Title: MicroBooNE's First Results and the MiniBooNE Low Energy Excess

Speakers: Nicholas Kamp

Series: Particle Physics

Date: May 24, 2022 - 1:00 PM

URL: https://pirsa.org/22050066

Abstract: In this talk, I will present MicroBooNE's first results probing the nature of the excess of low-energy interactions observed by the MiniBooNE collaboration. The talk will cover all four electron neutrino analyses that comprise MicroBooNE's first results, with a particular focus on the exclusive search for CCQE-like electron neutrino interactions containing one electron and one proton in the final state (1e1p). The result of the 1e1p analysis, along with results from the other electron analyses and the single-photon analysis, will be discussed in terms of their implications for the MiniBooNE excess. Specifically, I will examine the viability of the single sterile neutrino explanation of the MiniBooNE excess in light of the MicroBooNE electron neutrino results. Additionally, I will introduce the Coherent CAPTAIN-Mills (CCM) experiment at Los Alamos National Laboratory. CCM has unique sensitivity to a number of exotic BSM models, including leptophobic vector-portal dark matter and axion-like particles, some of which may be able to explain the MiniBooNE anomaly.

Zoom Link: https://pitp.zoom.us/j/93290406752?pwd=ajIvZkhvVU5YMW90WjVpU3IySUphdz09

MicroBooNE's First Results on the MiniBooNE Low Energy Excess

Nick Kamp
Massachusetts Institute of Technology

Perimeter Institute Seminar
24 May 2022

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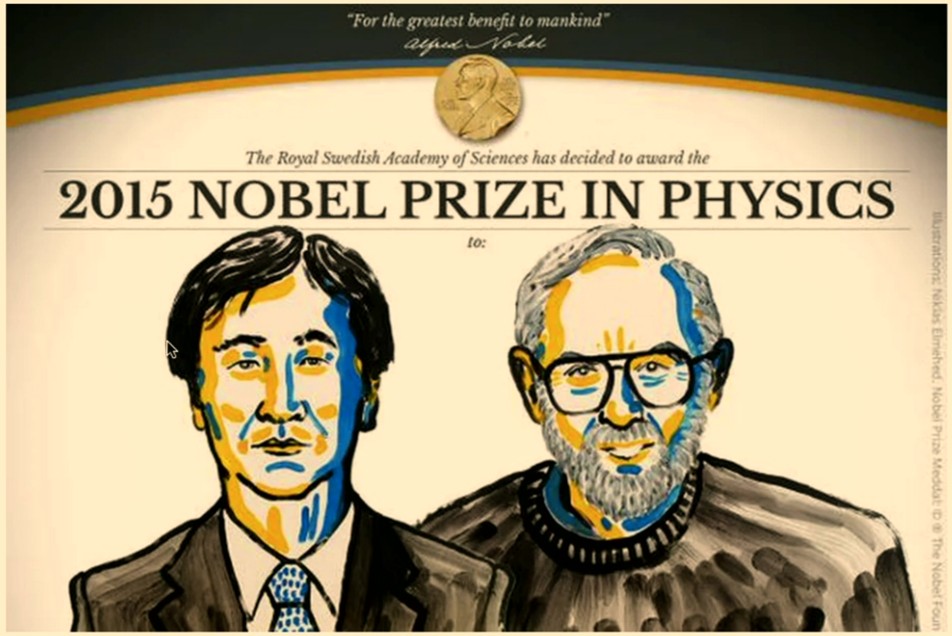
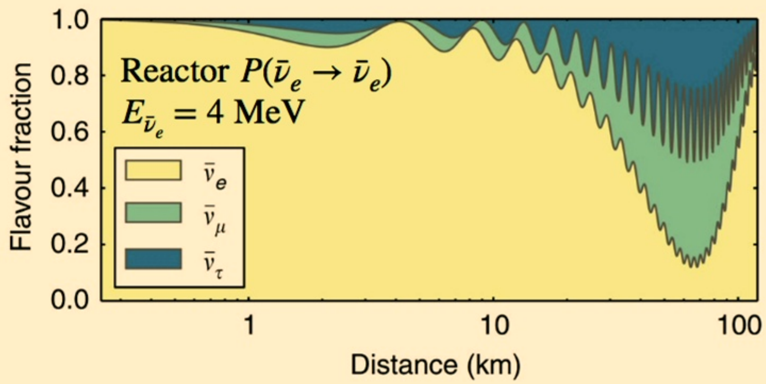


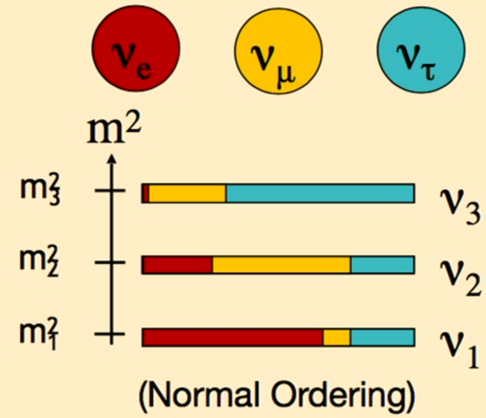


Nature Communications
volume
6, Article number: 6935 (2015)

Neutrinos

- Oscillations between three flavor states imply small but nonzero masses

$$\begin{bmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{bmatrix} = \begin{bmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{bmatrix} \begin{bmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{bmatrix}$$



$$P(\nu_\alpha \to \nu_\beta) = |\langle \nu_\beta(t) | \nu_\alpha(t) \rangle|^2$$

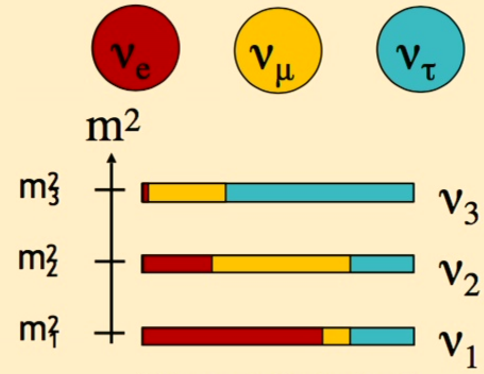
$$= \left| \sum_i U_{\alpha i} U_{\beta i}^* e^{-i \frac{m_i^2 L}{2E}} \right|^2$$

$$\approx \sin^2(2\theta) \sin^2\left(1.27 \Delta m^2 \frac{L}{E}\right)$$

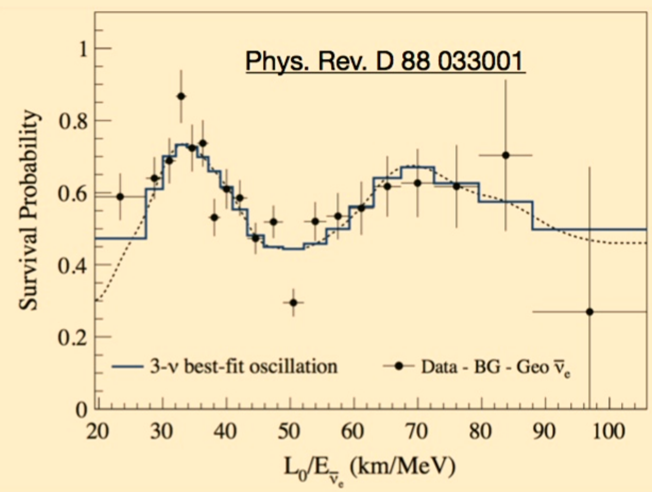
Two-Neutrino Approximation

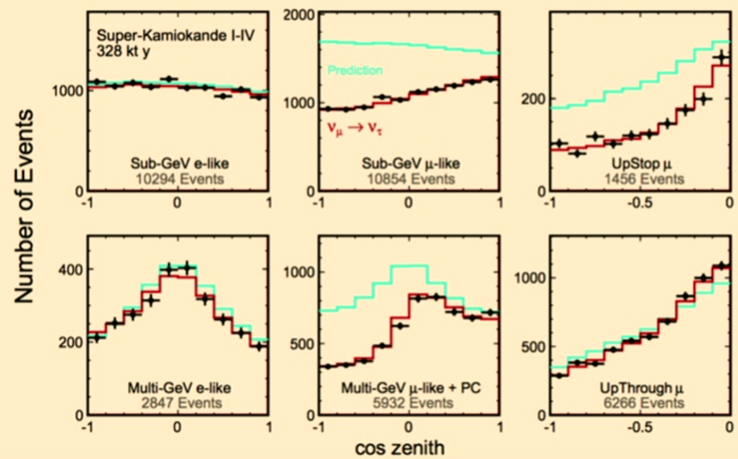
Neutrinos

- Oscillations between three flavor states imply small but nonzero masses
- Mixings and mass splittings well-measured by accelerator, reactor, atmospheric, and solar experiments



(Normal Ordering)



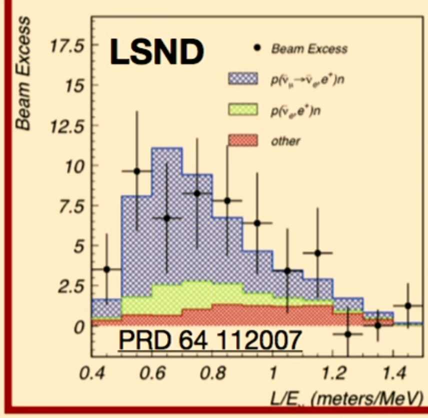


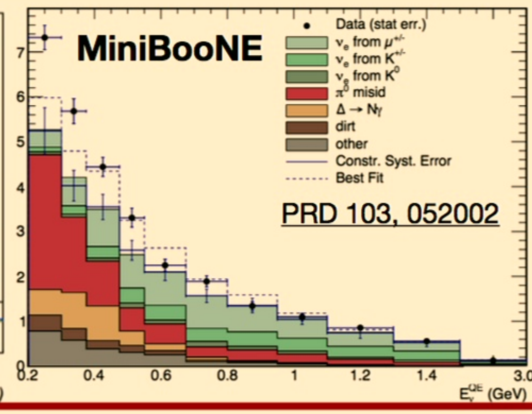
Neutrino Sector Anomalies

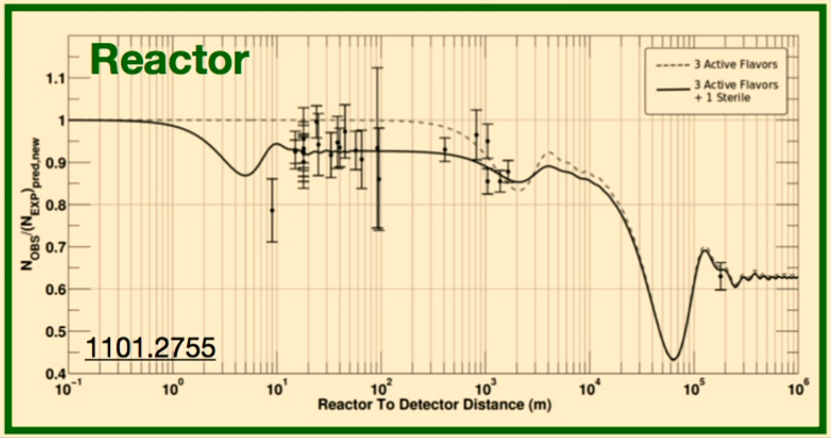
- Difficult to explain within the standard three-neutrino oscillation paradigm
- Explanations often invoke oscillations with a fourth "sterile" neutrino*

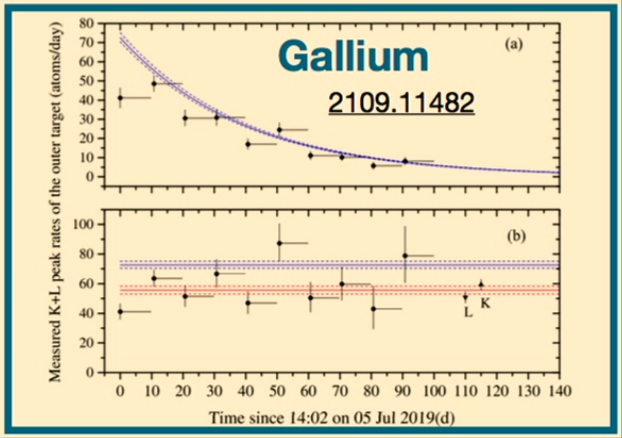
*tension in global picture

Short Baseline Accelerator



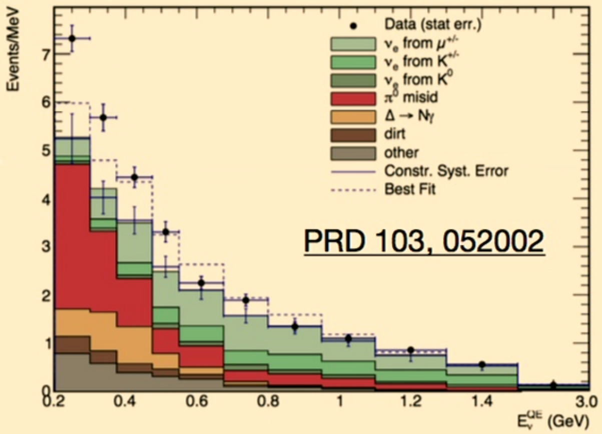


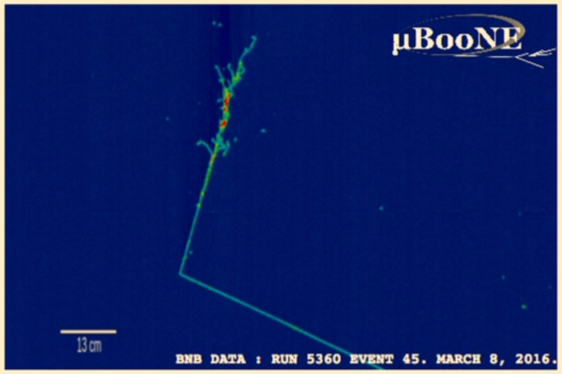




The MiniBooNE Anomaly

- This talk focuses on the **MiniBooNE anomaly:** an excess of electron neutrino-like events in a predominately muon neutrino beam
- Tested by the follow-up MicroBooNE experiment, a liquid argon time-projection chamber situated on the same beam-line
- **Presented today: MicroBooNE's first results exploring the nature of the MiniBooNE low energy excess**





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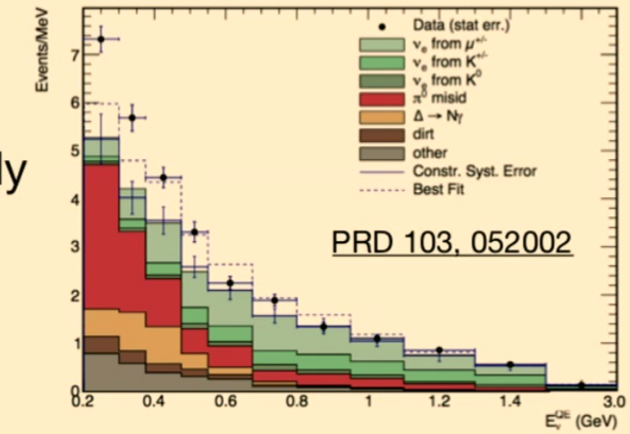

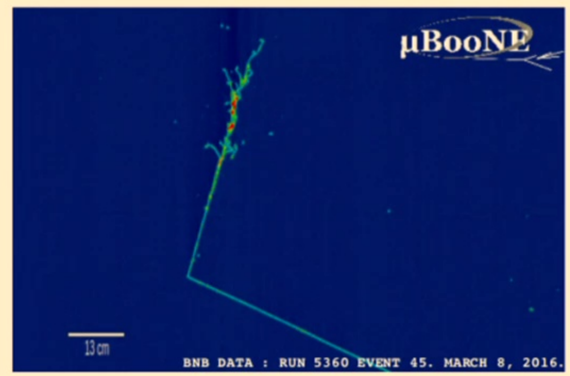

Outline

1. The MiniBooNE anomaly
2. The MicroBooNE experiment
3. MicroBooNE's first results
4. **Bonus:** Coherent CAPTAIN-Mills @ Los Alamos

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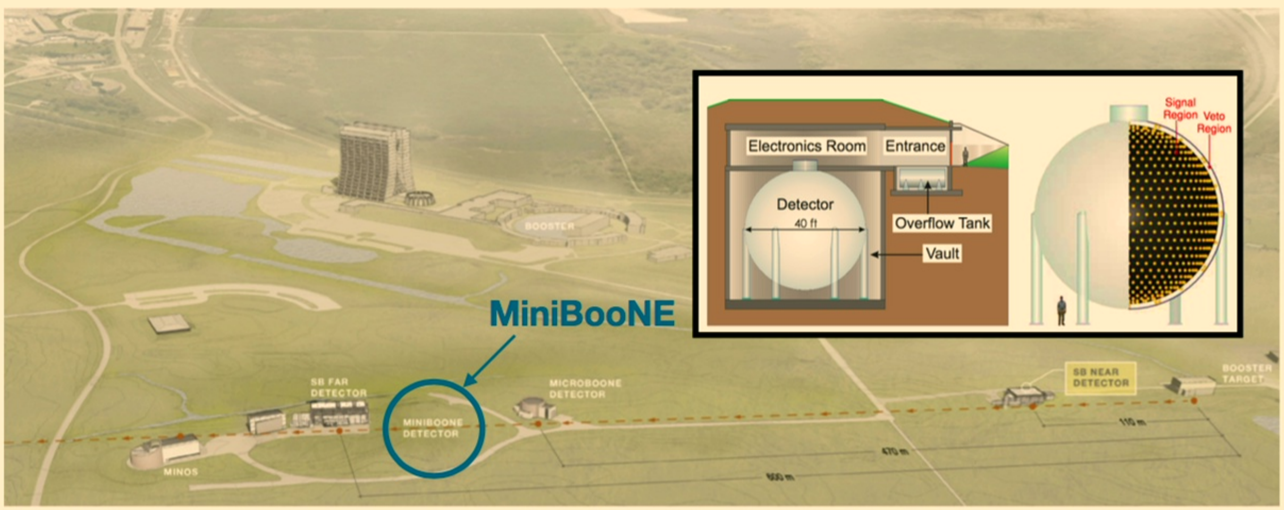
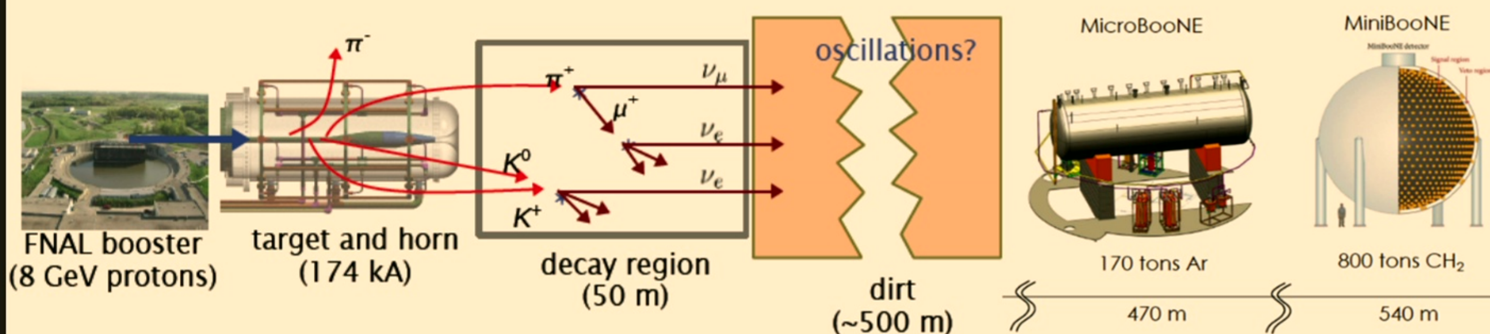
Outline

1. **The MiniBooNE anomaly**
2. The MicroBooNE experiment
3. MicroBooNE's first results



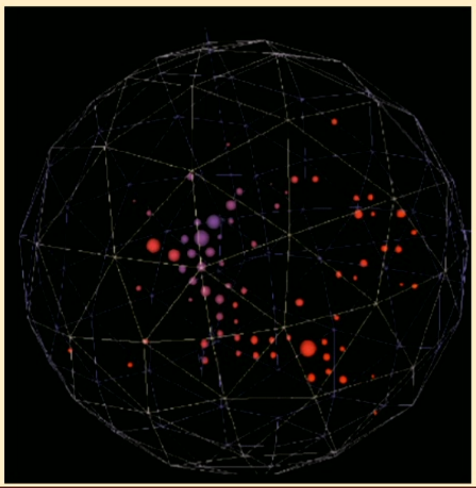
The MiniBooNE Experiment

- 800-ton Cherenkov detector
- Situated along Fermilab's Booster Neutrino Beam
  - ~540 m from the beryllium target
  - ~70 m downstream from MicroBooNE
- Originally designed to test oscillation interpretation of LSND

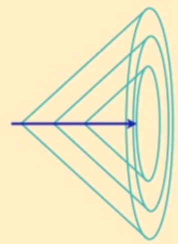


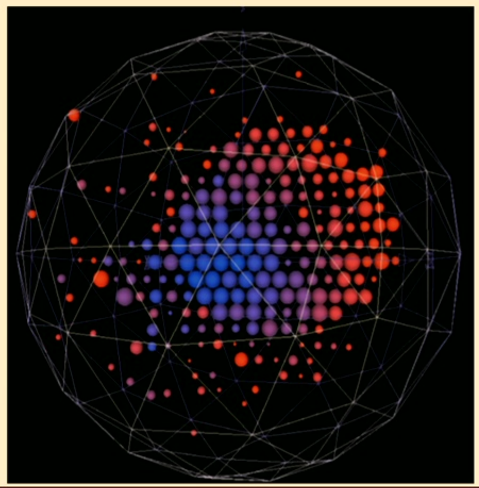
The MiniBooNE Detector

Electrons: “fuzzy” rings from multiple scattering

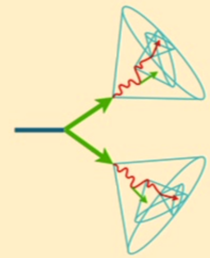


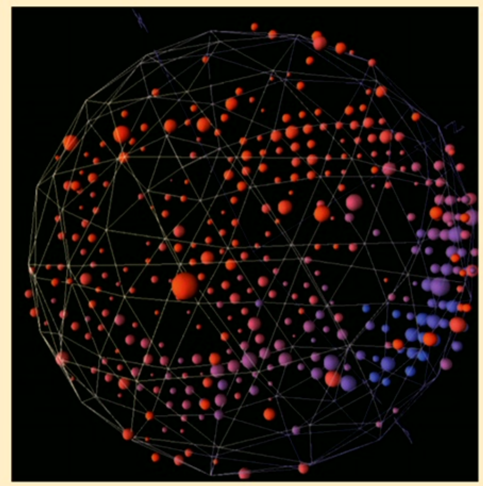
Muons: “clean” rings from long, straight tracks





Neutral Pions: two rings from decay to two photons





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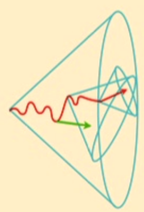
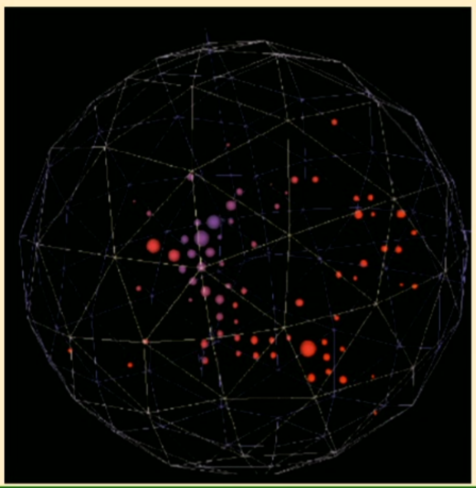
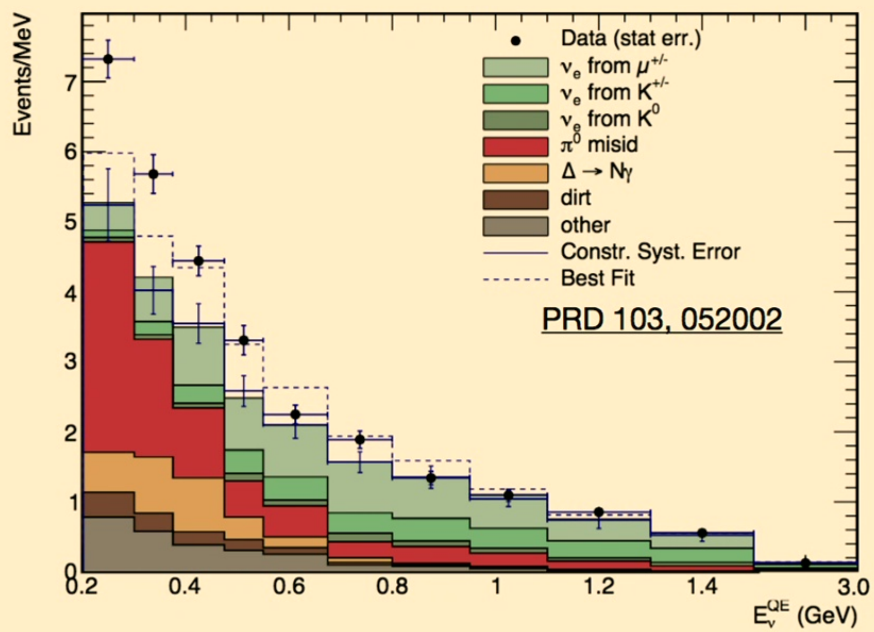




4.8σ excess observed in the electron-like channel



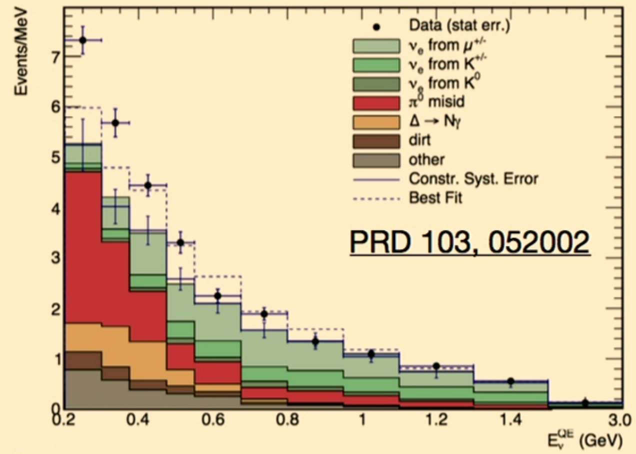
The MiniBooNE Excess

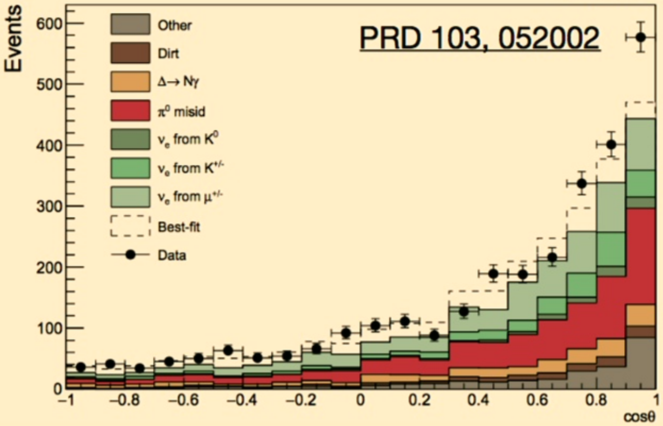
Cherenkov limitations:

- Electrons/photons indistinguishable
- No hadronic information

The excess could be…

1. Mis-modeled photon background?
2. Electron-like (e.g. sterile-driven oscillations?)
3. More exotic new physics (e.g. dark sector e^+e^- production?)





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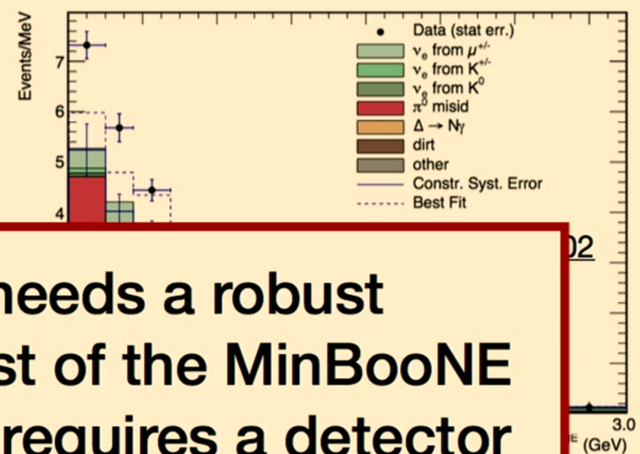
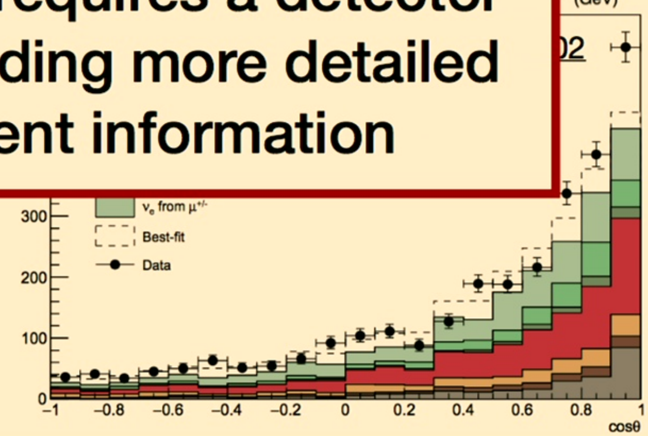




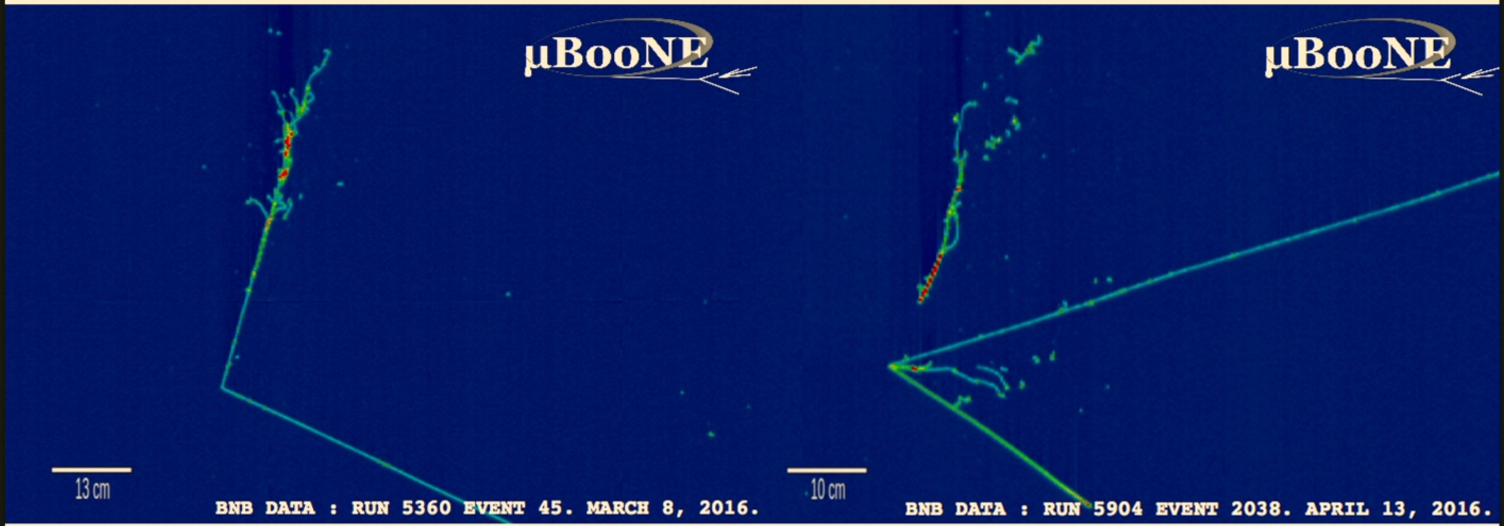
One really needs a robust experimental test of the MinBooNE anomaly, which requires a detector capable of providing more detailed event-by-event information

Outline

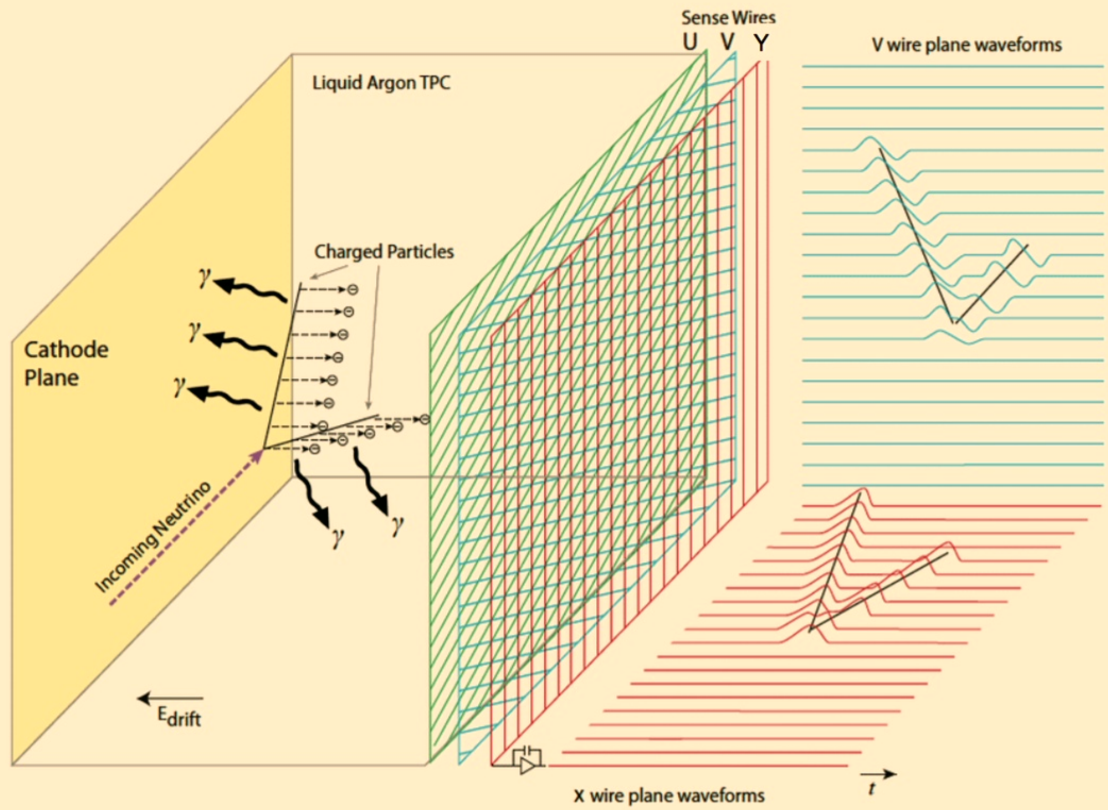
1. The MiniBooNE anomaly
2. **The MicroBooNE experiment**
3. MicroBooNE's first results

MicroBooNE

- Designed to directly address the MiniBooNE anomaly
- Harnesses the imaging power of liquid argon time projection chamber (LArTPC) technology to observe detailed pictures of neutrino interactions

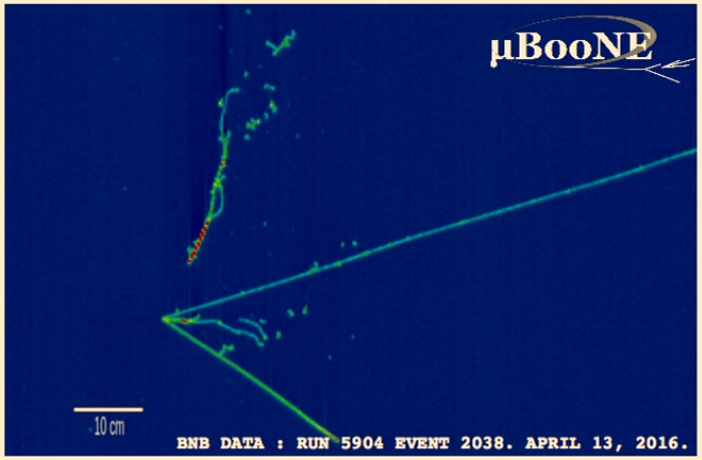


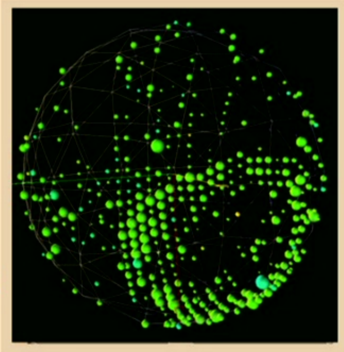
How does a LArTPC Work?

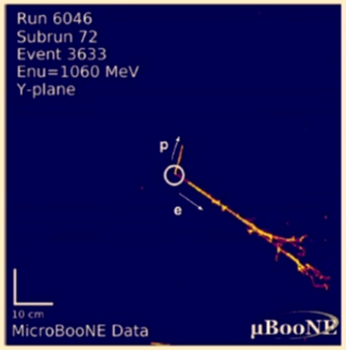


The MicroBooNE Detector

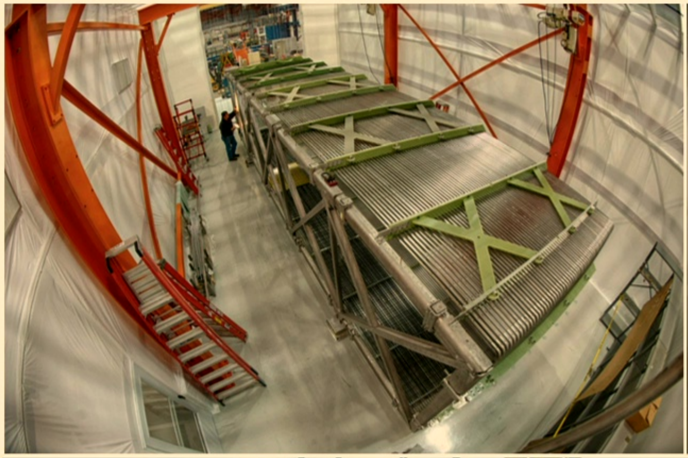
- 170-ton LArTPC
- O(mm) spatial resolution
- Ability to reconstruct hadronic activity
- Important contributions to our understanding of LArTPCs:
  - Electric field distortions from space charge effects
    P. Abratenko et al 2020 JINST 15 P12037
  - Noise characterization/filtering
    R. Acciarri et al 2017 JINST 12 P08003
  - Neutrino-Ar cross sections
    Phys. Rev. Lett. 123, 131801
  - GENIE event generator tuning
    arXiv 2110.14028 (submitted to PRD)
  - Data-driven detector uncertainties
    arXiv 2111.03556 (submitted to EPJ-C)

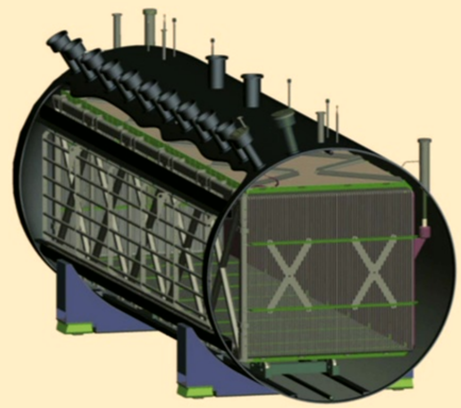




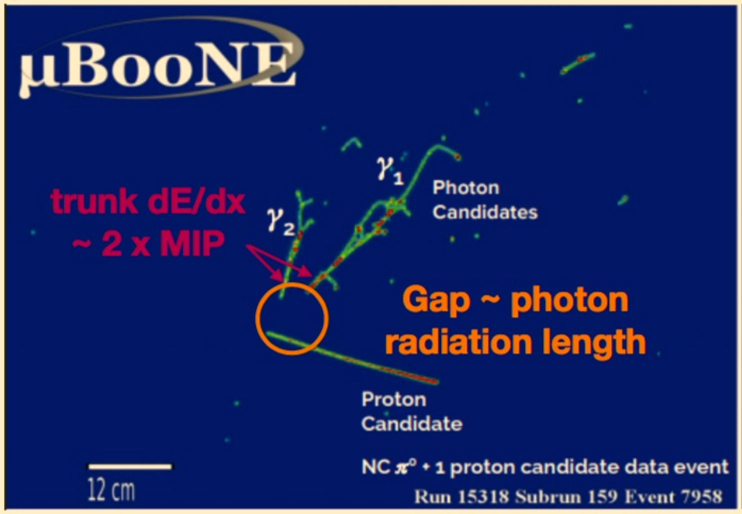


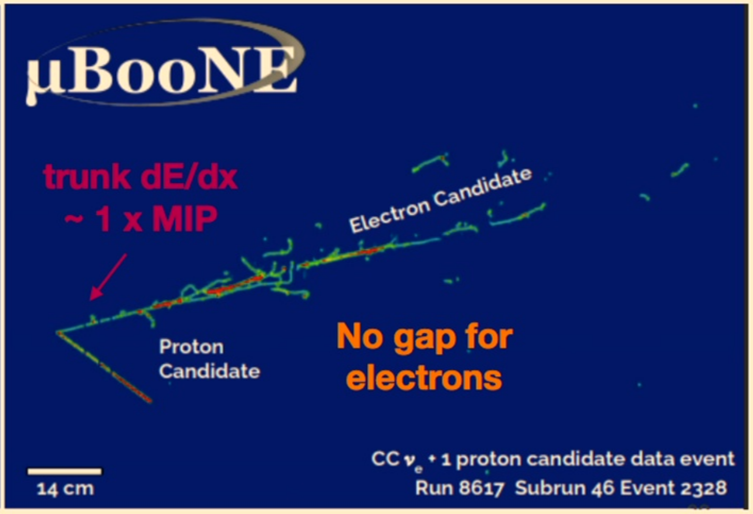
The MicroBooNE Detector





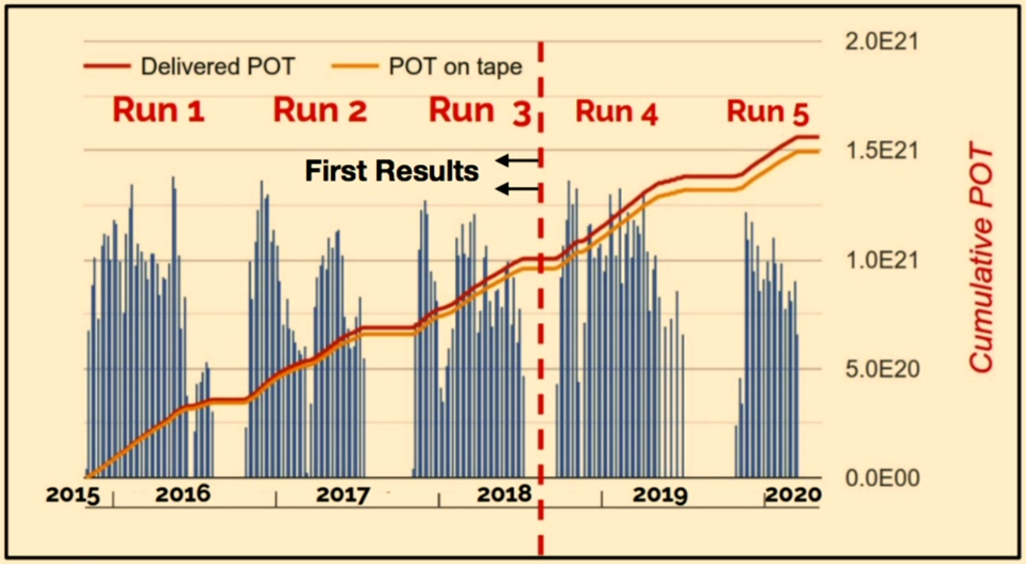
Photon/Electron Discrimination





The MicroBooNE Dataset

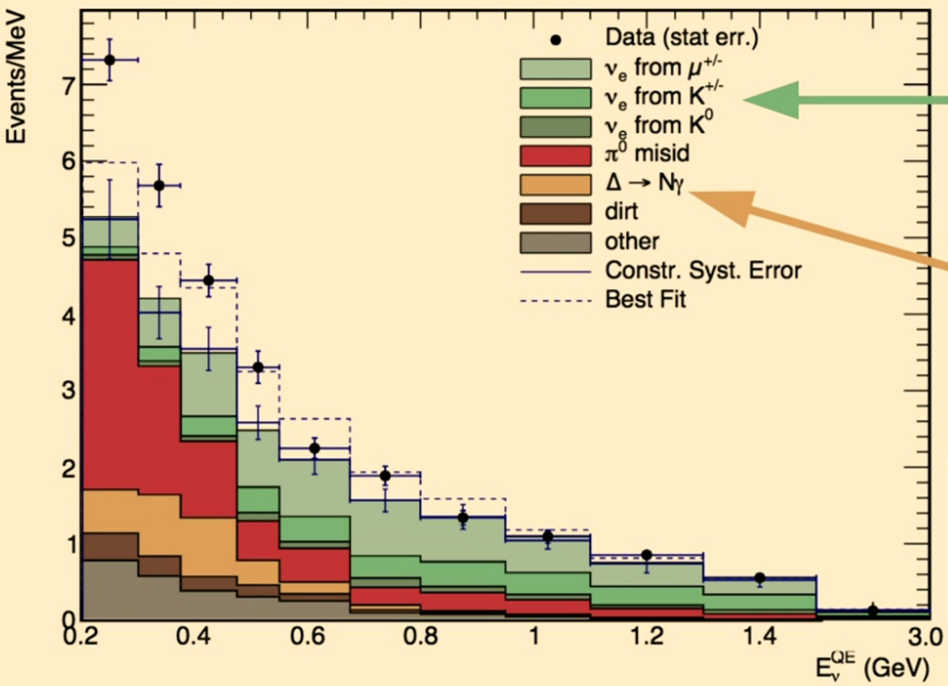
- Data taken from 2015-2021
- The analyses covered today consider the first ~7e20 protons-on-target (~1/2 of the full dataset)



Outline

1. The MiniBooNE anomaly
2. The MicroBooNE experiment
3. **MicroBooNE's first results**

What is tested in MicroBooNE's first results?



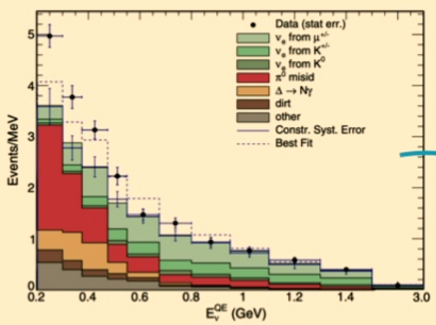
Three independent analyses have targeted ν_e final states, testing whether the excess is due to an enhancement of ν_e interactions?

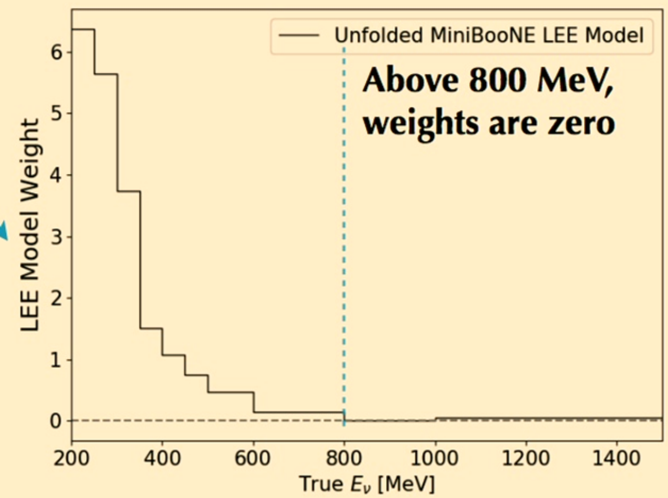
Another analysis has searched for an enhancement of NC $\Delta \to N\gamma$ events

MicroBooNE has **not** yet performed a generic single photon search—stay tuned!

The Simplified LEE Model

- MicroBooNE focused on a simplified, phenomenological model for an excess of low-energy ν_e events based on MiniBooNE results
- MiniBooNE observation is unfolded under a ν_e assumption to obtain LEE model weights as a function of true neutrino energy
- Weights are applied to MicroBooNE simulated intrinsic CC ν_e events
- **NOTE: this method assumes the MiniBooNE excess would have the same neutrino energy dependence in MicroBooNE**

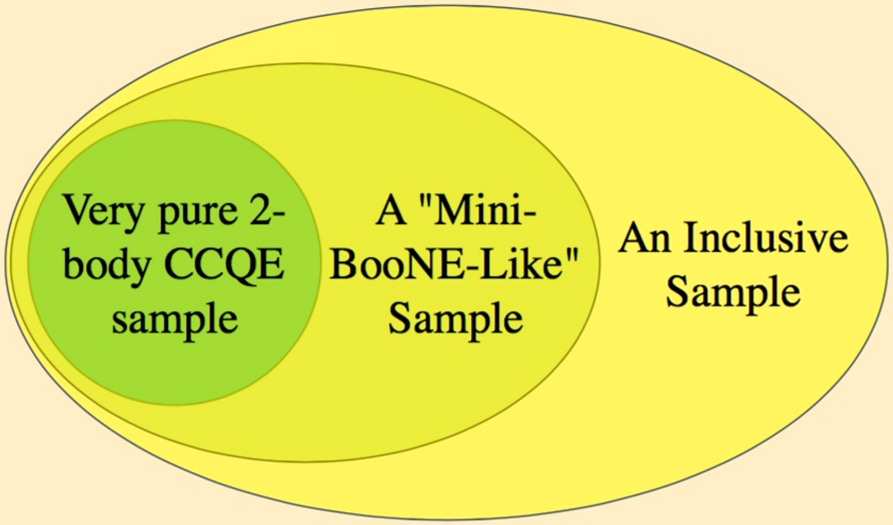




MiniBooNE inputs:
PRL 121, 221801 (2018)

Unfolding method:
MICROBOONE-NOTE-1043-PUB

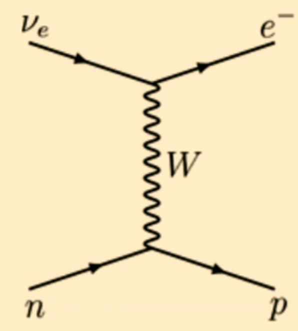
Electron Neutrino Results

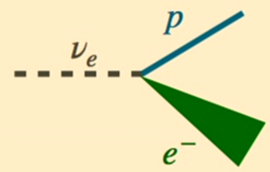


- Three analyses which use the same input data but have been developed independently, each using different reconstruction tools
- You can find the full suite of papers at: http://ubdllee.org

The CCQE Analysis in a Nutshell

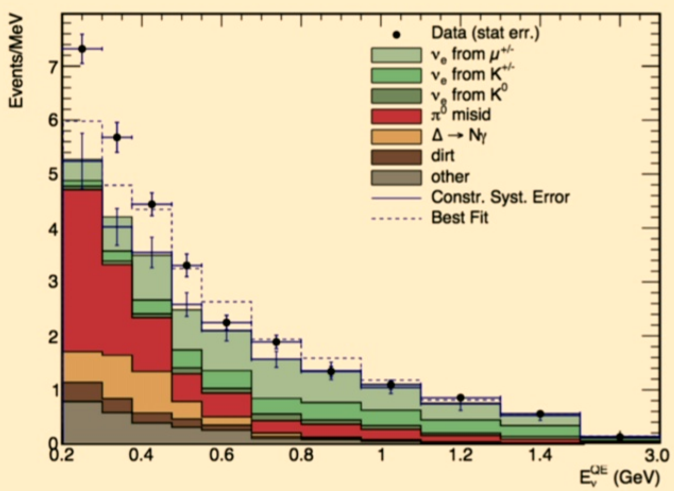
- This analysis uses novel image-based deep learning algorithms alongside traditional reconstruction algorithms to isolate a highly-pure sample of electron neutrinos in the MicroBooNE detector
- We focus on **charged-current quasi-elastic (CCQE)** interactions creating **one electron and one proton (1e1p)** in the final state
  - These requirements give strong kinematic and topological handles on event selection

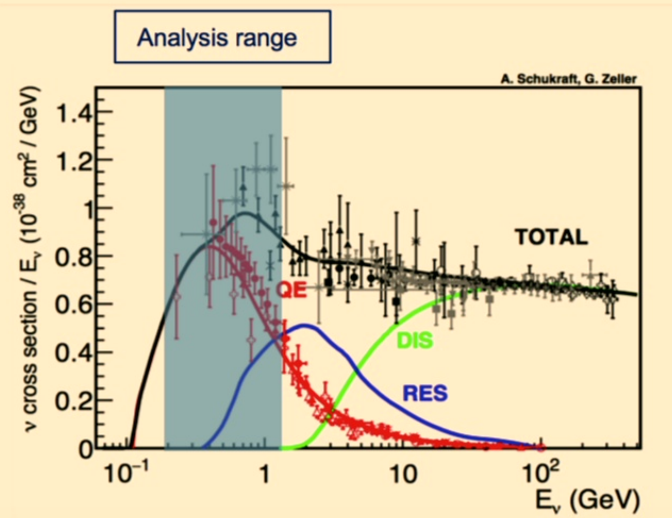




CCQE 1e1p Motivation

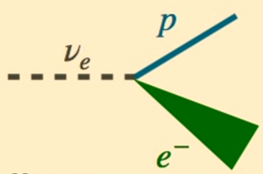
- The QE cross section is dominant around the peak of the MiniBooNE excess (200-500 MeV)
- The QE cross section is also better understood than other neutrino interactions





CCQE 1e1p Motivation

- Simple topology: one track from the proton and one electromagnetic shower from the electron

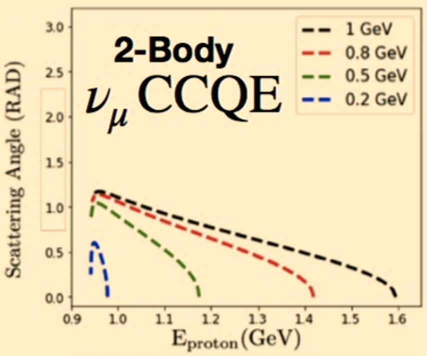


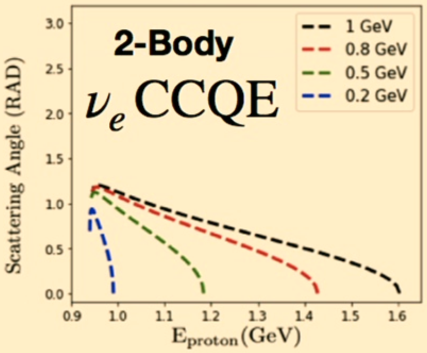
- Kinematic handles:
  - Forward-going protons
  - CCQE-consistent reconstructed energy
  - Bjorken x near unity

$$E_\nu^{\text{range}} = \mathrm{K}_p + \mathrm{K}_\ell + M_\ell + M_p - (M_n - B),$$

$$E_\nu^{QE-p} = \left(\frac{1}{2}\right) \frac{2 \cdot (M_n - B) \cdot E_p - ((M_n - B)^2 + M_p^2 - M_\ell^2)}{(M_n - B) - E_p + \sqrt{(E_p^2 - M_p^2)} \cdot \cos\theta_p},$$

$$E_\nu^{QE-\ell} = \left(\frac{1}{2}\right) \frac{2 \cdot (M_n - B) \cdot E_\ell - ((M_n - B)^2 + M_\ell^2 - M_p^2)}{(M_n - B) - E_\ell + \sqrt{(E_\ell^2 - M_\ell^2)} \cdot \cos\theta_\ell},$$



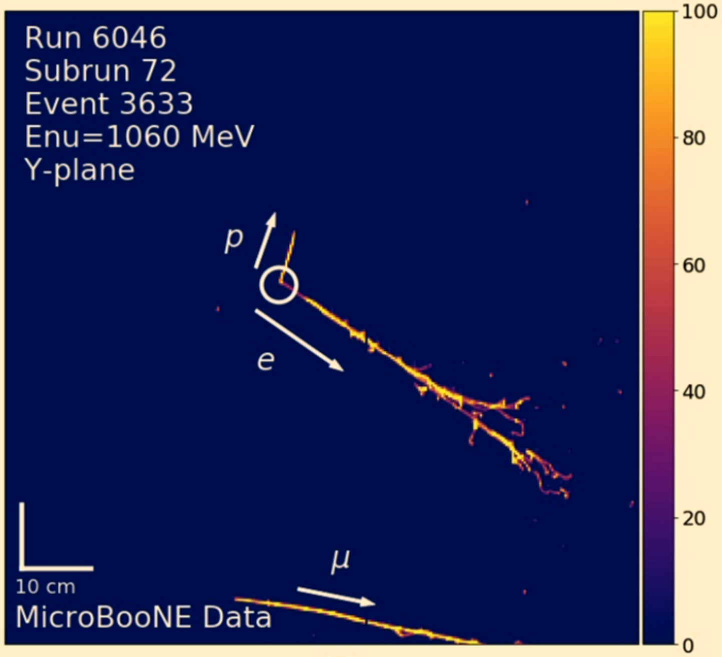


Deep Learning Motivation

- LArTPC data come in the form of high-resolution images of charged particles
- MicroBooNE spatial resolution:

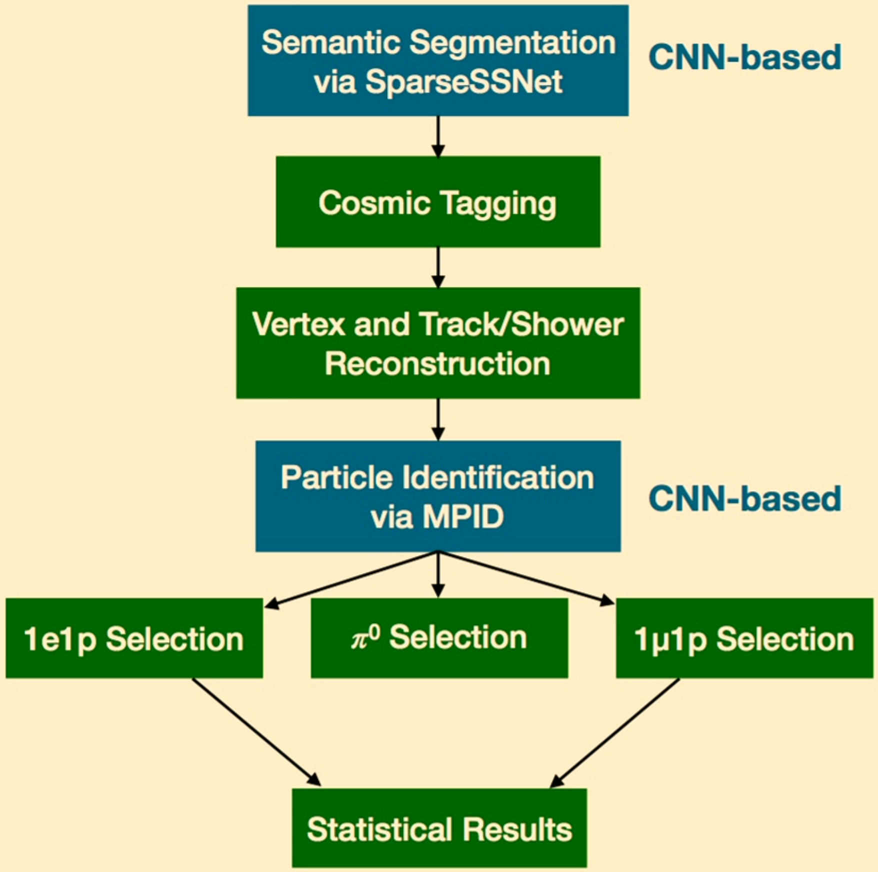
$$3 \times 3.3\,\mathrm{mm}$$

- This lends itself to the use of image-based deep learning algorithms like convolutional neural networks (CNNs)



(a)

Analysis Chain

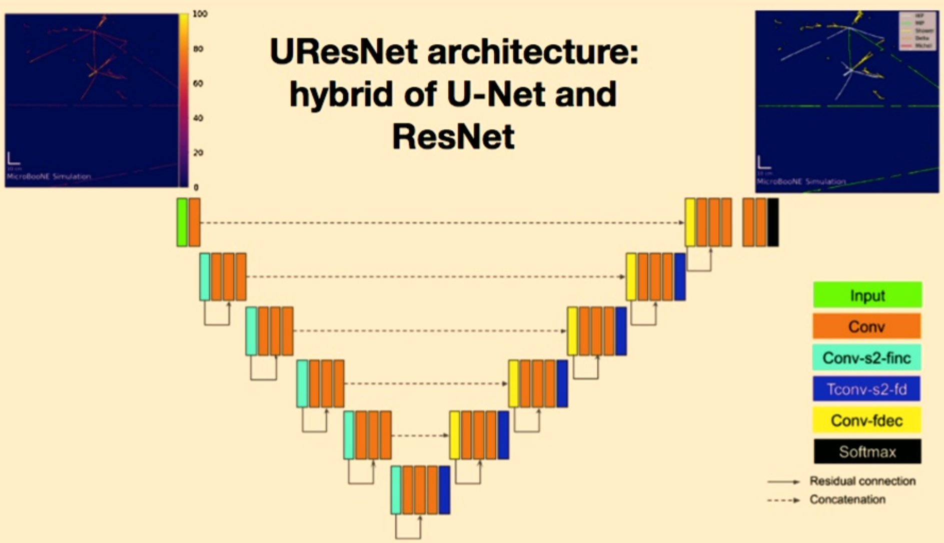


SparseSSNet

Phys. Rev. D 103, 052012

- We use the Sparse Semantic Segmentation Network to perform pixel-level labeling of LArTPC images
- Built using sparse convolutions, more efficient given the sparse nature of our data   arXiv 1706.01307

UResNet architecture: hybrid of U-Net and ResNet



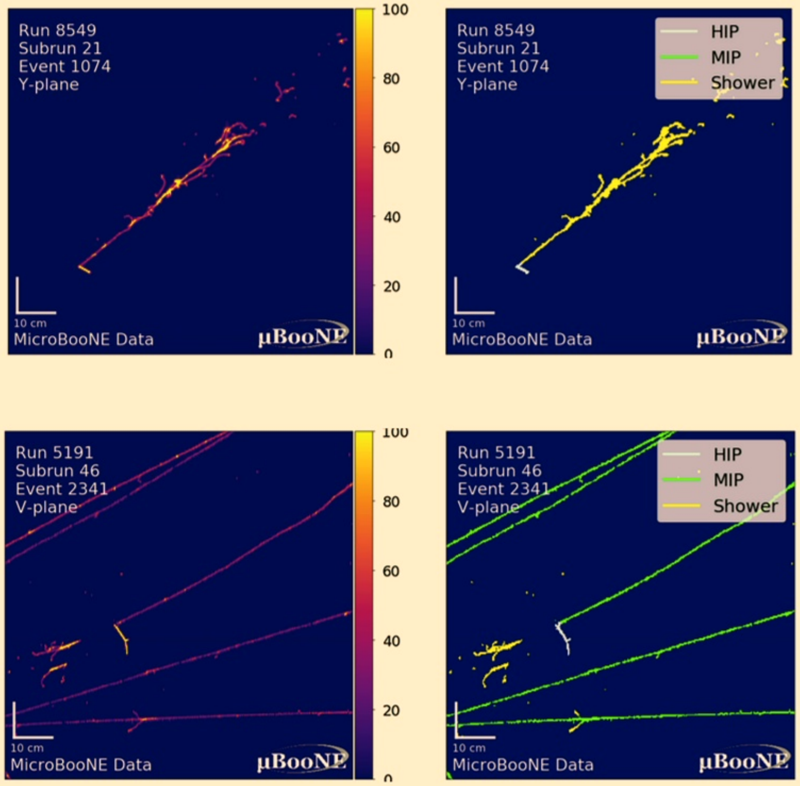
One-hot Labels

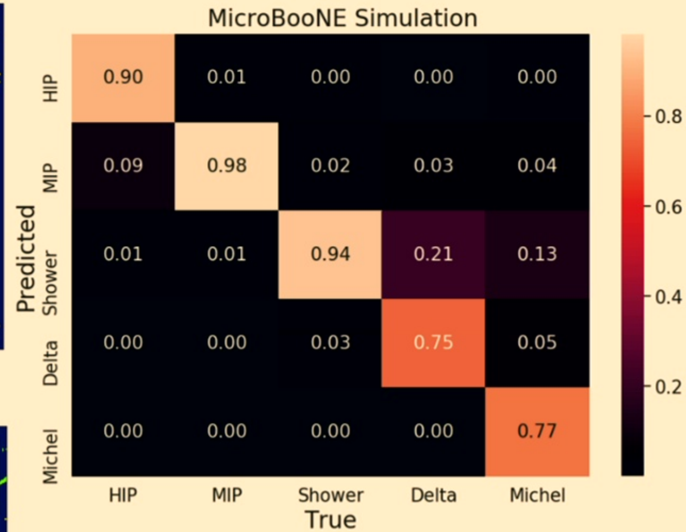
Track
- Highly ionizing particle (protons)
- Minimum ionizing particle (muons, charged pions)

Shower
- EM shower (electrons, photons)
- delta (knock-on electrons)
- Michel electrons (from muon decay)

SparseSSNet

Phys. Rev. D 103, 052012



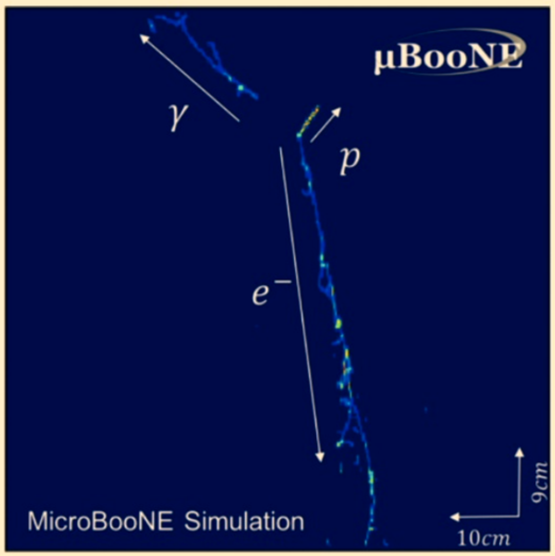


Accuracy	Test	Intrinsic ν_e	Full-BNB
Track	0.992	0.992	0.998
Shower	0.996	0.859	0.823

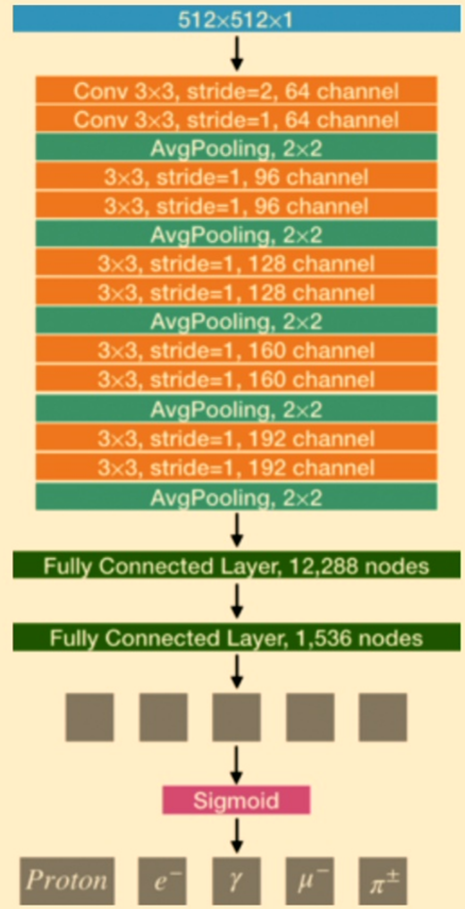
Phys. Rev. D 103, 092003

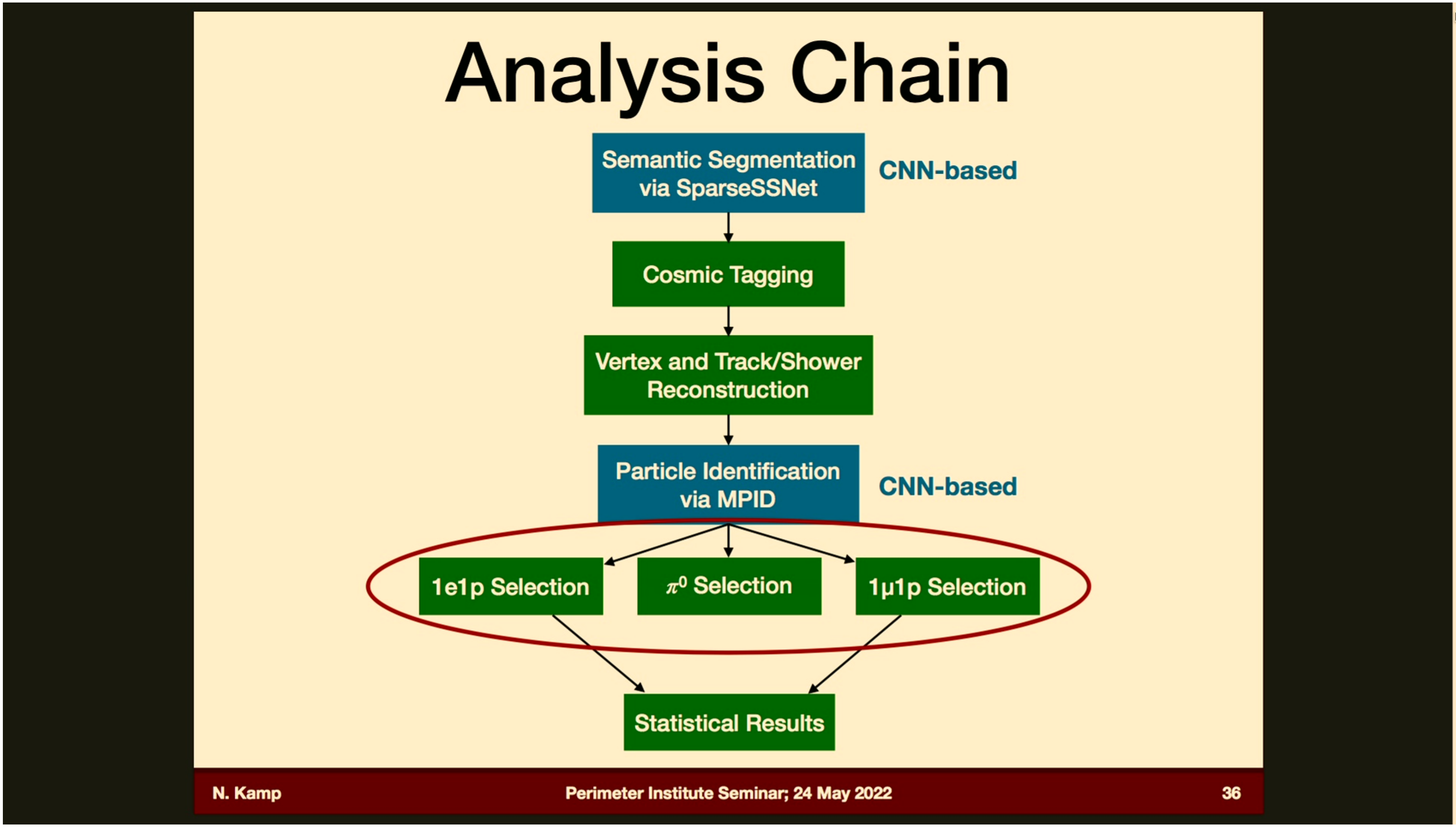
MPID

- Multi Particle IDentification network
- Outputs likelihood that a particle exists in a given LArTPC image



	p	e^-	γ	μ^-	$\pi^\pm$
MPID Score	0.89	0.95	0.85	0.06	0.17




Analysis Chain
Semantic Segmentation via SparseSSNet
CNN-based
Cosmic Tagging
Vertex and Track/Shower Reconstruction
Particle Identification via MPID
CNN-based
1e1p Selection
π^0 Selection
1μ1p Selection
Statistical Results
N. Kamp
Perimeter Institute Seminar; 24 May 2022
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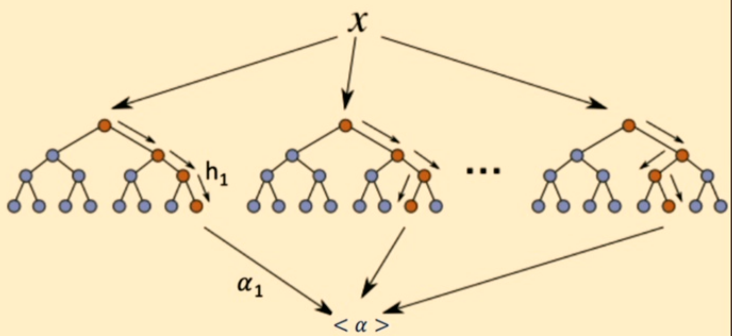
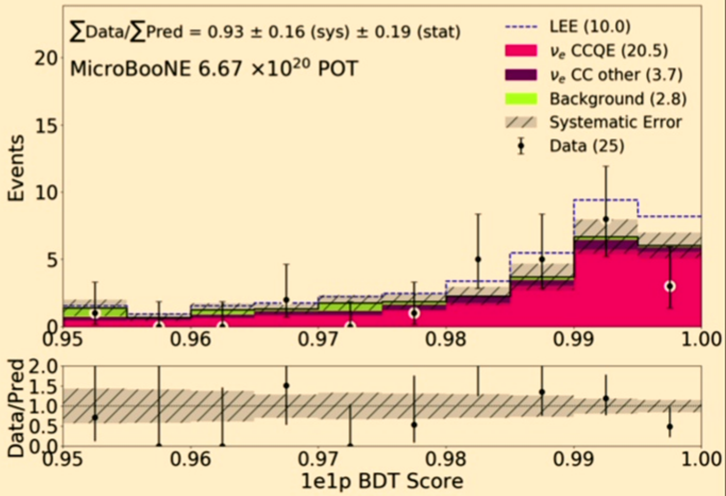
1e1p Sample

Selection Criteria

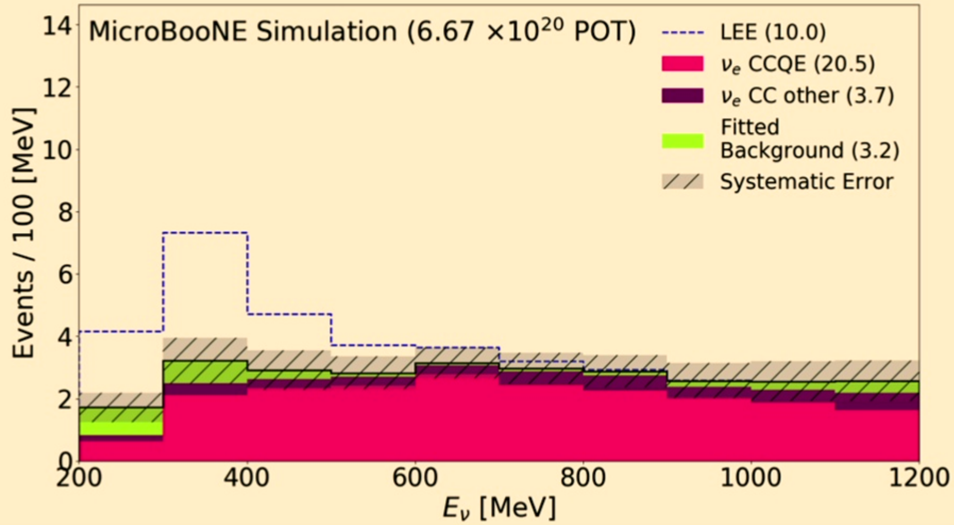
1. Broad data quality requirements
   - e.g. forward-going proton
2. Ensemble of boosted decision trees
   - 19 kinematic variables (e.g. electron/proton energies and angles)
   - 4 topological variables (e.g. fraction of SparseSSNet-labeled shower pixels)
   - Accept/reject based on the average score
3. Particle content requirements
   - e.g., low MPID muon/photon scores





1e1p Sample

- Final sample is dominated by ν_e CCQE events, with 76% purity and 6.6% efficiency
- This is by design—we optimize for purity at the expense of efficiency in this exclusive analysis

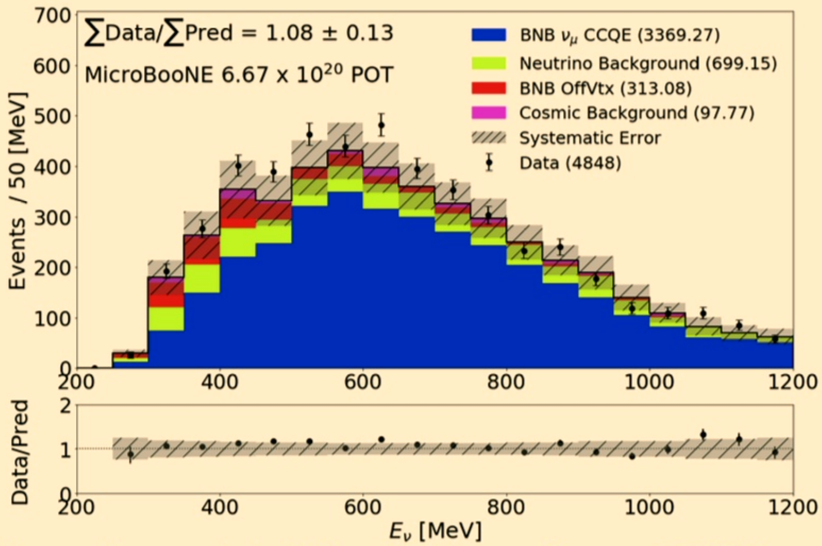


1μ1p Sample

- We isolate a sample of ν_μ 1μ1p events in the final state to constrain the ν_e 1e1p prediction and uncertainties

Selection Criteria

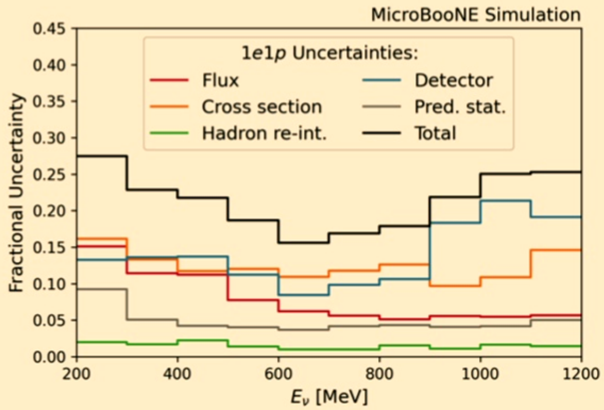
1. Broad data quality requirements
2. Ensemble of boosted decision trees
3. Require high MPID proton score to reject cosmics

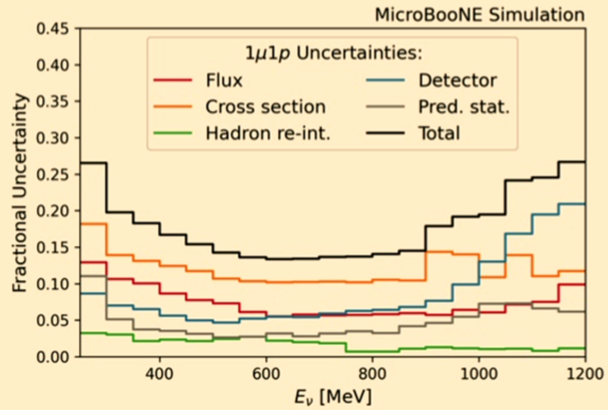


- Final selection has 77.3% purity and 4.3% efficiency for ν_μ CCQE events
- Small excess at lower energies (within systematic error)

Uncertainties on the Prediction

- This analysis considers uncertainties on the prediction due to the following five sources:
  1. Neutrino beam flux model (BNB, shared with MiniBooNE)
  2. Neutrino–nucleus interaction model (GENIE)
  3. Hadron re-interaction model for protons, π^+, and π^- (GEANT4)
  4. Detector response model
  5. Finite statistics in event samples used to form the prediction

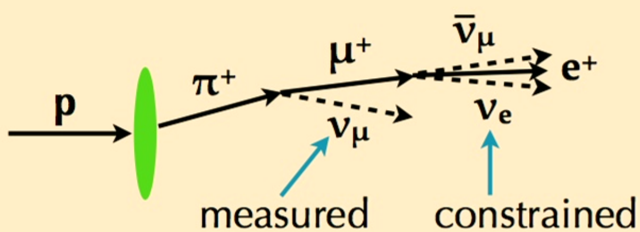


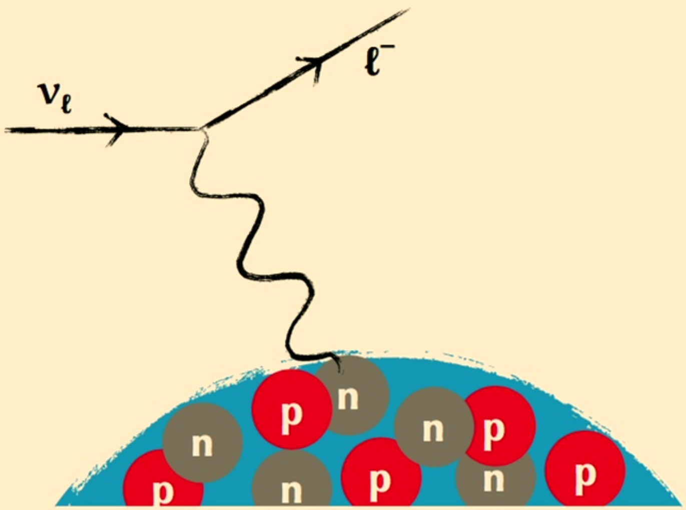


Constraining 1e1p Prediction

Our ν_e and ν_μ events have much in common, so measurement of ν_μ can constrain expectations for intrinsic ν_e events

- Flux: both species of neutrinos come from the same beam, from decays of the same population of hadrons
- Cross-section: both interacting with argon nuclei via the weak interaction





Constraining 1e1p Prediction

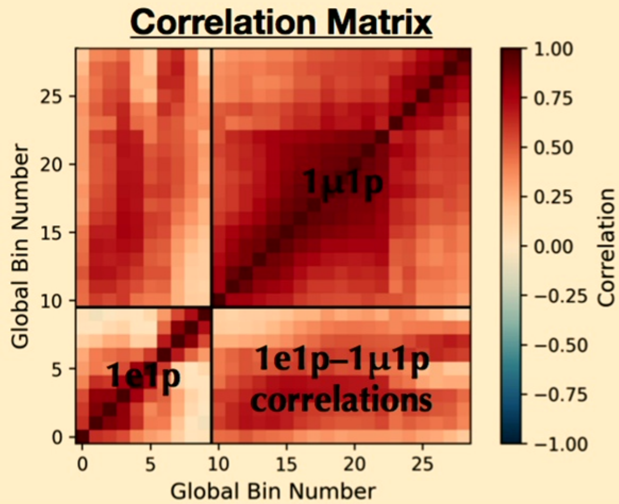
- Constraint procedure leverages the fact that the joint 1e1p+1μ1p covariance matrix describes a multivariate Gaussian distribution and conditions the 1e1p prediction on the 1μ1p observation
- Constrained 1e1p prediction depends on the joint covariance matrix and the 1μ1p observation compared to its prediction

$$\Sigma = \begin{pmatrix} \Sigma^{ee} \Sigma^{e\mu} \\ \Sigma^{\mu e} \Sigma^{\mu\mu} \end{pmatrix}$$

$$\mu^{e,\text{ constr.}} = \mu^e + \Sigma^{e\mu} \left(\Sigma^{\mu\mu}\right)^{-1} \left(x^\mu - \mu^\mu\right)$$

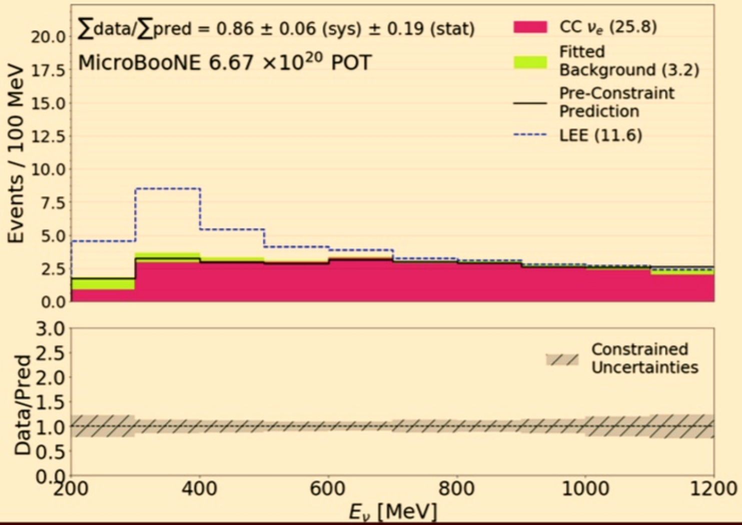
$$\Sigma^{ee,\text{ constr.}} = \Sigma^{ee} - \Sigma^{e\mu} \left(\Sigma^{\mu\mu}\right)^{-1} \Sigma^{\mu e}$$

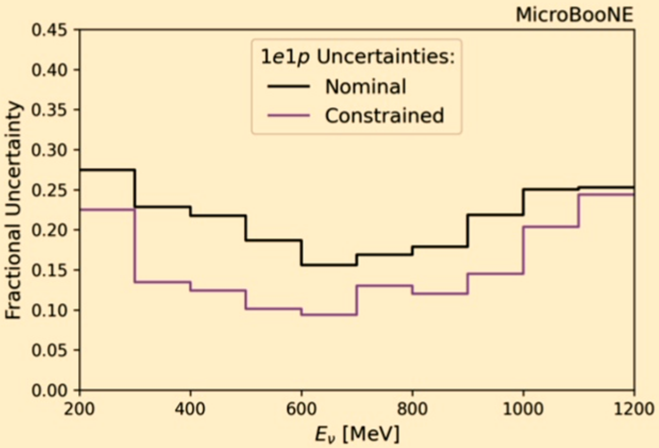
where x^μ is the 1μ1p observation, and μ^μ (μ^e) is the 1μ1p (1e1p) prediction



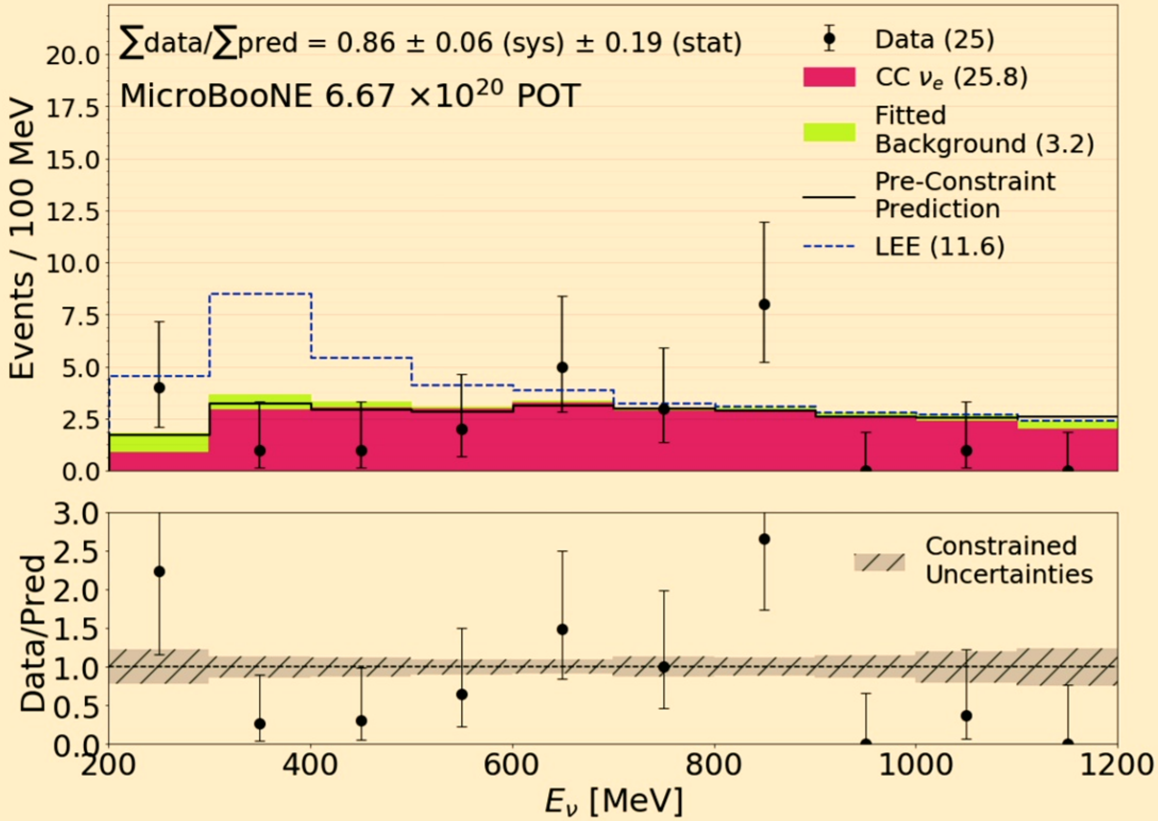
Constraining 1e1p Prediction

- Result is a ~6% increase in the number of expected 1e1p events, and a substantial reduction in the systematic uncertainties
  - Analysis sensitivity is limited by data statistics, $\mathcal{O}(50\%)$ per bin
- The constrained 1e1p prediction and uncertainties are inputs to all statistical tests for quantifying and interpreting results





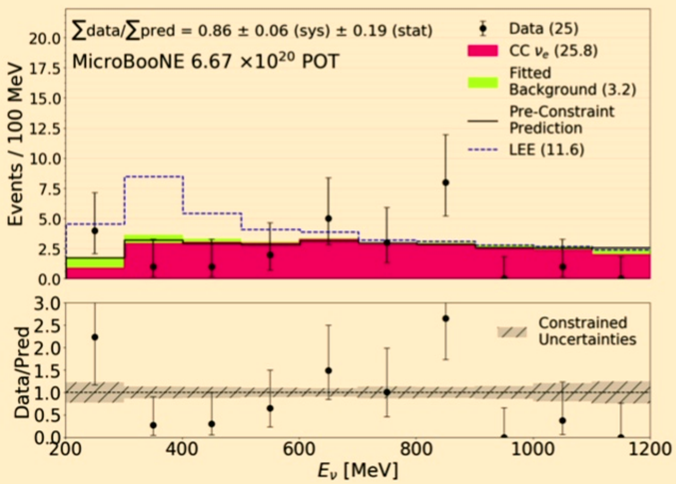
Result



$\sum$data/$\sum$pred = 0.86 ± 0.06 (sys) ± 0.19 (stat)
MicroBooNE 6.67 $\times 10^{20}$ POT
Data (25)
CC ν_e (25.8)
Fitted Background (3.2)
Pre-Constraint Prediction
LEE (11.6)
Events / 100 MeV
Constrained Uncertainties
Data/Pred
E_ν [MeV]

Goodness-of-Fit Tests

- Compare observation to predictions using a goodness-of-fit test with the combined Neyman–Pearson χ^2 test statistic [1]
  - H_0 prediction is intrinsic CC ν_e and misidentified backgrounds
  - H_1 prediction adds in the LEE signal model prediction
- Observe tension with both H_0 and H_1 predictions, but more with H_1



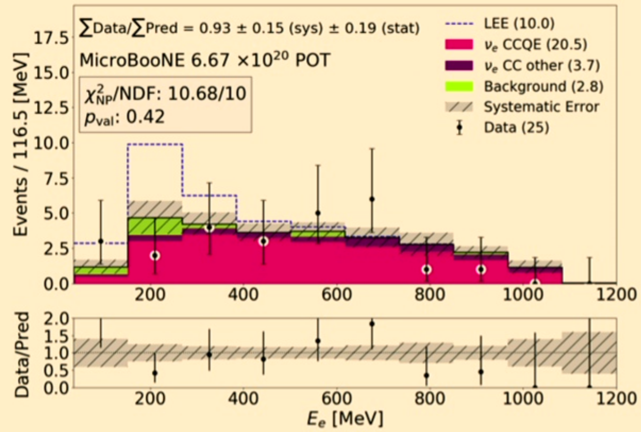
Constrained Predictions				
Range	H_0		H_1	
	$\chi^2_{\text{CNP}}/\text{dof}$	p-value	$\chi^2_{\text{CNP}}/\text{dof}$	p-value
200–500 MeV	7.91/3	0.075	17.3/3	0.002
200–1200 MeV	25.28/10	0.014	36.35/10	5.0×10^{-4}

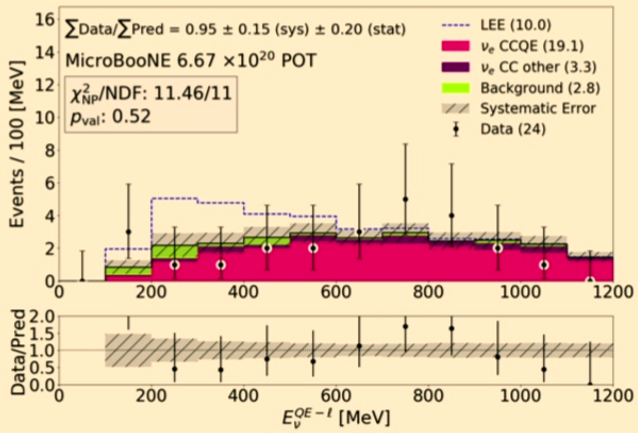
2.5σ tension **3.6σ tension**

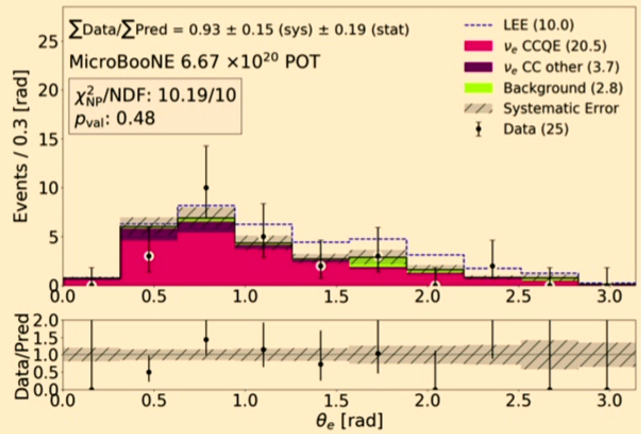
[1] Ji, Xiangpan *et al*. 1903.07185

Goodness-of-Fit in Other Variables

- Observe less tension with H_0 in most other variables than in E_ν
- Similar features in reconstructed electron-based QE energy as E_ν
- Other variables don't apply the 1μ1p constraint

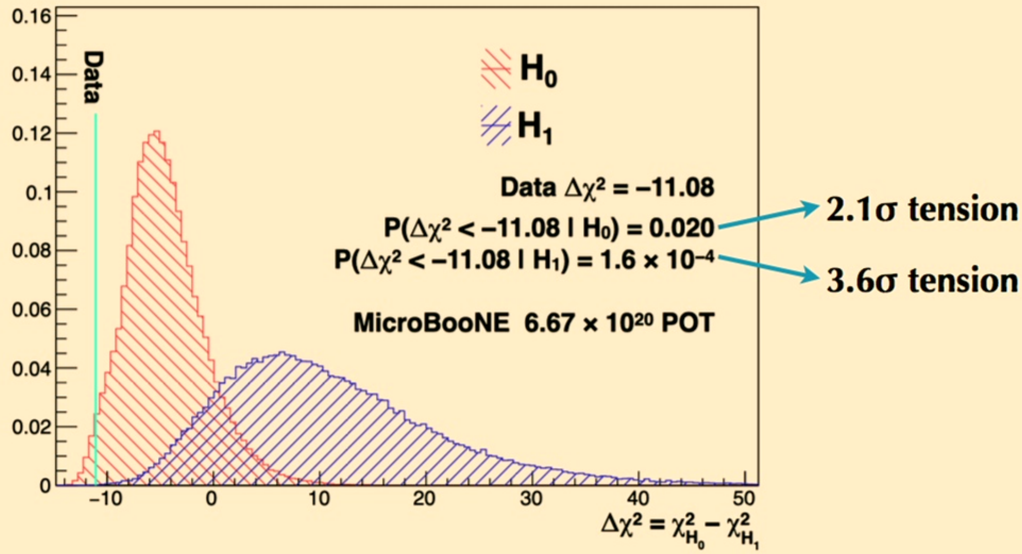






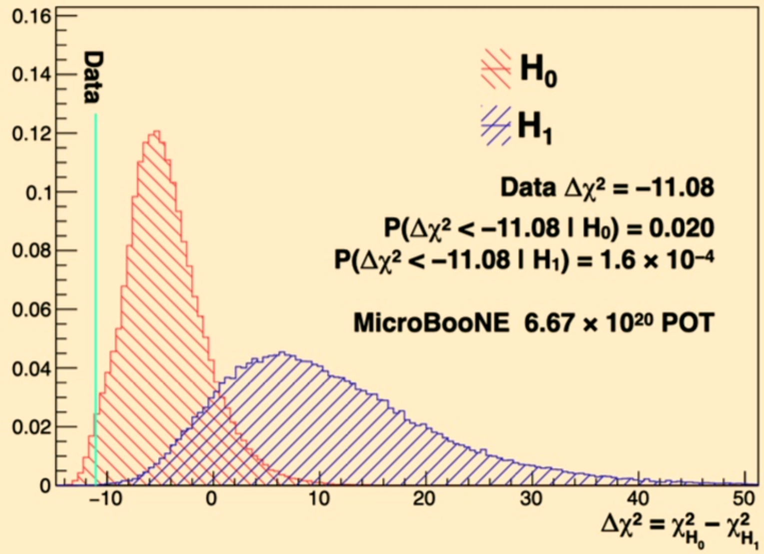
Simple Hypothesis Tests

- Perform simple hypothesis tests using a $\Delta\chi^2$ test statistic
- Value of the $\Delta\chi^2$ for data observation is -11.08, which is on the low side of both the H_0 and H_1 distributions
- Probability of a lower value is 0.020 for H_0 and 1.6×10^{-4} for H_1



Simple Hypothesis Tests

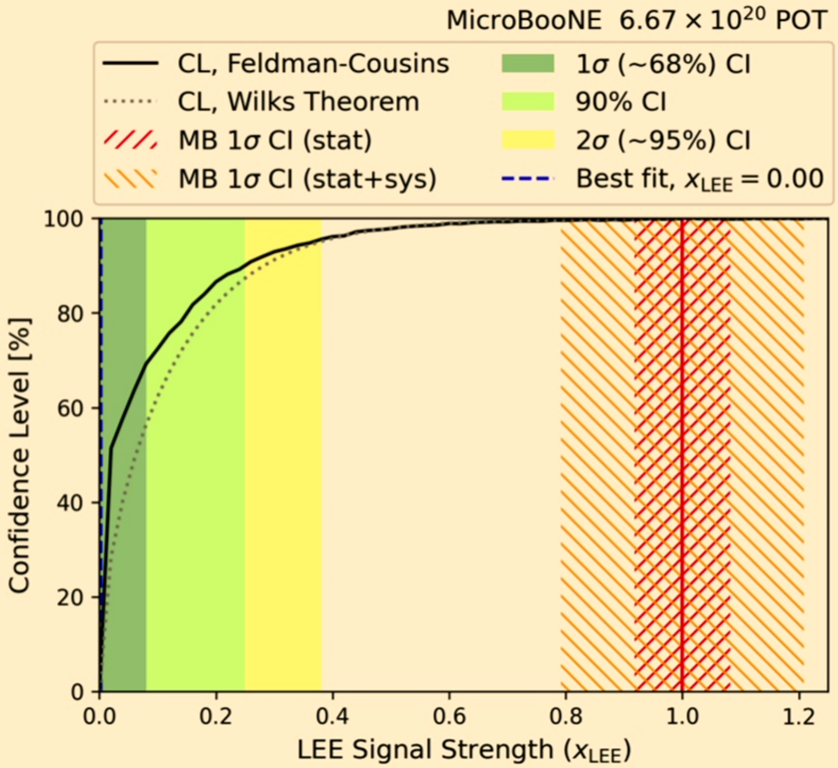
- Given that the observation is an apparent under-fluctuation of H_0, also apply the CL_s method [1] to the simple hypothesis test results
- CL_s value is $p_{H_1}/p_{H_0} = (1.6\times10^{-4})/(0.020) = 0.080$, which leads us to reject of H_1 in favor of H_0 with a significance of 2.4σ

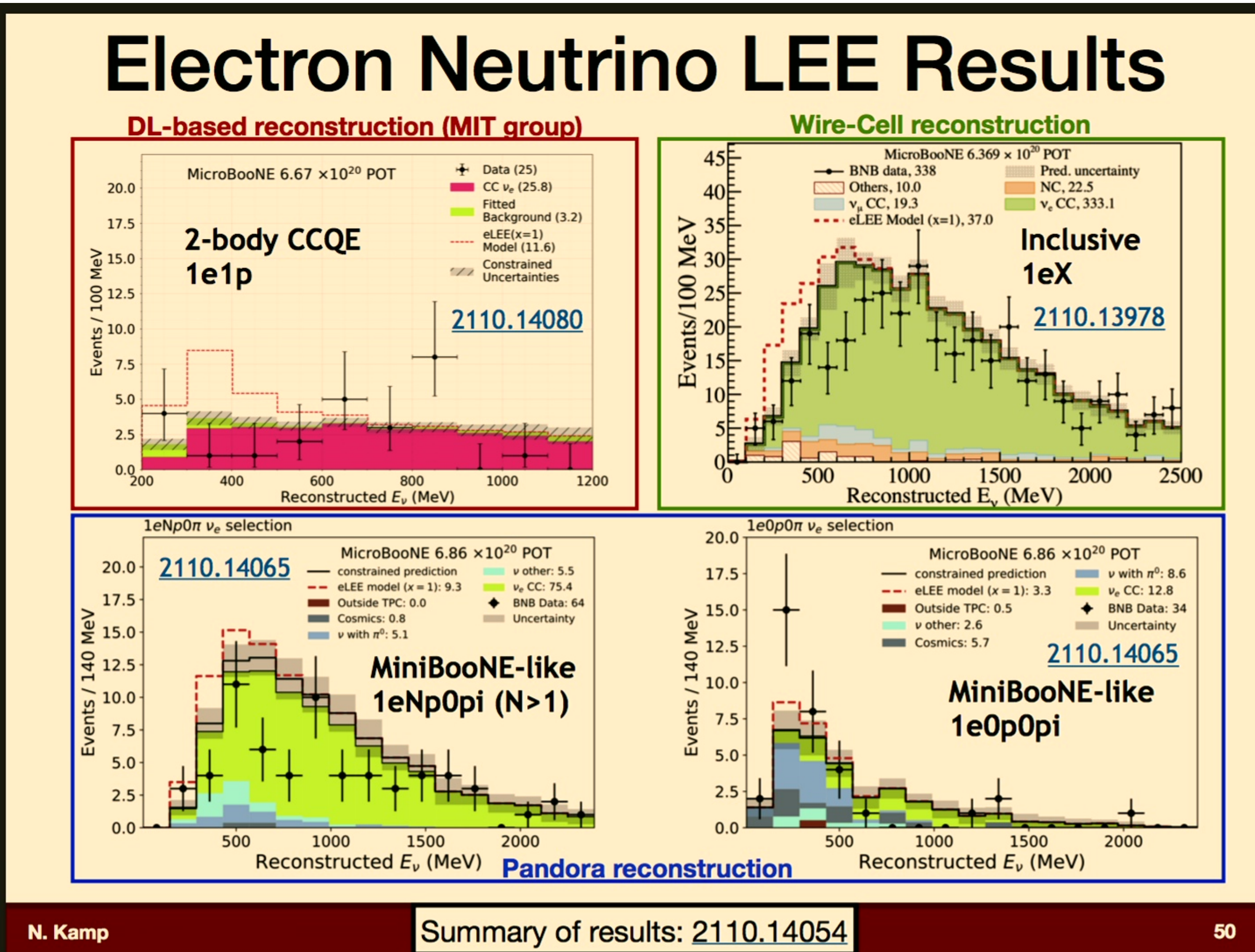


[1] A.L. Read. (2000)

eLEE Signal Strength Fit

- For the final statistical test, allow LEE signal strength x_{eLEE} to float
- Obtain confidence intervals using the Feldman–Cousins procedure
  PRD 57, 3873 (1998)
- Observation rules out $x_{eLEE} = 0.38$ at 2σ C.L.
  - Compared to expected upper limit for H_0 at 2σ C.L. of $x_{eLEE} = 0.98$

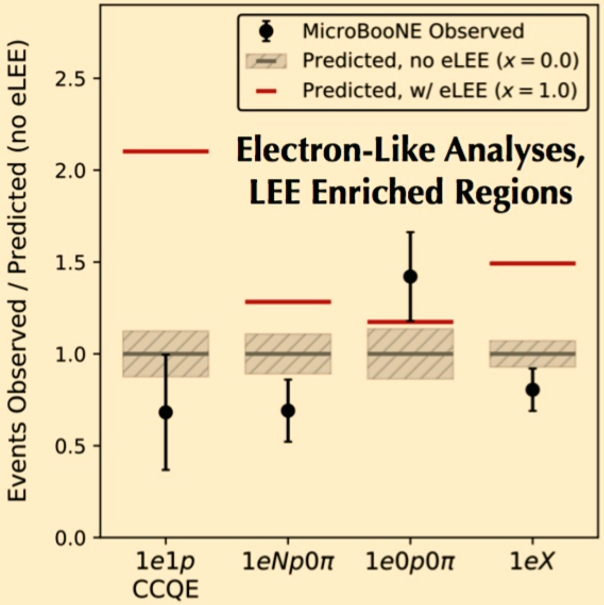


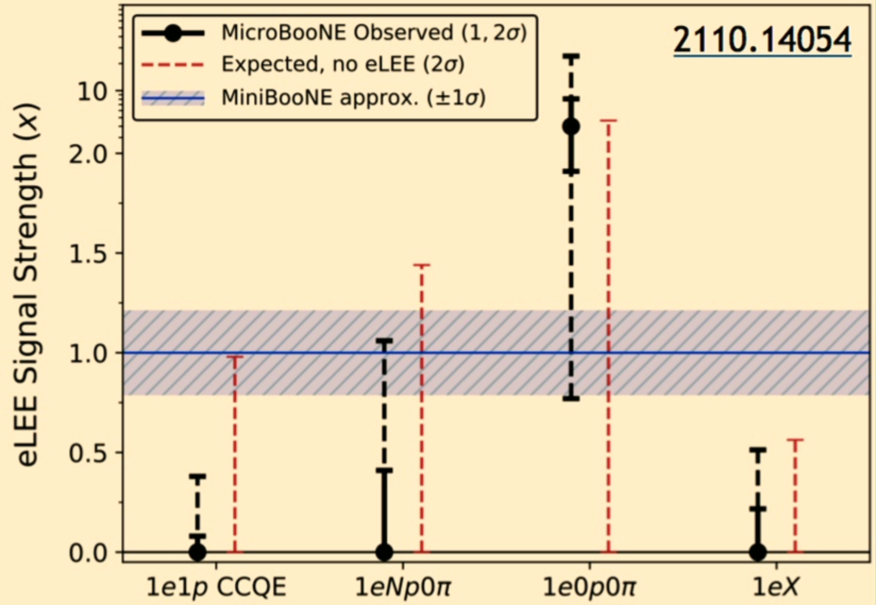


Electron Neutrino LEE Results
DL-based reconstruction (MIT group)
MicroBooNE 6.67 ×10^20 POT
Data (25)
CC νe (25.8)
Fitted Background (3.2)
eLEE(x=1) Model (11.6)
Constrained Uncertainties
2-body CCQE
1e1p
2110.14080
Events / 100 MeV
Reconstructed Eν (MeV)
Wire-Cell reconstruction
MicroBooNE 6.369 × 10^20 POT
BNB data, 338
Others, 10.0
νμ CC, 19.3
eLEE Model (x=1), 37.0
Pred. uncertainty
NC, 22.5
νe CC, 333.1
Inclusive
1eX
2110.13978
Events/100 MeV
Reconstructed Eν (MeV)
1eNp0π νe selection
2110.14065
MicroBooNE 6.86 ×10^20 POT
constrained prediction
eLEE model (x = 1): 9.3
Outside TPC: 0.0
Cosmics: 0.8
ν with π0: 5.1
ν other: 5.5
νe CC: 75.4
BNB Data: 64
Uncertainty
MiniBooNE-like
1eNp0pi (N>1)
Events / 140 MeV
Reconstructed Eν (MeV)
1e0p0π νe selection
MicroBooNE 6.86 ×10^20 POT
constrained prediction
eLEE model (x = 1): 3.3
Outside TPC: 0.5
ν other: 2.6
Cosmics: 5.7
ν with π0: 8.6
νe CC: 12.8
BNB Data: 34
Uncertainty
2110.14065
MiniBooNE-like
1e0p0pi
Events / 140 MeV
Reconstructed Eν (MeV)
Pandora reconstruction
N. Kamp
Summary of results: 2110.14054
50

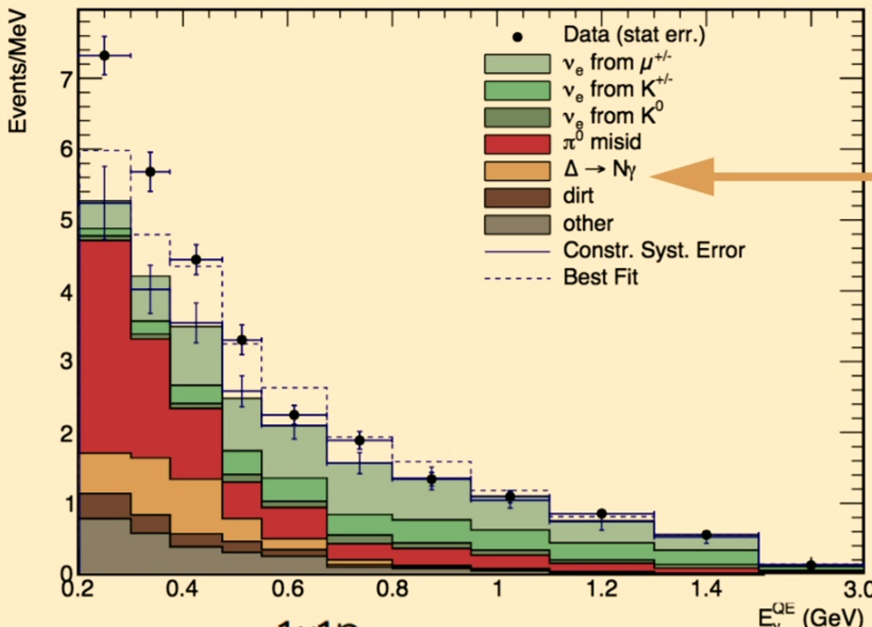
Electron LEE Model Tests

- Most analyses observe a deficit of electron neutrino events at the lowest energies, inconsistent with a MiniBooNE-like excess
- Scale the LEE model by a signal strength parameter -> limit on the electron neutrino contribution to the MiniBooNE excess





What about the Photons?

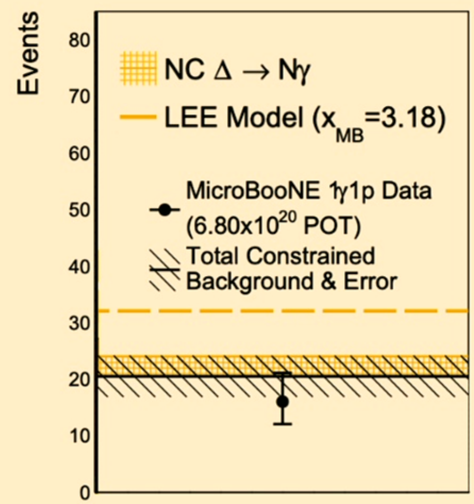


$1\gamma 1p$

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

16
Data Events Observed

MicroBooNE has also looked for an excess of $\Delta \to N\gamma$ events as an explanation for the MiniBooNE anomaly

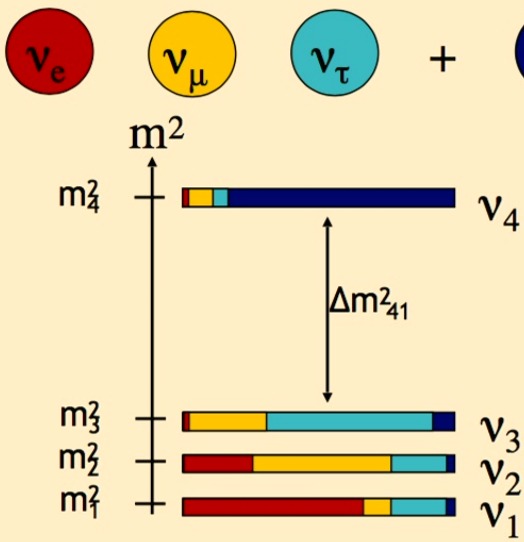


1γ1p

See 2110.00409 for more details!

The Sterile Neutrino Hypothesis

- MicroBooNE's initial results did not make any explicit claims about the original proposed explanation of MiniBooNE: the eV-scale sterile neutrino



$$\begin{bmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\\ \nu_s\end{bmatrix} = \begin{bmatrix}U_{e1} & U_{\mu 1} & U_{\tau 1} & U_{s1}\\ U_{e2} & U_{\mu 2} & U_{\tau 2} & U_{s2}\\ U_{e3} & U_{\mu 3} & U_{\tau 3} & U_{s3}\\ U_{e4} & U_{\mu 4} & U_{\tau 4} & U_{s4}\end{bmatrix} \begin{bmatrix}\nu_1\\ \nu_2\\ \nu_3\\ \nu_4\end{bmatrix}$$

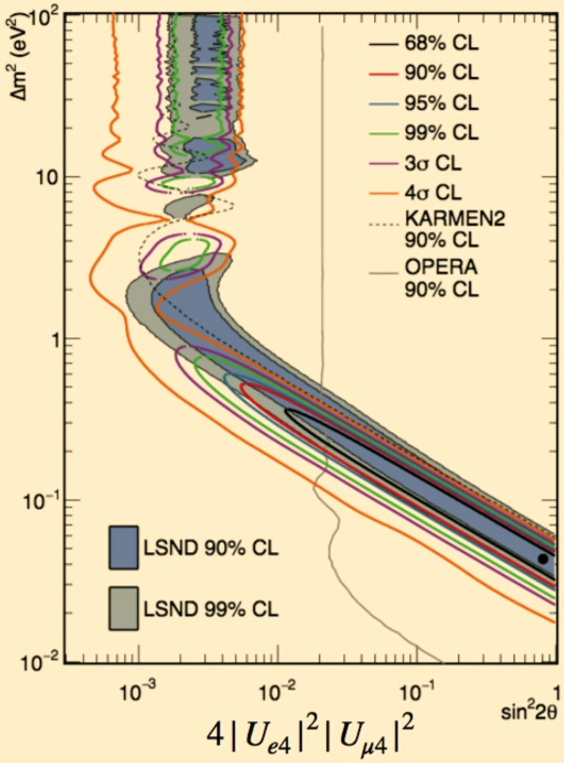
$$P(\nu_\mu \rightarrow \nu_e) = 4\,|U_{e4}|^2\,|U_{\mu 4}|^2 \sin^2\left(1.27\Delta m^2 \frac{L}{E}\right)$$

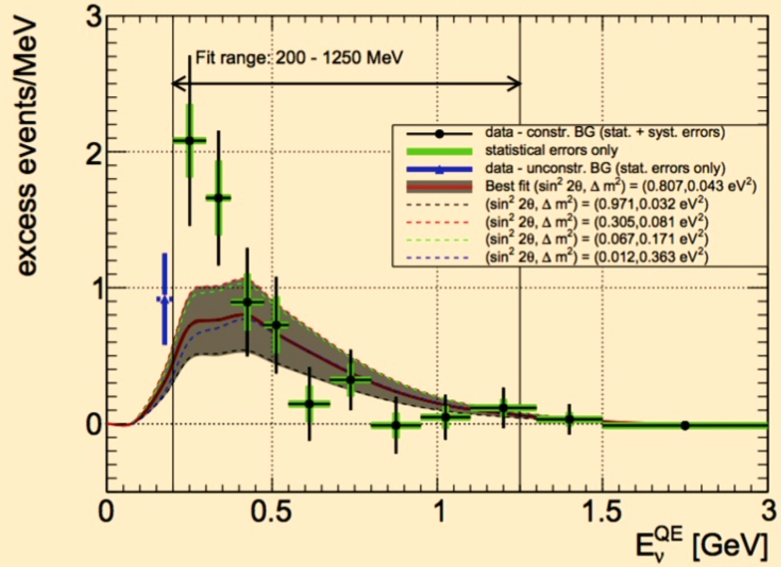
$$P(\nu_\mu \rightarrow \nu_\mu) = 1 - 4\,|U_{\mu 4}|^2 (1 - |U_{\mu 4}|^2)(\sin^2\left(1.27\Delta m^2 \frac{L}{E}\right)$$

$$P(\nu_e \rightarrow \nu_e) = 1 - 4\,|U_{e4}|^2 (1 - |U_{e4}|^2)(\sin^2\left(1.27\Delta m^2 \frac{L}{E}\right)$$

The Sterile Neutrino Hypothesis

- Final $\nu_\mu \to \nu_e$ fit using the full MiniBooNE dataset

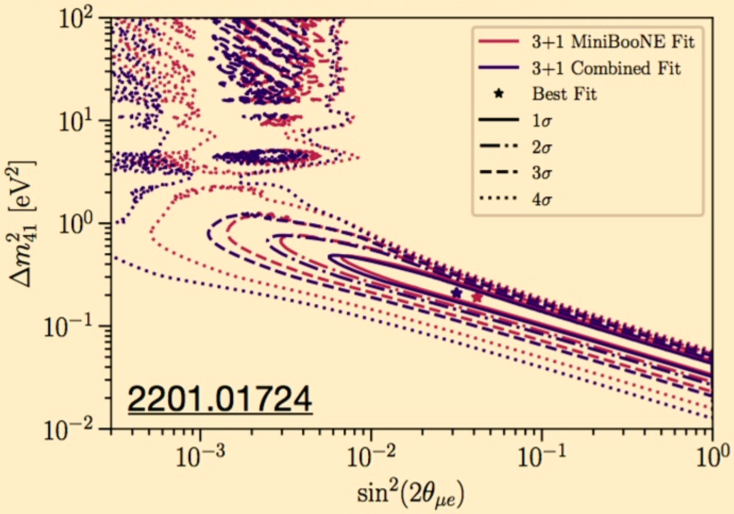


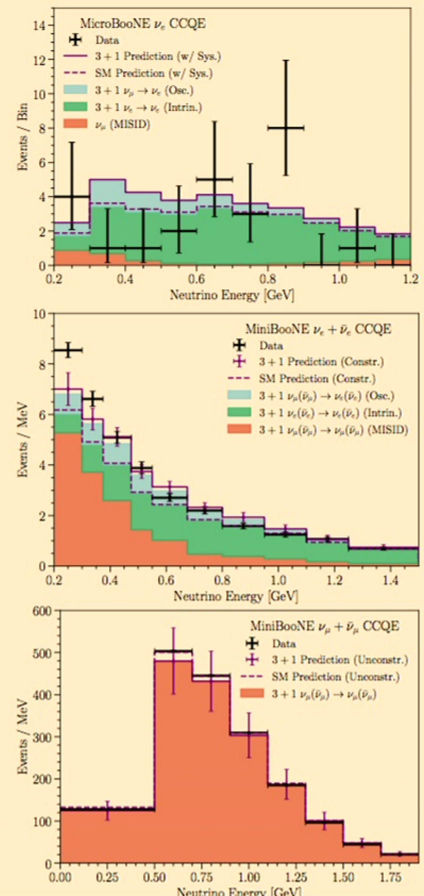


PRD 103, 052002 (2020)

3+1 after MicroBooNE

- The MiniBooNE collaboration has recently preformed a combined fit to the full 3+1 model incorporating data from the MicroBooNE CCQE analysis

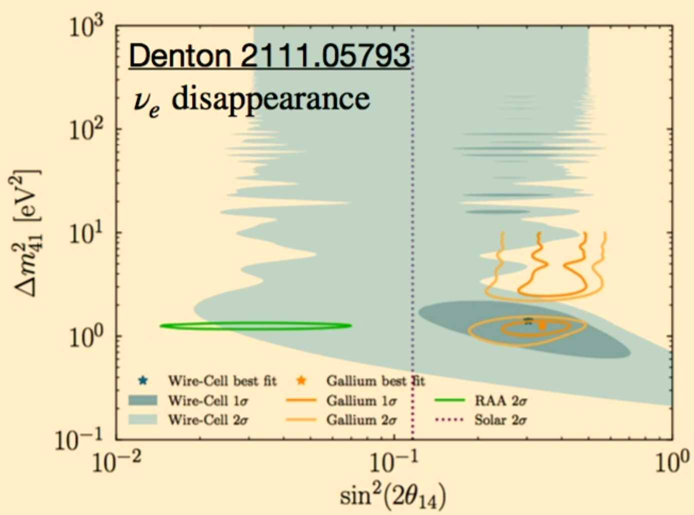


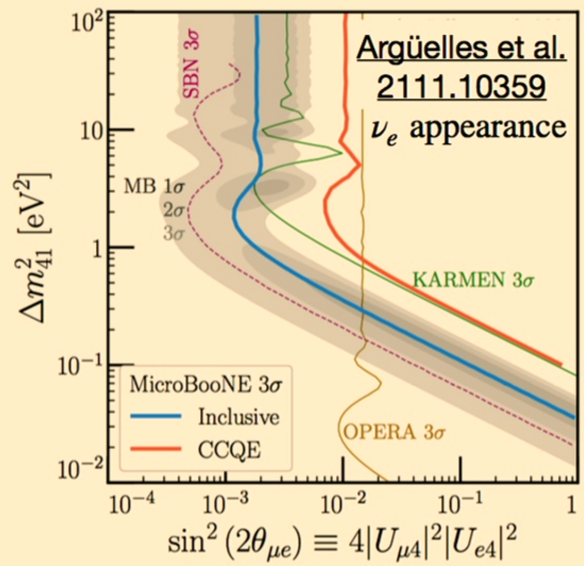


Stability of preferred regions after including MicroBooNE CCQE result suggests much of sterile neutrino parameter space not ruled out!

3+1 after MicroBooNE

- Others in the neutrino community have also recast MicroBooNE's first results from the electron-like excess search into bounds on a single sterile neutrino model
- MicroBooNE is working on an internal sterile neutrino analysis—stay tuned!





3+1 Model Tension

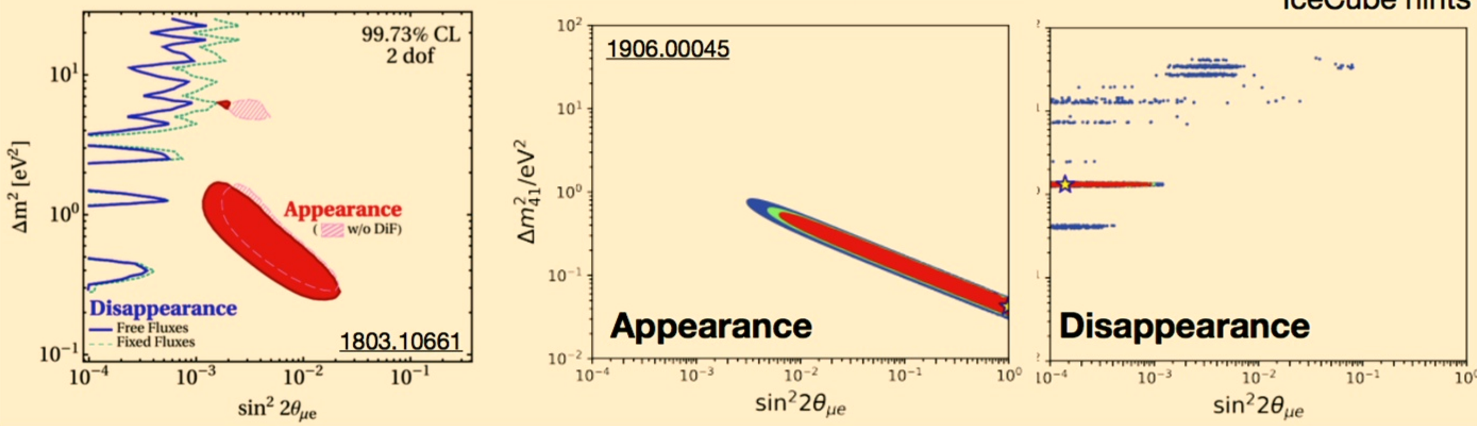
$$P(\nu_\mu \to \nu_e) = 4|U_{e4}|^2|U_{\mu4}|^2\sin^2\left(1.27\Delta m^2\frac{L}{E}\right)$$ **SBL Accelerator**

$$P(\nu_\mu \to \nu_\mu) = 1 - 4|U_{\mu4}|^2(1-|U_{\mu4}|^2)(\sin^2\left(1.27\Delta m^2\frac{L}{E}\right)$$ **LBL Accelerator/Atmospheric**

$$P(\nu_e \to \nu_e) = 1 - 4|U_{e4}|^2(1-|U_{e4}|^2)(\sin^2\left(1.27\Delta m^2\frac{L}{E}\right)$$ **SBL Reactor/Gallium**

Lack of muon neutrino disappearance* in tension with electron neutrino appearance/disappearance anomalies

*up to some IceCube hints



N. Kamp   Perimeter Institute Seminar; 24 May 2022   59

Theoretical 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							✔	✔	✔

*Requires heavy sterile/other new particles also

MicroBooNE Summary

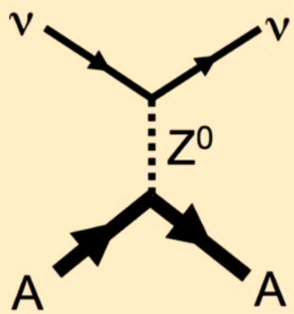
- The analysis presented today addresses the MiniBooNE anomaly by searching for ν_e CCQE 1e1p interactions using deep learning
- This analysis finds:
  - Using simple hypothesis test with $\Delta\chi^2$ test statistic and CL_s method, reject H_1 in favor of H_0 with 2.4σ significance
  - Using Feldman–Cousins, rule out signal strength $x_{eLEE} = 0.38$ at 2σ C.L.
- Overall, recently-released MicroBooNE results disfavor both ν_e CC and NC $\Delta \to N\gamma$ as the primary source of the MiniBooNE excess

This is the first phase of MicroBooNE and SBN results that will test an array of BSM explanations for the MiniBooNE anomaly

Outline

1. The MiniBooNE anomaly
2. The MicroBooNE experiment
3. MicroBooNE's first results
4. **Bonus: Coherent CAPTAIN-Mills @ Los Alamos**

Figures borrowed from Richard Van de Water's seminar @ Rutgers University



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CAPTAIN = "Cryogenic Apparatus for Precision Tests of Argon Interactions with Neutrinos"

Physics Goal: Leptophobic DM

Consider a local U(1)B gauge symmetry with gauge boson VB (e.g. 1405.7049)

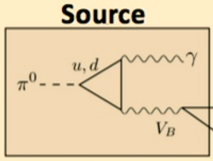
$$\mathscr{L}_B^{\text{int}} \supset V_B^\mu (g_B J_\mu^B + g_\chi J_\mu^\chi + \epsilon_B e J_\mu^{\text{EM}})$$

$$J_\mu^B = \frac{1}{3} \sum_i \bar{q}_i \gamma^\mu q_i$$

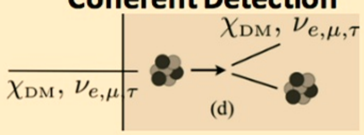
$$J_\mu^\chi = i(\chi^* \partial_\mu \chi - \chi \partial_\mu \chi^*)$$

$$J_\mu^{\text{EM}} = \sum_i Q_i \bar{f}_i \gamma^\mu f_i$$

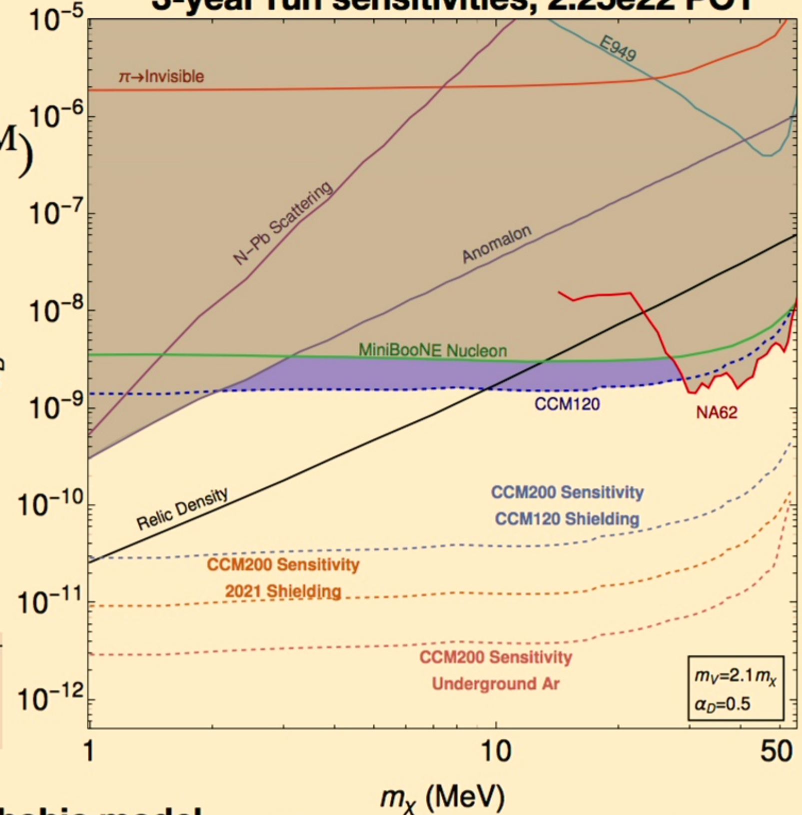
Source



Coherent Detection



3-year run sensitivities; 2.25e22 POT



Larger coherent cross section in leptophobic model => world-leading constraints from CCM120 alone

For more details see 2109.14146 (accepted by PRL)

Exotic MiniBooNE Explanations @ CCM

2110.11944

Model 1: Vector-portal DM

$$\mathcal{L}_V \supset e(\epsilon_1 V_{1,\mu} + \epsilon_2 V_{2,\mu}) J^{\mu}_{\rm EM} + (g_1 V_{1,\mu} + g_2 V_{2,\mu}) J^{\mu}_{D} + (g'_1 V_{1,\mu} + g'_2 V_{2,\mu}) J'^{\mu}_{D}, \quad (1)$$

Model 2: (pseudo)scalar DM

$$\mathcal{L}_S \supset g_\mu \phi \bar{\mu}\mu + g_n Z'_\alpha \bar{u}\gamma^\alpha u + \frac{\lambda}{4}\phi F'_{\mu\nu}F^{\mu\nu} + \text{h.c.}, \quad (2)$$

$$\mathcal{L}_P \supset i g_\mu a \bar{\mu}\gamma^5 \mu + g_n Z'_\alpha \bar{u}\gamma^\alpha u + \frac{\lambda}{4} a F'_{\mu\nu}\tilde{F}^{\mu\nu} + \text{h.c.}, \quad (3)$$

- Both models give a good fit to energy and angular distributions of the MiniBooNE excess
- **CCM200 has sensitivity to the high energy photon-like final states!**

Production

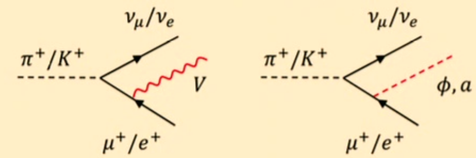


FIG. 1. Three-body charged meson decay into a scalar, pseudoscalar, or vector.

Detection

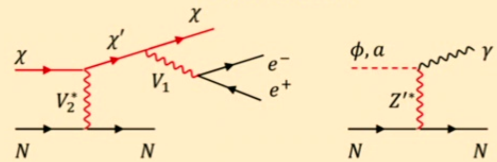
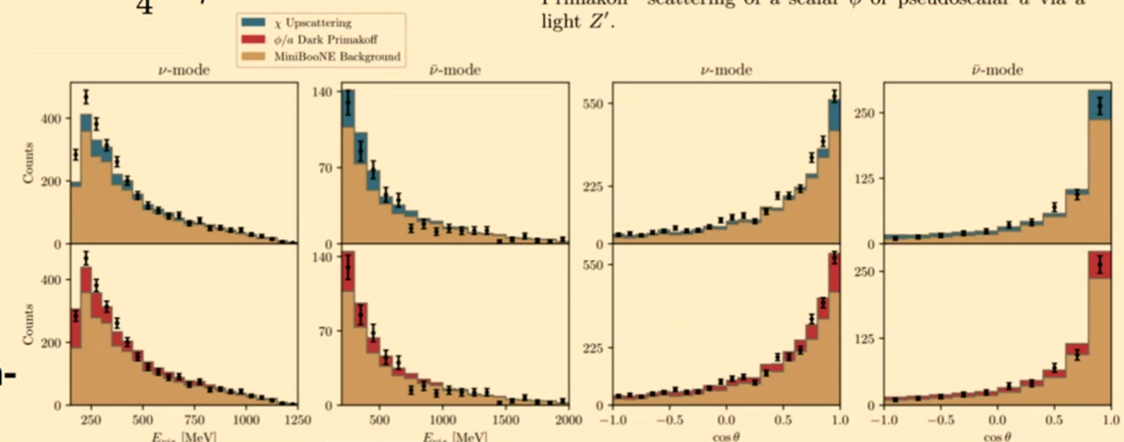


FIG. 2. (a): Dark-matter upscattering via a vector mediator. In the single-mediator scenario, $V_2 = V_1$. (b): "Dark Primakoff" scattering of a scalar ϕ or pseudoscalar a via a light Z'.



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Exotic MiniBooNE Explanations @ CCM

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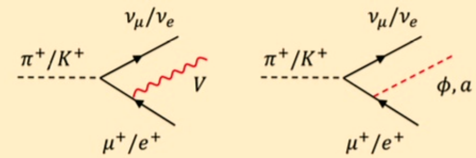

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Detection

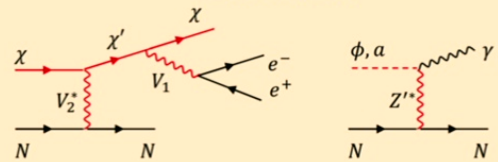
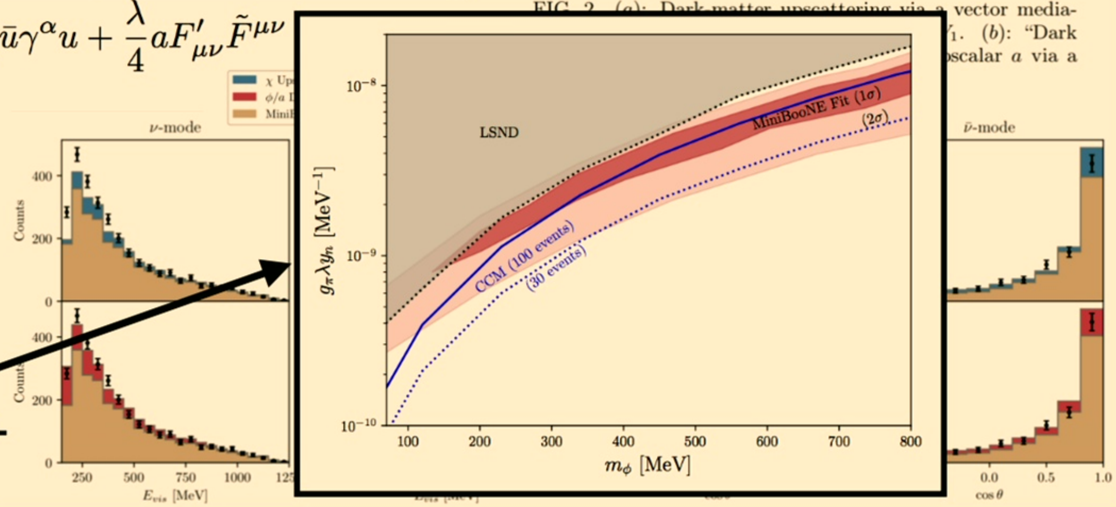


FIG. 2. (a): Dark-matter upscattering via a vector media- … V_1. (b): "Dark … scalar a via a



CCM Summary

- CCM has completed its 120-PMT prototype run
  - Constraints set on vector portal dark matter models—world leading constraints on leptophobic DM
- CCM200 currently in commissioning phase
  - Greater sensitivity to dark sector models, including ALP scenarios
  - Pushing down energy thresholds via better photo-coverage, shielding, and Ar filtration—necessary for detecting CEvNS

Stay tuned for CCM200 results!

Thank you!