Constraining the NC π^0 Background for MicroBooNE's Single Photon Search

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On behalf of the MicroBooNE Collaboration

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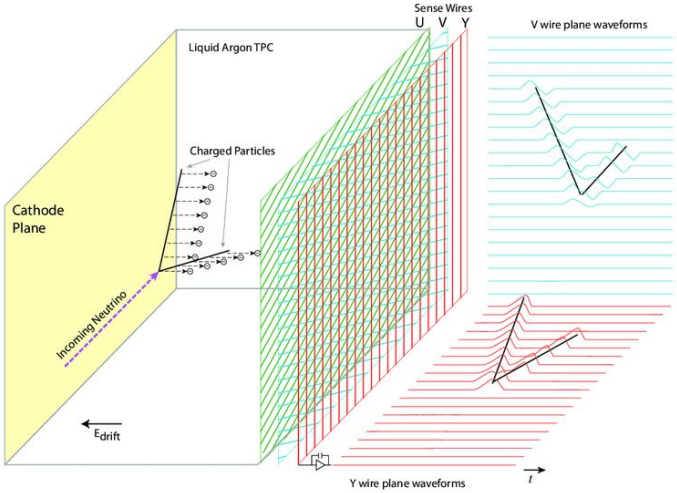
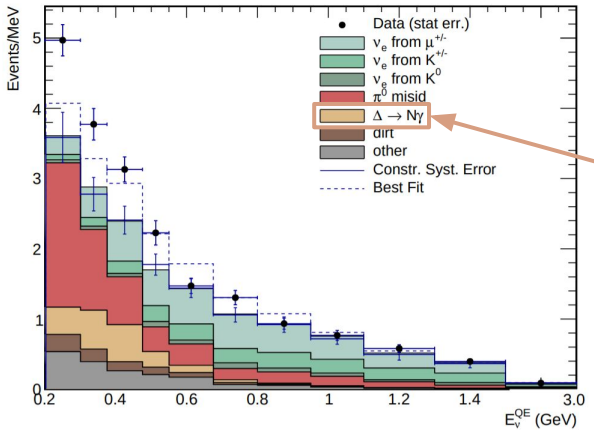
The MicroBooNE Experiment

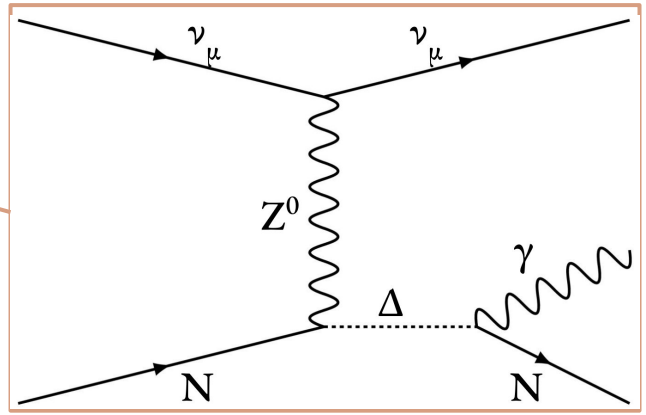
- 170-ton (89 ton active volume) Liquid Argon Time Projection Chamber (LArTPC)
- Operating along Fermilab's Booster Neutrino Beam (BNB) since 2015
- Primary goal: investigation of the MiniBooNE Low-Energy Excess (LEE)



MiniBooNE Low-Energy Excess

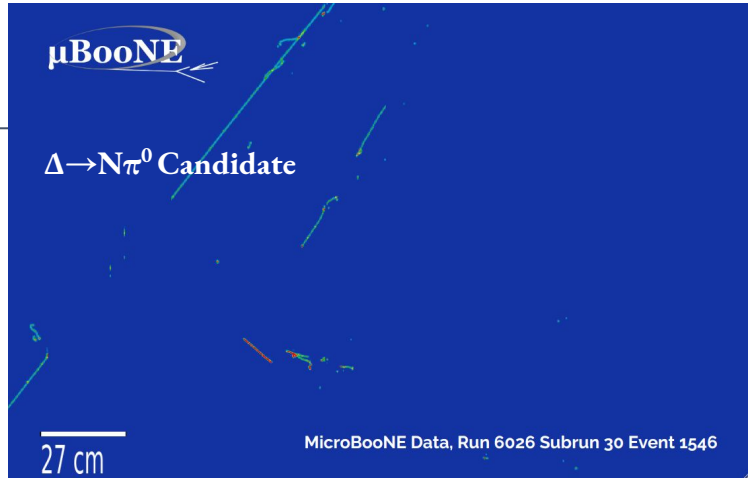
- Observed excess of electron neutrino-like events below 600 MeV
- Cherenkov detector; difficulty distinguishing photons and electrons
  - **Photon-like** and electron-like hypotheses
- MicroBooNE is searching for **Δ → Nγ** to investigate photon-like hypothesis
  - See [K. Sutton's talk] from NP 1.0

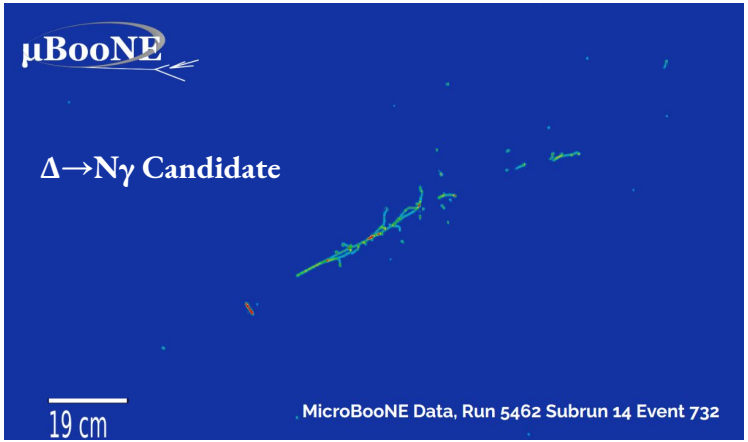




Neutral Current (NC) π^0

- NC π^0s comprise **~80% of backgrounds** for the NC Δ radiative decay search
  - $\Delta \rightarrow N\gamma$ branching ratio: ~0.6%
  - $\Delta \rightarrow N\pi^0$ branching ratio: ~99.4%
- NC π^0 events in which only one photon is reconstructed look nearly identical to radiative decays
- Plan: use single-photon framework to select NC π^0 events for **data-driven rate constraint**





Analysis Flow

1. Select Signal Topology

- Start with reconstructed tracks and showers [1]
- Select events with two shower (2γ) and either one or zero tracks (1p or 0p)

2. Reject Backgrounds

- Use tailored Boosted Decision Tree (BDT) [2] trained on background events
- Reject backgrounds by cutting on BDT response

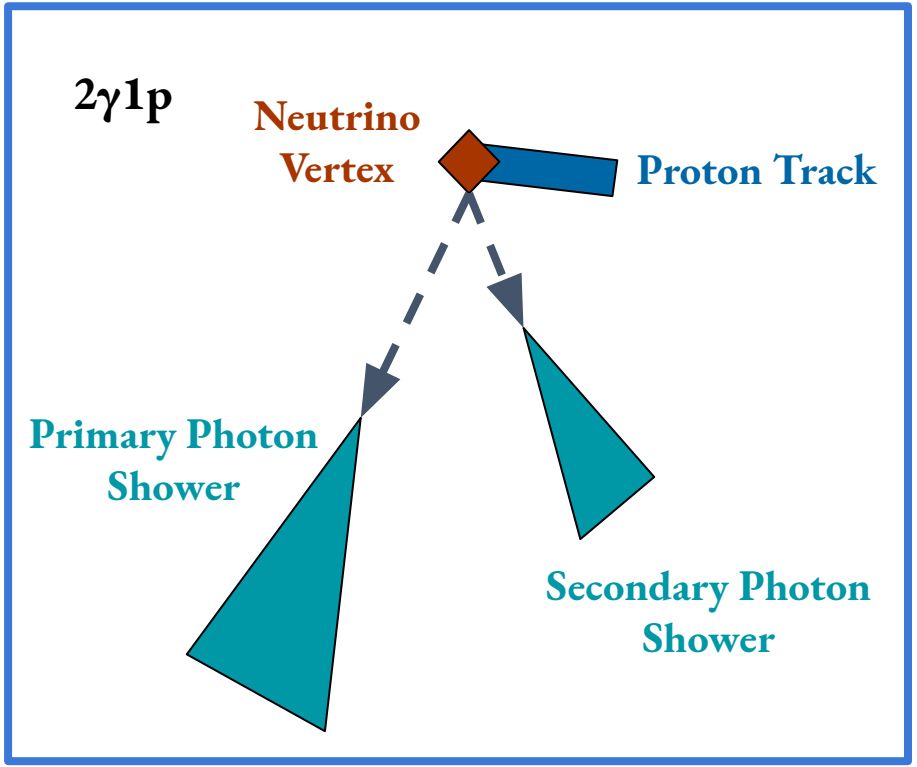
3. High-Stats NC π^0 Selection

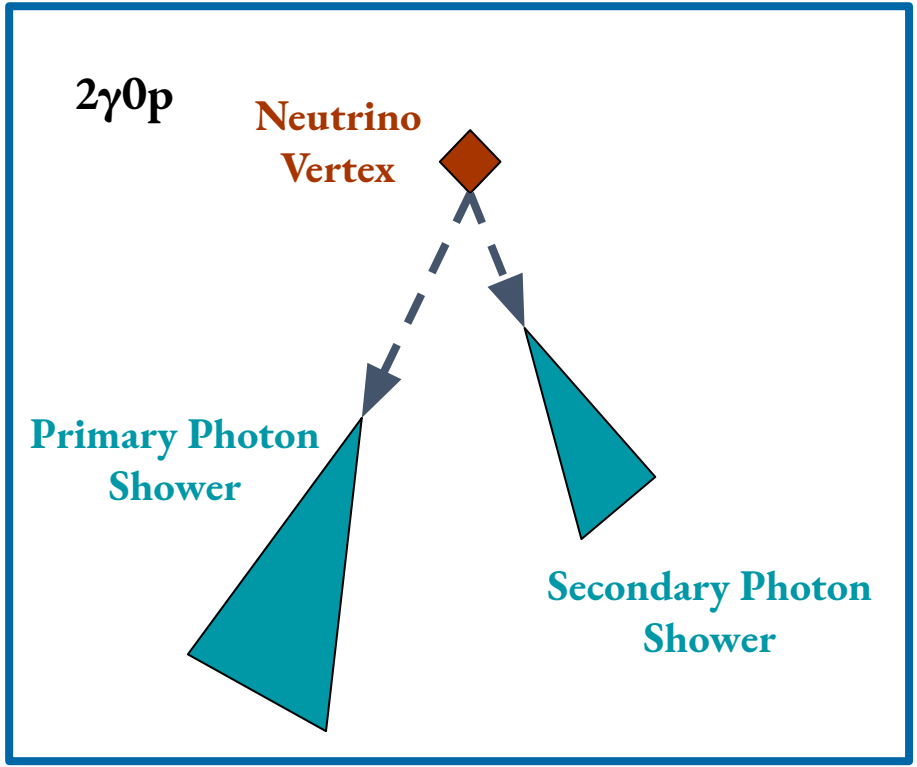
- Result is the **world's highest-stats NC π^0 selection on Argon**
- Constrain single-photon NC π^0 background

[1] Acciarri, R. et. al. The Pandora multi-algorithm approach to automated pattern recognition of cosmic-ray muon and neutrino events in the MicroBooNE detector. *The European Physical Journal C*, *78*(1), 1-25.

[2] Chen, T., He, T., Benesty, M., Khotilovich, V., & Tang, Y. (2015). Xgboost: extreme gradient boosting. *R package version 0.4-2*, 1-4.

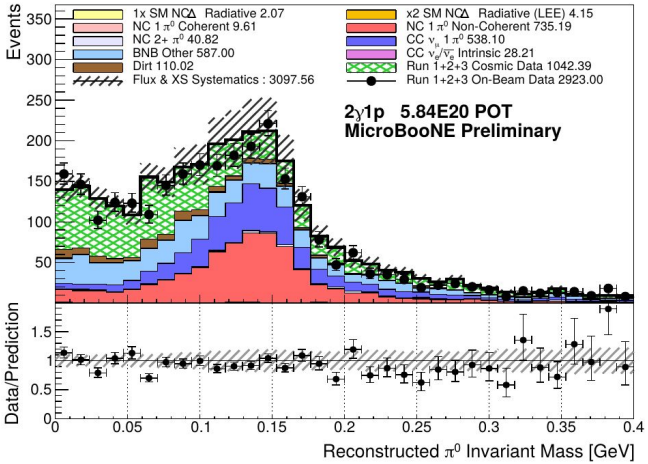
Signal Topology



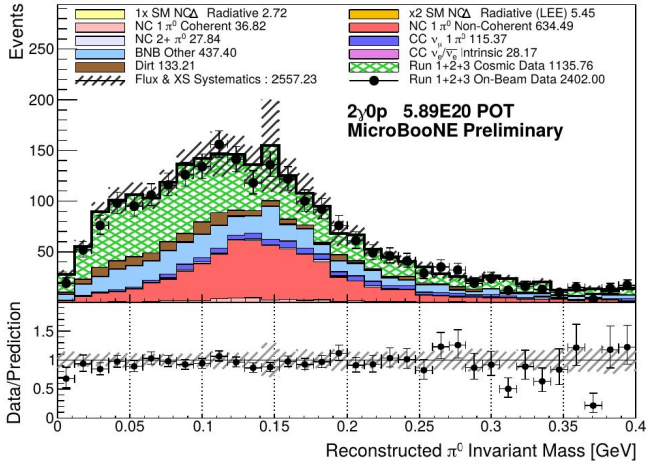


Pre-Selection Distributions

- Before BDTs, apply some conservative pre-selection cuts
  - Shower energies, conversion distance, etc.
- Signal (red) dominated by off-beam (green) and on-beam backgrounds (blue and brown)

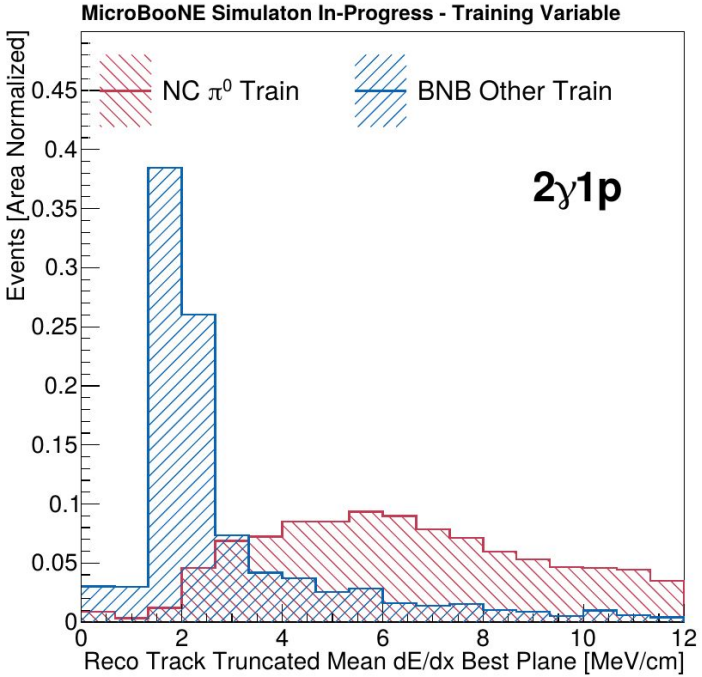


(Data/MC: 0.94) (KS: 0.976) (χ^2/n*DOF*: 25.97/34) (χ^2 P^{val}: 0.836)



(Data/MC: 0.94) (KS: 1.000) (χ^2/n*DOF*: 22.06/34) (χ^2 P^{val}: 0.943)

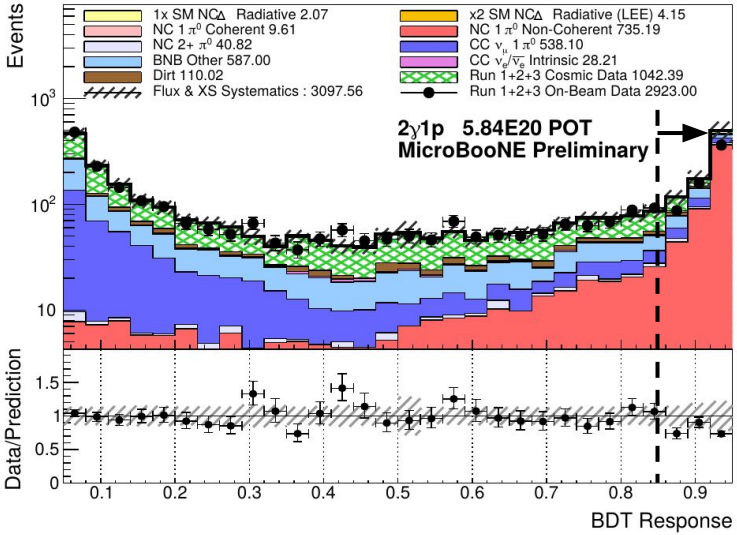
BDT Training



- Train BDT on various kinematic and calorimetric variables in simulation
- Training variables chosen based on separation power between signal and background
- Example: track dE/dx (left)
  - dE/dx: energy deposition per unit length
  - Separates events with proton-like track for 2g1p selection
  - Peak at 2 MeV/cm mostly from minimally-ionizing muon tracks

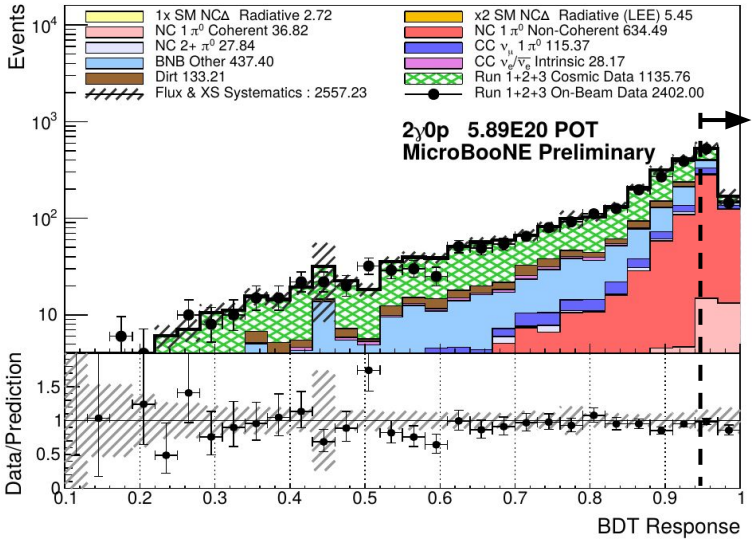
BDT Response

- Cut on BDT response to maximize efficiency times purity in the final selection



(Data/MC: 0.94) (KS: 0.360) (χ^2/n*DOF*: 16.06/30) (χ^2 P^{val}: 0.982)

Background-like ← → Signal-like

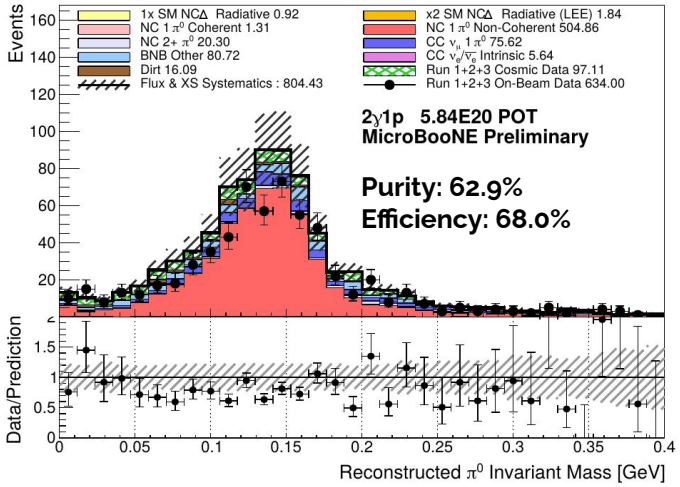


(Data/MC: 0.94) (KS: 1.000) (χ^2/n*DOF*: 24.56/30) (χ^2 P^{val}: 0.746)

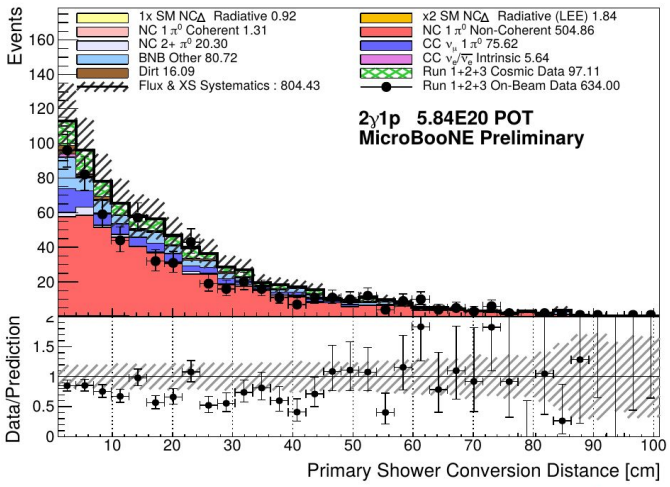
Background-like ← → Signal-like

2γ1p Final Selection

- ~20% normalization difference between data and MC
  - Covered by systematic uncertainties
- Gaussian fit to mass peak gives a mean of 137.6 ± 2.1 MeV and a width of 44.1 ± 1.8 MeV



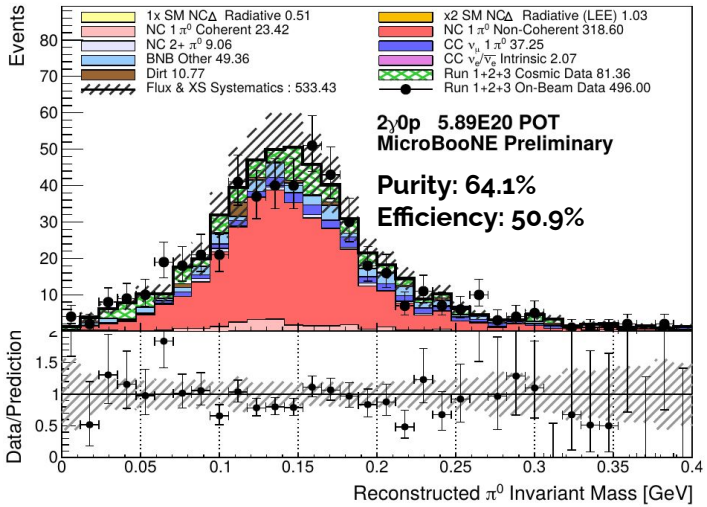
(Data/MC: 0.79) (KS: 0.995) (χ^2/n*DOF*: 23.00/34) (χ^2 P^{val}: 0.924)



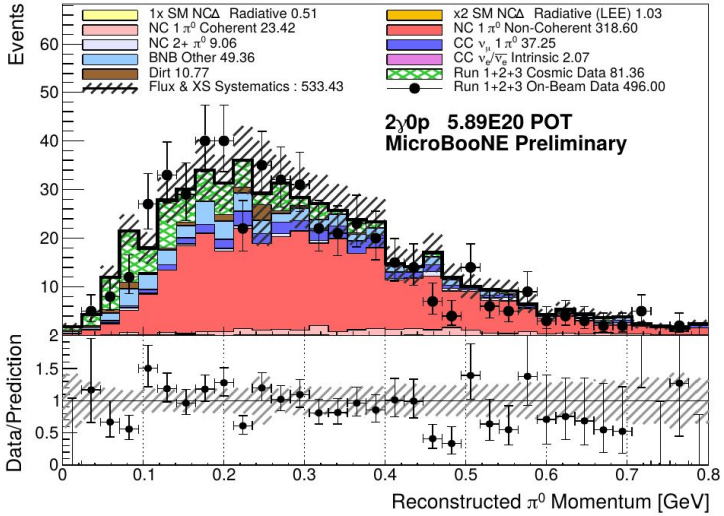
(Data/MC: 0.79) (KS: 0.994) (χ^2/n*DOF*: 24.10/34) (χ^2 P^{val}: 0.896)

2γ0p Final Selection

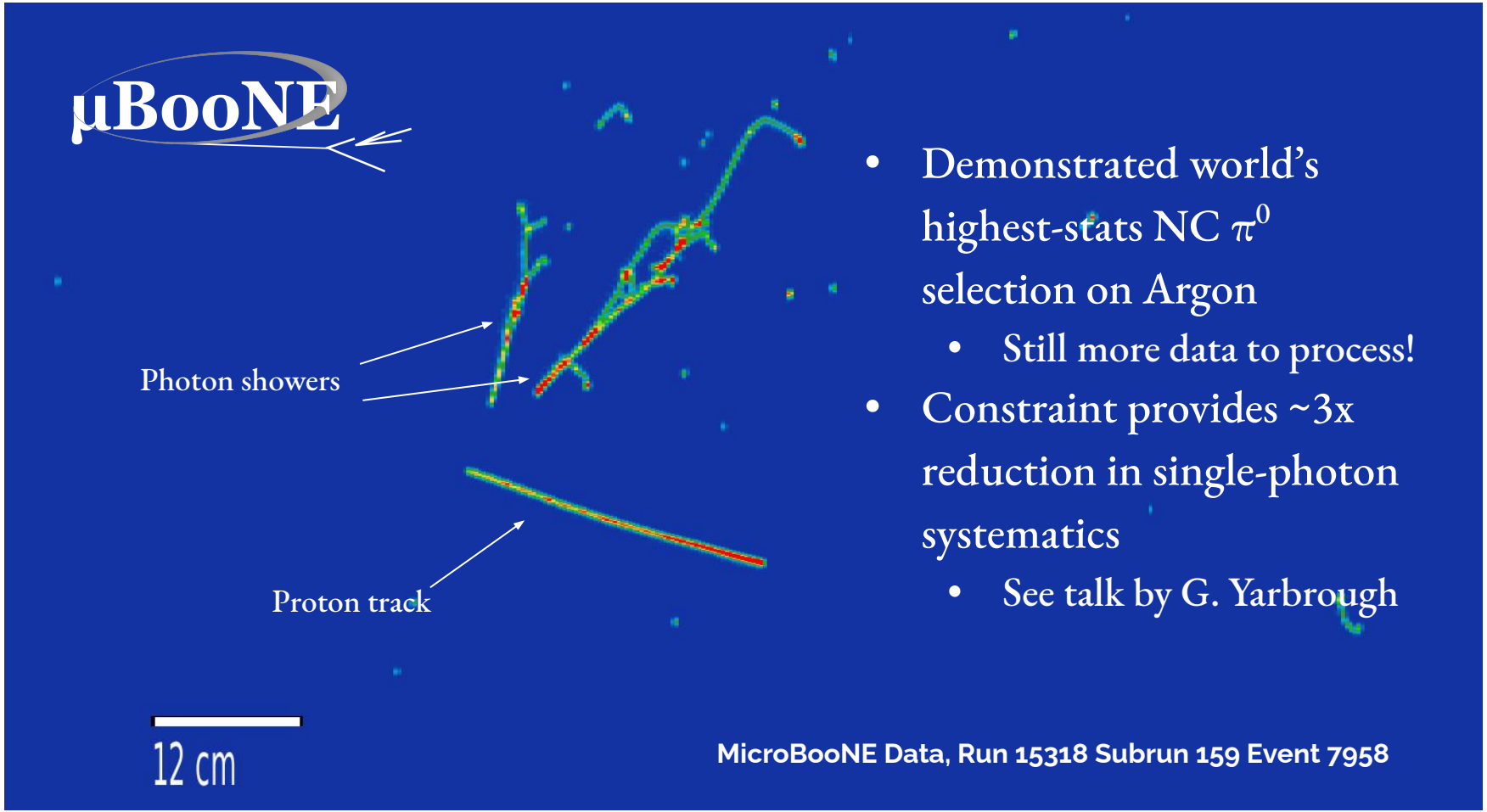
- Normalization difference < 10%
- Gaussian fit to mass peak gives a mean of 140.2 ± 2.8 MeV and a width of 49.9 ± 2.7 MeV



(Data/MC: 0.93) (KS: 0.901) (χ^2/n*DOF*: 30.04/34) (χ^2 P^{val}: 0.662)



(Data/MC: 0.93) (KS: 0.437) (χ^2/n*DOF*: 31.16/34) (χ^2 P^{val}: 0.608)



- Demonstrated world's highest-stats NC π^0 selection on Argon
  - Still more data to process!
- Constraint provides ~3x reduction in single-photon systematics
  - See talk by G. Yarbrough

Backup

Pre-Selection Cuts

- 2g1p pre-selection cuts:
  - 5 cm fiducial volume on vertex
  - Both shower conversion distances > 1 cm
  - Leading shower energy > 30 MeV
  - Subleading shower energy > 20 MeV
  - Distance from track start point to vertex < 10 cm
- 2g0p pre-selection cuts:
  - 5 cm fiducial volume on vertex
  - Leading shower energy > 30 MeV
  - Subleading shower energy > 20 MeV

Training Variables

- 2g1p Training variables:
  - Both shower conversion distances
  - Both shower impact parameters
  - Track length
  - Track θ_{yz}
  - Distance from track end point to nearest TPC wall
  - Track mean truncated dE/dx (shown here)
  - Ratio of track start/end dE/dx
- 2g0p Training variables:
  - Both shower conversion distances
  - Both shower impact parameters
  - Both shower energies
  - Both ratios of shower length/energy
  - Leading shower θ_{yz}
  - Pandora neutrino slice score

BNB Backgrounds in Final Selection

Background	Percentage
π^0 Charge Exchange	11.9
CC Multi-π^0	5.3
CC Other	14.7
NC Other	6.3
η	18.8
Overlay	28.3
Other	14.8

- Percentages relative to BNB Other, which comprise ~10% of final selection
- Single largest component is cosmic contamination
- Other large backgrounds include general CC events, η's, and "other"

CC π^0 Backgrounds in Final Selection

Background	Percentage
Proton track	49.6
Muon track	11.5
Shower Mis-ID	31.4
Overlay	2.2
Other	5.4

- Percentages relative to CC π^0, which comprise ~10% of final selection
- Most have track matched to proton, not muon
  - Muon tracks sometimes not reconstructed
  - Looks exactly like signal

2g1p Signal Composition

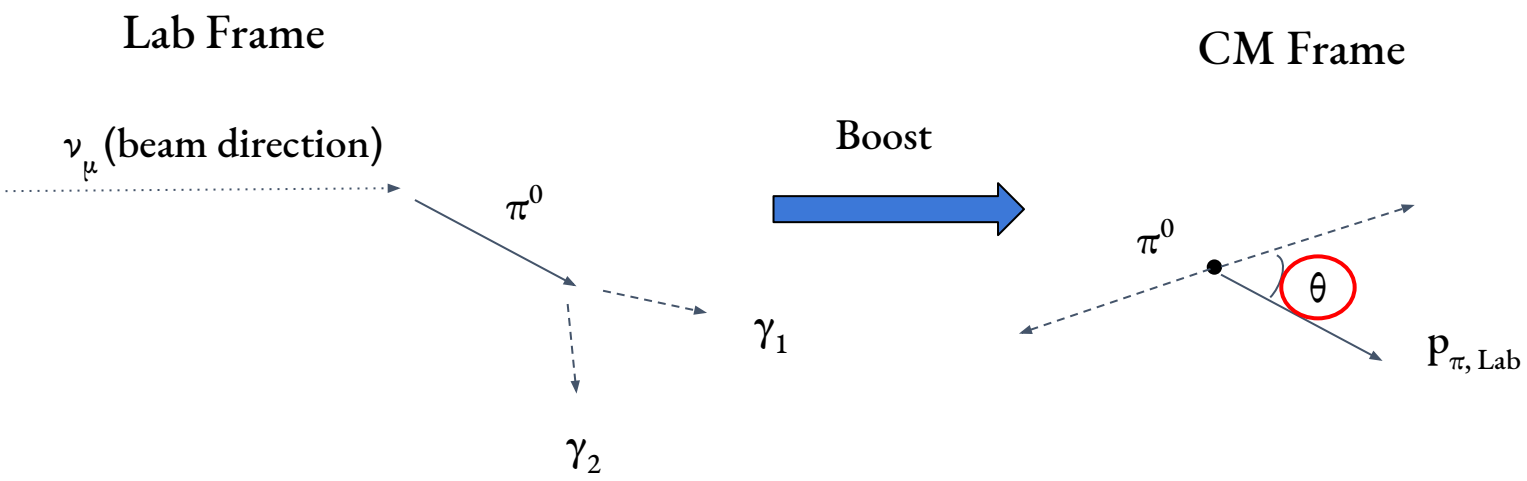
Generated NC π^0

	Resonant	DIS	QE	Coherent	MEC
Run 1	77.2%	19.7%	0.82%	2.2%	0.04%
Run 3	77.7%	19.3%	0.80%	2.2%	0.04%

Signal NC π^0

	Resonant	DIS	QE	Coherent	MEC
Run 1	84.6%	13.5%	1.3%	0.41%	0.09%
Run 3	84.8%	13.9%	0.97%	0.29%	0.10%

Center-of-Mass Decay Angle



$$\cos\theta_\gamma^{\mathrm{CM}} = \frac{1}{\beta_{\pi^0}}\frac{|E_{\gamma^1} - E_{\gamma^2}|}{E_{\gamma^1} + E_{\gamma^2}} = \frac{|E_{\gamma^1} - E_{\gamma^2}|}{p_{\pi^0}}$$