Results from the MicroBooNE Low-Energy Excess Search

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On Behalf of the MicroBooNE Collaboration

CoSSURF 2022

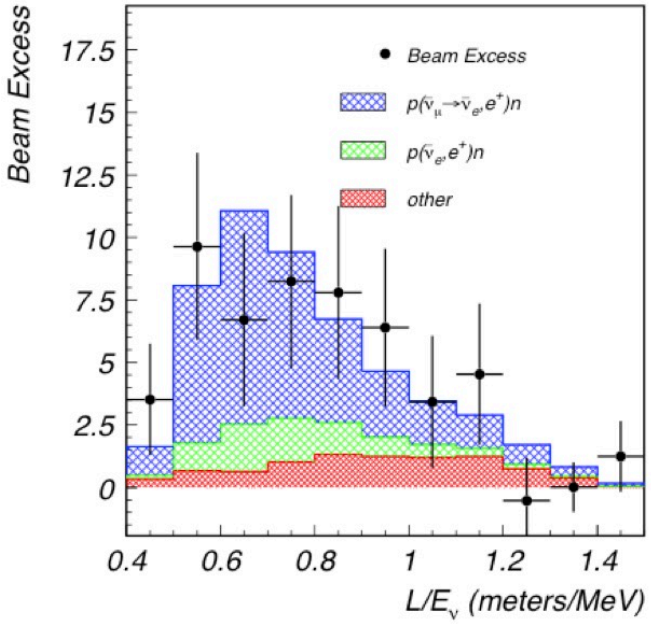
11-May-2022

μBooNE Fermilab Colorado State University

Anomalies at Short Baselines

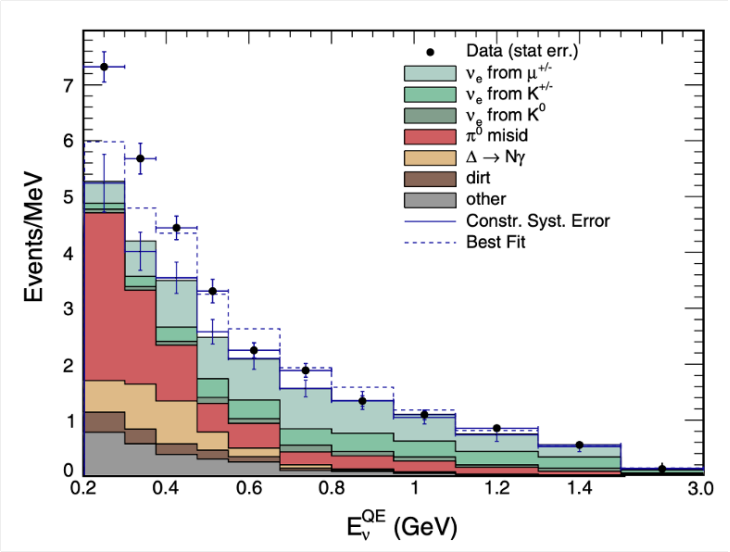
LSND PRD 64, 112007 (2001)

- Measure neutrino oscillations
- $\overline{\nu_\mu}$ beam from pions-at-rest
- $\langle E_\nu \rangle = \sim 30\ MeV; \mathrm{L} = \sim 30\ \mathrm{m}$
- Excess at 3.8σ



MiniBooNE Phys. Rev. D 103, 052002

- ν_μ beam from accelerator
- $\langle E_\nu \rangle = \sim 500\ MeV; \mathrm{L} = \sim 500\mathrm{m}$
- Similar L/E as LSND
- Excess at 4.8σ

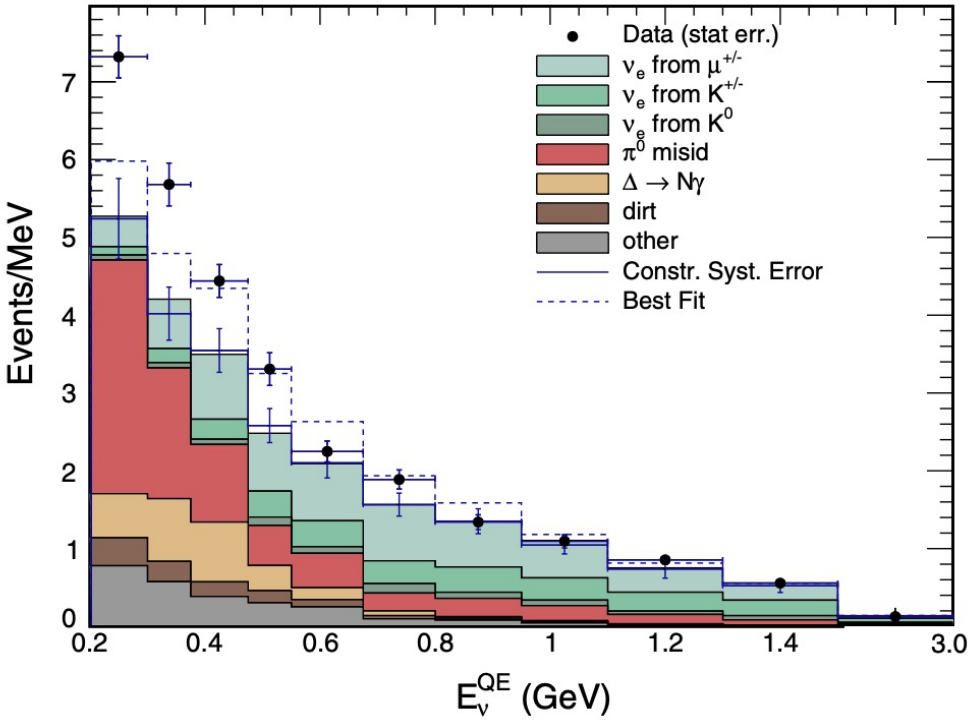


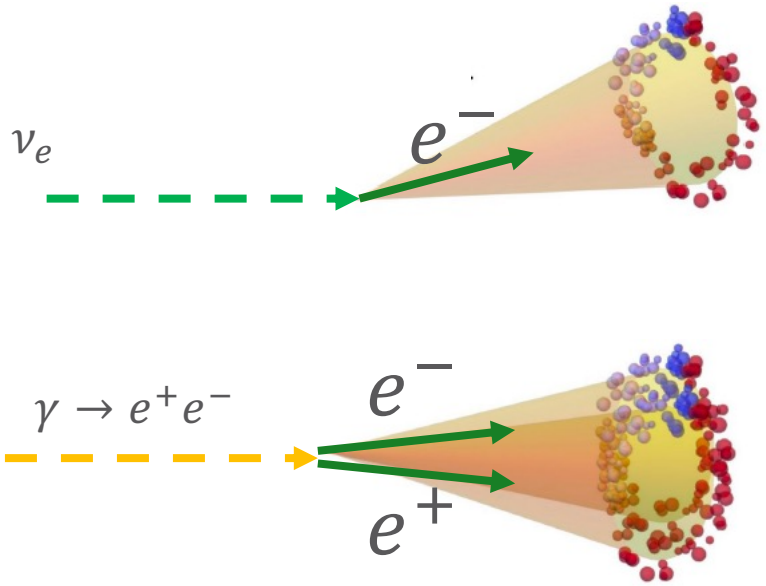
Anomalies at Short Baselines: MiniBooNE

- Cherenkov detector
  - Signal is a single electromagnetic shower; e^-/γ indistinguishable
  - Only sensitive to particles above the Cherenkov threshold:
    - No sensitivity to protons
- Possible sources for the anomaly:
  - ν_e excess
  - $\Delta \rightarrow N\gamma$

$$\nu_\mu \xrightarrow{\text{oscillation}} \nu_e + n \rightarrow e^- + p$$

$$\nu_e + C \rightarrow 1e\mathrm{X}p0\pi$$



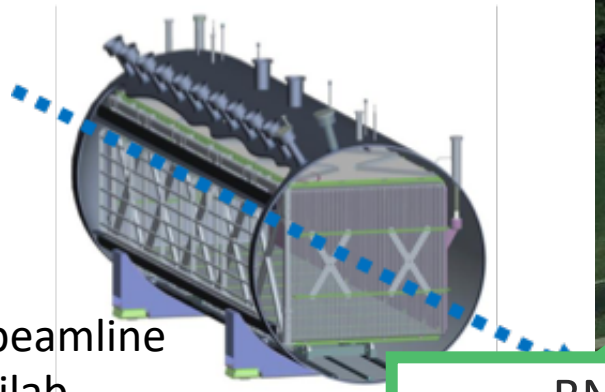


γ vs. e^- Cherenkov rings

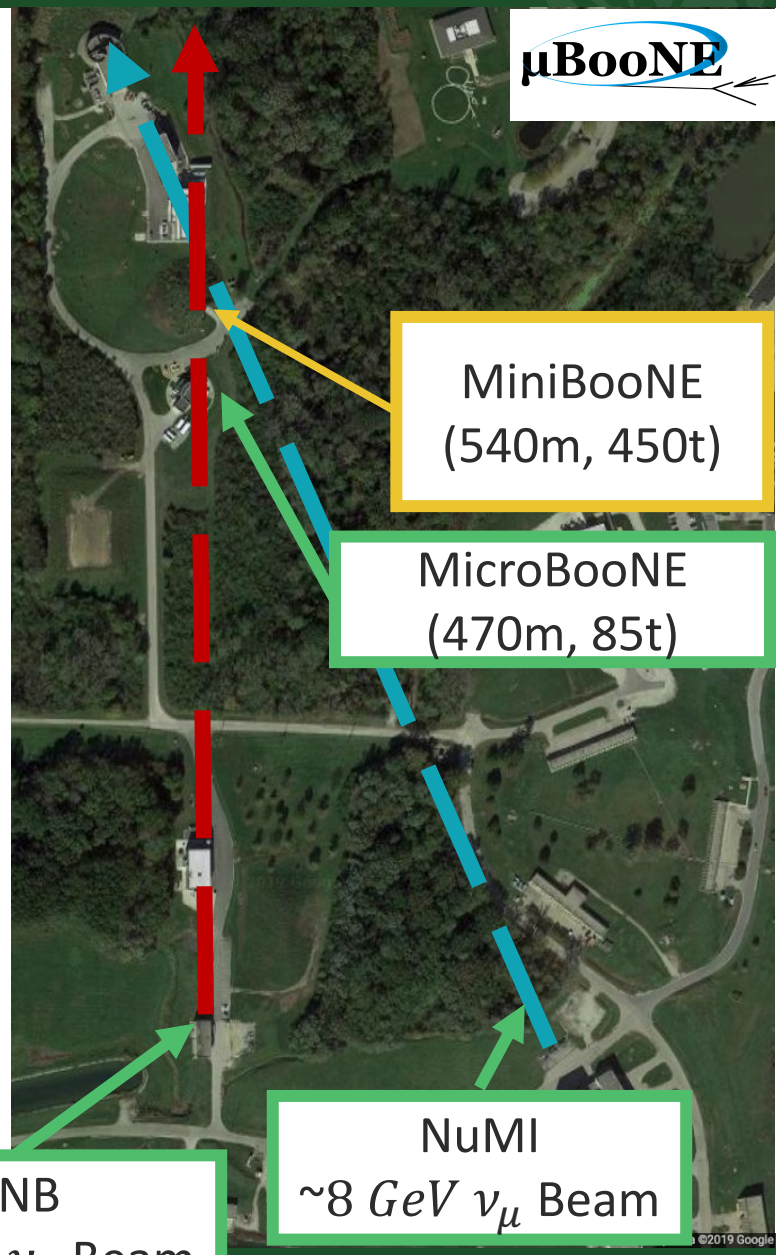
Phys. Rev. D 103, 052002

The MicroBooNE Experiment

- "Micro Booster Neutrino Experiment" (MicroBooNE)
- Uses a Liquid Argon Time Projection Chamber (LArTPC) as the detector technology
  - e/γ separation
- 170-ton (89-ton active volume) LArTPC
- Sits on two beam lines:
  - BNB: On-Axis
  - NuMI: Off-Axis

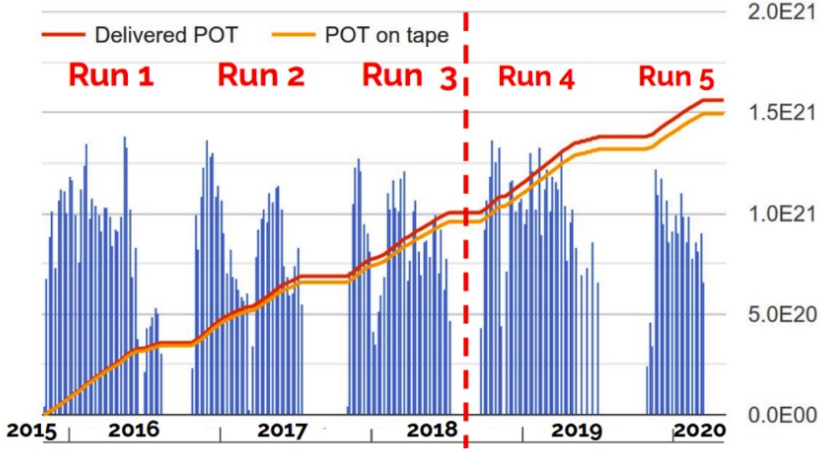


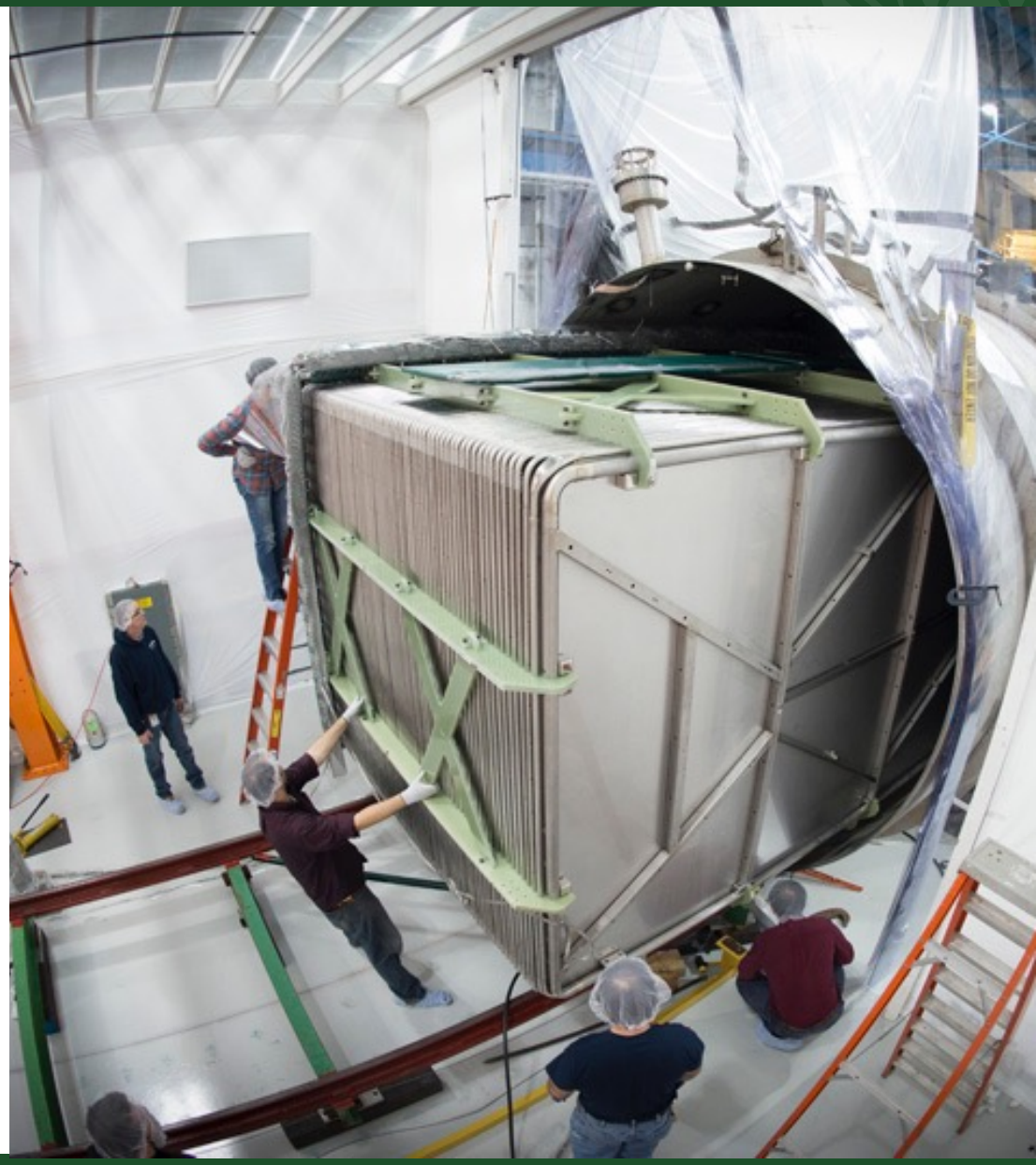
ν_μ BNB beamline
@ Fermilab



Status of MicroBooNE

- Collected ~1.5 x 10^{21} protons-on-target (POT) from 2015 to 2021
  - Analysis shown here uses a subset of full data
- Detector operated smoothly, with 96% detector + DAQ uptime



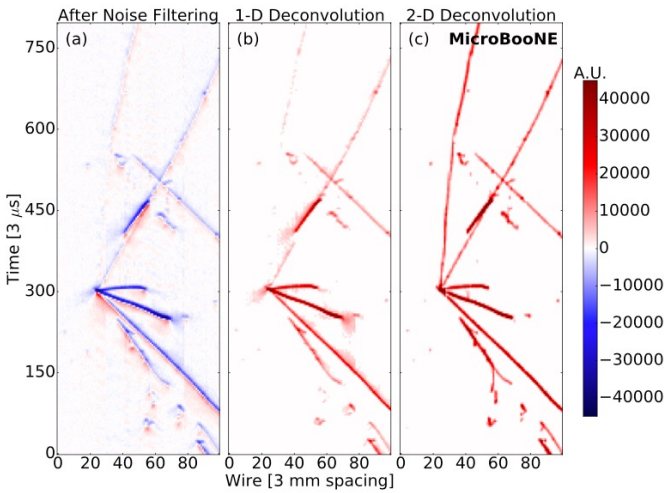


MicroBooNE Goals

LArTPC R&D

- Noise filtering
- Signal processing
- Energy reconstruction
- Detector Calibrations

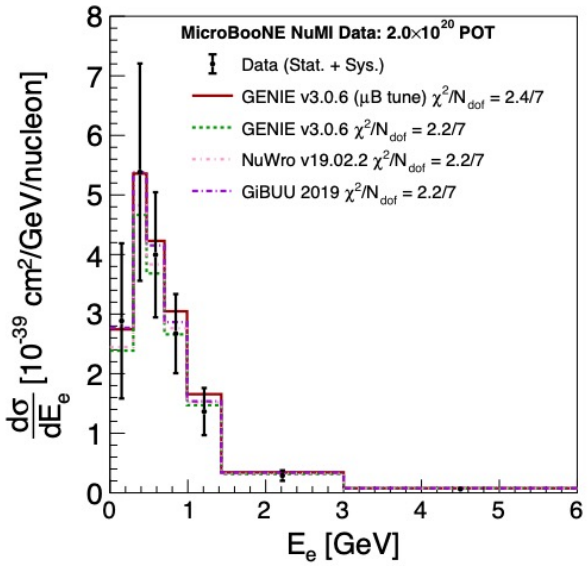
JINST **13** P07006



ν-Ar Cross-Sections

- Explore low energy ν-Ar scattering
- Test ν-Ar models

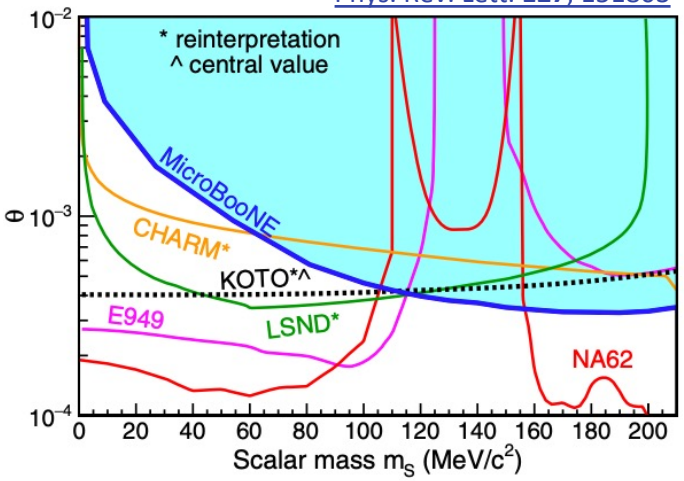
Phys. Rev. D **105**, L051102



Exotic Physics

- Test Higgs portal model
- Dark sector
- Heavy neutral leptons

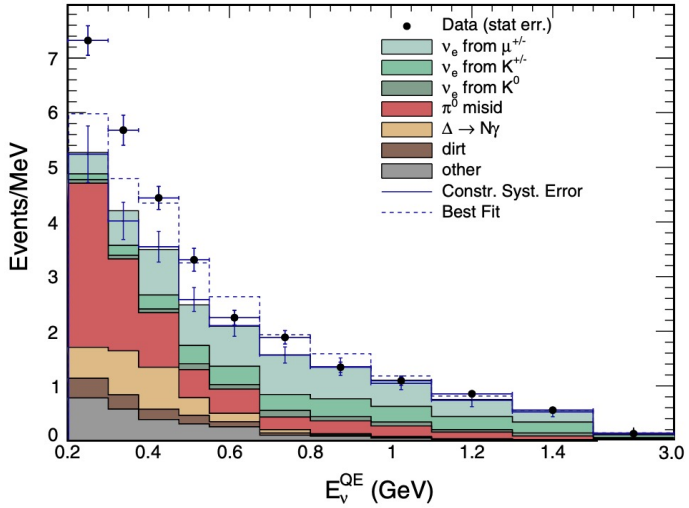
Phys. Rev. Lett. **127**, 151803



Anomaly Search

- Test MiniBooNE findings

Phys. Rev. D 103, 052002



MicroBooNE Goals

JINST **13** P07006

LArTPC R&D

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See Daisy Kalra's talks tomorrow!

Phys. Rev. D **105**, L051102

ν-Ar Cross-Sections

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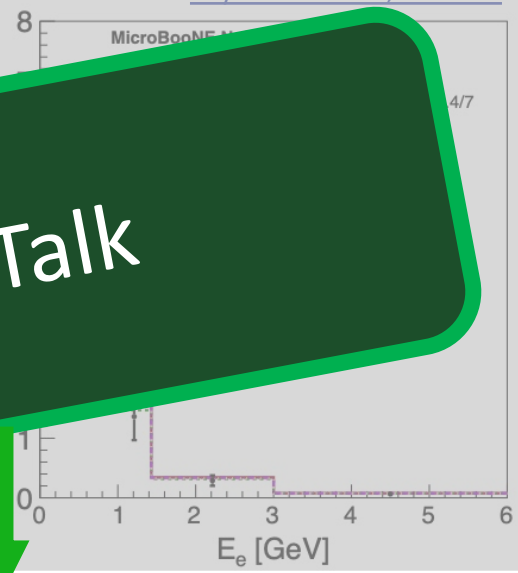

This Talk

Phys. Rev. Lett. **127**, 151803

Exotic Physics

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- Dark sector
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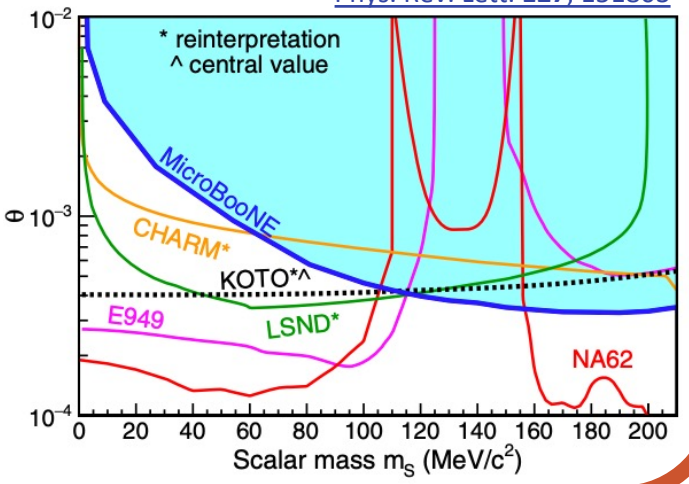

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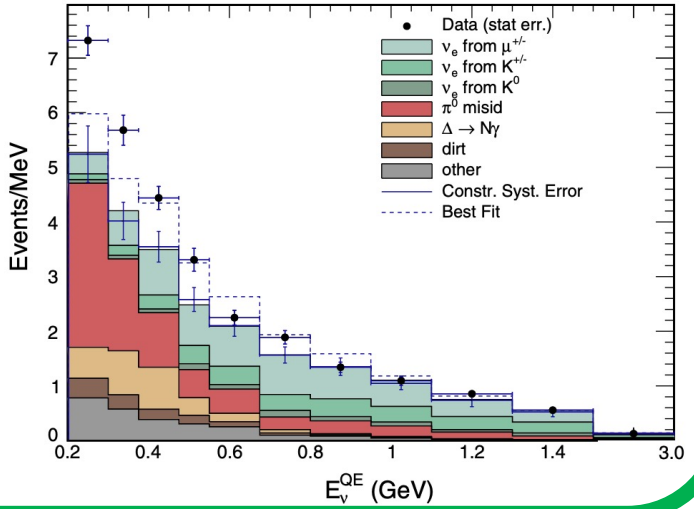
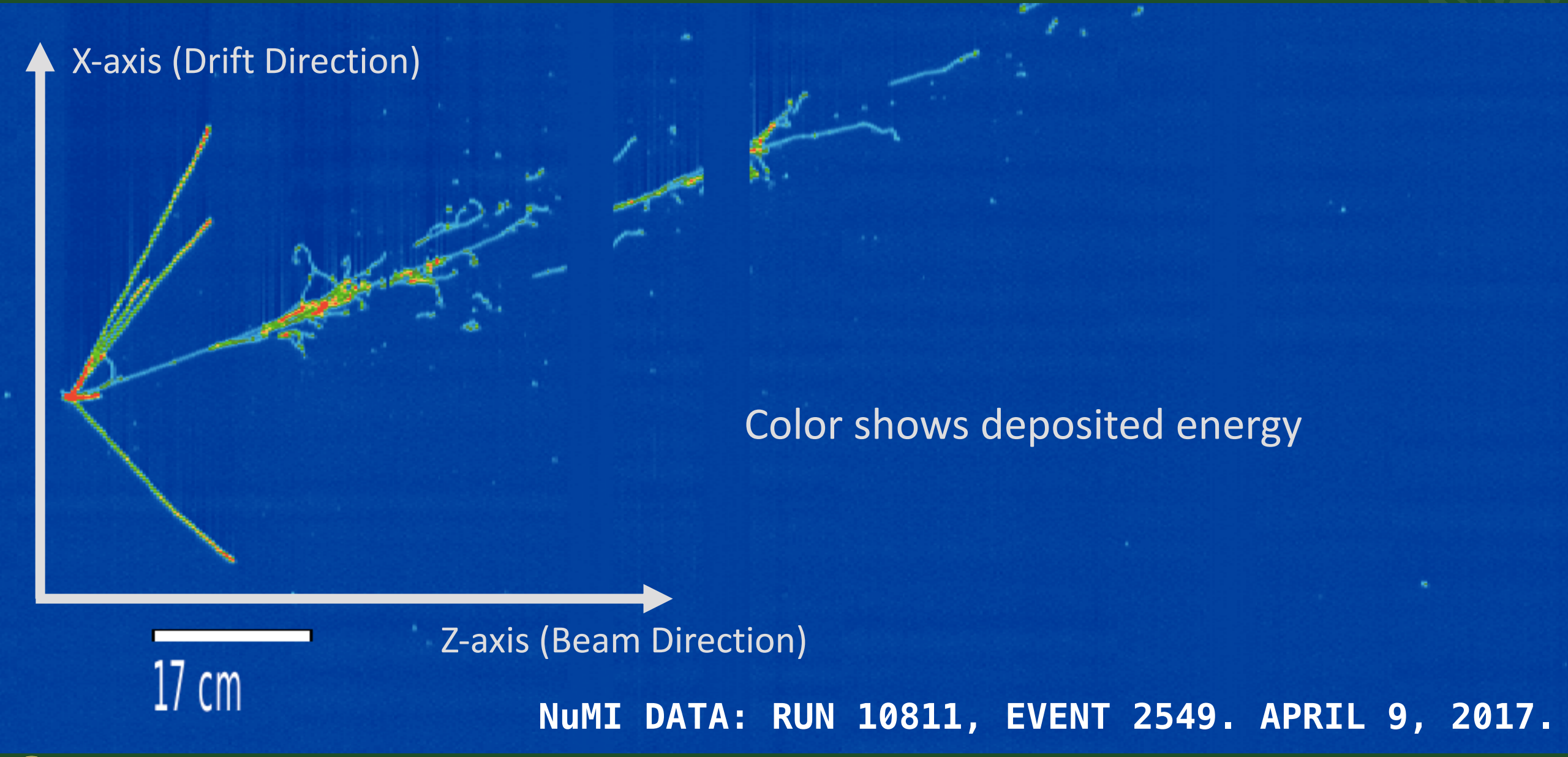


LArTPC Event



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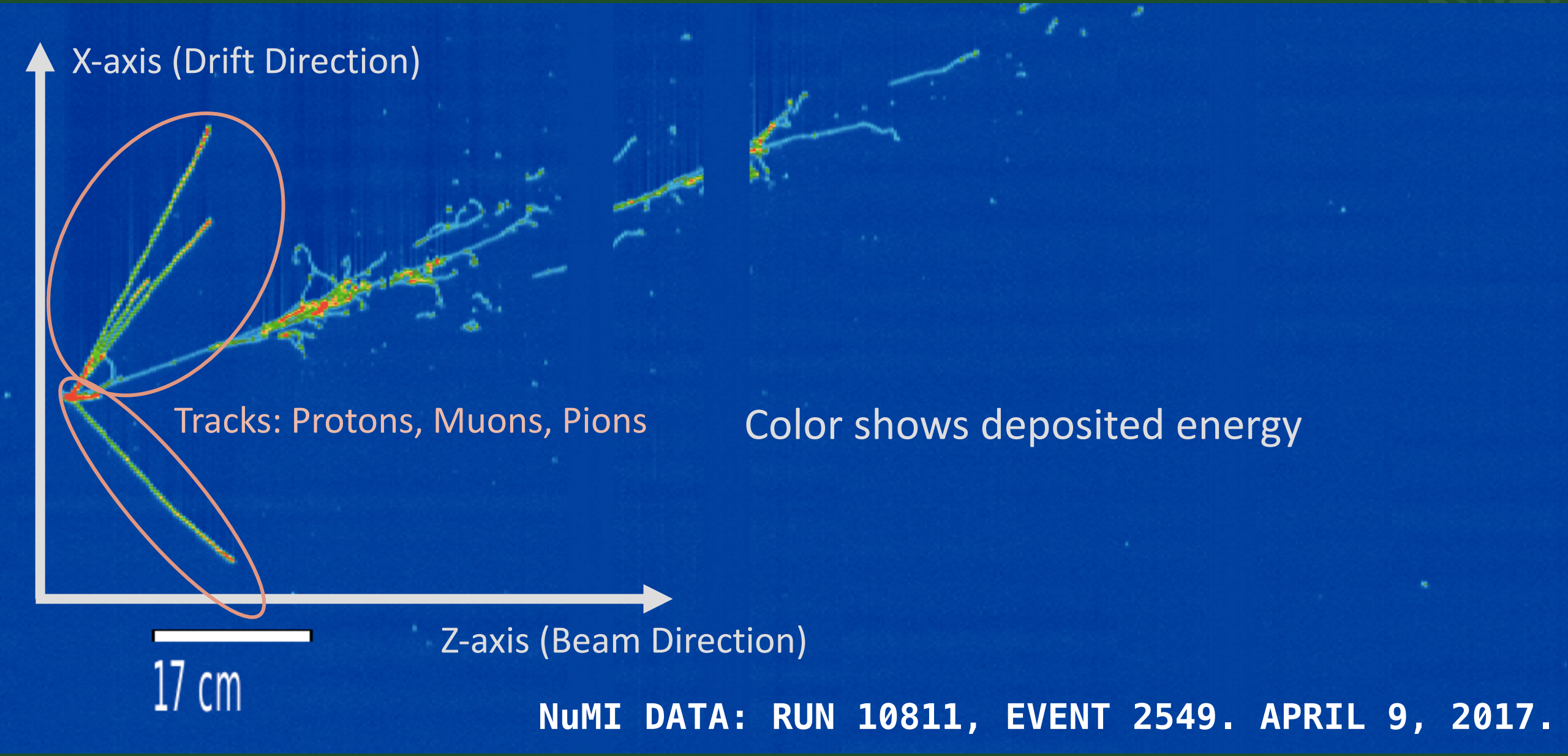

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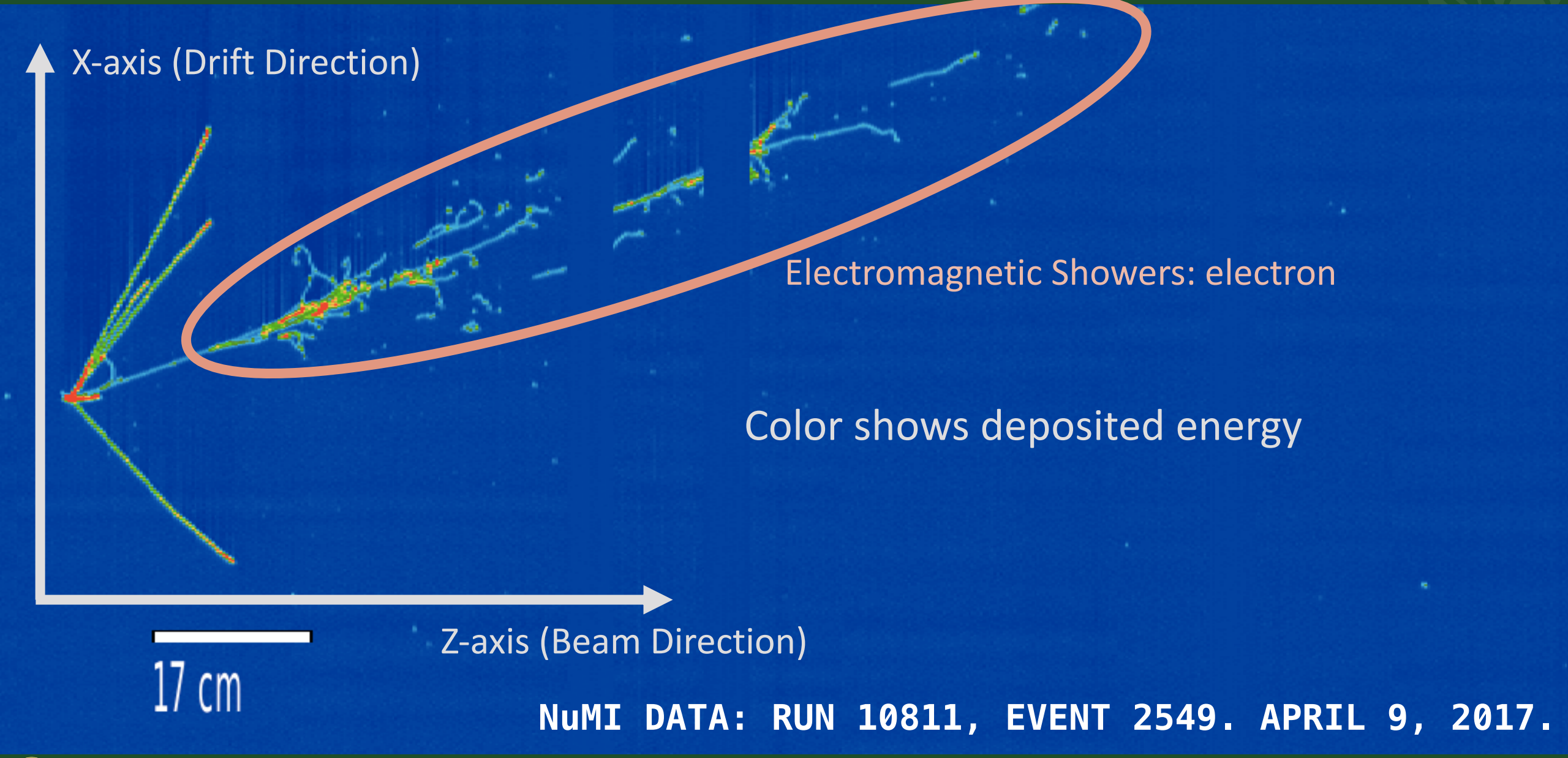
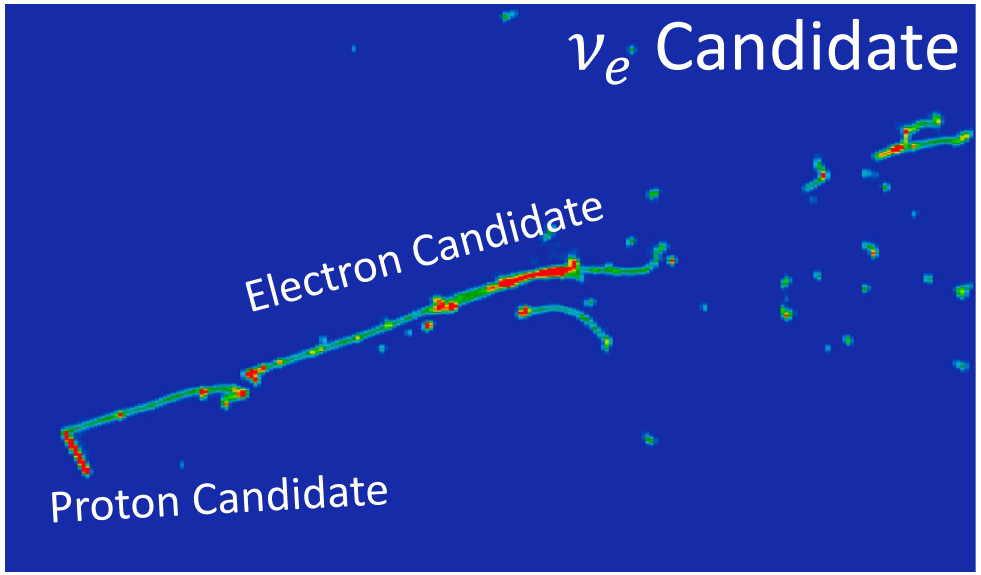
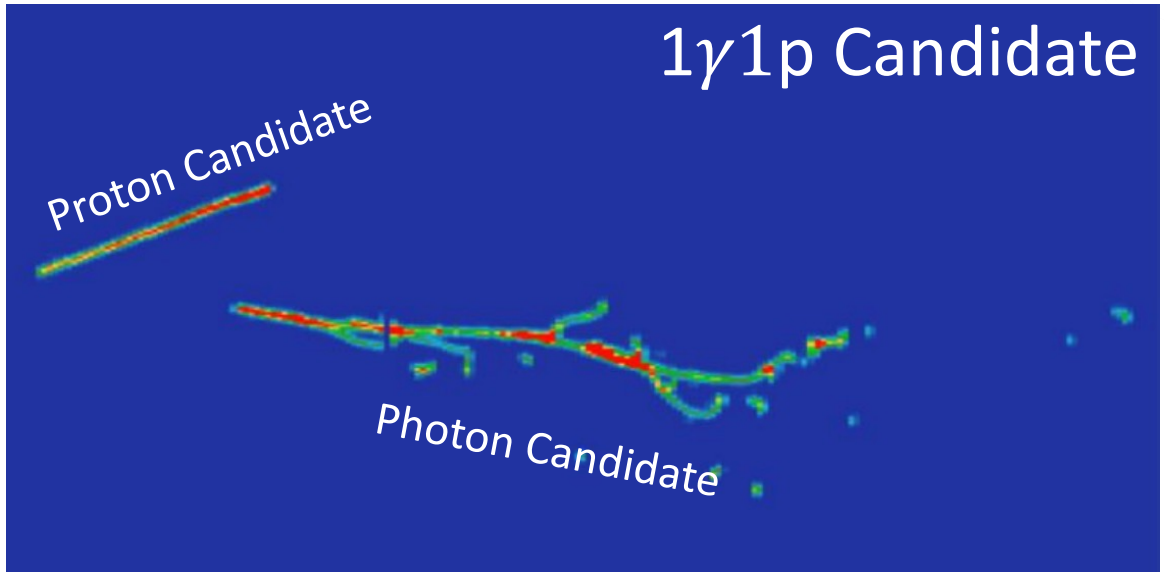


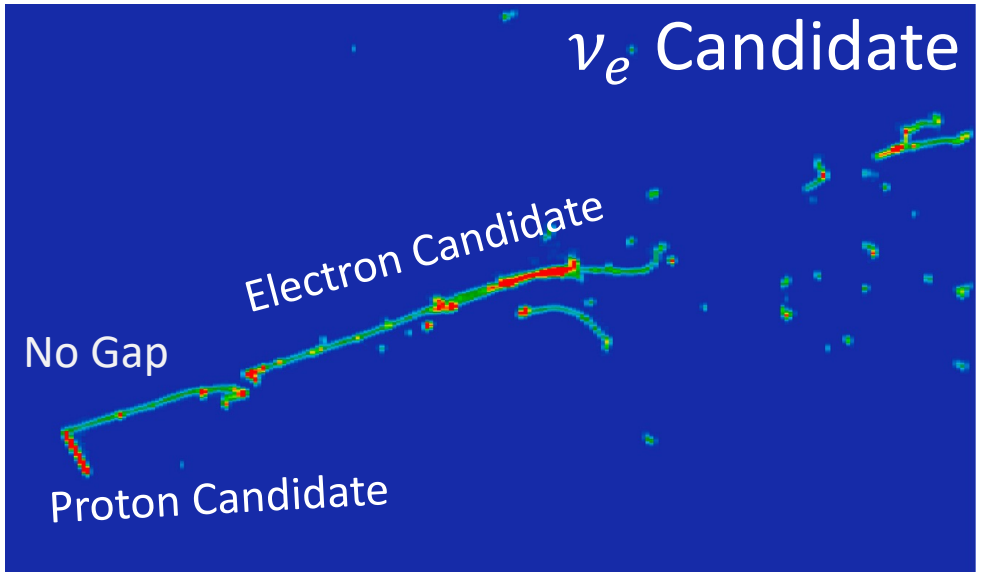
e^-/γ Separation in LArTPCs

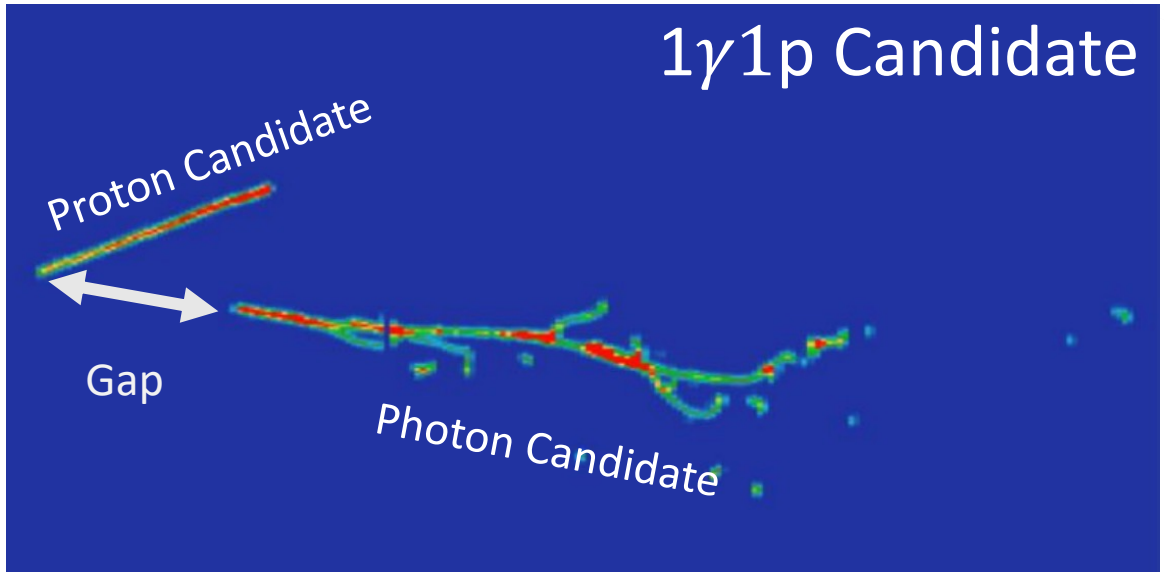




Main draw of LArTPCs is that they can separate photons from electrons

e^-/γ Separation in LArTPCs

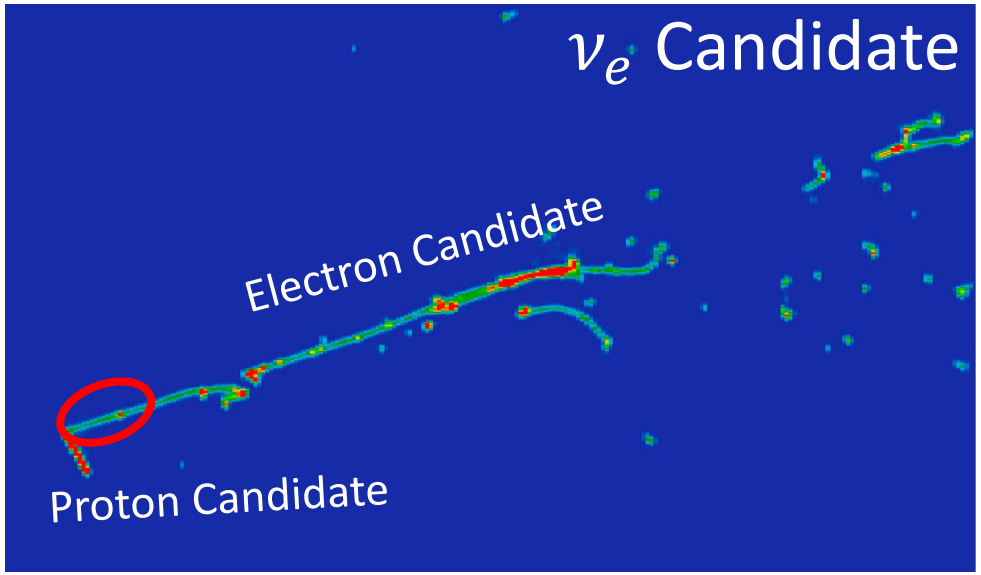


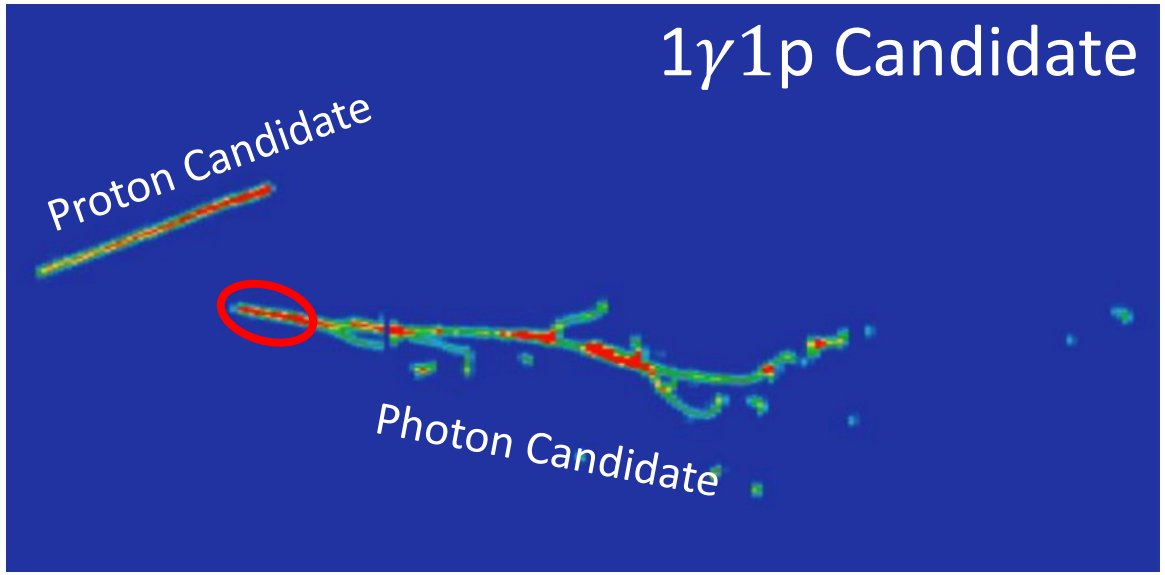


Main draw of LArTPCs is that they can separate photons from electrons

- Fine spatial resolution

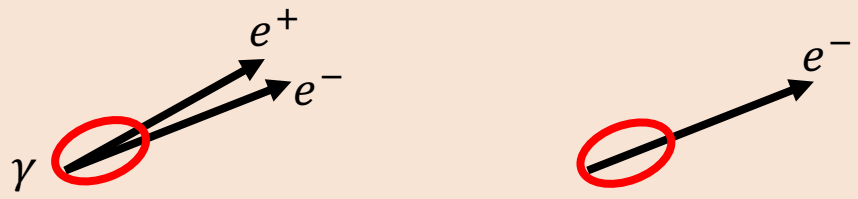
e^-/γ Separation in LArTPCs





Main draw of LArTPCs is that they can separate photons from electrons

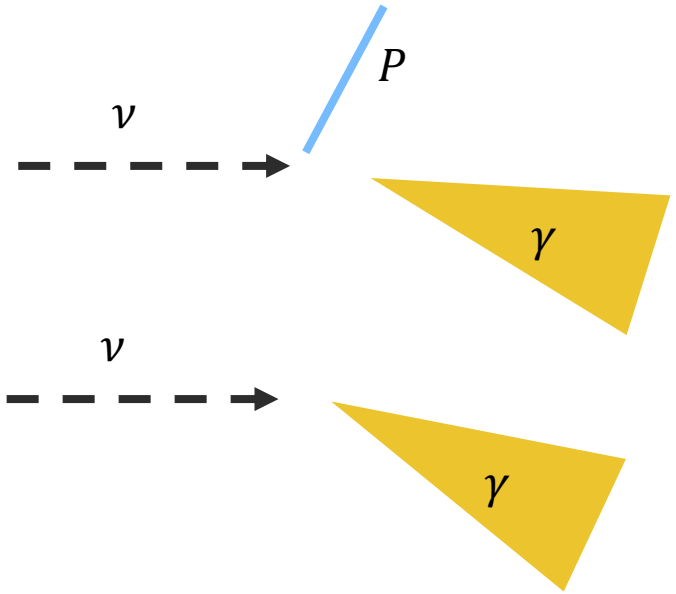
- Fine spatial resolution
- Calorimetry



Pair production from photons produces twice the number of minimally ionizing electrons, **so has twice the charge deposited at the start of the shower**

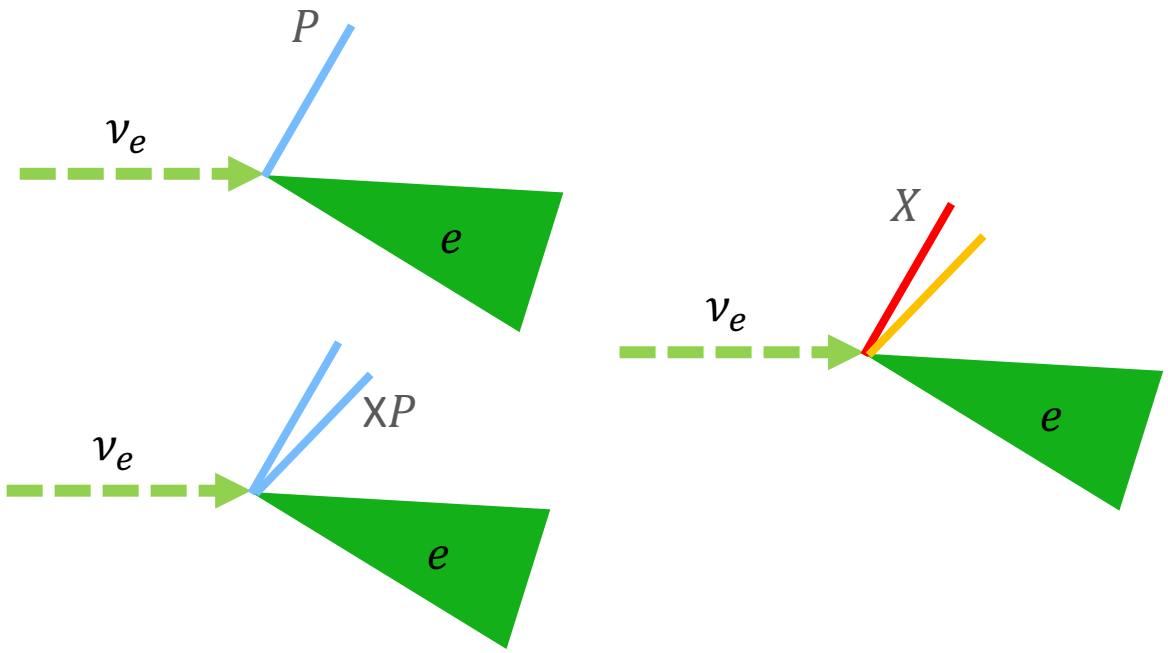
Anomaly Search

NCΔ Single-Photon Search



- $NC\ \Delta \rightarrow N\gamma$
- Shower detached from the neutrino vertex
- Single Photon
- arXiv:2110.00409, accepted by PRL

Electron Search



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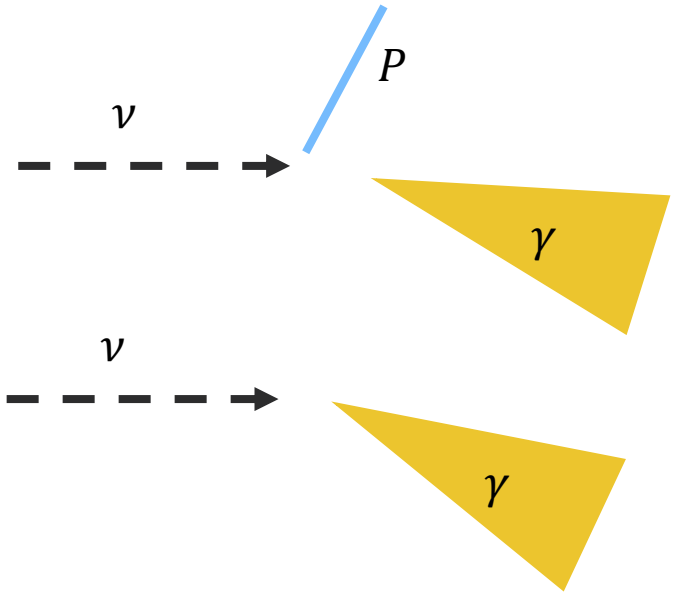

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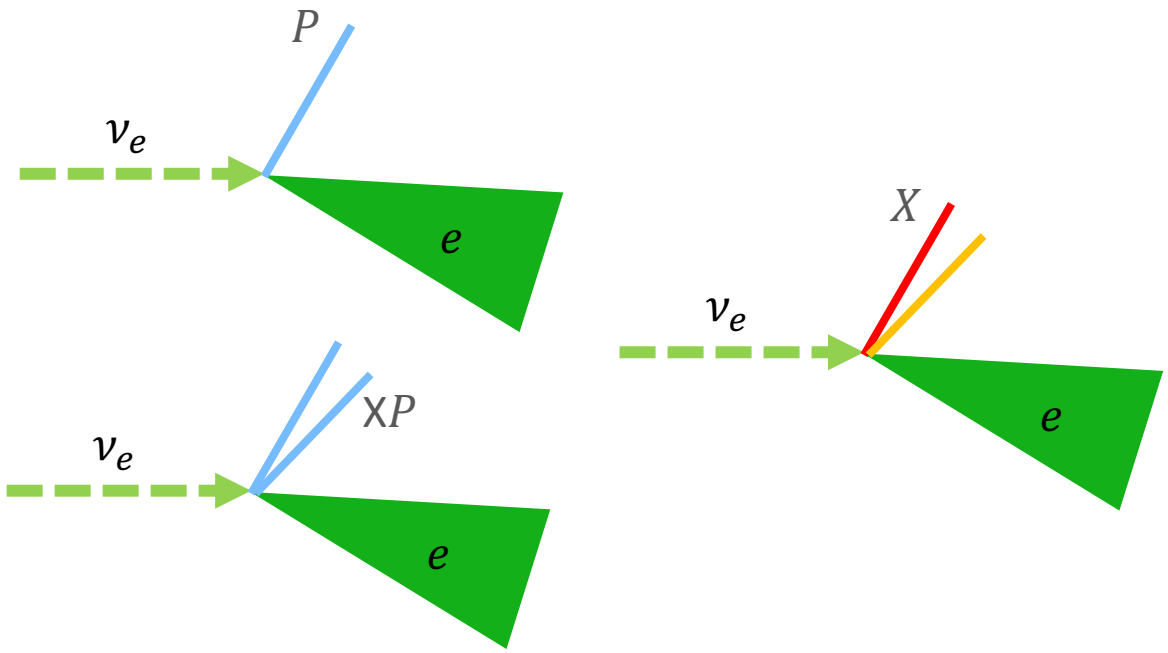

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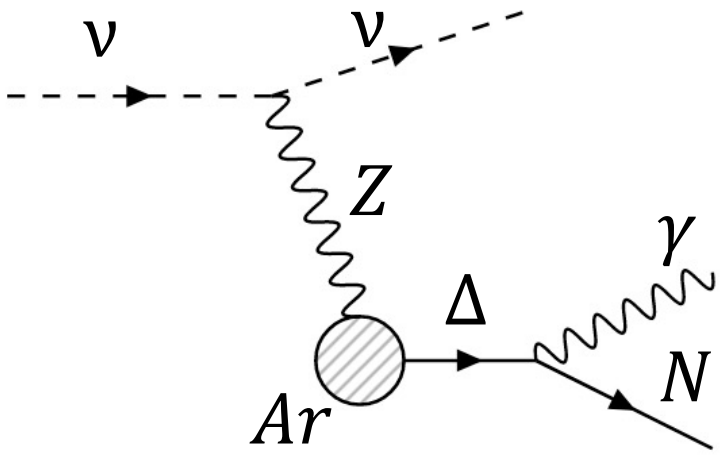
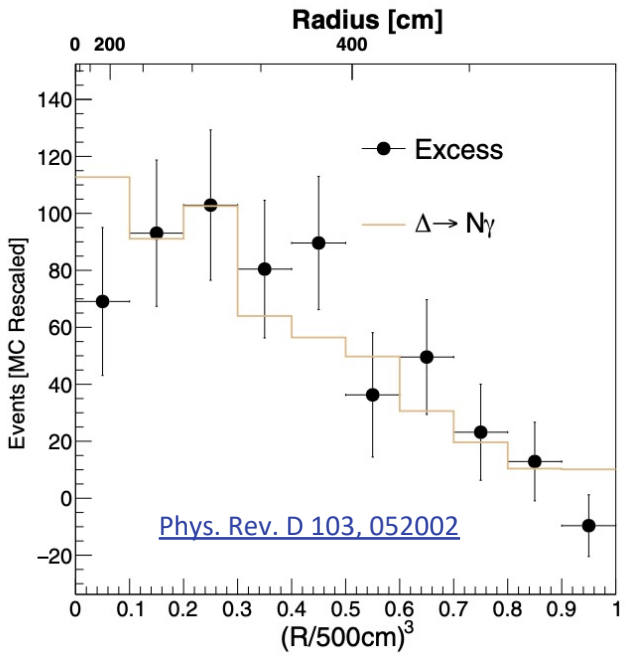
NCΔ Single-Photon Search: Δ Radiative Decay

- Standard model process
  - Predicted Br $\Delta(1232) \rightarrow N\gamma$ is < 1%
- To date, never directly observed in neutrino scattering
- Enhancement of $\Delta \rightarrow N\gamma$ signal x3.18 would agree with observed anomaly at MiniBooNE





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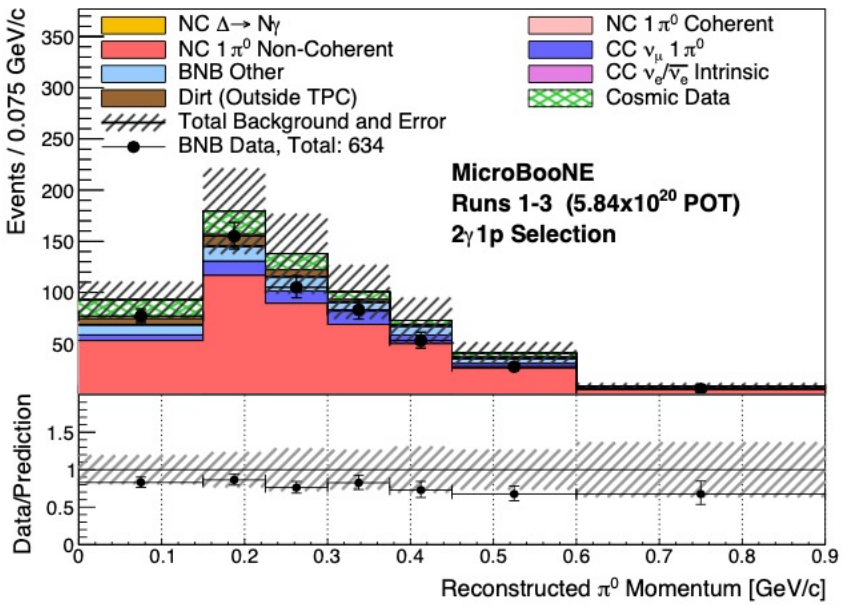
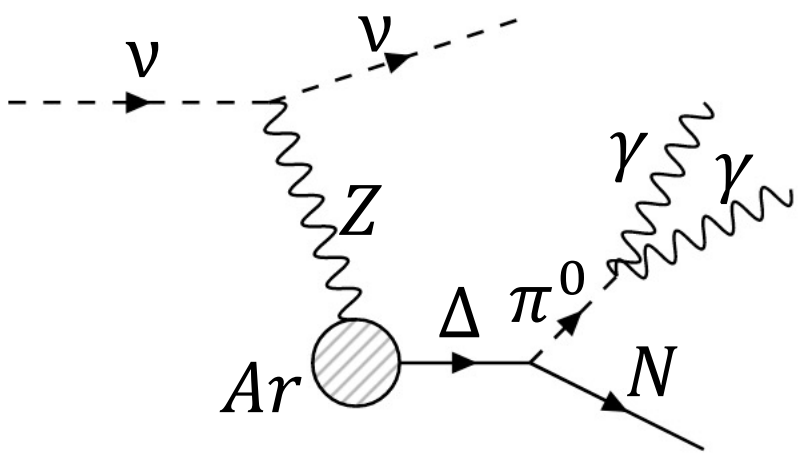
NCΔ Single-Photon Search: Analysis

- Utilize Pandora Multi-Algorithmic Reconstruction [EPJC 78, 182 (2018)]
- Major challenge is $NC\pi^0$ backgrounds:
  - Second shower difficult to reconstruct
- Leverage five BDTs to target key backgrounds
  - Cosmic activity, two focusing on $NC\pi^0$, $CC\nu_e$, other backgrounds from the BNB
- Backgrounds further constrained with high-purity $NC\pi^0$ sample





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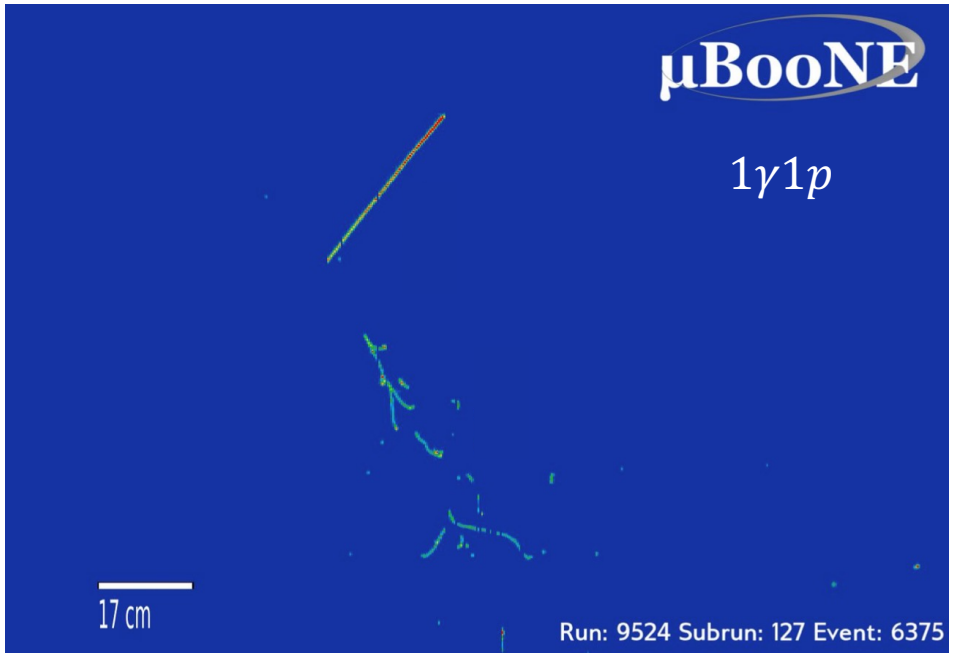
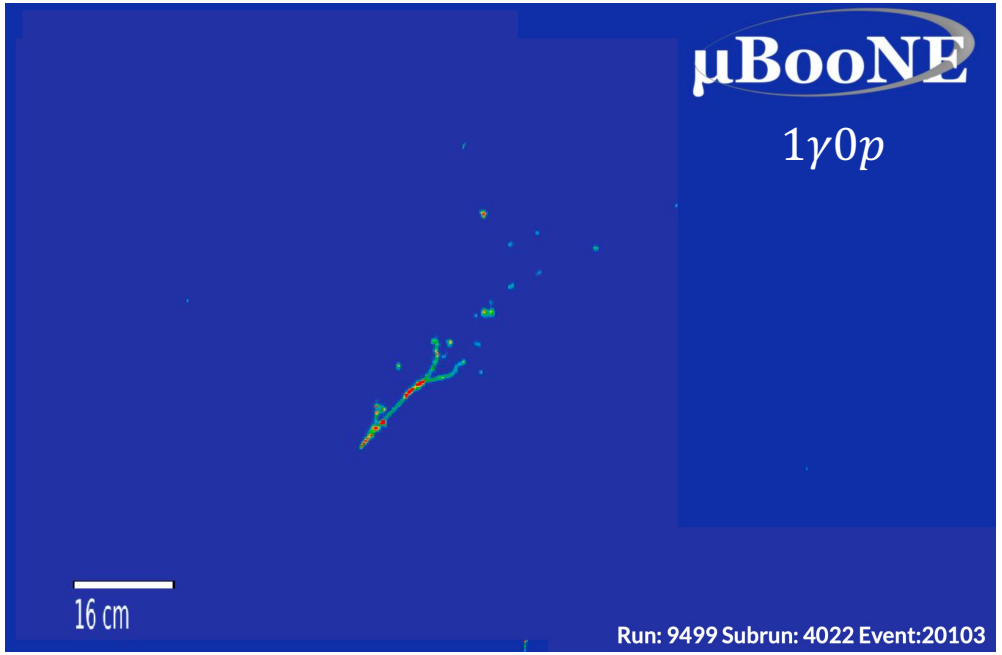
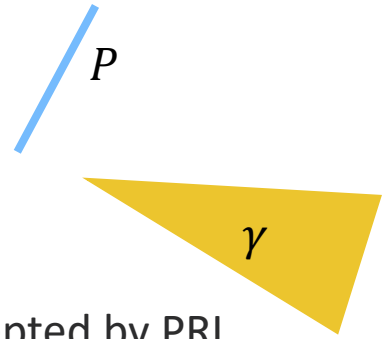
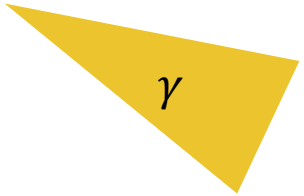
NCΔ Single-Photon Search: Selected Events

- Signal for $\Delta \rightarrow N\gamma$: $1\gamma 1p$ and $1\gamma 0p$









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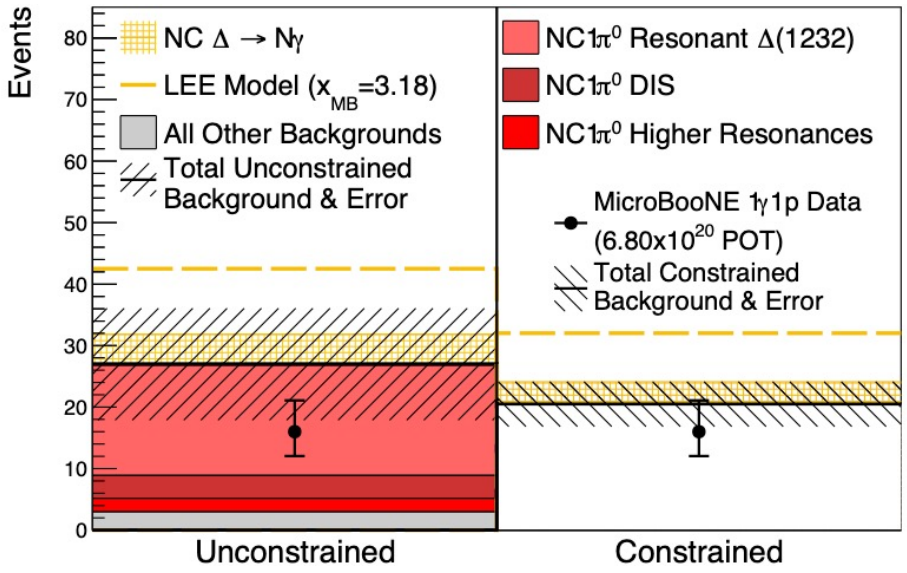
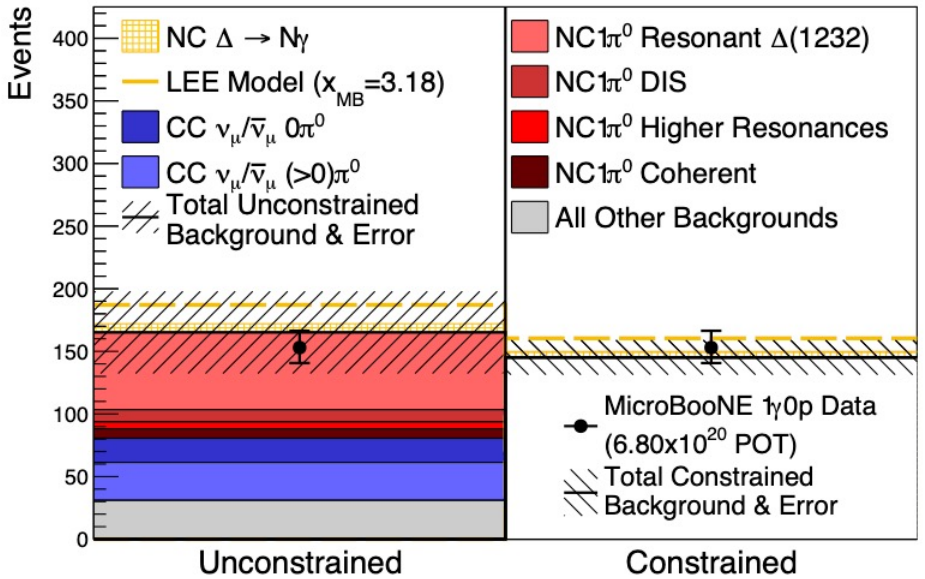
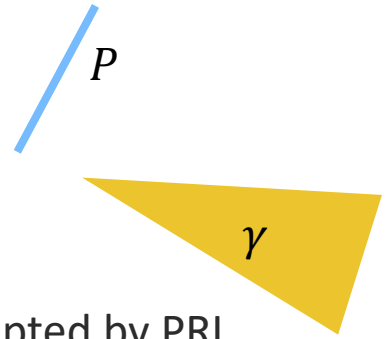
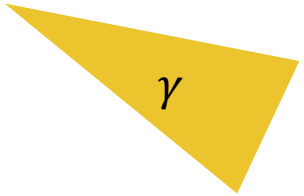
NCΔ Single-Photon Search: Results

- Disfavor NC Delta radiative decay interpretation of the MiniBooNE LEE at the 94.8% CL









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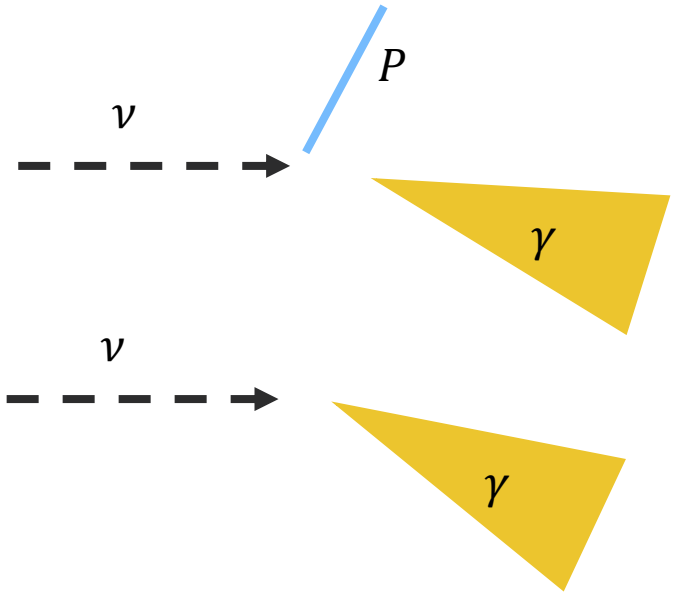
Anomaly Search

NCΔ Single-Photon Search



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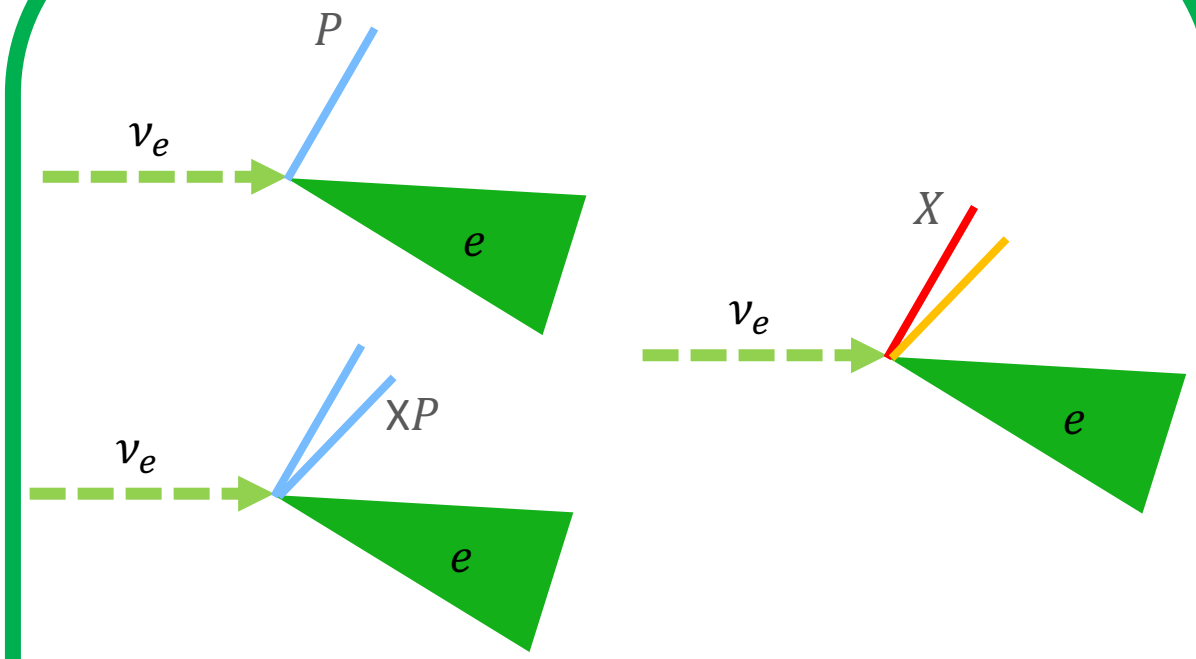

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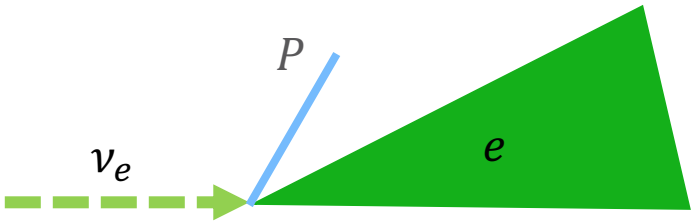
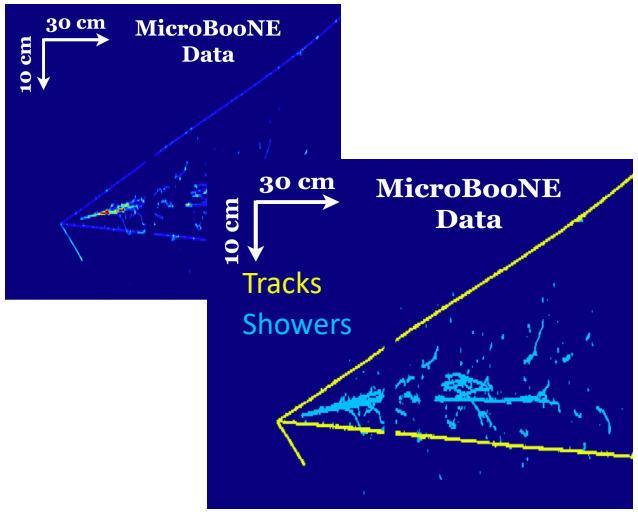
Electron Search: Analysis Topologies



$\nu_e + Ar \rightarrow 1e1p0\pi$

- Deep learning approach
- Low to medium energy nue ν_e
- Targeting CCQE interactions



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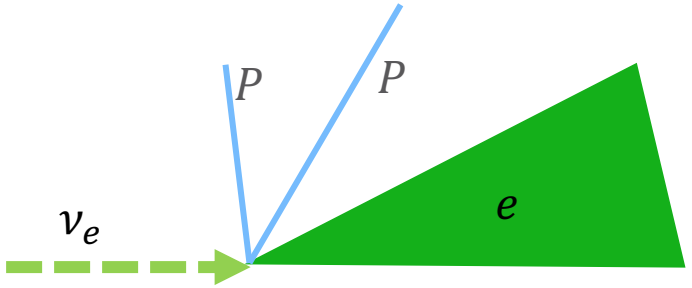
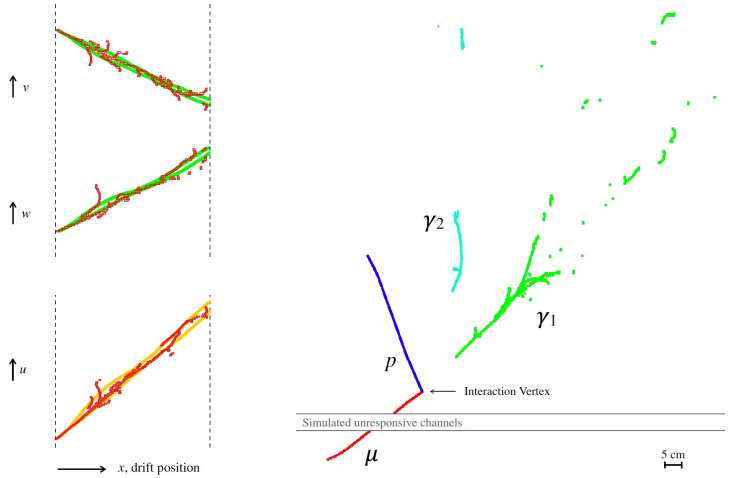


$\nu_e + Ar \rightarrow 1eXp0\pi$

- Pandora reconstruction
- Low to medium energy ν_e
- Two channels: 0p and Np (N>0)
  - MiniBooNE signal



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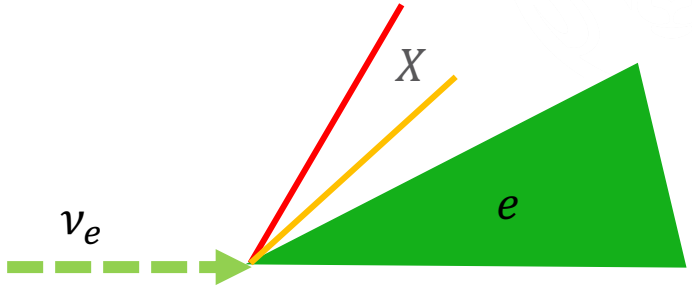
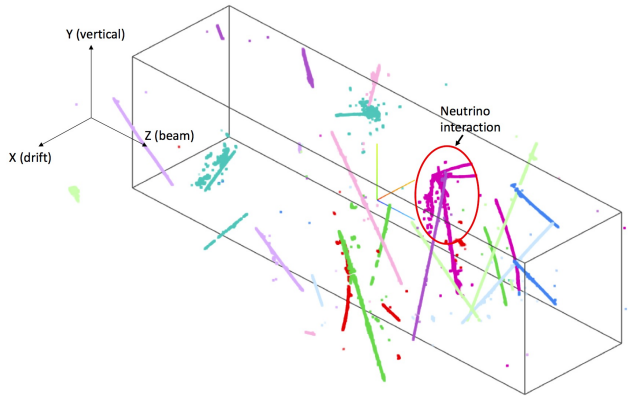


$\nu_e + Ar \rightarrow 1eX$

- Wire-Cell reconstruction
- High statistics
- Inclusive selection

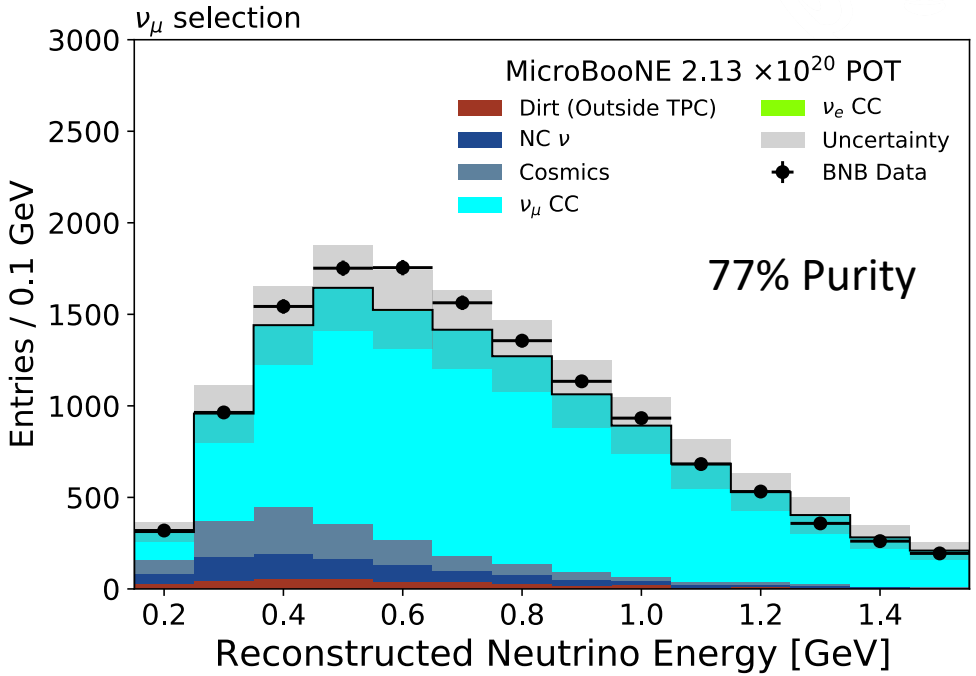


arXiv:2110.13978, submitted to PRD

Electron Search: Constraint and Systematic Uncertainties

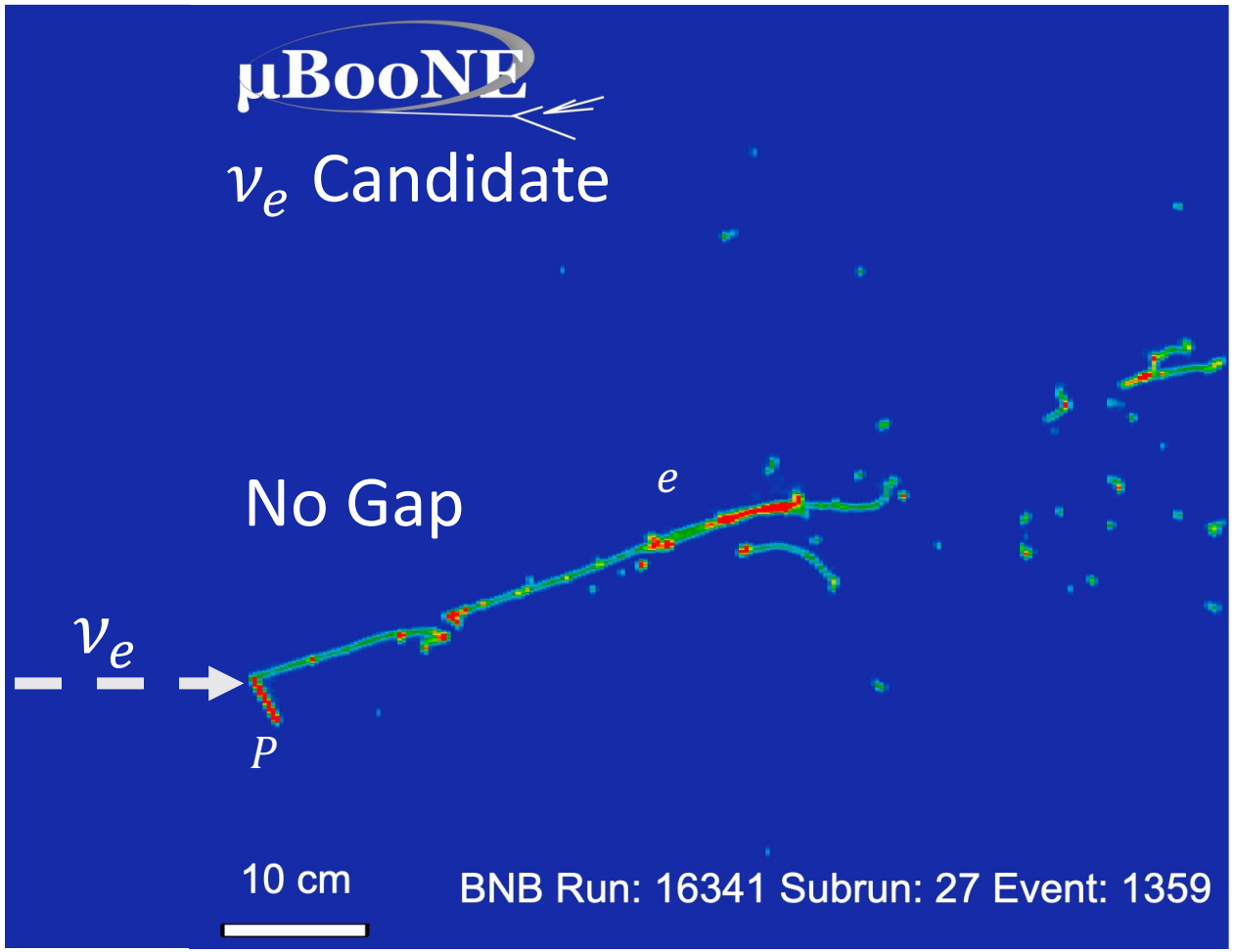
- Use high-statistics ν_μ sample to constrain ν_e uncertainties
  - Flux: ν_μ and ν_e come from same beam
  - Cross-Section: ν_μ and ν_e share ν-Ar interaction model
- Validate neutrino rate modeling
- Constrain uncertainties on prediction:

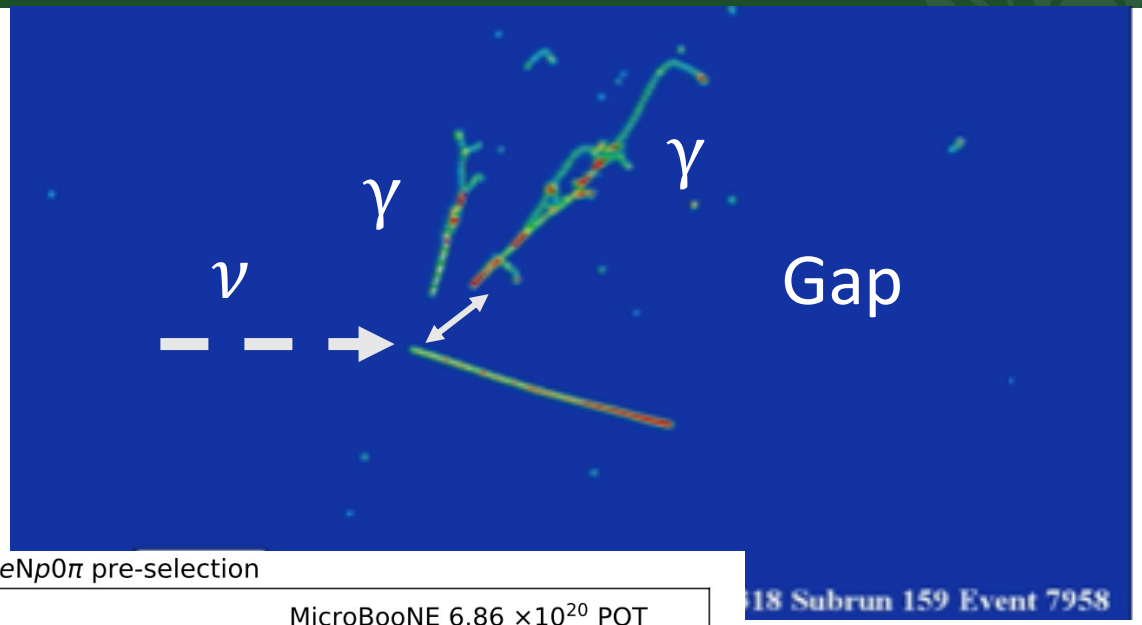
Channel	Reduction Factor
$1e1p0\pi$	2.0
$1eNp0\pi$ and $1e0p0\pi$	1.7
$1eX$	3.5

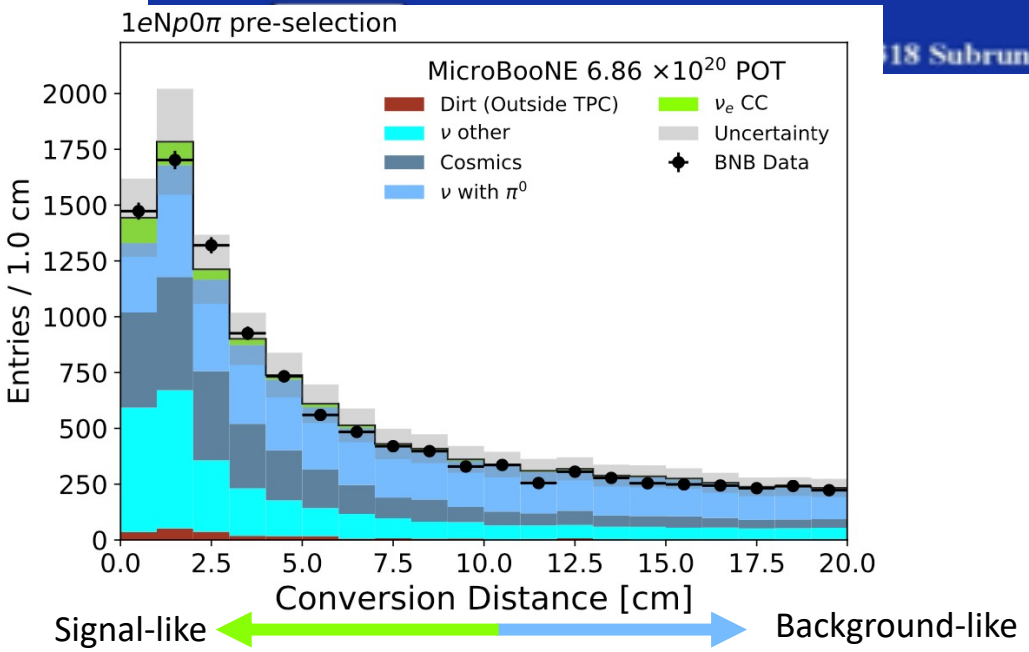


Electron Search: e^-/γ Separation – Conversion distance

- Distance between start point of shower and track
  - Photon-induced showers are detached from neutrino vertex

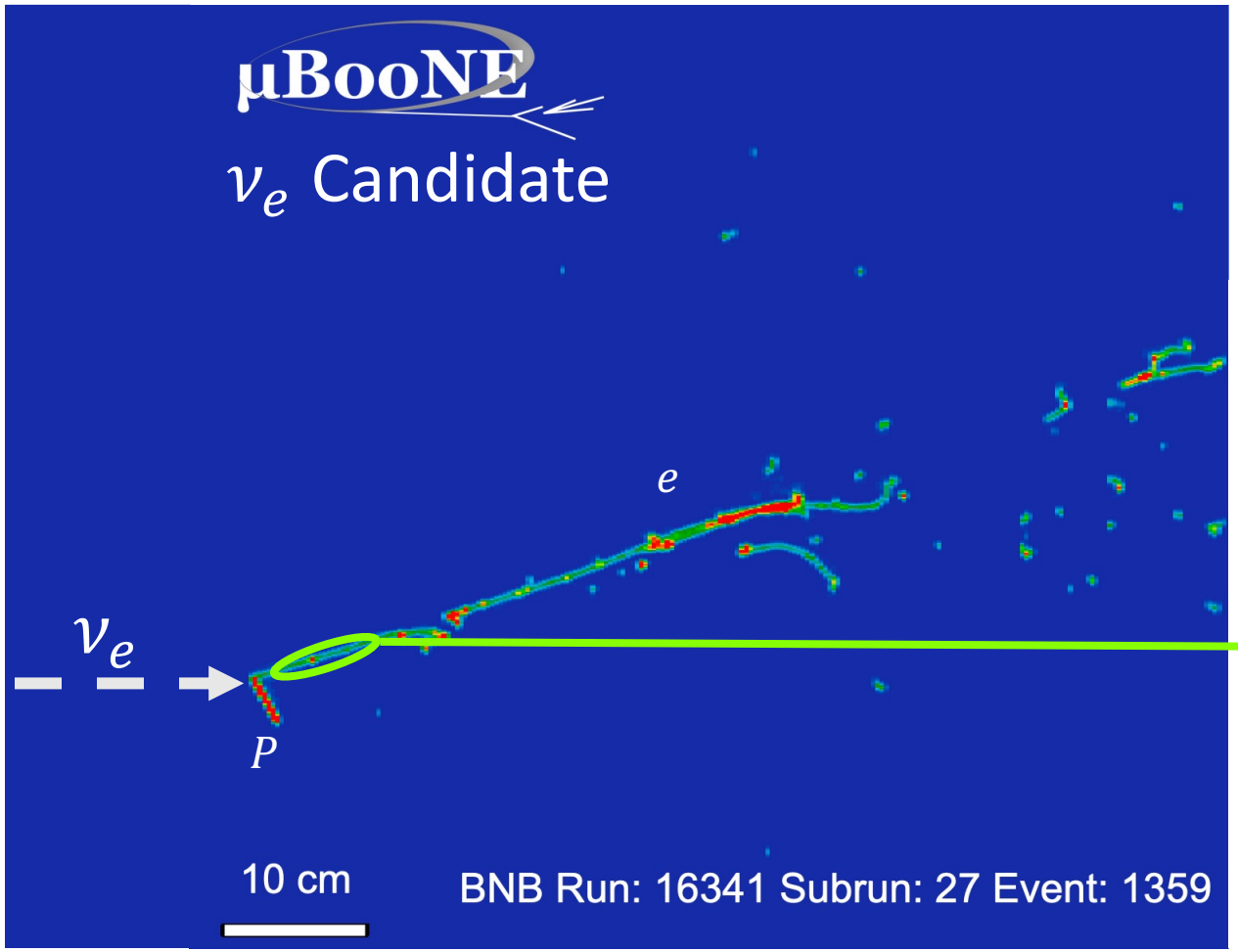


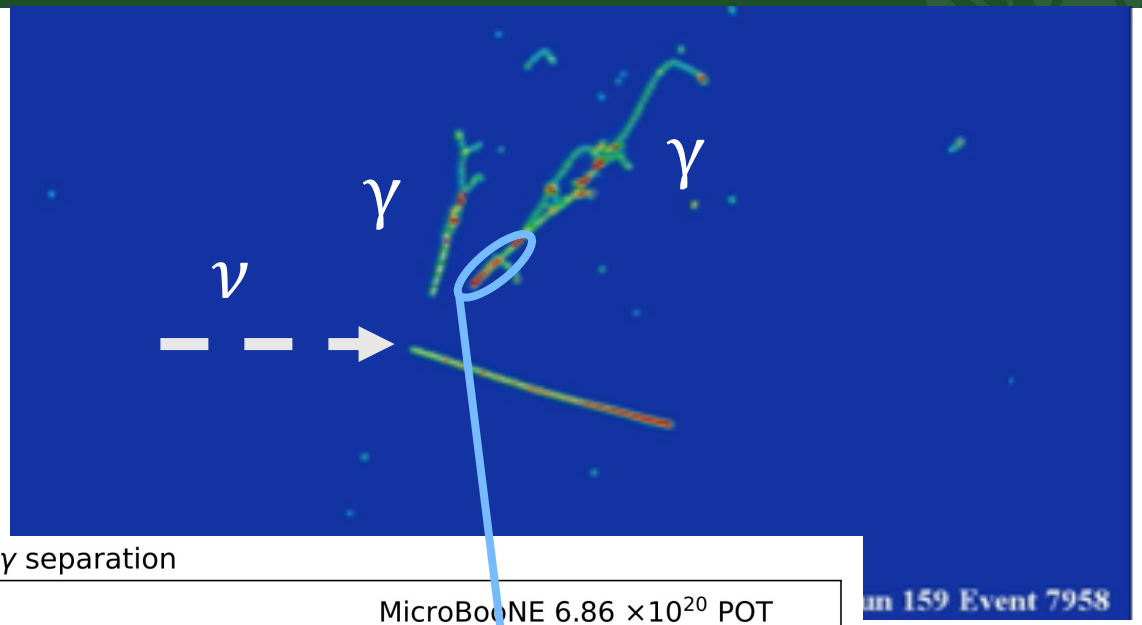


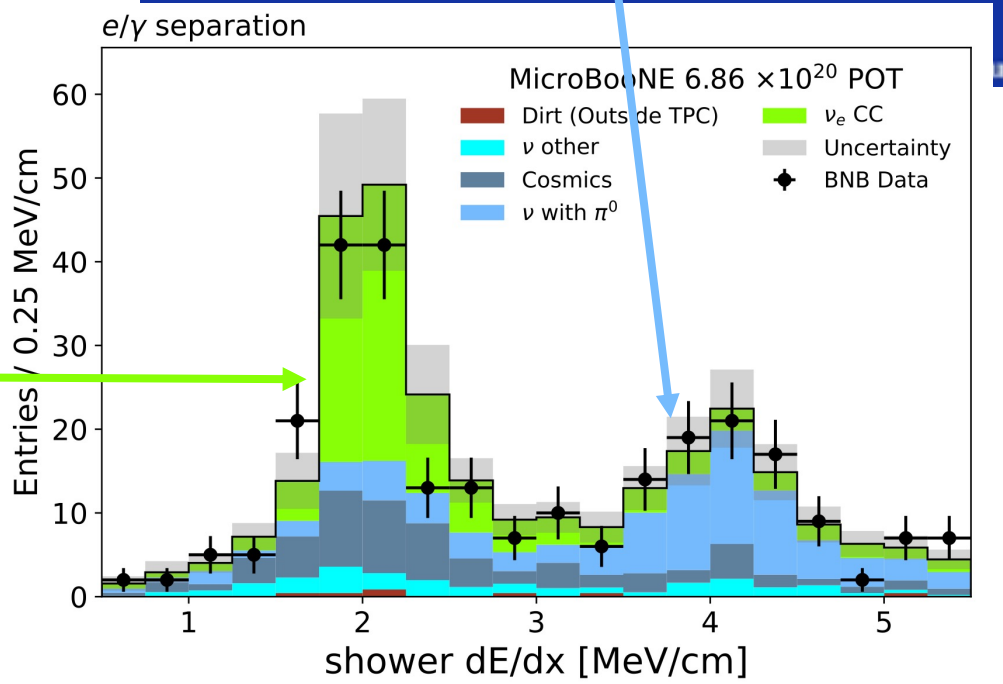


Electron Search: e^-/γ Separation – dE/dx

- Amount of energy deposited per unit length (dE/dx) at start of shower
  - Median of first 4 cm of shower trunk

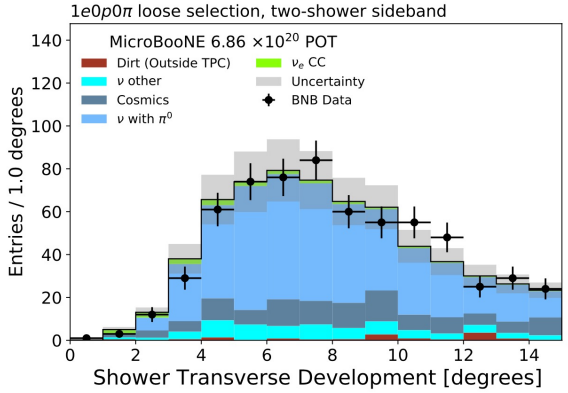


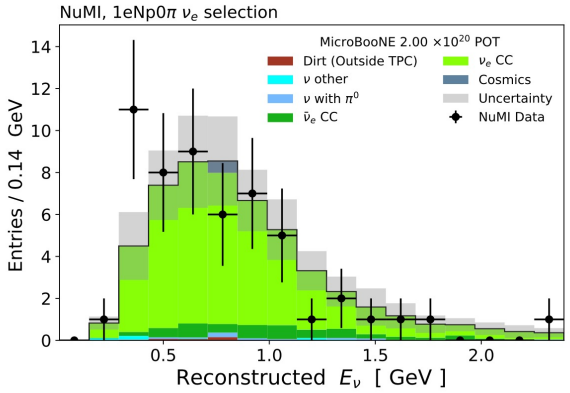




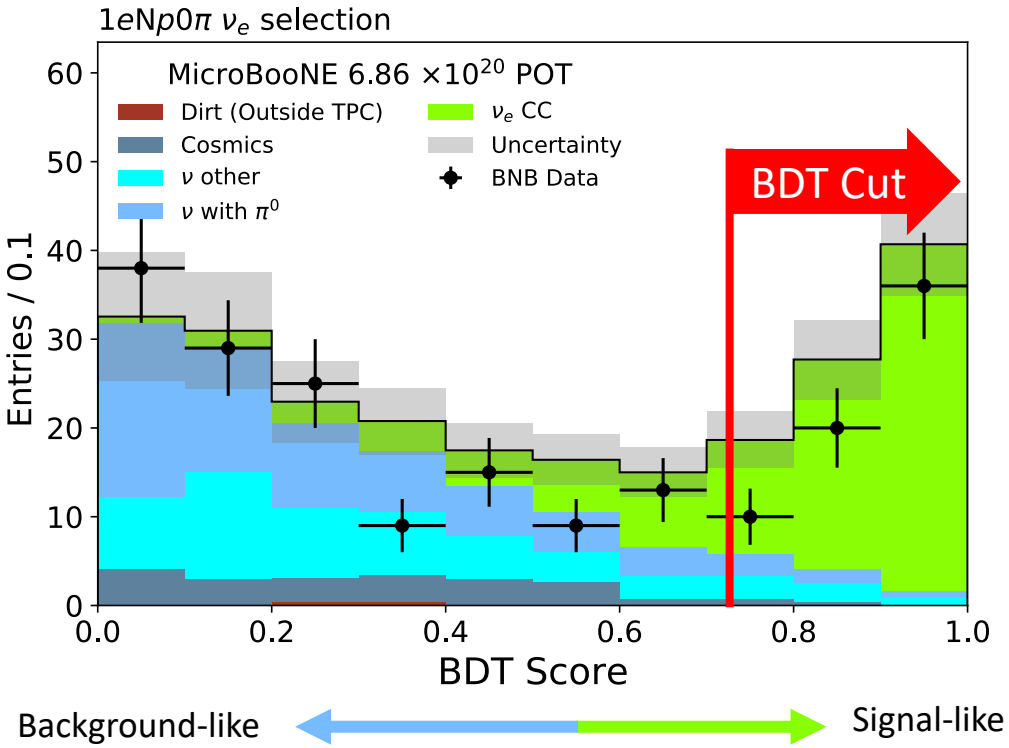
Electron Search: Selections

- Blind analysis: Use data that is not in the signal region to validate analysis
- Examples:

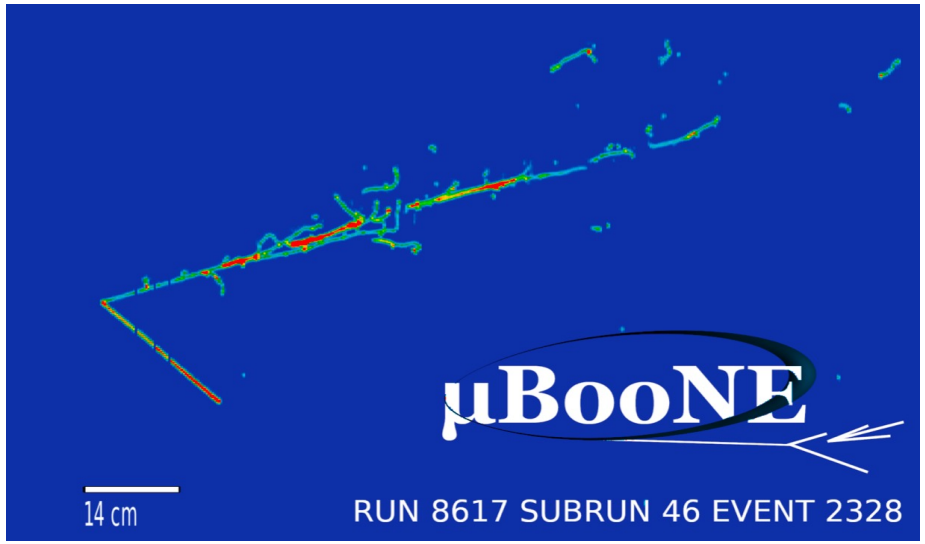


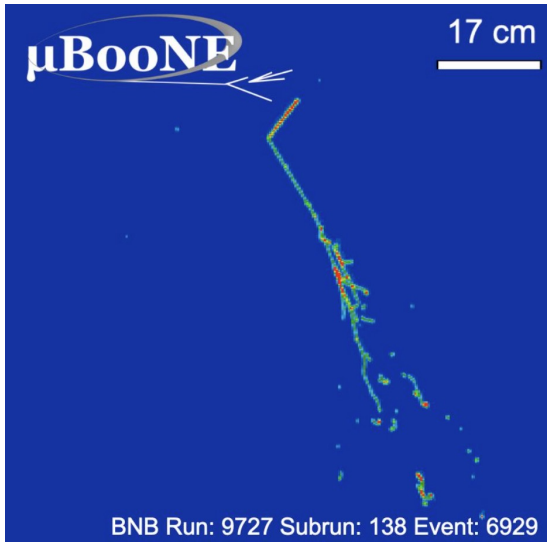


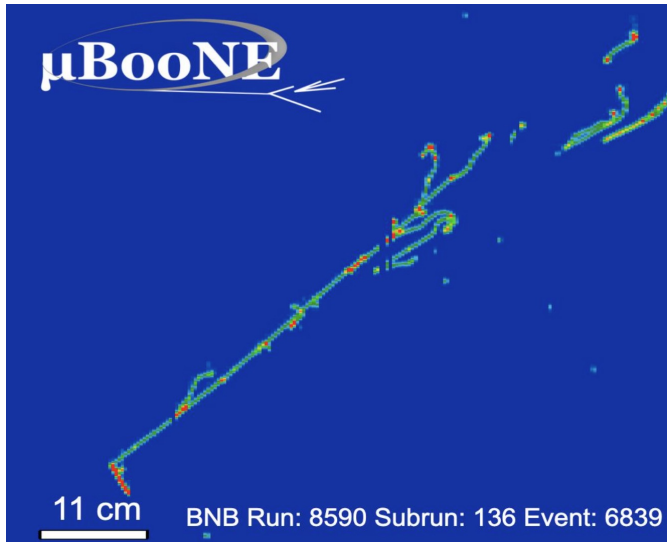
- Each analysis employs Boosted Decision Trees (BDT):
  - Further separate ν_e from other background
  - Cut on BDT score is chosen to provide high purity

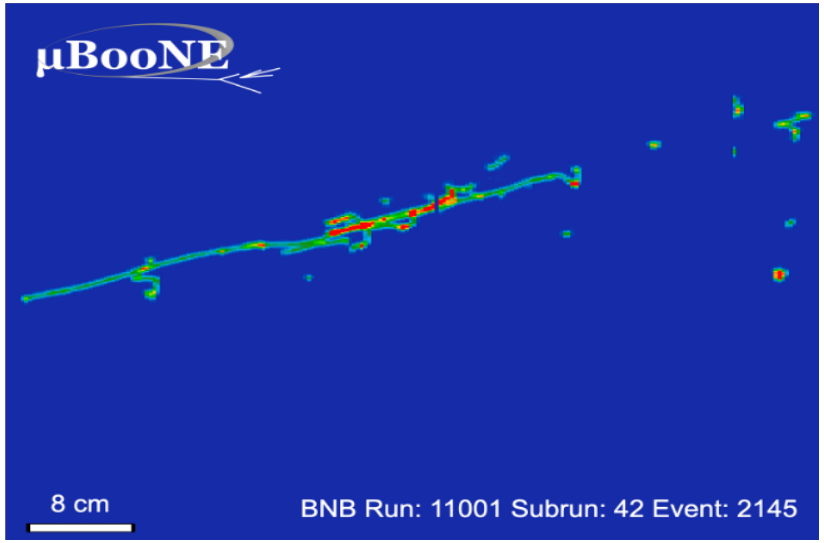


Electron Search: Selected Events

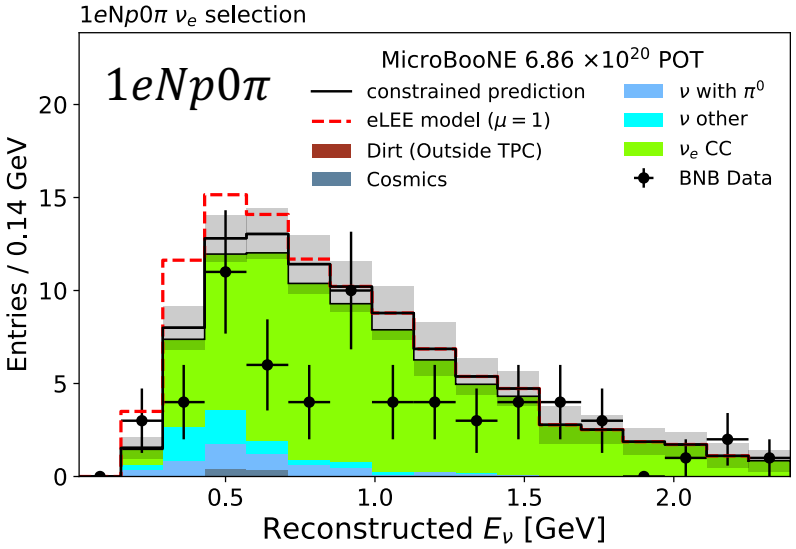


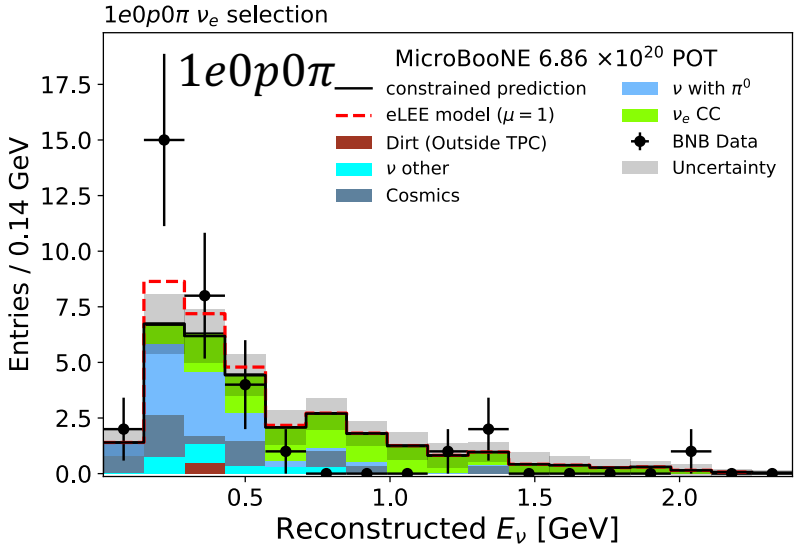


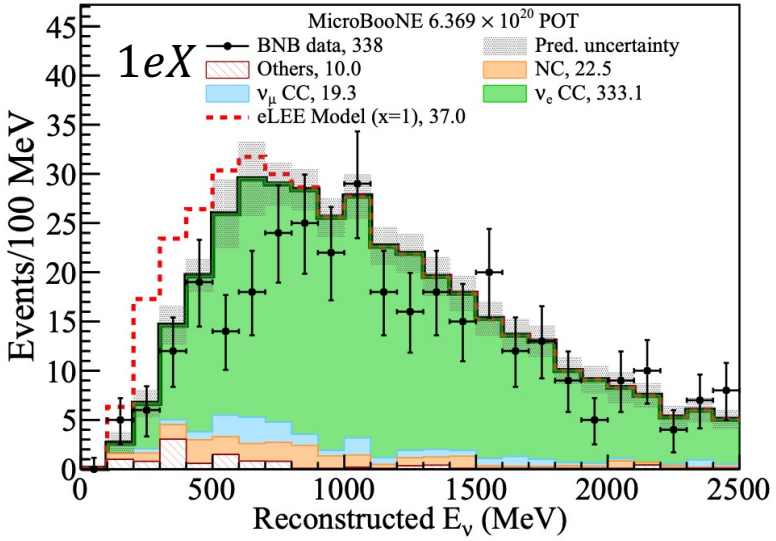


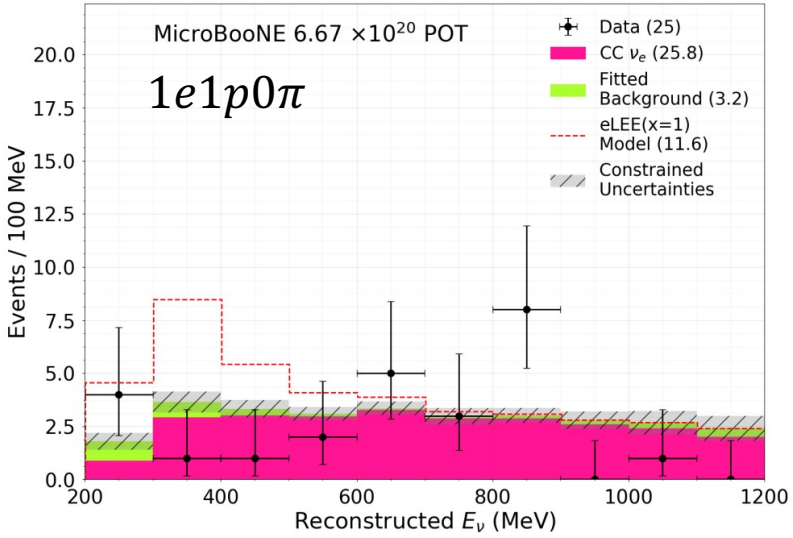


Electron Search: ν_e Energy Spectra



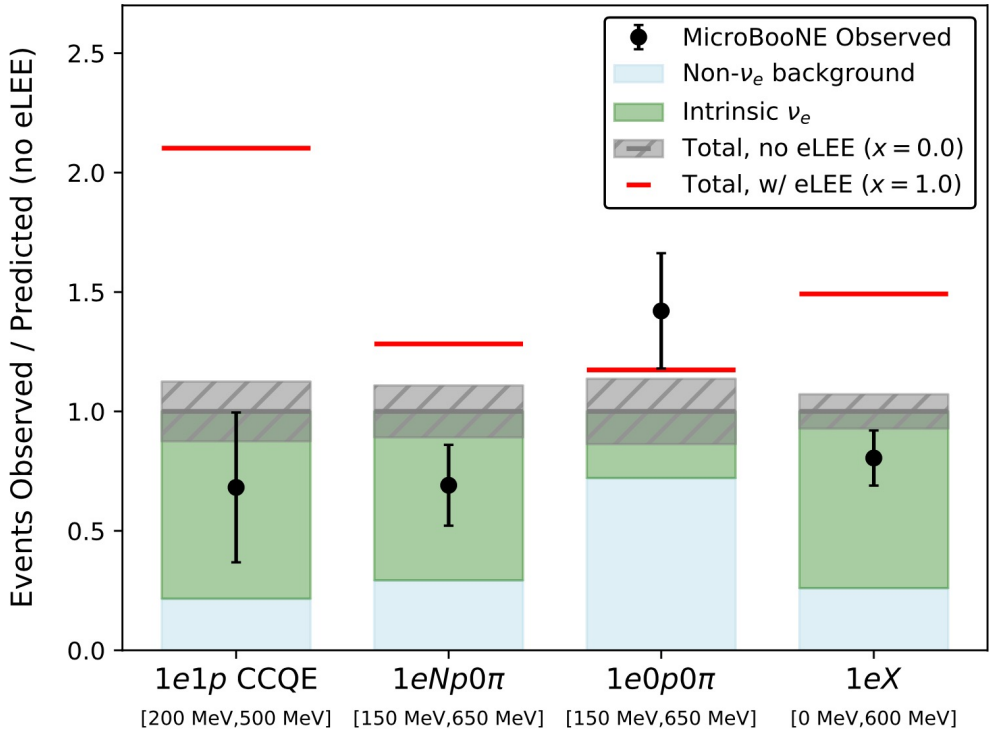






Electron Search: Results

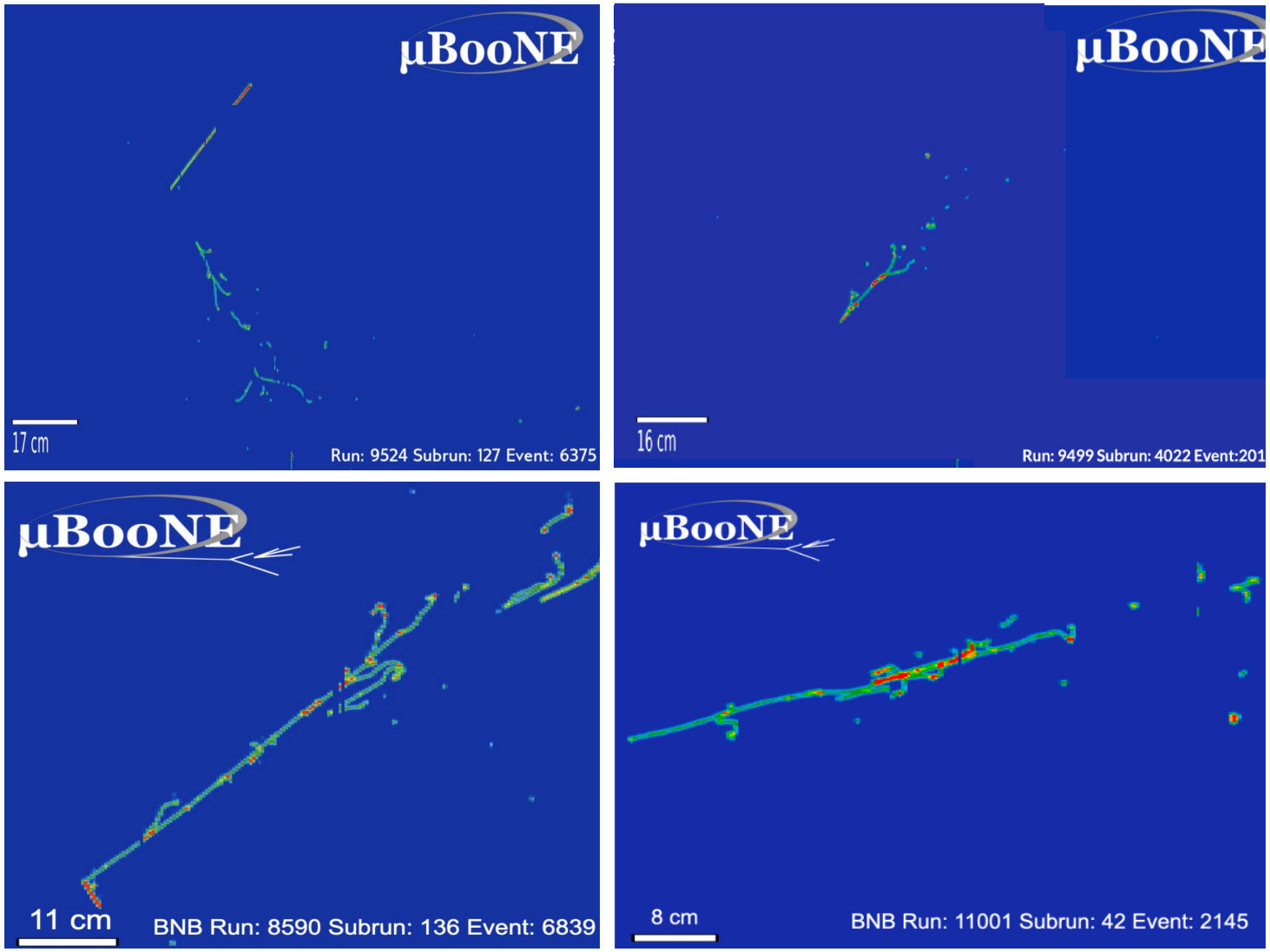
- Observations show $\nu_e CC$ event rates in agreement, or below, the predicted rate
- We reject our simple eLEE model at >97% CL for both exclusive (1e1p CCQE, 1eNp0π) and inclusive (1eX) event classes
- $1e0p0\pi$ shows slight excess
  - Low sensitivity
  - γ background dominated
- We disfavor generic ν_e interactions as the primary contributor to the excess



arXiv:2110.14054, accepted to PRL

Conclusion

- First search for MiniBooNE low-energy excess in MicroBooNE was performed
- No evidence for excesses of ν_e or $NC\Delta \rightarrow N\gamma$
- MicroBooNE actively pursuing new measurements to explain MiniBooNE anomaly
  - See Daisy's Talks tomorrow!



Colorado State University

Thank You!

This work is supported by the United States Department of Energy under Grant No. DE-SC0021191.

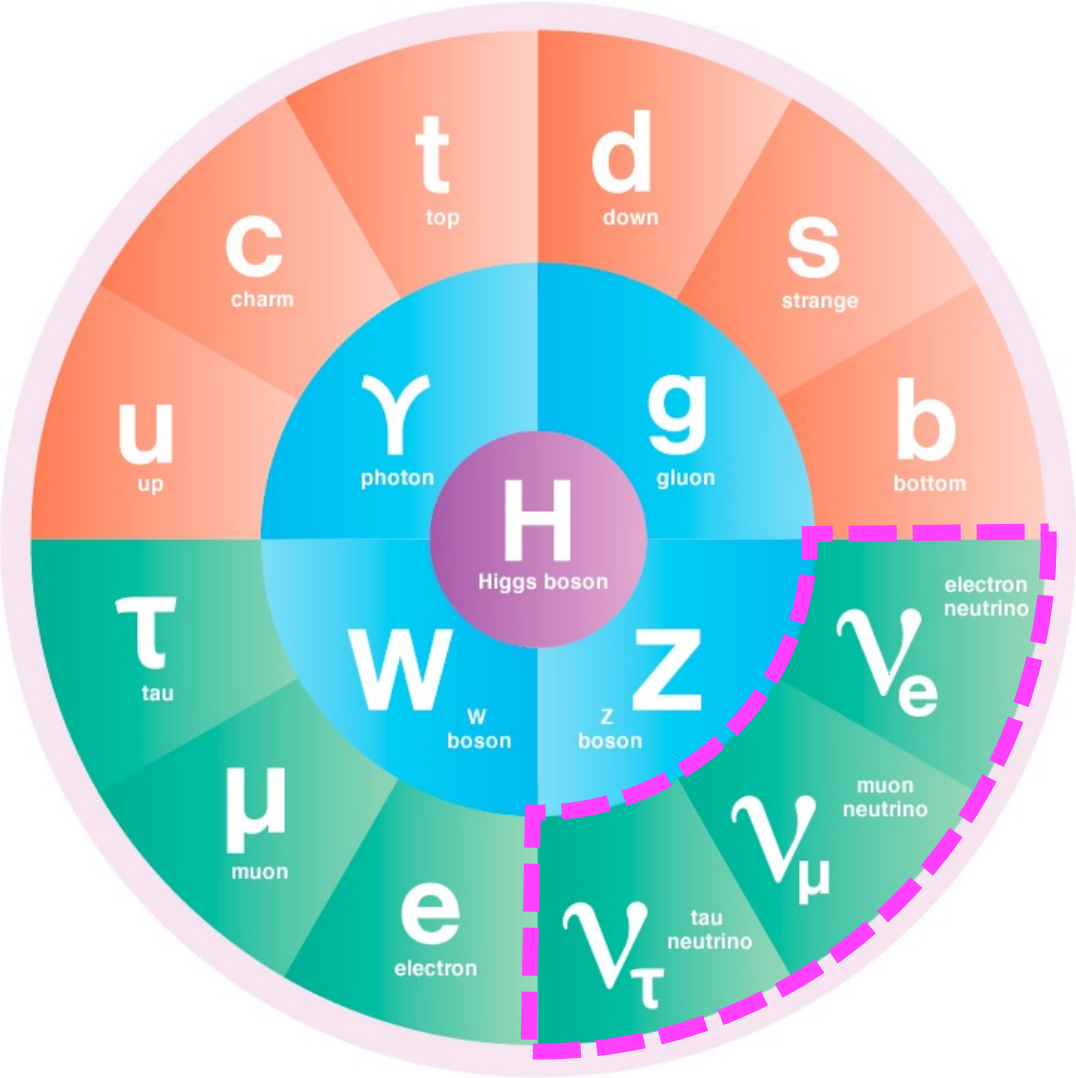
μBooNE

Fermilab

U.S. DEPARTMENT OF ENERGY

Neutrinos in the Standard Model

- Neutrinos come in three flavors in the Standard Model: electron, muon and tau
- Only neutral leptons
- Only interact via the weak interaction and gravity
- Neutrinos Oscillates:
  - Propagate as mass states, interact as flavor states
  - Produce some neutrino ν_α and detect it as ν_β



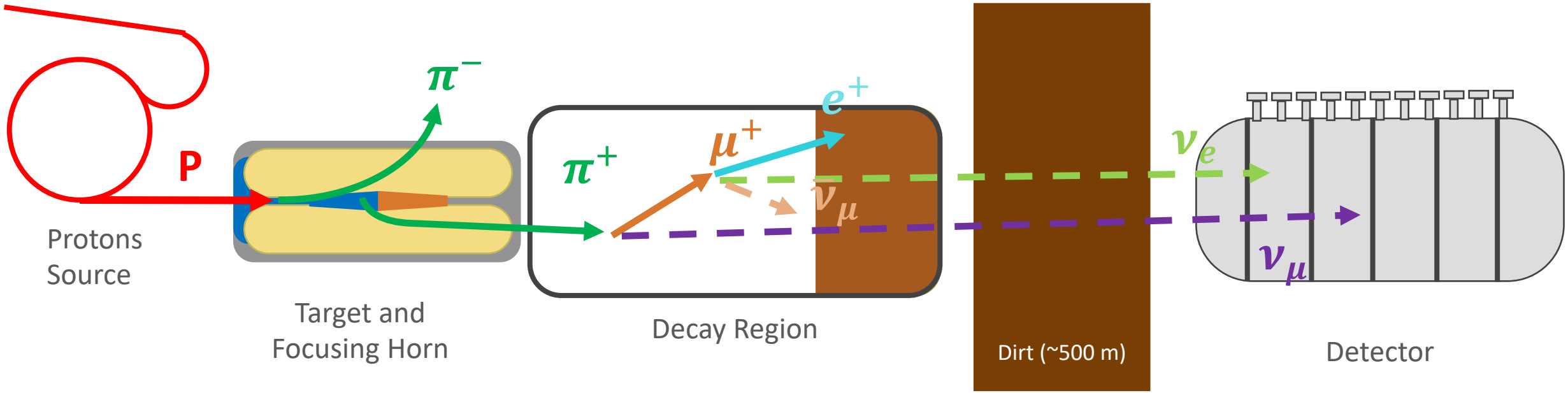
Neutrino Oscillations

Probability of detecting a neutrino of a given flavor <u>oscillates</u> as:

$$P(osc) \sim Sin^2\left(\frac{1.27\ \Delta m_{ij}^2 L}{E}\right)$$

$$\Delta \mathrm{m}_{ij}^2 = \mathrm{m}_\mathrm{i}^2 - \mathrm{m}_\mathrm{j}^2$$

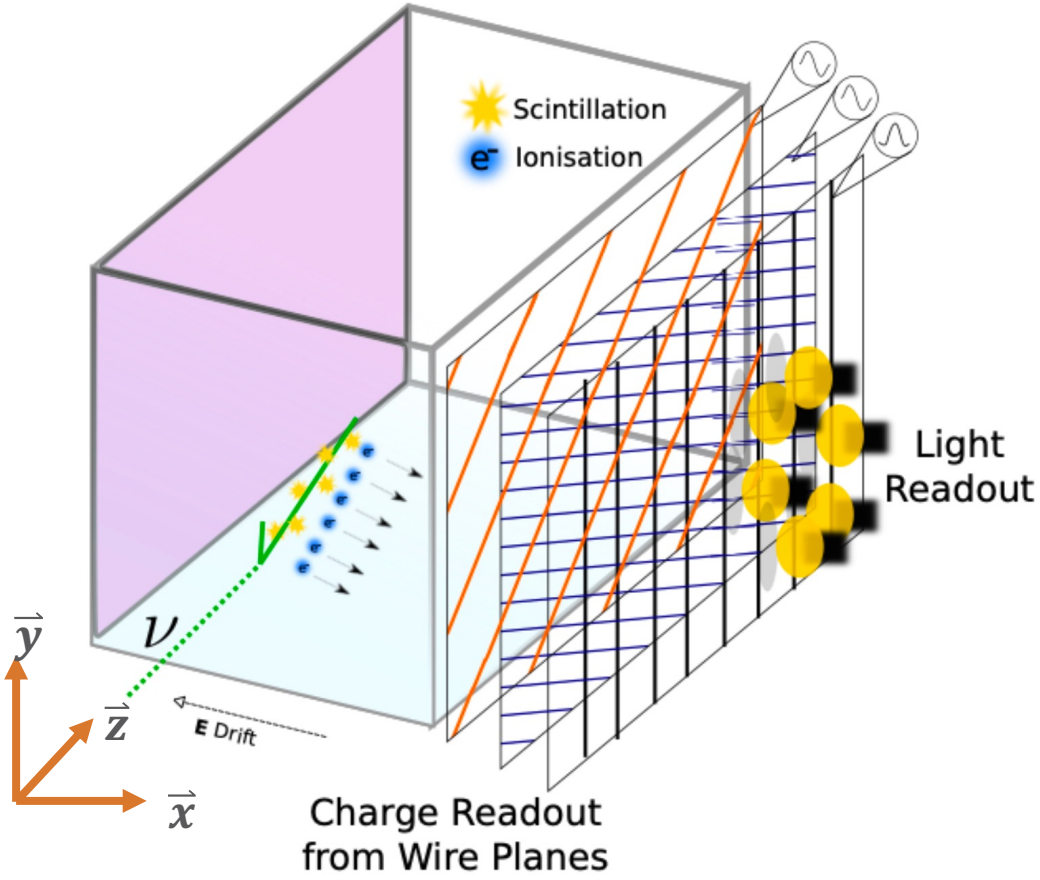
Accelerator Neutrinos



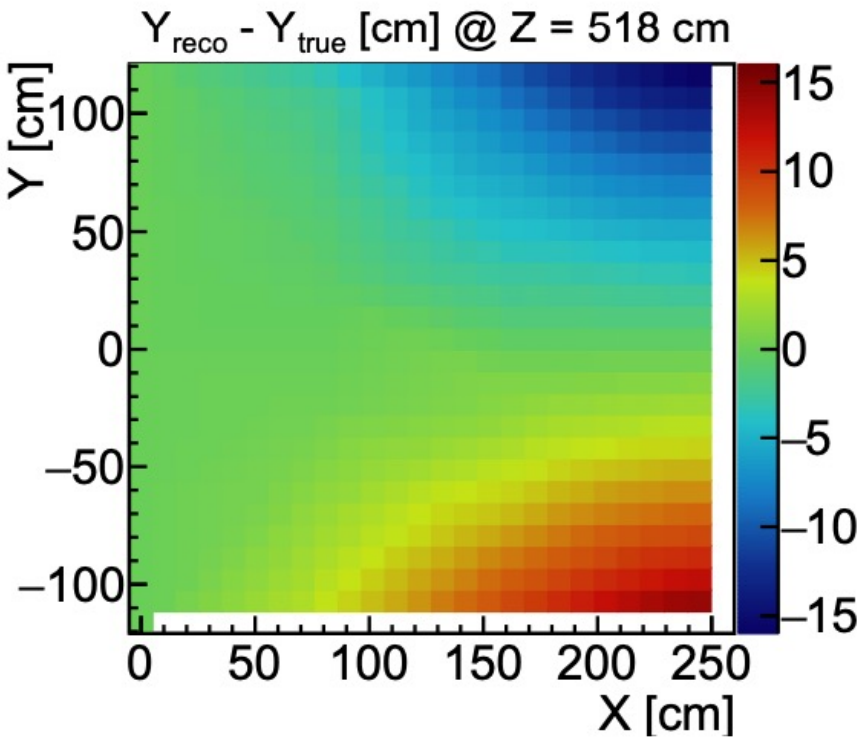
- Accelerator neutrino experiments use a neutrino beam from the decay of (mostly) pions and kaons
- Neutrinos categorized by distance of flight L and energy E
  - Short-baseline experiments have L/E ~1 km/GeV (not sensitive to three-flavor oscillations)
  - Long-baseline experiments have L/E ~10^3 km/GeV

LArTPC Technology

- Liquid Argon Time Projection Chamber (LArTPC)
- Impinging charged particles leads to ionization of argon
- Scintillation light also produced ~O(ns)
  - Excitation (Ar*)
  - Recombination
- Ionization electrons drift according to electric field ~O(ms)

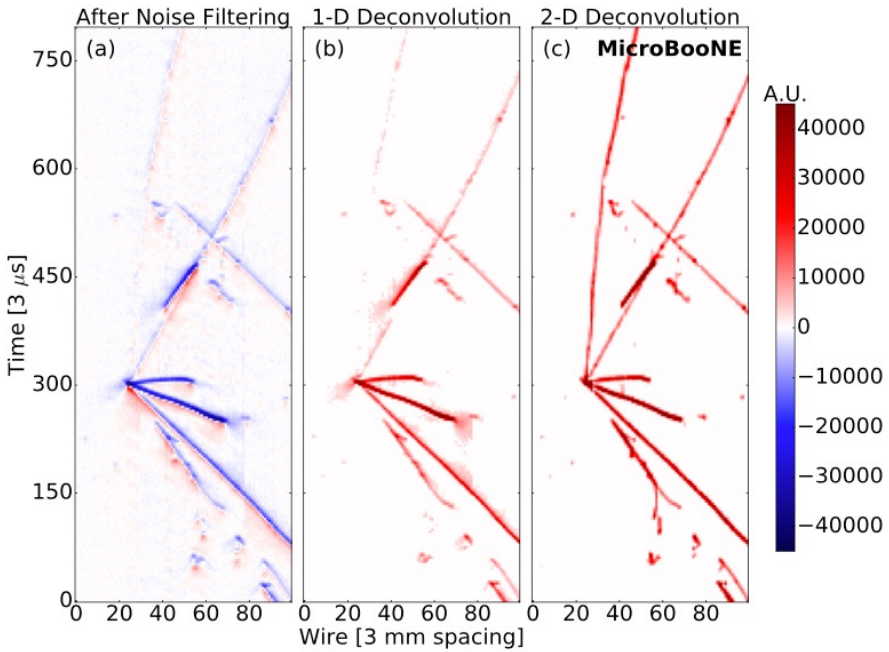


Understanding the Detector: Modeling



Space charge effects modify local E-field

JINST 15 P07010

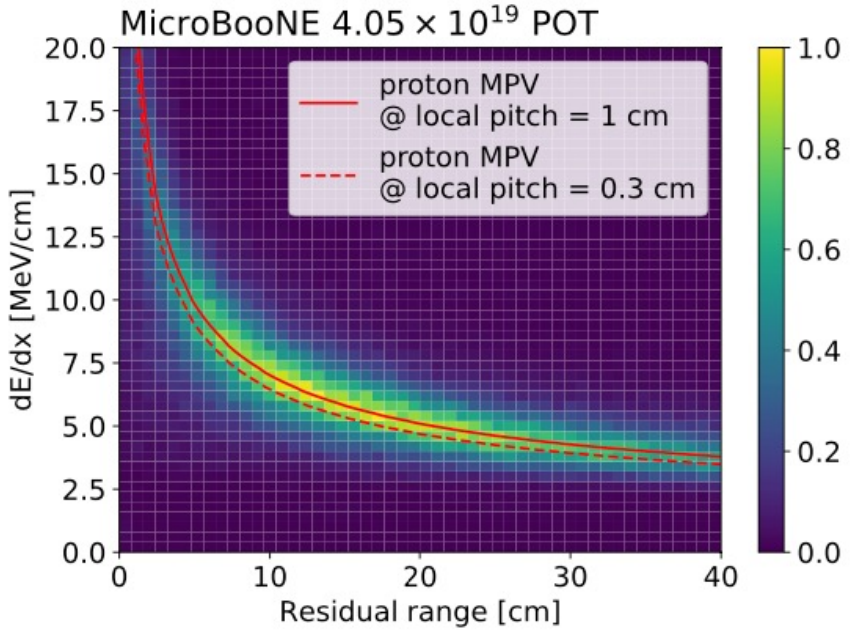


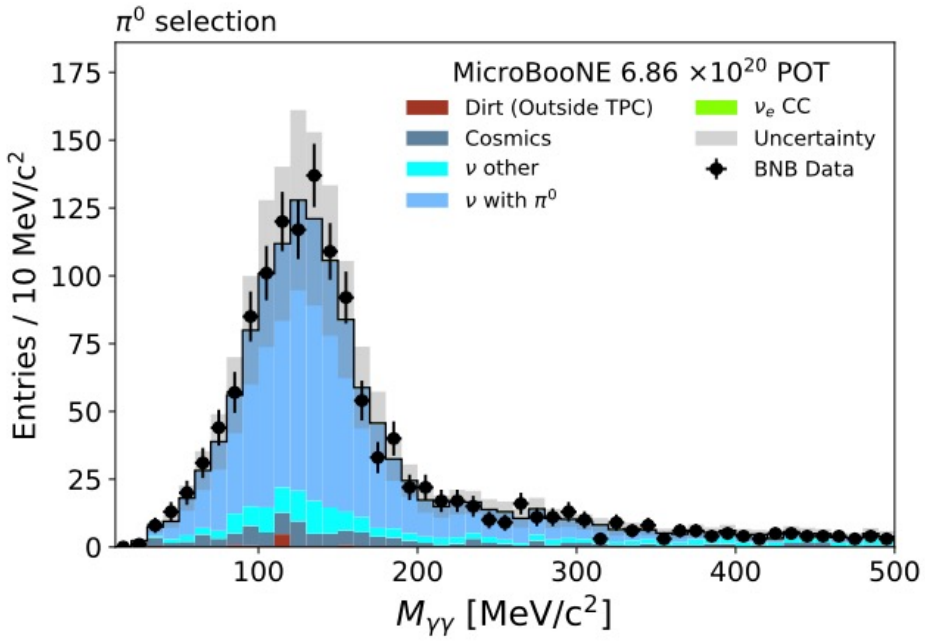
Noise filtering and signal processing improve signal-to-noise ratio

JINST **12** P08003
JINST **13** P07006
JINST **13** P07007

Understanding the Detector: Calibrations

MicroBooNE TPC Calibration: JINST 15 P03022
Electric Field Calibrations: JINST 15 P07010 & JINST 15 P12037
EM Shower Calibrations: JINST 15 P02007, JINST 09 P09014 & arXiv:2110.11874





Proton dE/dx vs residual range
Key to particle ID

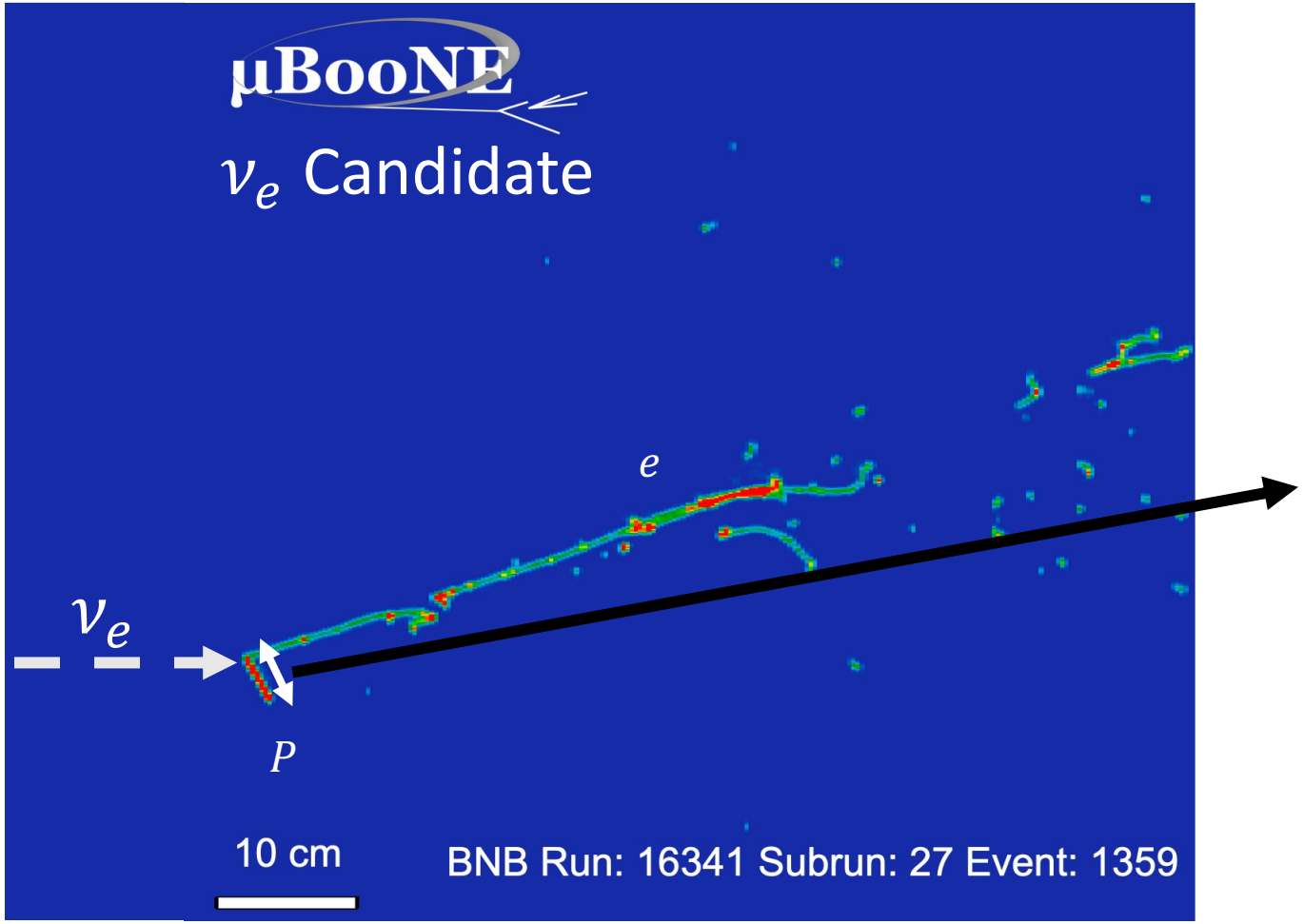
JHEP12(2021)153

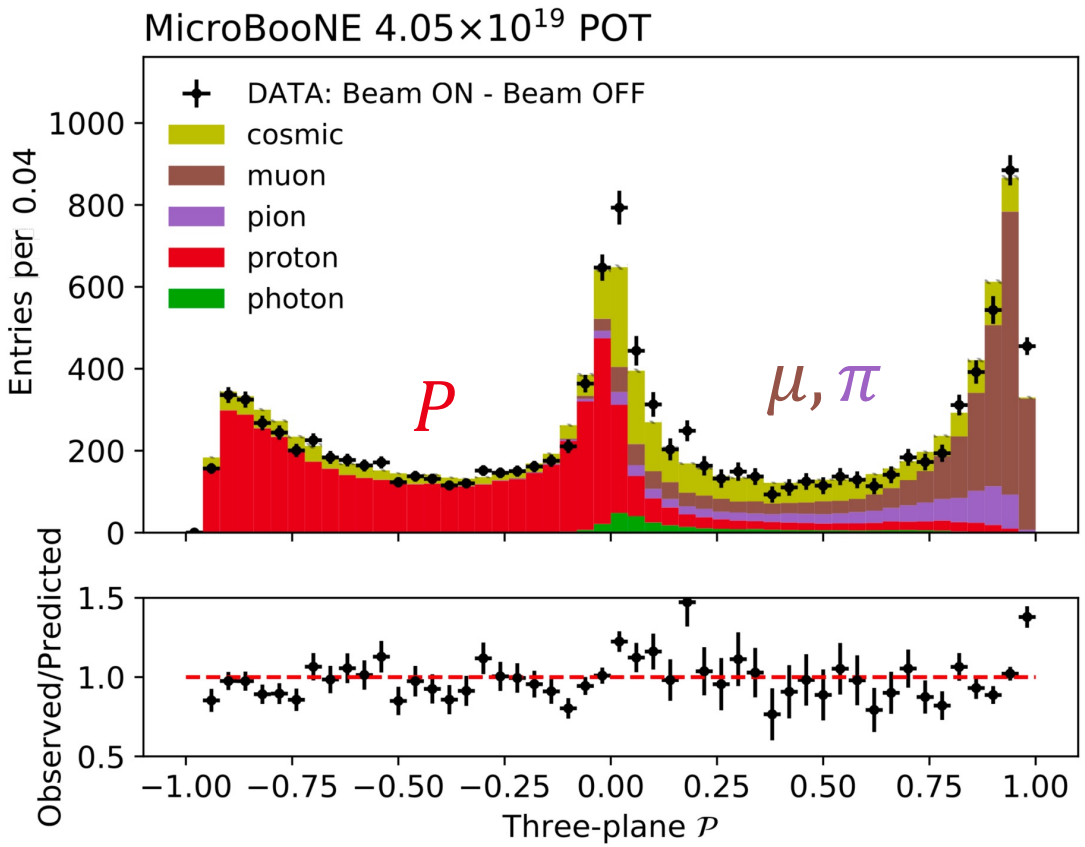
Invariant mass from $\pi^0 \rightarrow \gamma\gamma$
Key to electron energy scale

JINST 15 P02007

Characterizing ν_e Events: Track Identification

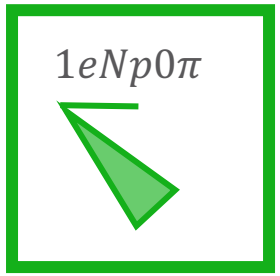
- Likelihood function to evaluate dE/dx relative to particle range

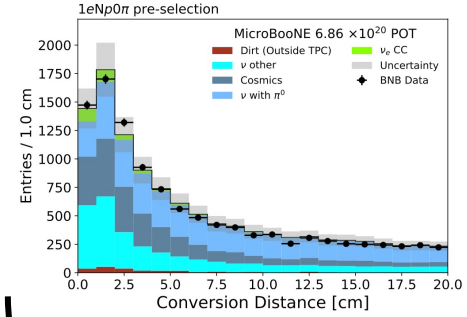


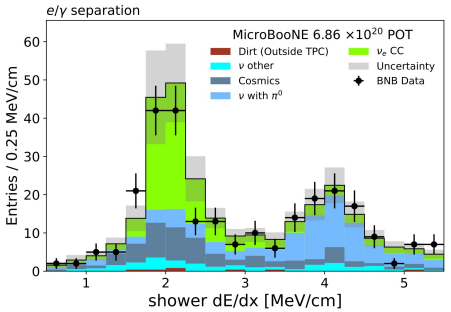


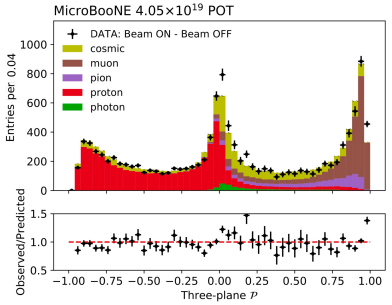
Boosted Decision Tree (BDT) Selections

- Classification of ν_e from other background
- No weight on energy, no use of kinematics related variables









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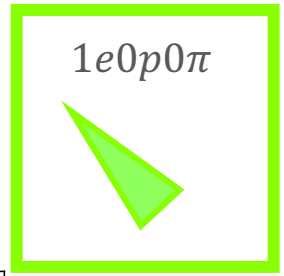
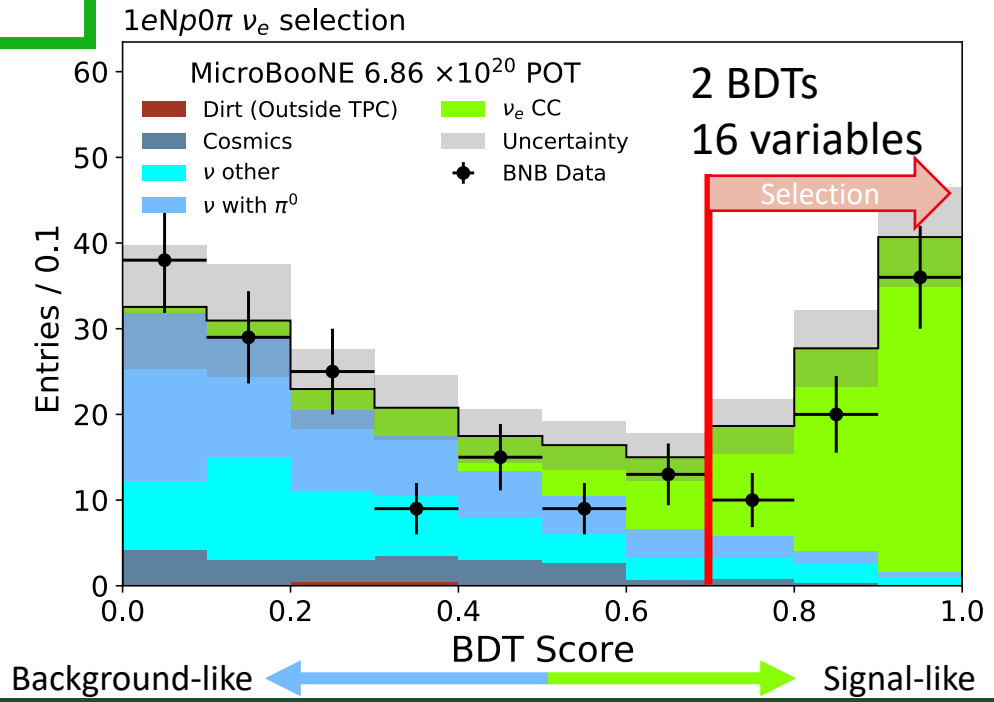
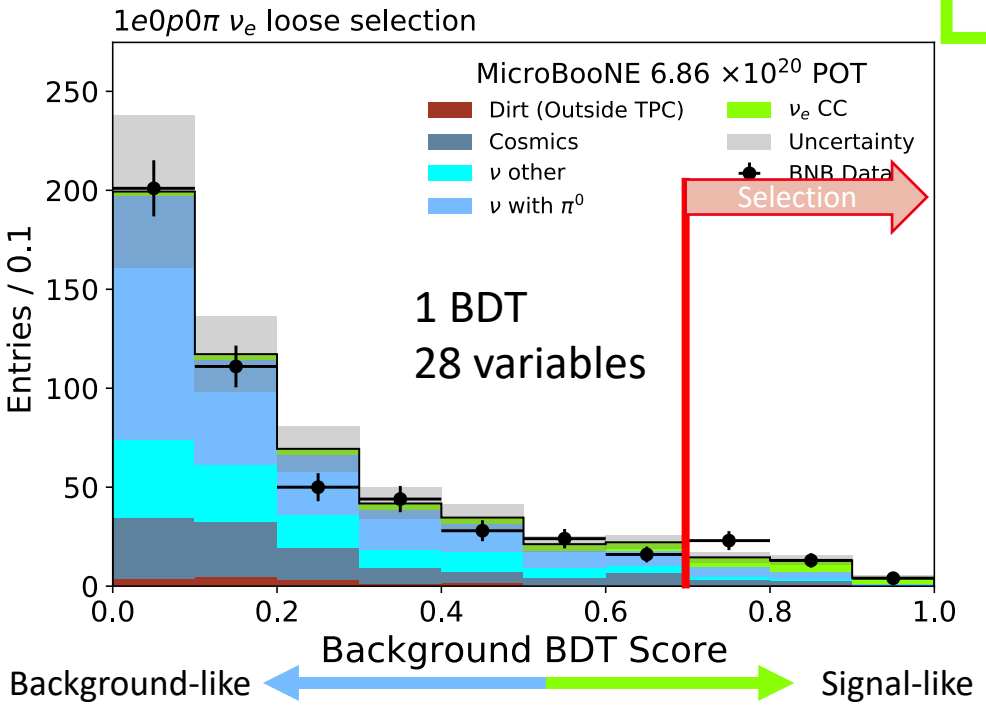
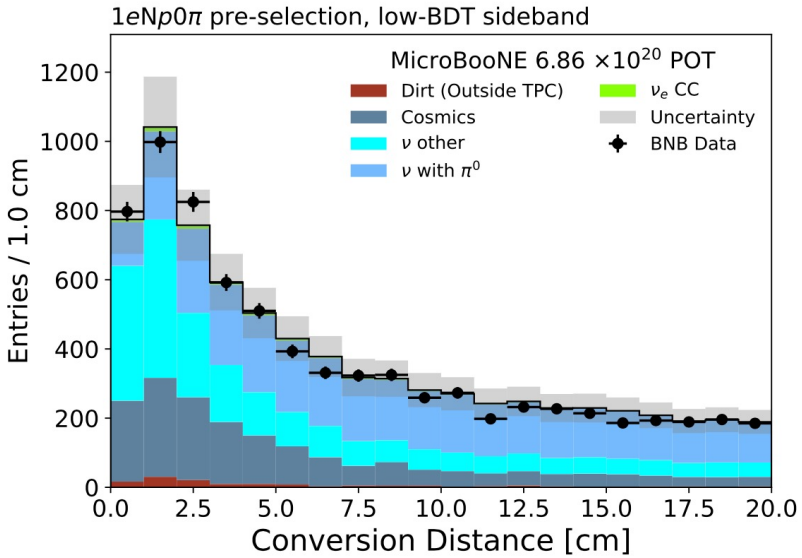


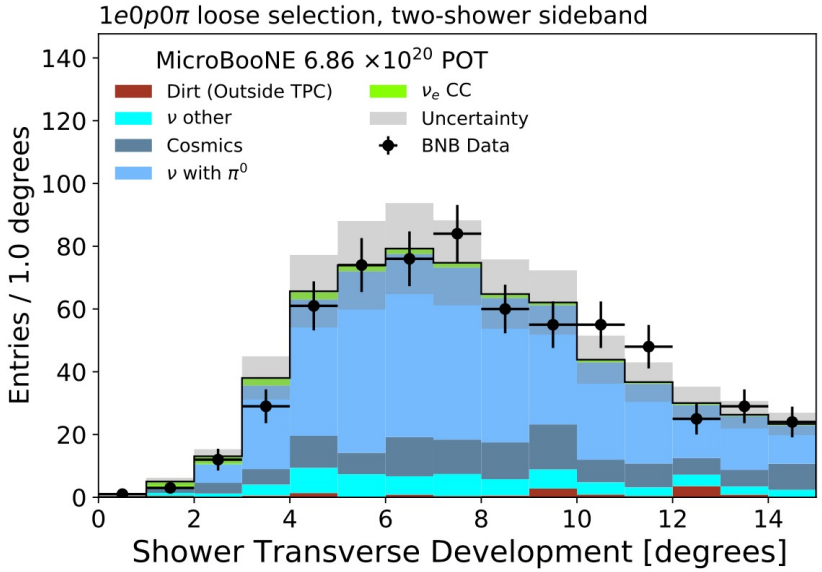




Sidebands: Background Validation

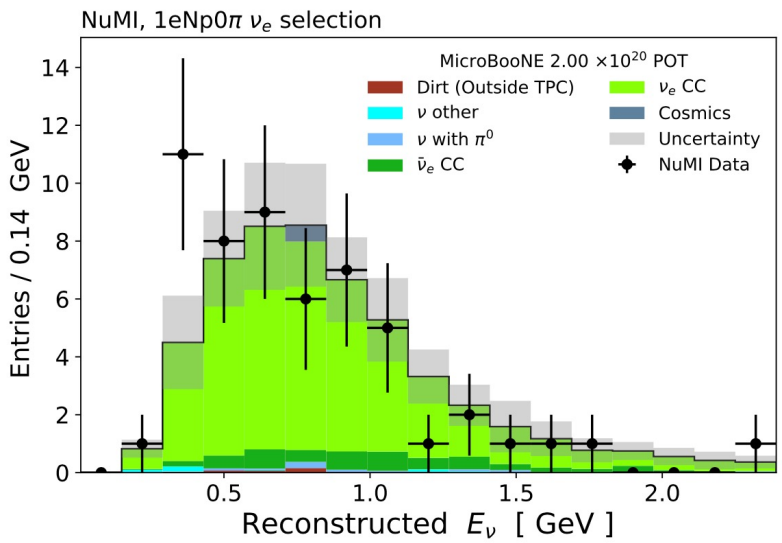
- Blind analysis: Use data that is not in the signal region to validate analysis
- Background rich samples: Low-BDT and two shower sidebands
  - Good data-simulation agreement of selection variables

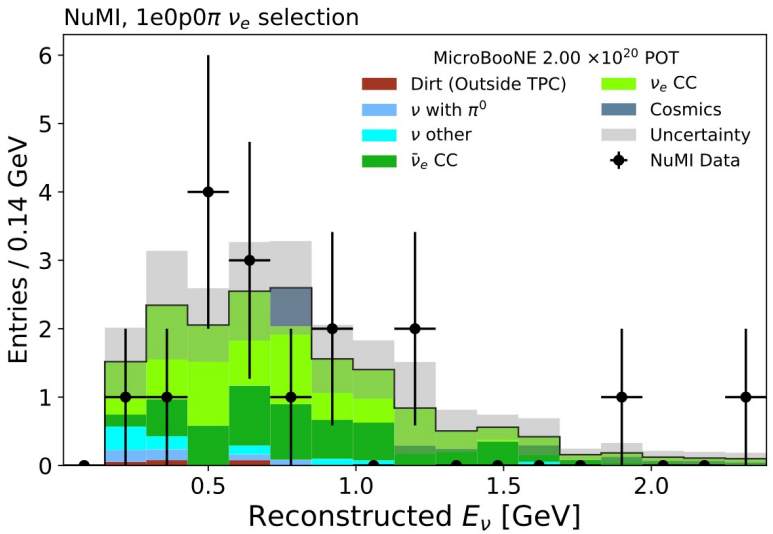




Sidebands: NuMI

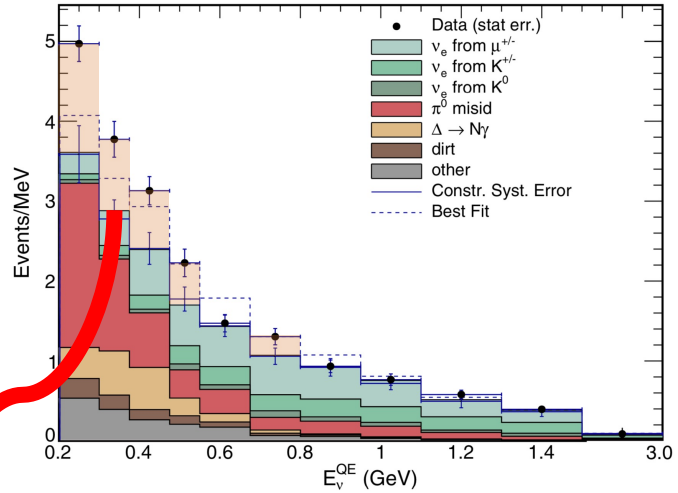
- Blind analysis: Use data that is not in the signal region to validate analysis
- Background rich samples: Low-BDT and two shower sidebands
  - Good data-simulation agreement of selection variables
- NuMI samples:
  - Hight intrinsic ν_e relative to BNB
  - Selections not tuned on NuMI data: applied after frozen, before unblinding BNB data

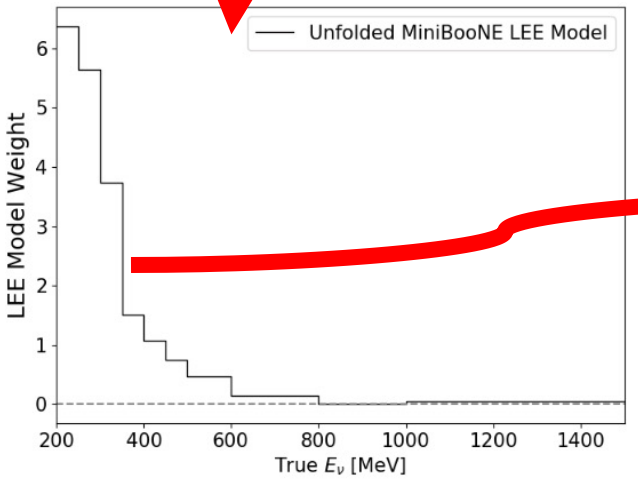


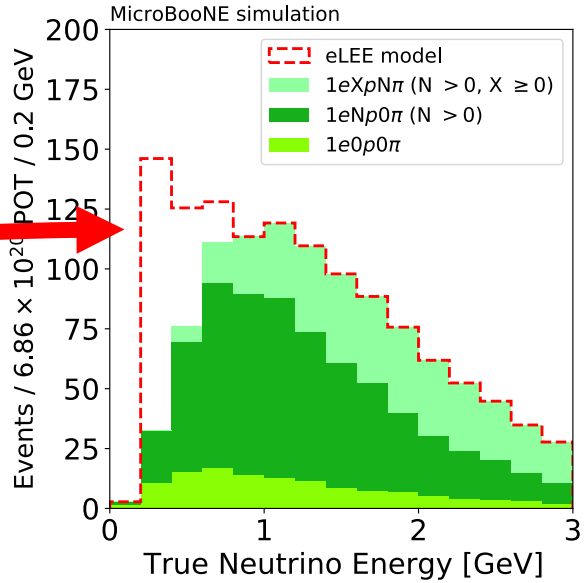


Electron Search: Excess Model

- Unfold MiniBooNE excess under a ν_e hypothesis
  - Only considers E_ν dependence
- Apply scaling to MicroBooNE intrinsic ν_e component

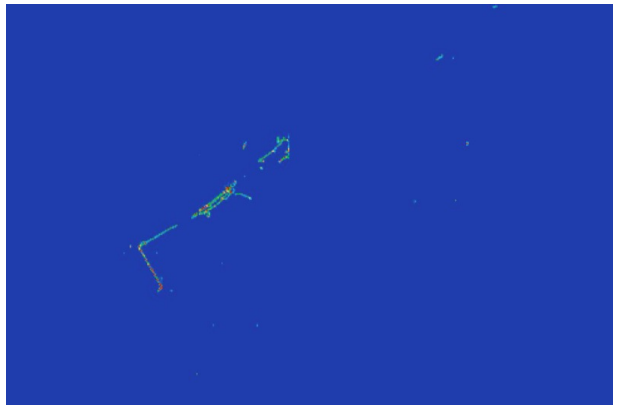




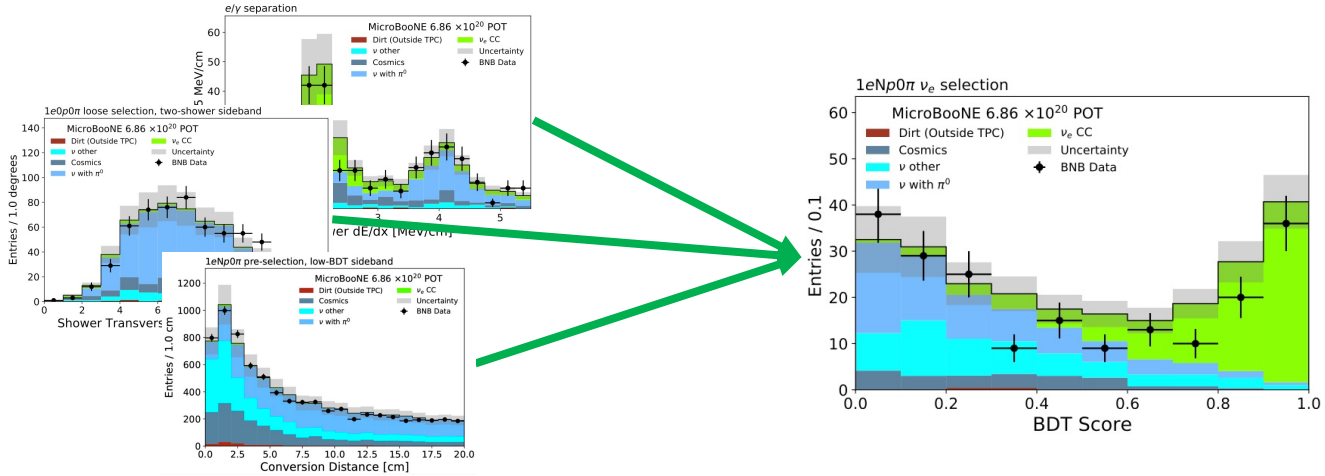


Analysis Strategy

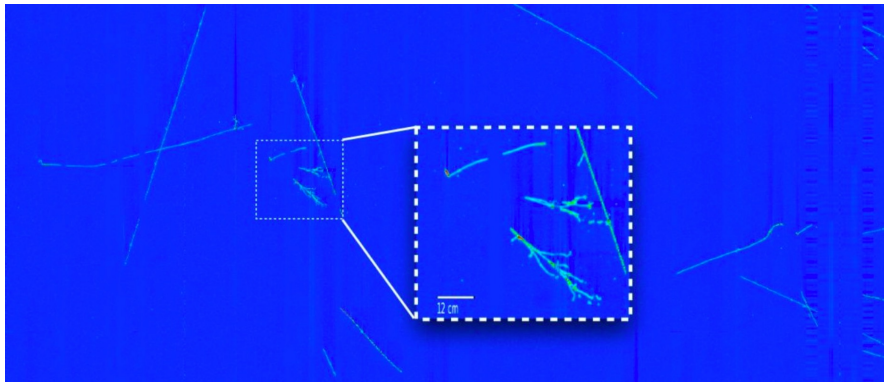
1) Event Reconstruction



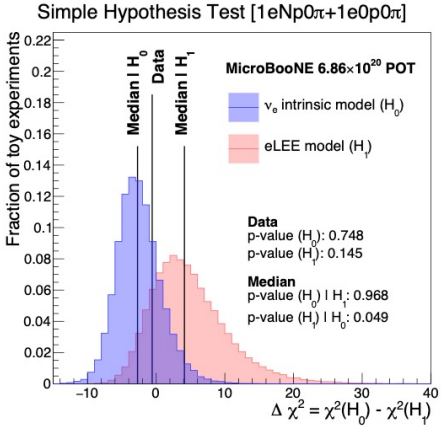
3) Variable creation and Event Selection

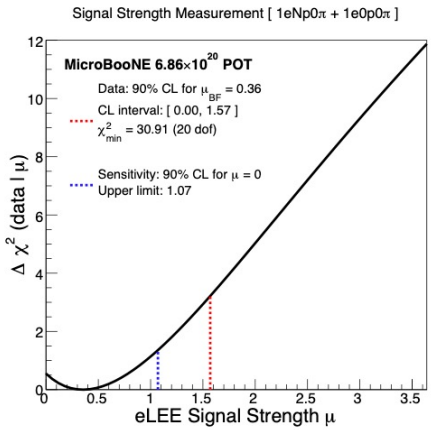


2) Neutrino Event Identification and Characterization



4) Statistical Analysis and Signal Strength Measurement



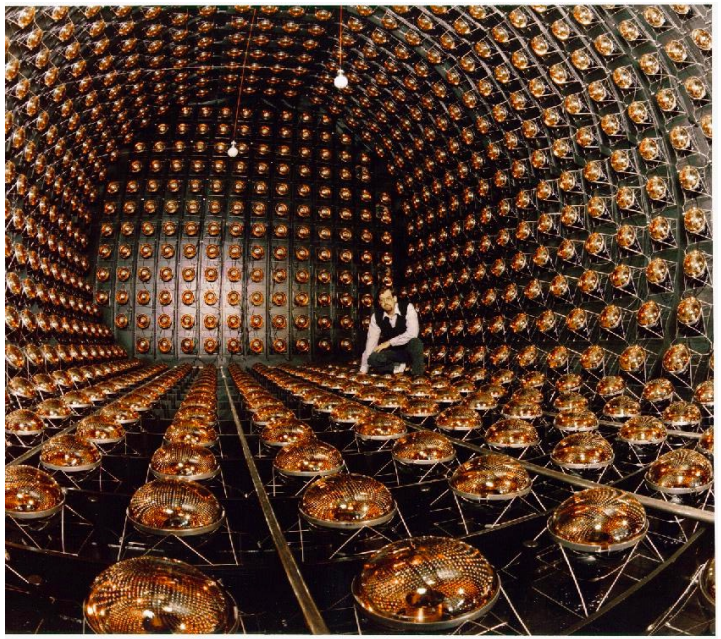


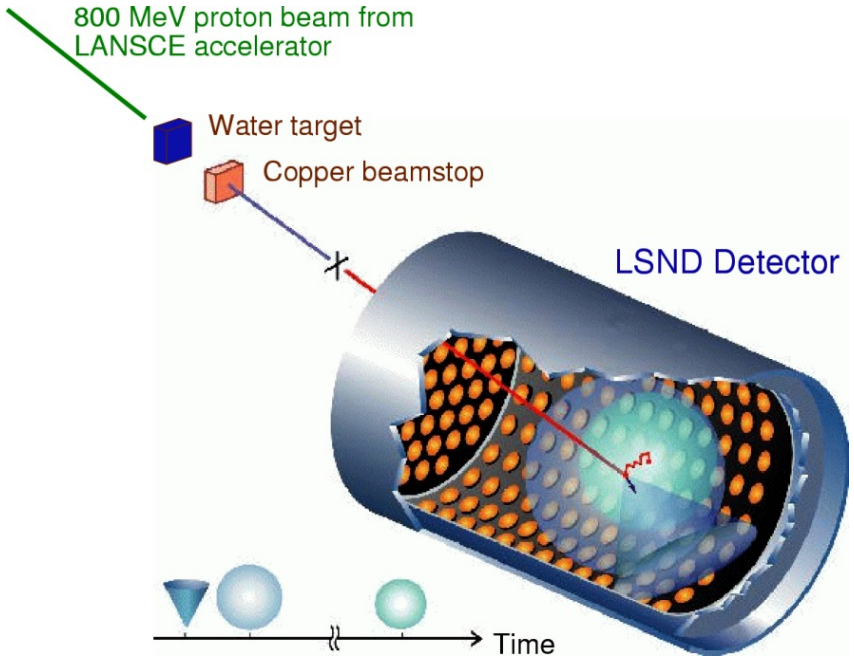
Anomalies at Short Baselines

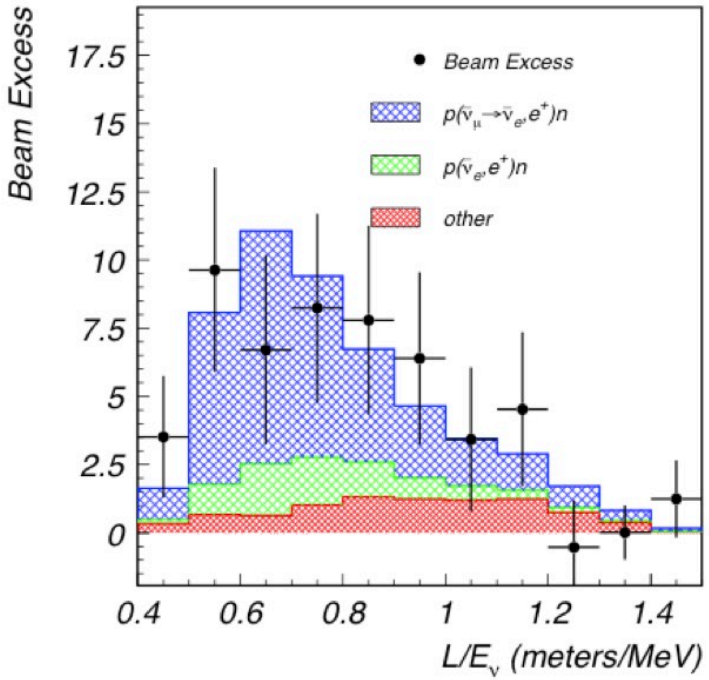
LSND

- Cherenkov detector
- Measure neutrino oscillations
- Observed a possible 3.8σ excess of $\overline{\nu_e}$-like events
  - ➢ $\overline{\nu_\mu} \rightarrow \overline{\nu_e}$ oscillation could be associated to potential sterile neutrinos

$$\overline{\nu_\mu} \xrightarrow{\text{oscillation}} \overline{\nu_e} + p \rightarrow e^+ + n$$
$$\mathrm{n} + p \rightarrow d + \gamma$$



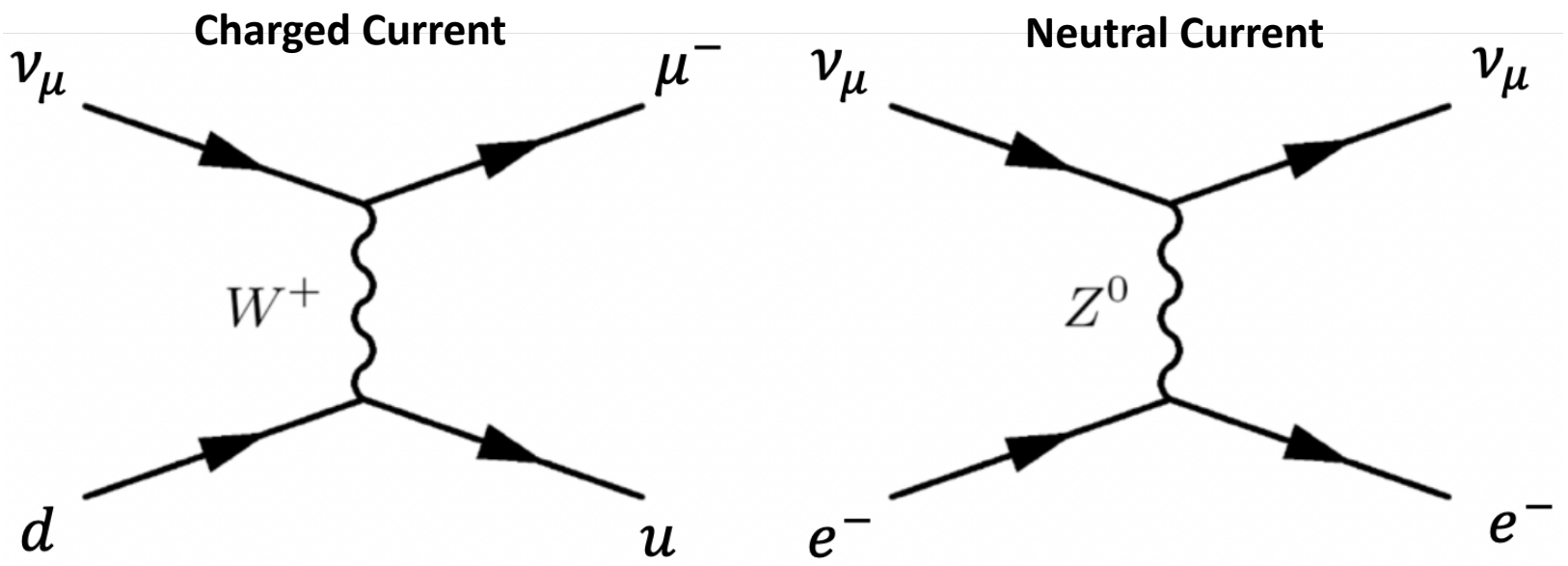




PRD 64, 112007 (2001)

Neutrinos Interactions

- In the Standard Model, neutrinos are created and detected via weak interactions mediated by the *W* and *Z* bosons
  - Charged current interactions are mediated by the *W* boson
  - Neutral current interactions are mediated by the *Z* boson
- Charged current interactions couple the neutrinos to their charged lepton counterparts

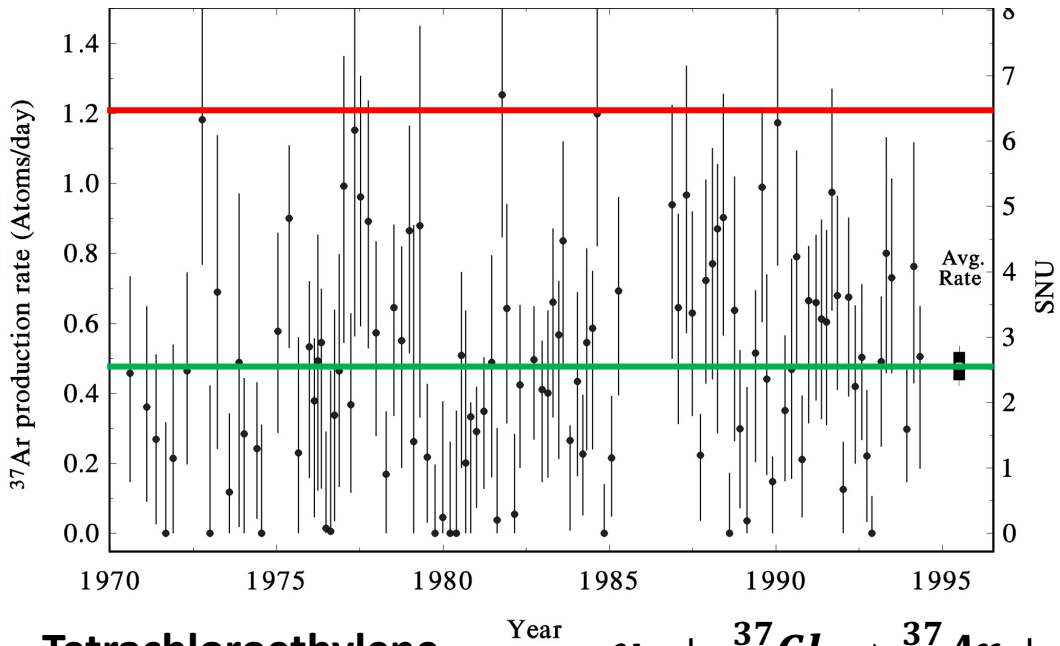


Neutrino Oscillations

- Neutrinos oscillate between different flavors in flight
- First observed by the Homestake experiment in the 60's
- Oscillations confirmed by Super-Kamiokande in the 90's

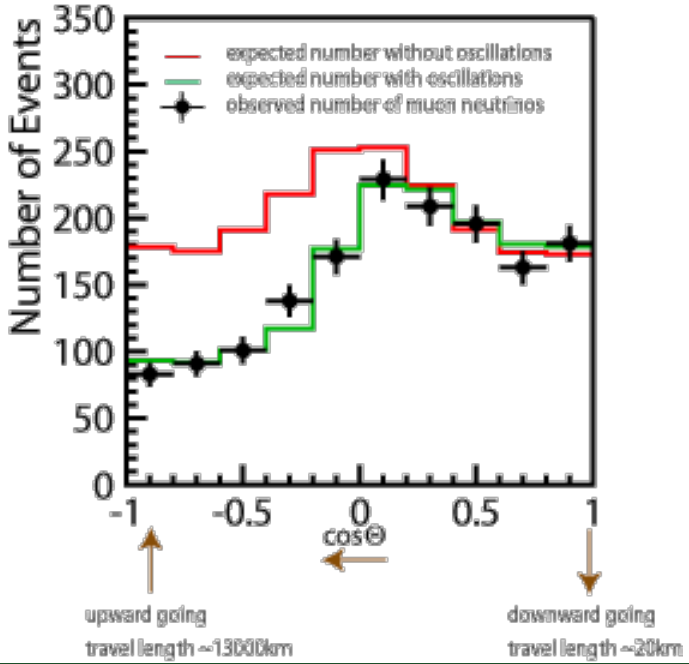
Legend
Expected
Measured

Electron Neutrinos from the Sun
Homestake Experiment – 1960's



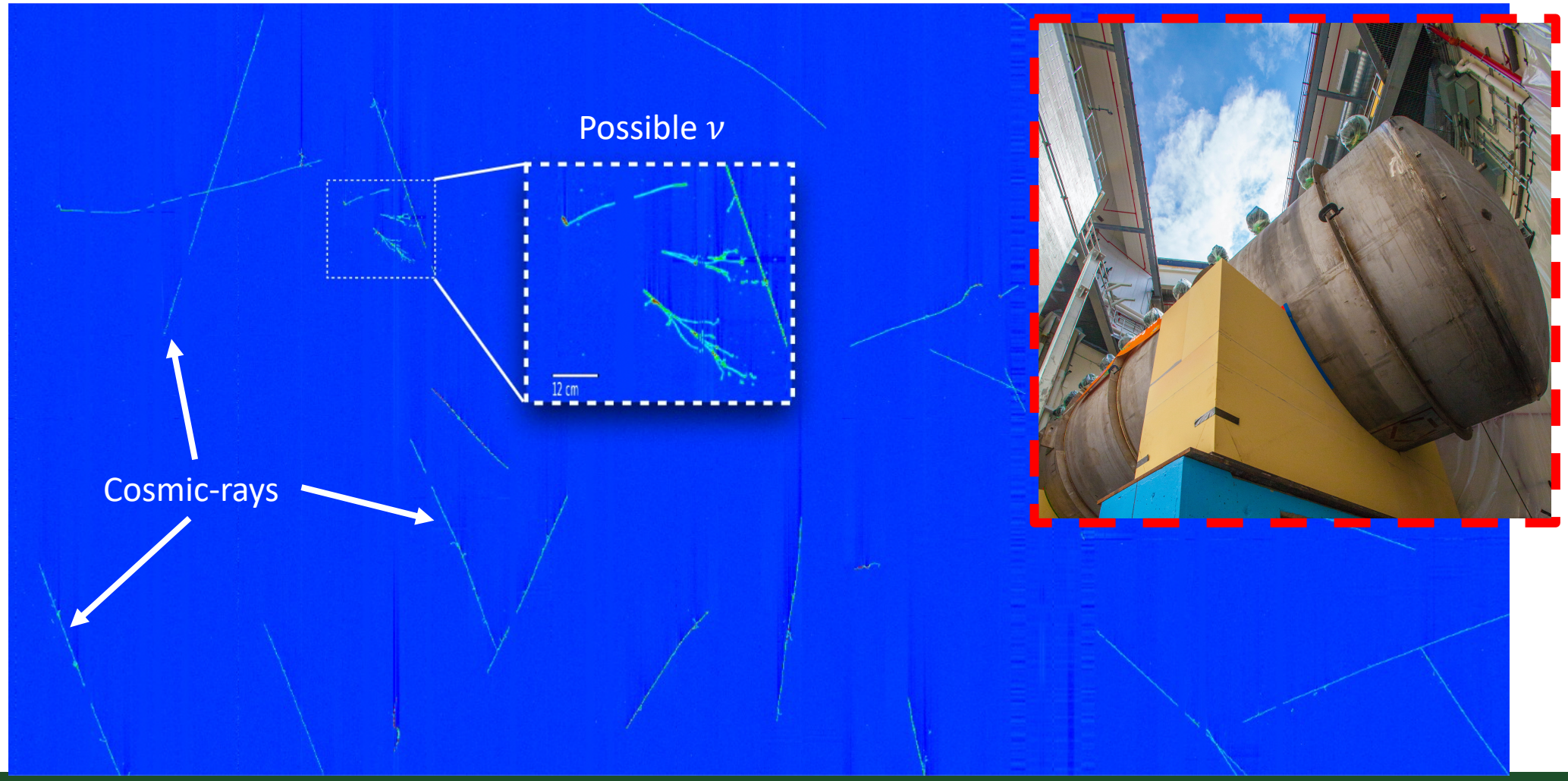
Tetrachloroethylene $\nu_e + {}^{37}Cl \rightarrow {}^{37}Ar + e^-$

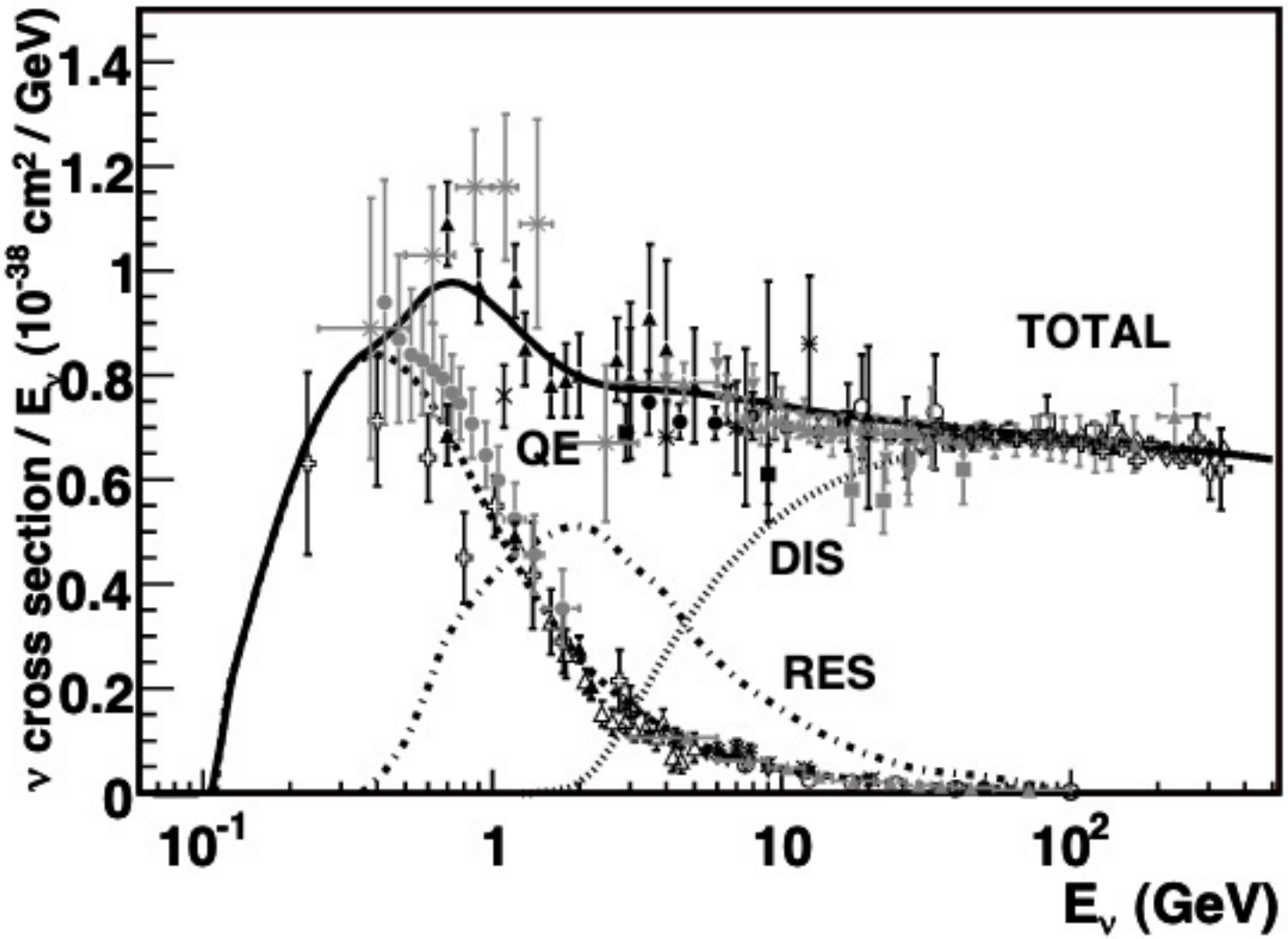
Muon neutrinos from the atmosphere
Super-Kamiokande - 1998



On the Surface Detector

- Surface LArTPC + slow e- drift → large cosmic background
- O(10) cosmic rays/event




ν cross section / E_ν (10^-38 cm^2 / GeV)
1.4
1.2
1
0.8
0.6
0.4
0.2
0
10^-1
1
10
10^2
E_ν (GeV)
TOTAL
QE
DIS
RES

Signal Processing Chain

Drifting Electrons

Field Response

Signal on Wire

Electronics Response

Shaped/Amplified Signal

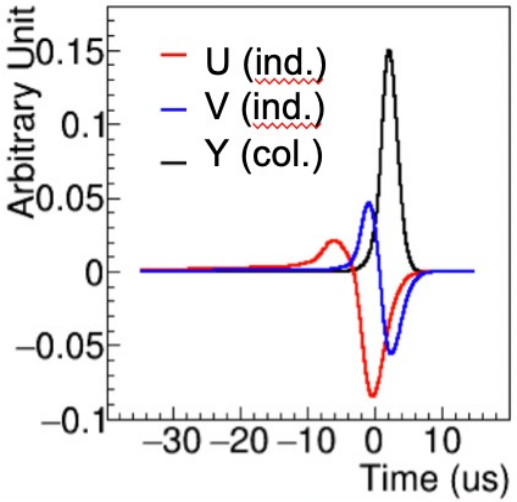
Digitization

Signal Data Acquisition

Deconvolution

Extraction of Charge from Signal

Response Functions (Field + Electronics)

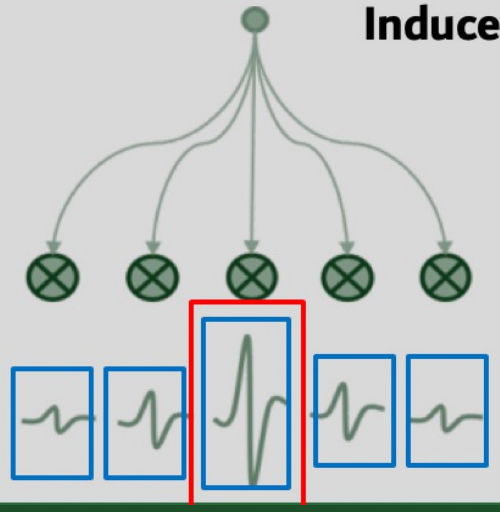


Signal Deconvolution

$$\textit{Estimated Sig} = \frac{\textit{Measured Sig.}}{\textit{Resp. Func.}} * \textit{Filter Func.}$$

Frequency Domain

Induced Signals on Neighboring Wires



- **1D Deconvolution:** Time Domain
- **2D Deconvolution:** Time AND Wire Domain