Status of the MicroBooNE Low-Energy Excess Search

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Nevis Laboratories
Columbia University

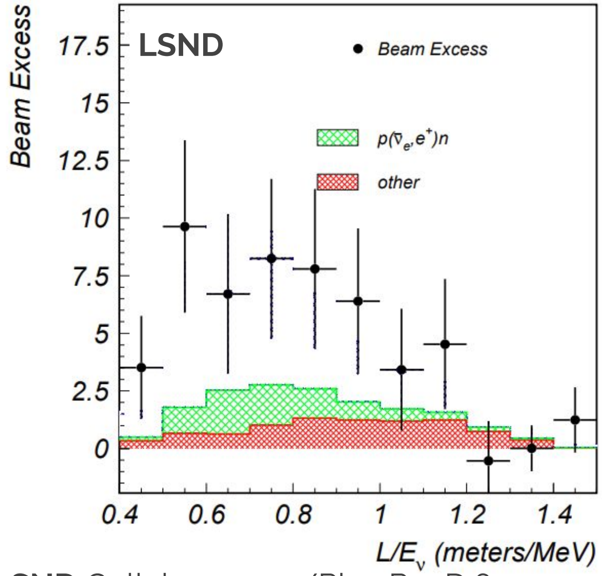
Fermilab

NSF

μBooNE

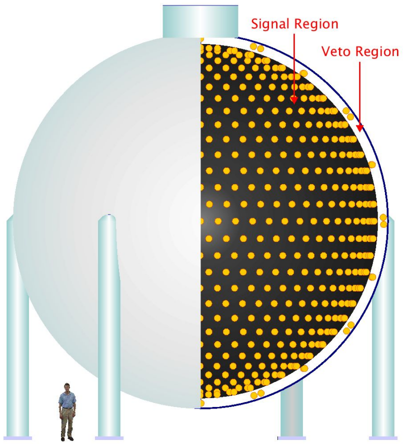
Overview of LSND and MiniBooNE

In 1995, **LSND** published **evidence for neutrino oscillations** between $\overline{\nu}_\mu$ to $\overline{\nu}_e$ corresponding to a 2ν neutrino mass splitting of **$\Delta m^2 \sim 1$ eV²**, using neutrinos from decay-at-rest μ^+. In conjunction with the known Δm^2_{ATM} and Δm^2_{SOL} mass splittings, this interpretation would require the existence of a **4th, sterile, neutrino.**



LSND Collab: 10.1103/PhysRevD.64.112007

MiniBooNE Detector



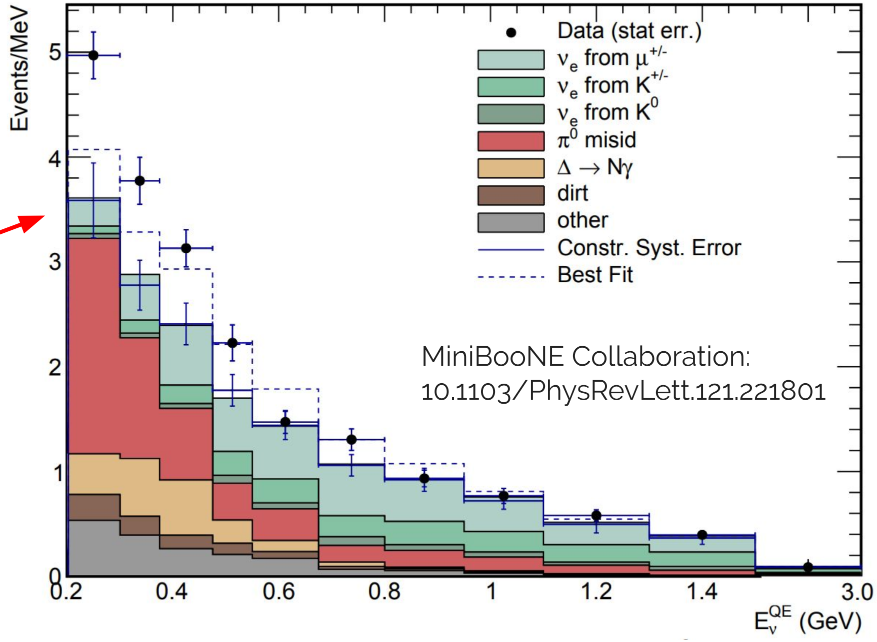
The **MiniBooNE** experiment was designed to probe the **same L/E_ν**, albeit with different baseline (L~500m) and different neutrino energy (E~800 MeV).

Sitting in the Fermilab Booster Neutrino Beam (BNB), MiniBooNE has collected data for ~17 years from 2002 until 2019, with intermediate neutrino and antineutrino mode running.

MiniBooNE Results

A low-energy excess (**LEE**) predominately below 600 MeV reconstructed neutrino energy

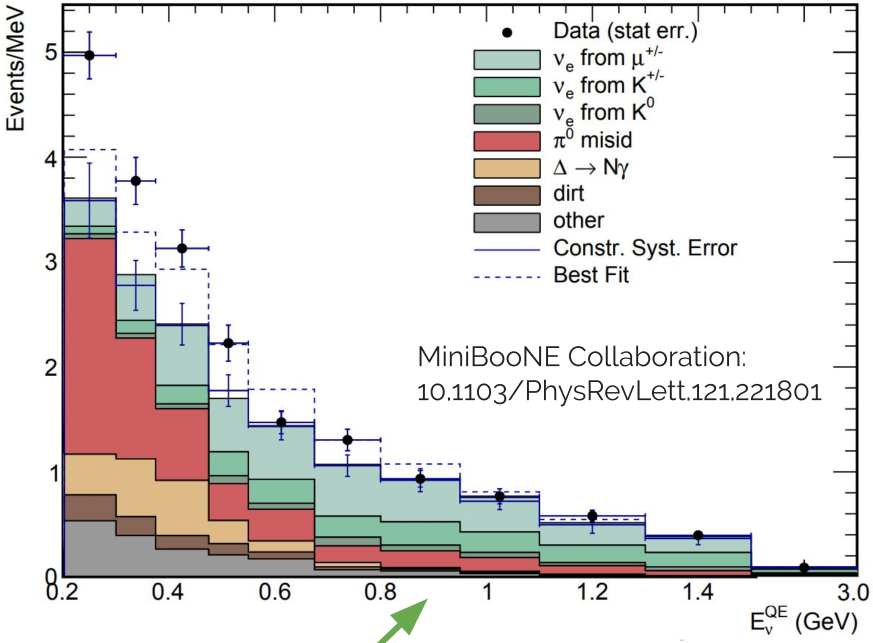
4.5σ significance when combining all neutrino mode data



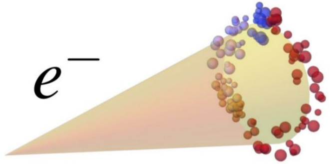
MiniBooNE Collaboration: 10.1103/PhysRevLett.121.221801

Backgrounds to ν_e appearance

MiniBooNE was a 12.2m tank of mineral oil (CH²) that used the **cherenkov light** of charged particles to detect neutrino interactions. Backgrounds can roughly be split into 2 categories:



At higher energies, where the LSND best fit point would be expected to give a large signal, backgrounds are **dominated by true electrons** originating from **intrinsic ν_e** in the BNB (three **green** histograms)

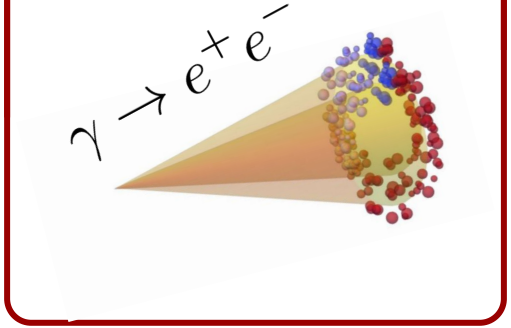


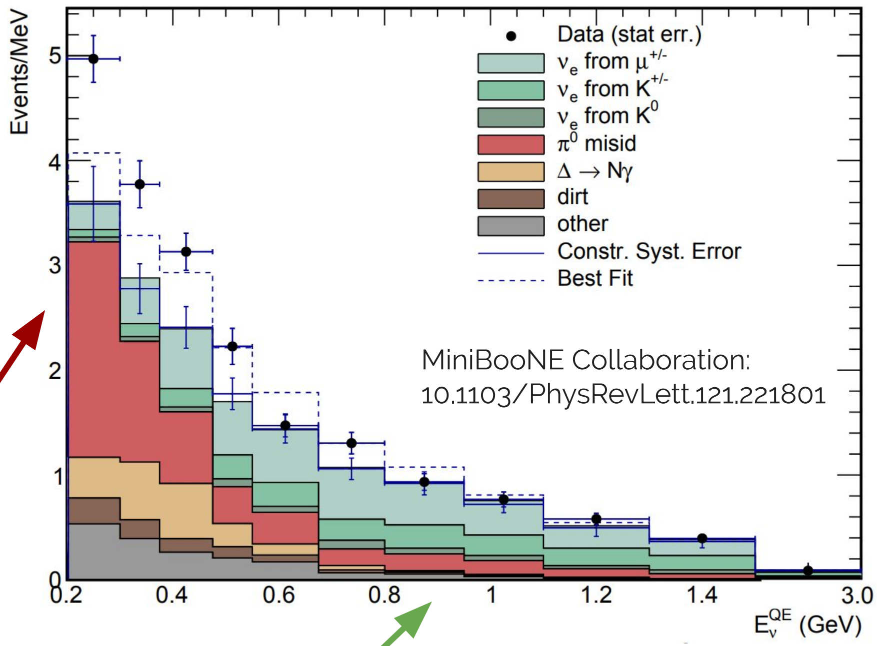
Backgrounds to ν_e appearance

MiniBooNE was a 12.2m tank of mineral oil (CH^2) that used the **cherenkov light** of charged particles to detect neutrino interactions. Backgrounds can roughly be split into 2 categories:

At **lower reconstructed neutrino energies**, **photon backgrounds** such as NC π^0's (**red**) and Δ radiative decay (**tan**) start to become dominant.

Photons pair-producing tightly collimated e^+e^- pairs produce Cherenkov cones indistinguishable from that of a single electron in MiniBooNE





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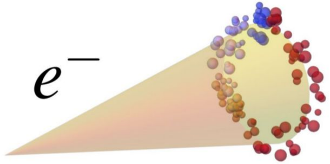


Enter MicroBooNE

MicroBooNE is an 89-ton surface based Liquid Argon Time Projection Chamber (LArTPC) that has been collecting data in the same Fermilab BNB since Autumn 2015.

One of its **primary goals** is to definitively identify if the origin of the observed MiniBooNE Low Energy Excess **(LEE)** is **due to electrons** or **photons.**

This can be achieved due to LArTPC's **excellent spatial resolution and calorimetry**

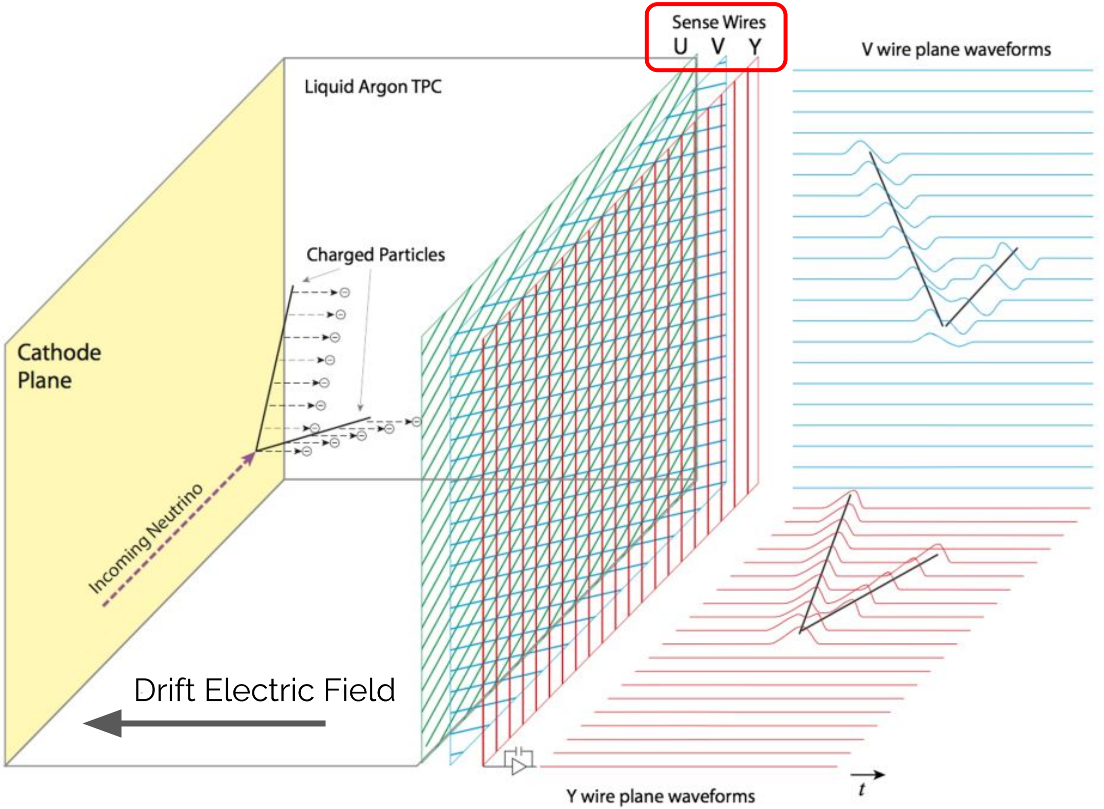


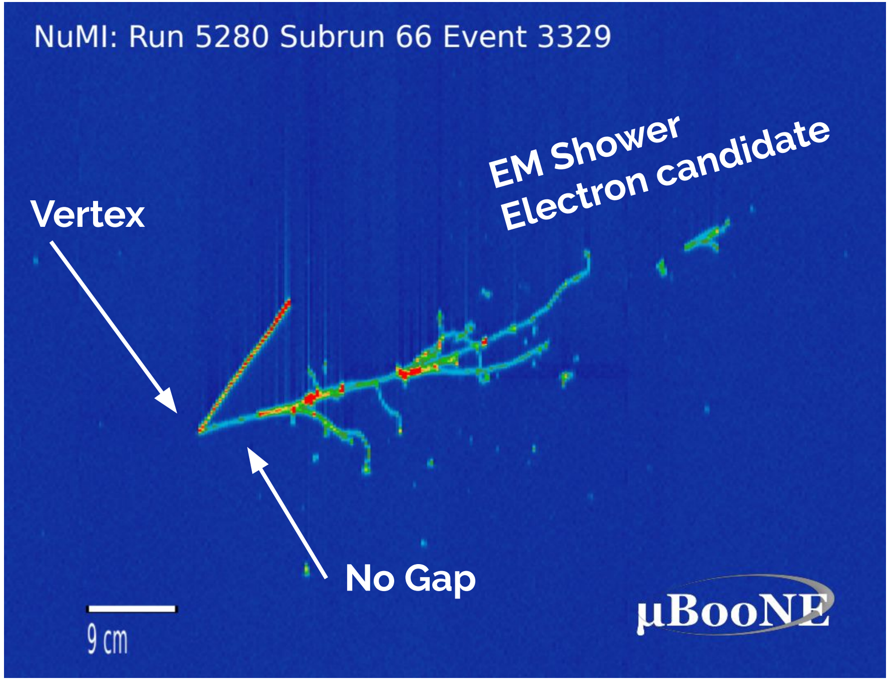
Figure 2 in JINST 12 P02017

For further details and the working principles of the MicroBooNE Detector itself and latest publications, see Adrien Houlier's talk on Tuesday [LINK]

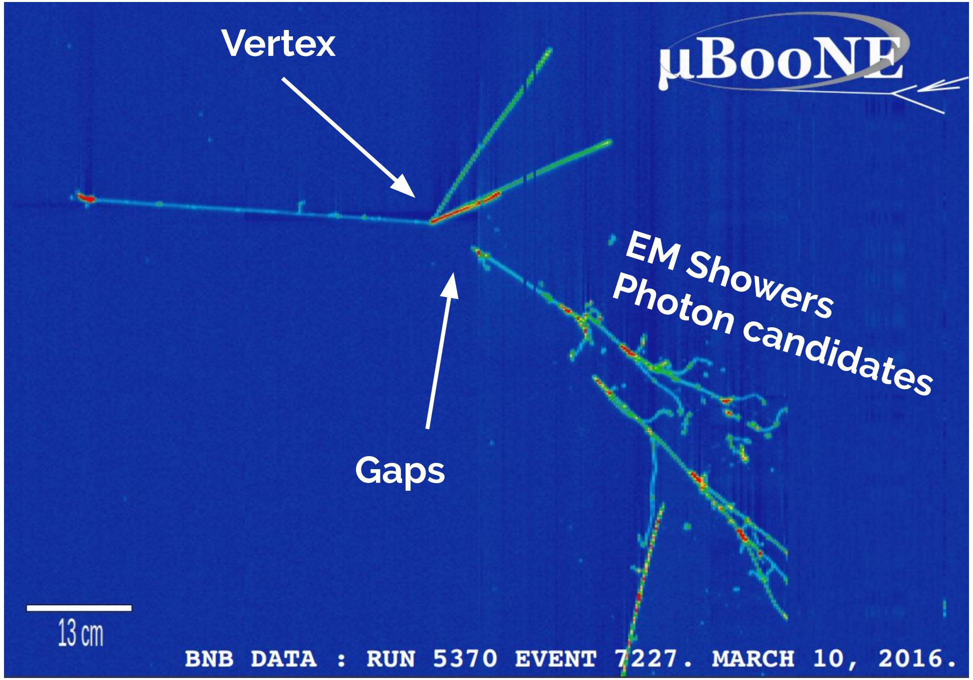
Spatial Resolution: Photon Conversion Distance

LArTPC's are like a **digital bubble chamber.** In argon photons travel with a mean free path of ~15cm before pair converting, and as the photons are neutral this appears as a distinct gap.

ν_e CC candidate in NuMI data



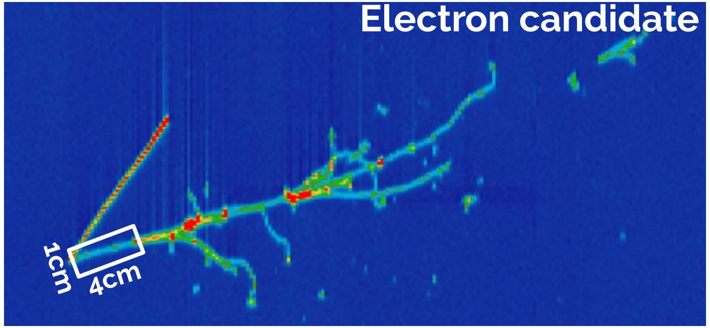
CC π^0 candidate in BNB data

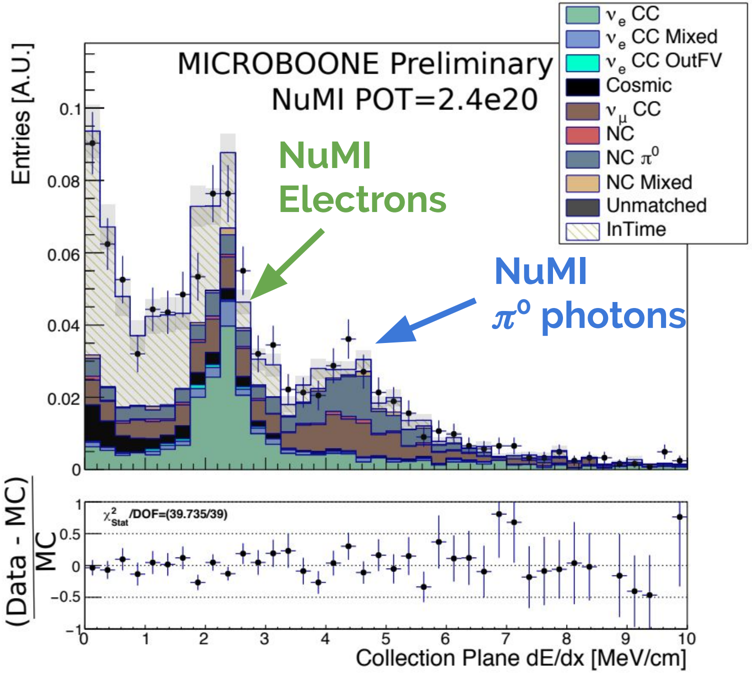


Calorimetry: Electromagnetic Shower dE/dx

The amount of energy deposited per unit length in the trunk (first 4cm) of the Electromagnetic shower:

- **Electrons** are one Minimally ionizing particle (MIP) ~ 2 MeV/cm
- Where as **photons** pair convert to produce an aligned e^+e^- pair, which are two MIPs: ~4 MeV/cm





Example of shower dE/dx for candidate CC ν_e events in the NuMI beam at MicroBooNE

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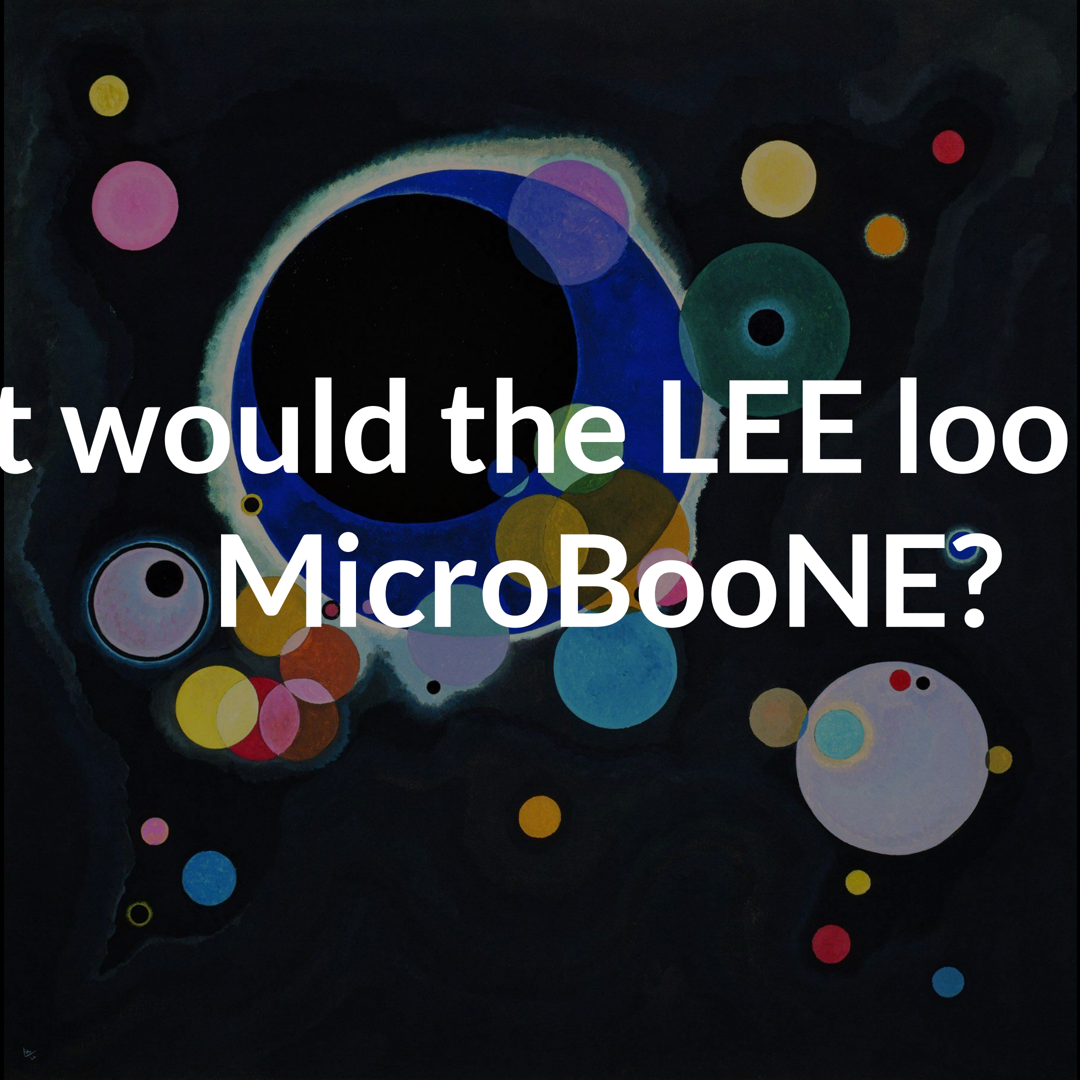
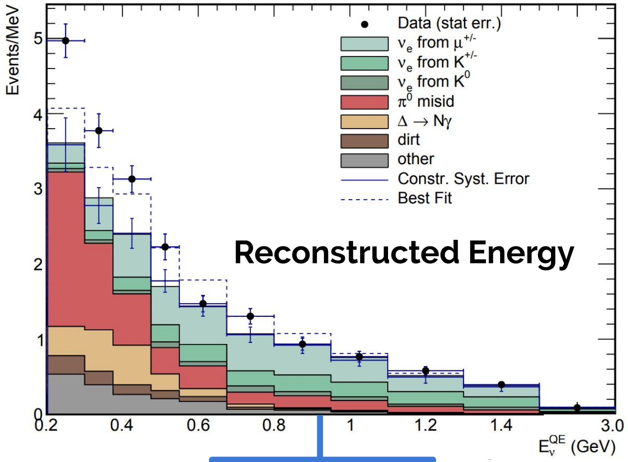
What would the LEE look like in MicroBooNE?



Unfolding the MiniBooNE Observed Excess



Unfolding

Remove
Detector Smearing,
Reconstruction Effects,
Analysis Selections,
..etc..

Use the MiniBooNE MC simulations to form a response matrix, and given an underlying signal hypothesis, use **SVD unfolding** and **D'Agostini's iterative method** to map to true underlying variables

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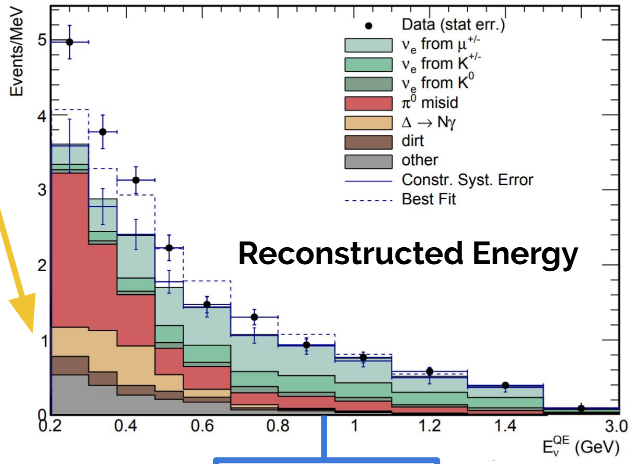
Unfolding results for a photon hypothesis

Assuming the LEE is due to an increase in the rate of **NC resonant Δ with subsequent radiative decays**



Unfolding

Remove
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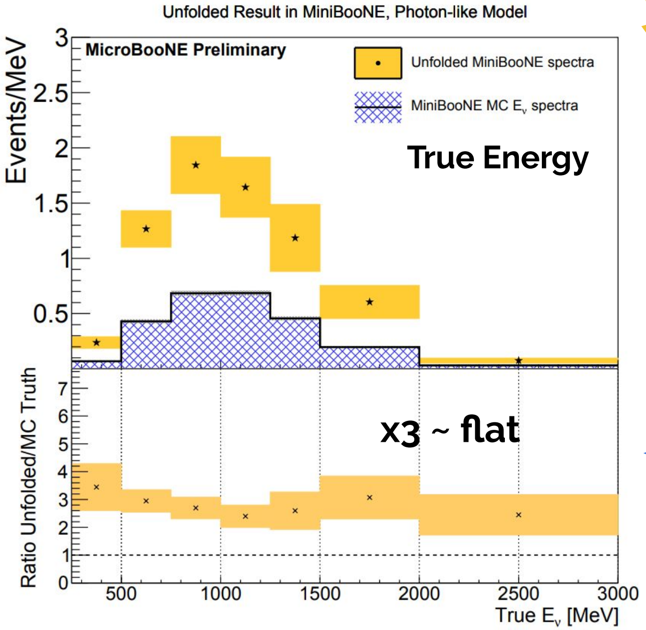
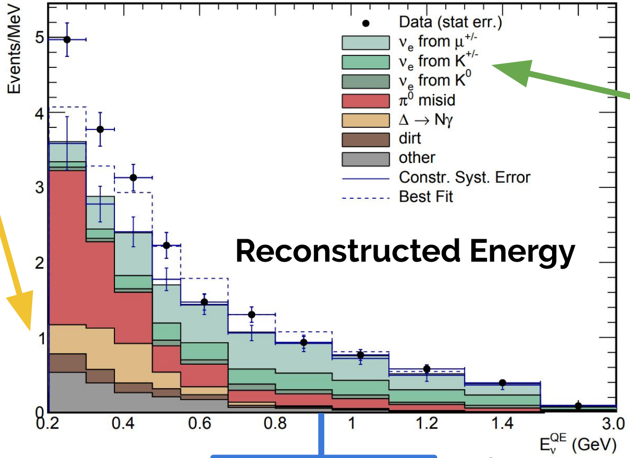


Unfolding results for an electron hypothesis

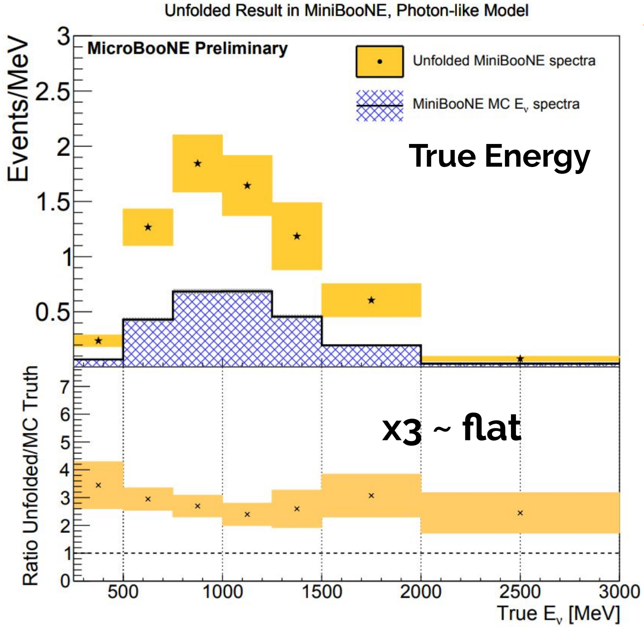
Assuming the LEE is due to an increase in the rate of **NC resonant Δ with subsequent radiative decays**

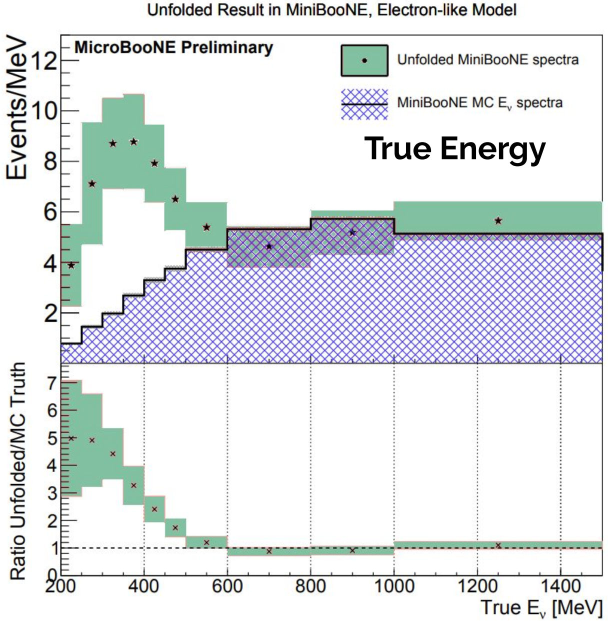


Assuming the LEE is due to an energy dependant **increase in the rate of CC ν_e** events

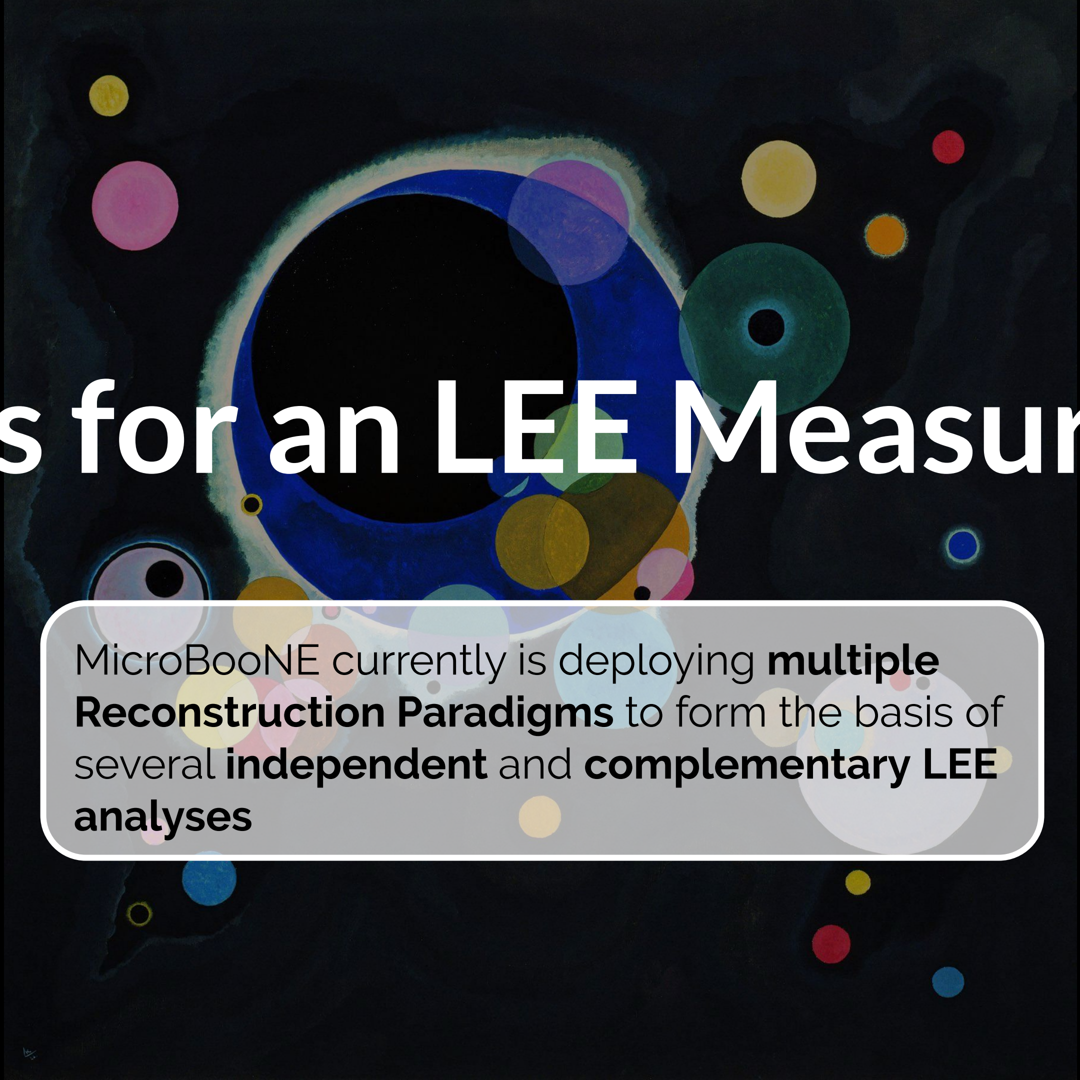
Unfolding

Remove
Detector Smearing,
Reconstruction Effects,
Analysis Selections,
..etc..





Tools for an LEE Measurement



MicroBooNE currently is deploying **multiple Reconstruction Paradigms** to form the basis of several **independent** and **complementary LEE analyses**

Multiple Complementary Reconstruction Frameworks and Analysis topologies

Topology	Reconstruction Framework
1e1p	**Deep-Learning**
1eNp	**Pandora**
ν_e Inclusive	Pandora
ν_e Inclusive	Wire-Cell
1γ1p	**Pandora**
1γ0p	Pandora

Electron Analyses (first four rows)

Photon Analyses (last two rows)

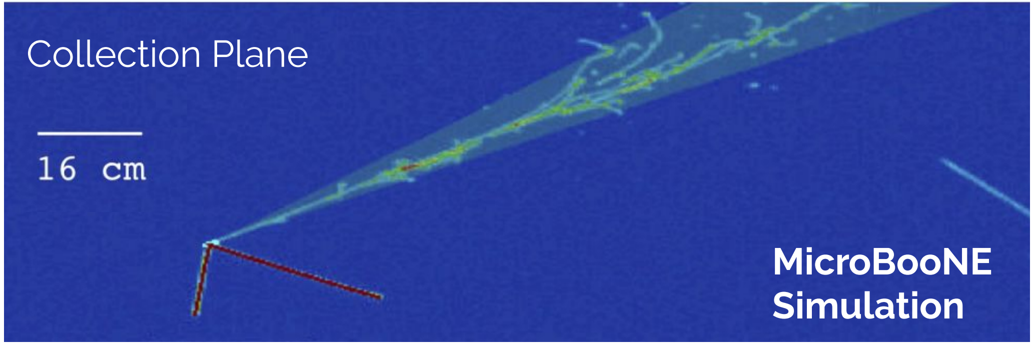
All LEE analyses at MicroBooNE are **blind**, with only 5e19 POT of data currently open for testing and comparison (~4% out of a total 13.2e20 POT in full data set)

This **multiple topology approach** is crucial robustness of results and for testing different LEE hypothesis.

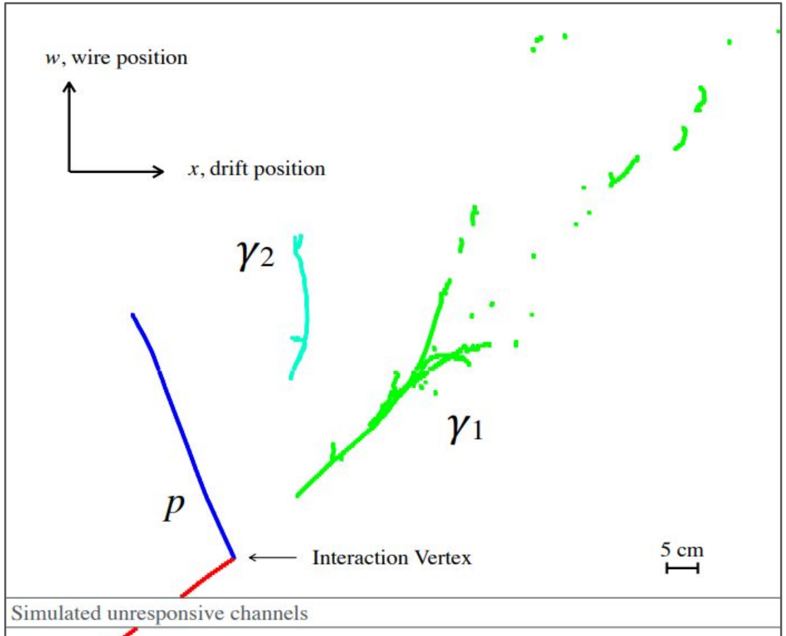
Pandora Multi-Algorithm Pattern Recognition

First **clusters reconstructed hits in 2D** independently on each plane of the TPC, then match in time across all planes to form 3D tracks and showers. Has seen significant use and development in the LArTPC community

1eNp Signal Topology



Simulated ν_e 1e2p event showing a classic electromagnetic shower due to electron, reconstructed with the Pandora framework MICROBOONE-NOTE-1038-PUB



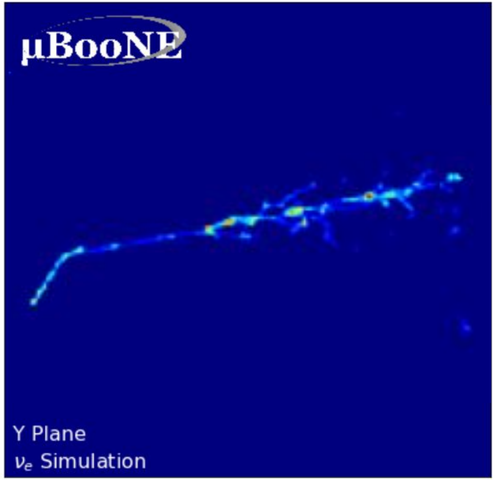
Eur. Phys. J. C (2018) 78: 82.
https://arxiv.org/abs/1708.03135

The reconstruction of a simulated 1.4-GeV CC ν_μ interaction with resonant neutral-pion production

Deep Learning Image Based Reconstruction

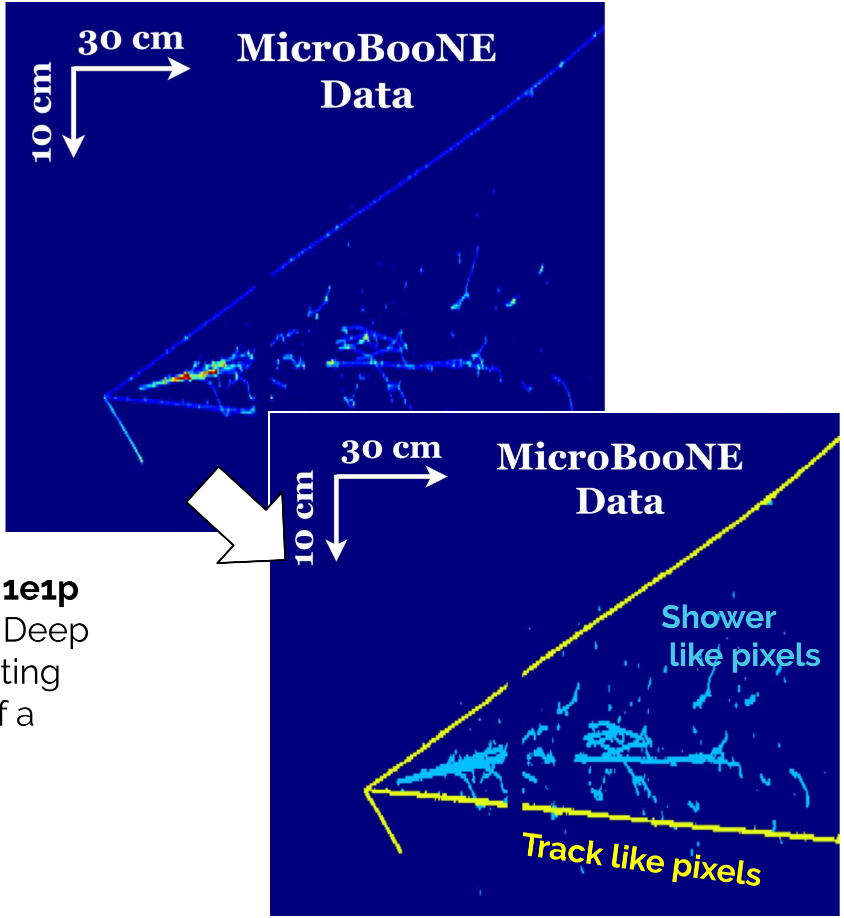
An image based analysis that uses **Convolutional Neural Networks (CNN)** in both particle identification as well as classification of individual pixels as shower-like or track-like

1e1p Signal Topology



	Proton	Electron	Gamma	Muon
MPID Score	0.74	0.92	0.23	0.35

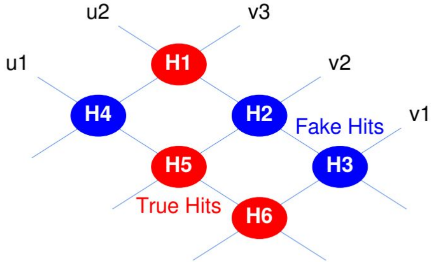
[*Left*] A simulated low energy **1e1p** event reconstructed with the Deep Learning framework, highlighting the **multi-particle ID score** of a custom CNN



10.1103/PhysRevD.99.092001, JINST 12, P03011 (2017)

Wire-Cell Tomographic Reconstruction

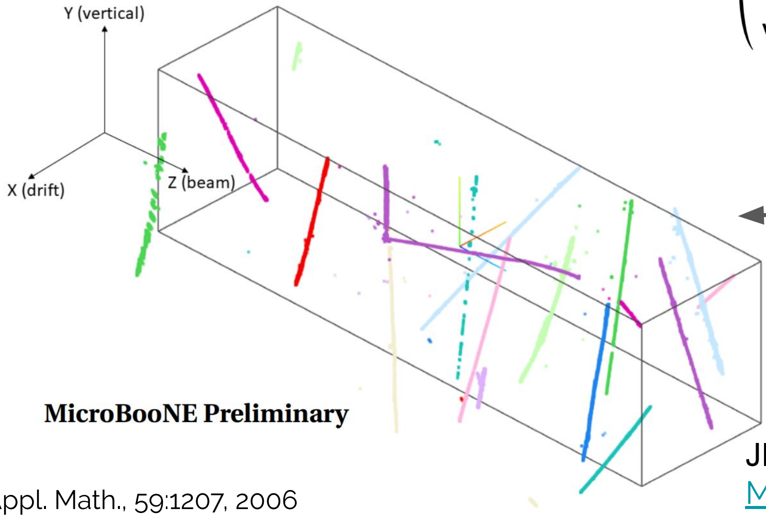
Directly reconstruct in 3D using techniques of **Tomography**. Ambiguities in 3D reconstruction due to missing information can be mitigated by using **charge information** and the technique of **compressed sensing*** well known in computer science and statistics fields.



Measured charge on wires

Solve for true hits

$$\begin{pmatrix} u1 \\ u2 \\ v1 \\ v2 \\ v3 \end{pmatrix} = \begin{pmatrix} 0 & 0 & 0 & 1 & 1 & 1 \\ 1 & 1 & 1 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 & 1 \\ 0 & 1 & 0 & 0 & 1 & 0 \\ 1 & 0 & 0 & 1 & 0 & 0 \end{pmatrix} \cdot \begin{pmatrix} H1 \\ H2 \\ H3 \\ H4 \\ H5 \\ H6 \end{pmatrix},$$

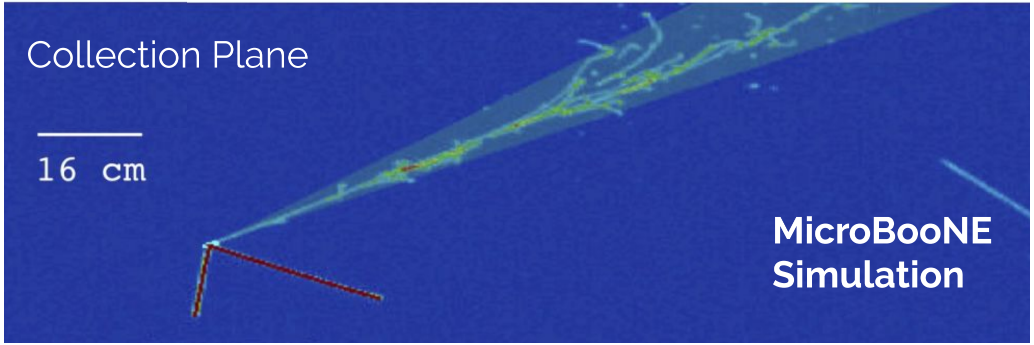


JINST 13, P05032 (2018)
MICROBOONE-NOTE-1040-PUB

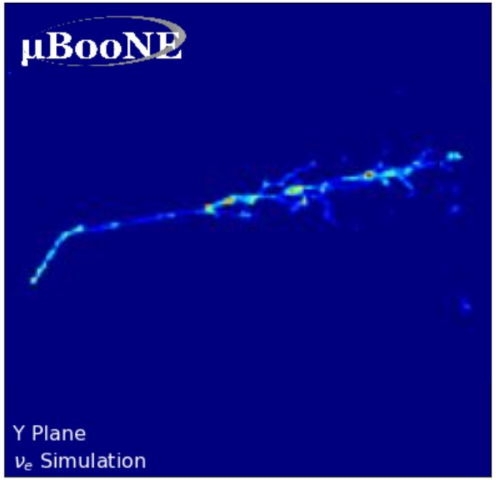
*E. J. Candès, J. K. Romberg, and T. Tao. Comm. Pure Appl. Math., 59:1207, 2006

CC ν_e LEE Analyses

1eNp Signal Topology



1e1p Signal Topology



1e1p and 1eNp Backgrounds

There are several **potential backgrounds** to such a search:

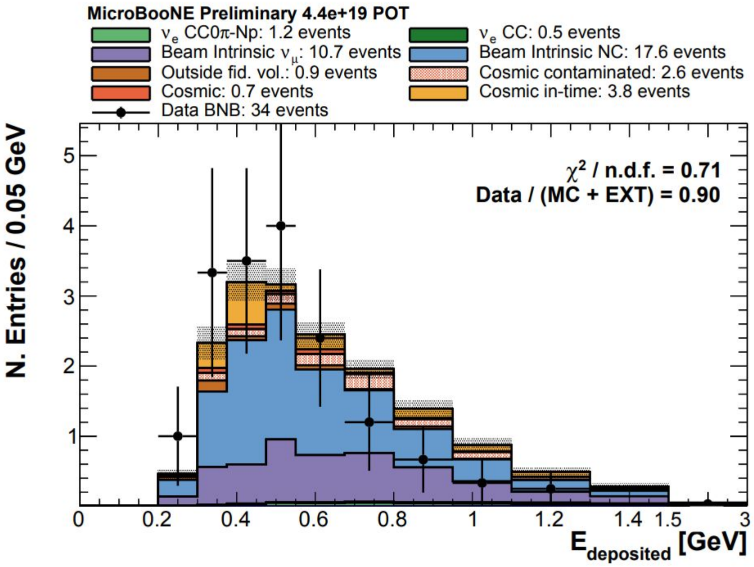
- **NC π^0 events** in which one photon converts quickly and one photon is missed.
- Low energy **CC ν_μ events** can mimic electrons, as very low energy electrons do not have the same extent of characteristic EM showering
- An irreducible background in the form of the **intrinsic ν_e component** of the Booster neutrino beam.

Need to **study sidebands** to ensure these backgrounds are well modelled in our Monte Carlo!

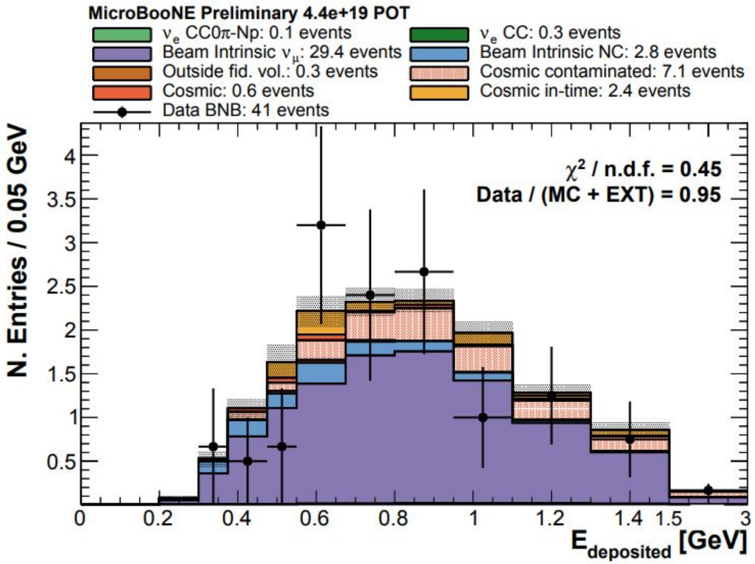
Sideband checks in place to ensure backgrounds understood

Sidebands constructed by reversing cuts tailored to remove the specific backgrounds

π^0 Enhanced Sideband



CC ν_μ Enhanced Sideband



Pandora 1eNp analysis: MICROBOONE-NOTE-1038-PUB

Constraining Systematics of Irreducible Backgrounds

The **intrinsic ν_e** in the booster neutrino beam remains an **irreducible background to ν_e LEE model searches**.

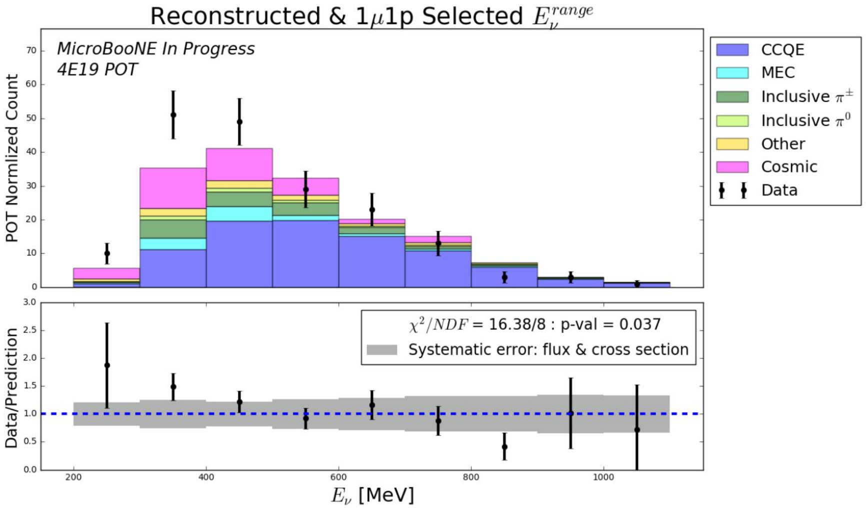
As such, understanding the systematic uncertainty on the ν_e rate is crucial. The ν_e are strongly correlated with our primary ν_μ flux component:

Our primary ν_μ flux

$$\pi^+ \rightarrow \mu^+ + \nu_\mu$$
$$\hookrightarrow e^+ + \bar{\nu}_\mu + \nu_e$$

ν_e Background

In addition they share many similar Argon cross-section systematics. Therefore we can use a **high statistics ν_μ sideband channel** to constrain the systematic uncertainties on the low statistics intrinsic ν_e backgrounds to the LEE analysis

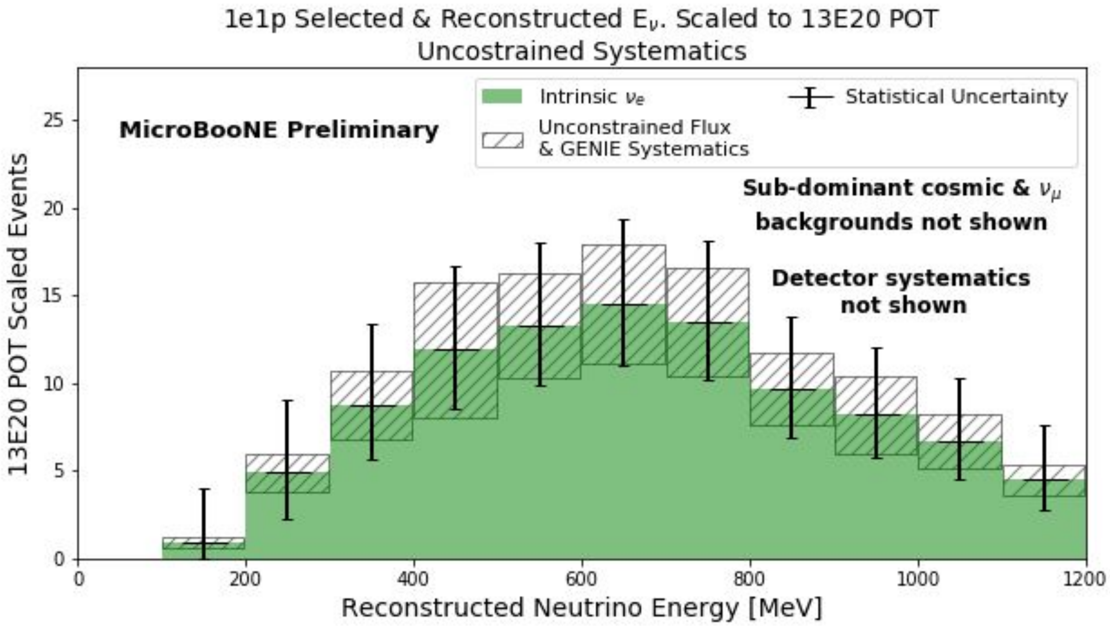


Example: Reconstructed and selected **1μ1p** events in the Deep Learning framework to be used as a sideband constraint on the **1e1p** analysis

MICROBOONE-NOTE-1039-PUB

Intrinsic ν_e background uncertainty in Deep Learning 1e1p analysis

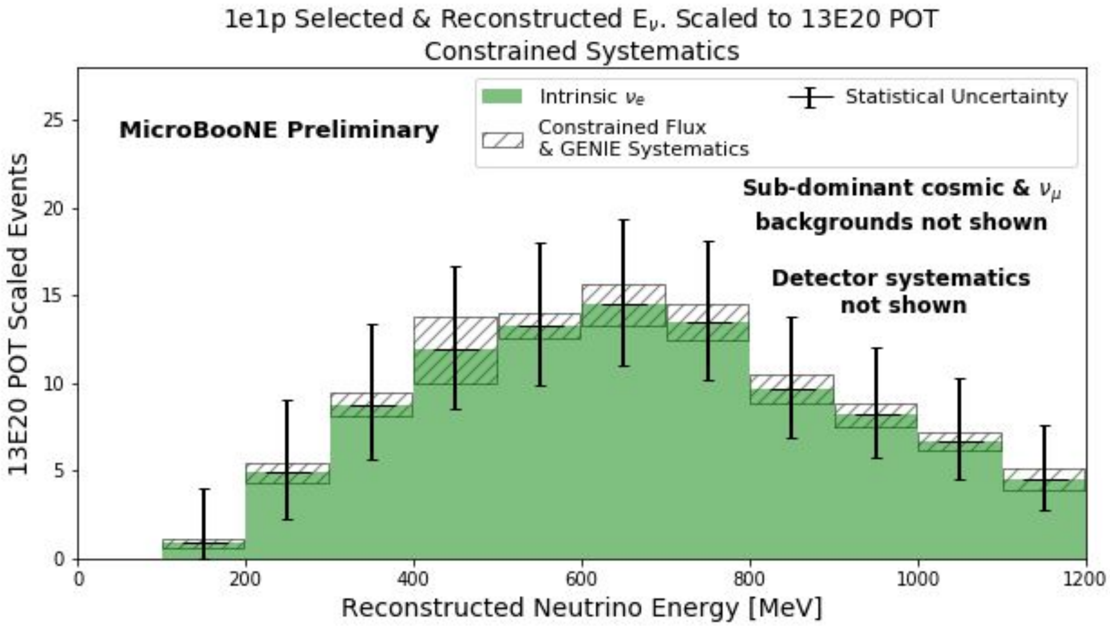
Unconstrained systematic Error Bars



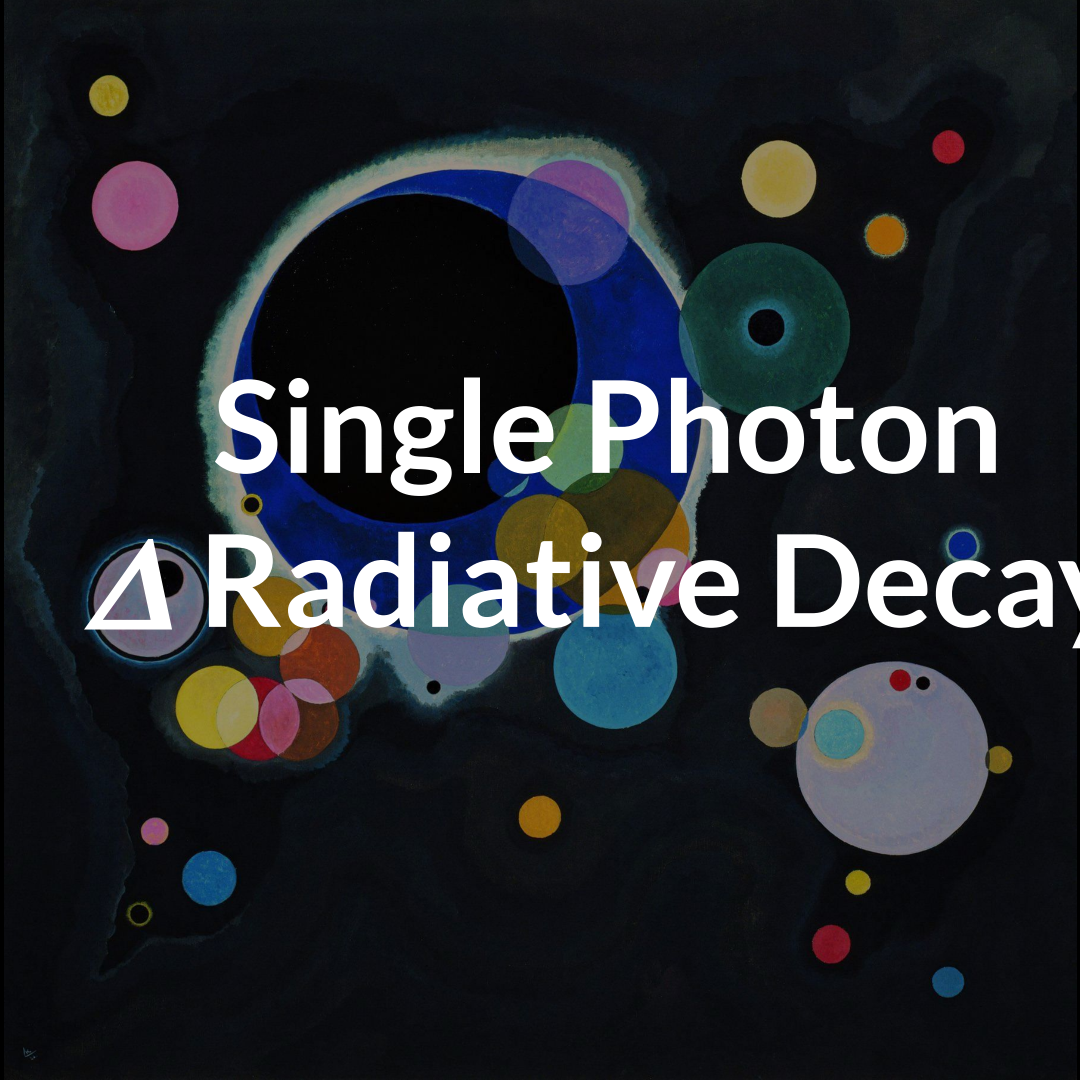
MICROBOONE-NOTE-1039-PUB

Intrinsic ν_e background uncertainty in Deep Learning 1e1p analysis

Constrained systematic Error Bars



MICROBOONE-NOTE-1039-PUB

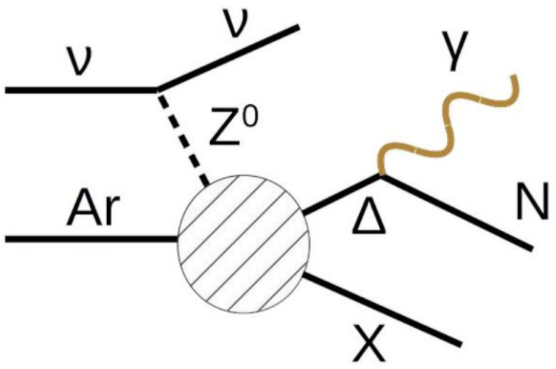


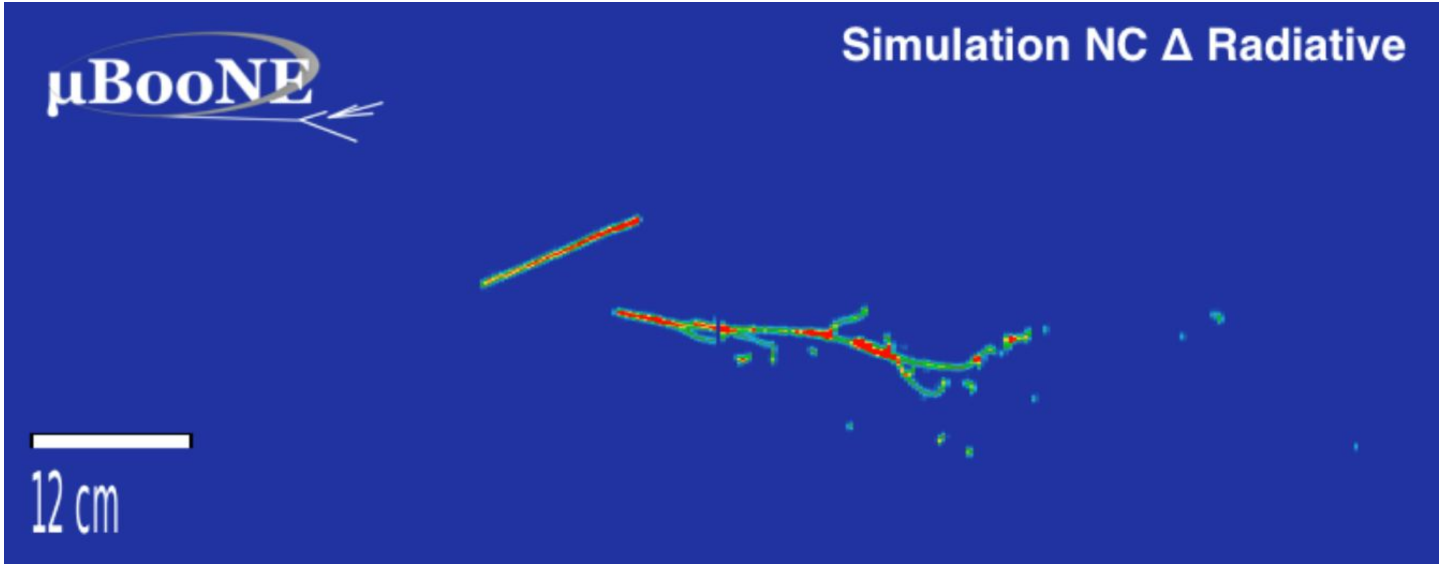
Single Photon
∆ Radiative Decay

Single Photons via Resonant Δ Radiative Decay

Search for **single photon events** consistent with originating from a **resonant Δ radiative decay** (~0.5% of Δ decays)

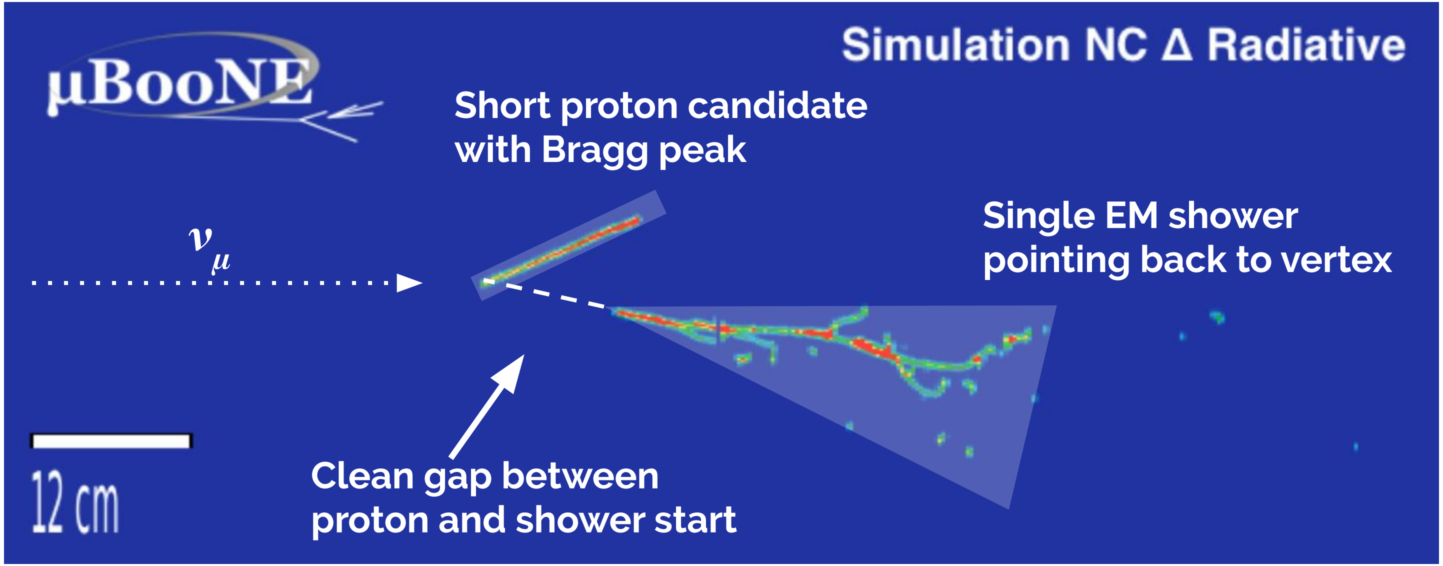
We are searching for events both with a visible proton (**$1\gamma1p$** topology) and without (**$1\gamma0p$** topology) although the case of a visible proton is the primary analysis





Anatomy of the 1γ1p signal topology

Use Pandora Multi-Algorithm Pattern Reconstruction to find all candidate neutrino events where there is exactly 1 shower and 1 track which share a common vertex (although shower can be displaced significantly).

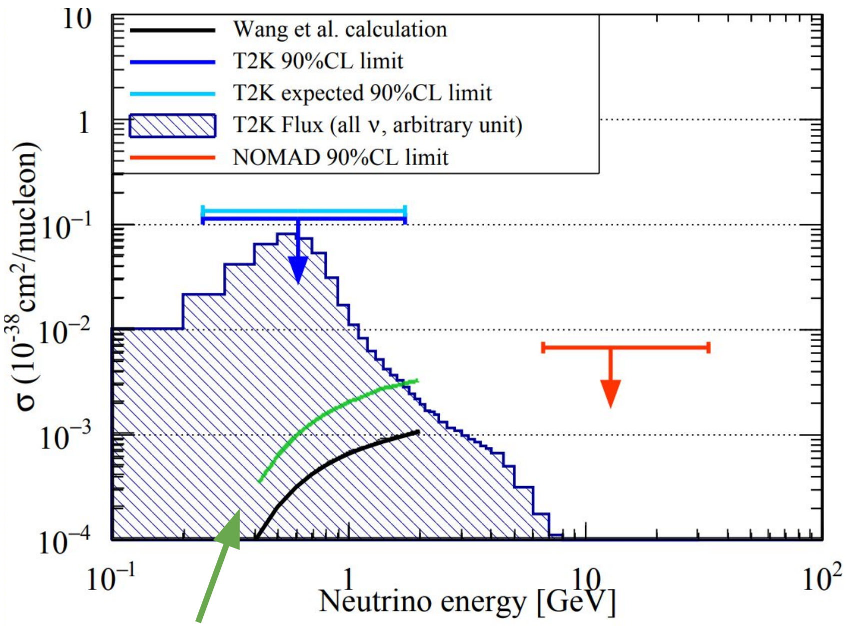


Current bounds on Neutrino induced Δ Radiative Decay

The **shape** of the Δ Radiative Decay events agree extremely well with the observed low-energy excess, can explain it if the rate were **increased by a factor of ~ x3** from its standard model predictions

Neutrino induced Δ Radiative Decay has **never been observed**, with the strongest bounds in this energy region from T2K being 10^2 times larger than theory prediction

K Abe et al 2019 J. Phys. G: Nucl. Part. Phys. 46 08LT01



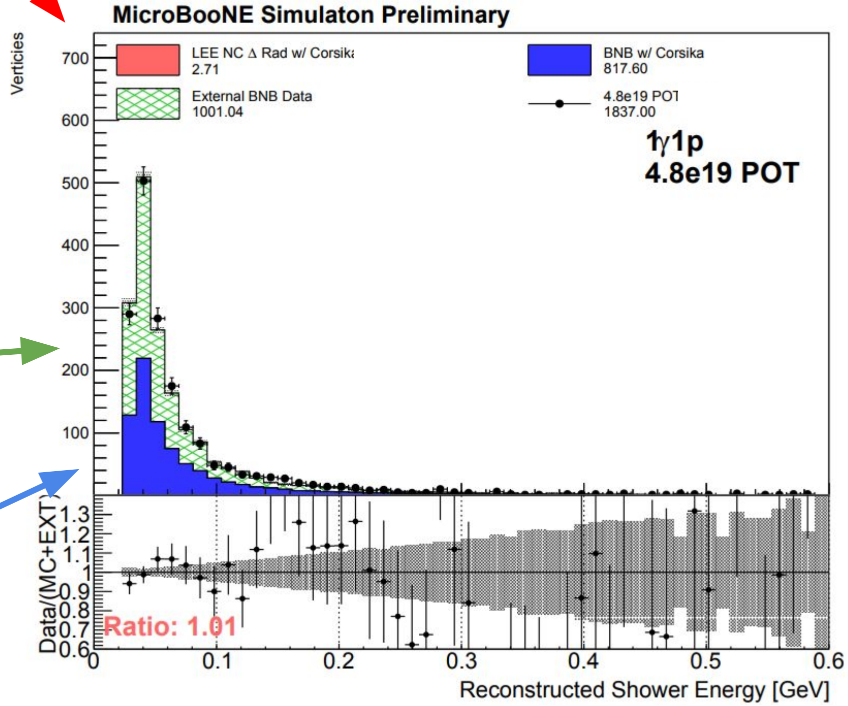
Green is added x3 SM expected rate, roughly what would explain the MiniBooNE Low Energy excess

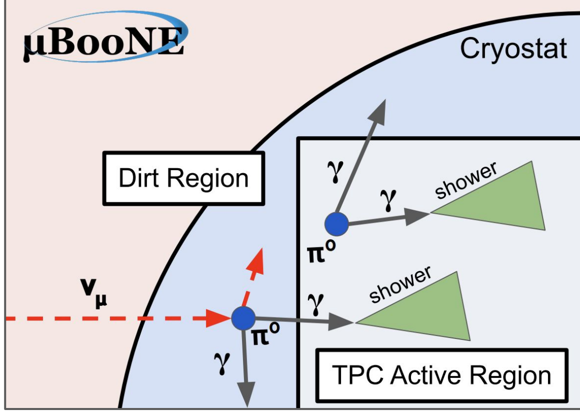
1γ1p Topology in Open Data

Signal Δ Radiative (x3 SM): Rate too small to be seen on this scale. Very rare process: ~7 true events expected in 4.8e19 POT

Cosmic Backgrounds: Cosmic events that occur during BNB spills and are mistake for neutrinos interactions. This is real data, taken when BNB is off.

Neutrino induced backgrounds: All other backgrounds such as CCν_e and π^0 events that have a shower reconstructed





Dirt Backgrounds: Newer simulations also include the important effect of Dirt: Neutrino events originating outside of TPC, and scattering in.

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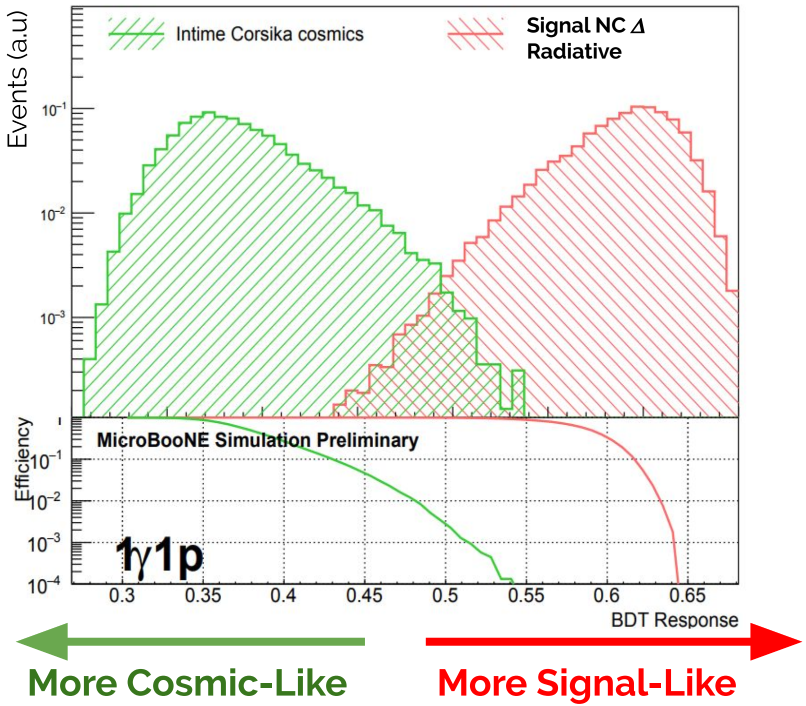
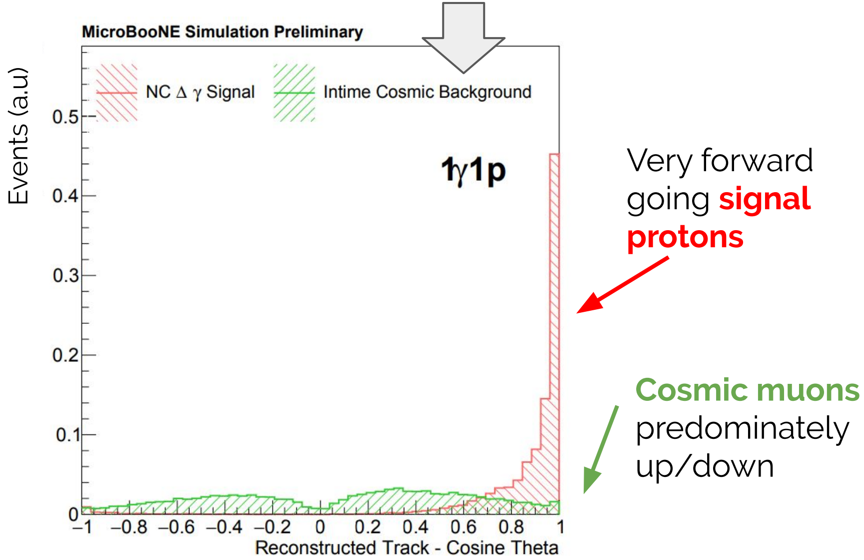
Boosted Decision Tree (BDT) for background Removal



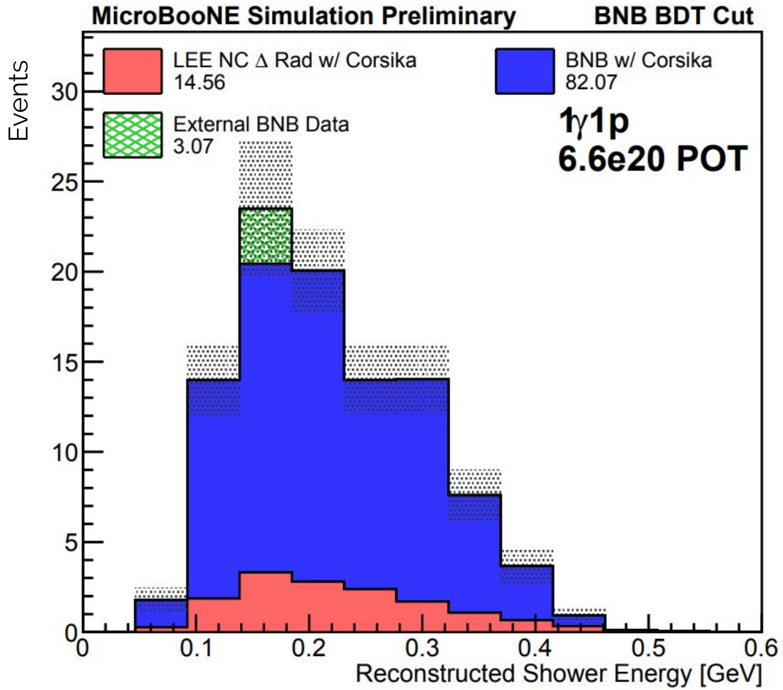
Train a tailored BDT to distinguish cosmic-like events from our signal using 20 kinematic and calorimetric variable such as :

- Track length
- Track and shower dE/dx
- Reconstructed Δ Invariant Mass
- Track and shower **direction**



Results shown here using AdaBoost BDT, moving towards XGBoost in current analysis. MICROBOONE-NOTE-1041-PUB

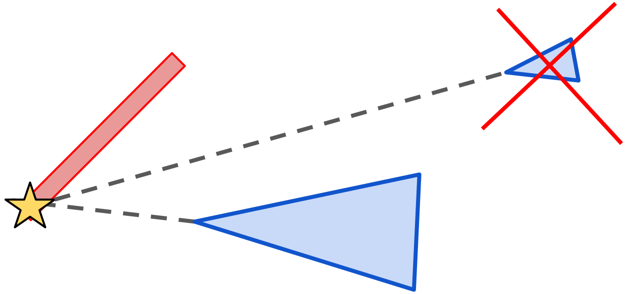
Post-Cosmic and Neutrino Background Rejection



- Over 99.99% of Cosmic induced backgrounds are removed with this cut.

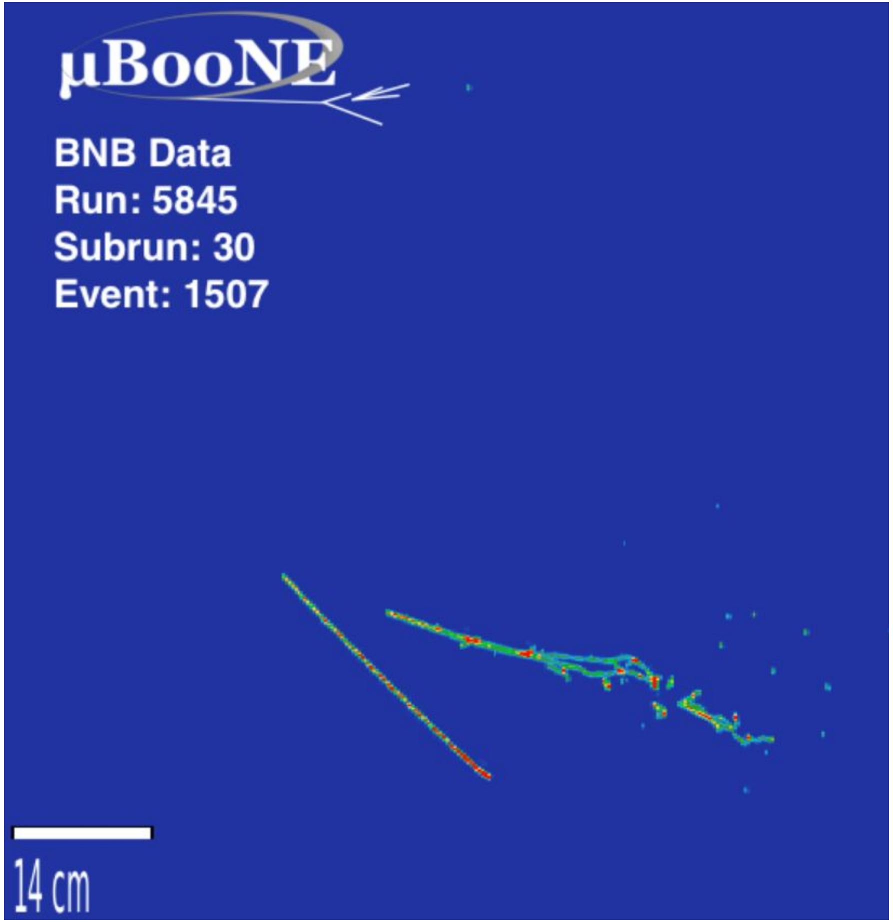
A similar approach is taken by training a second BDT to remove other neutrino induced backgrounds (see backup slides for more details)

- Of remaining (**BNB)** neutrino induced backgrounds, our Monte Carlo simulations tell us that **85%** are true NC π^0 interactions where the second shower was not reconstructed



MICROBOONE-NOTE-1041-PUB

Single-Photon candidate event in data

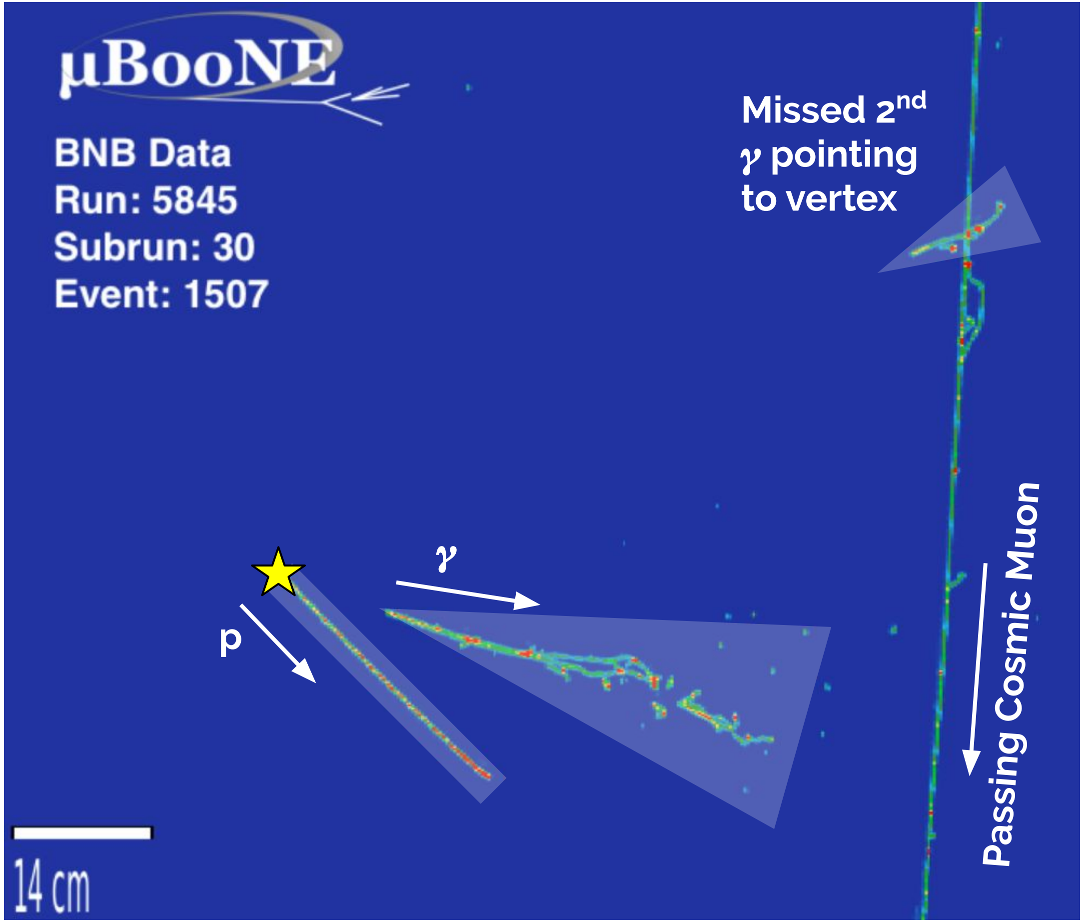


This **data event scores very highly as signal** in tailored background rejection BDT's

Overall topology, kinematics and calorimetry match that of a NC Δ radiative decay extremely well

However,...

Single-Photon candidate event in data (Likely NC π^0 background)



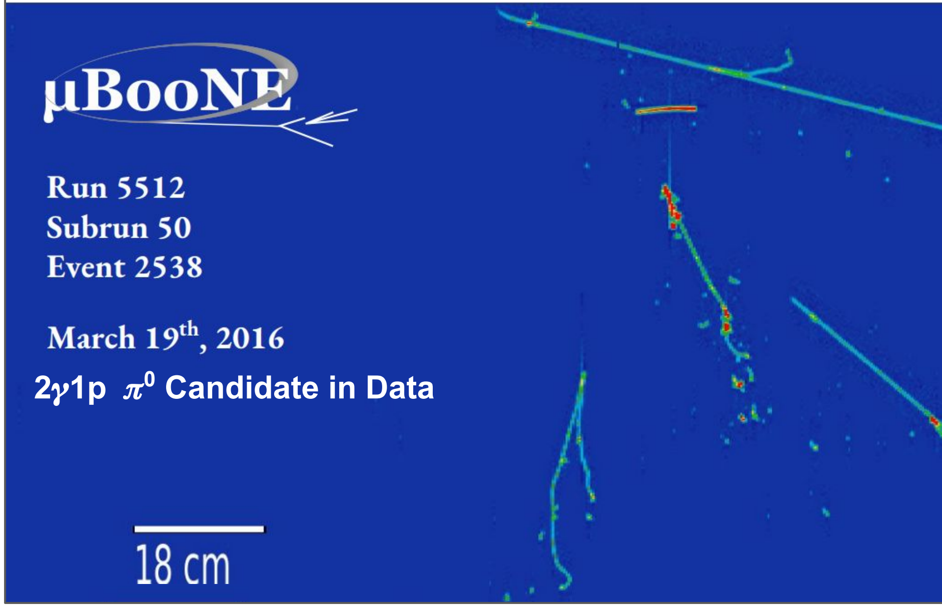
Zooming out:

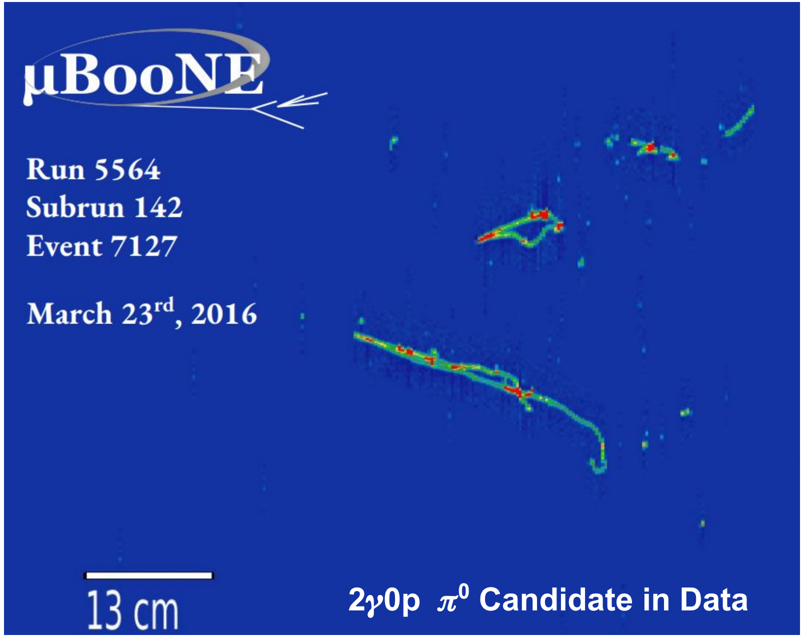
Missed secondary shower makes it much more likely to be **NCπ^0** event

Coincidence intersecting cosmic muon increased probability that second shower was tagged as a delta-ray off the cosmic muon

Constraining the NC π^0 backgrounds

To tackle this background, we are developing a **second shower veto** as even extremely low energy second photons from a π^0 decay that cannot be reconstructed fully, can still leave enough charge to be vetoed in the 1γ1p search





Alongside this, a **high statistics sideband selection of 2γ1p NC π^0** will help constrain the systematic uncertainty on the irreducible NCπ^0 backgrounds in the same vein as the CCν_μ sideband to the electron LEE studies (2 examples of selection given here)

Conclusions

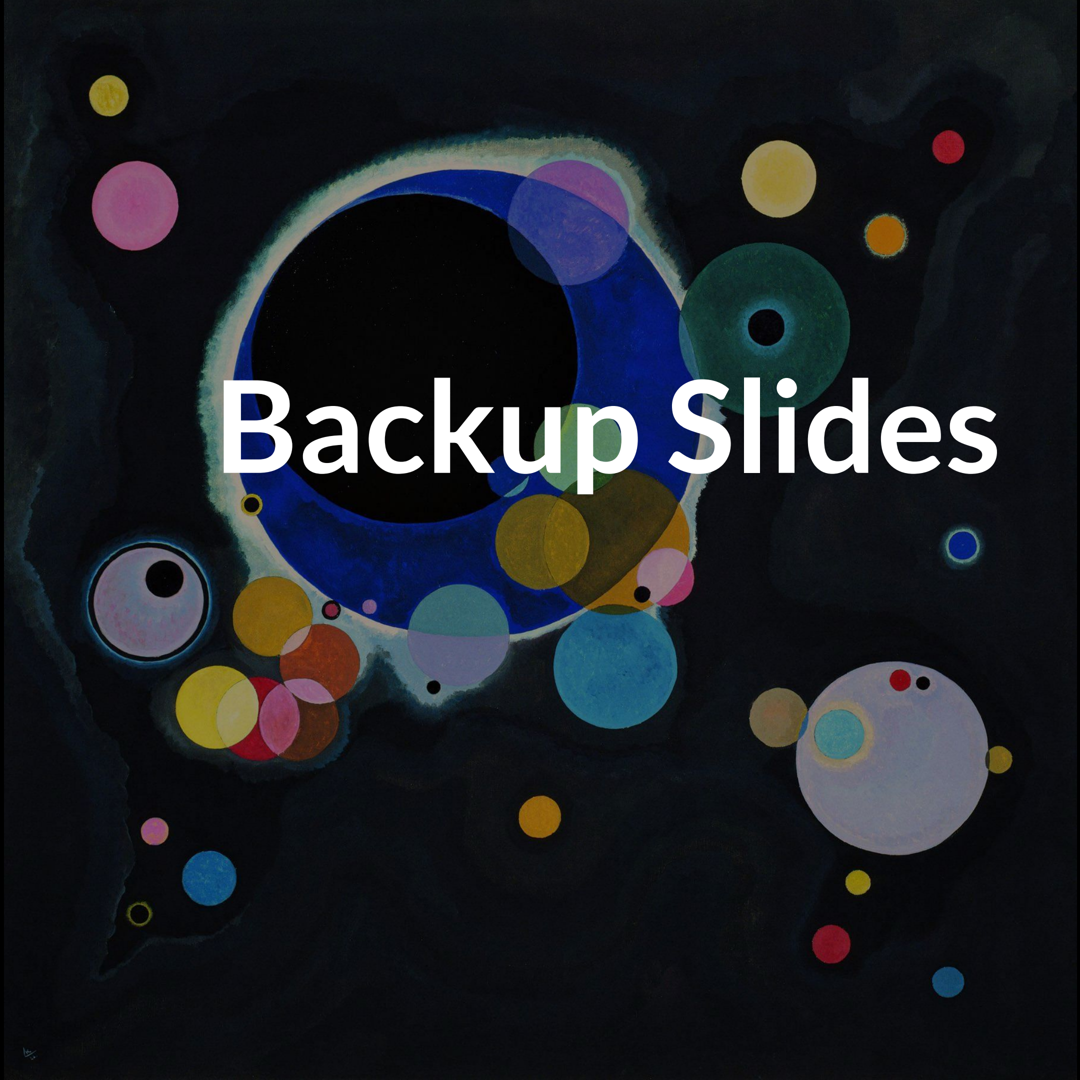
MicroBooNE's LEE search involves using **multiple reconstruction frameworks** on **multiple complementary analysis topologies** for a variety of signal hypotheses

All analysis's have now moved to our latest state-of-the-art Monte Carlo simulation involving the **Genie v3** event generator **overlayed with real cosmic data recorded *in-situ* at MicroBooNE**, use of the **Cosmic Ray Tagger** (CRT) as well as latest improvements in **signal processing** and **reconstruction**

Both electron and photon specific LEE analysis are tailoring further refinements to the sideband selections to provide the **strongest constraints** to the **systematic uncertainties of any irreducible backgrounds**

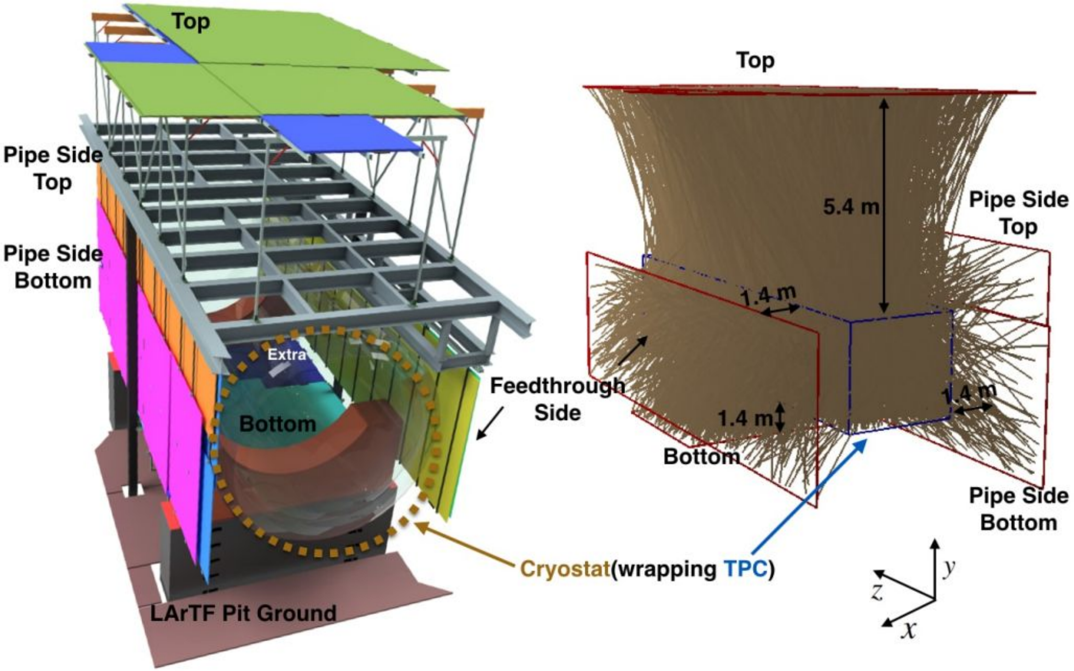
Primary focus now is on fully incorpering and understanding all possible **detector systematics** of our LArTPC to ensure as robust a measurement as possible

Backup Slides



MicroBooNE Cosmic Ray Tagger

https://arxiv.org/pdf/1901.02862.p



Theory Prediction, Single Photon production

$$\nu(\bar{\nu}) + N \rightarrow \nu(\bar{\nu}) + N + \gamma\,, \qquad (1)$$

is defined by the set of Feynman diagrams for the hadronic current shown in Fig. 1.

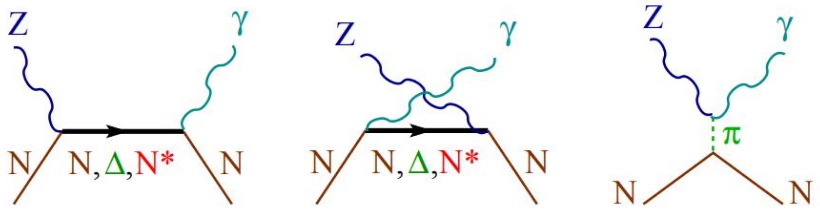


FIG. 1. (Color online) Feynman diagrams for the hadronic current of NC photon emission considered in Ref. [18]. The first two diagrams stand for direct and crossed baryon pole terms with nucleons and resonances in the intermediate state: BP and CBP with $B = N$, $\Delta(1232)$, $N^*(1440)$, $N^*(1520)$, $N^*(1535)$. The third diagram represents the t-channel pion exchange: πEx.

https://arxiv.org/pdf/1407.6060.pdf

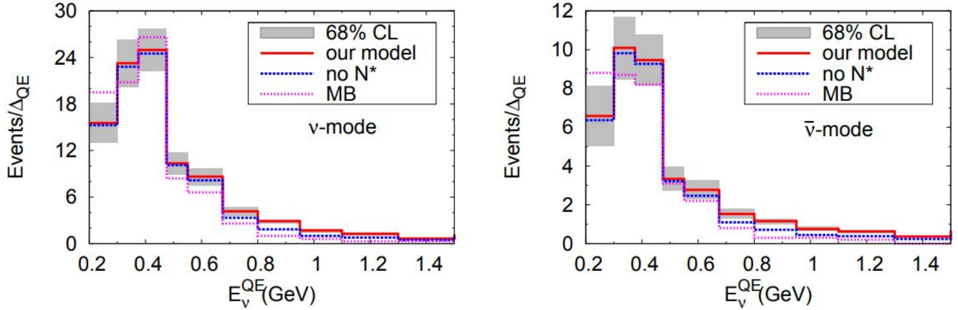
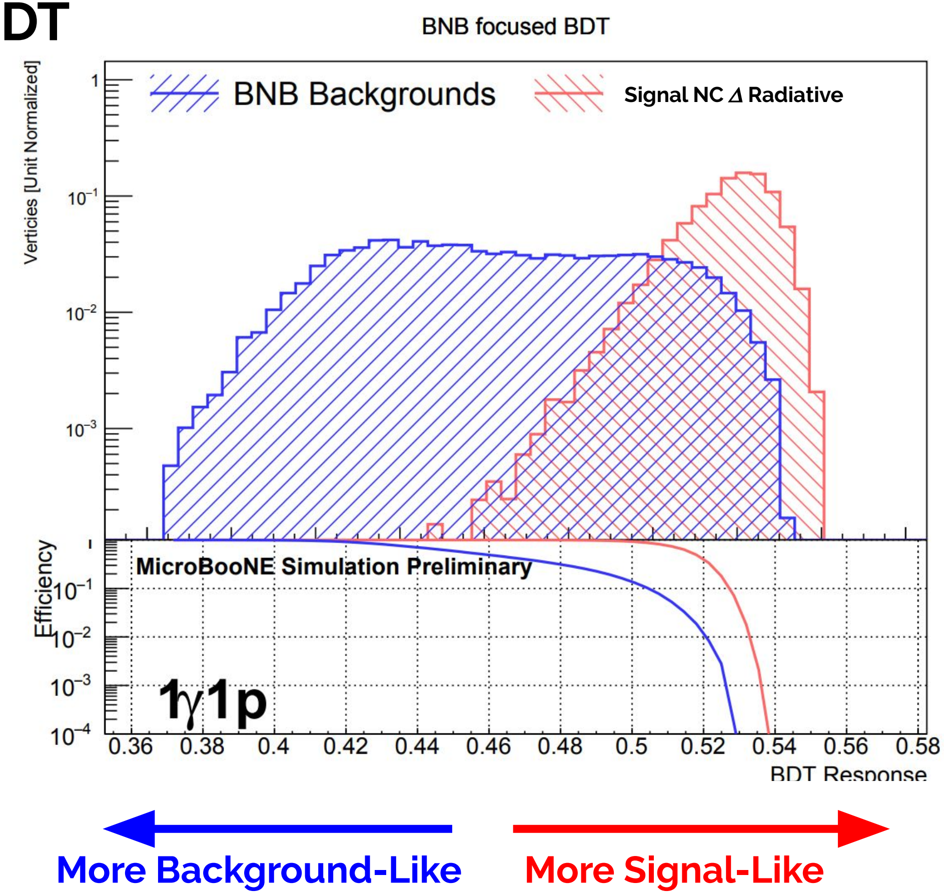
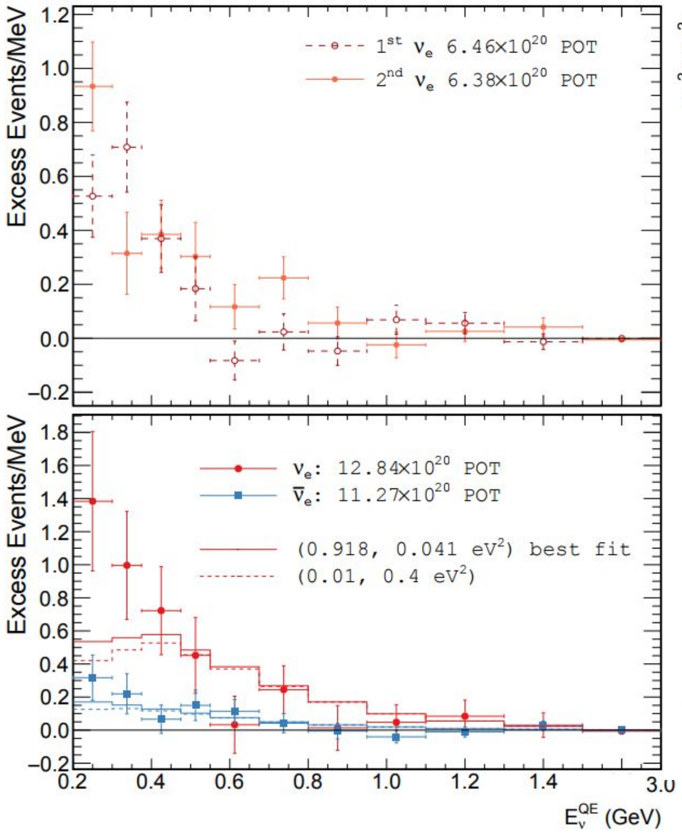


FIG. 4. (Color online) E_ν^{QE} distributions of total NCγ events for the ν (left) and $\bar{\nu}$ (right) modes. Our results, given by the red solid lines are accompanied by grey error bands corresponding to a 68 % confidence level. The curves labeled as "no N^*" show results from our model without the $N^*(1440)$, $N^*(1520)$ and $N^*(1535)$ contributions. The "MB" histograms display the MiniBooNE estimates [20]. Δ_{QE} denotes the size of the E_ν^{QE} bin in the experimental setup.

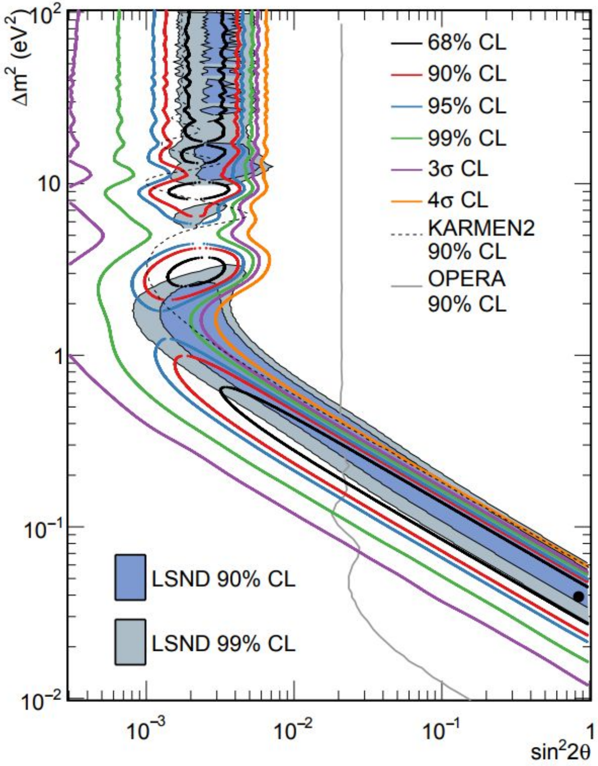
Single-Photon BDT



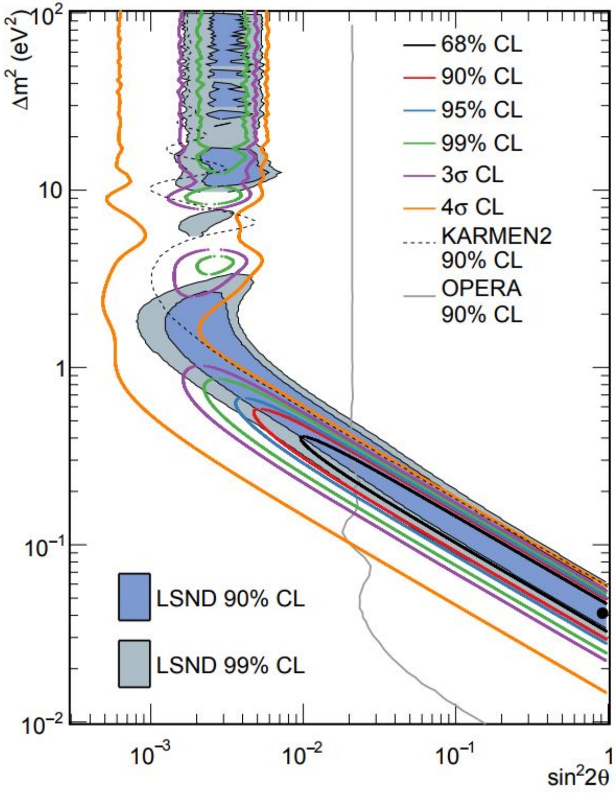
MiniBooNE LEE Allowed region

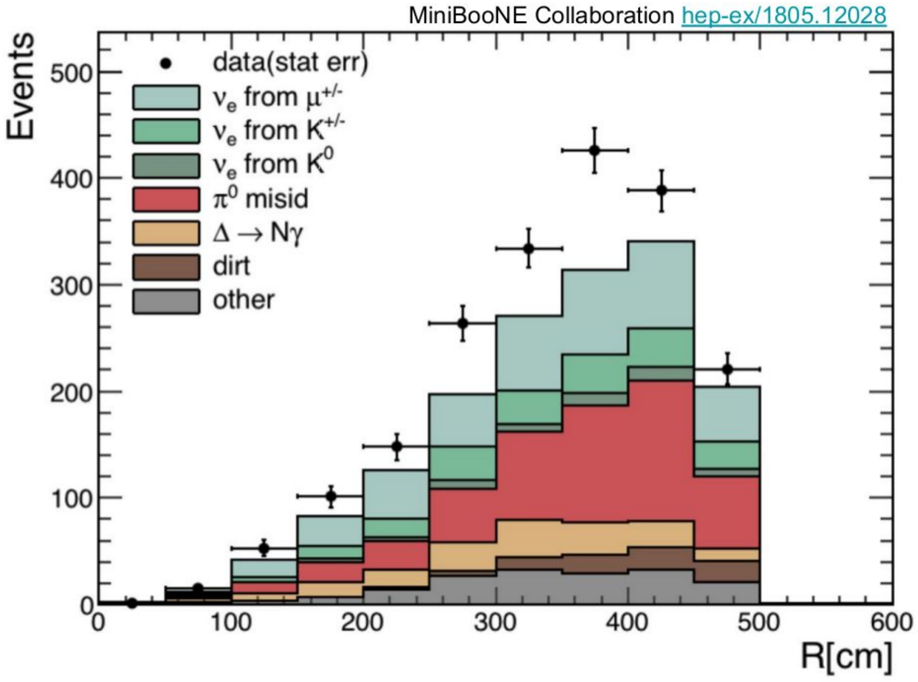


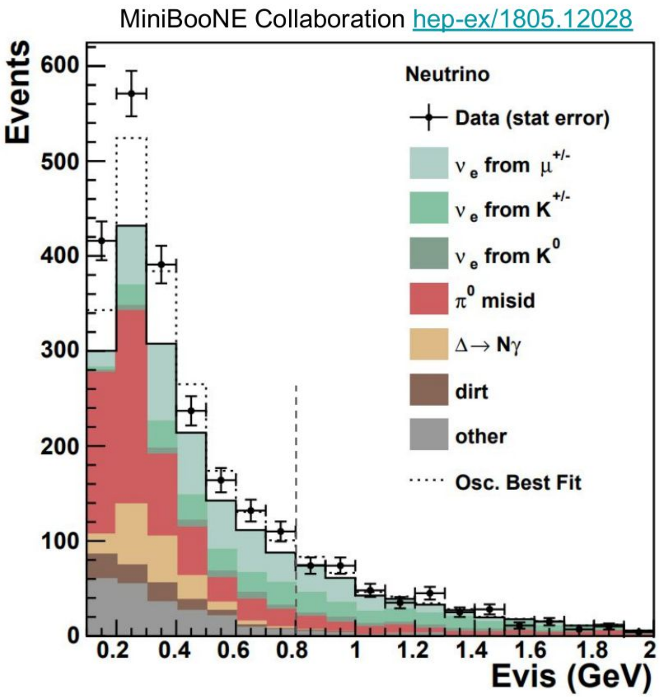
Neutrino Only Fit

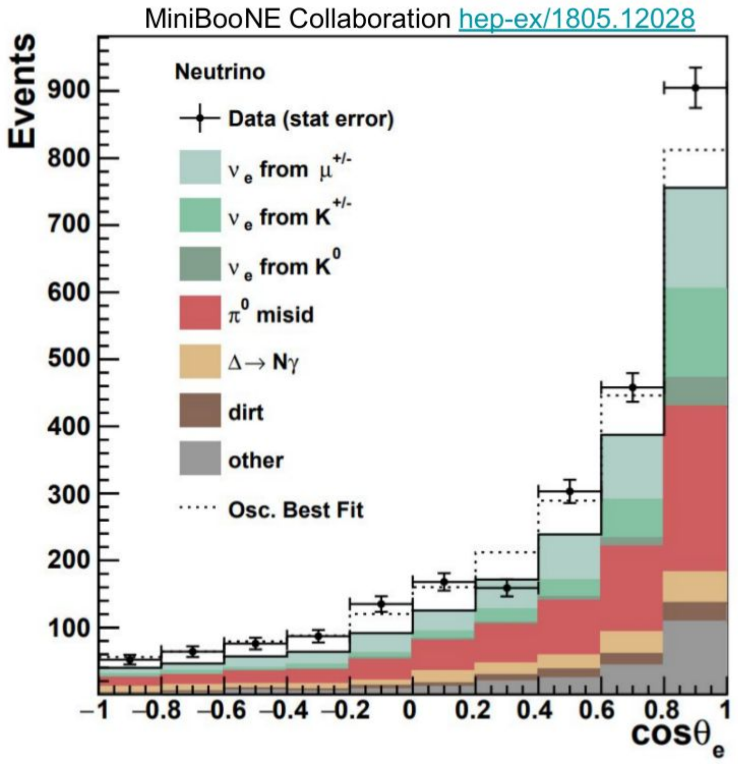


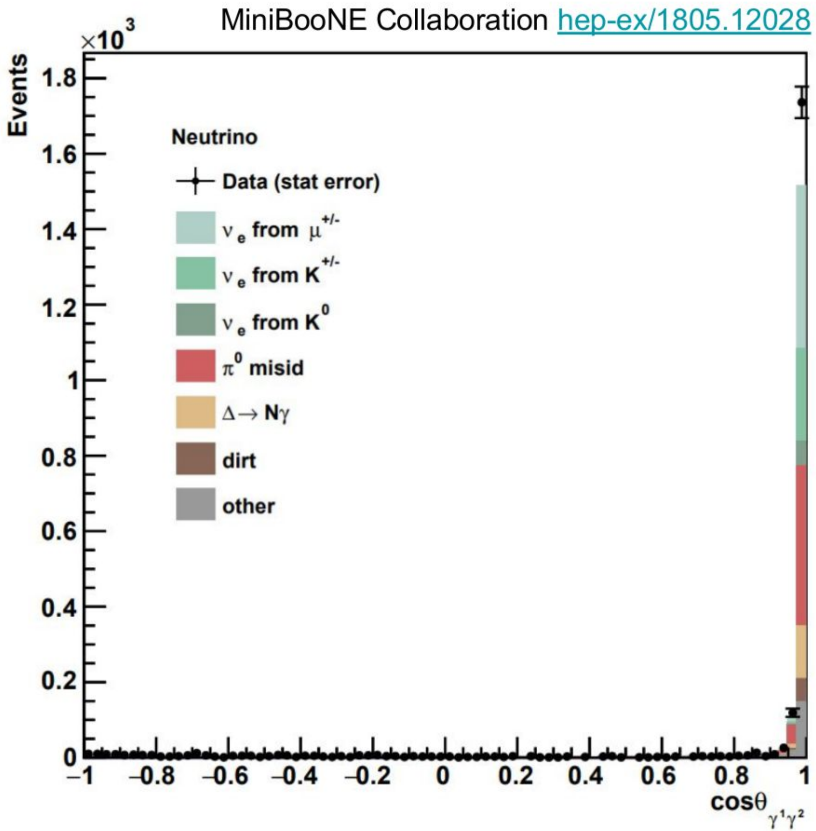
Neutrino+Anti-Neutrin Fit




MiniBooNE Collaboration hep-ex/1805.12028
Events
data(stat err)
ν_e from $\mu^{+/-}$
ν_e from $K^{+/-}$
ν_e from K^0
π^0 misid
$\Delta \rightarrow N\gamma$
dirt
other
R[cm]


MiniBooNE Collaboration hep-ex/1805.12028
Events
Neutrino
Data (stat error)
ν_e from $\mu^{+/-}$
ν_e from $K^{+/-}$
ν_e from K^0
π^0 misid
$\Delta \rightarrow N\gamma$
dirt
other
Osc. Best Fit
Evis (GeV)


MiniBooNE Collaboration hep-ex/1805.12028
Events
Neutrino
Data (stat error)
ν e from μ +/-
ν e from K +/-
ν e from K 0
π 0 misid
Δ→ Nγ
dirt
other
Osc. Best Fit
cosθ e


MiniBooNE Collaboration hep-ex/1805.12028
×10 3
Events
Neutrino
Data (stat error)
ν e from μ +/-
ν e from K +/-
ν e from K 0
π 0 misid
Δ→ Nγ
dirt
other
cosθ γ1γ2

MiniBooNE
In situ Pi0 constraint

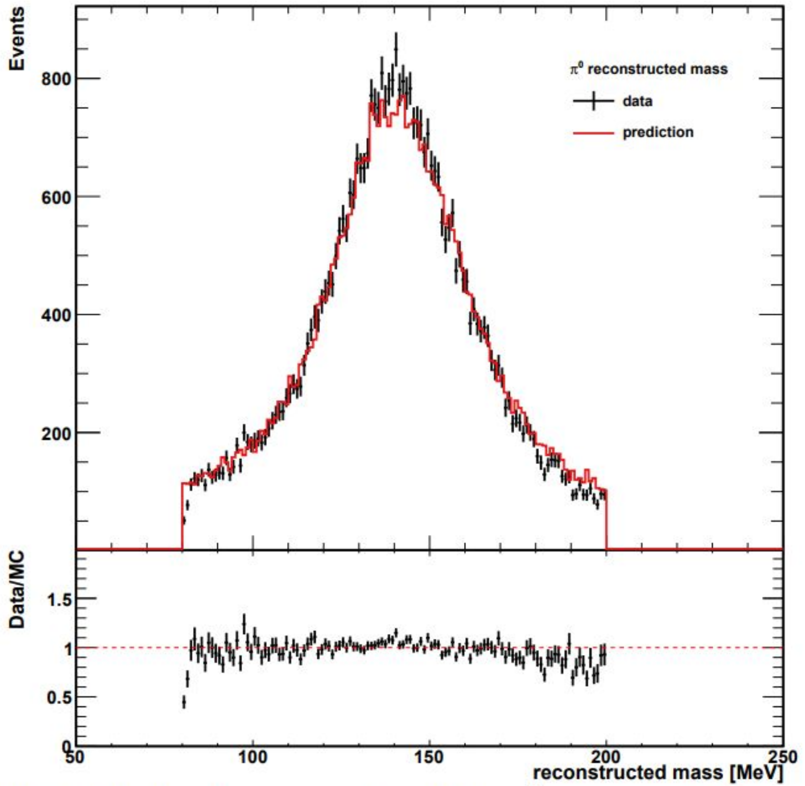


FIG. 7: An absolute comparison of the π^0 reconstructed mass distribution between the neutrino data (12.84×10^{20} POT) and the simulation for NC π^0 events (top). Also shown is the ratio between the data and Monte Carlo simulation (bottom). The error bars show only statistical uncertainties.

MicroBooNE unfolding LEE, method comparason