Recent Results from MicroBooNE

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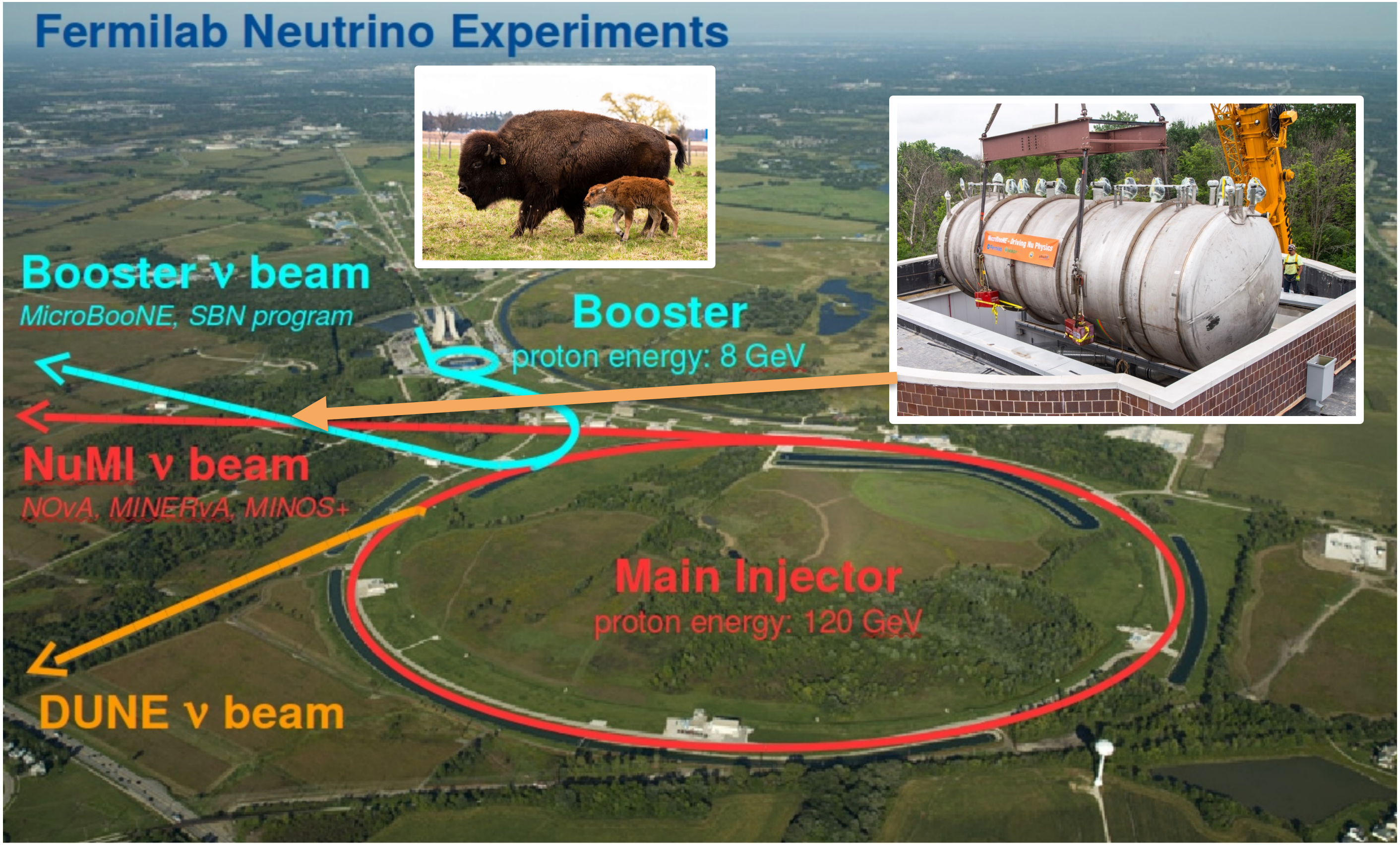
on behalf of the MicroBooNE Collaboration

33rd Rencontres de Blois

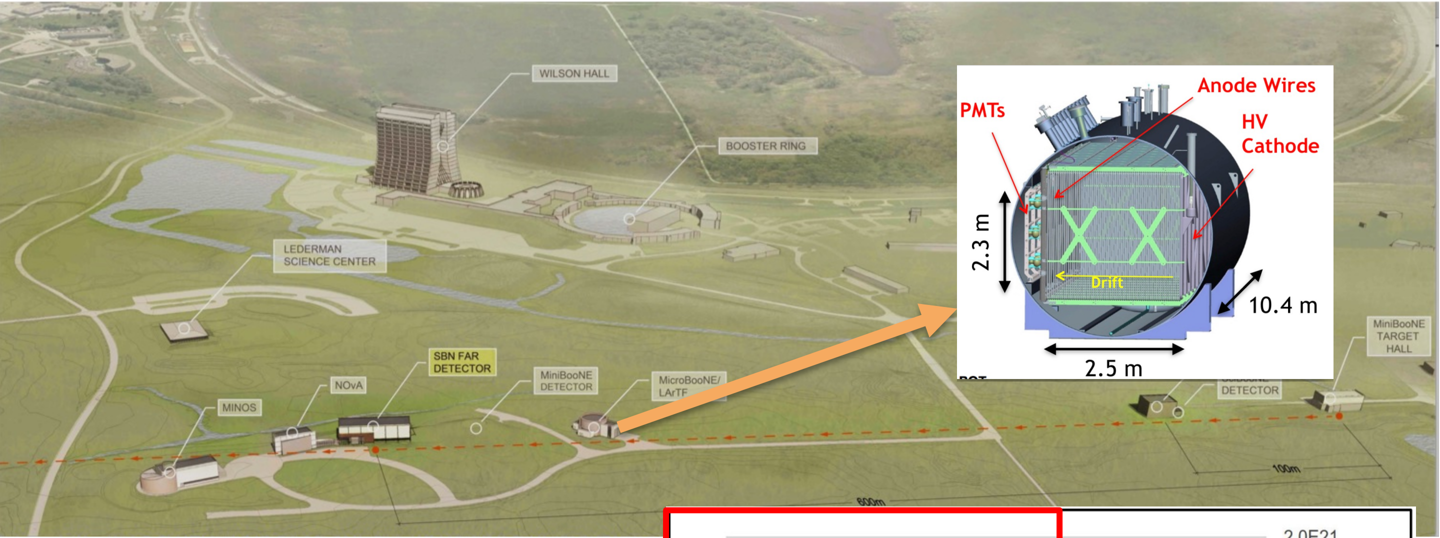
24 May 2022

Micro Booster Neutrino Experiment at Fermilab

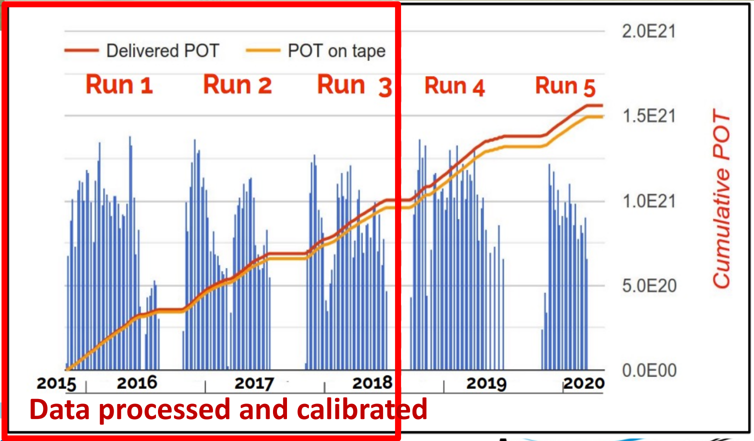


μBooNE

MicroBooNE Detector



- First operating detector in Short Baseline Neutrino program
- Surface-based, 85 tonne active volume liquid argon projection chamber
- UV laser calibration system
- Cosmic Ray tagger system
- Start taking data Fall 2015

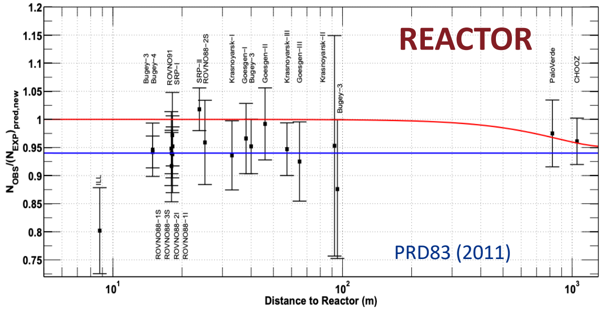


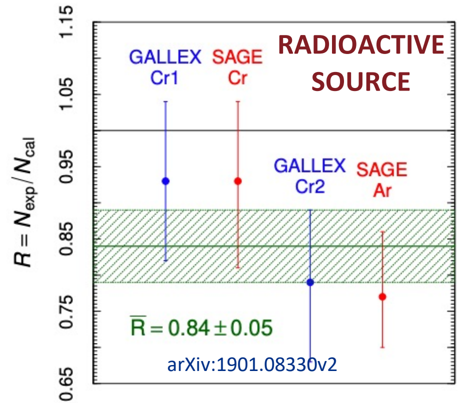
MicroBooNE Physics Goals

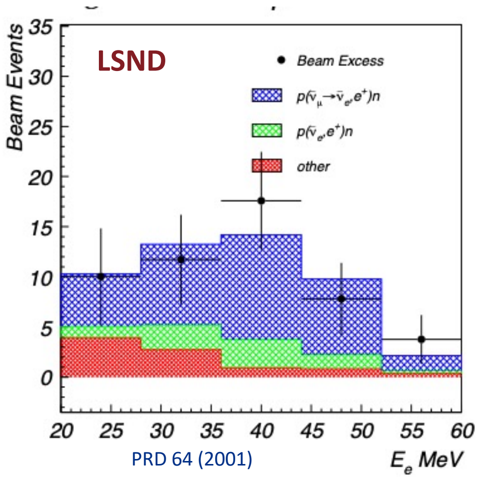
1. Investigate the MiniBooNE Low Energy Excess
2. Precision Cross-Section Measurement on Argon ~O(1 GeV)
3. Beyond Standard Model and Supernovae Detection

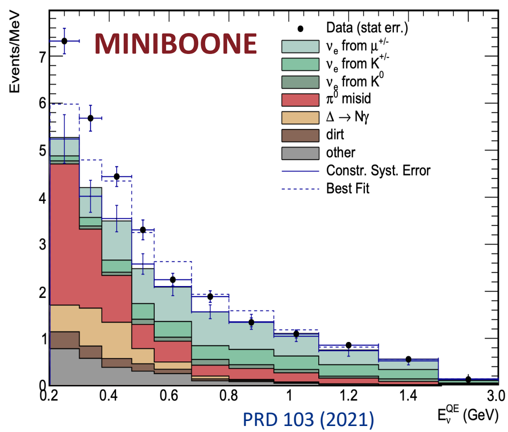
μBooNE

Short Baseline Anomalies



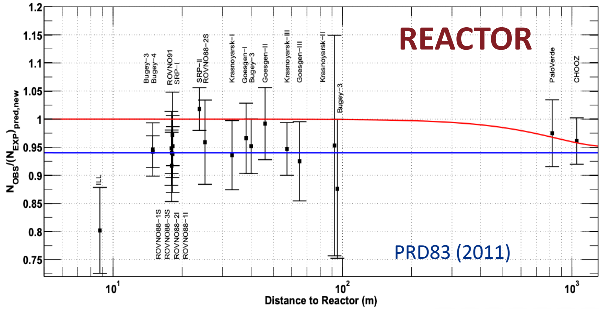


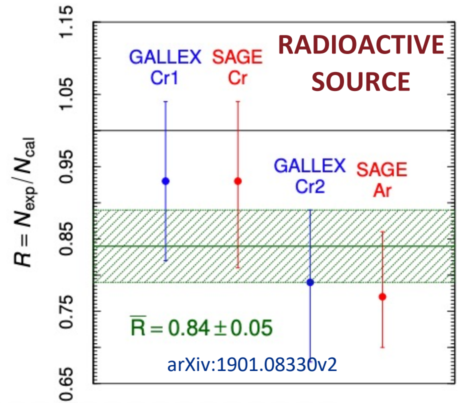


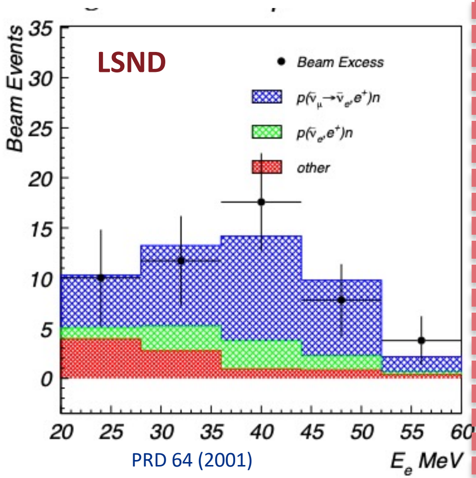


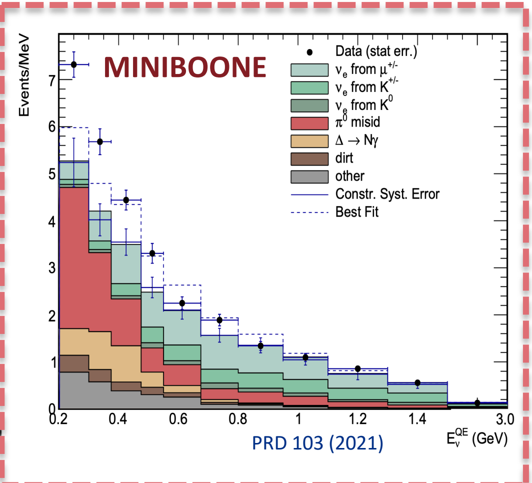
- Series of short baseline neutrino oscillation experiments introduced unexpected results
- Hint towards the possible existence of a sterile (mass scale ~ 1 eV)

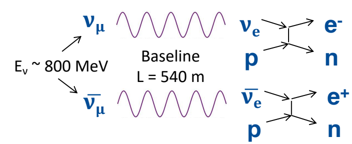
Short Baseline Anomalies





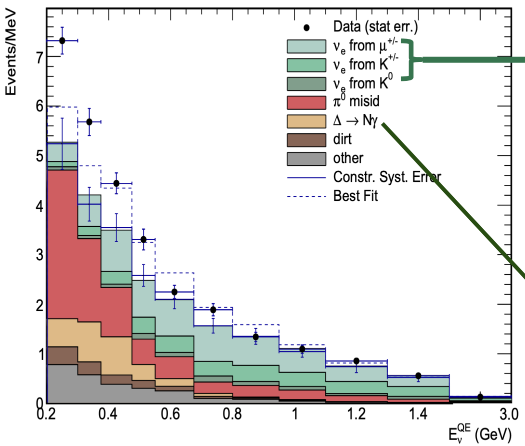


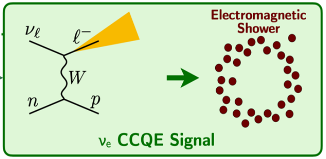


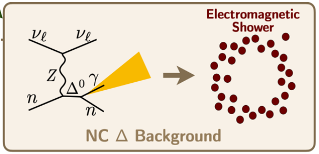


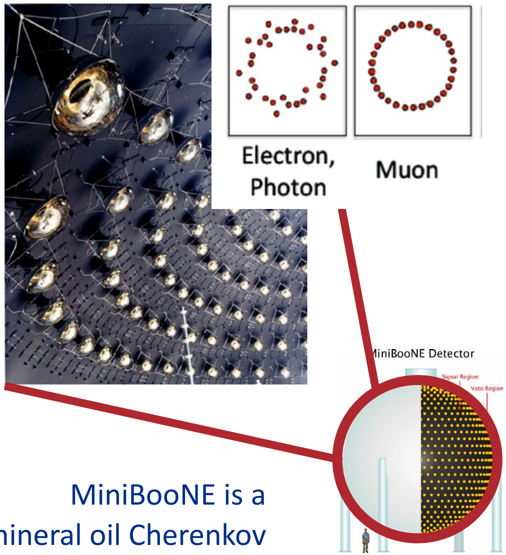
- Excess: 4.7σ significance in neutrino mode
- Not consistent with "3+1" hypothesis
- Source of excess is still unknown.

Zooming in on MiniBooNE Low Energy Excess







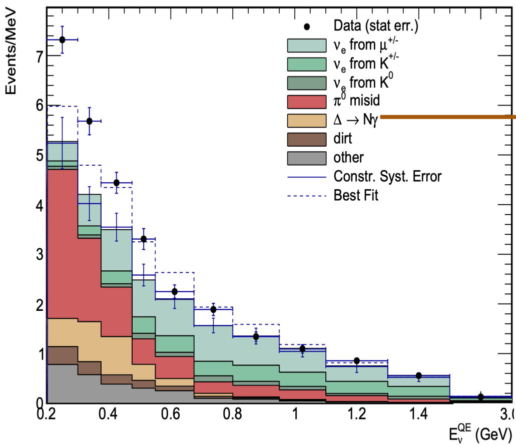


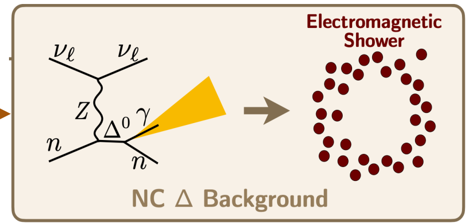
MiniBooNE is a mineral oil Cherenkov Detector

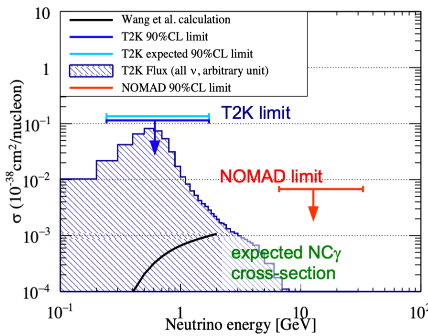
PID from the Cherenkov ring

MiniBooNE cannot distinguish electrons from γ

NC Δ→Nγ

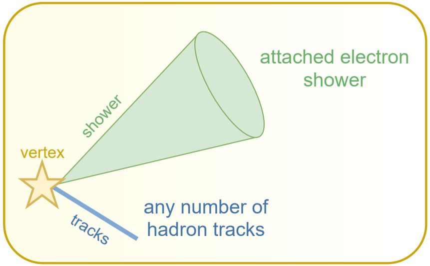


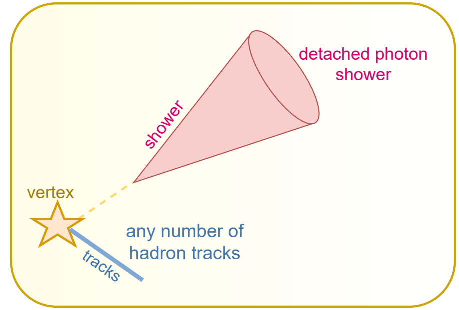


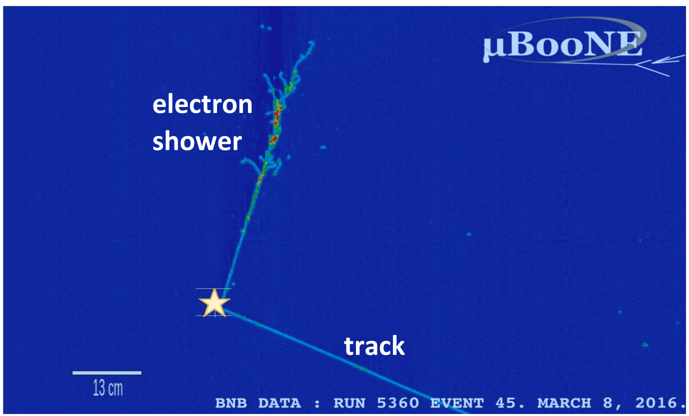


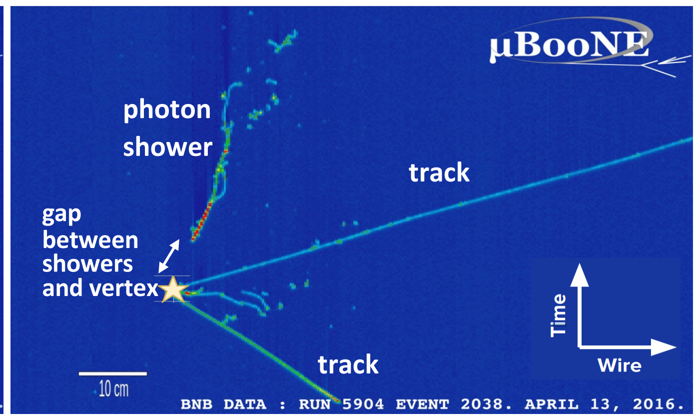
- NC Δ process is not experimentally identified.
- T2K and NOMAD set limits on this process,best limit is ~100x higher than theoretical prediction
- **x3.18 higher cross-section** can explain MiniBooNE excess

LArTPC Power: Superior e/γ separation

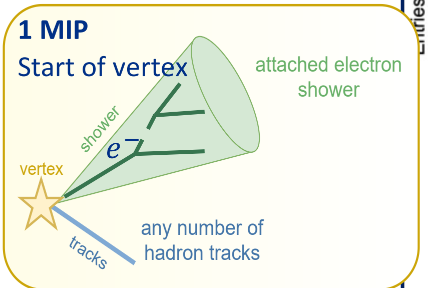


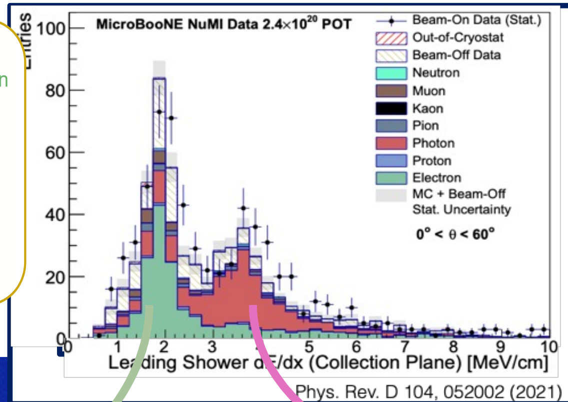


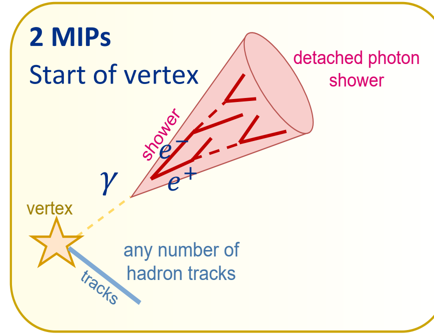


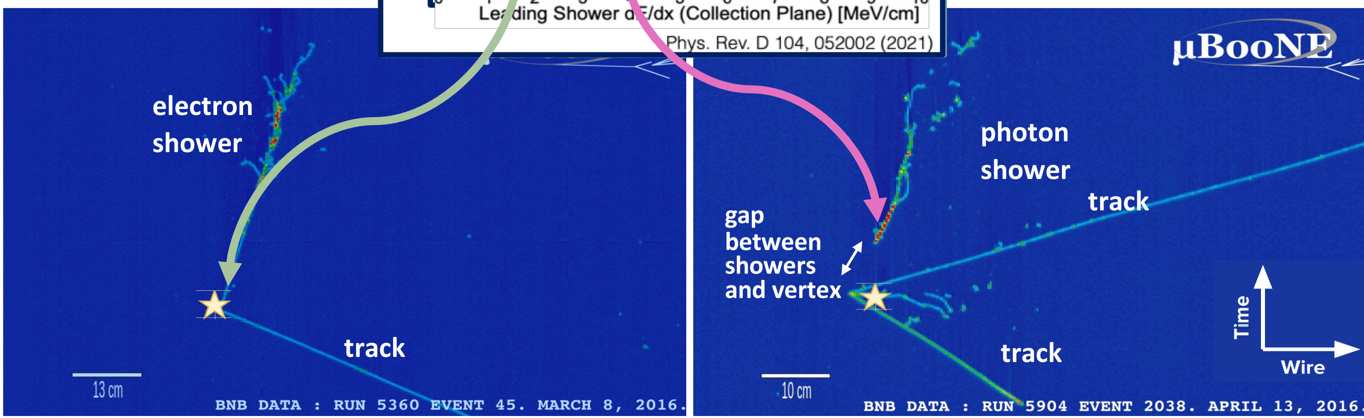


LArTPC Power: Superior e/γ separation

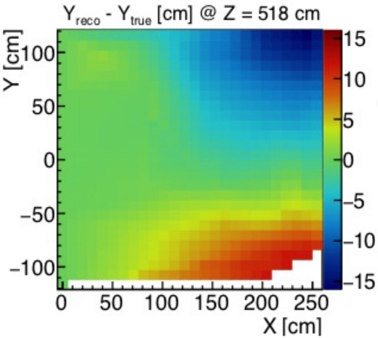


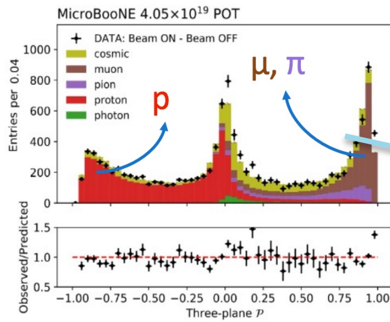


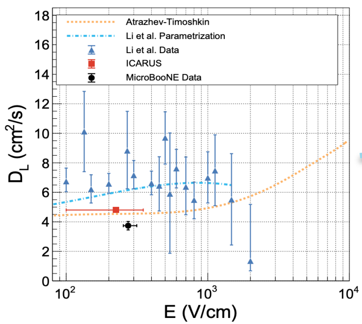


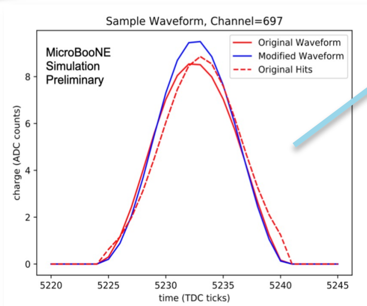


Well Understood Detector





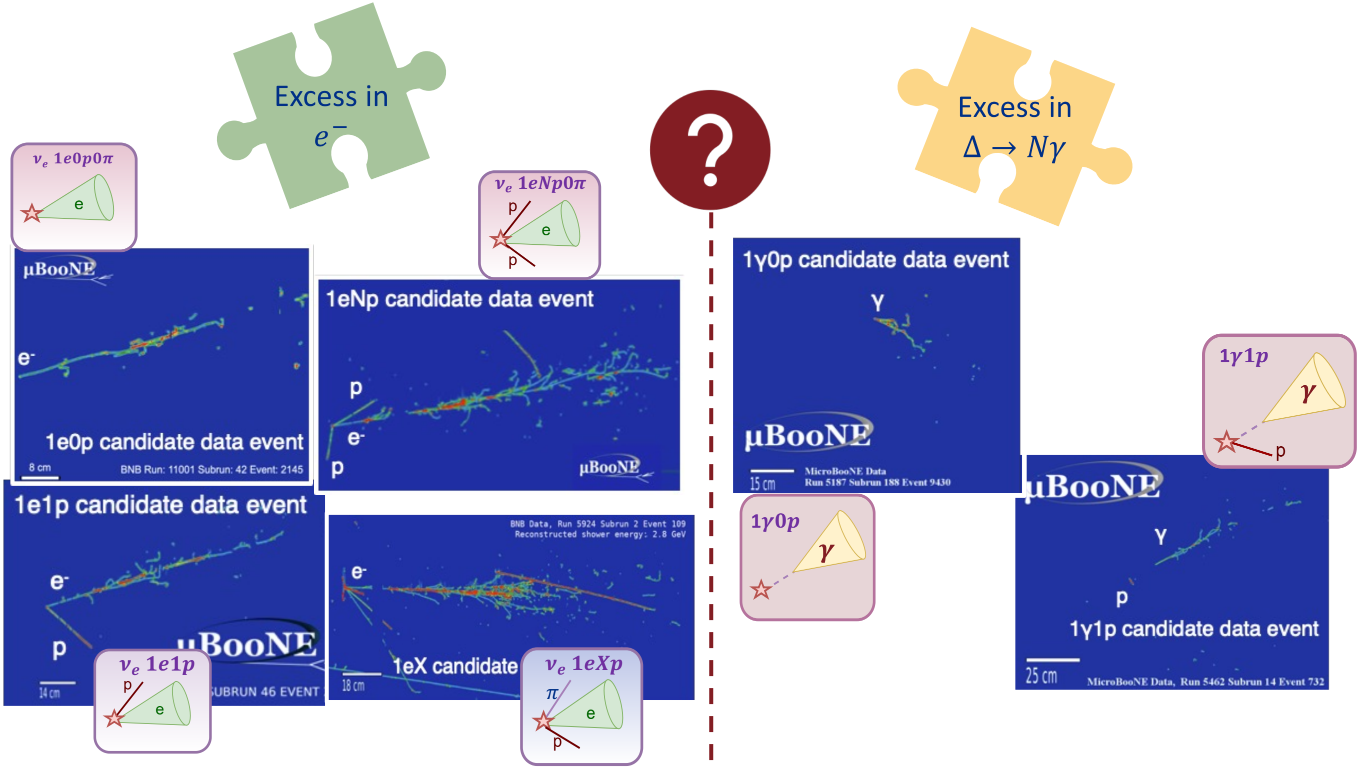




- Advanced techniques for noise filtering and signal processing :
  - JINST 13, P07006 (2018), JINST 13, P07007 (2018)
- Data-driven electric field maps
  - UV laser: JINST 15, P07010 (2020)
  - cosmic muons: JINST 15, P12037 (2020)
- Calorimetric and EM shower calibrations and PID
  - JINST 15 P03022 (2020), JINST 15 P02007 (2020), JHEP12(2021)153
- Longitudinal diffusion of ionization e^-'s
  - JINST 16, P09025 (2021)
- Novel data-driven technique using wire responses
  - EPJC 82, 454 (2022)

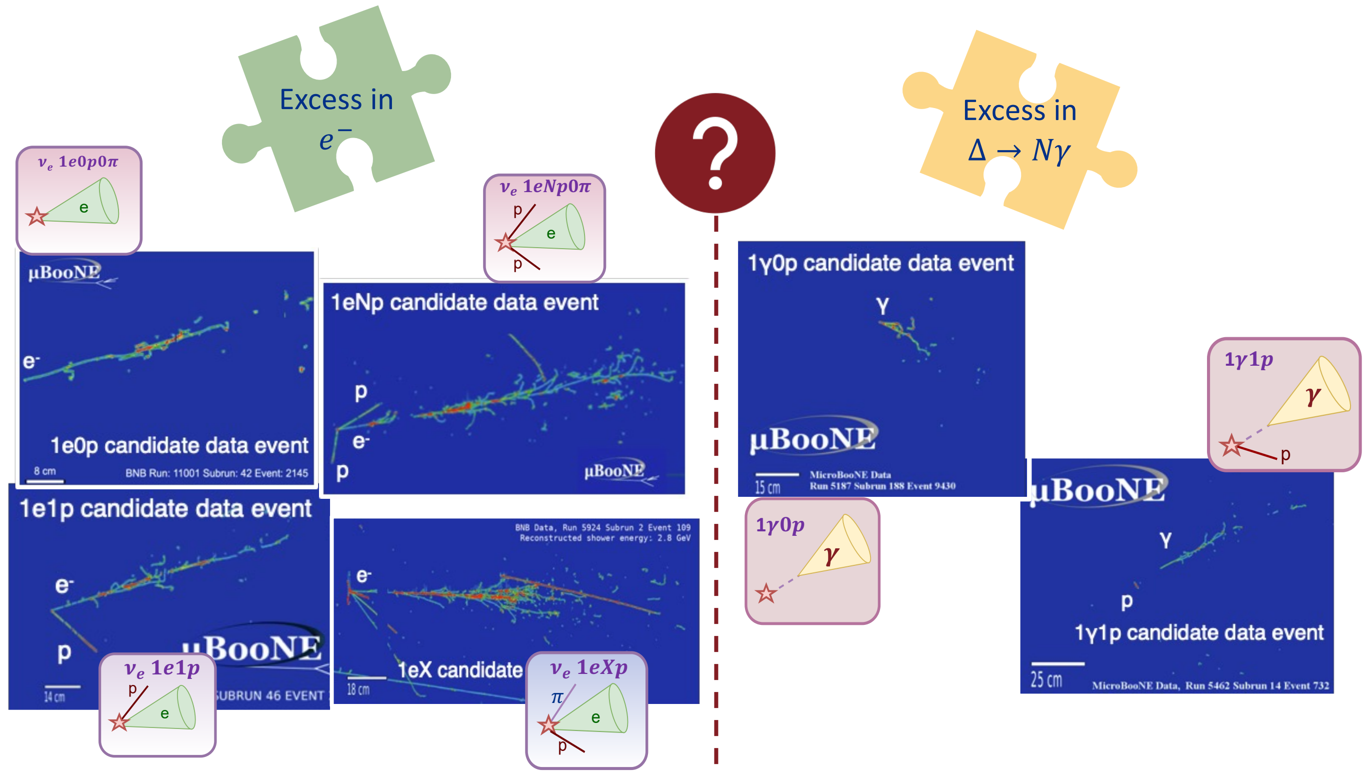
→ good understanding of detector response and precise measurement of particle kinematics.

How to test MiniBooNE Low Energy Excess?



- Characterize the nue events and benchmark wrt the unfolded MiniBooNE LEE template – **"eLEE model"**
- Characterize the single photon events and test wrt the scaling x3.18 higher cross-section in NC Δ – **"LEE model"**

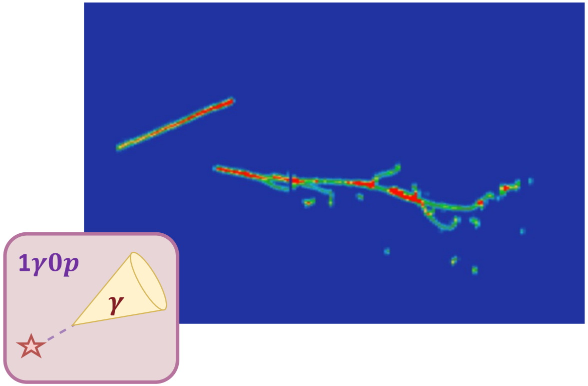
How to test MiniBooNE Low Energy Excess?

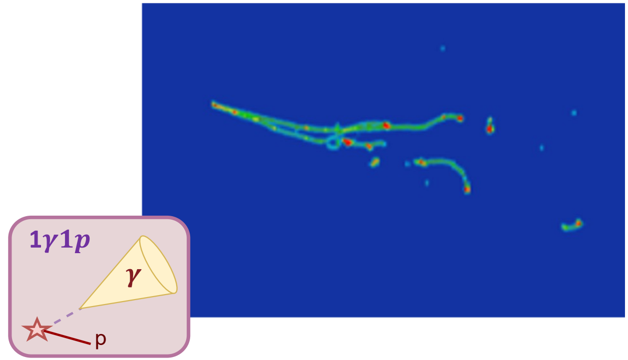


- **3 detailed papers**: arXiv:2110.13978, arXiv:2110.14065, arXiv:2110.14080, accepted by PRD
- **1 summary paper**: arXiv:2110.14054, accepted by PRL

arXiv:2110.00409, accepted by PRL

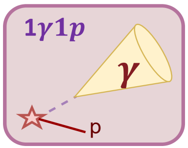
The Single Photon LEE Search



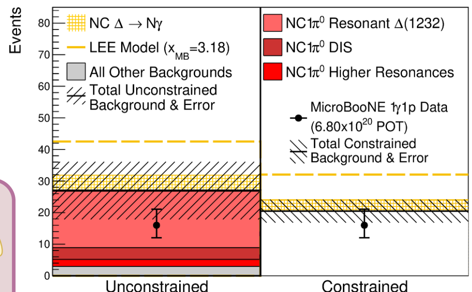


- $\Delta \rightarrow N\gamma$ search utilizes $1\gamma 1p$ and $1\gamma 0p$ to maximize signal statistics
- Uses pandora reconstruction **EPJC 78, 82 (2018)**
- Major challenge is understanding and rejecting NC π^0 backgrounds
- Topology for these is $2\gamma 1p$ or $2\gamma 0p$, but second shower can be difficult/impossible to reconstruct.
- In situ measurement used to constrain the background
- Performed as blind analysis

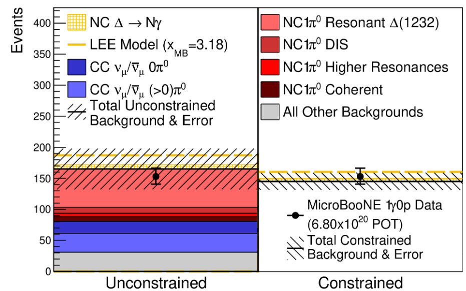
Single Photon LEE Search Results

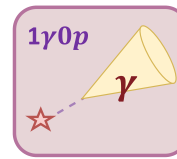


1γ1p



1γ0p





1γ1p

Unconstr. bkgd.	27.0 ± 8.1
Constr. bkgd.	20.5 ± 3.6
NC $\Delta \to N\gamma$	+ 4.88
LEE ($x_{\mathrm{MB}} = 3.18$)	+ 15.5

16
Data Events Observed

1γ0p

Unconstr. bkgd.	165.4 ± 31.7
Constr. bkgd.	145.1 ± 13.8
NC $\Delta \to N\gamma$	+ 6.55
LEE ($x_{\mathrm{MB}} = 3.18$)	+ 20.1

153
Data Events Observed

Limit on NC Δ→Nγ

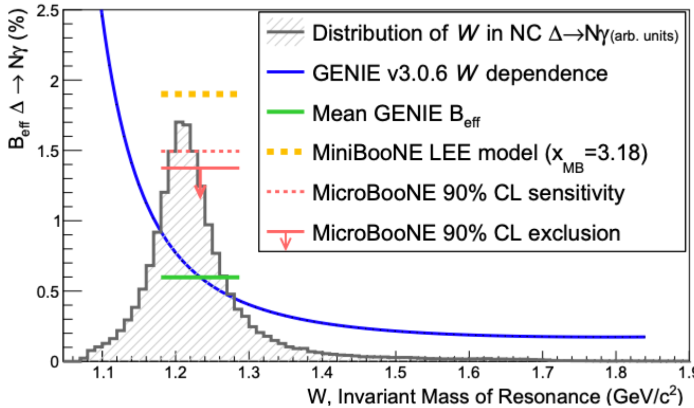
No evidence for an enhanced rate of single photons from NC Δ→Nγ decay above nominal GENIE expectations

- **x3.18 scaling disfavoured at 94.8% C.L.**

Data places one-sided bound on the normalisation of NC Δ→Nγ events of **$x_\Delta < 2.3$** (90% C.L.).

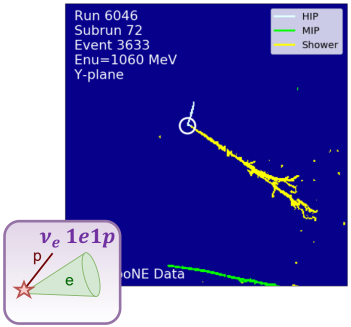
→ **$B_{eff}(\Delta \rightarrow N\gamma) < 1.38\%$ (90% CL).**

> 50 times better than the world's previous limit in neutrino sector

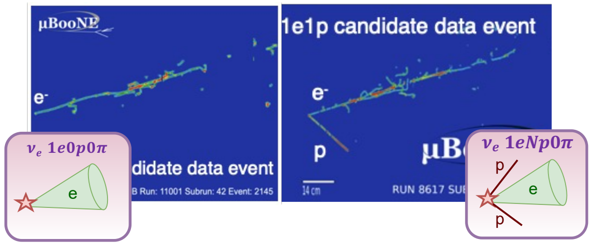


The Electron Channel LEE Search

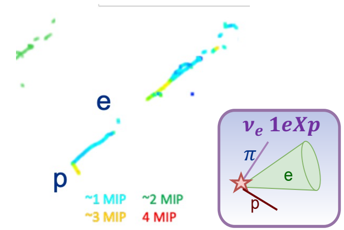
Three complimentary analyses using 3 fully automated reconstruction probing different final states, *performed as blind analyses*



1e1p CCQE



1eN(≥ 1)p0π, 1e0p0π



1eX

The Electron Channel LEE Search

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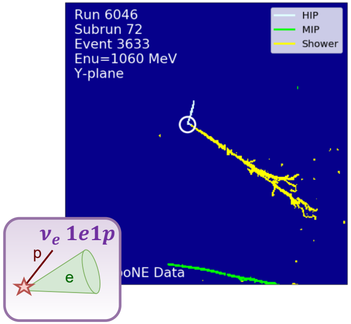


1e1p CCQE

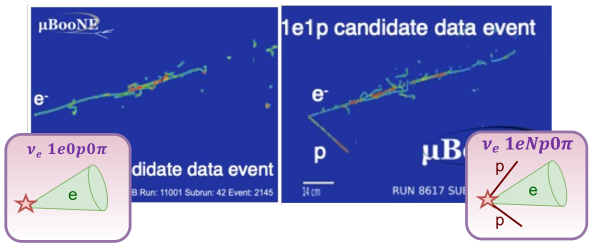
Aim for high purity of CCQE signal selection (oscillation signal)

Deep Learning

Phys. Rev. D 103, 052012 (2021) : use Convolutional Neural Net to label tracks and showers from input pixel image

The Electron Channel LEE Search

Three complimentary analyses using 3 fully automated reconstruction probing different final states , *performed as blind analyses*



1eN(≥ 1)p0π, 1e0p0π

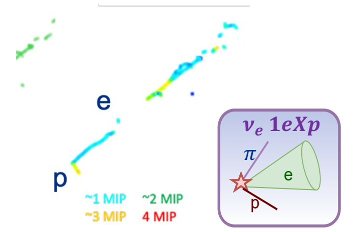
1eNp: most sensitive to empirical model of MiniBooNE result

1e0p: Mitigate uncertainties related to proton multiplicity, kinematics, and reconstruction

Pandora reconstruction: use patterns recognition in 2D to build 3D reconstruction of interaction

The Electron Channel LEE Search

Three complimentary analyses using 3 fully automated reconstruction probing different final states , *performed as blind analyses*

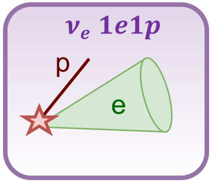


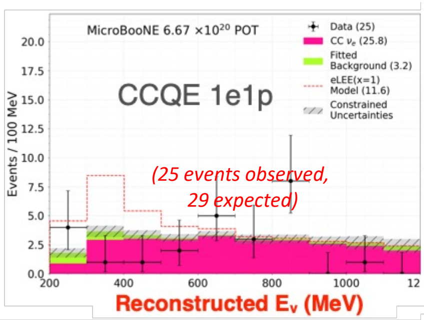
1eX

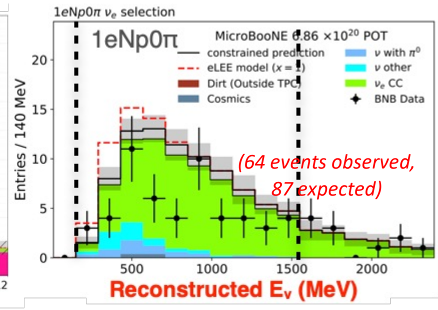
- Inclusive selection
- Least sensitive to the cross-section models

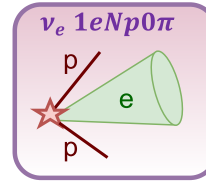
Wirecell reconstruction JINST 13, P05032 (2018) use tomographic image to turn 2D charge information to 3D charge.

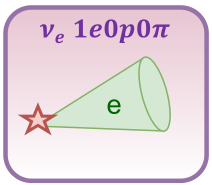
Electron Channel LEE Search Results

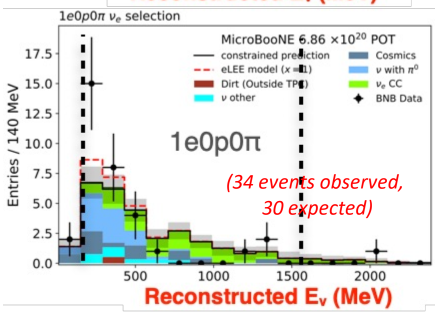


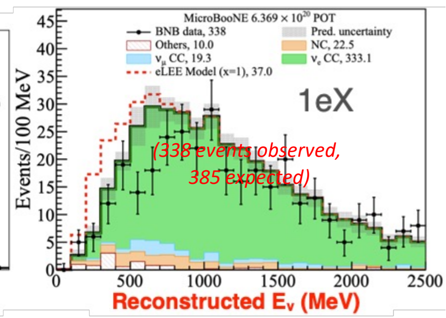


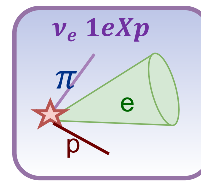






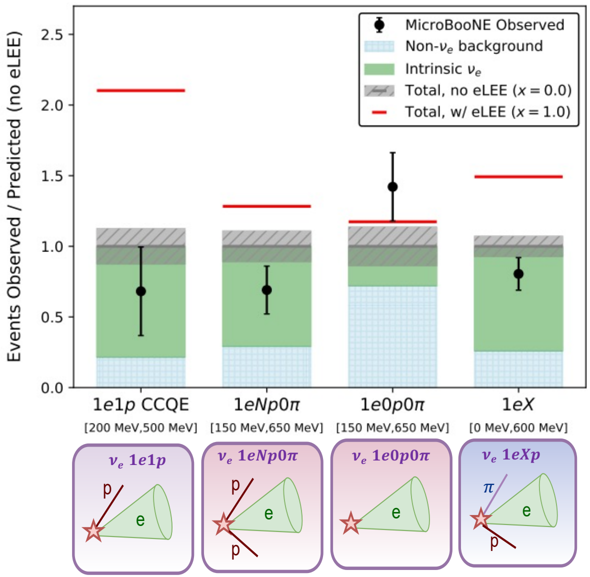






µBooNE

Summary of Electron Channel LEE Search Results



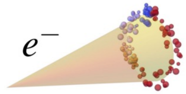
- Investigated the hypothesis if the MiniBooNE excess originate from of ν_e, no significant excess is observed in the MicroBooNE data
- The different analyses are in agreement with each other and the expectation
    - the overall rates fall slightly below prediction (exception is the least-sensitive 1e0p selection)
- No evidence for excesses relative to prediction at 95% CL to 3σ

µBooNE

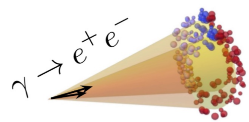
Evolving Theory Landscape

- Decay of O(keV) Sterile Neutrinos to active neutrinos
  - [13] Dentler, Esteban, Kopp, Machado Phys. Rev. D 101, 115013 (2020)
  - [14] de Gouvêa, Peres, Prakash, Stenico JHEP 07 (2020) 141
- New resonance matter effects
  - [5] Asaadi, Church, Guenette, Jones, Szelc, PRD 97, 075021 (2018)
- Mixed O(1eV) sterile oscillations and O(100 MeV) sterile decay
  - [7] Vergani, Kamp, Diaz, Arguelles, Conrad, Shaevitz, Uchida, arXiv:2105.06470
- Decay of heavy sterile neutrinos produced in beam
  - [4] Gninenko, Phys.Rev.D83:015015,2011
  - [12] Alvarez-Ruso, Saul-Sala, Phys. Rev. D 101, 075045 (2020)
  - [15] Magill, Plestid, Pospelov, Tsai Phys. Rev. D 98, 115015 (2018)
  - [11] Fischer, Hernandez-Cabezudo, Schwetz, PRD 101, 075045 (2020)
- Decay of upscattered heavy sterile neutrinos or new scalars mediated by Z' or more complex higgs sectors
  - [1] Bertuzzo, Jana, Machado, Zukanovich Funchal, PRL 121, 241801 (2018)
  - [2] Abdullahi, Hostert, Pascoli, Phys.Lett.B 820 (2021) 136531
  - [3] Ballett, Pascoli, Ross-Lonergan, PRD 99, 071701 (2019)
  - [10] Dutta, Ghosh, Li, PRD 102, 055017 (2020)
  - [6] Abdallah, Gandhi, Roy, Phys. Rev. D 104, 055028 (2021)
- Decay of axion-like particles
  - [8] Chang, Chen, Ho, Tseng, Phys. Rev. D 104, 015030 (2021)
- A model-independent approach to any new particle
  - [9] Brdar, Fischer, Smirnov, PRD 103, 075008 (2021)

Produces true **electrons**

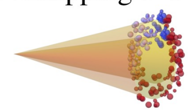


Produces true **photons**



Produces **e^+e^-** pairs

Overlapping e^+e^-



Leverage the power of LArTPC technology to distinguish between models based on exclusive final state topologies!

µBooNE

Evolving Theory Landscape

Already started probing with first LEE results

Models \ Reco topology	1e0p	1e1p	1eNp	1eX	e^+e^- + nothing	e^+e^-X	$1\gamma 0p$	$1\gamma 1p$	$1\gamma X$
eV Sterile ν Osc	✔	✔	✔	✔					
Mixed Osc + Sterile ν	✔ [7]	✔ [7]	✔ [7]	✔ [7]			✔ [7]		
Sterile ν Decay	✔ [13,14]	✔ [13,14]	✔ [13.14]	✔ [13,14]			✔ [4,11,12,15]	✔ [4]	✔ [4]
Dark Sector & Z' *	✔ [2,3]				✔ [2,3]	✔ [2,3]	✔ [1,2,3]	✔ [1,2,3]	✔ [1,2,3]
More complex higgs *					✔ [10]	✔ [10]	✔ [6,10]	✔ [6,10]	✔ [6,10]
Axion-like particle *					✔ [8]		✔ [8]		
Res matter effects	✔ [5]	✔ [5]	✔ [5]	✔ [5]					
SM γ production							✔	✔	✔

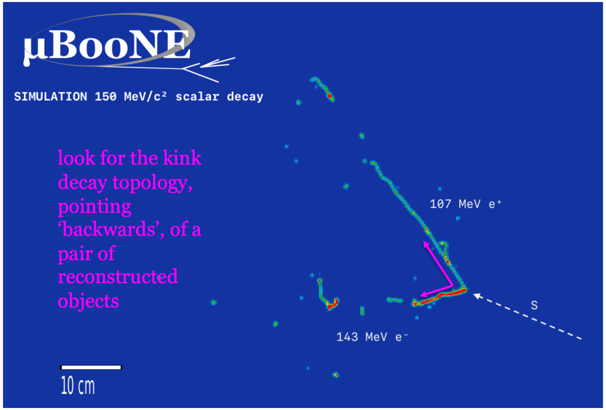
Already in the work

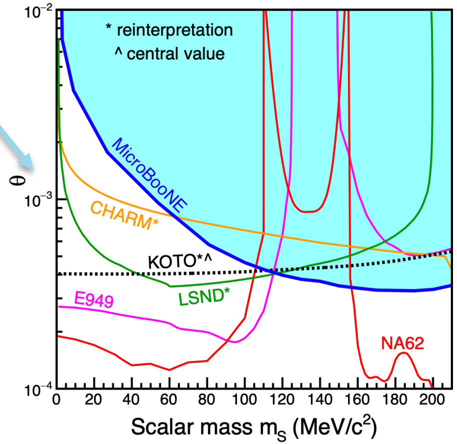
*Requires heavy sterile/other new particles also

Leverage the power of LArTPC technology to distinguish between models based on exclusive final state topologies!

BSM Physics

- Higgs portal scalar (e^+e^- final state)PRL 127, 151803 (2021)
  - **Motivation:** portal to dark sector, connection to Higgs sector
  - Search for e+e- decays from scalars coming from NuMI hadron absorber
  - 1 event observed → 95% C.L. excludes KOTO central value
- supernova burst neutrino readout
  - JINST 16, P02008 (2021)
- cosmic muon rates
  - JINST 16, P04004 (2021)
- heavy neutral leptons (μ π final state)
  - PRD 101, 052001 (2020)
- MeV scale physics:
  - Radon injection study: arXiv:2203.10147





PRL 127, 151803 (2021)

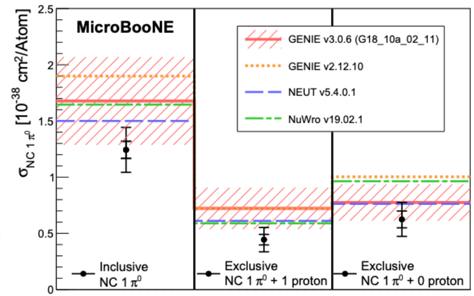
Rich Cross-Section Program

High-statistics data samples on Argon allowed for a very rich and active neutrino cross section program (background to DM searches) Many “firsts” analyses and provide a head start for current and future LArTPC programs: SBN, DUNE.

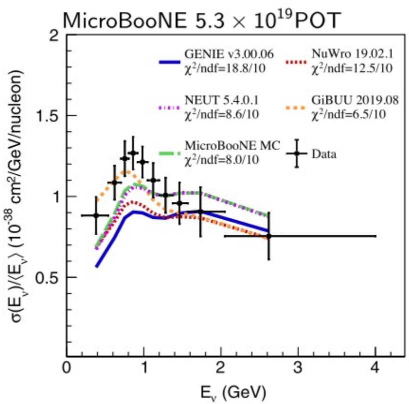
- NC π^0
  - [arXiv: 2205.07943 (2022)]
- CC Inclusive (ν_μ + Ar → μ + X)
  - [PRL 128, 151801 (2022)]
- CC Inclusive $\nu_e + \overline{\nu}_e$ (NuMI beam)
  - [PRD 105, L051102 (2022)]
  - [PRD 104, 052002 (2021)],
- CC Np (ν_μ + Ar → μ + 0 π)
  - [PRD 102, 112013 (2020)]
- QE-like (ν_μ + Ar → μ + p)
  - [PRL 125, 201803 (2020)]

- more cross-section results coming soon! Probing into different final states and new results on NC elastic, CC 2p, transverse kinematics, CC π^0, CC π^+, CC coherent π^+, kaon and Δ production

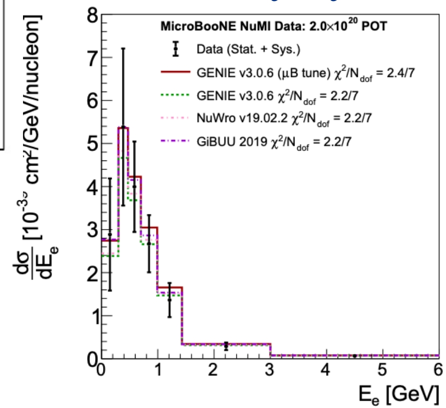
NC π^0



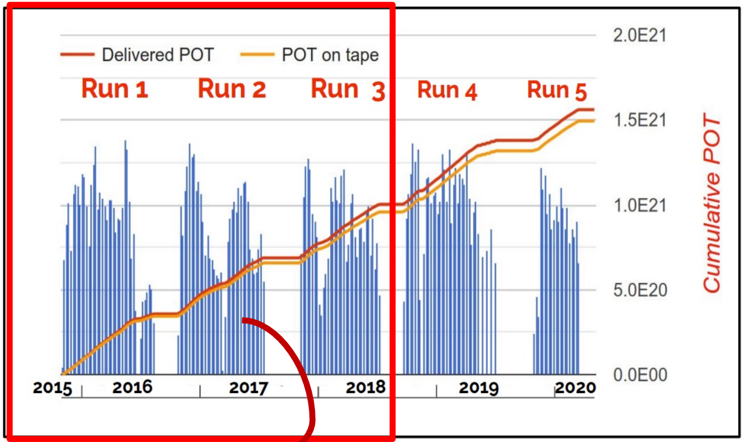
CC Inclusive ν_μ



CC $\nu_e + \overline{\nu}_e$



More Statistics



Analyses are stats-limited. Full datasets will give fuller pictures

Data used for this analysis

More statistics to come. Increasing the statistics by 2-fold

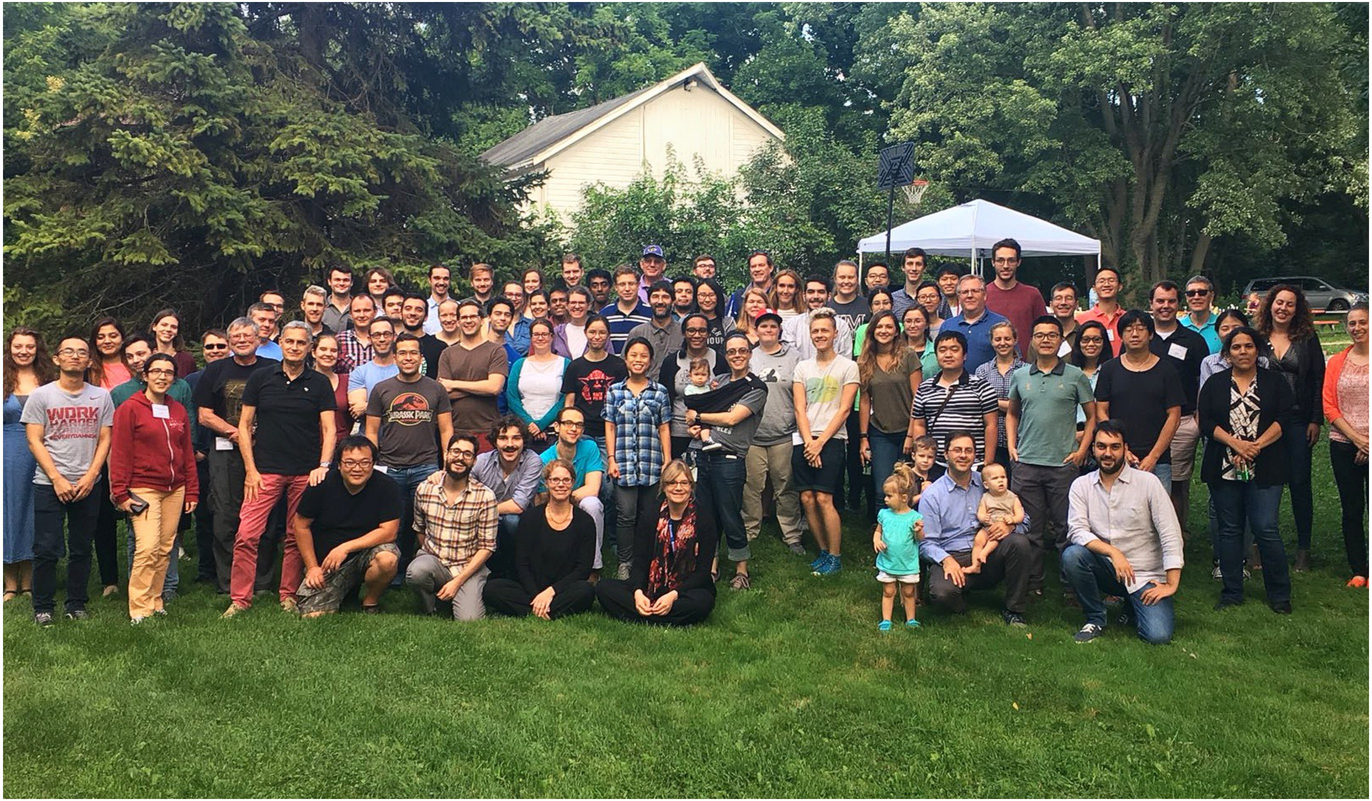
Summary

- MicroBooNE has concluded its first search into the long-standing MiniBooNE LEE anomaly
- MicroBooNE's investigation of the MiniBooNE anomaly shows no evidence for anomaly in single electron or $\Delta \rightarrow N\gamma$ single photon samples
- MicroBooNE has demonstrated the excellent power of LArTPCs as the tool for precision measurement
  - Pioneering high statistics ν-Ar cross-sections measurements, and BSM searches
  - Published detailed detector performance results to be used by new and upcoming LArTPCs, such as DUNE and SBN program
- More statistics to come and more analyses planned for probing into different channels and probing into more BSM searches

Stay tune for our many upcoming results!

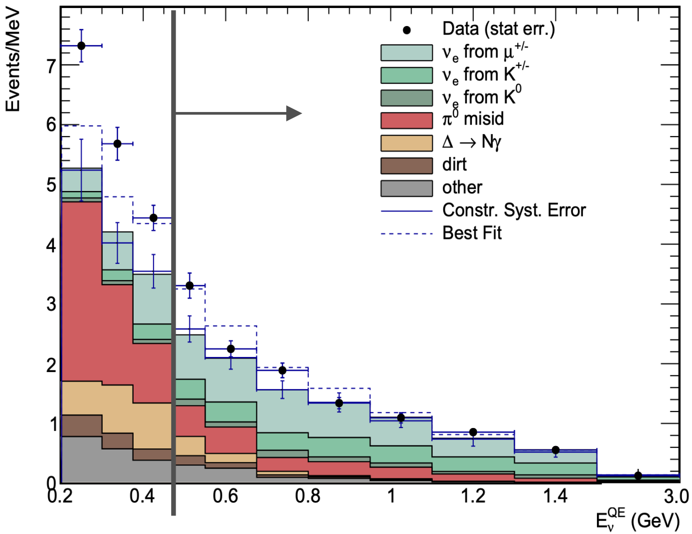
Fermilab · U.S. Department of Energy Office of Science · NSF · FNSNF Swiss National Science Foundation · Science & Technology Facilities Council · The Royal Society

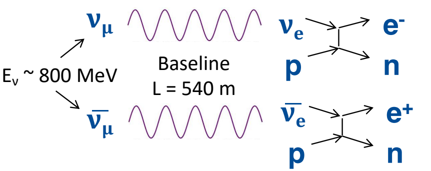
Thank you!



BACKUP

MiniBooNE anomaly



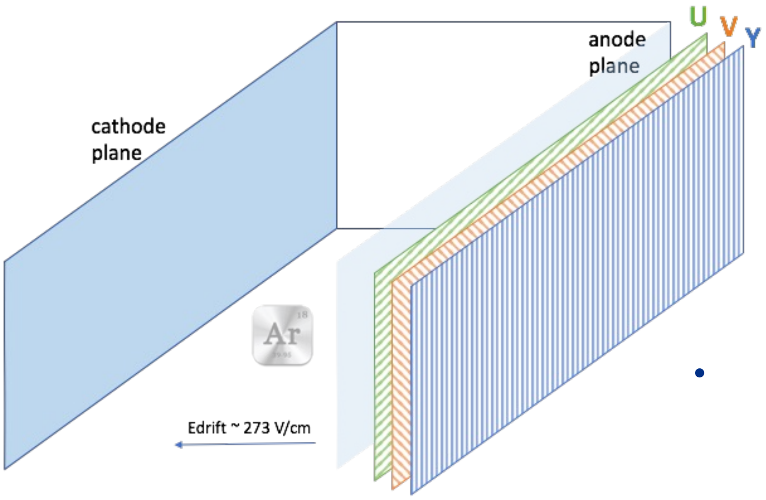


- Similar L/E oscillation
- New low-energy anomaly for E < 475 MeV that doesn't fit the 3+1 hypothesis

Excess of electromagnetic events on a scale of $\Delta m^2 \sim 1\ eV^2$, different with the "standard" mass splittings for 3 neutrinos

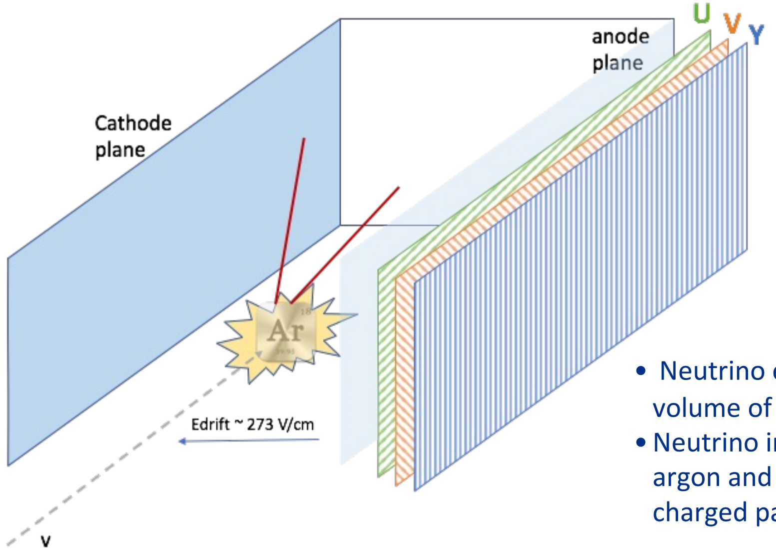
- Oscillation signal from additional sterile neutrino?
- Unmodeled background?
- New physics?

LArTPC principles



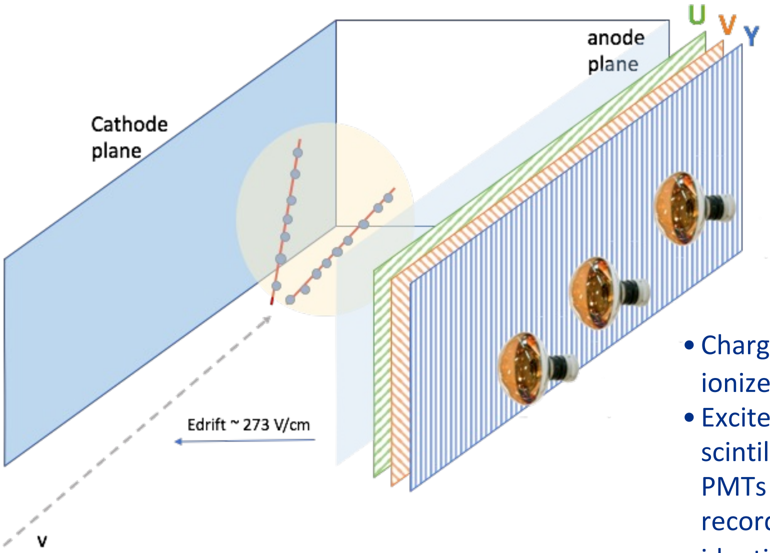
- Start with a large volume of liquid argon and a cathode and and anode

LArTPC principles



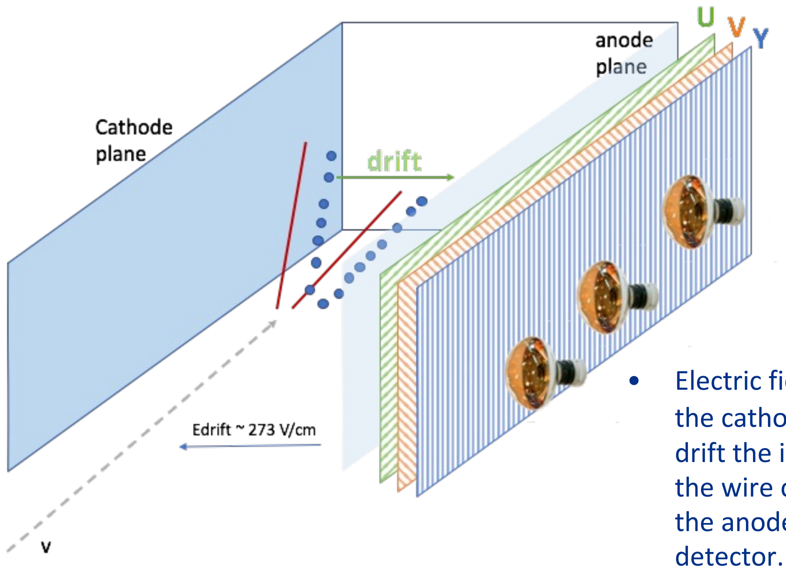
- Neutrino enters the large volume of liquid argon.
- Neutrino interacts with argon and produces charged particles

LArTPC principles



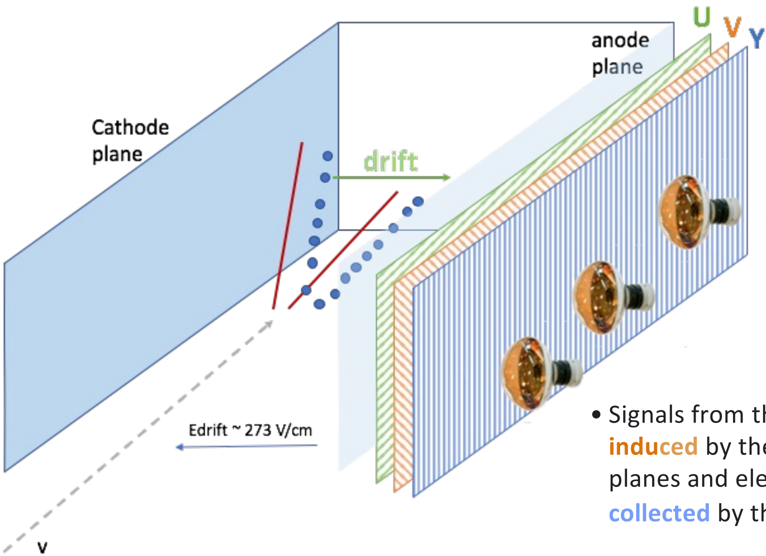
- Charged particle can ionize/excite the argon atoms.
- Excited argons produce scintillation light and arrays of PMTs behind the wire planes recorded the lights and used to identify the time the interaction occurs

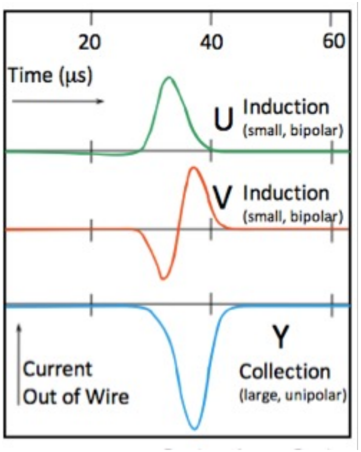
LArTPC principles



- Electric field set up between the cathode and the anode drift the ionized electron to the wire chamber planes on the anode side of the detector.

LArTPC principles

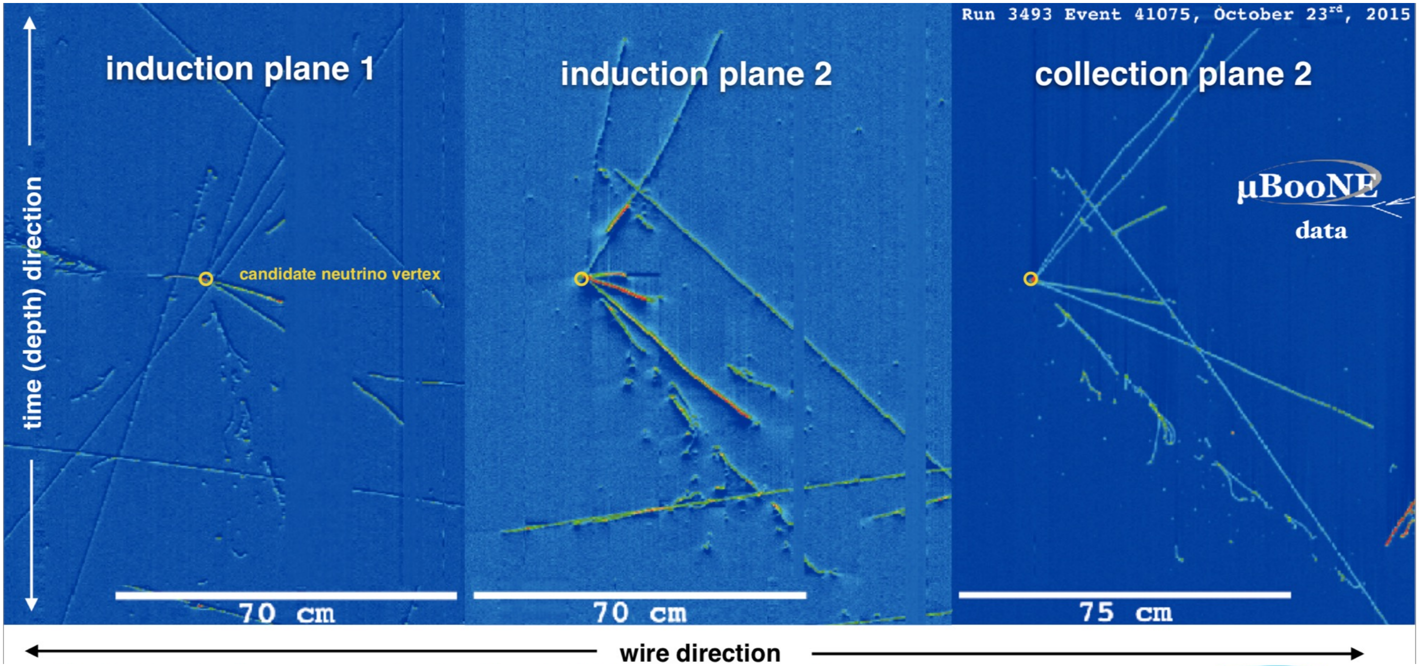




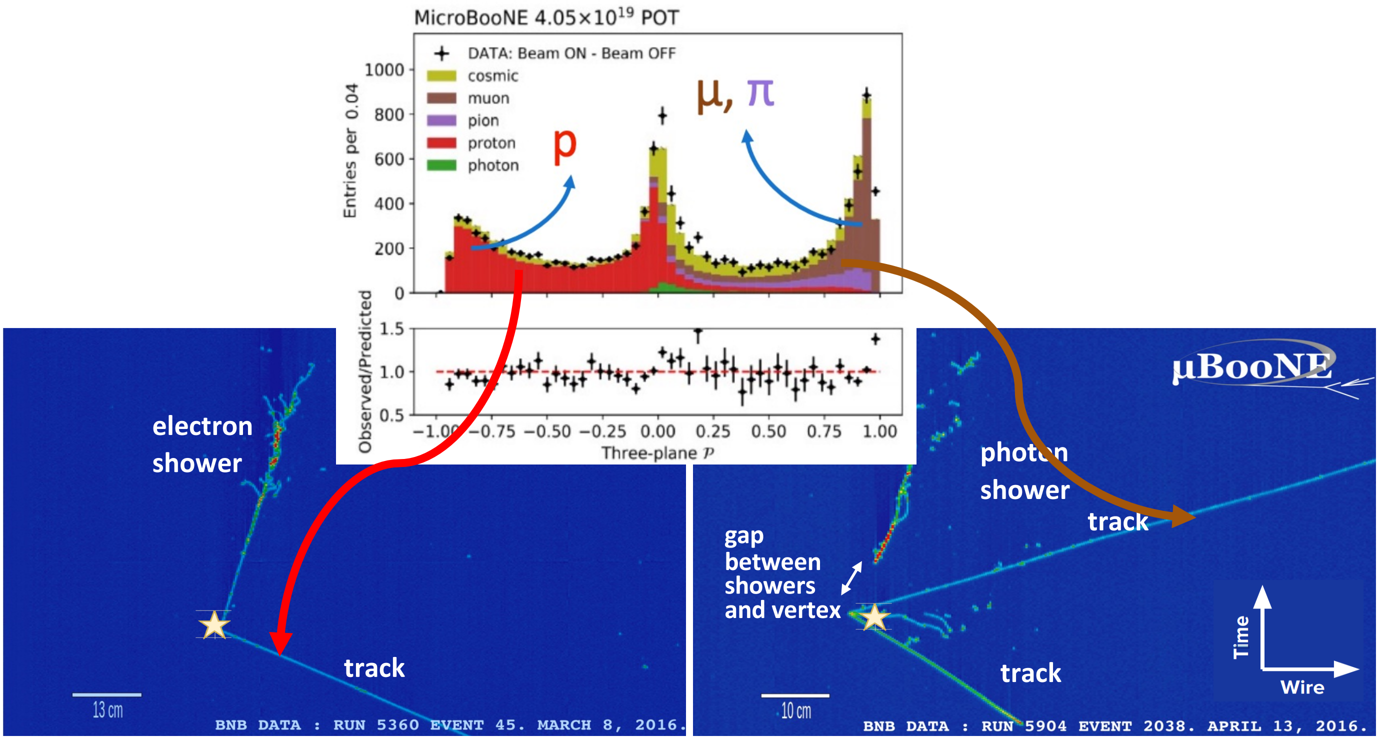
- Signals from the event are **induced** by the first two wire planes and electrons are **collected** by the last plane

LArTPC Power

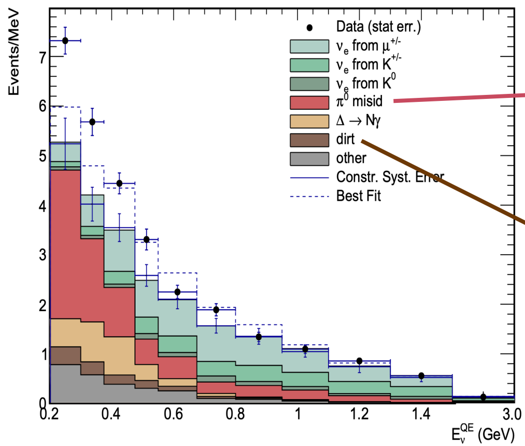
Digital “Bubble-chamber”-like images with 3D topology and calorimetry information

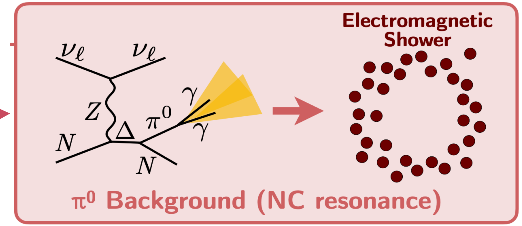


LArTPC Power: PID for tracks

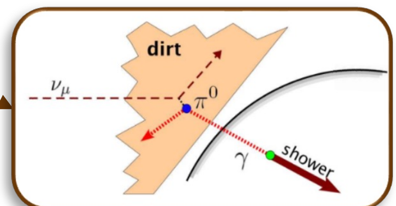


Zooming in on MiniBooNE Low Energy Excess





π^0 MisID constrained from in situ measurement of NC π^0 rate



constrained from in situ dirt data sample and beam timing

Common Strategy

Cosmic Rejection

e^-, γ ID

p, μ, π^0 tagging

Event Selection
Final and sidebands selection

Systematics Constraint

Statistical Interpretation

Simple hypothesis test

Signal strength measurement

Signal Event Selection

Cosmic Rejection

e^-, γ ID

p, μ, π^0 tagging

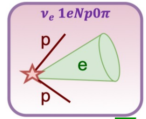
Event Selection Final and sidebands selection

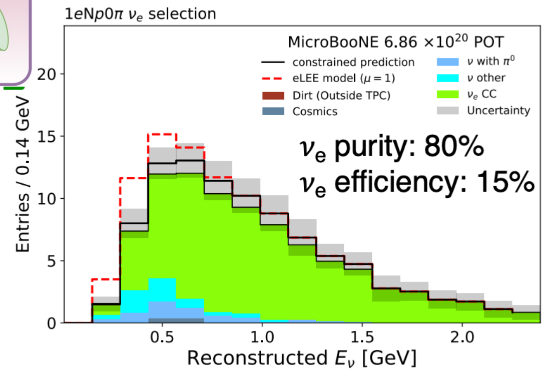
Systematics Constraint

Statistical Interpretation

Simple hypothesis test

Signal strength measurement





- Reject over 99.7% of background events from cosmic muons or π^0
- Boosted Decision Tree (BDT) is a common tool used for event selection. Each analysis uses different BDT features to get the best performance
- Select ν_e with high purity despite large backgrounds

μBooNE

High Statistics Sideband Sample

Cosmic Rejection

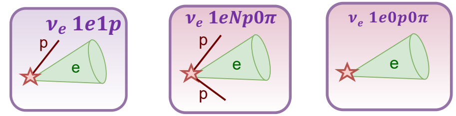
e^-, γ ID

p, μ, π^0 tagging

Event Selection
Final and sidebands selection

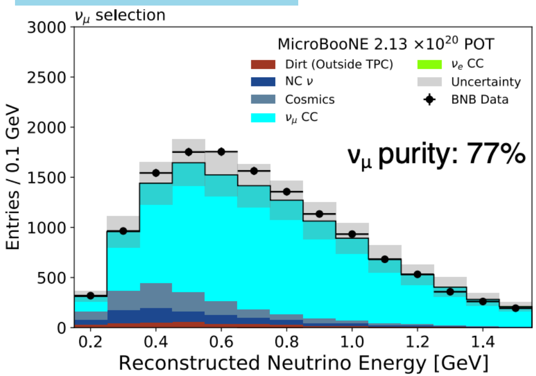
Systematics Constraint

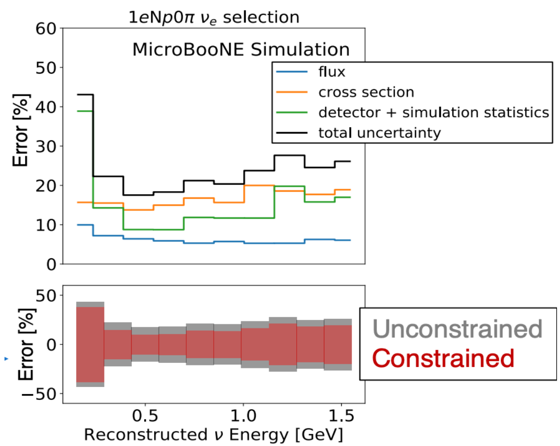
Sim
hypothe



High statistic inclusive contained ν_μ selection to constrain ν_e systematics

- Flux: both νe and νμ come from the same beamline, and hadrons
- Cross section: Both interact in argon





Blind Analysis

Cosmic Rejection

e^-, γ ID

p, μ, π^0 tagging

STAGED UNBLINDING

Event Selection Final and sidebands selection

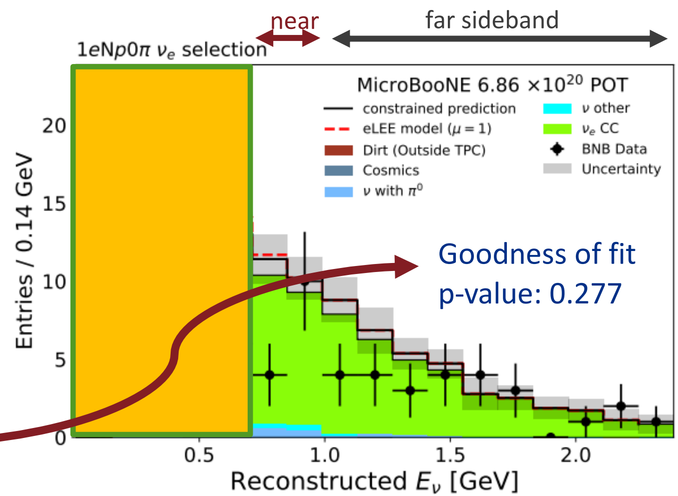
Systematics Constraint

FROZEN

Simple hypothesis

Signal strength

- Data in **non-signal region** used to validate analysis strategy and modeling.
- Selection is frozen before looking at **sideband** data.
- The **energy threshold is lowered gradually** towards full unblinding.



Goodness of fit test relative to constrained prediction motivated the unblinding

µBooNE

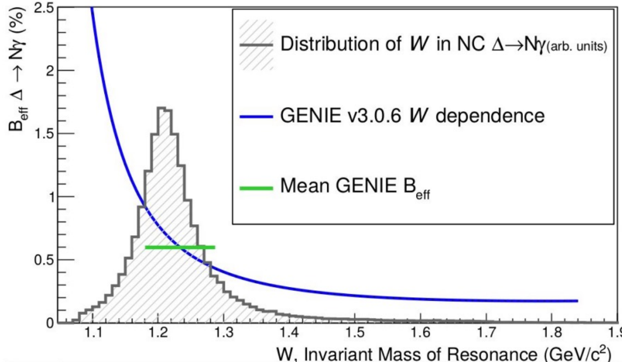
NC $\Delta \rightarrow N\gamma$ in MicroBooNE Simulations

MicroBooNE uses a custom tune of the **GENIE v3.0.6 event generator** (Nucl.Instrum.Meth.A 614 (2010) 87-104) for simulating all neutrino interactions in our detector

At BNB energies, dominant single-photon production is expected to be resonant $\Delta(1232)$ radiative decay

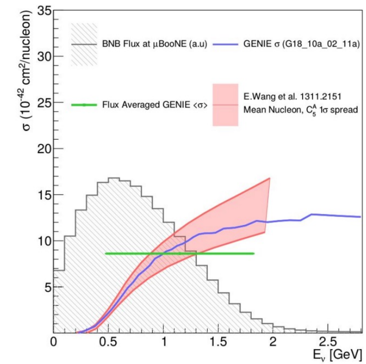
All resonances in GENIE v3 are modeled with the **Berger-Sehgal** (Phys. Rev. D 76, 113004) model

Once a $\Delta(1232)$ resonance has been simulated GENIE will then decay it to various final states based on the assumed branching fractions of $\Delta \rightarrow N\gamma$ and $\Delta \rightarrow N\pi^0$



NC $\Delta \rightarrow N\gamma$ in MicroBooNE Simulations

Neutrino-induced NC $\Delta \rightarrow N\gamma$ cross-section on argon



Resulting **GENIE cross sections** for producing NC $\Delta \rightarrow N\gamma$ on argon agree well with recent NC single photon production **theoretical predictions** for argon (E. Wang, L. Alvarez-Ruso, J. Nieves 10.1103/PhysRevC.89.015503)

Credit: M. R. Lonergan's talk Fermilab Wine and Cheese (Oct 1st 2021)