Latest Results from MicroBooNE: Search for the Low Energy Excess

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on behalf of the MicroBooNE Collaboration

Wright Laboratory, Yale University

20th Lomonosov Conference
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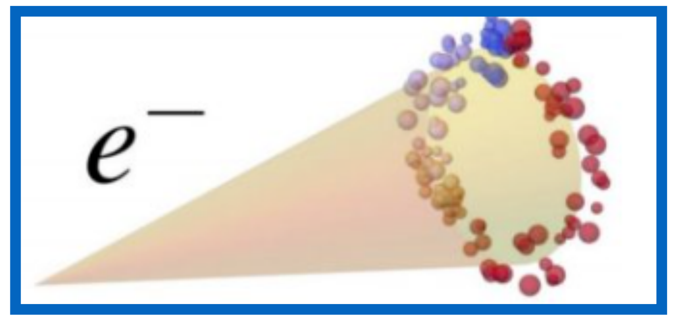
MiniBooNE low energy excess

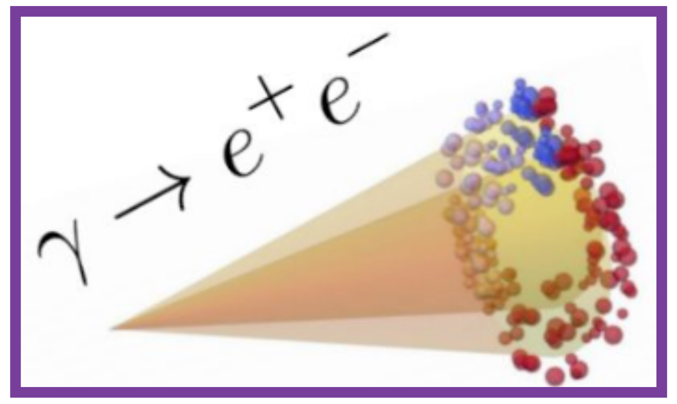
PRD 103 (2021) 052002

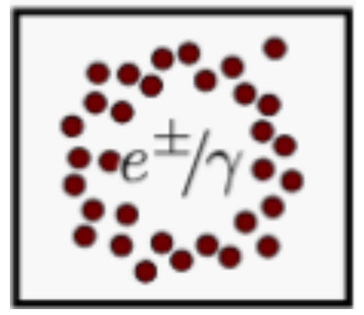
- MiniBooNE observed the 4.8σ excess in low-energy region in ν_e CCQE-like events

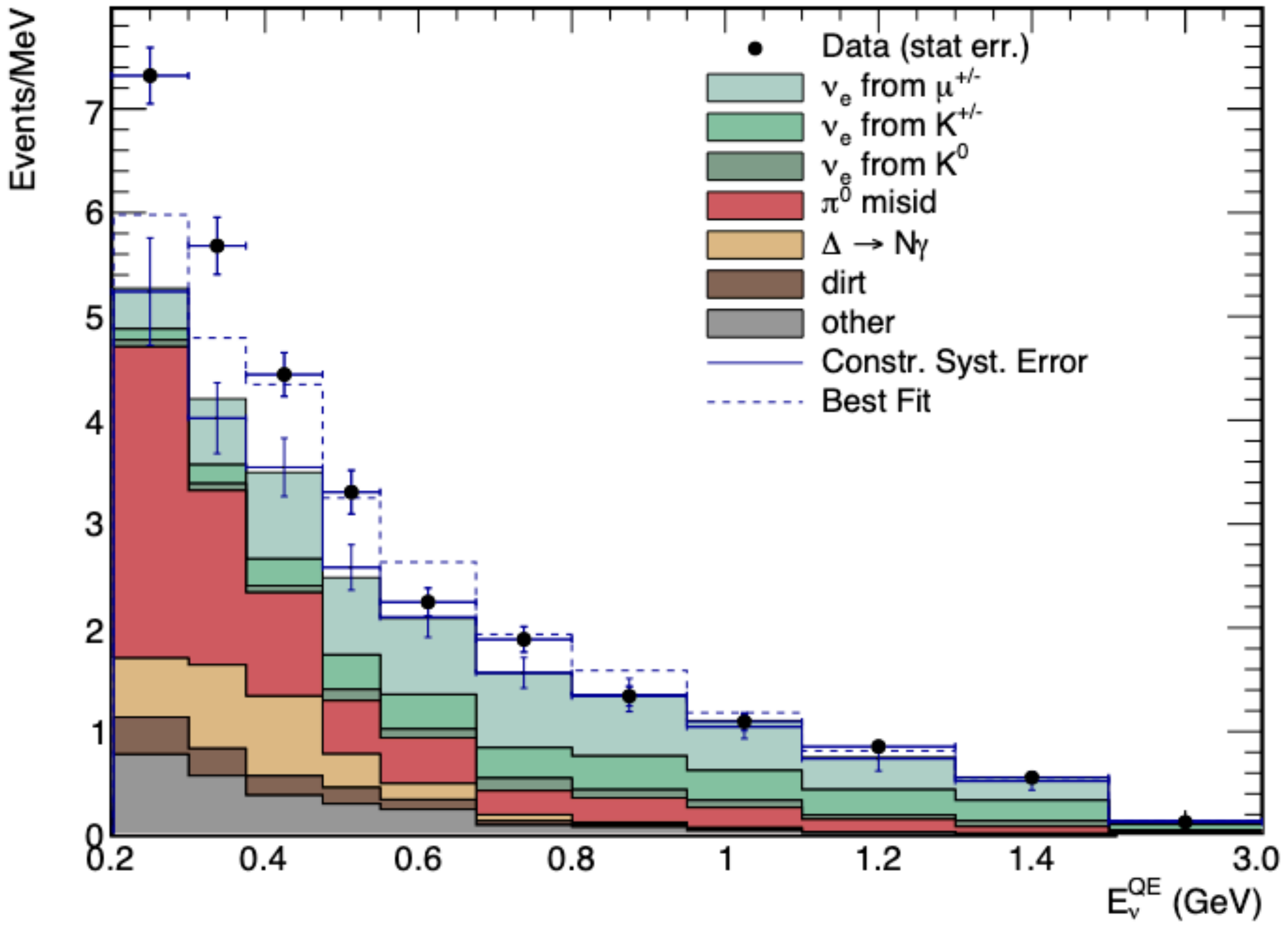
- nature of the excess could be "electron-like" (eLEE) or "photon-like" (γLEE)
  - at low energy, largest background in MiniBooNE is misidentified NCπ^0 events
  - MiniBooNE cannot distinguish between electrons and photons, also without hadron information

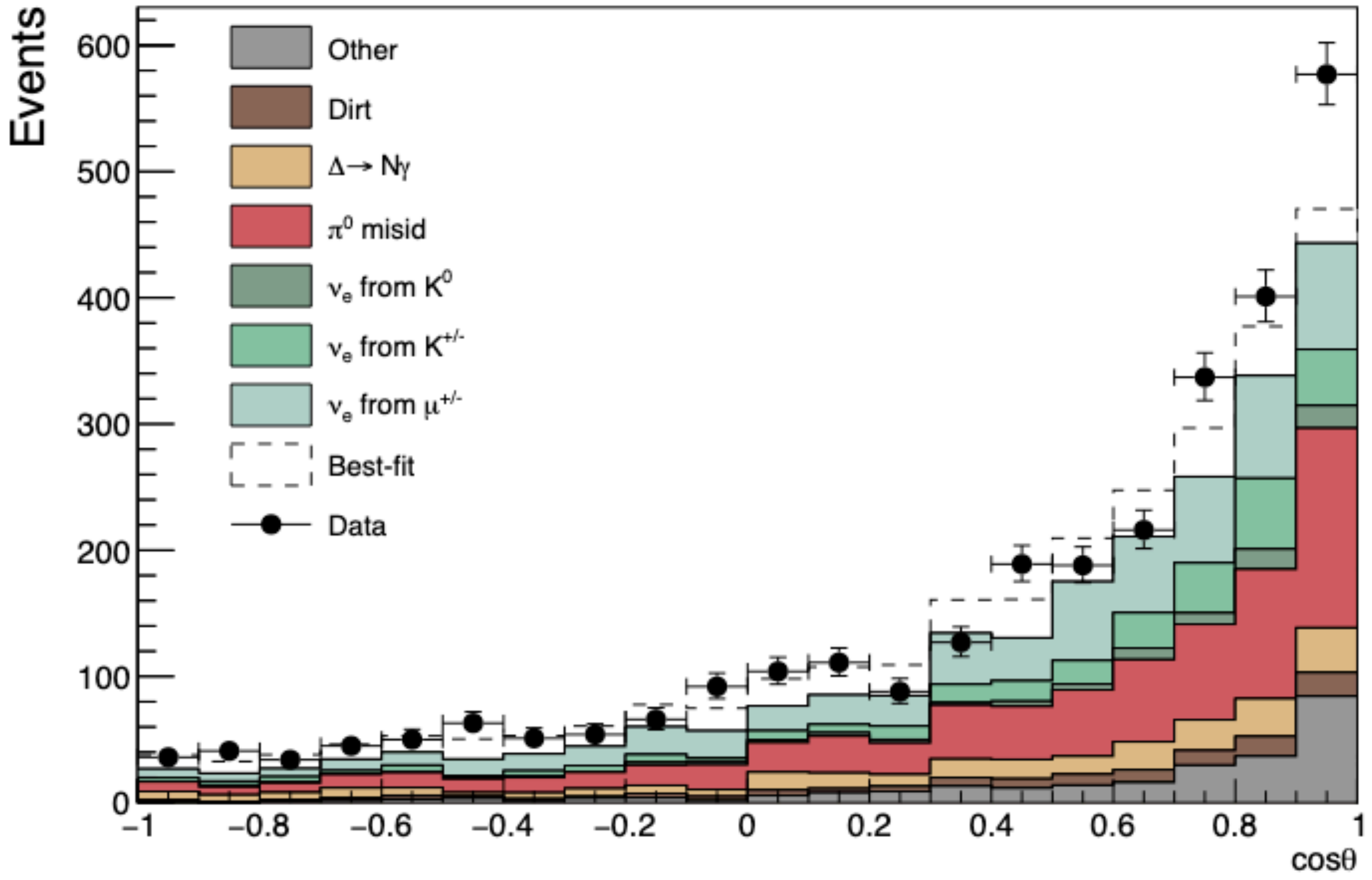
- *can we separate electrons and photons? can we understand the excess with enough event topology information such as hadronic activities?*







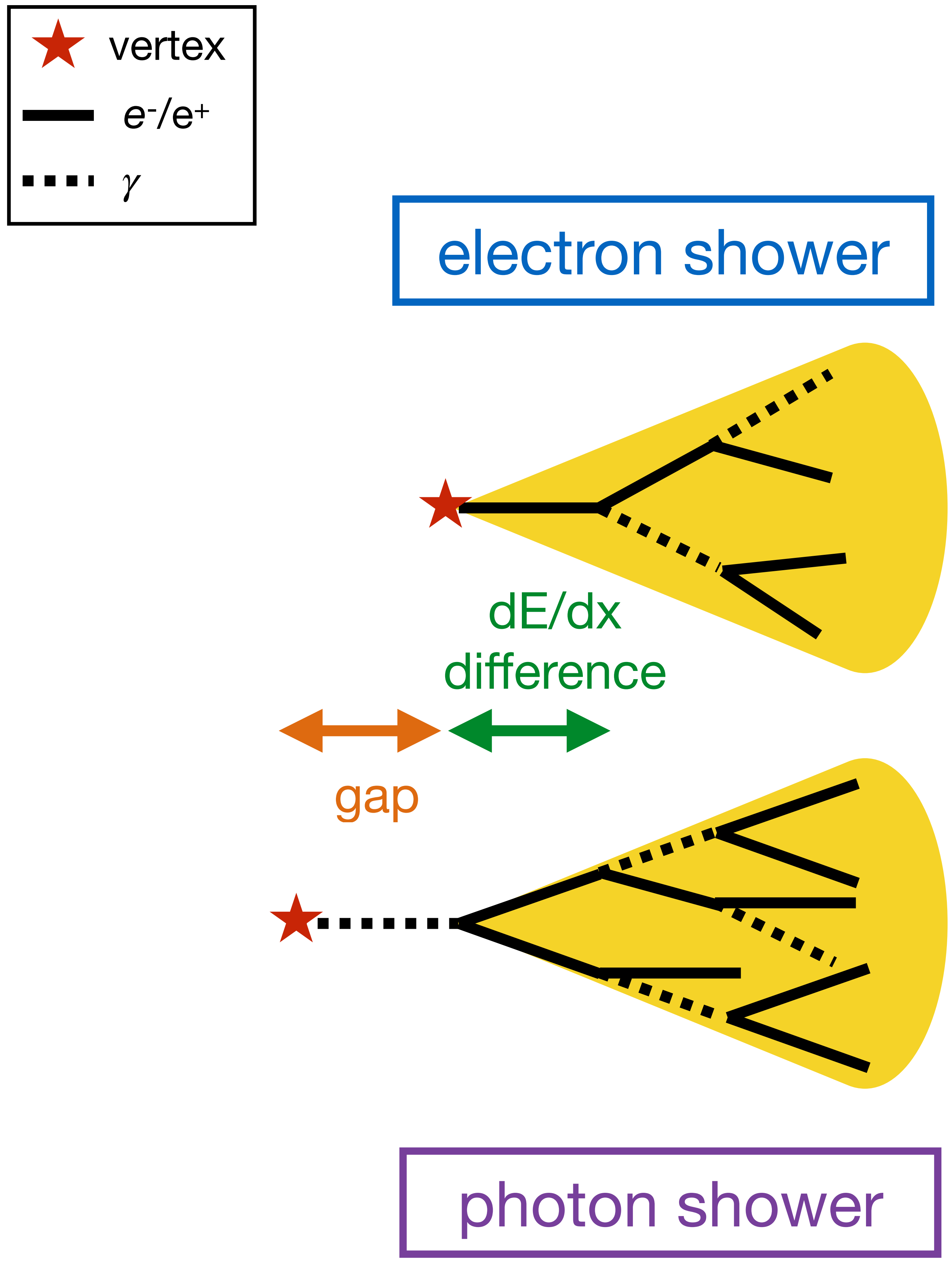




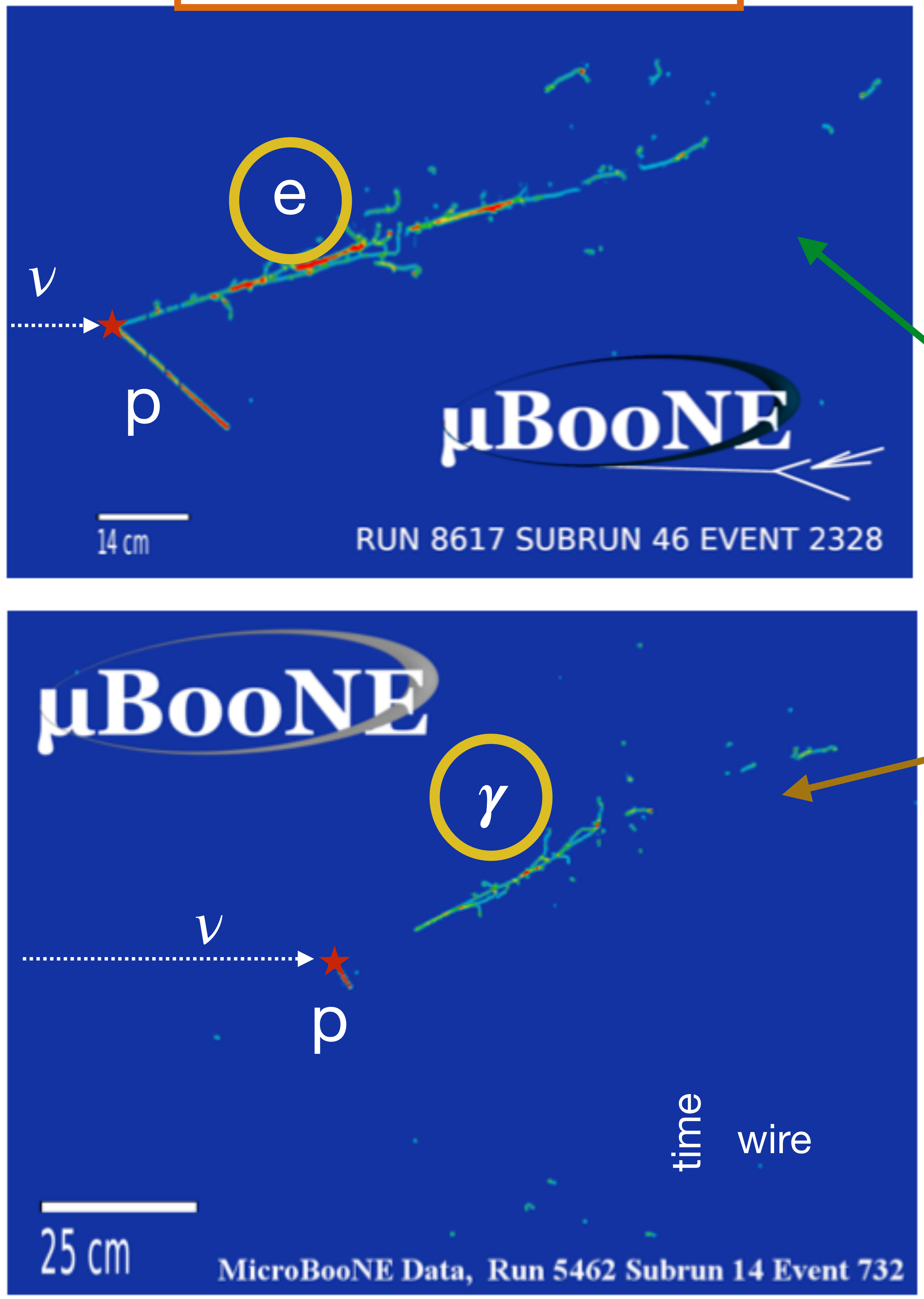
testing eLEE vs. γLEE hypotheses with MicroBooNE

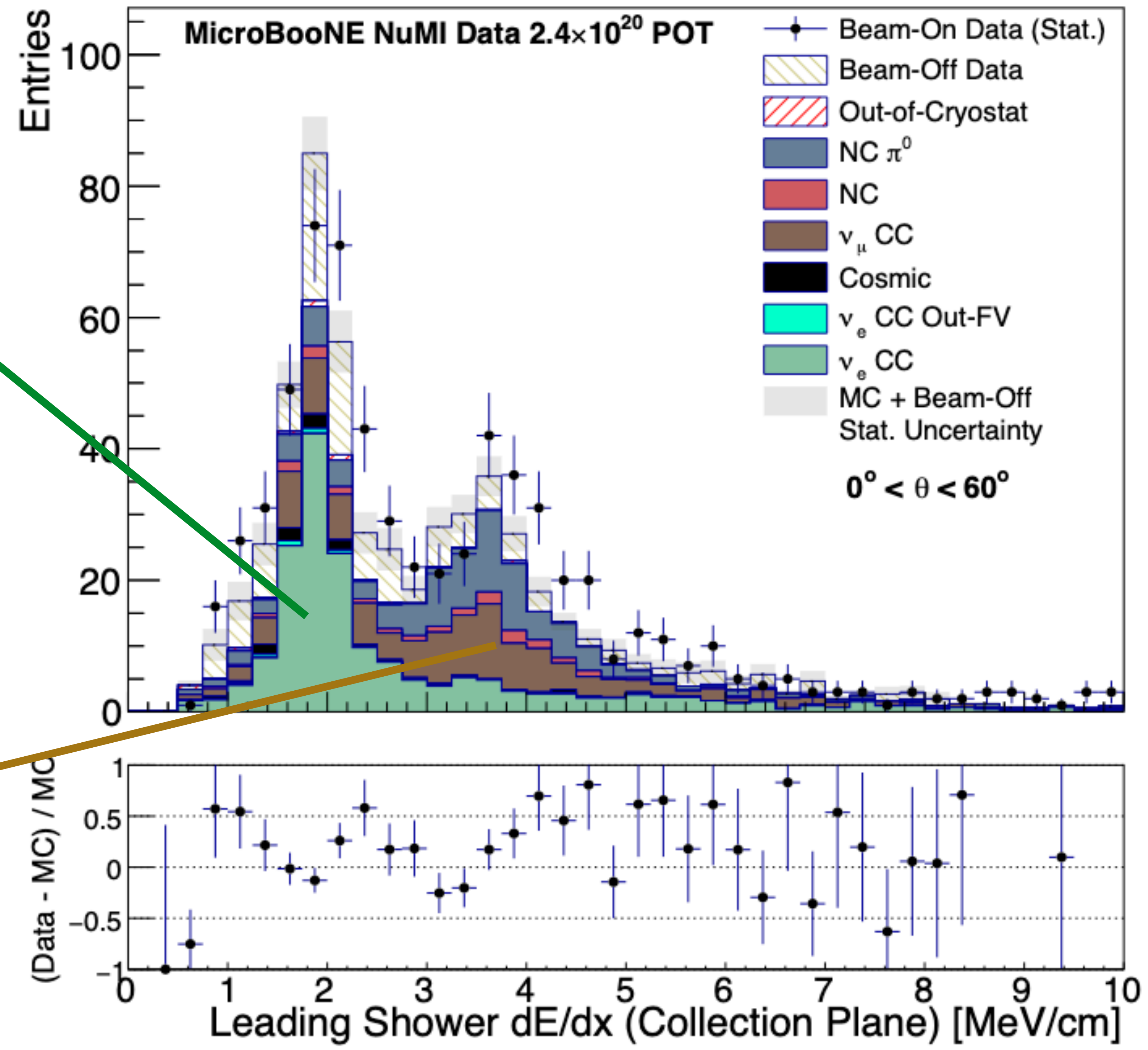
µBooNE

arxiv:2101.04228



topology information



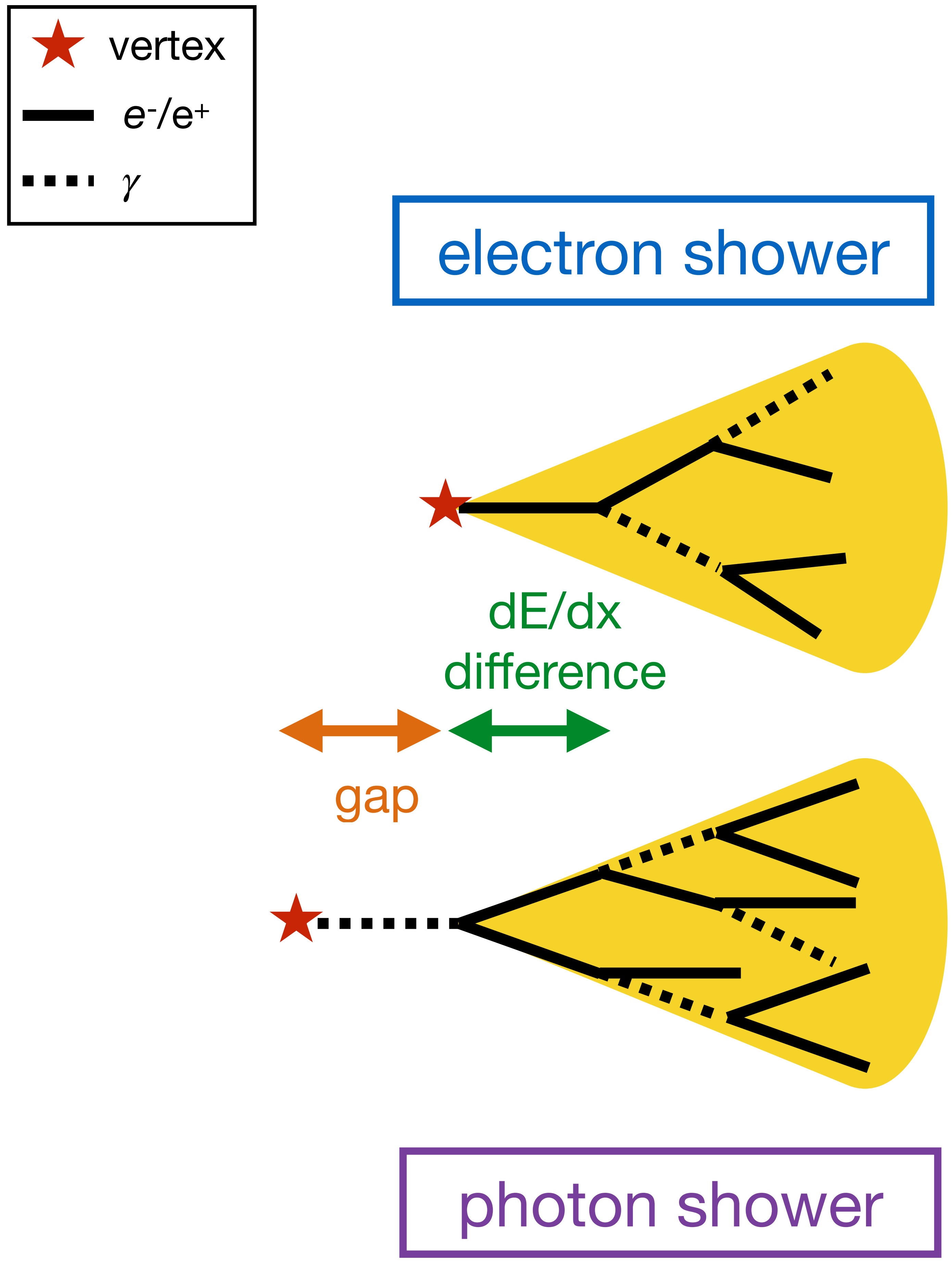


ionization dE/dx

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

testing eLEE vs. γLEE hypotheses with MicroBooNE

arxiv:2101.04228



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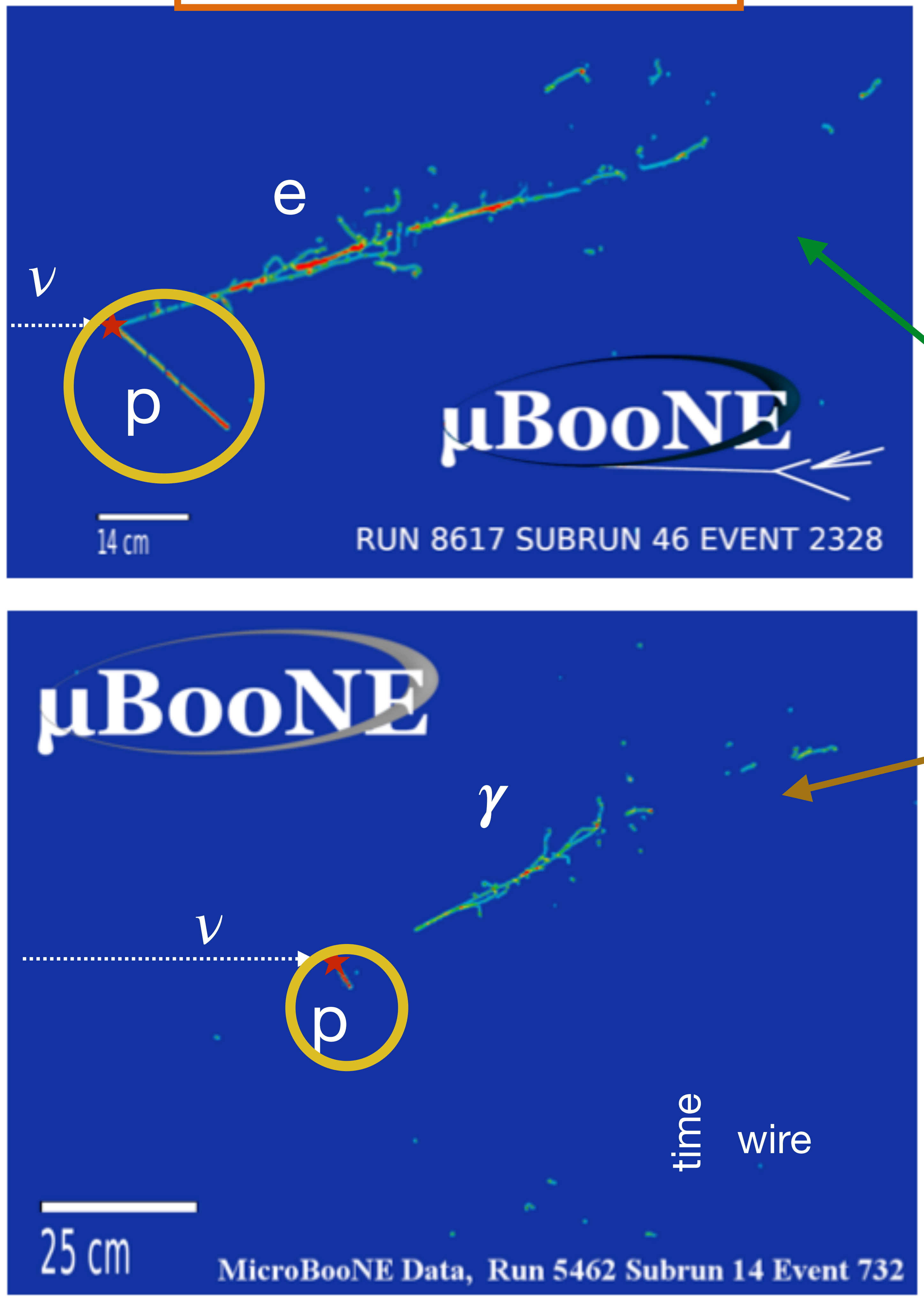
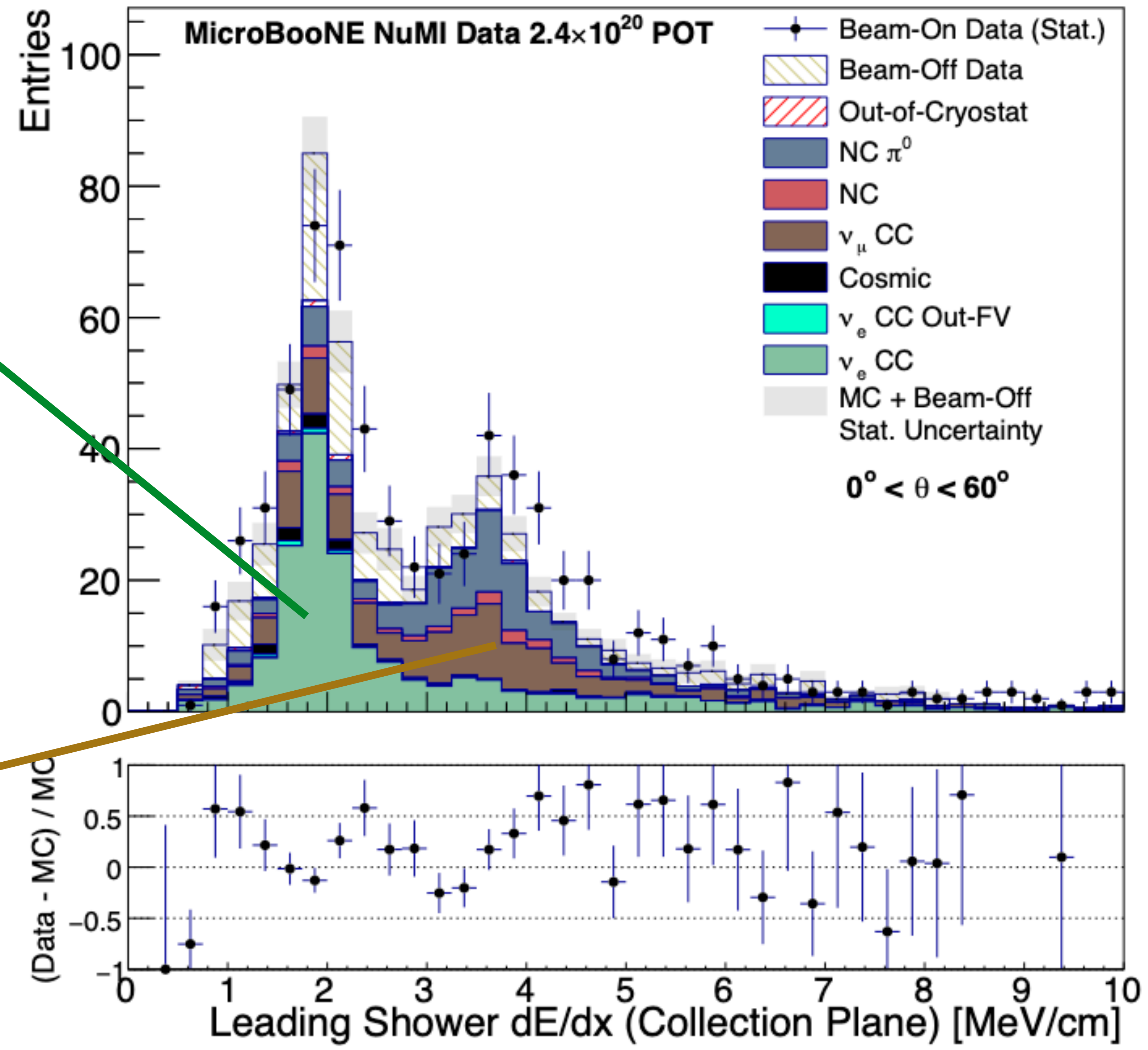




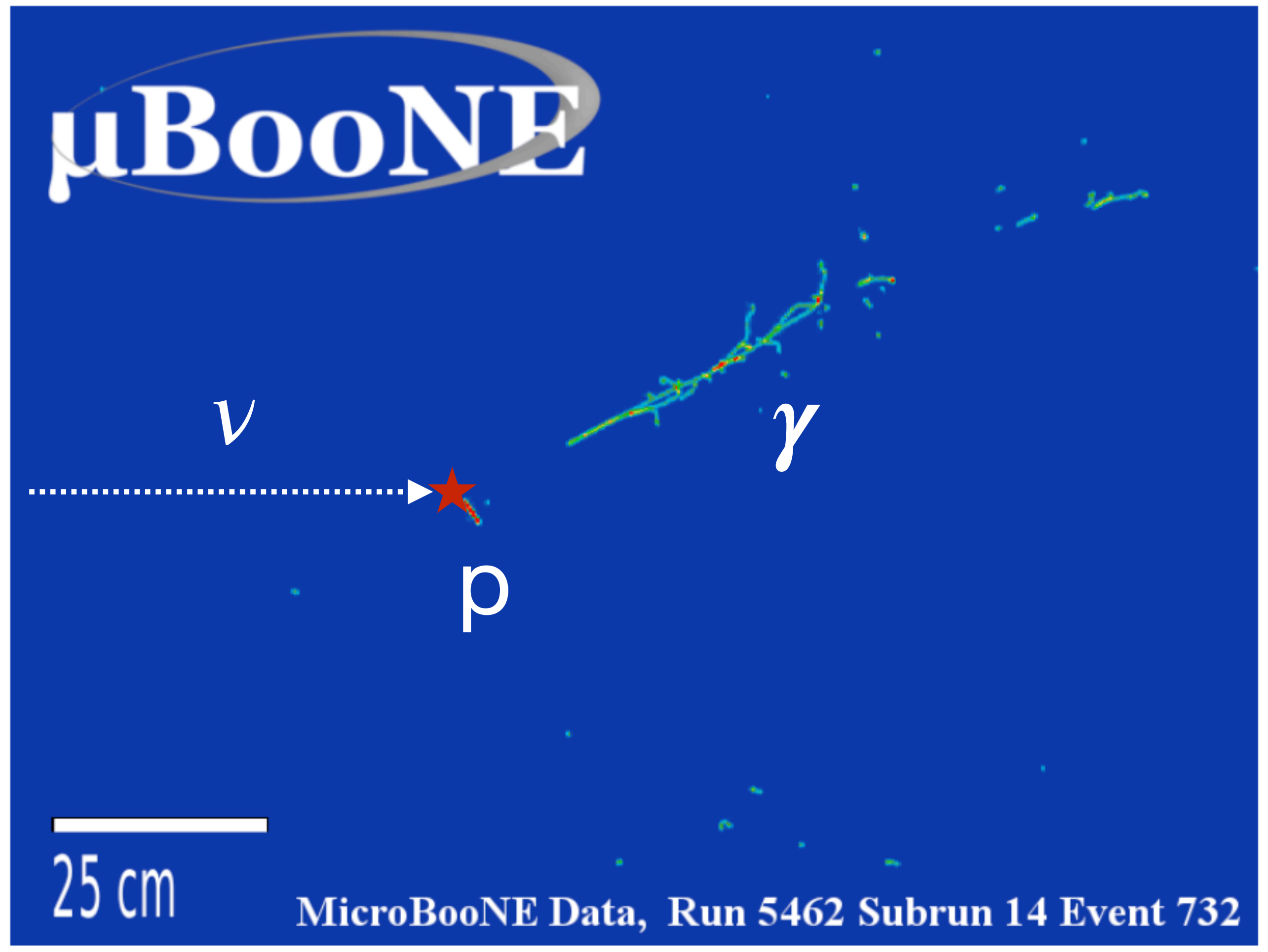
ionization dE/dx

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

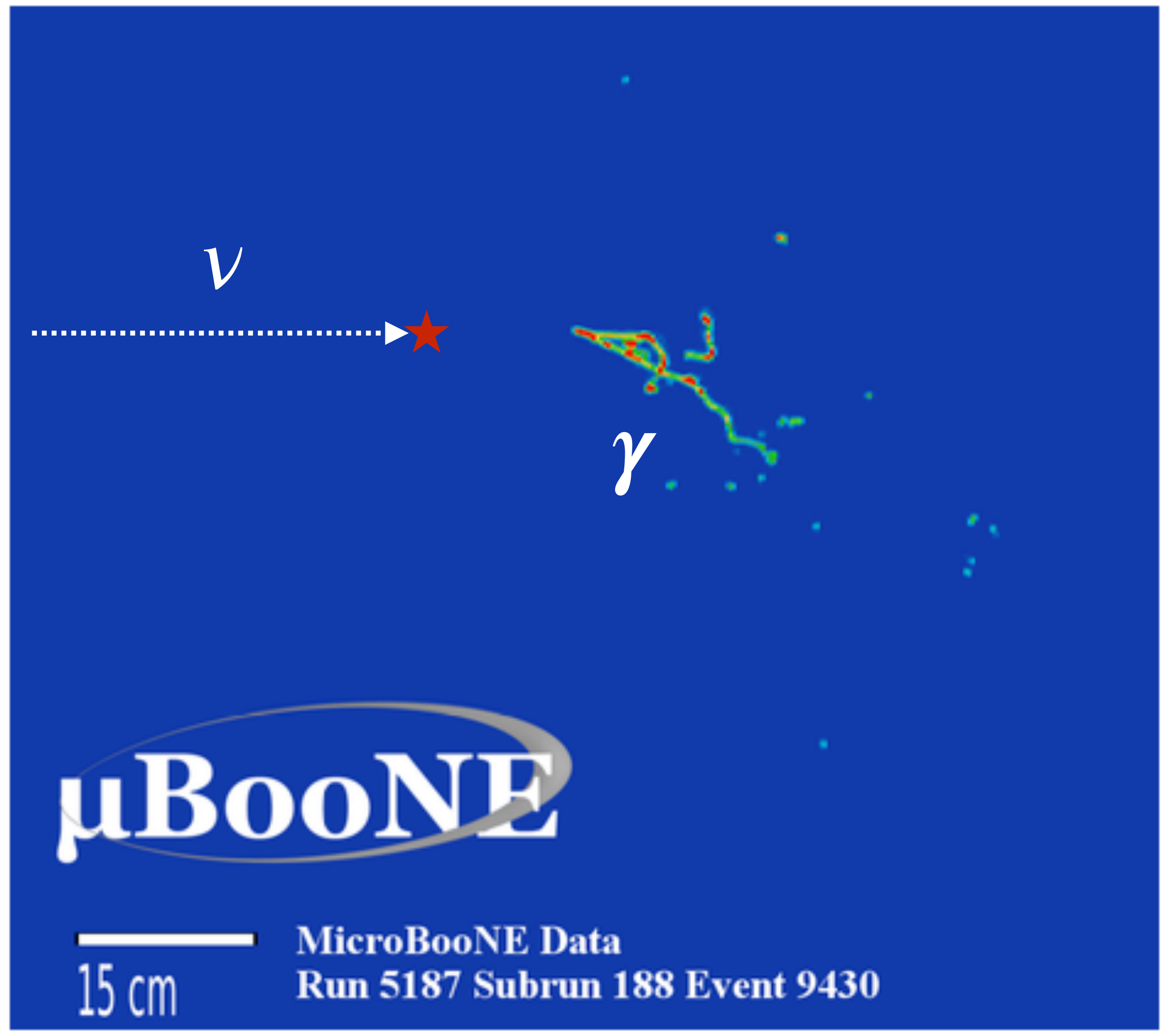
MICROBOONE-NOTE-1087-PUB

- targets $1\gamma0p$ and $1\gamma1p$ topologies consistent with NC $\Delta \to N\gamma$
  - applying a ~3x flat scaling to NC $\Delta \to N\gamma$ can explain the observed MiniBooNE excess
- using "Pandora" reconstruction [EPJC 78 (2018) 82], with BDT-based selection
- uses NCπ^0 events as sideband, correction to the GENIE-predicted NCπ^0 production rate normalizations

$1\gamma0p$



$1\gamma1p$



µBooNE

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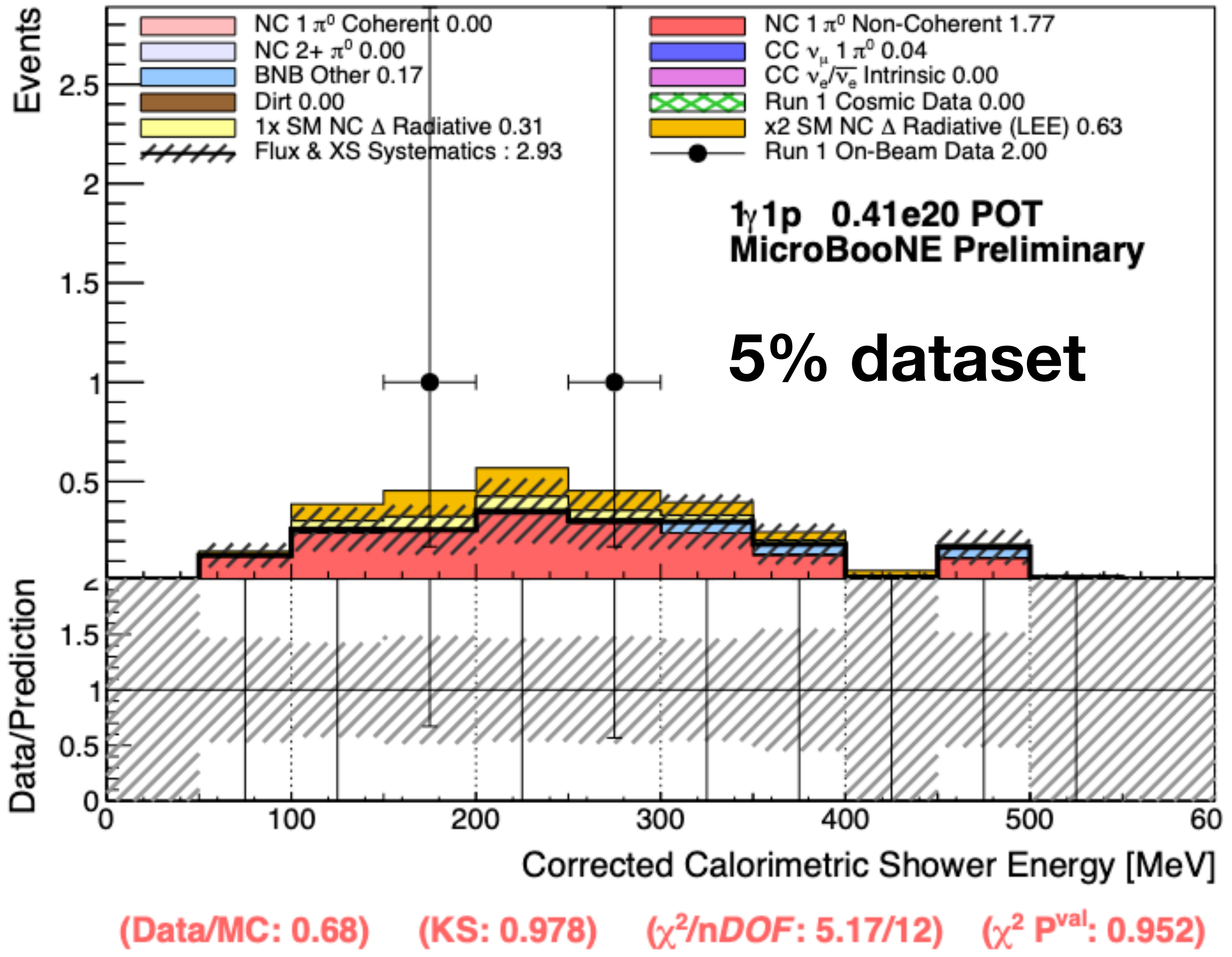
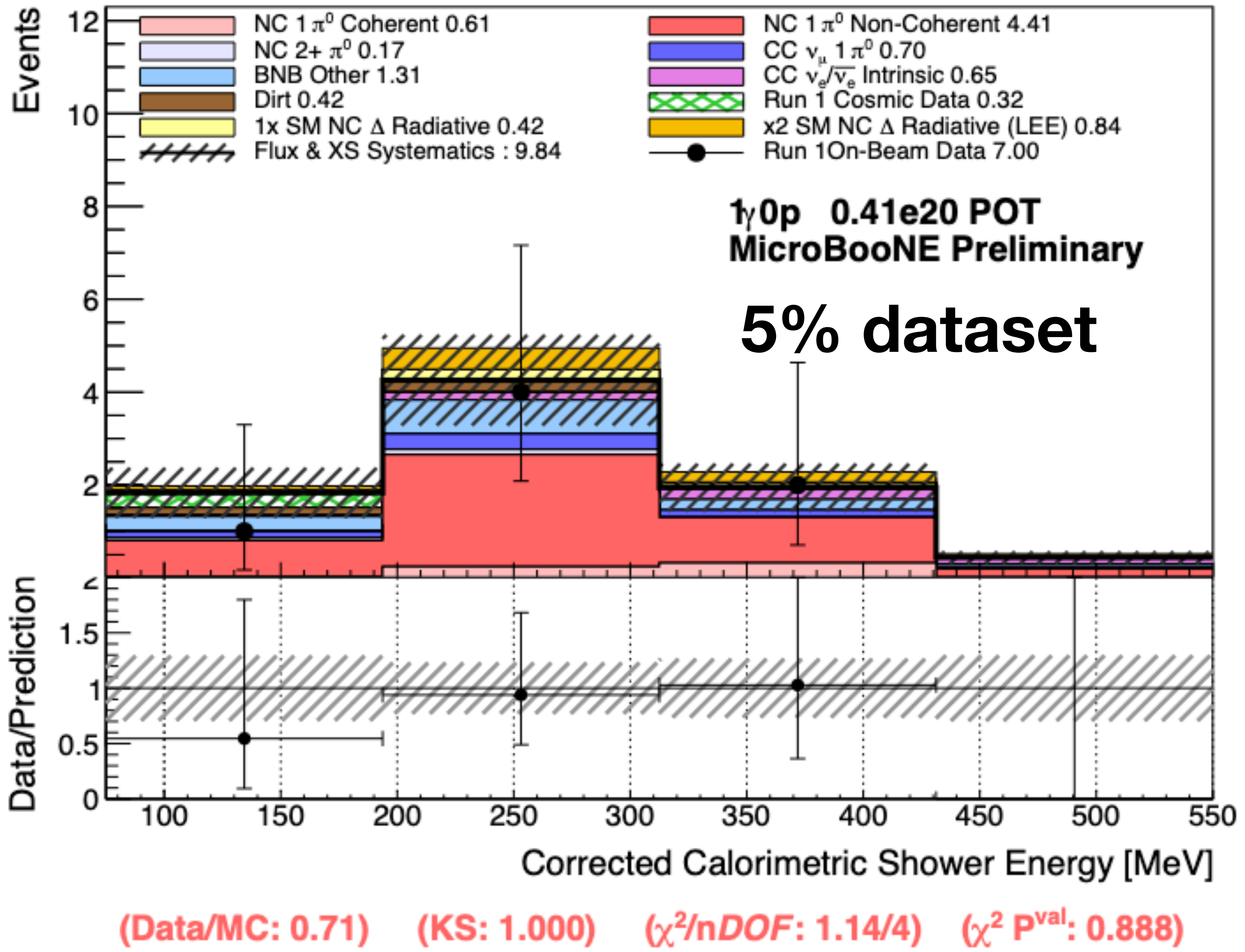
$1\gamma0p$



$1\gamma1p$



γLEE search

µBooNE

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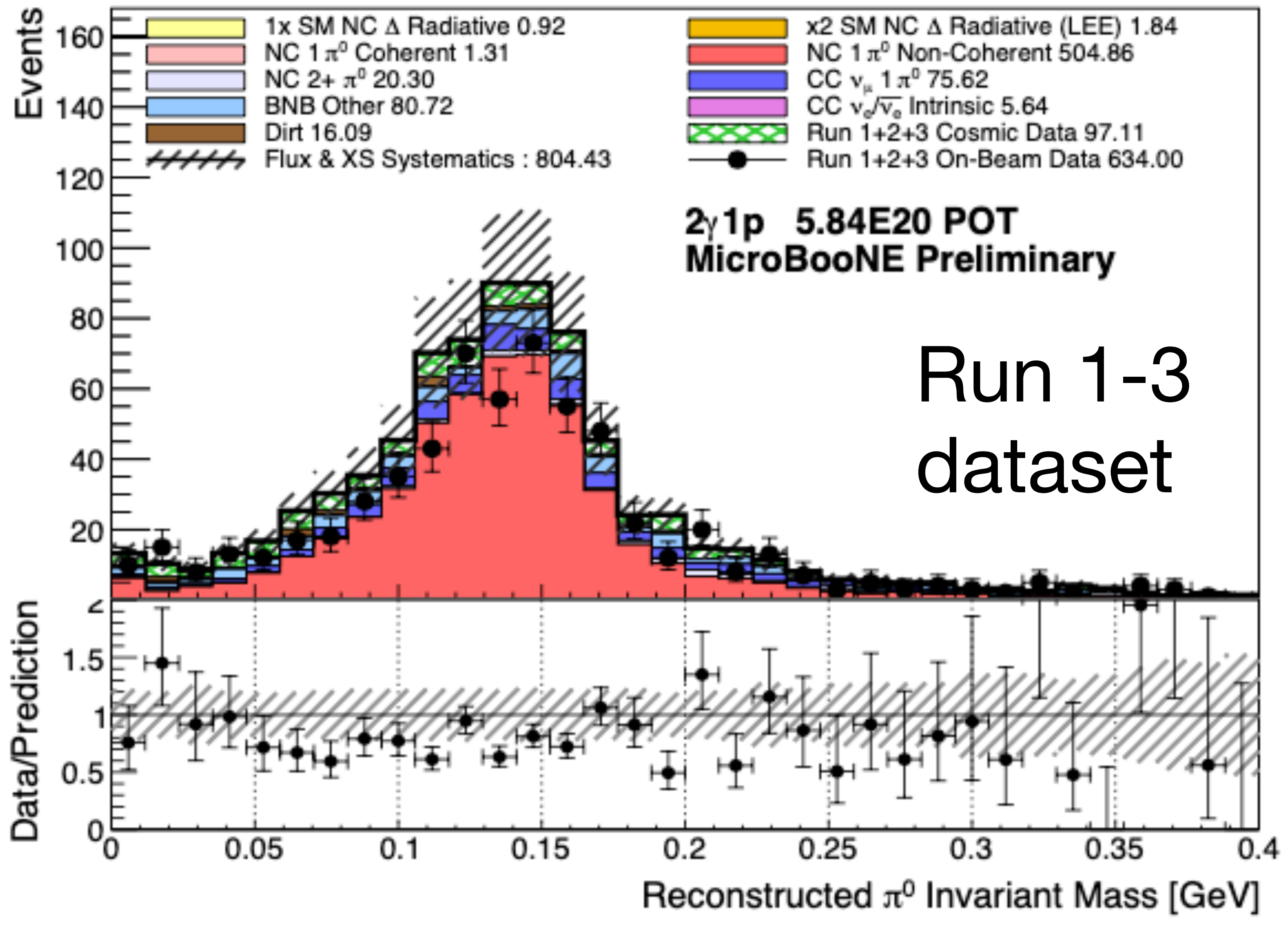
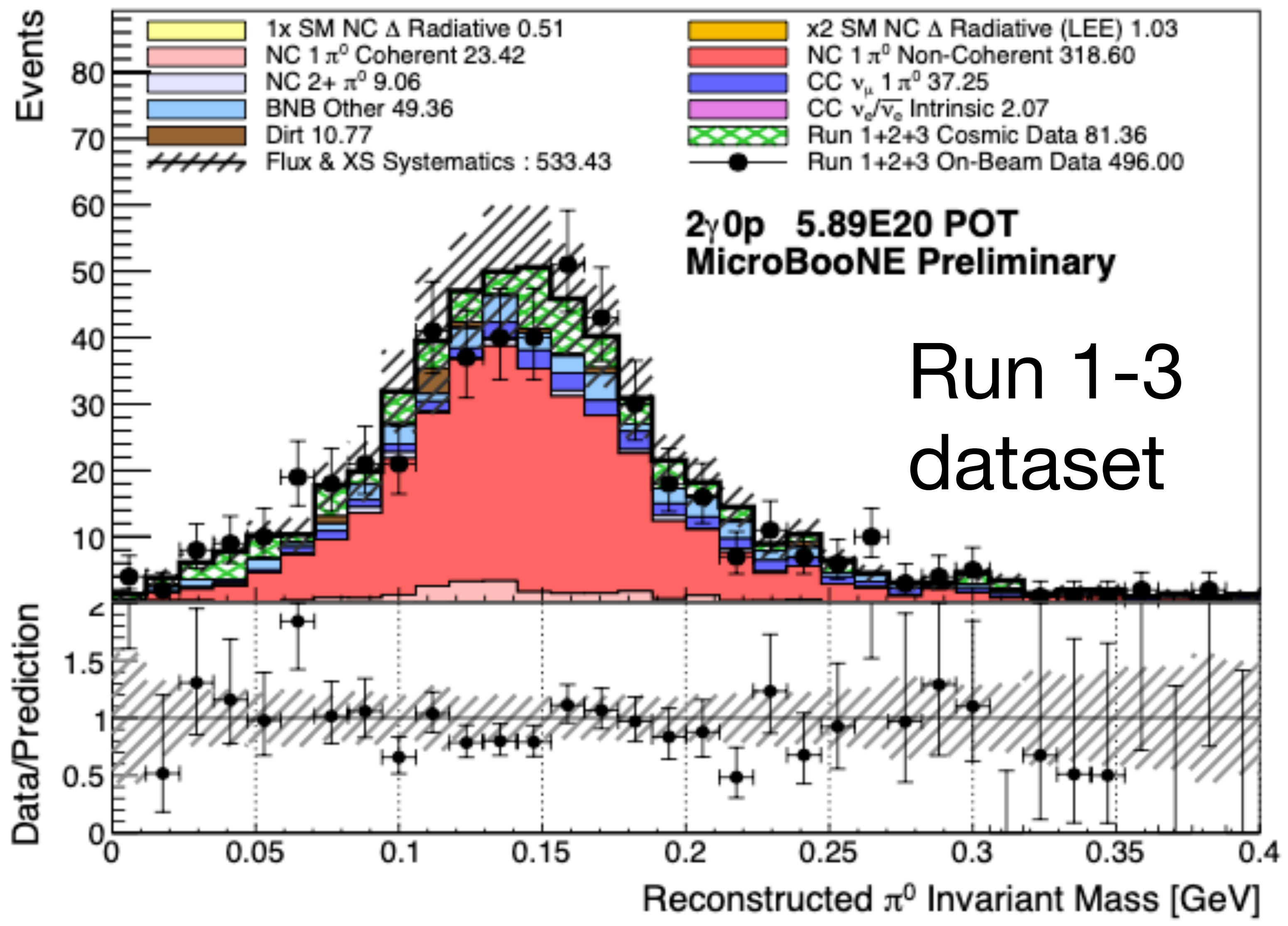
MICROBOONE-NOTE-1087-PUB

$2\gamma0p$



(Data/MC: 0.79) (KS: 0.995) (χ^2/nDOF: 23.00/34) (χ^2 P^{val}: 0.924)

$2\gamma1p$

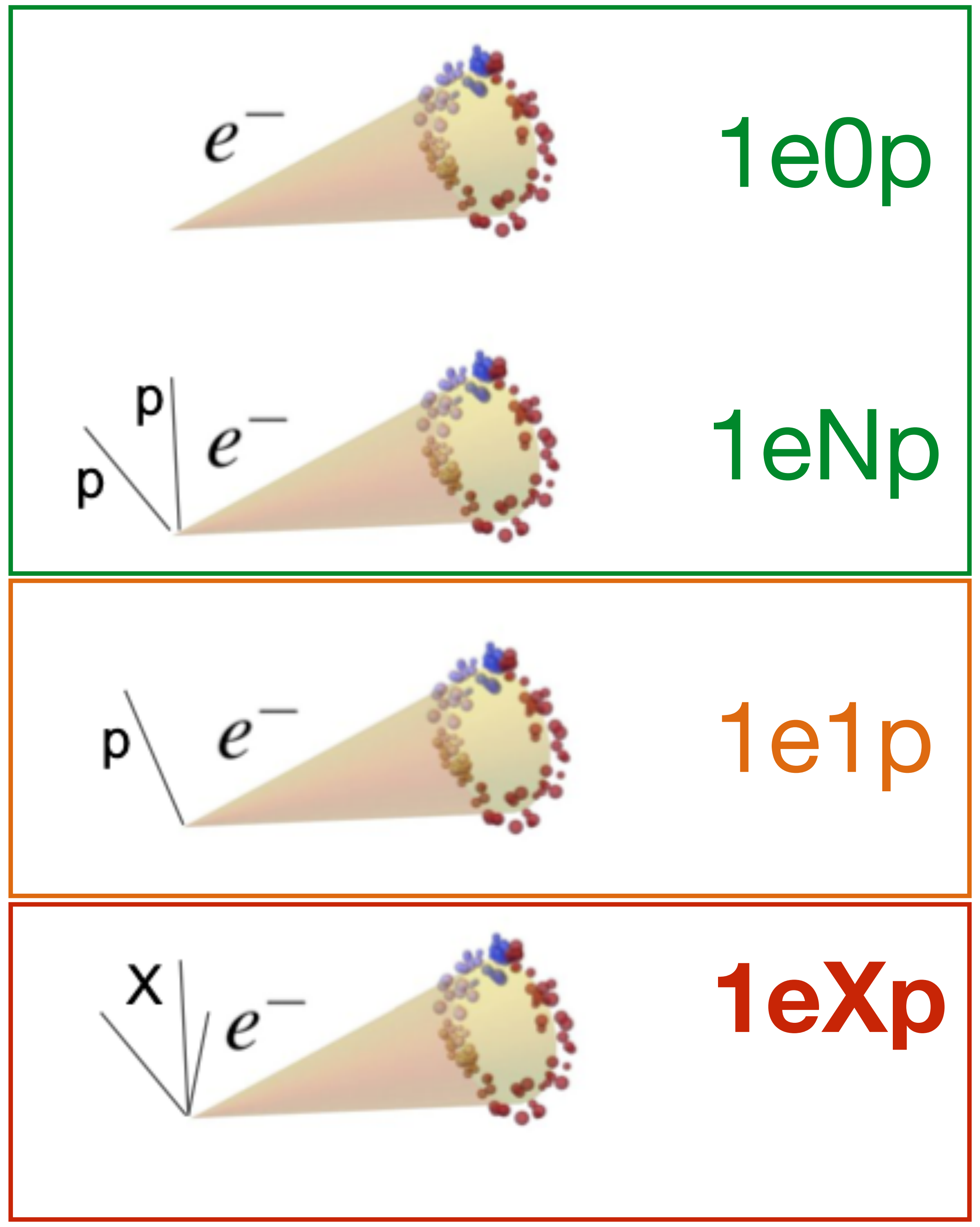


(Data/MC: 0.93) (KS: 0.901) (χ^2/nDOF: 30.04/34) (χ^2 P^{val}: 0.662)

eLEE search: three complementary searches

μBooNE

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

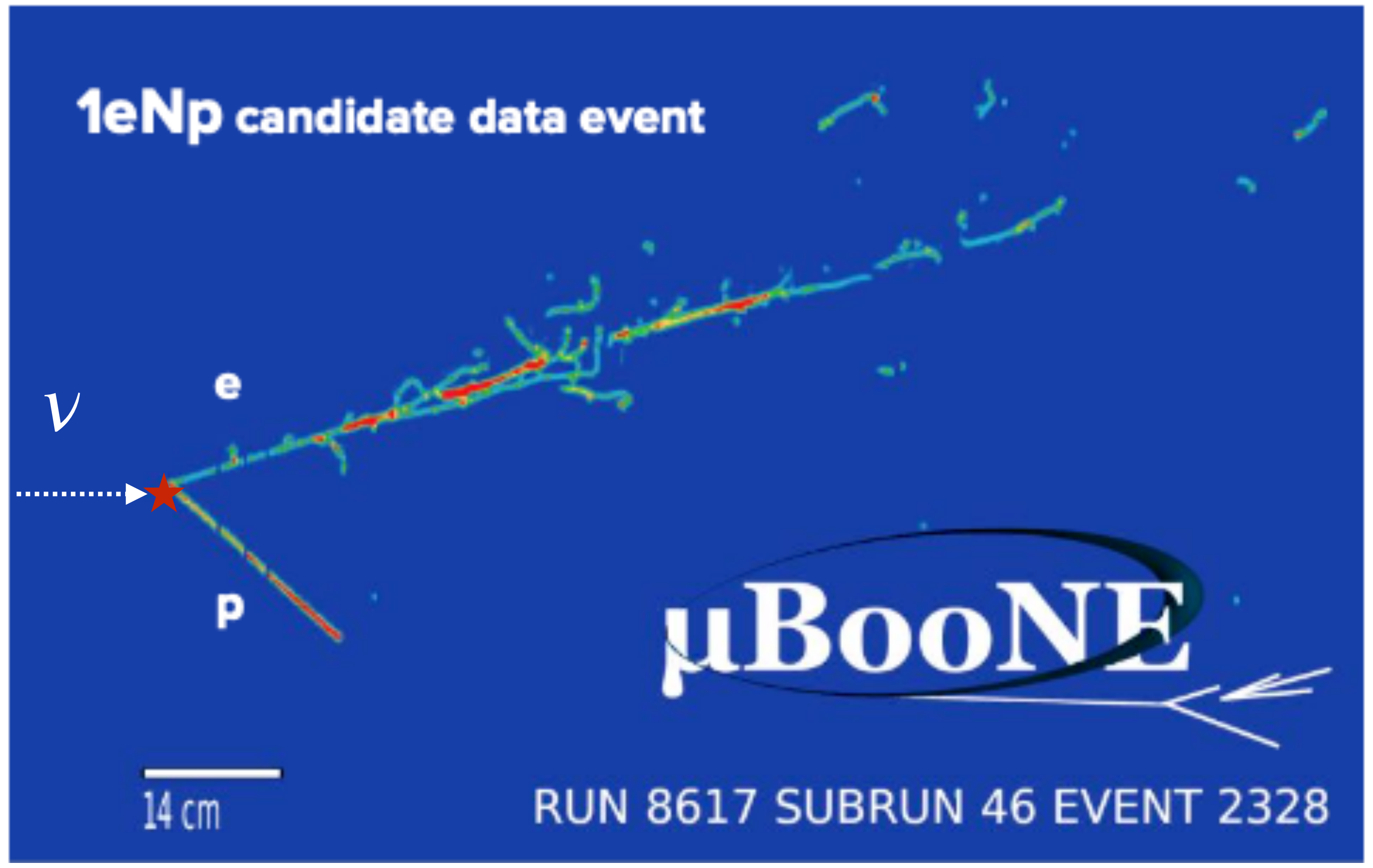


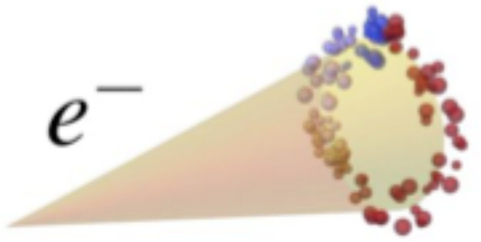
	1e0p	1e1p	1eNp	1eX
sterile ν	✔	✔	✔	✔
Higgs physics		✔	✔	✔
dark ν	✔			
Z’ boson	✔			
axion-like particles	✔			

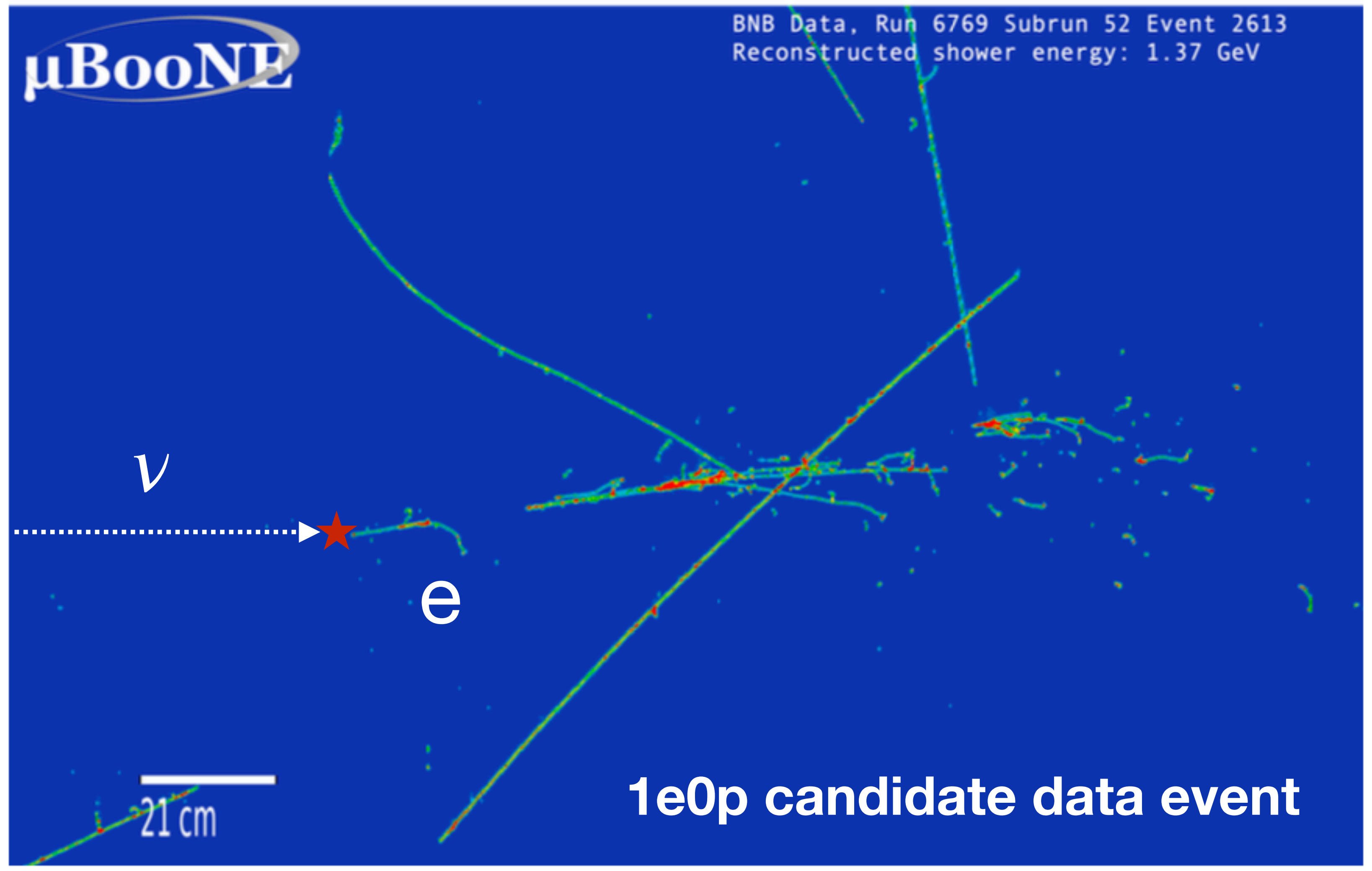
eLEE search: Pandora

MICROBOONE-NOTE-1085-PUB

- Pandora based eLEE search
  - with topology- and calorimetry-based PID tools [EPJC 78 (2018) 82]
  - $1e0p0\pi$ and $1eNp0\pi$ selection
    - pure ν_eCC 1eNp selection achieved, down to low energy
    - high-energy ν_eCC events show reasonable data-MC agreement







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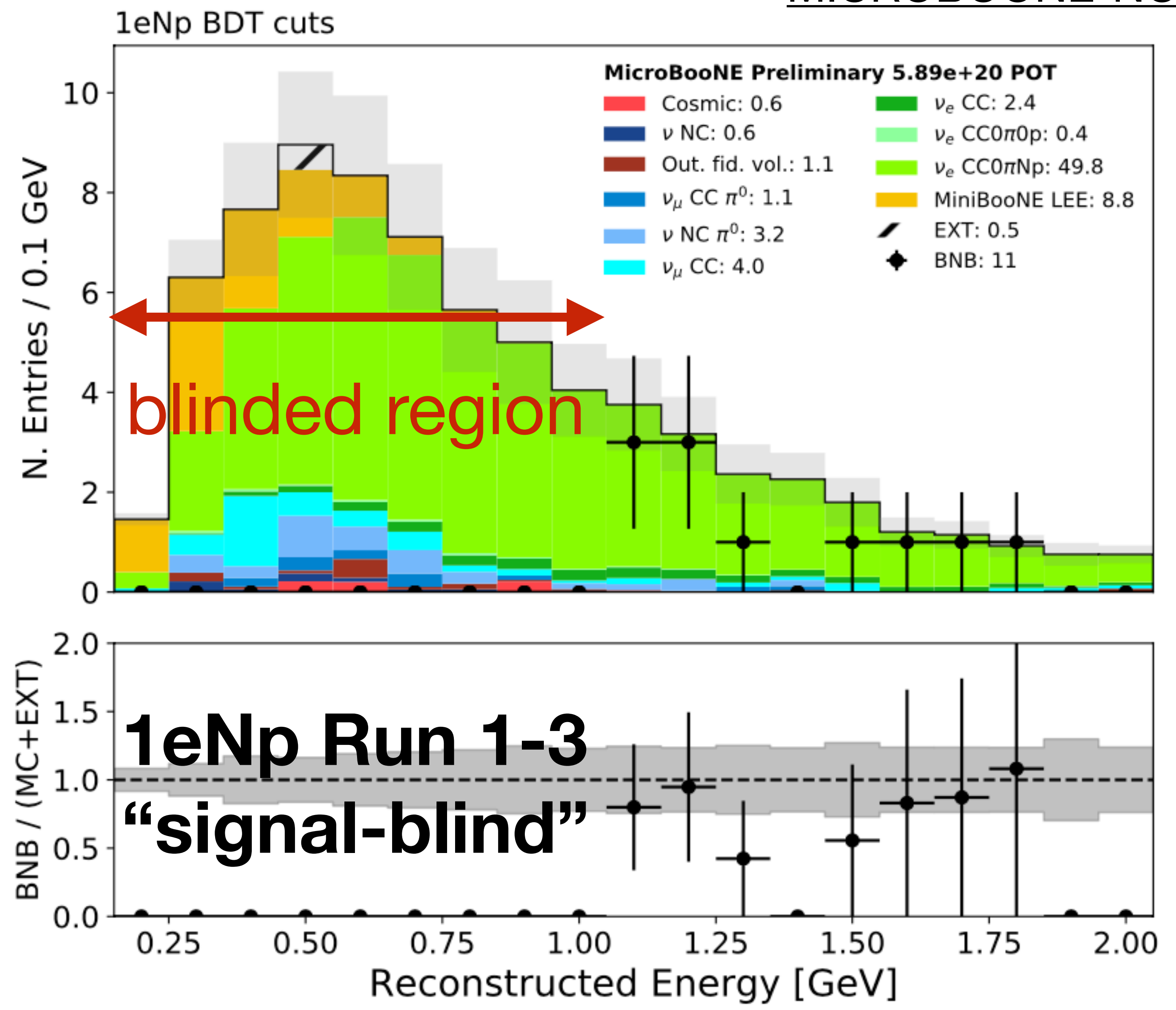
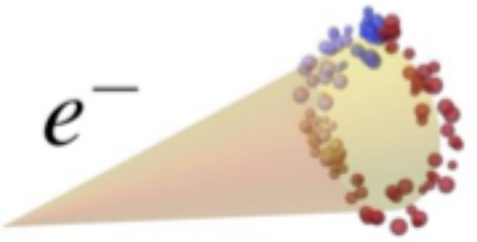
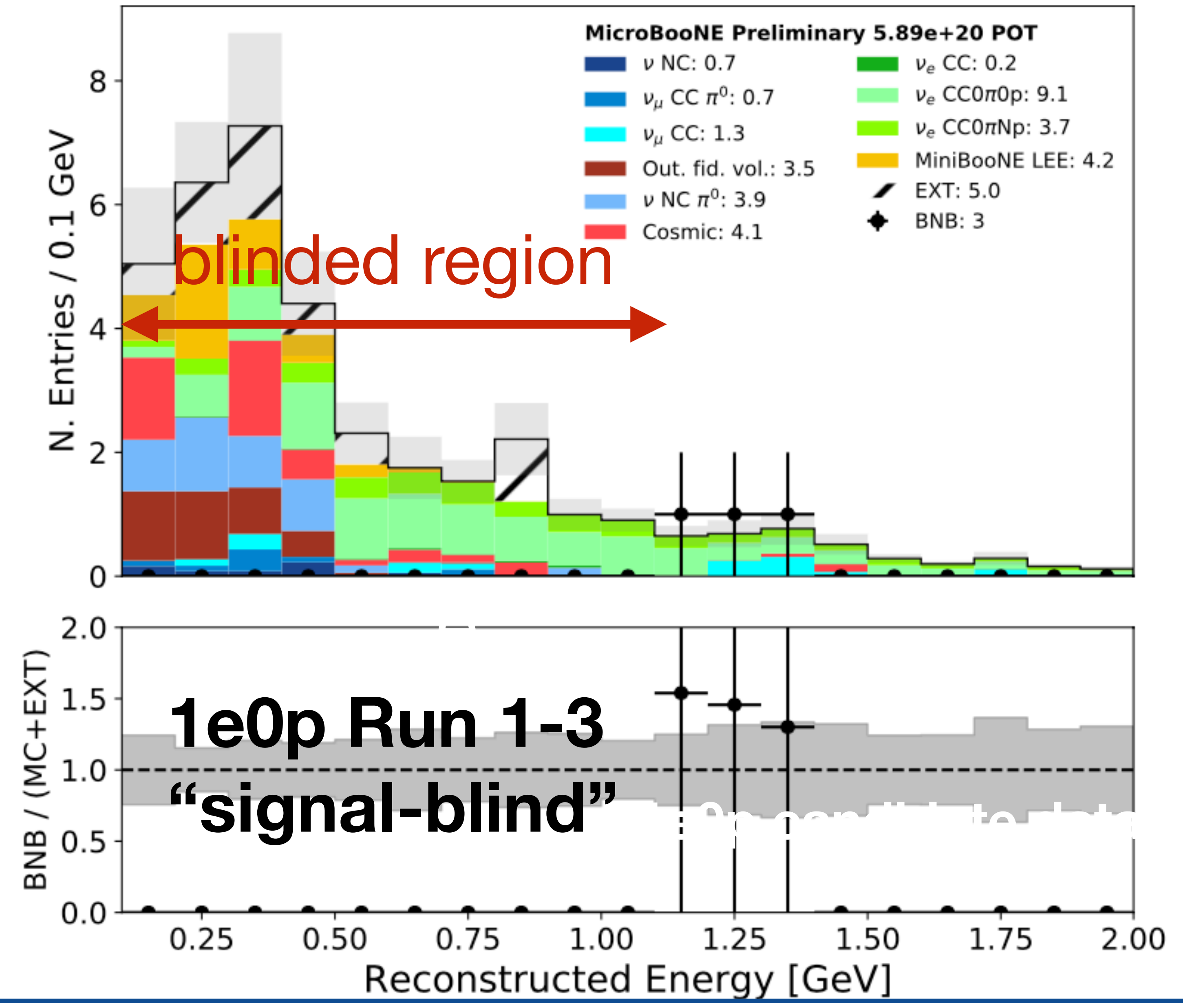


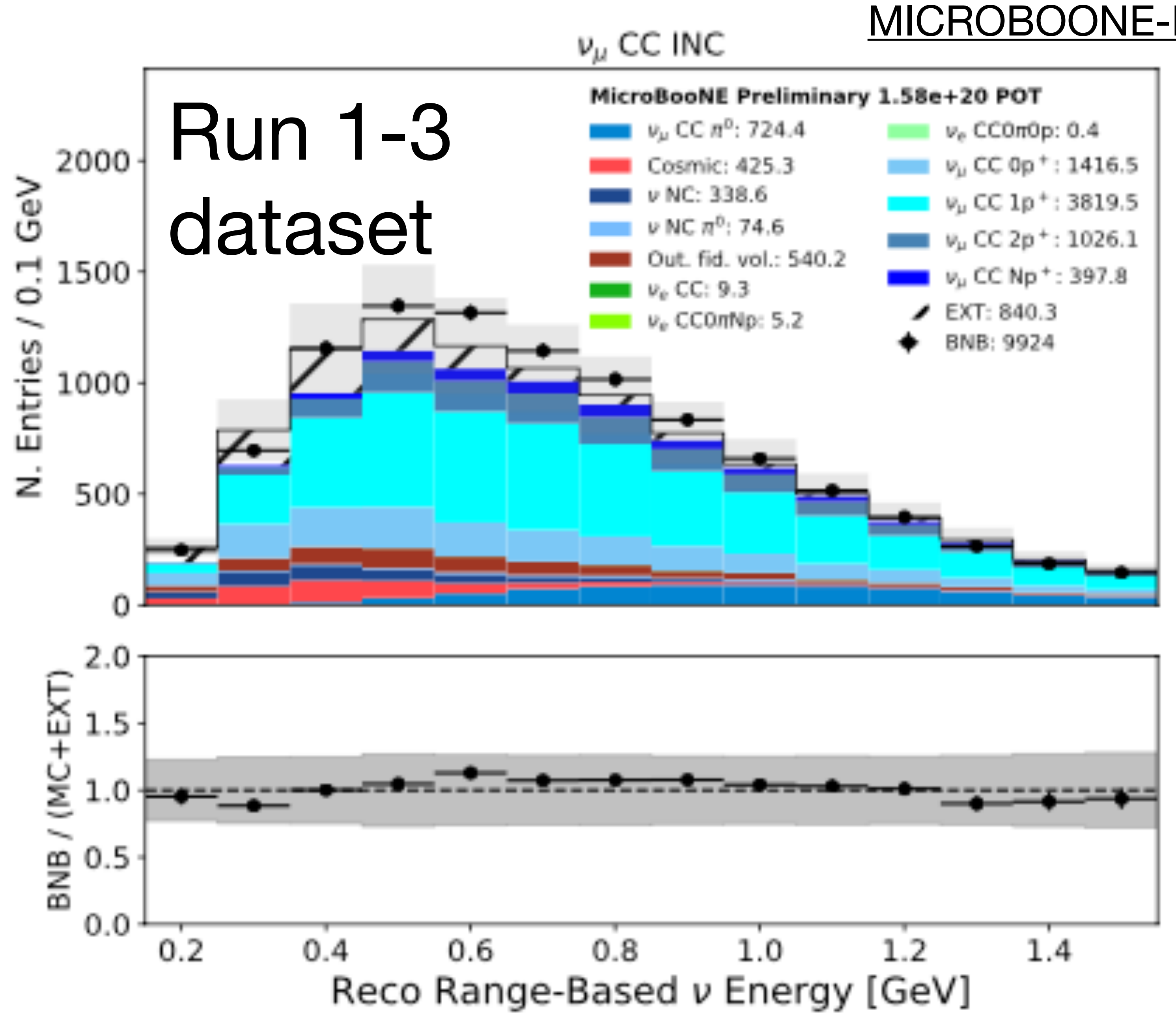


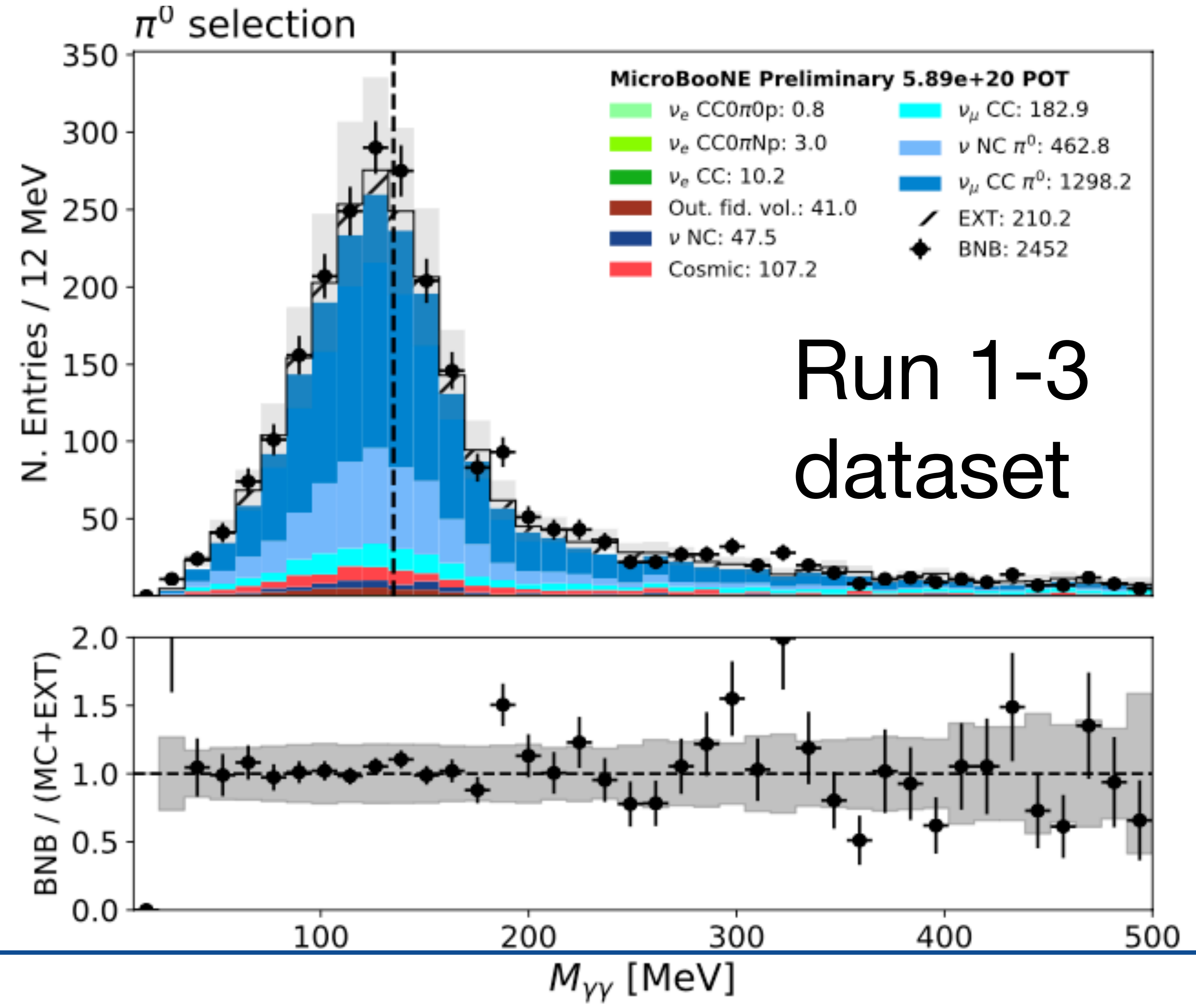


eLEE search: Pandora

MICROBOONE-NOTE-1085-PUB

- Pandora based eLEE search
  - ν_μCC inclusive sideband for validating flux and cross-section modeling, and constraining ν_eCC backgrounds
  - shower reconstruction and calorimetry validation with dedicated π^0 selection

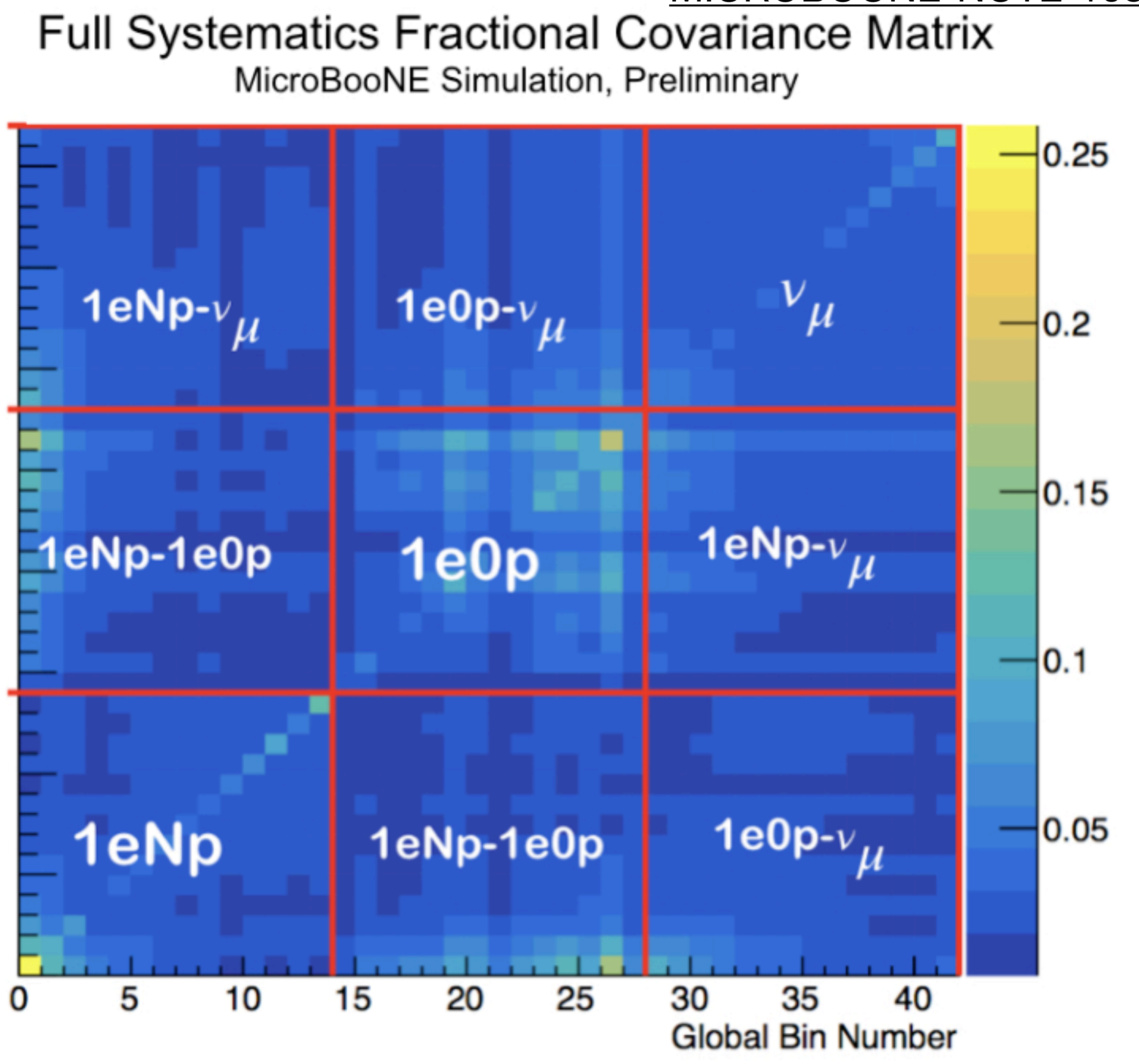


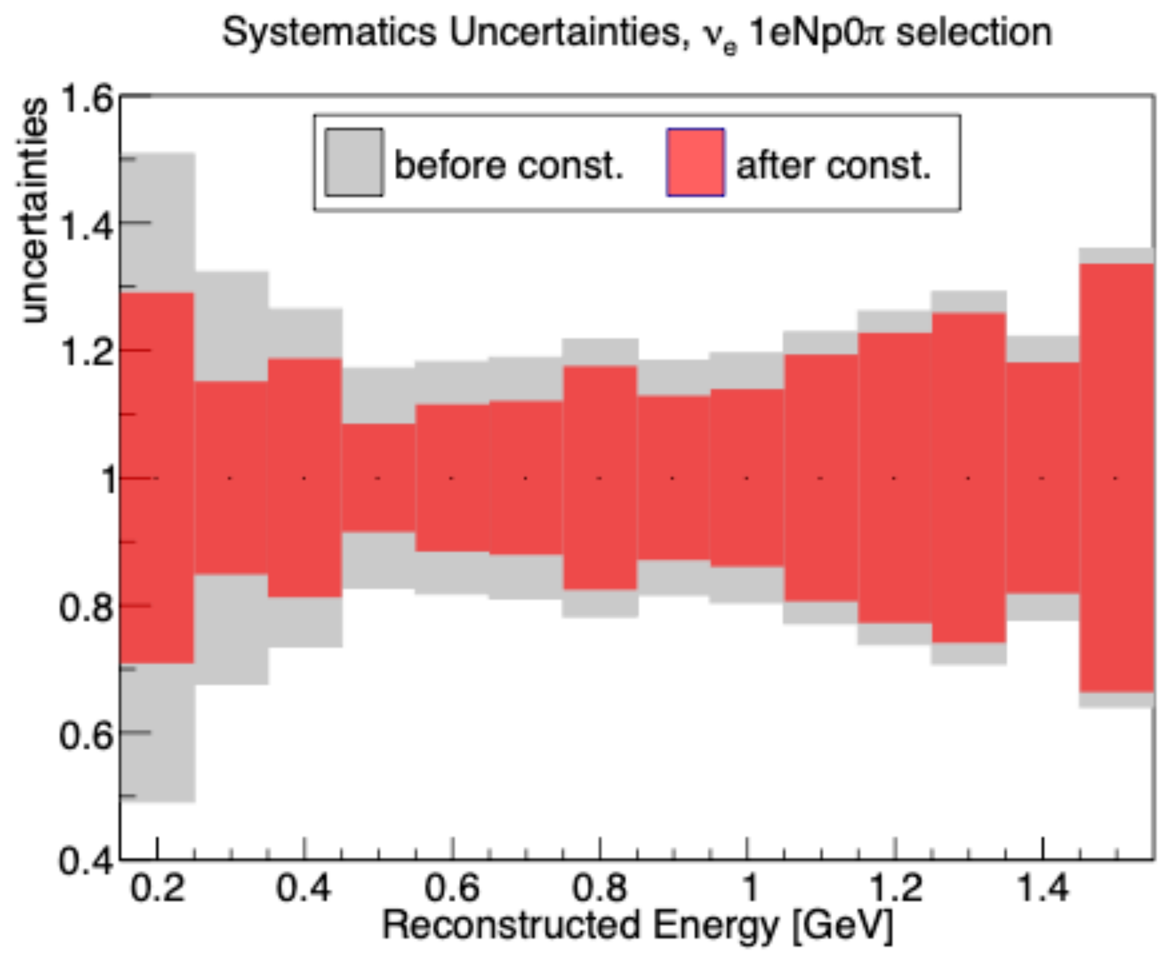


eLEE search: Pandora

MICROBOONE-NOTE-1085-PUB

- Pandora based eLEE search
  - a side-by-side fit to 1eNp, 1e0p and ν_μCC selections constrains 1eNp and 1e0p background predictions
  - systematic uncertainty reduces significantly after such constraints



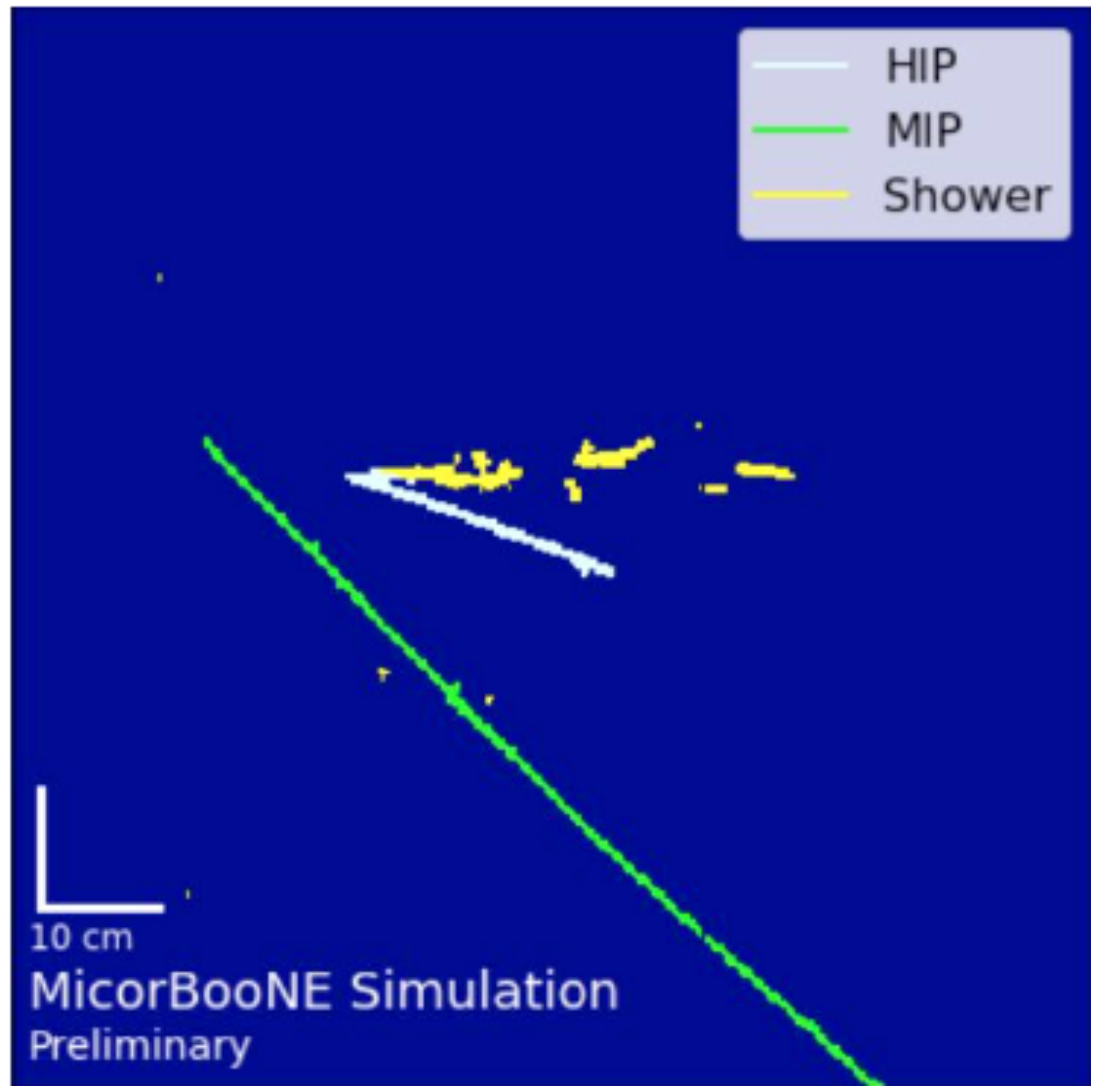


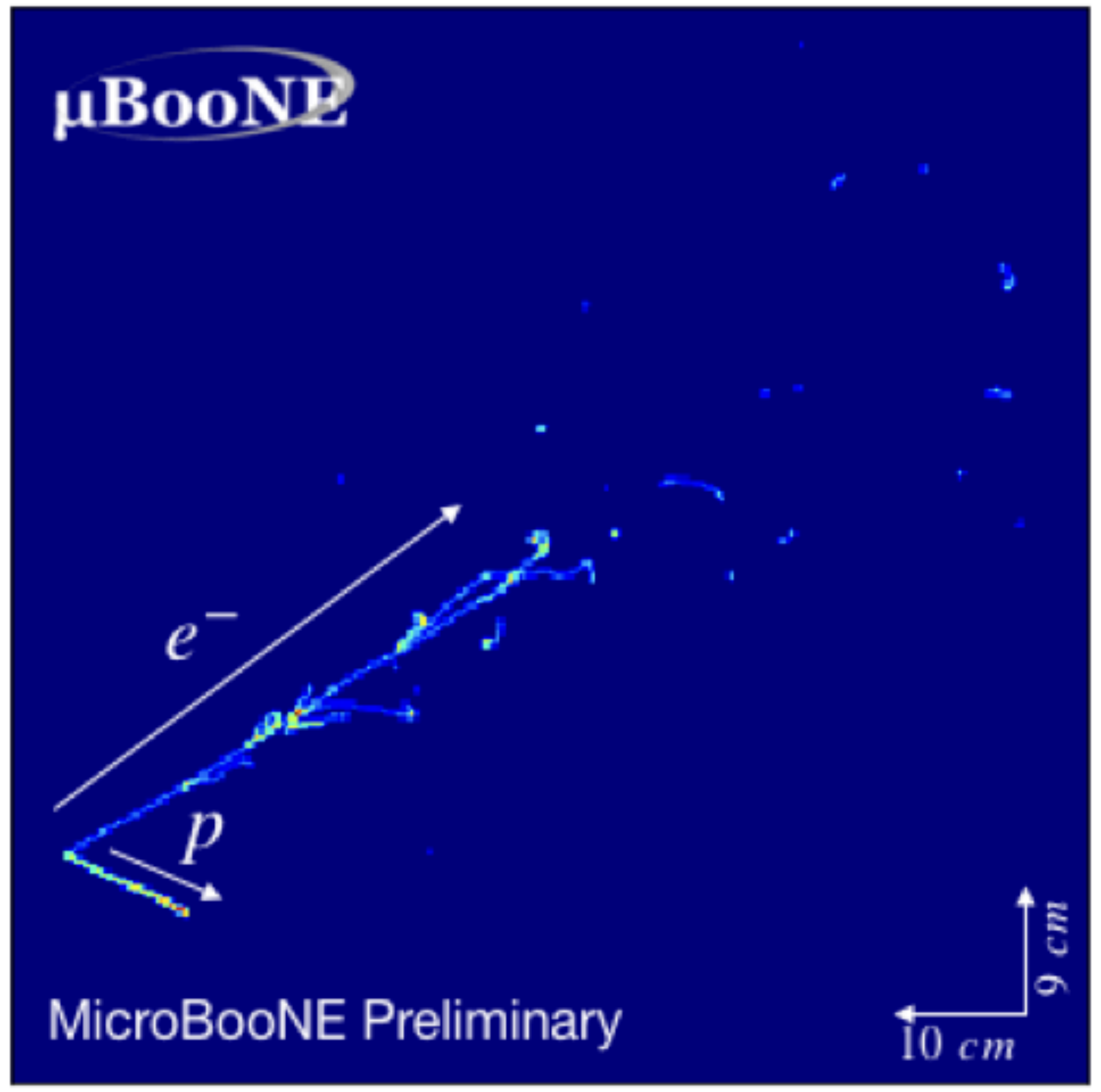
eLEE search: Deep Learning

MICROBOONE-NOTE-1080-PUB

- Deep Learning based eLEE search
  - track/shower separation with semantic segmentation [PRD 103 (2021) 052012]
  - PID with convolutional neural network [PRD 103 (2021) 092003]
  - 1e1p0π selection (CCQE-dominated) & 1μ1p selection (sideband)
    - high purity samples are selected

pixel-level identification, using semantic segmentation



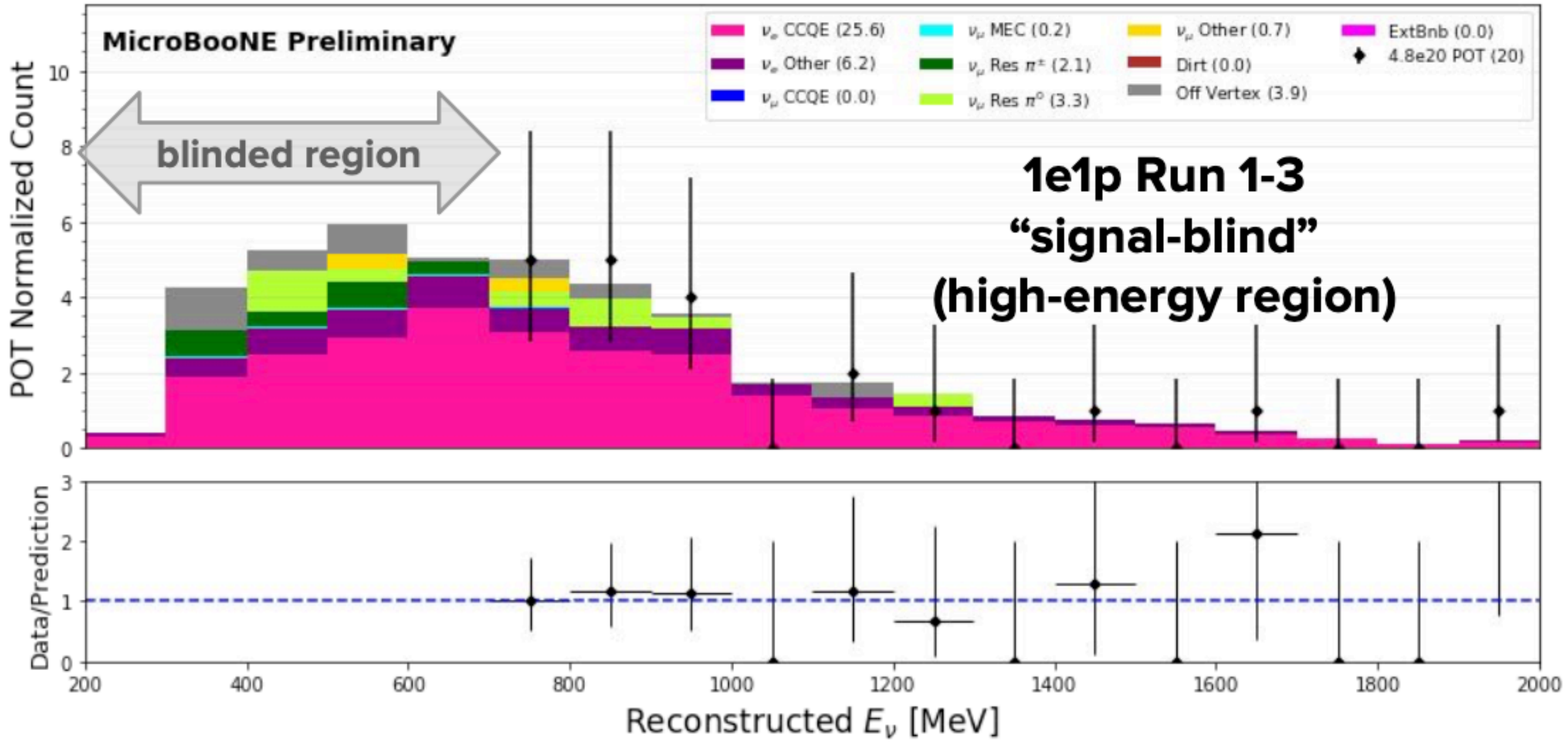


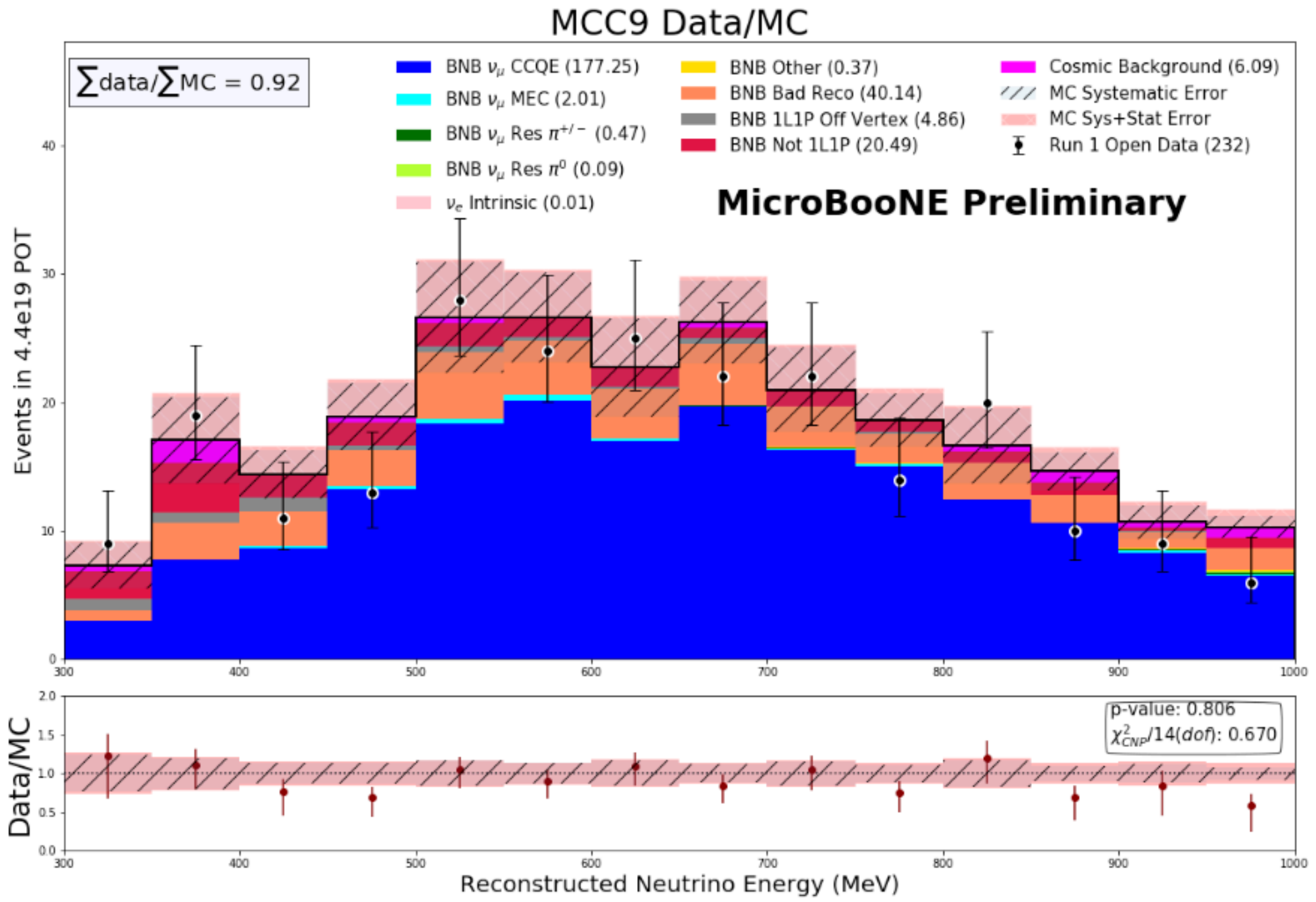
multi-particle identification using convolutional neural network

eLEE search: Deep Learning

MICROBOONE-NOTE-1086-PUB

- Deep Learning based eLEE search
  - track/shower separation with semantic segmentation [PRD 103 (2021) 052012]
  - PID with convolutional neural network [PRD 103 (2021) 092003]
  - 1e1p0π selection (CCQE-dominated) & 1μ1p selection (sideband)
    - high purity samples are selected



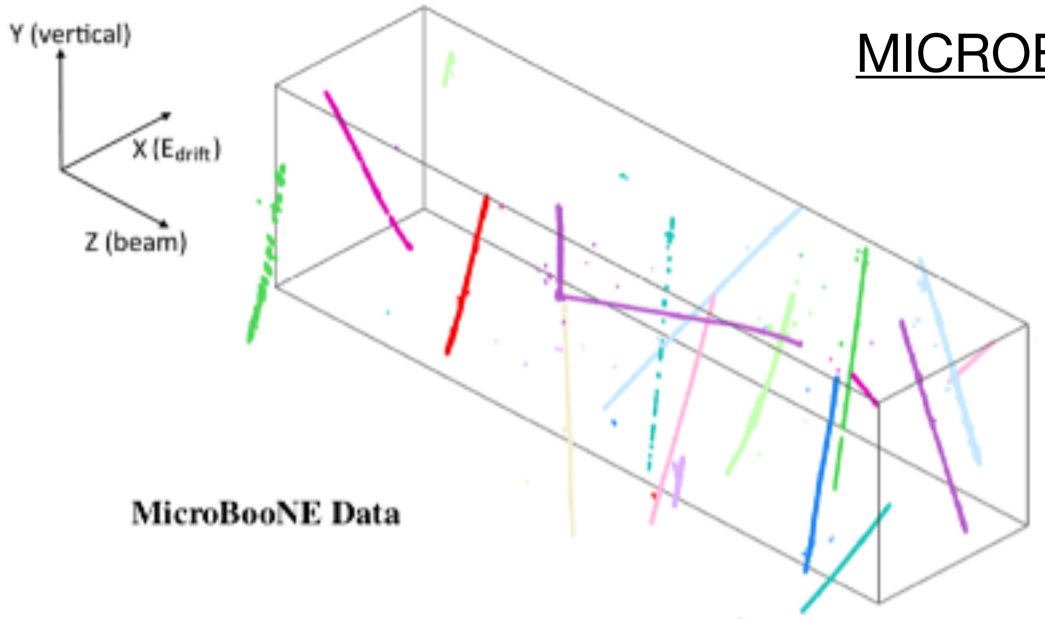


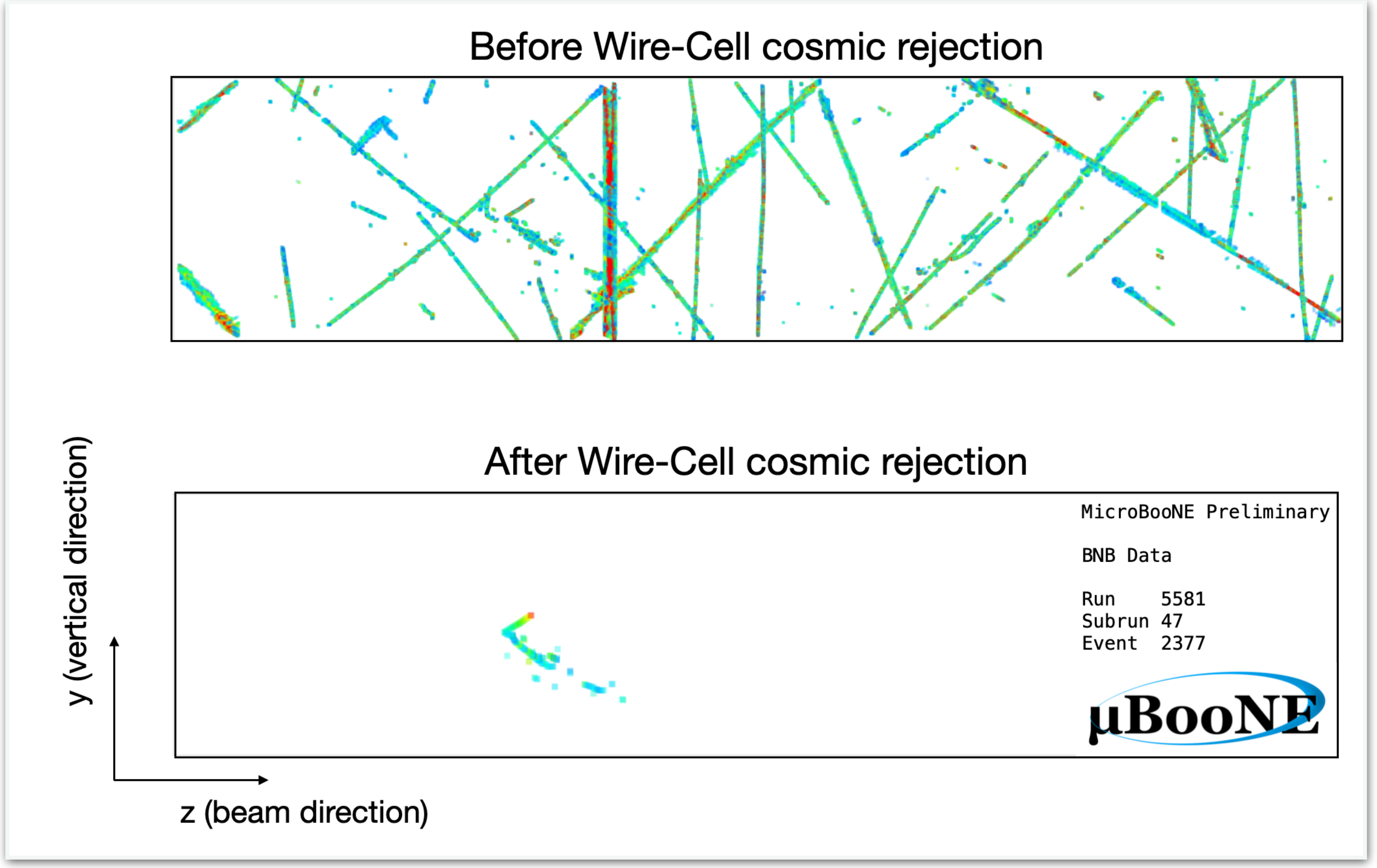
1μ1p Run 1-3 dataset

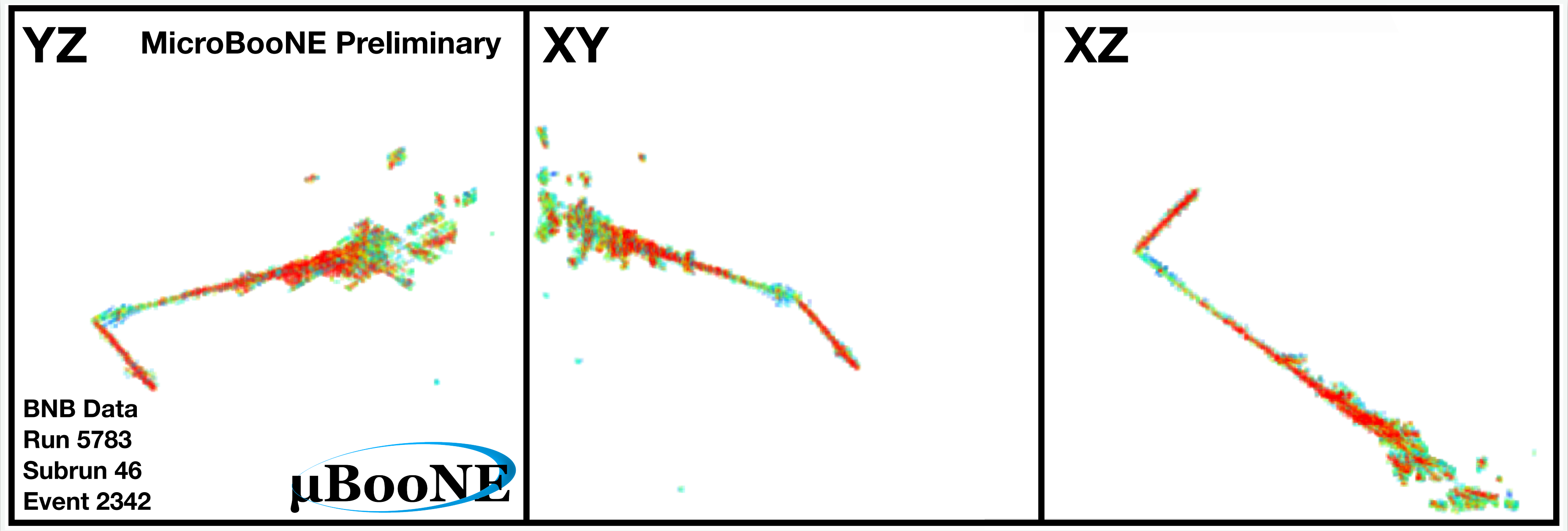
eLEE search: Wire-Cell

MICROBOONE-NOTE-1083-PUB

- Wire-Cell based eLEE search
  - based on 3D images
  - topology-agnostic event reconstruction [JINST 16 (2021) P06043]
  - excellent cosmic rejection power [PRApplied 15 (2021) 064071]
  - fully inclusive 1eXpXπ selection: least model dependent
    - very pure & high stat ν_e and ν_μ selection achieved
  - using 6 different sideband samples to constrain signal channel



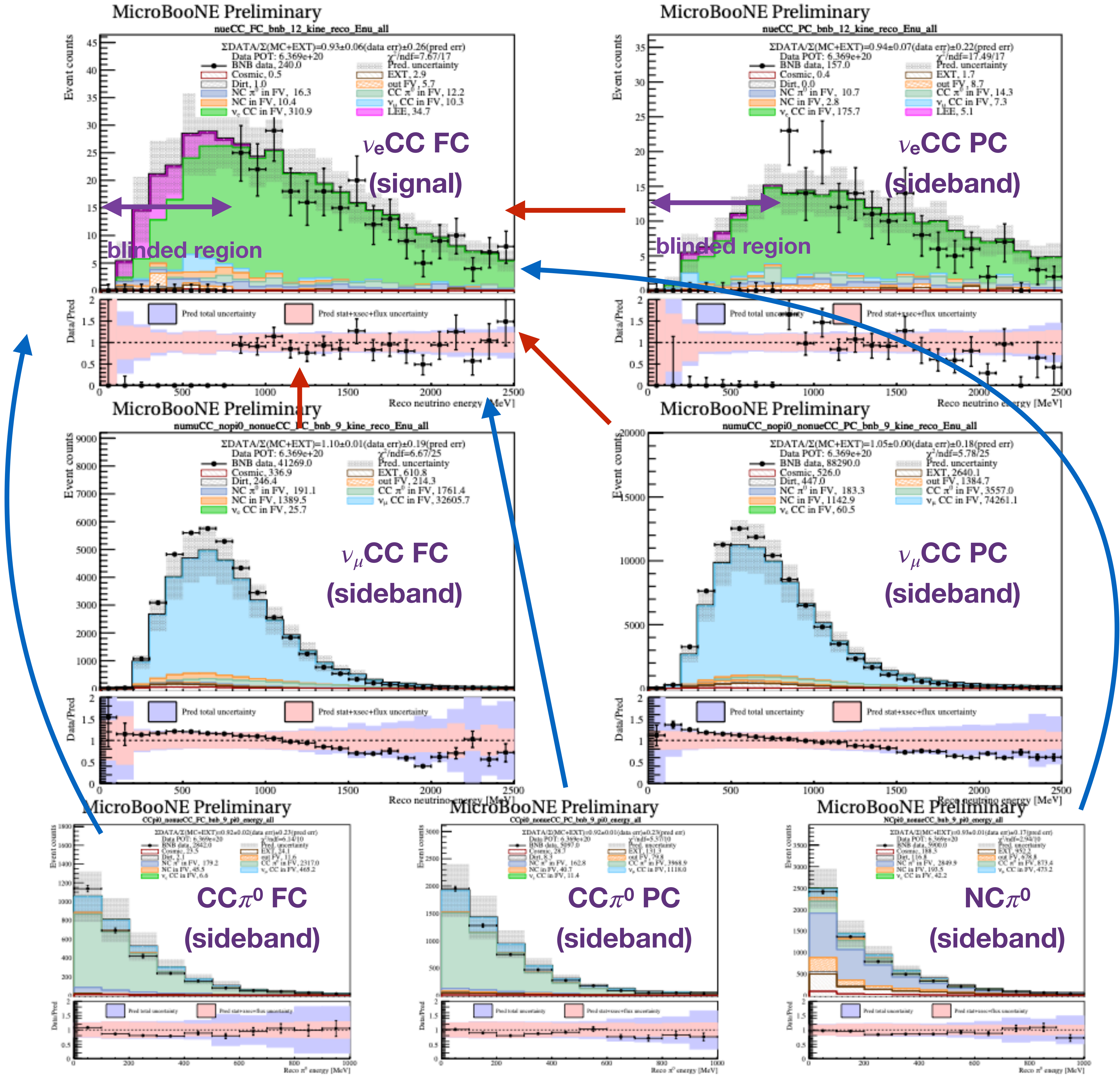




eLEE search: Wire-Cell

MICROBOONE-NOTE-1100-PUB

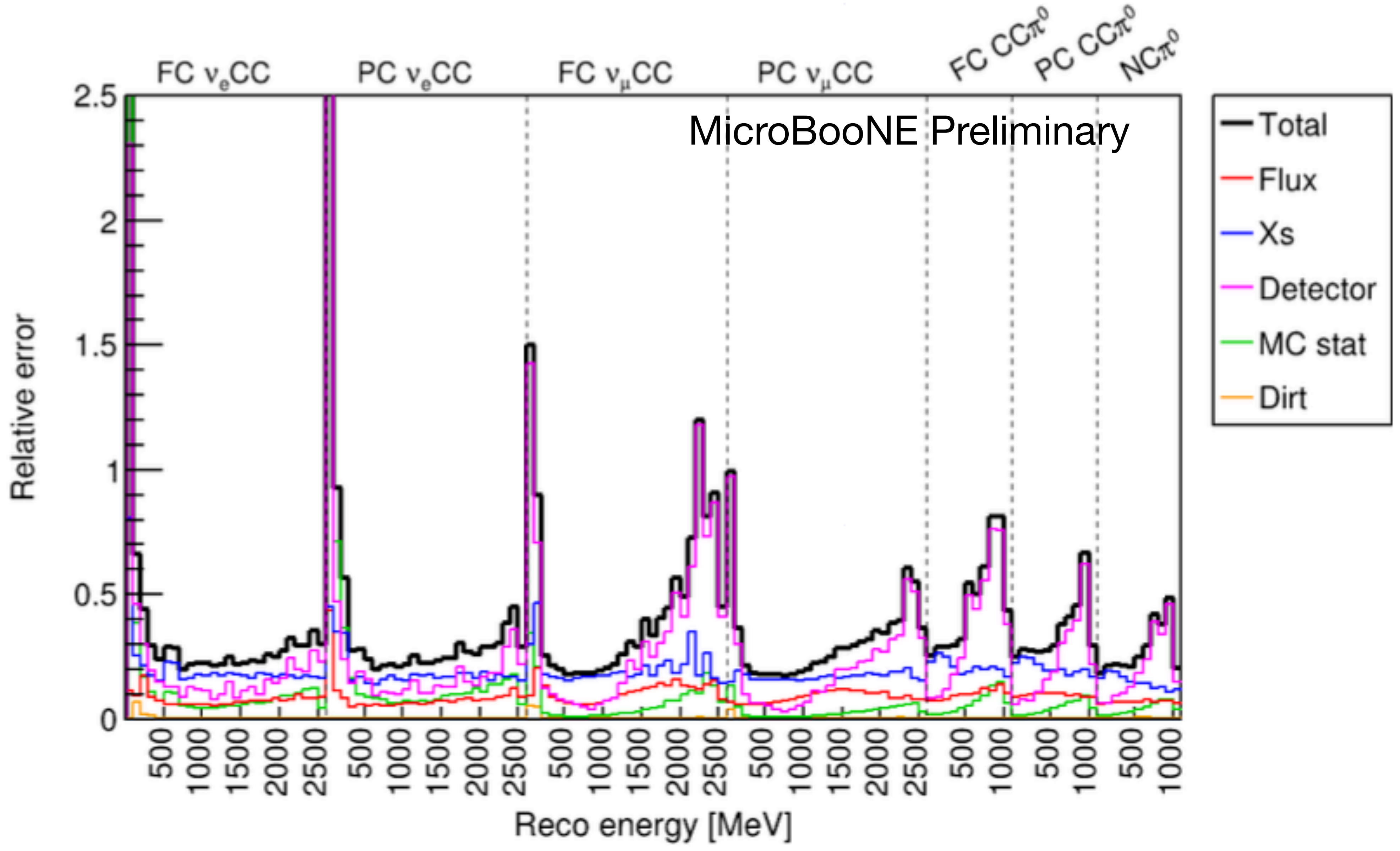
- Wire-Cell based eLEE search
  - based on 3D images
  - topology-agnostic event reconstruction
    [JINST 16 (2021) P06043]
  - excellent cosmic rejection power
    [PRApplied 15 (2021) 064071]
  - fully inclusive 1eXpXπ selection: least model dependent
    - very pure & high stat ν_e and ν_μ selection achieved
  - using 6 different sideband samples to constrain signal channel

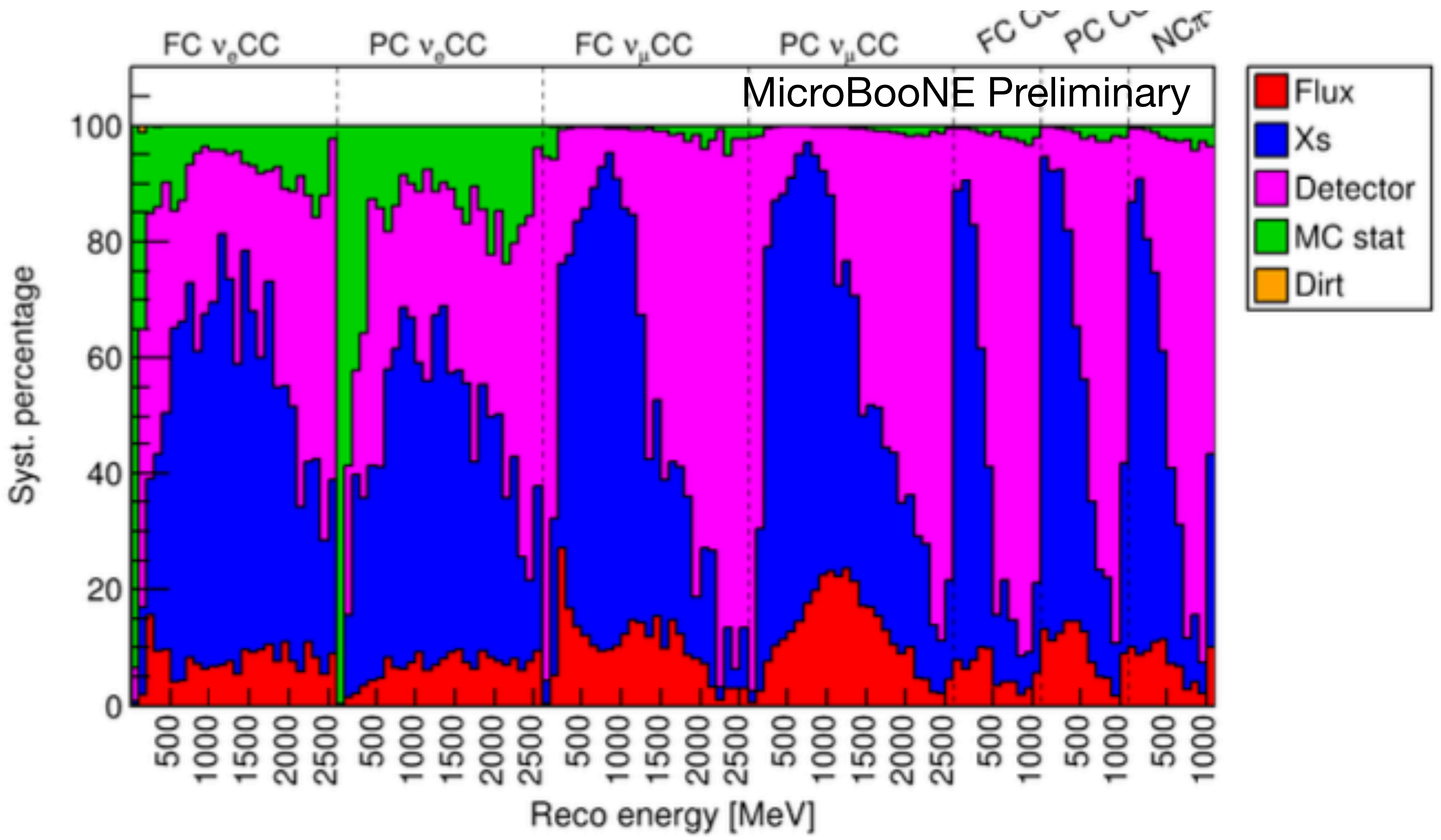


eLEE search: Wire-Cell

MICROBOONE-NOTE-1100-PUB

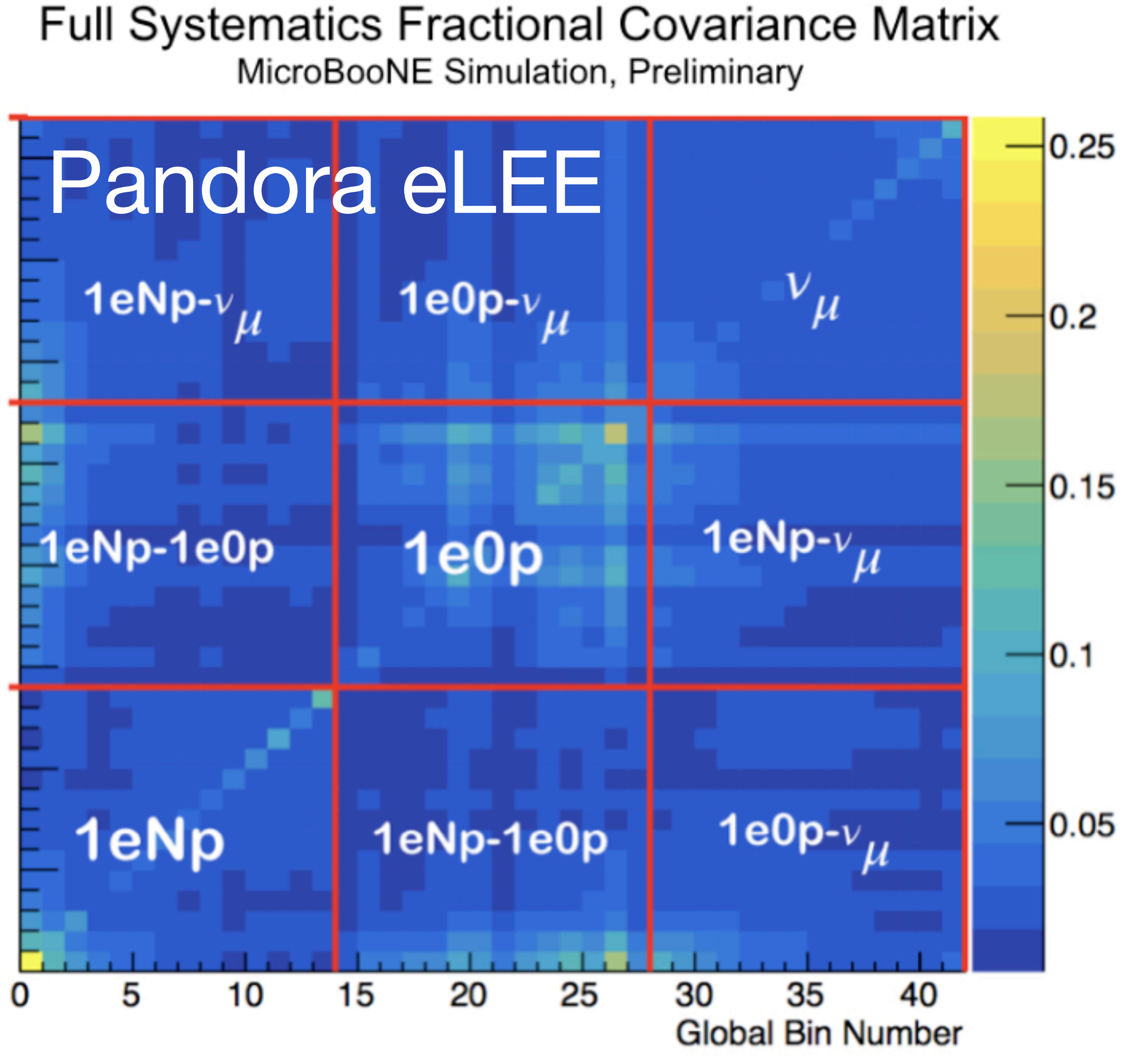
- Wire-Cell based eLEE search
  - cross-section (GENIE) and flux uncertainty estimation with event-reweighting
  - Bayesian statistical uncertainty estimation
  - the most dominant systematics in ν_e channel is cross-section uncertainty





γLEE & eLEE search: conditional constraints & sensitivity projection

- **conditional constraint method shared among all LEE searches**
  - constrain signal channel by utilizing sideband samples
  - γLEE: 1γ signal constrained with 2γ sideband
  - eLEE: ν_e signal constrained with ν_μ/π^0 sidebands
- **projected sensitivities**
  - tested against LEE model, unfolded from MiniBooNE, scaling NC Δ/intrinsic ν_e event rates
  - γLEE: 2.1σ sensitivity to reject LEE hypothesis
  - eLEE (Wire-Cell case): 3.3σ sensitivity to reject LEE hypothesis



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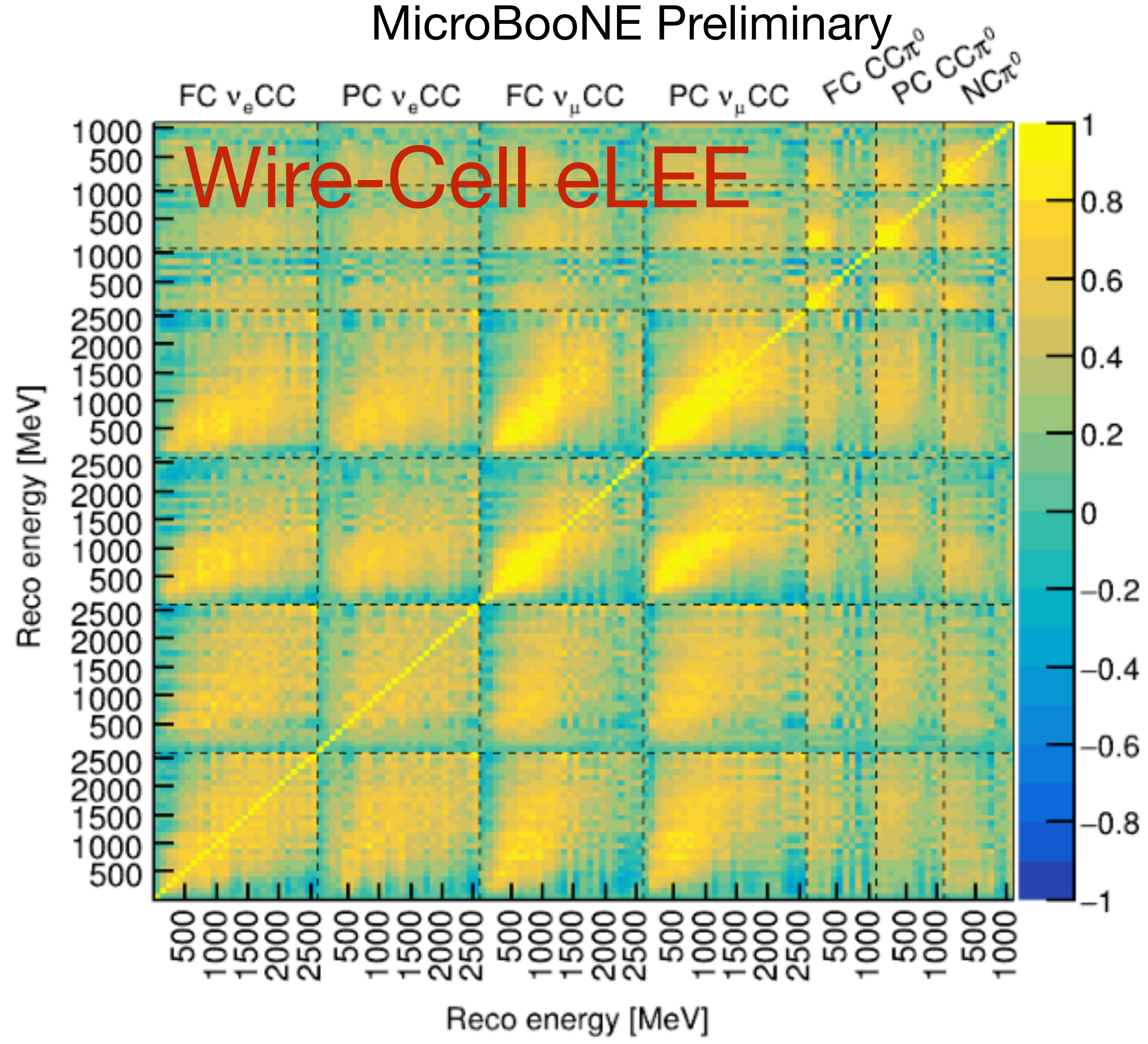

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Wire-Cell eLEE Run 1-3

MicroBooNE Preliminary

Data POT	Null hypotesis: SM	Null hypothesis: eLEE (x=1)
6.37E+20	4.7σ	3.3σ

MICROBOONE-NOTE-1100-PUB

MicroBooNE in the works!

μBooNE

2017 | 2018 | 2019 | 2020 | 2021

strong track record of papers since 2017:
33 publication to date
- ~1/2 in JINST
- ~1/2 in Phys. Rev/EPJC

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 Detector
Cosmic Ray Background Rejection with Wire-Cell LAr TPC 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 in MicroBooNE
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 LAr TPC near the Earth's Surface with the MicroBooNE Detector
Neutrino Event Selection in the MicroBooNE LAr TPC 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
The Continuous Readout Stream of the MicroBooNE Liquid Argon Time Projection Chamber for Detection of Supernova Burst Neutrinos
Vertex-Finding and Reconstruction of Contained Two-track Neutrino Events in the MicroBooNE Detector
Measurement of Differential Cross Sections for Muon Neutrino CC Interactions on Argon with Protons and No Pions in the Final State
Measurement of Space Charge Effects in the MicroBooNE LAr TPC Using Cosmic Muons
First Measurement of Differential Charged Current Quasi-Elastic-Like Muon Neutrino Argon Scattering Cross Sections with 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 LAr TPC
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

significantly improving signal processing, calibrations, event reconstruction, systematics, and neutrino interaction modeling

MicroBooNE in the works!

µBooNE

2017 2018 2019 2020 2021

Search for a H roBooNE Detector
Measurement ector
Cosmic Ray Back n the MicroBooNE Detector
Measurement of th nd Antineutrino Cross Section on Argon using the NuMI Beam in MicroBooNE
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Semantic Segmentat nstruction in MicroBooNE
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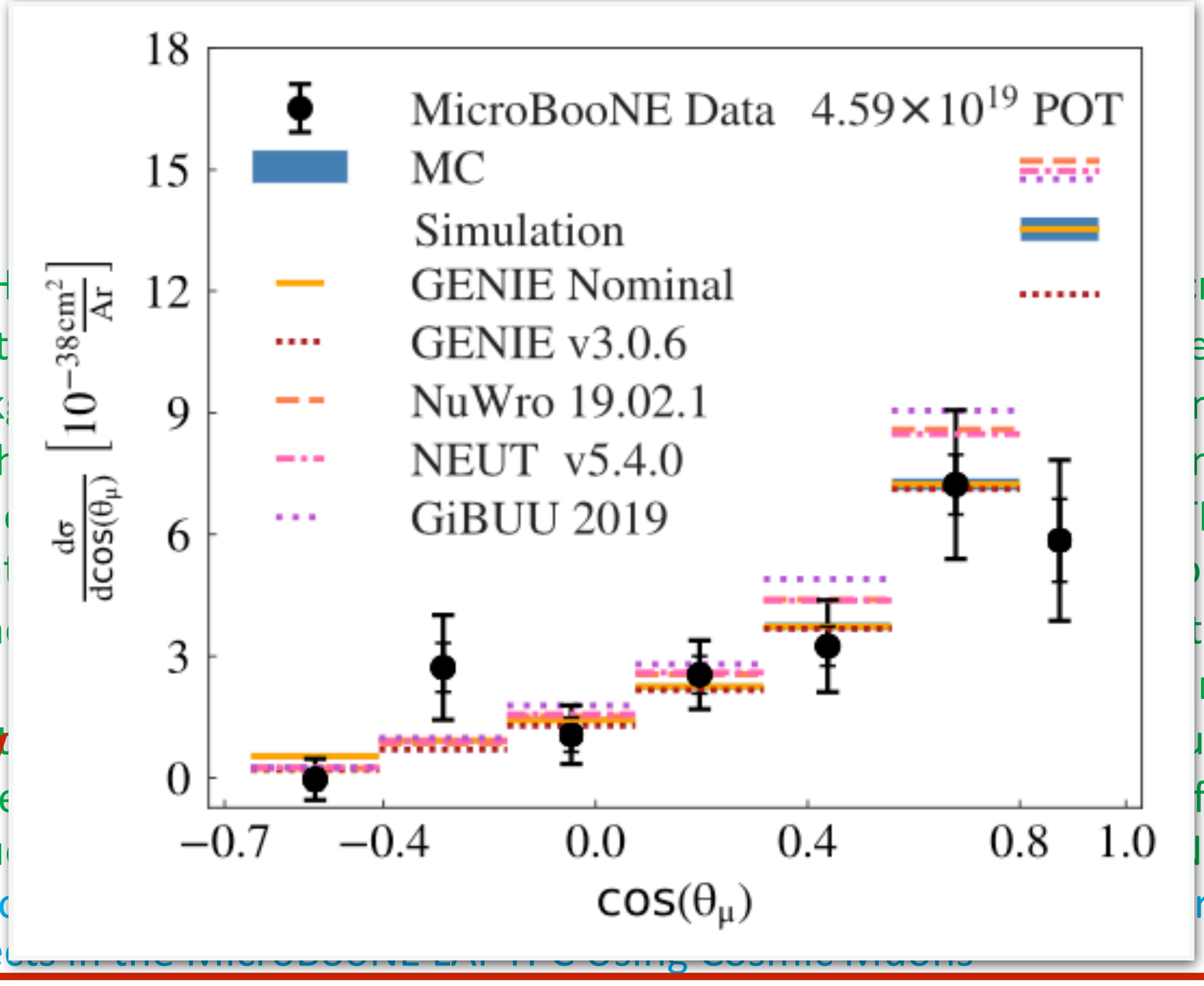

PRL 125 (2020) 201803

ν_μ CCQE-like

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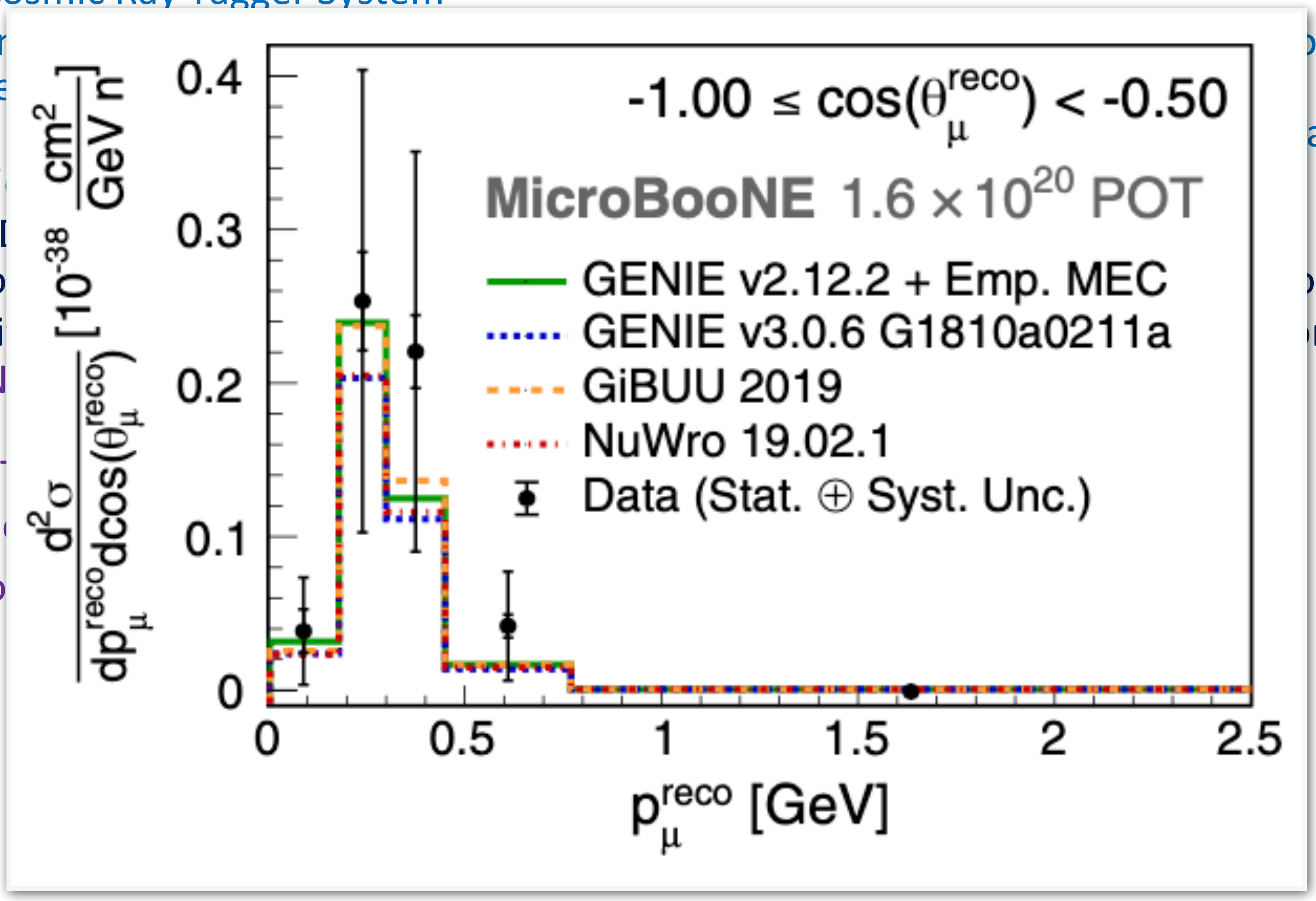
Comparison of Muon-Neutrino-Argon Multiplicity Distributi
Ionization Electron Signal Processing in Single Phase LArTPCs II: I
Ionization Electron Signal Processing in Single Phase LArTPCs I: Algo n
The Pandora Multi-Algorithm Approach to Automated Pattern Recogni r
Measurement of Cosmic Ray Reconstruction Efficiencies in the MicroBooN
Noise Characterization and Filtering in the MicroBooNE Liquid Argon TPC
Michel Electron Reconstruction Using Cosmic Ray Data from the MicroBooNE LAr T
Determination of Muon Momentum in the MicroBooNE LAr TPC Using an Improved M
Convolutional Neural Networks Applied to Neutrino Events in a Liquid Argon Projectio
Design and Construction of the MicroBooNE Detector



ν_μCC inclusive

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- MiniBooNE's low energy excess search result with MicroBooNE is near
  - with LArTPC technology in MicroBooNE, can probe many different particle content and kinematic properties of the excess events
  - novel reconstruction algorithms are developed for cosmic rejection & particle identification
  - on the cusp of the first LEE results with 6.95×10^{20} POT (half of the full dataset) are imminent
- stay tuned for more results to come!

backup slides

short-baseline anomalies

μBooNE

PMNS mixing matrix

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \underbrace{\begin{pmatrix} 1 & 0 & 0 \\ 0 & +c_{23} & +s_{23} \\ 0 & -s_{23} & +c_{23} \end{pmatrix}}_{\text{Atmospheric}} \underbrace{\begin{pmatrix} +c_{13} & 0 & +s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & +c_{13} \end{pmatrix}}_{\text{Reactor/Accelerator}} \underbrace{\begin{pmatrix} +c_{12} & +s_{12} & 0 \\ -s_{12} & +c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}}_{\text{Solar}} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

flavor eigenstates

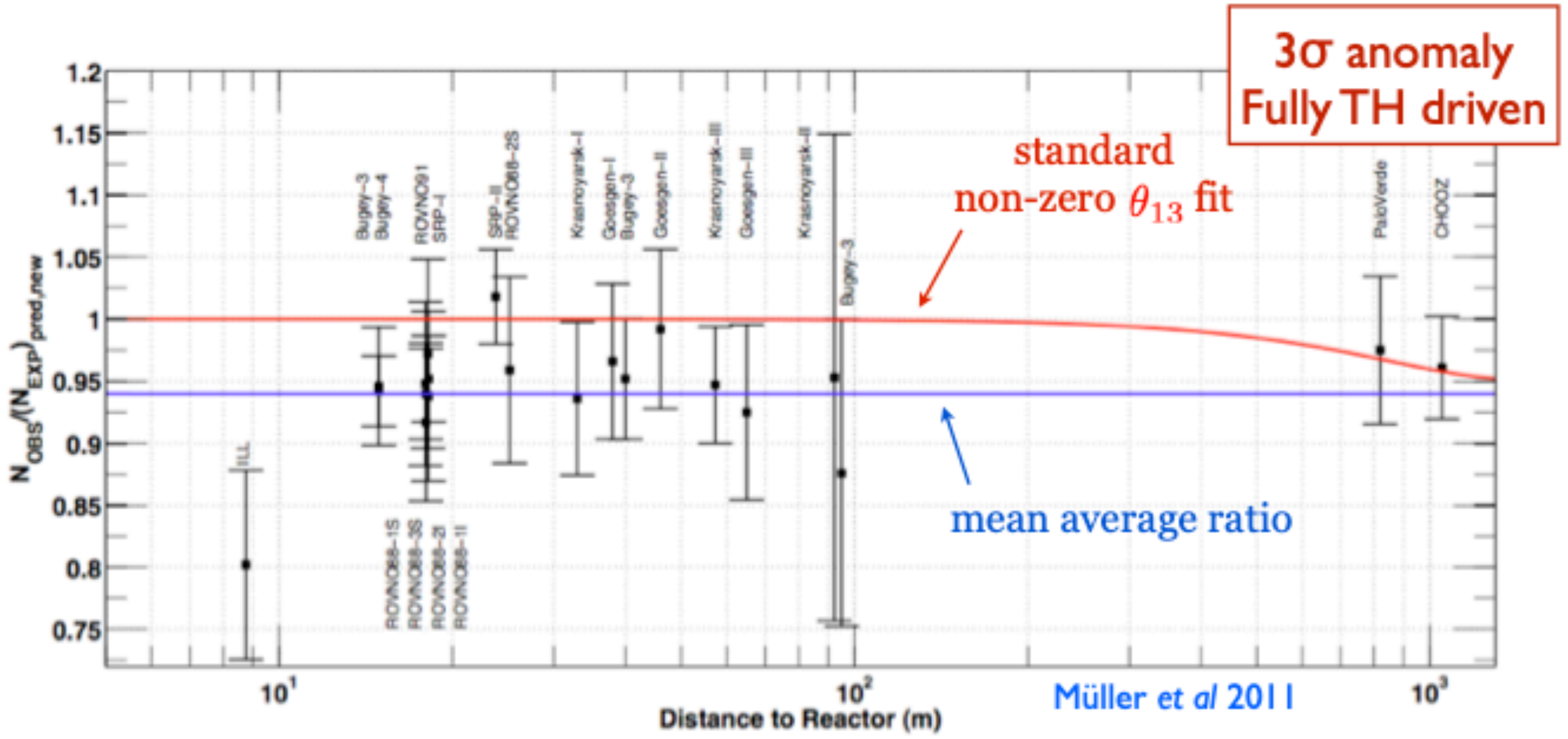
mass eigenstates

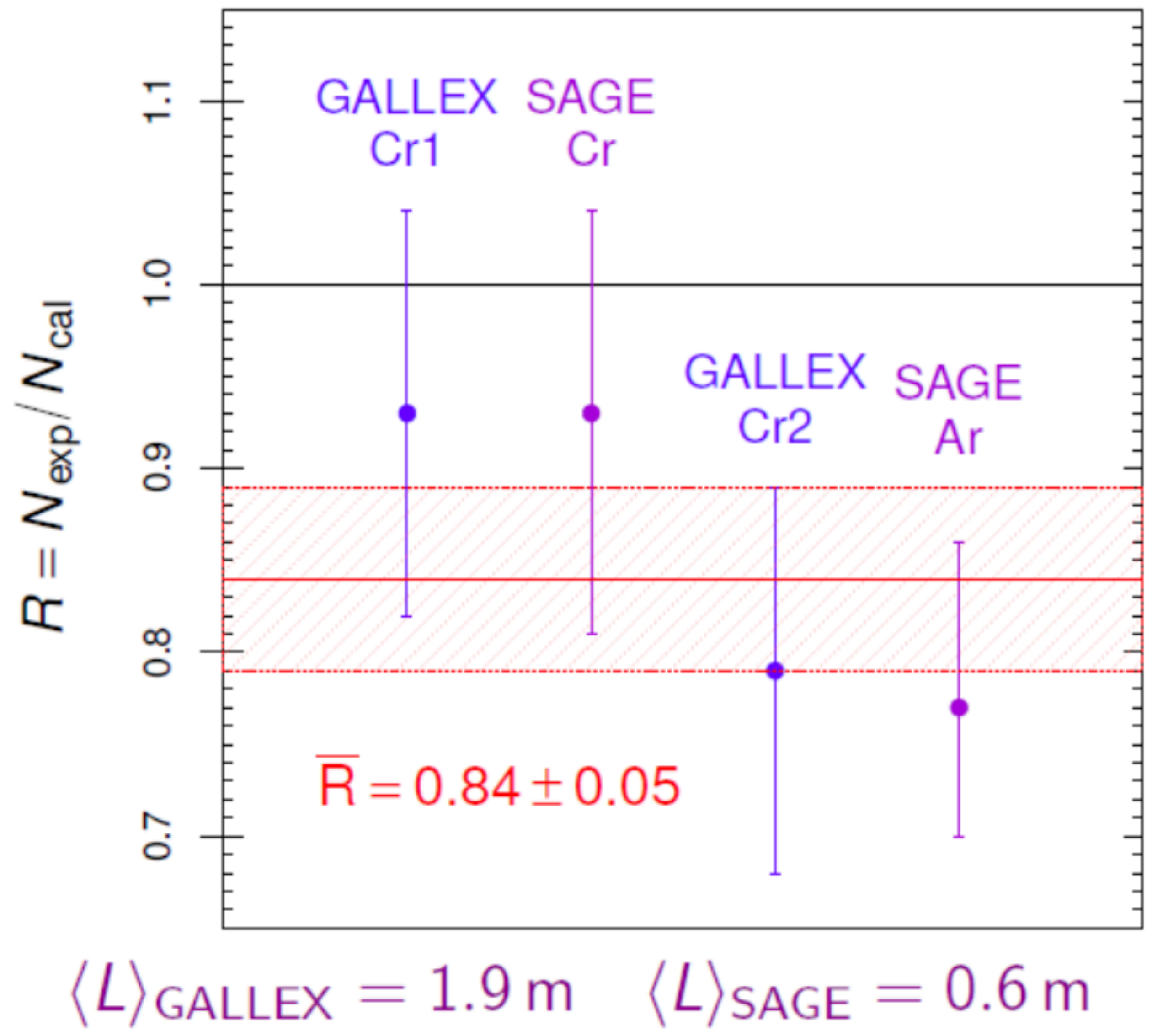
$$(c_{ij} = \cos\theta_{ij}, s_{ij} = \sin\theta_{ij})$$

- three flavor neutrino states is well established by neutrino oscillation physics in solar, atmospheric, reactor, and accelerator domains
- puzzling collection of short-baseline anomalies: reactor anomaly, gallium anomaly, LSND & MiniBooNE anomaly
  - possible portal for new physics: the holy grail of the particle physics community
  - correctly estimating backgrounds/oscillation is important for the future neutrino program such as DUNE
  - need to resolve the anomalies -> MicroBooNE & SBN program

reactor anomaly and gallium anomaly

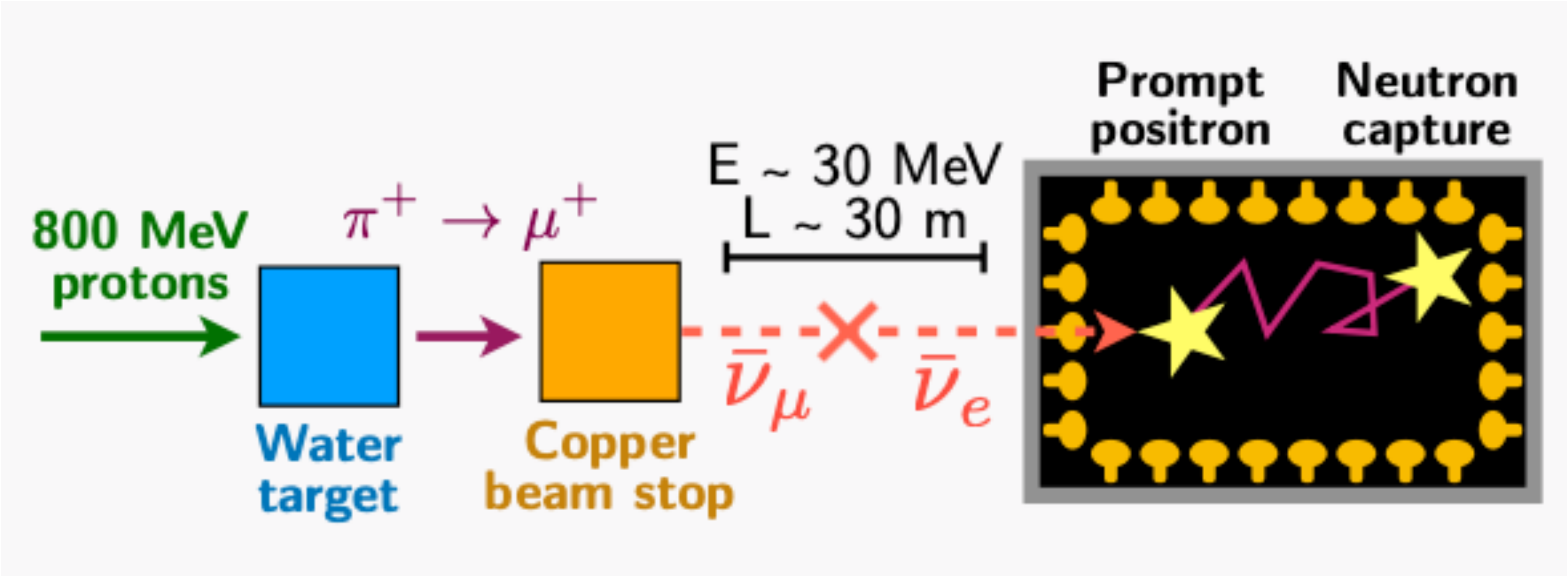
- measurements of $\overline{\nu}_e$ disappearance from nuclear reactor
- ~6% discrepancy from the standard fit
- current running experiments to address this (e.g. PROSPECT, STEREO)
- is this indicative of sterile neutrinos?

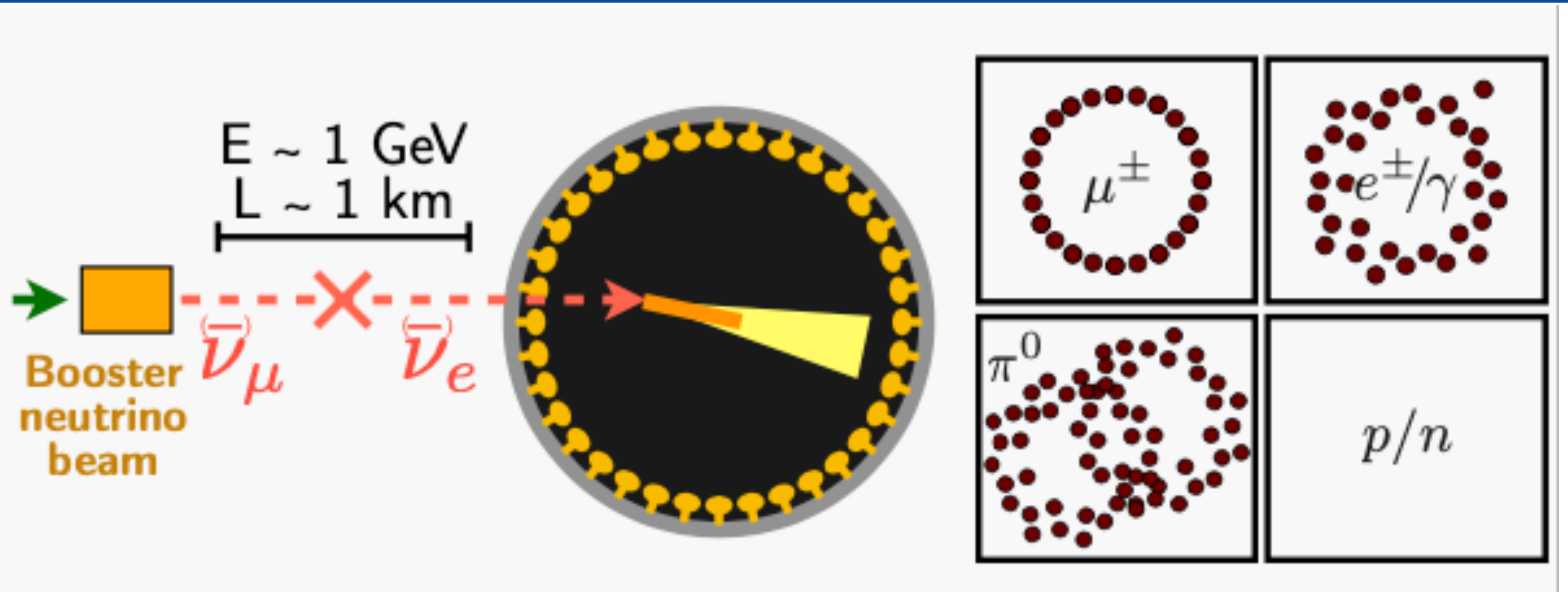




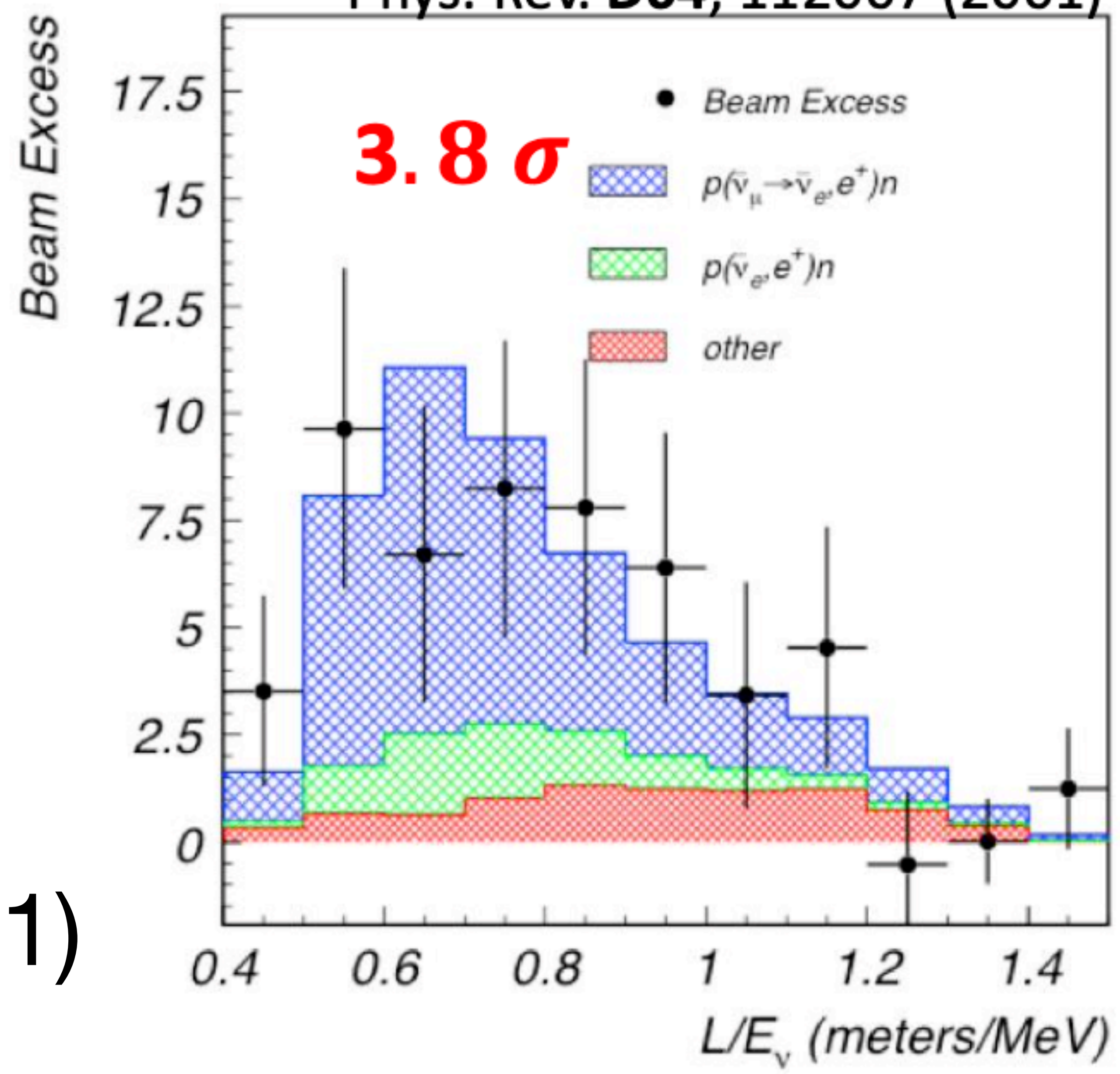
- gallium-based experiments (GALLEX, SAGE) measured a deficit of ν_e in their calibration run
- possible hint of ν_e disappearance?

LSND & MiniBooNE anomaly

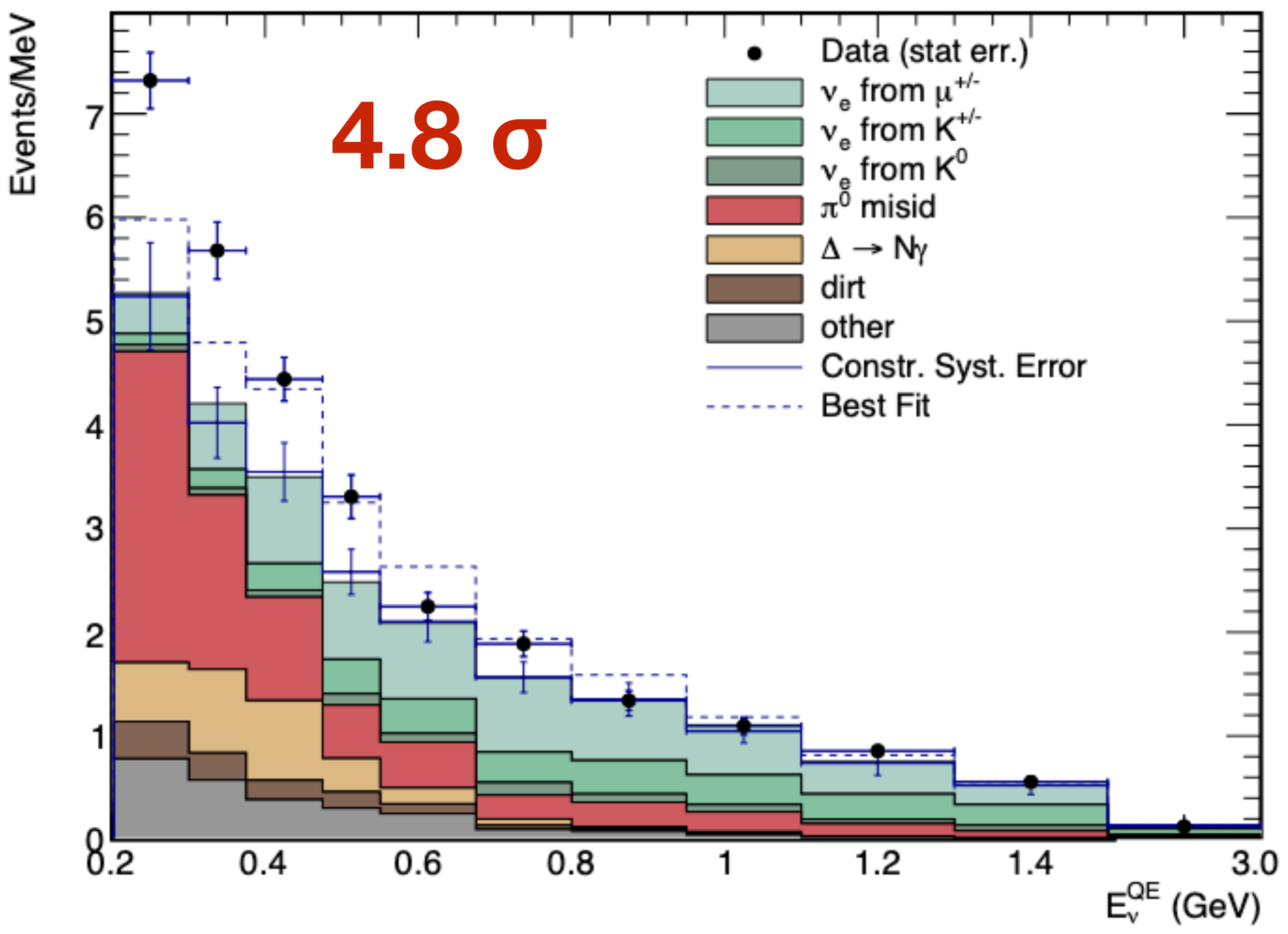




Phys. Rev. **D64**, 112007 (2001)



arxiv:2006.16883

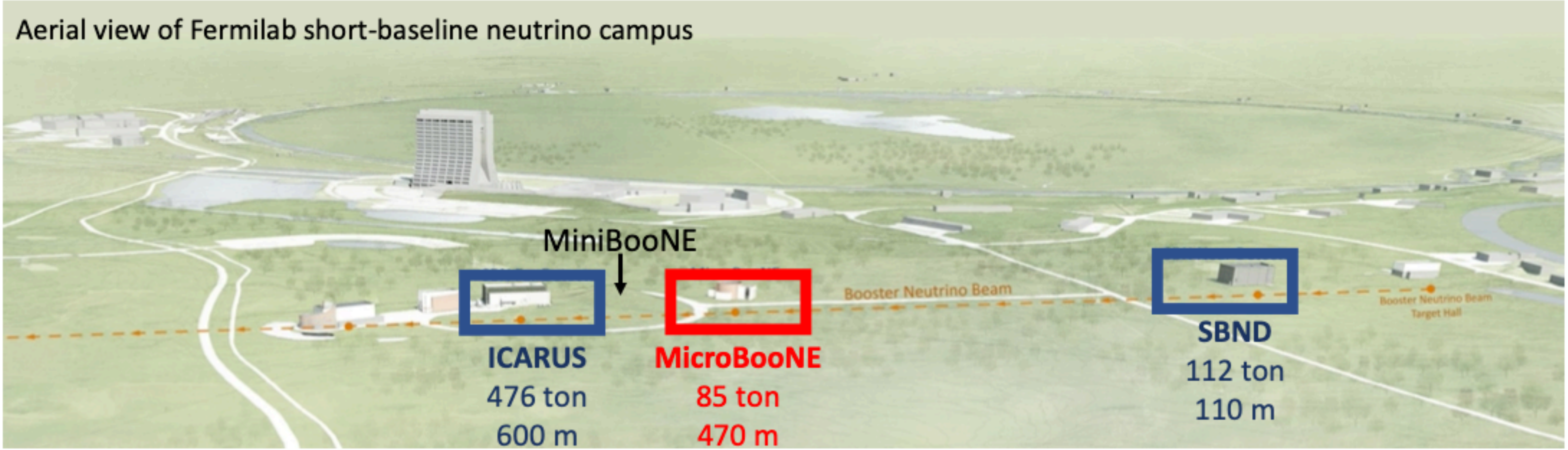


- **LSND** (1990-2001)
- $\bar{\nu}_\mu$ -> $\bar{\nu}_e$ excess over background suggests evidence for oscillation at $\Delta m^2 \sim 1 eV^2$

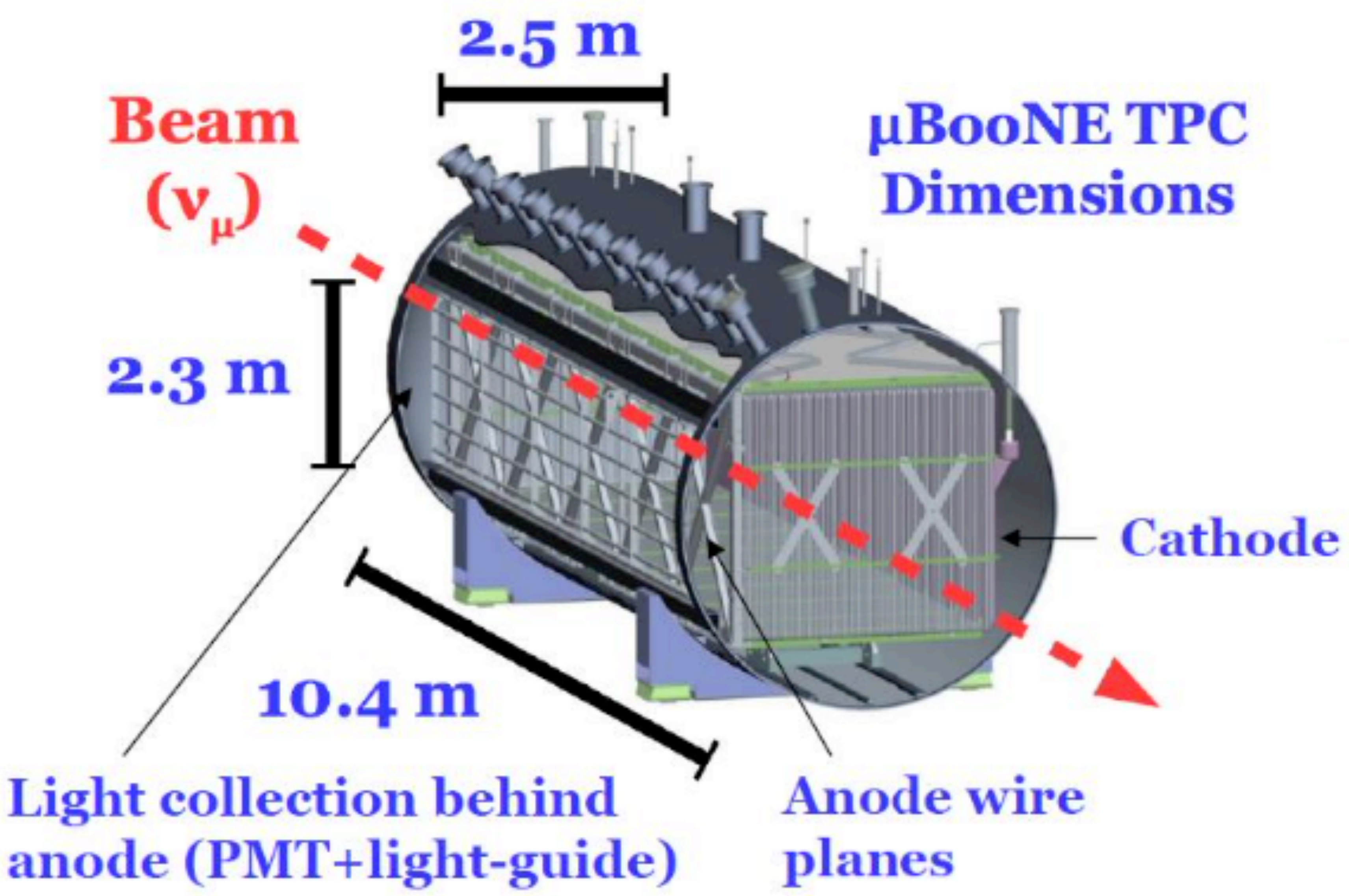
- **MiniBooNE** (1998-2020)
- measured ν_μ-> ν_e and $\bar{\nu}_\mu$-> $\bar{\nu}_e$ appearance
- the excess of events corresponding to 200<Eν<475 MeV

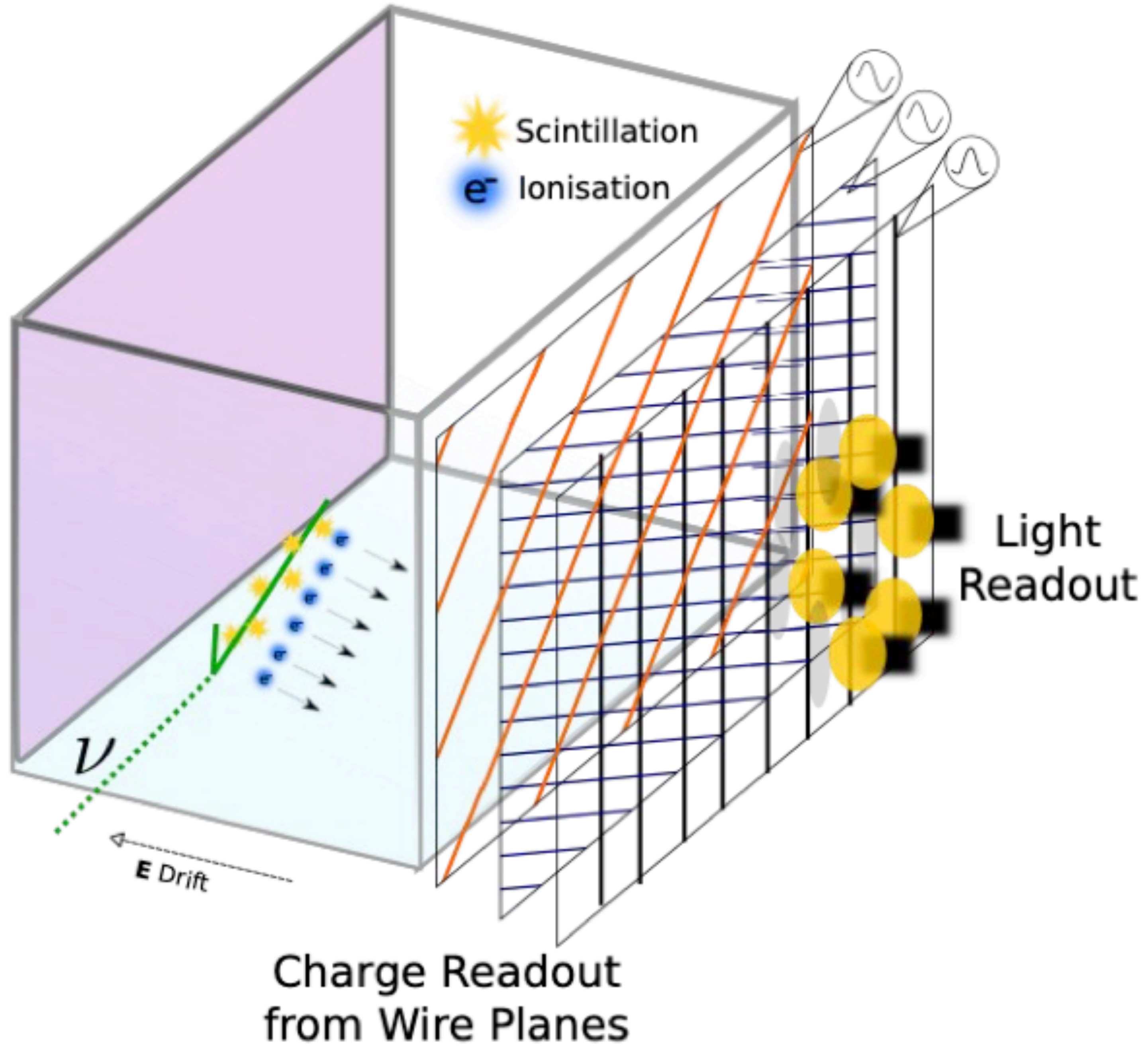
Fermilab SBN program

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



- **LArTPC Detector**
  - 85 tons of LAr active volume
  - TPC: 8256 anode sense wires in 3 planes
    PMT: 32 8-inch PMTs
  - fine-grained 3D tracking with local dE/dx information and fully active target medium: good electron-photon separation power
- **physics goal**
  - strong understanding of the detector and highly developed event reconstruction, paving the way to future LAr detectors (SBN & DUNE)
  - neutrino interaction measurements
  - towards low-energy excess: definitively address the MiniBooNE anomaly





ν-Argon cross section measurements @ uBooNE

µBooNE

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

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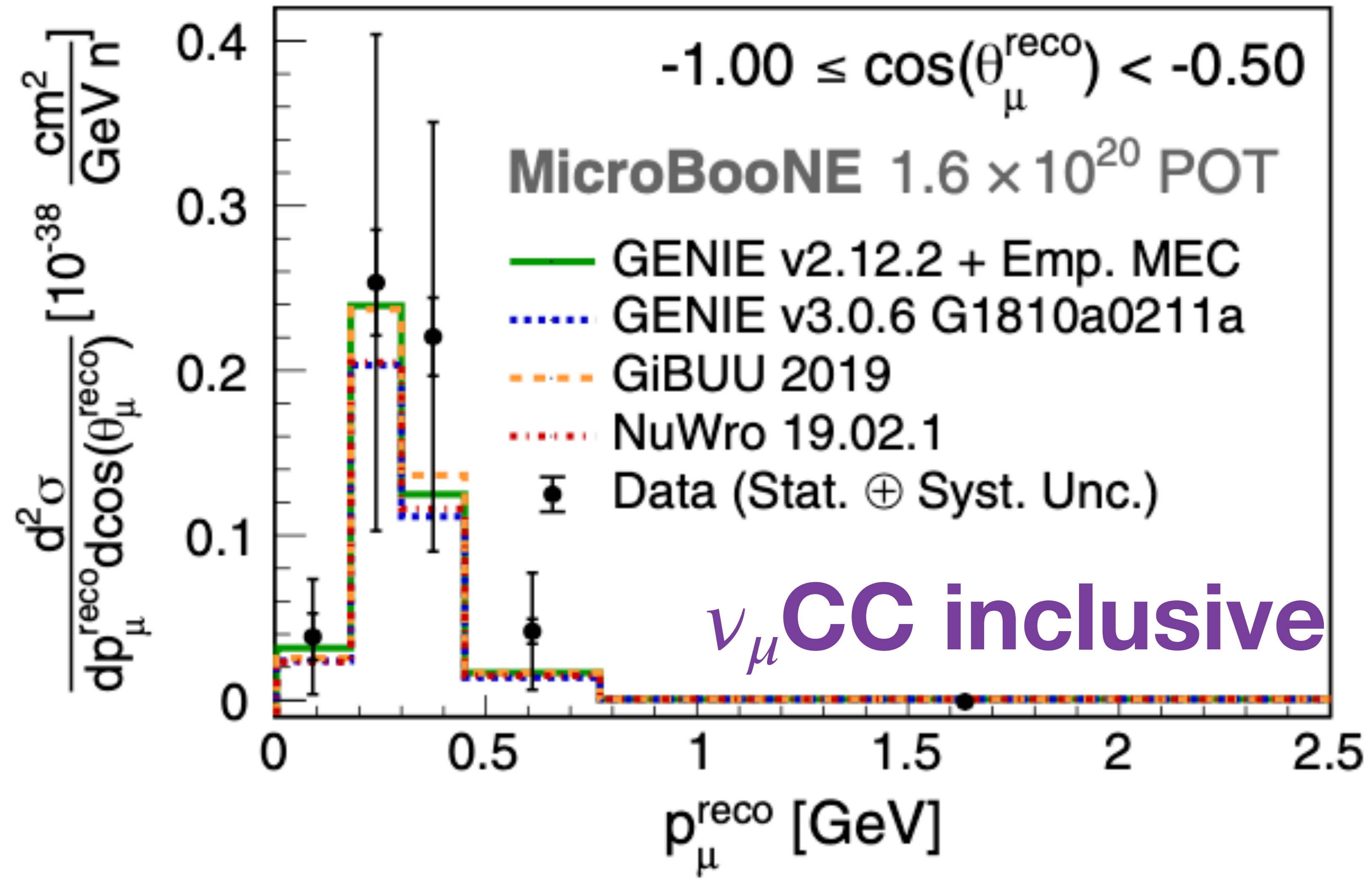
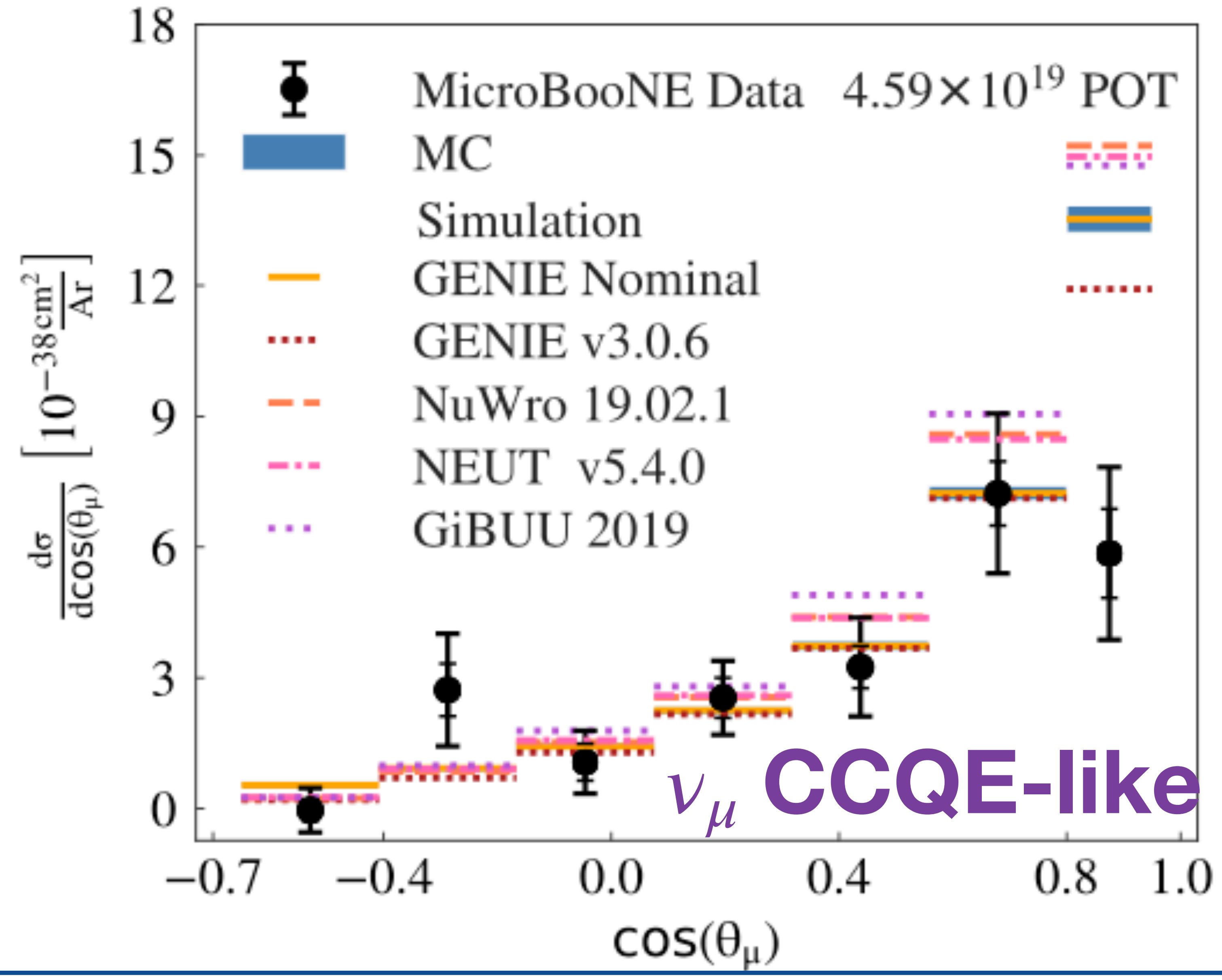


PRL 125 (2020) 201803

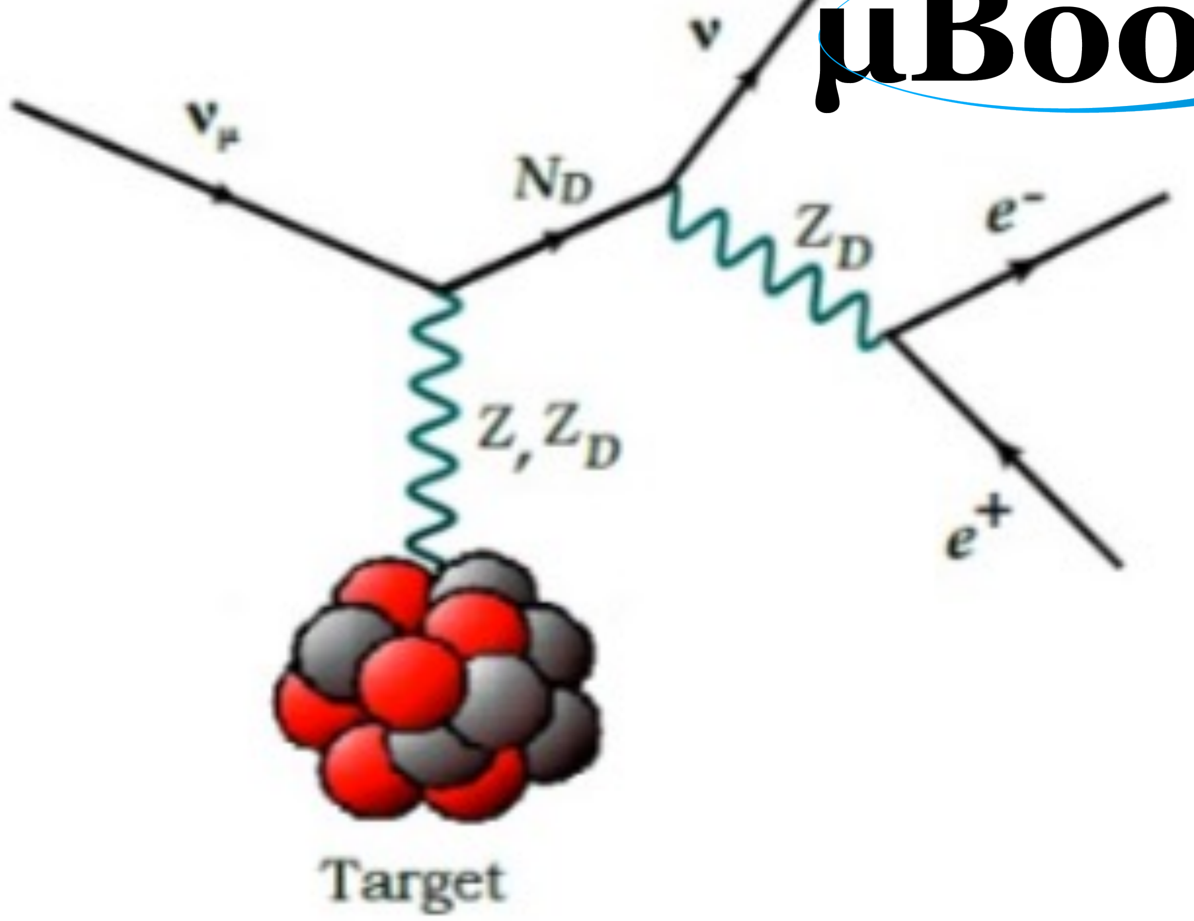


Rich and Evolving Theory Landscape

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

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

(caution: not an exhaustive list)



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

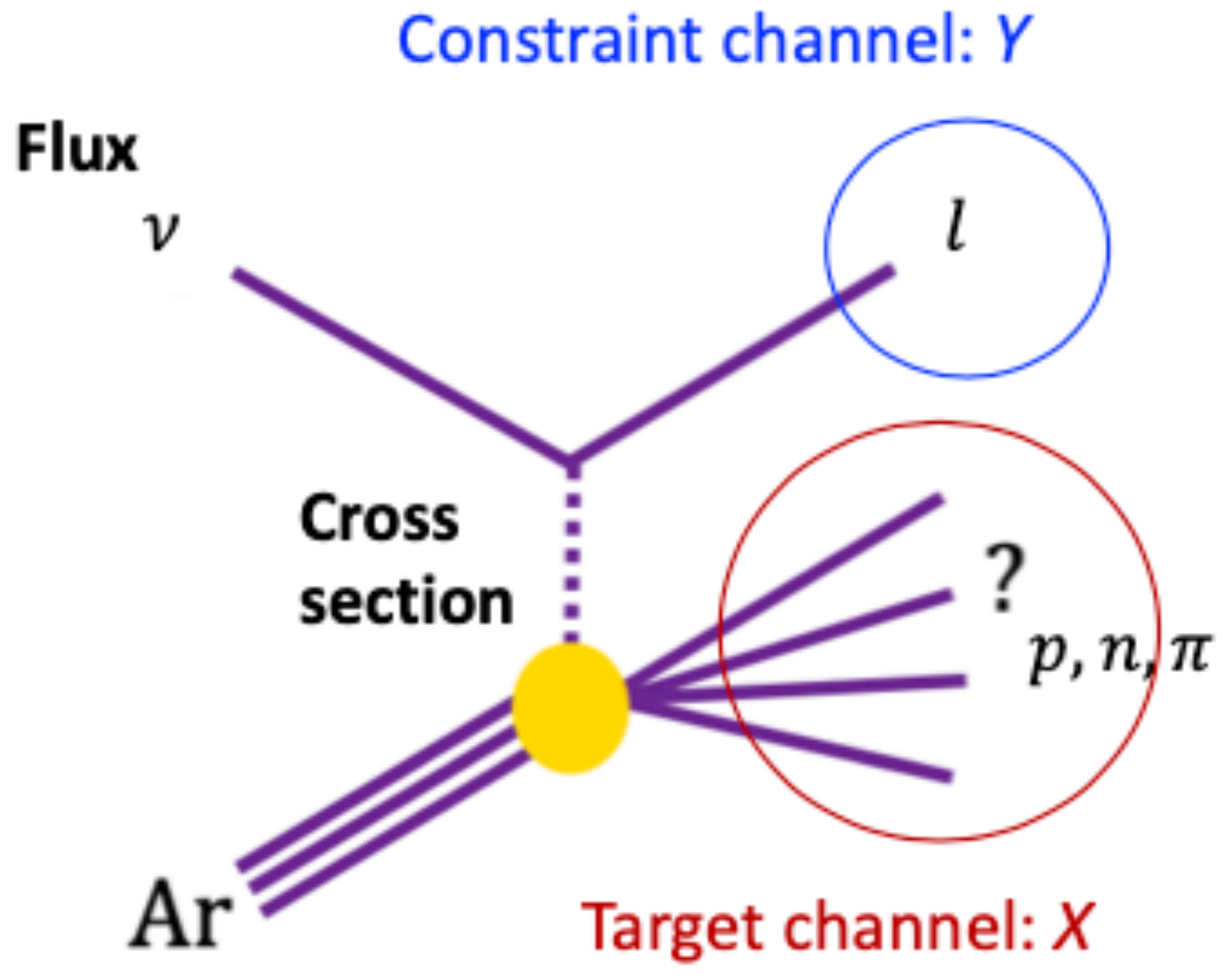
- many of these models predict more complex final states (e^+e^-) & differing levels of hadronic activity
- want a more agnostic approach than solely testing a sterile neutrino hypothesis ($1e^-$ + X)
- we are fortunate that LAr TPCs are sensitive to these possibilities

MicroBooNE's Exploration of the MiniBooNE Excess

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

hadronic energy reconstruction validation

µBooNE



X: target channel
Y: constraint channel
n: measurement
μ: mean of model
Σ: covariance matrix of model

Constraint:
conditional mean and conditional covariance

$$\mu^{X,constrained} = \mu^X + \Sigma^{XY} \cdot (\Sigma^{YY})^{-1} \cdot (n^Y - \mu^Y),$$
$$\Sigma^{XX,constrained} = \Sigma^{XX} - \Sigma^{XY} \cdot (\Sigma^{YY})^{-1} \cdot \Sigma^{YX}.$$

- **Monte-Carlo prediction** is ***corrected*** based on the data/MC discrepancy in the constraint channel.
- **Systematic uncertainty** is ***reduced***
- Constraint respects the allowed error ranges in the cross section, flux, and detector systematics