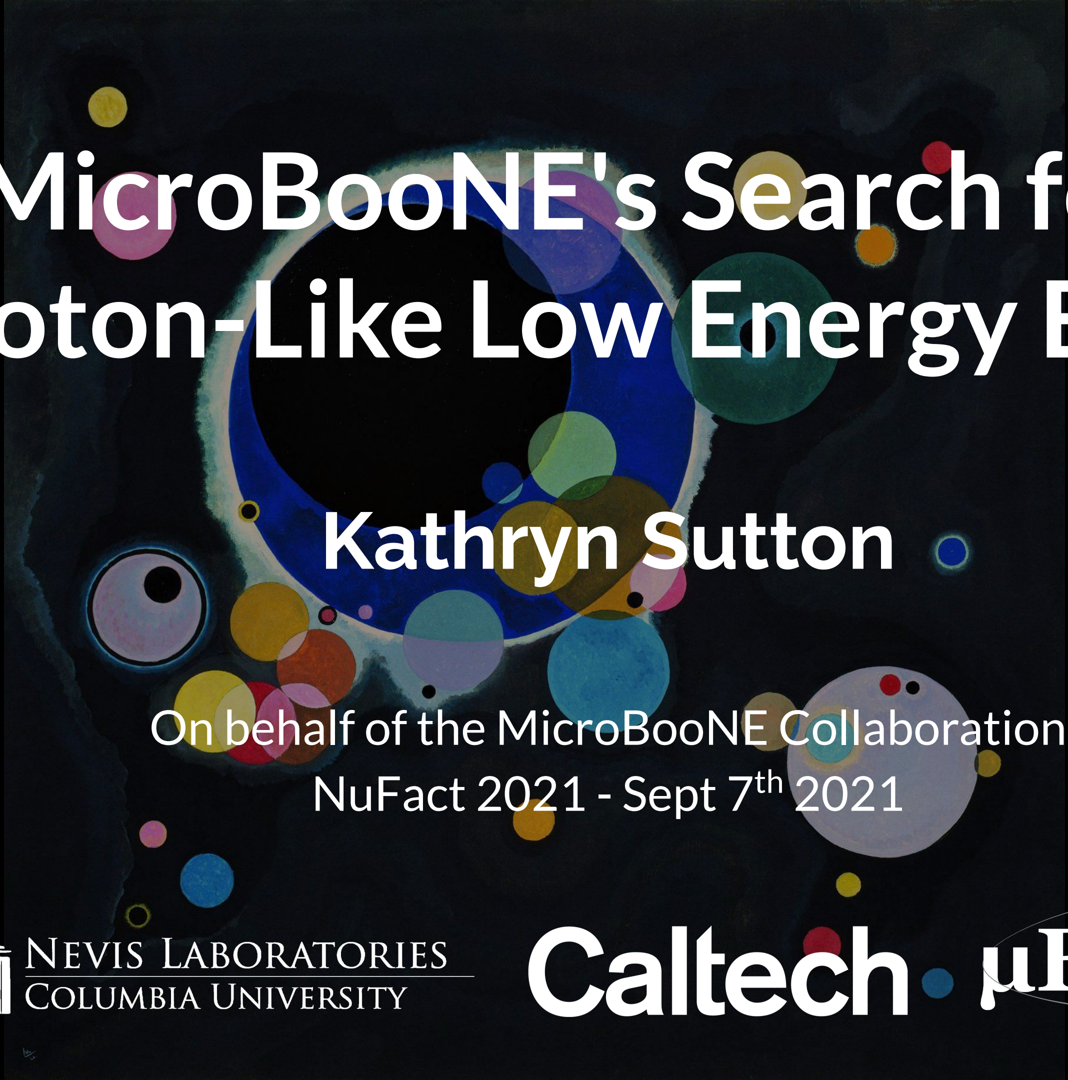


MicroBooNE's Search for a Photon-Like Low Energy Excess

Kathryn Sutton

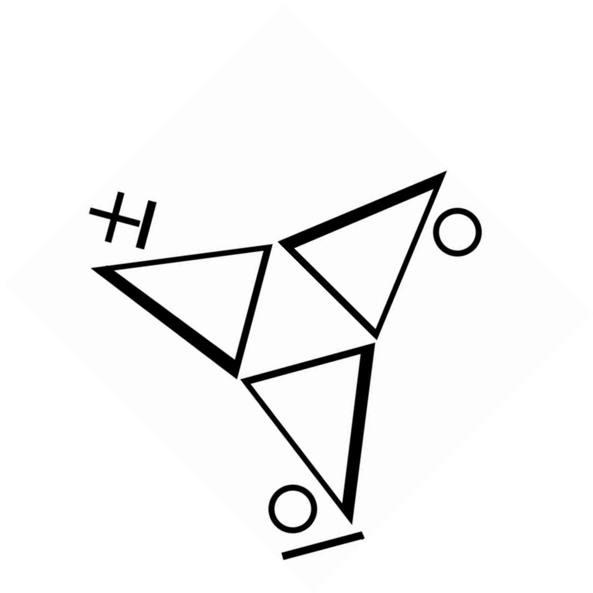
On behalf of the MicroBooNE Collaboration

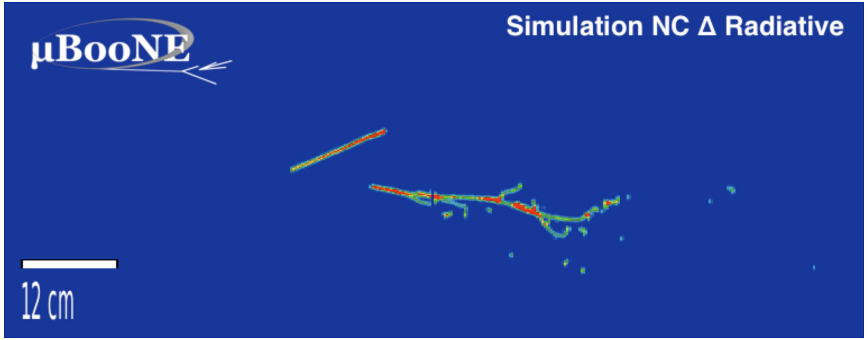
NuFact 2021 - Sept 7th 2021

Nevis Laboratories
Columbia University
Caltech
μBooNE

Overview

- MiniBooNE “Low Energy Excess” anomaly
- Photon-like and electron-like interpretations
- MicroBooNE experiment as follow up to MiniBooNE
- MicroBooNE single-photon search and status

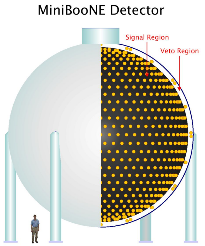




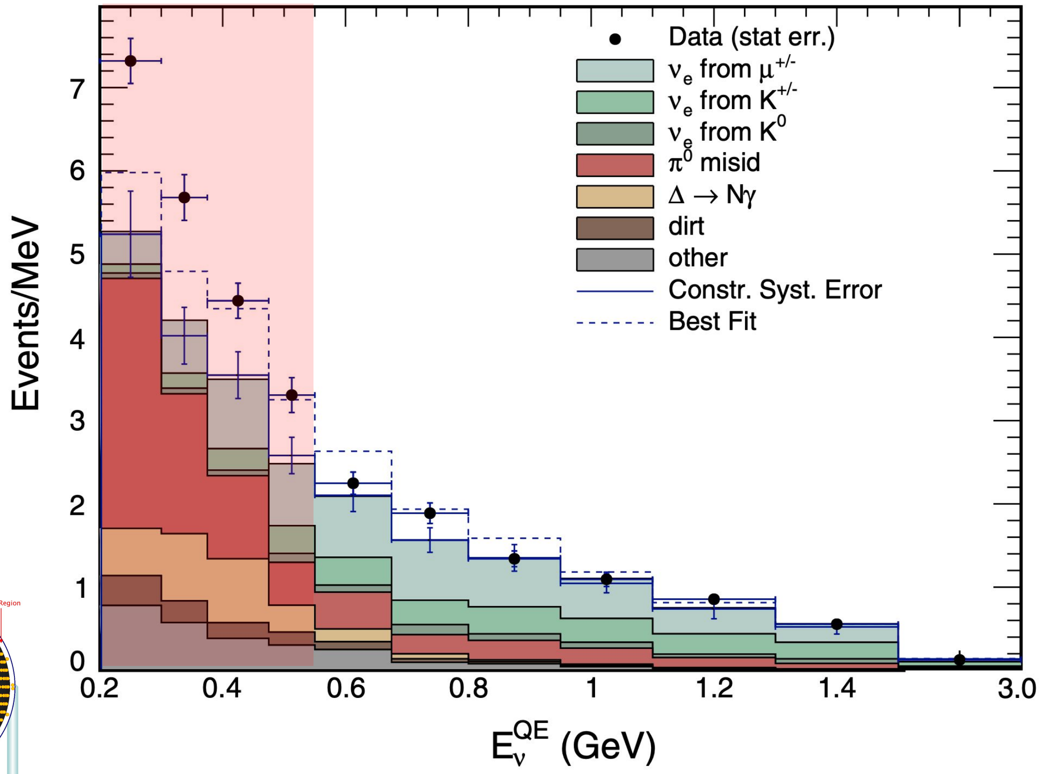
Interpreting the MiniBooNE Anomaly

MiniBooNE "Low Energy Excess"

- **MiniBooNE** is a Cherenkov detector along the Fermilab Booster Neutrino Beam (BNB) that took data from 2002-2019
- BNB is ~94% pure ν_μ beam, <1% ν_e contamination, with a mean energy of ~800 MeV
- Observed **excess of electromagnetic events at low energy*** in the ν_e selection



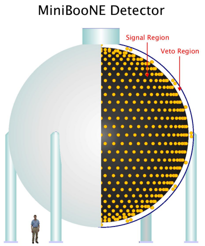
Reconstructed Neutrino Energy for ν_e Charged Current (CC) Quasielastic Interactions



*Phys. Rev. D 103, 052002 (2021)

Sterile Neutrino Interpretation

- MiniBooNE result could be interpreted as **a sterile neutrino** oscillation to an electron (anti)neutrino
- This would mean the observed excess is **electron neutrinos from $\nu_\mu \rightarrow \nu_s \rightarrow \nu_e$ oscillation**



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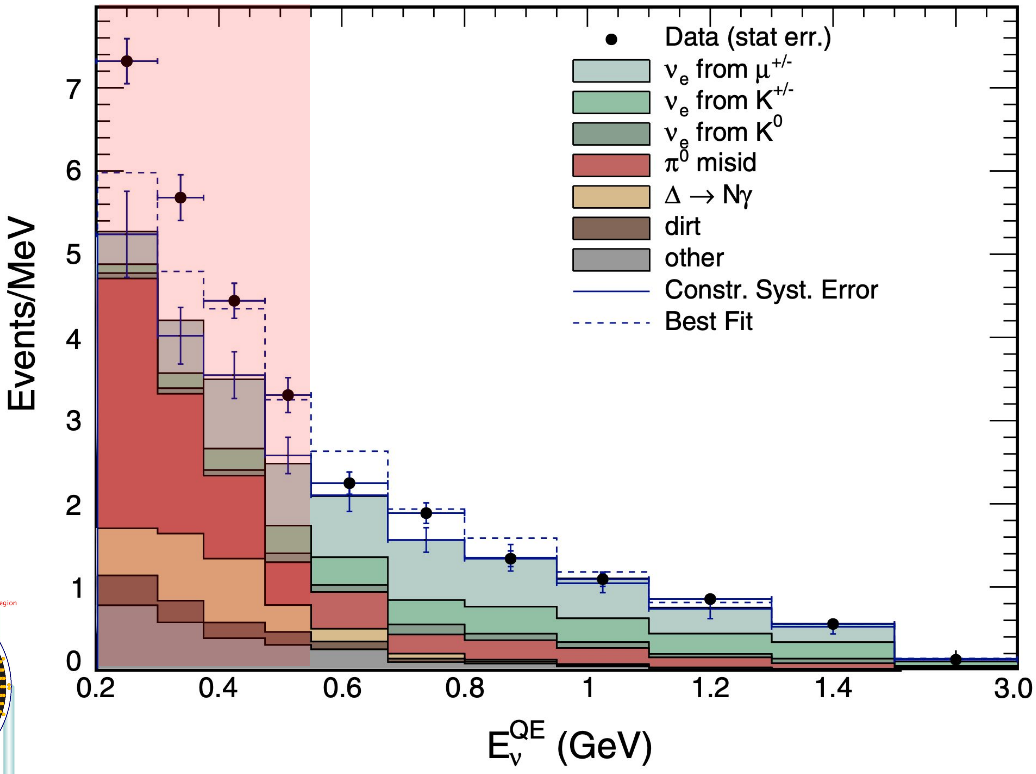


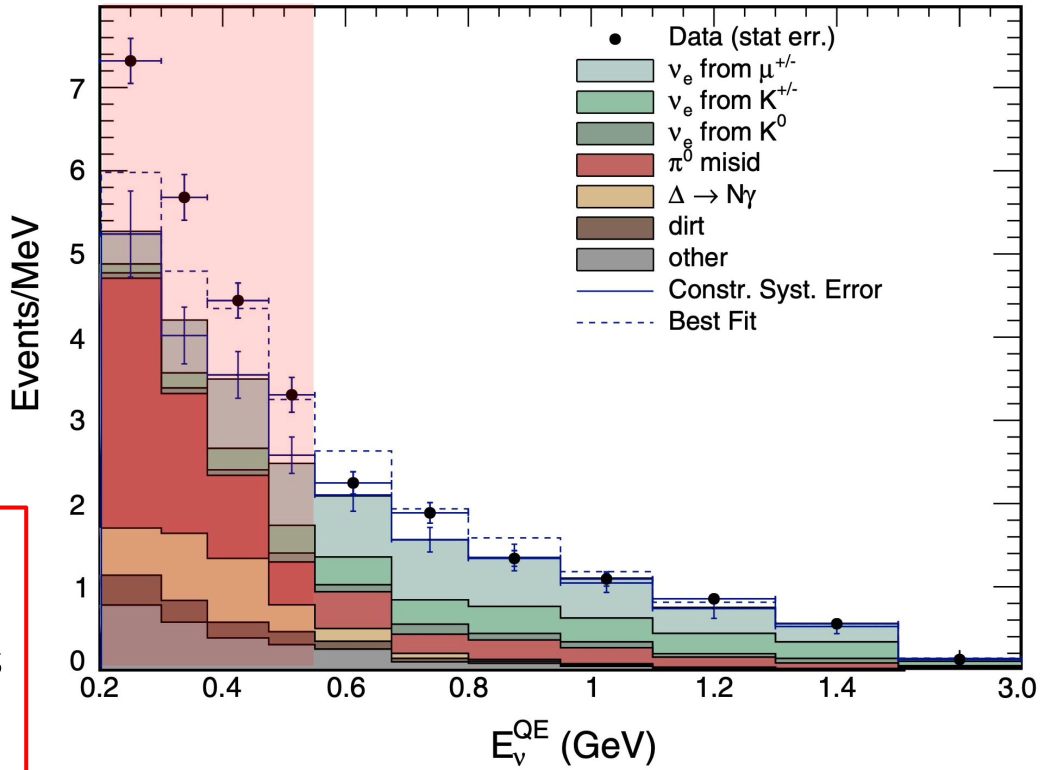
Phys. Rev. D 103, 052002 (2021)

Sterile Neutrino Interpretation

- MiniBooNE results could be interpreted as **a sterile neutrino** oscillation to an electron (anti)neutrino
- This would mean the observed excess is **electron neutrinos from $\nu_\mu \to \nu_s \to \nu_e$ oscillation**

However, because MiniBooNE was a Cherenkov detector, the question remains whether the observed excess of electromagnetic showers is **photon-like** or **electron-like**.

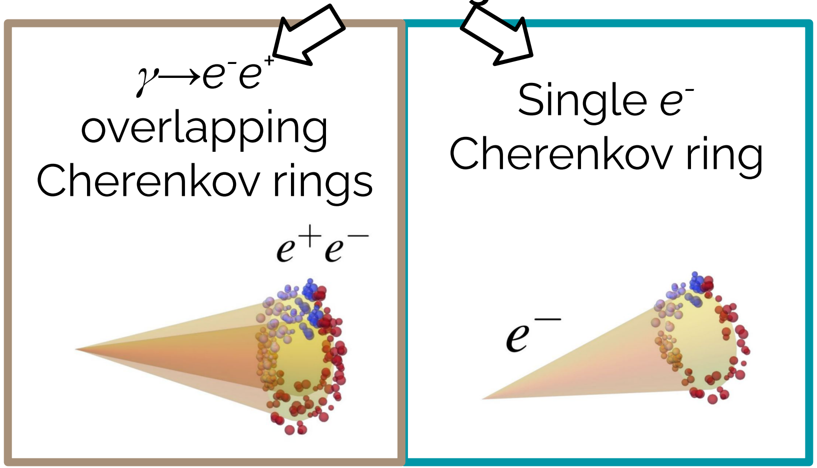
Reconstructed Neutrino Energy for ν_e Charged Current (CC) Quasielastic Interactions

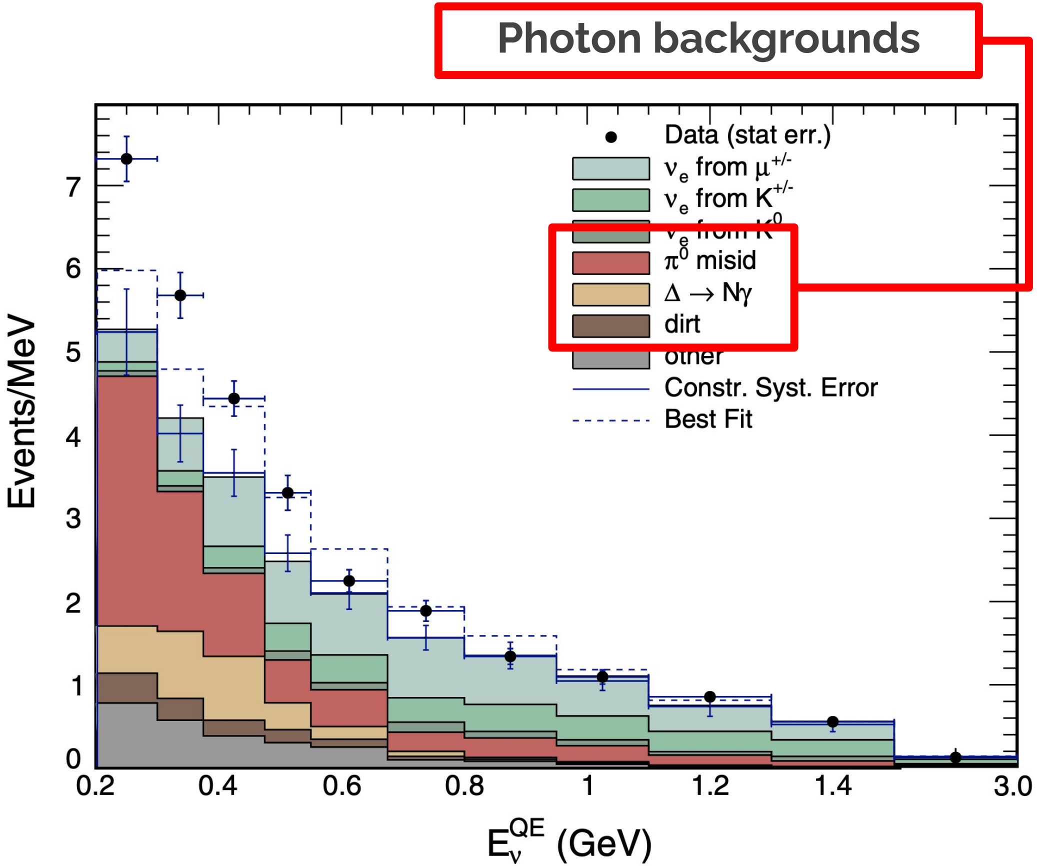


Phys. Rev. D 103, 052002 (2021)

Electron/Photon Separation in MiniBooNE

Hard to distinguish

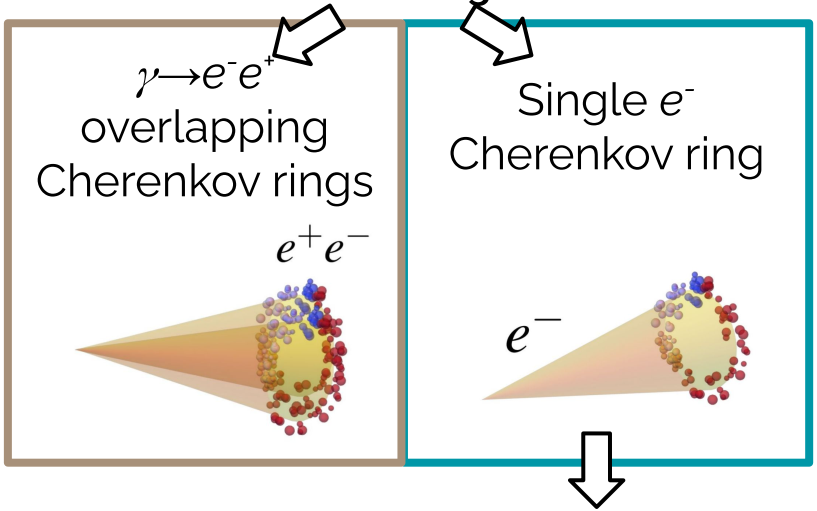




Phys. Rev. D 103, 052002 (2021)

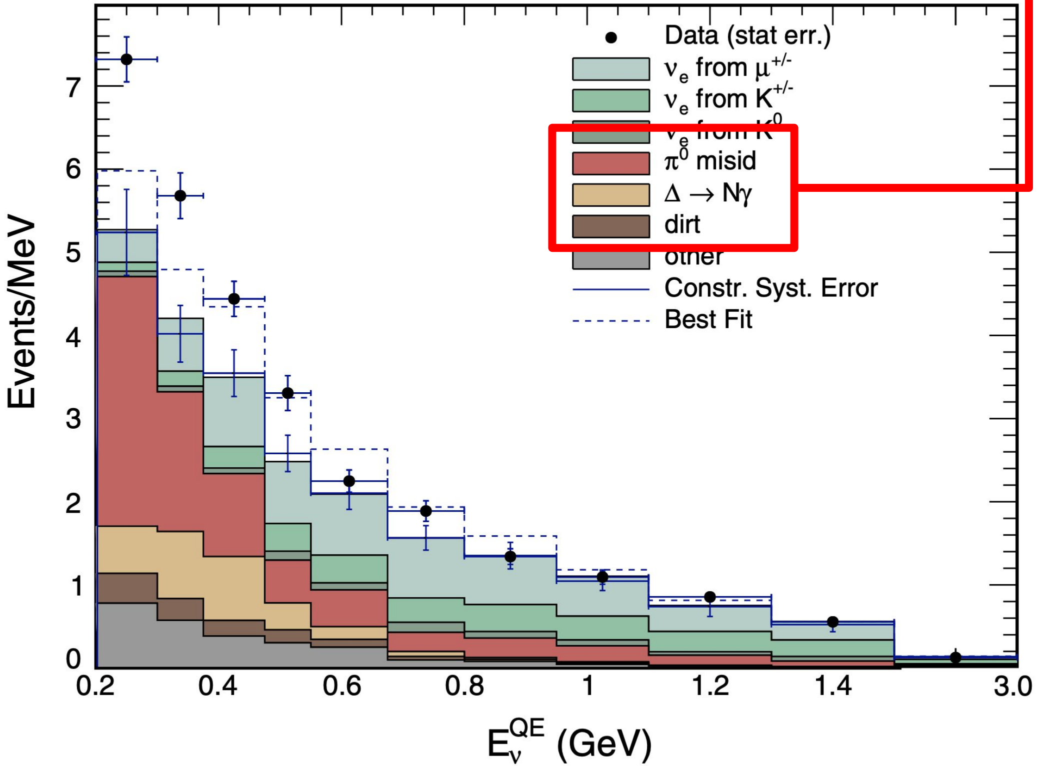
Electron/Photon Interpretation of MiniBooNE

Hard to distinguish



A source of **electron neutrinos** that isn't accounted for in the prediction. **This could be a sign of sterile neutrinos.**

Photon backgrounds

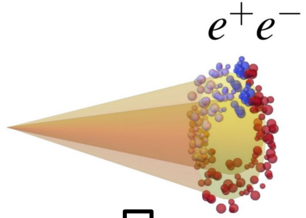


Phys. Rev. D 103, 052002 (2021)

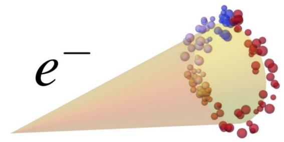
Electron/Photon Interpretation of MiniBooNE

Hard to distinguish

$\gamma \rightarrow e^- e^+$
overlapping
Cherenkov rings



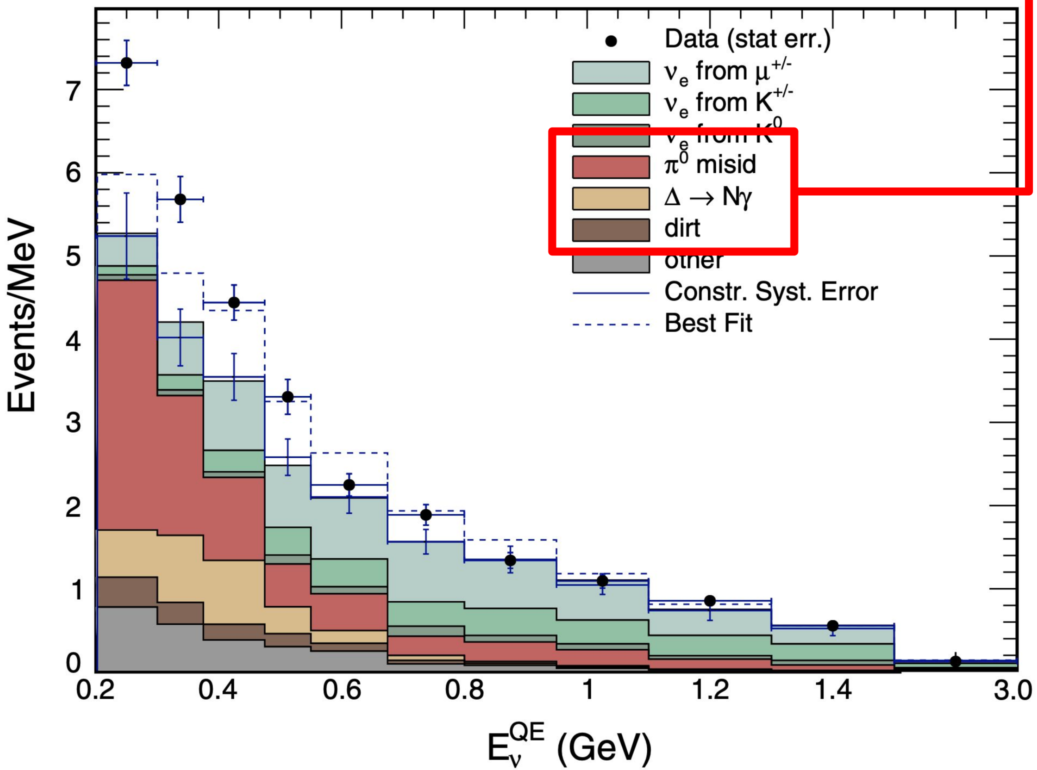
Single e^-
Cherenkov ring



A source of **neutrino-induced photon interaction** that isn't accounted for in the prediction. **This could be a SM or exotic process.**

A source of **electron neutrinos** that isn't accounted for in the prediction. **This could be a sign of sterile neutrinos.**

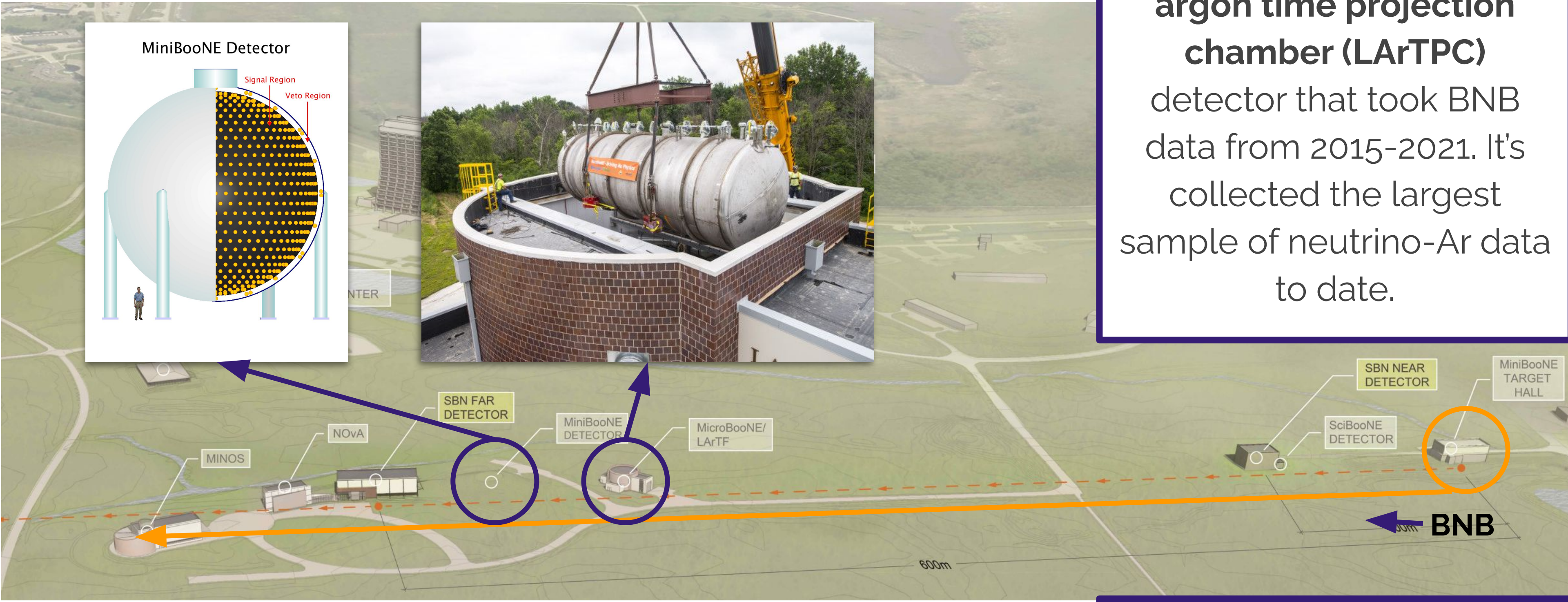
Photon backgrounds



Phys. Rev. D 103, 052002 (2021)

The MicroBooNE Detector

The Fermilab Booster Neutrino Beam (BNB)



MicroBooNE is a **liquid argon time projection chamber (LArTPC)** detector that took BNB data from 2015-2021. It's collected the largest sample of neutrino-Ar data to date.

MiniBooNE baseline ~ 500m

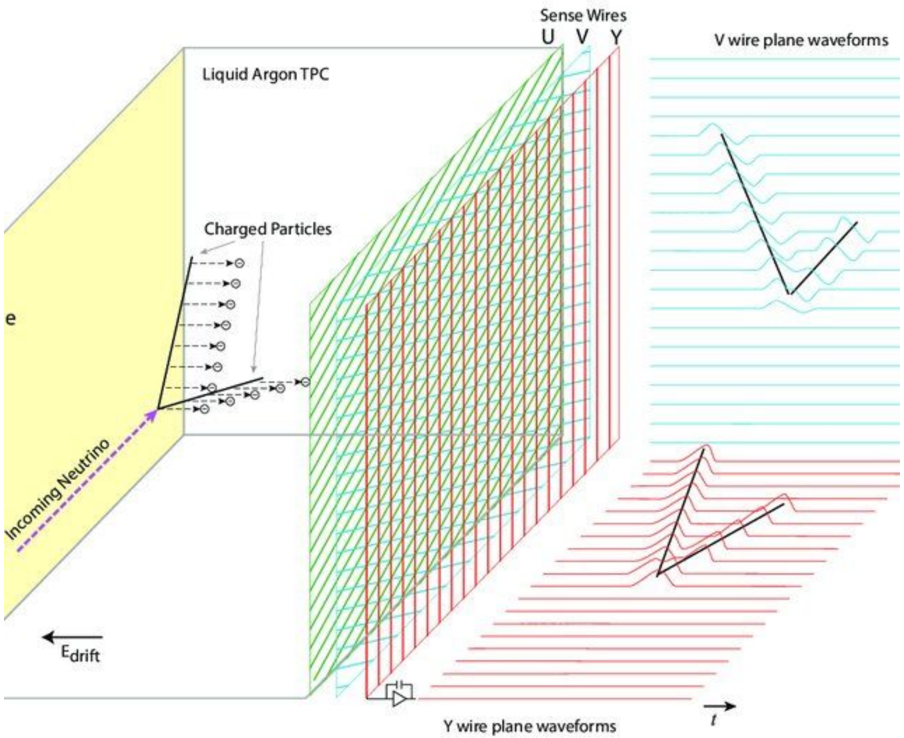
MicroBooNE baseline ~ 470m

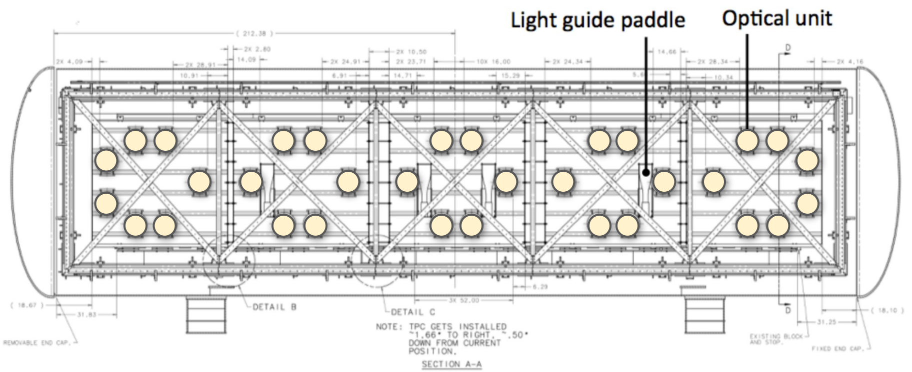
Introduction to MicroBooNE and SBN in talk yesterday

LArTPC Detectors

Wires

PMTs





A LArTPC takes images of neutrino interactions. Charged particles that pass through the Ar create **ionization tracks** which are collected by the **wire planes.** These 2D projections of interactions are then **reconstructed into 3D** using **timing information** from the **PMTs**.

Investigating MiniBooNE with a LArTPC Detector

Neutrino interaction shown as a 2D projection on a single wire plane in MicroBooNE

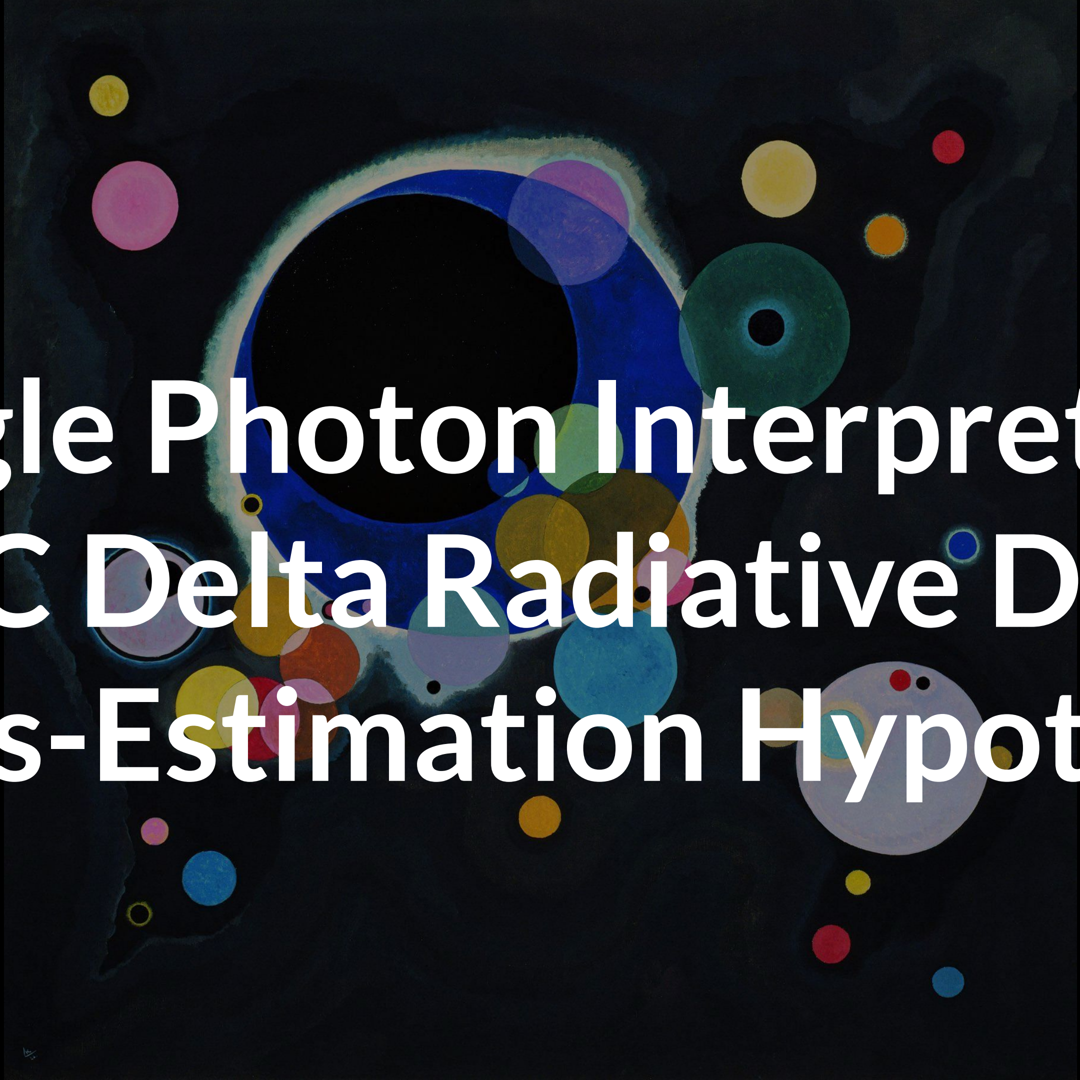
time

wire

Color scale shows the charge deposited, with red being more ionizing.

LArTPCs demonstrate precise spatial and calorimetric resolution, which makes them ideal for distinguishing between photons and electrons.

MicroBooNE experiment motivated as a follow up to investigate the MiniBooNE anomaly.

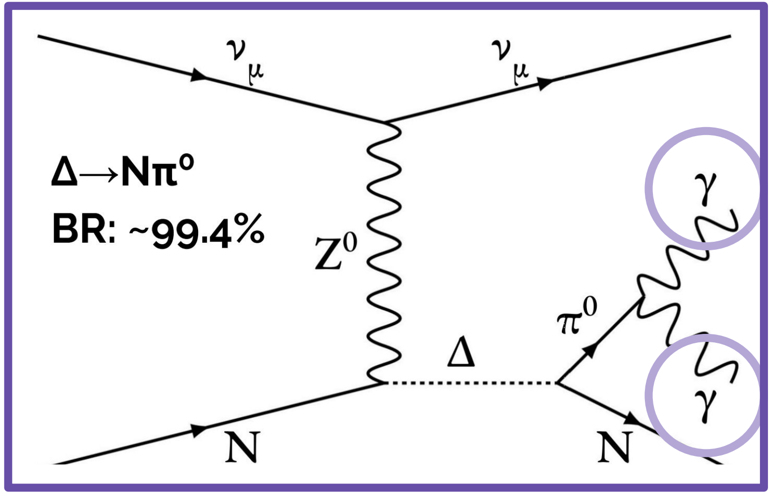


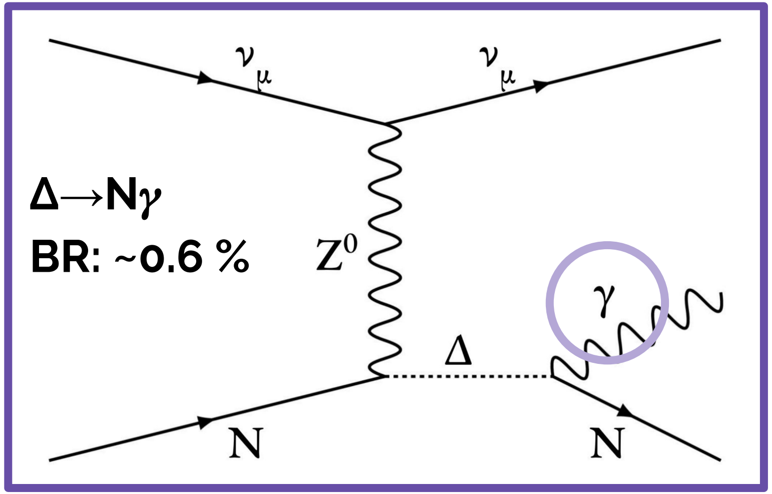
Single Photon Interpretation: NC Delta Radiative Decay Mis-Estimation Hypothesis

Delta Radiative Decay

- $\Delta \to N\gamma$ is a rare process with a single photon in the final state that was the **leading single-photon background in MiniBooNE**
- It is predicted by the Standard Model but has **never been directly measured** in neutrino scattering
- For $\Delta(1232)$, the branching ratio according to the PDG is:
  - $\Delta \to N\pi^0$ (99.4%)
  - $\Delta \to N\gamma$ (0.6 %)
- This is based off of a phenomenological calculation using pion photon-production data*.

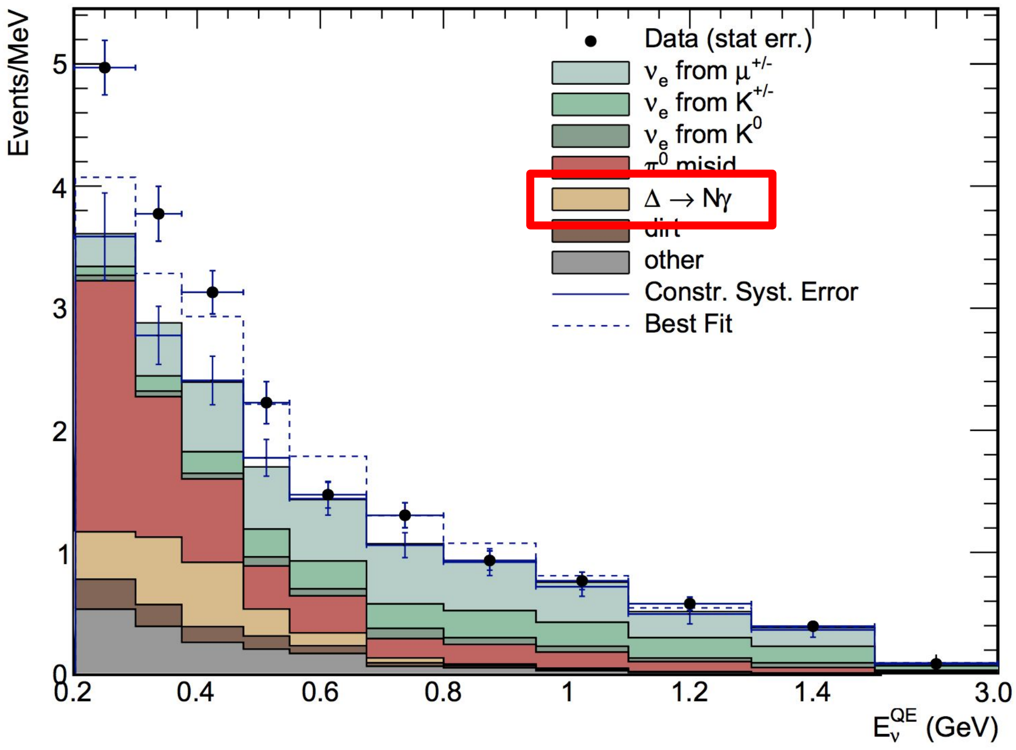
*Phys. Rev. C 65, 065204 (2002)





Photon Backgrounds in MiniBooNE

- **MiniBooNE estimated NC Δ →Nγ rate** in MC from an in situ NC π^0 measurement using branching ratio
- **Could an enhanced rate of Δ→Nγ could explain the observed excess** under a photon-like hypothesis?

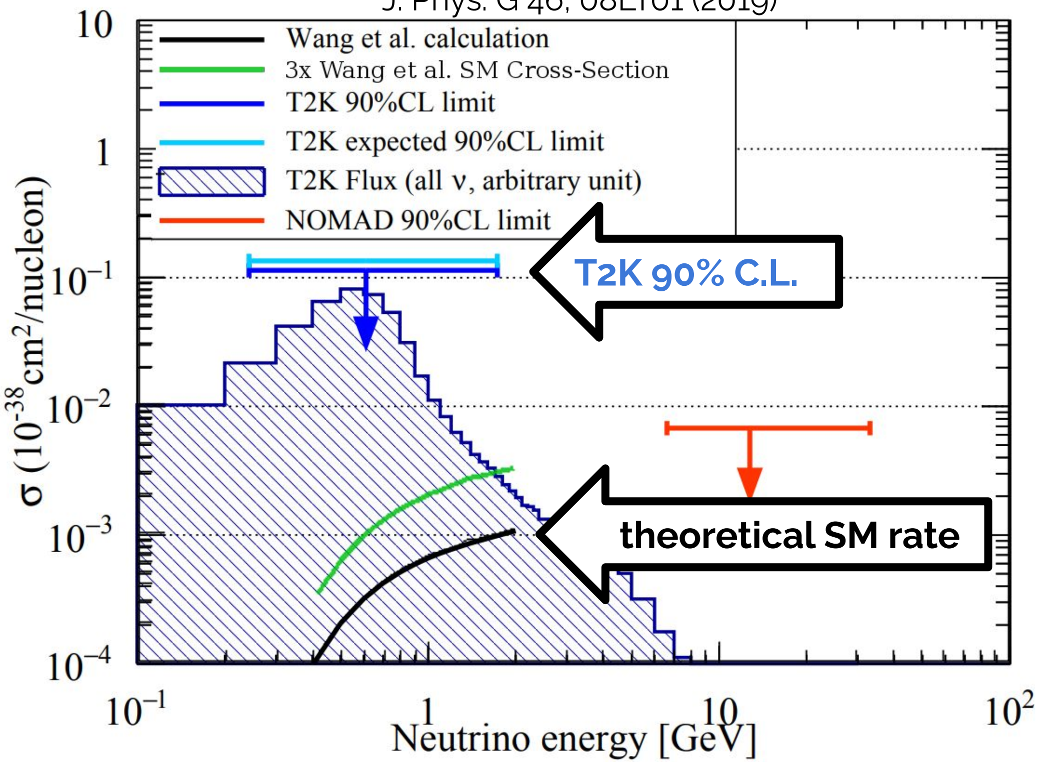


Phys. Rev. Lett. 121, 221801 (2018)

Current Limits on NC $\Delta \rightarrow N\gamma$

- Current best limit in the neutrino energy range <1 GeV is from T2K measurement made in the tracker near detector
- **2019 T2K 90% C.L.* is O(100x) the SM prediction**

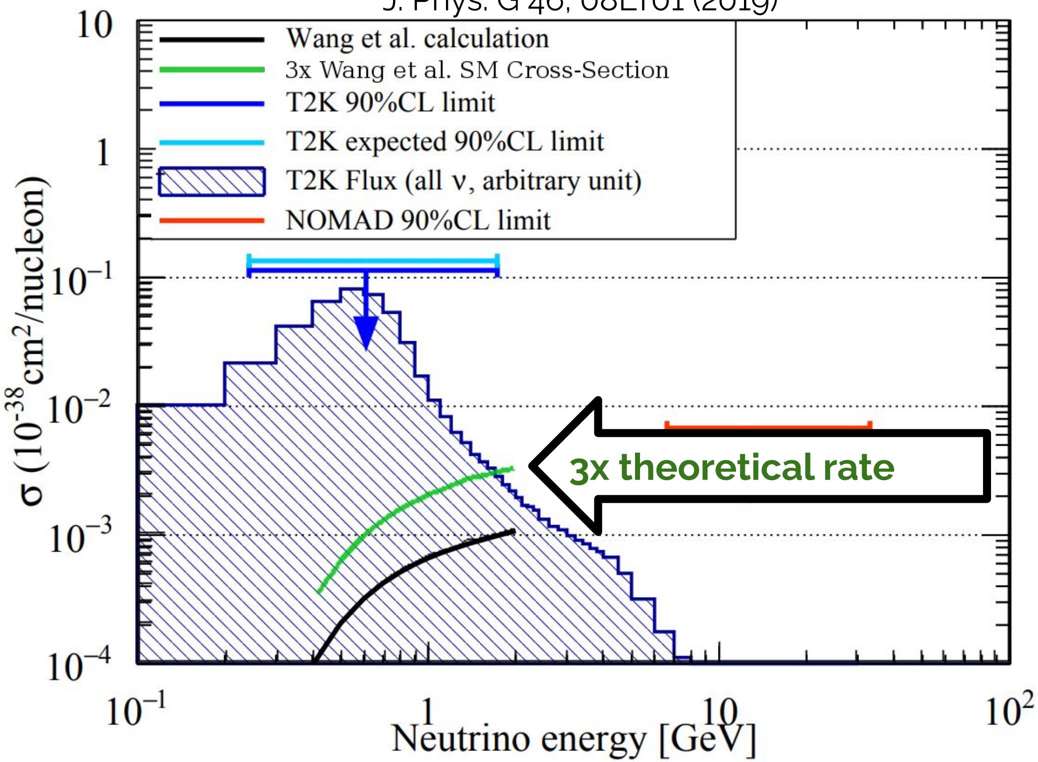
*J. Phys. G 46, 08LT01 (2019)



NC Δ Radiative Decay Signal Prediction

- Using the MiniBooNE Nuance MC, it was found that **3.18x predicted rate** of NC $\Delta \rightarrow N\gamma$ could explain MiniBooNE anomaly*
- Currently well within the experimental limits but **even an enhanced rate of this rare process is challenging to measure**

J. Phys. G 46, 08LT01 (2019)



*Nucl.Phys.Proc.Suppl. 112 (2002) 161-170

The MicroBooNE Single Photon Search

Selection Stages

Take reconstructed tracks and showers → Find candidate vertices matching 1γ topologies → Apply pre-selection cuts to remove obvious backgrounds → Remove backgrounds using tailored boosted decision trees (BDTs)

↓

Goal is a high sensitivity search for NC $\Delta \rightarrow N\gamma$ events over background prediction, fit to an excess using in-situ NC π^0 constraint

Selection Stages

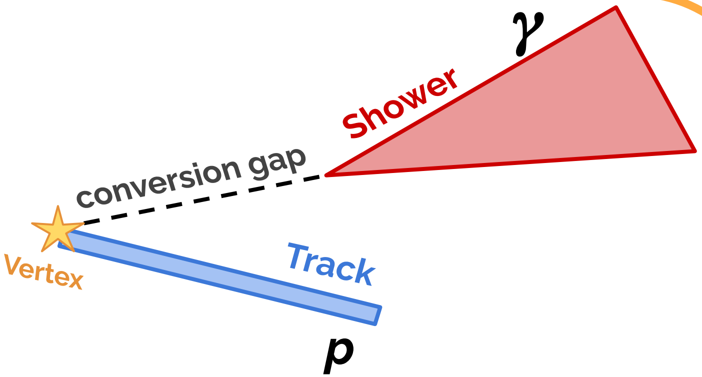
Take reconstructed tracks and showers*

Find candidate vertices matching 1γ topologies

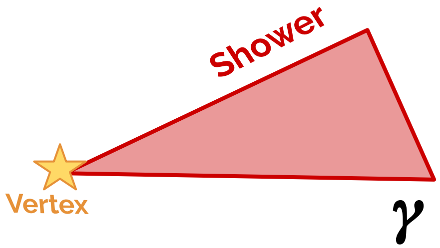
*The Pandora multi-algorithm approach to automated pattern recognition of cosmic-ray muon and neutrino events in the MicroBooNE detector. Eur.Phys.J. C78 (2018) no.1, 82

Topological Selections

Find candidate vertices matching 1γ topologies



1γ1p is our primary analysis. The existence of a short proton-like track improves reconstruction efficiency. **45.3% of true 1γ events.**



1γ0p is slightly more difficult, but provides a secondary dataset for comparison and a joint fit yields maximum sensitivity. **54.7% of true 1γ events.**

Selection Stages

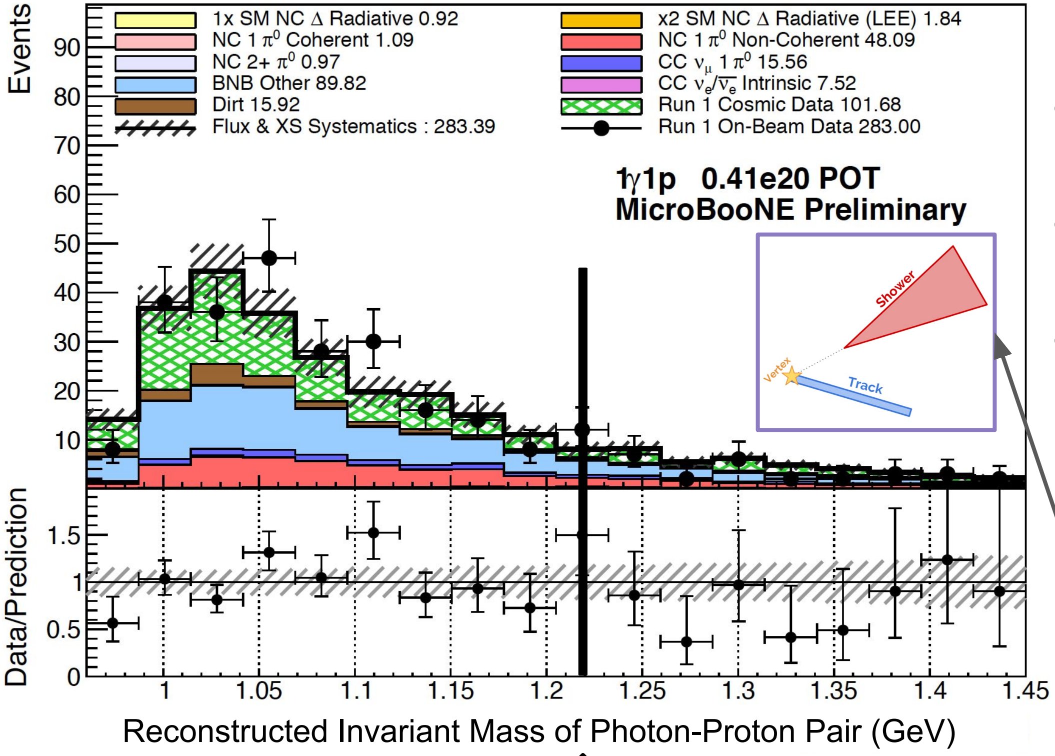
Take reconstructed tracks and showers → **Find candidate vertices matching 1γ topologies** → **Apply pre-selection cuts to remove obvious backgrounds**

These **target obvious backgrounds** like cosmic events and mis-reconstructions. Includes cuts on:

- Fiducial volume and containment
- Minimum shower energy
- Track calorimetry (1p only)

1γ1p Topological+Precuts Selection Stage

Apply pre-selection cuts to remove obvious backgrounds



M_Δ = 1.232 GeV

- Showing results using a small unblinded data set
- Applied topological requirements and pre-selection cuts
- **Signal:background ~1:300**
- Would expect signal events to peak around Δ invariant mass but background events skew to low reconstructed invariant mass

1γ1p = 1 track + 1 shower

Selection Stages

Take reconstructed tracks and showers → Find candidate vertices matching 1γ topologies → Apply pre-selection cuts to remove obvious backgrounds → Remove backgrounds using tailored boosted decision trees (BDTs)

BDT Structure For Selections

Remove backgrounds using tailored boosted decision trees (BDTs)

For each topology (1γ1p and 1γ0p) a series of BDTs targeting key backgrounds **trained independently and the selection cuts optimized simultaneously.**

Each BDT trains on **tailored set of kinematic and calorimetric variables** and output a score per event from background-like to signal-like.

For 1γ1p there are 5 BDTs:

- **Cosmic**
- **NC π^0**
- **Second shower π^0 mis-ID**
- ν_e
- **All other neutrino backgrounds**

For 1γ0p there are 3:

- **Cosmic**
- **NC π^0**
- **All other neutrino backgrounds**.

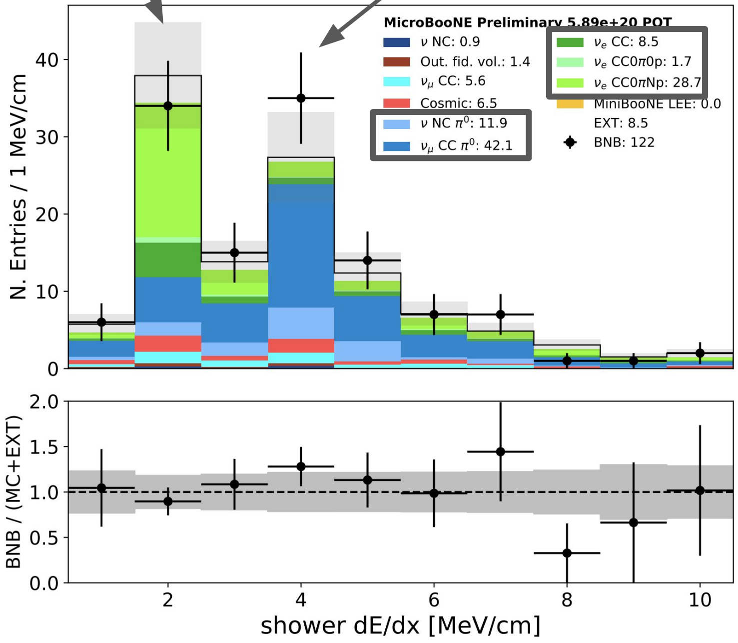
Because there are fewer reconstructed parameters for a single shower topology with no track the background training, the definitions for 1γ0p were consolidated (i.e. all other neutrino encompasses ν_e rejection)

1γ1p BDT Training Variable: Shower dE/dx

Remove backgrounds using tailored boosted decision trees (BDTs)

Electrons from ν_e peak at 2 MeV/cm

Photons from π^0's peak at 4 MeV/cm

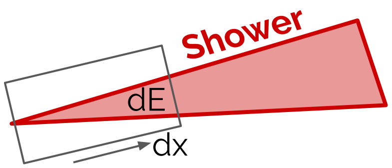


The dE/dx is the energy deposited per unit length at the start (4cm) of the shower.

Because photons pair produce into e^+e^-, they deposit twice the charge as a single e^-.

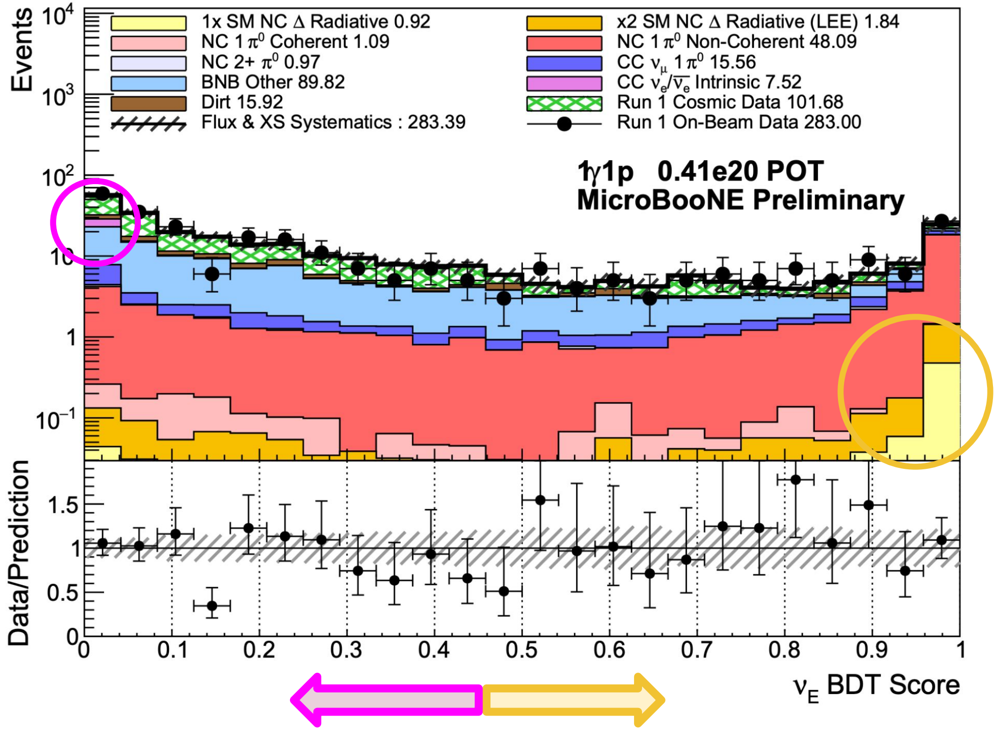
A minimum ionizing particle deposits 2MeV/cm in Ar:

- single $e^{+/-}$ → **2 MeV/cm**
- $\gamma \rightarrow e^-e^+$ → **4 MeV/cm**



1γ1p ν_e Background Rejection BDT

Remove backgrounds using tailored boosted decision trees (BDTs)

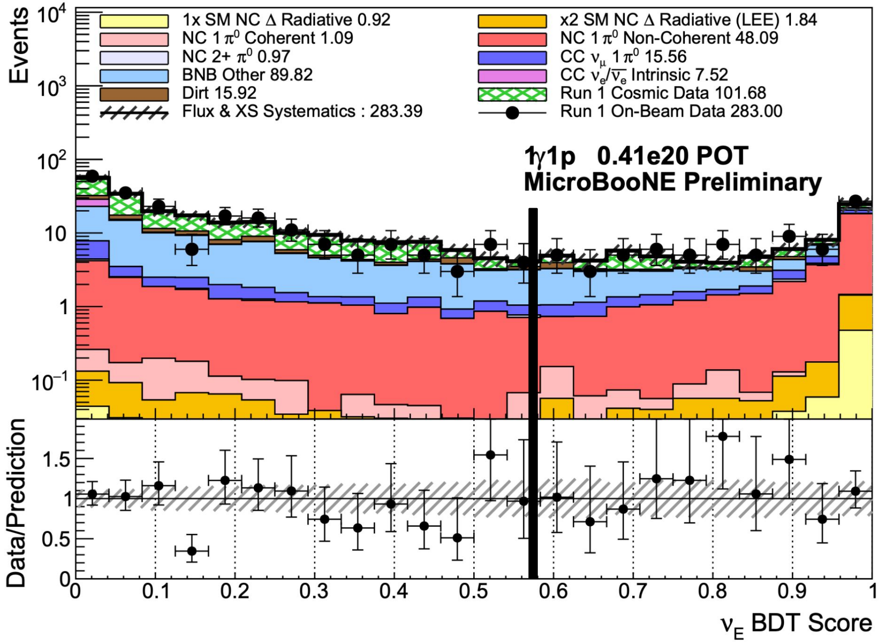


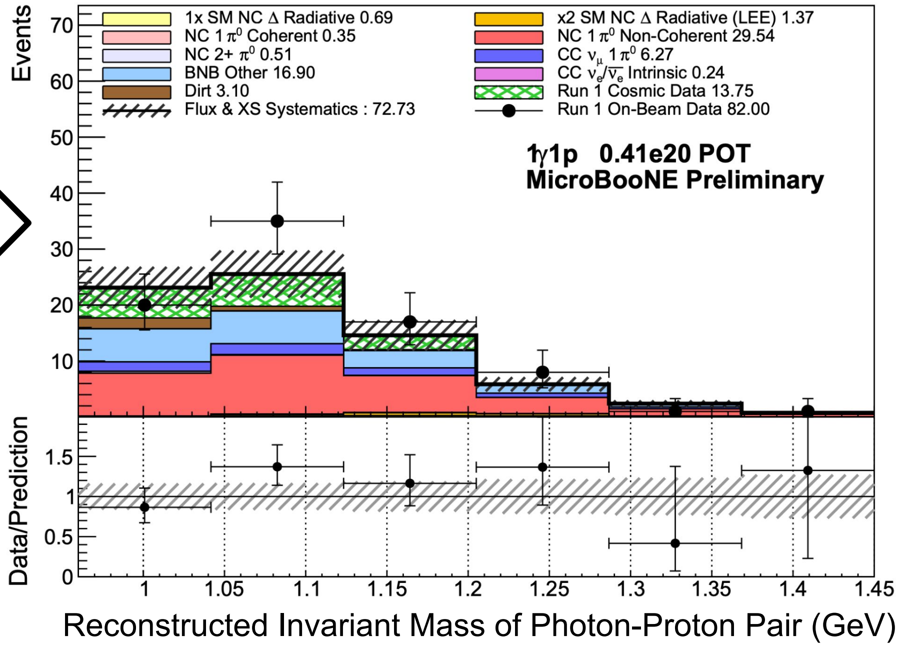
ν_e Background NC Δ Radiative Signal

- Trains on 1γ1p signal and ν_e background
- See strong separation between signal and background
- Majority of ν_e background events clustered at 0 showing strong rejection e/γ separation

$1\gamma 1p$ ν_e Background Rejection BDT Cut

Remove backgrounds using tailored boosted decision trees (BDTs)





Optimized BDT cut at 0.57 **removes 96.8% of ν_e background** events relative to pre-selection cuts stage.

Selection Stages

Take reconstructed tracks and showers *

Find candidate vertices matching 1γ topologies

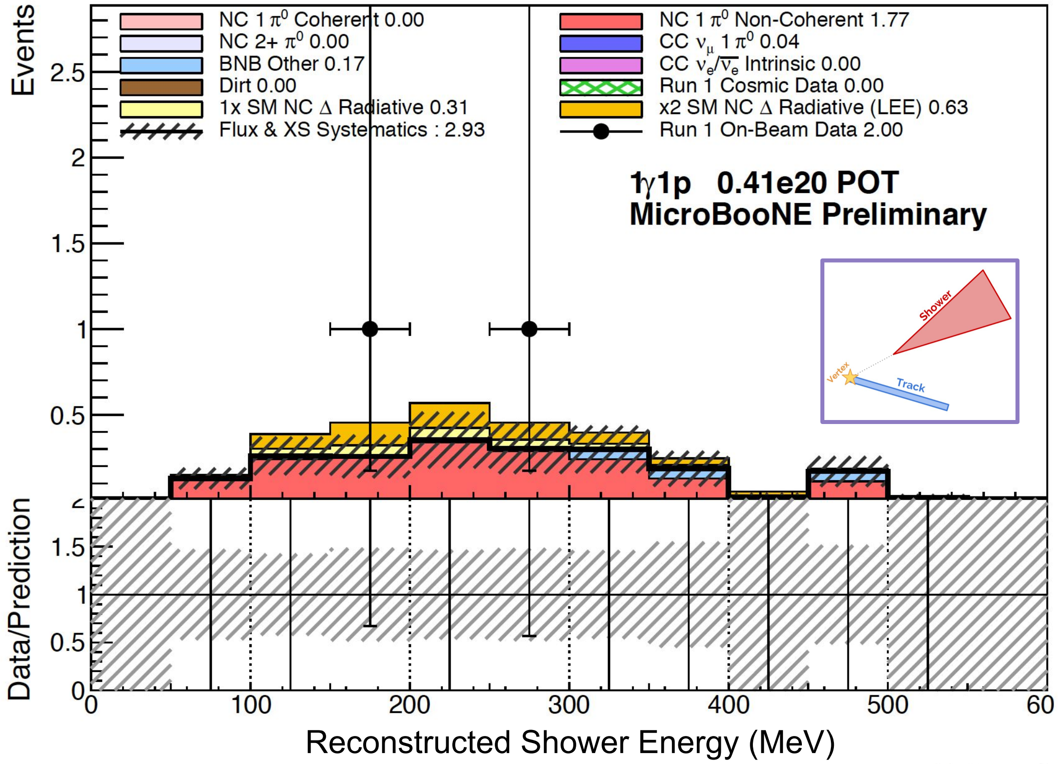
Apply pre-selection cuts to remove obvious backgrounds

Remove backgrounds using tailored boosted decision trees (BDTs)

Goal is a high sensitivity search for NC $\Delta \rightarrow N\gamma$ events over background prediction, fit to an excess using in-situ NC π^0 constraint

Final Selection

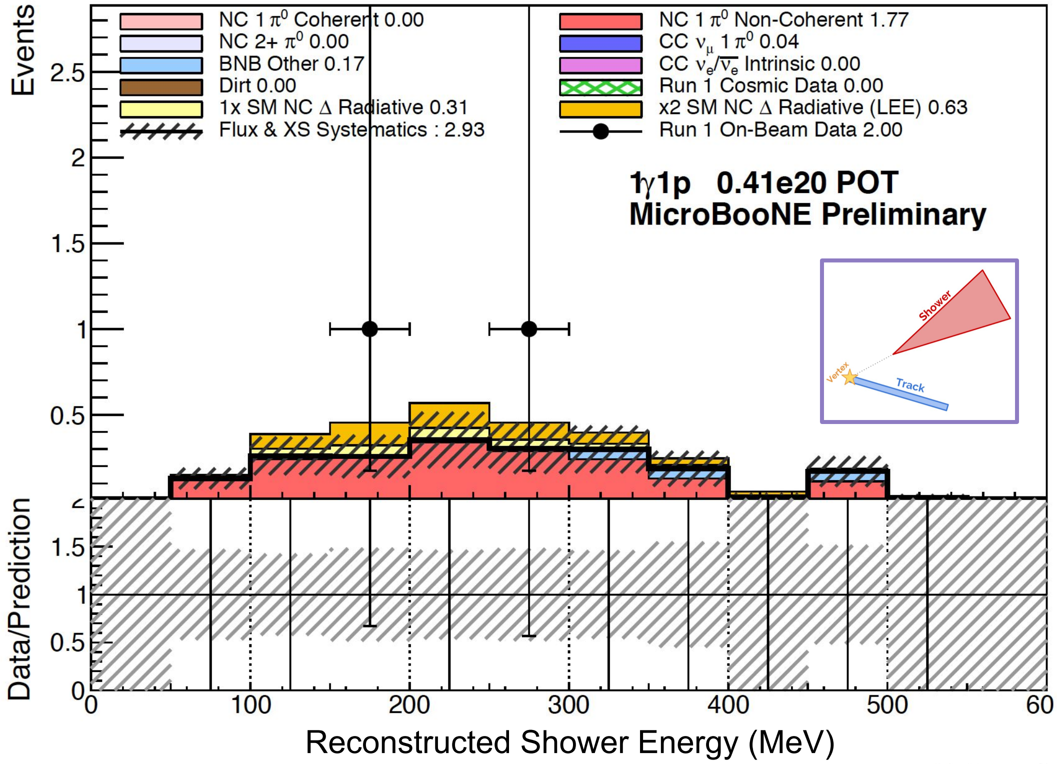
Goal is a high sensitivity search for NC Δ→Nγ events



- **1γ1p final selection** with topological, pre-selection, and 5 optimized BDT cuts applied
- Showing results using the unblinded sample, full data set is ~25x larger
- See 2 data events, expect ~3 events from MC that are mostly backgrounds

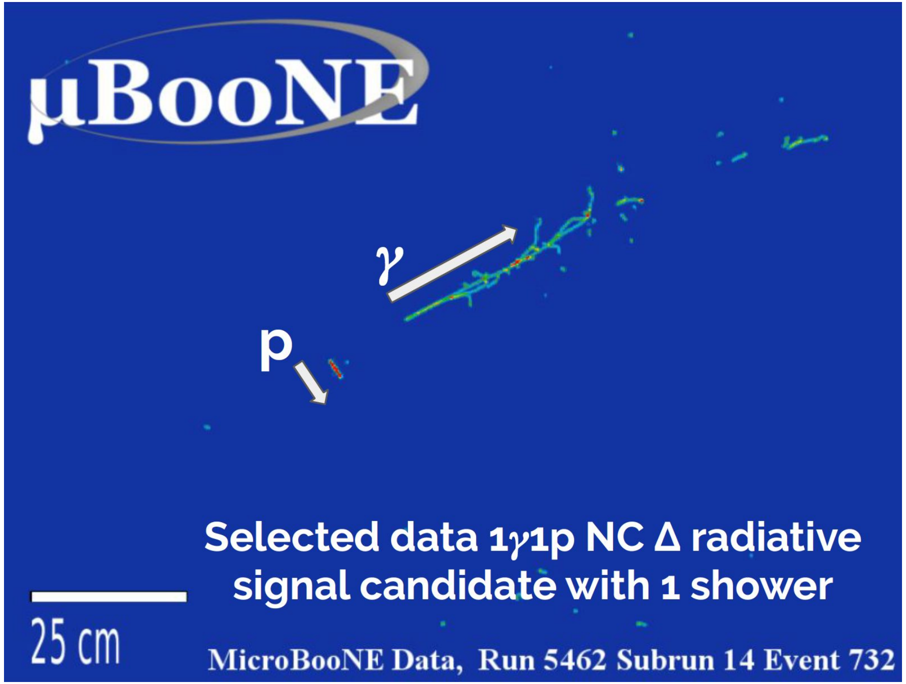
Final Selection

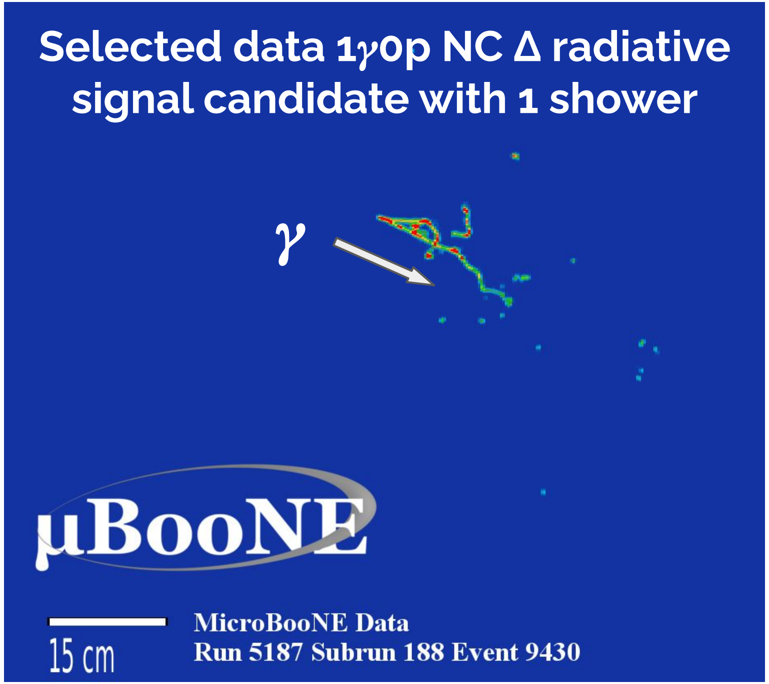
Goal is a high sensitivity search for NC Δ→Nγ events

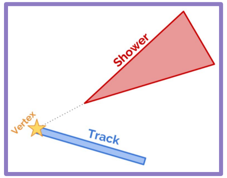


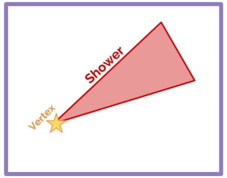
- **Reject >99% of total backgrounds** relative to the precuts stage, **strong rejection of ν_e backgrounds** to test photon hypothesis
- **NC π⁰ events comprise >85% selected backgrounds**
- Note that selected photons from the NC π⁰ background overlap in shower energy with the signal.

Selected Data Candidate Events



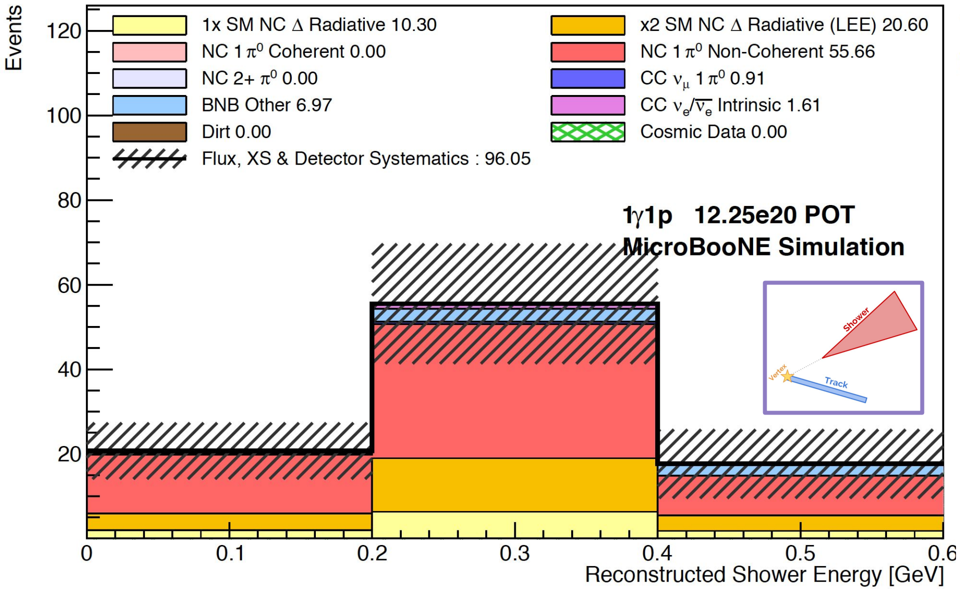


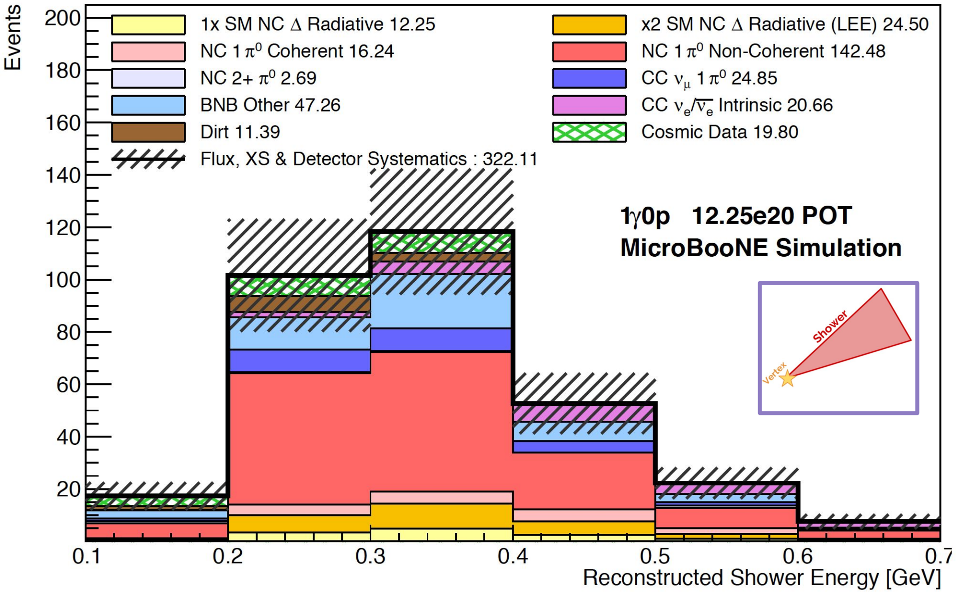




Projected Final Selection

Goal is a high sensitivity search for NC $\Delta \to N\gamma$ events

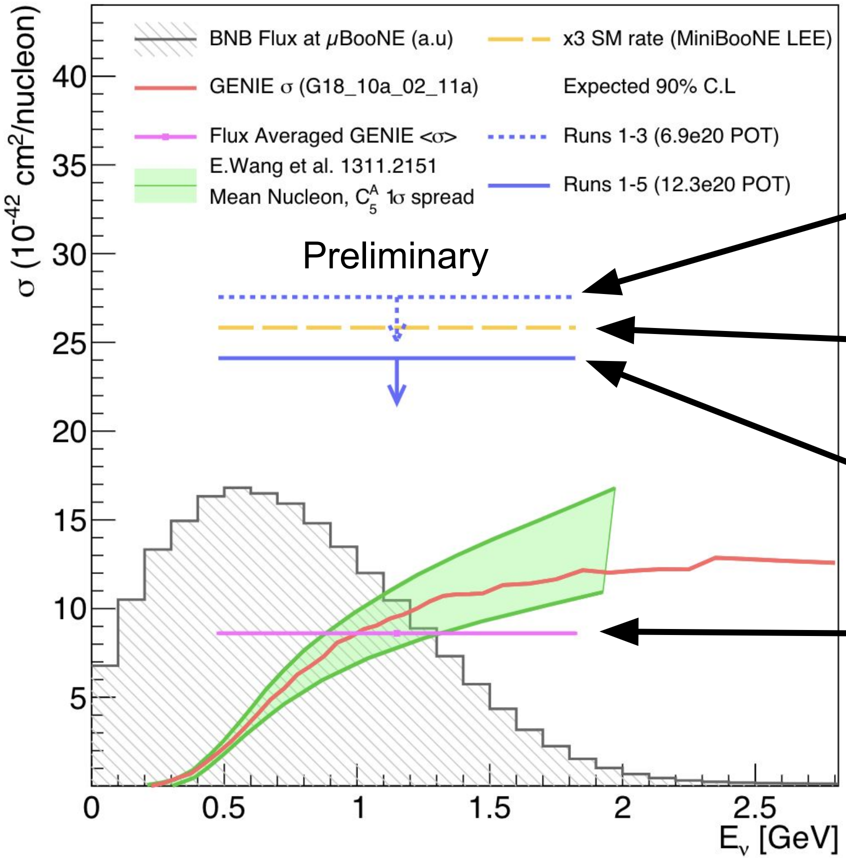




- MC prediction for final selections scaled to full MicroBooNE data set
- Systematic errors on the order of ~25-30%, can fit simultaneously to MicroBooNE in situ NC π^0 selections to reduce flux and cross section uncertainties

Projected Sensitivity

MicroBooNE Projected Sensitivity



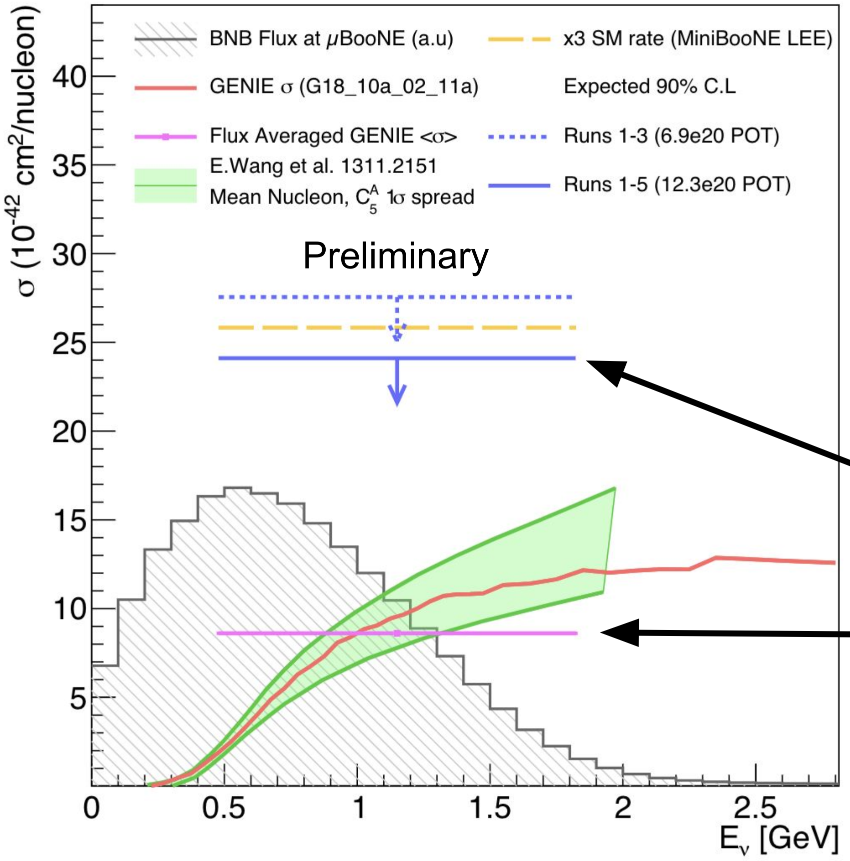
90% C.L. for **50% data**

3x SM rate $\Delta \rightarrow N\gamma$

90% C.L. for **100% data**

GENIE flux averaged xsec

MicroBooNE Projected Sensitivity



>30x improvement over current best limit from T2K

Expect to be able to probe into region of 3x SM rate for MiniBooNE interpretation with full data set.

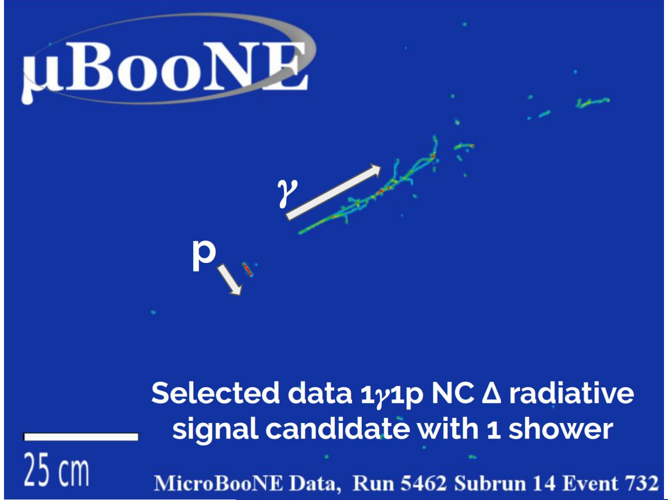
90% C.L. for **100% data**

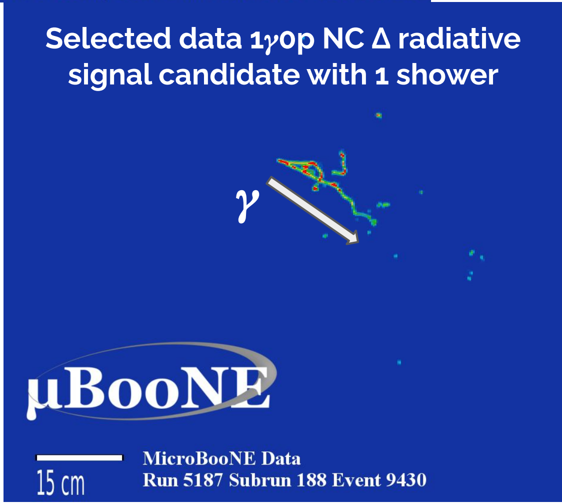
GENIE flux averaged xsec

Conclusions

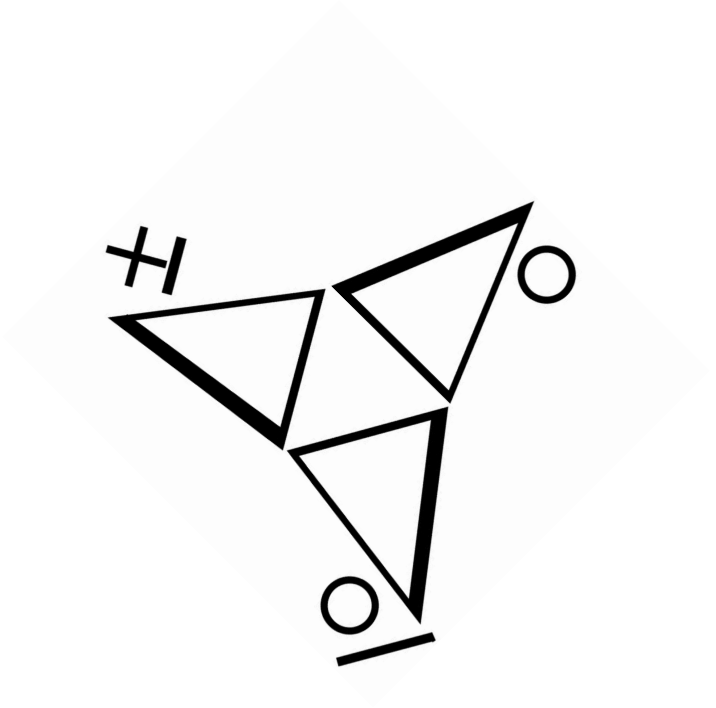
MicroBooNE Single Photon Analysis

- Expecting publication soon on **world-leading constraint neutrino-induced NC Δ⟶Nγ**, and this result will offer a first look at the true source of the MiniBooNE anomalous excess
- For the full MicroBooNE data set (12.25e20 POT), projected to **exclude the MiniBooNE anomalous excess in favor of the Standard Model NC Δ→Nγ hypothesis at >95% C.L.** under a photon hypothesis.
- MicroBooNE is demonstrating how LArTPC detector technology can be used to search for rare neutrino interactions with a photon in the final state. In the near future these include coherent photon production and more exotic photon-like processes.





Thanks!



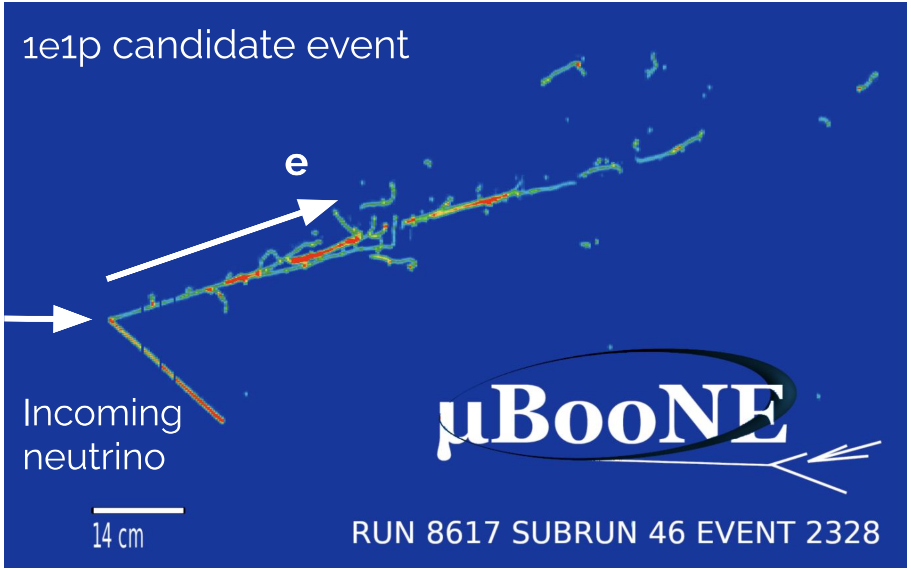
Backup

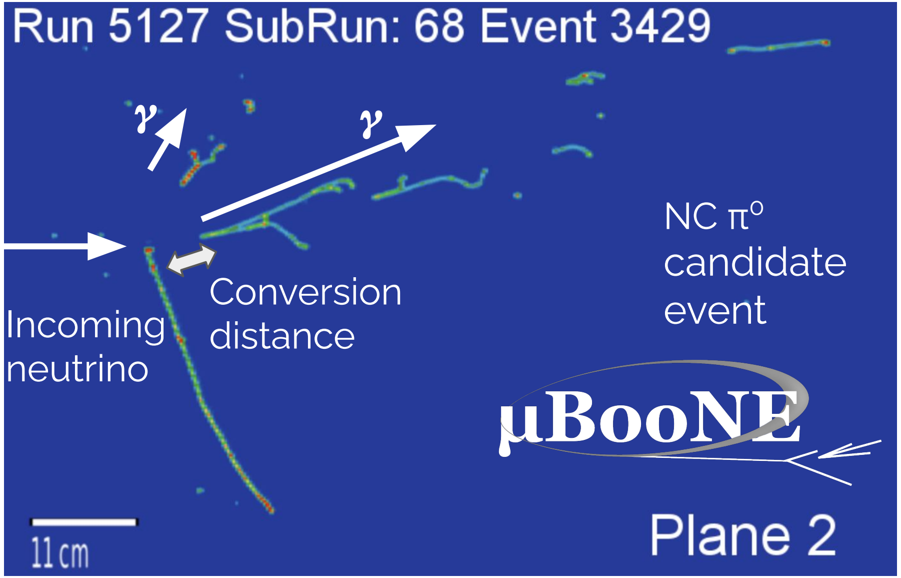
Photon Conversion Distance

* Phys. Rev. D99, 091102(R) (2019)

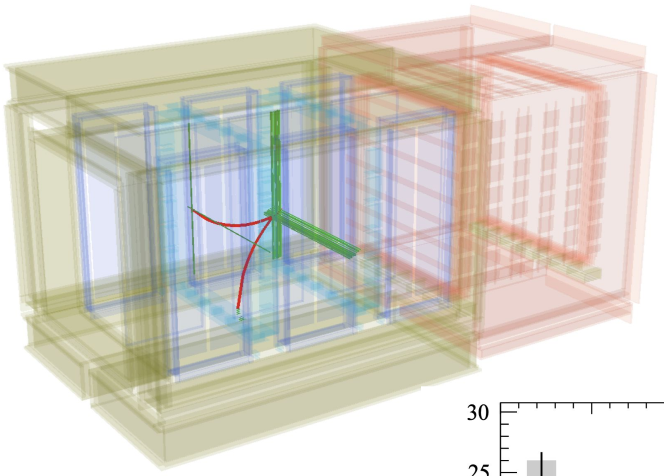
In a LArTPC we can observe the photon conversion distance:

- A **single electron will immediately start to ionize the Ar** starting at the interaction vertex.
- A **photon travels before it pair-produces** into e^+e^- creating a **gap between the vertex and the shower start.** The photon conversion length in Ar is ~20cm*.

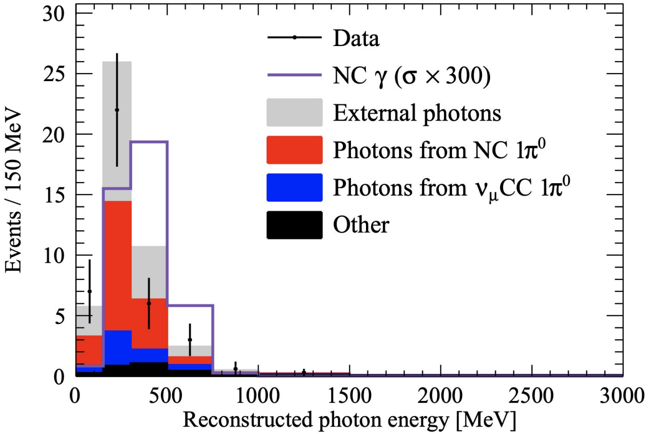




T2K NC Single Photon Search



Example T2K NC1γ data candidate



Reconstructed photon energy of the T2K NC1γ selection

J. Phys. G 46, 08LT01 (2019)

- Used the ND280 tracker detector, the T2K near detector
- Peak neutrino energy similar to BNB, ~0.6GeV
- NEUT as neutrino event generator
- Define signal topology as two tracks from e^+e^- pair
- Final selection 95% photons but dominated by external backgrounds (photons that originate outside the detector) and NC π^0, sensitivity limited by associated uncertainties

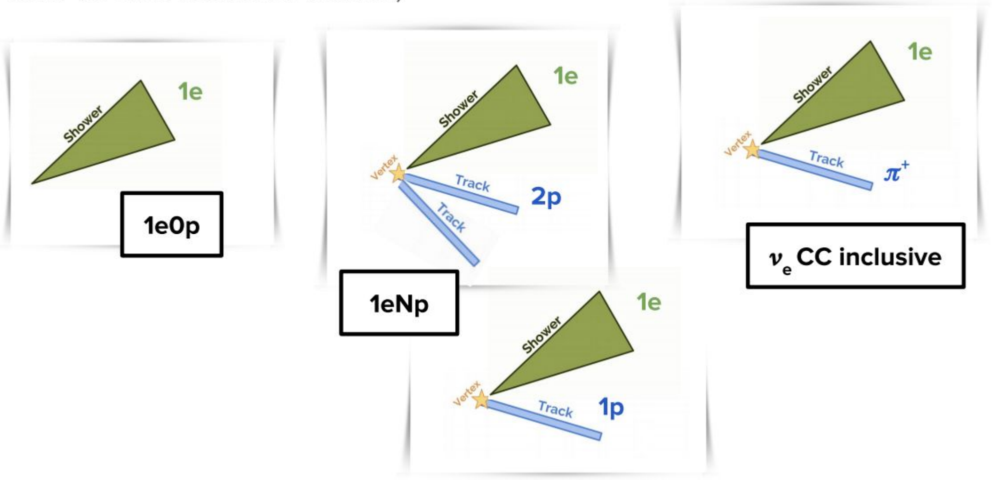
MicroBooNE eLEE Searches

Three independent, complementary analyses are underway, targeting different topologies (**1e** and **0p, Np, or CC inclusive**) and using different end-to-end reconstruction, particle identification, and selection methods:

(1) Pandora Based

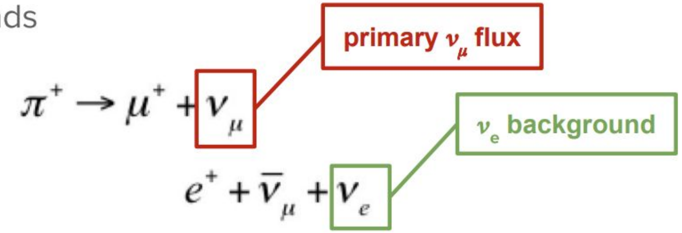
(2) Deep Learning Based

(3) Wire Cell + Pandora Based (Hybrid)



Strategy shared among all eLEE analyses:

- **Reduction of cosmogenic background**
- **Reduction of π^0 background** and **validation** through NC/CC π^0 sidebands
- **Constraint of intrinsic ν_e CC background** through ν_μ CC sidebands



Total NC Single Photon Cross Section

Percent	Resonance	Mass [MeV]	BR to $N\gamma$	ξ
44.79	Δ^0	1230	0.55–0.65	**49.9%**
37.07	Δ^+	1230	0.55–0.65	**41.3%**
3.37	N^0	1535	0.01–0.25	**1.44%**
2.45	N^0	1520	0.31–0.52	**2.18%**
1.96	N^+	1535	0.15–0.30	**1.01%**
1.50	N^0	1440	0.02-0.04	0.10%
1.36	N^+	1520	0.3-0.53	**1.24%**
0.987	N^+	1440	0.035–0.048	0.08%
0.886	N^0	1720	0.0–0.016	0.03%
0.734	Δ^{++}	1230	0.55-0.65	**0.81%**
0.647	N^0	1680	0.021–0.046	0.05%
0.616	Δ^0	1700	0.22–0.60	**0.63%**
0.514	Δ^+	1700	0.22–0.60	**0.53%**
0.463	N^+	1720	0.05–0.25	0.02%
0.440	N^+	1680	0.21–0.32	**0.24%**
0.248	N^+	1675	0-0.02	0.01%
0.201	N^0	1710	0.002–0.08	0.03%
0.188	Δ^0	1905	0.012–0.036	0.01%
0.184	N^+	1700	0.01–0.05	0.02%
0.162	Δ^+	1905	0.012–0.036	0.01%
0.136	Δ^0	1950	-	-
0.130	Δ^+	1950	-	-
0.127	Δ^0	1620	0.03–0.10	0.02%
0.121	N^0	1675	0–0.15	0.03%
0.102	Δ^+	1620	0.03–0.10	0.02%
0.101	N^+	1650	0.04–0.20	0.03%
0.0964	Δ^0	1920	-	-
0.0856	Δ^+	1920	-	-
0.0768	N^+	1710	0.0–0.02	$<$0.01%
0.0689	Δ^0	1910	0.0–0.02	$<$0.01%
0.0640	N^0	1650	0.003–0.17	0.02%
0.0630	N^0	1700	0.01–0.13	0.01%
0.0512	Δ^+	1910	0.0–0.02	$<$0.01%

MicroBooNE MC uses GENIE neutrino event generator.

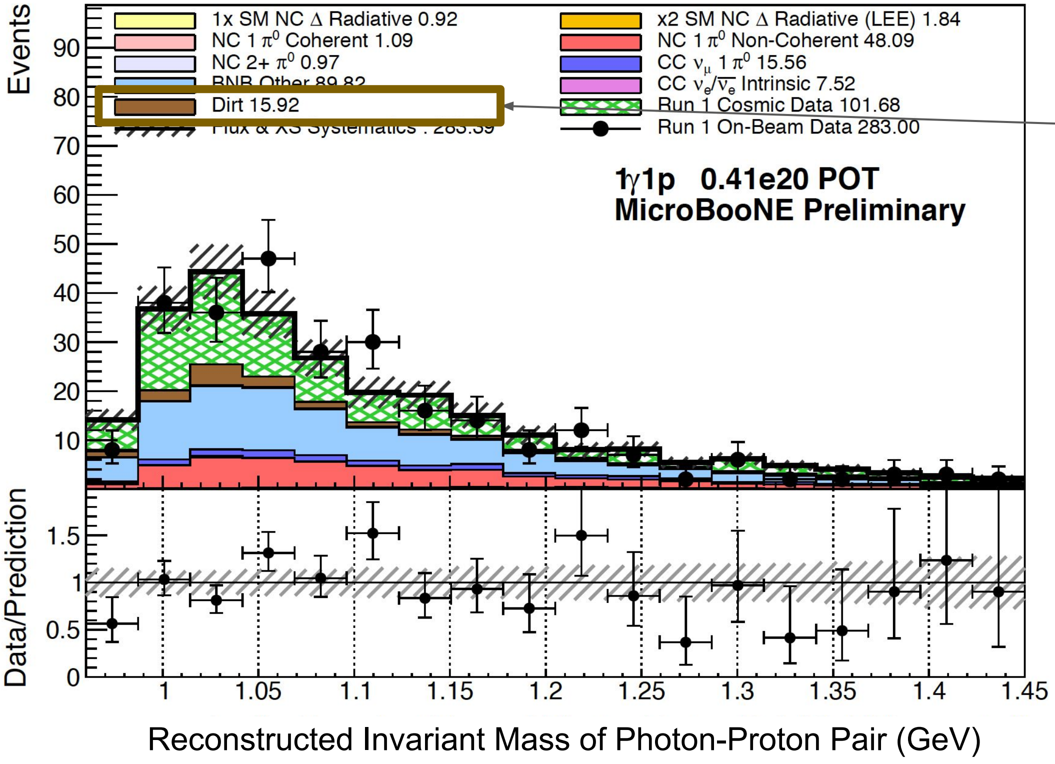
This isn't a generic NC single photon search:

- Not considering **higher order resonances** (~8%): these decay channels not enabled in GENIE by default
- Not considering other modes of Δ production like **coherent**(~10%) that would be subleading, not currently simulated in GENIE

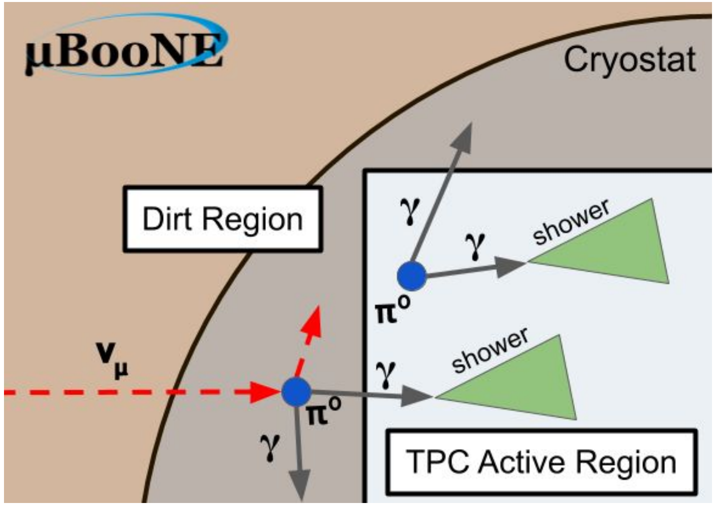
Expect resonant NC Δ(1232)→Nγ signal to account for ~80% of the expected single photon events at energies <1GeV.

⇦ Estimated contributions to Nγ rate for each parent resonance

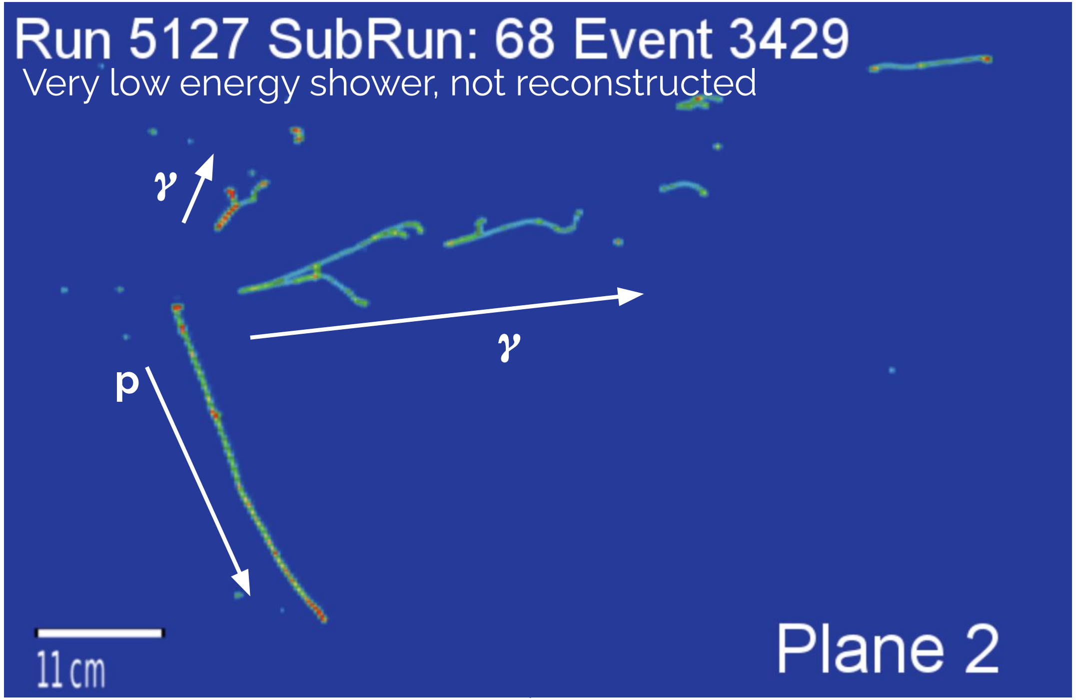
Dirt Backgrounds



Dirt events are neutrino interactions that occur outside of the active TPC volume. Although they comprise only ~6% of total background events here, they were an important category for MiniBooNE.



NC π^0 Background Example

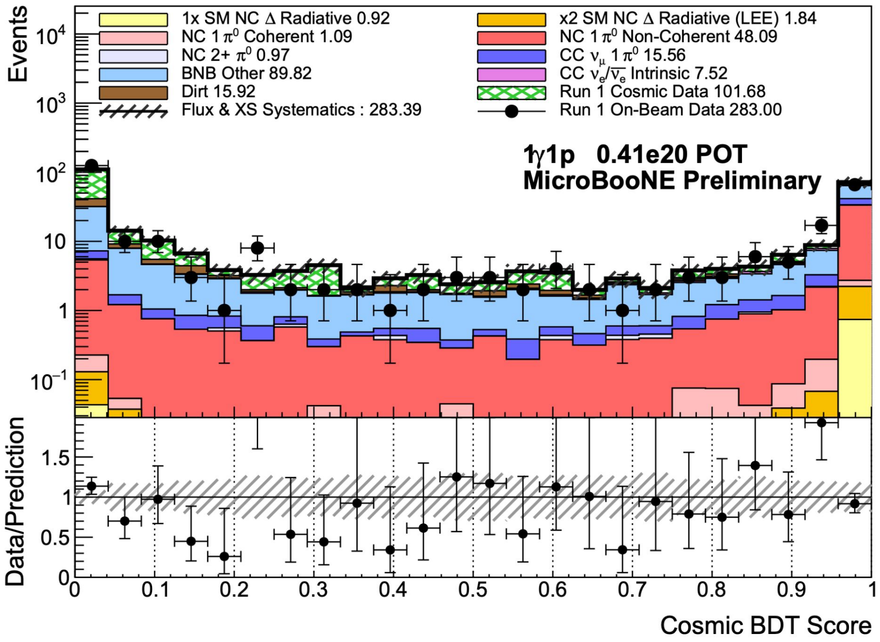


This is one of the most signal-like candidate data events, although it isn't selected in the final stage. The reconstructed M_Δ = 1.17 GeV.

- **If second photon shower is missed/ mis-reconstructed, looks nearly identical to signal**
- Reconstructed invariant mass can be close to expected value of M_Δ if second photon is low energy

$$\nu_\mu + p \to \nu_\mu + \Delta^+$$
$$\hookrightarrow p + \pi^0$$
$$\hookrightarrow \gamma + \gamma$$

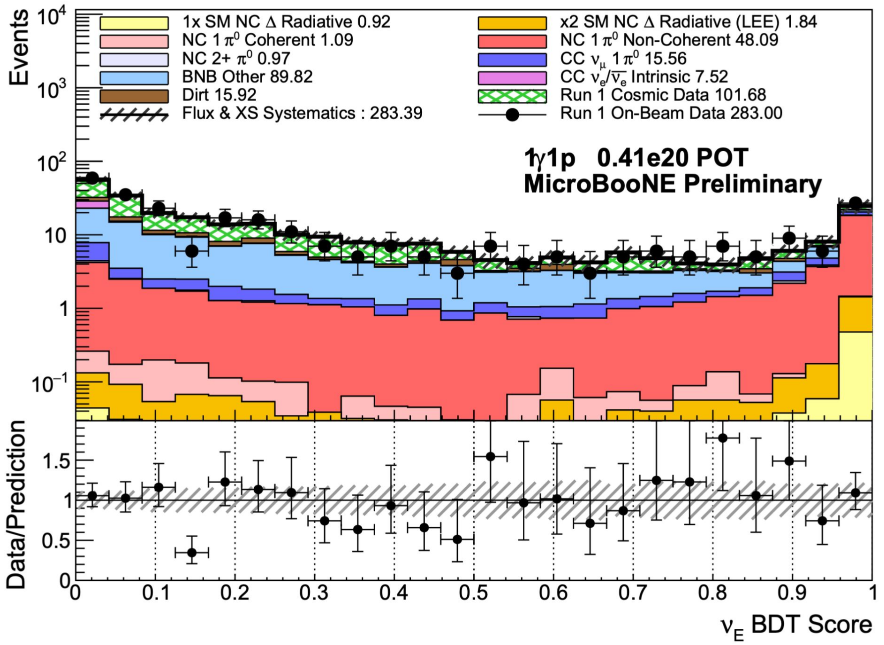
1γ1p BDT Responses: Cosmic



Top training variables:

1. Reconstructed track truncated mean dE/dx
2. Ratio of the shower impact parameter to the shower conversion distance
3. Reconstructed Δ momentum in the Z direction
4. Pandora neutrino score
5. Pandora track score

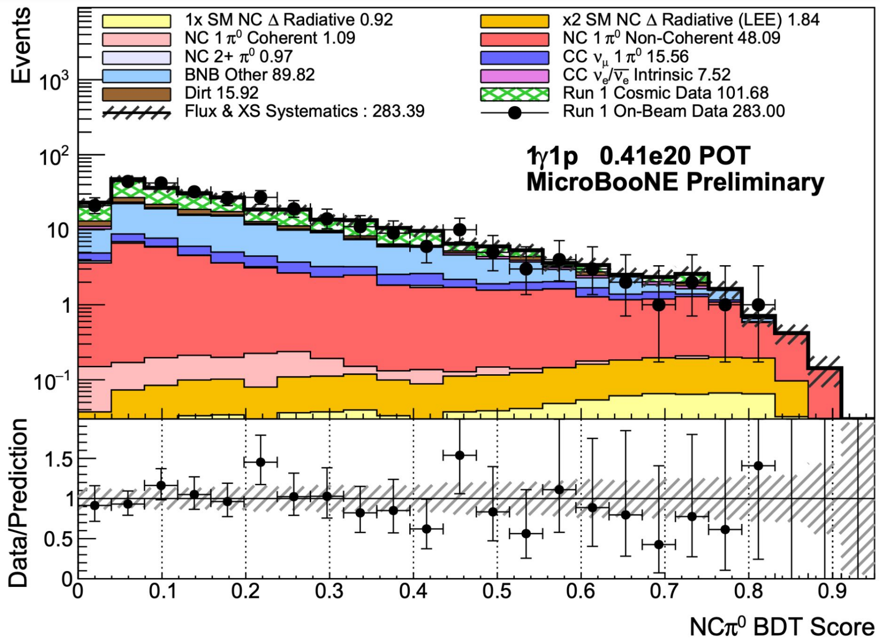
$1\gamma1p$ BDT Responses: Nue



Top training variables:

1. Reconstructed shower conversion distance
2. Reconstructed Δ invariant mass
3. Minimum distance from the shower to the track start or end
4. Reconstructed shower dE/dx
5. Minimum distance between any point in the track and any hit in the shower

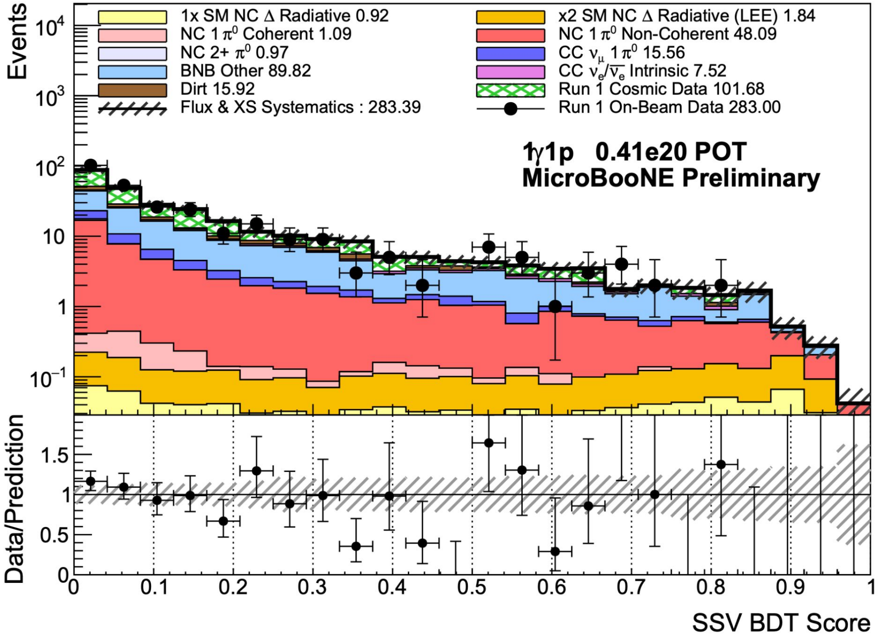
1γ1p BDT Responses: NC π^0



Top training variables:

1. Reconstructed Δ invariant mass
2. Ratio of the shower impact parameter to the shower conversion distance
3. Reconstructed shower energy
4. Photon transverse momentum
5. Distance from shower end to active TPC boundary

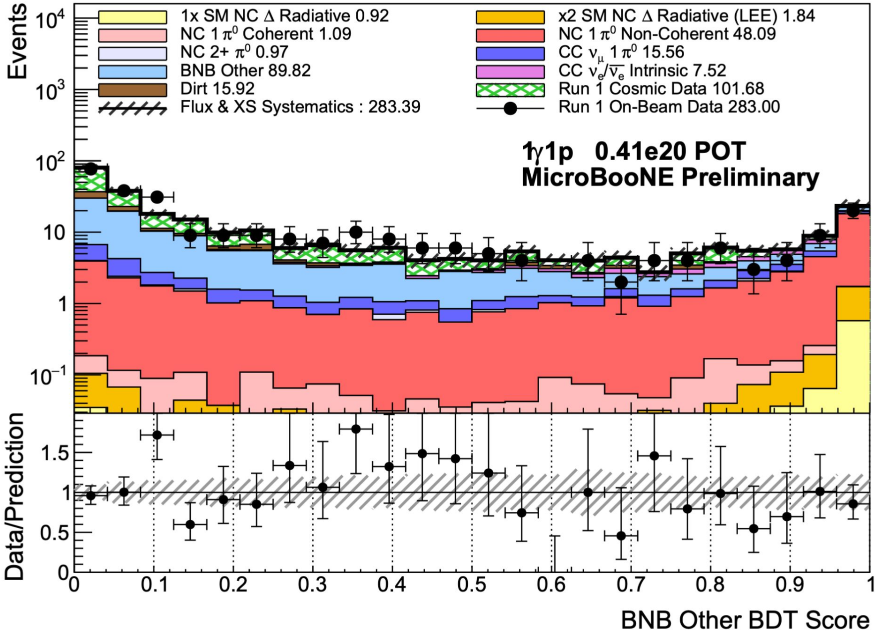
1γ1p BDT Responses: SSV



Top training variables:

1. Number unassociated hits within 10cm of vertex
2. Conversion distance of the closest 2D hit cluster candidate
3. Best reconstructed invariant mass of any 2D hit cluster candidate
4. Impact parameter of the closest 2D hit cluster candidate
5. Reconstructed shower energy of the closest 2D hit cluster candidate

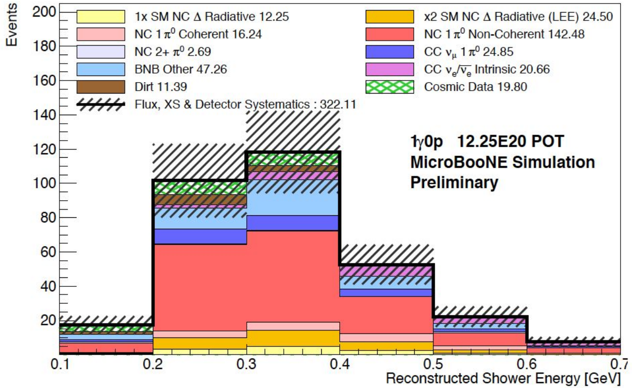
1γ1p BDT Responses: BNB Other

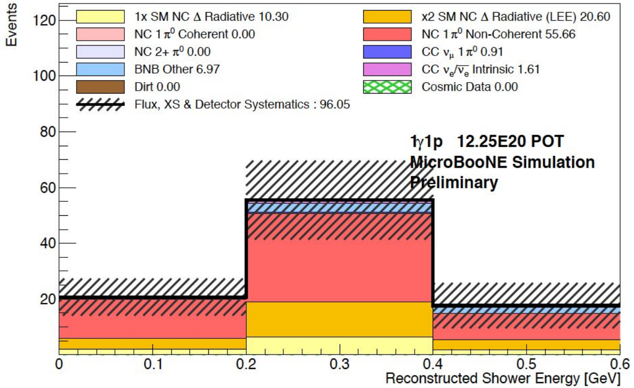


Top training variables:

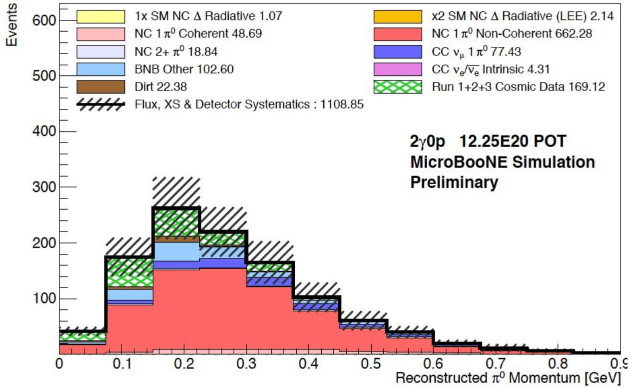
1. Ratio of the shower impact parameter to the shower conversion distance
2. Pandora shower score
3. Reconstructed track truncated mean dE/dx
4. Minimum distance from the shower to the track start or end
5. Reconstructed Δ invariant mass

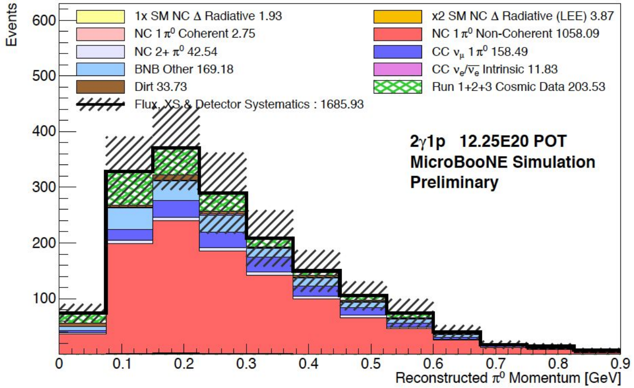
In-Situ NC π^0 Measurement





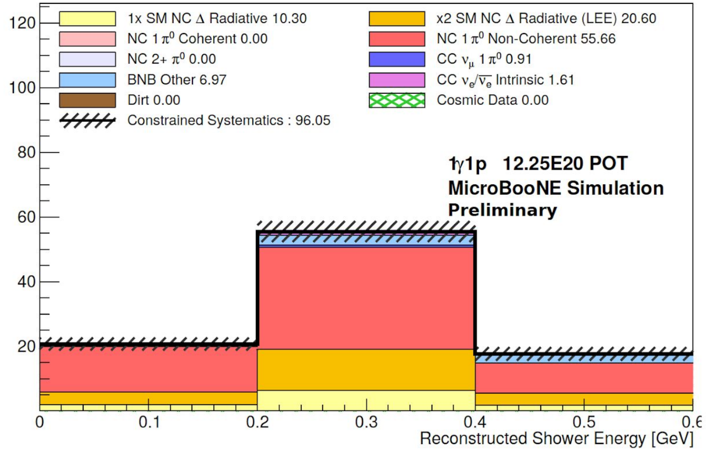
Single photon 1γ0p and 1γ1p selections

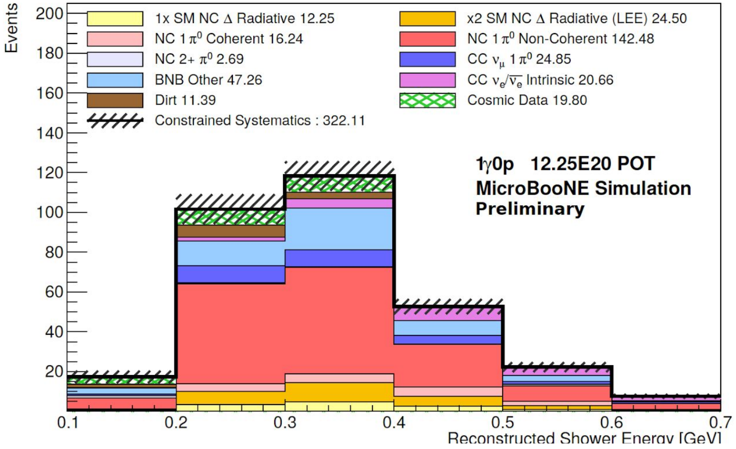




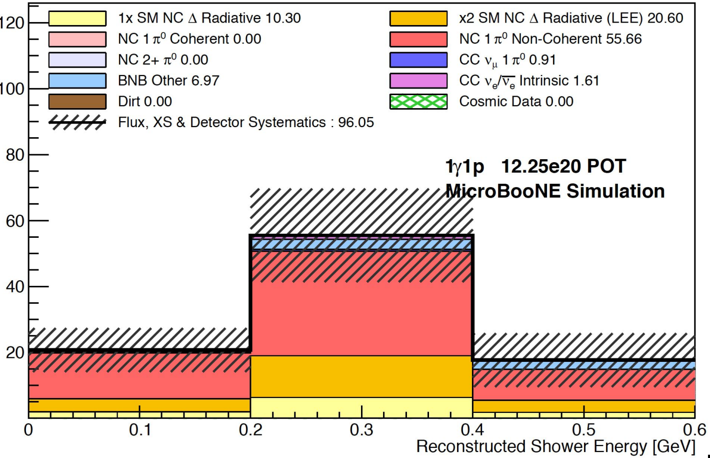
Complementary NC π^0 2γ0p and 2γ1p selections

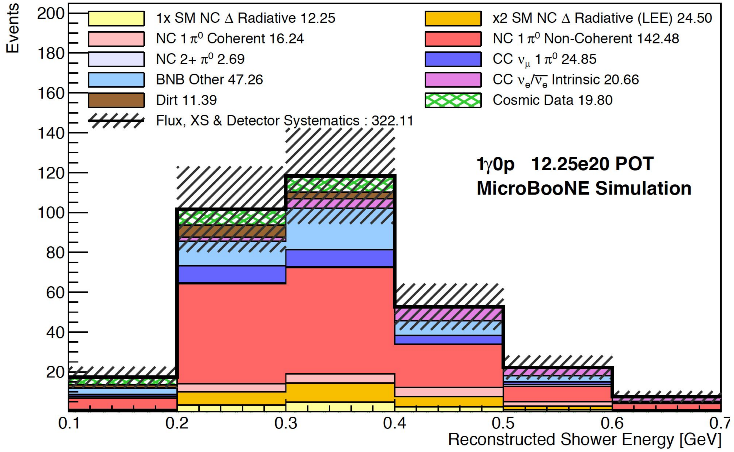
NC π⁰ Systematics Constraint for Single Photon Selection





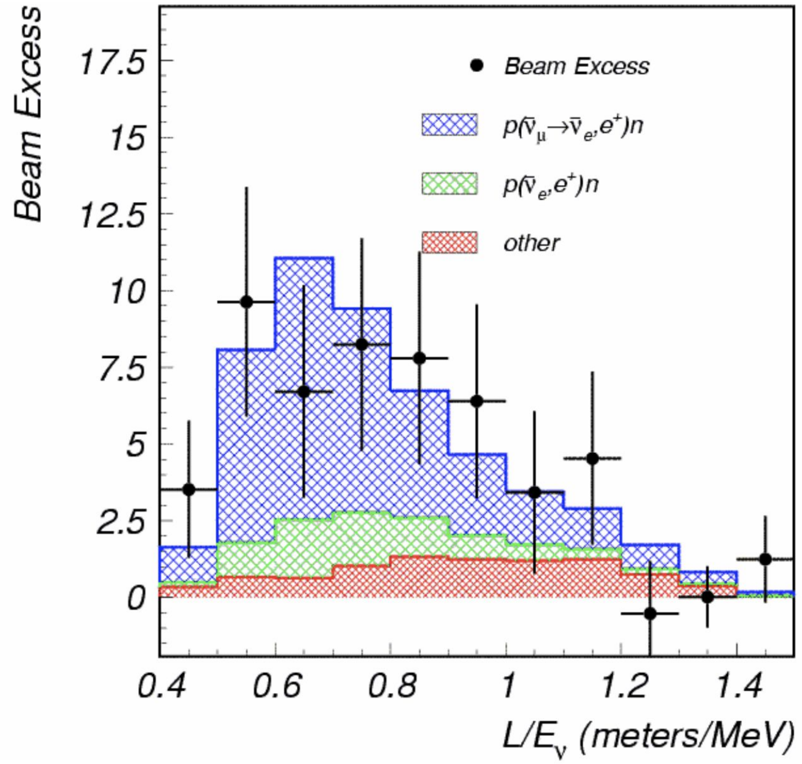
Constrained Systematics





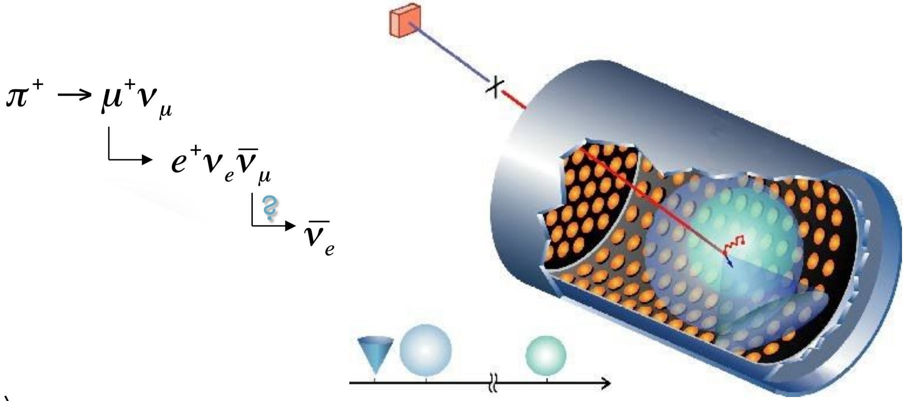
Unconstrained Systematics

Short Baseline Anomalies: LSND



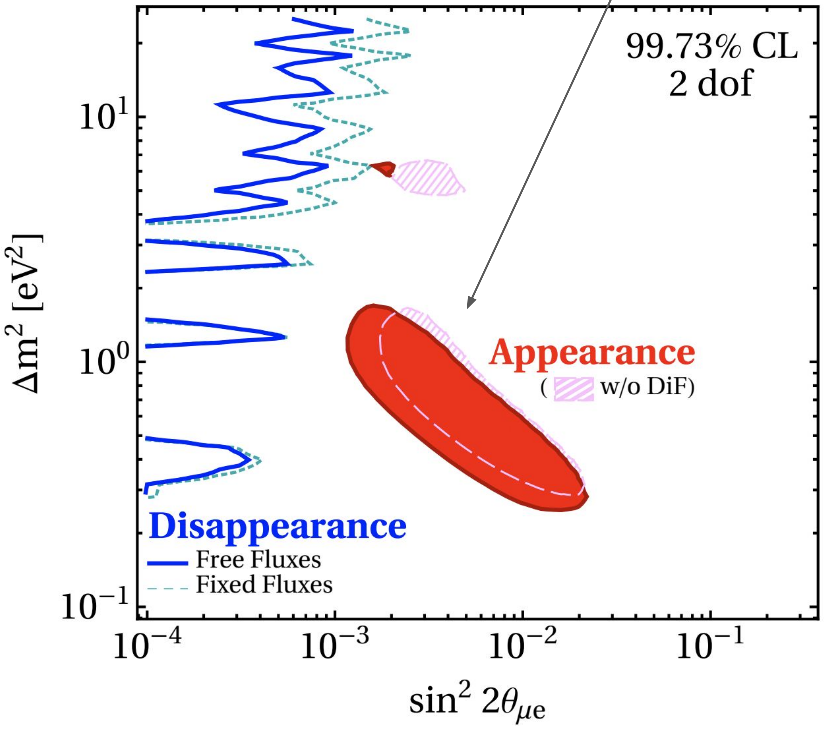
C. Athanassopoulos et al., Phys. Rev. Lett. 75, 2650 (1995); 81,1774(1998); A.Aguilar et al., Phys. Rev. D64, 112007(2001)

- LSND was a scintillation detector at LANL operating from 1993-1998
- Measured neutrinos from a μ^+ decay-at-rest source with a peak neutrino energy <60MeV
- Saw an excess of events, attributed to an anomalously high $P(\bar{\nu}_\mu \to \bar{\nu}_e)$



Tension with Sterile Neutrino Interpretation

MiniBooNE and LSND fall in electron (anti)neutrino appearance allowed region



One of the largest tensions is that given the **observed increase in $\nu_\mu \to \nu_e$ (appearance)**, there has **not been evidence of a corresponding decrease in $\nu_\mu \to \nu_\mu$ (disappearance)**, including in MiniBooNE.

The evidence for the existence of steriles is currently inconclusive and alternate interpretations are needed to fully understand these anomalies.

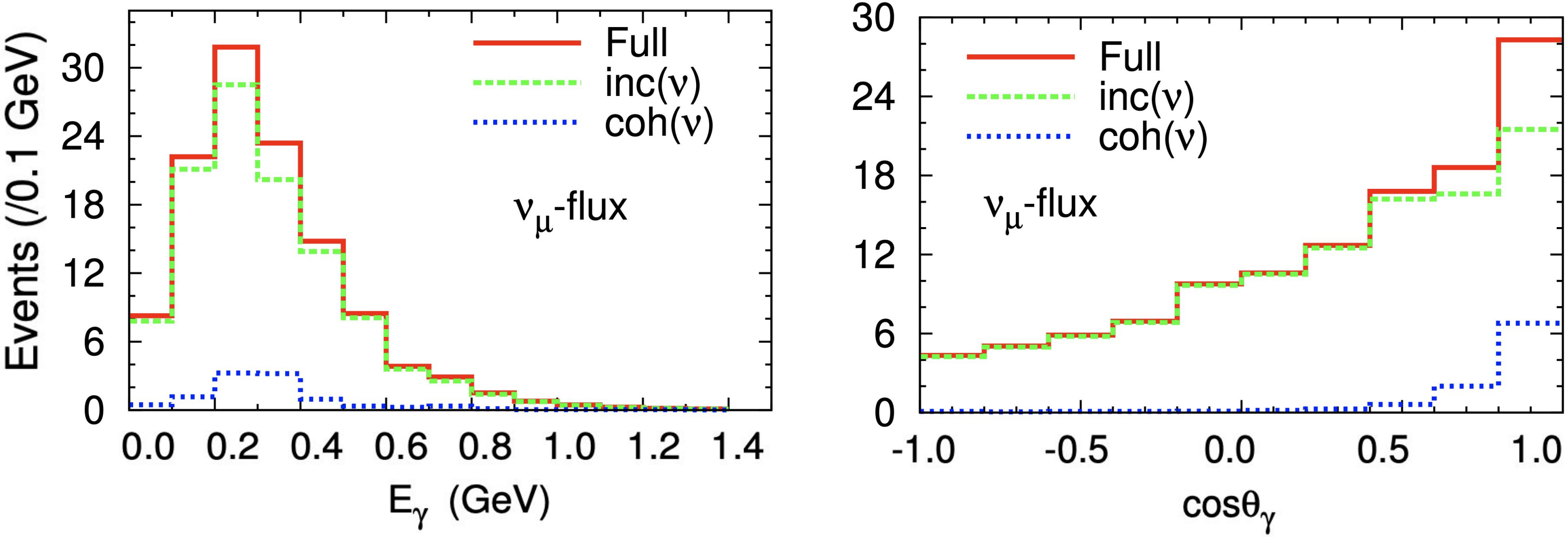
Dentler et al., 10.1007/JHEP08(2018)010

Coherent NC γ in MicroBooNE

Phys. Rev. C 89, 015503 (2014), J. Phys.: Conf. Ser. 1056 012001

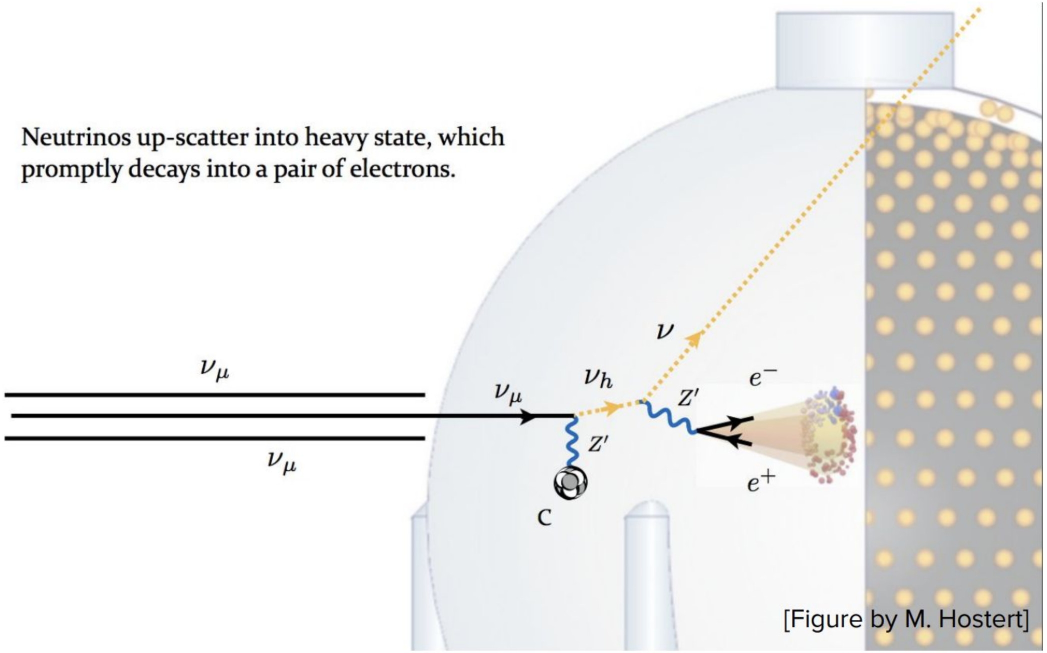
- **~10% increase in NC γ** in MicroBooNE by including coherent interaction
- **Peak in γ energy ~300MeV,** strongly **forward-peaked** in beam direction
- Potentially can distinguish incoherent (resonant Δ production) from coherent with sufficient angular resolution

Predicted NC coherent and incoherent single photon events in MicroBooNE

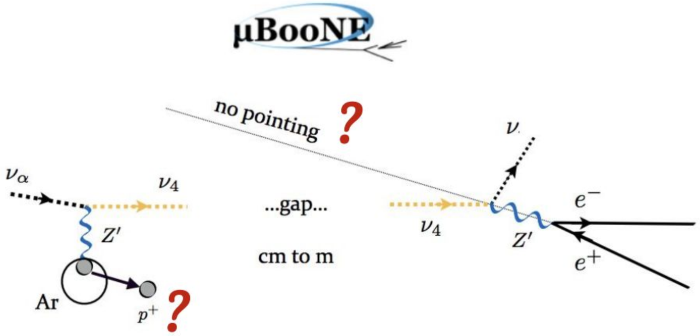


Z' Boson Decay

E.g., Z' mediated heavy neutrino production and decay into e+e- pair
[Phys.Rev.D 99 (2019) 071701, *Phys.Rev.D* 101 (2020) 11, 115025]



[Figure by M. Hostert]



Presence of hadronic activity and pointing or forwardness/opening angle of e+e- shower(s) can help resolve between different models and model parameters