ0p and 1γ1p topologies consistent with NC $\Delta \rightarrow N\gamma$
  - applying a ~3x flat scaling to NC $\Delta \rightarrow N\gamma$ can explain the observed MiniBooNE excess
- blind analysis: currently only 5% of total dataset opened & analyzed for validation
  - entire selection & analysis chain frozen, expect unblinded result soon!

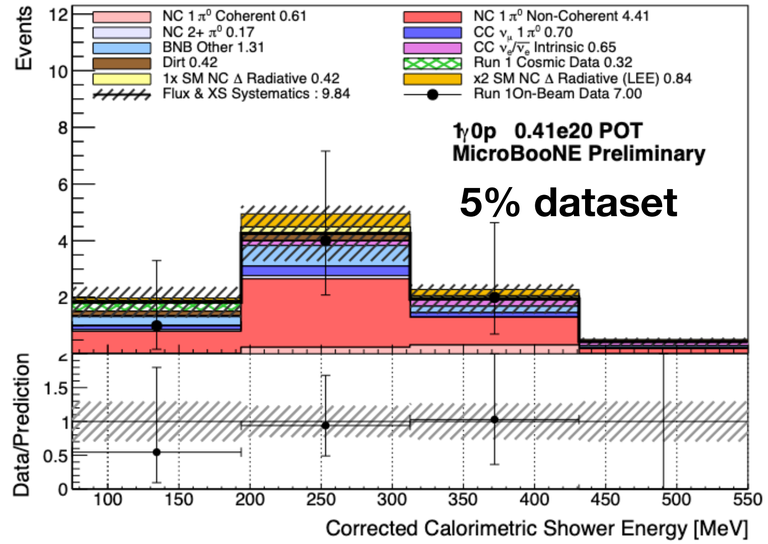
MICROBOONE-NOTE-1087-PUB

1γ0p



(Data/MC: 0.68) (KS: 0.978) (χ^2/n*DOF*: 5.17/12) (χ^2 P^{val}: 0.952)

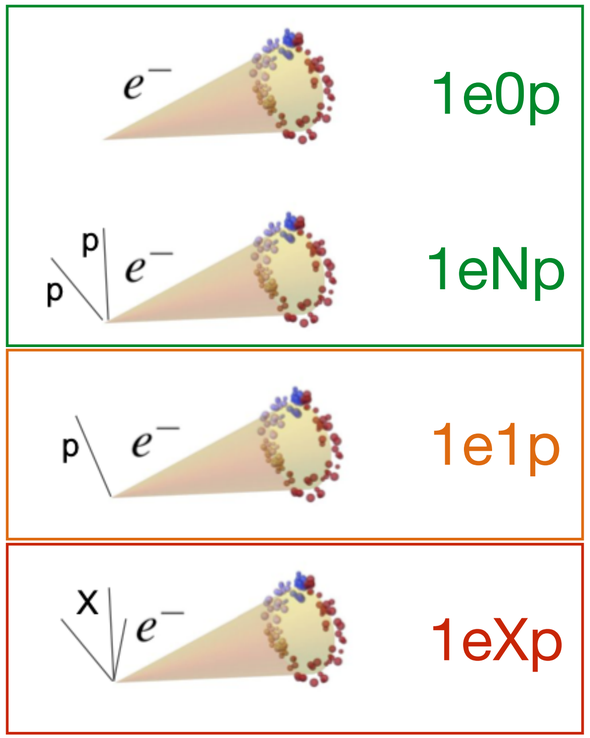
1γ1p



(Data/MC: 0.71) (KS: 1.000) (χ^2/n*DOF*: 1.14/4) (χ^2 P^{val}: 0.888)

eLEE search: three complementary searches

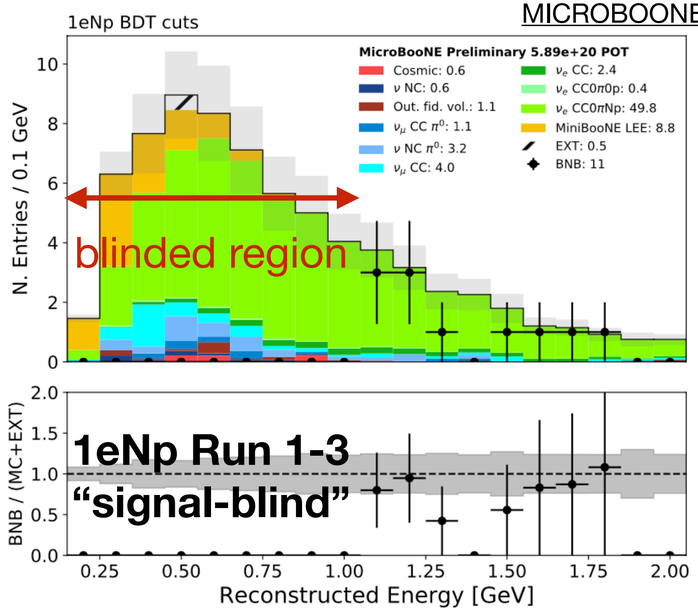
- three independent, complementary analyses
- targeting different topologies and using different reconstruction, particle identification, and selection methods
  - "Pandora" based: targeting 1e0p0π and 1eNp0π (N>0)
  - "Deep Learning" based: targeting 1e1p0π
  - "Wire-Cell" based: targeting 1eXpXπ (X>=0)
- **different final state topologies with various hadronic activities can probe many new physics models to explain MiniBooNE anomaly**

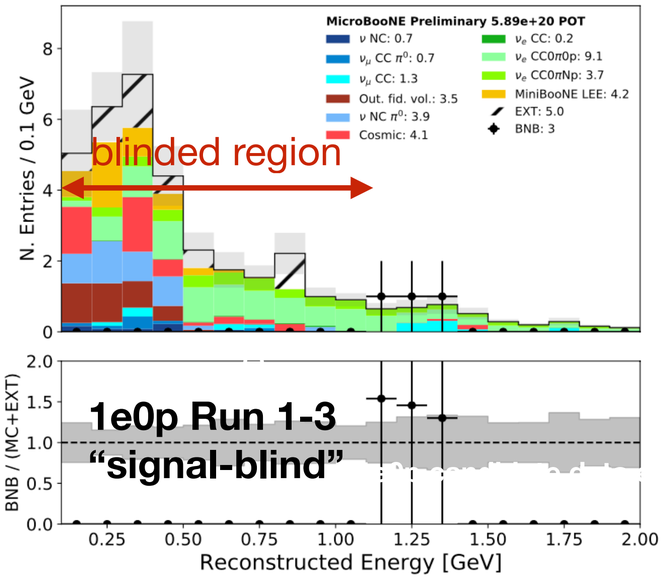


	1e0p	1e1p	1eNp	1eX
sterile ν	✔	✔	✔	✔
Higgs physics		✔	✔	✔
dark ν	✔			
Z' boson	✔			
axion-like particles	✔			

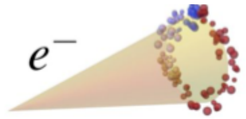
eLEE search: three complementary searches

MICROBOONE-NOTE-1085-PUB





1eNp



1e0p

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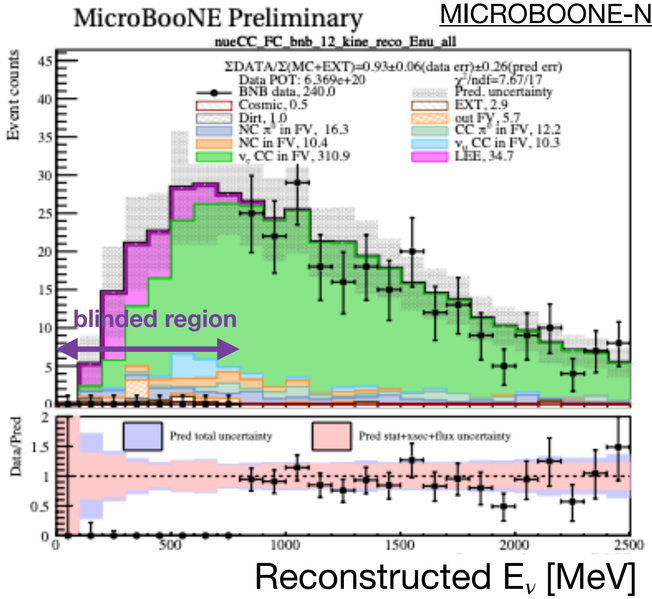
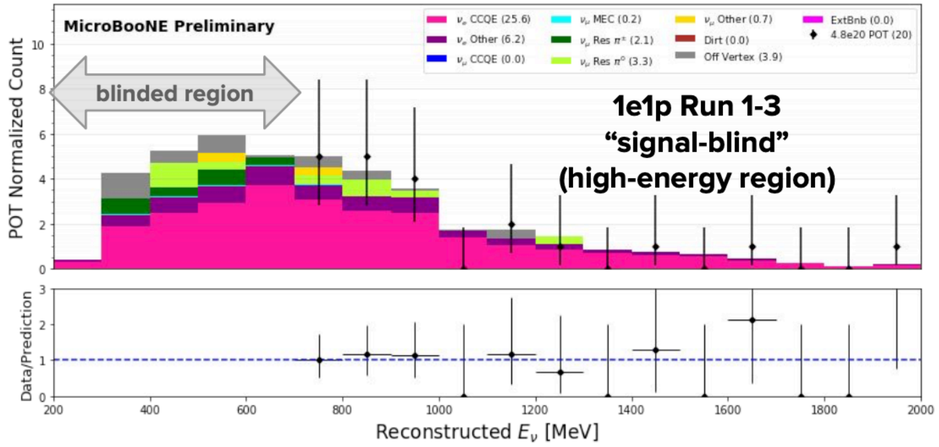


1eXp

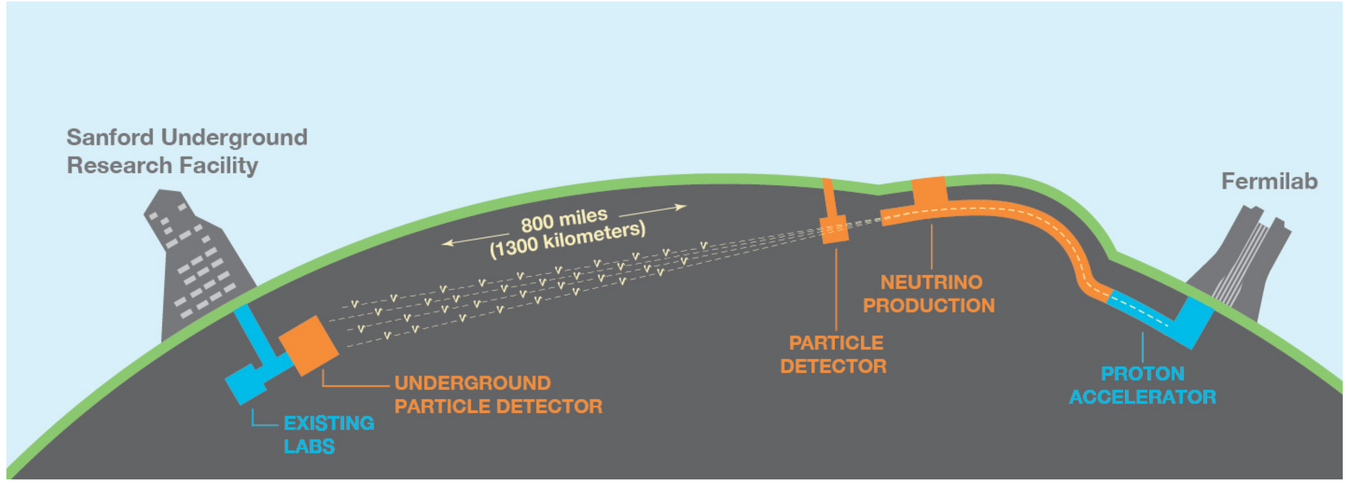


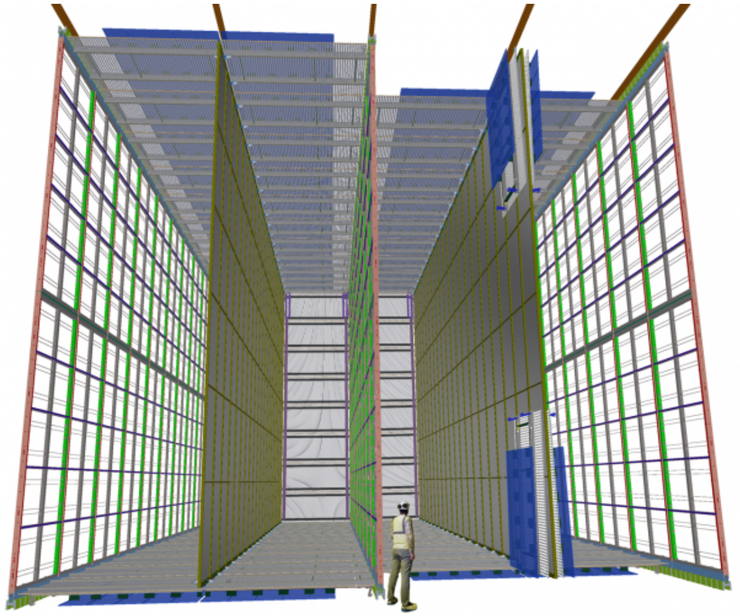
1e1p

blind analysis:
LEE-sensitive energy region (<600 MeV) is currently blinded, expect unblinded result soon!

MicroBooNE & LArTPC beyond LEE searches

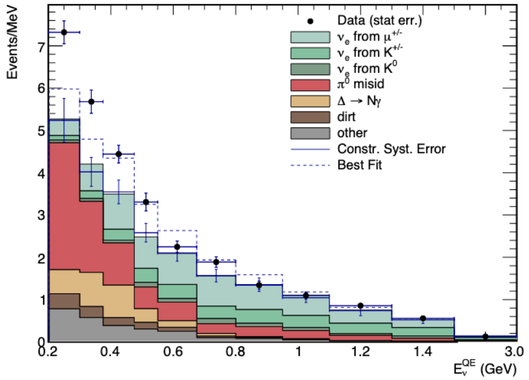
- DUNE experiment expects x400 larger LArTPC than MicroBooNE
- with excellent particle identification capability of LArTPC, DUNE will be searching for many exciting new physics, along with precision measurement of neutrino oscillation parameters
  - main goal of measuring δ_{CP}
  - new physics search for proton decay, exotic dark matter, …
- for this, MicroBooNE's knowledge of LArTPC detector, neutrino-Ar interaction, and mature event reconstruction is vital

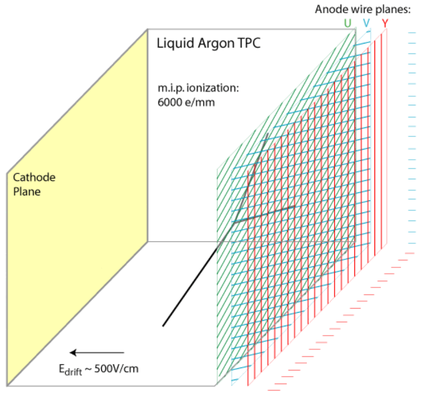


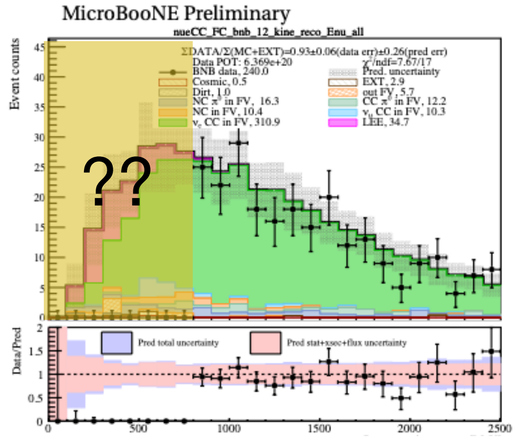


dunescience.org, fnal.gov

summary







- Liquid Argon Time Projection Chamber allows us to probe uncharted territory of neutrino precision measurement as well as new physics
- one of many unsolved questions in neutrino physics is MiniBooNE low energy excess, which could be due to new type of neutrino
- MicroBooNE, using LArTPC technology, is on the cusp of the first result for searching for low energy excess events
- with MicroBooNE's understanding of LArTPC detector, neutrino-Argon interactions, and event reconstruction, future Mega-LArTPC experiment will explore even deeper into beyond the standard model physics

summary

https://theory.fnal.gov/events/event/search-for-anomalous-single-photon-production-in-microboone-as-a-first-test-of-the-miniboone-low-energy-excess/

Joint Experimental-Theoretical Physics Seminar

Oct. 1	Search for anomalous single-photon production in MicroBooNE as a first test of the MiniBooNE low-energy excess

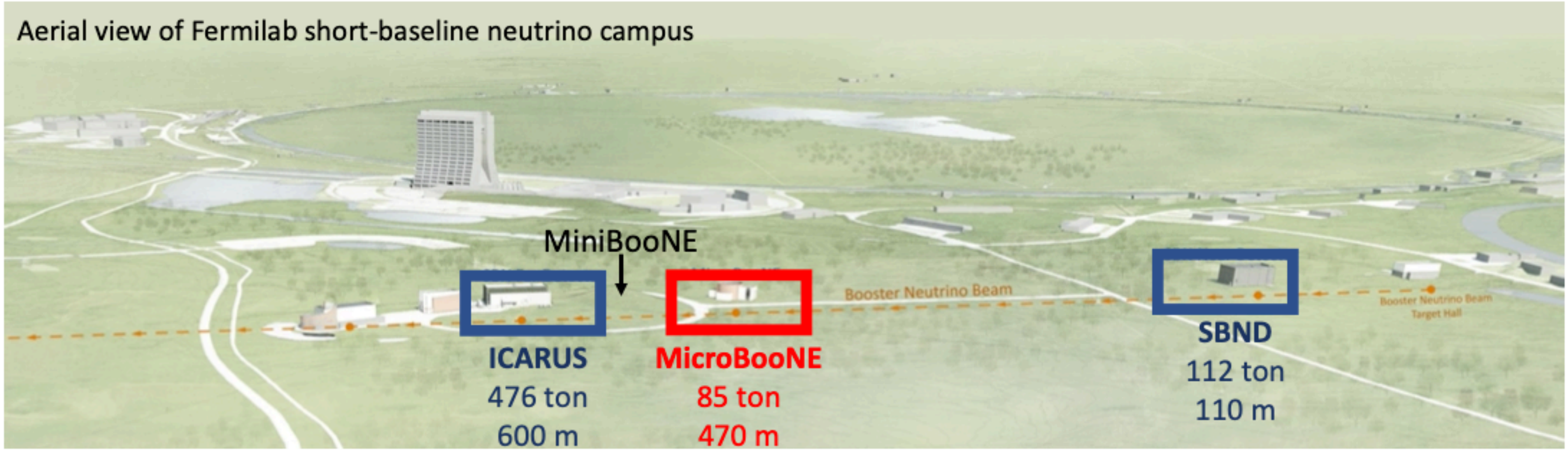
It's happening real soon!

- MicroBooNE, using LArTPC technology, is on the cusp of the first result for searching for low energy excess events

backup slides

Fermilab SBN program

- three LArTPC detectors, staged approach to address short baseline anomalies
  - phase 1: MicroBooNE - definitive test of the MiniBooNE low energy excess
  - phase 2: SBND+MicroBooNE+ICARUS - ν_e appearance and ν_μ disappearance searches
- reduce statistical uncertainties with large mass far detector
- reduce systematic uncertainties with same LArTPC detector technology

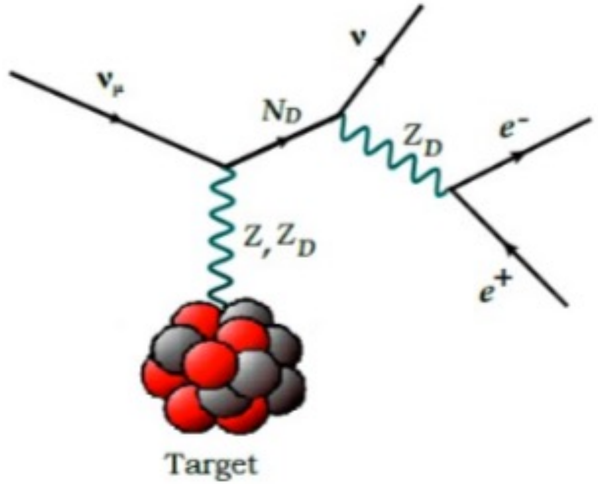


Rich and Evolving Theory Landscape

- in part, this has been motivated by attempts to explain SBL anomalies; ex., ν_e appearance but no ν_μ disappearance

- dark tridents, dark scalars, dark neutrinos
  - *Bertuzzo, Jana, Machado, Zukanovich Funchal, PRL 121, 241801 (2018)*
  - *Abdullahi, Hostert, Pascoli, arXiv:2007.11813*
  - *Alvarez-Ruso, Saul-Sala, arXiv:1705.00353*
- heavy sterile neutrinos, heavy neutral leptons
  - *Ballett, Pascoli, Ross-Lonergan, PRD 99, 071701 (2019)*
  - *Gninenko, PRD 83, 093010 (2011)*
- more complex Higgs physics
  - *Dutta, Ghosh, Li, PRD 102, 055017 (2020)*
  - *Asaadi, Church, Guenette, Jones, Szelc, PRD 97, 075021 (2018)*
  - *Abdallah, Gandhi, Roy, arXiv:2010.06159*
- mixed models of neutrino oscillations and decay
  - *Vergani, Kamp, Diaz, Arguelles, Conrad, Shaevitz, Uchida, arXiv:2105.06470*
  - *Fischer, Hernandez-Cabezudo, Schwetz, PRD 101, 075045 (2020)*
- axion-like particles
  - *Chang, Chen, Ho, Tseng, arXiv:2102.05012*
- new particles produced in the beam
  - *Brdar, Fischer, Smirnov, PRD 103, 075008 (2021)*

(caution: not an exhaustive list)



Bertuzzo *et al.*, PRL 121, 241801 (2018)

- many of these models predict more complex final states (e^+e^-) & differing levels of hadronic activity
- want a more agnostic approach than solely testing a sterile neutrino hypothesis ($1e^-$ + X)
- we are fortunate that LAr TPCs are sensitive to these possibilities

MicroBooNE's Exploration of the MiniBooNE Excess

first series of results (1/2 the MicroBooNE data set)	1e0p	1e1p	1eNp	1eX	e^+e^- + nothing	e^+e^- + X	1γ0p	1γp	1γX
sterile ν	✔	✔	✔	✔					
Higgs physics		✔	✔	✔		✔			
dark ν	✔				✔				
Z' boson	✔				✔				
axion-like particles	✔				✔				
sterile ν + decay							✔		
heavy sterile ν							✔		
SM γ production							✔	✔	✔
???	✔	✔	✔	✔	✔	✔	✔	✔	✔

γLEE search

- targets 1γ0p and 1γ1p topologies consistent with NC $\Delta \rightarrow N\gamma$
  - applying a ~3x flat scaling to NC $\Delta \rightarrow N\gamma$ can explain the observed MiniBooNE excess
- using “Pandora” reconstruction [EPJC 78 (2018) 82], with BDT-based selection

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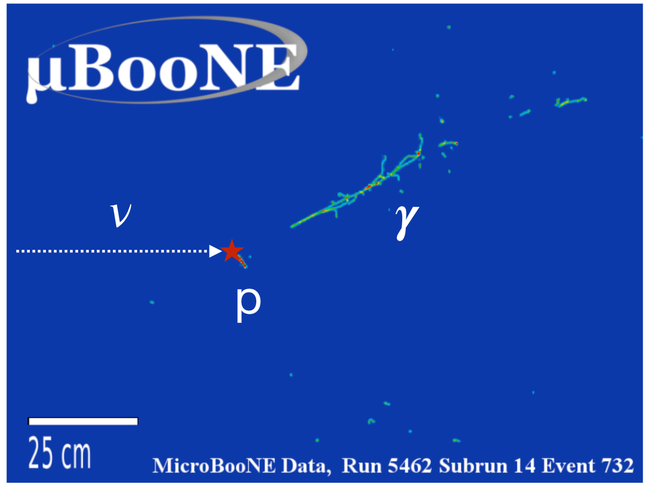
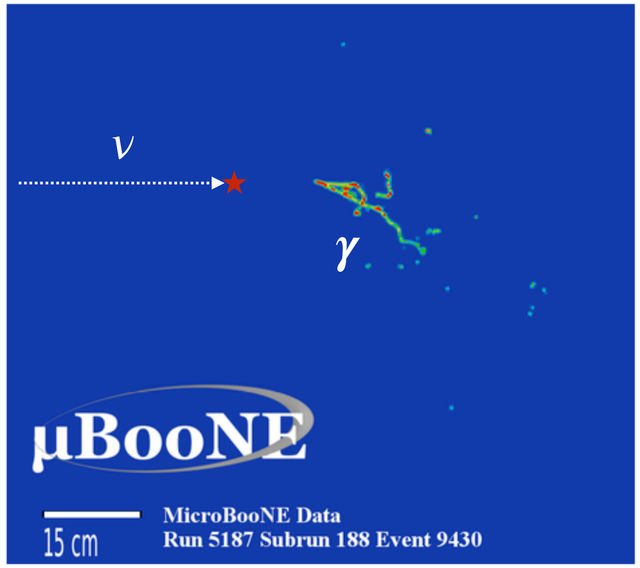
1γ0p



1γ1p



eLEE search: Pandora

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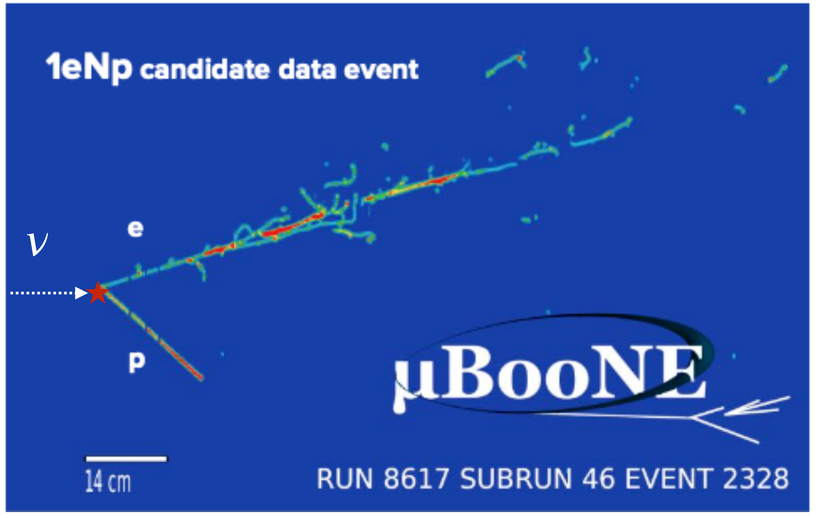
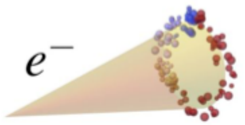
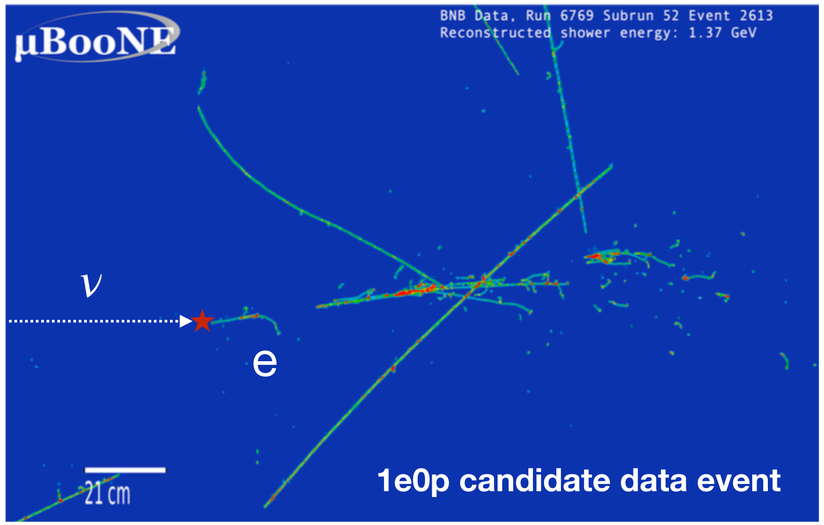
- Pandora based eLEE search



  - with topology- and calorimetry-based PID tools [EPJC 78 (2018) 82]
  - 1e0p0π and 1eNp0π selection
    - pure ν_eCC 1eNp selection achieved, down to low energy
    - high-energy ν_eCC events show reasonable data-MC agreement





eLEE search: Deep Learning

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- Deep Learning based eLEE search

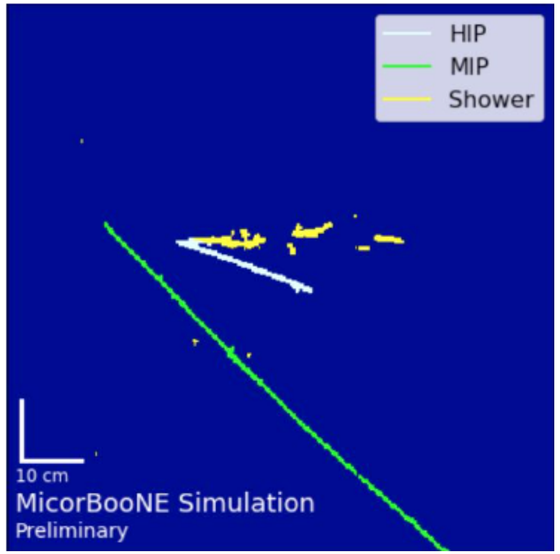
  - track/shower separation with semantic segmentation
    [PRD 103 (2021) 052012]

  - PID with convolutional neural network [PRD 103 (2021) 092003]

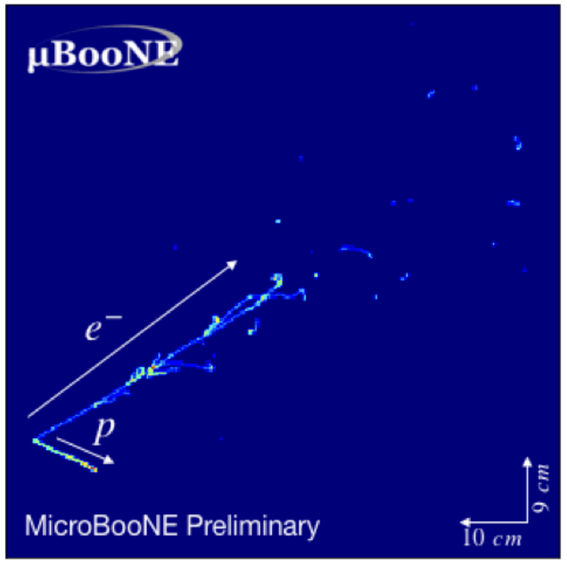
  - 1e1p0π selection (CCQE-dominated) & 1μ1p selection (sideband)

    - high purity samples are selected

pixel-level identification,
using semantic segmentation



multi-particle identification
using CNN



eLEE search: Wire-Cell

- Wire-Cell based eLEE search
  - based on 3D images
  - topology-agnostic event reconstruction
    [JINST 16 (2021) P06043]
  - excellent cosmic rejection power
    [PRApplied 15 (2021) 064071]
  - fully inclusive 1eXpXπ selection:
    least model dependent

    - very pure & high stat ν_e and ν_μ selection achieved
  - using 6 different sideband samples to constrain signal channel

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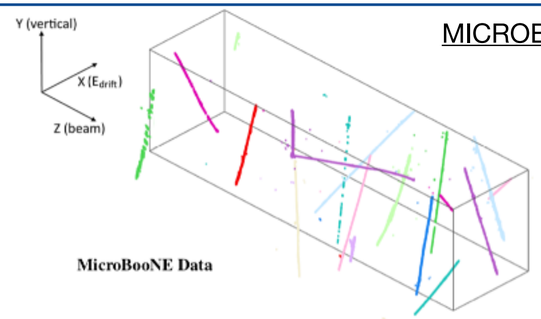
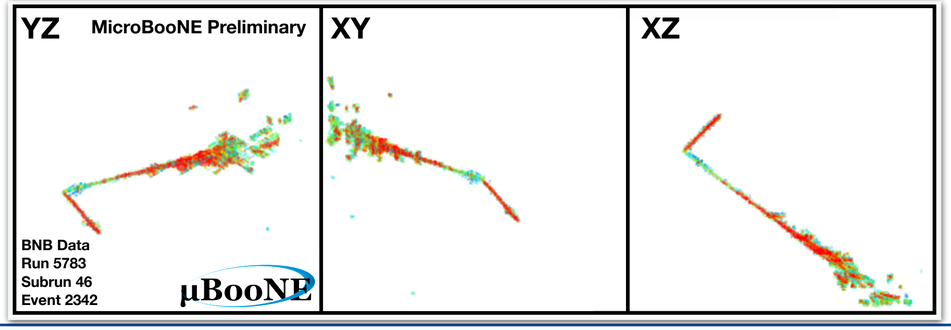


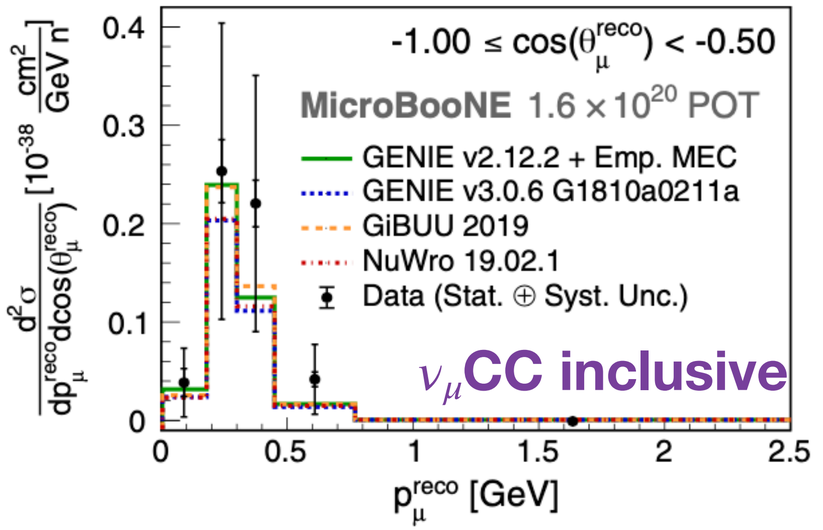


ν-Argon cross section measurements @ uBooNE

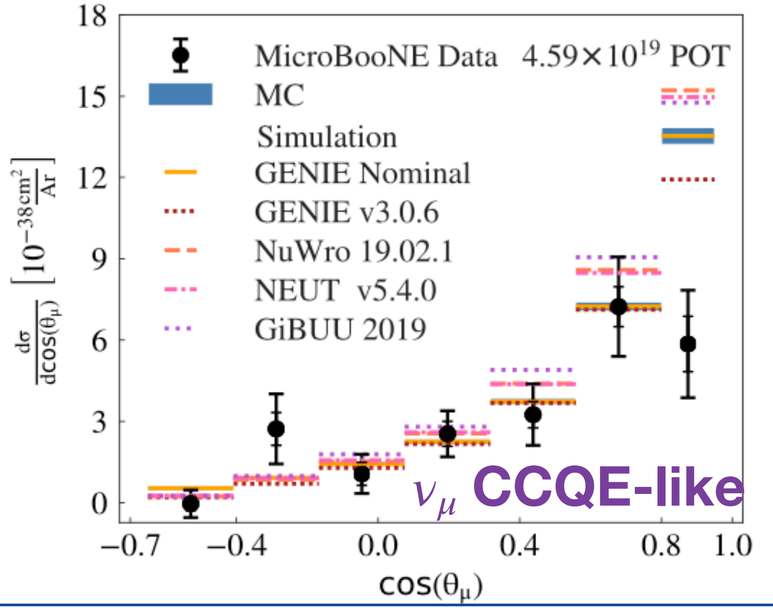
- cross section measurements of ν-Ar interactions will allow us to develop models that describe ν-Ar interaction data well

- MicroBooNE has collected the largest sample of ν-Ar interactions available to date and produced first set of cross section measurements with various final states
  - ν_μCC inclusive
  - ν_μ CCQE-like
  - ν_μCC 0πNp
  - ν_e + anti-ν_e CC inclusive
  - and many others to come!

PRL 123 (2019) 131801



PRL 125 (2020) 201803



challenges LArTPC faces

- we have less understanding of **how neutrino and LAr interact with each other**, compared to other conventional targets such as water, carbon, etc.
    - this can lead to mis-modeling of prediction, causing uncertainties in the final measurement
- as LArTPC is relatively new detector technology, **precise understanding detector effect** is still underway
- **event reconstruction** is challenging, with long drift time of electrons, especially if running on surface
    - more background events such as cosmic rays in neutrino selection
- ***overcoming these challenges are vital for future LArTPC's precise measurement of neutrinos!***