Recent Results *from* MicroBooNE

LIP-Lisbon Seminar

December 16, 2021

Andy Mastbaum
Rutgers University
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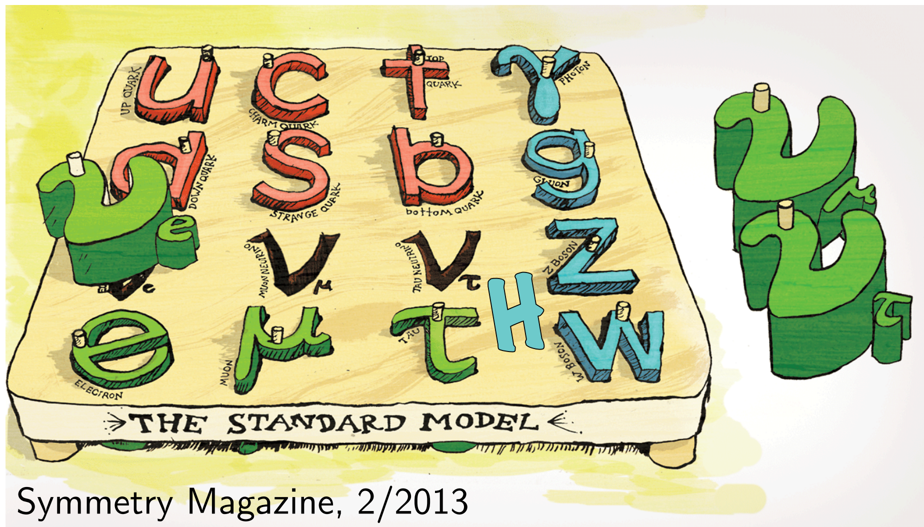
Standard Model

Three-Neutrino Oscillations



Symmetry Magazine, 2/2013

With massive neutrinos, flavor eigenstates of the weak interaction are related to mass eigenstates of the free-particle Hamiltonian:

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

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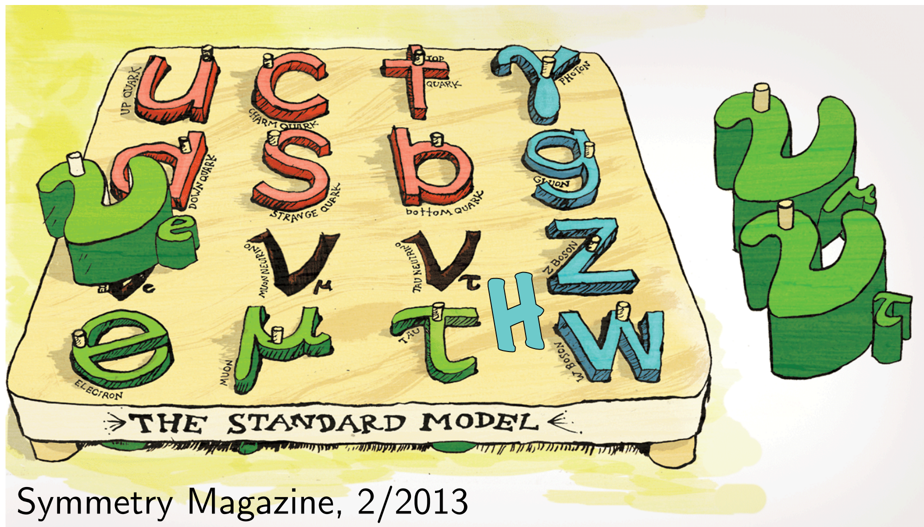

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Mixing matrix

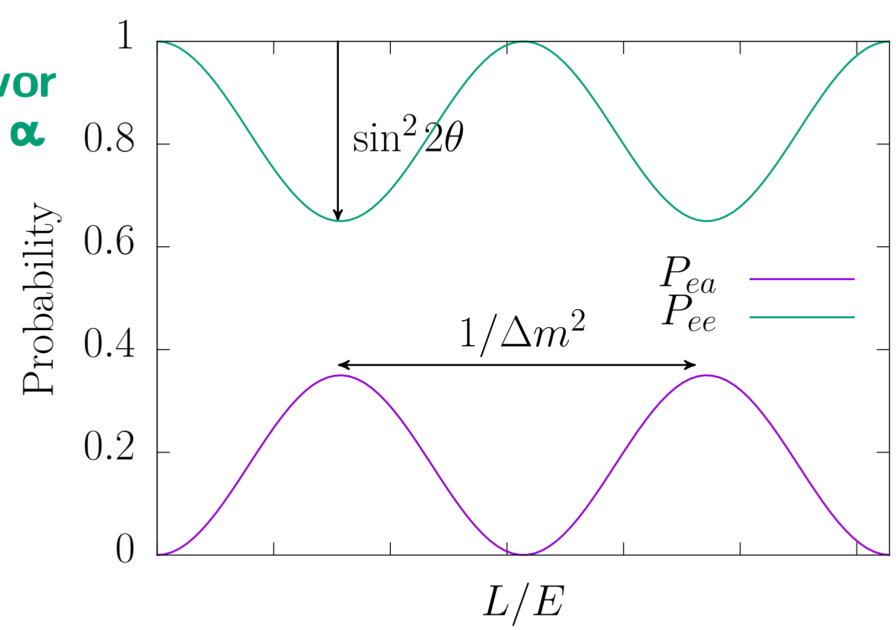
Flavor eigenstates participating in weak interactions

Mass eigenstates ν_1, ν_2, ν_3

Simplified two-neutrino model:

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

Born in flavor eigenstate α



Detected in flavor eigenstate α or β

Probability depends on

distance L, energy E (the experiment)

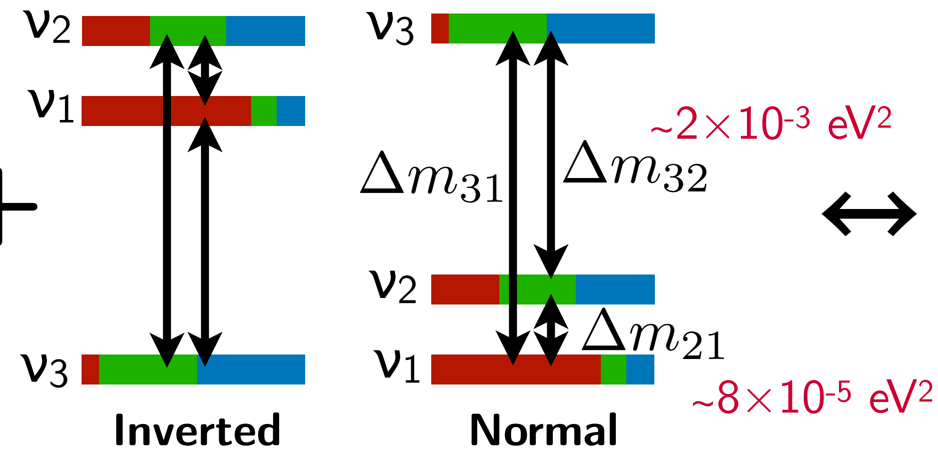
and

Δm^2, θ (nature)

Three Neutrinos with Mixing

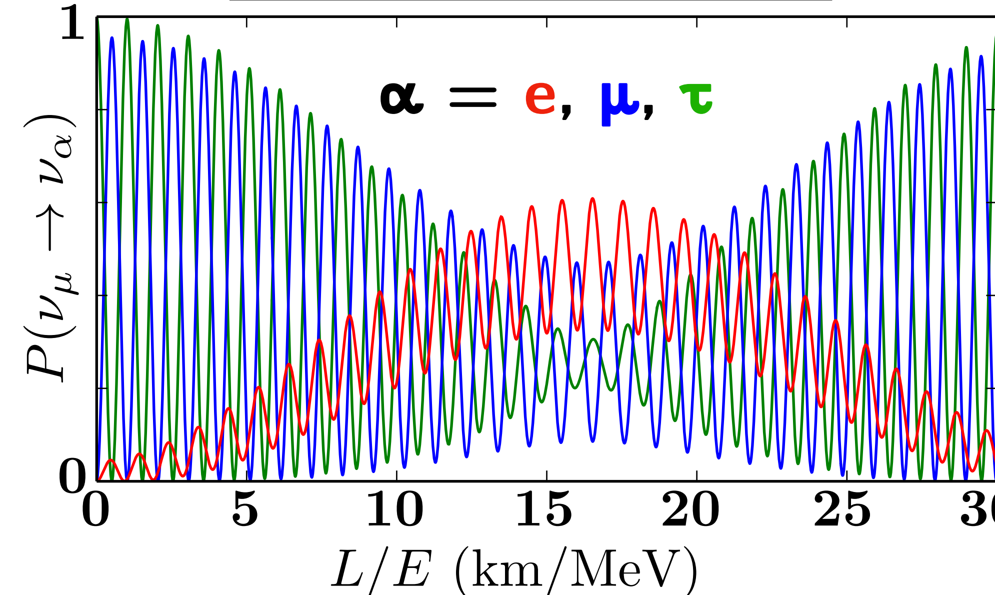
$$|\nu_\alpha\rangle = \sum_i U^*_{\alpha i} |\nu_i\rangle \; +$$

Mass Splittings (e μ τ)



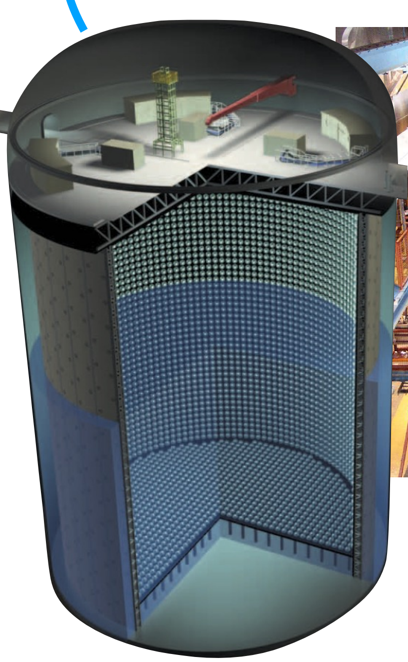
↔

Oscillation Probabilities



Atmospheric & Accelerator — **Reactor** — **Solar & KamLAND**

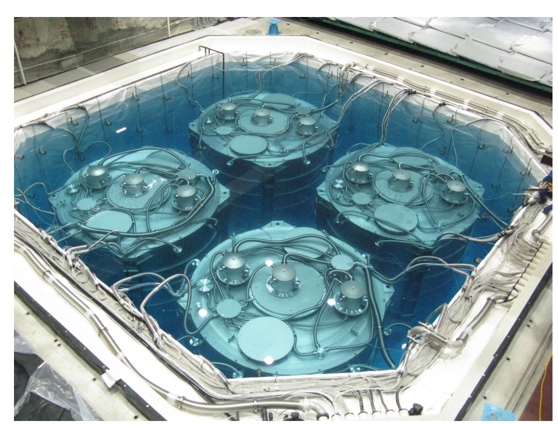
$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_{23} & \sin\theta_{23} \\ 0 & -\sin\theta_{23} & \cos\theta_{23} \end{pmatrix} \times \begin{pmatrix} \cos\theta_{13} & 0 & \sin\theta_{13} e^{i\delta} \\ 0 & 1 & 0 \\ -\sin\theta_{13} e^{-i\delta} & 0 & \cos\theta_{13} \end{pmatrix} \times \begin{pmatrix} \cos\theta_{12} & \sin\theta_{12} & 0 \\ -\sin\theta_{12} & \cos\theta_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$



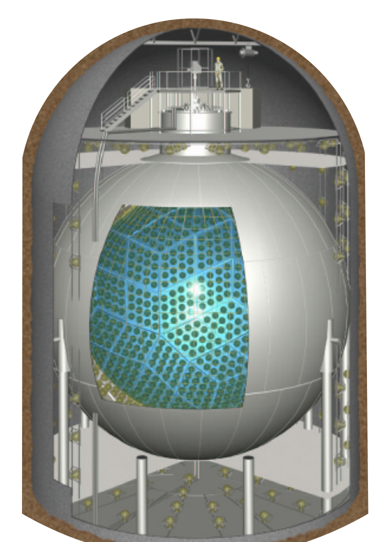
(Super-)Kamiokande

MINOS

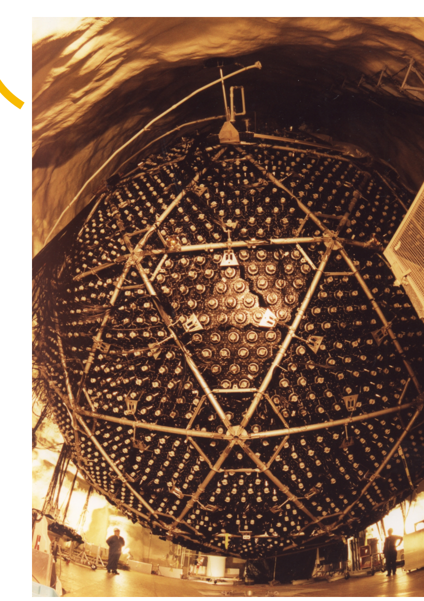
NOvA



Daya Bay



KamLAND



SNO

(and many more!)

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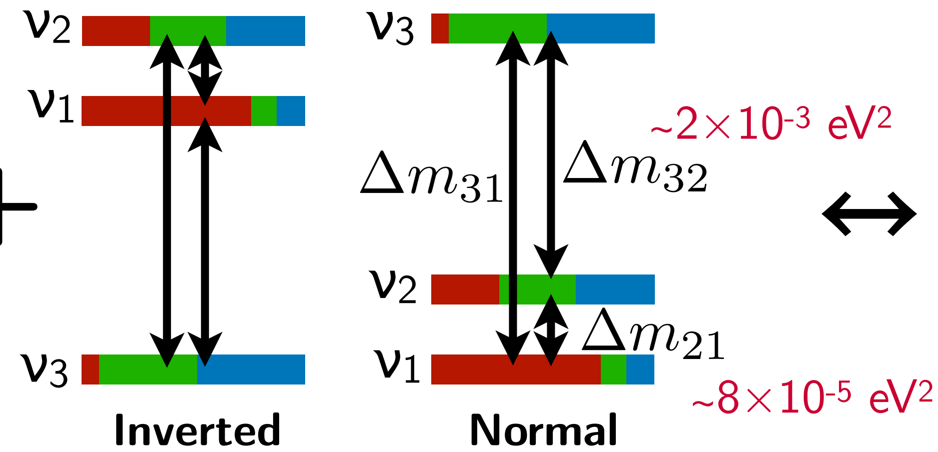
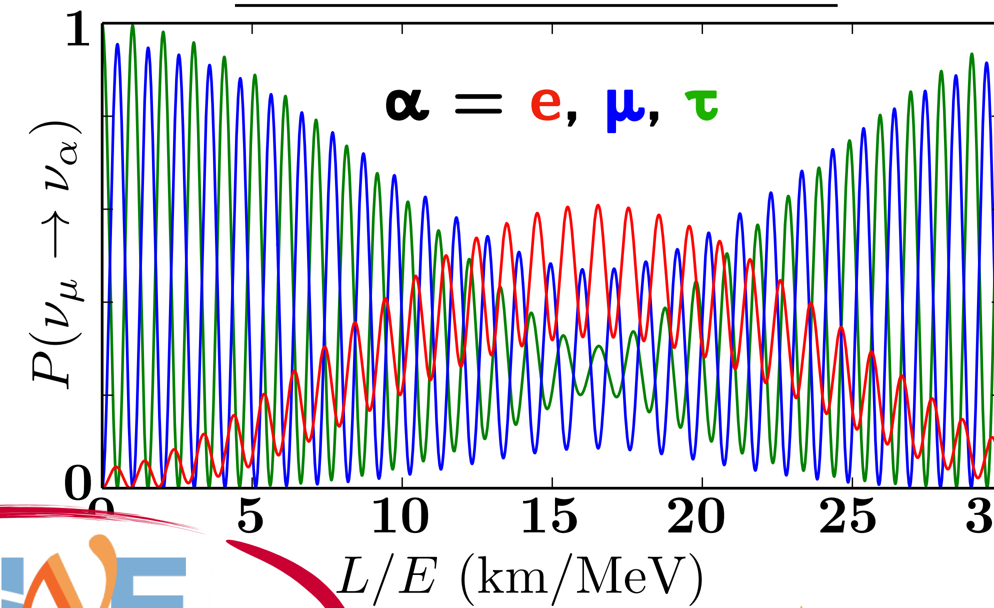


$\leftrightarrow$

Oscillation Probabilities



DUNE

Hyper-Kamiokande

Atmospheric & Accelerator

Solar & KamLAND

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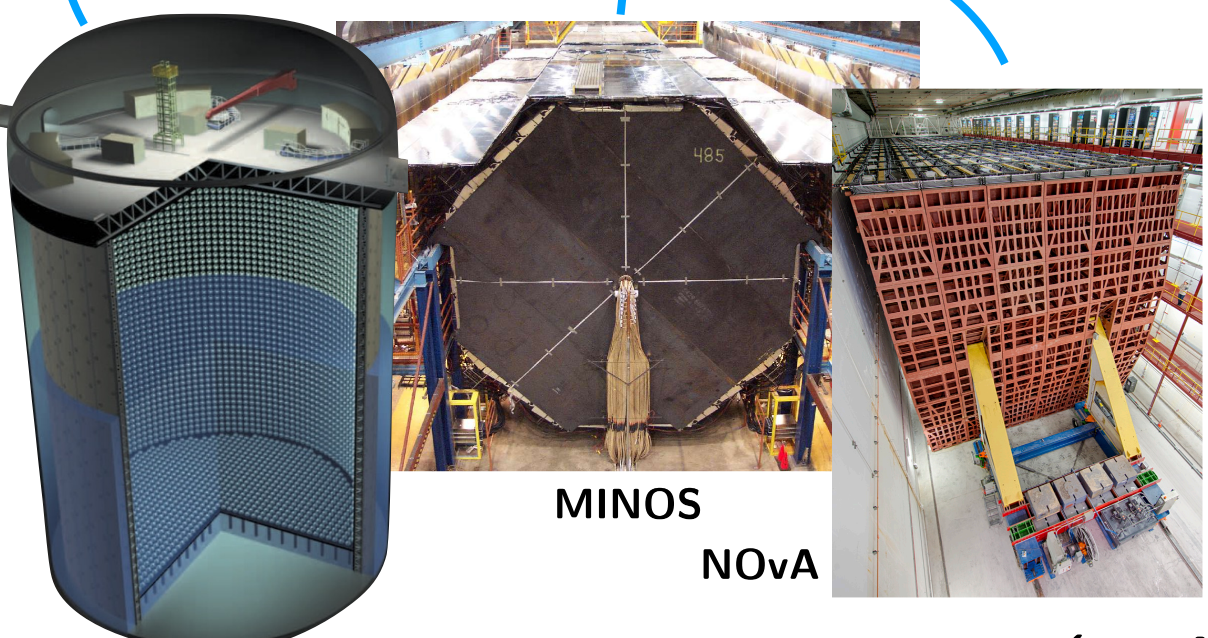

(Super-)Kamiokande

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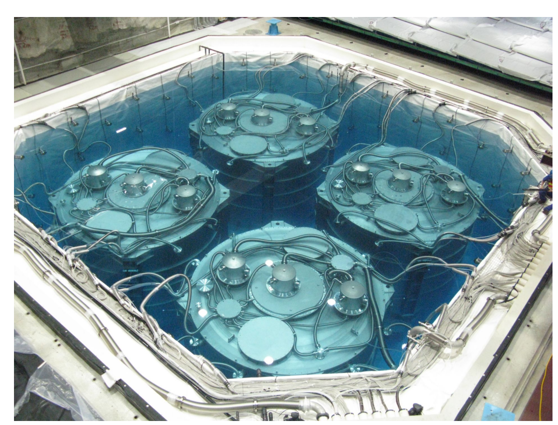

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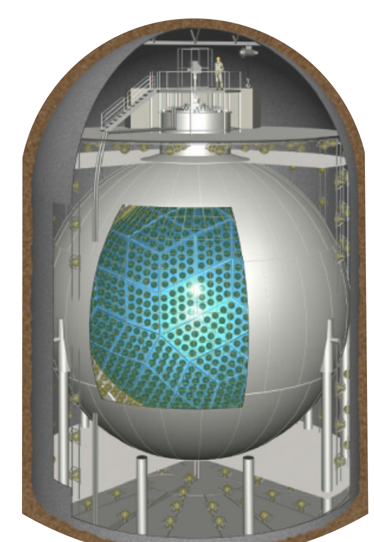
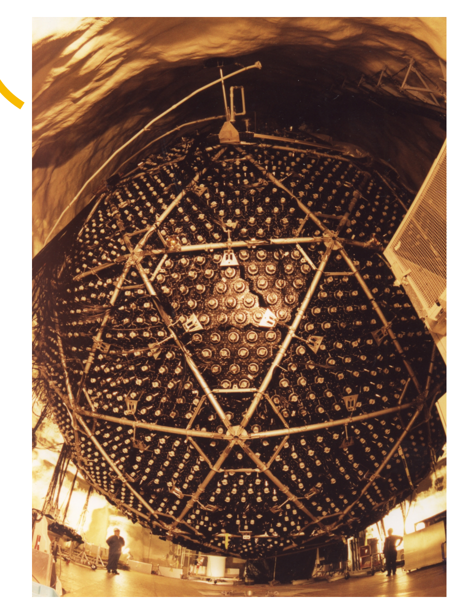


KamLAND

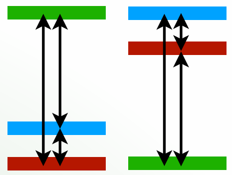


SNO

(and many more!)

δ_{CP}

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



What is the ordering of the neutrino masses?

$\nu \stackrel{?}{=} \bar{\nu}$

Is the neutrino its own antiparticle?

Standard Model Physics

Beyond the Standard Model

What is the mass of the neutrino, and why is it so small?

Are there new interactions we could discover via neutrinos?

ν_s

Are there additional neutrinos beyond the known three types?

These important questions demand unprecedented precision and novel detector technologies

Long Baseline

δ_{CP}

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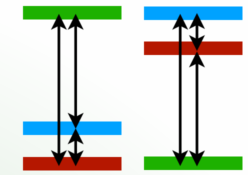
Long Baseline



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Short Baseline

ν_s

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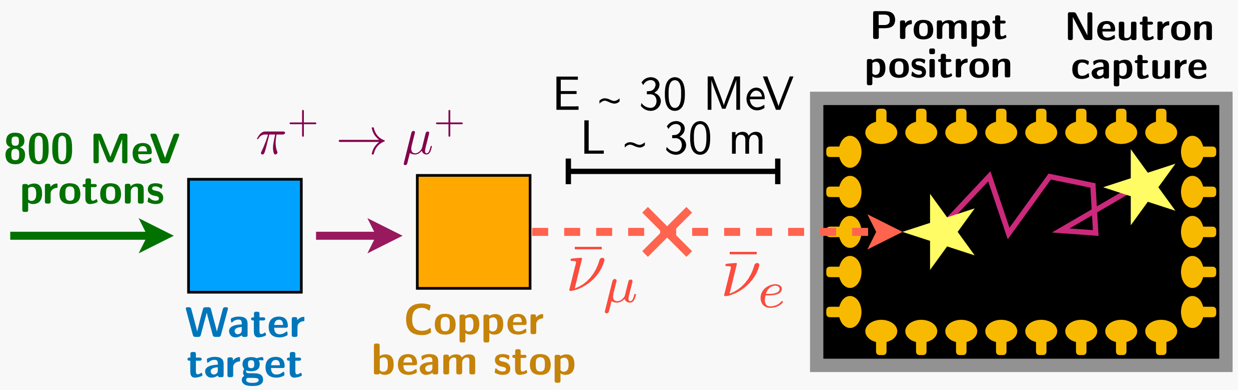
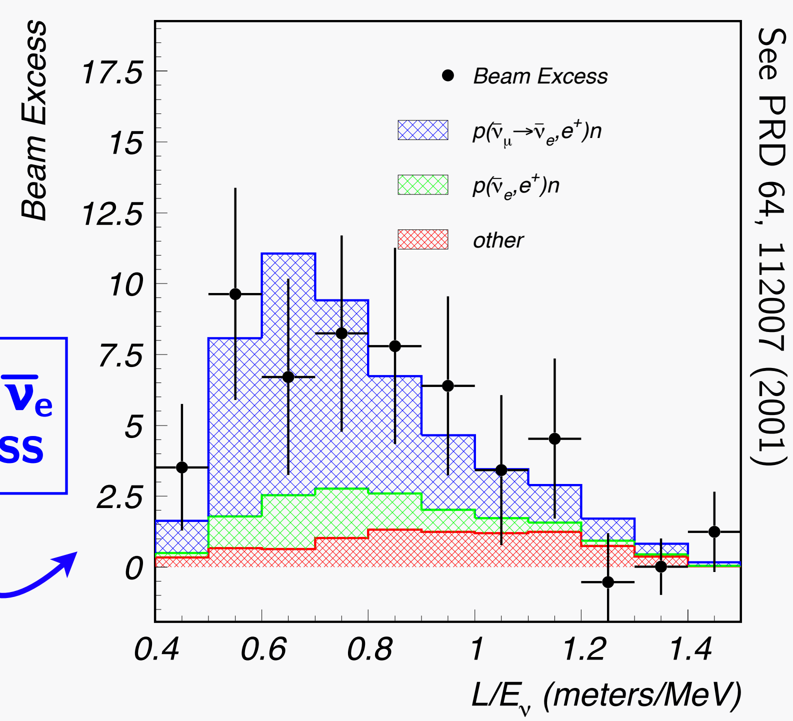
Anomalies (Selected)

Liquid Scintillator Neutrino Detector
Los Alamos National Laboratory



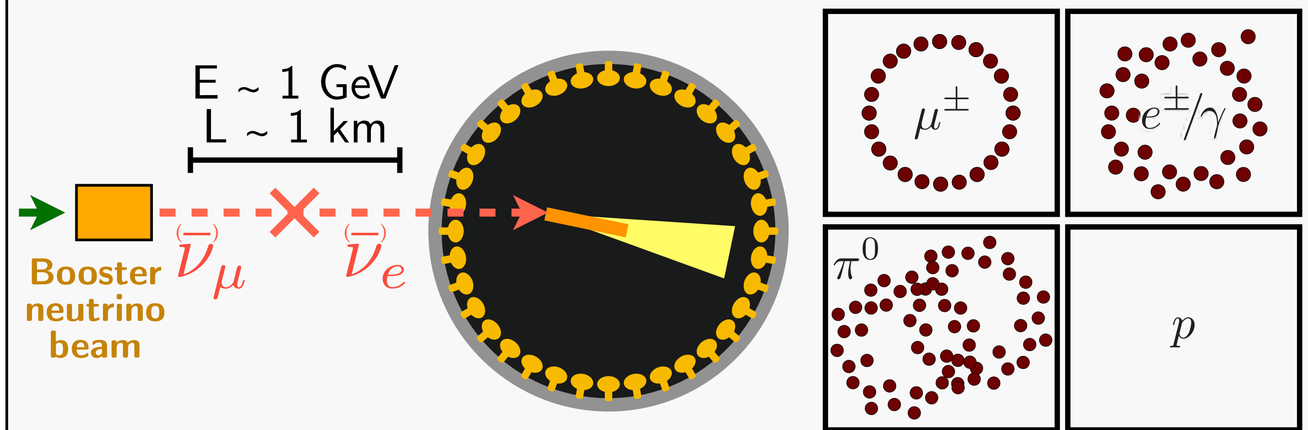
3.8σ $\bar{\nu}_e$ excess

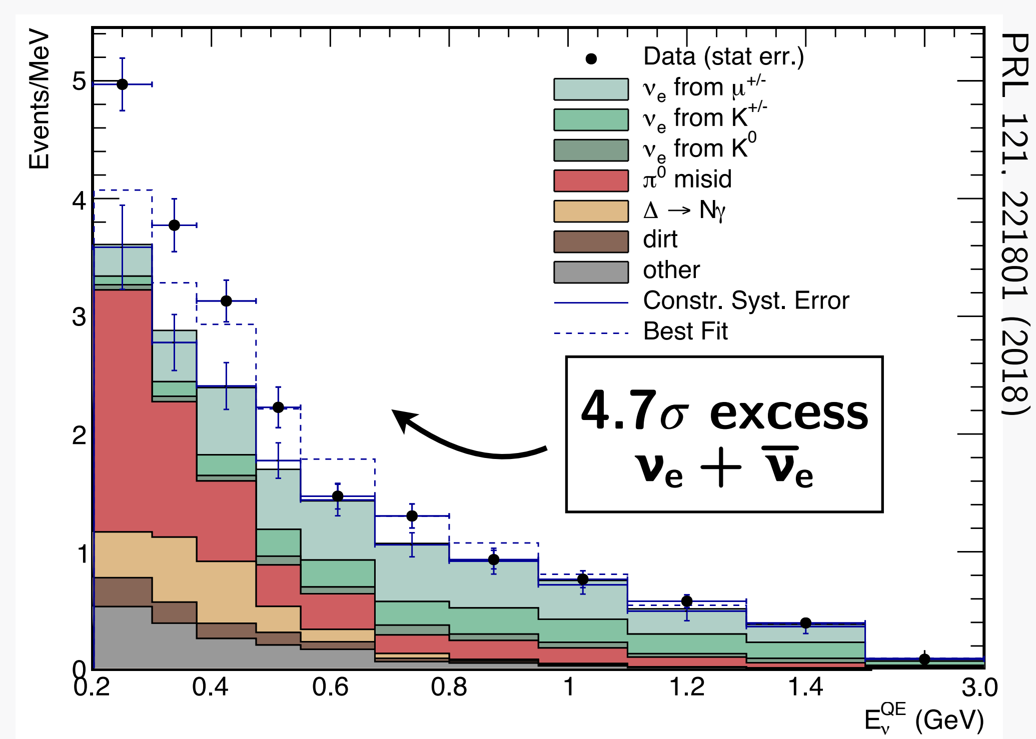


Interpreted as oscillations, this implies

Δm^2 ~ 1 eV^2, $\sin^2 2\theta_{\mu e}$ ~ 0.26%

MiniBooNE
Fermi National Accelerator Laboratory



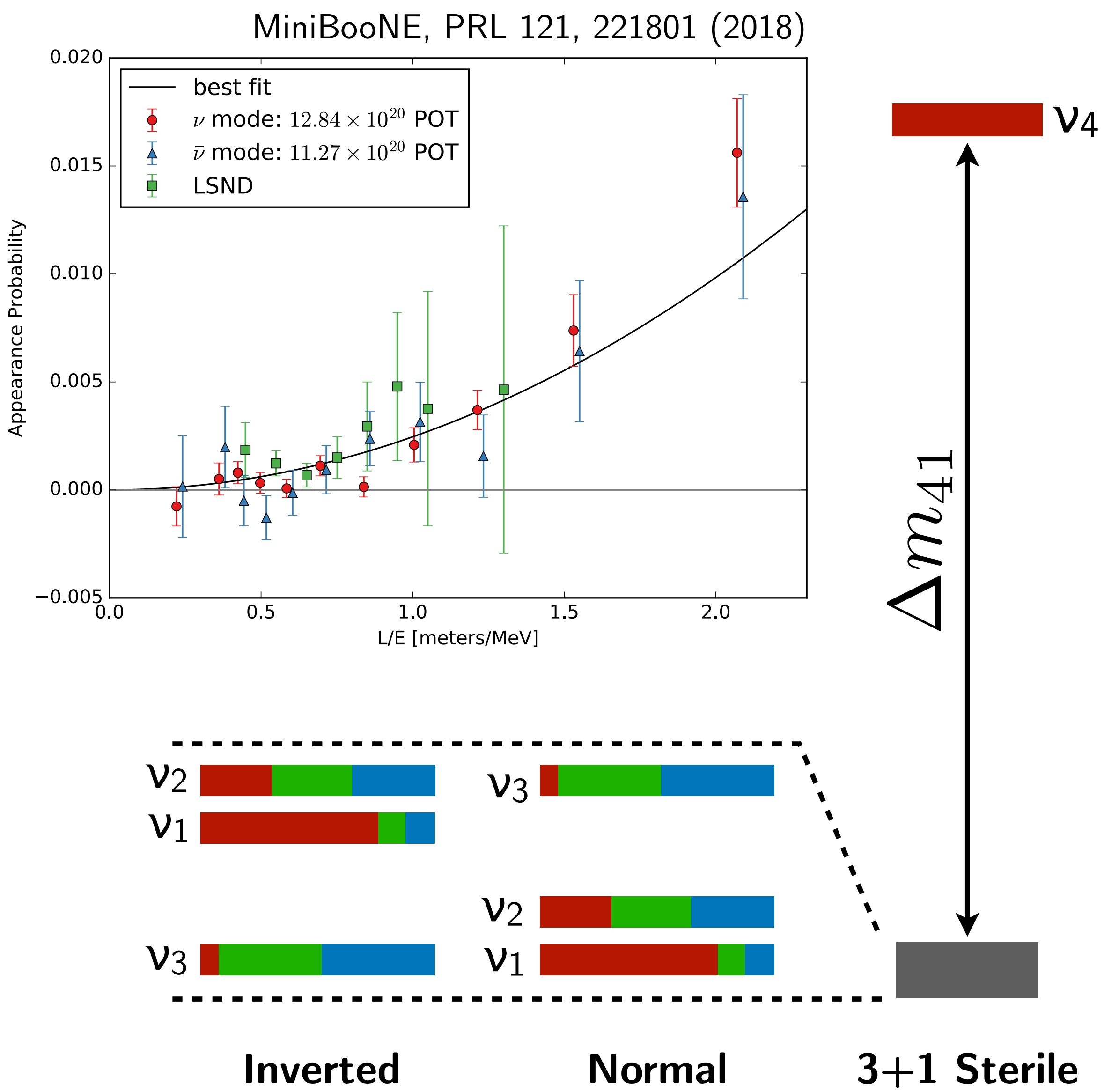


Consistent with LSND,

rise dubbed "Low Energy Excess"

New Physics?

3+1 (N?) sterile neutrinos?



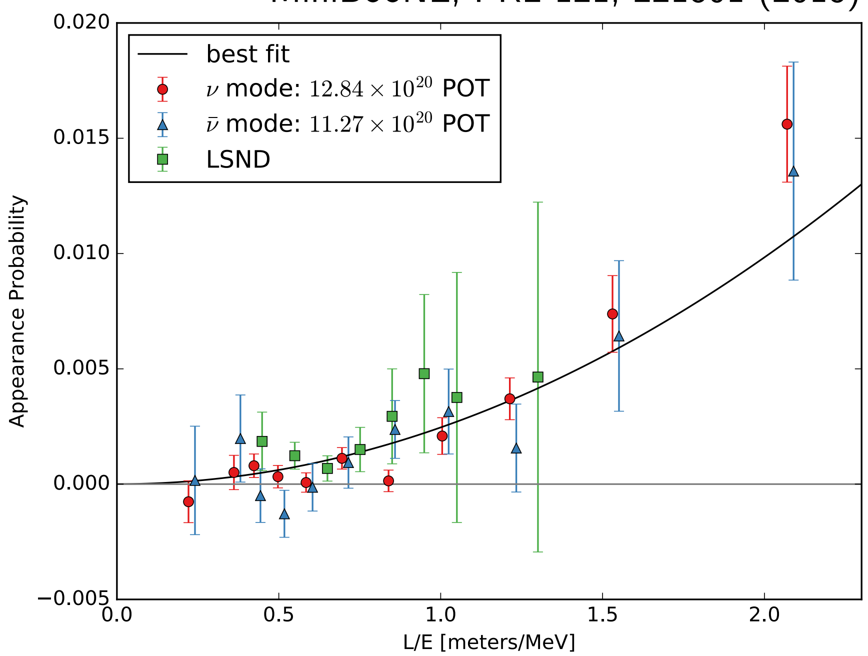
Flavor transitions via this new mixing:

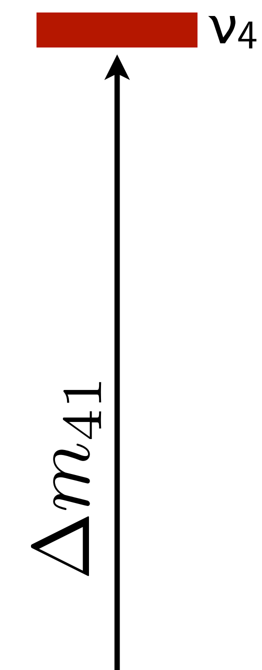
$$P_{\alpha\beta} = 4|U_{\alpha 4}|^2 |U_{\beta 4}|^2 \sin^2\left(1.27\frac{\Delta m_{41}^2 L}{E}\right)$$

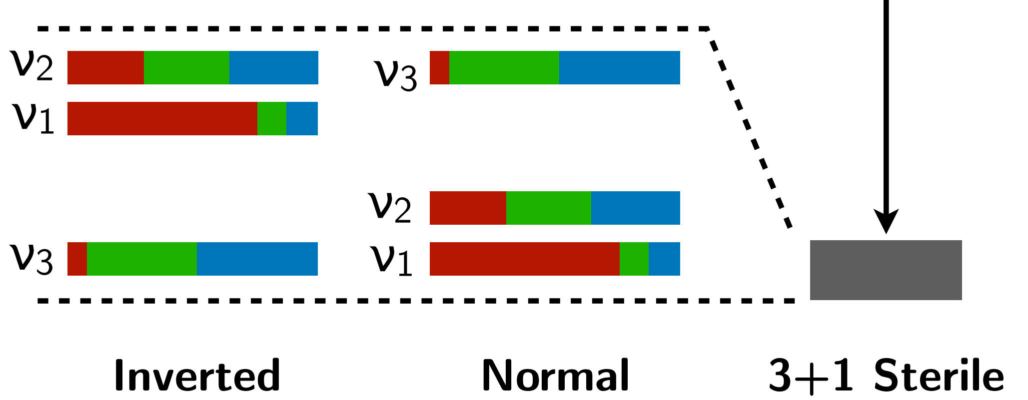
New Physics?

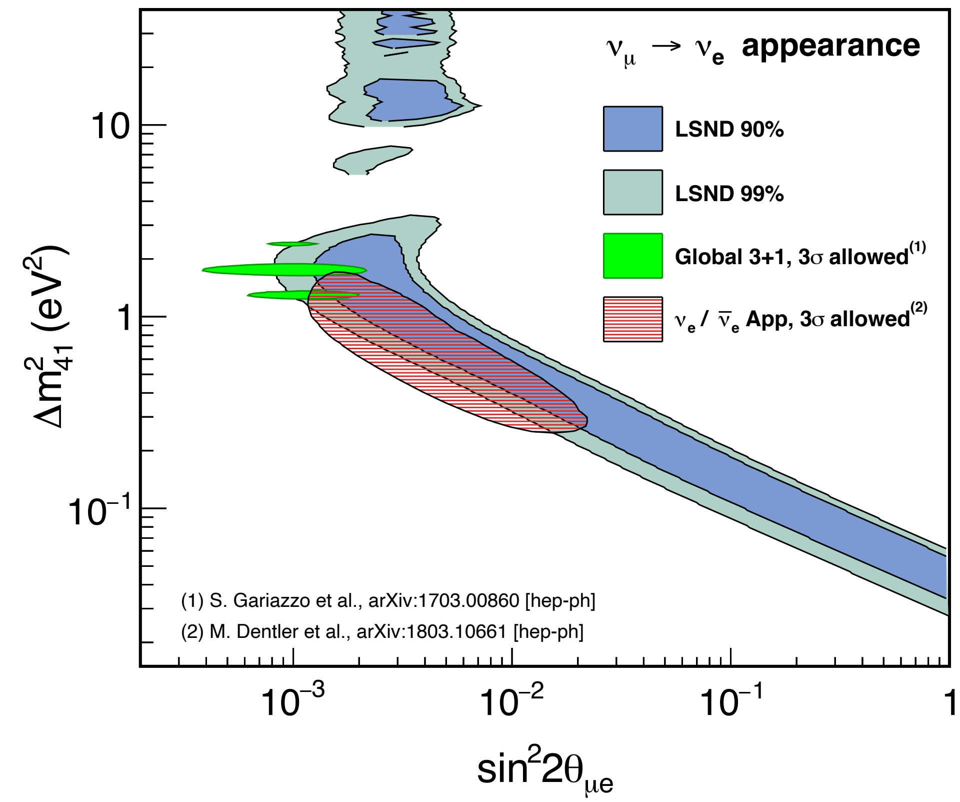
3+1 (N?) sterile neutrinos?

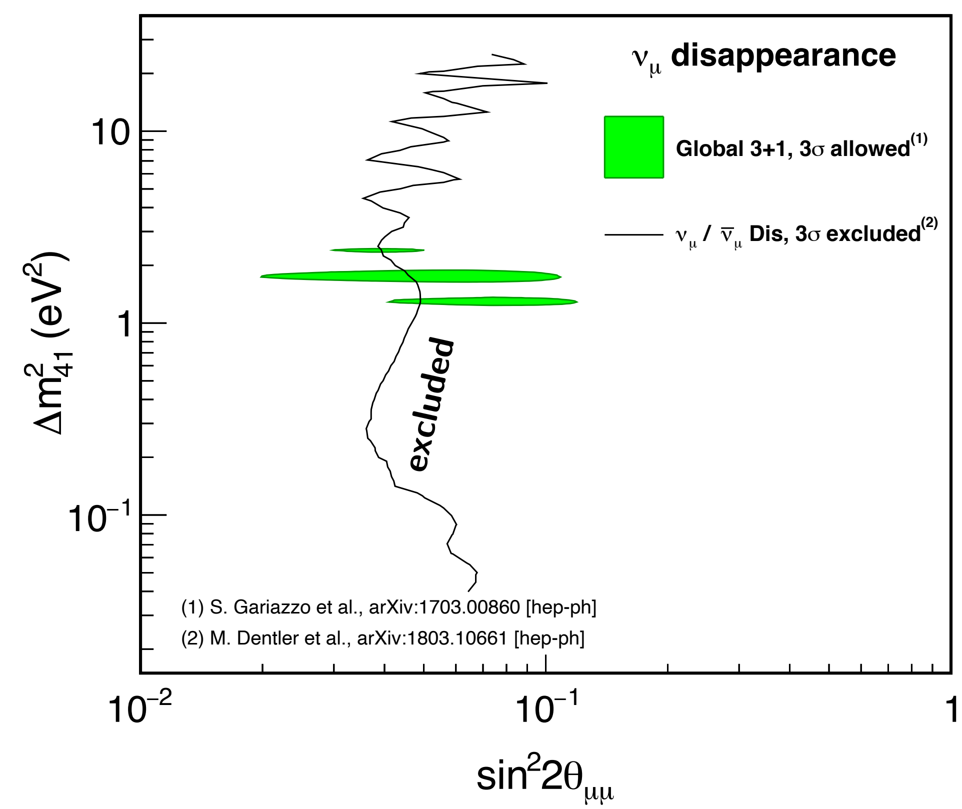
MiniBooNE, PRL 121, 221801 (2018)











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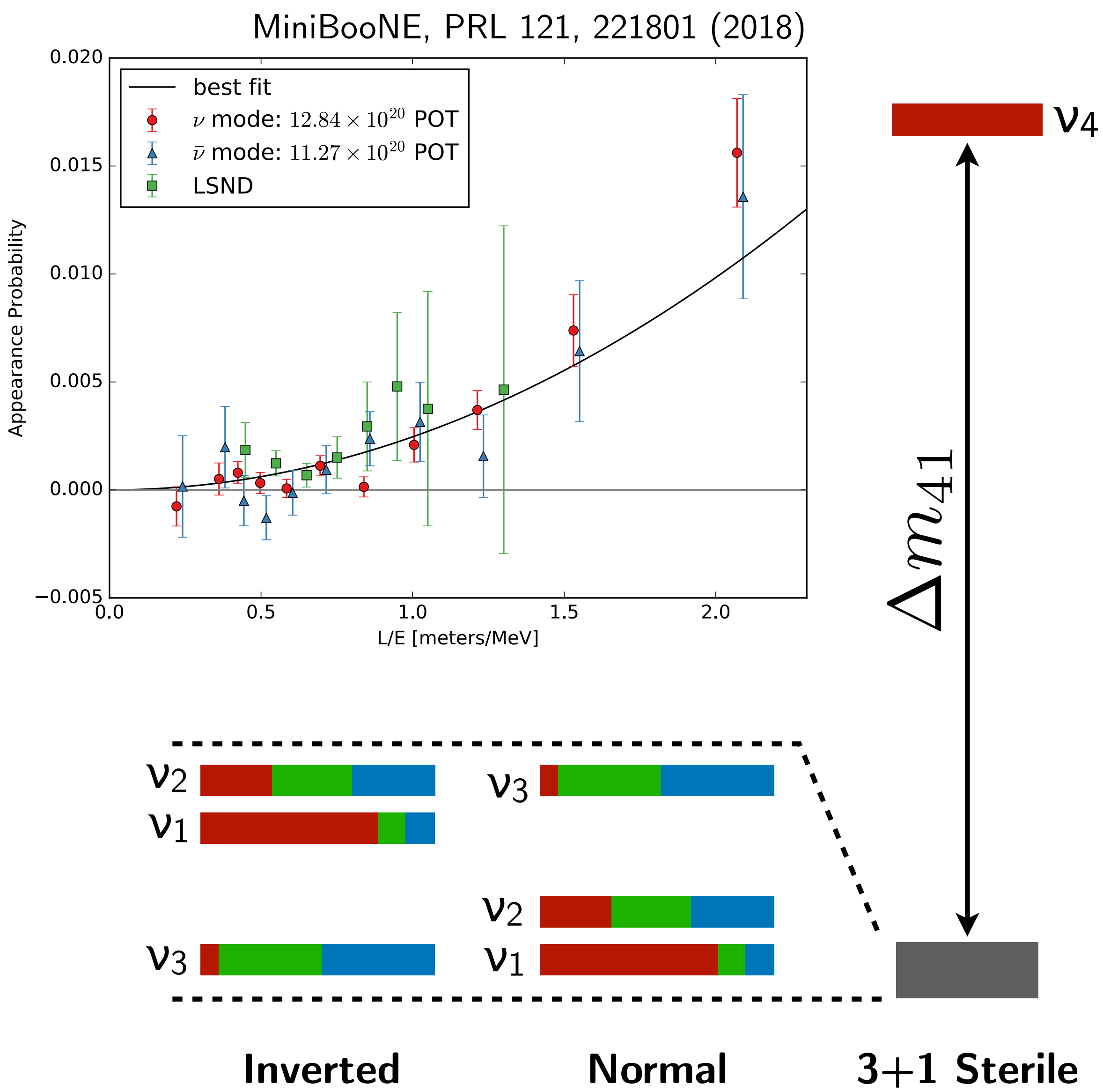
Significant tension among results in different, related signal channels

Figures courtesy of D. Schmitz

New Physics?

3+1 (N?) sterile neutrinos?



Flavor transitions via this new mixing:

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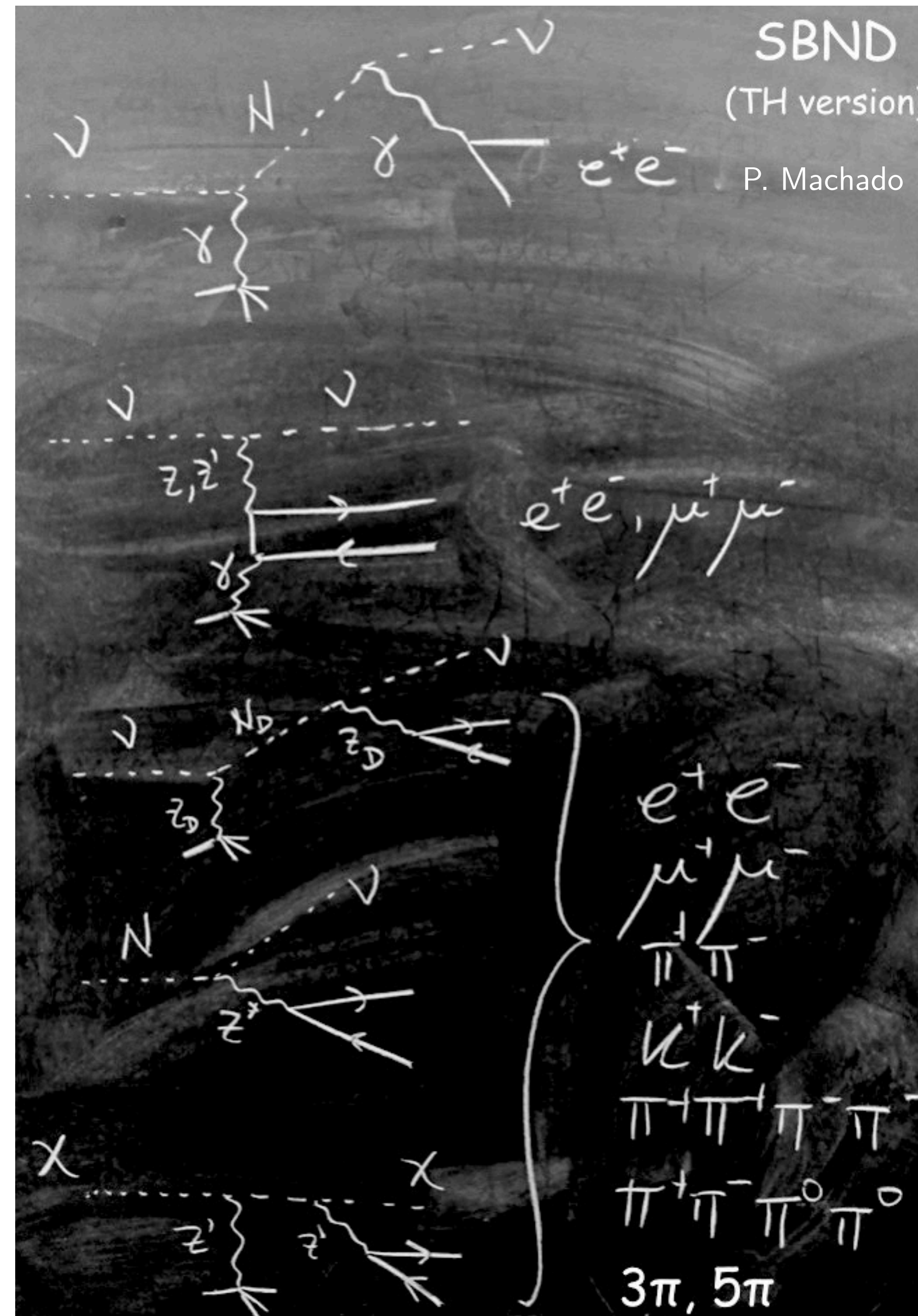
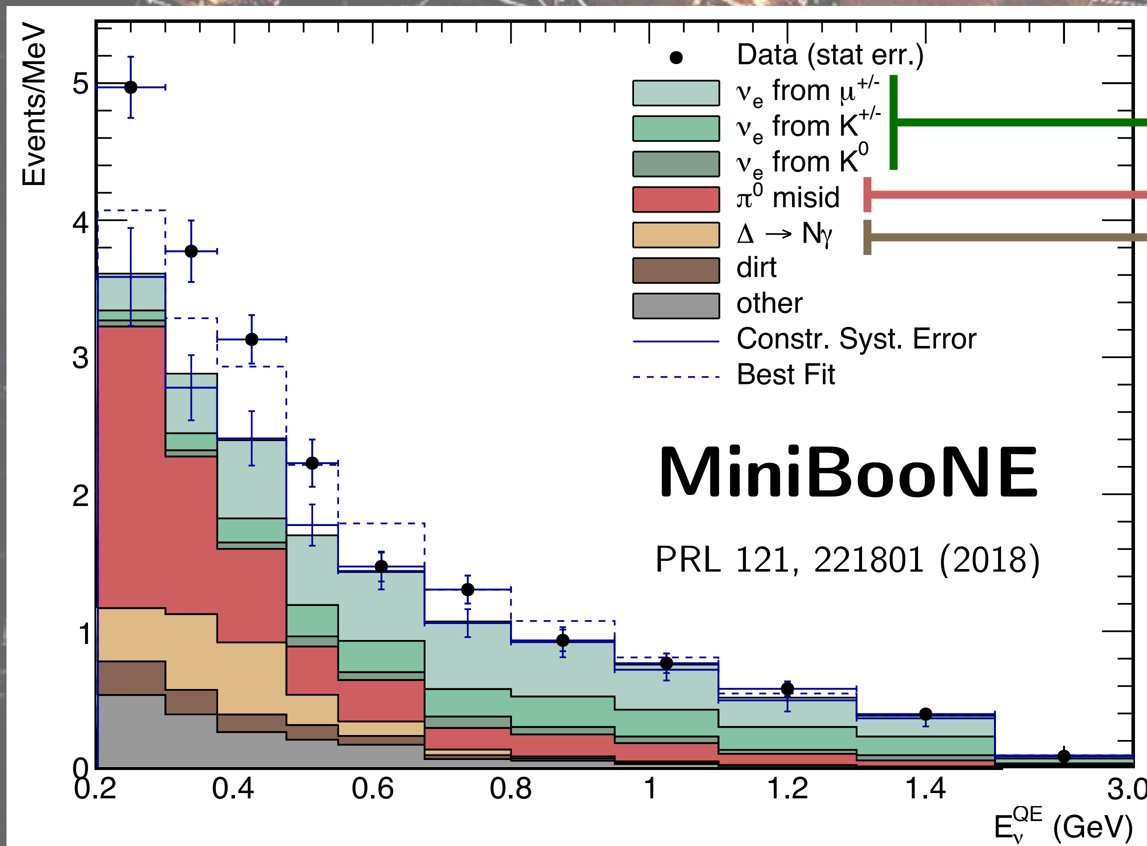
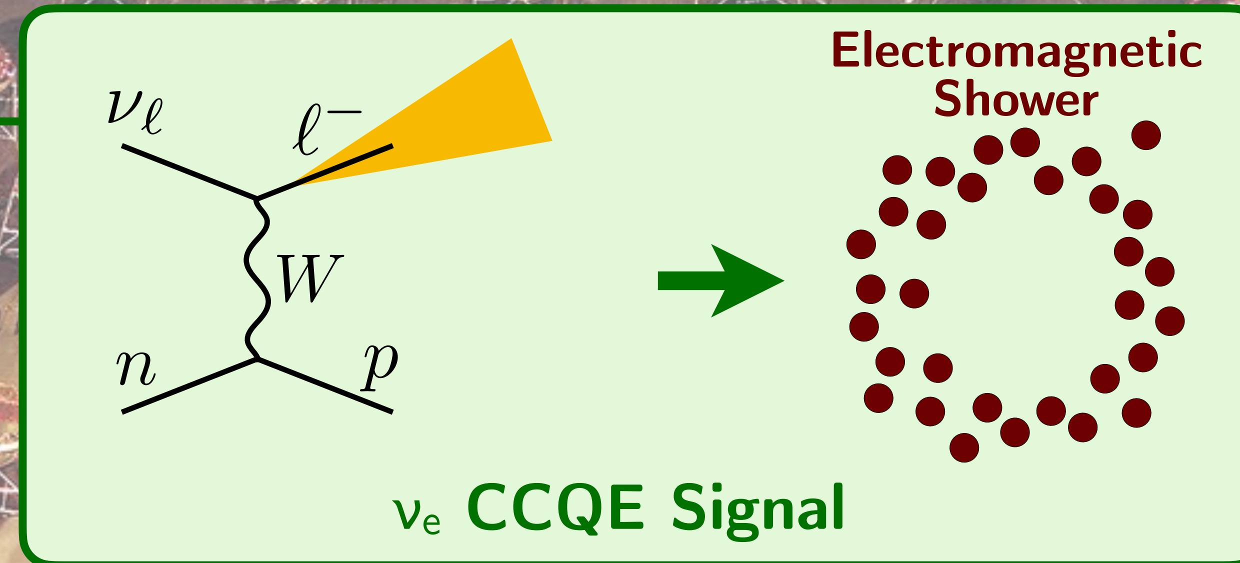
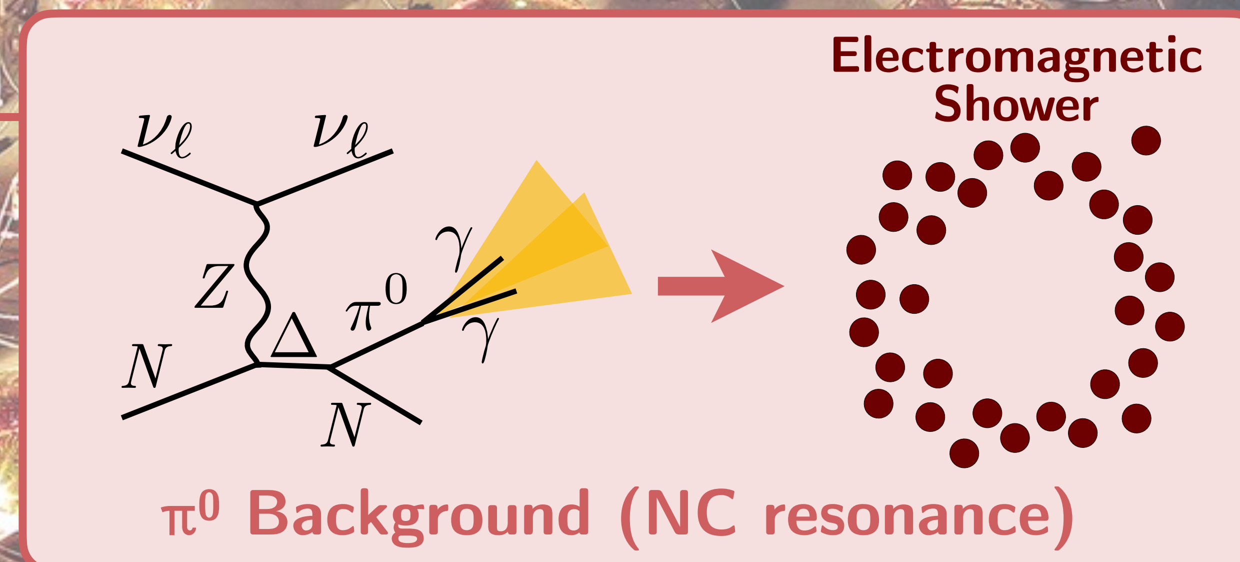
Other new physics scenarios?

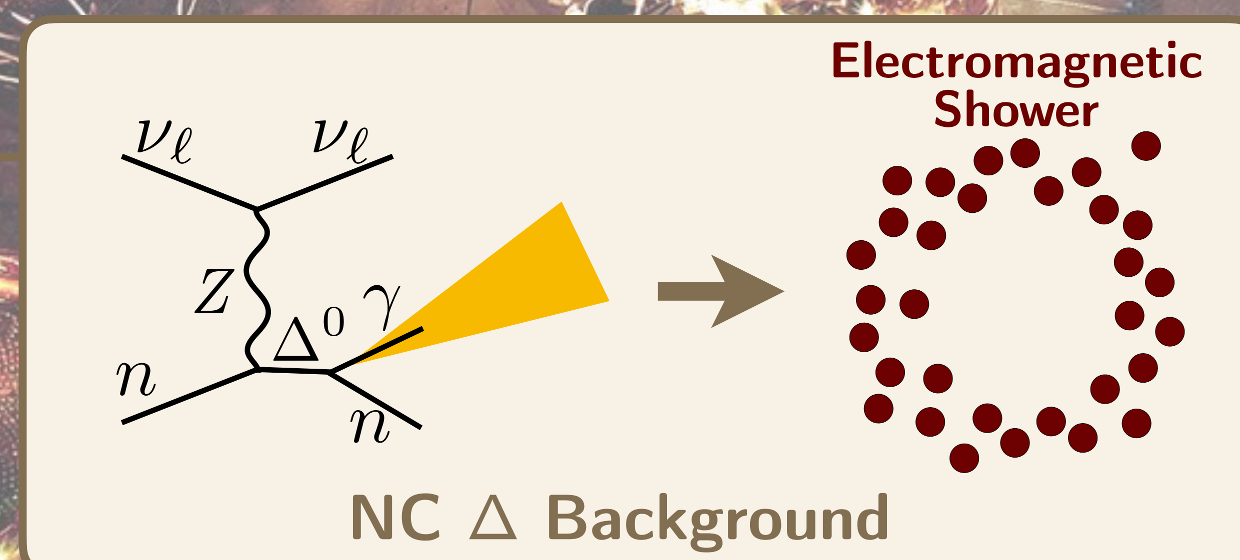



MiniBooNE
Fermilab
Image: MiniBooNE Collaboration









Electron excess	Sterile neutrinos? Something else?
Photon excess	$\Delta \rightarrow N\gamma$? π^0 mis-ID? Something else?

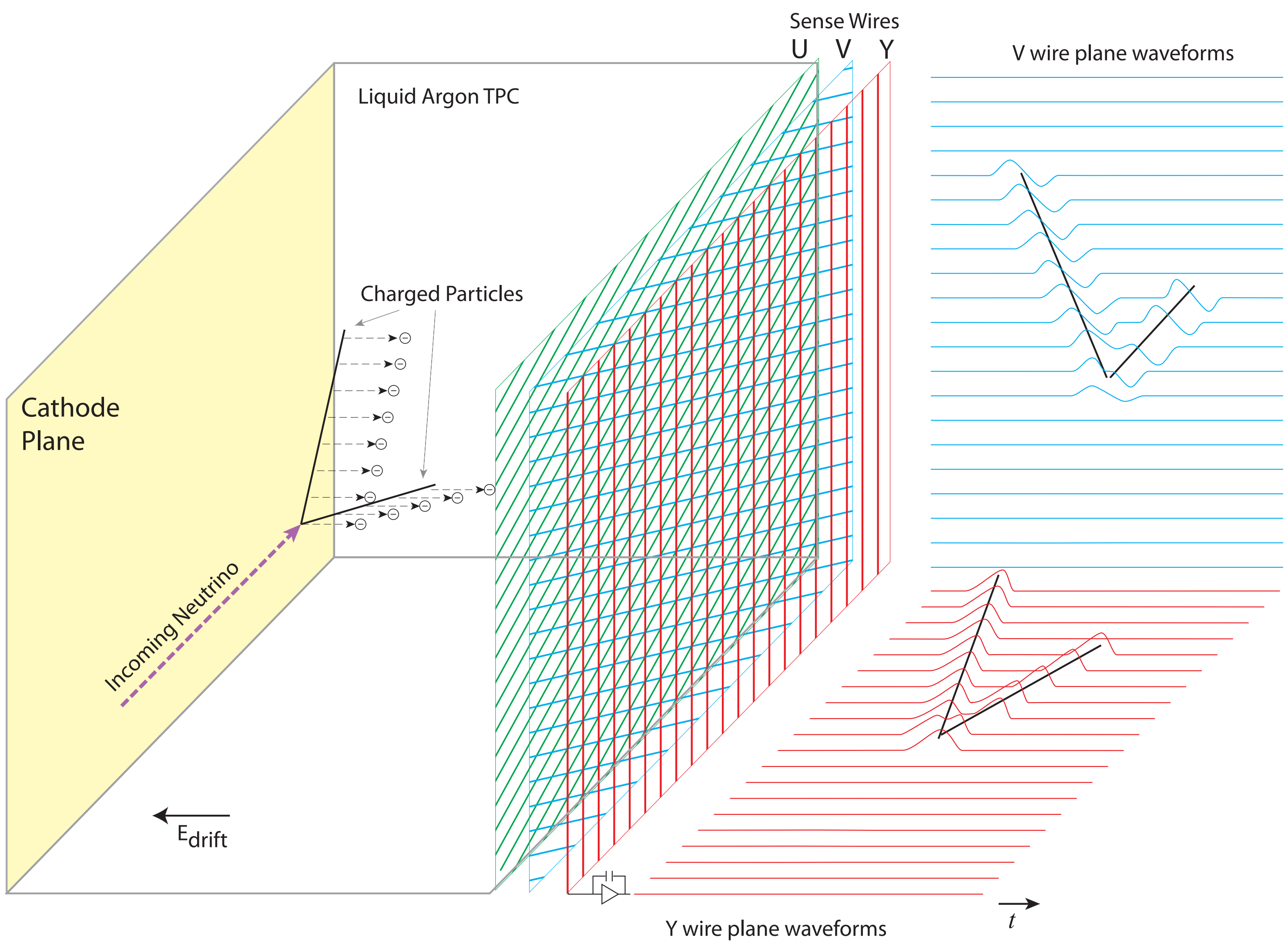
We need improved
event topology information

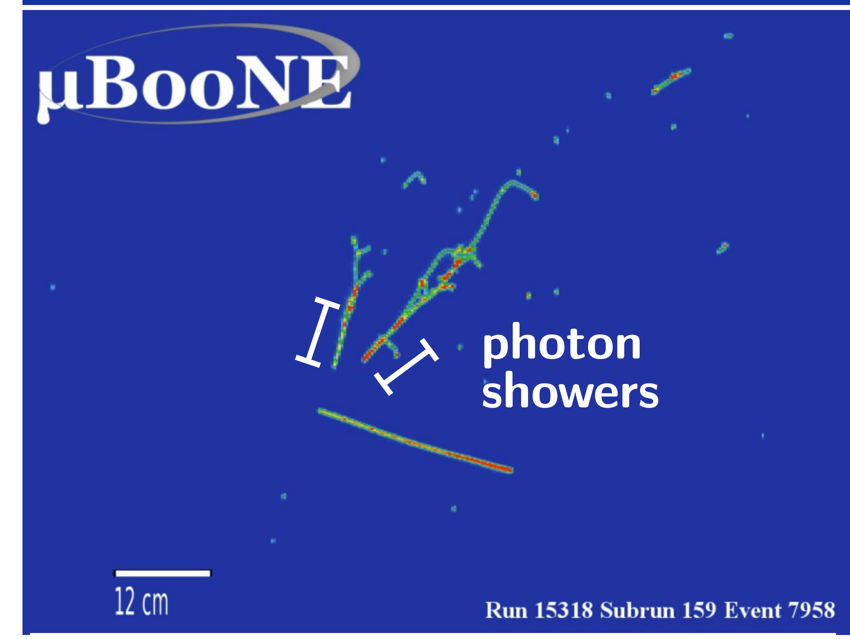
Liquid Argon TPCs

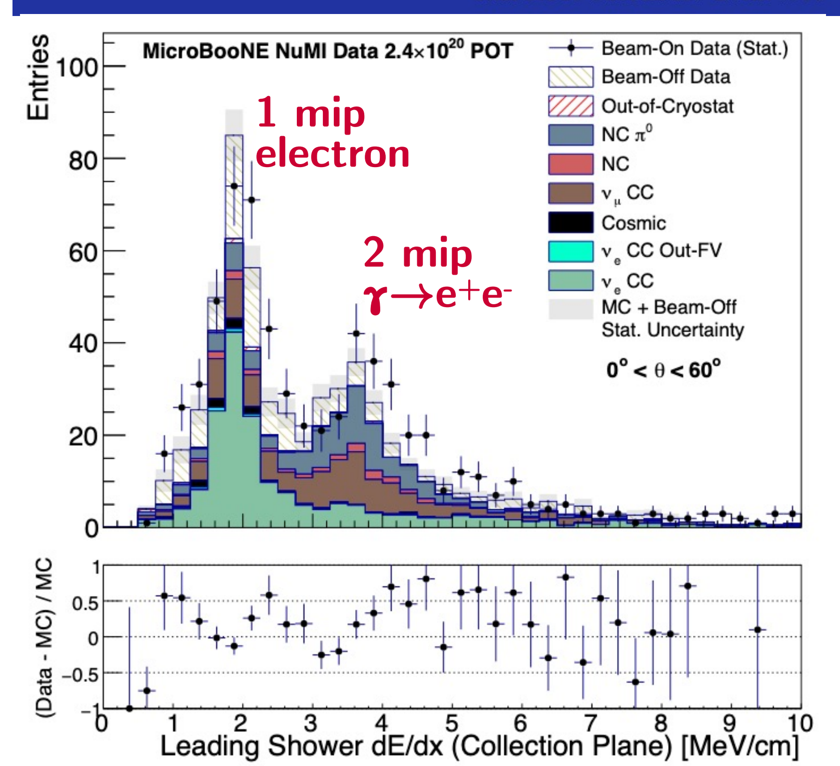
Precision Neutrino Instrumentation

LAr Time Projection Chambers

- Detailed 3D imaging of neutrino interactions
- Calorimetric energy reconstruction
- Vertex & dE/dx electron/photon discrimination







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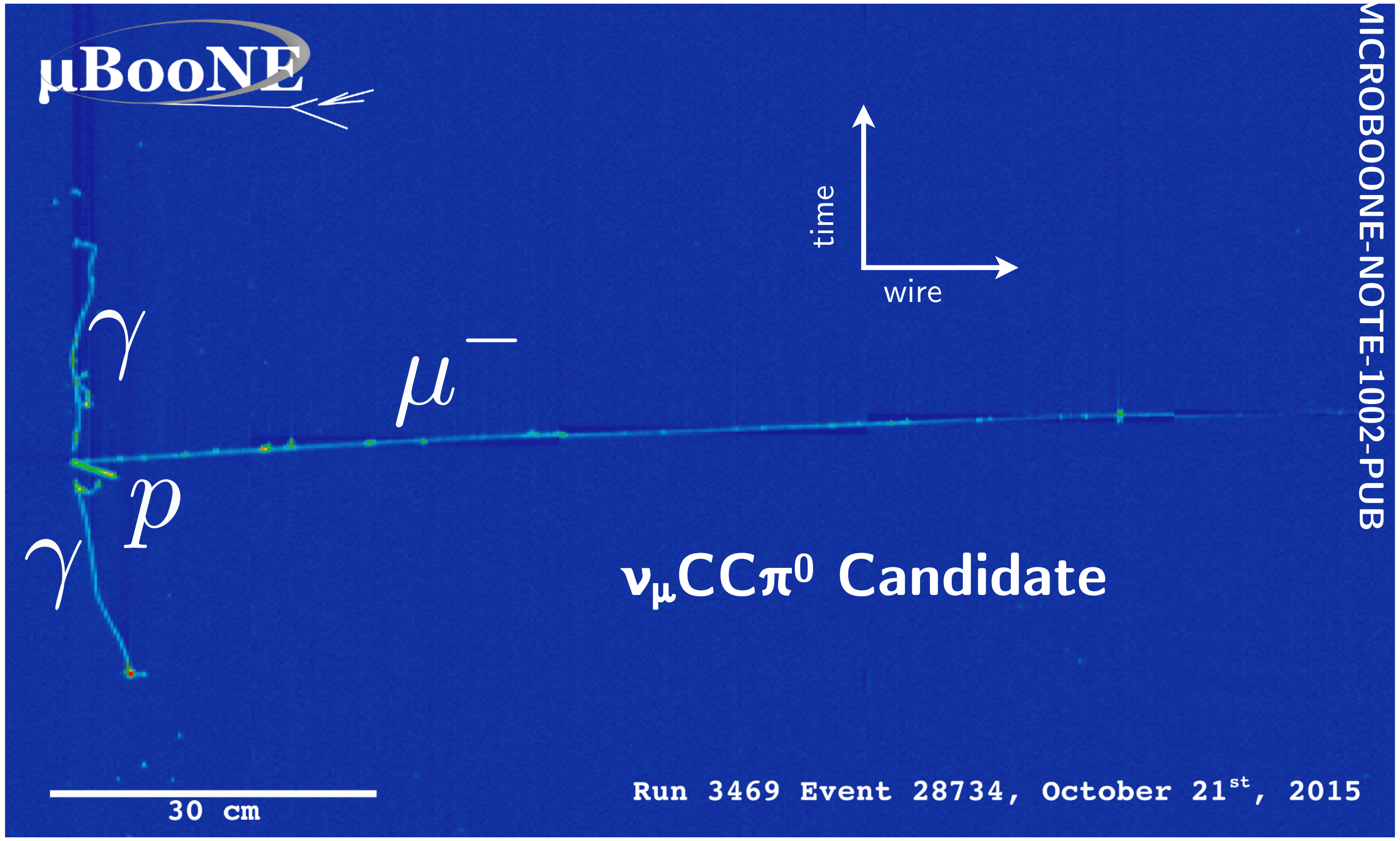
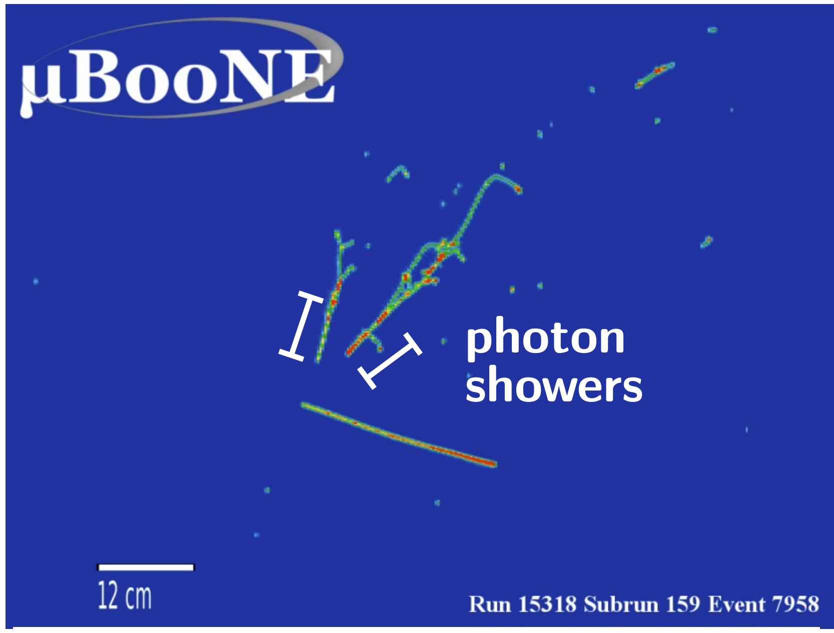
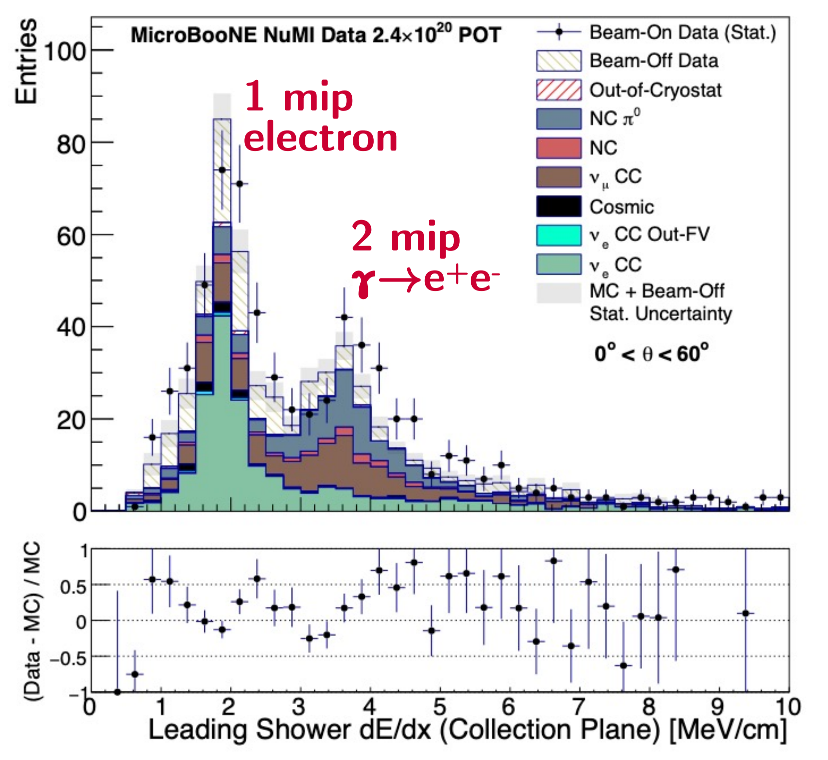
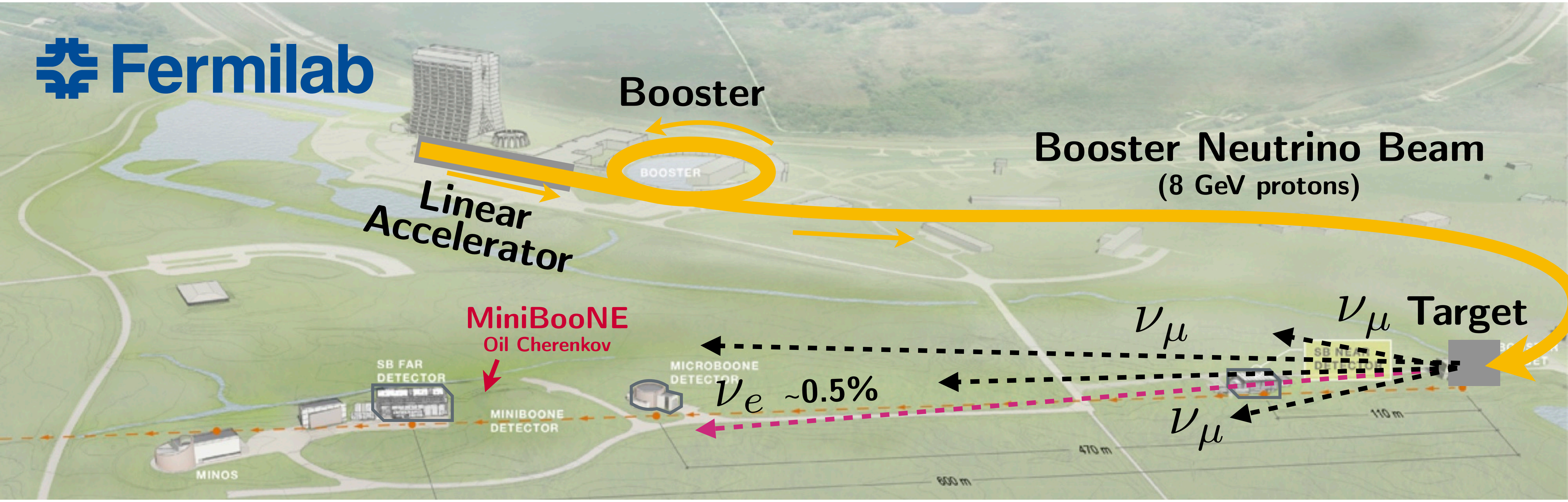
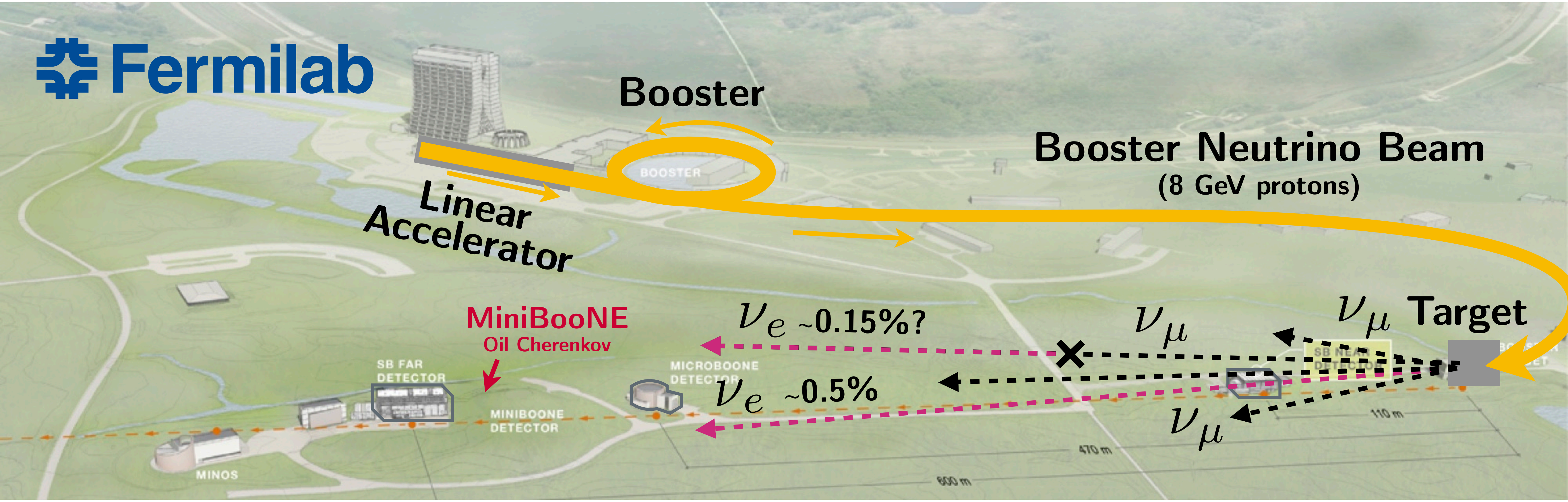








Fermilab
Booster
BOOSTER
Booster Neutrino Beam
(8 GeV protons)
Linear
Accelerator
MiniBooNE
Oil Cherenkov
SB FAR
DETECTOR
MINIBOONE
DETECTOR
MICROBOONE
DETECTOR
MINOS
ν_μ
ν_μ
Target
ν_e ~0.5%
ν_μ
110 m
470 m
600 m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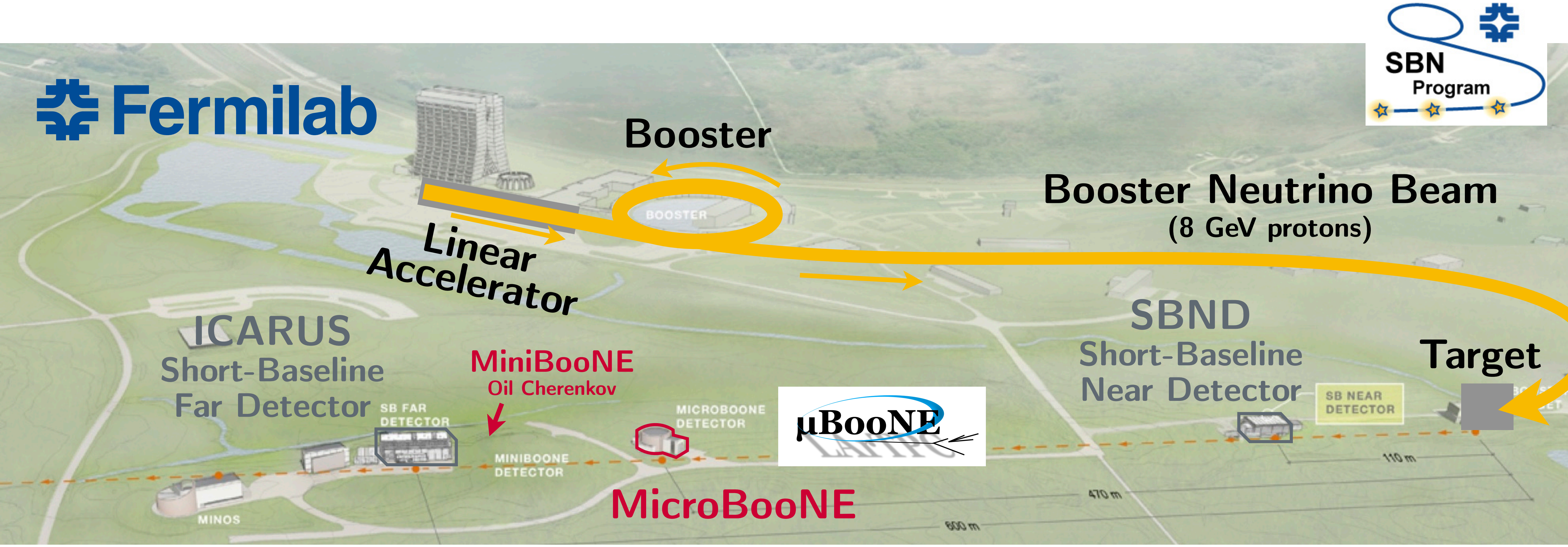
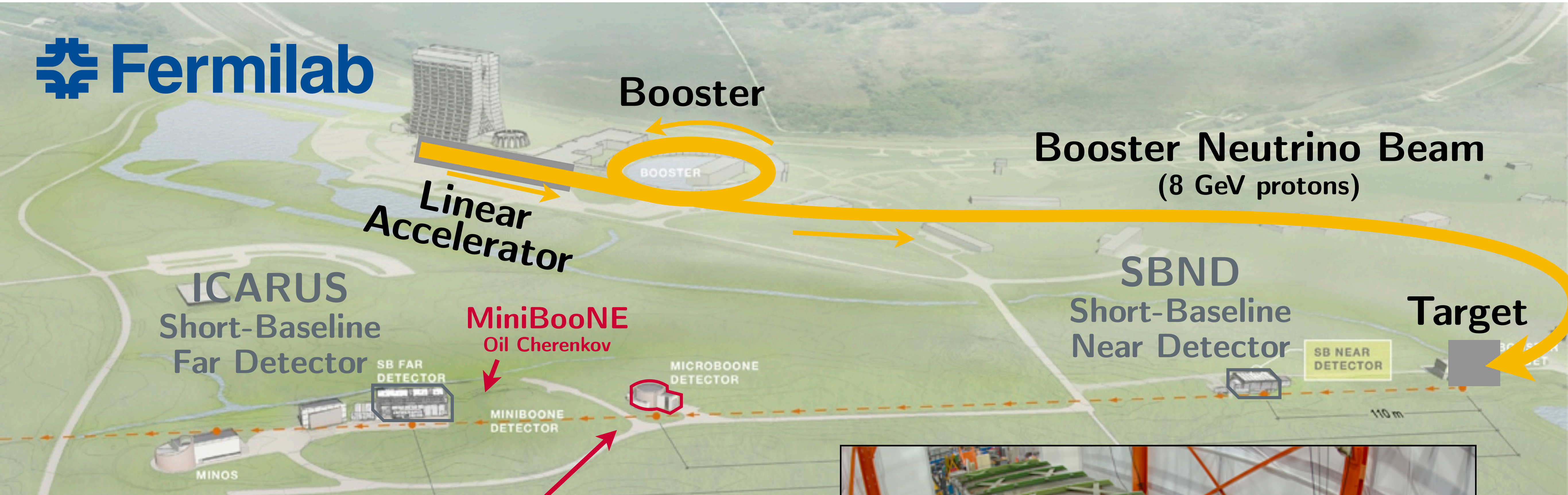


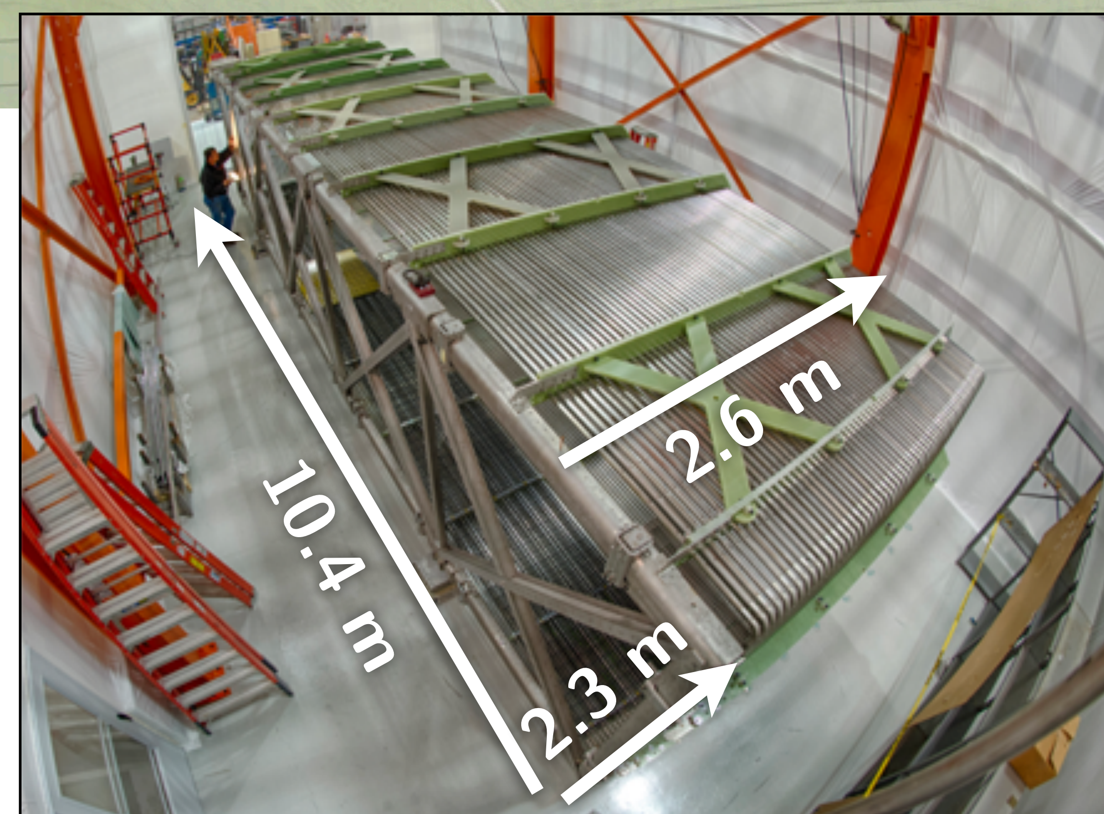
LArTPCs at multiple baselines in the Fermilab Booster Neutrino Beam

MicroBooNE

Addressing the MiniBooNE Excess



MicroBooNE
Liquid Argon TPC



- 85 tons instrumented LAr mass
- Running Oct 2015 — Oct 2021
- *What did MiniBooNE see?*

MicroBooNE

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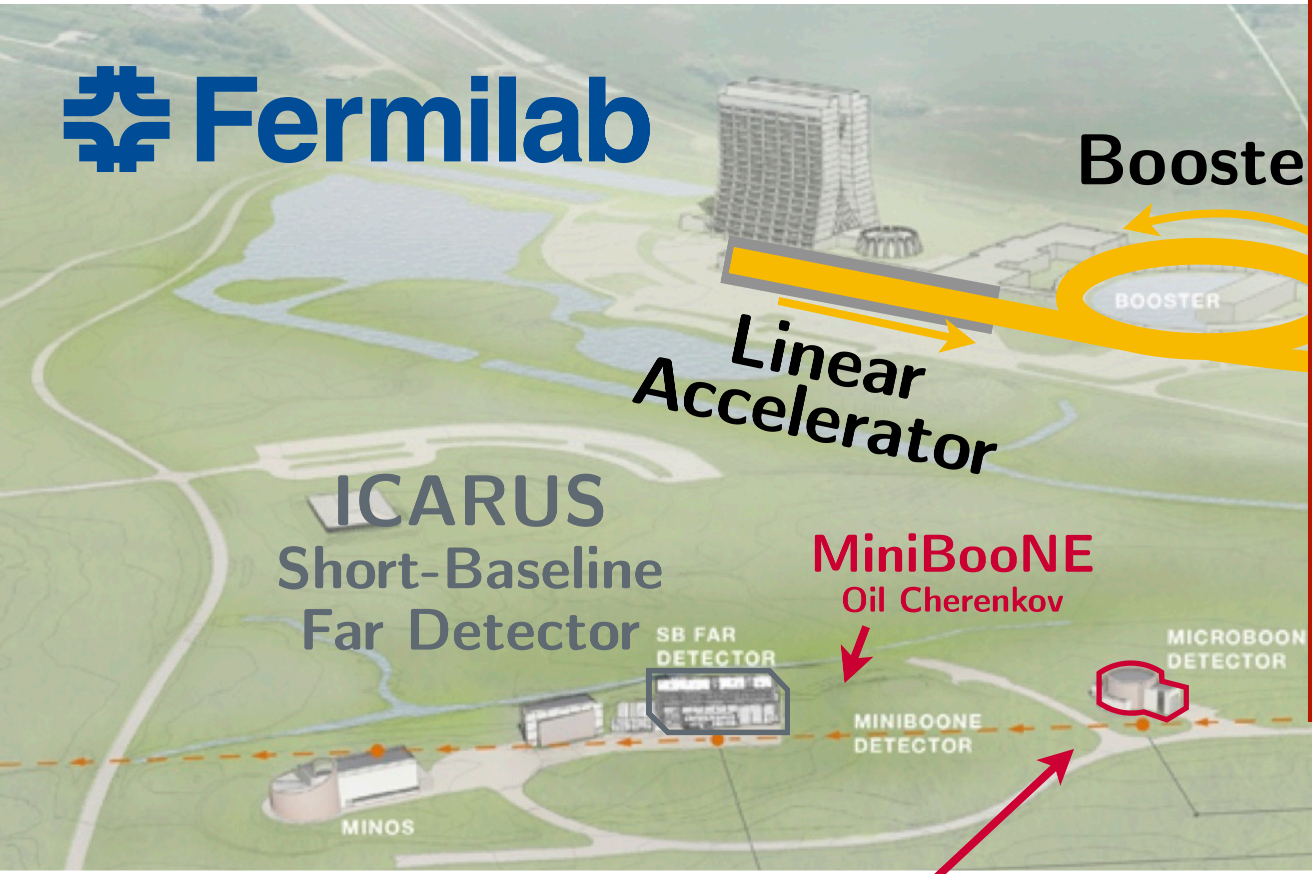

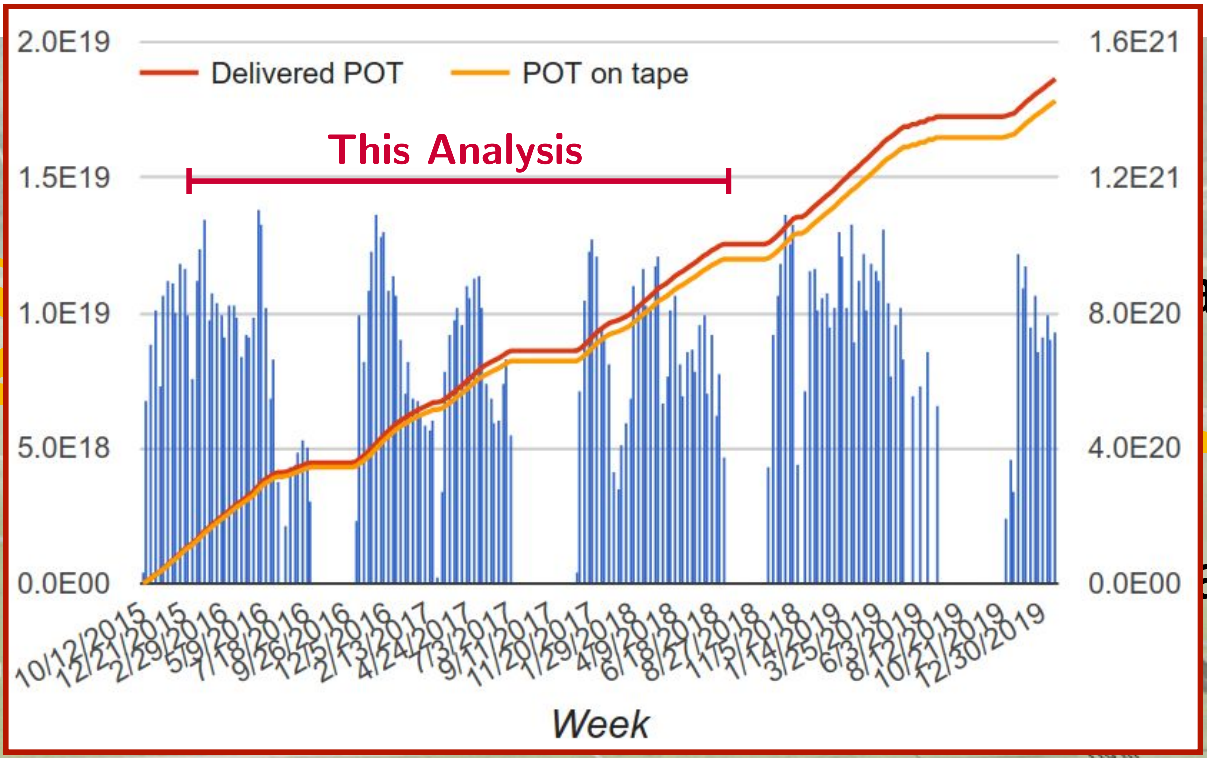

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Liquid Argon TPC

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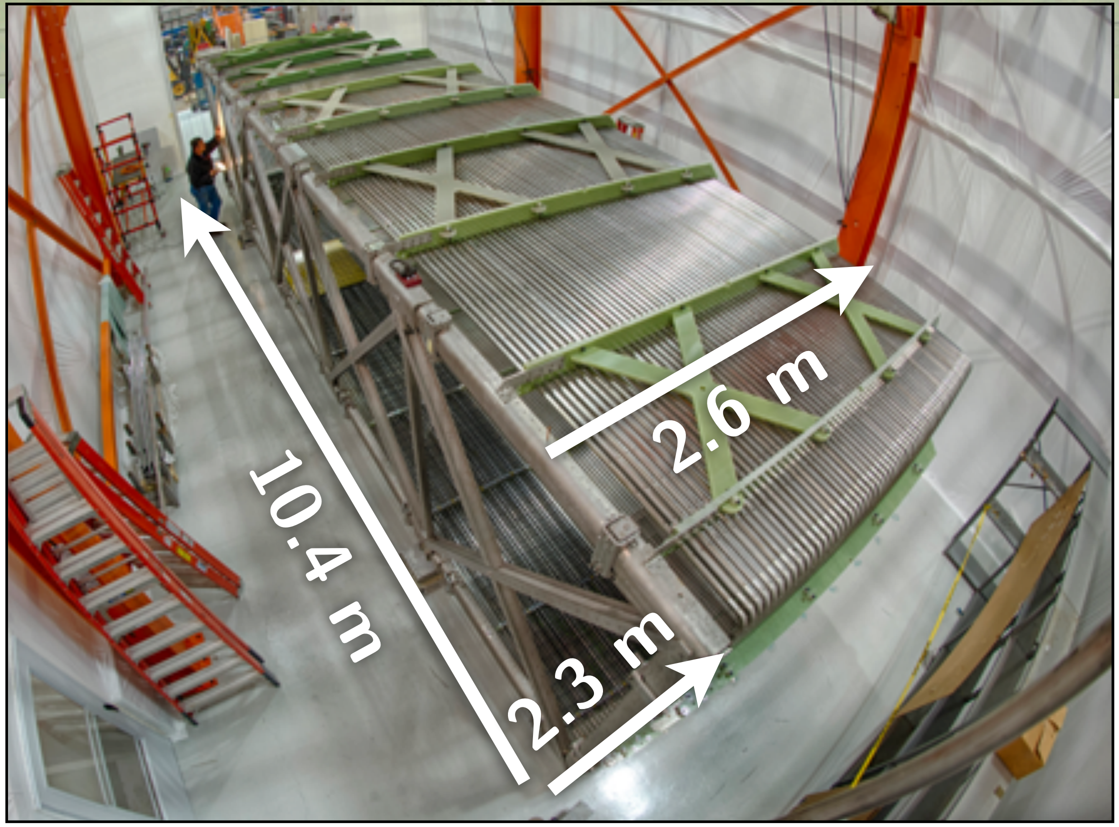
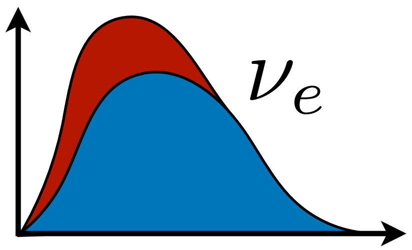


The Ingredients

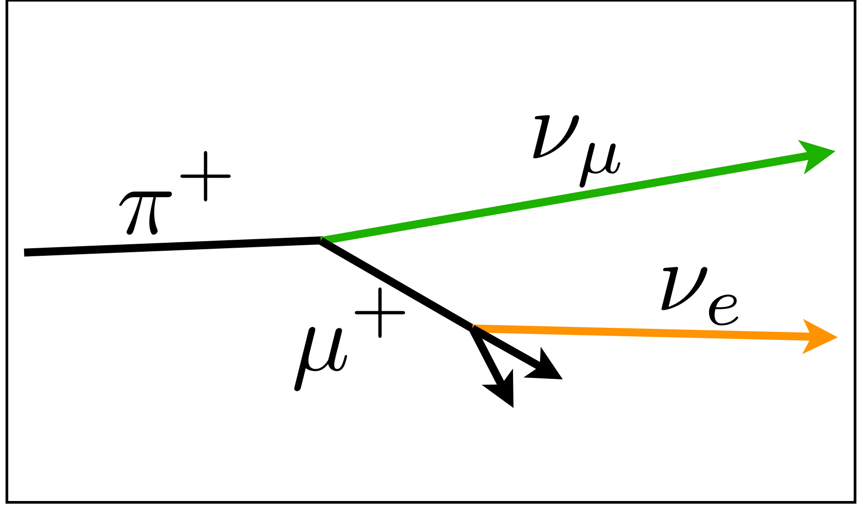
Leveraging Correlations to Minimize Systematics

A key to MicroBooNE's single-detector measurement is using high-statistics events to constrain intrinsic backgrounds

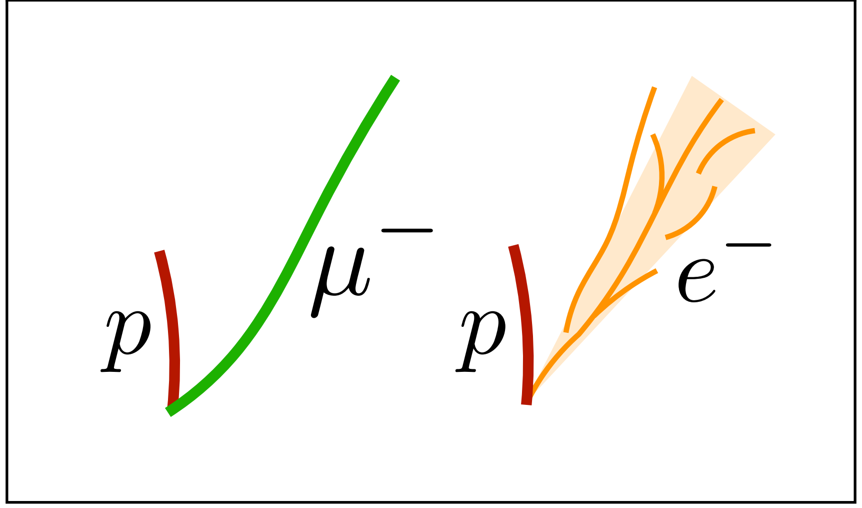
For an electron-like excess, e.g., we are looking for a small excess of ν_e interactions on top of the 0.5% intrinsic to the beam



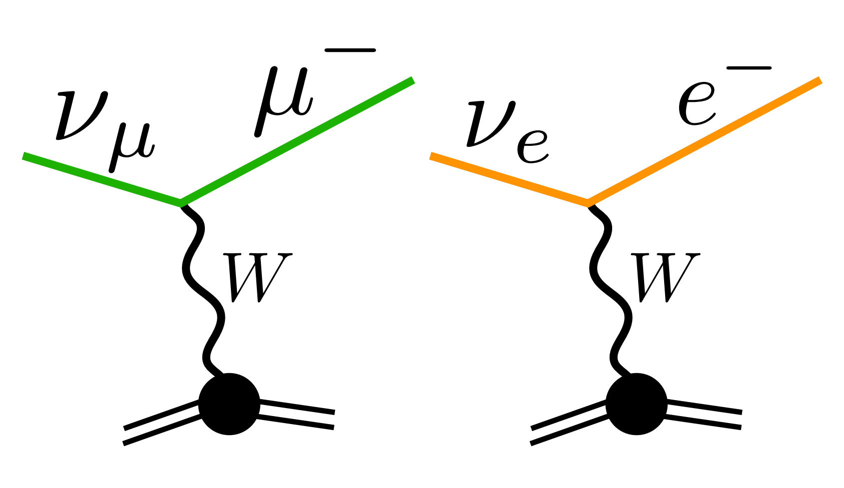
Flux



Detection



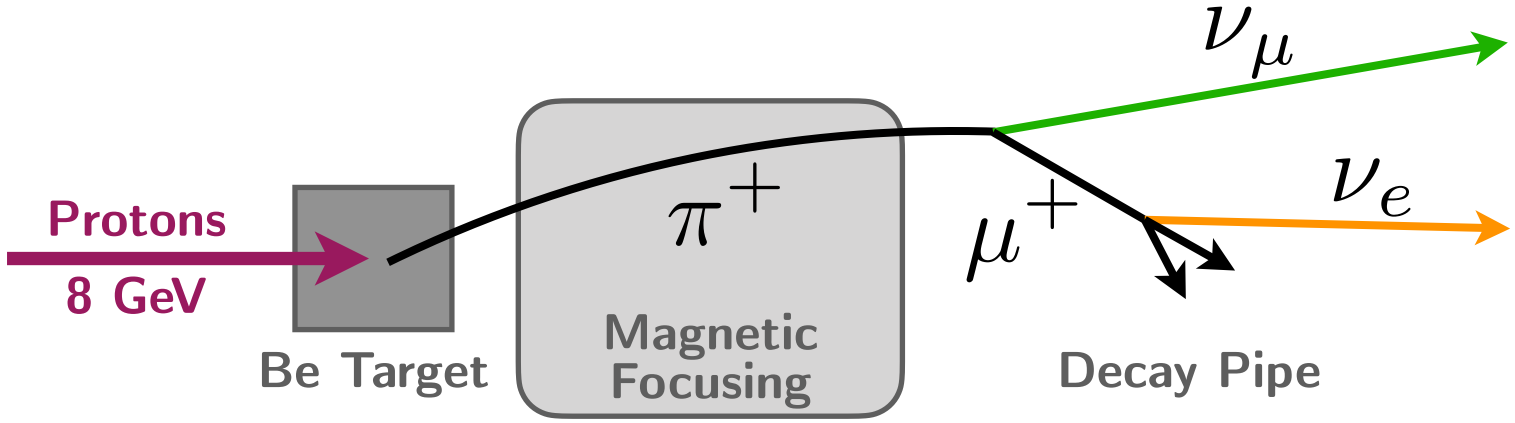
Interactions



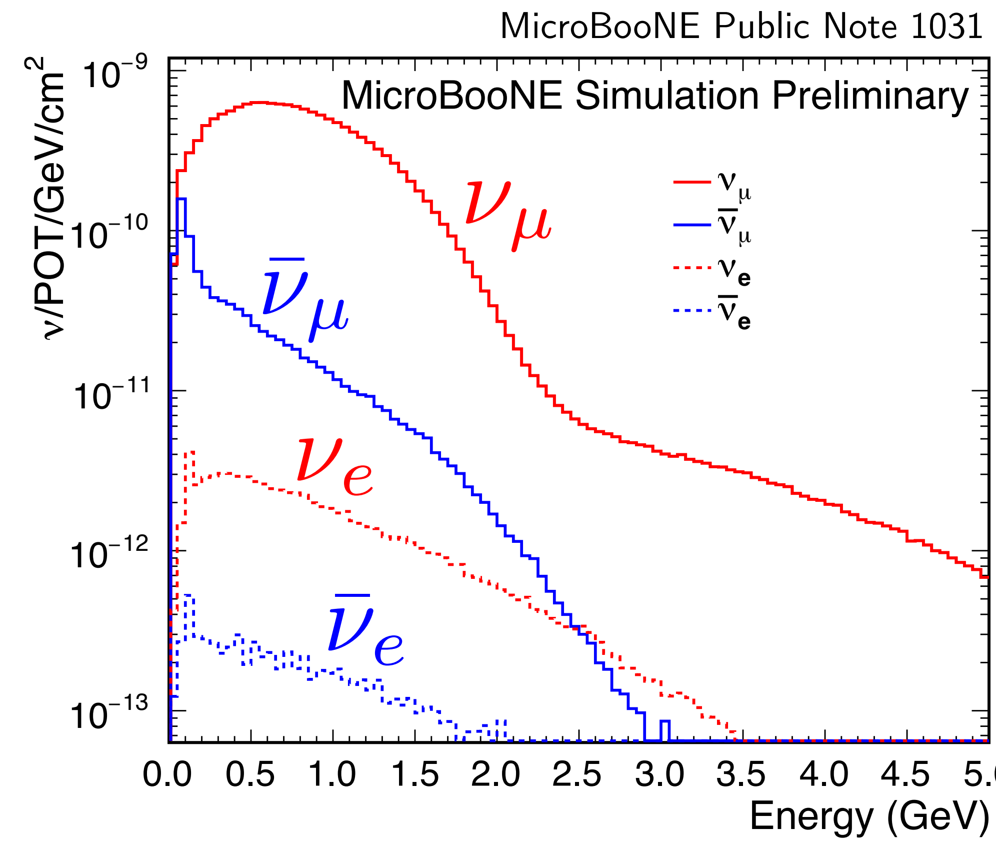
Neutrino Flux

Flux Modeling & Uncertainties

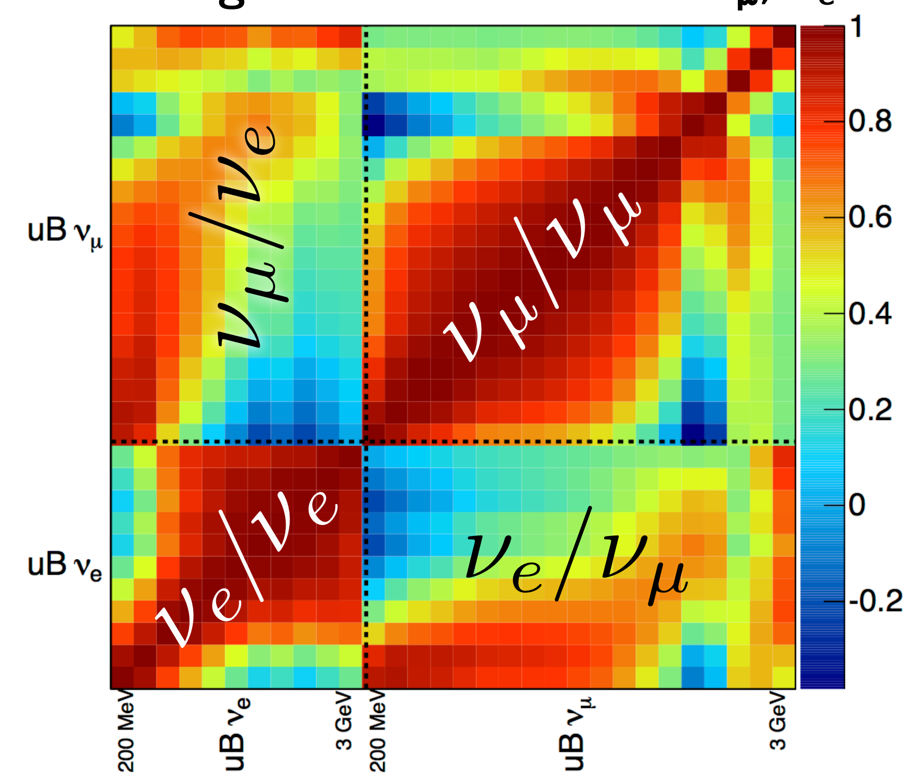
- Fermilab Booster Neutrino Beam
  - 8 GeV protons on a Be target
  - Primarily a ν_μ beam, with 0.5% ν_e



- MiniBooNE-based flux uncertainties
  - Beamline modeling in Geant4
    - π, K production (HARP, SciBooNE)
    - π, nucleon interactions
  - ~12% integral flux uncertainty
- Leverage strong ν_μ/ν_e correlations →



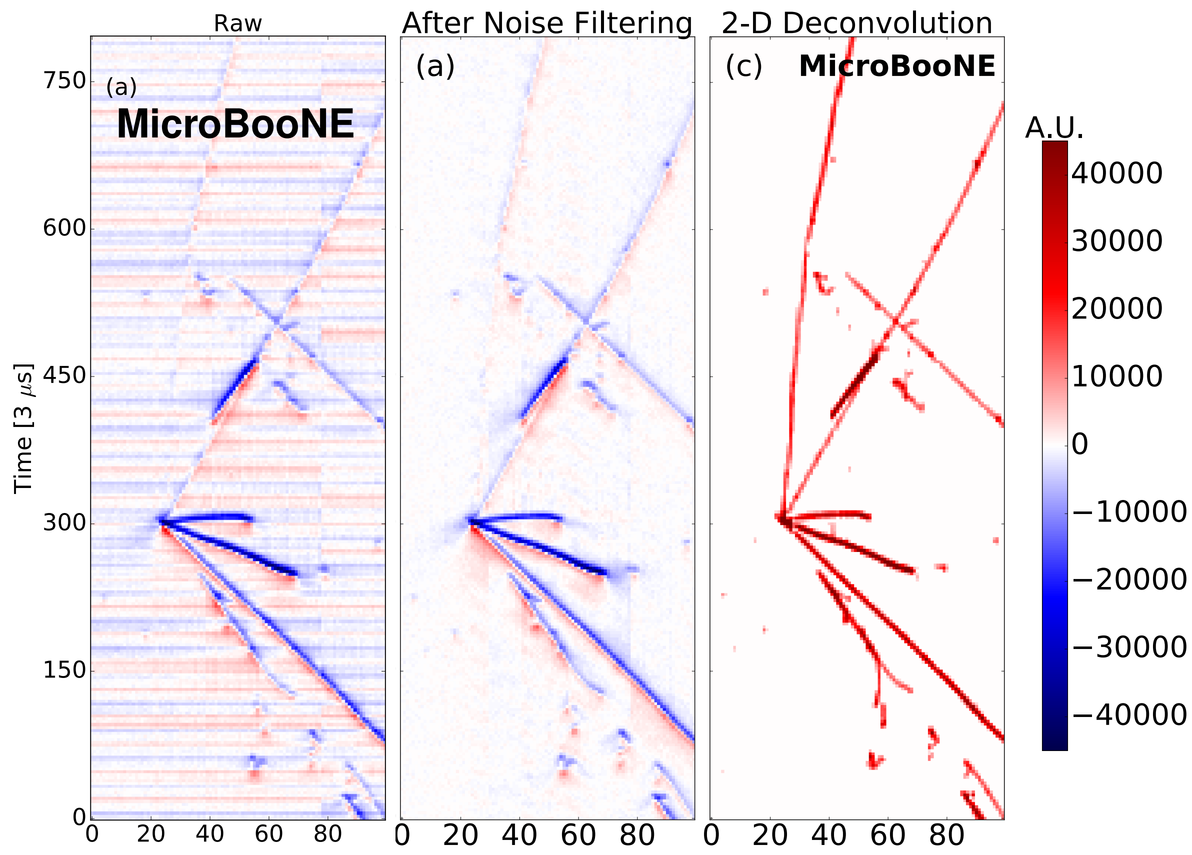
Strong flux correlations in ν_μ, ν_e



Detector Modeling

Detailed modeling of **particle propagation**, **electron drift & detector response**, and **photon propagation**

1. Signal processing (MicroBooNE, JINST 13 P07007, 2018 and JINST 13 P07007, 2018)

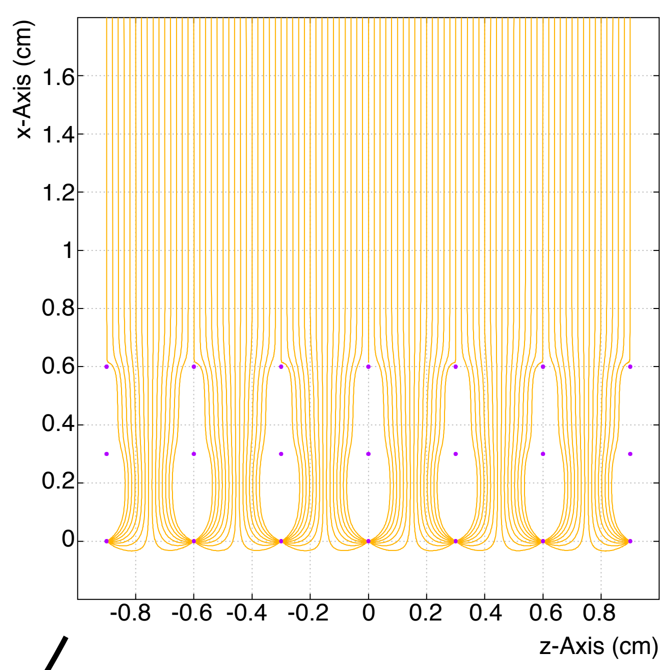


Raw Data

Software Noise Filtering

Improved Signal Response

2D field simulation for electron trajectories



State of the art *data-driven* modeling of LArTPC response, improving efficiency and particle identification

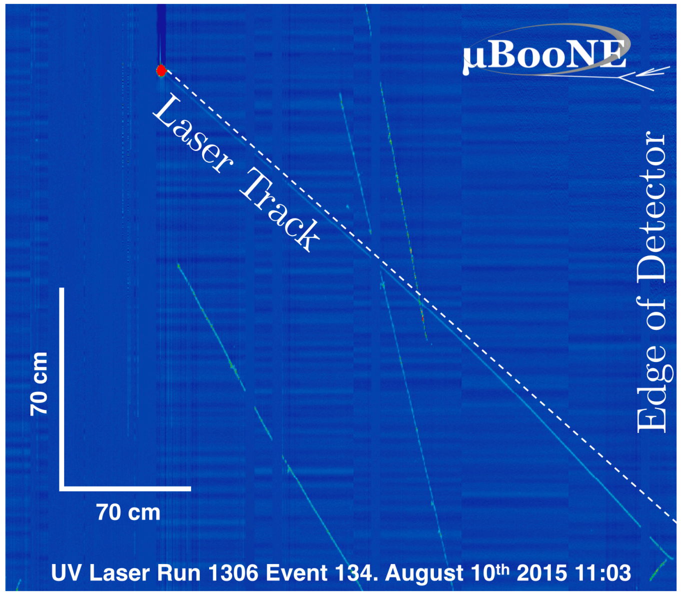
Detector Modeling

Detailed modeling of **particle propagation**, **electron drift & detector response**, and **photon propagation**

1. **Signal processing** (MicroBooNE, JINST 13 P07007, 2018 and JINST 13 P07007, 2018)
2. **Response Calibration** *or* How Things Go Wrong

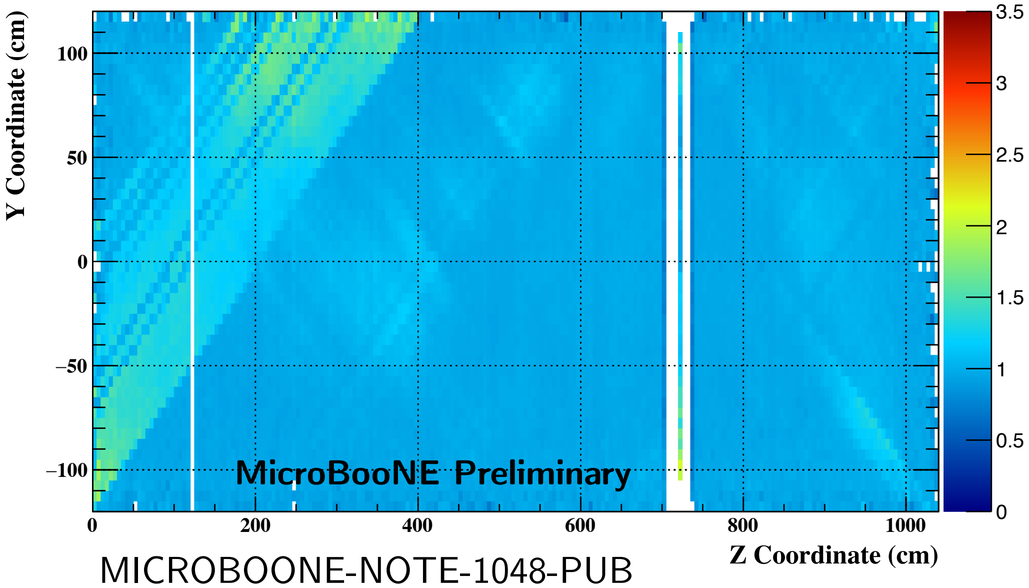
Electric Field	Electron Recombination	Electron Diffusion	Electron Attenuation	*dQ/dx* Response
Field distortions due to ion buildup	Electron loss due to ion recombination	Transverse & longitudinal spread during drift	Electron loss due to Ar impurities	High-level energy response calibration

***In Situ* Laser System**



MICROBOONE-NOTE-1018-PUB

***dQ/dx* Calibration with Cosmic Muons**



MICROBOONE-NOTE-1048-PUB

Detector Modeling

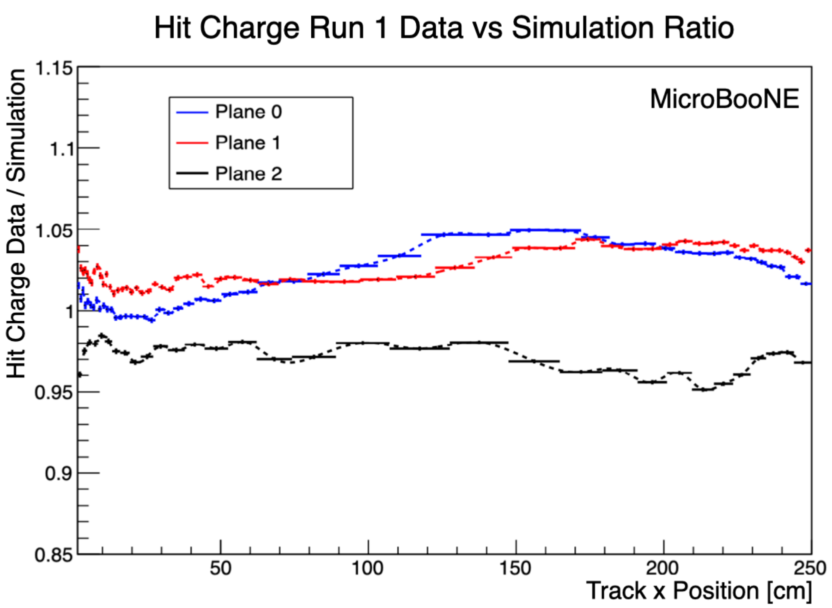
Diffusion: JINST 16, P09025 (2021)
Space charge: JINST 15, P12037 (2020)
Signal model: JINST 12, P08003 (2017); JINST 13, P07006 & P07007 (2018)
TPC Cal: JINST 15, P03022 (2020)
E Field: JINST 15, P07010 & P12037 (2020)
EM Showers: JINST 15, P02007 (2020), arxiv:2110.11874
Protons: arxiv:2109.02460 (accepted to JHEP)

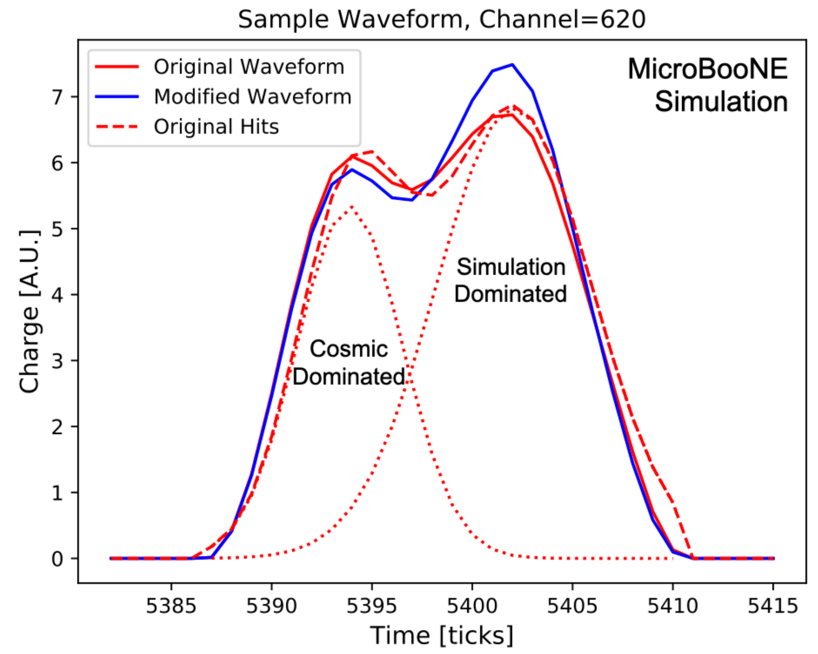
Detailed modeling of **particle propagation**, **electron drift & detector response**, and **photon propagation**

1. **Signal processing** (MicroBooNE, JINST 13 P07007, 2018 and JINST 13 P07007, 2018)
2. **Response Calibration** *or* How Things Go Wrong
3. **Systematic Uncertainties**

- Highest precision measurements yet performed with LArTPC technology
- Many subtle and correlated effects in the detector response model
- **A novel approach:** Capture waveform-level data/MC differences in response as a function of x, yz, angles, etc. as a correction and residual modeling systematic
- Augment with light, G4, and other systematics

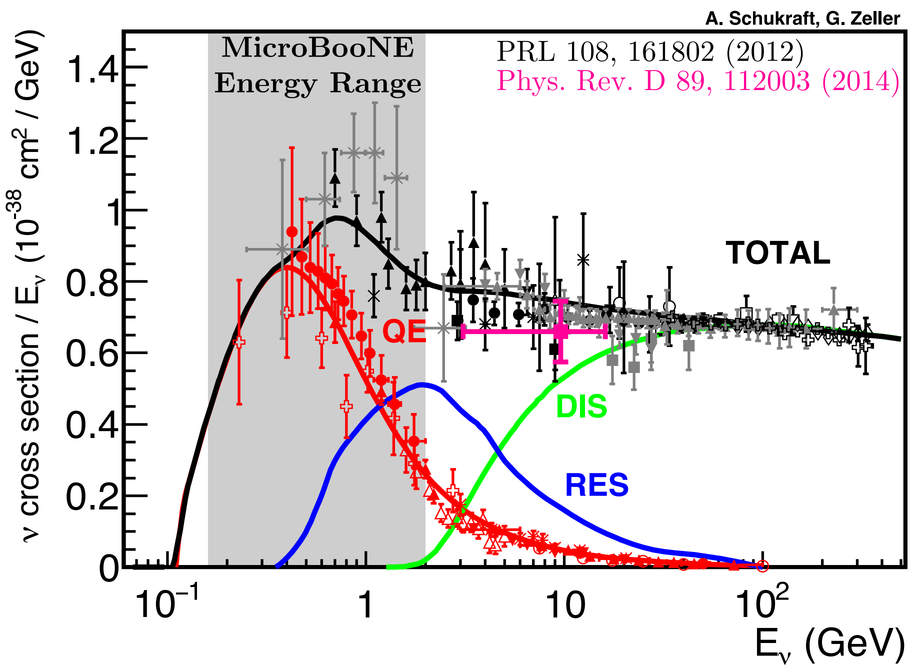
arxiv:2111.03556, submitted to *EPJC*

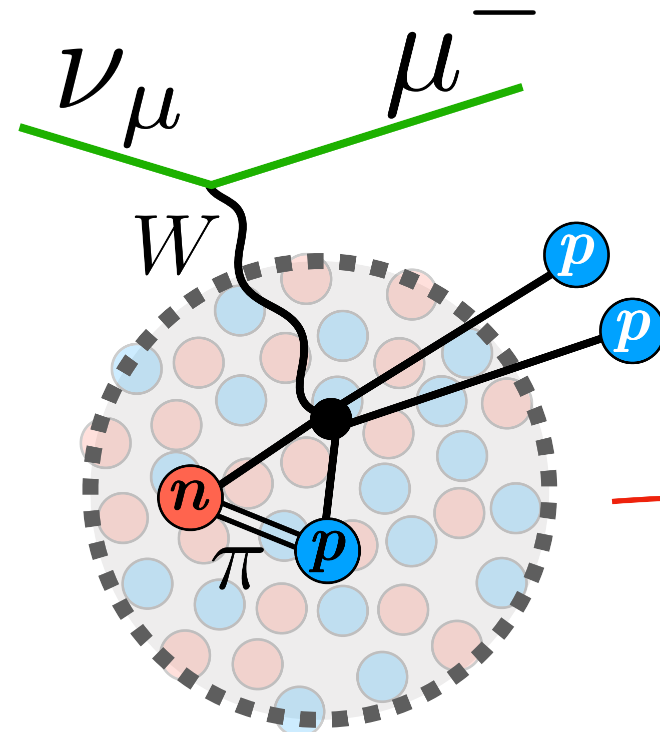


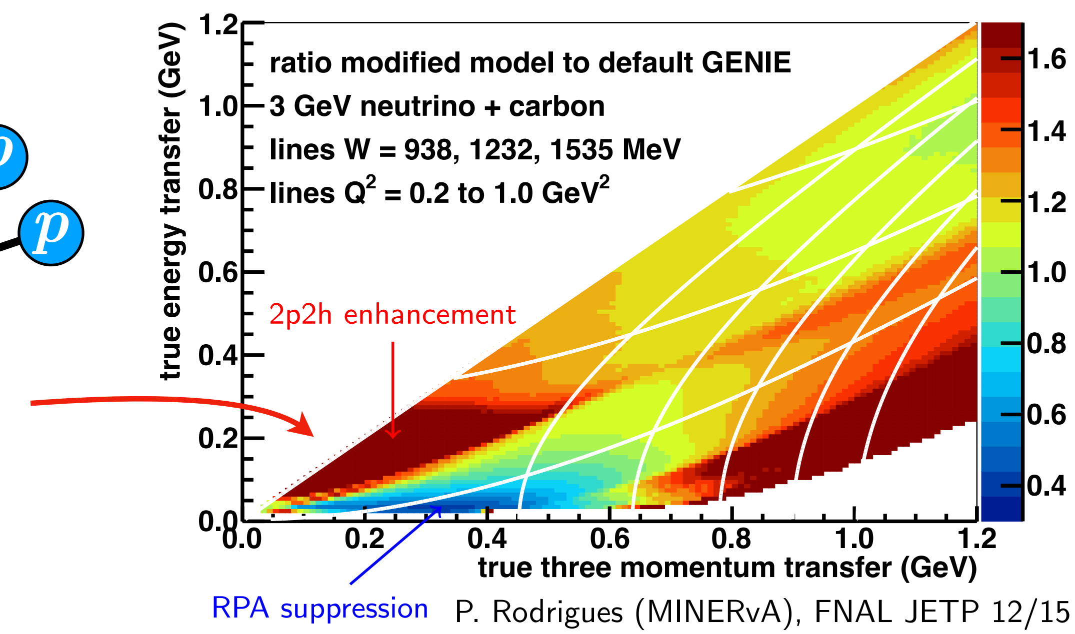


Neutrino Interactions

Interaction Modeling & Uncertainties





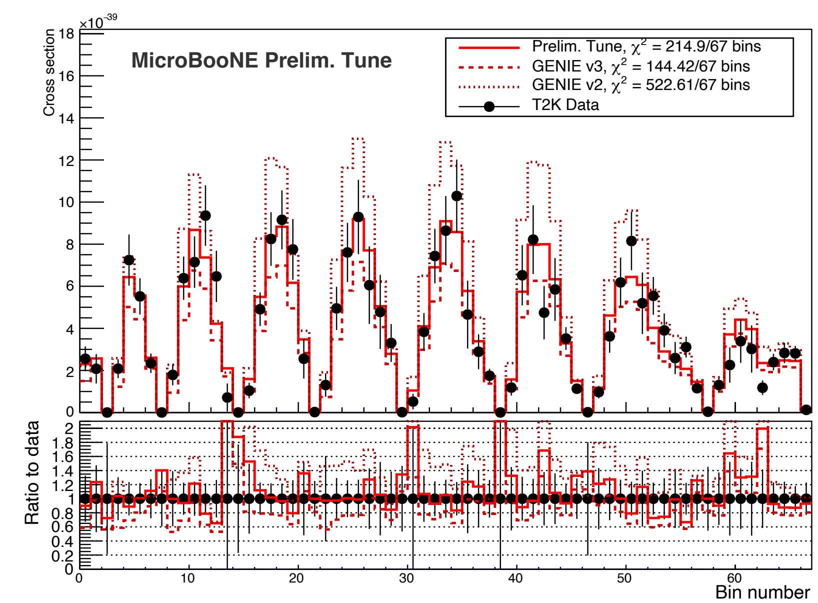


P. Rodrigues (MINERvA), FNAL JETP 12/15

Searching for possible new physics in a regime with poor *a priori* constraints (ν-Ar interactions at 200 MeV)

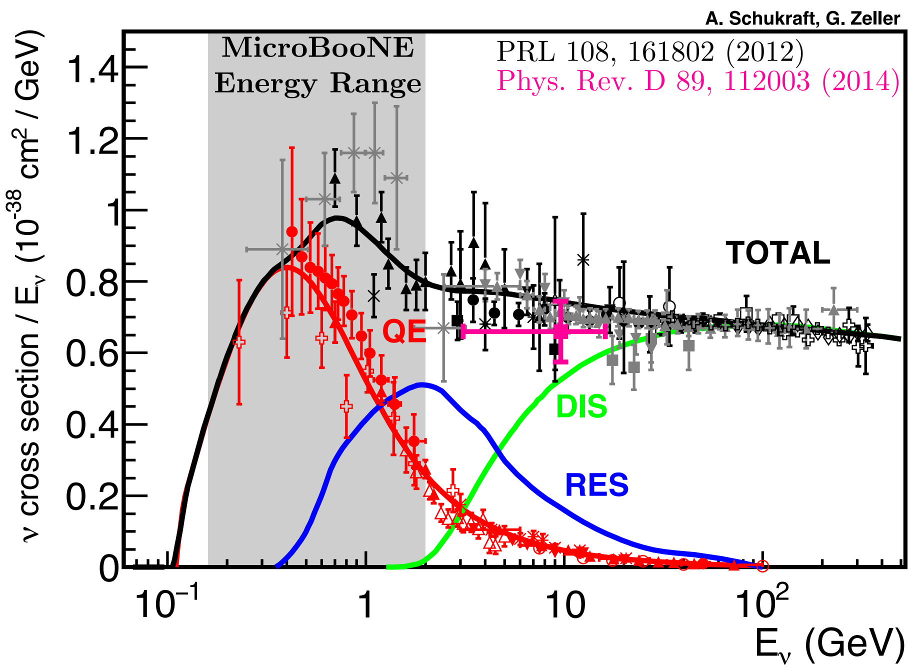
Nuclear physics effects
e.g. interactions with correlated nucleon pairs (*2p2h*, or MEC)

- Pioneered the use GENIE version 3
  - Latest theory-driven modeling
- New tunes including T2K CC0π data
  - Tuning & uncertainties for the most important model degrees of freedom
  - arxiv:2110.14028, submitted to PRD



Neutrino Interactions

Interaction Modeling & Uncertainties



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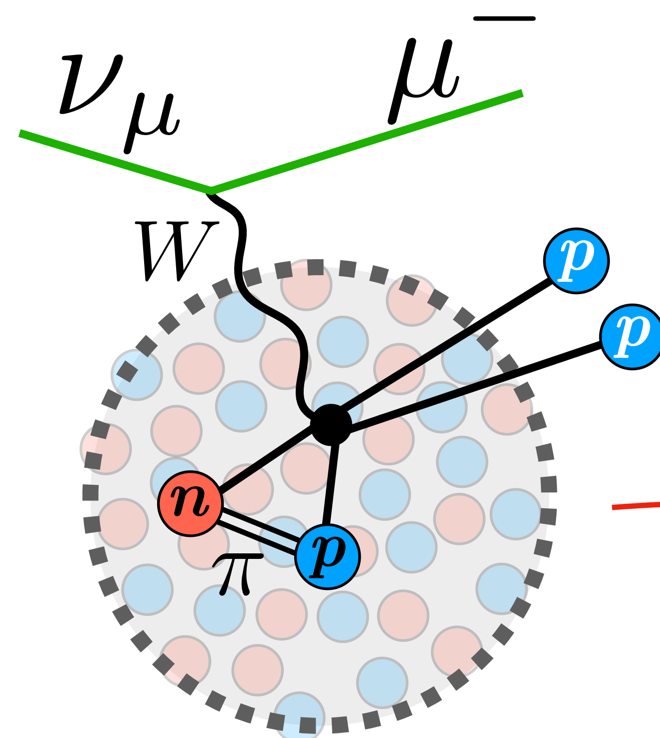

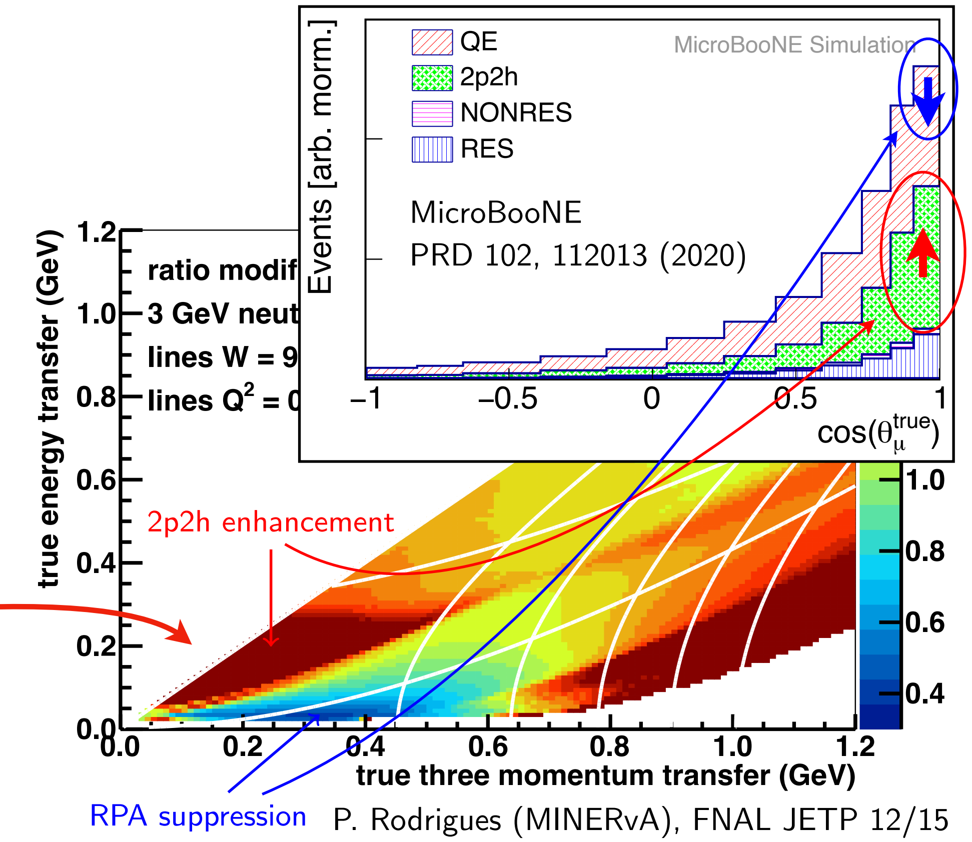

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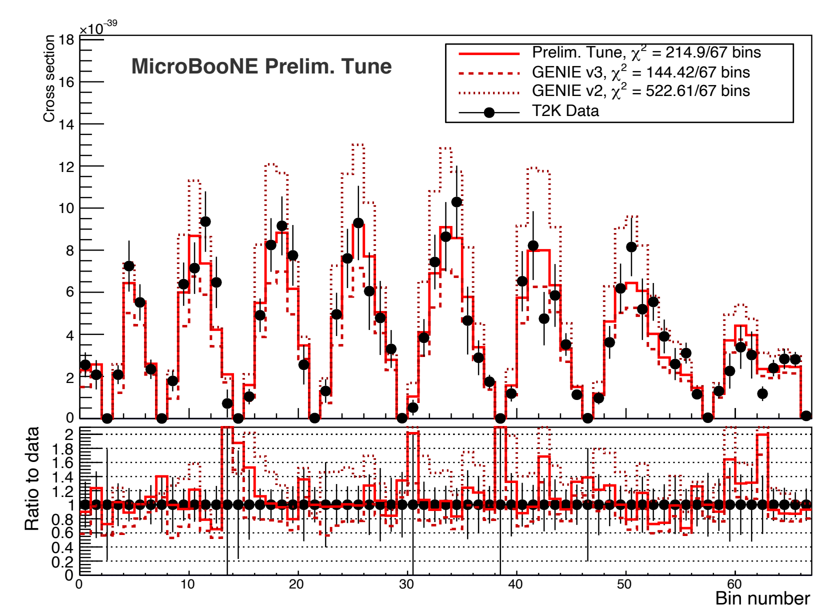
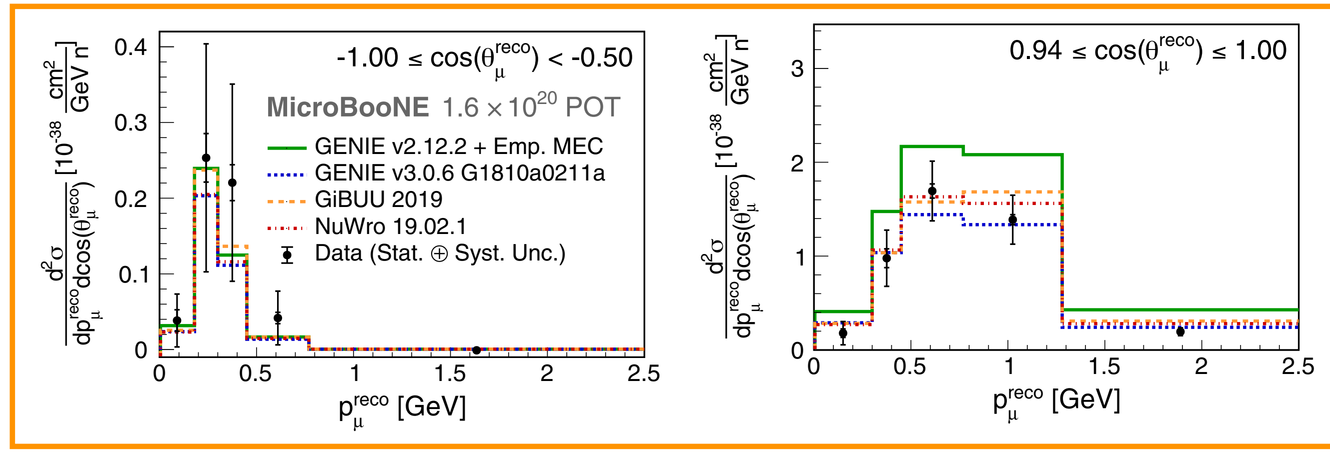
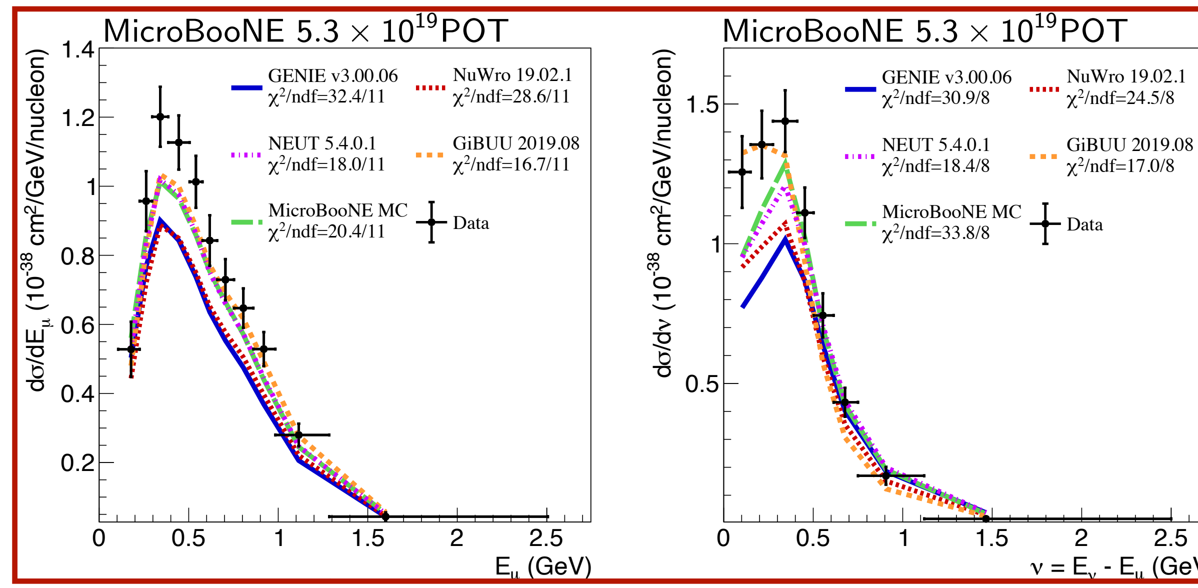


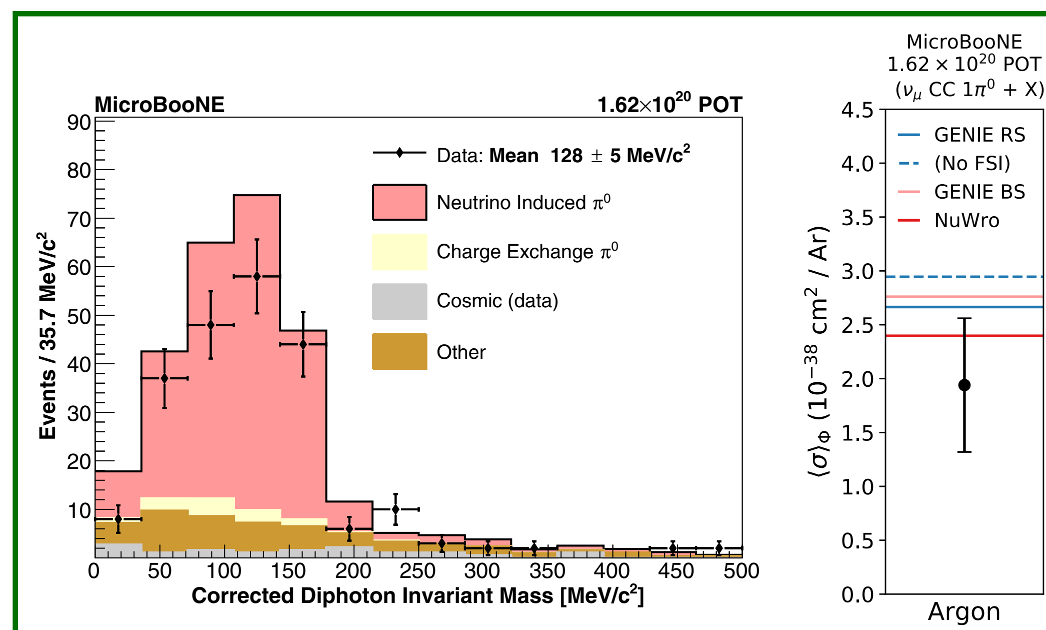
Neutrino Interactions

Selected Cross Section Results

- **ν_μ-Argon CC Inclusive**
  - **PRL 123 13, 131801 (2019)**
  - Double-differential (p_μ, $\cos\vartheta_\mu$) cross section with 4π angular coverage
  - Suppression at high $\cos\vartheta_\mu$ favors newer models with low-Q^2 RPA suppression
- **Energy-dependent CC Inclusive**
  - **arXiv:2110.14023, sub. to PRL**
  - High-statistics measurement of νμ CC inclusive: total σ & vs. E_μ and ν
  - Updated uncertainty modeling
- **ν_μ CC π^0 production**
  - **Phys. Rev. D 99 9, 091102 (2019)**
  - Probes A dependence in FSI modeling
  - Electromagnetic shower reconstruction



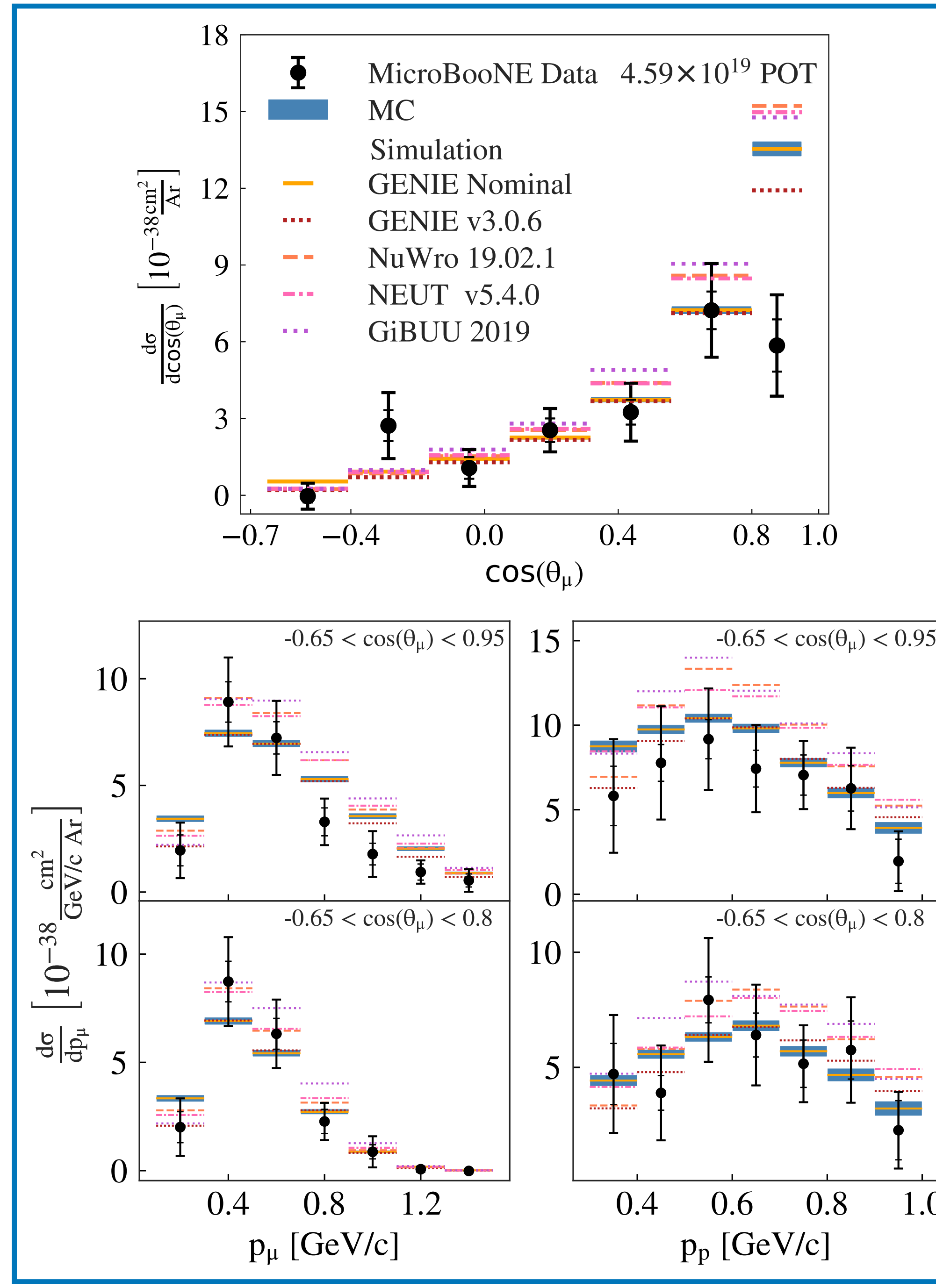


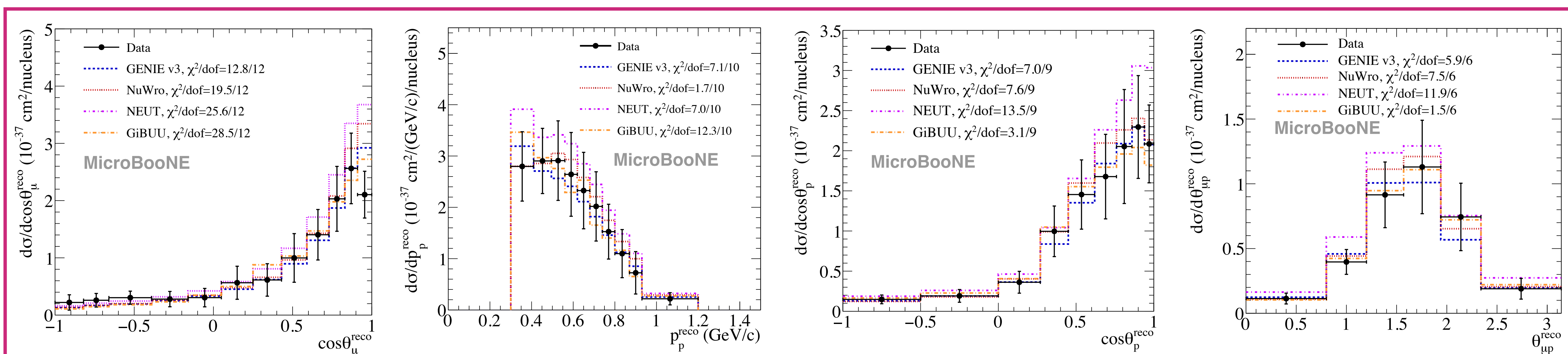


Neutrino Interactions

Selected Cross Section Results: Protons

- ν_μ **CC quasielastic-like ($1\mu 1p$)**
  - **Phys. Rev. Lett. 125 20, 201803 (2020)**
  - High-purity exclusive CCQE selection
  - 81% CCQE purity using $\Delta\varphi_{\mu p}$ coplanarity and transverse momentum $p_T < 350$ MeV/c
- ν_μ **CC $1\mu\ 0\pi$ Np**
  - **Phys. Rev. D 102, 112013 (2020)**
  - 1D differential in p_μ, p_p, ϑ_μ, ϑ_p, $\vartheta_{\mu p}$
  - Model comparisons in hadronic kinematics
  - Phase space matching detector response: p_μ>100 MeV/c, leading p_p 300–1200 MeV/c

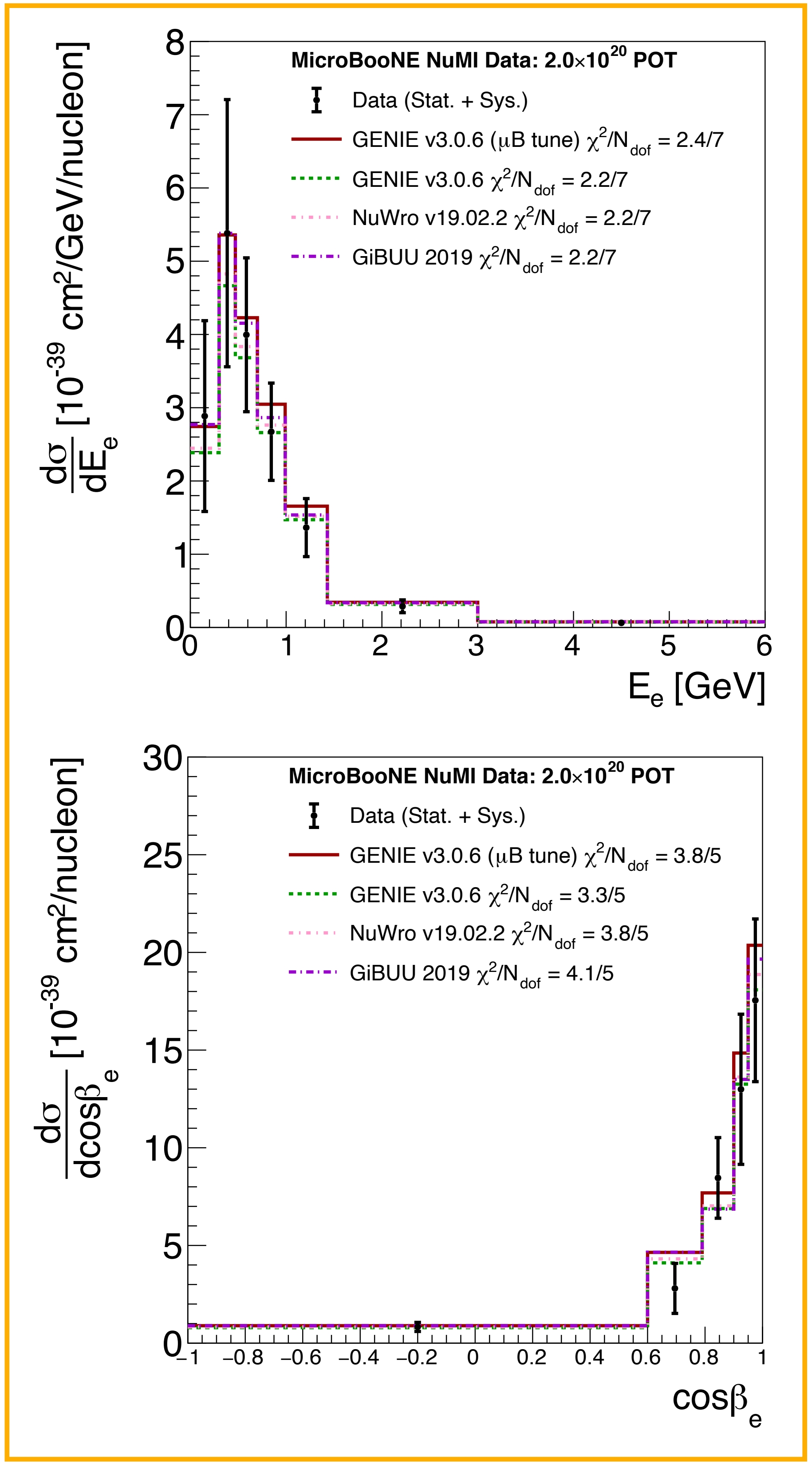


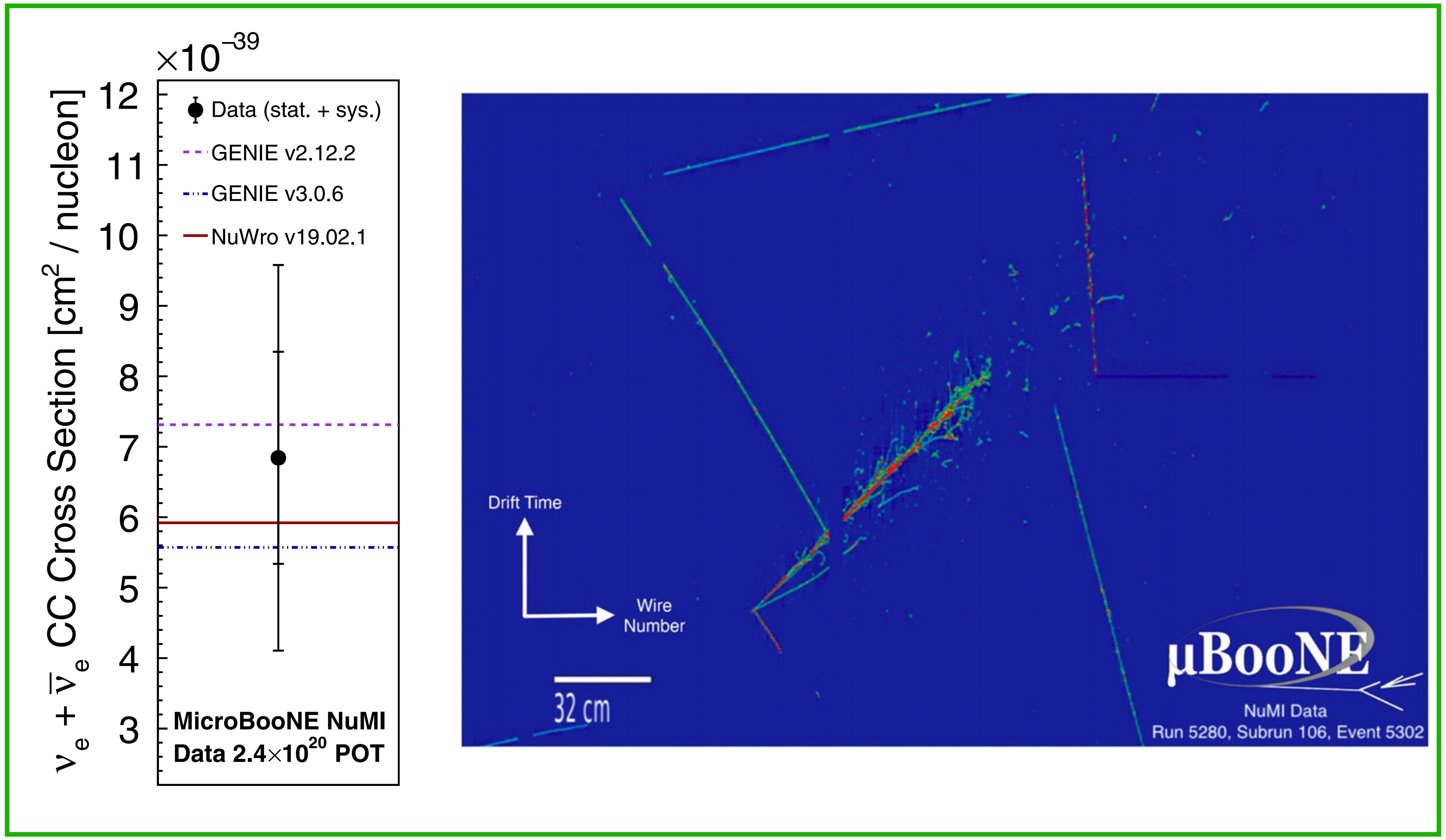


Neutrino Interactions

Cross Sections: NuMI Electron Neutrinos

- **ν_e CC Inclusive with the NuMI beam**
  - Separate, off-axis beam, ~5% ν_e contribution
  - **Flux-integrated**
    - PRD 104, 052002 (2021)
  - **Differential (E_e, cosβ_e)**
    - arxiv:2109.06832 (submitted to PRL)





MicroBooNE

2017 ↓ 2018 ↓ 2019 ↓ 2020 ↓ 2021

- First Measurement of Energy-dependent Inclusive Muon Neutrino Charged-Current Cross Sections on Argon with the MicroBooNE Detector
- Wire-Cell 3D Pattern Recognition Techniques for Neutrino Event Reconstruction in Large LArTPCs: Algorithm Description and Quantitative Evaluation with MicroBooNE Simulation
- New Theory-driven GENIE Tune for MicroBooNE
- Search for an anomalous excess of inclusive charged-current ν_e interactions in the MicroBooNE experiment using Wire-Cell reconstruction
- Search for an anomalous excess of charged-current ν_e interactions without pions in the final state with the MicroBooNE experiment
- Search for an anomalous excess of charged-current quasi-elastic ν_e interactions with the MicroBooNE experiment using Deep-Learning-based reconstruction
- Search for an Excess of Electron Neutrino Interactions in MicroBooNE Using Multiple Final State Topologies
- Electromagnetic Shower Reconstruction and Energy Validation with Michel Electrons and π^0 Samples for the Deep-Learning-Based Analyses in MicroBooNE
- Search for Neutrino-Induced Neutral Current Δ Radiative Decay in MicroBooNE and a First Test of the MiniBooNE Low Energy Excess Under a Single-Photon Hypothesis
- First Measurement of Inclusive Electron-Neutrino and Antineutrino Charged Current Differential Cross Sections in Charged Lepton Energy on Argon in MicroBooNE
- Calorimetric classification of track-like signatures in liquid argon TPCs using MicroBooNE data
- Search for a Higgs portal scalar decaying to electron-positron pairs in the MicroBooNE detector
- Measurement of the Longitudinal Diffusion of Ionization Electrons in the MicroBooNE Detector
- Cosmic Ray Background Rejection with Wire-Cell LArTPC Event Reconstruction in the MicroBooNE Detector
- Measurement of the Flux-Averaged Inclusive Charged-Current Electron Neutrino and Antineutrino Cross Section on Argon using the NuMI Beam and the MicroBooNE Detector
- Measurement of the Atmospheric Muon Rate with the MicroBooNE Liquid Argon TPC
- Semantic Segmentation with a Sparse Convolutional Neural Network for Event Reconstruction in MicroBooNE
- High-performance Generic Neutrino Detection in a LArTPC near the Earth's Surface with the MicroBooNE Detector
- Neutrino Event Selection in the MicroBooNE Liquid Argon Time Projection Chamber using Wire-Cell 3D Imaging, Clustering, and Charge-Light Matching
- A Convolutional Neural Network for Multiple Particle Identification in the MicroBooNE Liquid Argon Time Projection Chamber
- Measurement of Differential Cross Sections for Muon Neutrino Charged Current Interactions on Argon with Protons and No Pions in the Final State with the MicroBooNE Detector
- The Continuous Readout Stream of the MicroBooNE Liquid Argon Time Projection Chamber for Detection of Supernova Burst Neutrinos
- Measurement of Space Charge Effects in the MicroBooNE LArTPC Using Cosmic Muons
- First Measurement of Differential Charged Current Quasi-Elastic-Like Muon Neutrino Argon Scattering Cross Sections with the MicroBooNE Detector
- Vertex-Finding and Reconstruction of Contained Two-track Neutrino Events in the MicroBooNE Detector
- Search for heavy neutral leptons decaying into muon-pion pairs in the MicroBooNE detector
- Reconstruction and Measurement of O(100) MeV Electromagnetic Activity from Neutral Pion to Gamma Gamma Decays in the MicroBooNE LArTPC
- A Method to Determine the Electric Field of Liquid Argon Time Projection Chambers Using a UV Laser System and its Application in MicroBooNE
- Calibration of the Charge and Energy Response of the MicroBooNE Liquid Argon Time Projection Chamber Using Muons and Protons
- First Measurement of Inclusive Muon Neutrino Charged Current Differential Cross Sections on Argon at Enu ~0.8 GeV with the MicroBooNE Detector
- Design and Construction of the MicroBooNE Cosmic Ray Tagger System
- Rejecting Cosmic Background for Exclusive Neutrino Interaction Studies with Liquid Argon TPCs: A Case Study with the MicroBooNE Detector
- First Measurement of Muon Neutrino Charged Current Neutral Pion Production on Argon with the MicroBooNE detector
- A Deep Neural Network for Pixel-Level Electromagnetic Particle Identification in the MicroBooNE Liquid Argon Time Projection Chamber
- Comparison of Muon-Neutrino-Argon Multiplicity Distributions Observed by MicroBooNE to GENIE Model Predictions
- Ionization Electron Signal Processing in Single Phase LArTPCs II: Data/Simulation Comparison and Performance in MicroBooNE
- Ionization Electron Signal Processing in Single Phase LArTPCs I: Algorithm Description and Quantitative Evaluation with MicroBooNE Simulation
- The Pandora Multi-Algorithm Approach to Automated Pattern Recognition of Cosmic Ray Muon and Neutrino Events in the MicroBooNE Detector
- Measurement of Cosmic Ray Reconstruction Efficiencies in the MicroBooNE LAr TPC Using a Small External Cosmic Ray Counter
- Noise Characterization and Filtering in the MicroBooNE Liquid Argon TPC
- Michel Electron Reconstruction Using Cosmic Ray Data from the MicroBooNE LArTPC
- Determination of Muon Momentum in the MicroBooNE LAr TPC Using an Improved Model of Multiple Coulomb Scattering
- Convolutional Neural Networks Applied to Neutrino Events in a Liquid Argon Time Projection Chamber
- Design and Construction of the MicroBooNE Detector

Over 40 papers covering:

- Detector R&D, modeling, & calibration
- Analysis & reconstruction techniques
- Neutrino cross sections
- Beyond the Standard Model searches
- First Low-Energy Excess results

(Plus over 60 Technical Notes)
https://microboone.fnal.gov/public-notes/

Diagram courtesy of B. Fleming

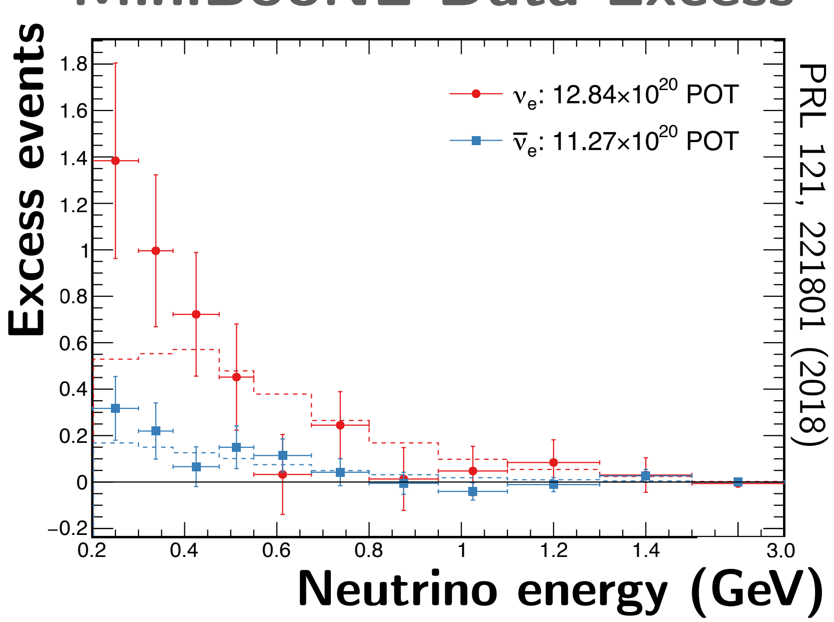
MicroBooNE

Addressing the MiniBooNE Excess

Questions: Is MicroBooNE's data compatible with...

- Background expectations?
- Short-baseline neutrino oscillations?
- The MiniBooNE Excess
  - An electron-like excess: ν_e CCQE?
  - A photon-like excess: NC 1γ?
  - Other interpretations?

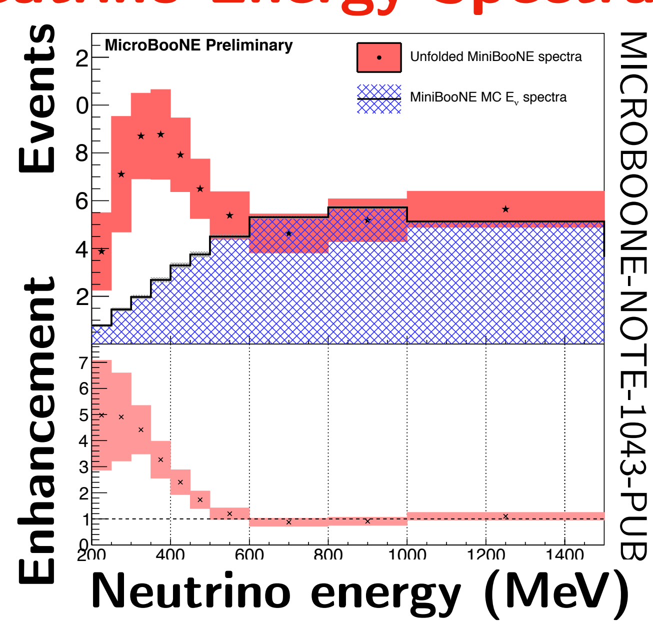
MiniBooNE Data Excess



MC Unfolding

(CCQE Hypothesis)

Neutrino Energy Spectrum



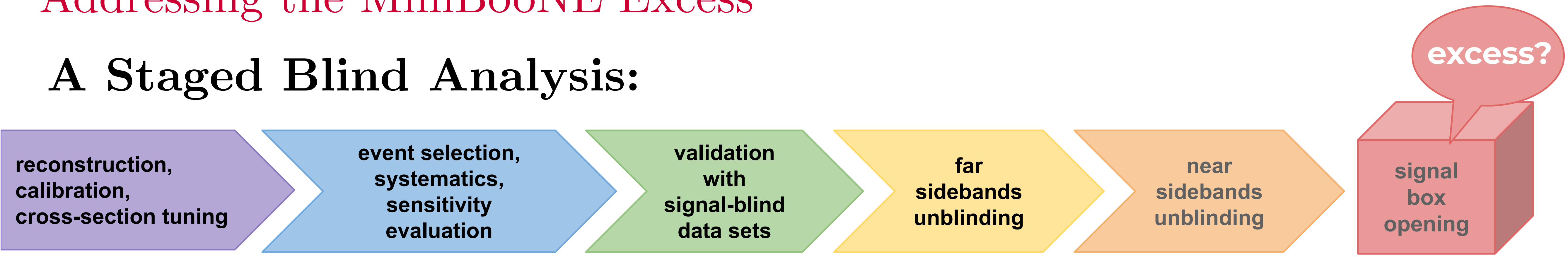
Simulation & Selection

MicroBooNE Sensitivity & Significance

MicroBooNE

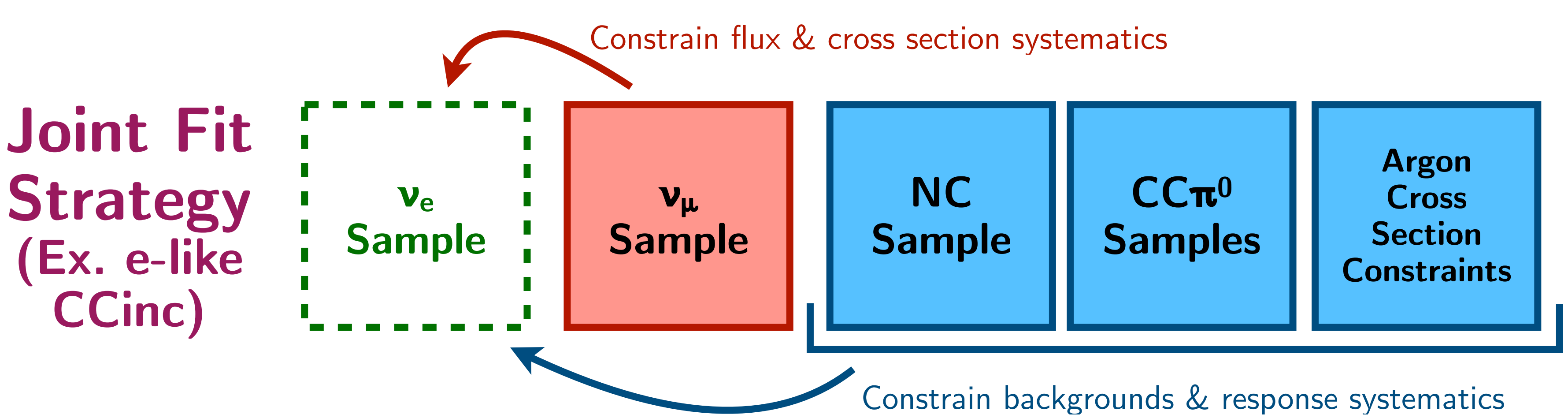
Addressing the MiniBooNE Excess

A Staged Blind Analysis:



G. Karagiorgi, Neutrino 2020

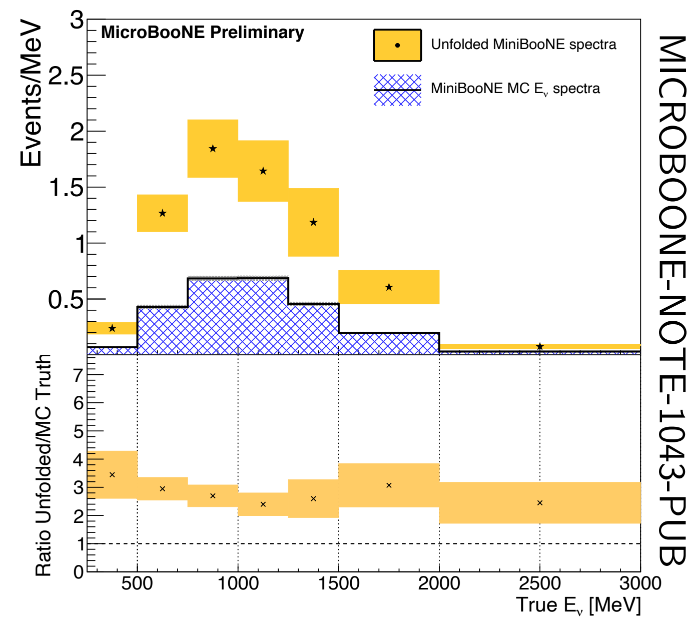
- **Staged blind analysis** — far and near energy/PID sidebands leading to the signal box
  - All analyses reviewed and "frozen" prior to unblinding
  - Developed on MC & ~3% data (5×10^{19} POT), applied to 7×10^{20} POT (of 15×10^{20} POT total)
- **Multiple complementary event reconstruction techniques** and **final states** (e/γ)
  - Photon-like ($\Delta\rightarrow N\gamma$) excess, using Pandora-based reconstruction
  - Electron-like excess in CC0π, Pandora-based reconstruction
  - Electron-like excess with QE-like $1\ell 1p$, Deep-Learning reconstruction
  - Electron-like excess in CC inclusive, using tomographic (WireCell) 3D reconstruction

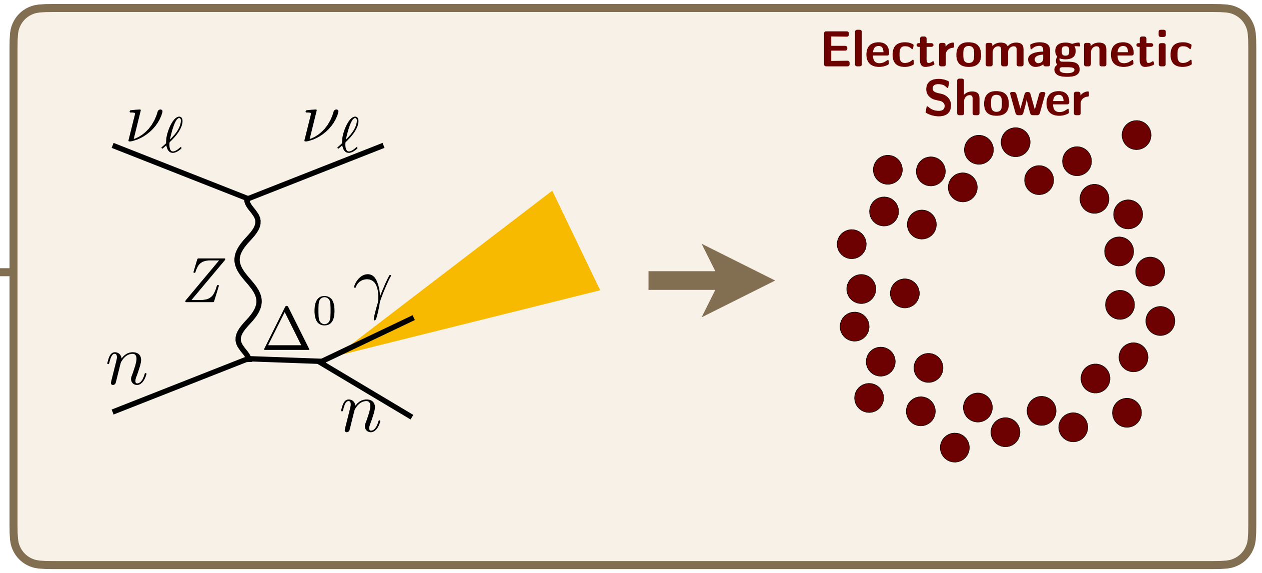


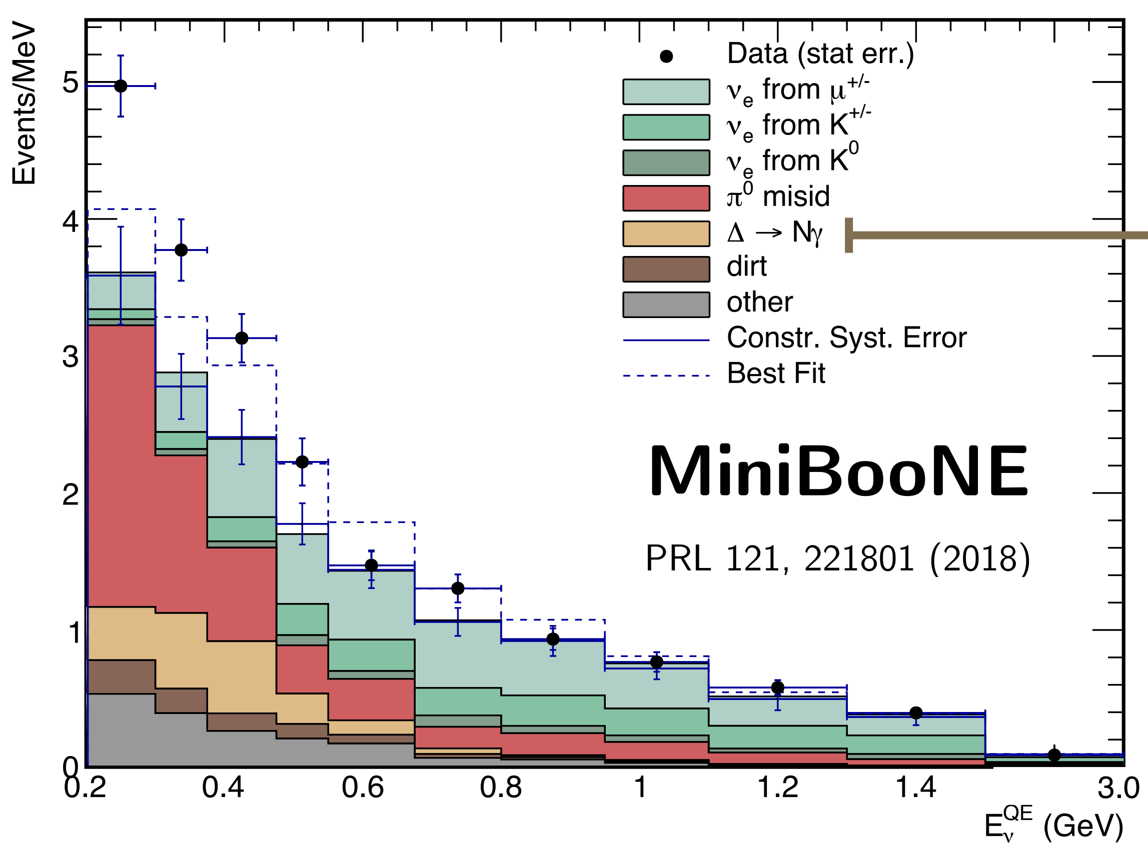
Single Photon Search

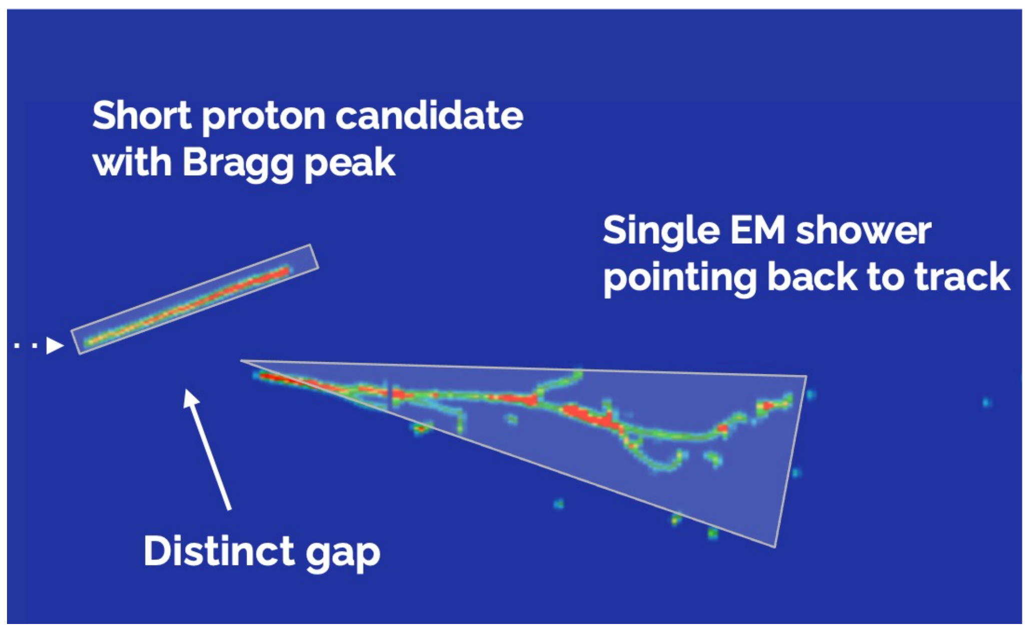
Neutral Current Single Photon Production

- **NC Δ(1232)→Nγ production**
- Unmeasured in neutrino scattering, T2K limit ~100× prediction (J.Phys.G **46**, 08LY01 (2019))
- Indirect constraint in MiniBooNE: theory and in situ π^0 measurement
- Flat enhancement ×3.18 could explain the MiniBooNE excess





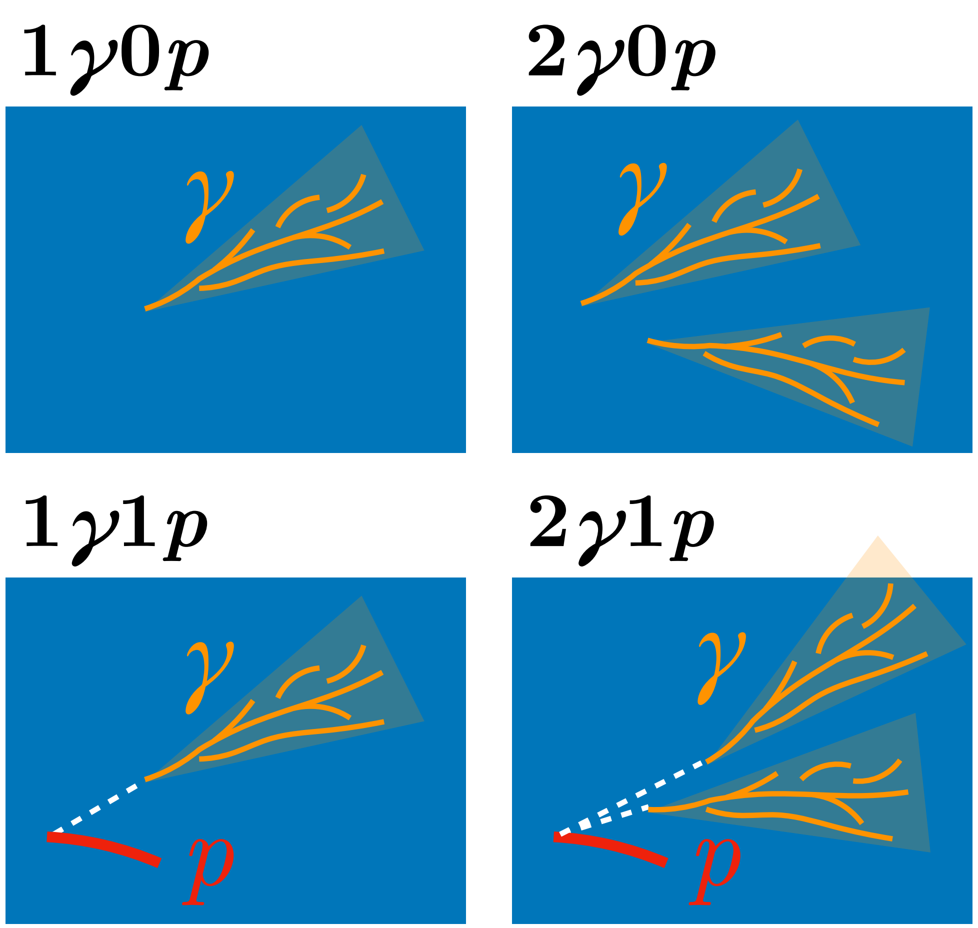


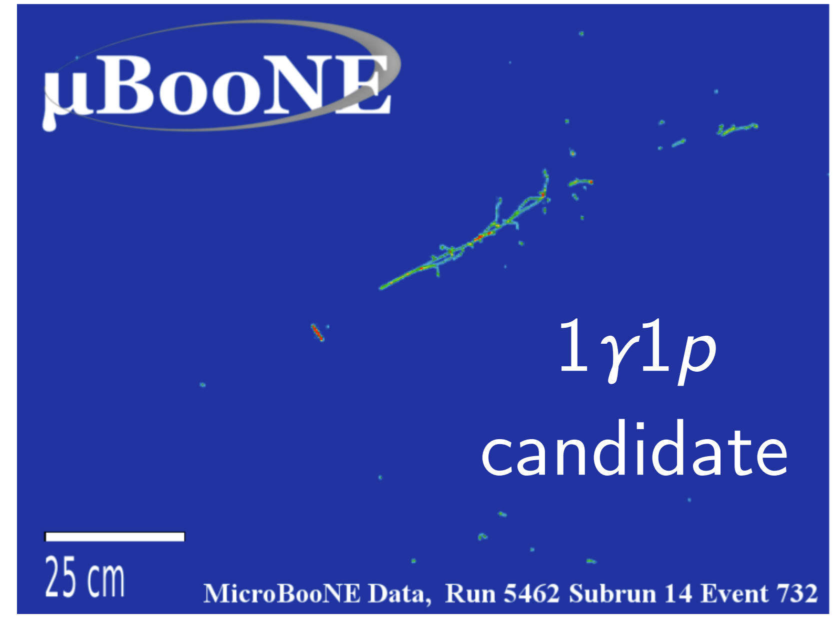


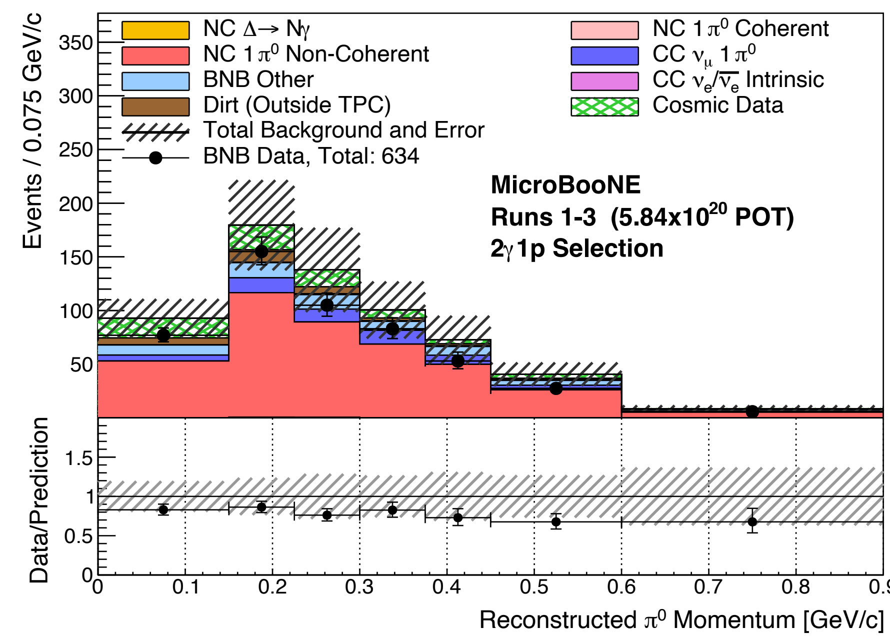
Single Photon Search

Neutral Current Single Photon Production

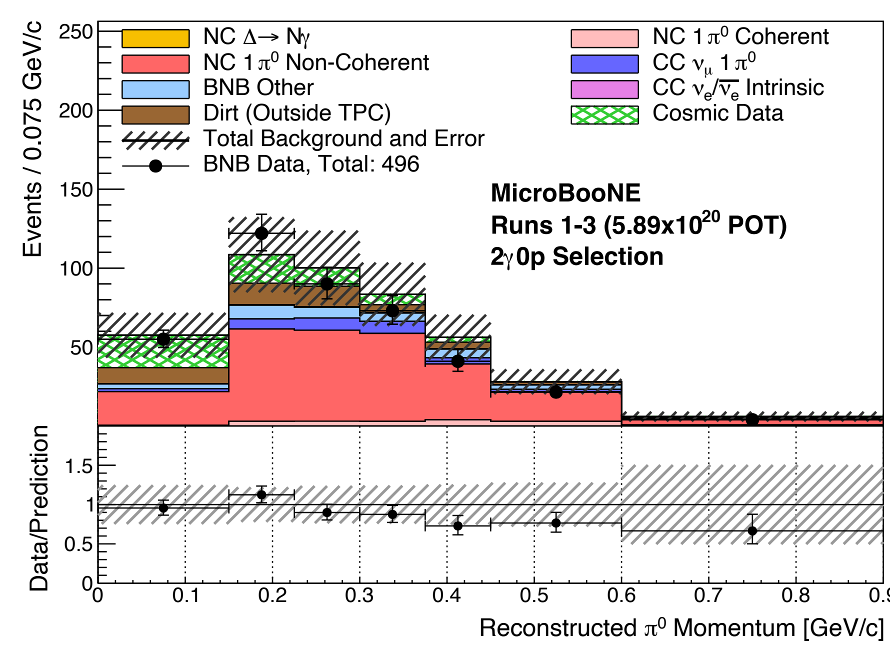
- Signal search in 1γ1p and 1γ0p
  - 5 (3) BDTs trained for background ID
- 2γ1p and 2γ0p constrain π0 background →
- GENIE v3.0.6: Berger-Sehgal resonance model with updated tuning to ν-A data
- Pandora event reconstruction (EPJC **78**, 82 (2018))







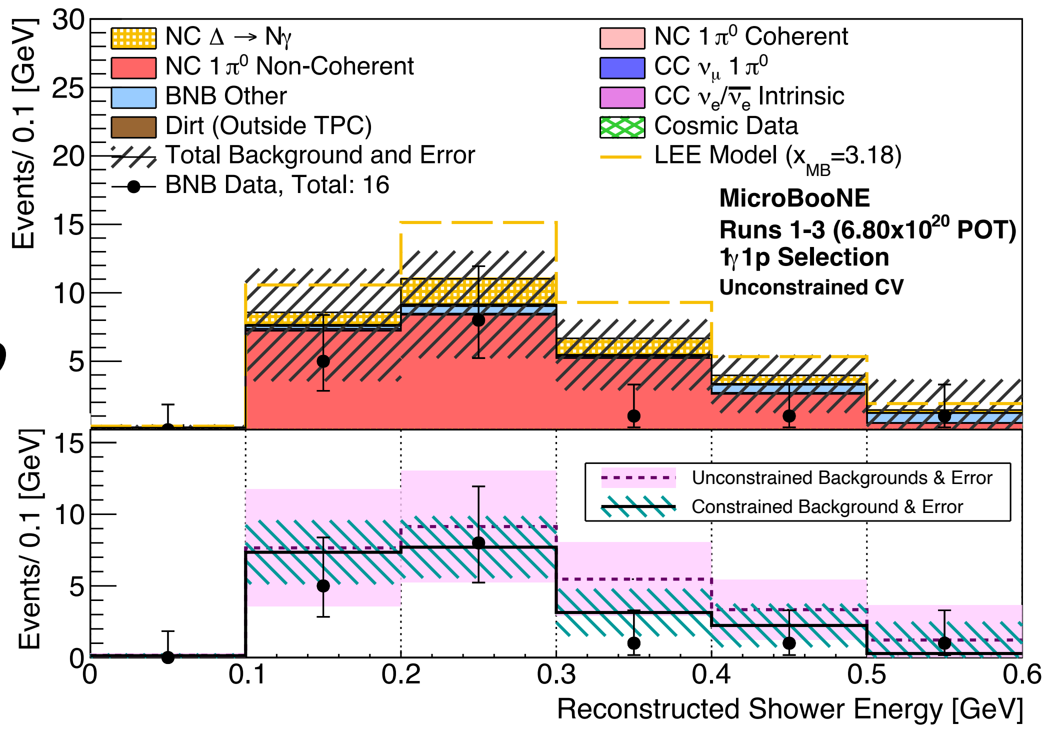
(a)



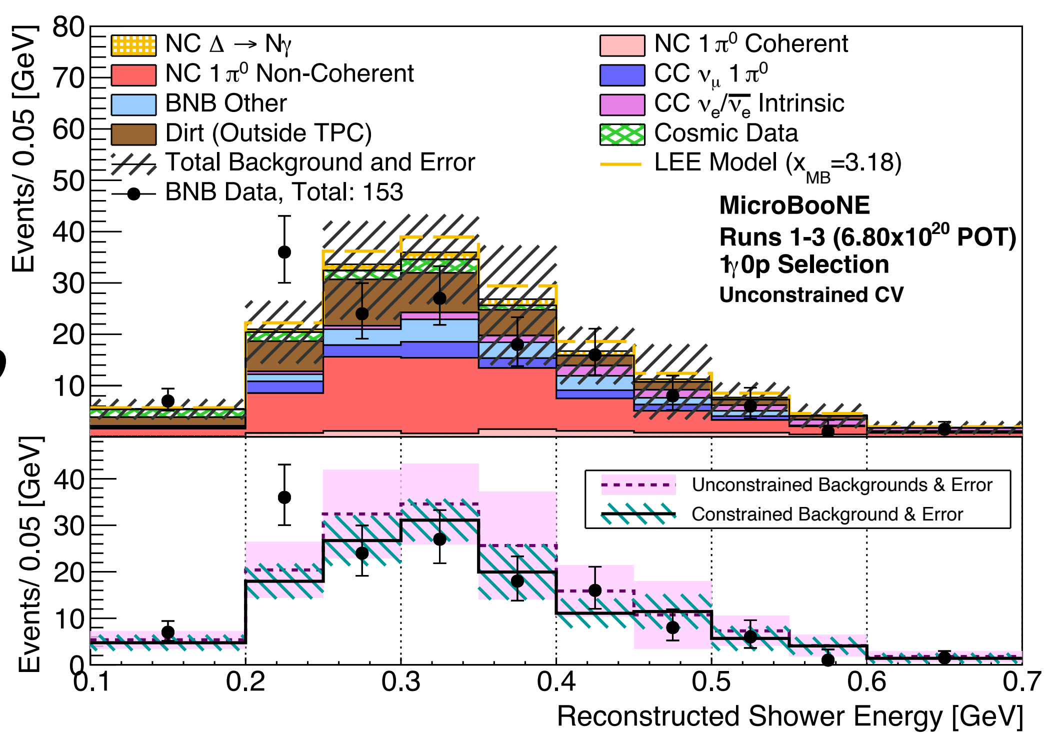
Single Photon Search

Results

$1\gamma 1p$

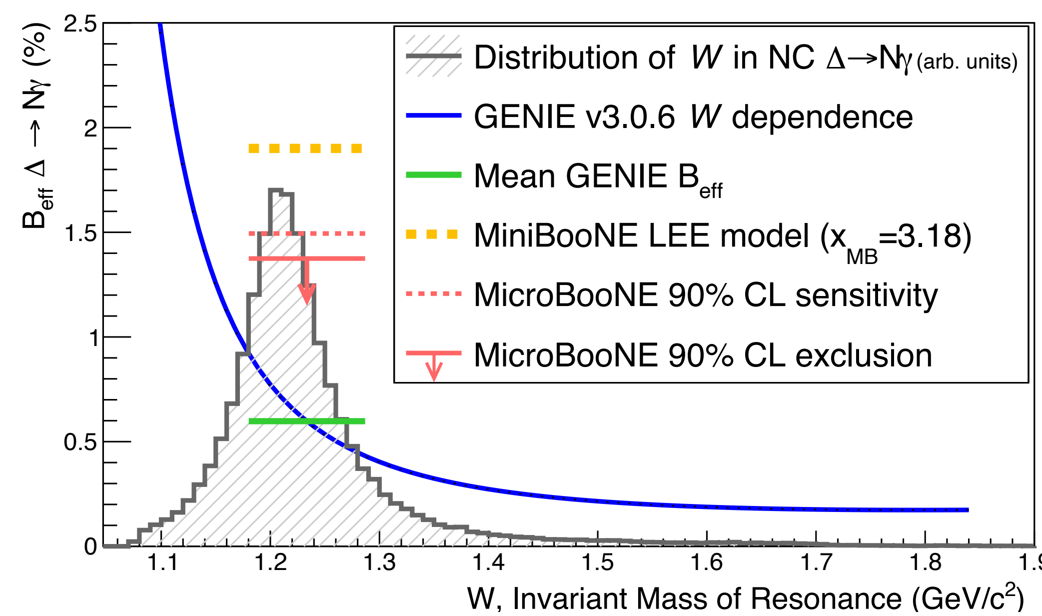


$1\gamma 0p$



Measurements disfavor the Δ→Nγ hypothesis as the sole explanation of the MiniBooNE anomaly at the 94.8% CL

Null result → 50× improvement in upper limit on the effective BR for this mode

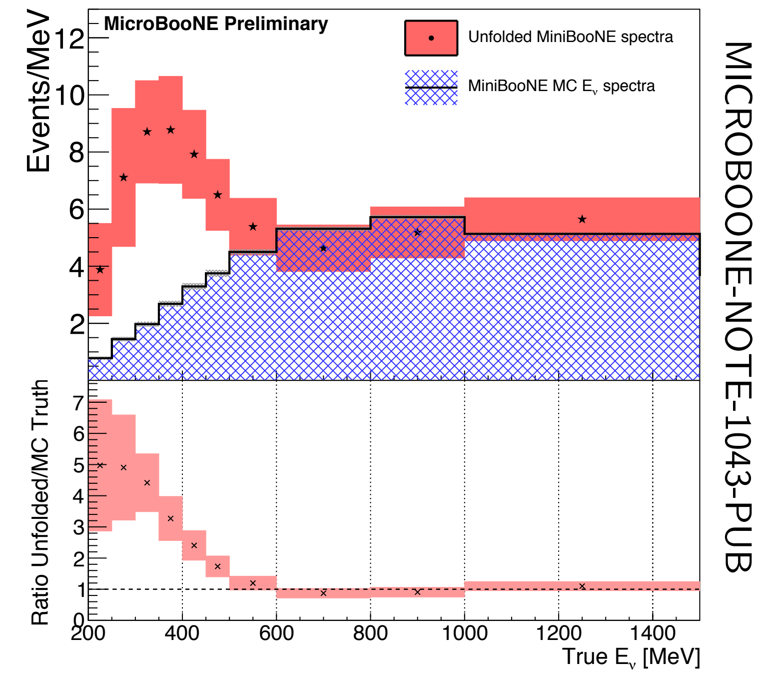


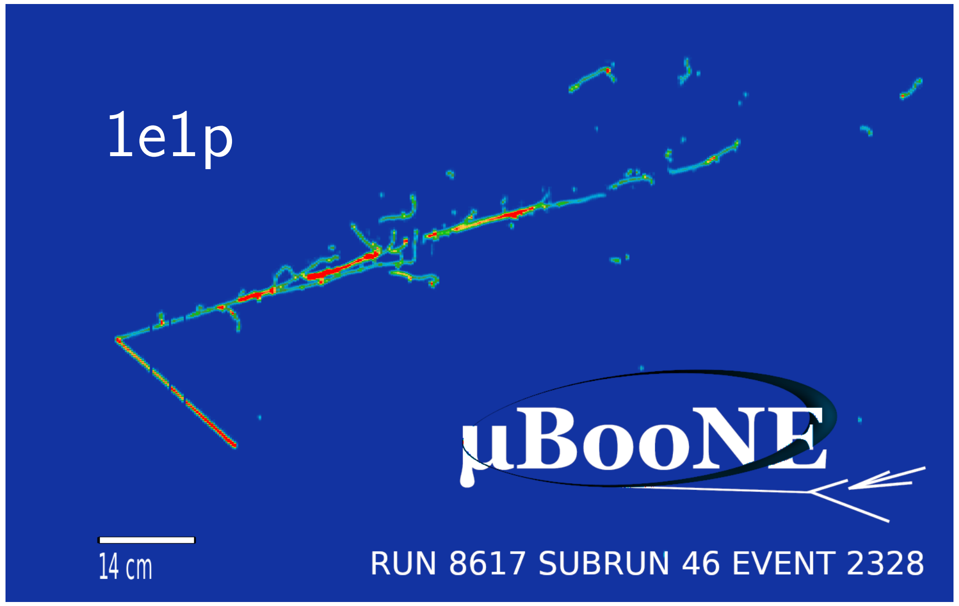
arxiv:2110.00409, submitted to *Phys. Rev. Lett.*

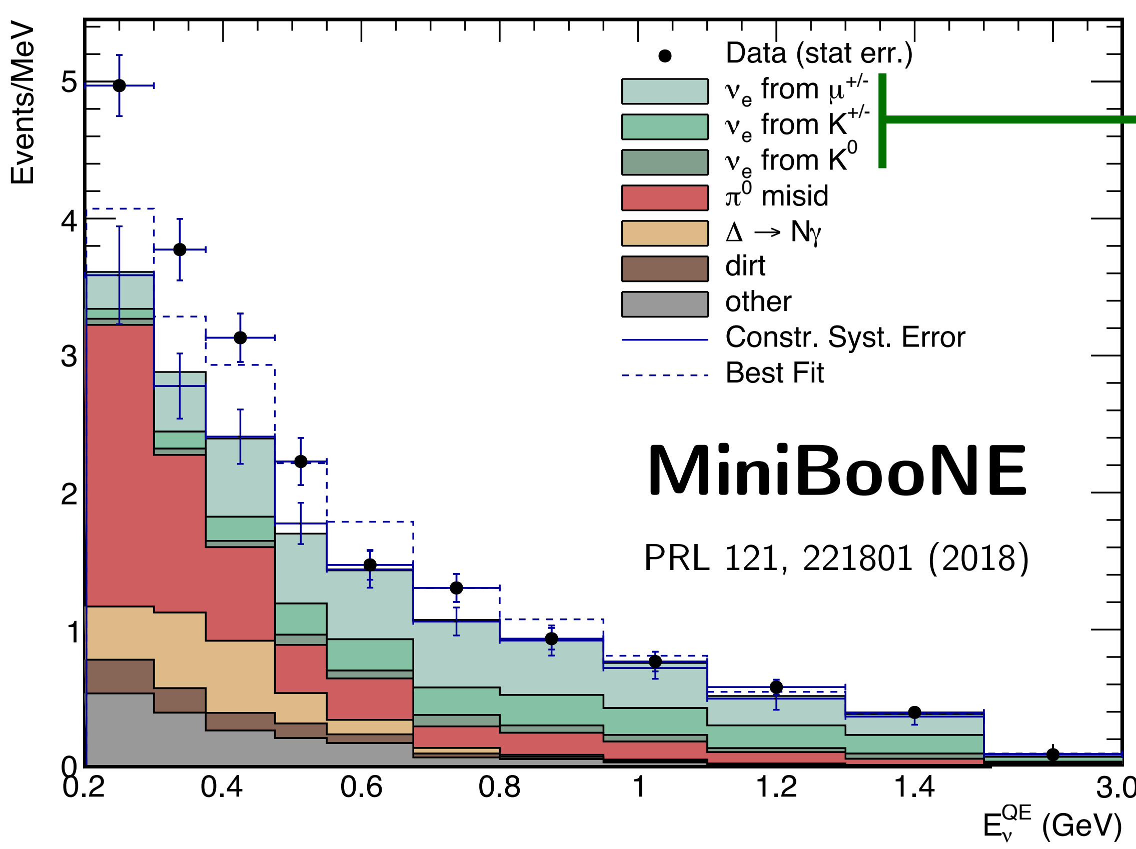
Electron Search

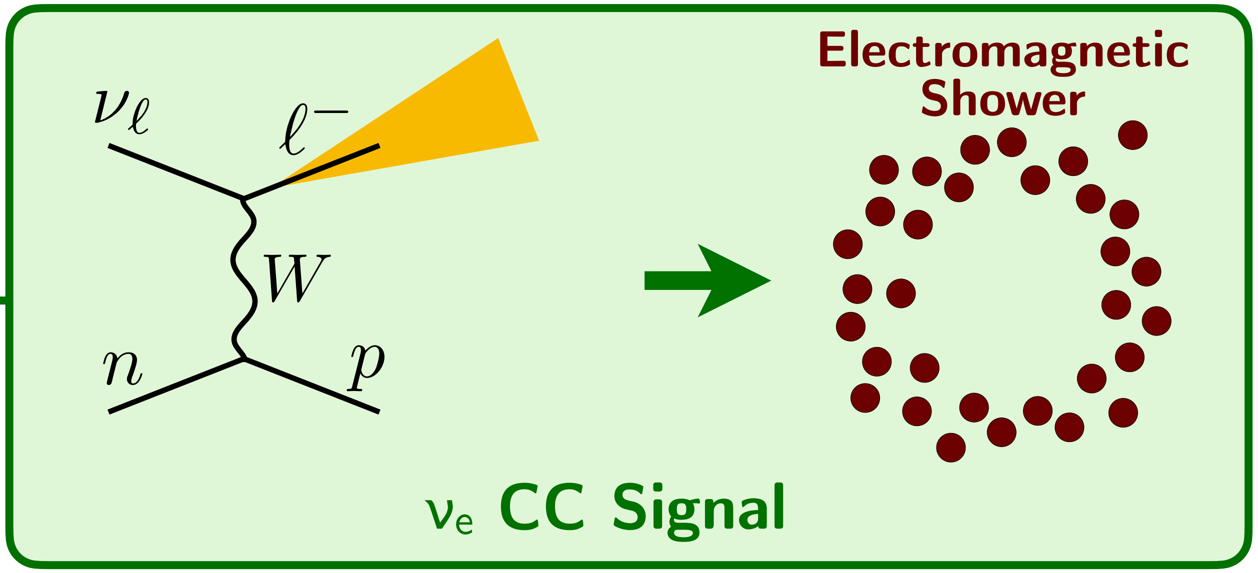
ν_e-like Interactions

- **Energy-dependent ν_e rate enhancement**
- Three complementary search channels
  - **CCQE-like:** Clean two-body kinematics
  - **CC0π:** MiniBooNE-like, kinematics-free
  - **CC inclusive:** High efficiency, little dependence on hadronic modeling
- GENIE v3.0.6 + QE tuning with T2K









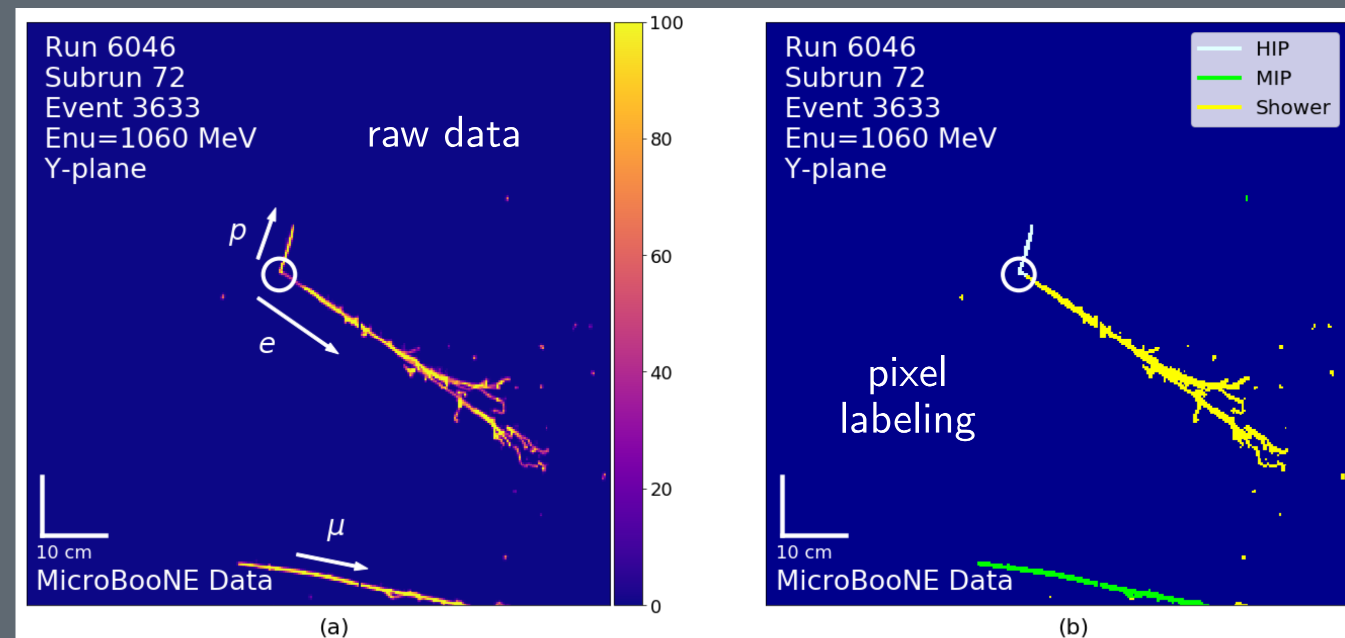
Electron Search

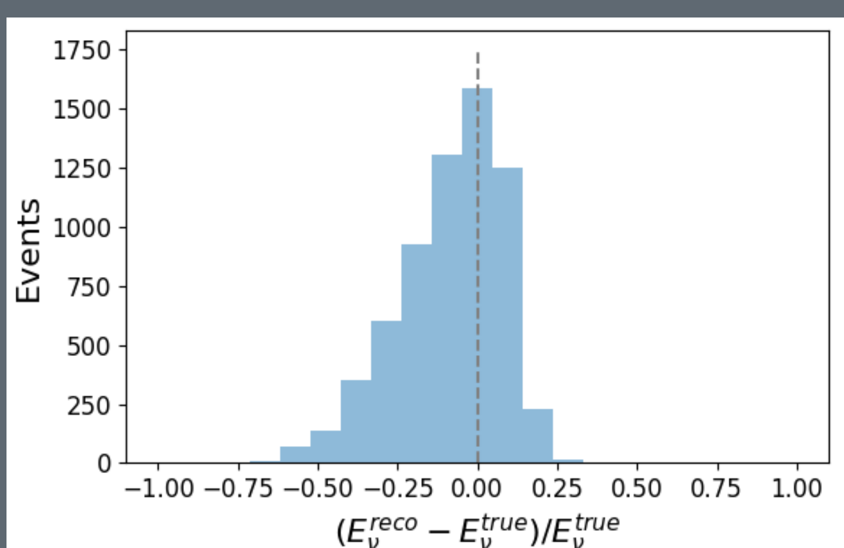
ν_e-like Interactions

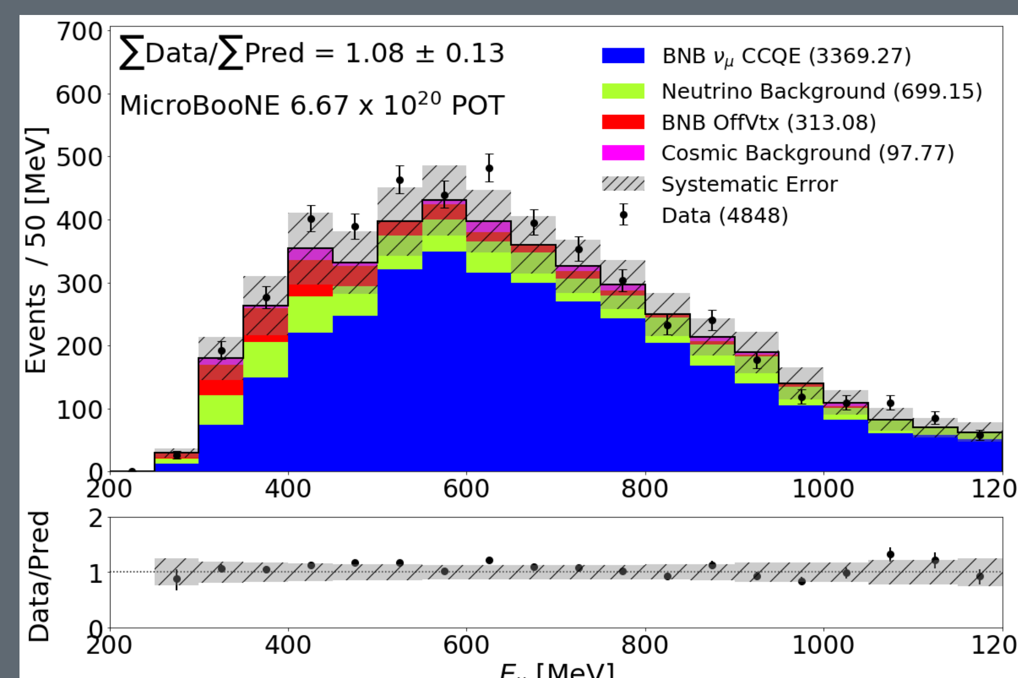
Shower reco: arxiv:2110.11874
Pixel tagging: PRD 103, 052012 (2021)
Particle ID: PRD 103, 092003 (2021)
Vertexing: JINST 16, P02017 (2021)
LArTPC reco: PRD 99, 092001 (2019)

CCQE-Like | CC Pionless | CC Inclusive

- Deep Learning-based reconstruction
- 1e1p with kinematic selection to achieve 75% purity in CCQE events
- Focus on precision in the dominant interaction at BNB energies
- Constrain with high-stats ν_μ CCQE







arxiv:2110.14080, submitted to *PRD*

Electron Search

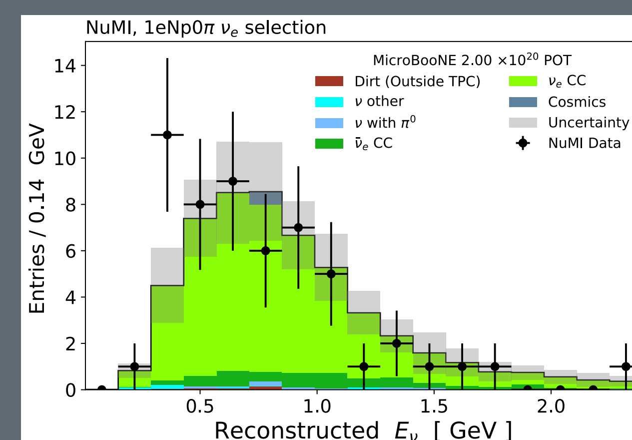
ν_e-like Interactions

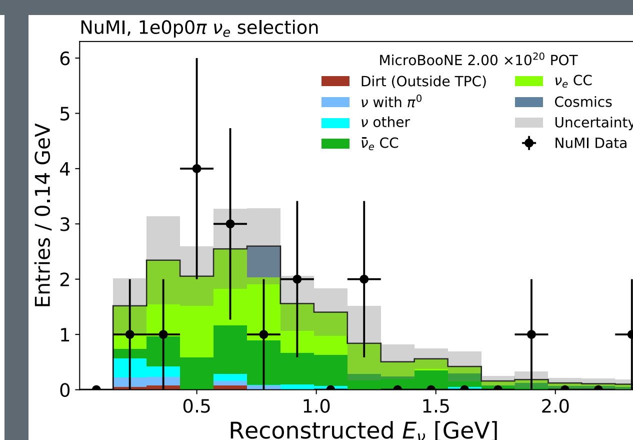
π^0 reco: JINST 15, P02007 (2020)
Cosmic tag: JINST 14, P04004 (2019)
Particle ID: arxiv:2109.02460
Pandora reco: EPJC 78 1, 82 (2018)

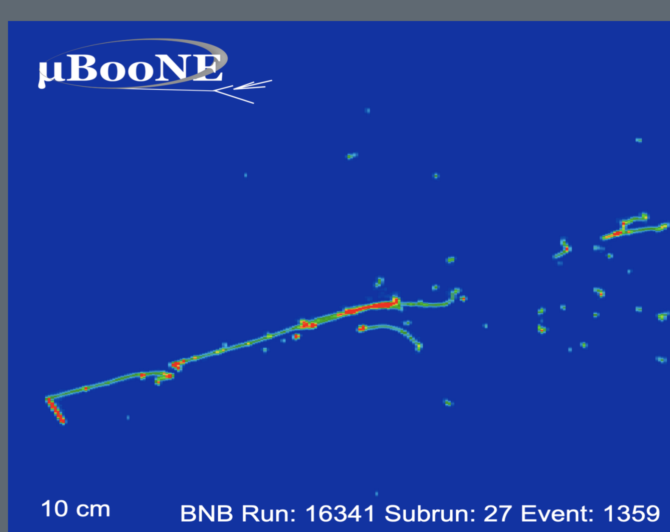
CCQE-Like | **CC Pionless** | CC Inclusive

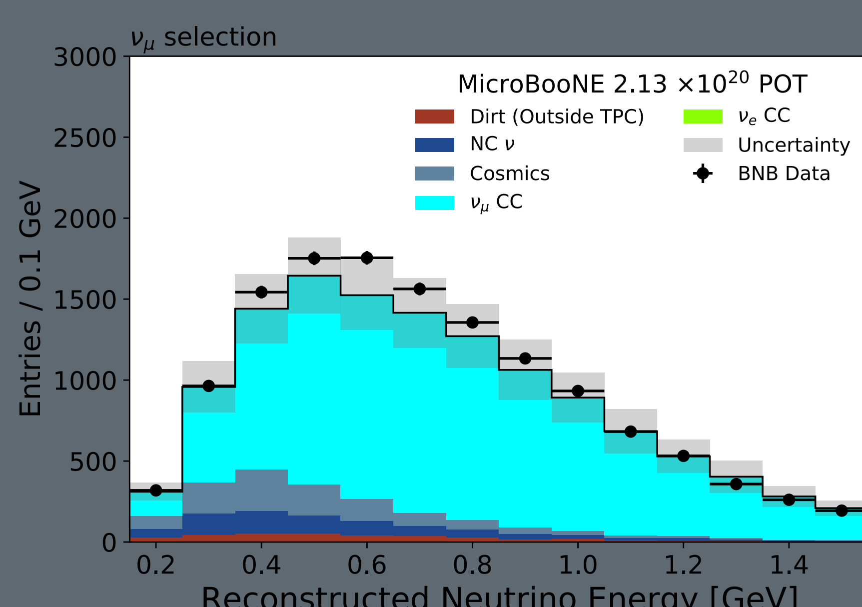
- Pandora particle flow reconstruction
- CC0π signal topology
  - No particles above MiniBooNE's Cherenkov threshold
- BDT-based selection for 0p and Np
- Validated with independent NuMI beam sample, constrained with ν_μ

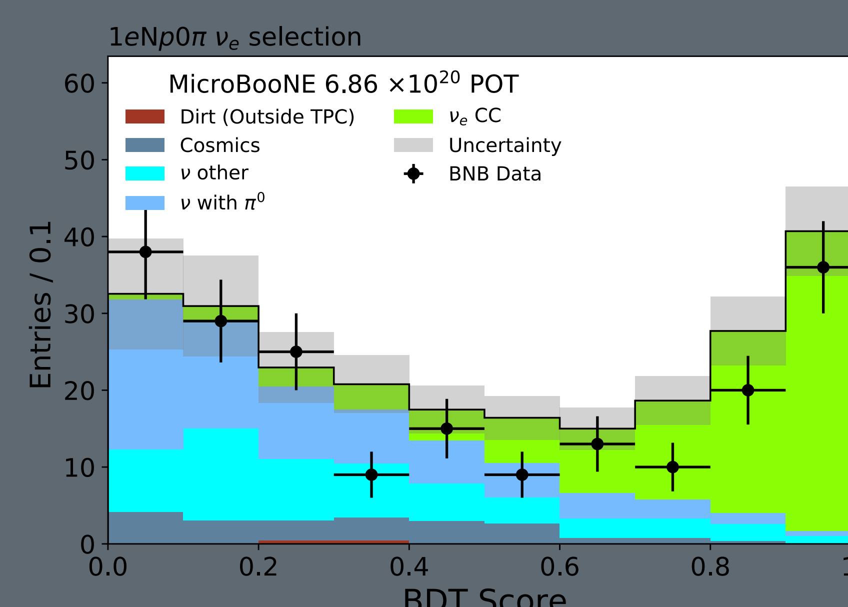
arxiv:2110.14065, submitted to *PRD*





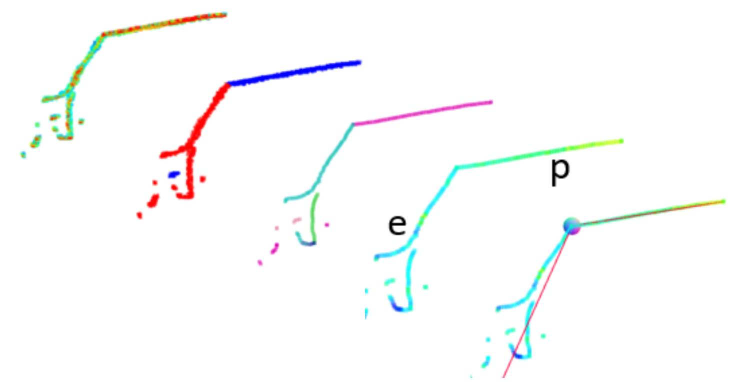






Electron Search

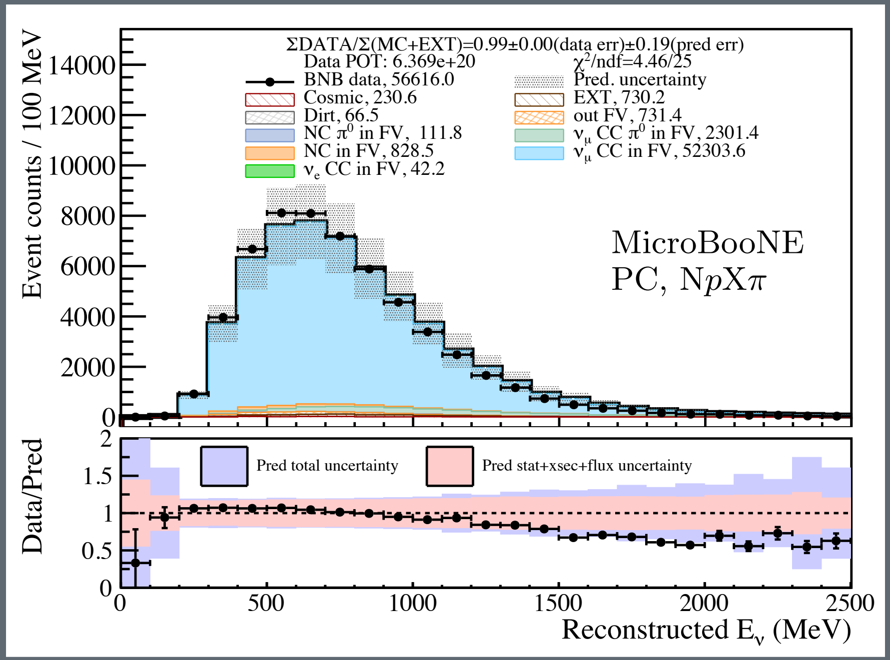
ν_e-like Interactions

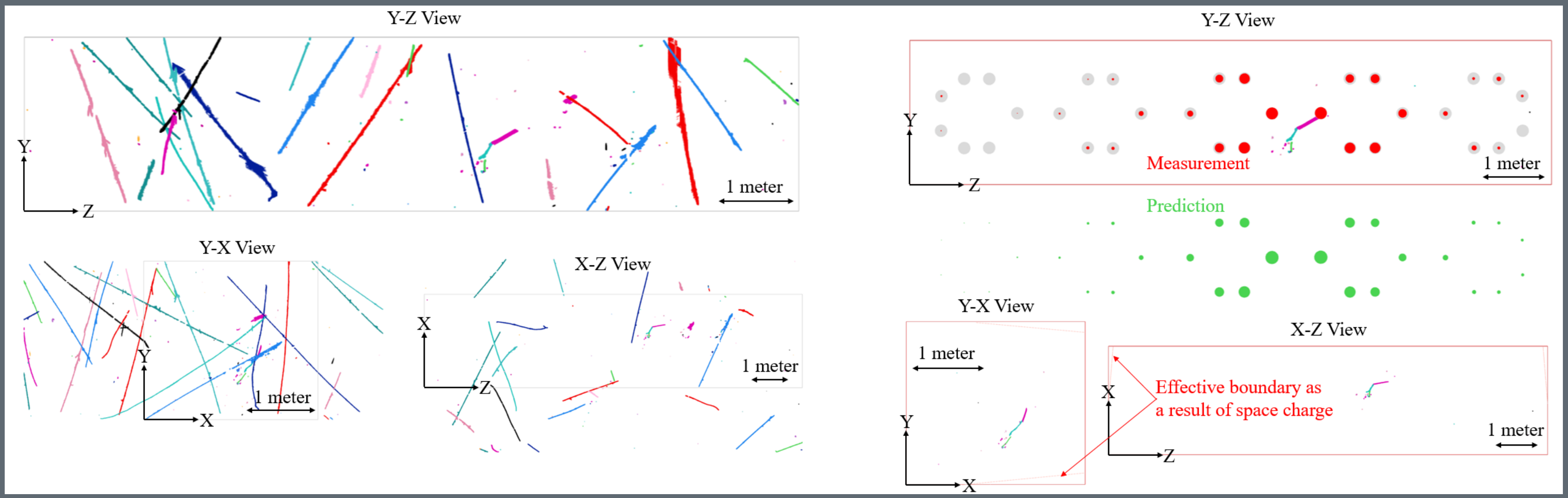


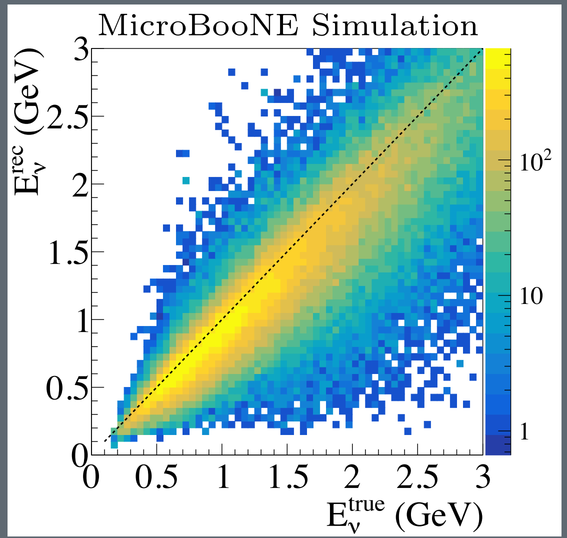
Pattern recognition: arxiv:2110.13961
Cosmic tag: PRApp. 15, 064071 (2021)
Selection: JINST 16, P06043 (2021)
WireCell reco: JINST 13, P05032 (2018)

CCQE-Like | **CC Pionless** | **CC Inclusive**

- WireCell tomographic reconstruction
- Inclusive selection signal topology
  - High efficiency, seeing all ν_e
- Simultaneous 7-sample fit: FC/PC for $CC\nu_e/CC\nu_\mu/CC\pi^0$ plus $NC\pi^0$
- BDT-based background rejection







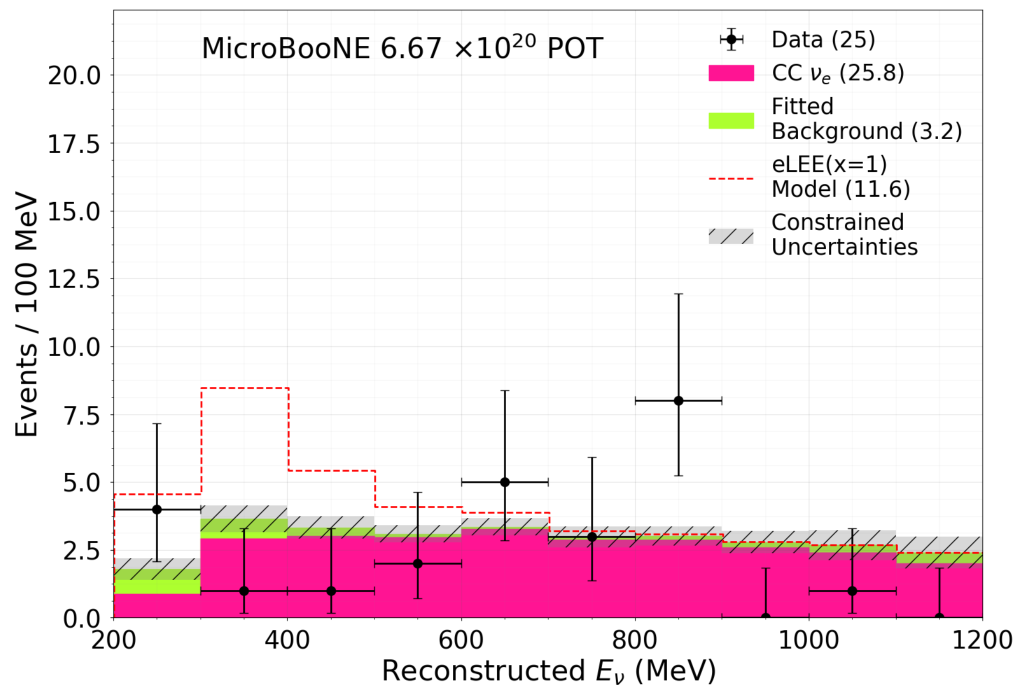
(c) ν_e CC candidates, FC

arxiv:2110.13978, submitted to *PRD*

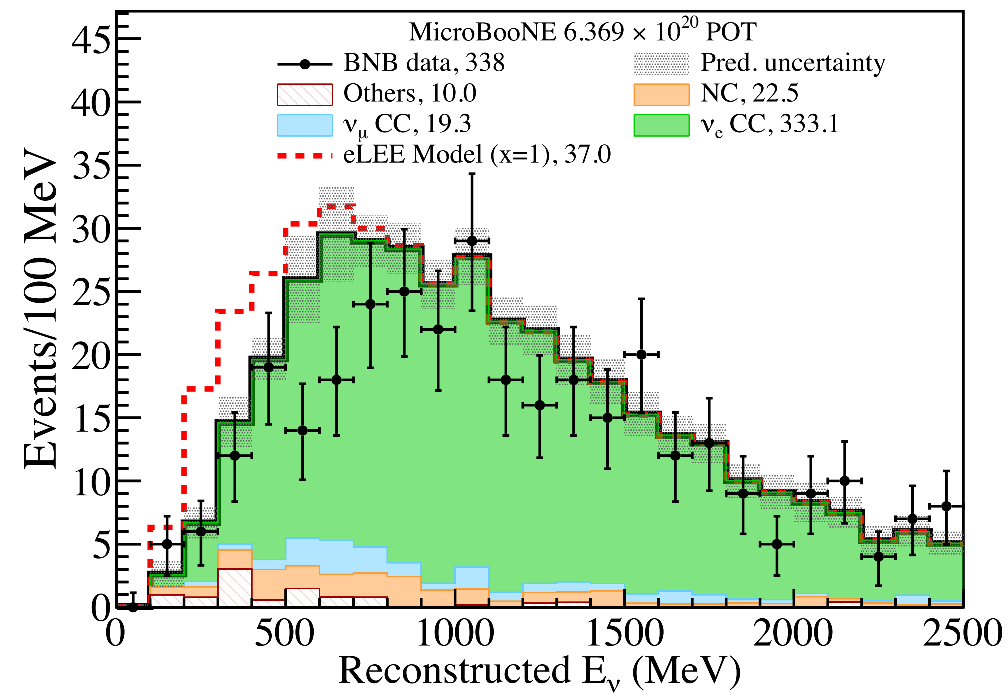
Electron Search

ν_e-like Interactions: Results

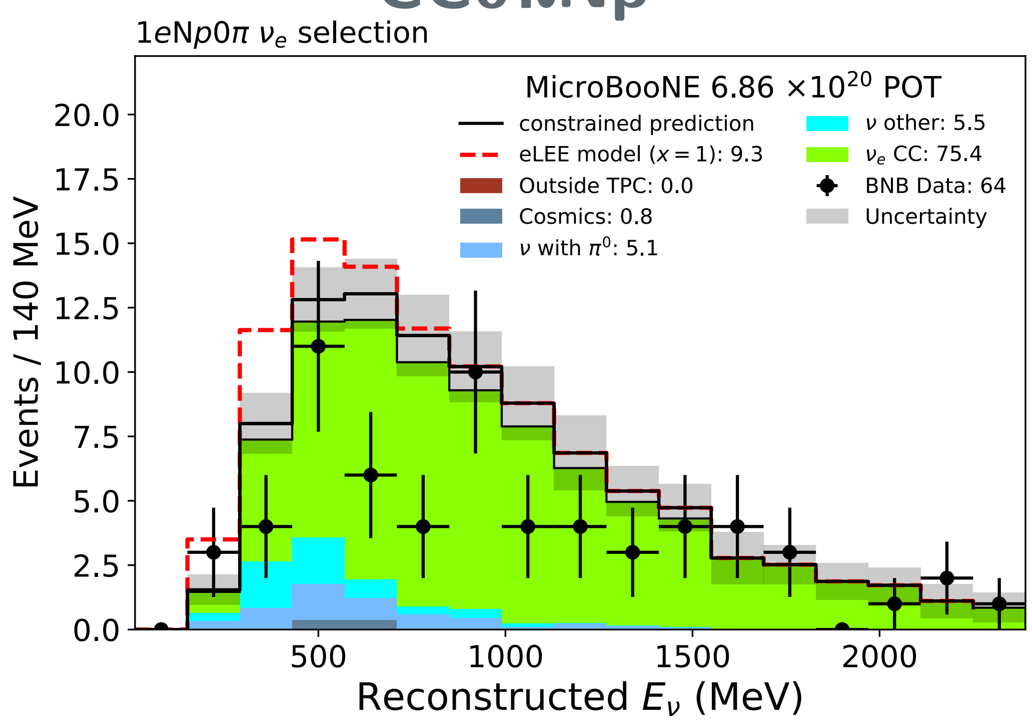
CCQE-Like (1e1p)



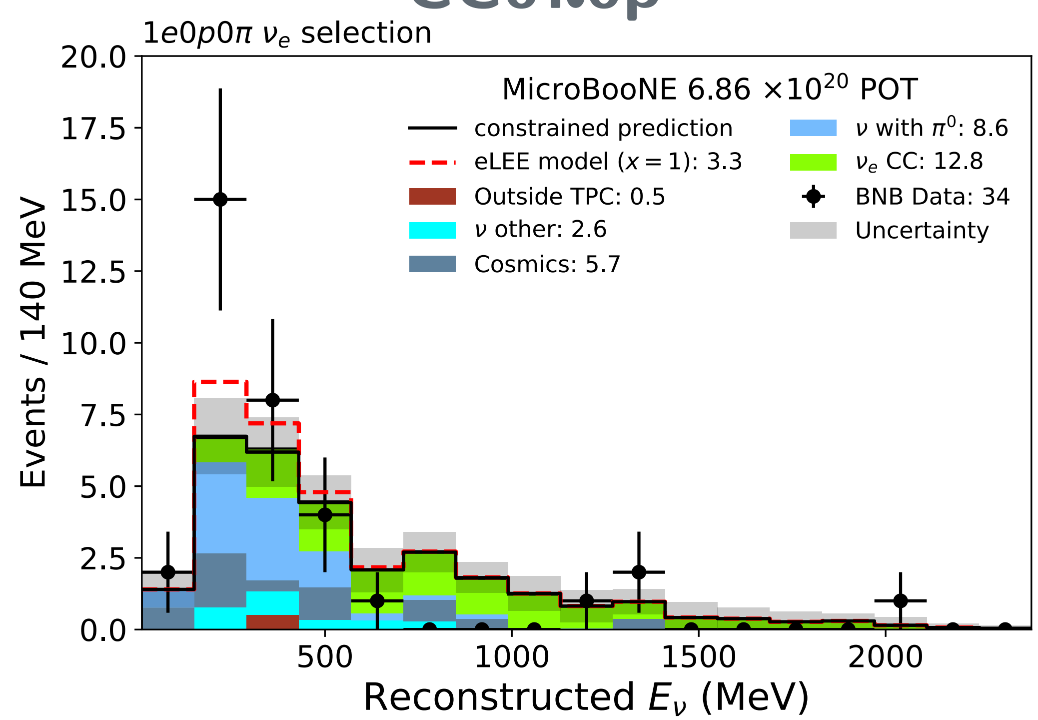
CC Inclusive



CC0πNp



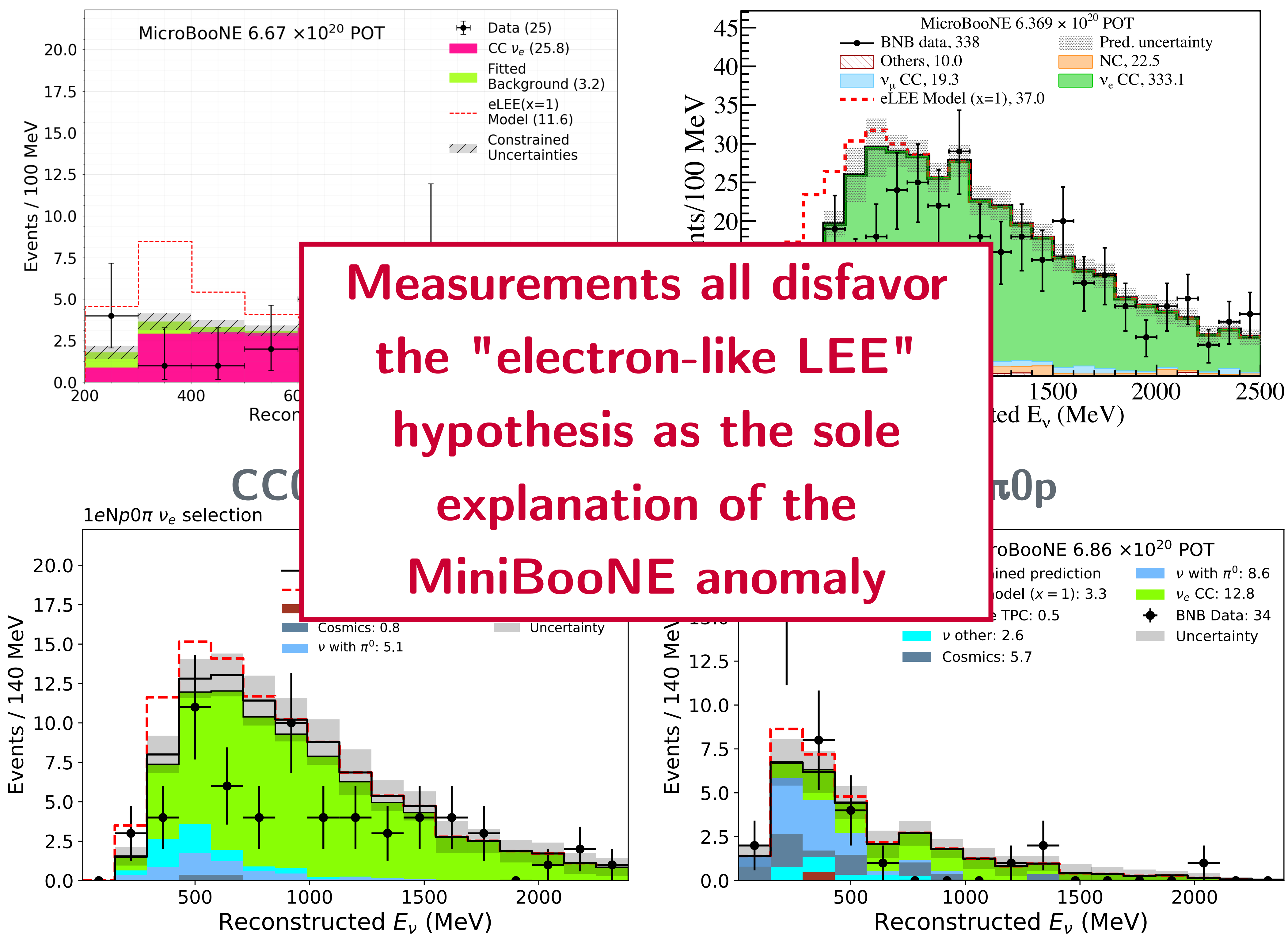
CC0π0p



Electron Search

ν_e-like Interactions: Results

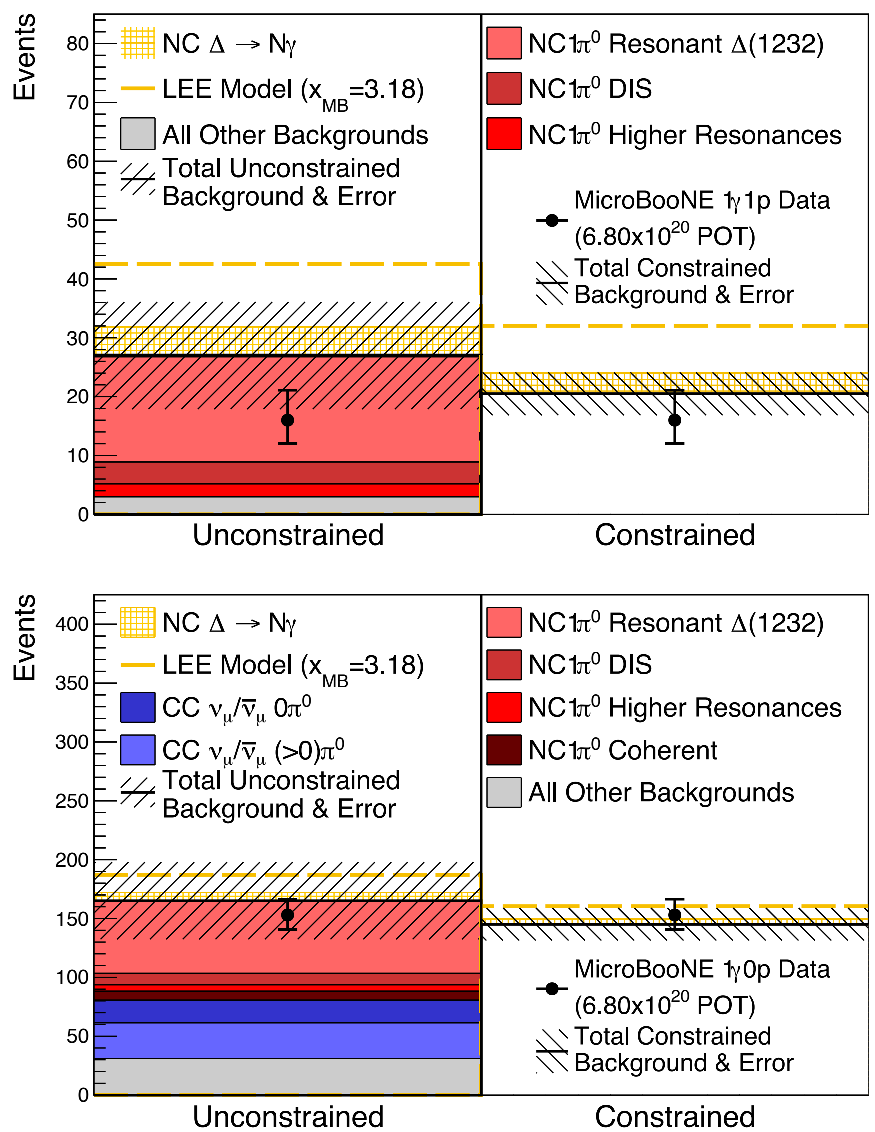
CCQE-Like (1e1p) | CC Inclusive



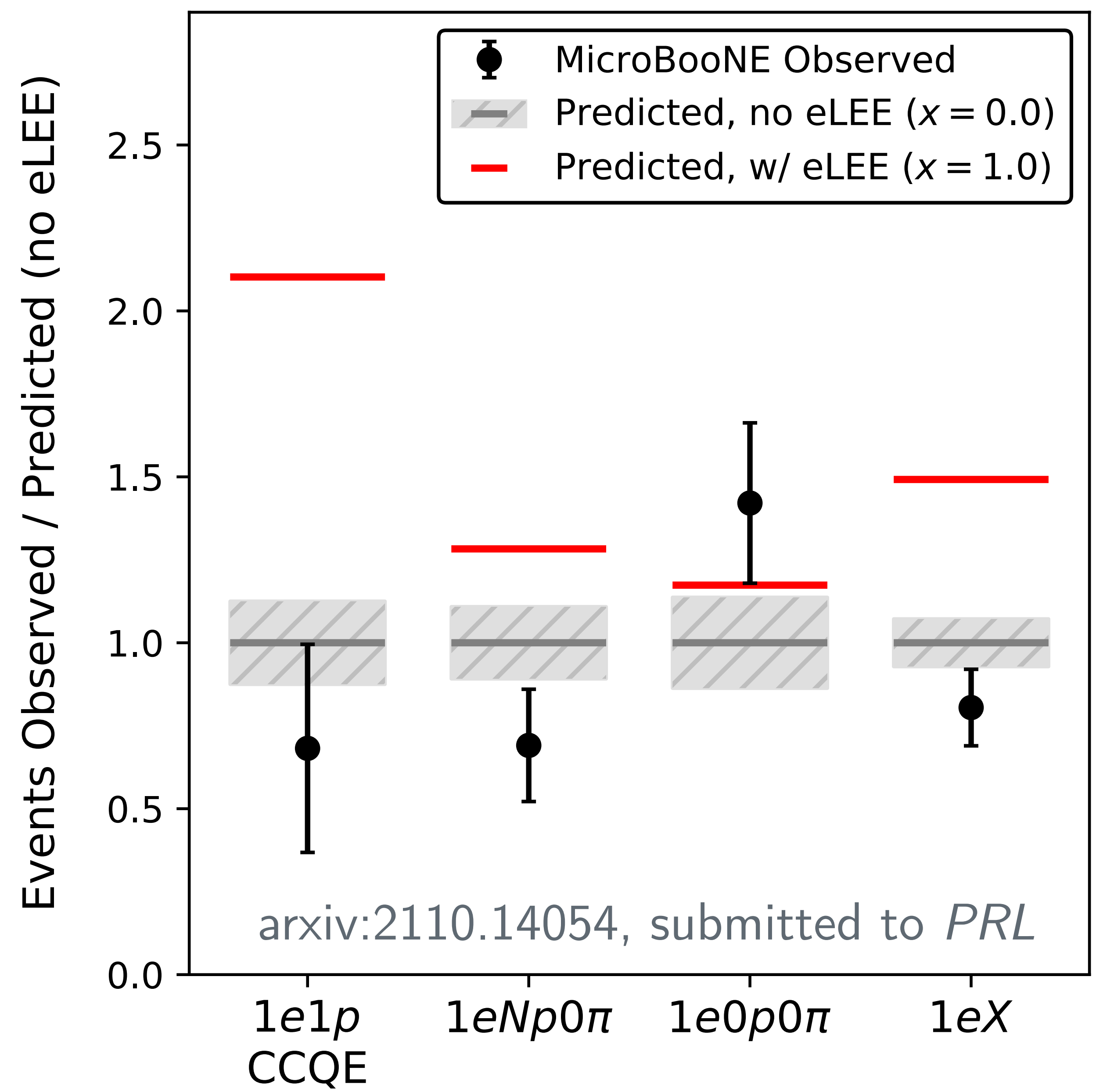
Measurements all disfavor the "electron-like LEE" hypothesis as the sole explanation of the MiniBooNE anomaly

Results

Single Photon like γLEE

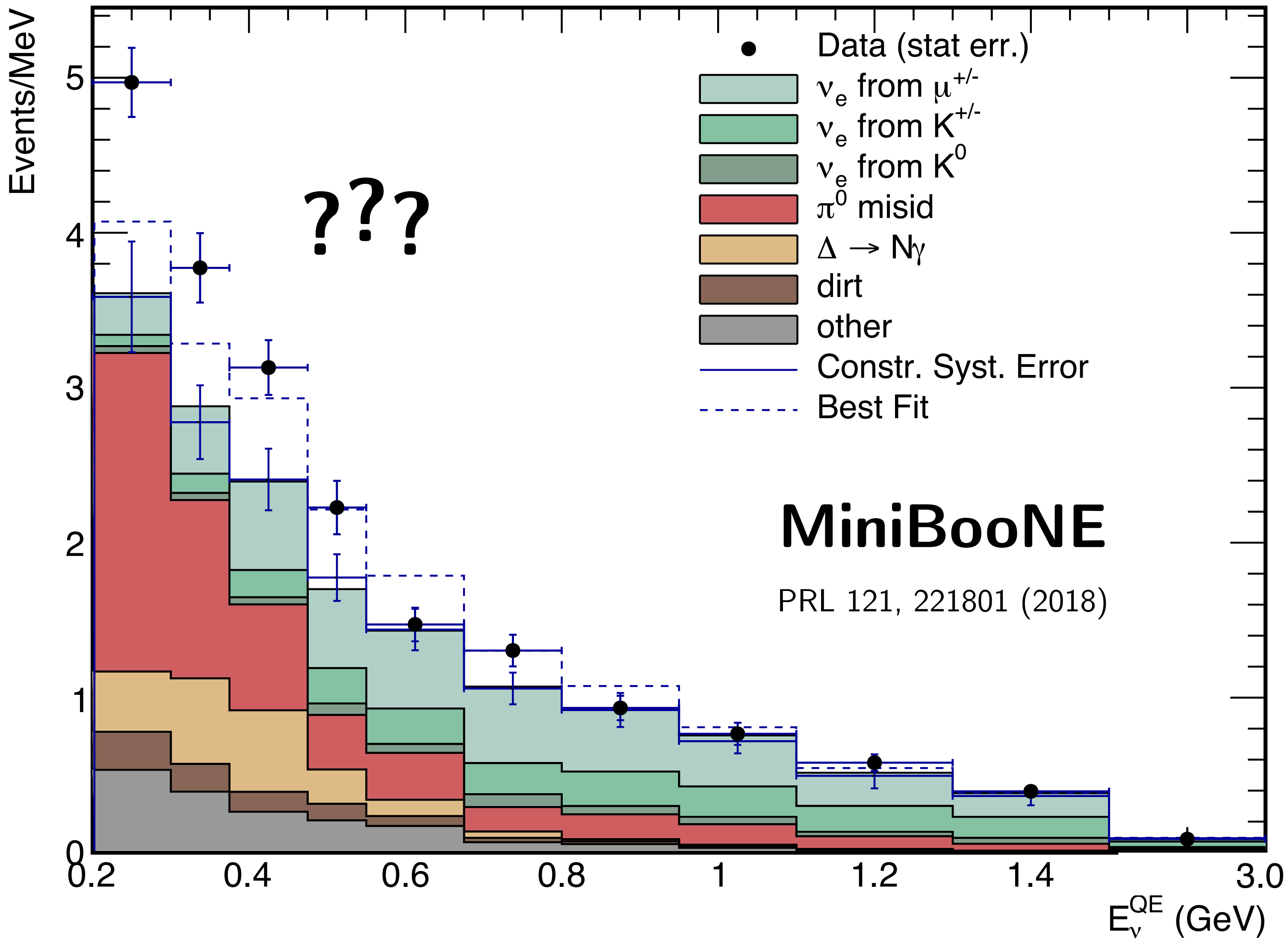


ν_e Electron-like eLEE



Rates in agreement with (or below) prediction → disfavor these hypotheses at 95% (γLEE) and >97% confidence (eLEE CCQE, CC0π(0+N)p, CCInc)

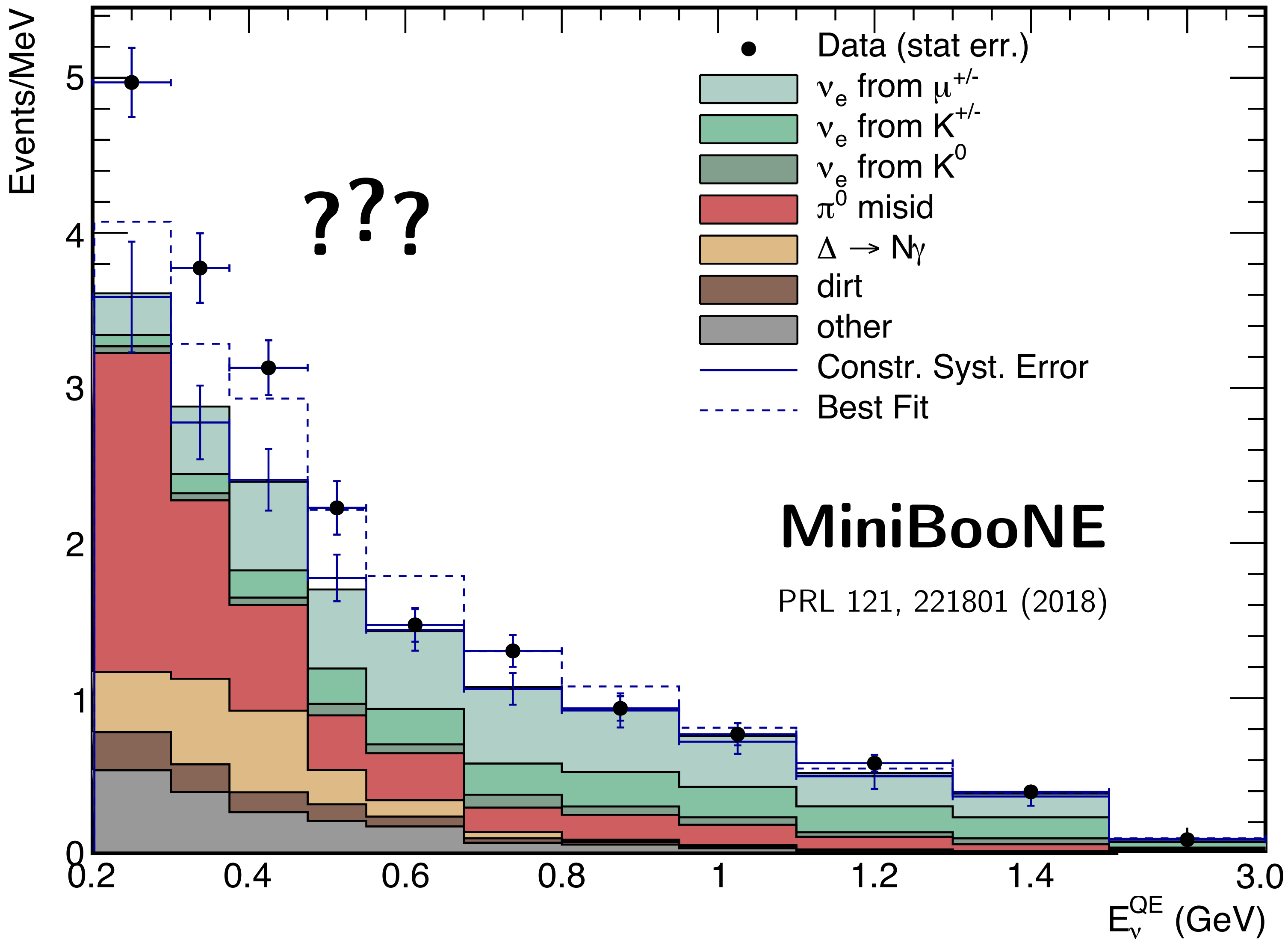
Beyond the Excess



Beyond the Excess

Decays to asymmetric e+e-?

Other new physics?



Very different kinematics in e.g. single γ or hadrons?

Decays to boosted e+e-?

A rich theory landscape!

Beyond the Excess

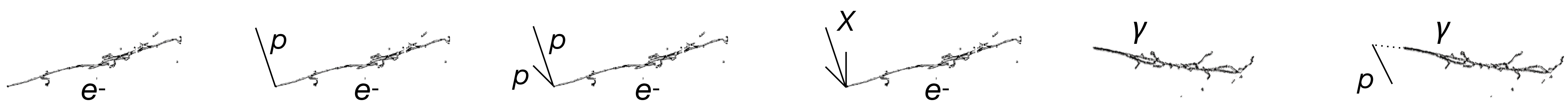
Additional Search Channels

Already started probing with first LEE results

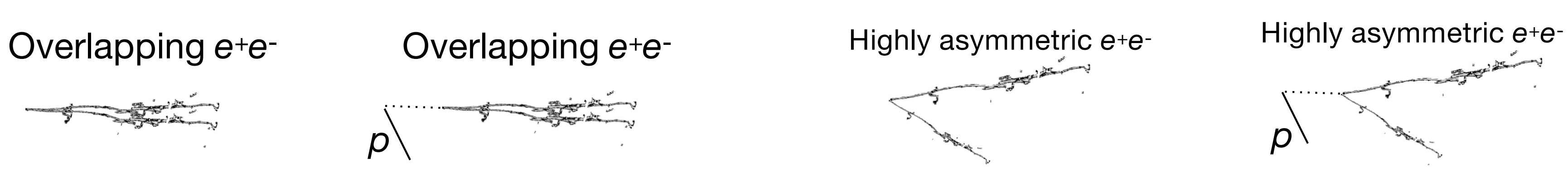
Models \ Reco topology	1e0p	1e1p	1eNp	1eX	e^+e^- + nothing	e^+e^-X	$1\gamma 0p$	$1\gamma 1p$	$1\gamma X$
eV Sterile ν Osc	✔	✔	✔	✔					
Mixed Osc + Sterile ν	✔ [7]	✔ [7]	✔ [7]	✔ [7]			✔ [7]		
Sterile ν Decay	✔ [13,14]	✔ [13,14]	✔ [13.14]	✔ [13,14]			✔ [4,11,12,15]	✔ [4]	✔ [4]
Dark Sector & Z' *	✔ [2,3]				✔ [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

Included in these searches:

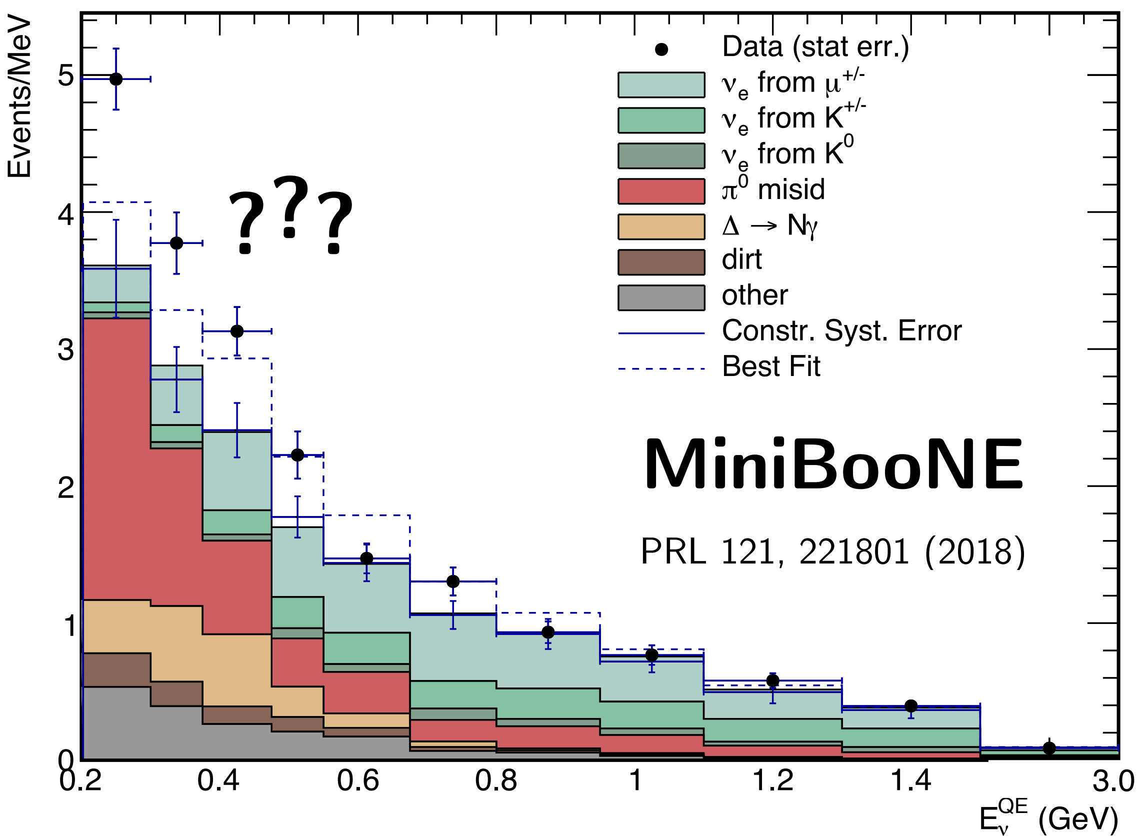


Now under development:

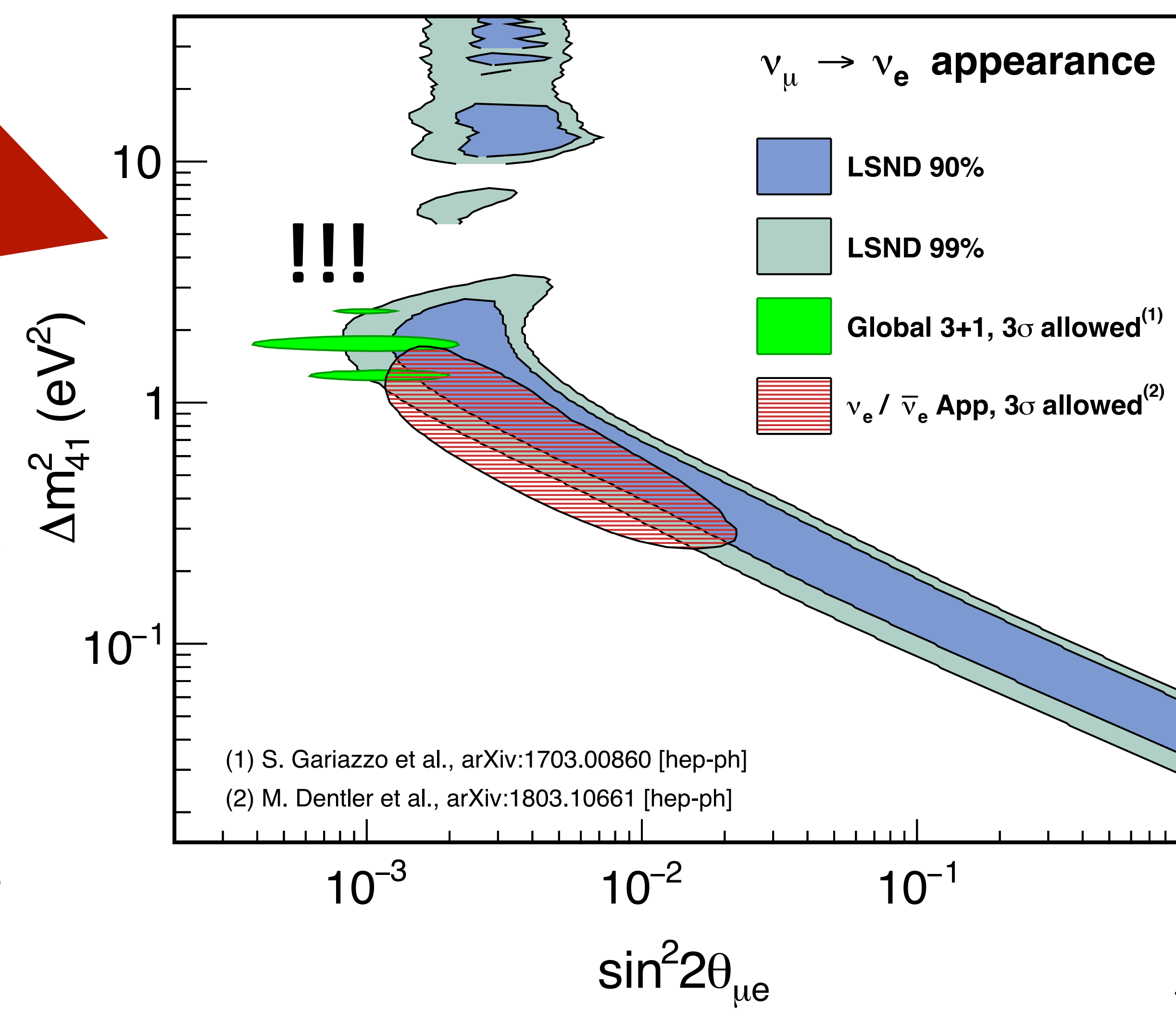


Beyond the Excess

Probing the Sterile Neutrino Anomalies



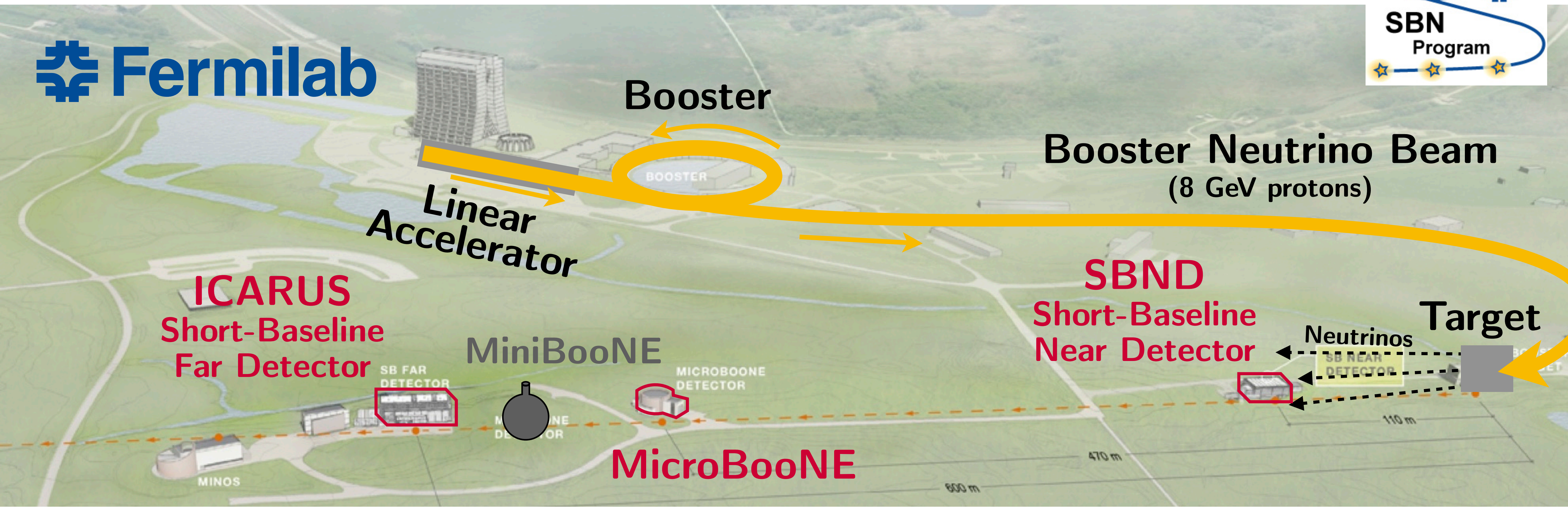
From understanding the origin of the MiniBooNE Low-Energy Excess...



...to comprehensively addressing the still-allowed parameter space for eV-scale sterile neutrino oscillations

The Short-Baseline Neutrino Program

A Definitive Test of Short-Baseline Oscillations



- Three LArTPCs in the Fermilab Booster Neutrino Beam
- 5σ test of LSND-allowed oscillations using three baselines
- Simultaneous ν_μ disappearance and ν_e appearance searches
- Vast BNB event statistics in SBND, 110 m from the target
- Larger NuMI event statistics in ICARUS
- Precision neutrino cross sections, detector R&D → DUNE!

The Short-Baseline Neutrino Program

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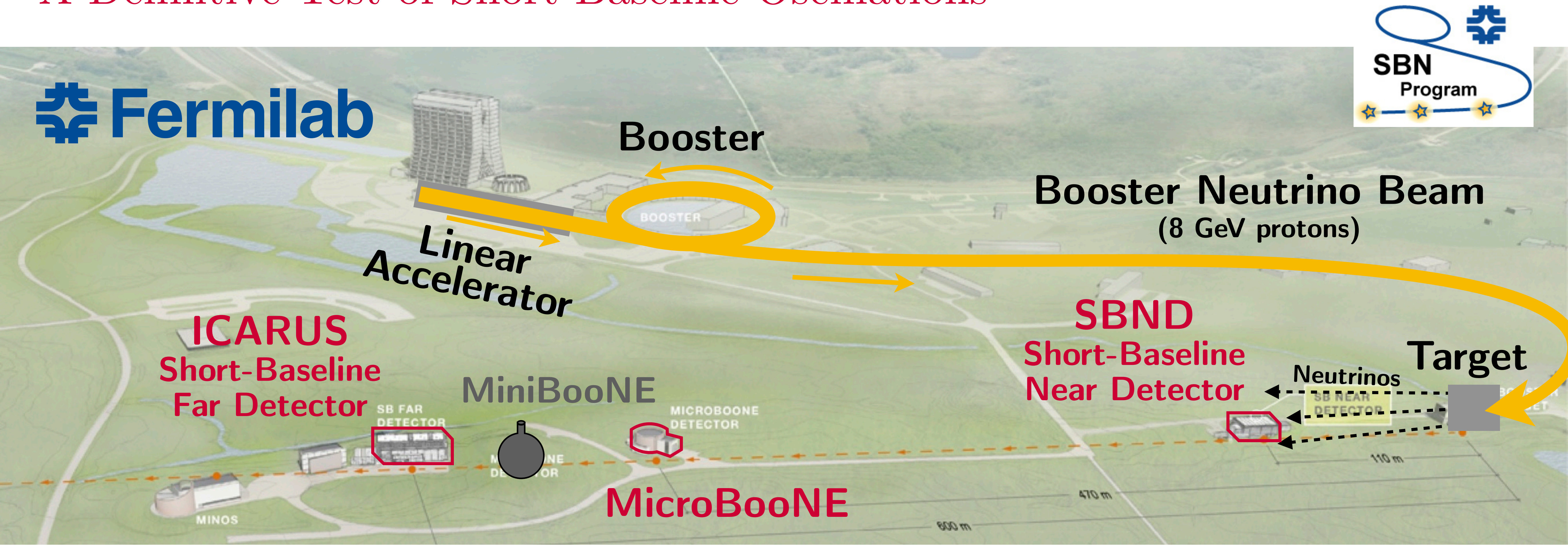

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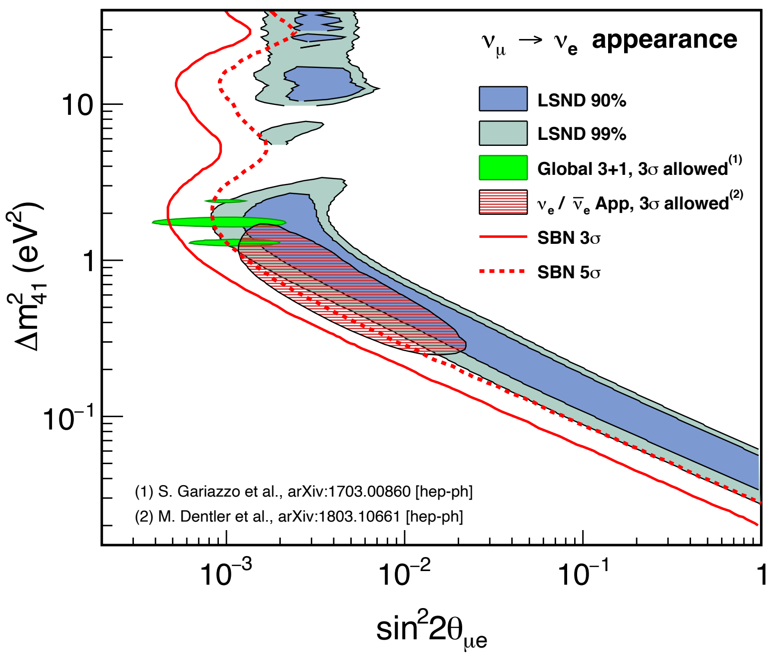


Summary

Key Takeaways

1. No excesses found in NC $\Delta \rightarrow N\gamma$ or ν_e

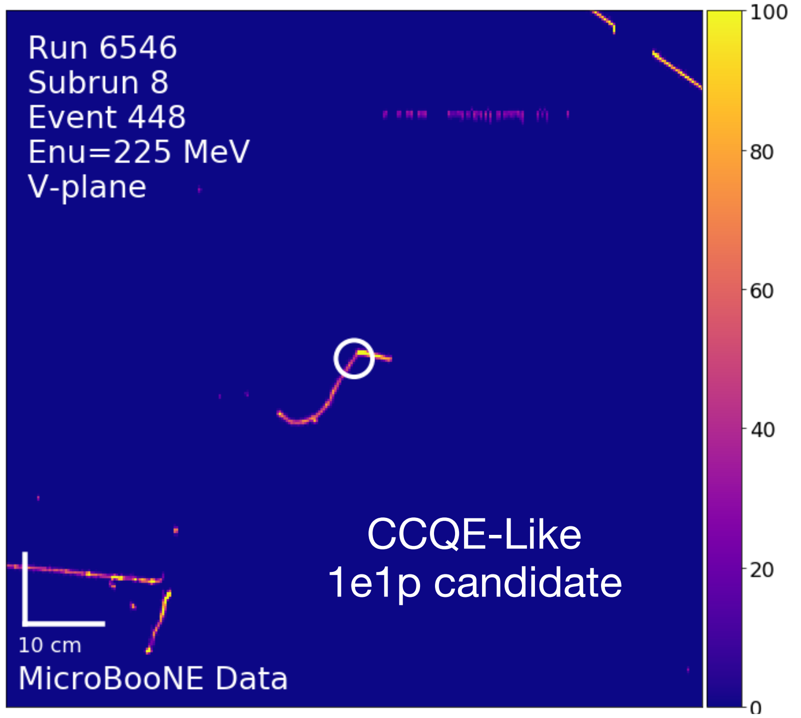
- Studied leading hypotheses for one of the most significant anomalies in neutrino physics
- Multiple complementary search channels

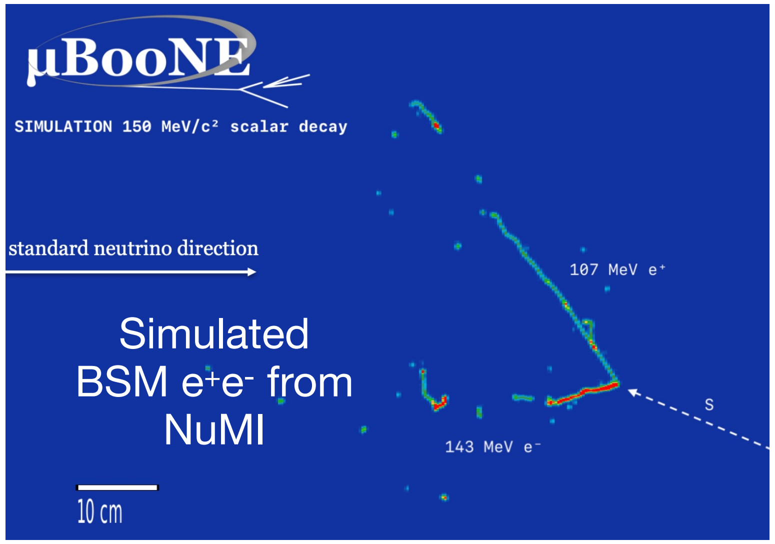
2. A rich landscape remains to be studied

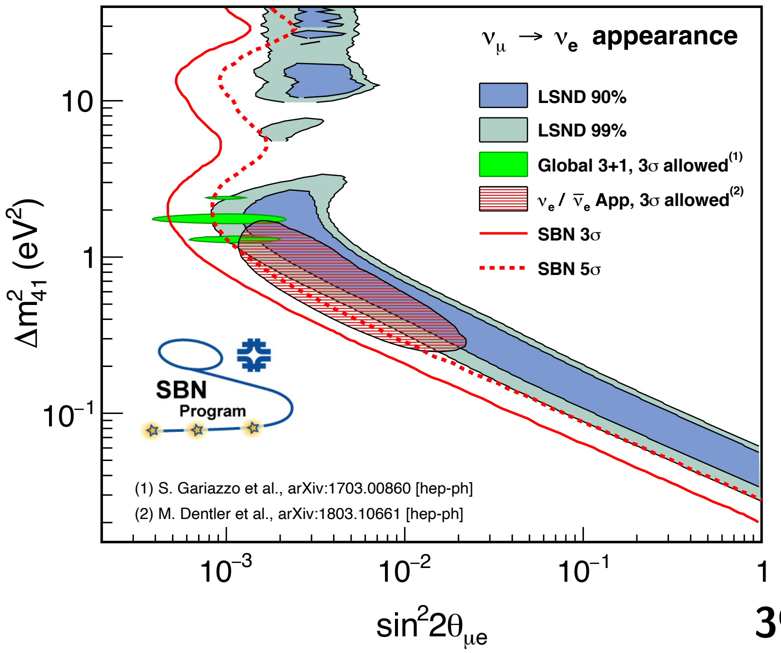
- The MiniBooNE anomaly remains!
- Higher statistics in MicroBooNE (~2×)
- Broader range of signatures now underway

3. Exciting future at the SBN & beyond

- Dramatically expanded reach with SBN
- Future LArTPC analysis at DUNE
- MicroBooNE's extensive analysis, reco, & systematics work supports these program







Thank You!

Questions?

CCQE-Like eLEE: arxiv:2110.14080 (→PRD)
CC0π eLEE: arxiv:2110.14065 (→PRD)
CCInc eLEE: arxiv:2110.13978 (→PRD)
All eLEE: arxiv:2110.14054 (→PRL)
NC Δ→Nγ γLEE: arxiv:2110.00409 (→PRL)

Fermilab U.S. DEPARTMENT OF ENERGY Office of Science NSF FNSNF SWISS NATIONAL SCIENCE FOUNDATION Science & Technology Facilities Council THE ROYAL SOCIETY

Evolving Theory Landscape

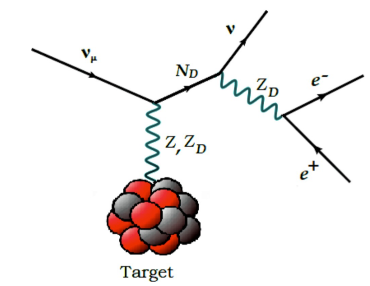
Motivated by attempts to explain the new MiniBooNE results as well as other experimental data; eg., ν_e appearance but no ν_μ disappearance *(Caution: not an exhaustive list!)*

- 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



PRL 121, 241801 (2018)

- Many of these models predict more complex final states (e^+e^-) and/or differing levels of hadronic activity

→ *The hadronic state is becoming increasingly more important as a model discriminator*

- We are fortunate that LArTPCs are sensitive to these possibilities