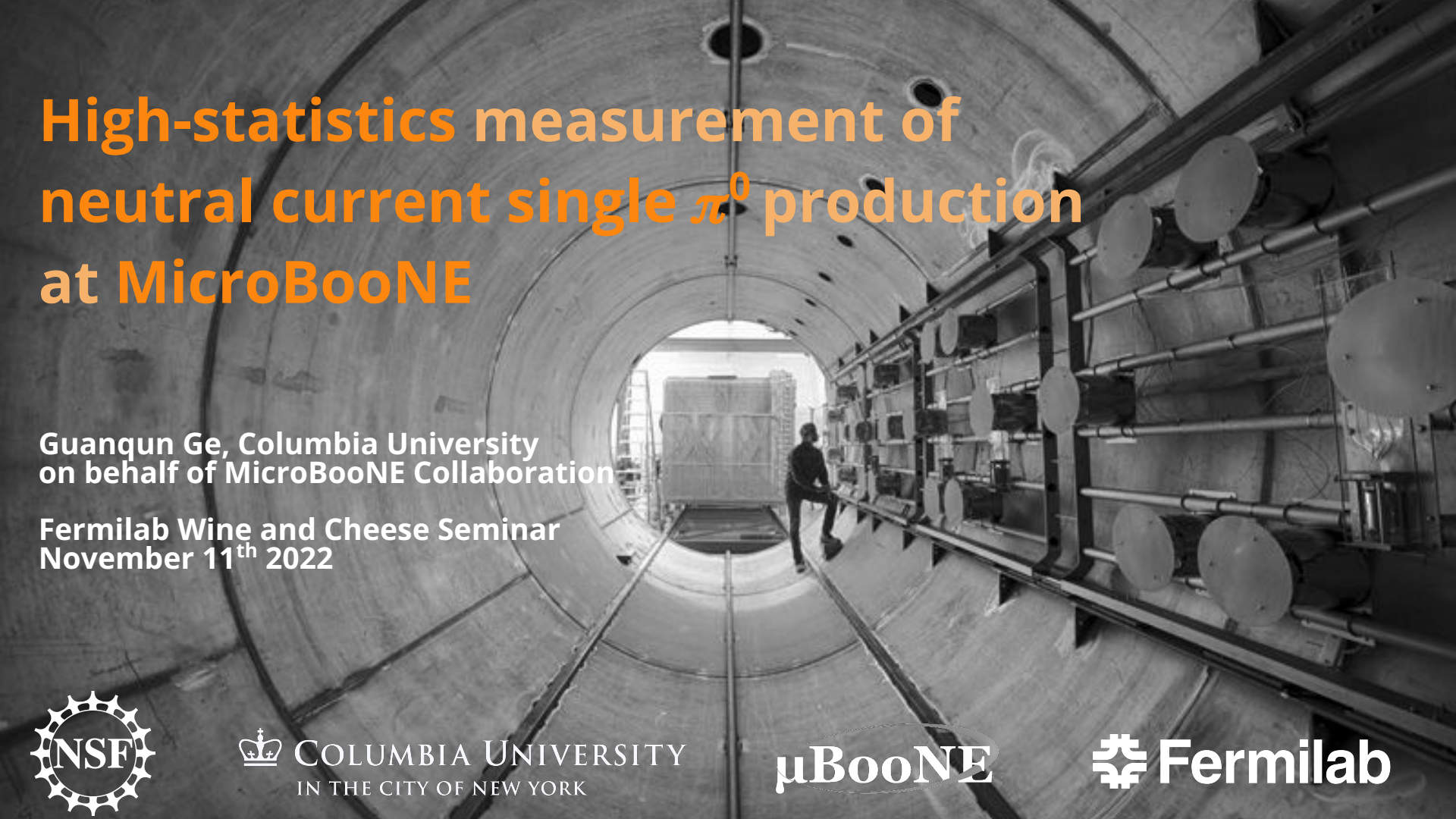
High-statistics measurement of neutral current single π^0 production at MicroBooNE

Guanqun Ge, Columbia University
on behalf of MicroBooNE Collaboration

Fermilab Wine and Cheese Seminar
November 11th 2022



NSF

Columbia University
in the City of New York

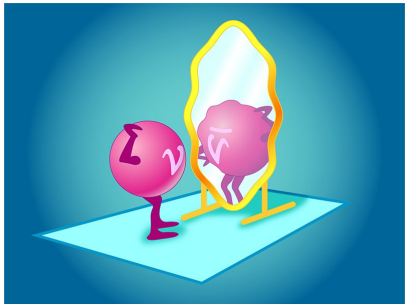
μBooNE

Fermilab

Open questions in neutrino physics…

- Neutrino oscillation parameters
  - CP violation ↔ matter-antimatter asymmetry
- What's the absolute mass of neutrinos? Mass hierarchy?
- How do neutrinos acquire mass?
- Are neutrinos Dirac or Majorana particles?
- Existence of additional neutrinos beyond SM ones?
- ….

APS/Carin Cain



Credit: Symmetry Magazine

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Credit: Sandbox Studio

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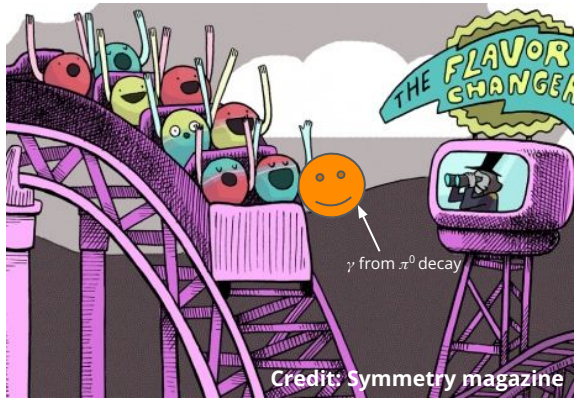
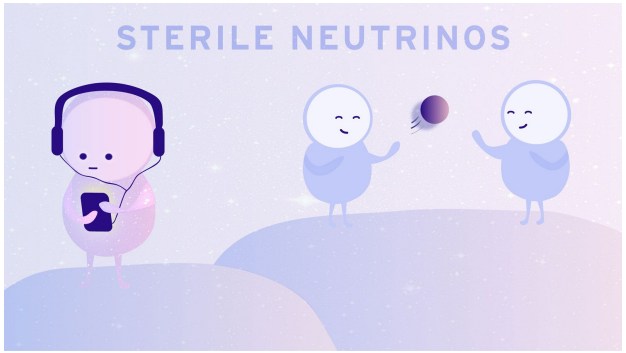
- ….

Our understanding of neutral current π^0 production can greatly affect our ability to answer these questions with high accuracy and precision…

Neutral Current π^0 Production and Neutrino physics

1. Neutral Current (NC) π^0 has presented itself as a **major background** in previous ν_e appearance measurements, especially for detectors that struggle to distinguish photons from electrons.
    - E.g, MiniBooNE: excess at low energy region for electron-like events measurement
2. NC π^0 also provides us a unique handle to **probe beyond-the-standard model (BSM) physics**, including "sterile" neutrino oscillations
3. Samples of π^0 act as a **"standard candle"** to develop and validate reconstruction techniques, and for calibration of our detectors



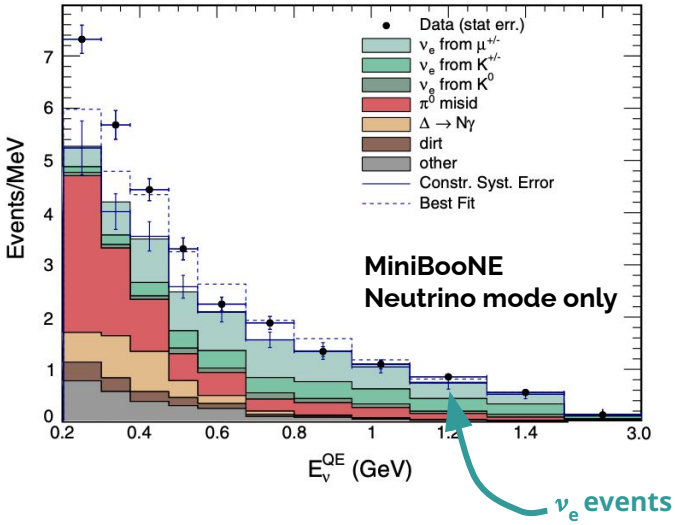


Credit: Sandbox Studio, Chicago

(1) NC π^0 as a **background**

Measurement on electron-like events

Phys. Rev. D 103, 052002 (2021)



Combining the neutrino and antineutrino data, the overall significance of the MiniBooNE excess is **4.8σ**

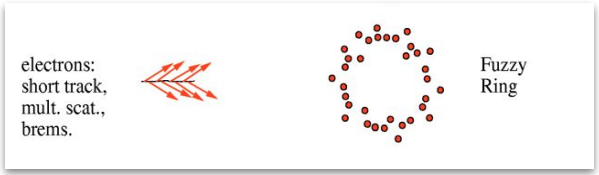
MiniBooNE is a mineral oil **Cherenkov** detector experiment at Fermilab

Target process is ν_e charge-current quasi-elastic (CCQE) scattering

$$\nu_e + n \rightarrow e^- + p$$

- Nucleons will go undetected
- Electron will create fuzzy cherenkov light ring due to scattering

Nucl.Phys.B Proc.Suppl. 168 (2007)



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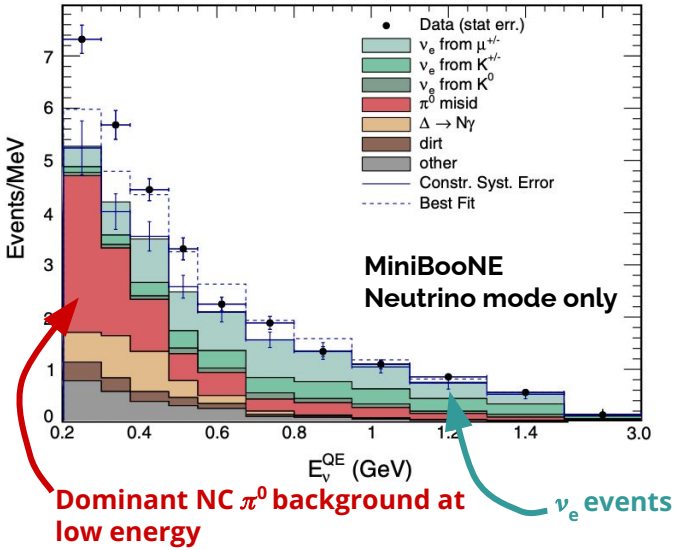
Phys. Rev. D 103, 052002 (2021)



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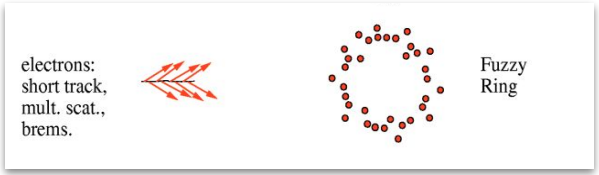
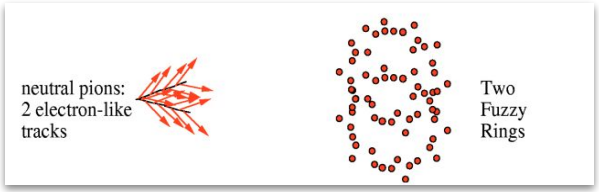
NC π^0 background ($\pi^0 \rightarrow \gamma\gamma$) could be mimic ν_e signal if:

- π^0 decay near the boundary
- Asymmetric photons
- Two photons are very collimated and reconstructed as one shower

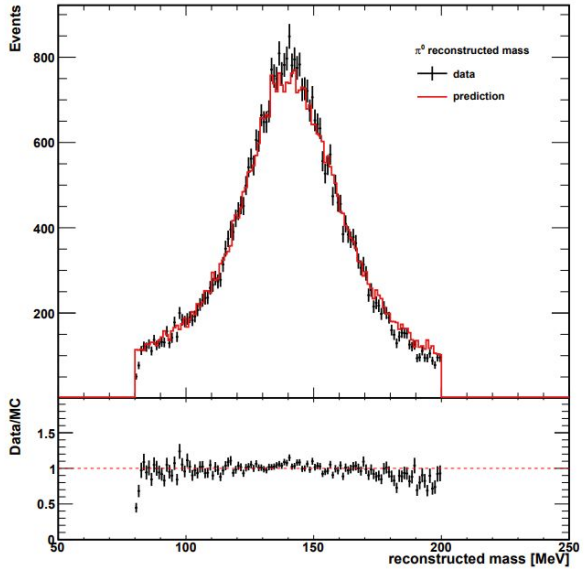
Nucl.Phys.B Proc.Suppl. 168 (2007)





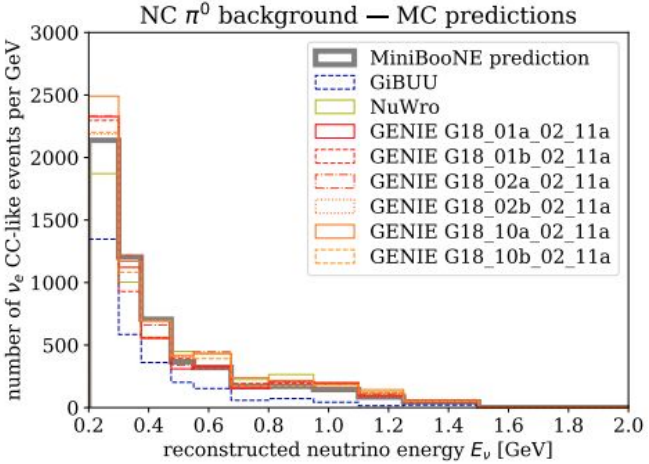
(1) NC π^0 as a **background**

MiniBooNE measured a high-statistics NC π^0 sample to validate and correct the MC prediction for this important background (42,530 expected NC π^0 !)



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

However, studies have shown that modern generators can disagree dramatically in NC π^0 predictions



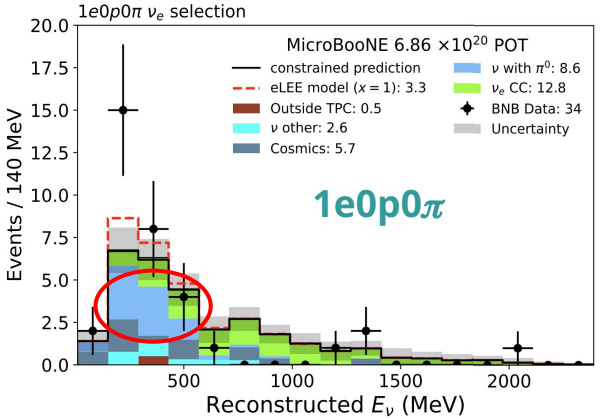
Phys. Rev. D ***105****, 115024 (2022)*

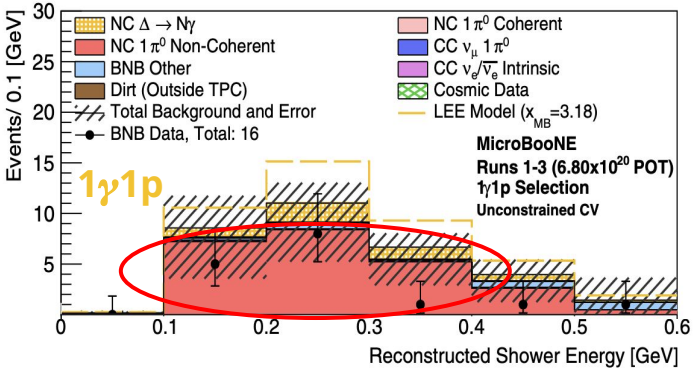
(1) NC π^0 as a **background**

To investigate possible explanation of MiniBooNE low energy excess (LEE), MicroBooNE has developed four analyses* targeting two interpretations:

- Excess from enhanced ν_e in the beam (1e1p, 1e0p0π, 1eNp0π, 1eX)
- Excess in anomalous single-photon production (1γ1p, 1γ0p)

While - due to MicroBooNE's excellent spatial and calorimetric resolution - electron analyses yield very high-purity ν_e signals, NC **π^0 events have significant impact on backgrounds,** especially for searches for single shower from electron/photon.





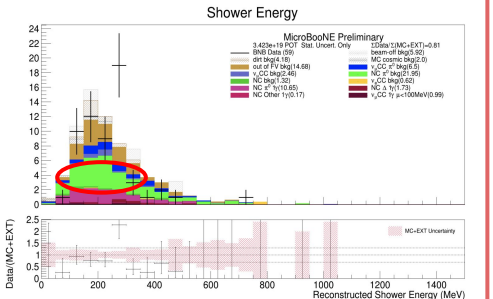
Phys. Rev. D105, 112005 (2022)
Phys. Rev. D105, 112004 (2022)
Phys. Rev. D105, 112003 (2022)
Phys. Rev. Lett. 128, 241801 (2022)
Phys. Rev. Lett. 128, 111801 (2022)
Details also in backup slides

(1) NC π^0 as a **background**

Understanding NC π^0 background is still of vital importance to ongoing and future measurements.

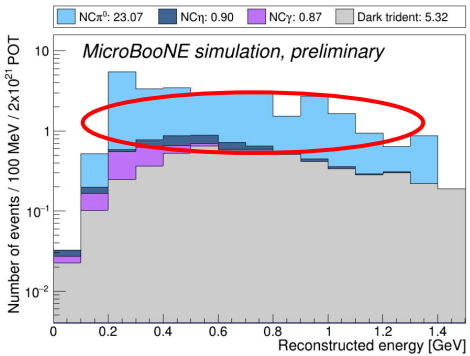
photon measurement

MicroBooNE, Inclusive single photon
MICROBOONE-NOTE-1103-PUB



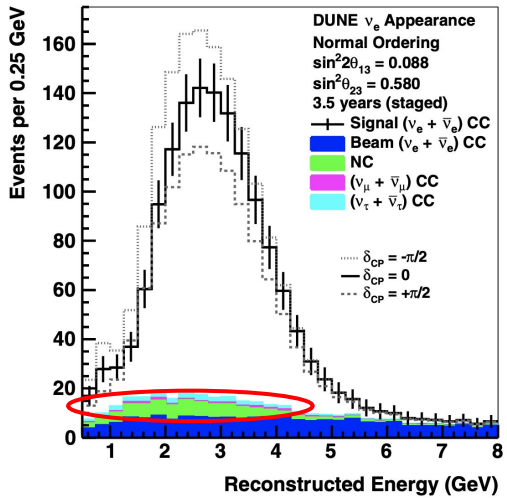
e^+e^- measurement

MicroBooNE, Dark Trident
MICROBOONE-NOTE-1118-PUB

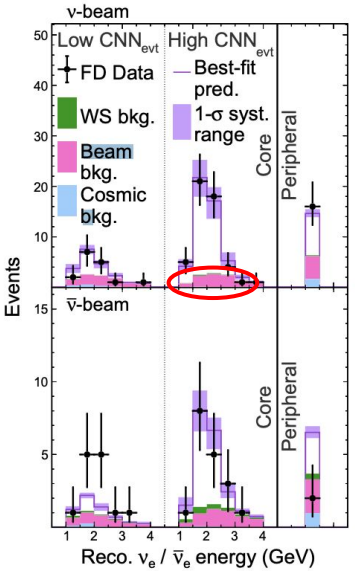


ν_e oscillation measurement

DUNE, predicted ν_e appearance
Eur. Phys. J. C 80, 978 (2020)



NOvA, ν_e oscillation
*Phys. Rev. D **106**, 032004 (2022)*



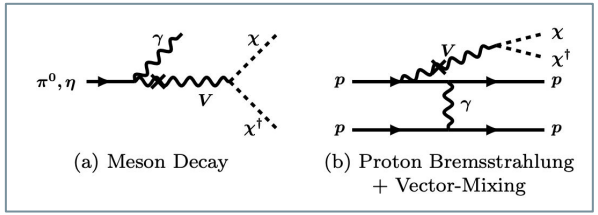
(2) NC π^0 as a probe of **BSM physics**

Precise measurement of NC channel can be used as a tool to search for BSM physics or to verify SM.

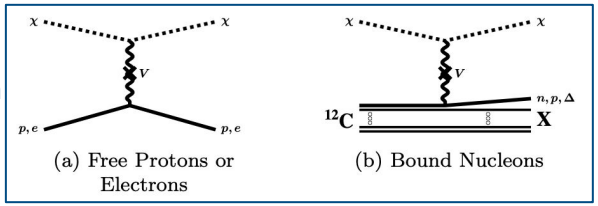
E.g. signal for sub-GeV **light dark matter search** *MiniBooNE, Phys. Rev. D 98, 112004 (2018)*

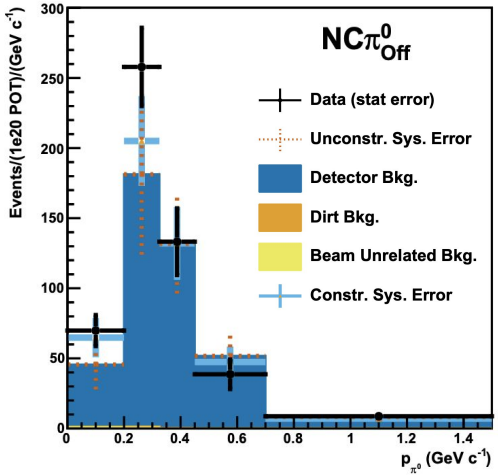
- Dark matter χ could scatter with nucleons in the detector, generating Δ resonance, which then decays to π^0

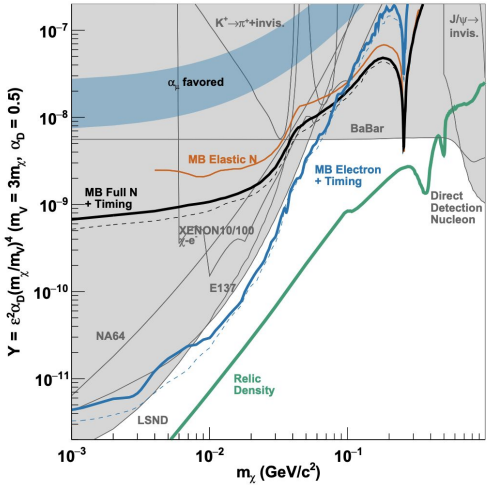
Production



Interaction







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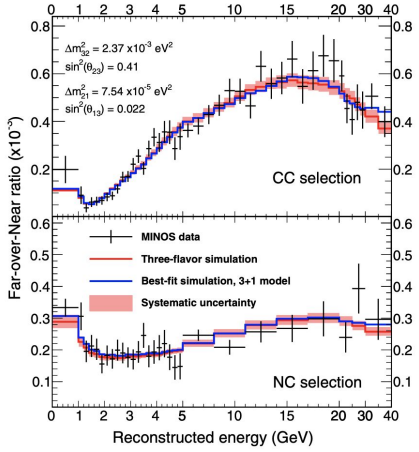
Precise measurement of NC channel can be used as a tool to search for BSM physics or to verify SM model.

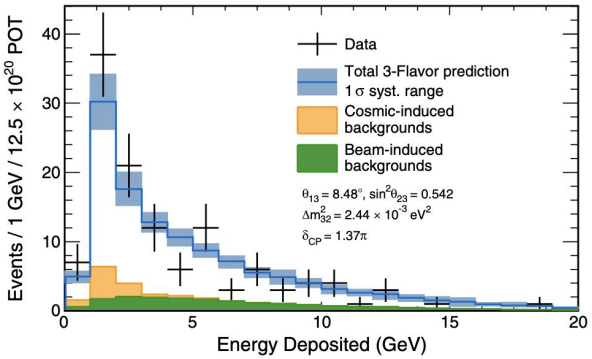
E.g. Search for “vanilla” **eV-scale sterile neutrinos**

- Majority of the oscillation searches so far focus on oscillation between active neutrinos through charge current (CC) channel, which is sensitive to $U_{\alpha 4}$ and Δm^2 ($\alpha = \nu_e, \nu_\mu, \nu_\tau$).
- Oscillation in NC channel would allow direct probe of U_{s4}

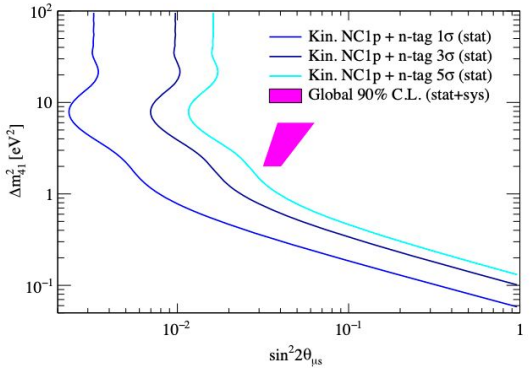


MINOS, Phys. Rev. Lett. ***117****, 151803 (2016)*

NOvA, Phys. Rev. Lett. ***127****, 201801 (2021)*



Phys. Rev. D ***103****, 112011 (2021)*



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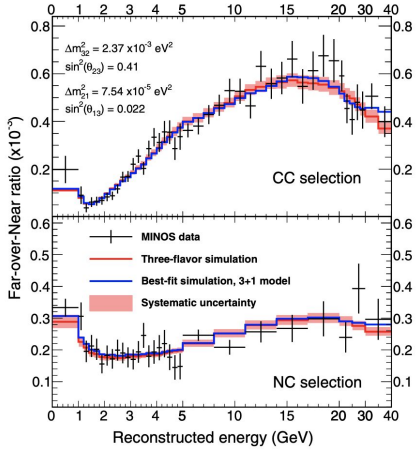
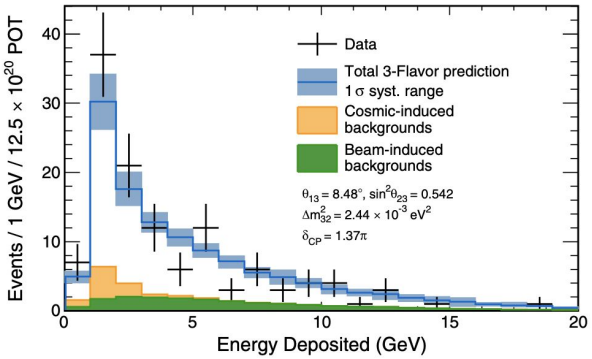
- Oscillation in NC channel would allow direct probe of U_{s4}

NC π^0 with signature of $\pi^0 \rightarrow \gamma + \gamma$ gives a "reconstruction" handle for us to use this specific subset of NC events to do physics with.

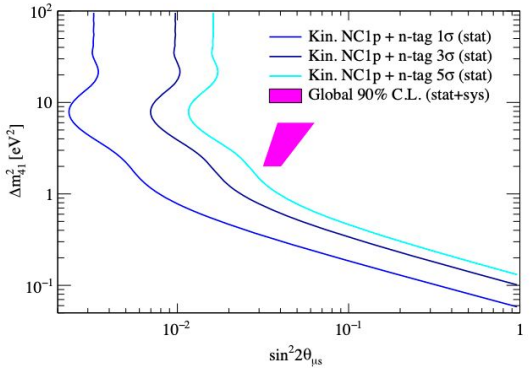


MINOS, Phys. Rev. Lett. ***117****, 151803 (2016)*

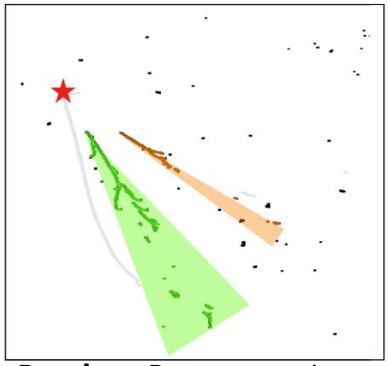
NOvA, Phys. Rev. Lett. ***127****, 201801 (2021)*



Phys. Rev. D ***103****, 112011 (2021)*

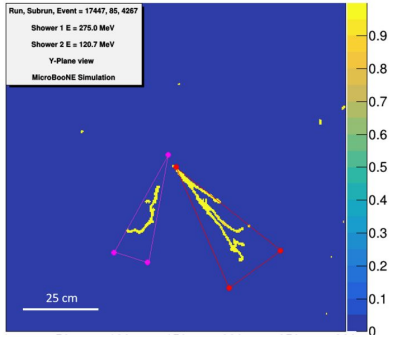


(3) π^0 as a **"standard candle"**

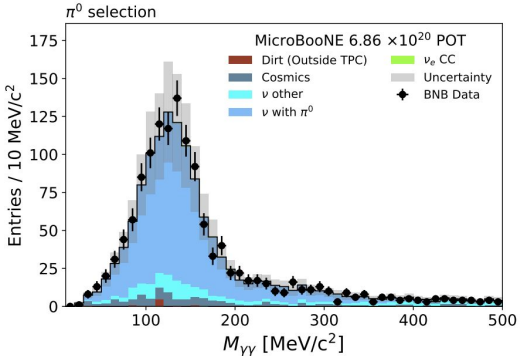


Pandora Reconstruction
JINST 15 (2020) 02, P02007

- MicroBooNE has multiple reconstruction paradigms
- In each case, π^0s can be used as a standard candle in validating and calibrating our electromagnetic shower reconstruction
- ***Note:*** *all these use sample of CC π^0s, as tagging events with a long, high-energy muon is easier.*
- *What about NC in comparison?*

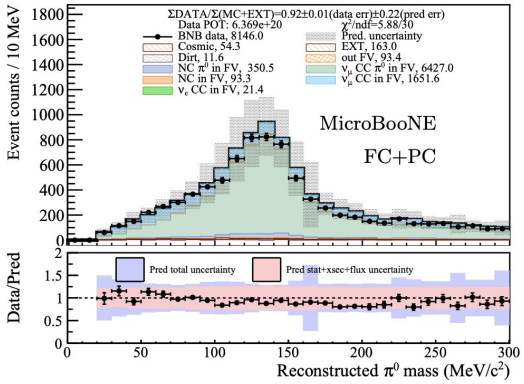


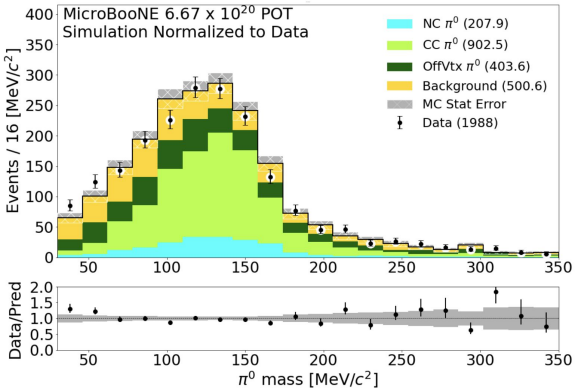
Deep-Learning reconstruction
JINST 16 (2021) 12, T12017



Phys. Rev. D105, 112004 (2022)

Wire-Cell Reconstruction
Phys. Rev. D105, 112005 (2022)

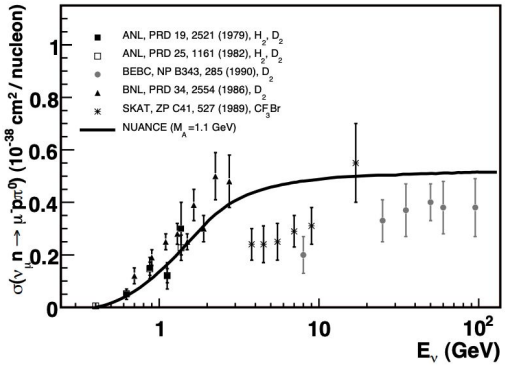




Neutral Current π^0

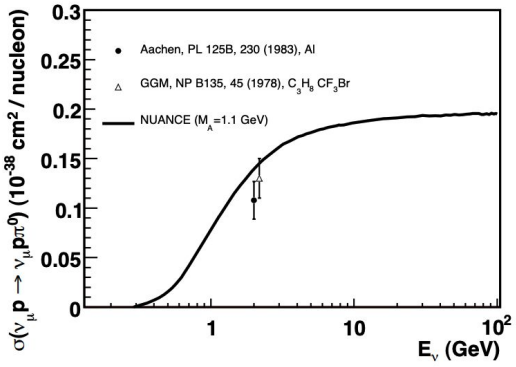
Historically, CC processes have always been more studied than NC, e.g.:

Charged Current ($\nu_\mu n \to \mu p \pi^0$)



Rev. Mod. Phys. ***84****, 1307 (2012)*

Neutral Current ($\nu_\mu p \to \nu_\mu p \pi^0$)



recent CC π^0 results

MINERvA	*Phys.Rev. D 100, 7 (2019)*
	Phys. Rev. D 102, 072007 (2020)
	Phys. Rev. D 94, 052005 (2016).
	Phys. Lett. B749 130-136 (2015).
	Phys. Rev. D92, 092008 (2015).
MiniBooNE	*Phys. Rev. D* ***83****, 052007 (2011)*
MicroBooNE	*Phys. Rev. D* ***99****, 091102(R) (2019)*
...	

NC measurements are relatively sparse compared to CC measurements.

NC π^0 is worthy of study in its own right, precise measurement of its cross section allows verification of π^0 production and final state interaction (FSI) models.

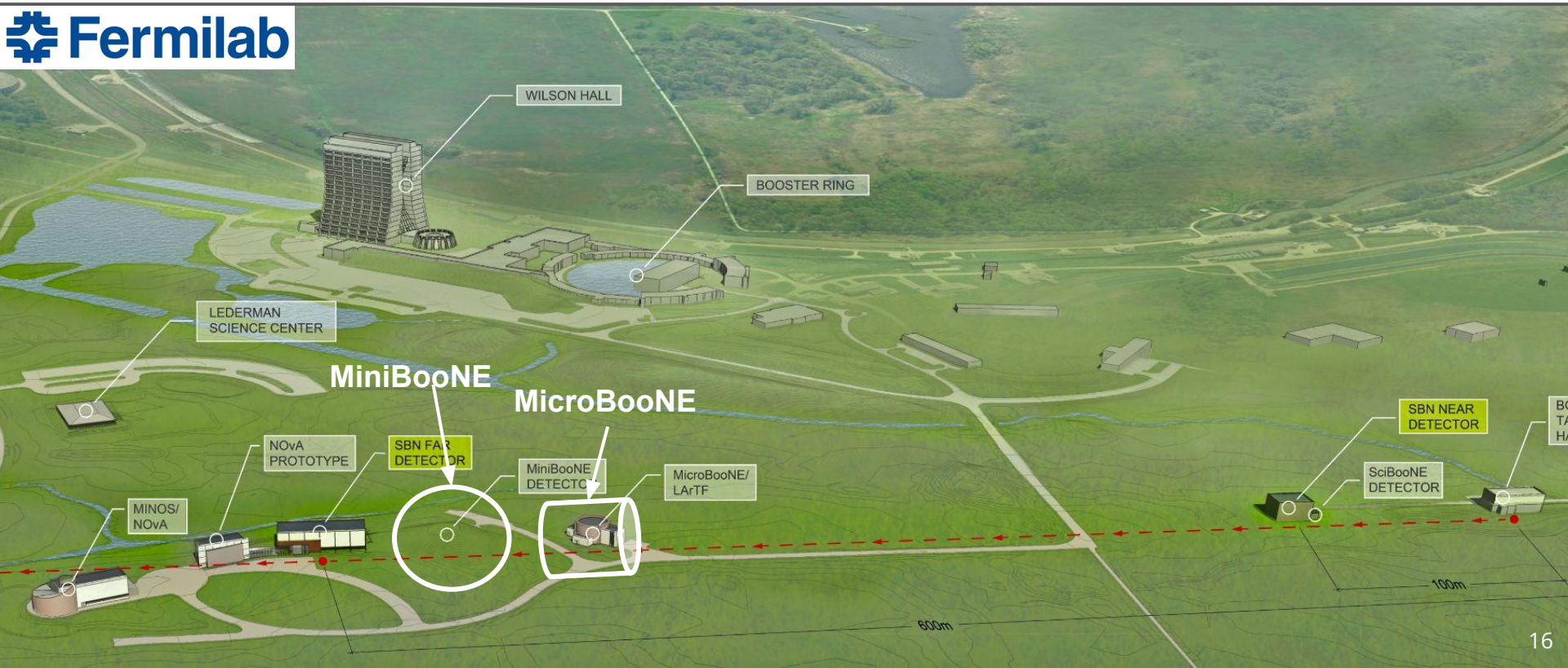
“Recent” Neutral Current π^0 measurements

Experiment	Target	Neutrino Energy <Eν> [GeV]	Targeted Signal	Measurement Type
T2K *Phys. Rev. D **97**, 032002 (2018)*	Water	0.6	NC $1\pi^0$	Rate ratio
SciBooNE *Phys. Rev. D 81, 033004 (2010)*	Polystyrene (C8H8)	0.8	NC $1\pi^0$	Ratio to CC inclusive
MiniBooNE *Phys. Rev. D **81**, 013005 (2010)*	Mineral oil (CH2)	0.8	NC $1\pi^0$	Direct
ArgoNeuT *Phys. Rev. D 96, 012006 (2017)*	Liquid Argon	9.6	NC $1\pi^0$	Direct + Ratio to CC inclusive
NOMAD *Phys. Lett. B 682 (2009) 177-184*	Composition of C, H, N, and O	24.8	NC coherent $1\pi^0$	Ratio to ν_μ-CC
NOvA *Phys. Rev. D **102**, 012004 (2020)*	Carbon dominated target	2.7	NC coherent $1\pi^0$	Direct
...				

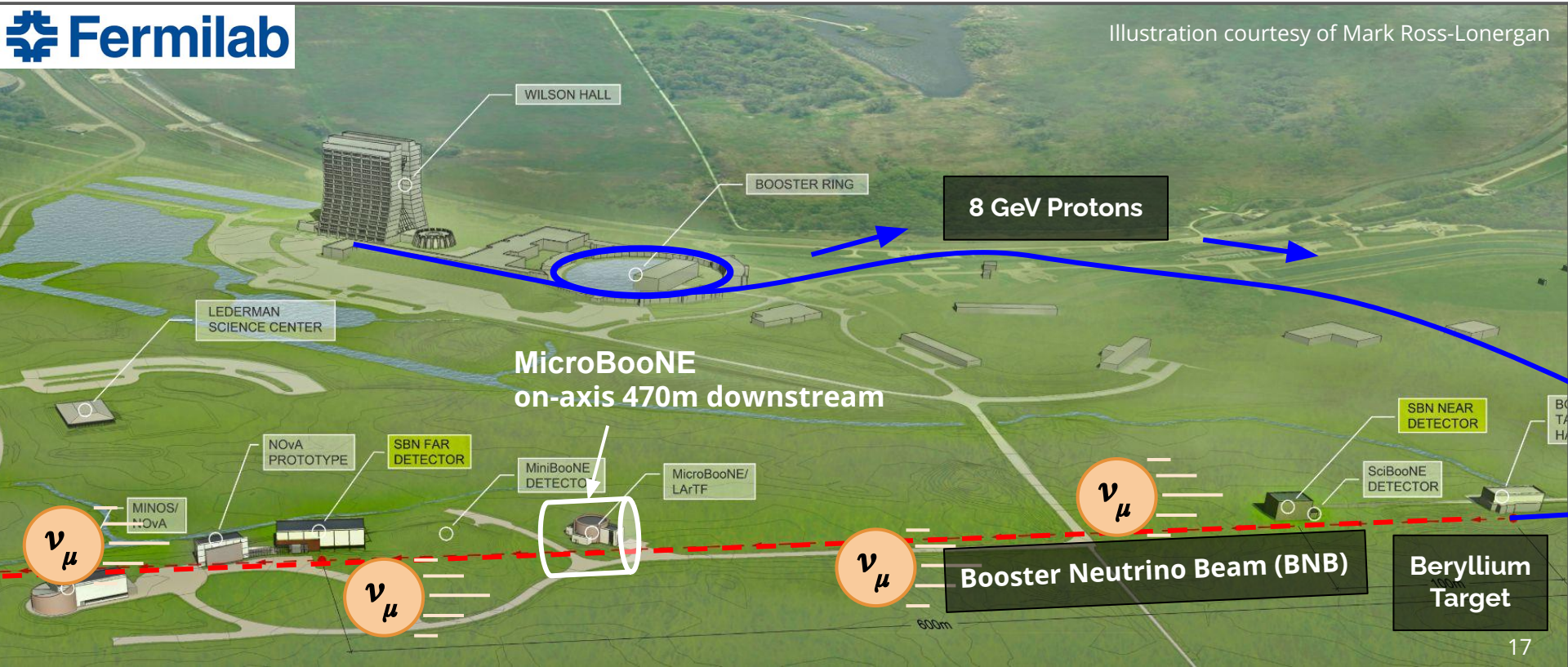
MicroBooNE (in **this talk**)
arXiv:2205.07943

This analysis selects a **high statistics NC $1\pi^0$ sample on argon**, and performs direct **exclusive** and **semi-inclusive cross section measurements** of this process

MicroBooNE at Fermilab



Booster Neutrino Beam at MicroBooNE



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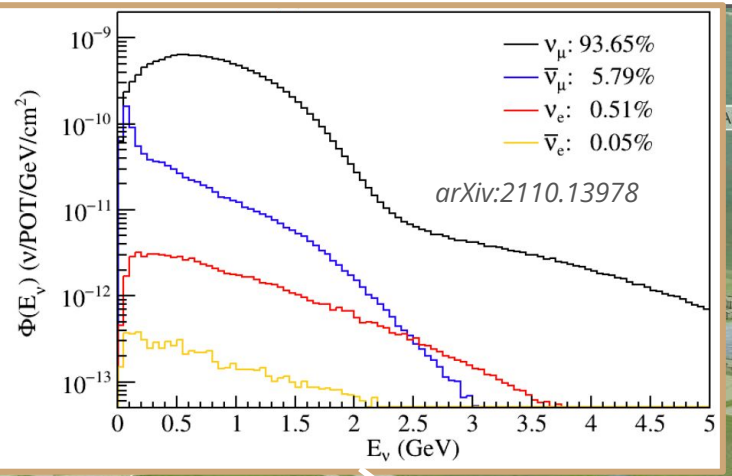


Illustration courtesy of Mark Ross-Lonergan

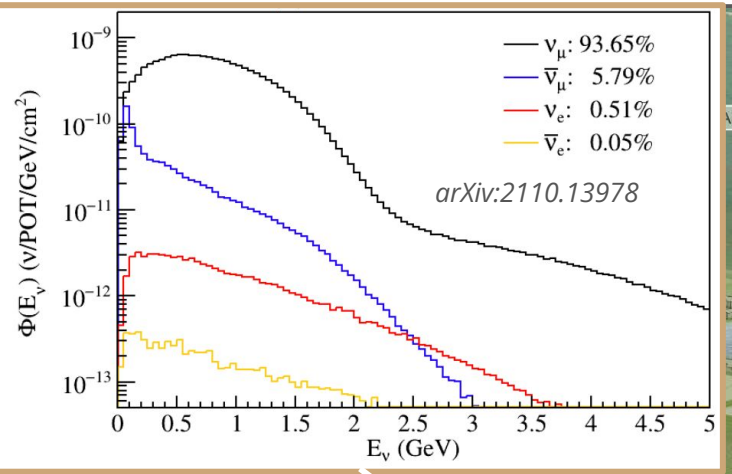
BNB in neutrino mode > 99% $\nu_\mu/\bar{\nu}_\mu$, with ~0.5% ν_e
E_ν ~ O(1) GeV

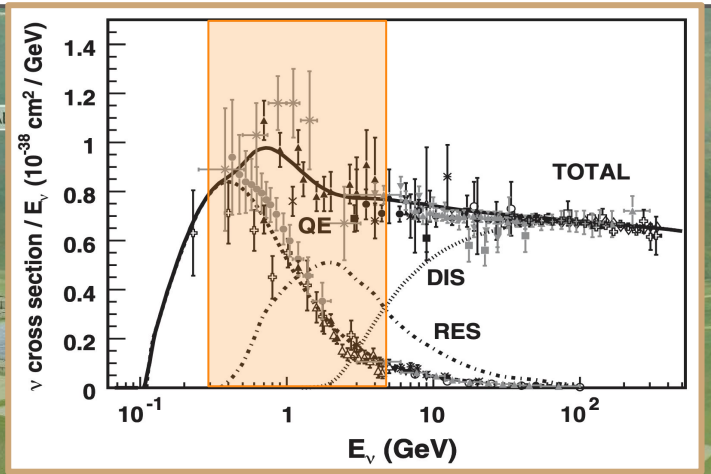
BOOSTER RING
MicroBooNE
NOvA PROTOTYPE
SBN FAR DETECTOR
MiniBooNE DETECTOR
MicroBooNE/ LArTF
MINOS/ NOvA
SBN NEAR DETECTOR
SciBooNE DETECTOR
ν_μ
Booster Neutrino Beam (BNB)
600m
100m

Booster Neutrino Beam at MicroBooNE

ν CC interaction cross section

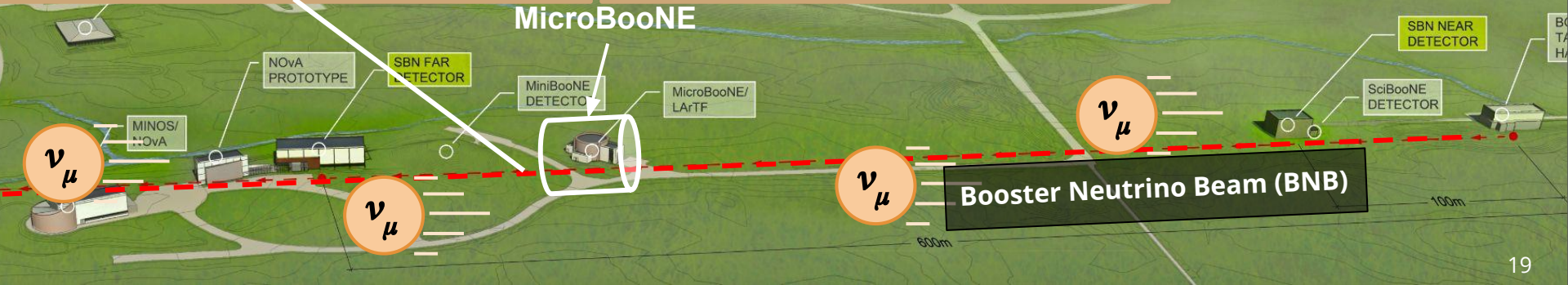
Rev. Mod. Phys. ***84****, 1307 (2012)*



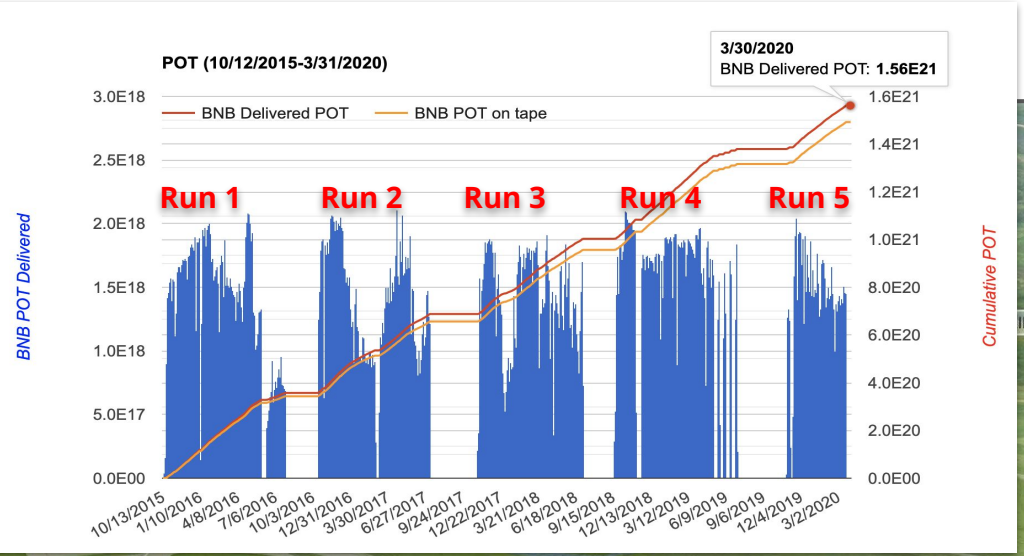


Dominated by quasi-elastic scattering and resonant production.

MicroBooNE's NC 1π^0 cross section measurement will be applicable to other neutrino experiments studying neutrino beams with similar energy ranges



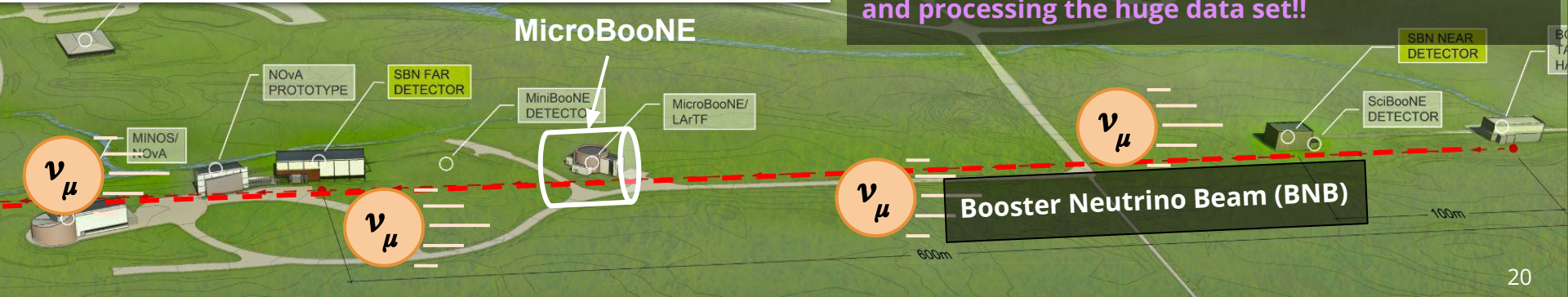
MicroBooNE **Data Collection**



MicroBooNE has collected data over 2015-2020 with beam delivery corresponding to **O(10^{21})** **protons-on-target** (POT), yielding the world's largest neutrino-argon interaction dataset!

Thank you, Accelerator Division!

Thank you, Cryogenics, Operations, and Scientific Computing Teams for keeping the detector running and processing the huge data set!!



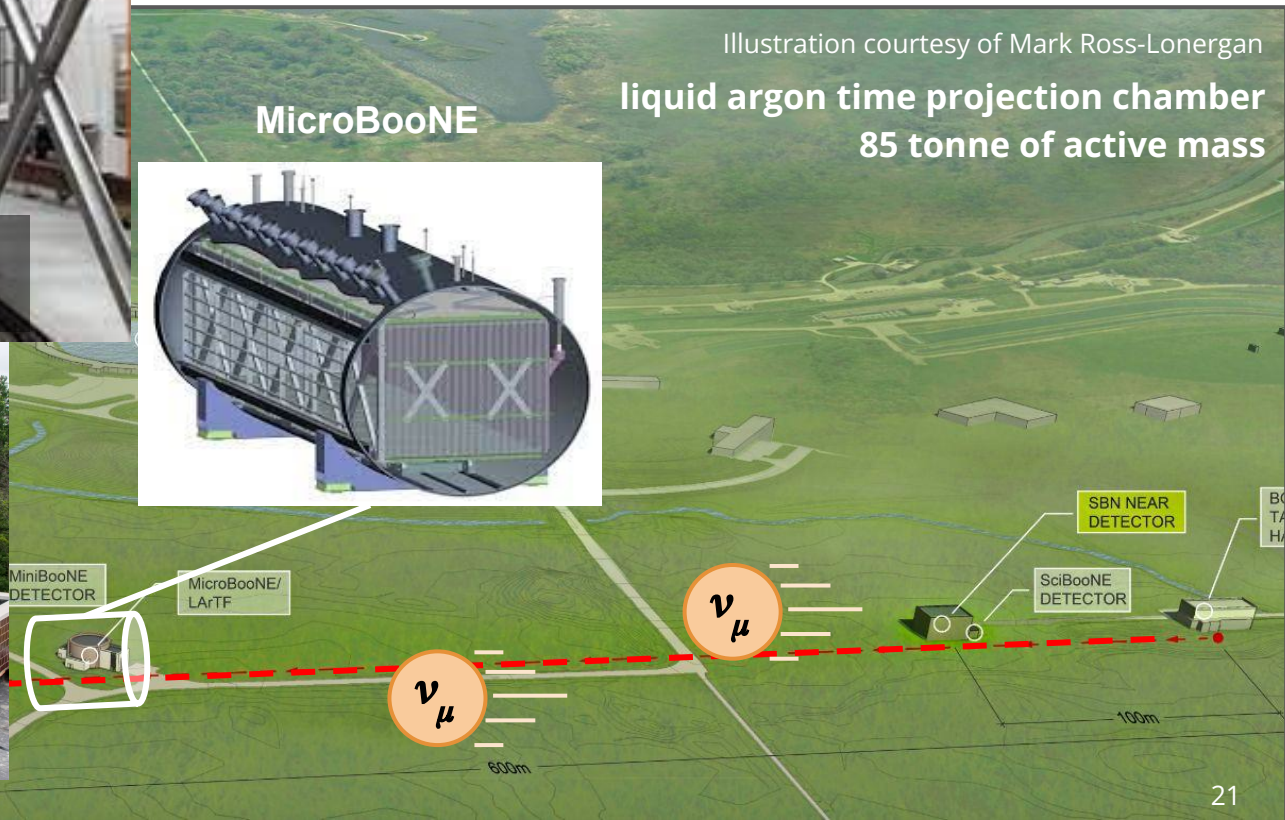
MicroBooNE **Detector**

Interior view
from the upstream end of the detector

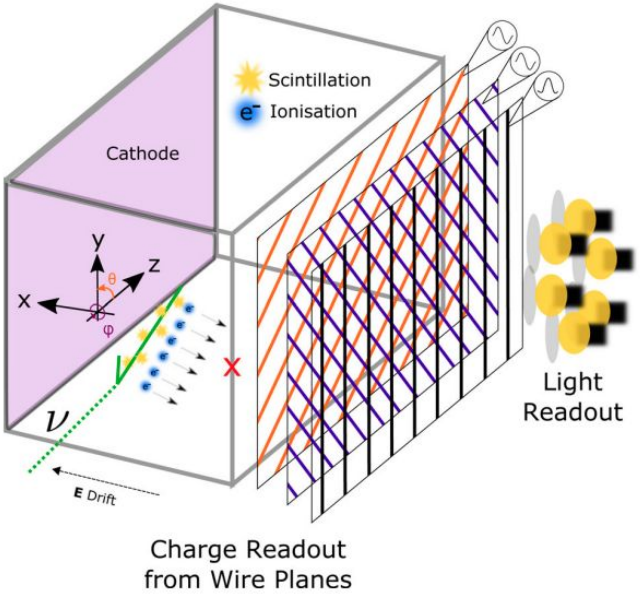
MicroBooNE being
lowered into LArTF

Illustration courtesy of Mark Ross-Lonergan

liquid argon time projection chamber
85 tonne of active mass



MicroBooNE **Technology**

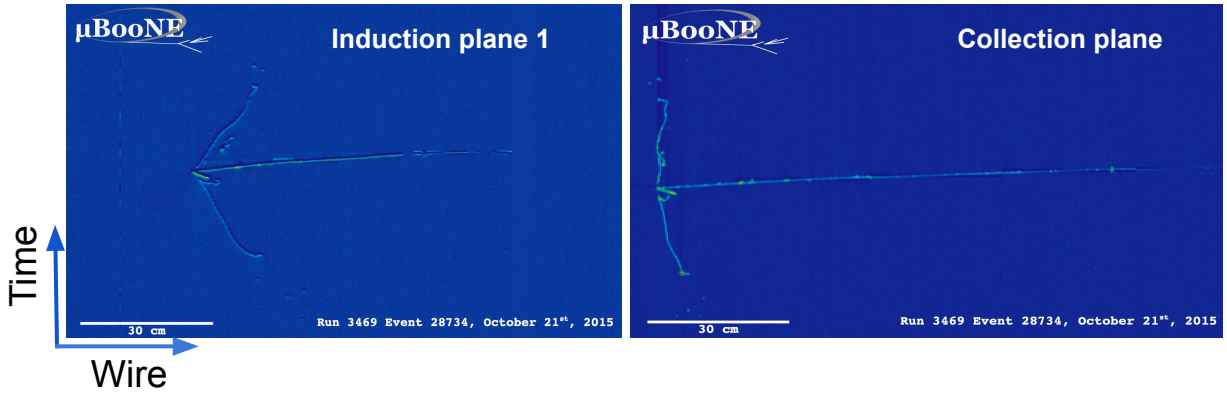


PHYS. REV. D 104, 052002 (2021)

Liquid Argon Time Projection Chamber

- Uniform E-field
- Wire planes read out induction and collection waveforms
- PMTs collect scintillation light from the interaction

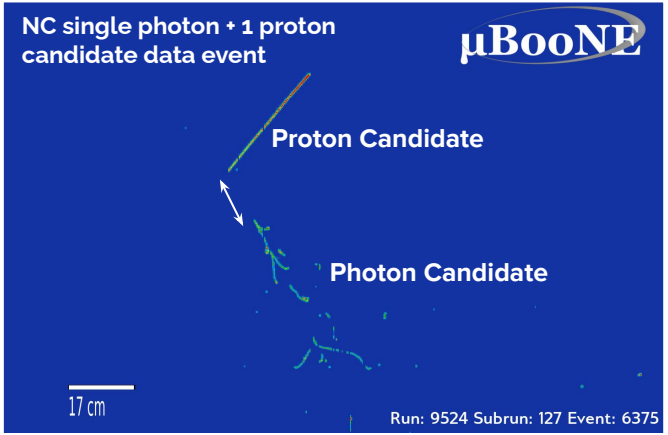
Detector readout can be viewed as an image with information of deposited ionization energy as a function of space (wire) and time

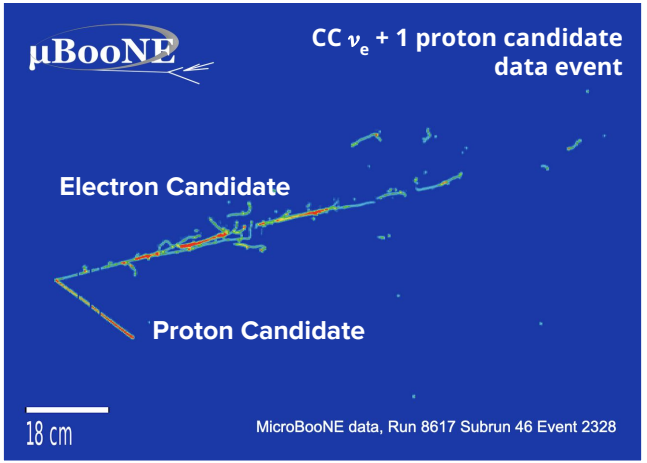


MicroBooNE **Technology**

Its LArTPC technology allows MicroBooNE to identify neutrino interactions with high accuracy and distinguish photons from electrons.

- Excellent resolution in space and deposited ionization energy
    - **Gap** between interaction vertex and photon shower start



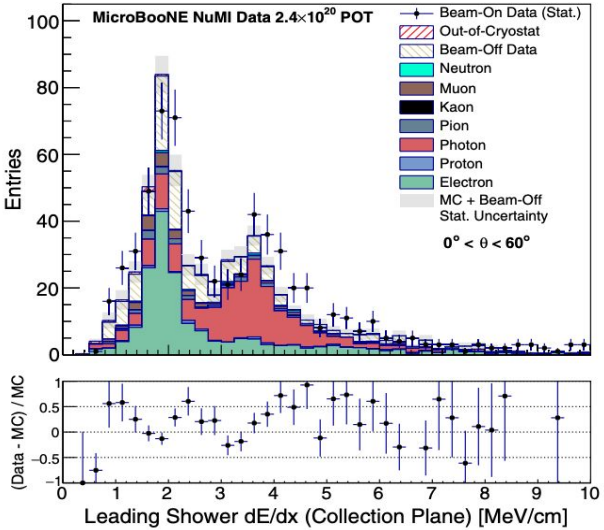


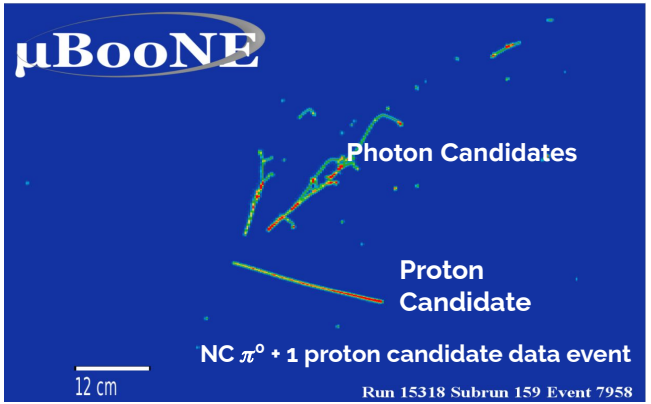
MicroBooNE **Technology**

Its LArTPC technology allows MicroBooNE to identify neutrino interactions with high accuracy and distinguish photons from electrons.

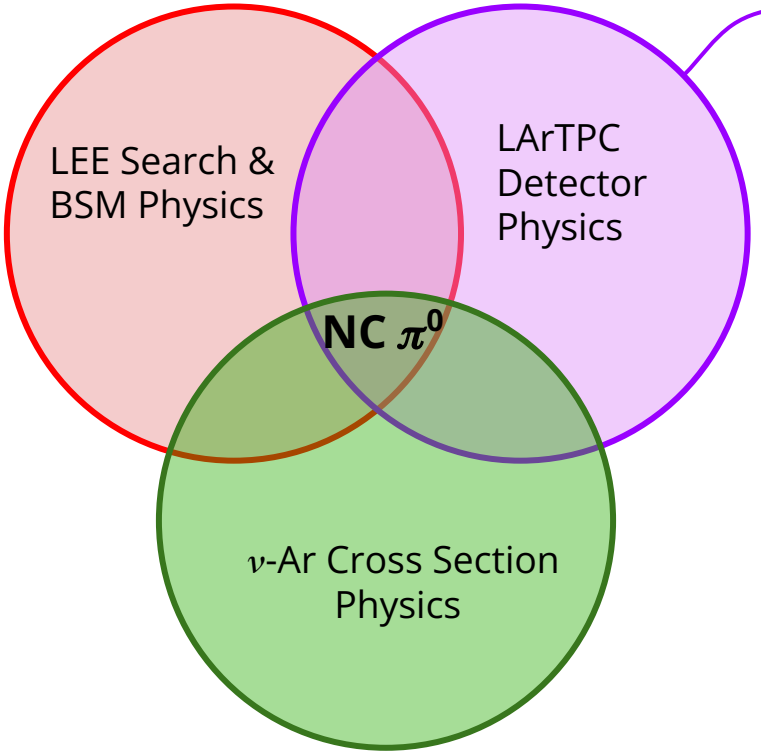
- Excellent resolution in space and deposited ionization energy
  - **Gap** between interaction vertex and photon shower start
  - Difference in **dE/dx** at the shower start due to photon pair-producing
- MicroBooNE detector is large enough to fully contain two γs from π^0 decay, which allows good reconstruction of π^0 kinematics

Phys. Rev. D 104, 052002 (2021)





MicroBooNE's **Goals**

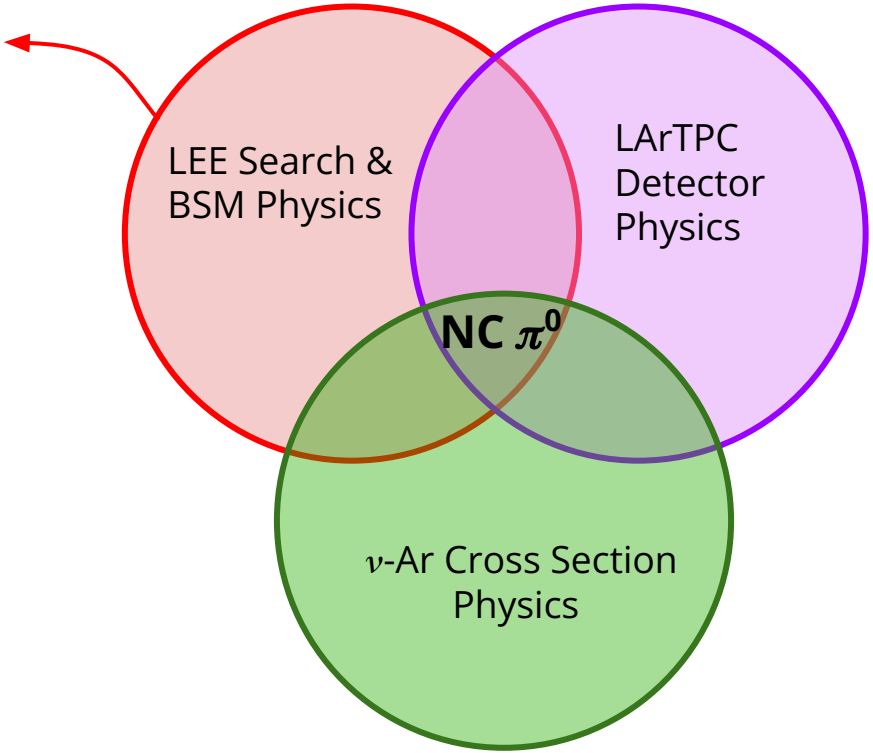


- LArTPC detector R&D
- Different detector effects
- Detector Calibration
- Event reconstruction
- …

NC π^0 can serve as calibration source

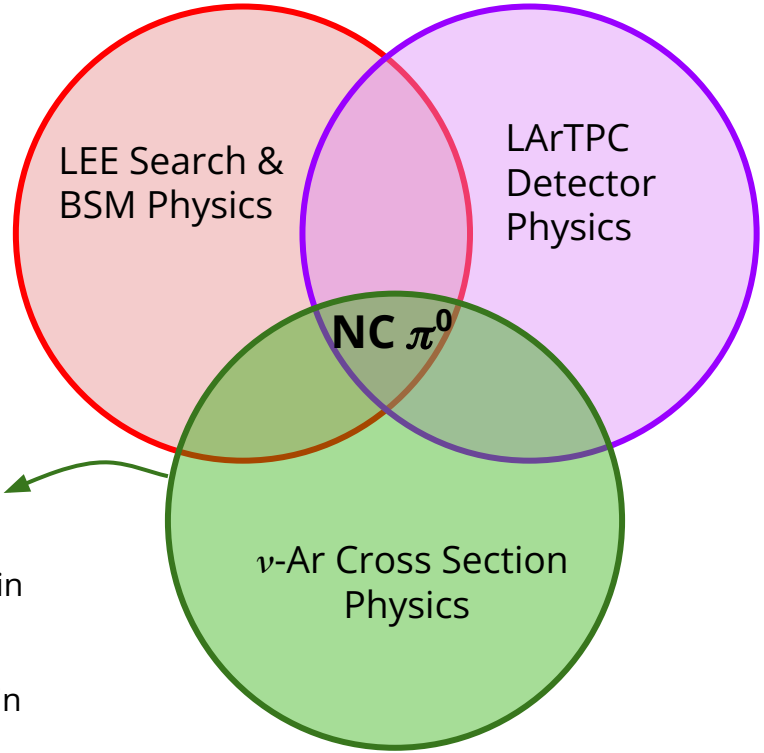
MicroBooNE's **Goals**

Investigate possible explanation of MiniBooNE LEE.
Search for exotic BSM physics, e.g. heavy neutral lepton[1] search



[1] *arxiv: 2207.03840*

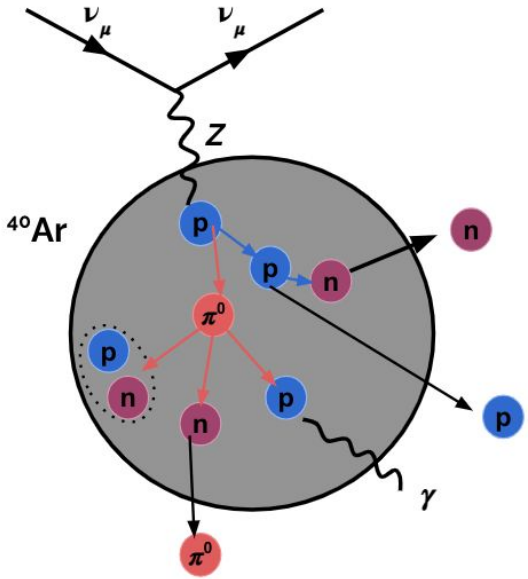
MicroBooNE's **Goals**

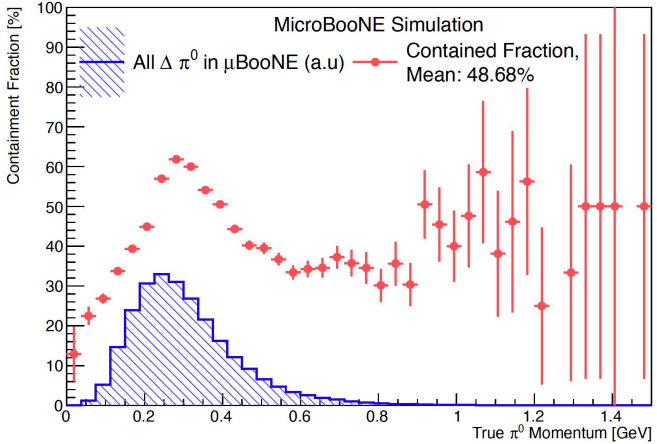


- LAr is an important future neutrino target
- MicroBooNE has put a tremendous amount of effort in cross section analyses to understand ν-Ar scattering
- Natural to study NC π^0s more in MicroBooNE

NC $1\pi^0$ Production in MicroBooNE

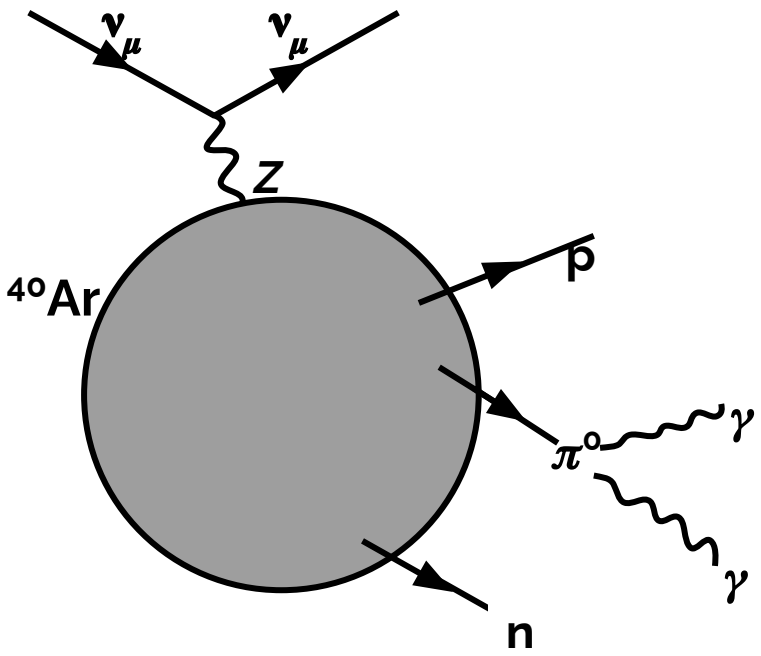
Dominant contribution for NC $1\pi^0$ in MicroBooNE is through resonance production.
After creation, π^0 s will see (and interact with) nuclear medium before coming out of the nucleus.
Nuclear and final state effects can affect the pions, and change the signature of an interaction.





Overall 49% of π^0 generated in the primary interaction do not escape the nucleus (GENIE prediction)

Signal Definition for MicroBooNE NC 1π^0 Measurement



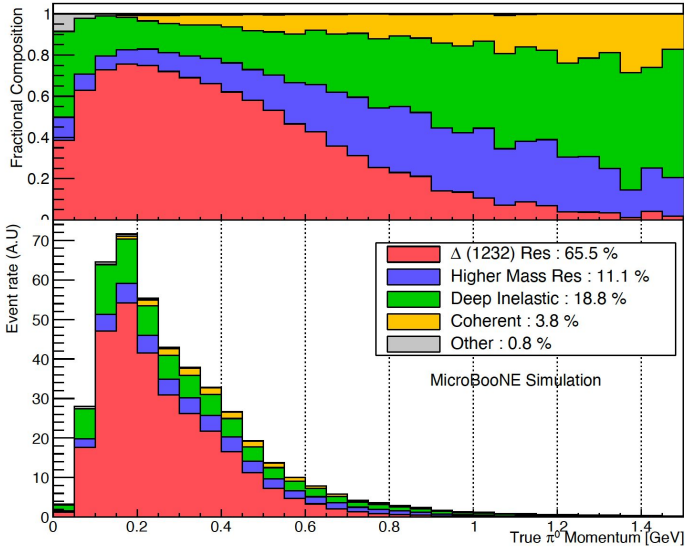
Focus on particles successfully escaping the nucleus at truth level:

- True interaction vertex inside the active volume
- Neutral current events
- Exactly 1 π^0 that exits the nucleus
- No exiting charged pions
- One or Zero protons exiting the nucleus, with no requirement on number of exiting neutrons
    - Proton multiplicity: number of protons that have kinetic energy > **50 MeV**

Simulation Overview

Monte Carlo Simulation:

- Neutrino interaction simulation with custom tune of **GENIE v3** [1]
  - The custom tune is based on fit to external T2K data, and specifically targets CCQE and CC multi-nucleon interaction models
  - The MicroBooNE custom tune has very little effect on this NC-focused analysis
  - The production of Δ and higher resonances (17) are included with the Berger-Sehgal model.
  - GENIE v3 includes improved treatment of final state interactions (FSI) and pion production
- **GEANT4**[2] v4 for particle propagation and re-interactions within the detector
- Detector response model implemented in **LArSoft**[3] framework is used for simulation of the wire signals and scintillation light in the PMTs

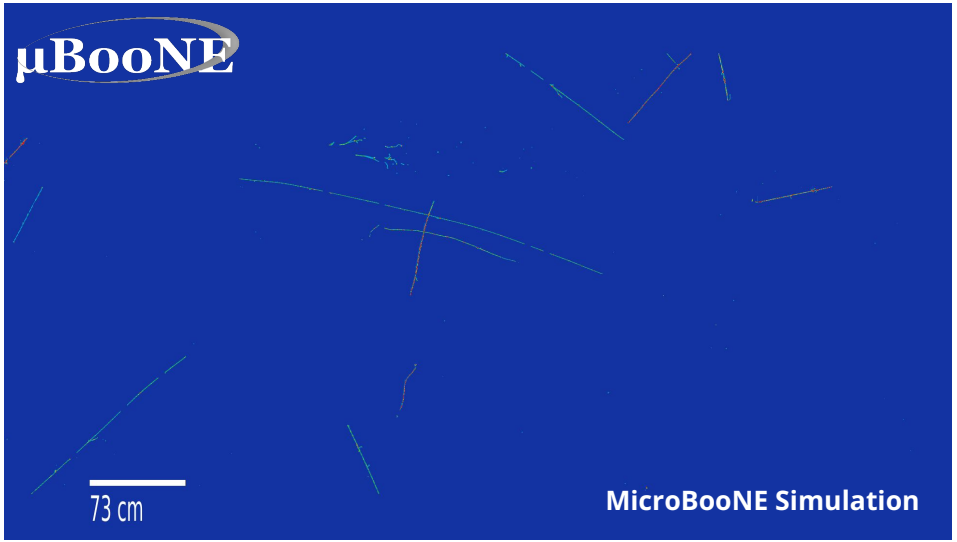


custom GENIE predicts major contribution is from Δ resonance for NC π^0 generated at primary ν interaction

[1] *Phys. Rev. D 105, 072001 (2022)* [2] *Nucl. Instrum. Meth. A 506, 250 (2003)* [3] *J. Phys.: Conf. Ser. 898 042057 (2017)*

Event Selection

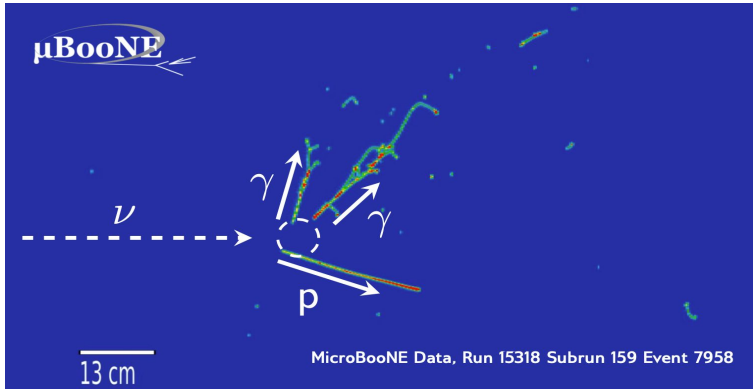
- Start with data collected during first three run periods of MicroBooNE, consisting of **5.89 x 10^{20} POT**
  - After "good data quality" cut and additional cuts to make sure this analysis remains blind to LEE signals
  - **Swamped with cosmic background**, as cosmic muon rate at MicroBooNE ~ 0.2/m^2/ms. Only 1 in 20 interactions recorded in coincidence with beam spill are neutrino-induced.



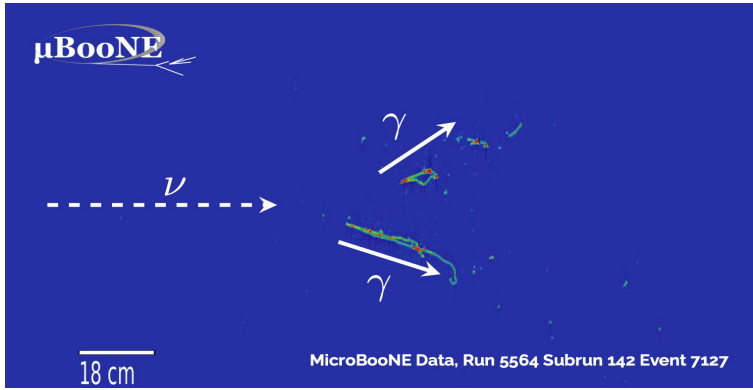
Event Selection

- Start with data from first three run periods (5.89 x 10^{20} POT)
- After Pandora[1] reconstruction, select events with **two mutually exclusive topologies**:
  - Two showers and one track (2γ1p) — $\nu + p \rightarrow \nu + p + \pi^0$
  - Two showers and zero track (2γ0p) — $\nu + n \rightarrow \nu + n + \pi^0$

2γ1p



2γ0p

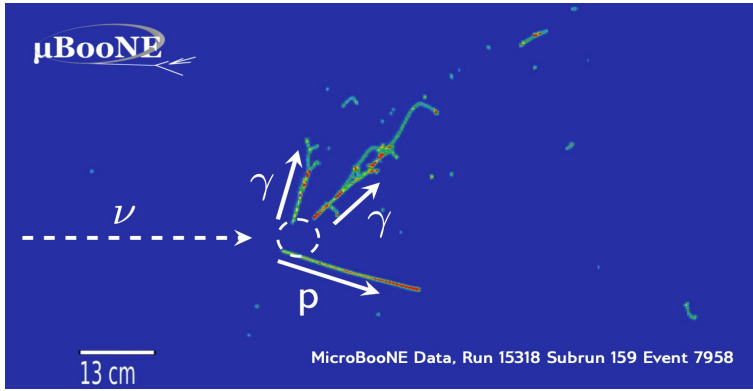


[1] *Eur. Phys. J. C 78, 82 (2018)*

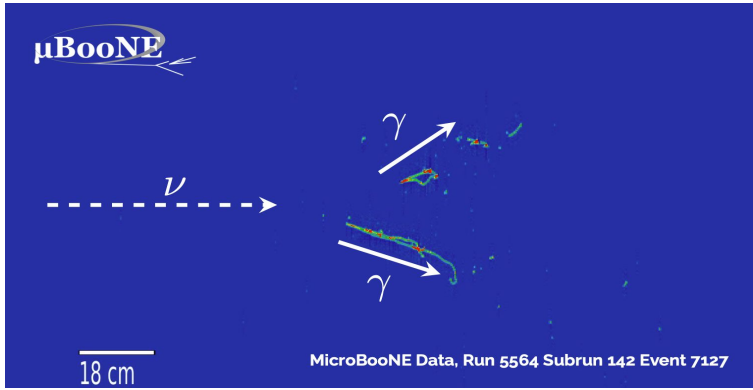
Event Selection

- Start with data from first three run periods (5.89 x 10^{20} POT)
- After Pandora[1] reconstruction, select events with two mutually exclusive topologies: 2γ1p and 2γ0p
- Apply **pre-selection cuts** to ensure good reconstruction of objects:
  - **Fiducial Volume cut:** Reconstructed interaction vertex at least 5cm from TPC wall
  - **Reconstructed energy cut**: > 30 (20) MeV for leading (subleading) shower
  - Cuts to 2γ1p only, to ensure blindness to electron LEE signals
    - Distance from reconstructed shower start to vertex, distance between track start and the vertex

2γ1p



2γ0p



Event Selection @**Preselection** Stage

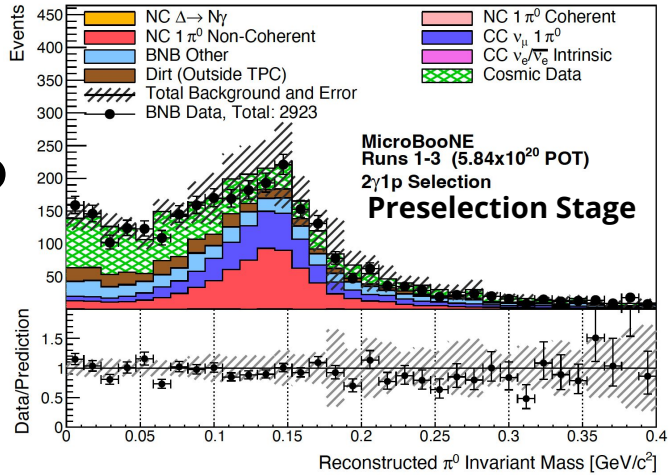
Signal:

- ★ **NC $1\pi^0$ Non-Coherent**
- ★ **NC $1\pi^0$ Coherent**

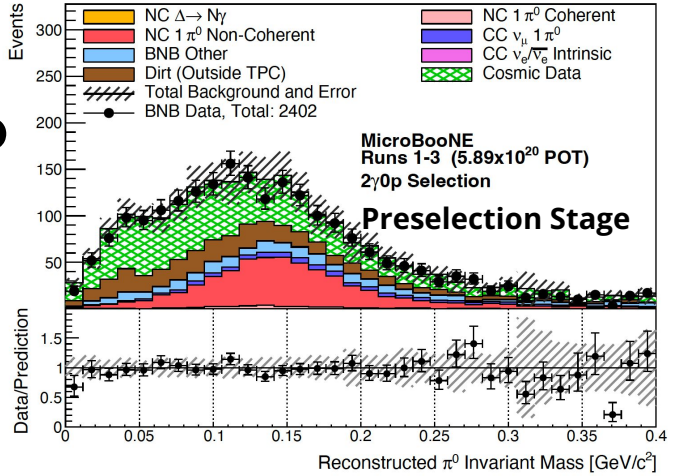
Backgrounds:

- Cosmic Data
- CC ν_μ $1\pi^0$
- Dirt
- BNB Other
- Intrinsic CC ν_e/anti-ν_e
- NC Δ radiative decay $\Delta \rightarrow N + \gamma$

2γ1p



2γ0p



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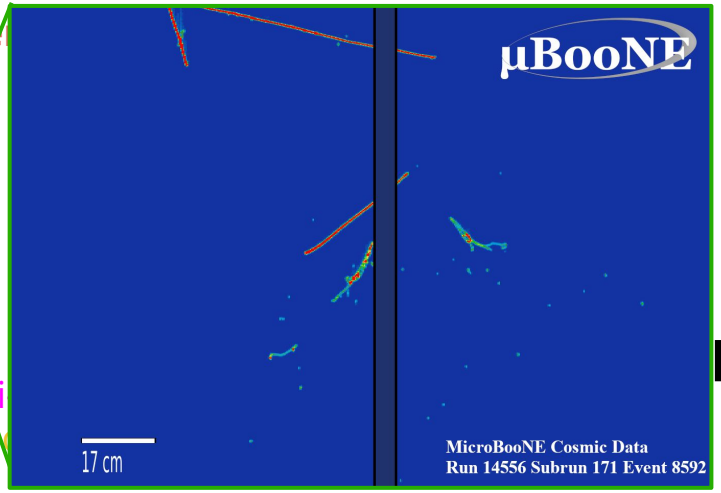
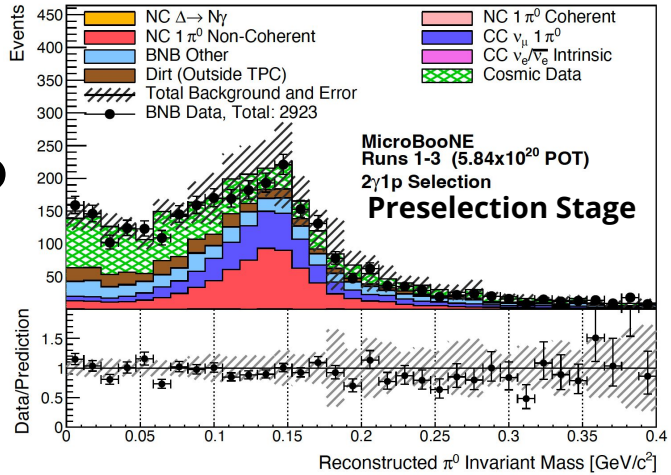


2γ1p



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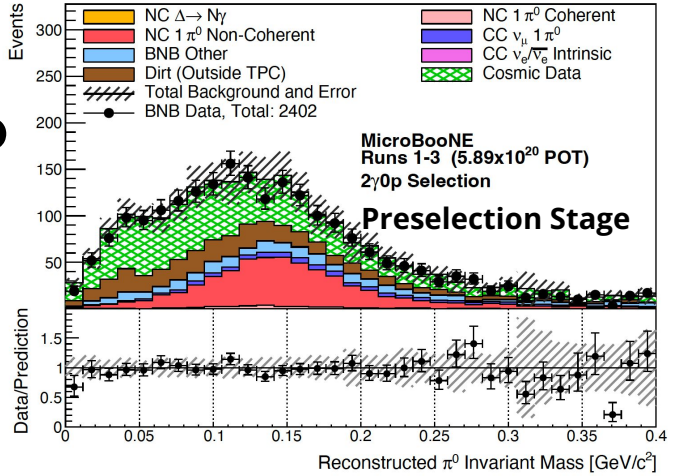


Cosmic background is estimated from data collected by MicroBooNE when **neutrino beam was off**.
MC simulation samples are also overlaid with off-beam data to account for cosmics entering the detector during beam event.

Event Selection @**Preselection** Stage

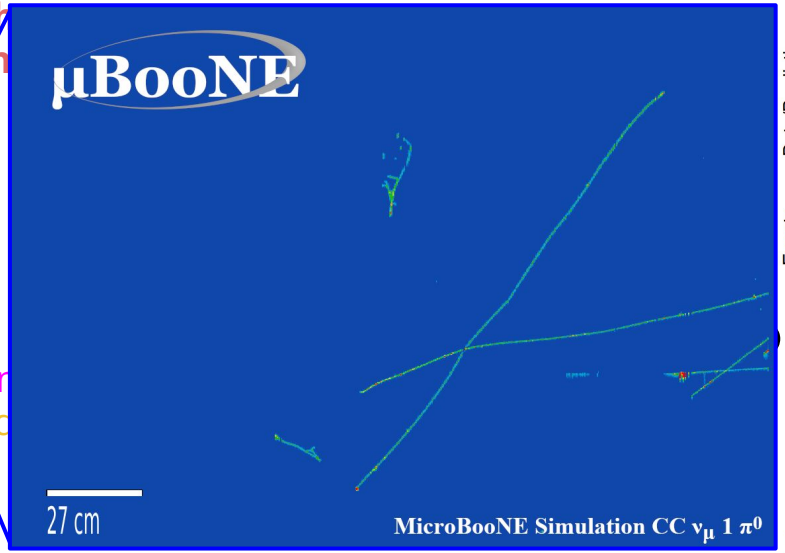
2γ1p

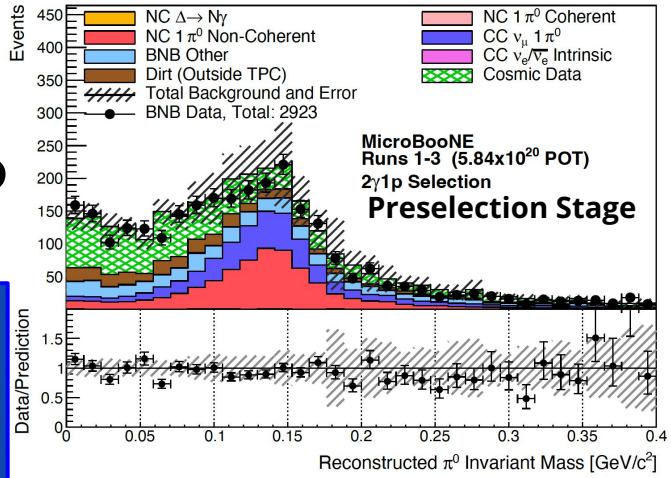
Signal:

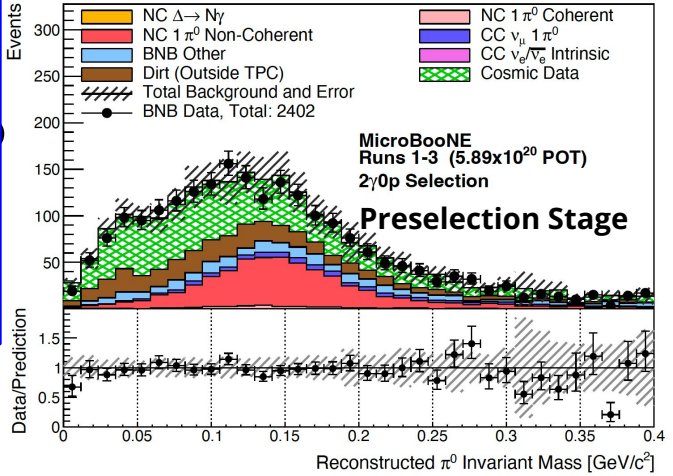
★ NC $1\pi^0$ Non-Coh
★ NC $1\pi^0$ Coheren

Backgrounds:

- Cosmic Data
- **CC ν_μ $1\pi^0$**
- Dirt
- BNB Other
- Intrinsic CC ν_e/ar
- NC Δ radiative c







Event Selection @**Preselection** Stage

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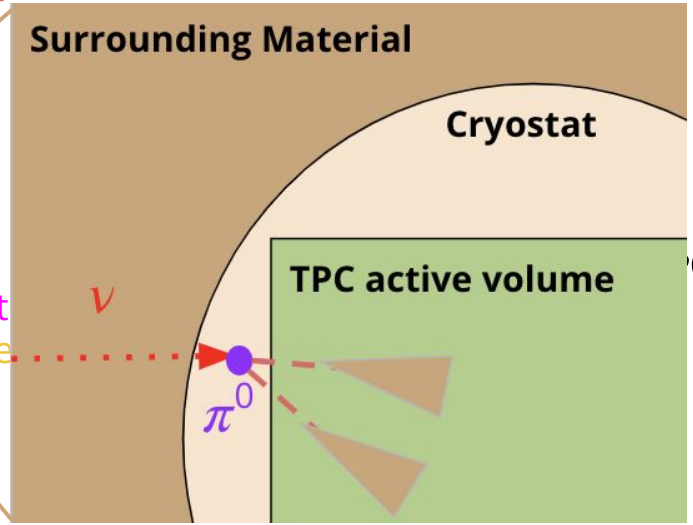
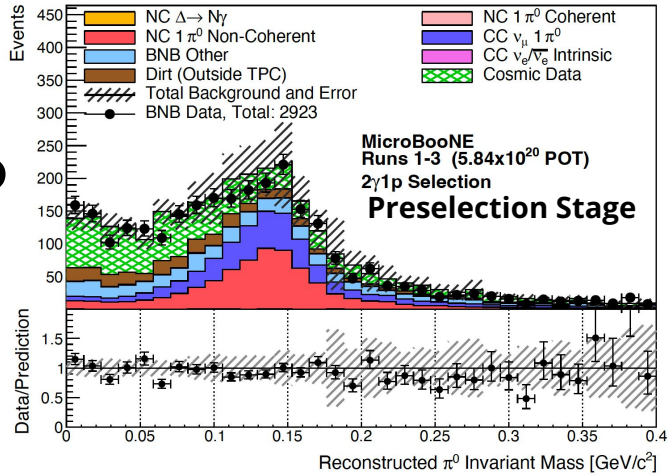
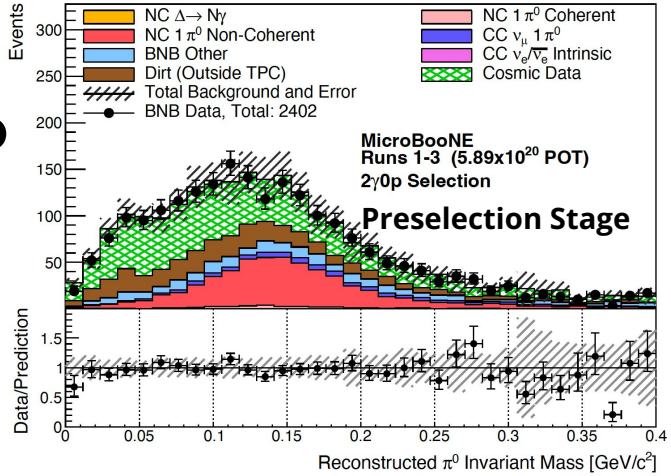
- NC Δ radiative de



2γ1p



0p



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Signal:

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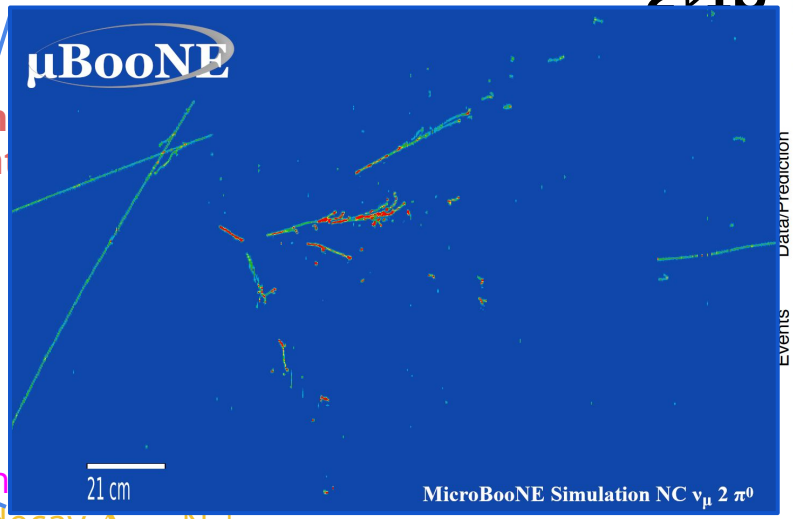

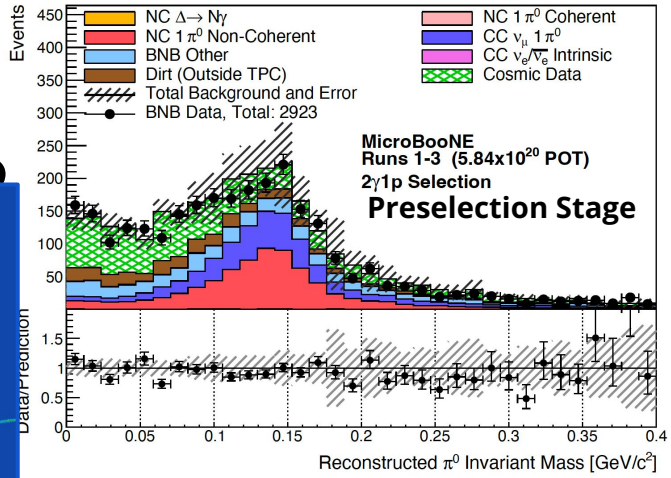

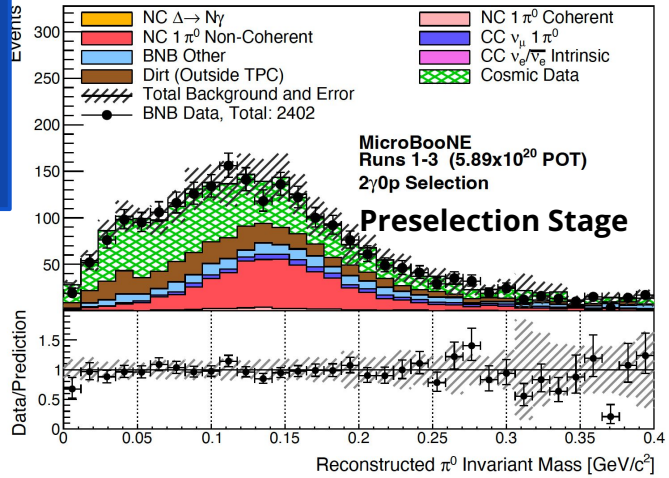

Event Selection @**Preselection** Stage

Signal:

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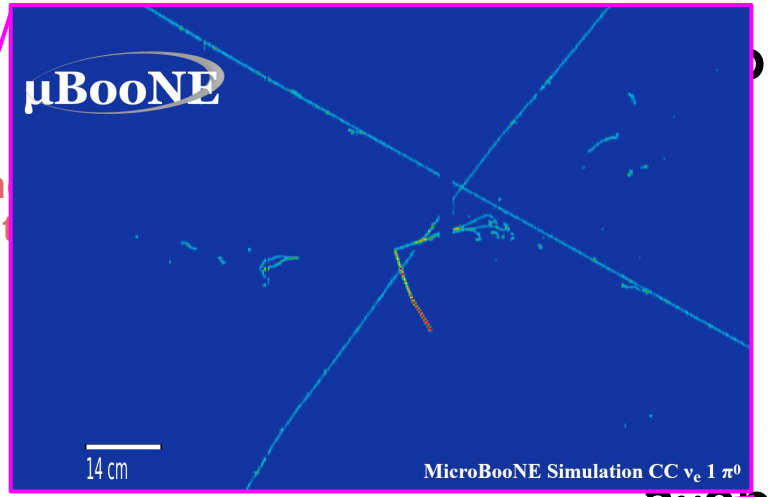
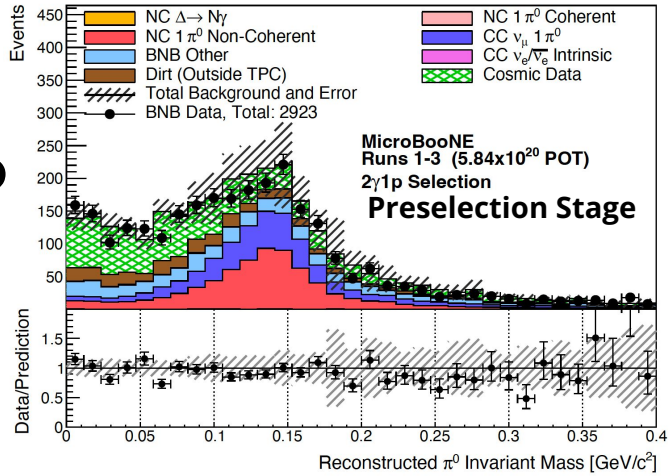
★ NC $1\pi^0$ Coherent

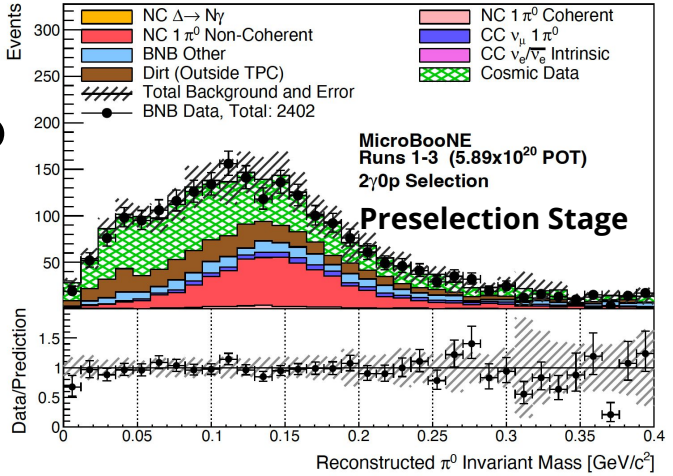
Backgrounds:

- Cosmic Data
- CC ν_μ $1\pi^0$
- Dirt
- BNB Other
- **Intrinsic CC ν_e/anti-ν_e**
- NC Δ radiative decay $\Delta \rightarrow N + \gamma$



2γ0p





Event Selection @**Preselection** Stage

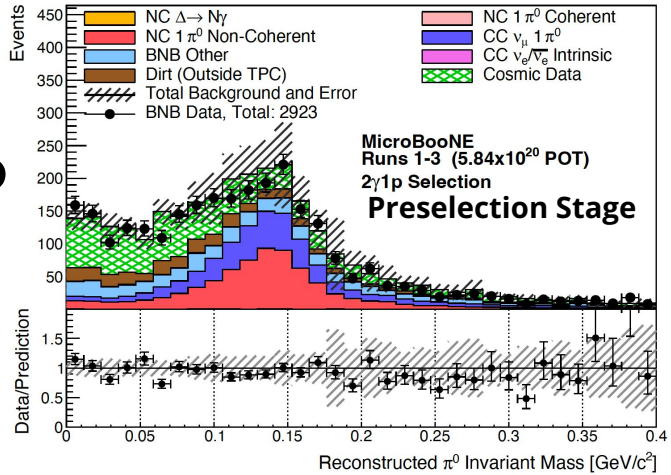
Signal:

- ★ **NC $1\pi^0$ Non-Coherent**
- ★ **NC $1\pi^0$ Coherent**

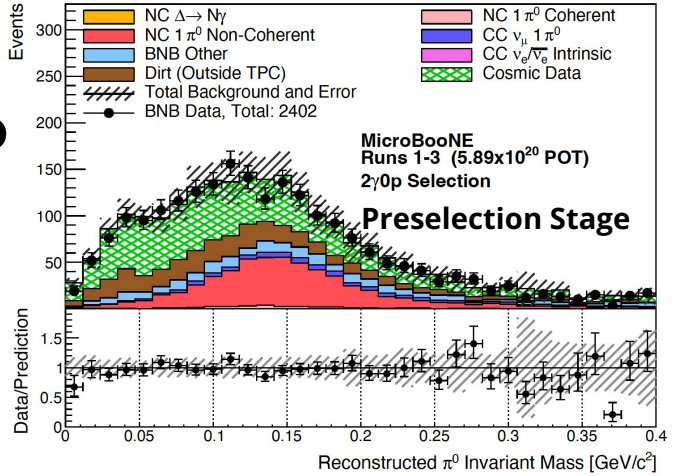
Backgrounds:

- Cosmic Data
- CC ν_μ $1\pi^0$
- Dirt
- BNB Other
- Intrinsic CC ν_e/anti-ν_e
- **NC Δ radiative decay Δ → N + γ**

2γ1p



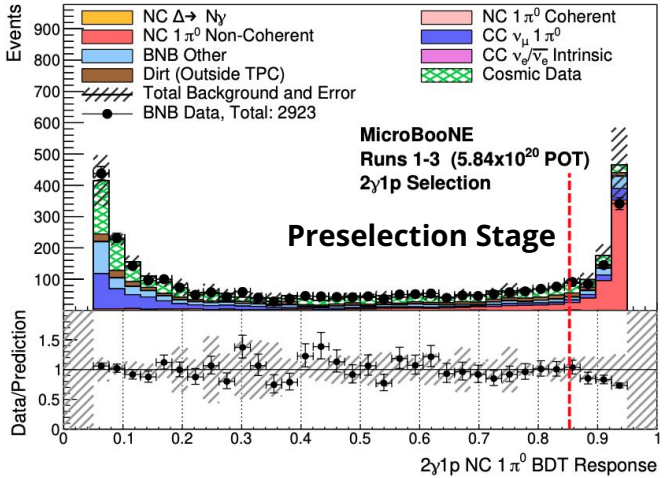
2γ0p



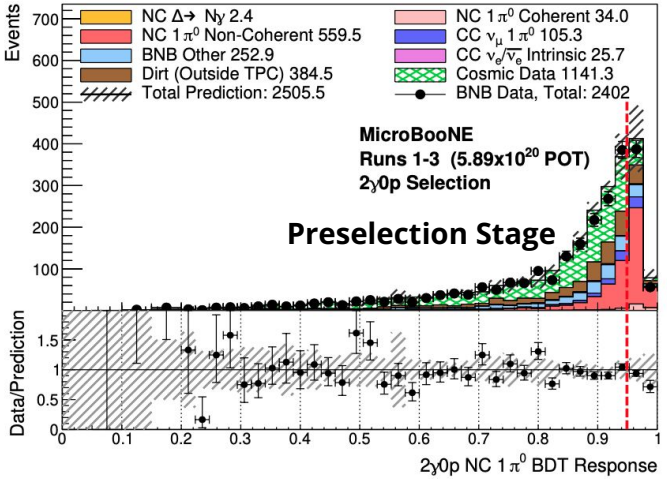
Event Selection @**Preselection** Stage

- After preselection stage, tailored boosted decision trees (BDTs) are used to help distinguish signal from backgrounds for each sample:
  - One BDT for each sample
    - Gradient boosting algorithm XGBoost is used to train BDTs
    - Training inputs: reconstructed kinematic, geometric, and calorimetric variables
      - $2\gamma1p$ & $2\gamma0p$: photon shower related variables
      - $2\gamma1p$ only: proton track related variables
  - Bimodal distribution for $2\gamma1p$ BDT scores, highlighting excellent BDT performance in isolating signal

$2\gamma1p$

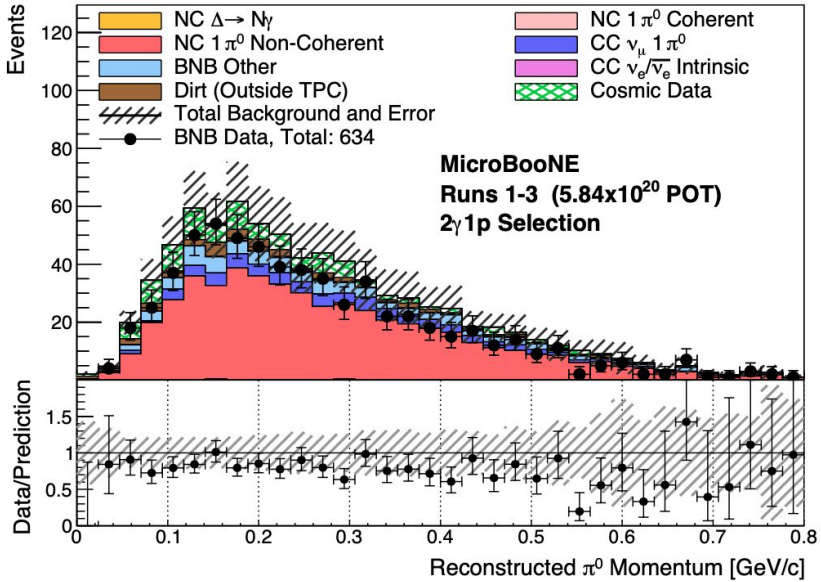


$2\gamma0p$



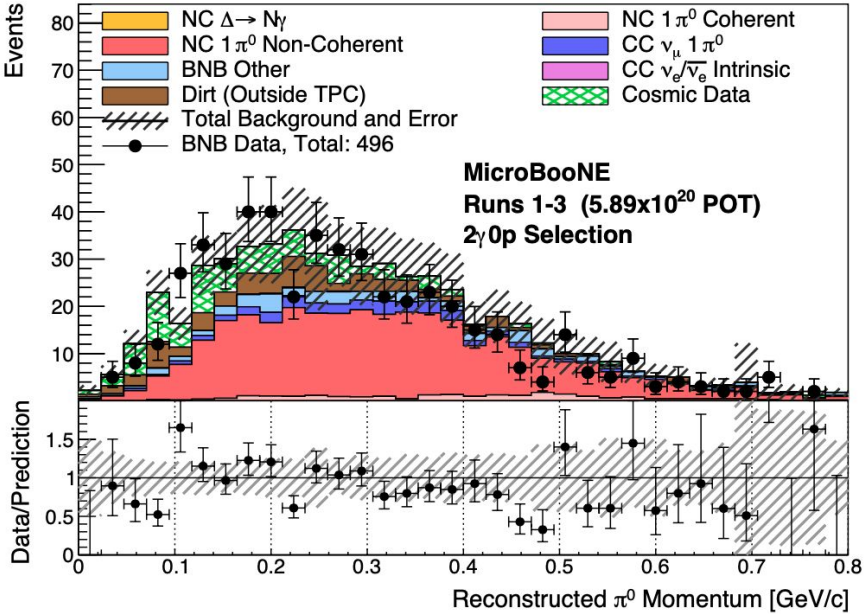
Final Selection: **2γ1p**

- BDT selection efficiency of 85.6%
- NC 1π^0 Purity 63.5%
- 634 selected data events
- 20% deficit seen in data, however covered by systematic and statistical uncertainties
- Dominant background from cosmic (12%), CC-ν_μ (9%) and BNB Other (9.8%)



Final Selection: **2γ0p**

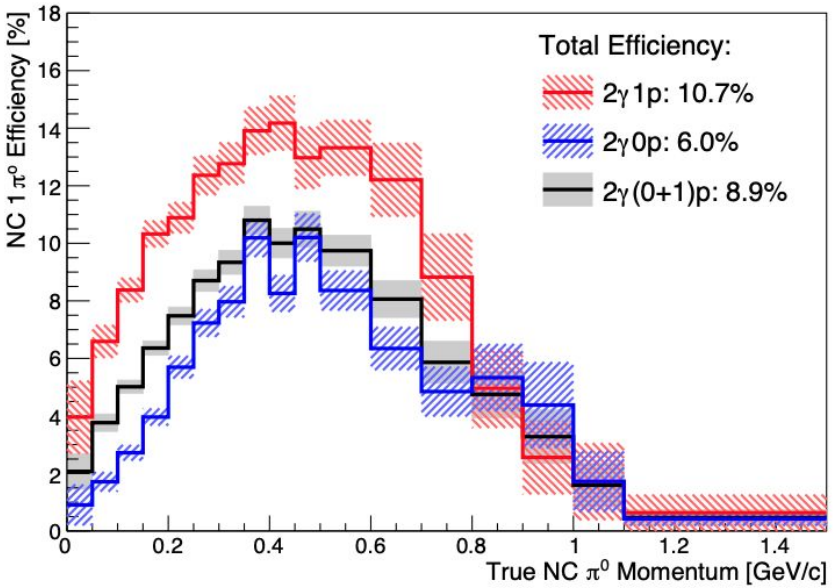
- BDT selection efficiency of 58.8%
- Total of 496 selected data events, with predicted NC 1π^0 purity of 52.9%
- Overall good agreement between data and MC prediction within systematic and statistical uncertainties
- Dominant background from cosmic(15%), dirt (11%), CC-ν_μ (6.4%) and BNB Other (7.5%)



Selection Efficiency

Overall 2γ1p selection is more efficient compared to 2γ0p, due to existence of reconstructed track

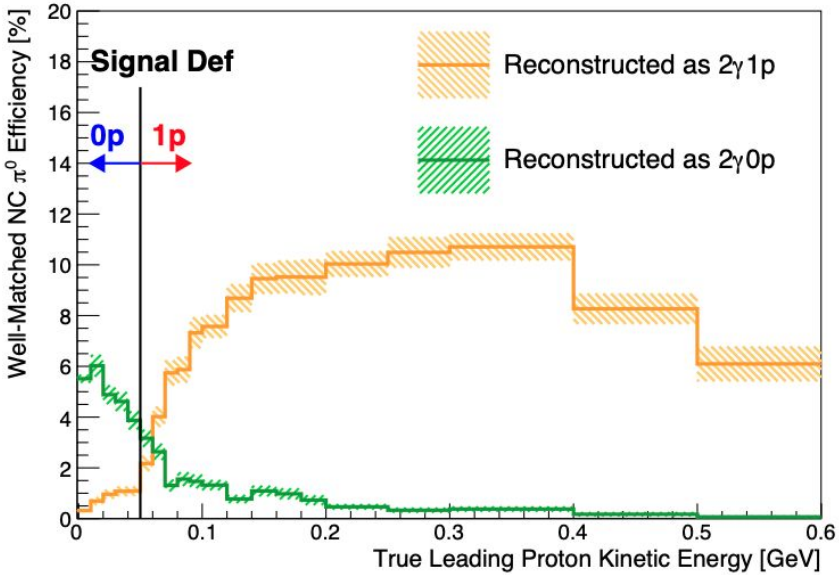
- helps identify the interaction vertex
- rejects CC-ν_μ background where muon track is expected instead of proton track as targeted by this analysis



Selection Efficiency

Low energy protons with KE < 50 MeV are more likely to not be reconstructed and enter 2γ0p selection

- This motivates us to perform exclusive cross section extraction with 2γ1p and 2γ0p individually with a 50 MeV threshold on the exiting proton KE

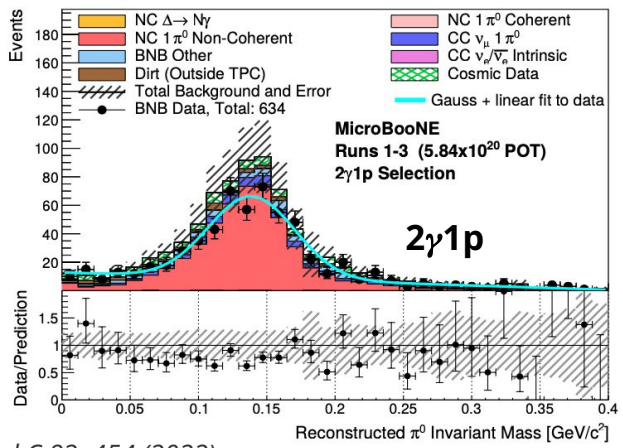


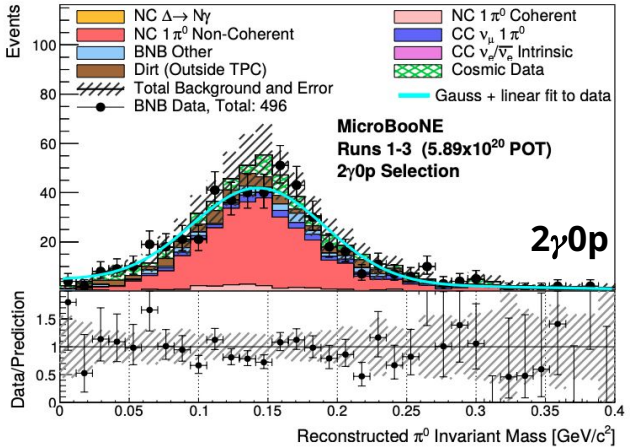
$$M^2_{\gamma\gamma} = 2E_{\gamma 1}E_{\gamma 2}(1-\cos\theta_{\gamma\gamma})$$

Final Selection - reconstructed π^0 mass

Gaussian + linear fit to the π^0 invariant mass distribution in each selected sample yields:

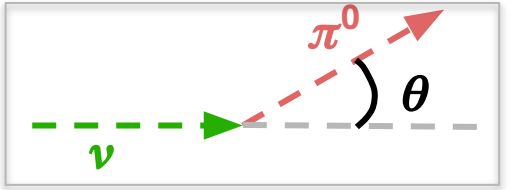
- 2γ1p: 138.9±2.1 MeV/c^2 with width of 31.7±2.4 MeV/c^2
- 2γ0p: 143.3±3.2 MeV/c^2 with width of 47.9±4.9 MeV/c^2
- Both results agree with expected π^0 invariant mass of 134.97 MeV/c^2 (within detector uncertainties[1])
- Broader spectrum in 2γ0p because of worse resolution in shower angle reconstruction



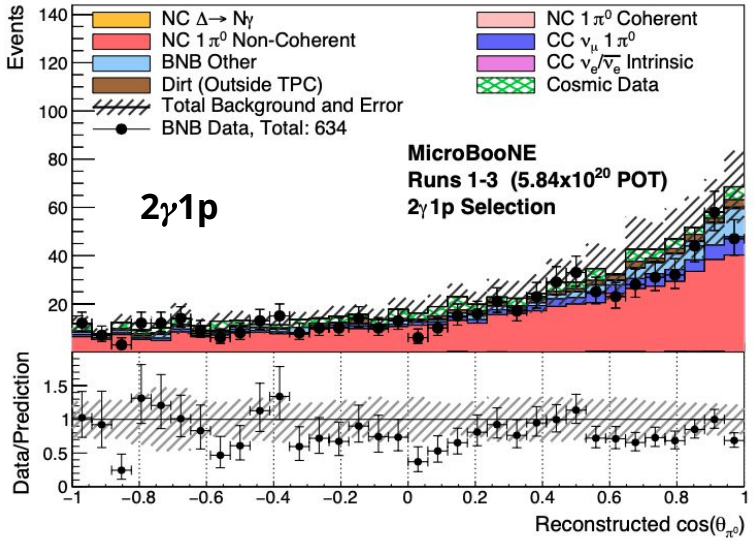


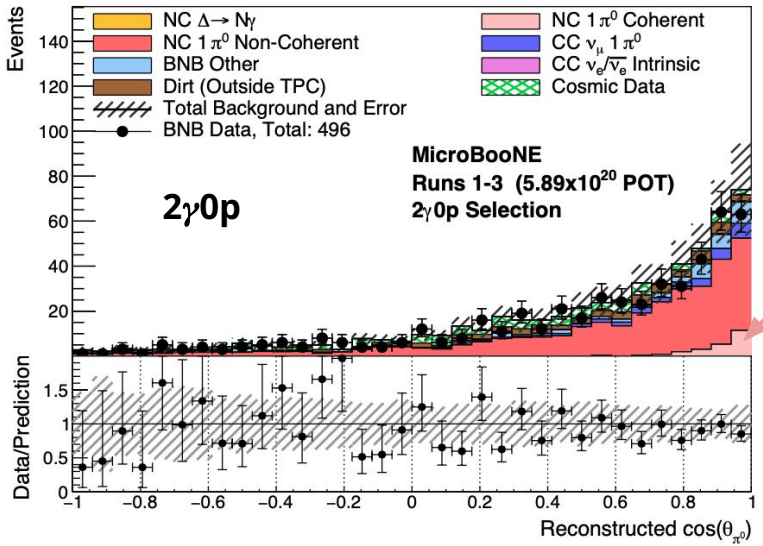
[1] *Eur. Phys. Journal C 82, 454 (2022)*

Final Selection - $\cos(\theta_{\pi})$



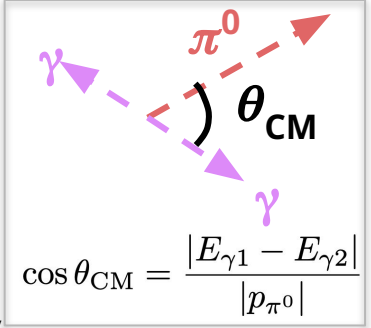
- Reconstructed cosine of π^0 angle with respect to neutrino beam
- NC coherent $1\pi^0$ tends to be more forward compared to resonant π^0s due to low Q^2 exchange



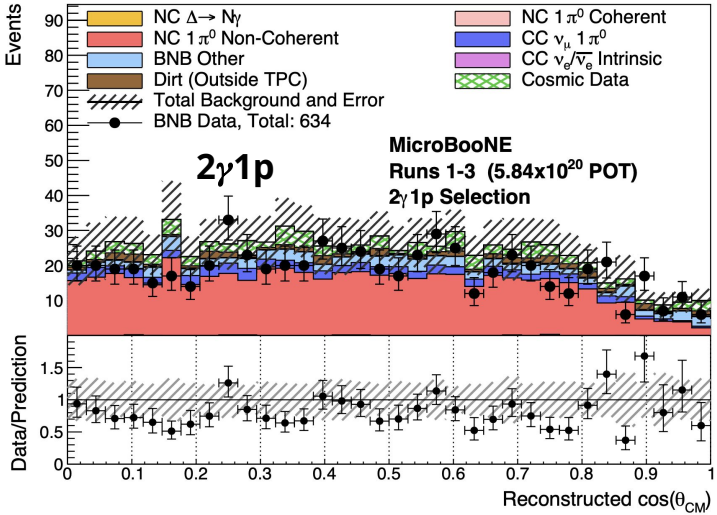


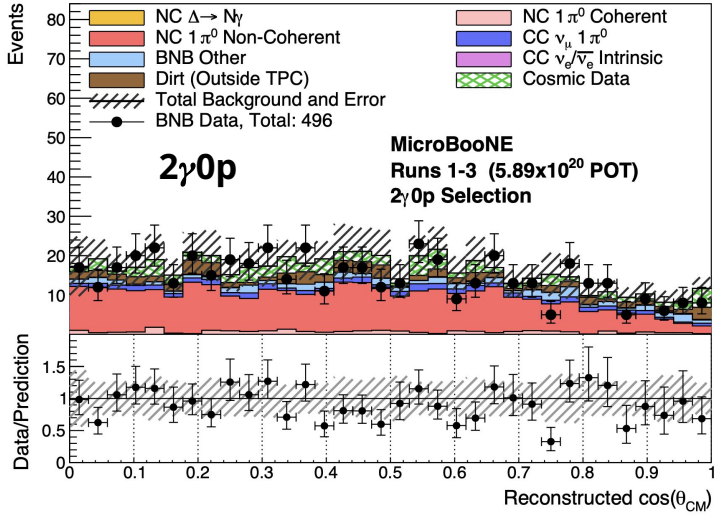
Forward NC coherent $1\pi^0$

Final Selection - $\cos(\theta_{CM})$

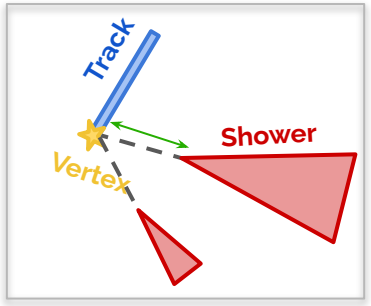


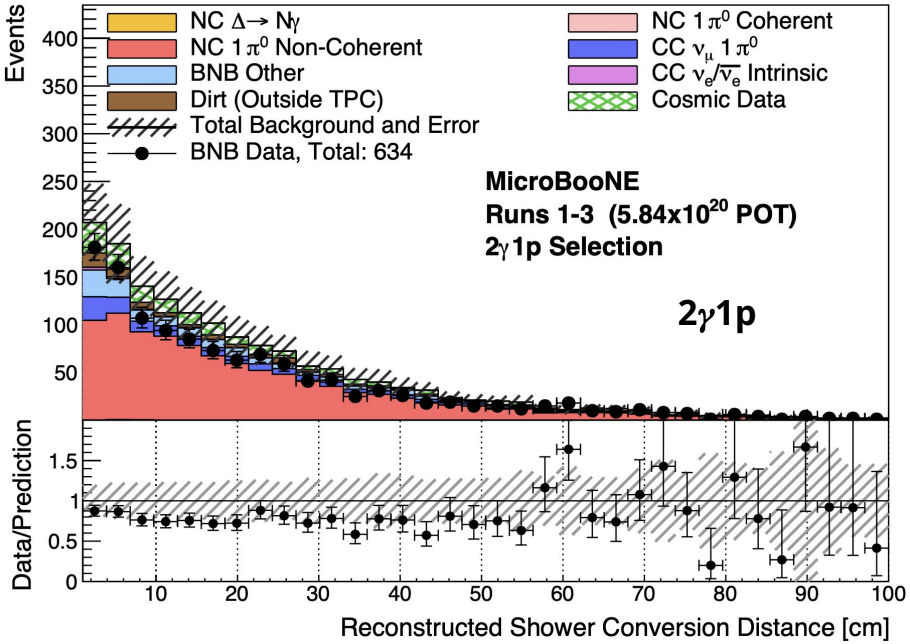
- Reconstructed cosine of center of mass decay angle
  - At truth level, flat distribution over $\cos(\theta_{CM})$
  - Events with largely asymmetric π^0 decay are reconstructed with lower efficiency
- Good data-MC agreement across the board within uncertainties





Final Selection - γ conversion distance





- Conversion distance for reconstructed showers in $2\gamma 1p$ selected sample
- Expected exponential shape

Background Breakdown

Dominant ν-induced background for both selection include CC-ν_μ and BNB Other

For 2γ1p sample, MC predicts **~10%** of selected events are BNB Other Background, and **9%** for CC ν_μ $1\pi^0$ background

Fraction [%]	**BNB Other Background Breakdown**
25	multiple π^0 exiting but only 1 reconstructed
25	no π^0 exiting but a π^0 subsequently created
20	NC $\eta \rightarrow \gamma\gamma$ decay event
25	no π^0 exiting, cosmic contamination resulting in a 2γ event; a NC proton is reconstructed as the track
5	Other

True photons

For 2γ1p **CC ν_μ $1\pi^0$ background**, 97.3% of background events have at least 1 shower matched to π^0 and 78% of tracks are correctly matched to a proton.

→ The background entering the final selection has very high photon/proton purity

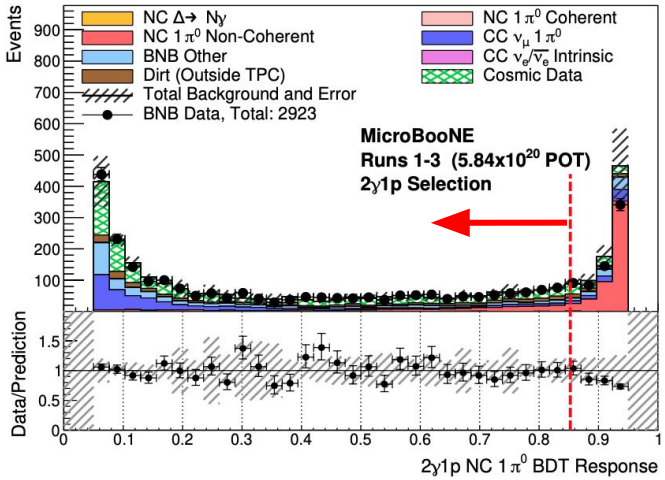
→ **Selection indeed selects true photons and protons.**

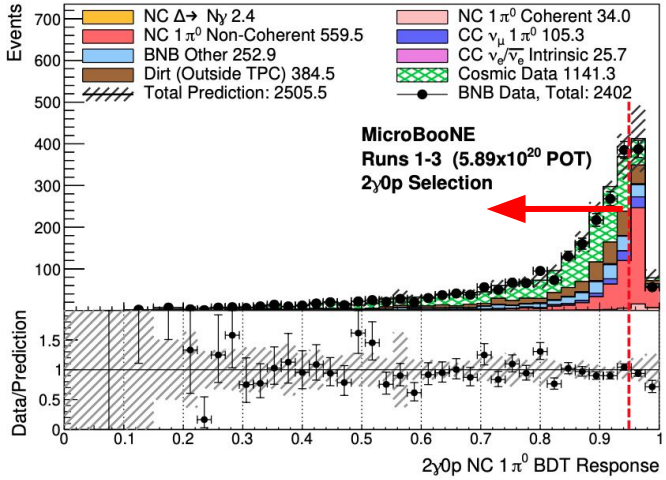
Background Validation

Our goal is to extract data-driven cross section for NC $1\pi^0$ production on argon, however prior to cross section calculation, it's important to make sure backgrounds are well-modeled.

For each sample, to get background-rich sample:

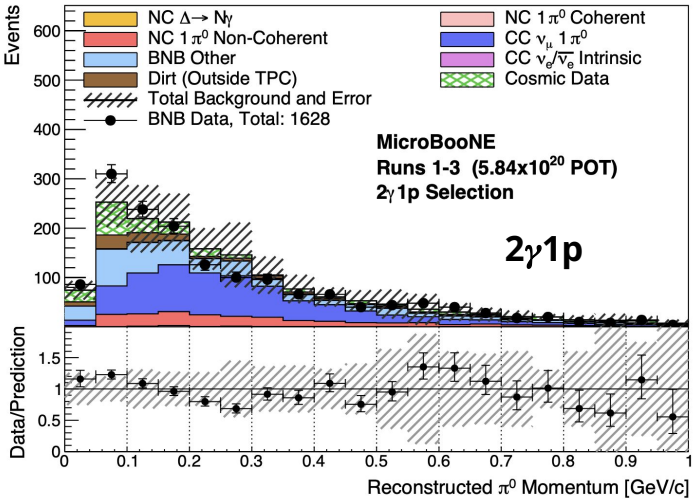
- Revert BDT cut
- Apply additional cosmic cut

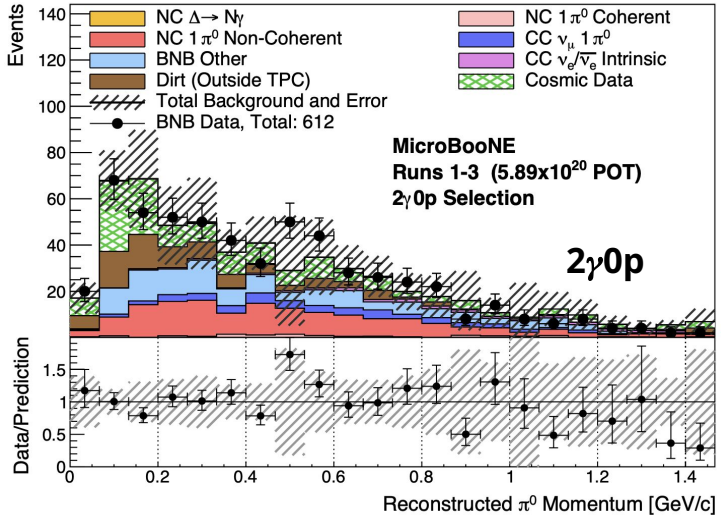




Background Validation

- Good agreement between data and MC prediction, within systematic uncertainties
  - χ^2/ndof of 24.61/20 and 17.49/22 for 2γ1p and 2γ0p respectively
- High purity of background events in **2γ1p** background sample
- **Higher portion of** NC $1\pi^0$ signal events in **2γ0p** background sample due to difficulty in isolating signal events with only shower information





NC $1\pi^0$ Cross Section

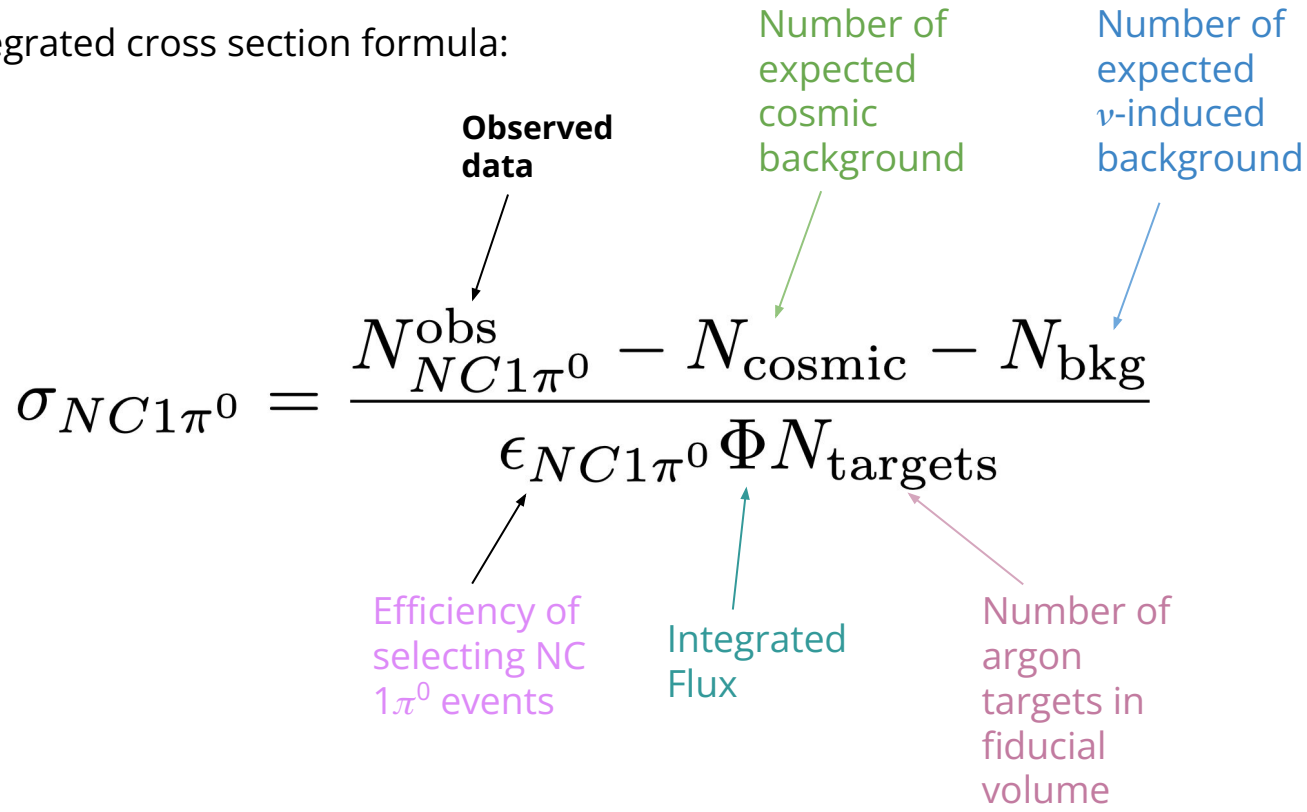
Having built confidence in backgrounds, we can now move on to cross section extraction!

Strategy as follows:

- Flux-averaged total **one-bin** cross section
- **Exclusive** cross sections of **NC $1\pi^0$+1p** and **NC $1\pi^0$+0p**
  - Each makes use of the exclusive 2γ1p and 2γ0p sample
- **Semi-inclusive** cross section extraction for **NC $1\pi^0$+ Xp**
  - Enable direct comparison to MiniBooNE's NC $1\pi^0$ result
  - Combine the 2γ1p and 2γ0p samples, and correct for 2+p final states

NC $1\pi^0$ Cross Section

Total flux-integrated cross section formula:



NC $1\pi^0$ Cross Section

Total flux-integrated cross section formula:

$$\sigma_{NC1\pi^0} = \frac{N^{\text{obs}}_{NC1\pi^0} - N_{\text{cosmic}} - N_{\text{bkg}}}{\epsilon_{NC1\pi^0} \Phi N_{\text{targets}}}$$

$$\epsilon = \frac{\text{Number of selected NC } 1\pi^0 \text{ events}}{\text{Total number of "signal" events before selection}}$$

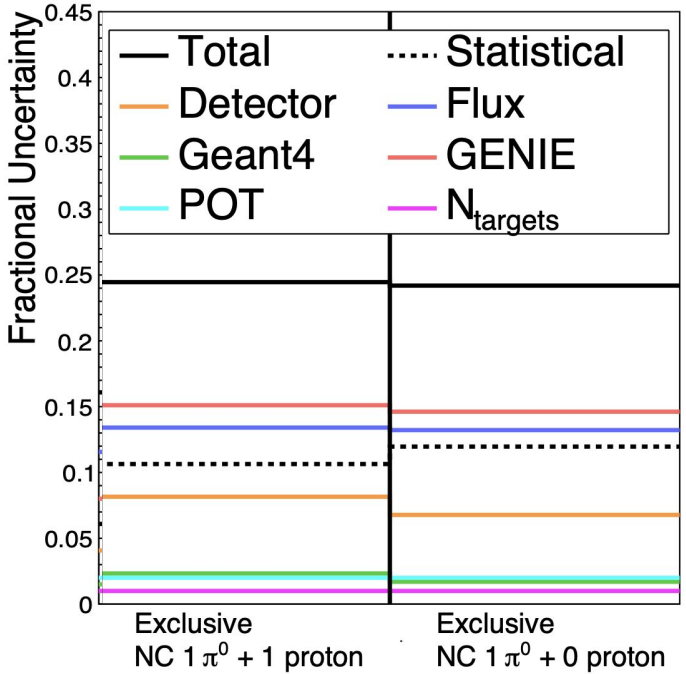
For different cross section cases, as the signal definition changes, the numerator in $\sigma_{NC1\pi^0}$ and efficiency ϵ would also vary

Systematic Uncertainty

Dominant systematic uncertainties are flux, GENIE

- Measurements are not statistically limited

The dominant contributions to the GENIE uncertainties are from the modeling of FSI and the axial and vector mass parameters governing CC resonant pion production.

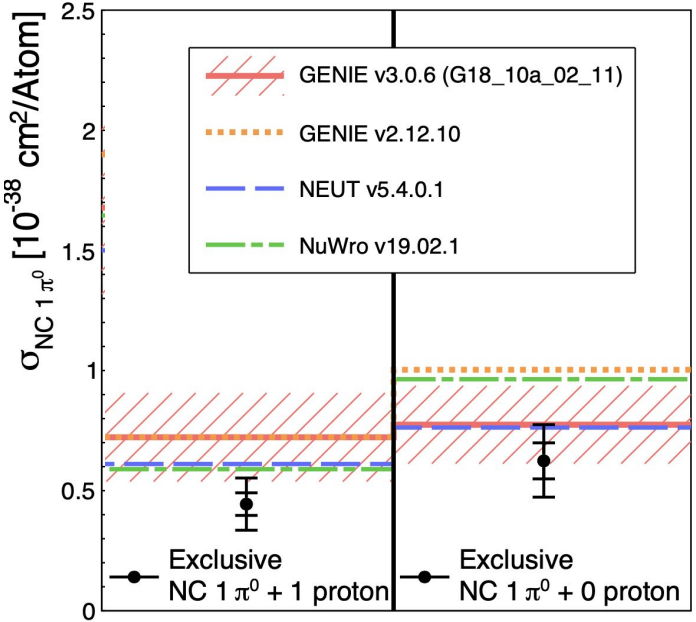


Cross Section Comparison - Exclusive Channels

$\sigma_{NC\ 1\pi+1p}$ = 0.444 ± 0.098 (syst) ± 0.047 (stat) [10^{-38} cm^2/Ar]
$\sigma_{NC\ 1\pi+0p}$ = 0.624 ± 0.131 (syst) ± 0.075 (stat) [10^{-38} cm^2/Ar]

- GENIE overpredicts the cross section for both exclusive channels
  - Consistent with what's seen in data-MC comparisons
- NEUT prediction most closely matches result from data
- χ^2 for NC $1\pi^0$+1p & NC $1\pi^0$+0p simultaneously (2 dof)

	GENIE v3	GENIE v2	NEUT	NuWro
χ^2	7.6	7.7	2.4	5.1



Semi-inclusive Cross-section

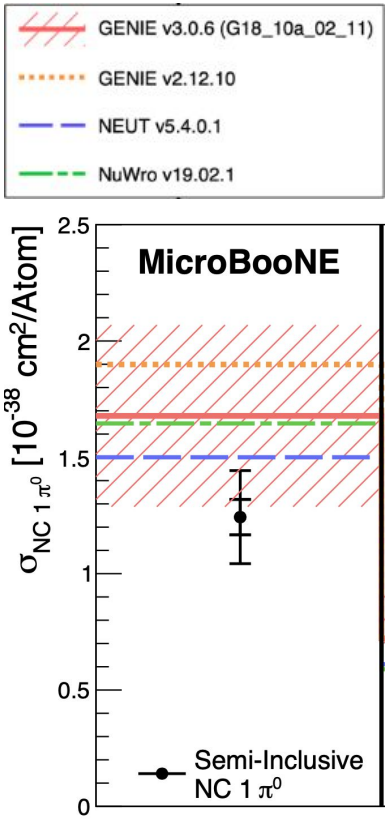
Semi-inclusive NC $1\pi^0$ +Xp cross section

- Combining 2γ1p and 2γ0p selected sample
- Efficiency corrected to take into account 2+ proton final states (11% of total number of NC $1\pi^0$ interaction per GENIE)

$\sigma_{\text{NC } 1\pi \text{ semi-inclusive}}$ = 1.243 ± 0.185 (syst) ± 0.076 (stat) [10^{-38} cm^2/Ar]

Similar trend is seen in semi-inclusive NC $1\pi^0$ cross section

- GENIE prediction: 1.68 [10^{-38} cm^2/Ar]

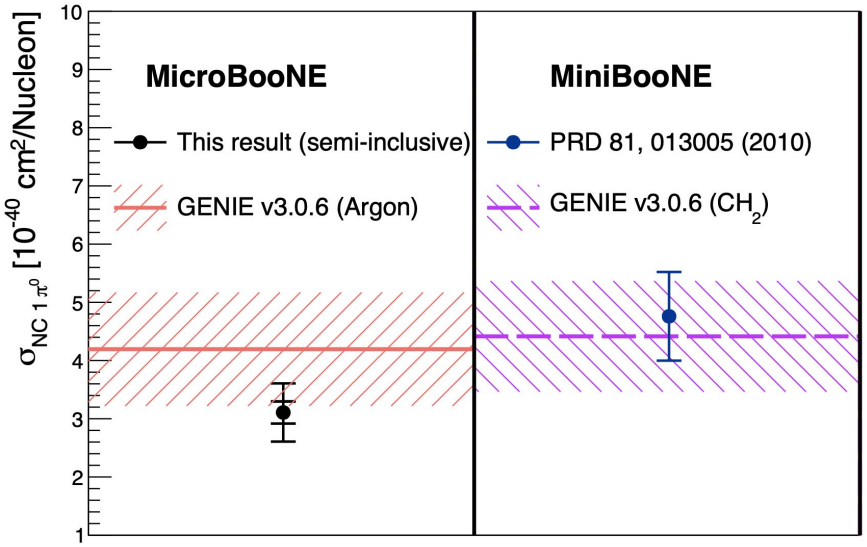


Semi-inclusive Cross-section Comparison w/ MiniBooNE

MiniBooNE: $1\pi^0$ + X nucleons + 0 charged leptons/mesons

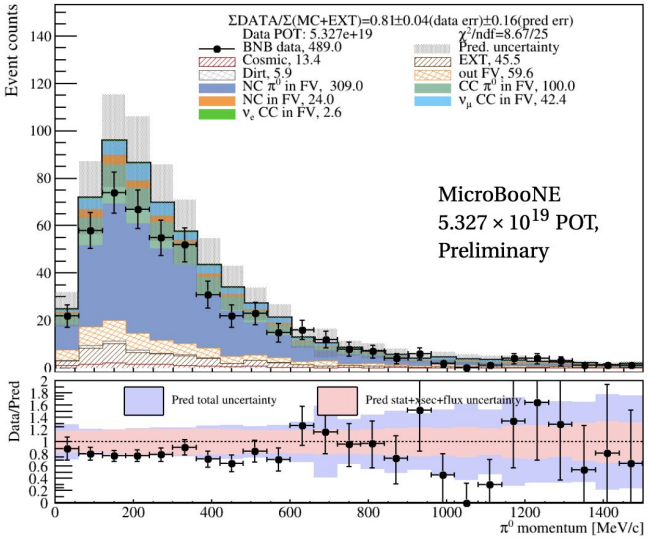
- Same neutrino beam
- Different detector target: CH_2
- **NUANCE** event generator used for simulation

Both MicroBooNE and MiniBooNE results agree with GENIE v3.0.6 within uncertainties.

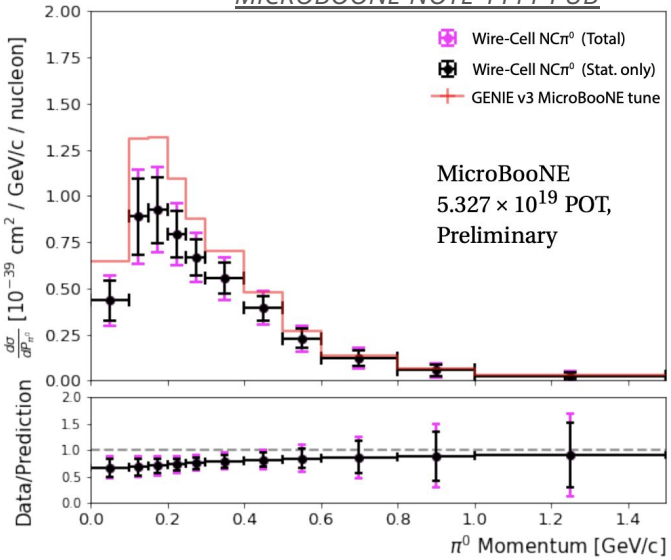


Looking Forward

- Ongoing efforts in 1D differential cross section extraction using the same samples
- Inclusive NC $1\pi^0$ cross section result utilizing Wire-Cell reconstruction with Run 1-3 data coming soon!



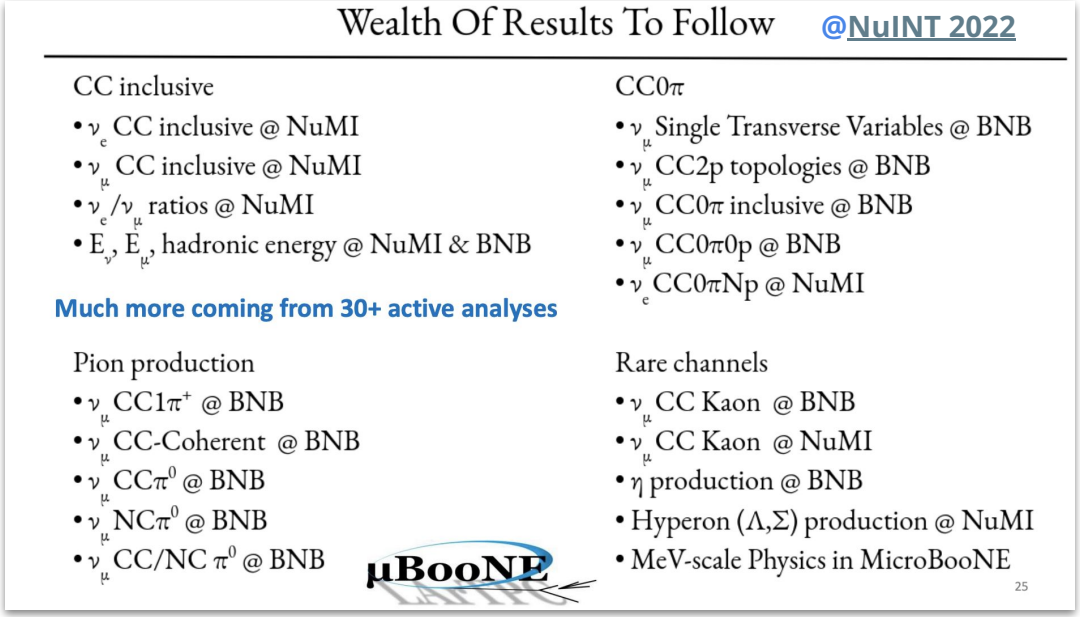
MICROBOONE-NOTE-1111-PUB



- MicroBooNE Runs 4 and 5 data will be ready soon, even higher statistics

Looking Forward

Having demonstrated its ability for cross section extraction, MicroBooNE has become a leader in the field, with plethora of cross section measurements on lots of different processes. And there is much more to come!

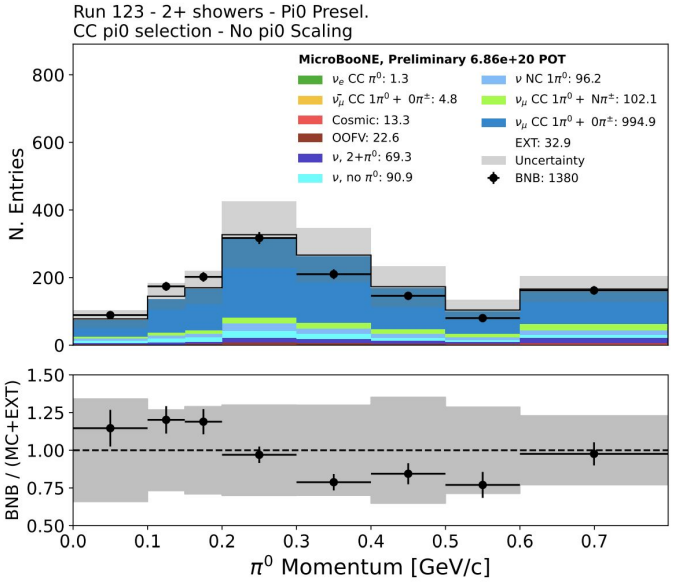


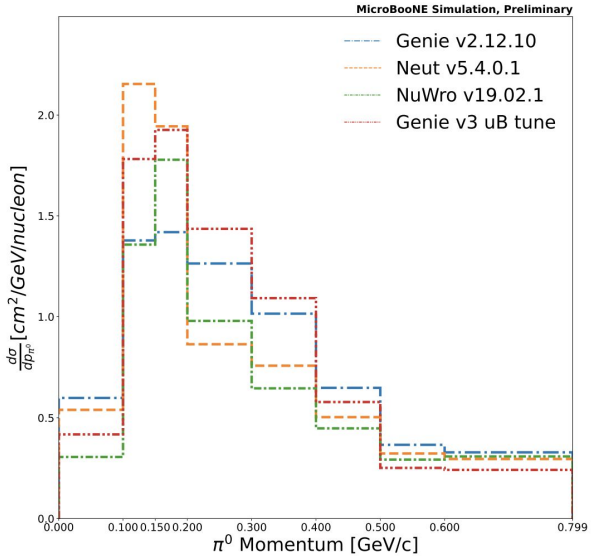
Slide courtesy of of Xin Qian

Looking Forward

Having demonstrated its ability for cross section extraction, MicroBooNE has become a leader in the field, with plethora of cross section measurements on lots of different processes. And there is much more to come!

CC $1\pi^0$ 1D differential cross section extraction *MICROBOONE-NOTE-1107-PUB*

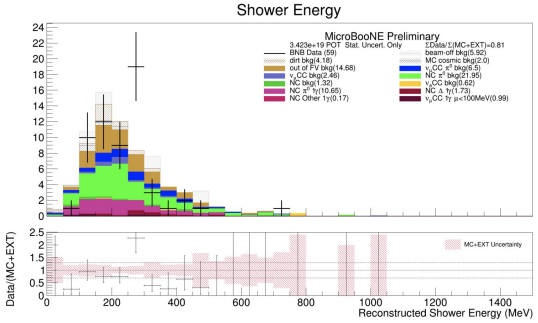




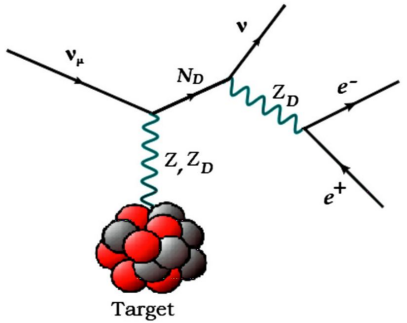
Looking Forward

MicroBooNE's ongoing and planned efforts in continued LEE searches, focusing on single-photon and BSM e^+e^- signatures

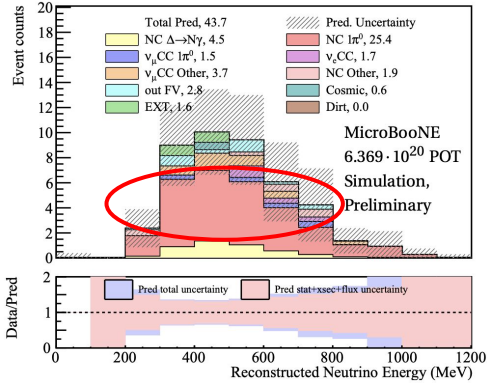
MicroBooNE, inclusive single photon
MICROBOONE-NOTE-1103-PUB



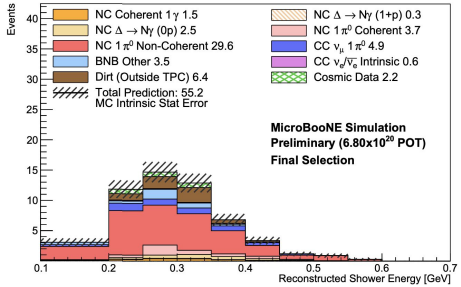
Phys. Rev. Lett. ***121***, *241801 (2018)*



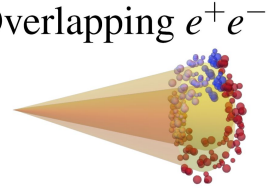
MicroBooNE, Wire-Cell NC Δ
MICROBOONE-NOTE-1104-PUB



MicroBooNE, coherent single photon
MICROBOONE-NOTE-1102-PUB



Overlapping e^+e^- can mimic MiniBooNE electron-like signals



Summary

- We report the highest statistics measurement to date of NC $1\pi^0$ production on argon, using MicroBooNE's data collected during first 3 run periods with Fermilab BNB neutrino beam of $\langle E_\nu \rangle$ =0 .8GeV
  - Two exclusive samples of 1130 total observed NC π^0 events
  - Extract both exclusive and semi-inclusive cross sections for NC π^0+1p, NC π^0+0p and NC π^0+Xp processes
  - GENIE overpredicts the cross section compared to data
- High-statistics NC $1\pi^0$ sample continues to serve as a very important sideband to help boost performance in MicroBooNE's next-generation low energy excess and BSM searches
- Ongoing efforts to check π^0 background modelling in more detail, contributes to MicroBooNE's broader goal of rich cross section measurements for future LAr community

MicroBooNErs at Rutgers U., May 2022

Thank you!

Backup

Overall Selection Efficiency

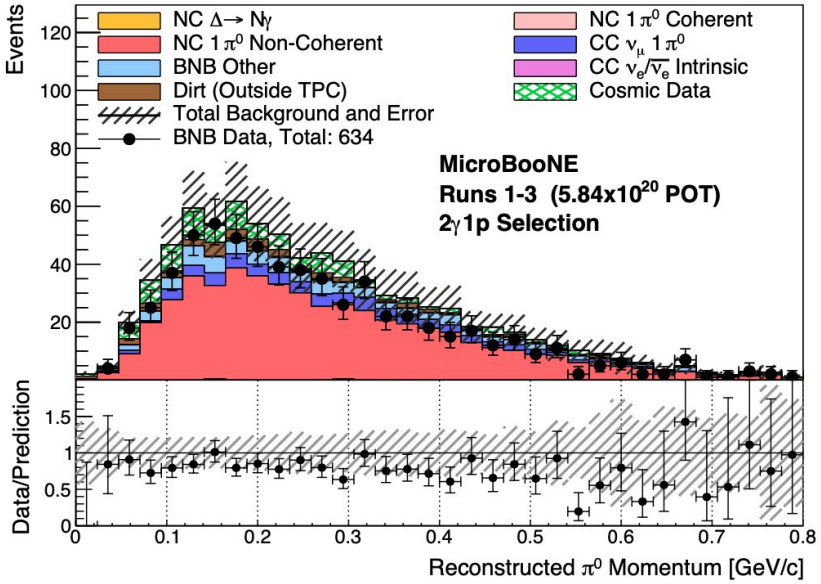
Selection efficiencies of different analysis stages

Selection Stage	$2\gamma 1p$ eff.
Topological	62.5%
Pre-selection	19.9%
BDT Selection	85.6%
Final Efficiencies	10.7%

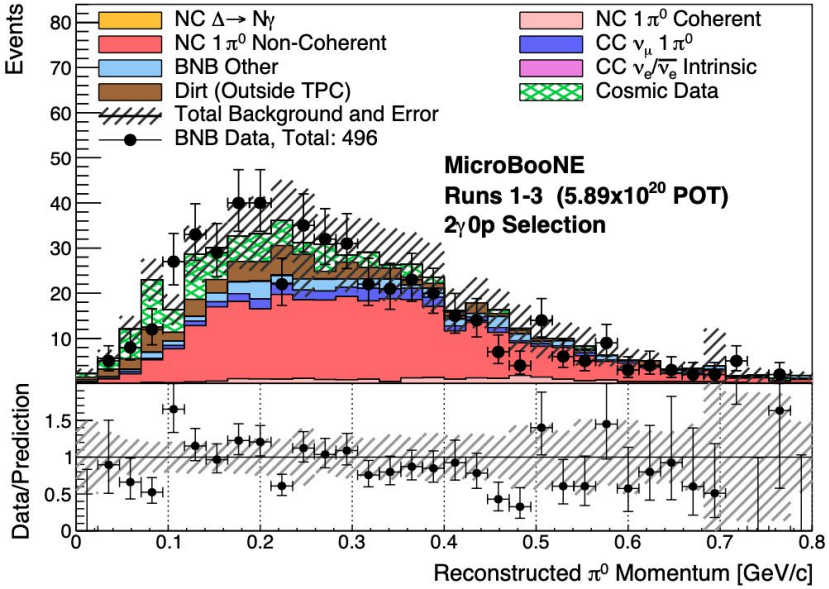
Selection Stage	$2\gamma 0p$ eff.
Topological	47.4%
Pre-selection	21.5%
BDT Selection	58.8%
Final Efficiencies	6.0%

Goodness of fit χ^2 at **final** selection

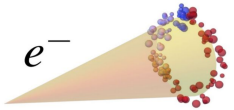
χ^2/ ndof = **19.45/34**



χ^2/ ndof = **23.50/34**



MicroBooNE LEE Search

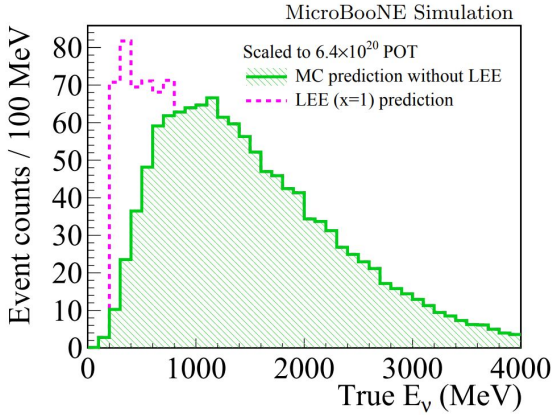


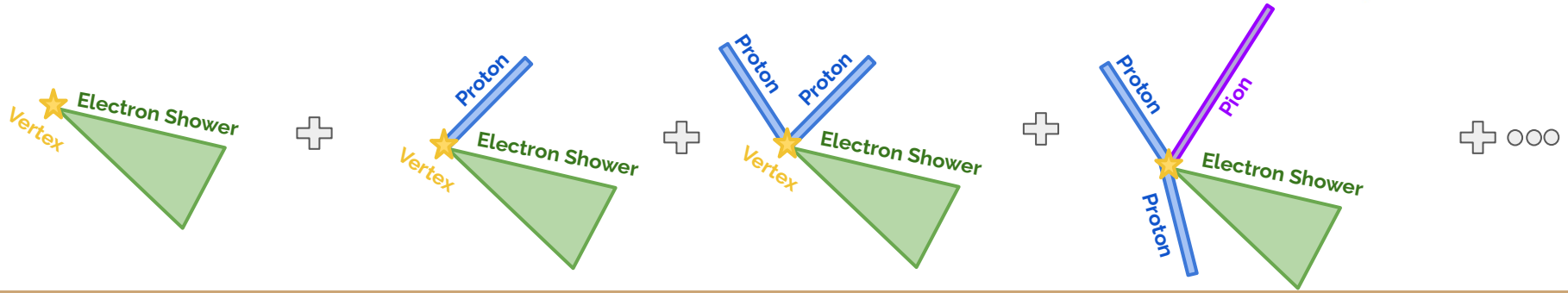
MicroBooNE developed four analyses targeting two hypotheses of MiniBooNE LEE:

- **Excess from enhanced ν_e in the beam**

Three distinct analyses with different final states and reconstruction techniques:

- Deep Learning Reconstruction: quasielastic like 1e1p
- Pandora Reconstruction: 1e0p0π, 1eNp0π
- Wire-Cell Reconstruction: 1eX





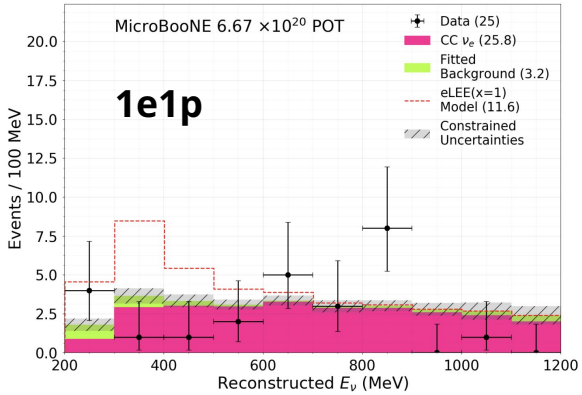
MicroBooNE LEE Search

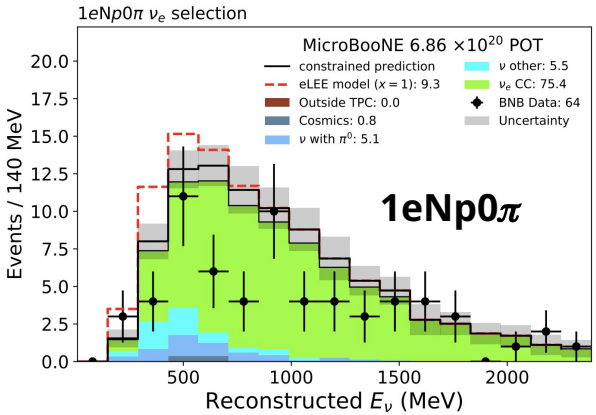
Phys. Rev. D105, 112005 (2022)
Phys. Rev. D105, 112004 (2022)
Phys. Rev. D105, 112003 (2022)
Phys. Rev. Lett. 128, 241801 (2022)

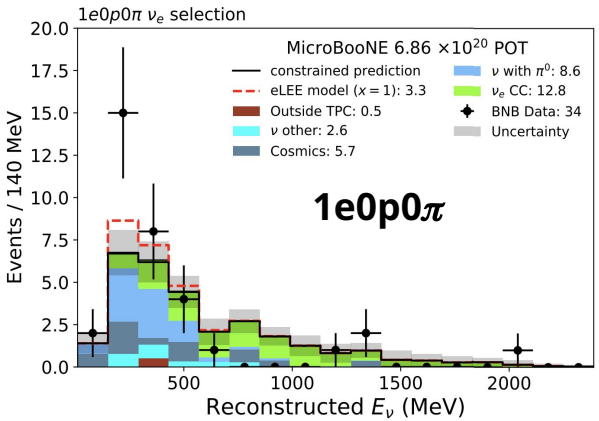
- **Excess from enhanced ν_e in the beam**

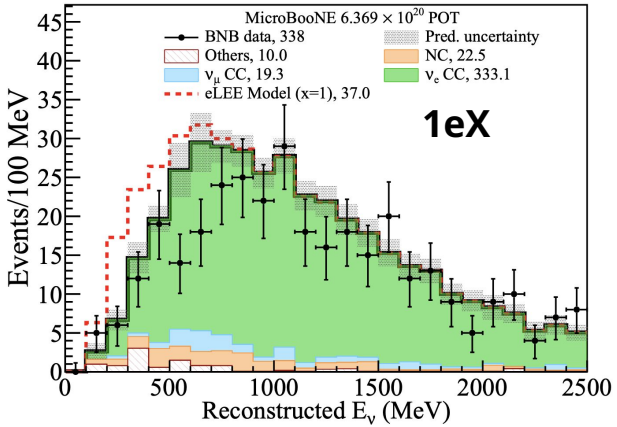
Thanks to LArTPC's capability to precisely record the energy deposition and spatial information, three analyses all show excellent background rejection and yield highly pure signal sample.

- 1e0p0π has slightly lower signal purity and higher π^0 contamination

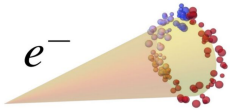






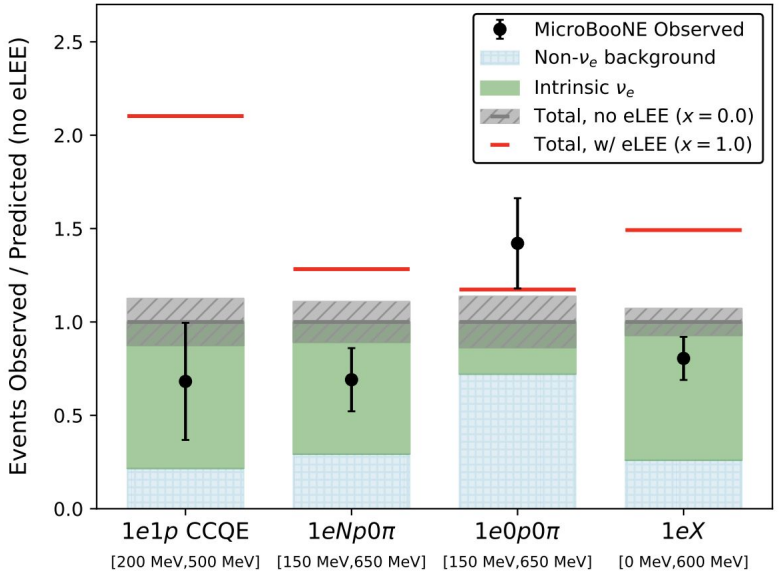


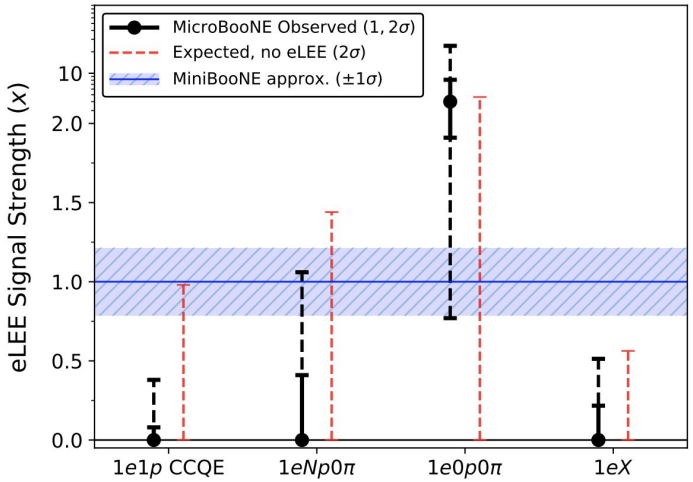
NC $1\pi^0$ measurement and LEE search



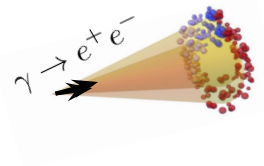
- No excess is observed in low energy ν_e events
- The hypothesis that the ν_e CC interaction is fully responsible for the MiniBooLE LEE is **disfavored.**

Phys. Rev. D105, 112005 (2022)
Phys. Rev. D105, 112004 (2022)
Phys. Rev. D105, 112003 (2022)
Phys. Rev. Lett. 128, 241801 (2022)





MicroBooNE LEE Search

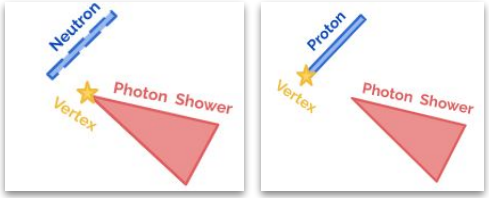


- **Excess from anomalous γ from Δ resonance production and decay**

Phys. Rev. Lett. 128, 111801 (2022)

One Pandora-reconstruction based analysis targeting NC Δ radiative decay:

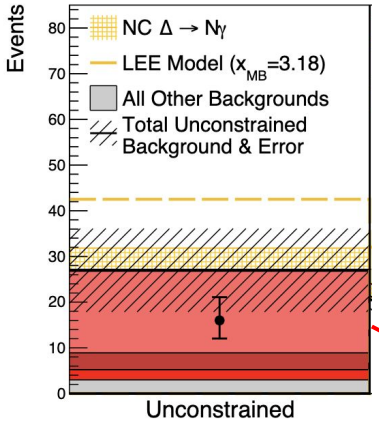
- $\Delta^0 \rightarrow n + \gamma$
- $\Delta^+ \rightarrow p + \gamma$



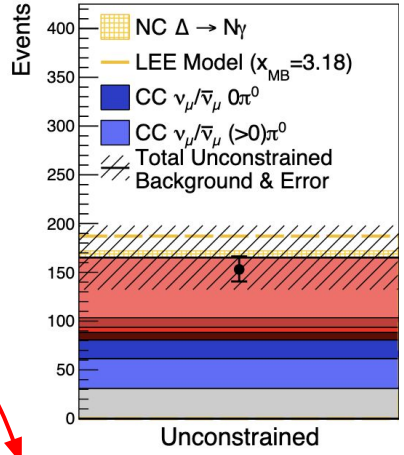
Getting rid of NC π^0 background is not so easy for photon excess search

- Given one photon, there is not way to tell if it's from π^0 decay or **Δ** decay!
- Photons from two processes can only be distinguished in a statistical way

$1\gamma 1p$

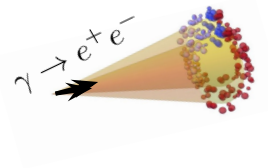


$1\gamma 0p$



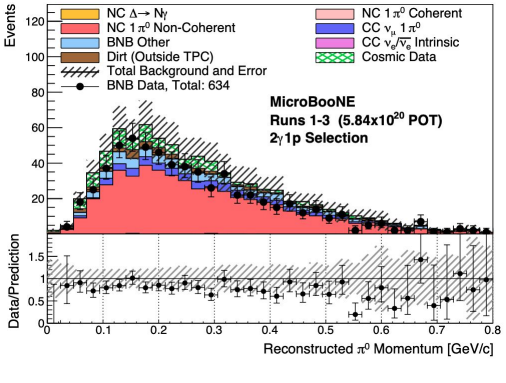
$1\gamma 1p$: 75% of the selected sample are NC π^0
$1\gamma 0p$: 44% of the selected sample are NC π^0

NC $1\pi^0$ measurement and LEE search

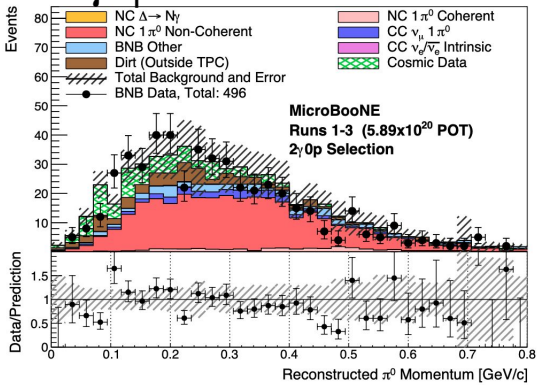


- Strong correlation between selected NC $1\pi^0$ sample and 1γ1p and 1γ0p samples.
  - major contribution for NC $1\pi^0$ at O(1) GeV neutrino beam is from **Δ** resonance production and **Δ** decay
  - ➕ relative large cross section uncertainty for NC $1\pi^0$
  - ➕ 2γ1p selection observes a mild deficit in data

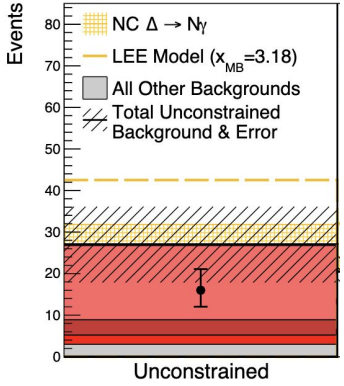
2γ1p



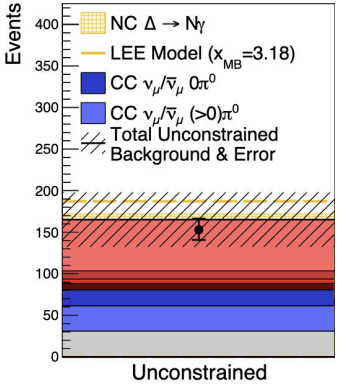
2γ0p



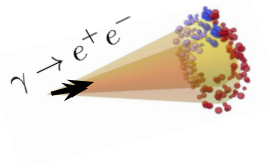
1γ1p



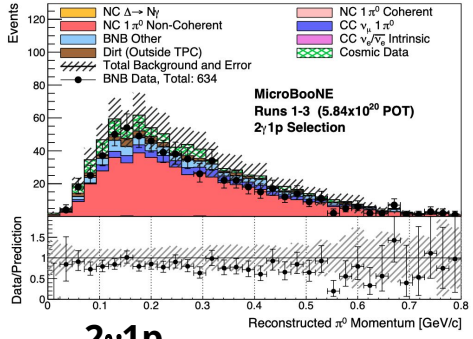
1γ0p



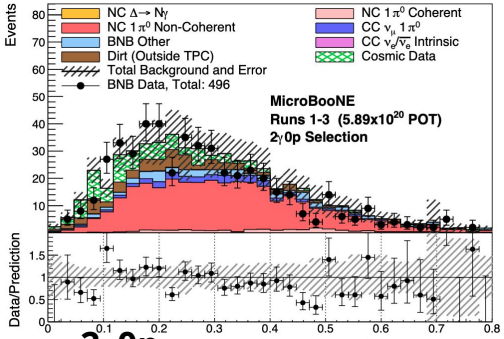
NC $1\pi^0$ measurement and LEE search



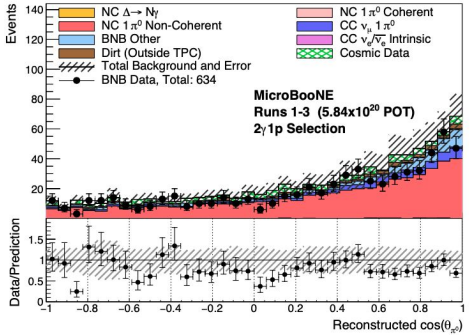
To use 2γ1p and 2γ0p as a constraining sample, rate validation has been done to make sure no scaling and modifications needed for π^0 modeling.

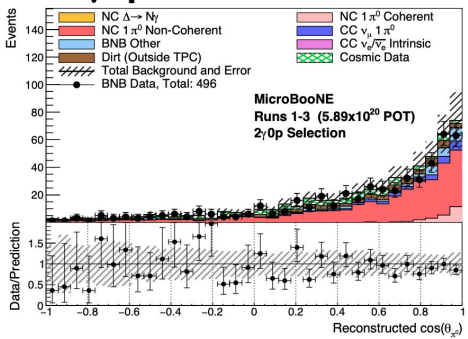


2γ1p



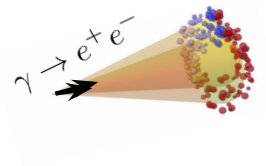
2γ0p





- Motivation:
  - Downhill slope in data/MC ratio as reconstructed π^0 momentum increases in 2γ1p selection
  - Higher fraction of NC coherent π^0 component in 2γ0p selection
- Rate fit with
  - N_{coh}: a flat scaling for coherent NC π^0
  - a + b * $p_{\pi 0}$: linear momentum-dependent scaling for non-coherent NC π^0

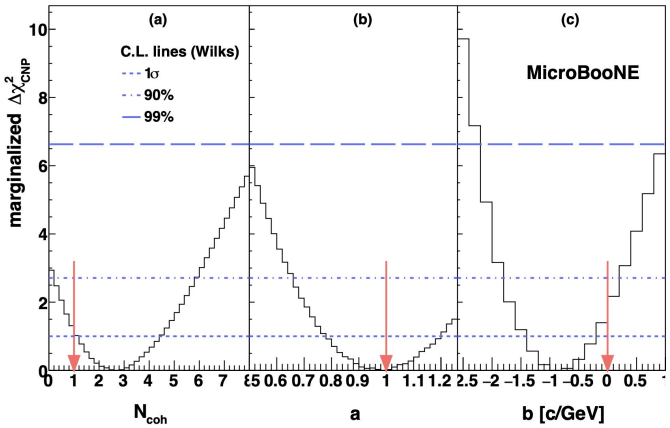
NC $1\pi^0$ measurement and LEE search

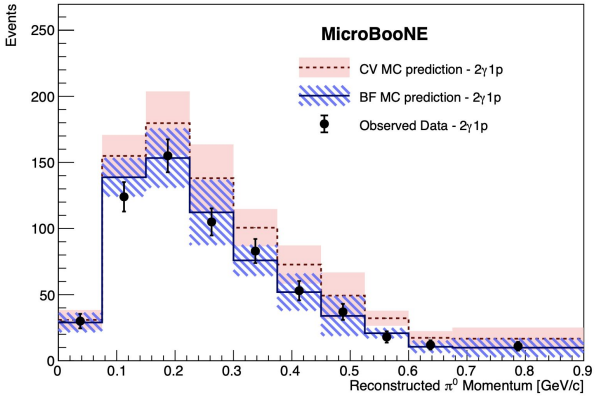


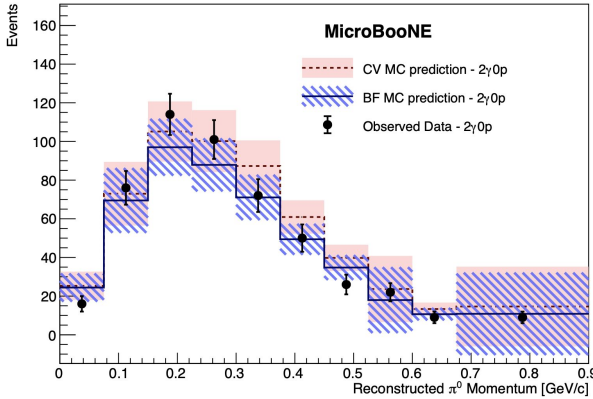
To use $2\gamma 1p$ and $2\gamma 0p$ as a constraining sample, rate validation has been done to make sure no scaling and modifications need to be done for π^0 predictions.

- Better data-MC agreement after fit
- Genie CV prediction still agrees with data within uncertainty

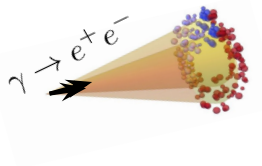
→ $2\gamma 1p$ and $2\gamma 0p$ can be used as constraining samples without any modification





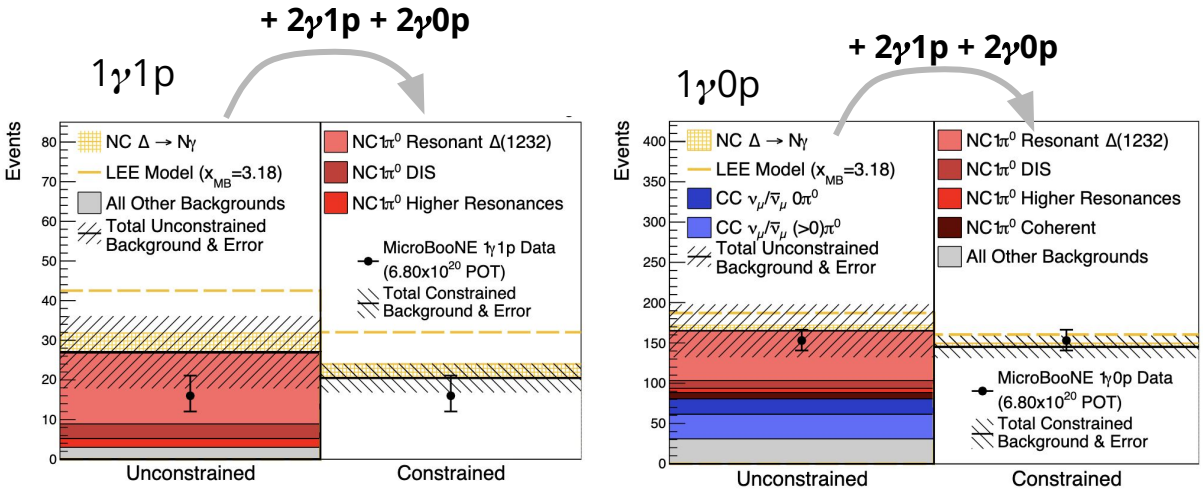


NC $1\pi^0$ measurement and LEE search



The effect of 2γ1p and 2γ0p sample constraint

- Modify the prediction of NC $1\pi^0$ background in 1γ selections (background drop by **24.1%** in 1γ1p)
- Reduce the size of systematic uncertainties in 1γ selections (overall uncertainty drop from **29.8% to 17.8%**)

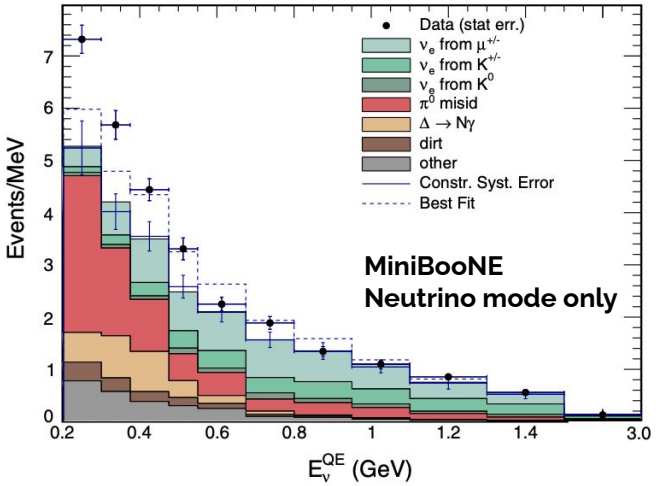


LEE hypothesis is disfavored at 94.8% confidence level

MiniBooNE NC π^0 correction

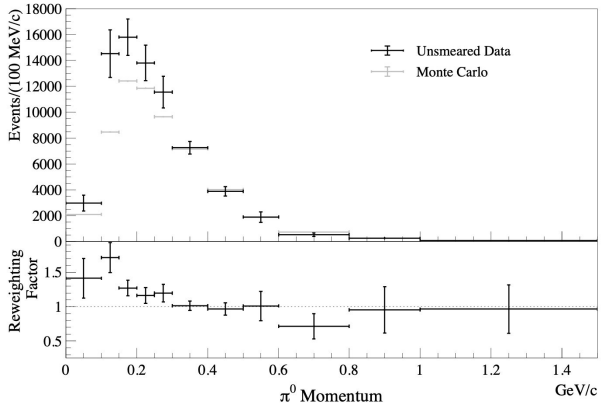
Measurement on electron-like events

Phys. Rev. D 103, 052002 (2021)

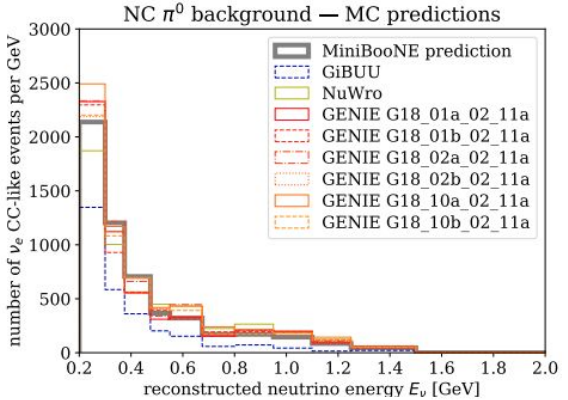


Combining the neutrino and antineutrino data, the overall significance of the MiniBooNE excess is **4.8**

- MiniBooNE has corrected the Monte Carlo prediction for π^0 through in-situ measurement
- NC π^0 is a very important background for ν_e appearance measurement - good understanding and precise modeling of this process is essential



Phys.Lett.B 664 (2008) 41-46



*Phys. Rev. D **105**, 115024 (2022)*

NC $1\pi^0$ Cross Section

Two exclusive selections allow us to extract both exclusive and inclusive cross sections:

	Exclusive Cross section		Inclusive Cross Section
Signal Definition	NC $1\pi^0$ + 1 proton*	NC $1\pi^0$ + 0 proton	NC $1\pi^0$ + X protons
Sample	**2γ1p**	**2γ0p**	**2γ1p** and **2γ0p** combined**

* Proton counts is defined as number of protons with KE > 50MeV
** 2γ0p sample (of higher POT) is scaled down by $POT_{2\gamma1p}$ / $POT_{2\gamma0p}$ before added to the 2γ1p sample

NC $1\pi^0$ Cross Section

Inputs to all variables: [value + σ_{syst} + σ_{stats}]

$$\sigma_{NC1\pi^0} = \frac{N^{\text{obs}}_{NC1\pi^0} - N_{\text{cosmic}} - N_{\text{bkg}}}{\epsilon_{NC1\pi^0} \Phi N_{\text{targets}}}$$

	NCπ^0 (semi-inclusive)	**NC$\pi^0 + 1p$ (exclusive)**	**NC$\pi^0 + 0p$ (exclusive)**
Samples Used	$2\gamma(0+1)p$ Selection	$2\gamma 1p$ Selection	$2\gamma 0p$ Selection
N_{targets} [10^{30} Ar atoms]	$1.187 \pm 0.119 \pm 0.00$		
Flux [10^{-10} ν/POT/cm^2]	$7.876 \pm 0.902 \pm 0.00$		
POT of sample [10^{20} POT]	$5.84 \pm 0.12 \pm 0.00$	$5.84 \pm 0.12 \pm 0.0$	$5.89 \pm 0.12 \pm 0.00$
Efficiency	$0.089 \pm 0.003 \pm 0.001$	$0.107 \pm 0.006 \pm 0.002$	$0.060 \pm 0.003 \pm 0.001$
Selected data [evts]	$1125.9 \pm 0.0 \pm 33.5$	$634.0 \pm 0.0 \pm 25.2$	$496.0 \pm 0.0 \pm 22.3$
Cosmic data [evts]	$177.0 \pm 0.0 \pm 8.9$	$96.1 \pm 0.0 \pm 6.5$	$81.5 \pm 0.0 \pm 6.1$
Background [evts]	$345.8 \pm 51.1 \pm 9.0$	$279.6 \pm 43.5 \pm 7.2$	$208.3 \pm 33.5 \pm 7.0$
Background-subtracted rate [evts]	$603.2 \pm 51.1 \pm 35.8$	$258.3 \pm 43.5 \pm 27.0$	$206.1 \pm 33.5 \pm 24.1$
$\sigma_{NC1\pi^0}$ [10^{-38}cm^2/Ar]	$1.243 \pm 0.185 \pm 0.076$	$0.444 \pm 0.098 \pm 0.047$	$0.624 \pm 0.131 \pm 0.075$

Comparison of different generators

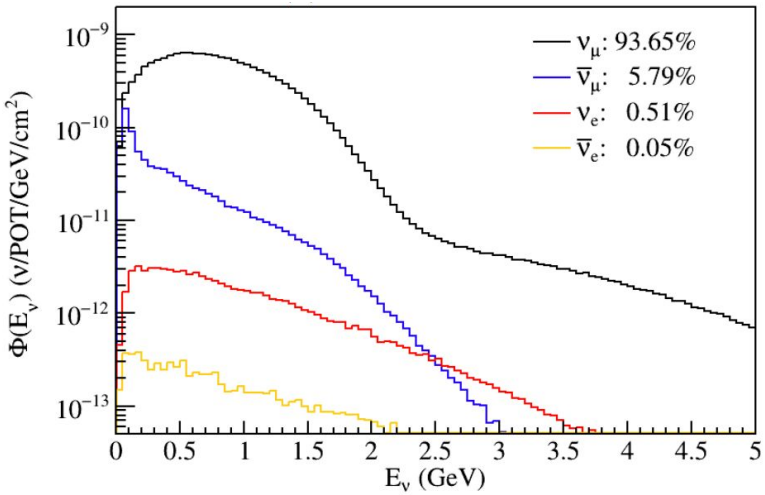
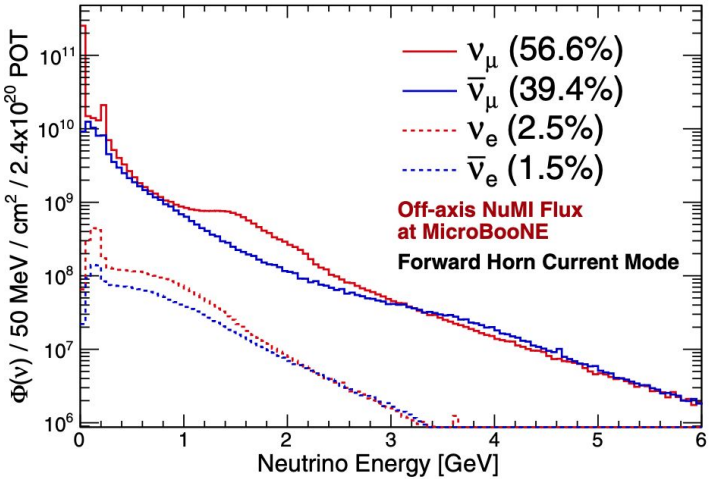
Phys. Rev. D ***105***, *092004 (2022)*

TABLE II. Models for pion production in the $\Delta(1232)$ resonance region. R-S refers to Rein-Sehgal [34], B-Y to Bodek-Yang [37], B-S to Berger-Sehgal [36], and S-O to Salcedo-Oset [38].

Generator	Resonance model	M_A^{RES} (GeV)	Nonresonant model	Form factor	π FSI model
GENIE v3 G18_02a	B-S	1.23	Scaled B-Y [39]	Ref. [40]	Empirical [15]
GENIE v3 G18_10a	B-S	1.23	Scaled B-Y	Ref. [40]	Empirical [15]
GENIE v3 G18_10b	B-S	1.23	Scaled B-Y	Ref. [40]	S-O
NuWro 19.02	Δ-only [40]	0.94	Scaled B-Y	Ref. [40]	S-O
NEUT v5.4.0.1	B-S	0.95	Scaled B-Y	Ref. [40]	S-O

BNB and NUMI beam

arXiv:2110.13978



PHYS. REV. D 104, 052002 (2021)