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

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Columbia University,
On behalf of the MicroBooNE Collaboration

NeuTel 2021, Feb 23rd 2021

NEVIS LABORATORIES
COLUMBIA UNIVERSITY

Fermilab

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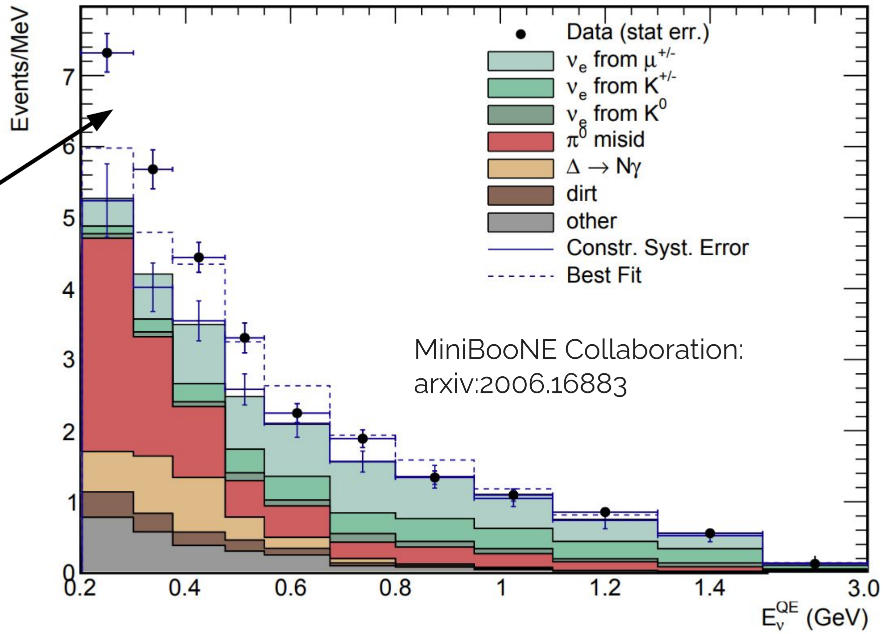
μBooNE

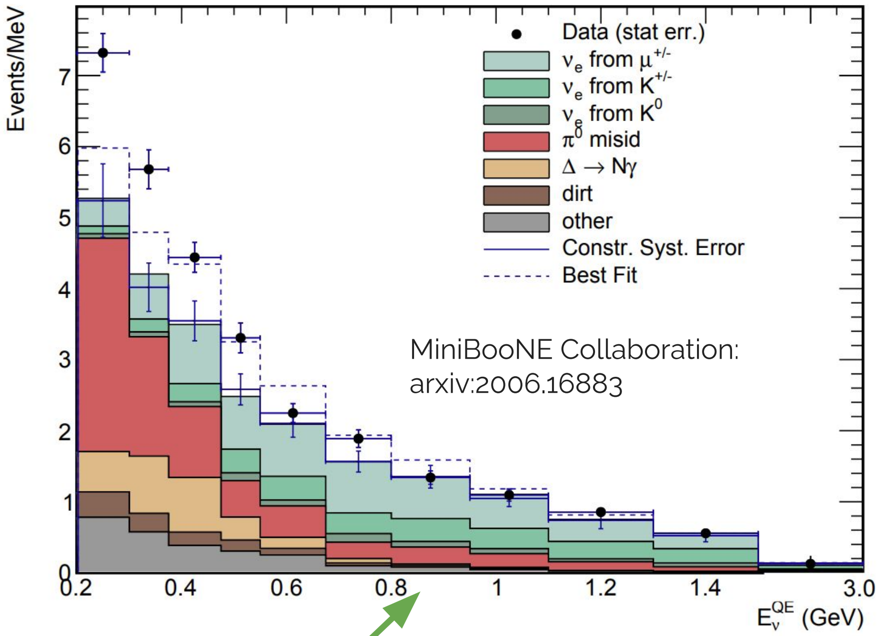
Testing the MiniBooNE LEE

MiniBooNE observed a **low-energy excess** (**LEE**) of CC ν_e-like events, predominately below 800 MeV reconstructed neutrino energy

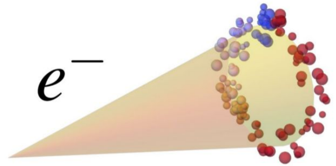
~4.8σ significance when combining all neutrino mode data



Electrons or Photons?



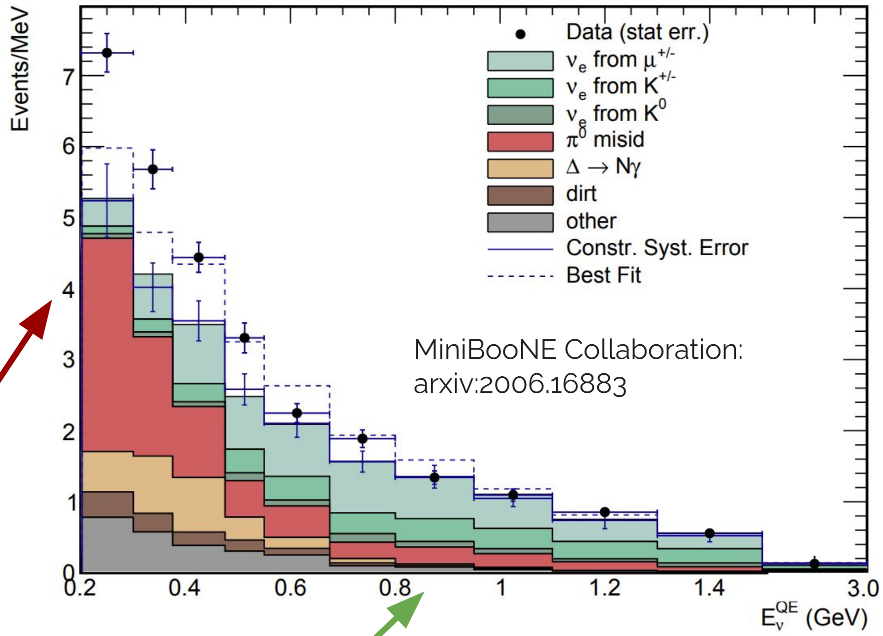
Being a mineral oil (CH²) Cherenkov detector, MiniBooNE observed **true electrons** originating from **intrinsic ν_e** in the beam (**green** histograms) by its Cherenkov rings

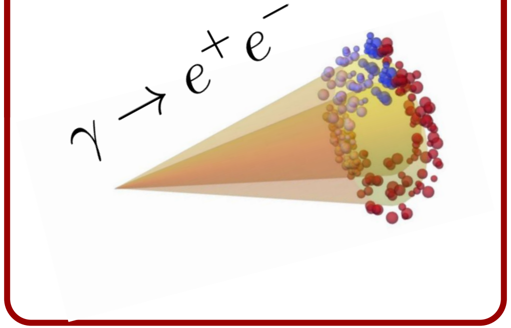


Electrons or Photons?

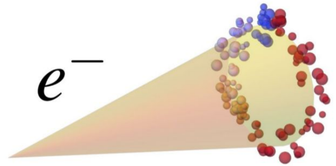
However, the bulk of backgrounds at **lower reconstructed neutrino energies** are **photons** such as NC π^0 's (**red**) and Δ radiative decay (**tan**).

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





I will only be speaking about the **photon interpretation** in this talk,
See **Hanyu Wei's** next talk for more on uBooNE's search for the electron-like interpretation! [Link]



Enter MicroBooNE

MicroBooNE is an 85-ton surface based Liquid Argon Time Projection Chamber (**LArTPC**) that has been collecting data in the **same** neutrino beam as MiniBooNE since Autumn 2015.

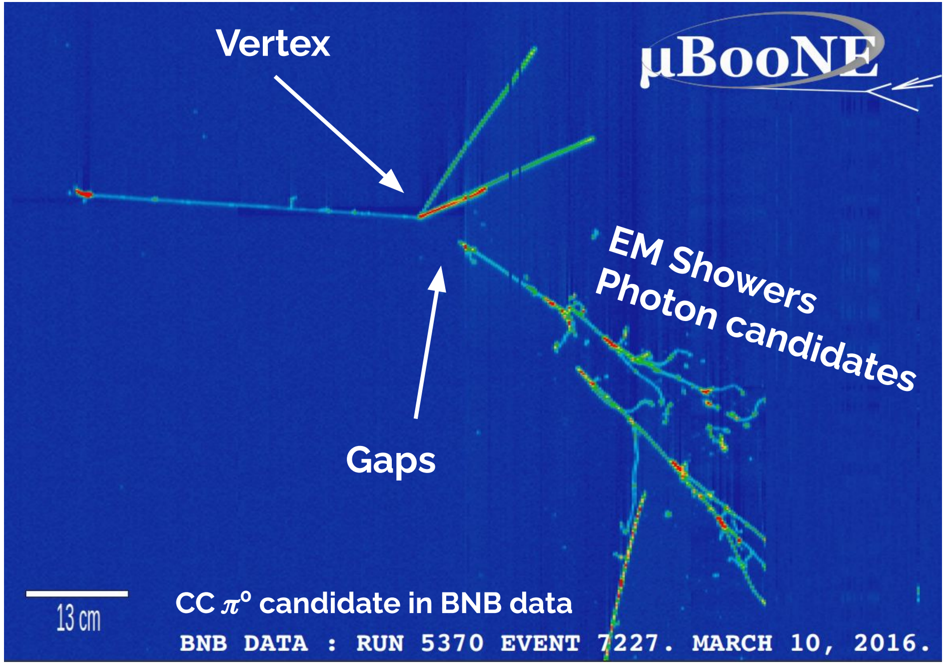
One of its **primary* goals** is to identify if the origin of the observed MiniBooNE Low Energy Excess **(LEE)** is **due to electrons** or **photons.**

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

*Primary but by no means only, See talks by Marina Reggiani Guzzo, Wenqiang Gu, Krishan Mistry, Pawel Guzowski and Maya Wospakrik!

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**.



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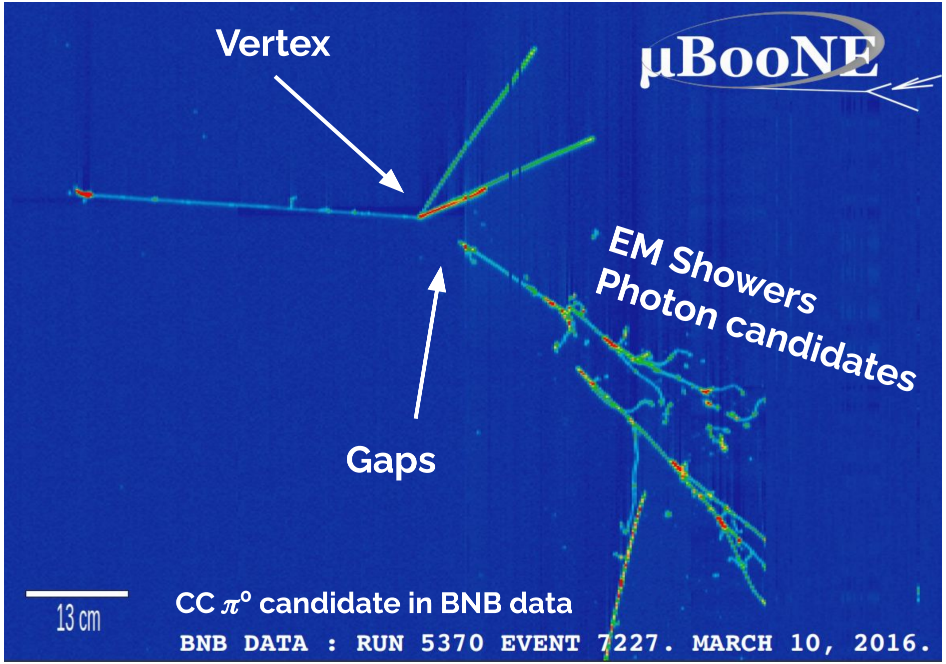
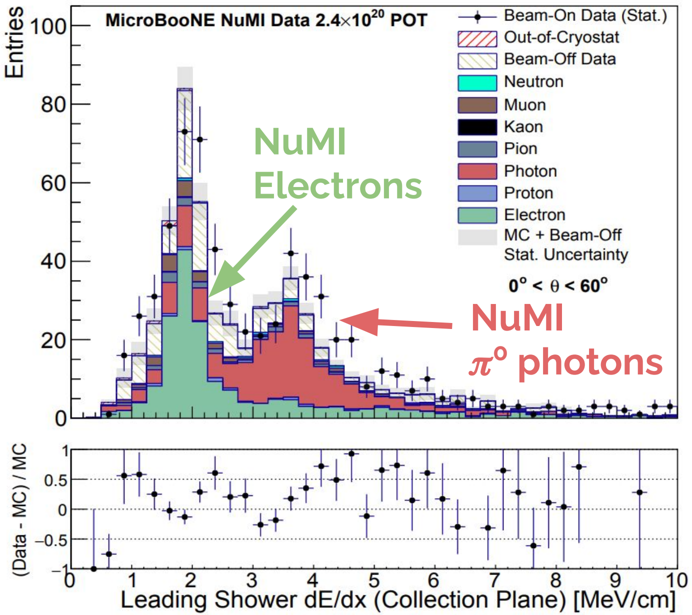


Calorimetry: Shower dE/dx

Photons producing e^+e^- pairs tend to **deposit twice the energy per unit length** as a single electron

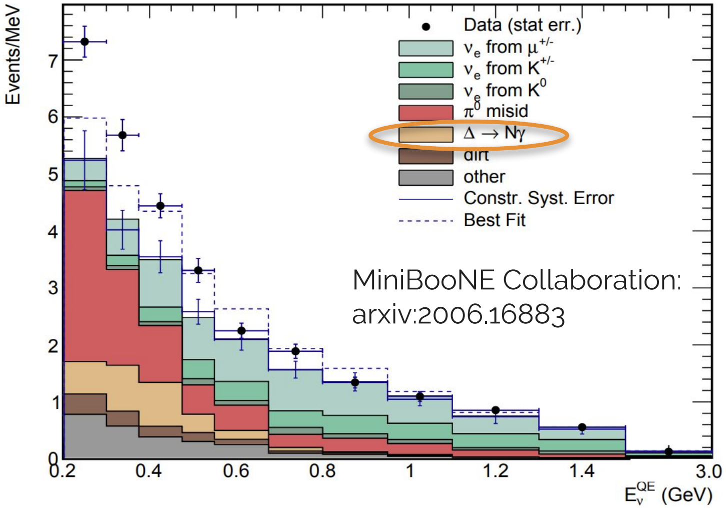


Example of shower dE/dx for candidate neutrino events in the NuMI beam at MicroBooNE arXiv:2101.04228

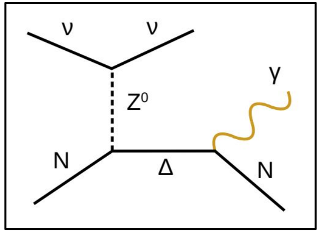
Photon interpretations of the MiniBooNE excess

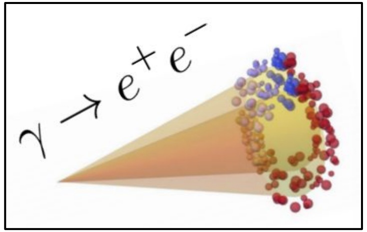
Although there are several sources of photons in MiniBooNE, this search is focusing on **NC Δ radiative decay ($\Delta \rightarrow N\gamma$).** Motivation for this is 3-fold:

- **SM process**, no need to invoke existence of sterile neutrinos



MiniBooNE Collaboration: arxiv:2006.16883





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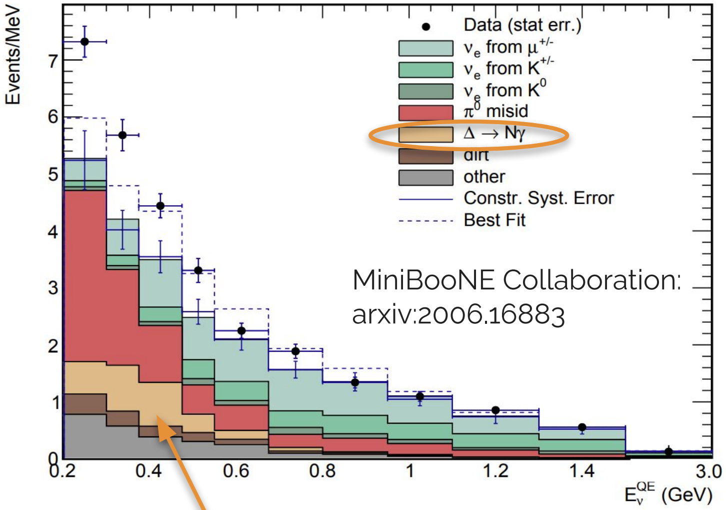
- The **shape of the Δ Radiative Decay events agree extremely well with the observed low-energy excess**, can explain it if the rate were increased by a factor of ~ x3 from its standard model predictions.



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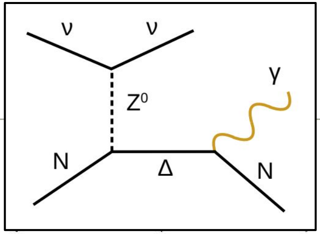
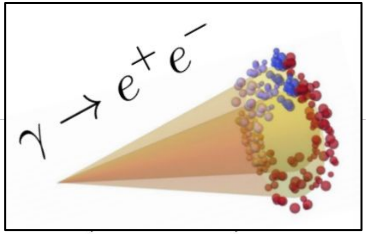
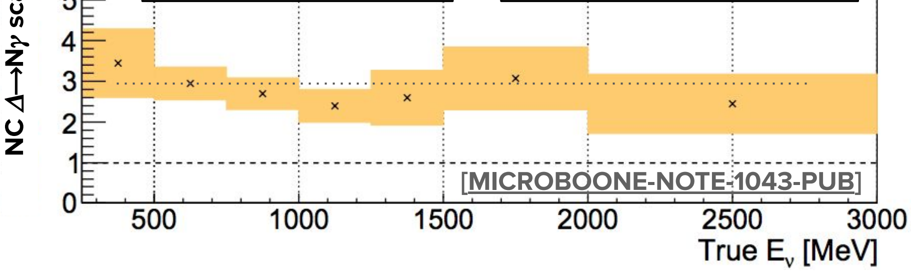
NC $\Delta \rightarrow N\gamma$ pile up at low reconstructed neutrino energy







[MICROBOONE-NOTE-1043-PUB]

A ~**3x** flat scaling to NC $\Delta \rightarrow N\gamma$ can explain the observed MiniBooNE excess. Use this as a **γLEE signal template for μBooNE**

Photon interpretations of the MiniBooNE excess

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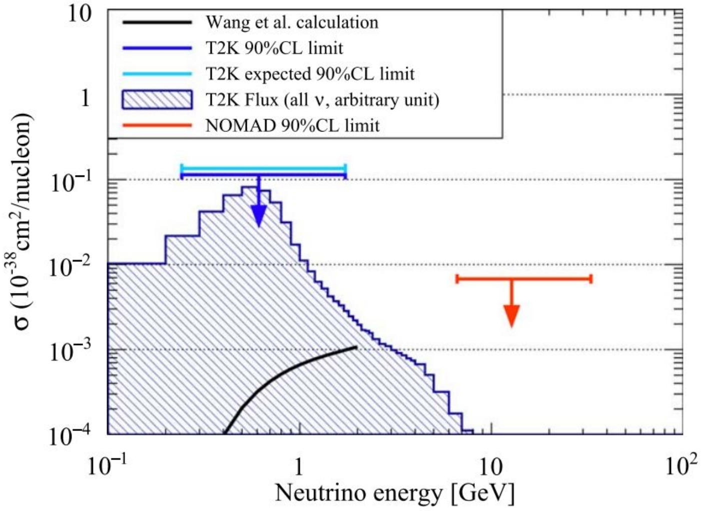
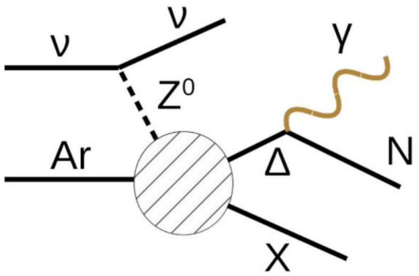
- **SM process**, no need to invoke existence of sterile neutrinos
- The **shape of the Δ Radiative Decay events agree extremely well with the observed low-energy excess**, can explain it if the rate were increased by a factor of ~ x3 from its standard model predictions
- The rate of neutrino induced Δ Radiative Decay has **never been observed**, with the strongest bounds in this energy region from T2K being O(100) times larger than current prediction

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

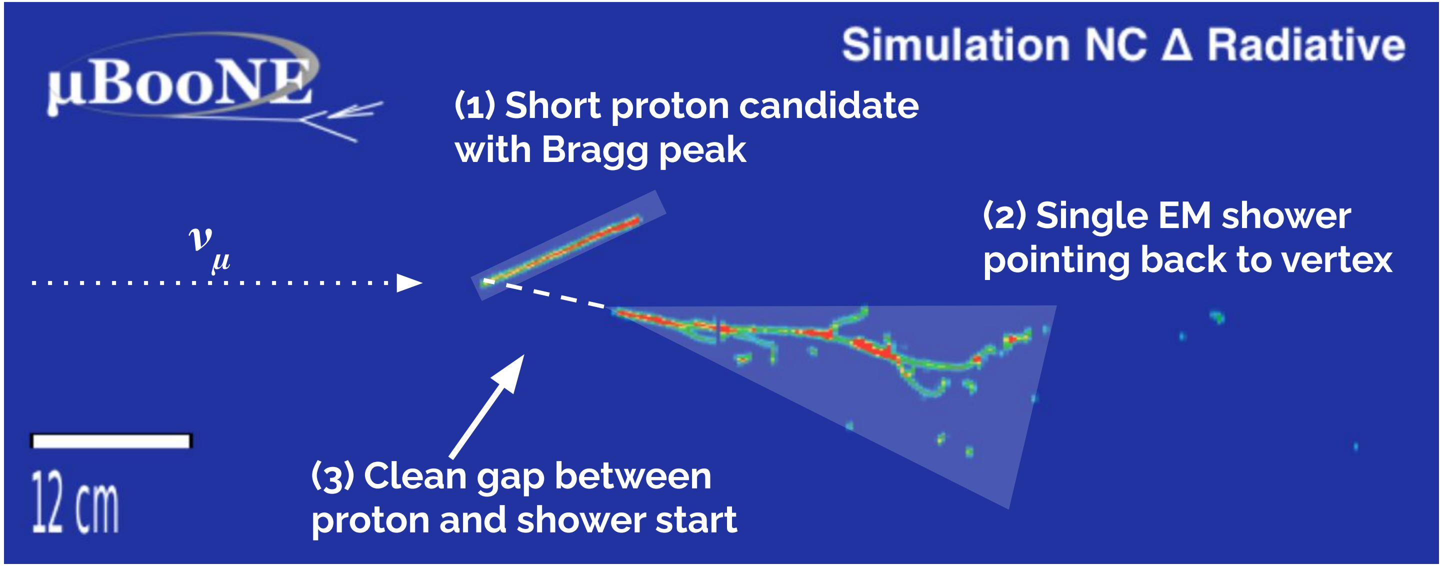


NC Δ Radiative Decay in MicroBooNE

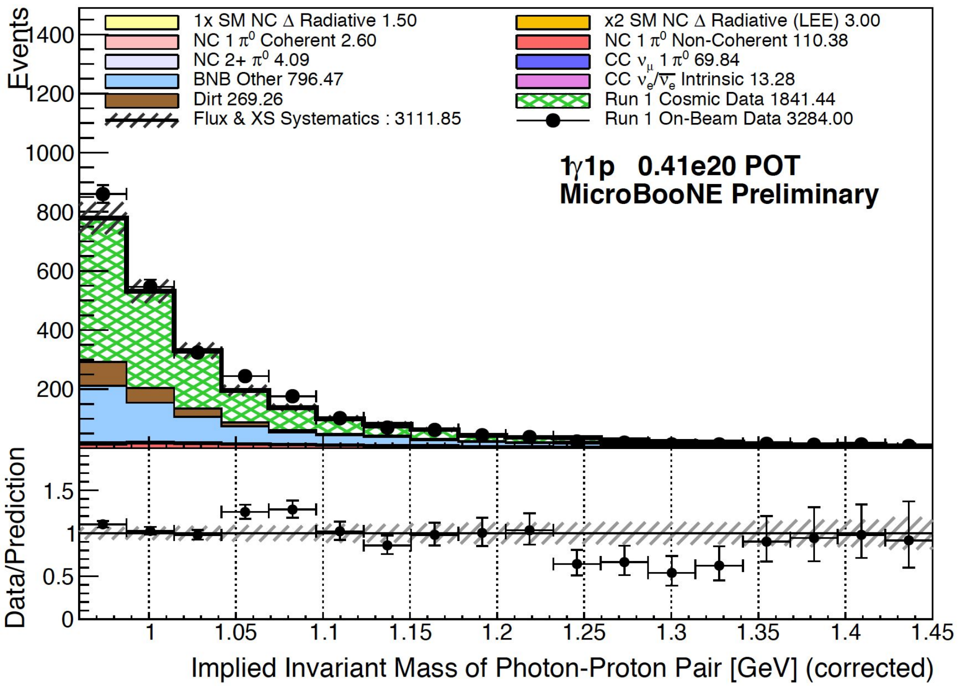


In MicroBooNE we are searching NC Δ radiative events both with a visible proton (**1γ1p** topology) and without (**1γ0p** topology) although in this talk I will be focusing on the primary **1γ1p** analysis.

Use Pandora Multi-Algorithm Pattern Reconstruction [Eur. Phys. J. C78, 1, 82 (2018)] framework 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).



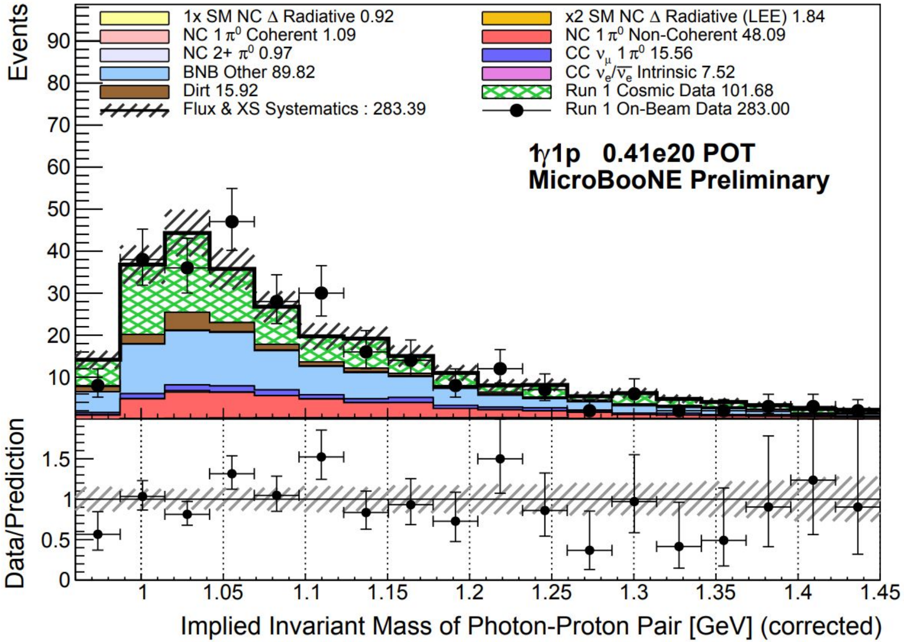
Topological Selection Stage



- Just asking for the existence of a single reconstructed track and a shower
- At this stage, our signal is massively dominated by **Cosmic**, BNB Charged current **(CC)** ν_μ backgrounds and **Dirt** (Neutrino events that interacted outside of the TPC and scattered in)
- **Signal-to-background ratio ~ 1:1000**
- Showing results using **a small sample of unblinded data (0.4×10^{20} POT)**. First results will be with **~17x** (First 3 years) more data, with final dataset being **~30x** what I show today (Full 5 years)

The true Δ Invariant Mass, M_Δ = 1.232 GeV

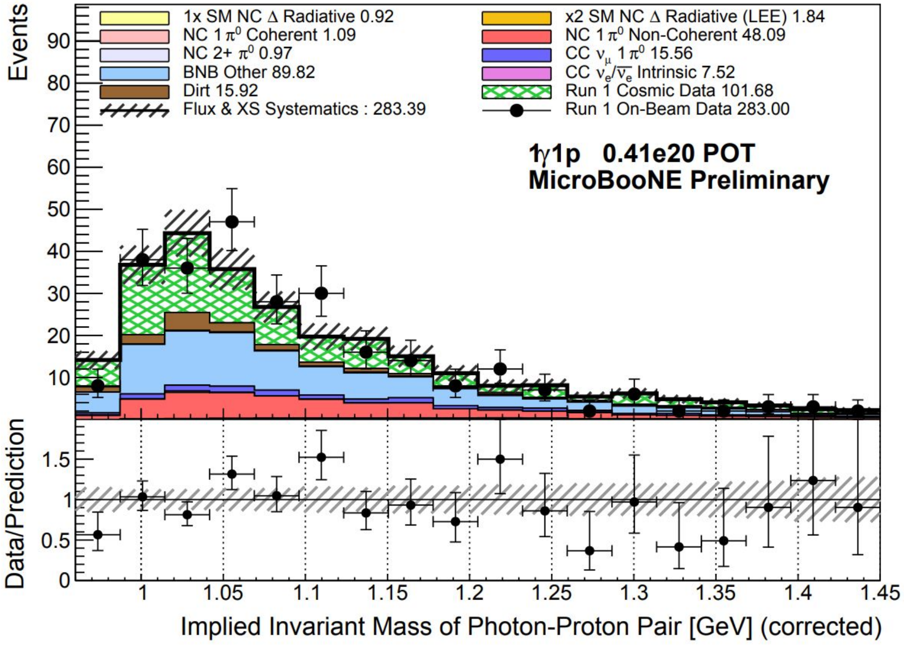
Pre-Selection Stage



We can reduce backgrounds by over an order of magnitude by first implementing a series of **pre-selection cuts** to remove the more clear cut backgrounds. Examples include:

- Ensuring the **track is contained** inside the TPC eliminates many cosmic muons entering
- Enforcing a **shower energy threshold of 40 MeV** reduces Michel electrons contamination

Pre-Selection Stage



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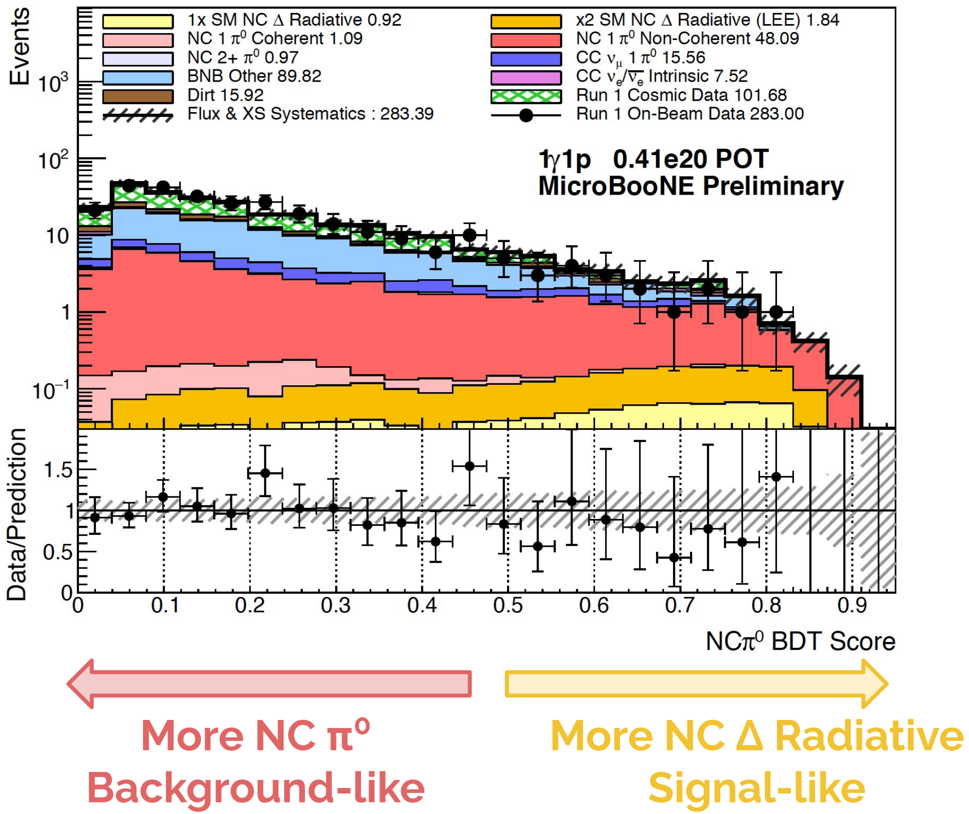
At this stage, we are still dominated by many cosmic and beam induced backgrounds. We train five **tailored Boosted Decision Trees** (BDT) each **targeting a key background**:

- **Cosmic** Rejection BDT
- **Intrinsic ν_e** Rejection BDT
- **Two NCπ^0** Rejection BDT's
  - One focused on **π^0 kinematics**, and the other looking to veto the existence of a non-reconstructed **secondary shower**
- **BNB "Other"** Rejection BDT
  - Primarily CC ν_μ events

Example: NC π^0 Rejection BDT

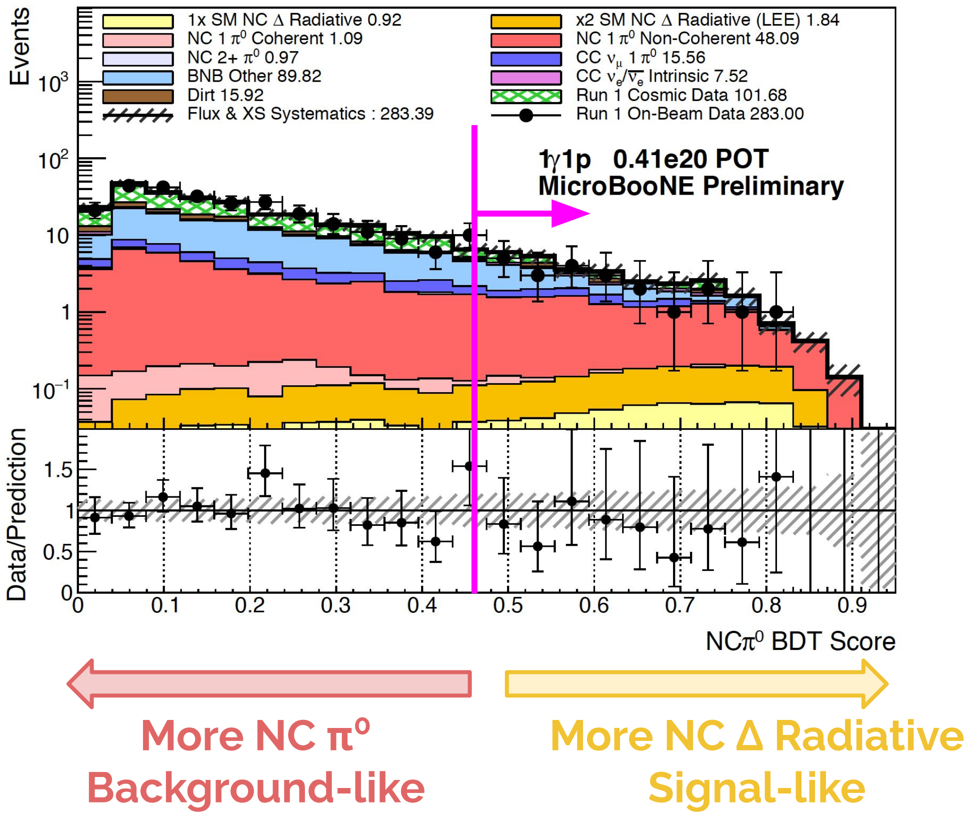


Here only showing example of **1γ1p NC π⁰ rejection BDT response,** showing good modelling of the backgrounds across the entire region of phase space.

The NC π⁰ BDT tries to make use of variables that would be sensitive to the parent Δ kinematics or the missing secondary shower of the π⁰ decay such as

- The reconstructed invariant mass of the photon-proton pair
- Photon Transverse Momentum

Example: NC π^0 Rejection BDT



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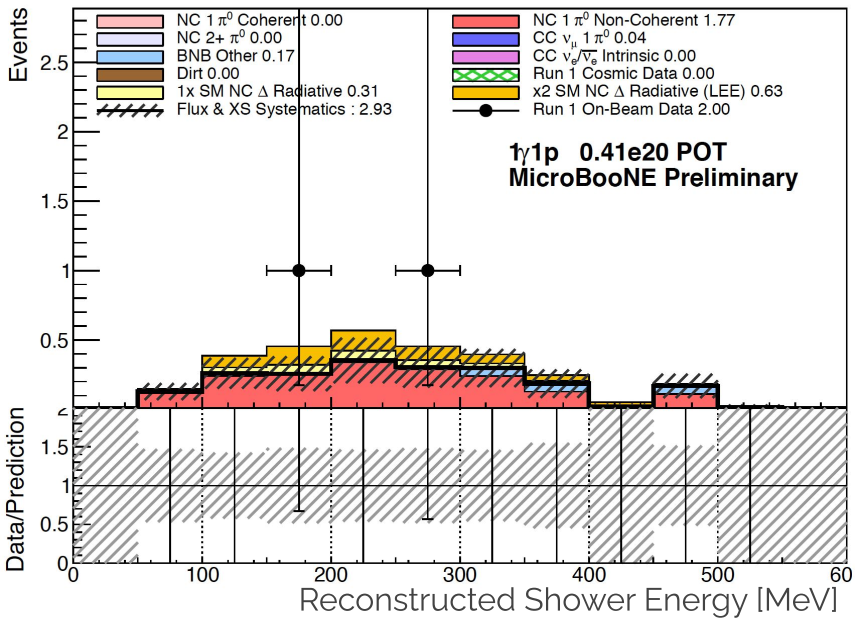
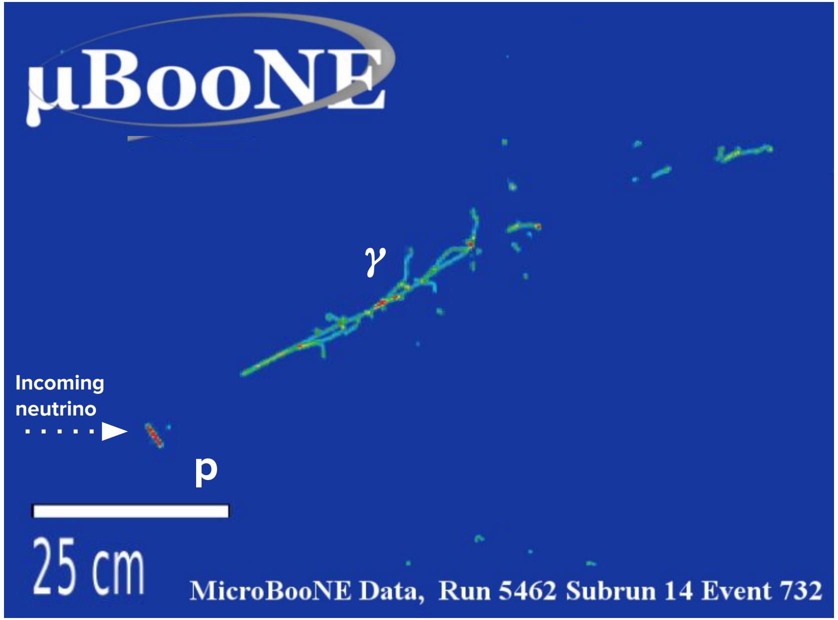
We then place a **simultaneous cut on all five BDT response scores** in an effort to maximize the sensitivity of the analysis to observing NC Δ Radiative decay

Post BDT cut, 1γ1p Final Selection

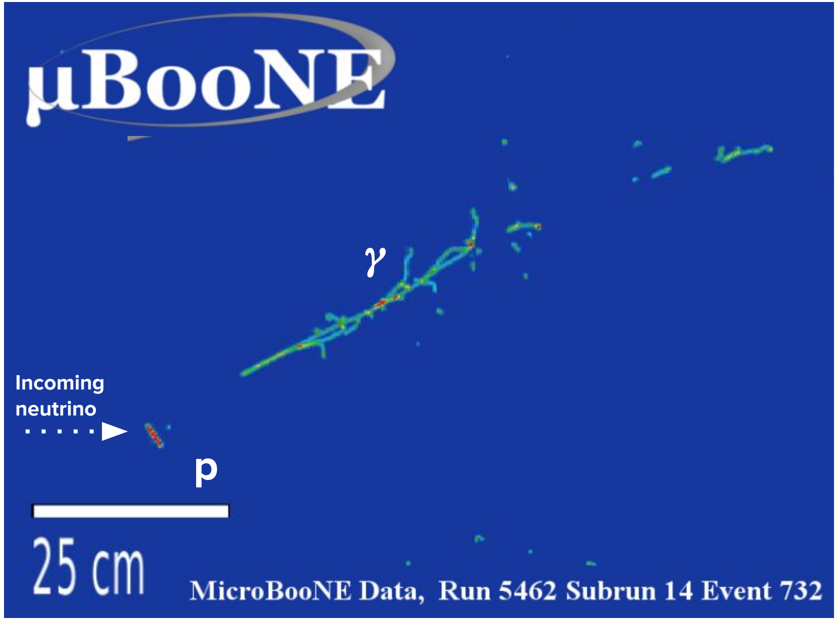


- Reminder, Showing results using **small sample unblinded data**, full data set is ~30x larger
- Observe 2 events with an expectation of 2.6 for the SM scenario.
- This targeted BDT approach has resulted in extremely strong rejection of Cosmics, Dirt, and CC backgrounds, to the extent they are no longer a major concern.
- By ***far*** the **dominant background is NC π^0** events (~90%) and it's easy to see why by looking at some events.

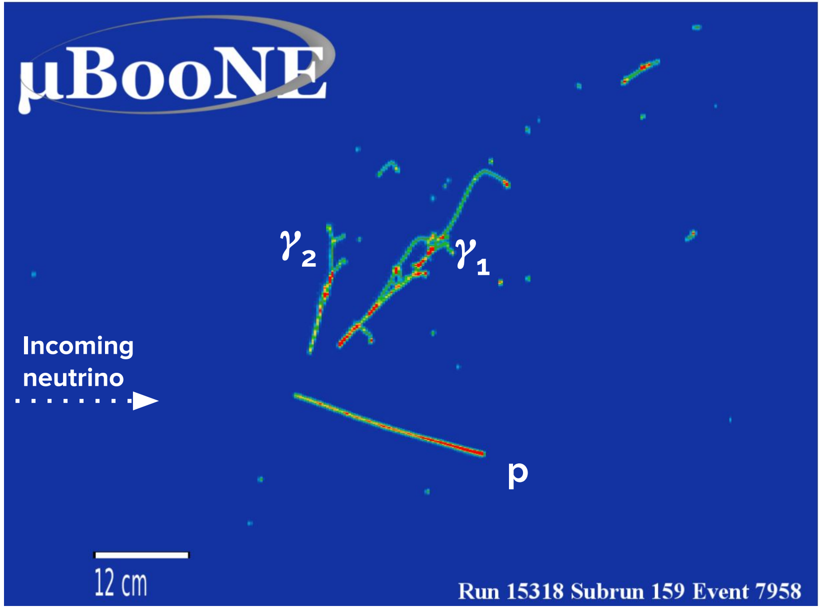
NC single photon candidate 1γ1p data event



NC single photon candidate $1\gamma 1p$ data event



NC π^0 + 1 Proton ($2\gamma 1p$) Candidate data event



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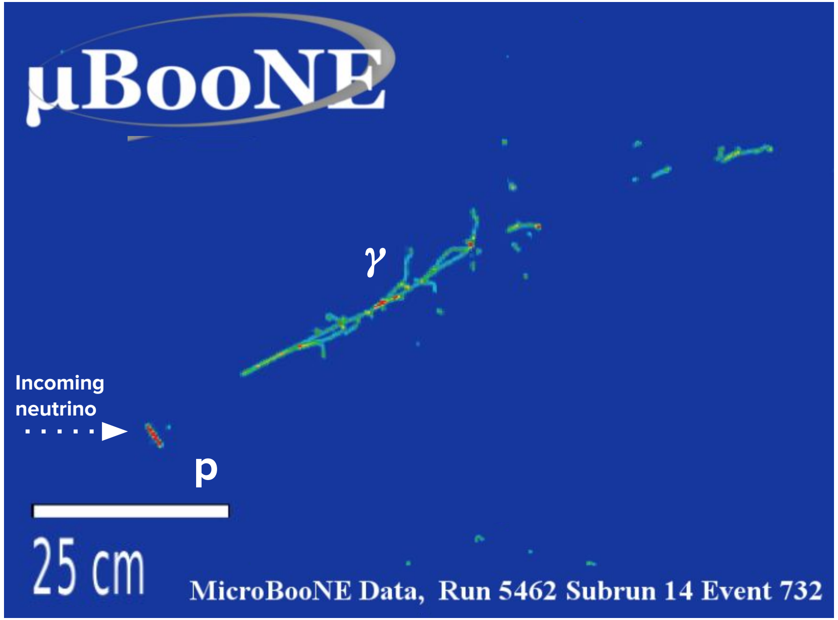
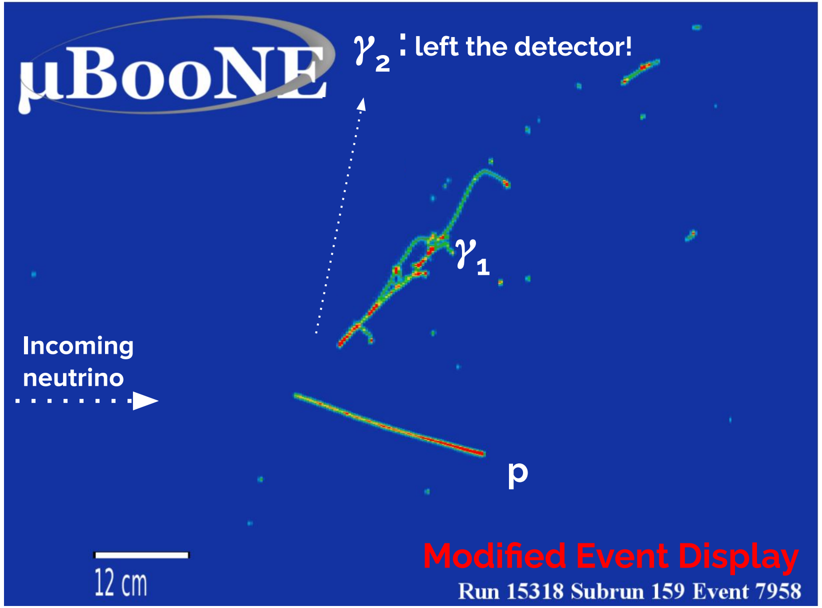


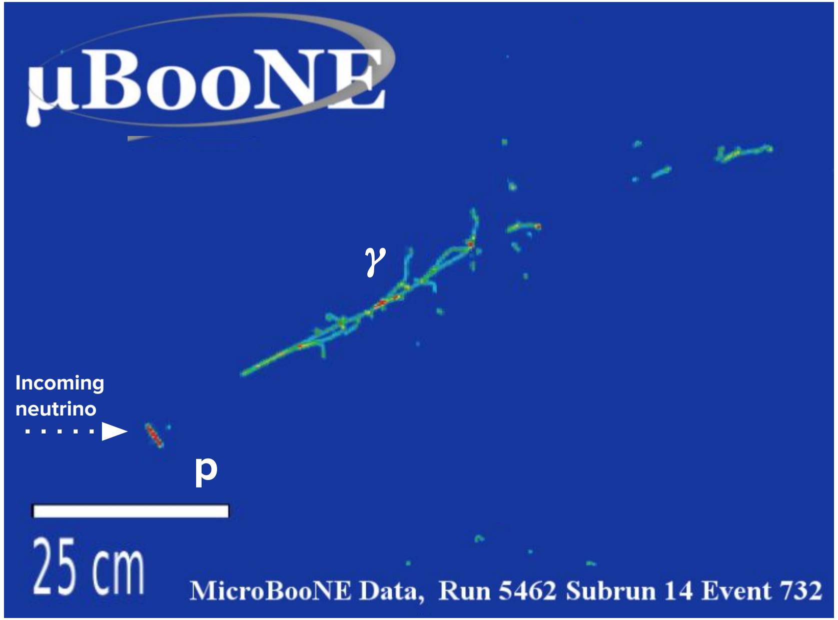
Hypothetical NC π^0 Event



- Topologically **indistinguishable** from our single photon signal
- Both cases have **true photon** and a **true proton**

Hypothetical: Subleading photon from π^0 exits detector before pair converting and is thus not reconstructed

NC single photon candidate $1\gamma1p$ data event



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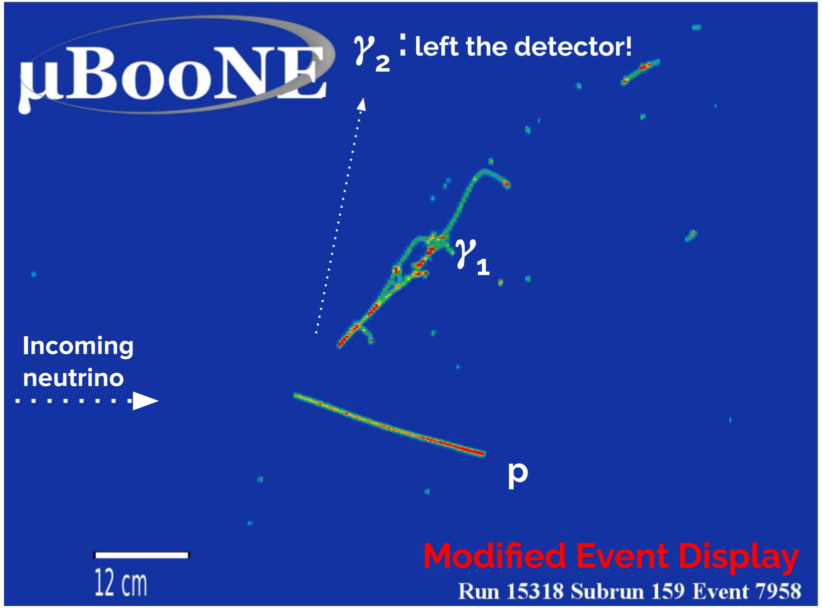


There are many ways with which the secondary shower is lost:

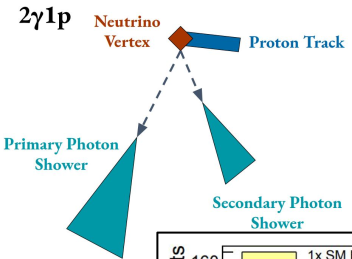
- **Escapes the detector** before pair-converting
- Highly **overlapping** with leading shower
- Very **low energy** (< 30 MeV) where reconstruction efficiency is lower
- Interference with coincident **cosmic rays**

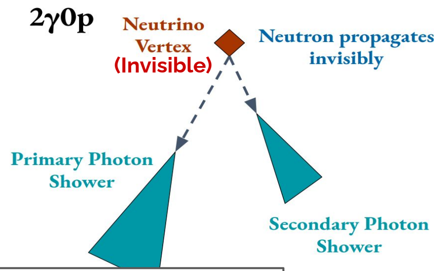
In-Situ NC π^0 Measurement

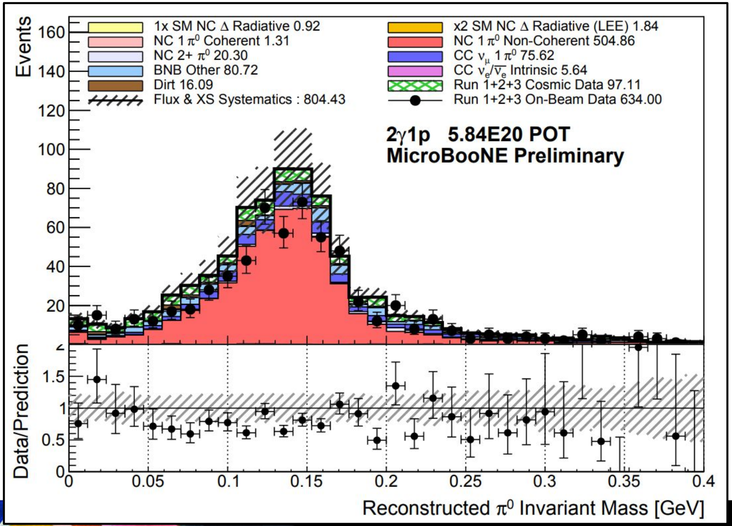
Highest-statistics sample of NC π^0 events in a LArTPC!

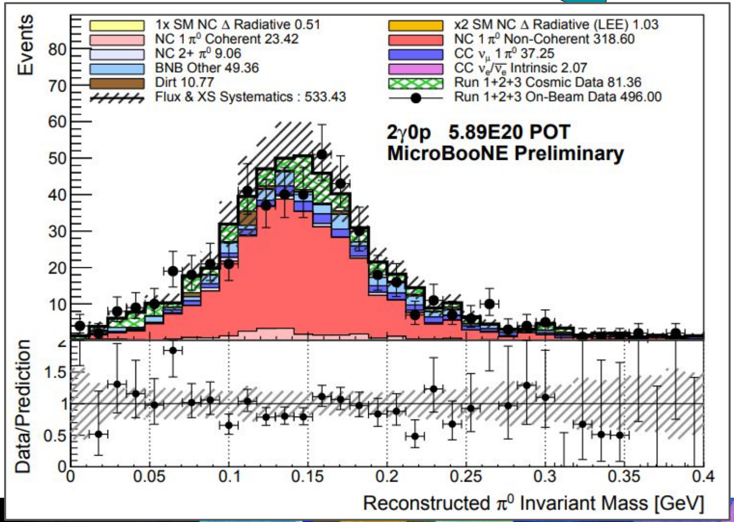
To **constrain** this dominating background we have utilized the same BDT based framework to develop a complementary in-situ **high statistics NC π^0 measurement**, in which both showers *were* reconstructed

Sneak Preview: See Andrew Mogan's Flash Talk for much more details [Friday 26th 11:45 @ Room 1 Link]





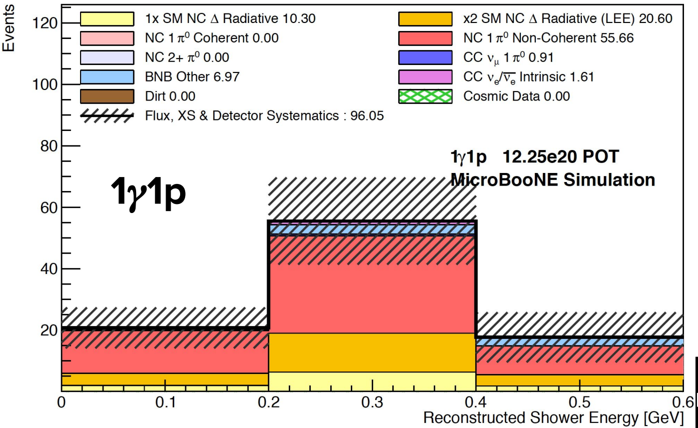




The NC π^0 Constraint

Side-by-side fit to 1γ and 2γ selections indirectly constraints NC π^0 background

Scale our prediction up
to the full dataset (~30x).



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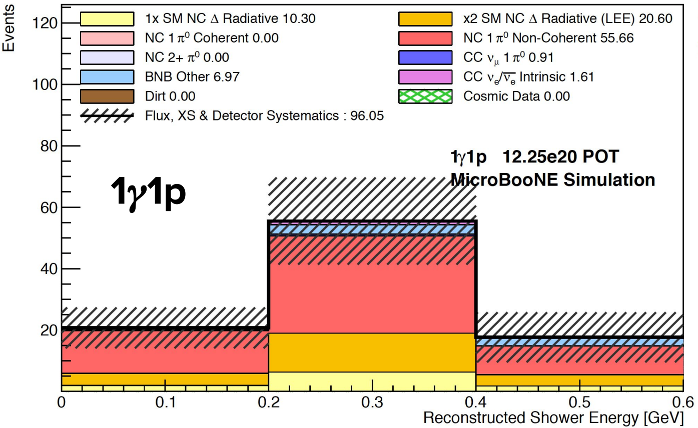

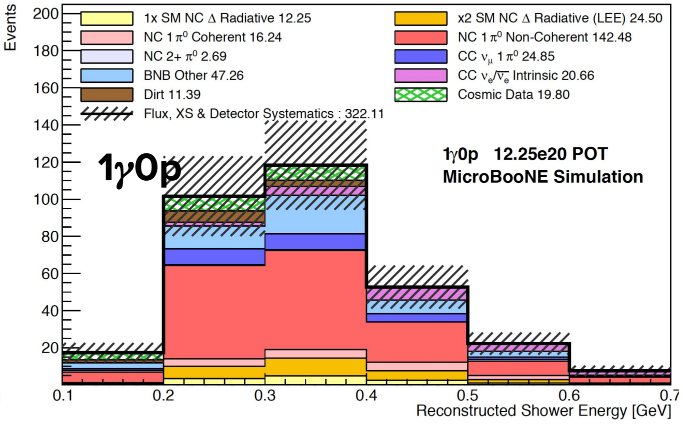

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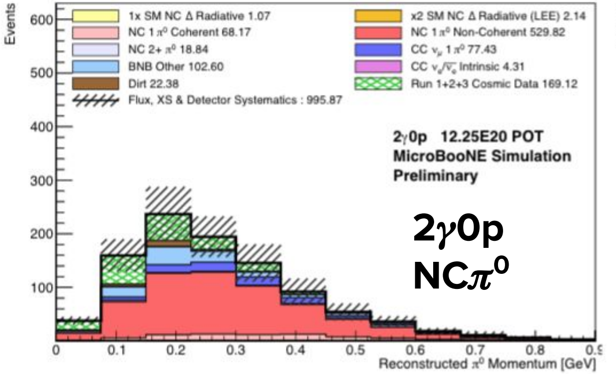

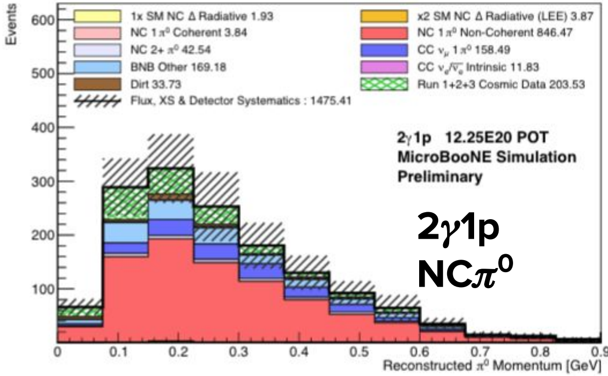

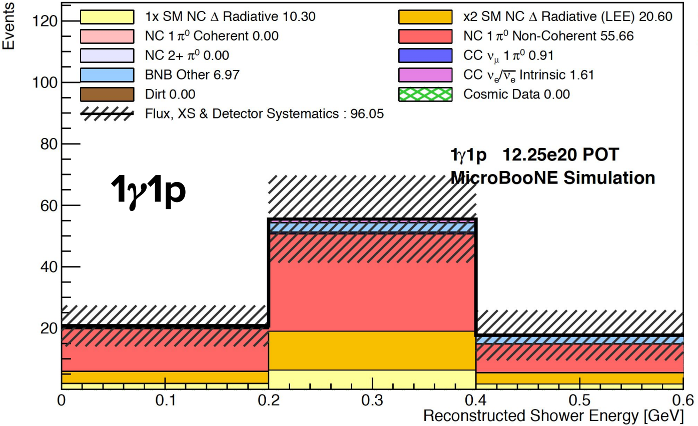

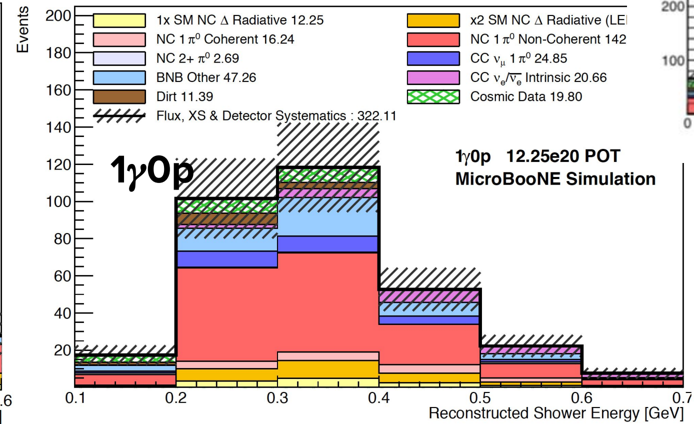

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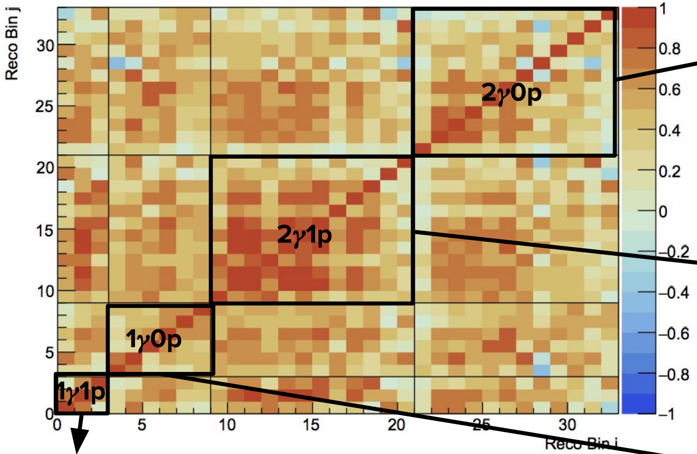
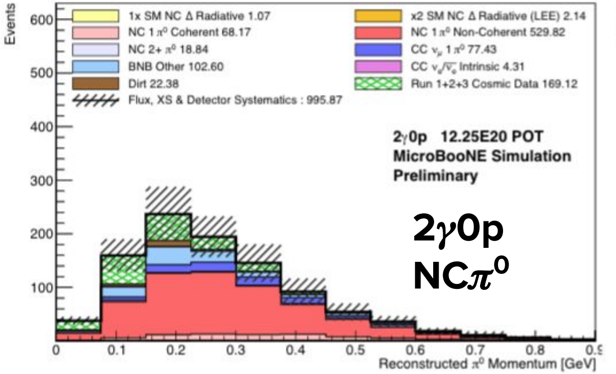
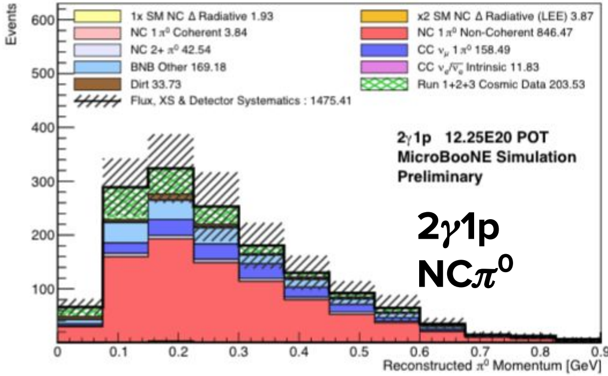
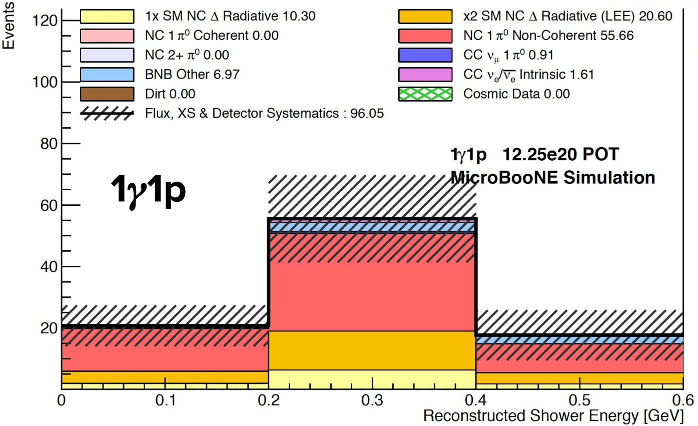
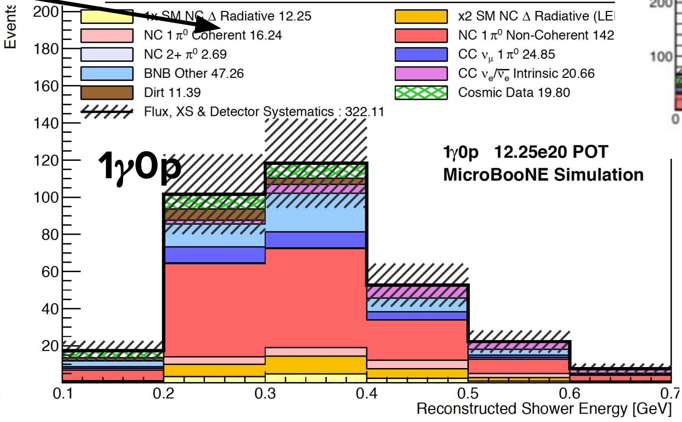
Correlation Matrix











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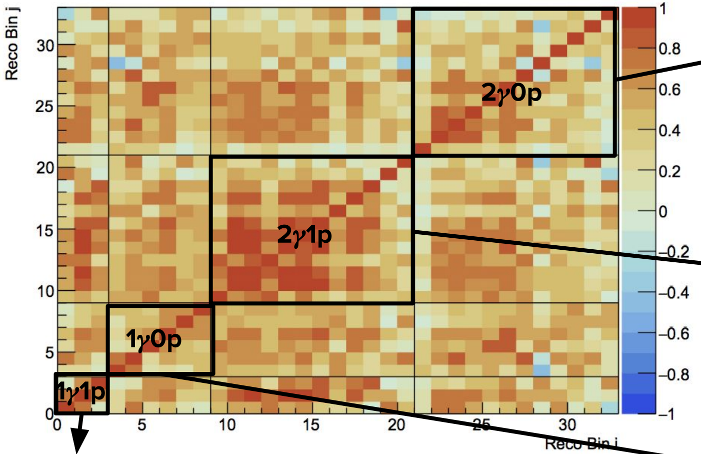
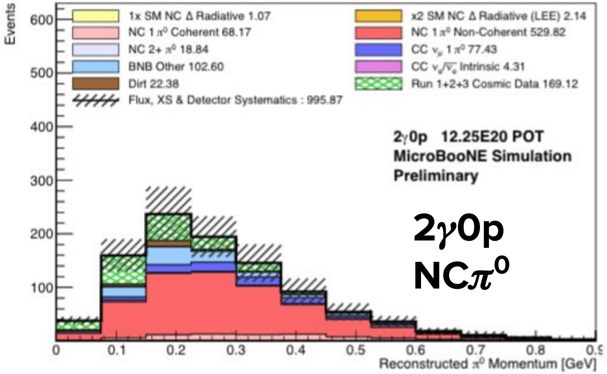
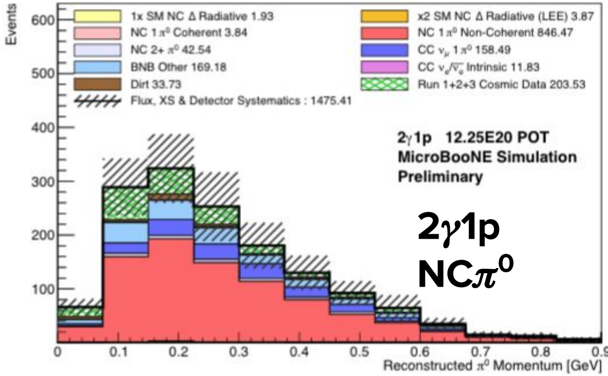
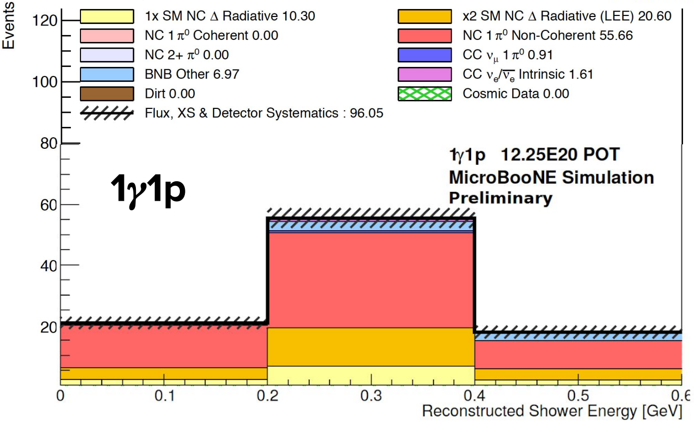
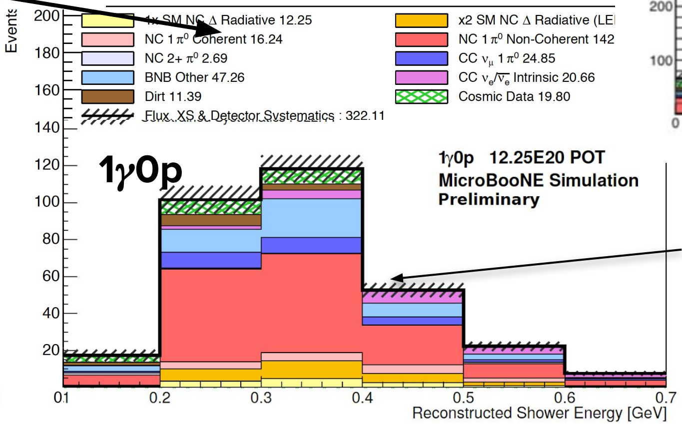










Effectively reduces the systematic uncertainty on the signal selections by a factor of 2-3

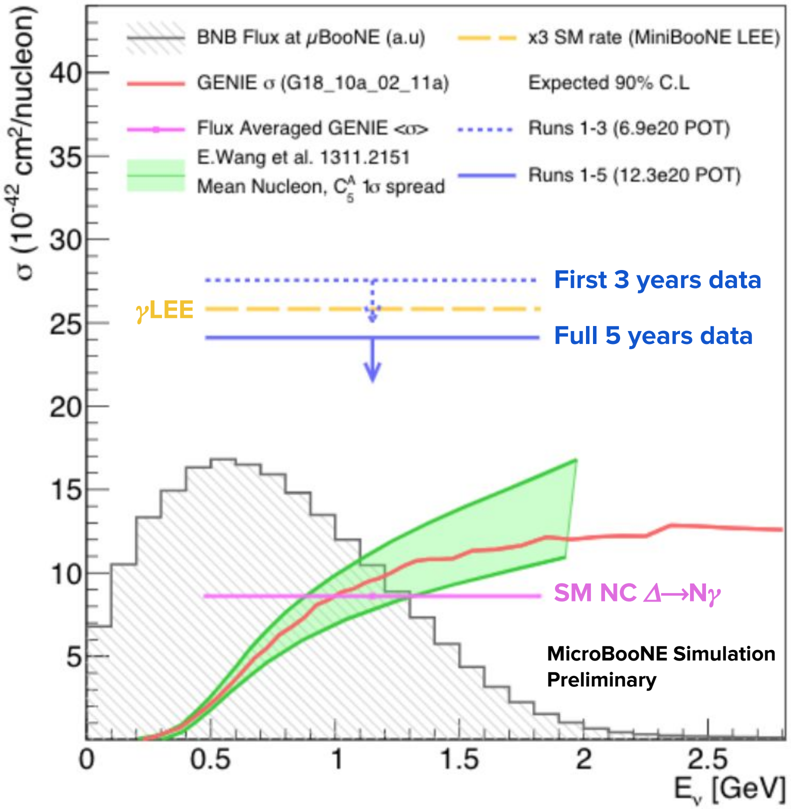
Current Status of μBooNE's Single-Photon Search

Analysis is **frozen.** 1γ selections have been **validated with current small unblinded data sets**, and analysis of ~x17 larger **signal blind sidebands is ongoing** (first 3 years of data).

Projected sensitivity to the the NC Δ radiative process:

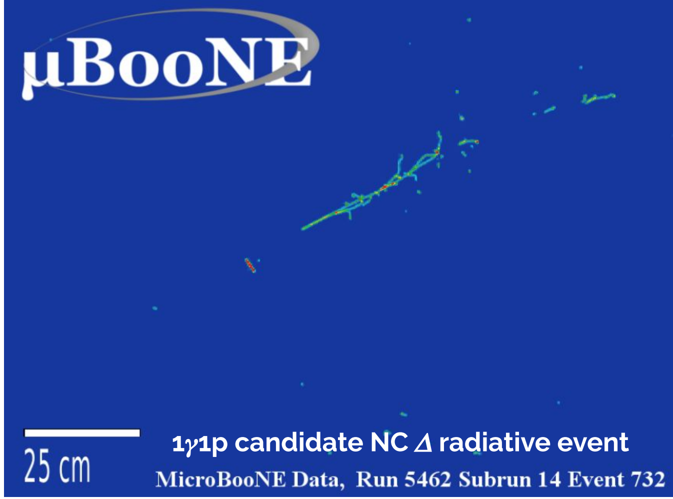
> **~40x more sensitive** measurement than current world's best limit in this energy range (T2K [J. Phys. G: Nucl. Part. Phys. 46 08LT01])

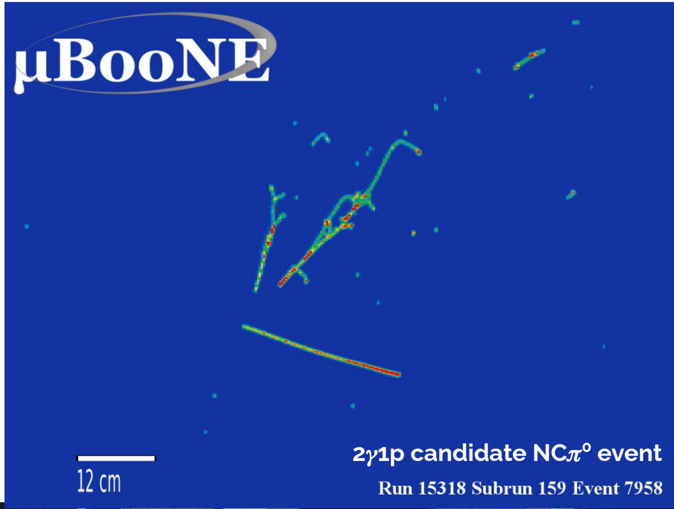
Projected Sensitivities

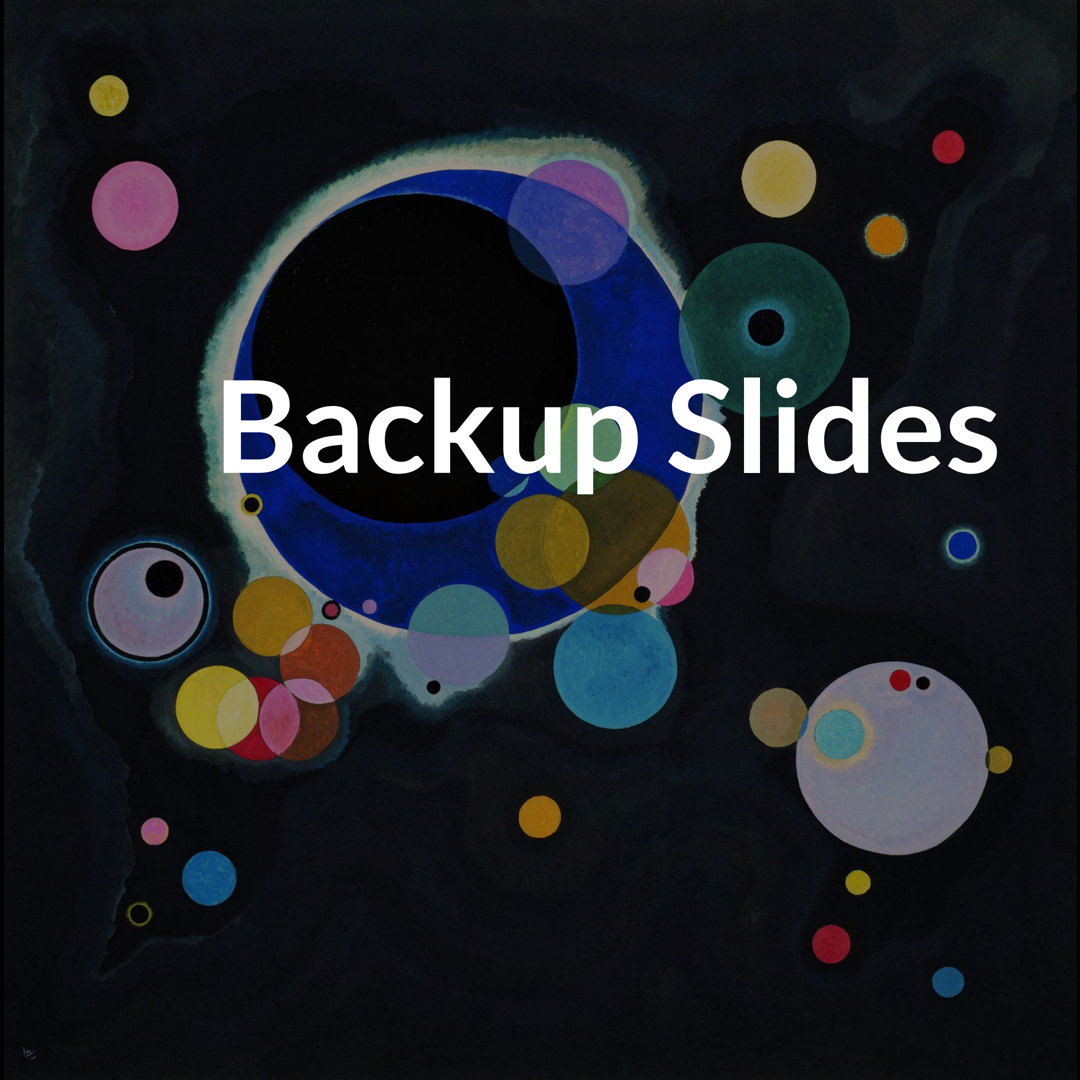


Conclusions

- Utilizing the unique capabilities of LArTPC technology, MicroBoone has developed a full end-to-end analysis searching for **Neutral Current Δ radiative decays**.
- Projected to produce a **world-leading constraint** on the SM NC Δ radiative process, never directly measured in neutrinos before!
- **Worlds largest selection of NC π^0 in a LArTPC** provides a strong constraint to the primary backgrounds that remain in the selection.
- Currently wrapping up studies of signal-blind sidebands, and are on the cusp of unblinding the signal box for the first result with 3 years of data (6.9×10^{20} POT).
- More information on this analysis can be found in the MicroBooNE single-photon public note: MICROBOONE-NOTE-1087-PUB,







Backup Slides

MicroBooNE Run Periods

Slide from: Georgia Karagiorgi, Neutrino 2020

Start of MicroBooNE running, October 2015

Software trigger at start of Run 1

Partial CRT during Run 2

Full CRT during Run 3 and onward

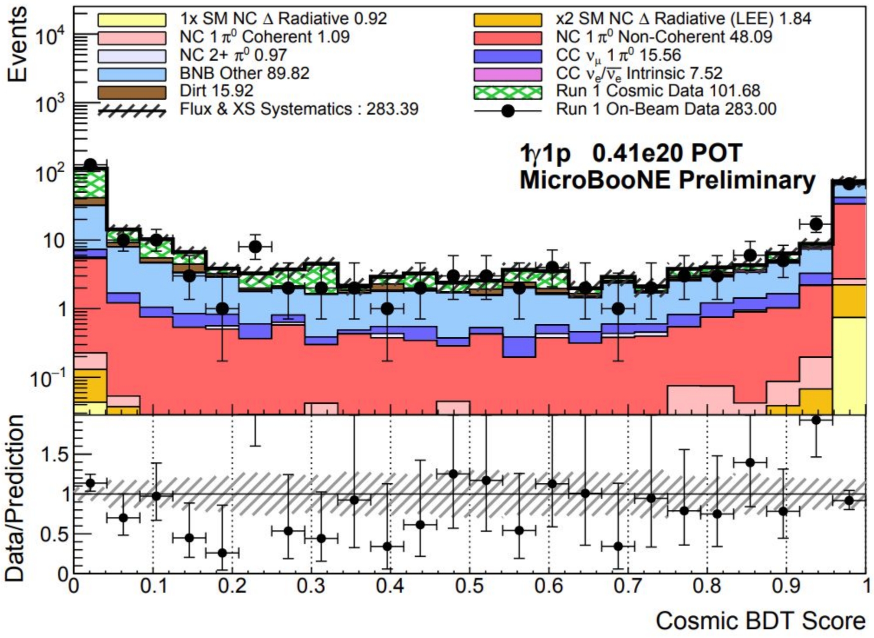
Lower e lifetime during Run 4

Brand-new, preliminary results shown today span data sets from this period (6.9×10^{20} POT)

Run 1, 1.7×10^{20} POT	**Run 2, 2.7×10^{20} POT**	**Run 3, 2.6×10^{20} POT**	**Run 4, 3.2×10^{20} POT**	**Run 5, 2.2×10^{20} POT**

Over its 5-year run, μBooNE has collected data corresponding to 12.25×10^{20} POT (past quality cuts)

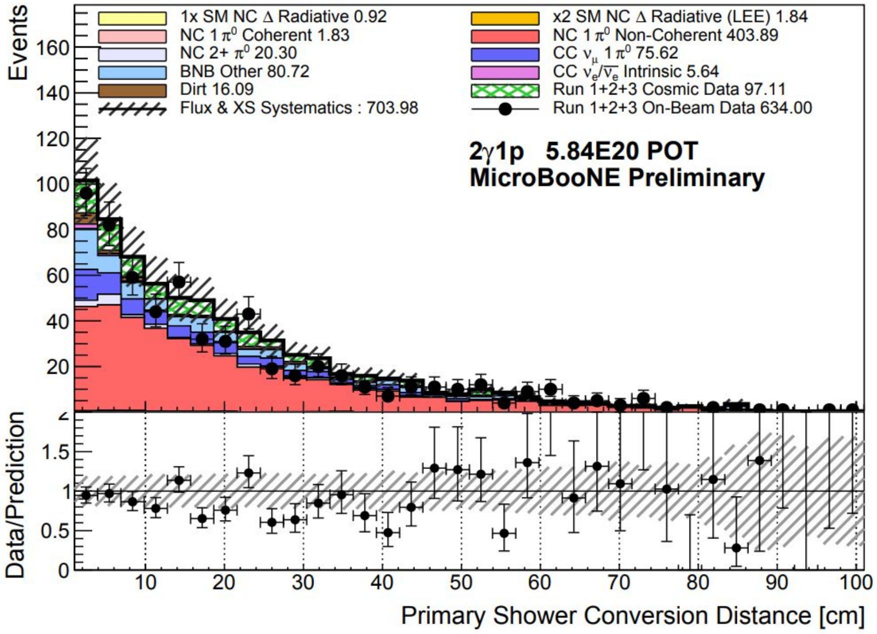
Example: Cosmic Rejection BDT



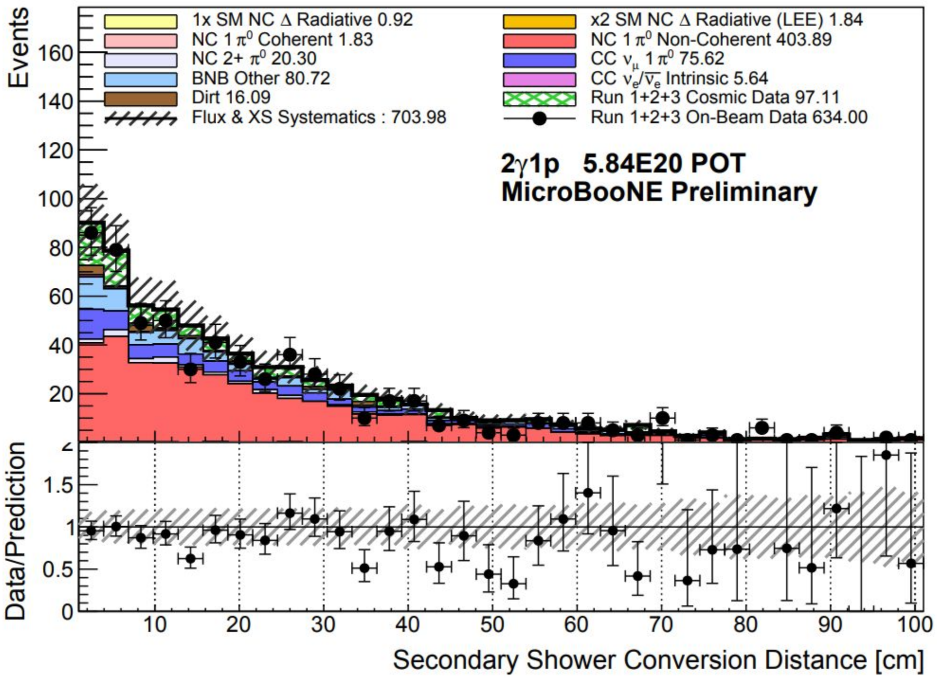
More Cosmic-like

More NC Δ Radiative Signal-like

Shower Conversion Distance



(Data/MC: 0.90) (KS: 0.990) ($\chi^2/nDOF$: 28.36/34) (χ^2 P^{val}: 0.740)



(Data/MC: 0.90) (KS: 1.000) ($\chi^2/nDOF$: 30.30/34) (χ^2 P^{val}: 0.650)

The MicroBooNE Detector

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**

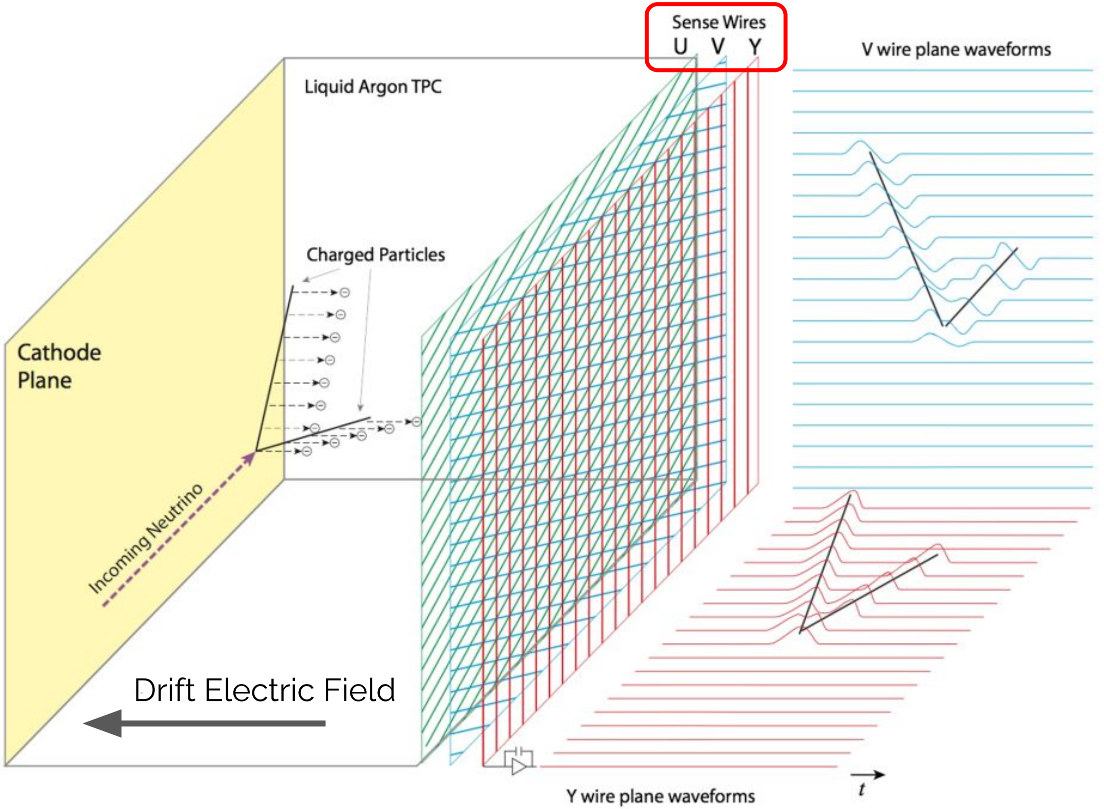
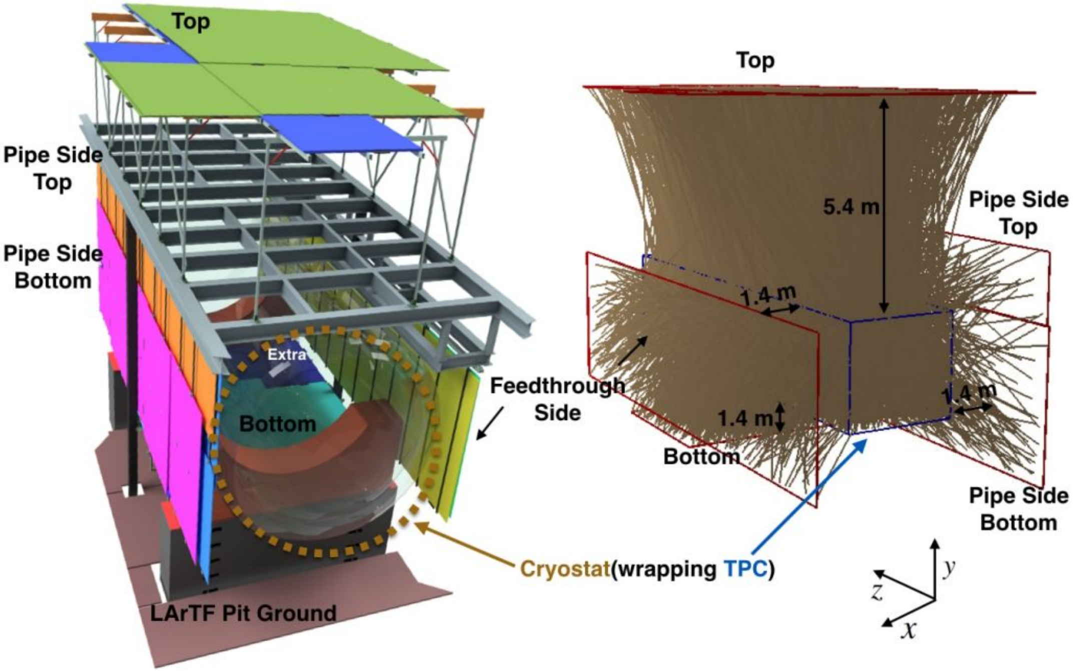


Figure 2 in JINST 12 P02017

For further details and the working principles of the MicroBooNE Detector itself see Ralitsa's talk

MicroBooNE Cosmic Ray Tagger

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



Theory Prediction, Single Photon production

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

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

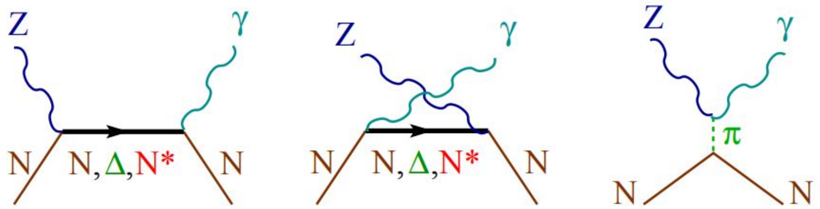


FIG. 1. (Color online) Feynman diagrams for the hadronic current of NC photon emission considered in Ref. [18]. The first two diagrams stand for direct and crossed baryon pole terms with nucleons and resonances in the intermediate state: BP and CBP with $B = N$, $\Delta(1232)$, $N^*(1440)$, $N^*(1520)$,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

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

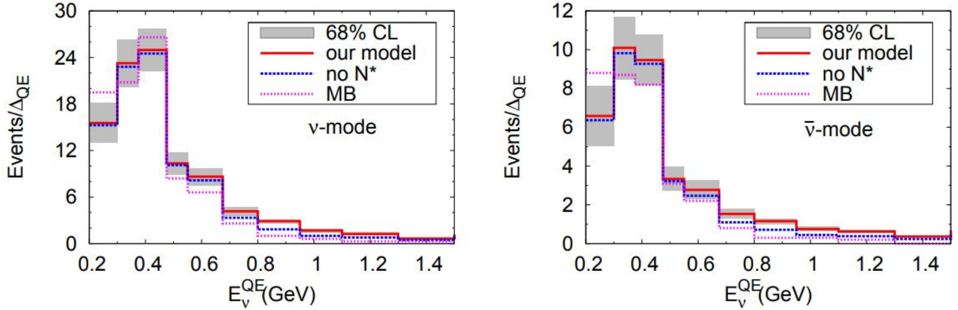


FIG. 4. (Color online) E_ν^{QE} distributions of total NCγ events for the ν (left) and $\bar{\nu}$ (right) modes. Our results, given by the red solid lines are accompanied by grey error bands corresponding to a 68 % confidence level. The curves labeled as "no N^*" show results from our model without 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.

MiniBooNE
In situ Pi0 constraint

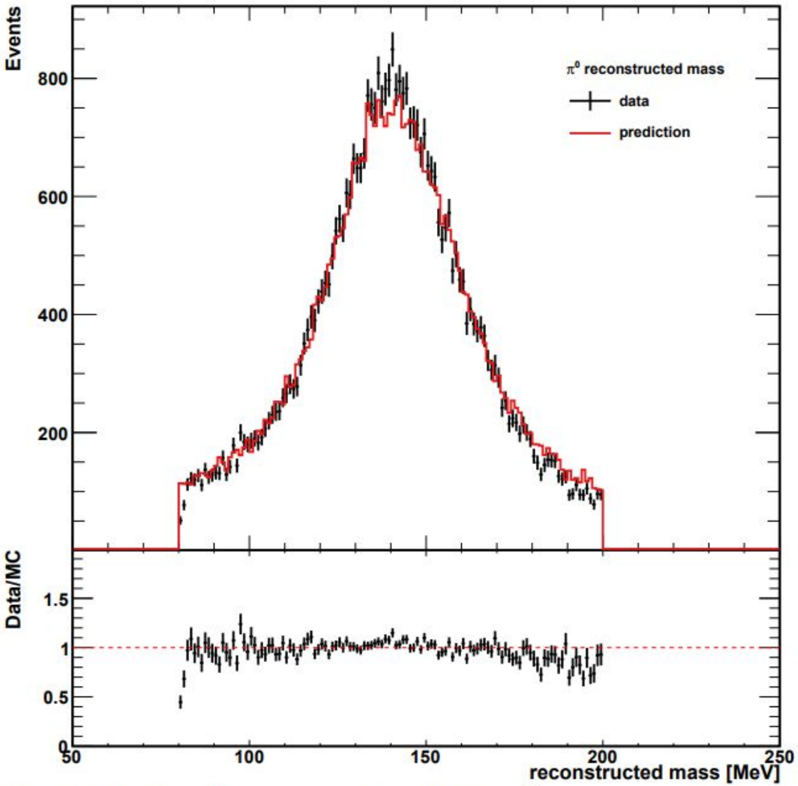
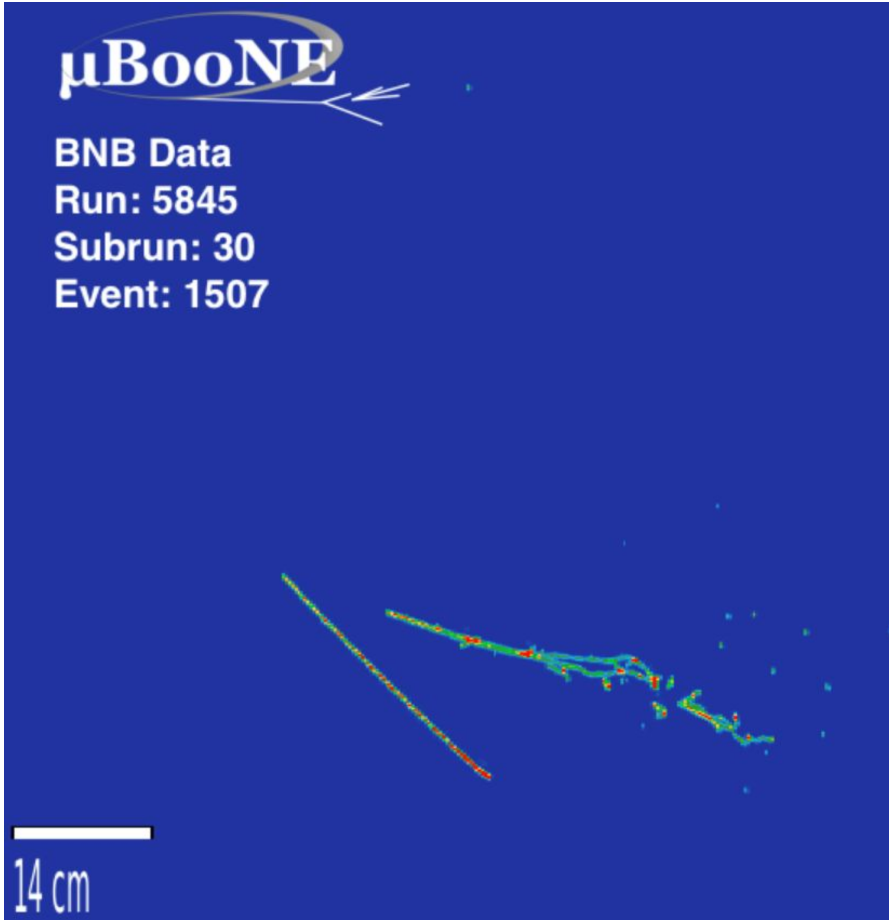


FIG. 7: An absolute comparison of the π^0 reconstructed mass distribution between the neutrino data (12.84×10^{20} POT) and the simulation for NC π^0 events (top). Also shown is the ratio between the data and Monte Carlo simulation (bottom). The error bars show only statistical uncertainties.

Single-Photon candidate event in data

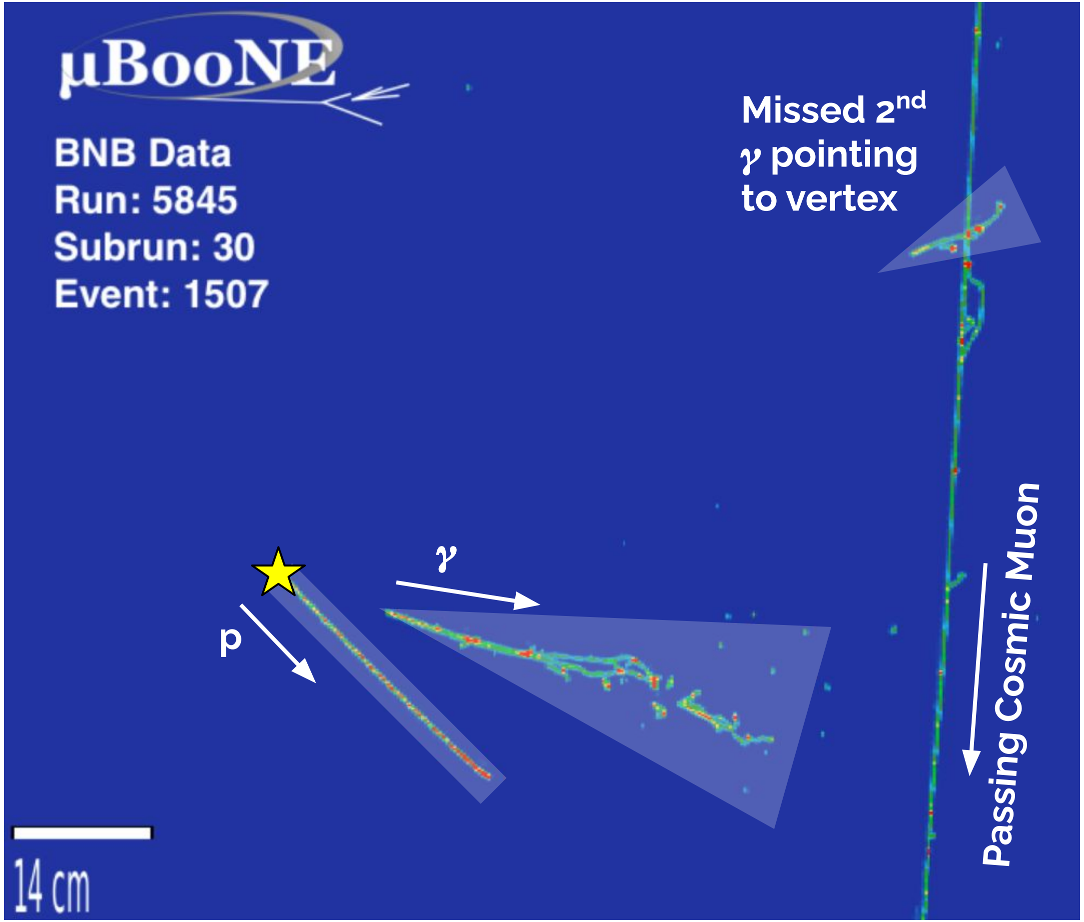


This **data event scores very highly as signal** in tailored background rejection BDT's

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)

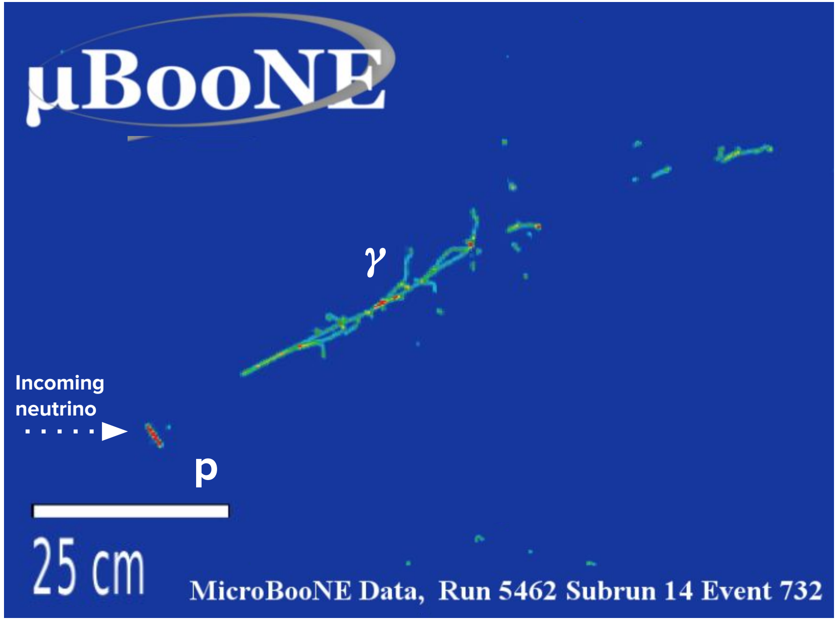


Zooming out:

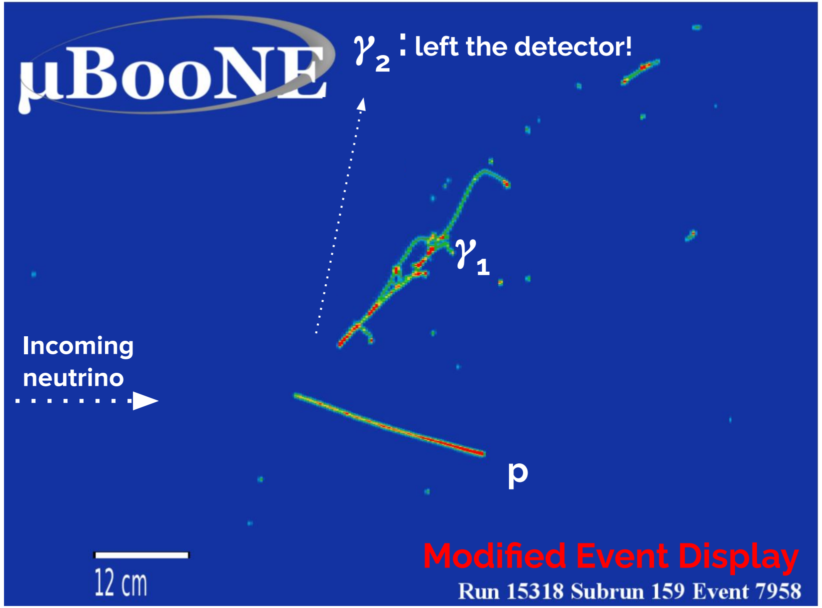
Missed secondary shower makes it much more likely to be **NCπ^0** event

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

NC single photon candidate $1\gamma1p$ data event



Hypothetical NC π^0 Event



Key takeaway: NC π^0 events outnumber true single-photon NC Δ radiative events by over **100-to-1** and there are *many ways* for the π^0's to mimic our signal