Neutral Current π^0 Rate Measurements with µBooNE

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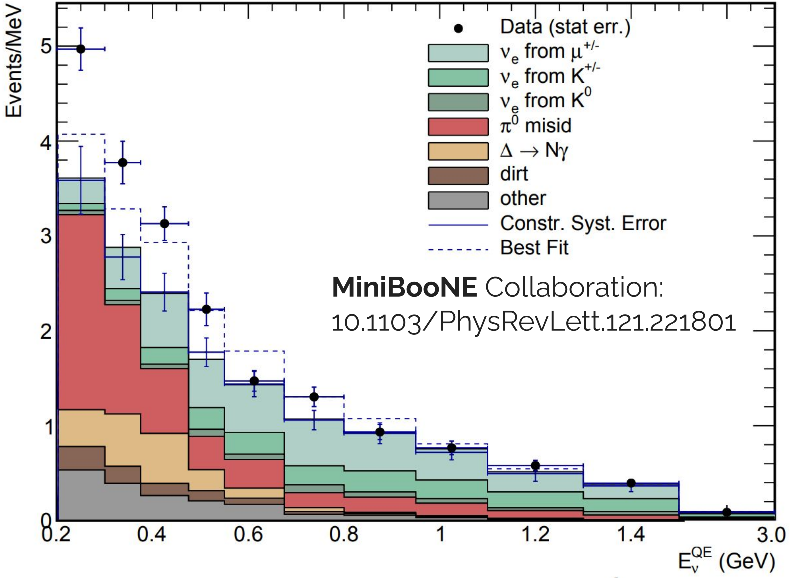
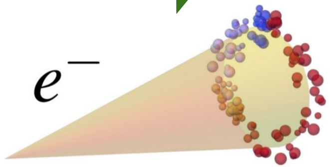
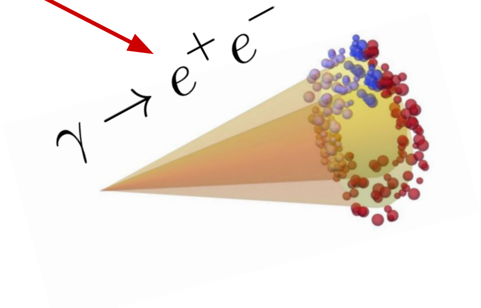
ICHEP 2020, Virtual Prague

July 28th 2020

Motivation for studying Neutral Current (NC) π^0 events comes directly from MicroBooNE's flagship analyses; investigating the MiniBooNE low-energy excess (right) and in particular determining if the source of the excess is **electron** or **photon** in origin.







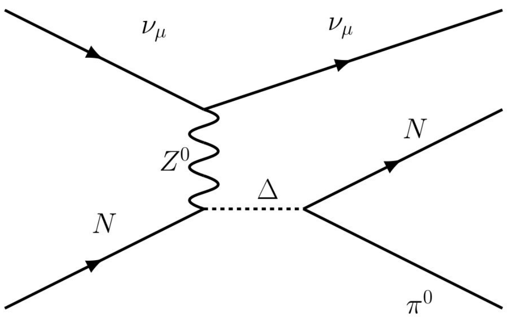
Whereas MiniBooNE could not distinguish between the Cherenkov cones produced from photons and electrons, but MicroBooNE can and has multiple analyses ongoing to select high-purity **single-electron** and **single-photon** samples

See **David Caratelli's talk** on the MicroBooNE low-energy excess searches later in this session for **more details**!

Motivation II: NC π^0 Production in Argon

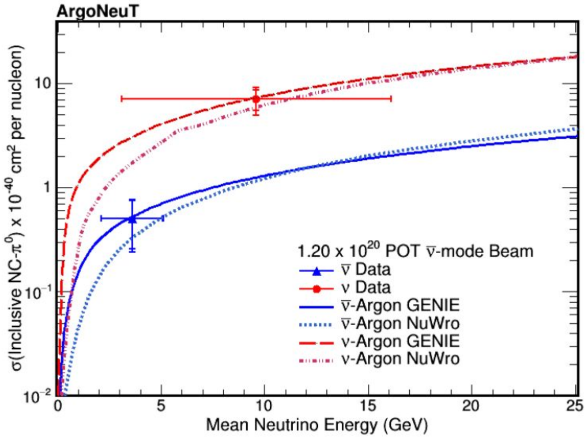
Using **GENIE**, the majority (~80%) of NC π^0s in MicroBooNE are expected to occur via **resonant production of a Δ baryon** which subsequently decays back to a nucleon and pion.

Remaining ~20% from other sources including **Coherent π^0** production, **Deep-Inelastic** scattering events as well as π^0 not created in the initial neutrino interaction but as a result of **Final State Interactions** (FSI) in the nucleus.



However, many of these important processes have **very large uncertainties**[1] in GENIE partially due to **very little data** in argon

- NC Coherent π^0 Normalization error: **100%**
- Fractional cross-section for π^0 charge exchange: **50%**
- Fractional cross-section for π^0 absorption: **30%**
- Axial Mass used in modelling resonant production : **20%**



[1] See Public Note: MICROBOONE-NOTE-1074-PUB

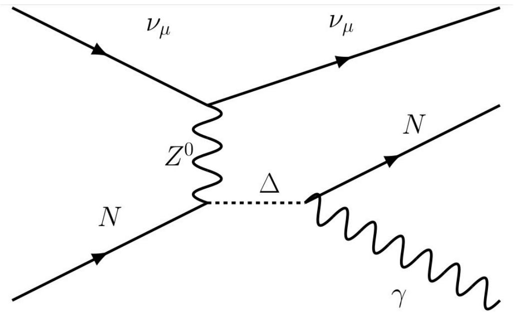
Inclusive NC π^0 rate measurement by ArgoNeut: 1511.00941

NC Radiative Δ Decay - MicroBooNE's Single-Photon Search

Process has **never been observed** in the neutrino sector.

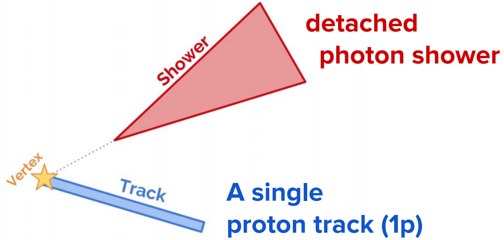
A Standard model source of single-photon events and a possible explanation of the MiniBooNE low-energy excess

Measuring this channel is the goal of MicroBooNE's first photon analysis

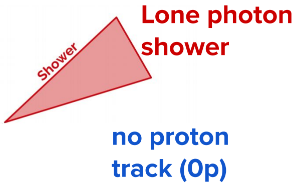


Approx ~0.6% Branching Ratio

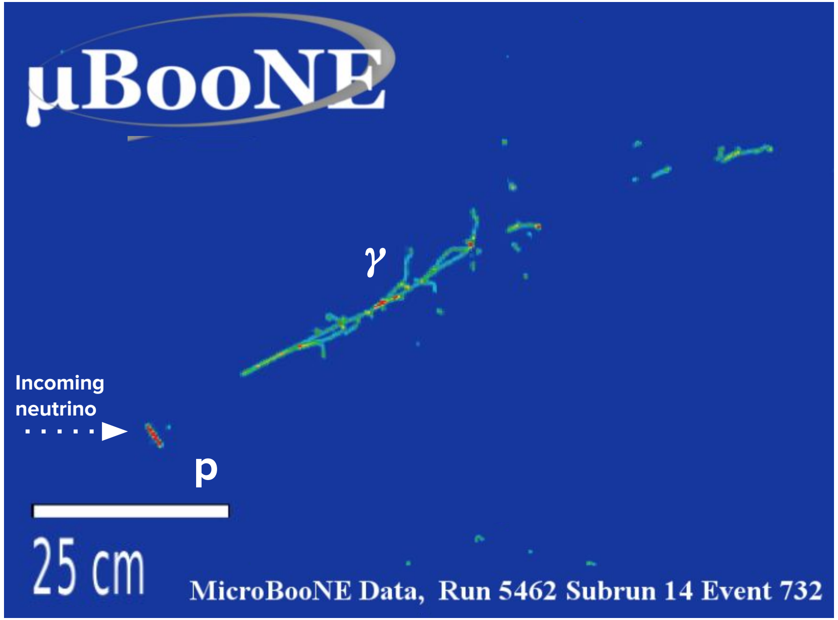
Two selections ongoing, where we select photons consistents with being from a Radiative Δ Decay both with an associated proton track (so called "**1γ1p**" selection)



and without a proton track (so called "**1γ0p**" selection):



NC single photon candidate $1\gamma1p$ data event



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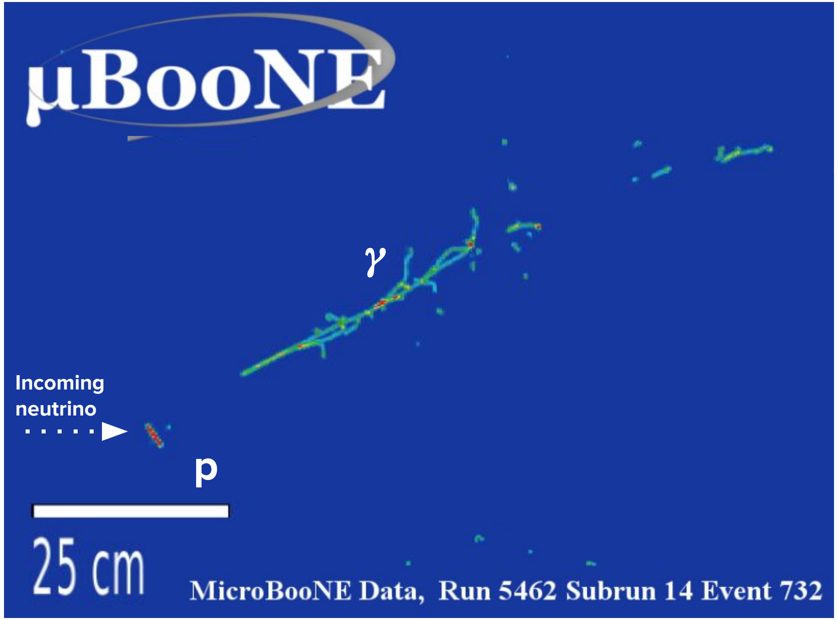
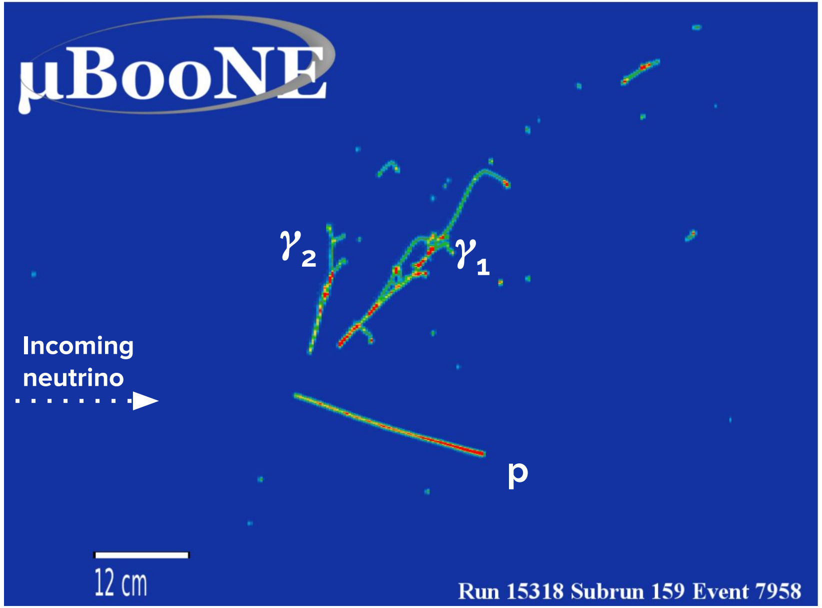


NC π^0 + 1 Proton ($2\gamma1p$) Candidate data event



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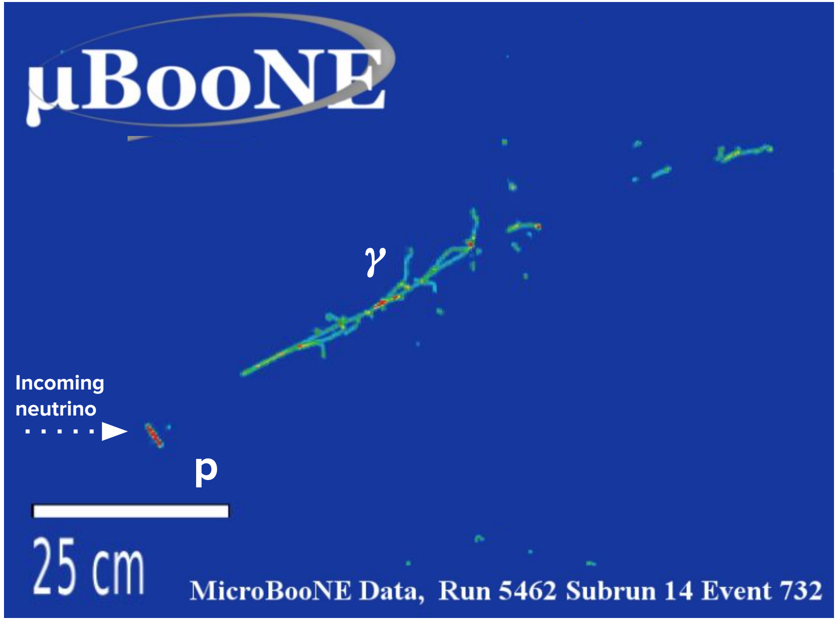
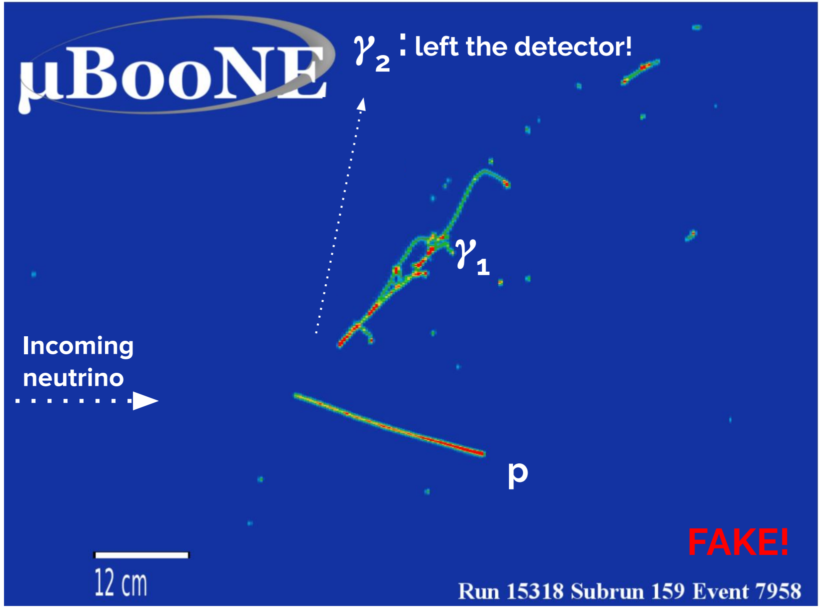


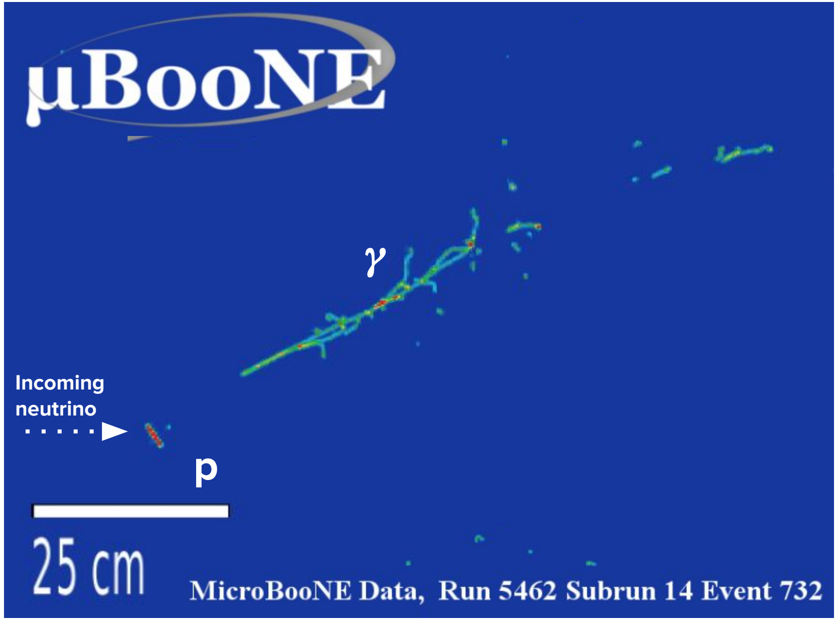
Topologically now **indistinguishable** from our single photon signal.

Hypothetical NC π^0 Event



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

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



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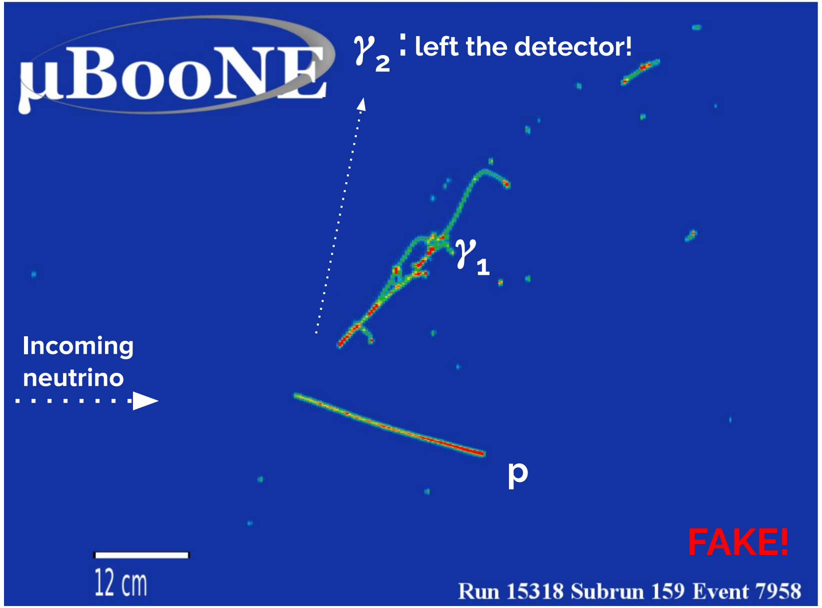
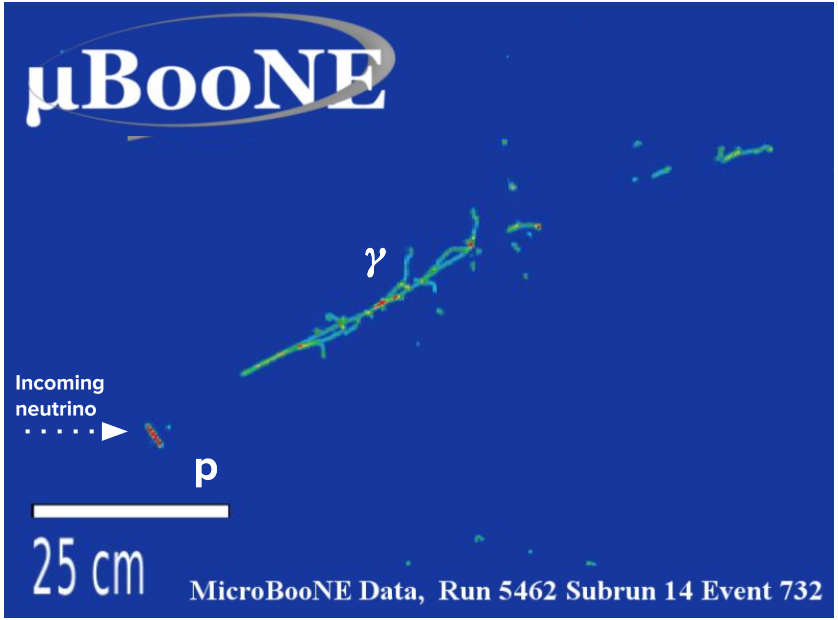


There are many ways with which the secondary shower is lost:

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

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



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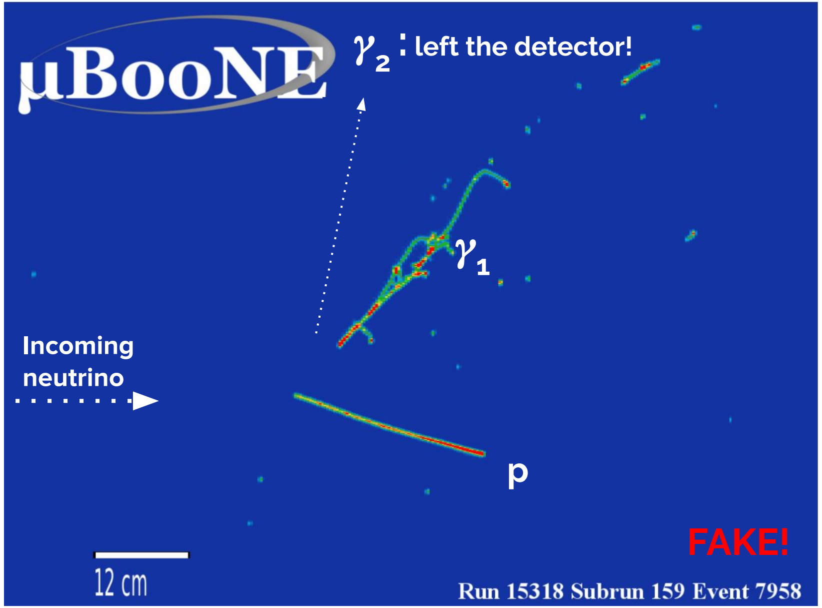


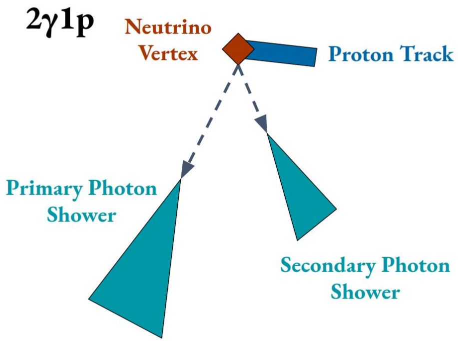
Key takeaway: NC π^0 events outnumber true single-photon NC Δ radiative events by over **100-to-1** and there are *many ways* for the π^0's to mimic our signal

As such we developed an **in-situ measurement of the NC π^0** events in MicroBooNE to ensure we are simulating them correctly

Developing a NC π^0 $2\gamma 1p$ selection

Selection begins with selecting all **2 shower and 1 track events** from **Pandora pattern recognition framework** [Eur. Phys. J. C78, 1, 82 (2018)] alongside some additional preselection cuts:

1. **Shower conversion distance > 1cm :** To minimize true electron showers (blindness)
2. **Neutrino vertex > 5cm from TPC wall:** Remove cosmic contamination
3. **Leading shower energy** > 30 MeV, subleading > 20 MeV



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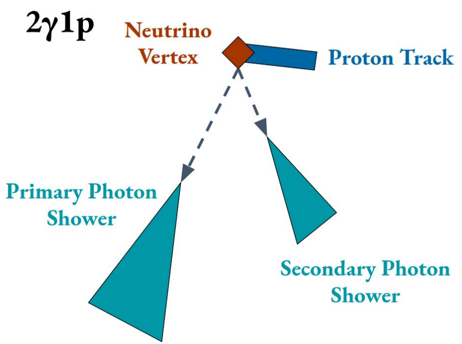
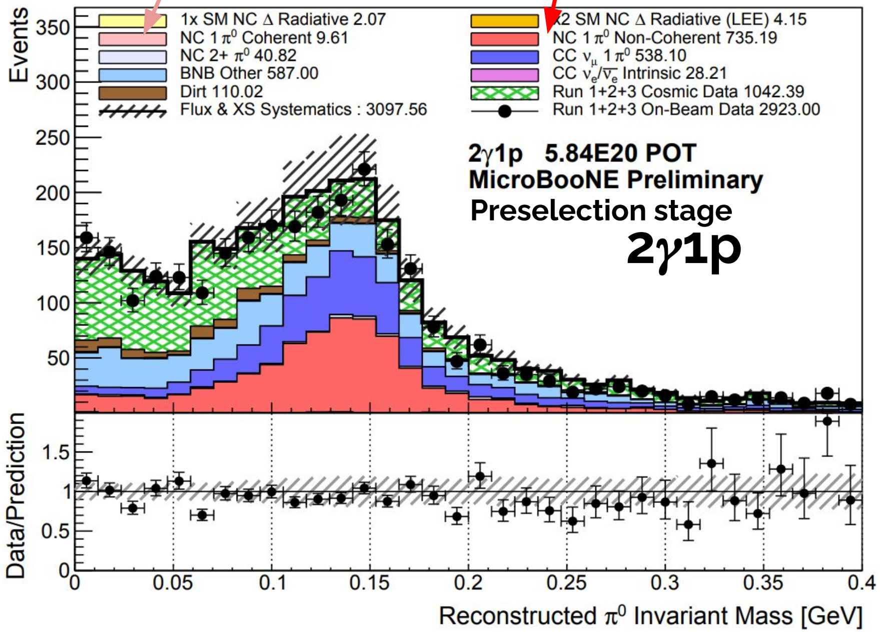


~**24% purity** of NC 1 π^0



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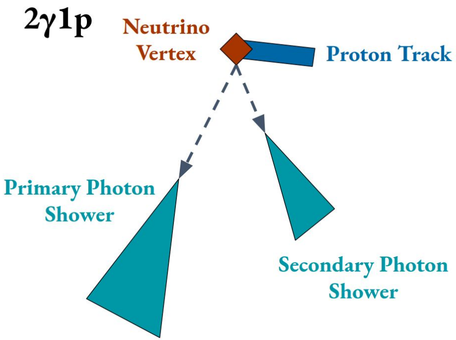
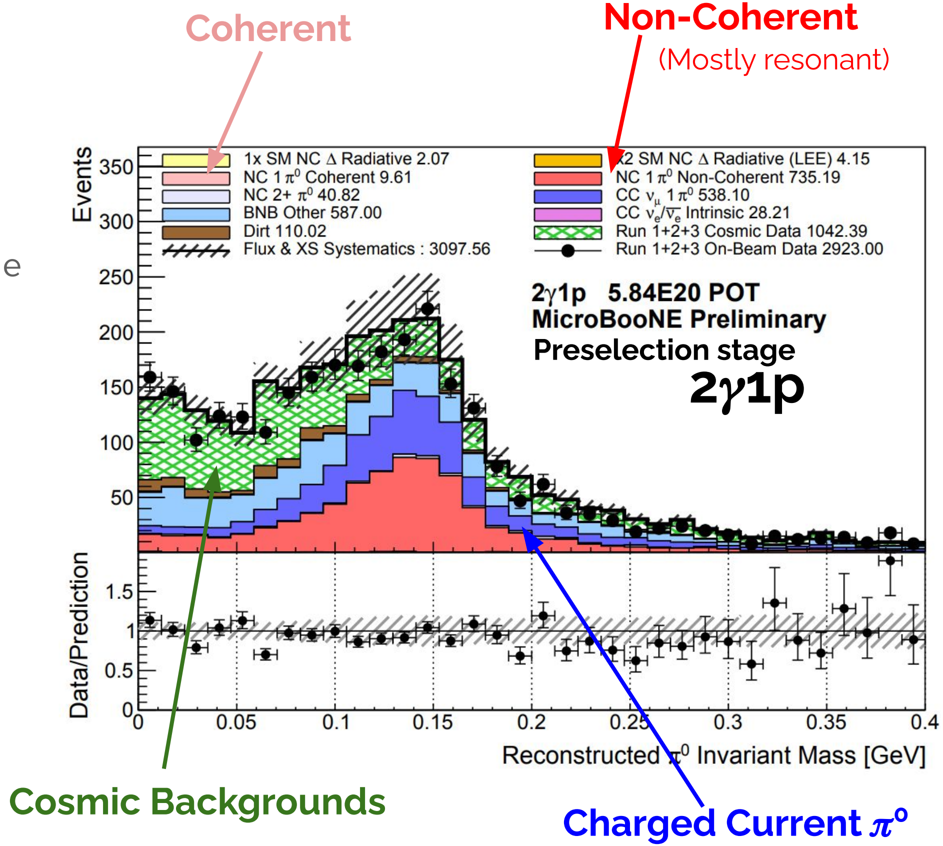
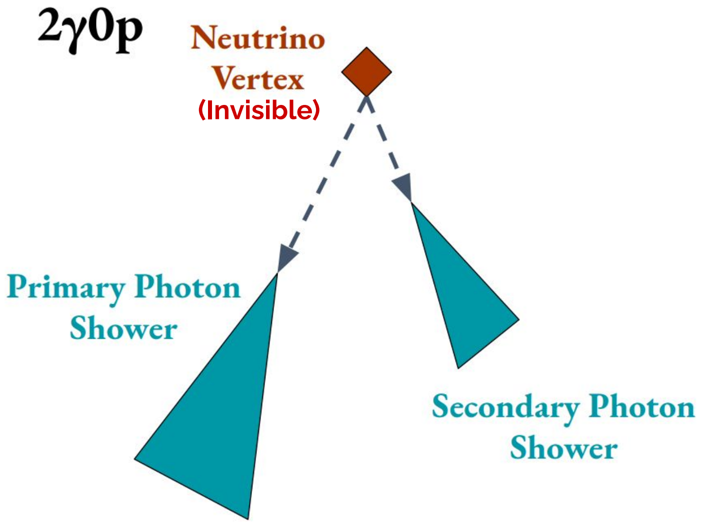
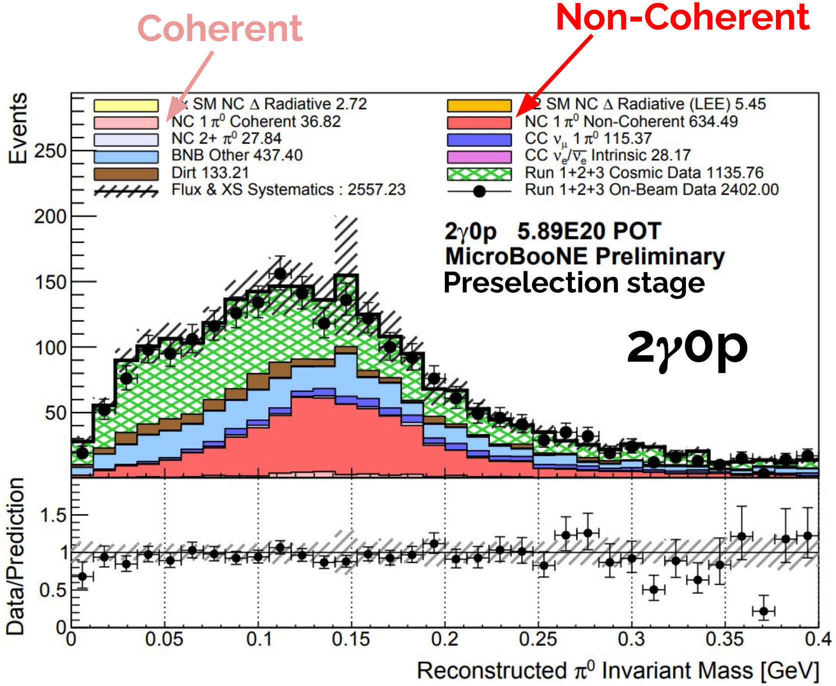




Repeat this for 2γ0p selection (i.e No Track)

~**26% purity** of NC 1 π^0





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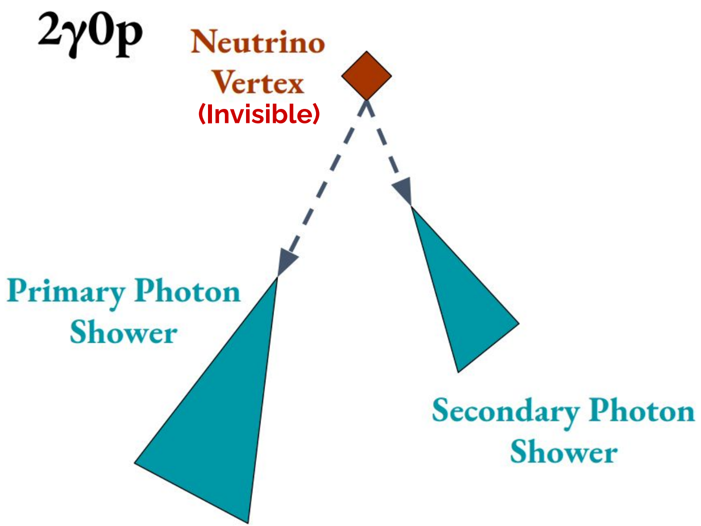
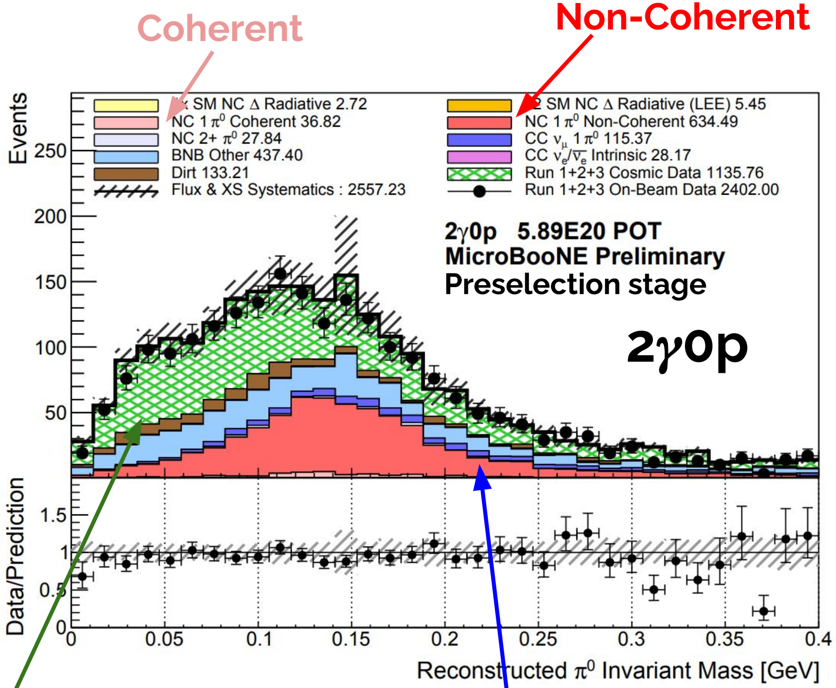




Cosmic Backgrounds

Much smaller **charged current π^0 backgrounds**, as longer **muon** track is harder to "miss"

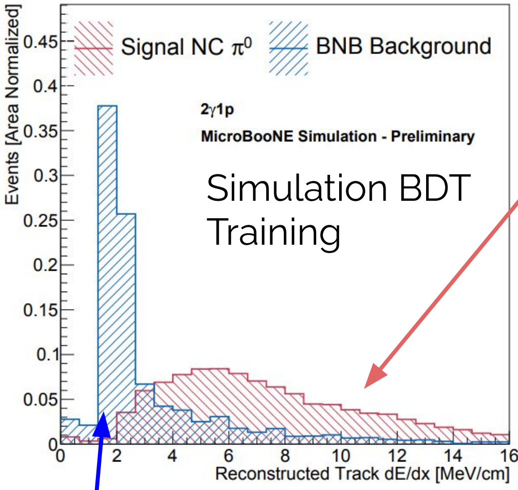
Boosted Decision Trees

In order to **increase the purity** of the selected events, we train **two tailored Boosted Decision Trees** (BDT) to reject the primarily charged current π^0 and cosmic backgrounds

The BDT's use 10 various kinematic and calorimetric variables

An example of an important variable is: **Track dE/dx** (Energy deposition per unit length)

- Isolates events with proton tracks (higher dE/dx) for 2γ1p selection



Highly ionizing **protons** travel short distances before stopping with a Bragg peak

Muons travel longer distances while minimally-ionizing at ~ 2 MeV/cm

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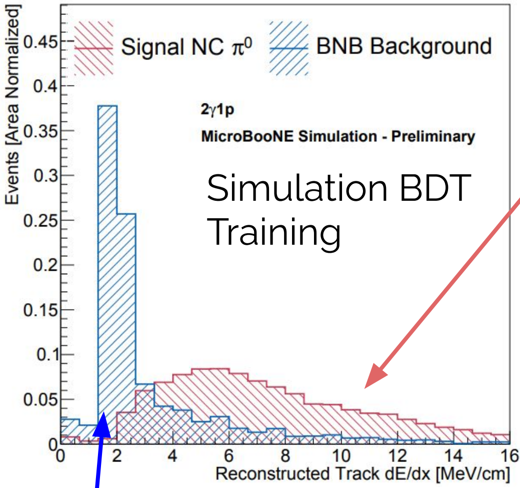

Simulation BDT Training

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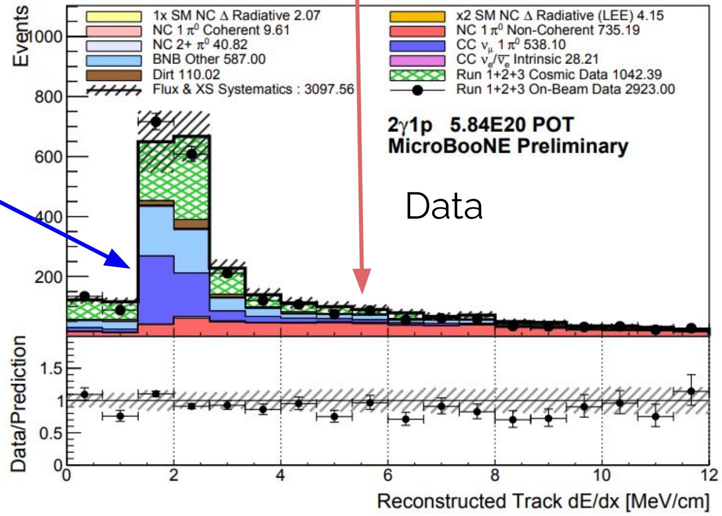
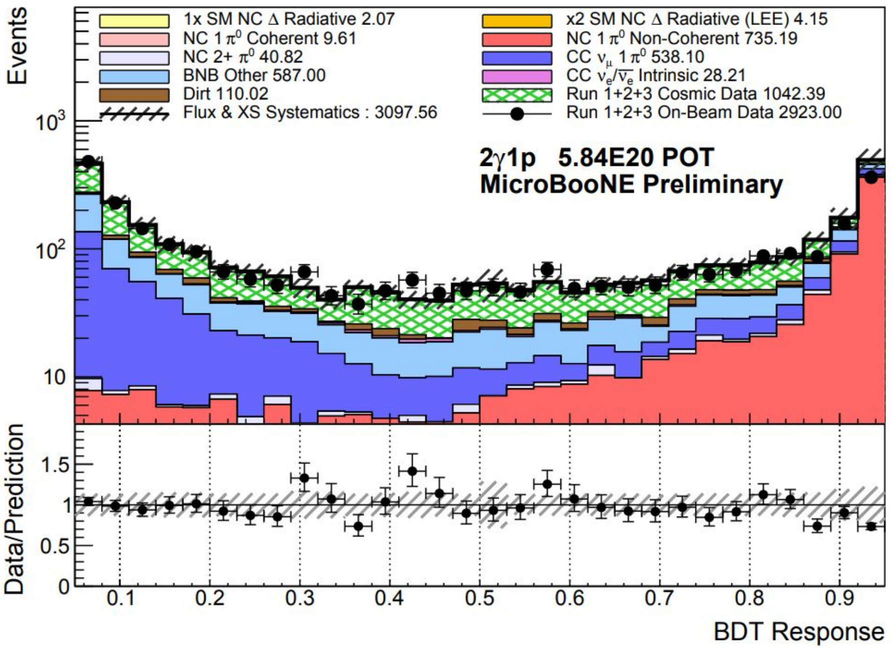


Data

NC π^0 BDT Response for 2γ1p

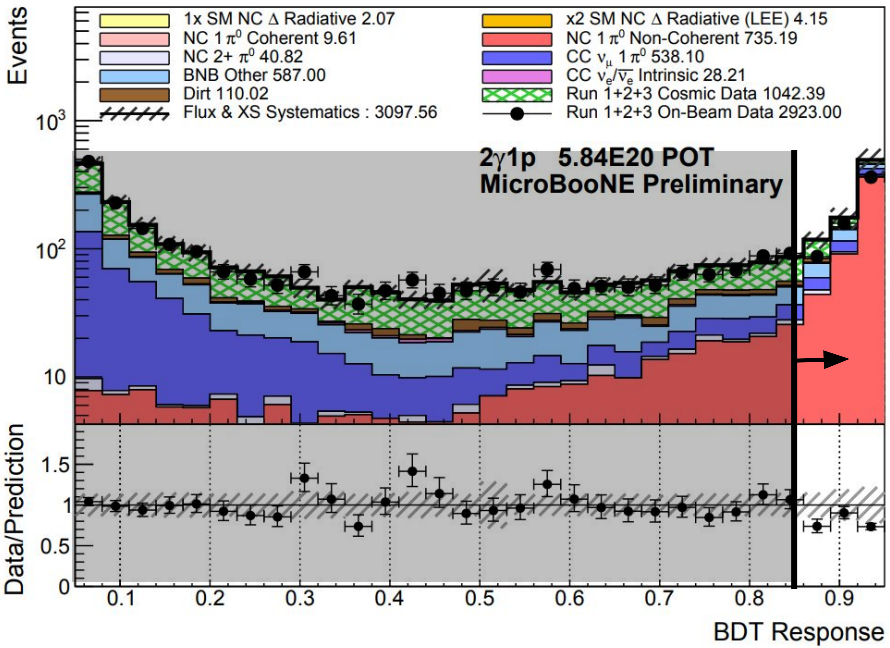


More Background like: e.g charged current π^0 events

More NC π^0 Signal-Like

Good agreement between the resulting simulated BDT response and MicroBooNE data.

NC π^0 BDT Response for $2\gamma 1p$



More Background like: e.g charged current π^0 events

More NC π^0 Signal-Like

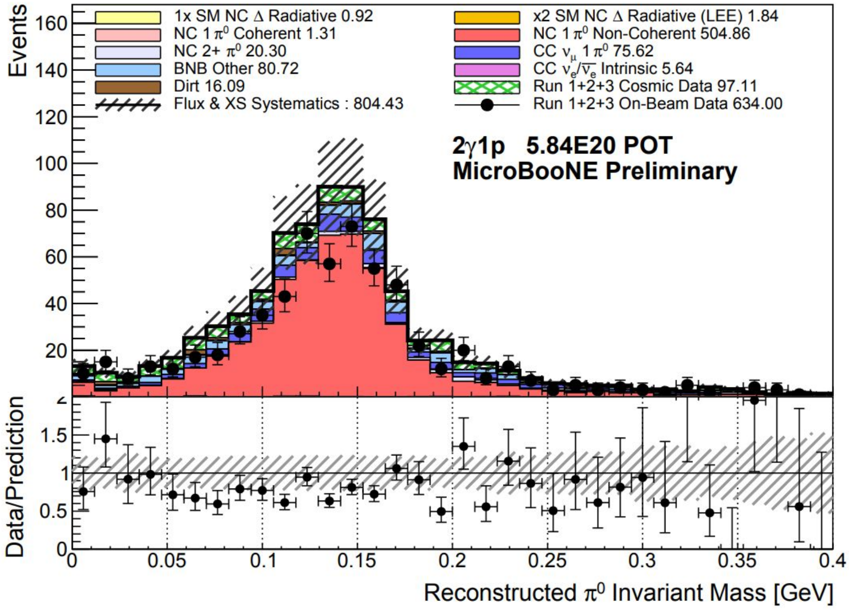
Good agreement between the resulting simulated BDT response and MicroBooNE data.

Place **a cut** on this BDT response in which we optimize the signal efficiency-times-purity

Train a similar BDT for the $2\gamma 0p$ selection (See Backup slides for details)

Final Selection - 2γ1p

Represents the largest NC π^0 selection in a LArTPC in the world!



- **63%** pure sample of NC 1 π^0
- Gaussian fit to data:
  - Mean: **137.6** ± 2.1 MeV
  - Width: 44.1 ± 1.8 MeV

As this sample demands that a proton candidate track is reconstructed, the NC coherent π^0 components is almost negligible, less than 0.3%

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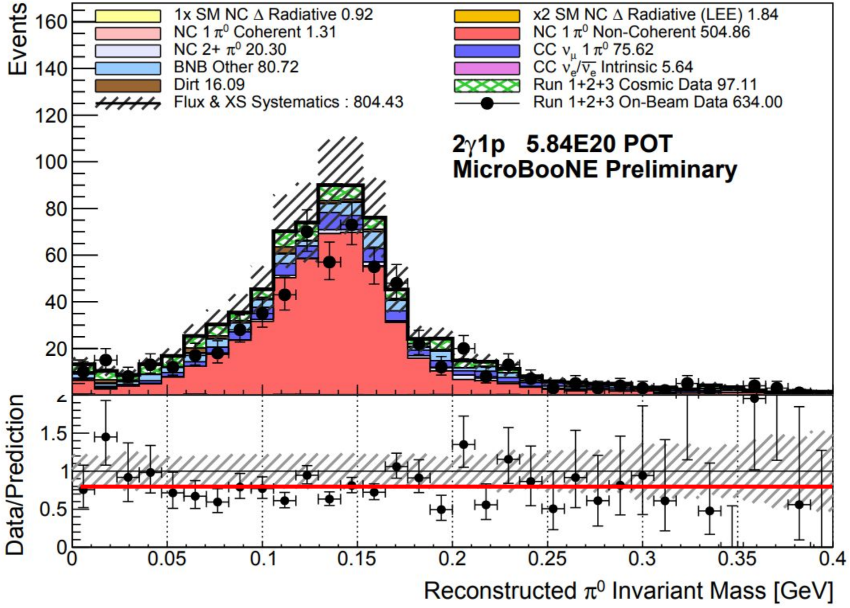

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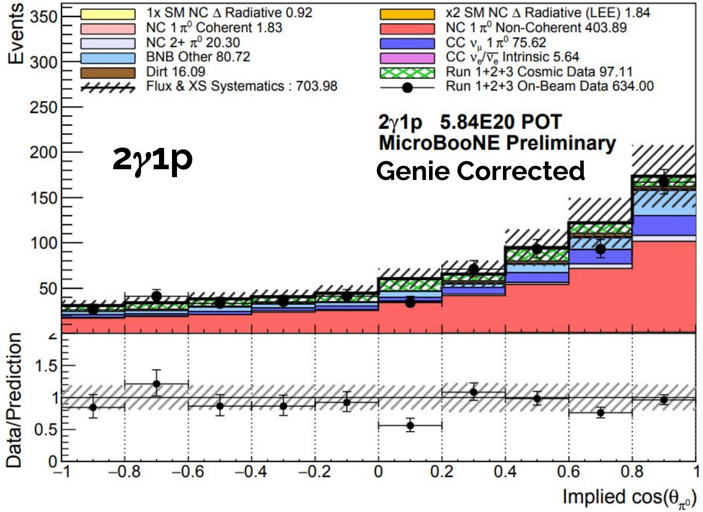
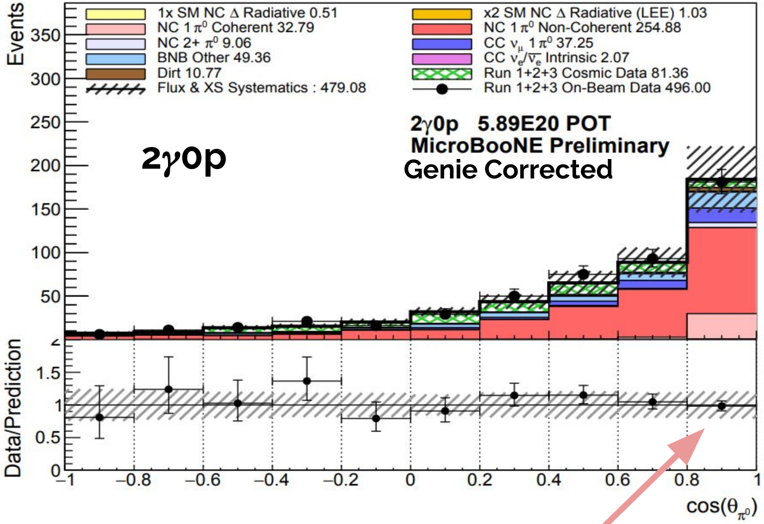
See approx **20%** less events in data than expected in this 2γ1p selection.
Perform an in-situ **fit** to the observed rate of NC π^0 's to correct the GENIE prediction in our simulation.

Fitting the Coherent and Non-Coherent π^0 rates





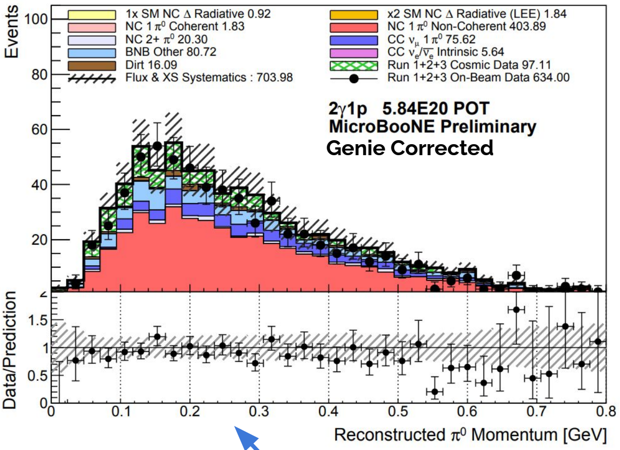
Θ_π is the angle the reconstructed π^0 makes relative to the neutrino beam. We fit in this variable to extract best sensitivity to coherent π^0 production

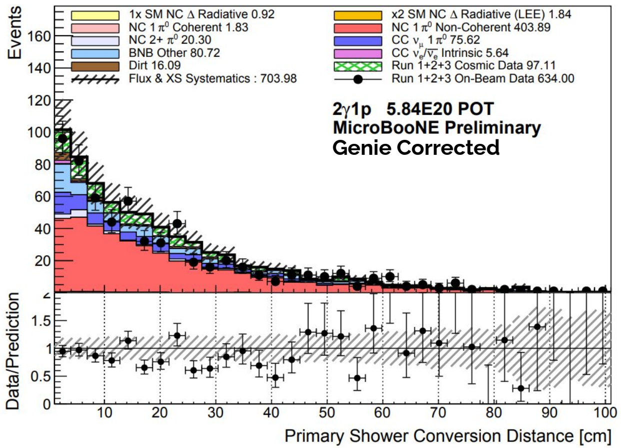
Best fit point (shown above)

- **40% Enhancement** of Coherent π^0 production
- **20% Decrease** of Non-Coherent π^0 production

Coherent π^0 production due to scattering off the nucleus tends to produce a **very forward going π^0** with no additional tracks

Other NC π^0 $2\gamma 1p$ reconstructed quantities





After correction of normalization, our simulation of the kinematics of NC π^0 and subsequent decays show **very good agreement to data,** can only briefly touch on them here

Gives us confidence in our NC π^0 simulation, crucial to **constraining our backgrounds** for the single-photon analysis.

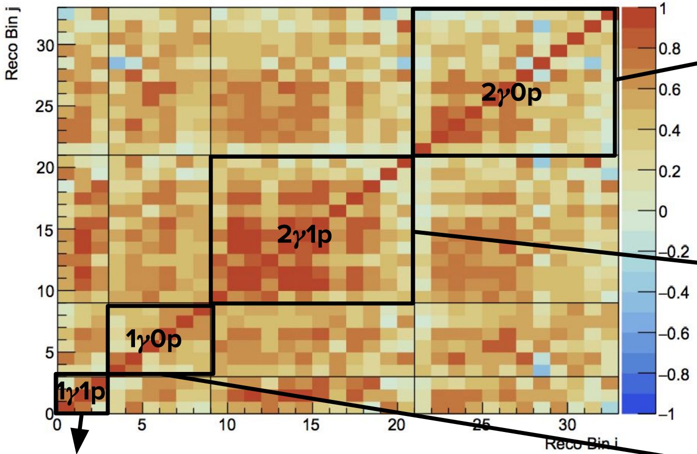
Use selected showers to reconstruct the parent π^0 momentum spectrum. Peaks just below 200 MeV as expected from the Booster Neutrino Beam.

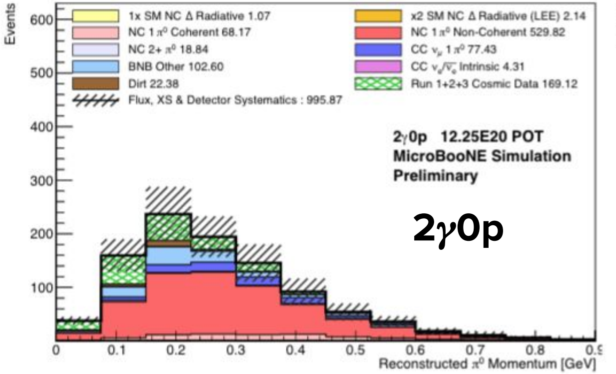
Reconstruct π^0 daughter photon showers as far as ~100cm from interaction vertex

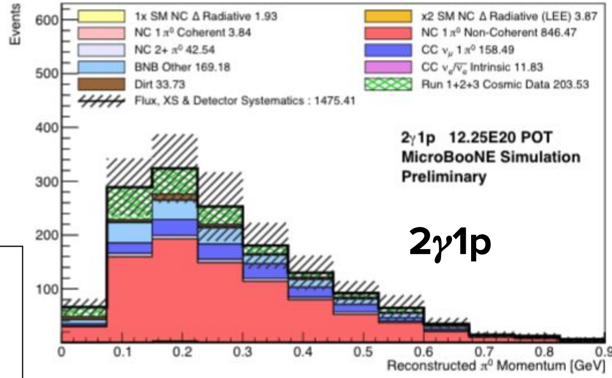
The NC π^0 Constraint

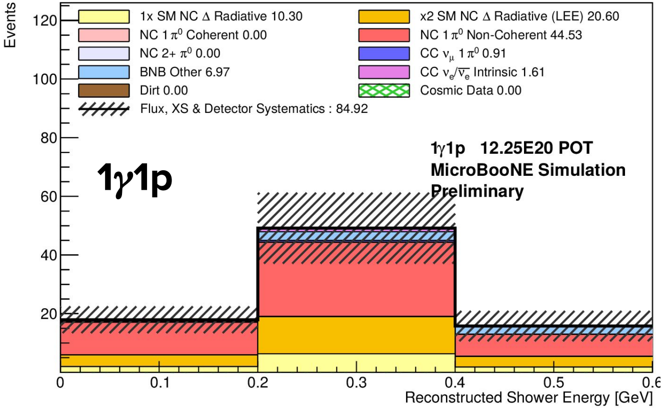
Side-by-side fit to 1γ and 2γ selections indirectly constraints NC π^0 background

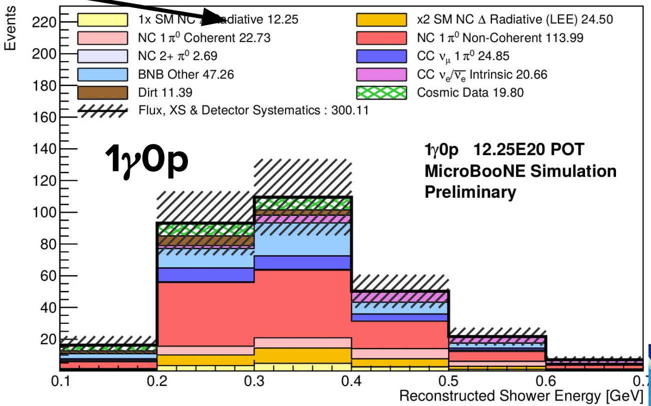
Correlation Matrix











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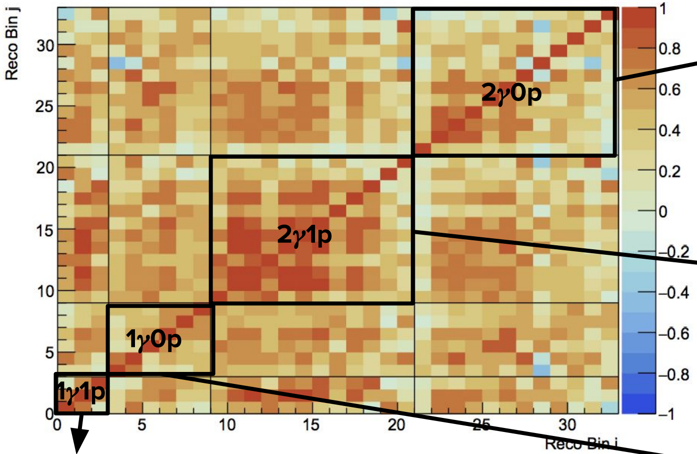
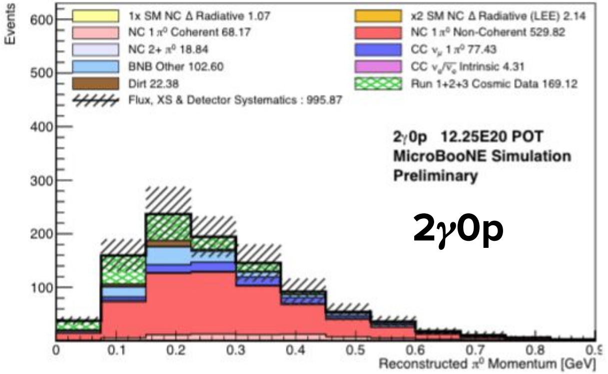
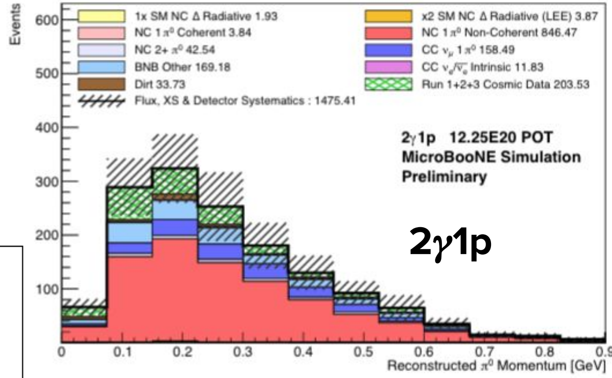
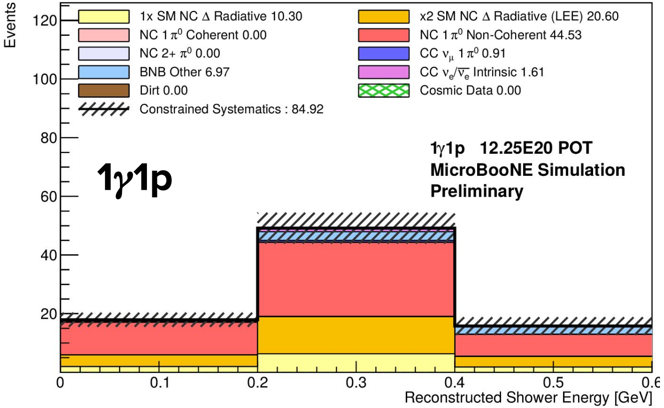
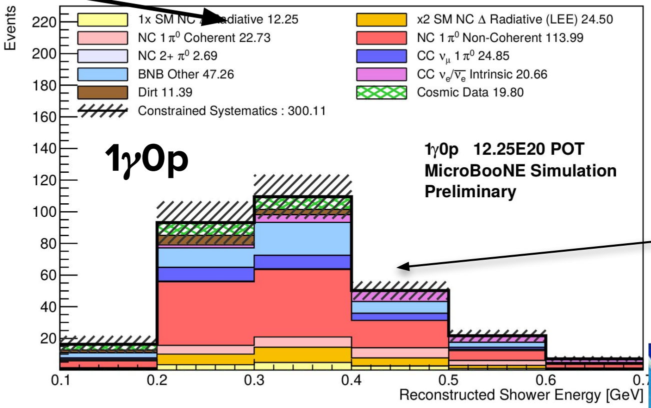










Effective x2 systematic uncertainty reduction before/after constraint!

Conclusions

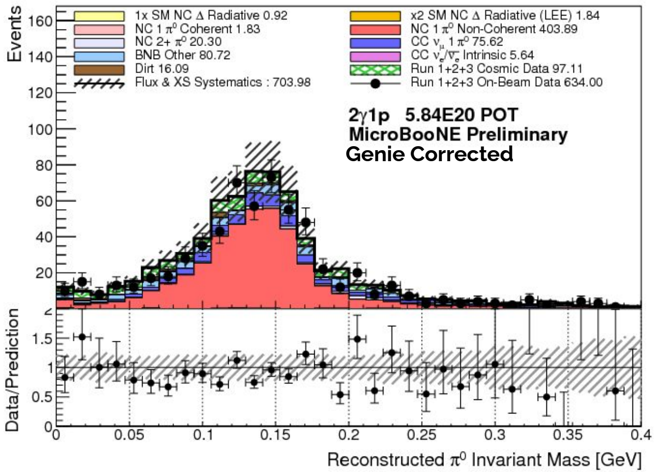
- Presented the **largest selection of NC π^0** in a LArTPC in the world

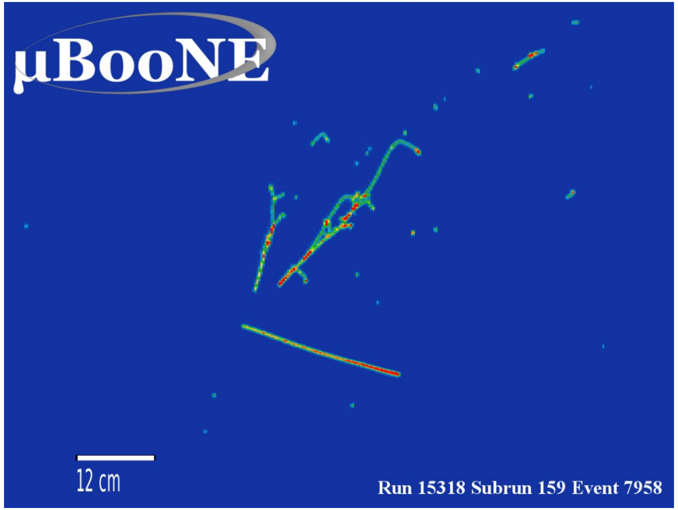
- Provides a **strong constraint** to the main backgrounds for MicroBooNE's single-photon low-energy excess analysis

- In-situ measurement allows for corrections to the default GENIE prediction, favouring a **40% increase in coherent** NC π^0 production and a **20% reduction in non-coherent** NC π^0 events.

- All results shown here are for an initial ~6e20 POT, with the final full MicroBooNE data set projected to double the data at 12.3e20 POT

- More information on this analysis can be found in the MicroBooNE single-photon **public note**: [MICROBOONE-NOTE-1087-PUB]





Backup Slides

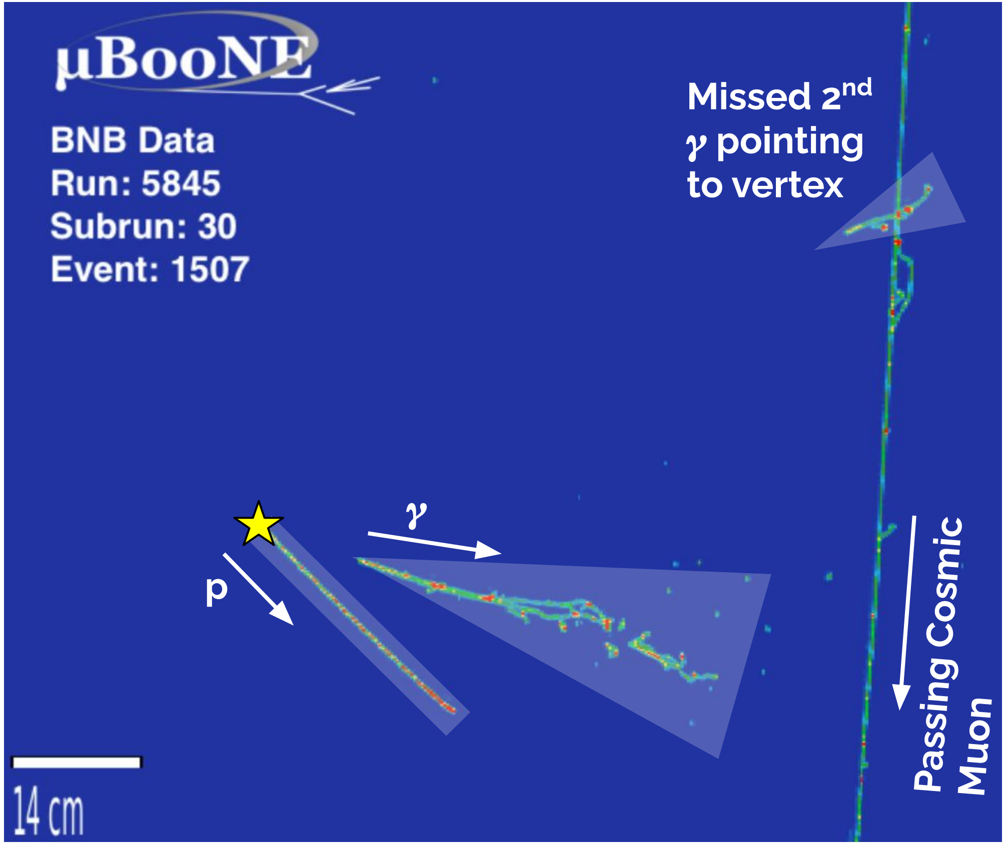
NC π^0's importance for MicroBooNE

Where as the π^0 backgrounds are under control in the electron selections due to **calorimetry** and **high spatial resolution**, [See talk by Wouter LINK] these tools are not as useful in the photon selection as both our signal and the NC π^0 background consist of true photons.

In fact NC π^0's make up **over 80%** of all backgrounds to the single-photon analysis.

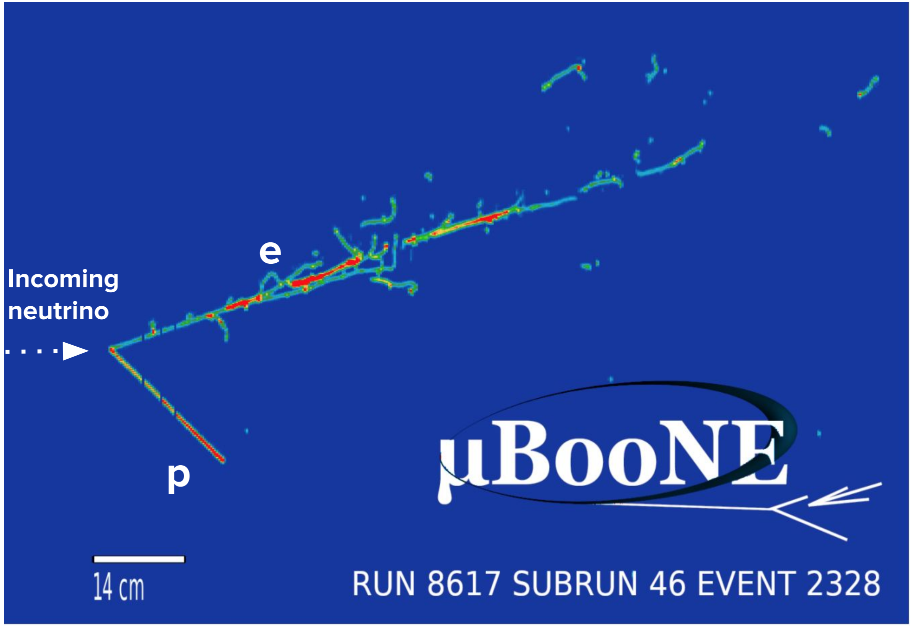
Understanding the NC π^0 's is thus a critical part of sMicroBooNE's strategy and for this we need a **high statistics, pure sample of NC 1 π^0 events**.

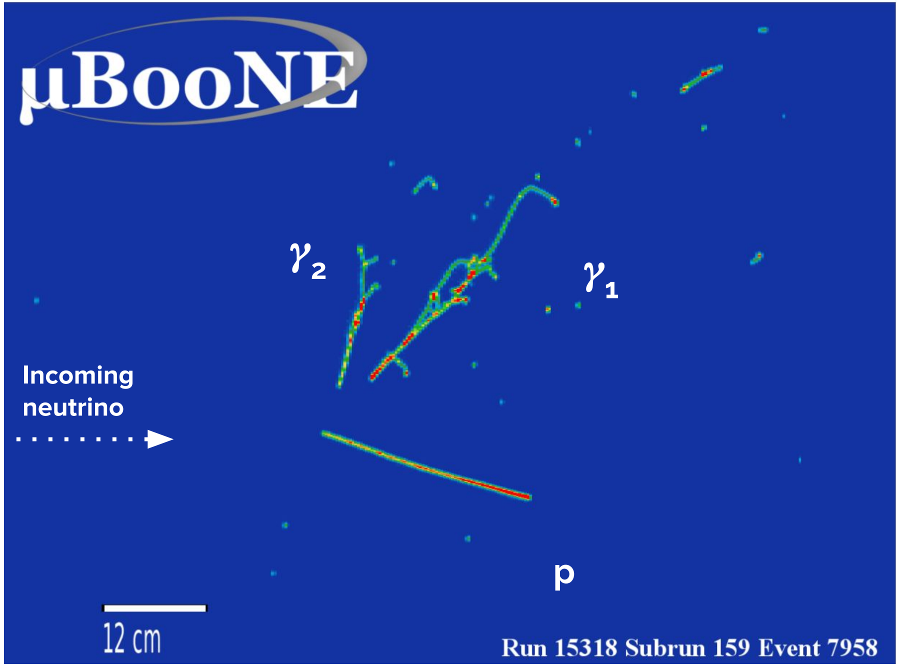
$1\gamma 1p$ candidate data event



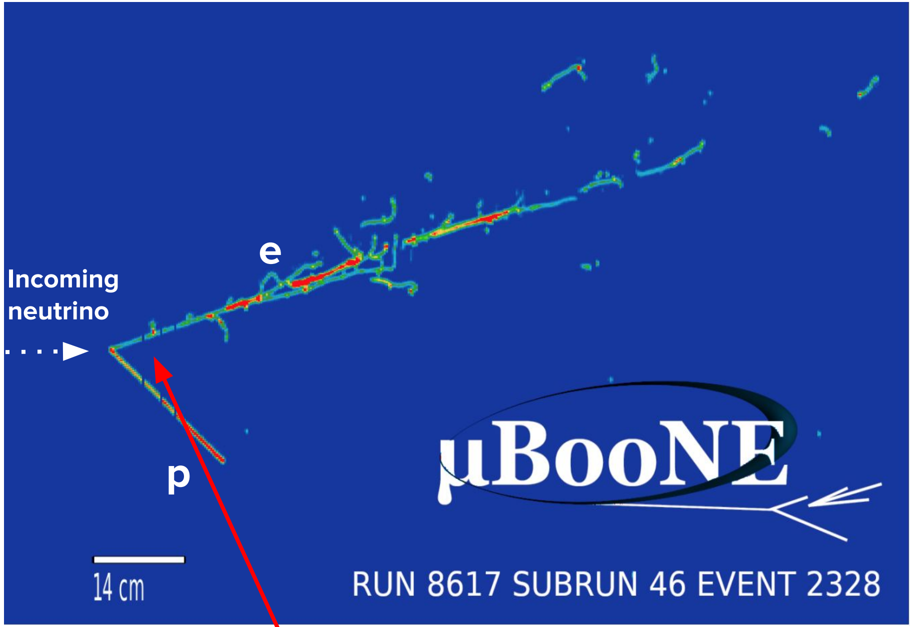
NCPi0’s as a background to MicroBooNE Electron Searches

CC ν_e candidate 1e1p data event

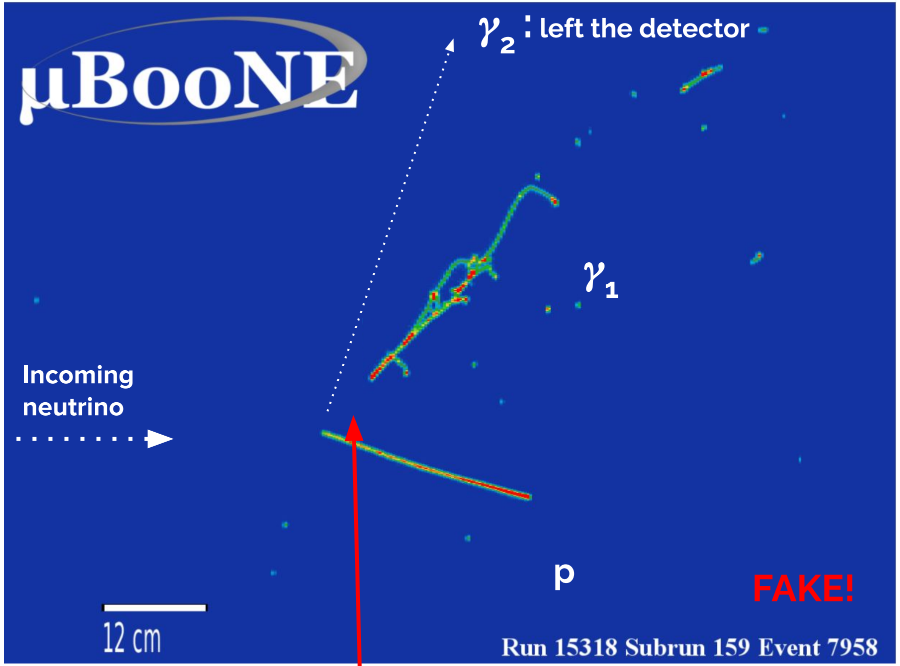




CC ν_e candidate 1e1p data event



Hypothetical NC 1 π^0



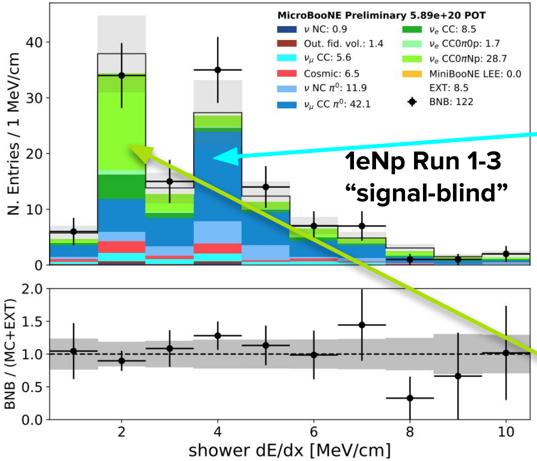
Even if one of the photons in the π^0 decay fails to be reconstructed, the **true electrons** begin to ionize the liquid argon immediately, where as the **photon** will, on average, travel a short distance before pair converting thus leaving a **visible gap**.

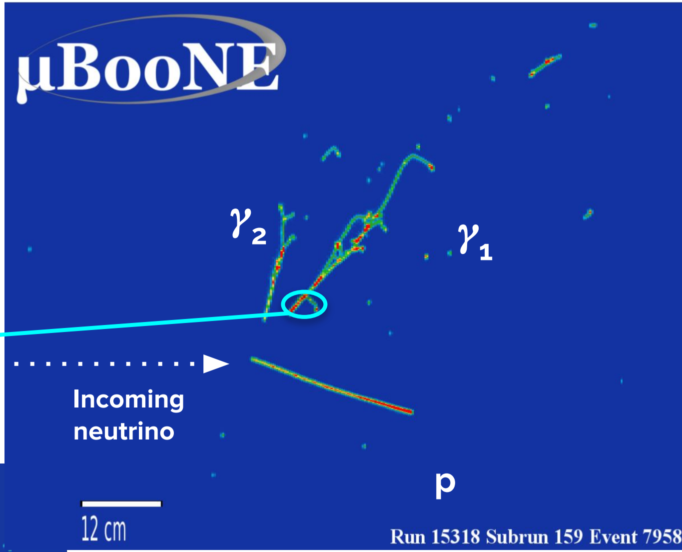
Calorimetric photon-electron separation

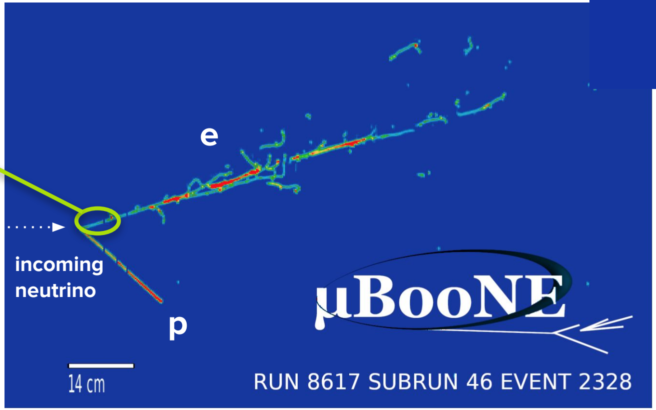
In addition to the visible gap between vertex and EM shower

Using ionization dE/dx:

- **Single electrons begin as minimally ionizing (2 MeV/cm)**
- **Photons pair convert to e^+/e^- pairs, double ionizing (4 MeV/cm)**







From eV to EeV: Neutrino Cross-Sections Across Energy Scales

https://arxiv.org/pdf/1305.7513.pdf

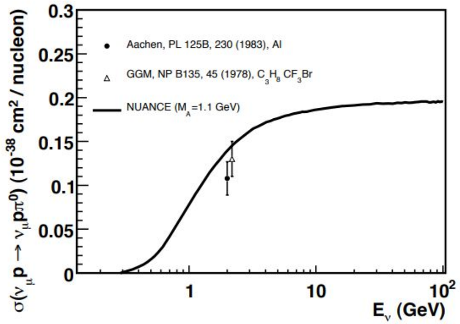


FIG. 16 Existing measurements of the cross section for the NC process, $\nu_\mu\, p \rightarrow \nu_\mu\, p\, \pi^0$, as a function of neutrino energy. Also shown is the prediction from Reference (Casper, 2002) assuming $M_A = 1.1$ GeV. The Gargamelle measurement comes from a more recent re-analysis of this data (Hawker, 2002).

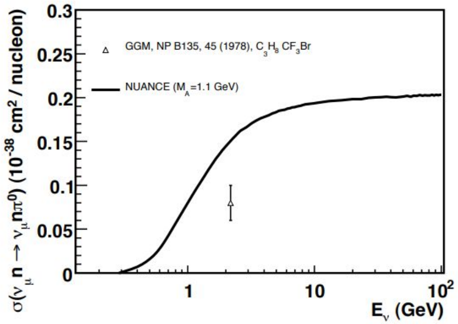
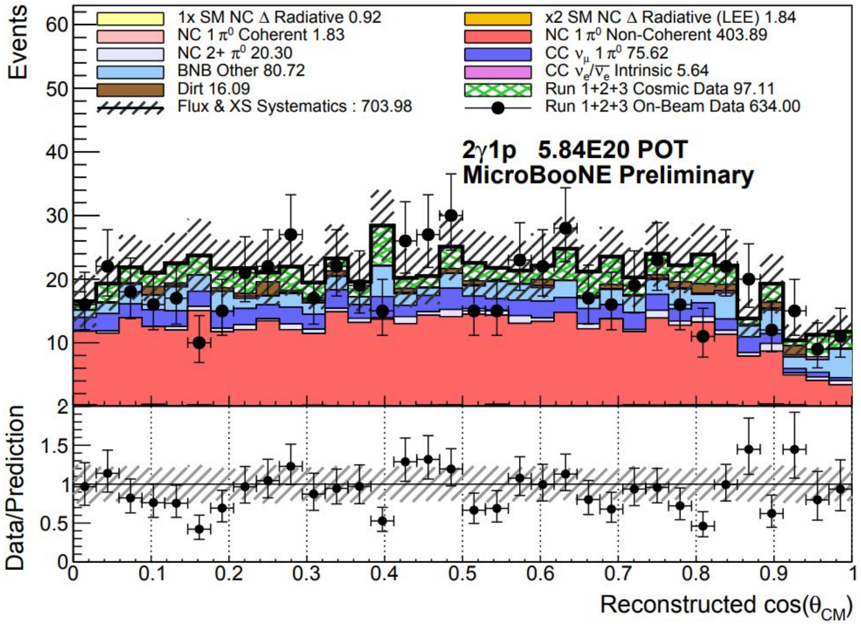
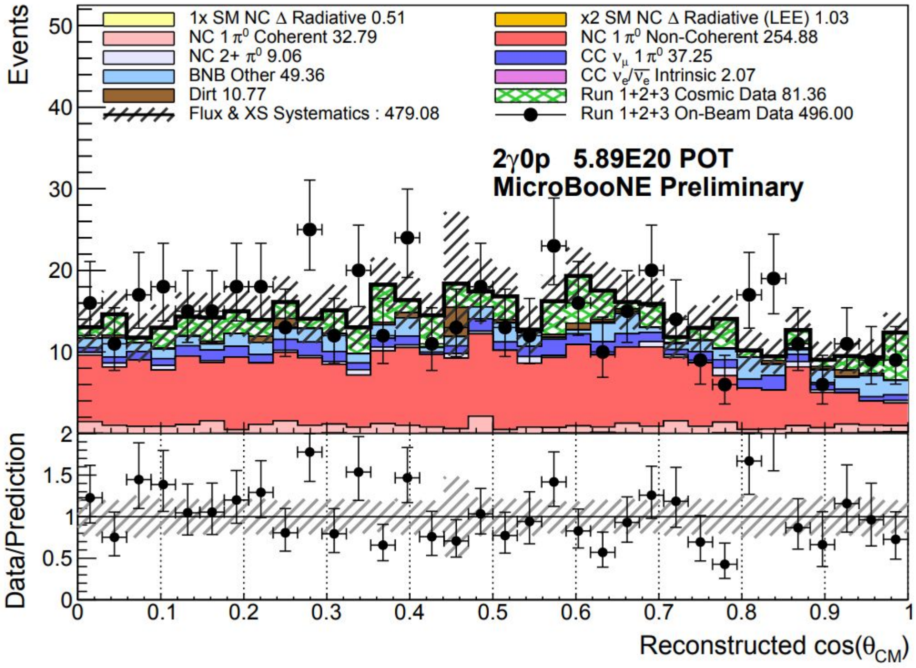


FIG. 18 Existing measurements of the cross section for the NC process, $\nu_\mu\, n \rightarrow \nu_\mu\, n\, \pi^0$, as a function of neutrino energy. Also shown is the prediction from Reference (Casper, 2002) assuming $M_A = 1.1$ GeV. The Gargamelle measurement comes from a more recent re-analysis of this data (Hawker, 2002).

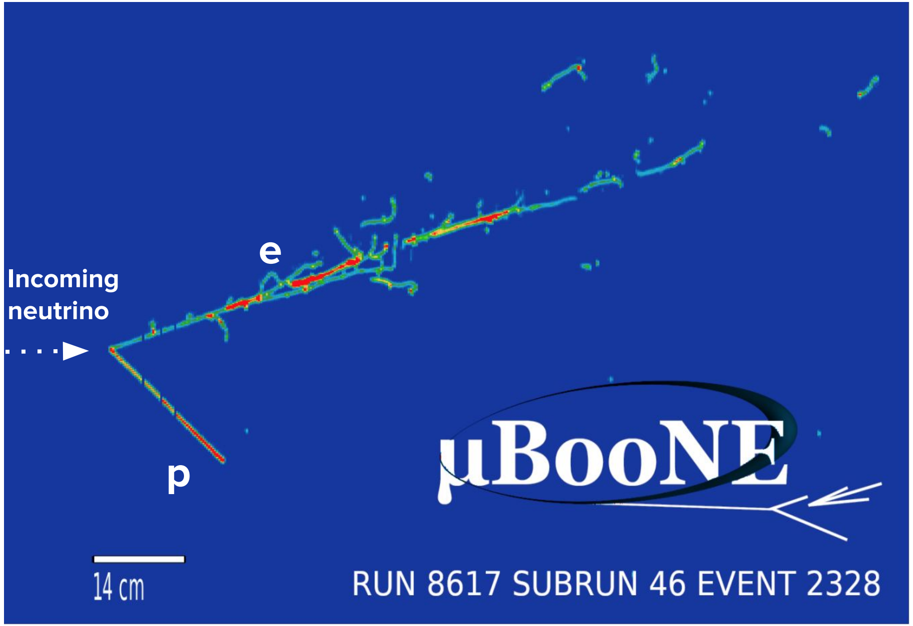


(Data/MC: 0.90) (KS: 0.951) (χ^2/n*DOF*: 23.33/34) (χ^2 P^{val}: 0.916)

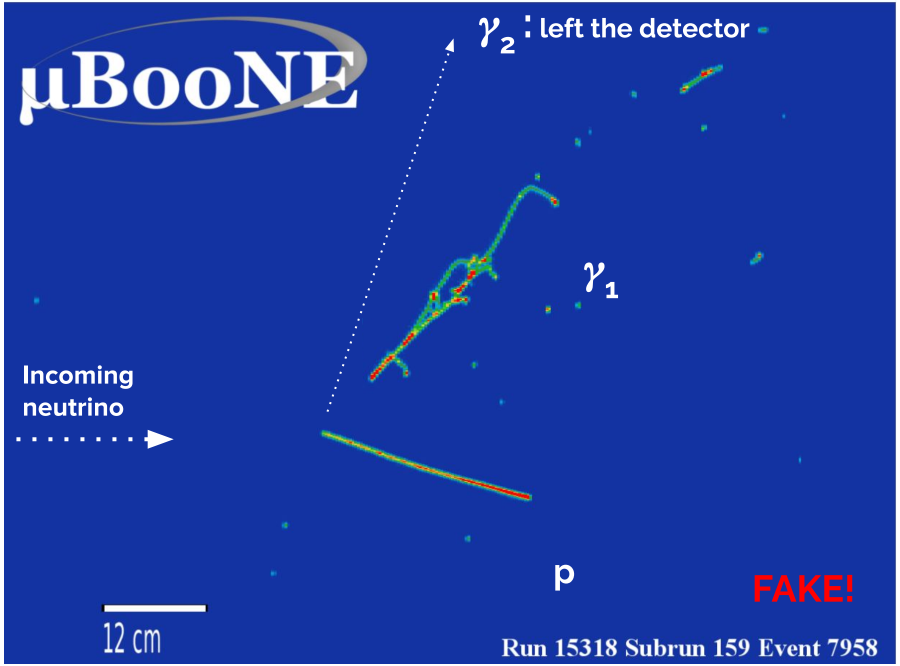


(Data/MC: 1.04) (KS: 0.532) (χ^2/n*DOF*: 35.97/34) (χ^2 P^{val}: 0.376)

CC ν_e candidate data event

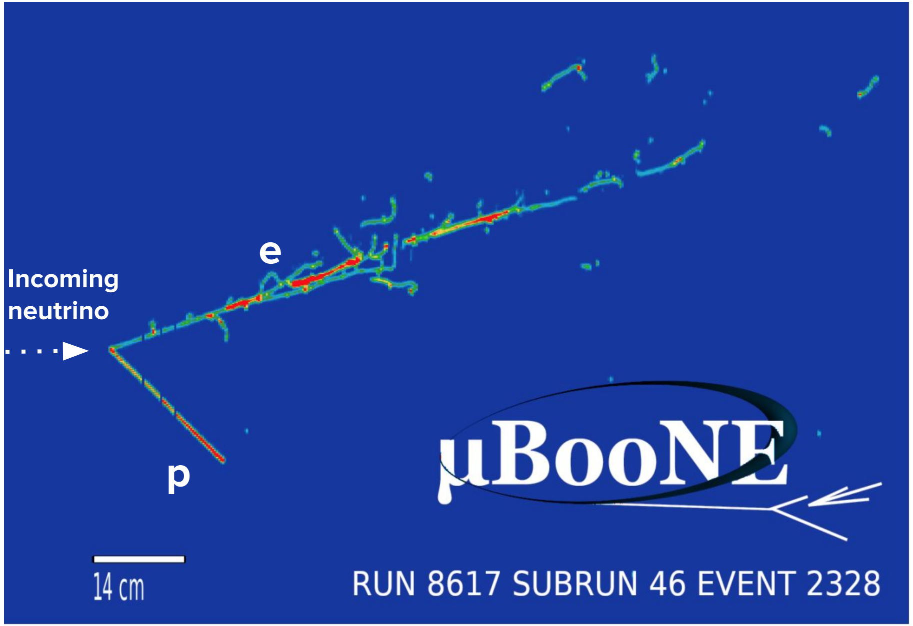


Hypothetical NC 1 π^0

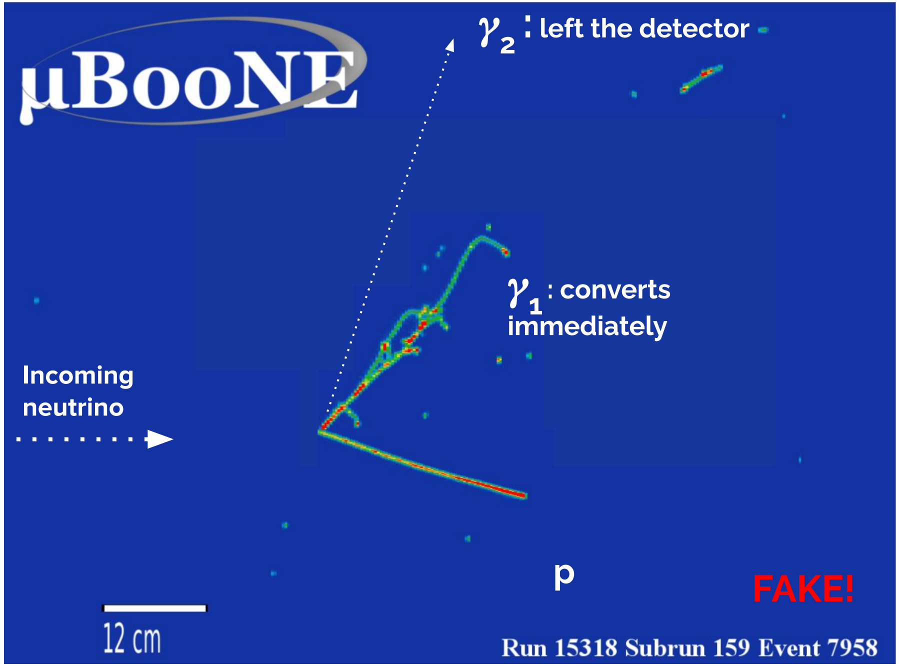


Hypothetical A: Subleading photon from π^0 exits detector before pair converting and is thus not reconstructed..

CC ν_e candidate data event



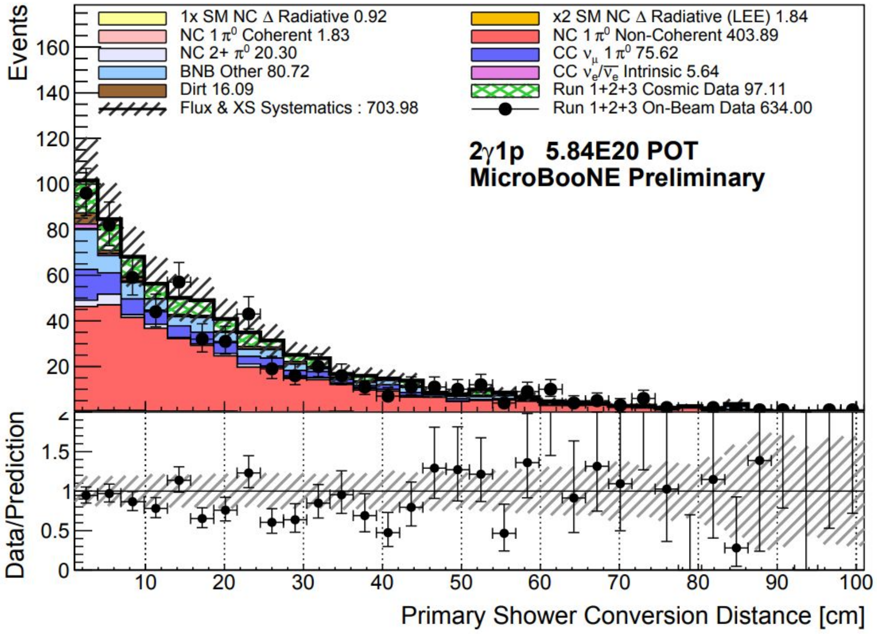
Hypothetical NC 1 π^0



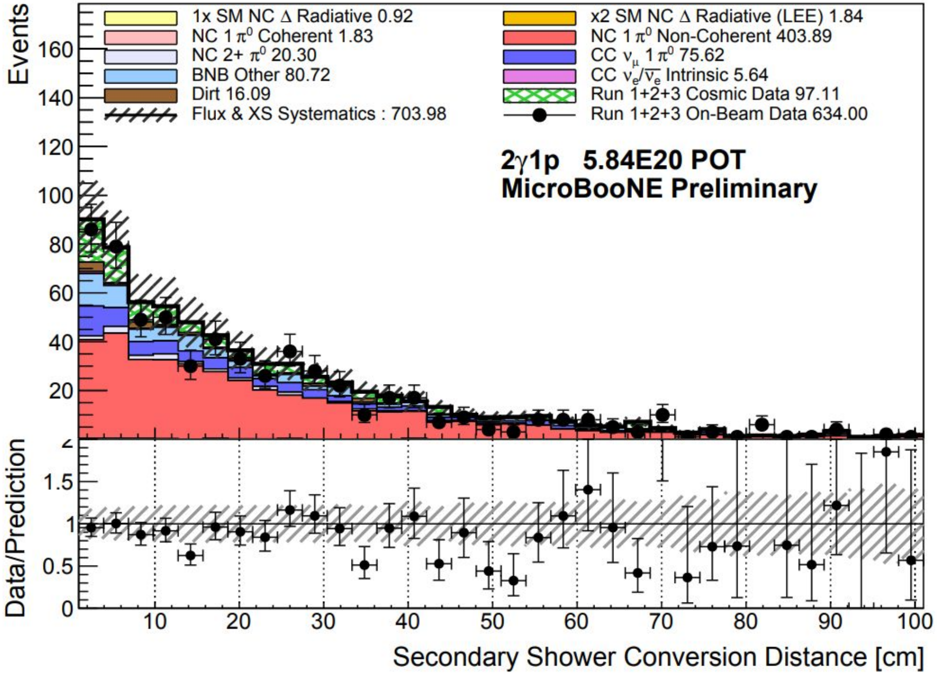
Topologically now **indistinguishable** from our single electron signal.

Hypothetical B: Subleading photon from π^0 exits detector before pair converting and is thus not reconstructed. Leading photoning cpair converts almost immediately

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**

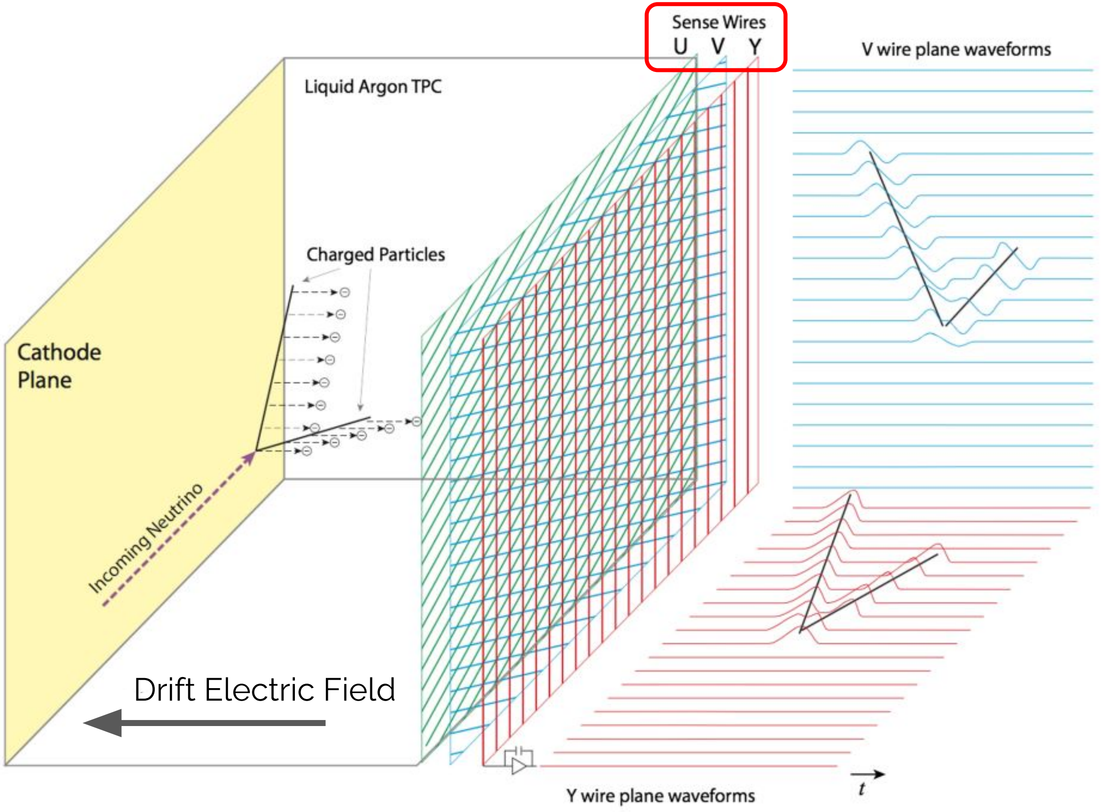
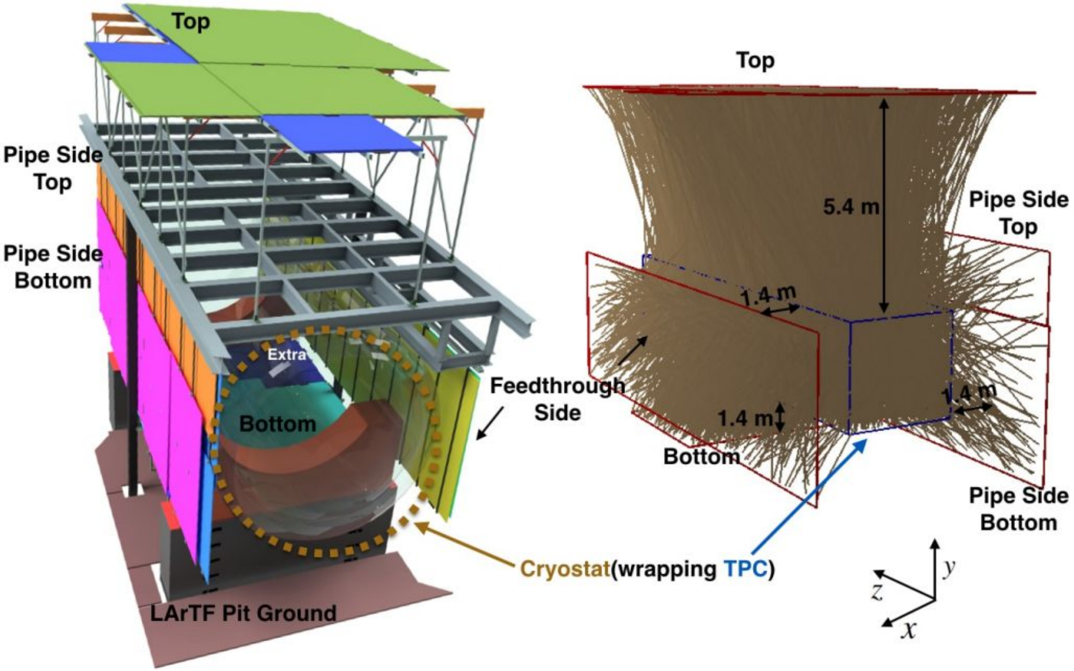


Figure 2 in JINST 12 P02017

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

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

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

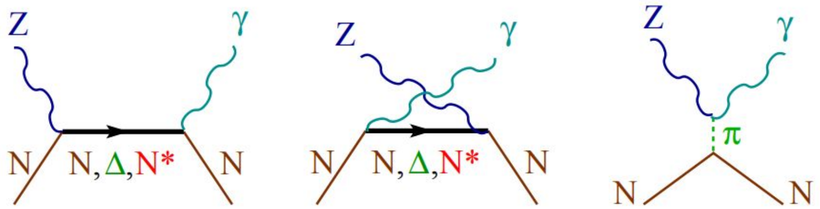


FIG. 1. (Color online) Feynman diagrams for the hadronic current of NC photon emission considered in Ref. [18]. The first two diagrams stand for direct and crossed baryon pole terms with nucleons and resonances in the intermediate state: BP and CBP with $B = N$, $\Delta(1232)$, $N^*(1440)$, $N^*(1520)$,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

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

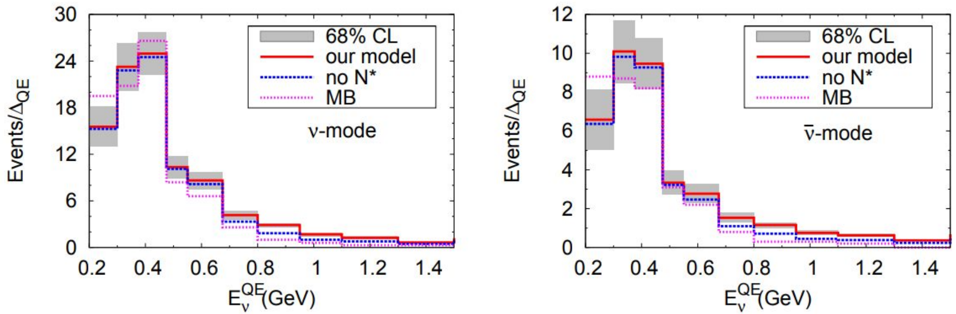


FIG. 4. (Color online) $E_\nu^{\rm QE}$ distributions of total NCγ events for the ν (left) and $\bar{\nu}$ (right) modes. Our results, given by the red solid lines are accompanied by grey error bands corresponding to a 68 % confidence level. The curves labeled as "no N^*" show results from our model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

MiniBooNE
In situ Pi0 constraint

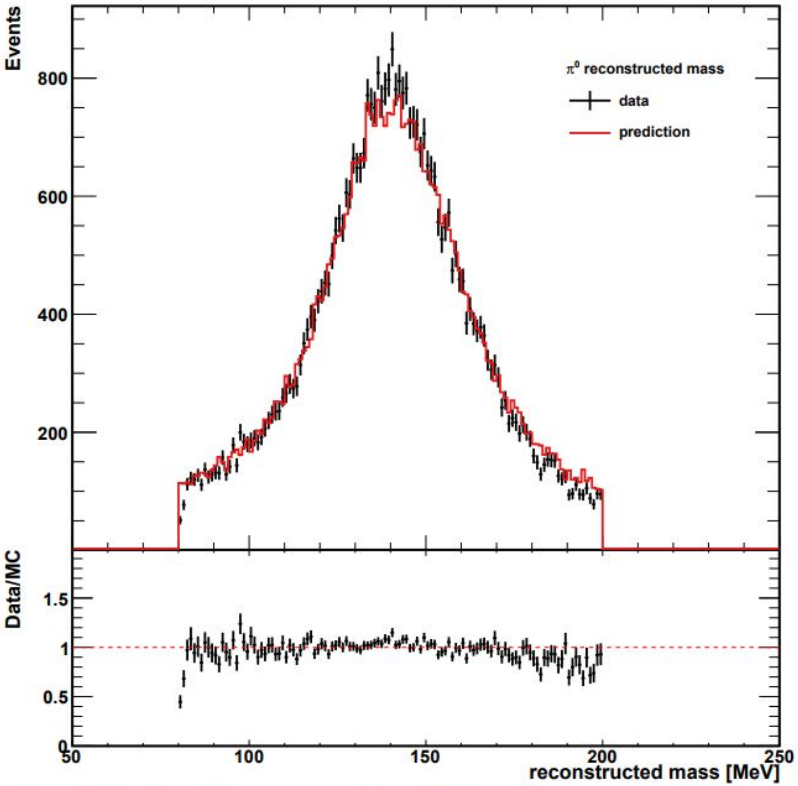
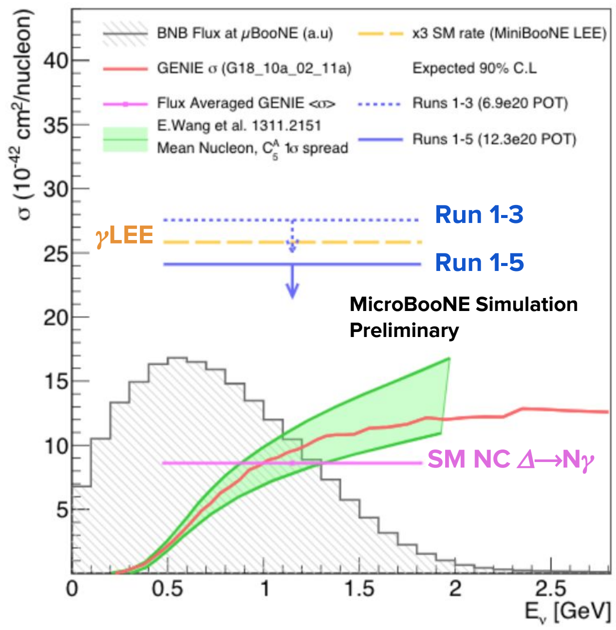


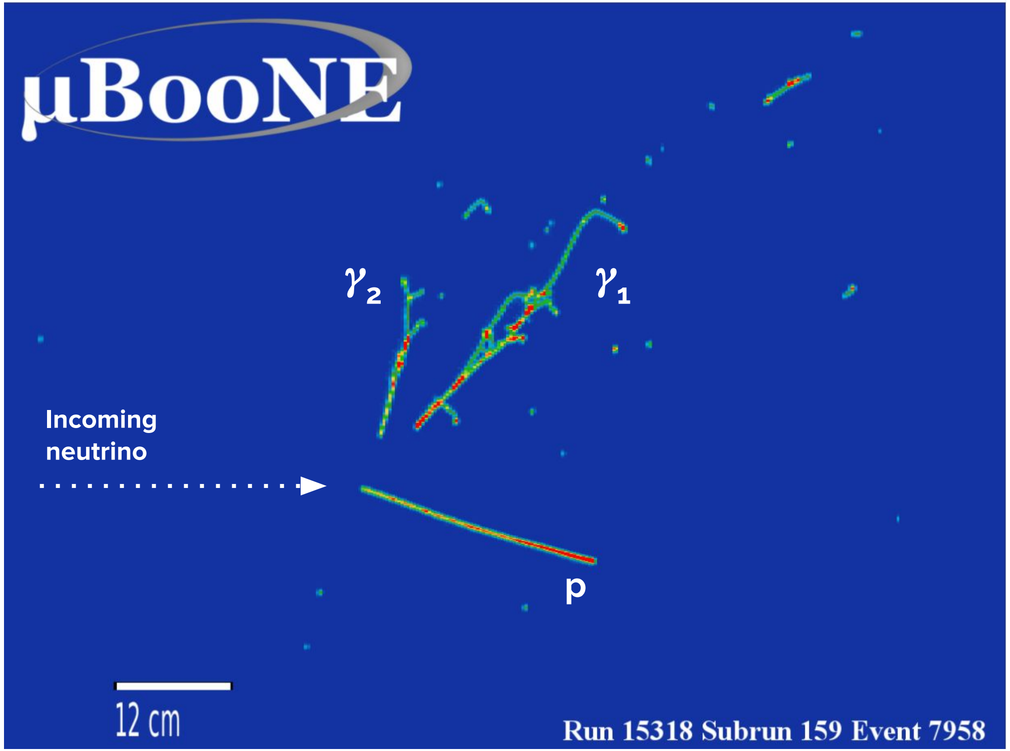
FIG. 7: An absolute comparison of the π^0 reconstructed mass distribution between the neutrino data (12.84×10^{20} POT) and the simulation for NC π^0 events (top). Also shown is the ratio between the data and Monte Carlo simulation (bottom). The error bars show only statistical uncertainties.

[K. Sutton Poster #121]

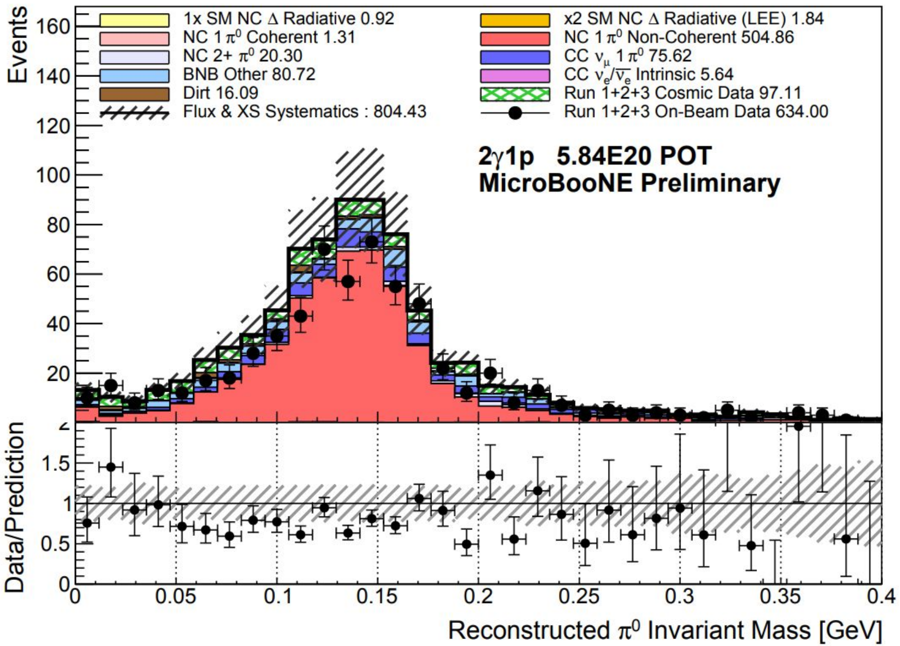


Representative example of a NC π^0 event in MicrobooNE

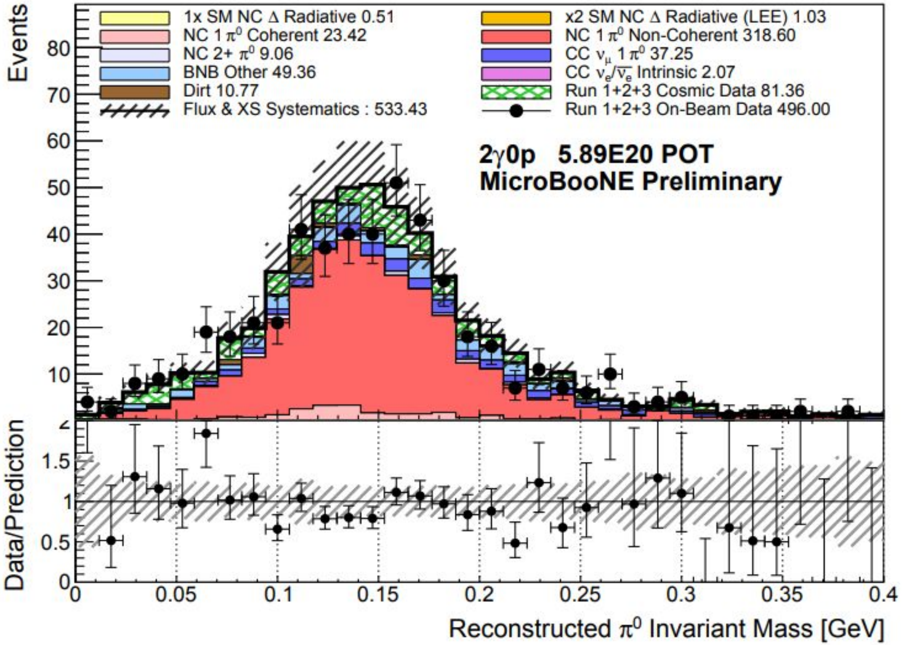
NC 1 π^0 Candidate $2\gamma 1p$ data event



Represents the largest NC π^0 selection in a LArTPC in the world!



- **63%** pure sample of NC 1 π^0
- Less than 0.3% coherent components.
- Gaussian fit to data: Mean: 137.6 ± 2.1 MeV, Width: 44.1 ± 1.8 MeV



- **64%** pure sample of NC 1 π^0
- ~30x higher percentage of coherent pion production (7.4%)
- Gaussian fit to data Mean: 140.2 ± 2.8 MeV, Width: 49.9 ± 2.7 MeV