Recent MicroBooNE cross-section results: inclusive channels and pion production

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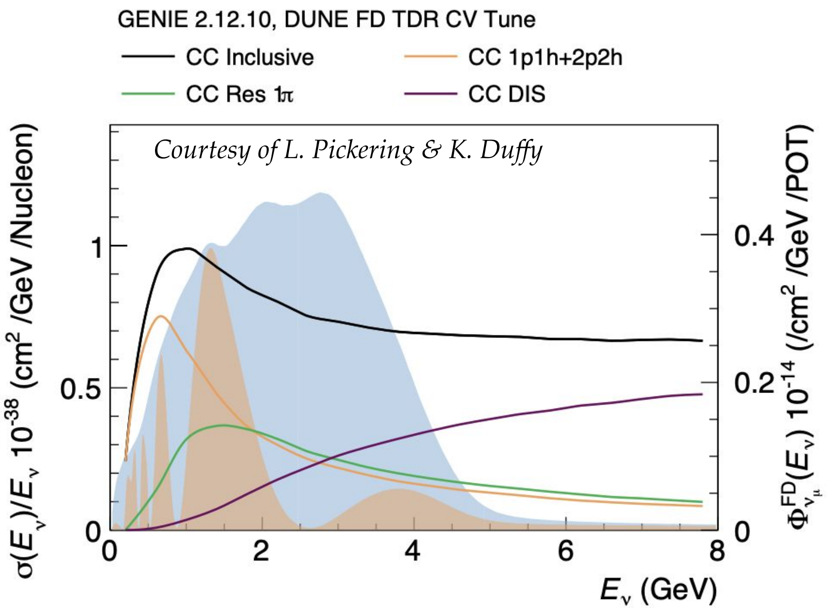
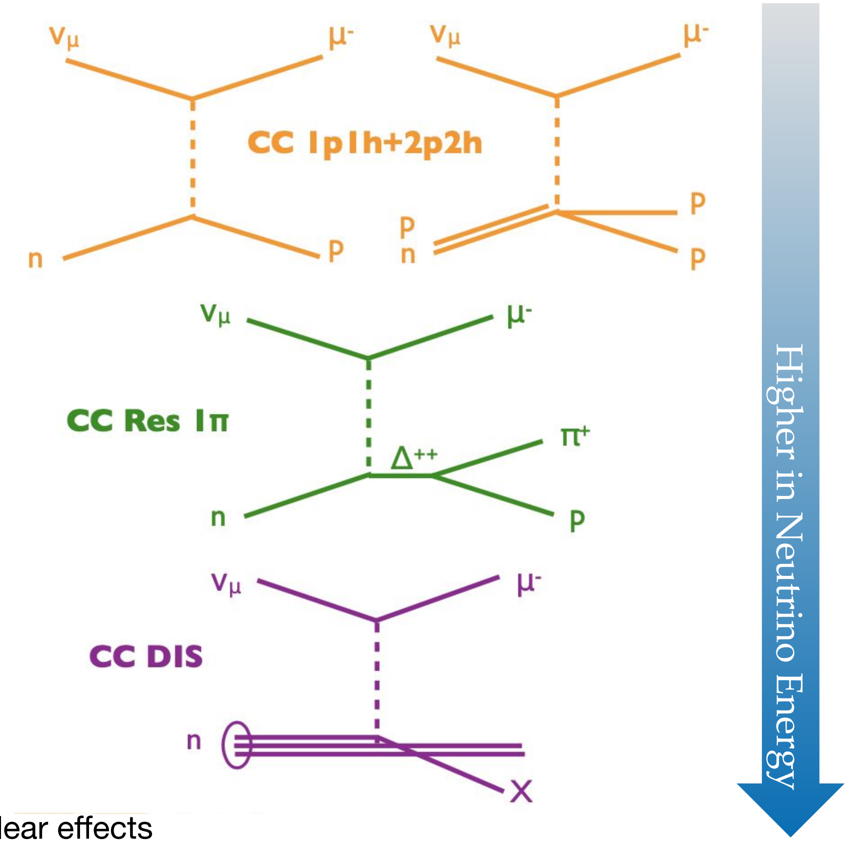
Lederman Fellow, Fermilab

August 5th, 2022, NuFact

Why inclusive?





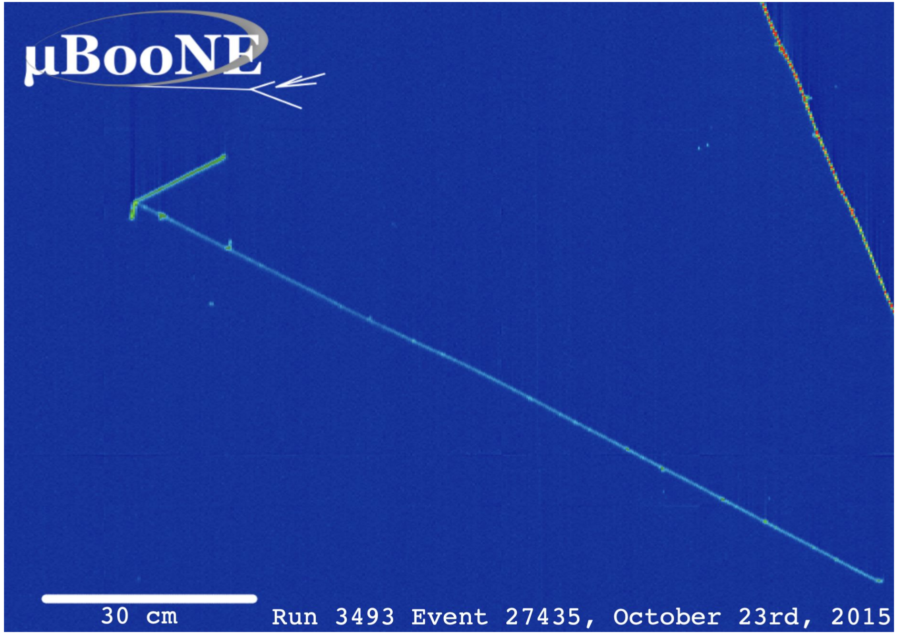
CC neutrino-nucleus interaction is the major channel for oscillation experiments

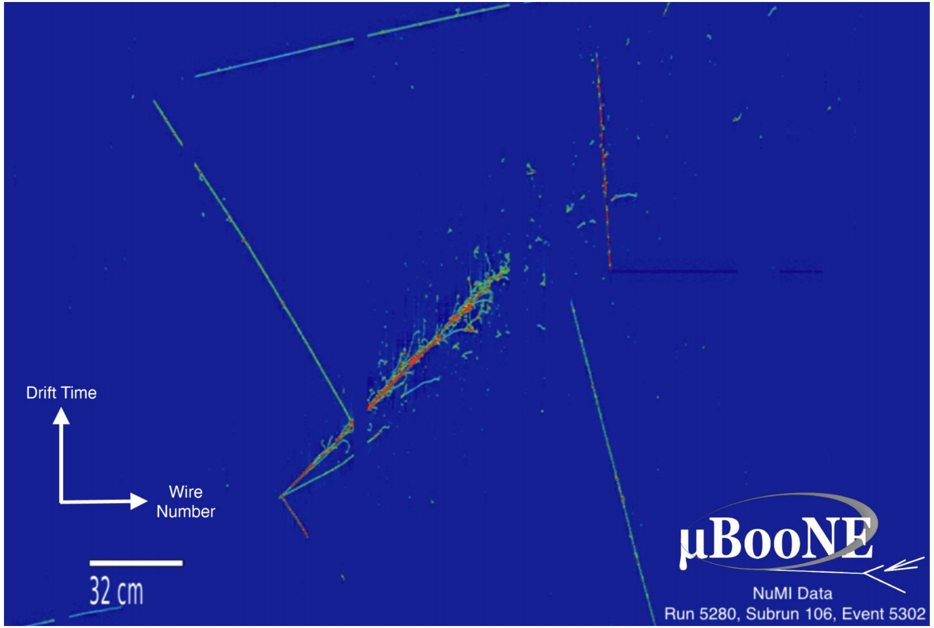
→ broad energy beams span a number of underlying fundamental interactions “muddled” by nuclear effects

Fermilab

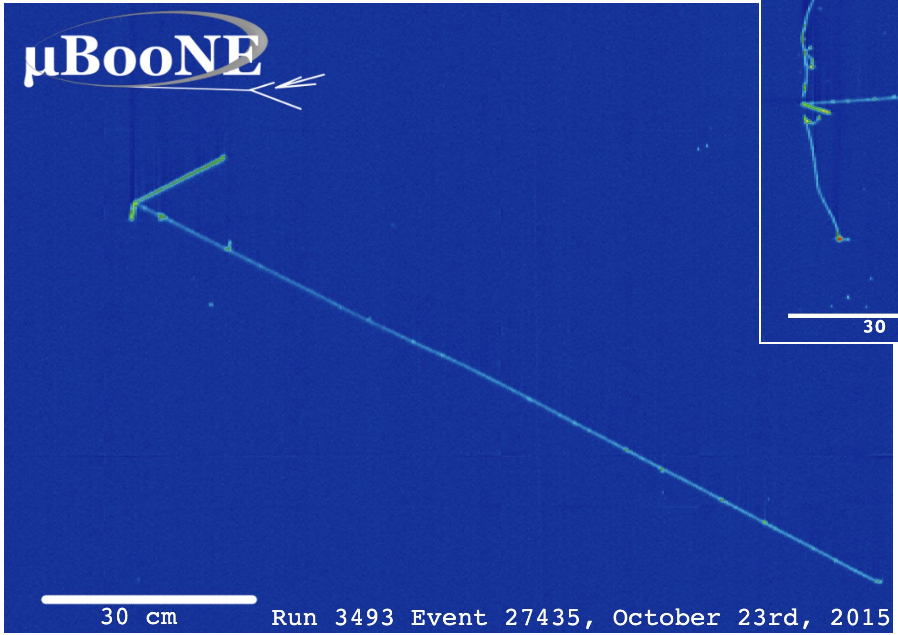
ν_μ CC Inclusive @ BNB

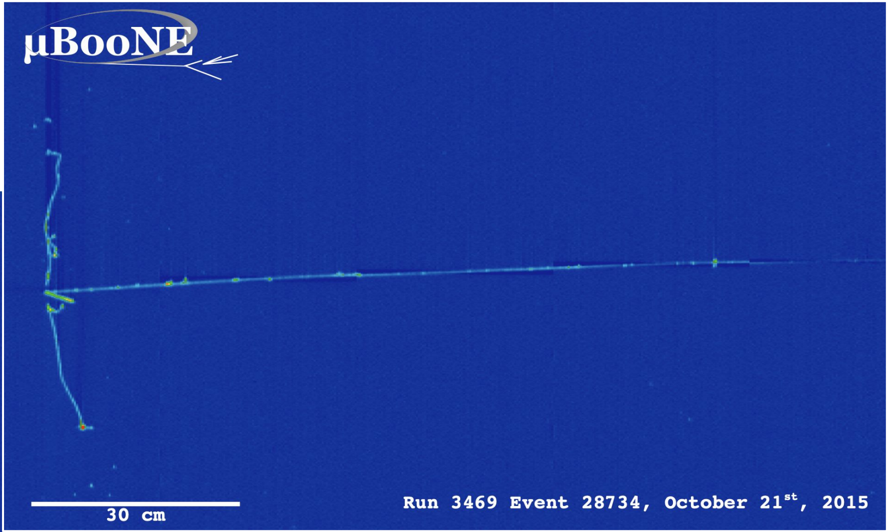
ν_e CC Inclusive @ NuMI

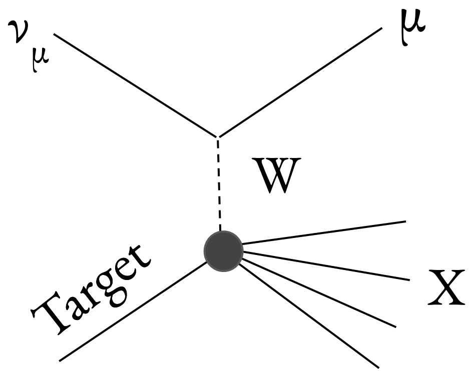




ν_μ CC Inclusive @ BNB





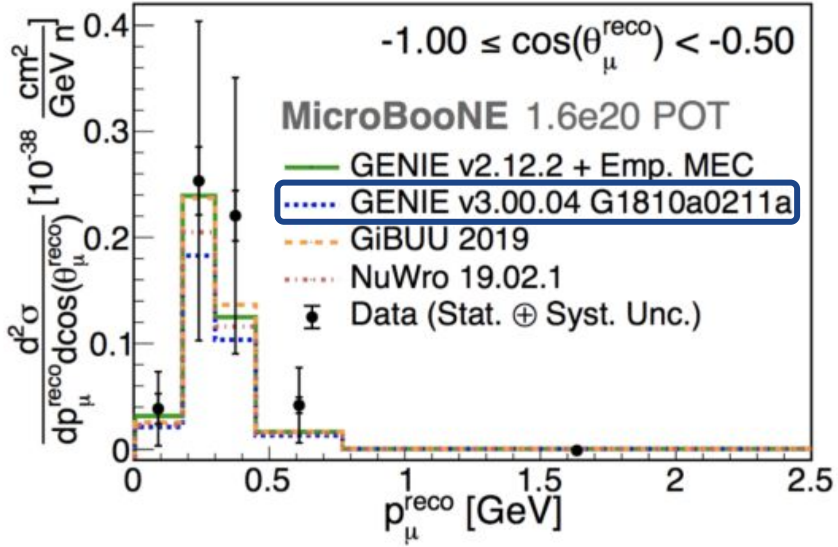


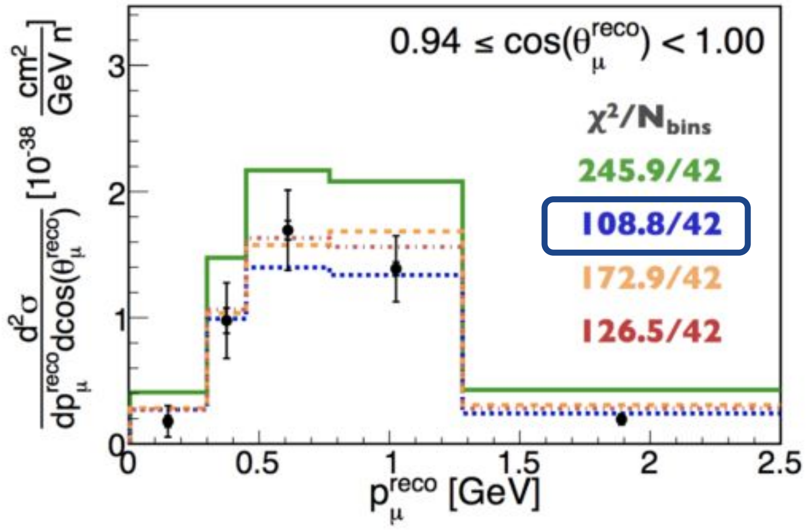
ν_μ CC Inclusive @ BNB (Flux Averaged)

Phys. Rev. Lett. 123, 131801 (2019)

First double differential measurement on Ar
27200 events, efficiency 57.2%, purity 50.4% → overall good agreement with theory

More recent models achieve better agreement at forward scattering angles.
Pandora reconstruction paradigm.





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ν_μ CC Inclusive @ BNB (Flux Averaged): Next Gen Analyses

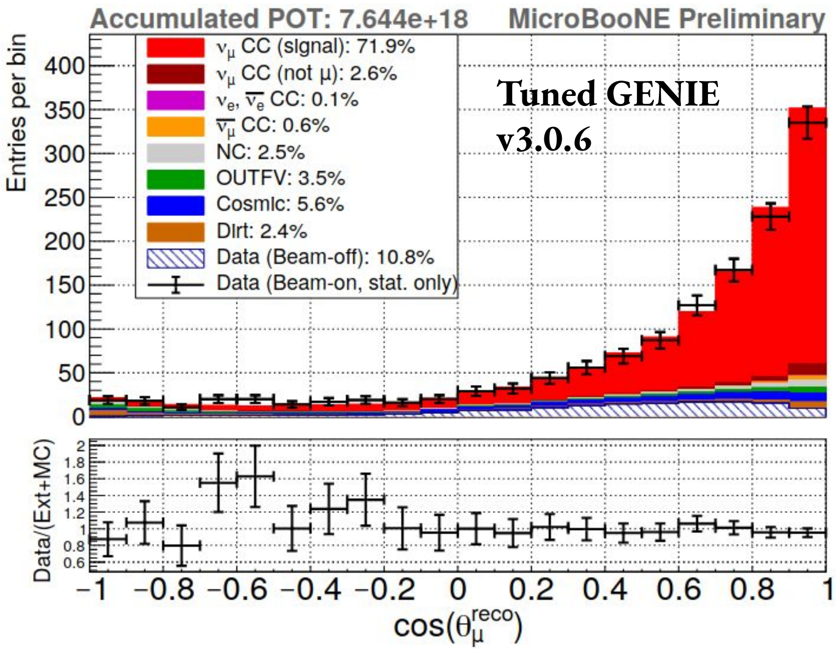
Updates included:

Better detector understanding:
signal processing from all planes & improved calorimetry
JINST 13, P07006 (2018), JINST 13, P07007 (2018)

Reduced systematic uncertainties via a data driven method for detector systematics and cosmics modelling
MICROBOONE-NOTE-1075-PUB

Improved neutrino interaction model
Phys.Rev.D 105 (2022) 7, 072001

Use of the Cosmic Ray Tagger



Update measurement
MICROBOONE-NOTE-1069-PUB

ν_μ CC Inclusive @ BNB (Flux Averaged): Next Gen Analyses

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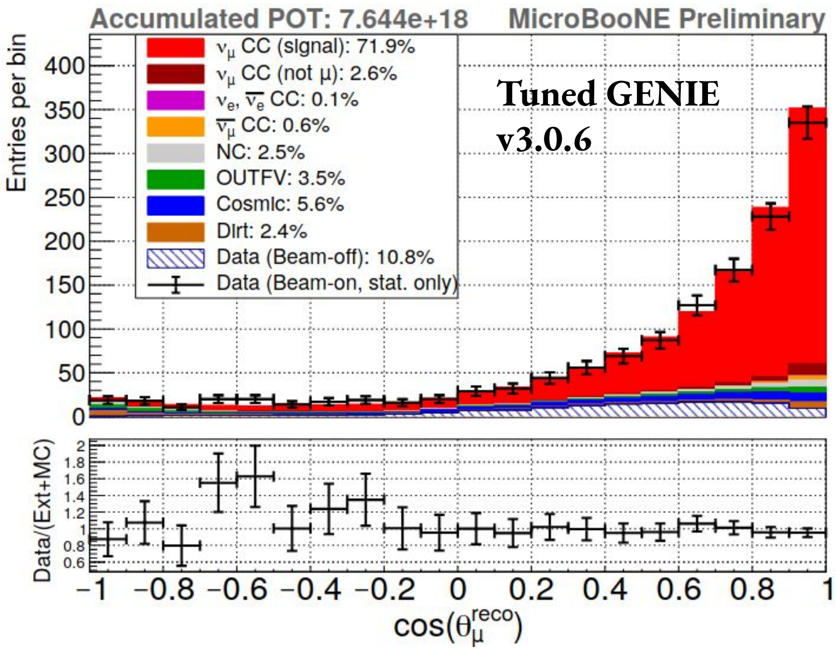

Results:
→ Purity: from 50% to 71.9%
→ 3x Reduction of cosmic contamination
→ Detector uncertainties from 16.2% to 3.3 %

Update measurement
MICROBOONE-NOTE-1069-PUB

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Energy-dependent ν_μ CC Inclusive @ BNB

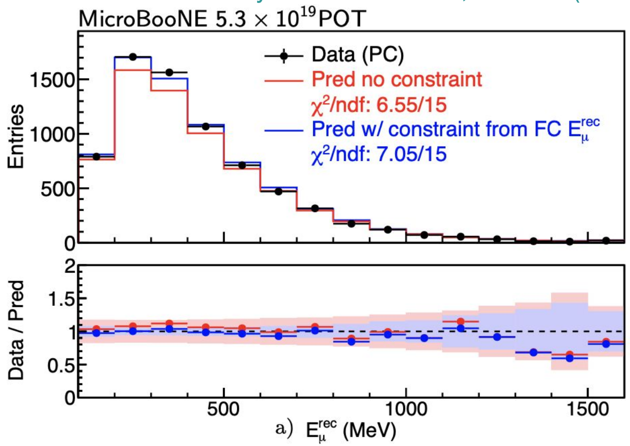
Phys. Rev. Lett. 128, 151801 (2022)

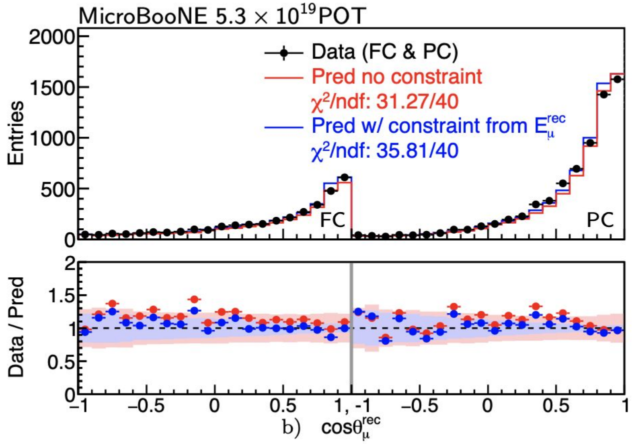
Energy-dependent total cross-section and differential in muon energy and energy transfer.

11528 selected ν_μ CC interactions:
Improved Purity ~92% & Efficiency ~68% thanks to new tomographic event reconstruction paradigm JINST 16, P06043 (2021)

The analysis uses the muon kinematics to constrain the prediction for missing hadronic energy:

True : $E_\nu = E_\mu + E_{had,vis} + E_{had,missing}$
Reco: $E_\nu = E_\mu + E_{had,vis}$





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Energy-dependent ν_μ CC Inclusive @ BNB

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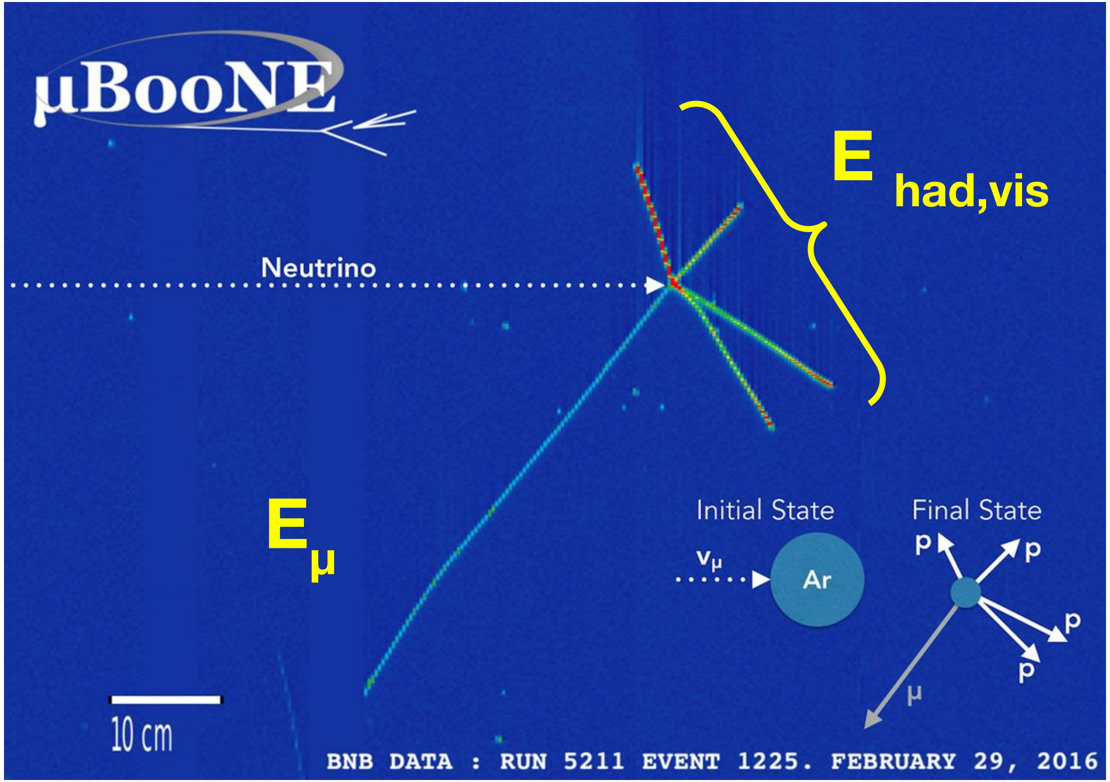
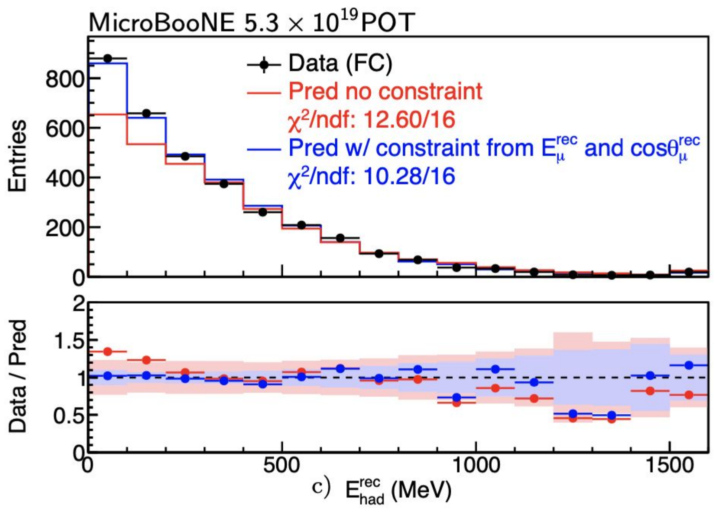
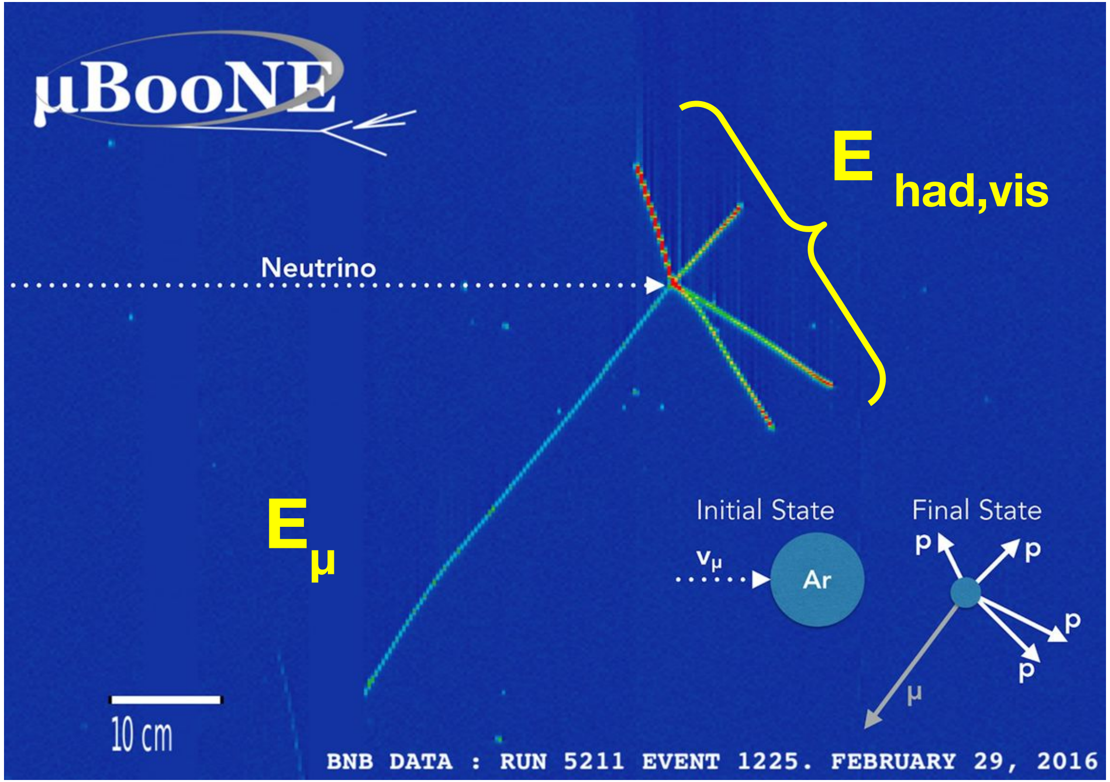


Energy-dependent ν_μ CC Inclusive @ BNB



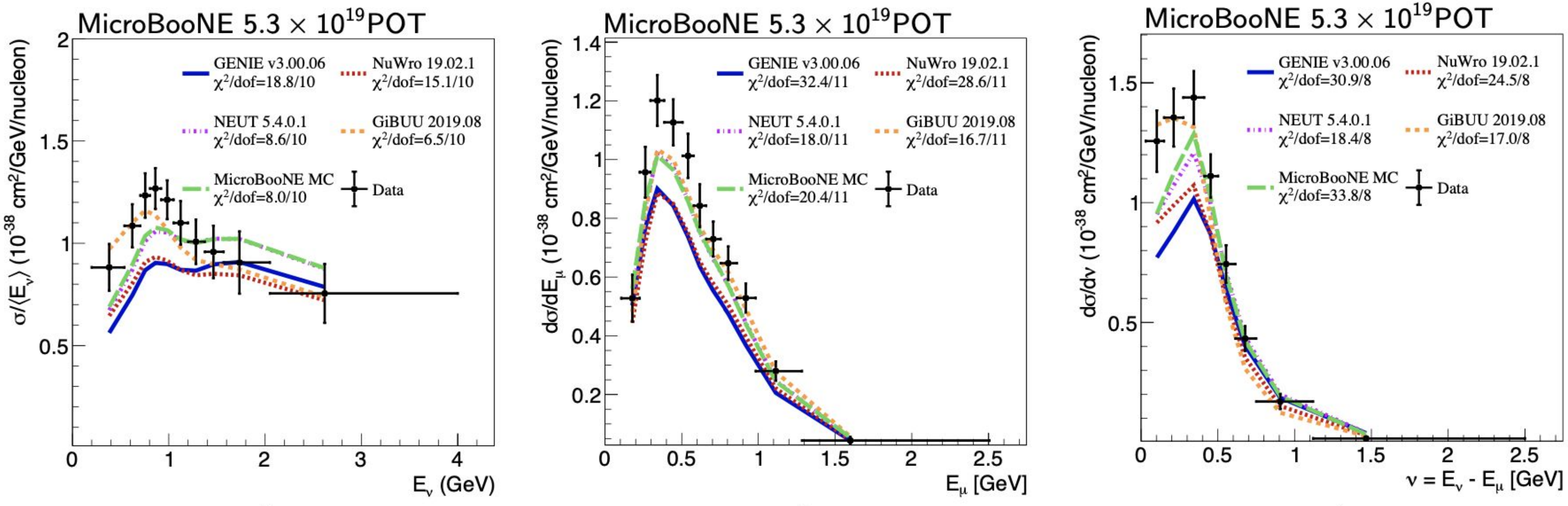
Extracted cross section with Wiener SVD spearheaded for this measurement
[2017 *JINST* 12 P10002]



Energy-dependent ν_μ CC Inclusive @ BNB

Phys. Rev. Lett. 128, 151801 (2022)

Good separation power of model predictions from different generators



The central predictions of GENIE v3 and NuWro are slightly disfavored compared to the other predictions.
GiBUU's central prediction gives best agreement at low energy transfer

→ GiBUU predicts larger cross section for 2p2h

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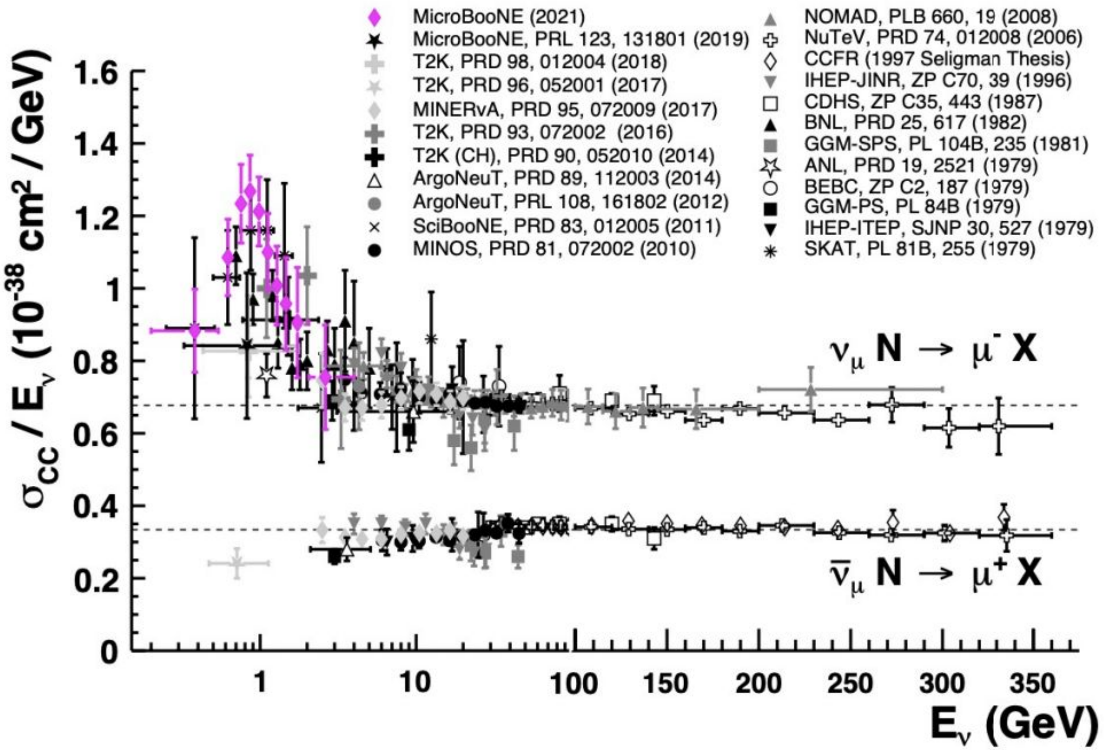
Energy-dependent ν_μ CC Inclusive @ BNB: in the global context



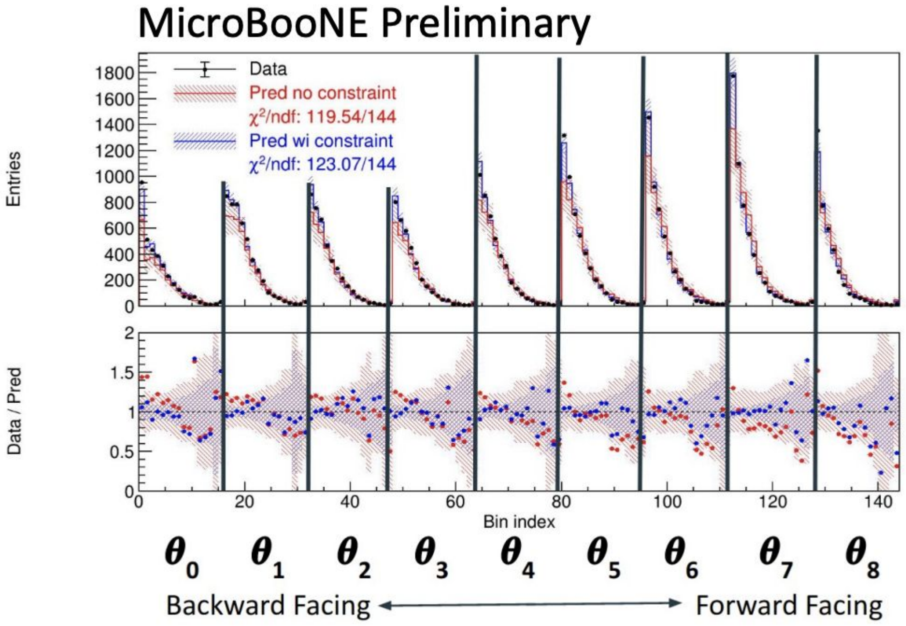
Phys. Rev. Lett. 128, 151801 (2022)

Next: 3-D inclusive cross section with 6.4×10^{20} POT

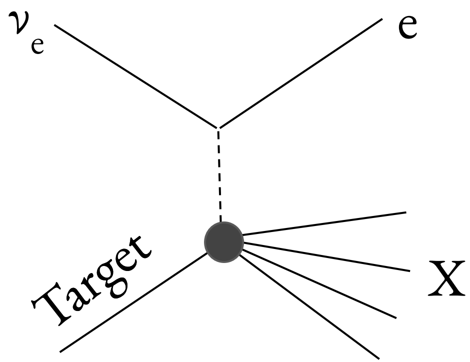
First 3-D cross-section measurement for ν_μ-Ar $d\sigma/dP^\mu d\cos\theta_\mu$ (E_ν) coming soon!

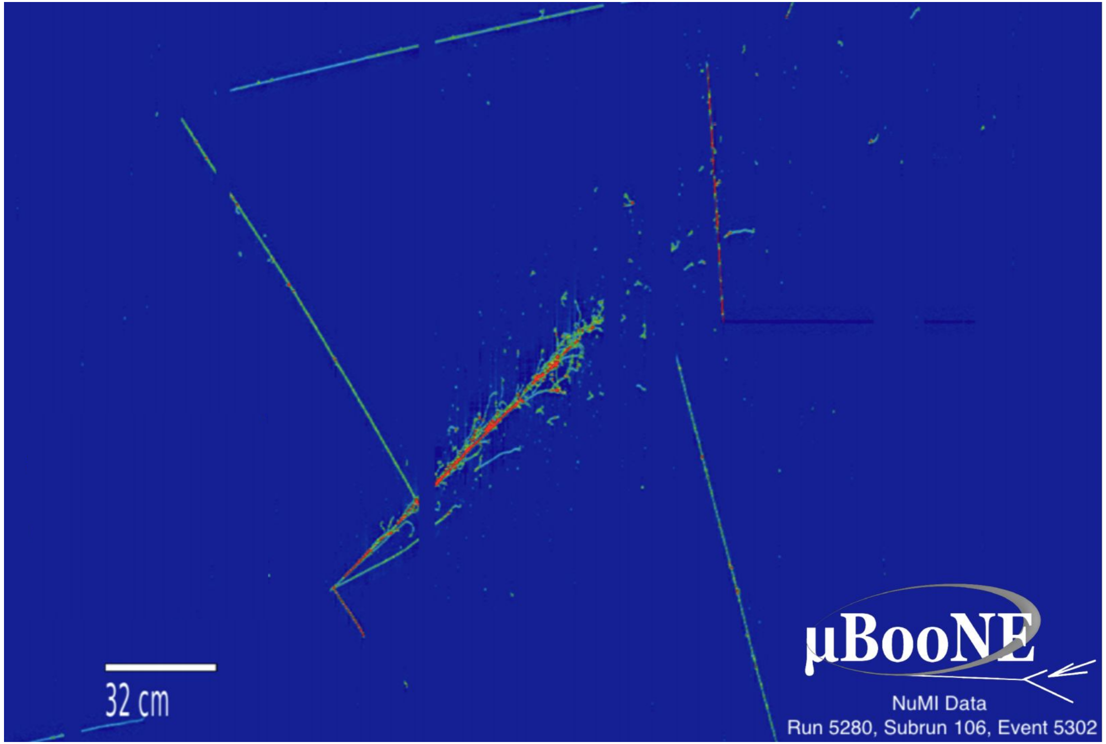
Same strategy for constraining missing energy
→ extended to involve more dimension
(muon polar angle).

Estimates of the statistical and correlated systematic uncertainties by a bootstrapping method ("resampling with replacement")
→ circumvent over-estimation of the detector variation uncertainty, a Gaussian Processes Regression smoothing technique (30% reduction)



$\nu_e + \bar{\nu}_e$ CC Inclusive @ NuMI



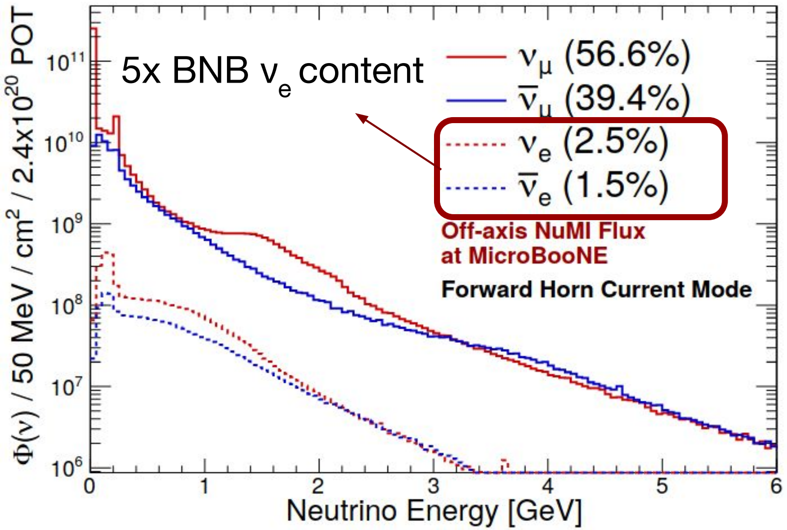


$\nu_e + \bar{\nu}_e$ CC Inclusive @ NuMI

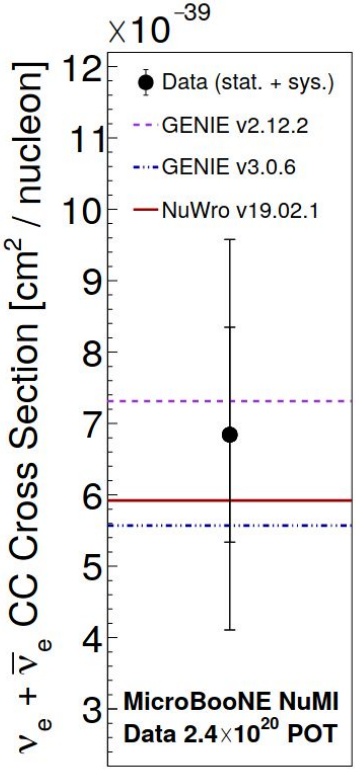
Phys.Rev.D 104 (2021) 5, 052002

Flux averaged total cross section. 214 selected events
Selection main requirement: at least one shower compatible with electron hypothesis: Purity ~40%, Efficiency ~10%.

In good agreement with models



Systematic Source	Relative Uncertainty [%]
Interaction	10
Detector Response	23
Beam Flux	22
POT Counting	2
Cosmic Simulation	4
Out-of-Cryostat Simulation	6
Total	34



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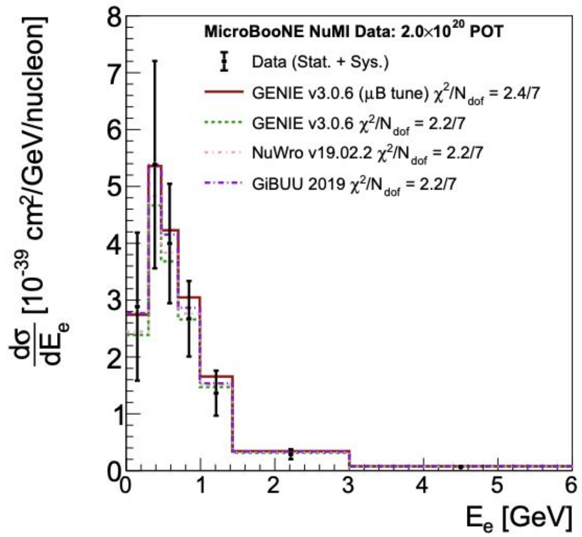
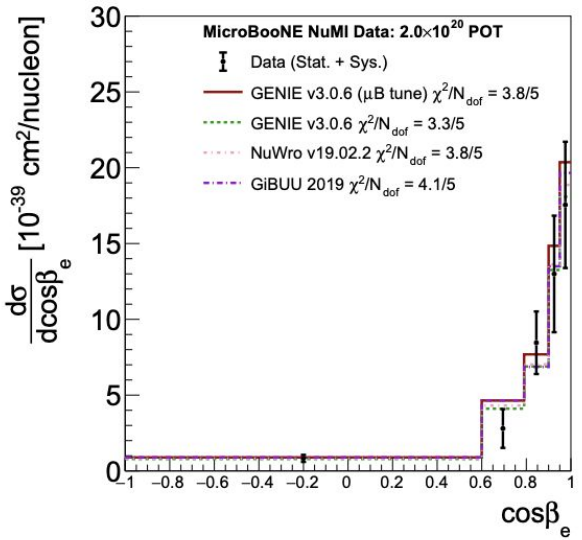
Differential $\nu_e + \bar{\nu}_e$ CC Inclusive @ NuMI

Phys. Rev. D (2022) 105, L051102

First Measurement of Inclusive ν_e and $\bar{\nu}_e$ CC differential in Lepton Energy and Angle on Argon.

Selection main requirement: at least one shower compatible with electron hypothesis.
Biggest sample of selected ν_e CC interaction on Argon to date: 243 events.
Purity ~70%, Efficiency ~20%. Extracted cross section in good agreement with models.





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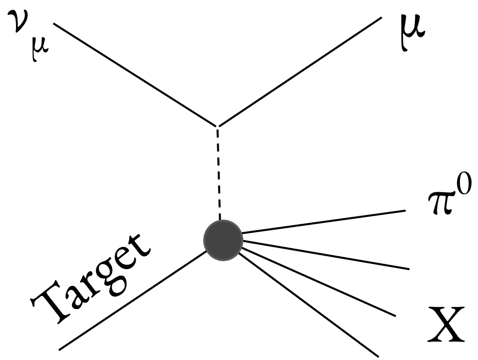
Source of Uncertainty	Relative Uncertainty [%]
Beam Flux	17.4
Detector	6.8
Cross Section	5.8
POT Counting	2.0
Out-of-Cryostat	1.8
Proton/Pion Reinteractions	1.2
Beam-off Normalization	0.1
Total Systematic Uncertainty	19.8
MC Statistics	0.8
Data Statistics	10.0
Total Uncertainty	22.2

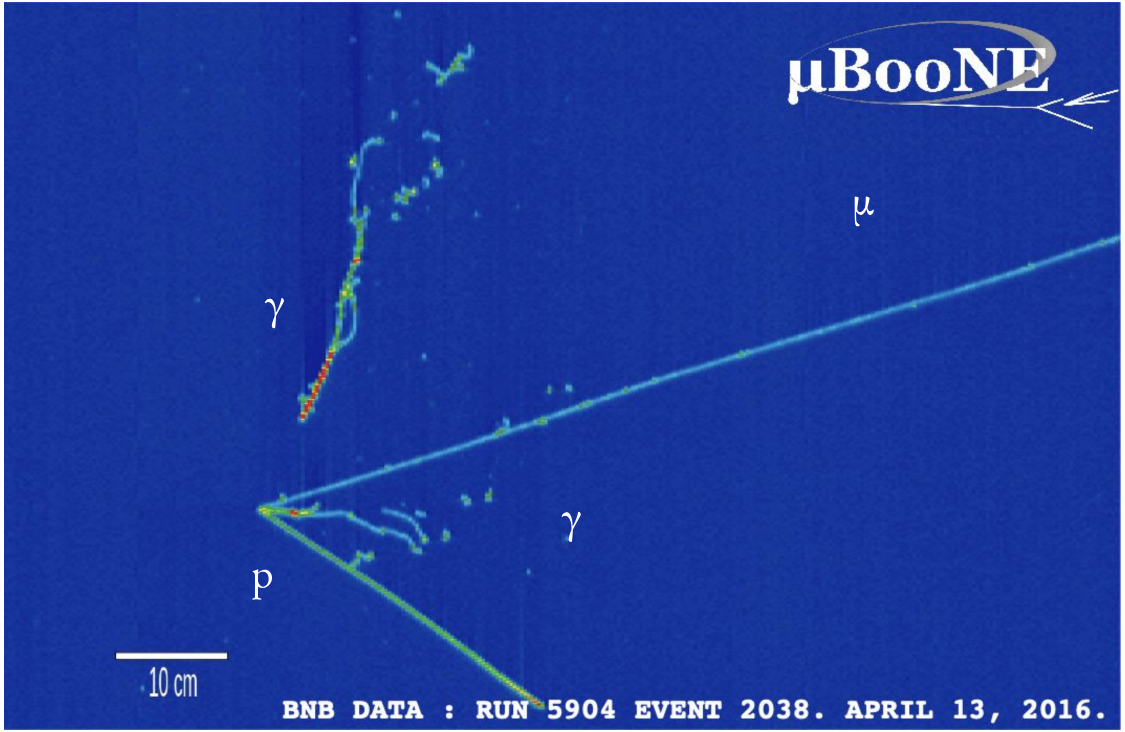
First analysis

Systematic Source	Relative Uncertainty [%]
Interaction	10
Detector Response	23
Beam Flux	22
POT Counting	2
Cosmic Simulation	4
Out-of-Cryostat Simulation	6
Total	34

Total cross section compatible with previous measurement, a significant uncertainty reduction.

Production of pions… of the neutral kind





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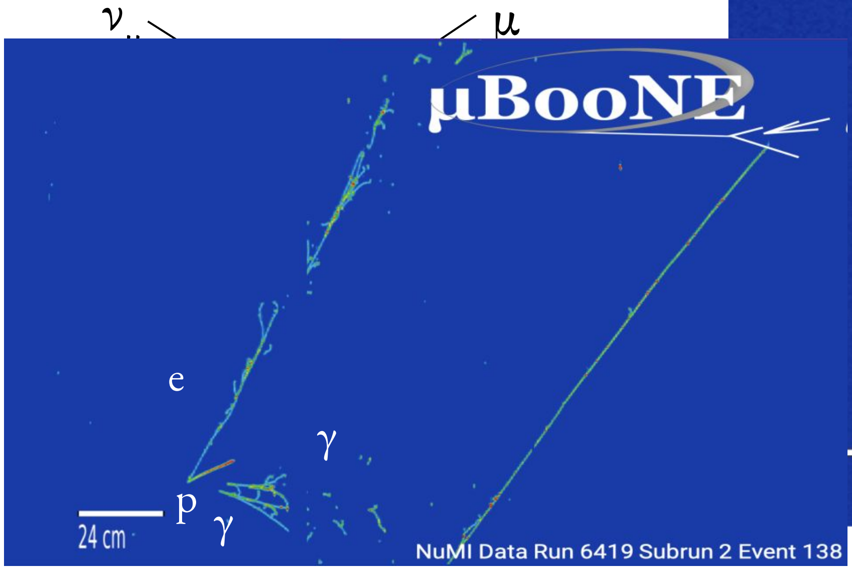

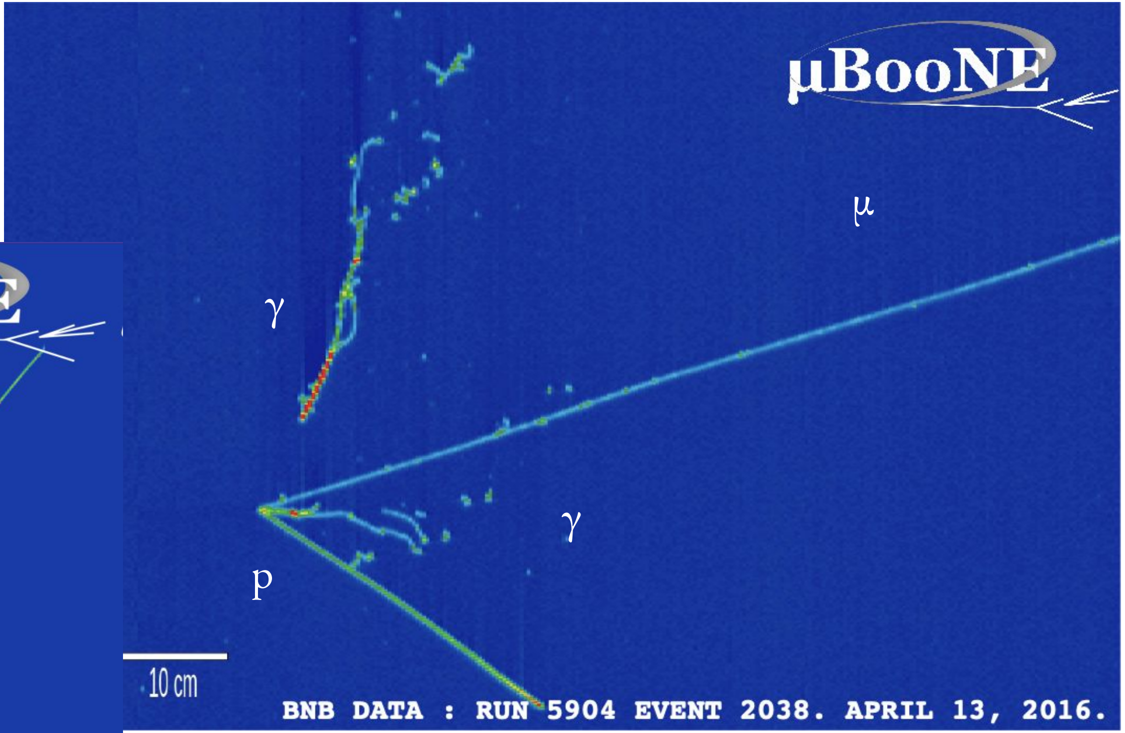

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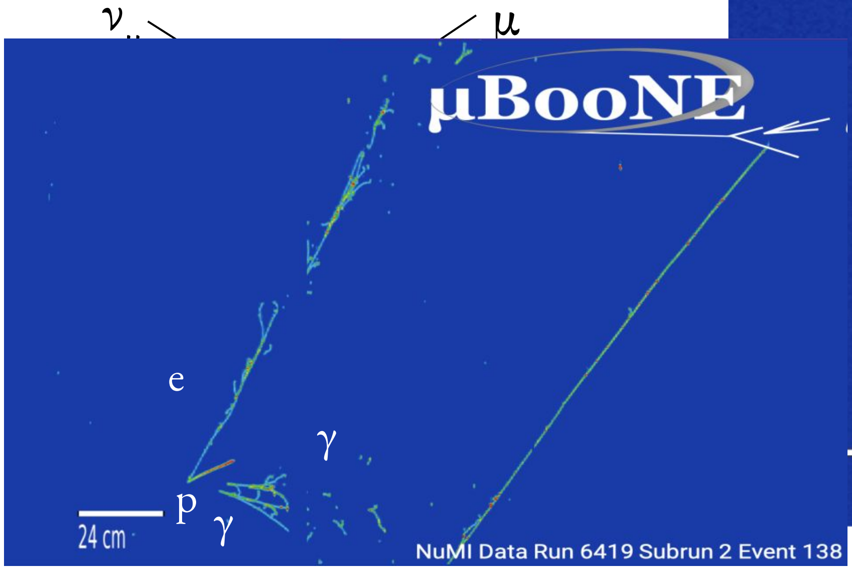
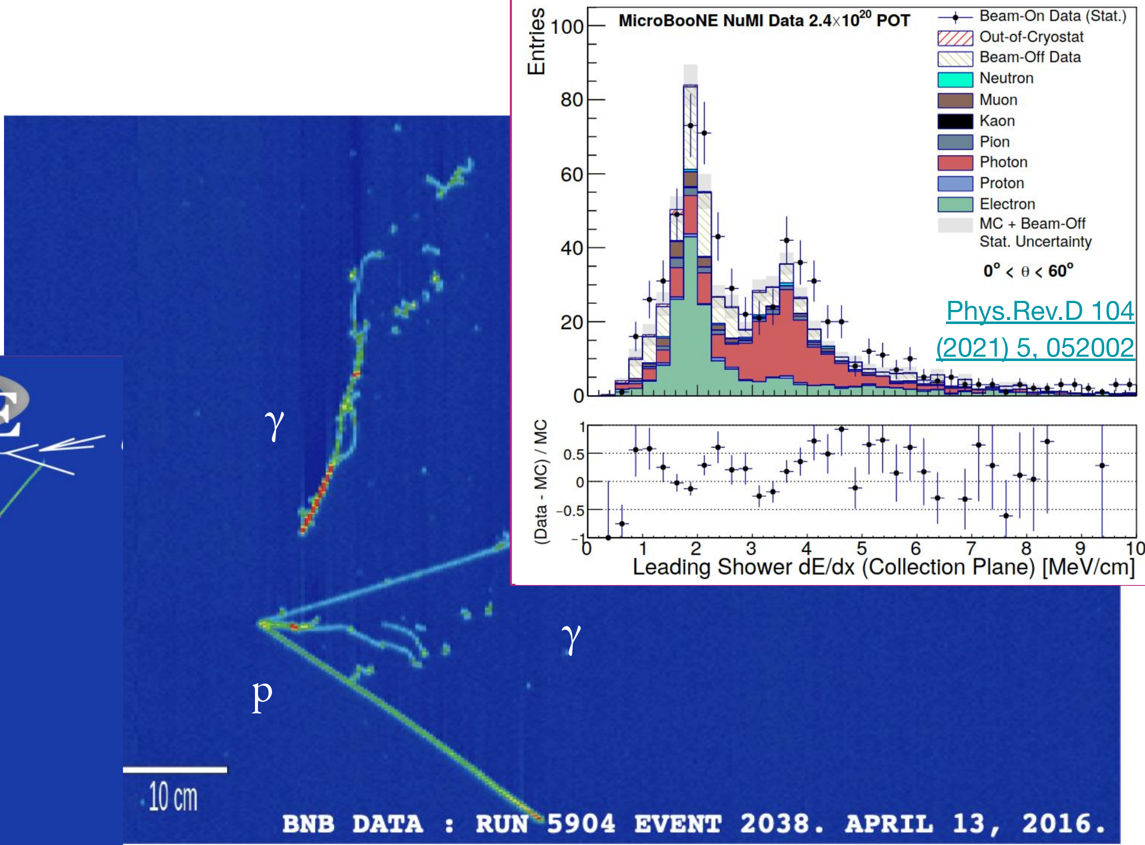


Particle ID: e/γ



Phys.Rev.D 104 (2021) 5, 052002

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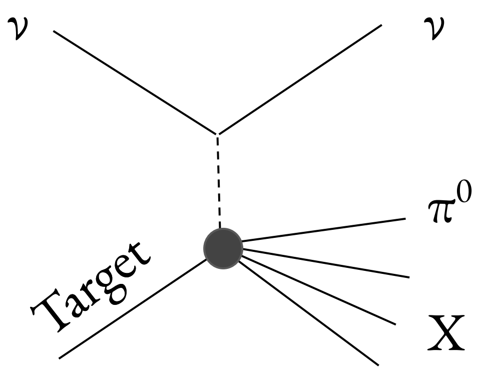
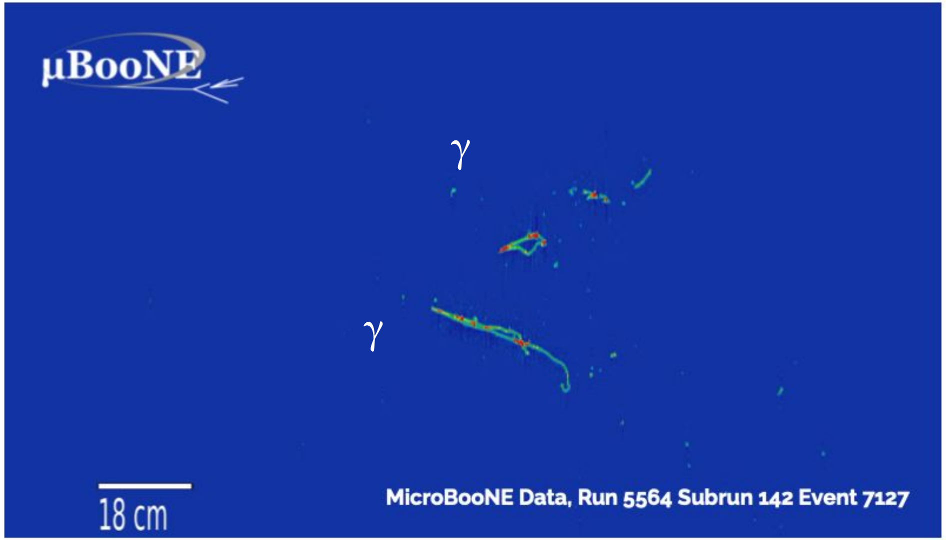
Production of pions: NC single π^0 production



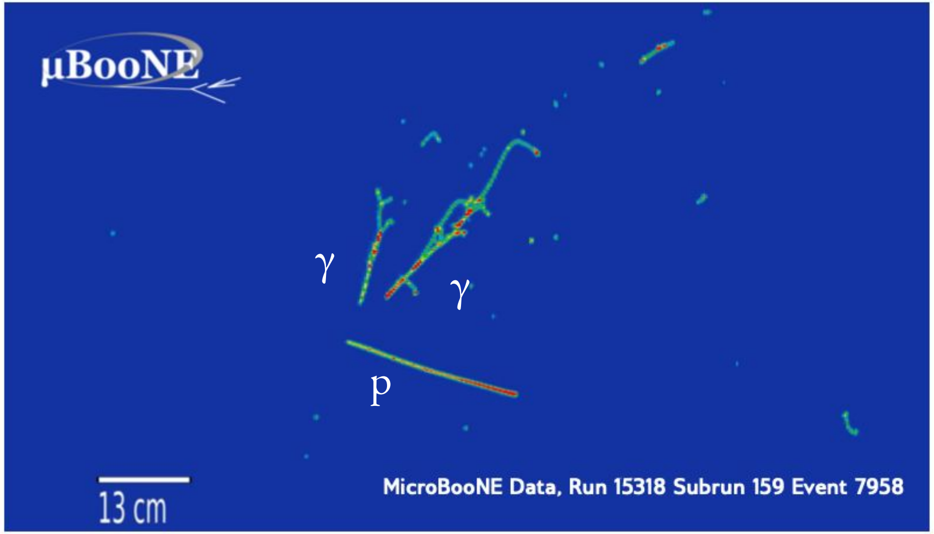


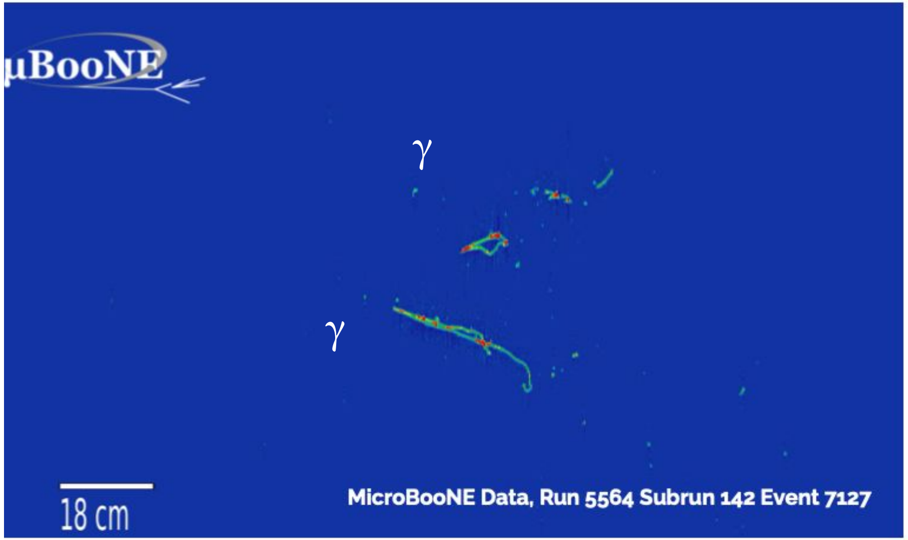
NC single π^0 production, no charged pions

Arxiv: 2205.07943
(Submitted to PRD)

2 final state topologies 2γ1p0π & 2γ0p0π + semi-inclusive measurement, in 5.89×10^{20} POT

Signal definition no other hadrons or leptons. True proton kinetic energy > 50 MeV, semi-inclusive: any number of protons





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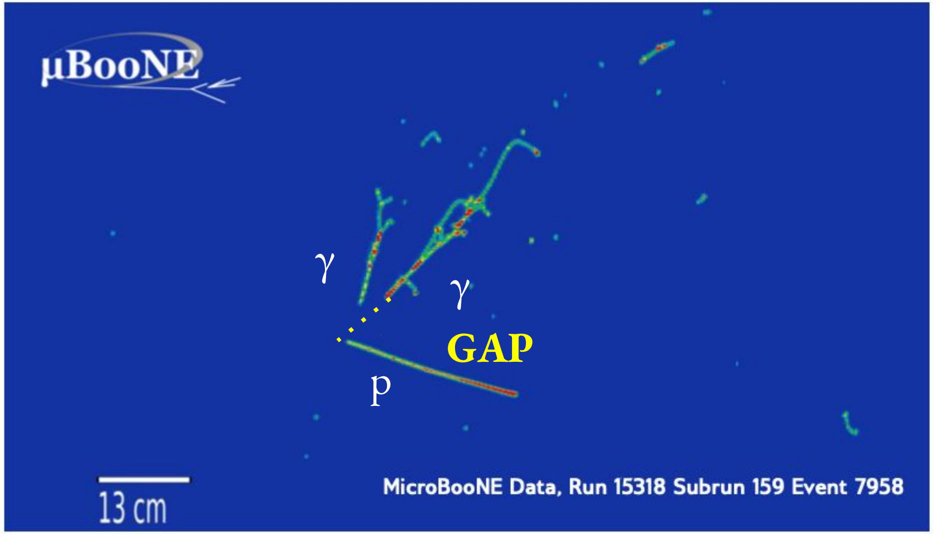
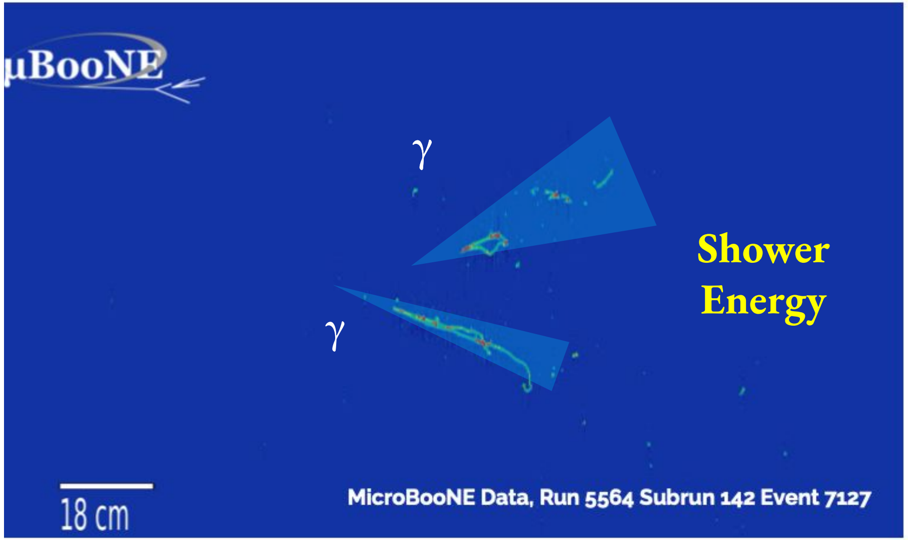
Pandora reconstruction framework, common preselection → BDT Strategy





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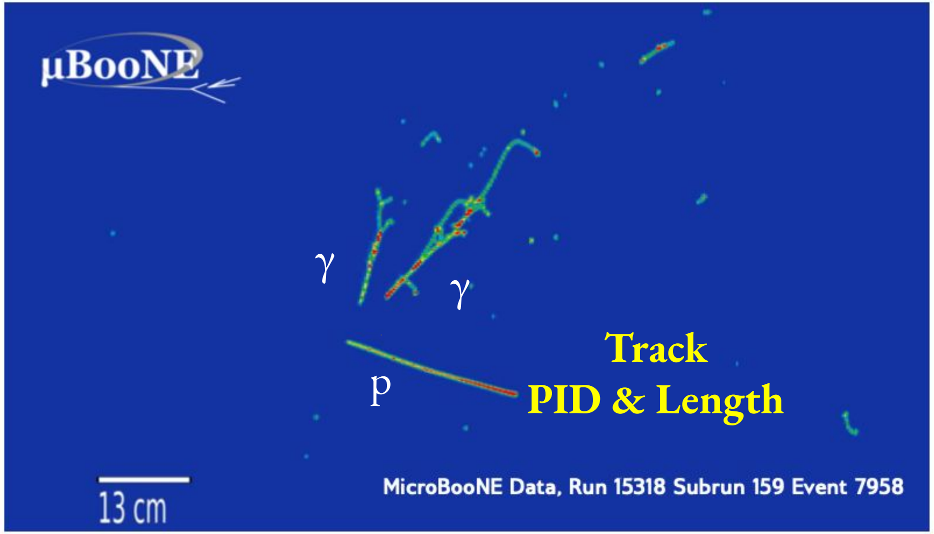

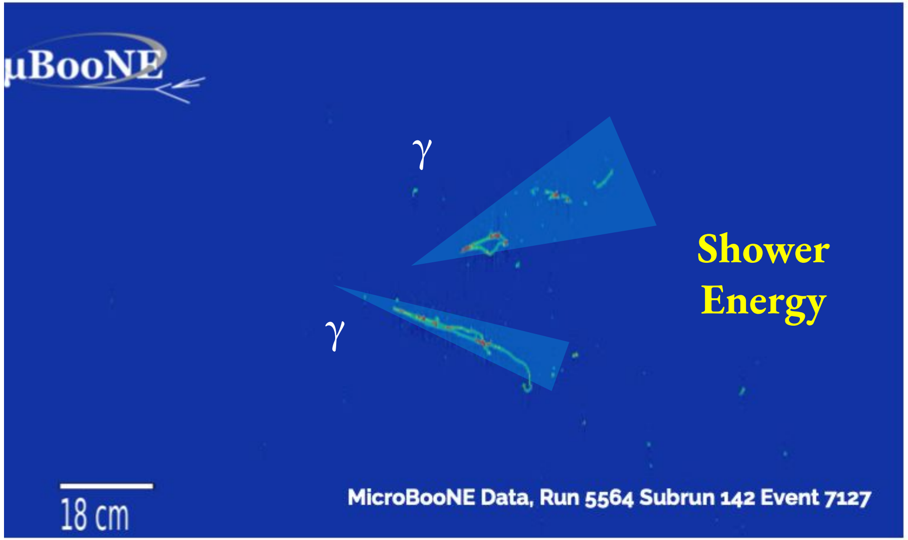

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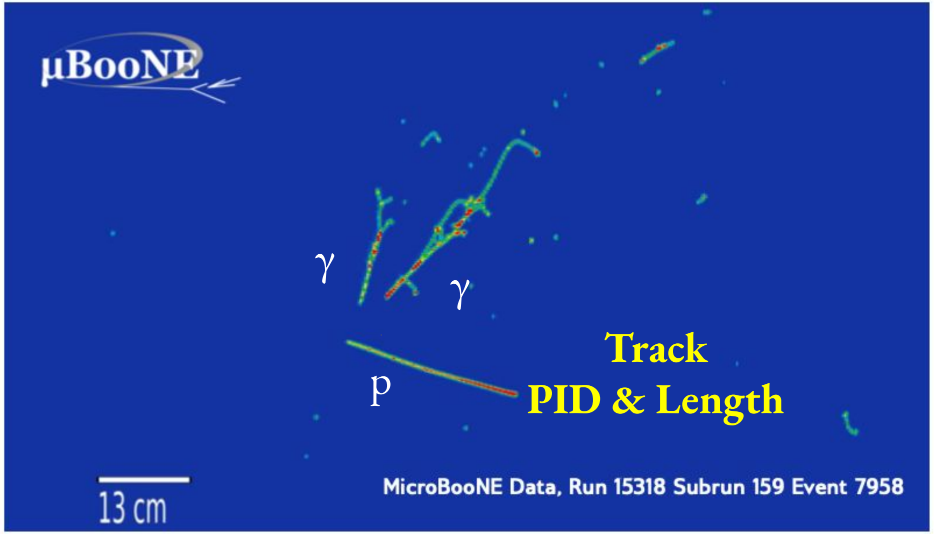
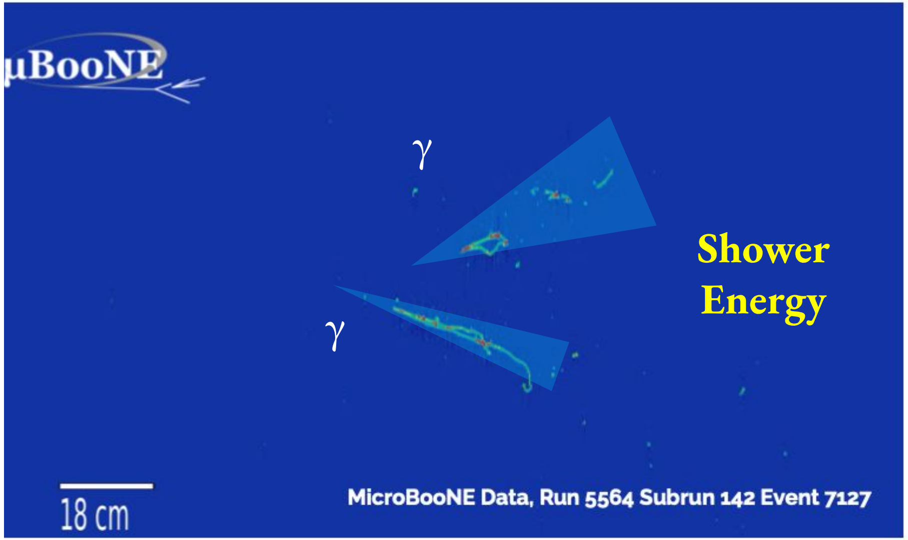




634 candidates, 4.4% efficiency, 63.5% purity

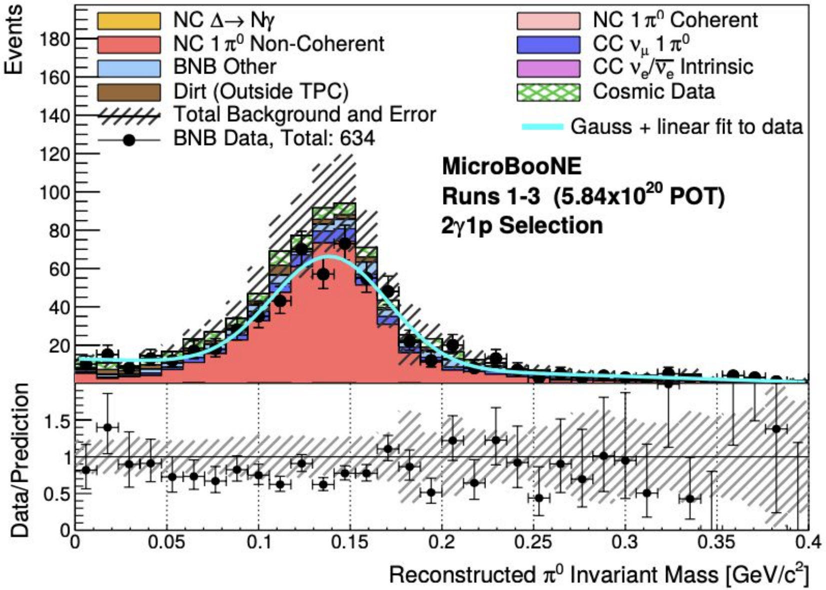
496 candidates, 2.3% efficiency, 59.6% purity

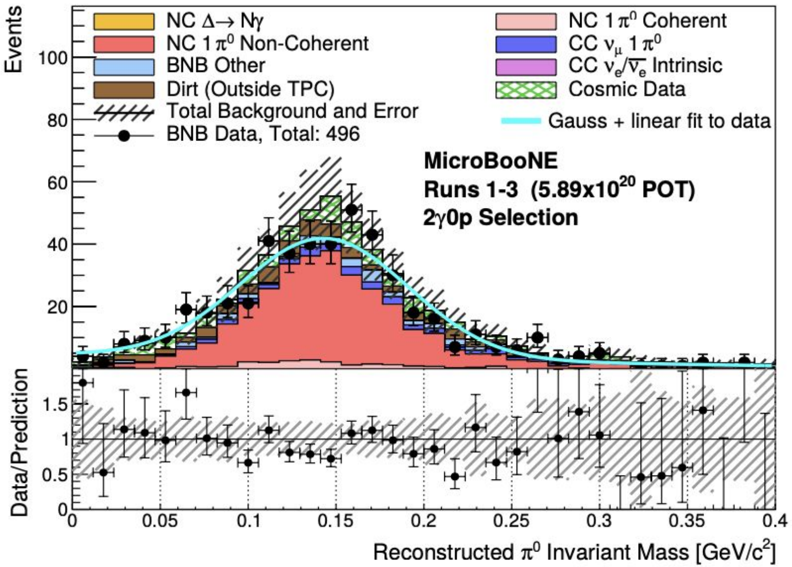
NC single π^0 production, no charged pions: cross-checks

Arxiv: 2205.07943
(Submitted to PRD)

2 final state topologies $2\gamma 1p0\pi$ & $2\gamma 0p0\pi$ + semi-inclusive measurement, in 5.89×10^{20} POT

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



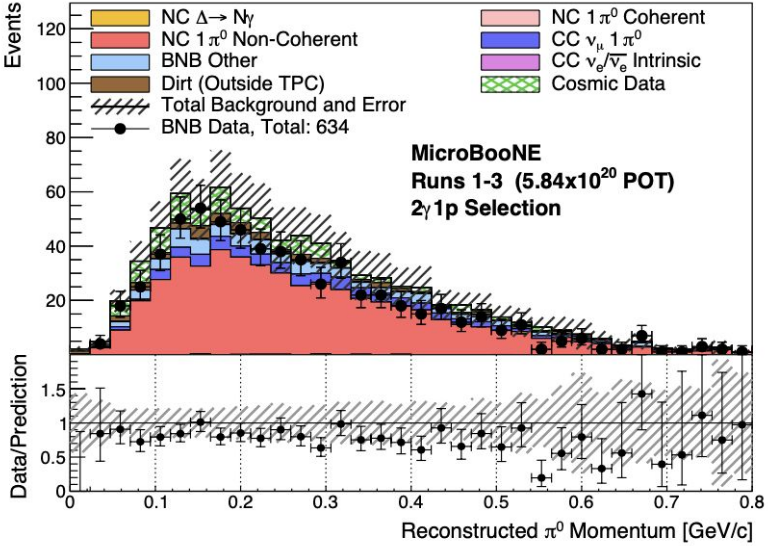


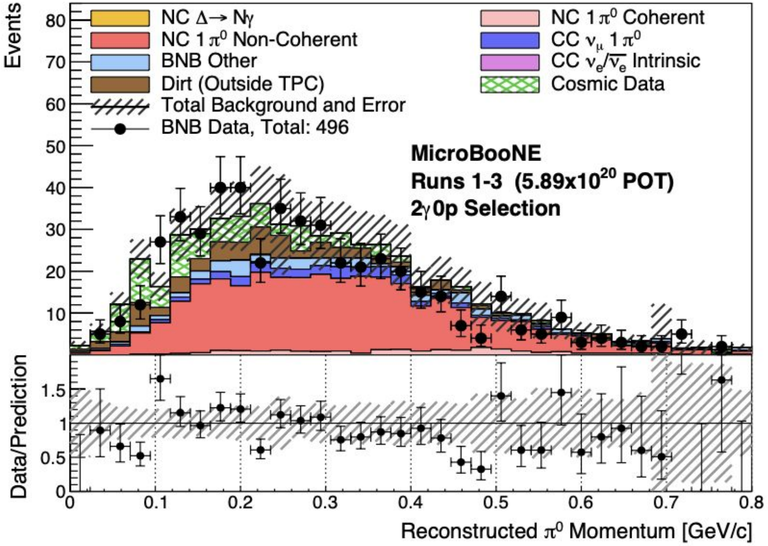
Additional checks for proper π^0 reconstruction: π^0 momentum & production angle

NC single π^0 production, no charged pions: cross-checks

Arxiv: 2205.07943
(Submitted to PRD)

2 final state topologies 2γ1p0π & 2γ0p0π + semi-inclusive measurement, in 5.89×10^{20} POT





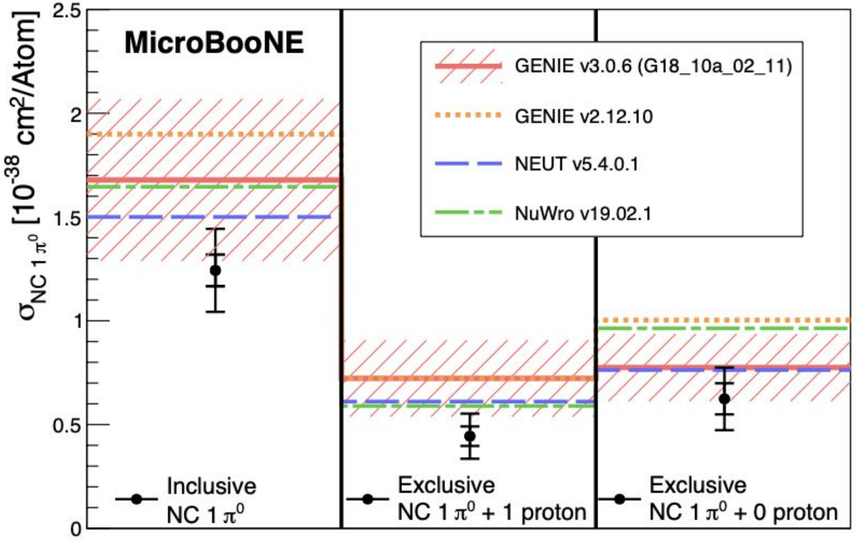
Coherent & non-coherent π^0 production fit in momentum with a linear scaling to account for the shape of the deficit. Data suggests that GENIE may overestimate NC non-coherent and underestimate NC coherent, but the GENIE predictions accurate within uncertainty.

NC single π^0 production, no charged pions: results

Arxiv: 2205.07943
(Submitted to PRD)

2 final state topologies 2γ1p0π & 2γ0p0π + semi-inclusive measurement, in 5.89×10^{20} POT

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



Semi-inclusive: both selection, efficiency-corrected to include 2+ proton final states.
We observe a consistent deficit in data compared to predictions.

NC single π^0 production, no charged pions: results

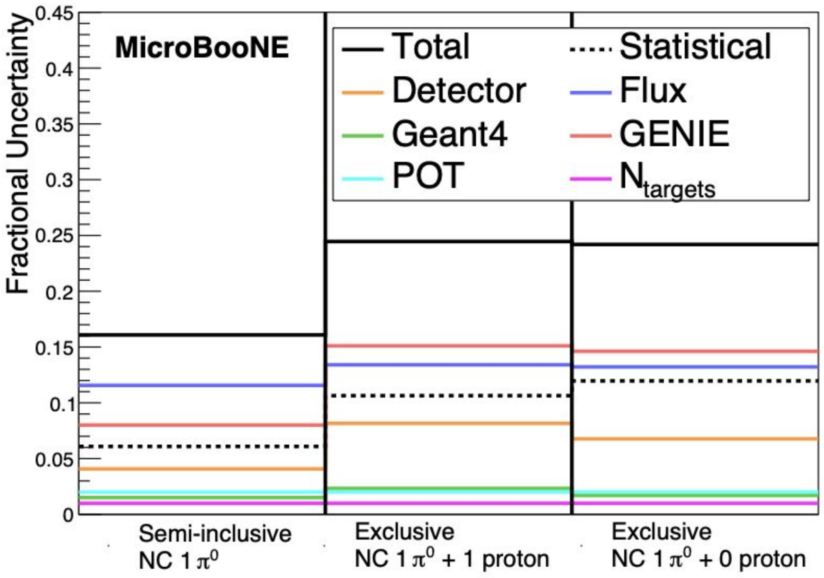
Arxiv: 2205.07943
(Submitted to PRD)

2 final state topologies 2γ1p0π & 2γ0p0π + semi-inclusive measurement. in 5.89×10^{20} POT

Semi-inclusive:
1.243 ± 0.185 (sys) ±0.076 (stat) [10^{-38}cm^2/Ar]

NCπ0+1p:
0.444 ± 0.098(sys) ± 0.047 (stat) [10^{-38}cm^2/Ar]

NCπ0+0p processes:
0.624 ± 0.131 (sys) ± 0.075(stat) [10^{-38}cm^2/Ar]



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NC single π^0 production, inclusive differential

5.327×10^{19} POT → available stat x10 after unblinding

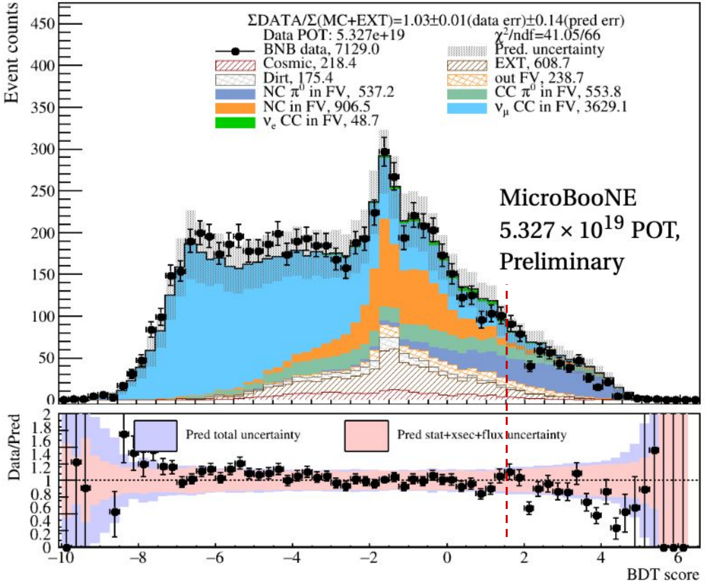
$$\nu_x + Ar \rightarrow \nu_x + \pi^0 + X$$

WireCell reconstruction paradigm

Cosmic rejection tools akin to the Inclusive ν_μCC cross section.

BDT implementation via eXtreme Gradient Boosting (XGBoost)

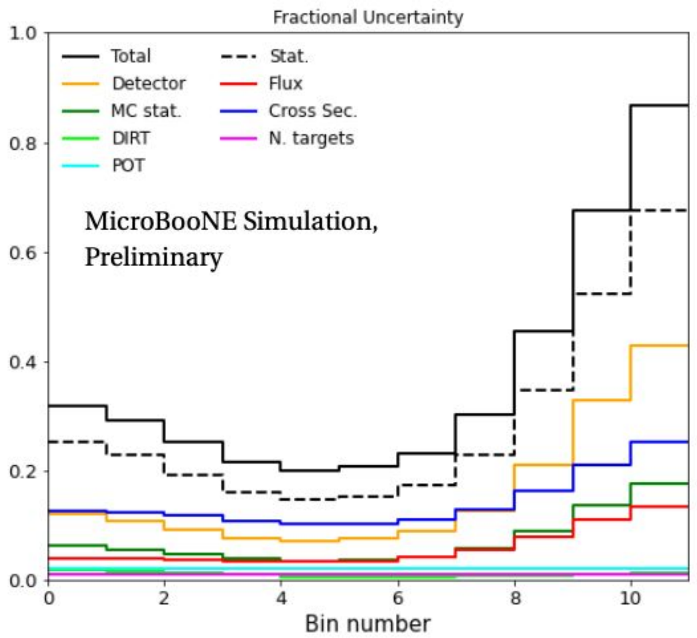
Overall efficiency above 30% and purity above 70%

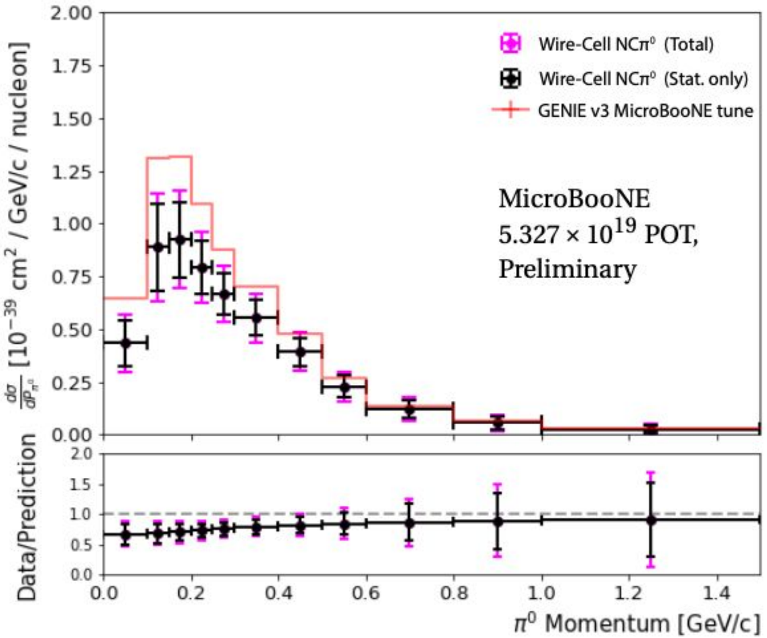


Fermilab

NC single π^0 production, inclusive differential

$$\nu_x + Ar \rightarrow \nu_x + \pi^0 + X$$



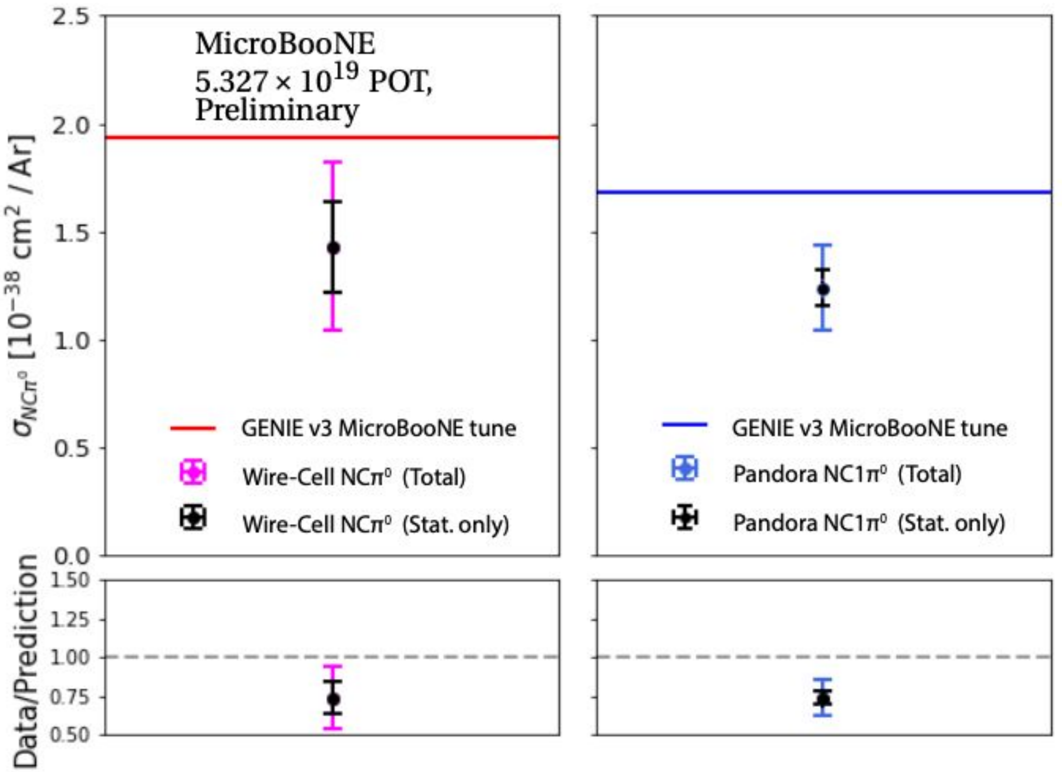


NC π^0 summary

Different reconstruction paradigms report similar findings:

A slight overprediction of NC π^0 production for GENIE v3.

Similar data-MC trends as a function of the π^0 momentum



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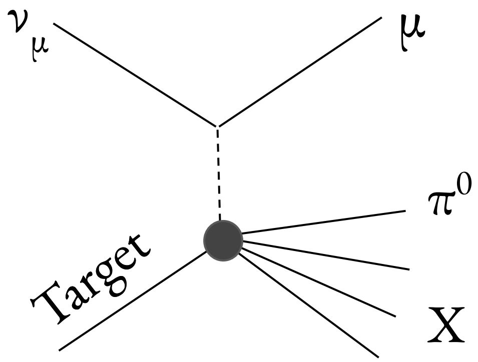
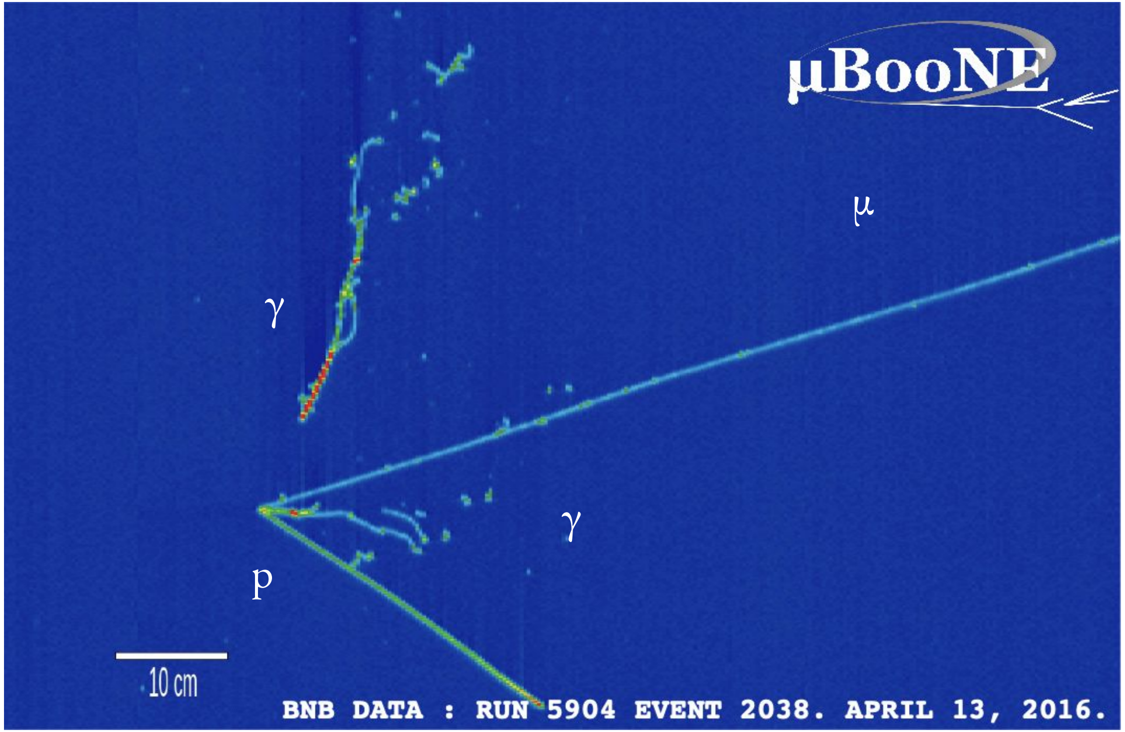
ν_μ CC π^0 pions





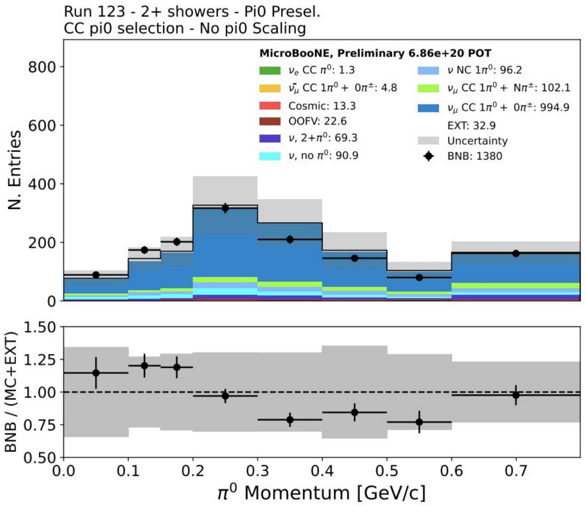
CCNpN$\pi^0$0$\pi^\pm$ production

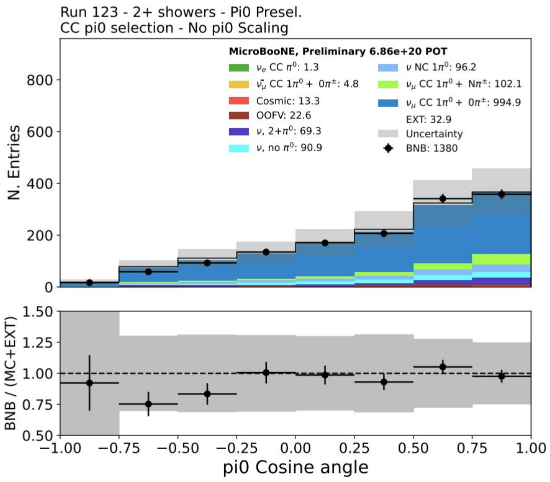
Signal definition:

1 muon with E_μ > 20 MeV, 1 π^0,
0$\pi^\pm$ with E> 40 MeV, any nucleon.

Selection:

- 1 and only MIP-like track [5]
- Leading shower: radial angle within 0.45 radians (cosine angle > 0.9), 2 cm < conversion distance < 80 cm OR (conversion distance < 2 cm AND dE/dx of > 2.5 MeV/cm)
- Sub-leading shower: E > 10 MeV, and a conversion distance > 1 cm OR dE/dx > 2.5 MeV/cm
- Reconstructed π^0 mass [50, 180] MeV.



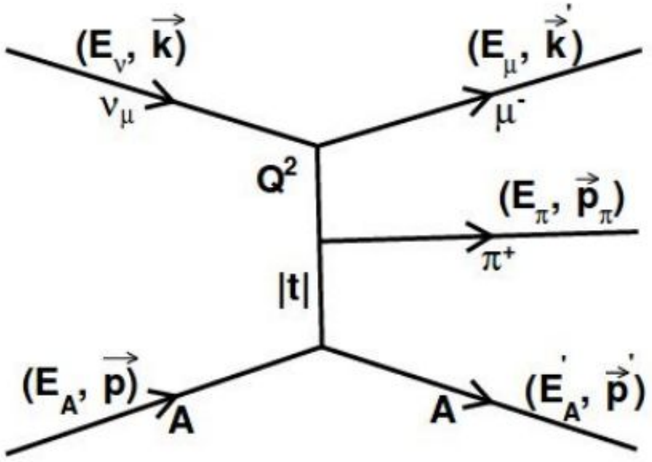


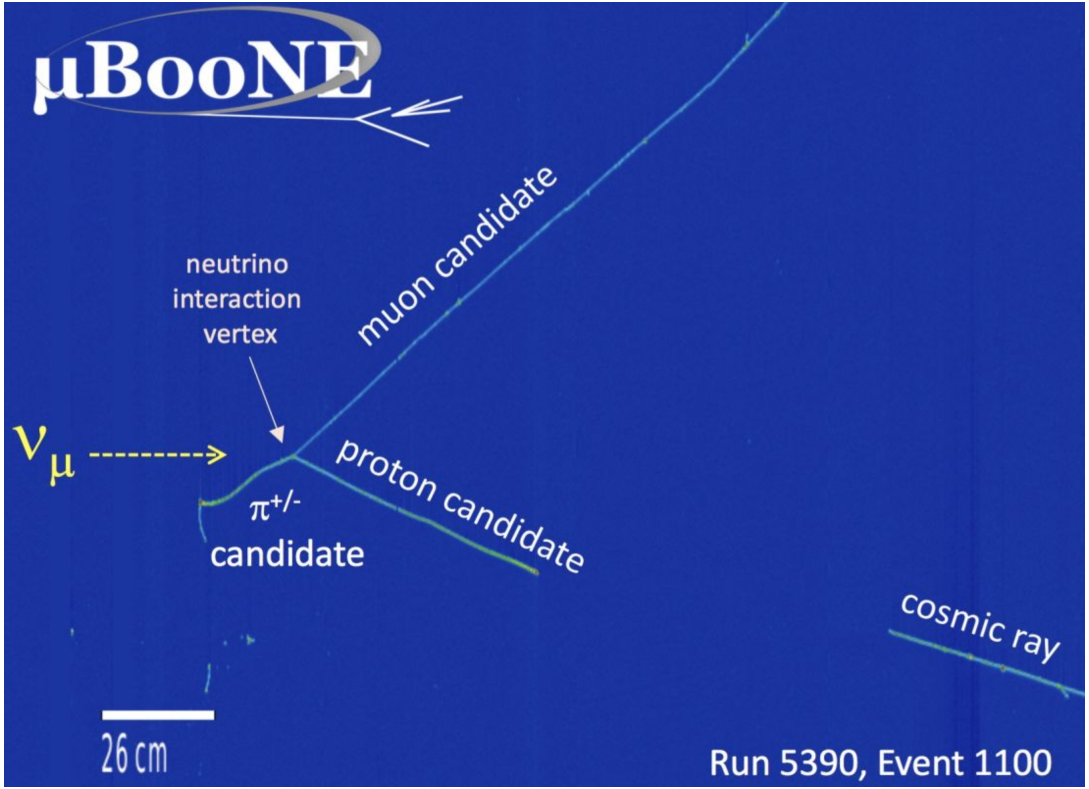
1380 candidates, efficiency = 7.5% and the purity = 70%,
Pandora reconstruction paradigm

Cross section extraction coming soon.

More on Pions

Charged Pion production (CC1πNp) & Coherent Pion Production: upcoming!





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Takeaways

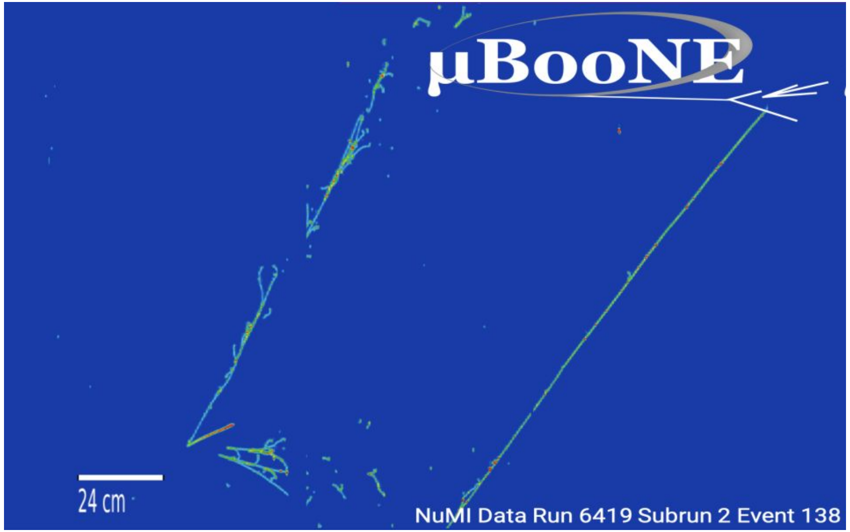
MicroBooNE has collected the **largest sample** of **neutrino-argon** interactions available to date.

The second generation of cross section analyses is underway

→ more statistics,

→ higher precision,

due to **notable improvements** concerning the interaction model employed, event reconstruction, detector simulation and modeling of the cosmics.

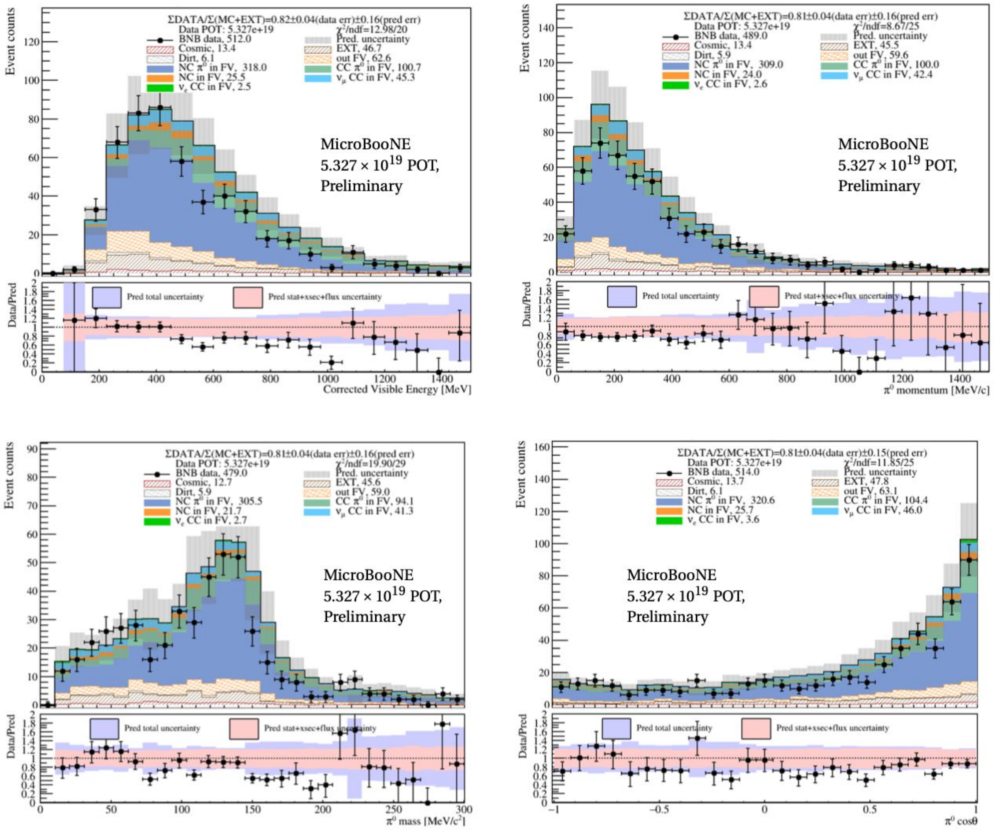


Measuring neutrino cross sections on argon with high precision **opens a new window in the exploration of the nucleus** and it is **foundational for BSM work** in LArTPCs.


Thanks!!!
MicroBooNE collaboration @ 2022

Backup

NC single π^0 production, inclusive differential



$$\nu_x + Ar \rightarrow \nu_x + \pi^0 + X$$

Deficit close to 20% observed.

Consistent trends with the total flux averaged cross section (different reconstruction paradigms)

Wiener SVD in a nutshell

Scope: meaningful comparisons of measured cross section w/ neutrino generators.
We need to correct the measured differential event rate for **inefficiency** and **finite detector resolution**.

We chose the **Wiener SVD Unfolding technique**:
Multivariate normal distribution for all uncertainties,
unfolded result is a linear transformation of
the measurement *[JINST 12 (2017) 10, P10002]*
→ elegant way to incorporate **flux shape uncertainties (dominant systematics)**

$$\left(\frac{dR}{dx}\right)_i = \frac{N_i - B_i}{N_{\text{target}} \times \Phi \times \Delta x_i},$$

Inputs:

- measured event rate,
- **covariance matrix** (stat & syst uncertainties)
- **response matrix** (smearing and efficiency)

Output:

- *unfolded* cross section in true kinematics,
- **covariance matrix** (total uncertainty on true XS)
- **additional smearing matrix**, A_c (regularization & bias)

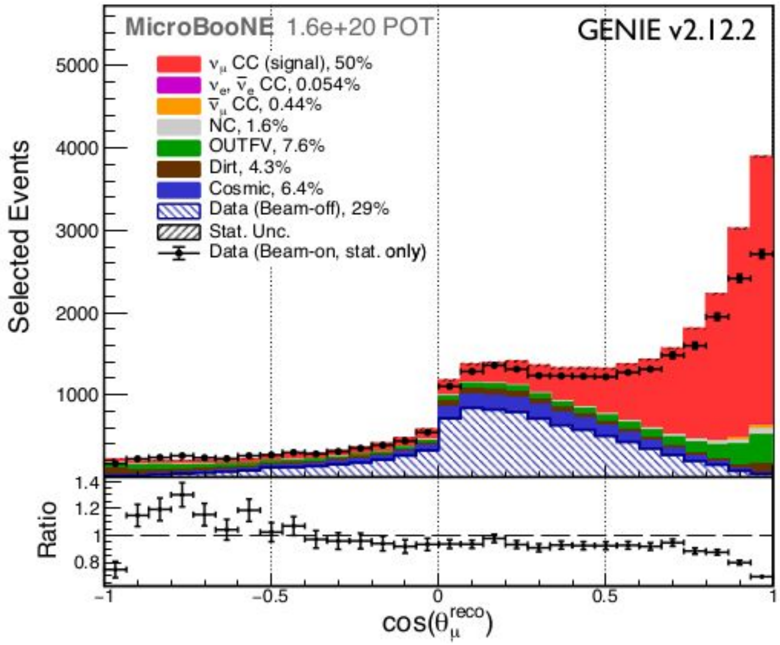
Wiener SVD in two nutshells

The correction is performed by minimizing a X^2 score comparing data to a prediction and includes a regularization term.
The regularization is determined from a Wiener filter by **minimizing** the mean square error between the **variance** and **bias** of the result.

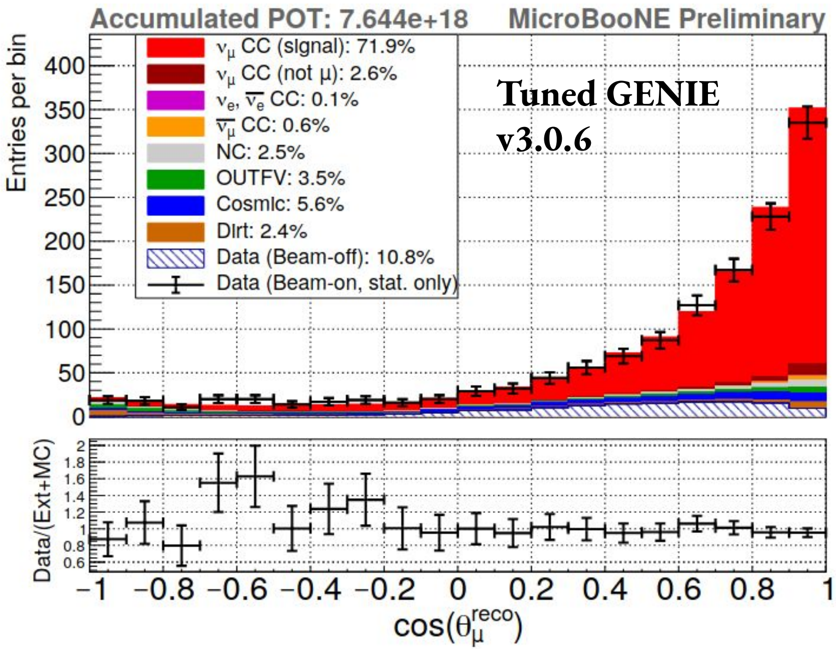
In addition to the measured event rate, the inputs to the method are a **covariance matrix** calculated from simulation (which describes the statistical and systematic uncertainties on the measurement), and a **response matrix** that describes the detector smearing and efficiency.
Treat all uncertainties using a multivariate normal distribution. Unfolded result is a linear transformation of the measurement. Simple recipes for assessing uncertainties & bias

The Wiener-SVD method produces an *unfolded* cross section in true kinematics, a covariance matrix describing the total uncertainty on this cross section, and an additional smearing matrix, A_c, which contains information about the regularization and bias of the measurement. The matrix A_c is applied to a true cross section prediction when comparing to the unfolded data.

ν_μ CC Inclusive @ BNB (Flux Averaged): Next Gen Analyses

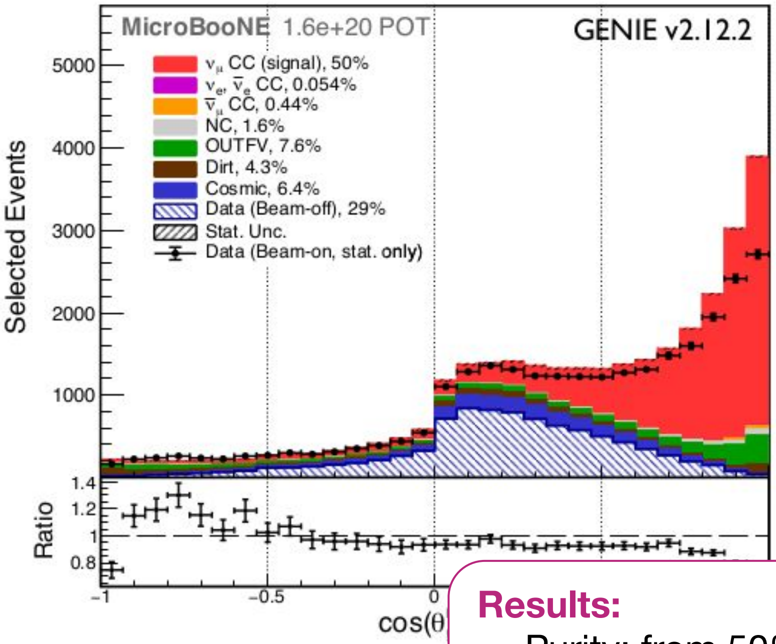


Previously published measurement
Phys. Rev. Lett. 123, 131801 (2019)

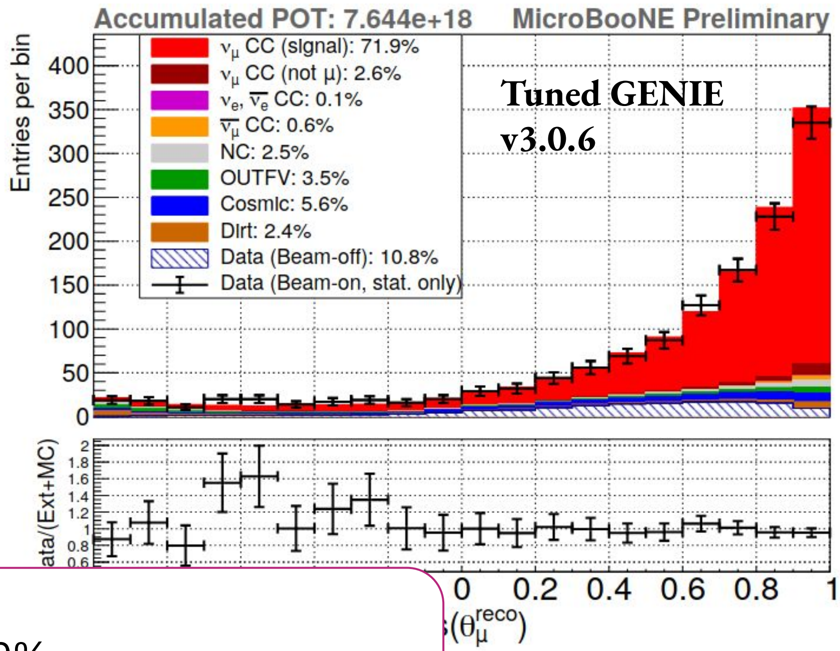


Update measurement
MICROBOONE-NOTE-1069-PUB

ν_μ CC Inclusive @ BNB (Flux Averaged): Next Gen Analyses



Previously published measurement
Phys. Rev. Lett. 123, 131801



Update measurement
MICROBOONE-NOTE-1069-PUB

Results:
→ Purity: from 50% to 71.9%
→ 3x Reduction of cosmic contamination
→ Detector uncertainties from 16.2% to 3.3 %

NC single π^0 production, no charged pions

Add link to public material

2 final state topologies $2\gamma 1p 0\pi$ & $2\gamma 0p 0\pi$ + semi-inclusive measurement, in 5.89×10^{20} POT
Signal definition no other hadrons or leptons. True proton kinetic energy > 50 MeV, semi-inclusive: any number of protons
Pandora reconstruction framework,
common preselection (leading shower energy > 30 MeV, subleading > 20 MeV, vtx in fiducial volume)

2γ1p

gap: > 1 cm from the reconstructed neutrino vtx.
Track start point < 10 cm from nu vtx

BDT: training signal $E^{True}_p > 20$ MeV

- Leading and subleading shower impact parameters
- Leading and subleading shower conversion distances
- Reco Energy of leading shower
- Reconstructed track length.
- Reconstructed track vertical angle
- Distance from track end to TPC wall
- Track dEdx & Bragg peak

634 candidates, 4.4% efficiency, 63.5% purity

2γ0p

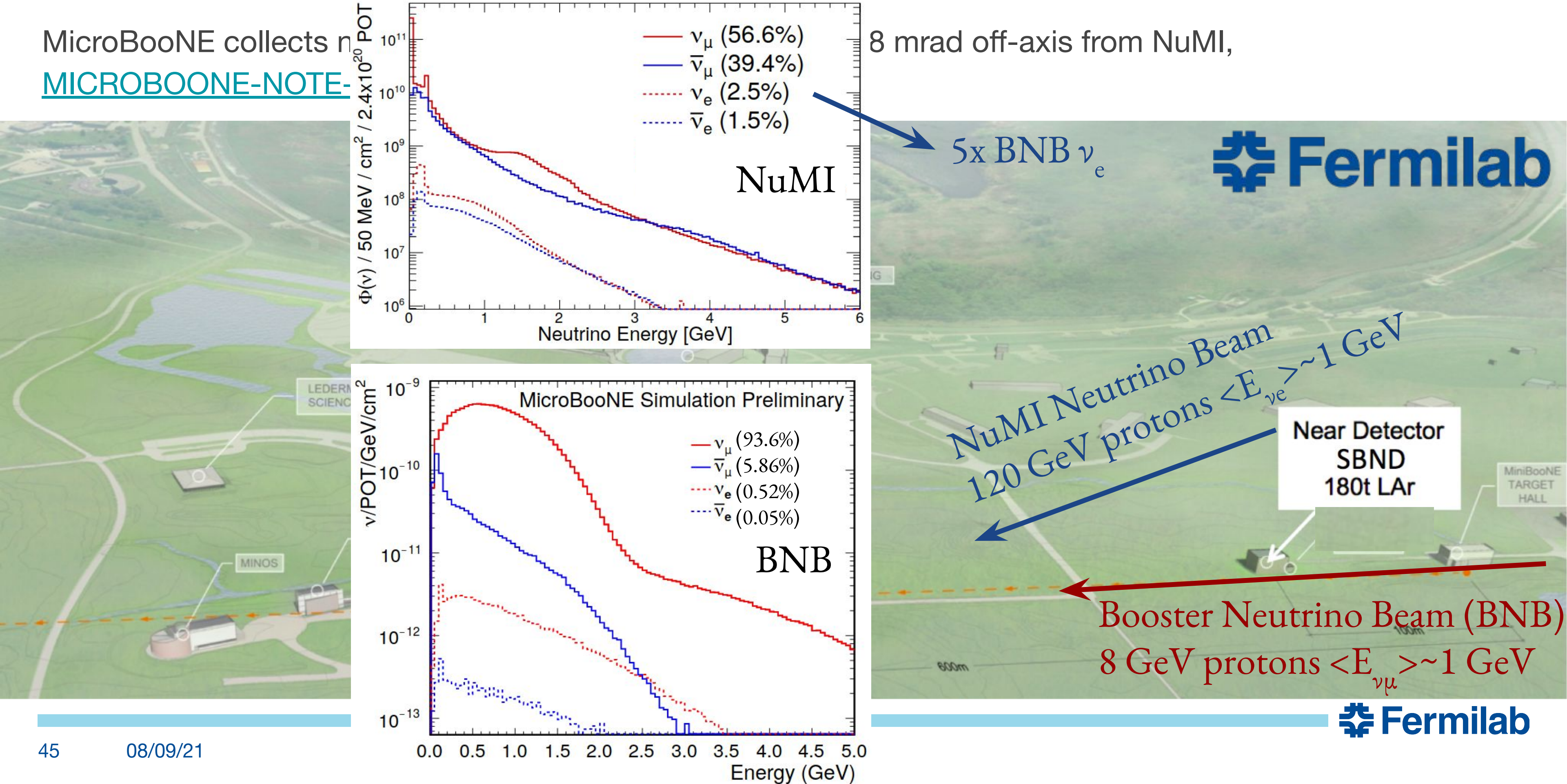
BDT: training signal $E^{True}_p < 20$ MeV

- Leading and subleading shower impact parameters
- Leading and subleading shower conversion distances
- Reco Energy of leading shower
- Reco Energy of subleading shower
- Leading and subleading shower geometric length
- Pandora Neutrino Score
- Reconstructed leading shower vertical angle

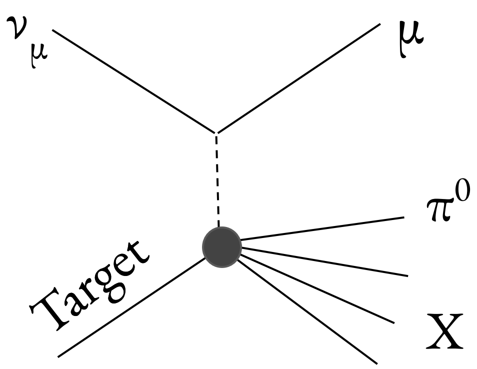
496 candidates, 2.3% efficiency, 59.6% purity

Beams at MicroBooNE

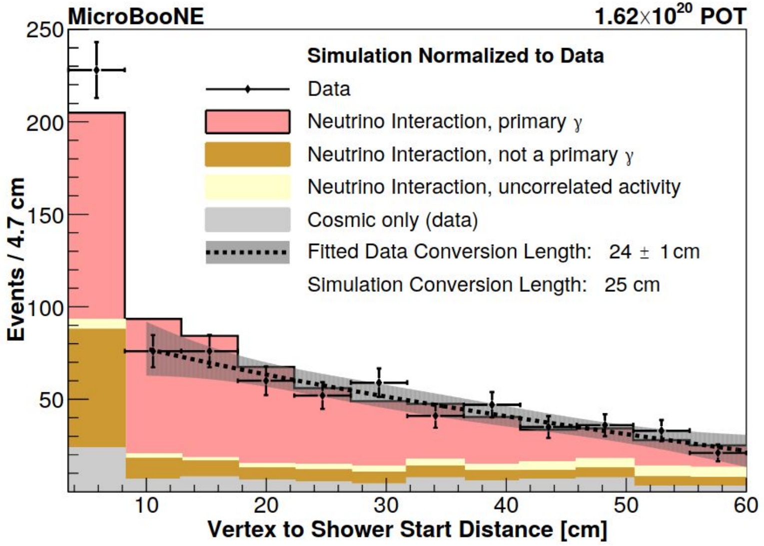
MicroBooNE collects n… 8 mrad off-axis from NuMI,
MICROBOONE-NOTE-…

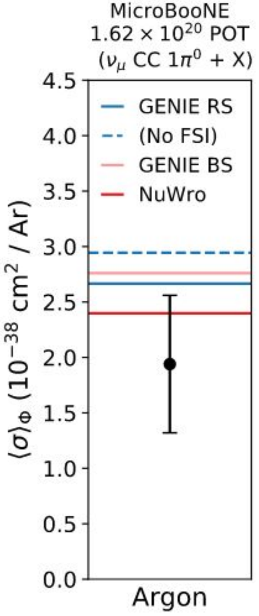


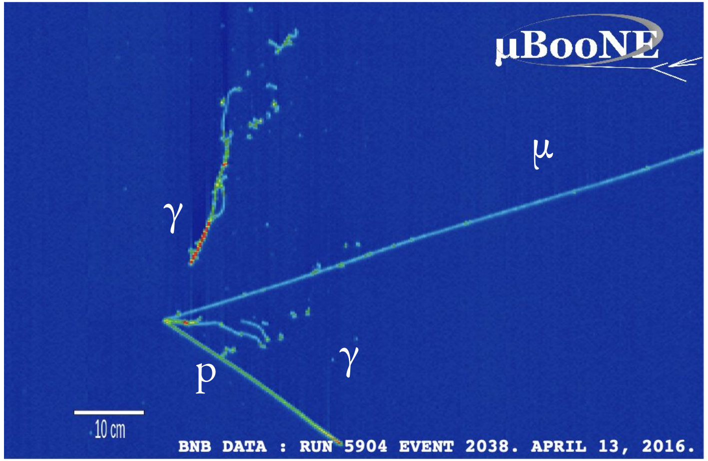
Production of neutral pions



Fundamental background to the LEE search
First measurement of flux averaged ν_μ-Ar CCπ^0 cross section
Phys. Rev. D99, 091102(R) (2019)







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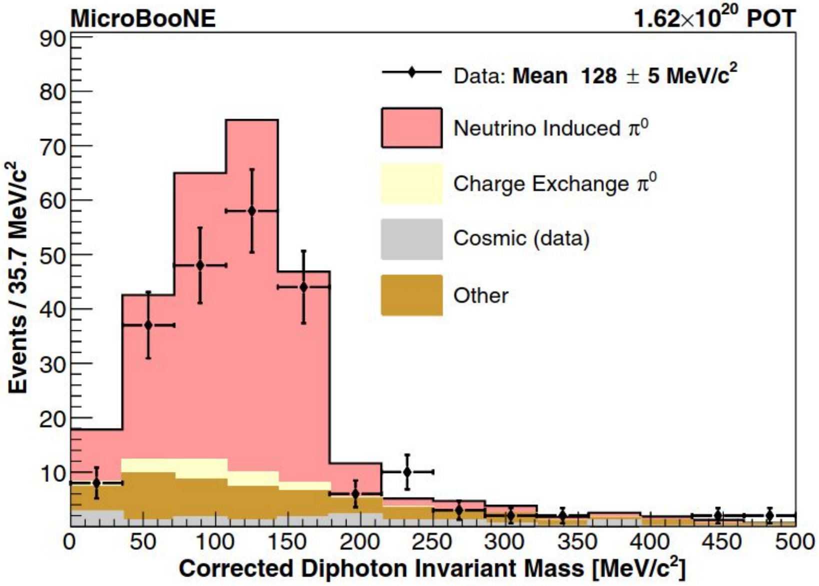
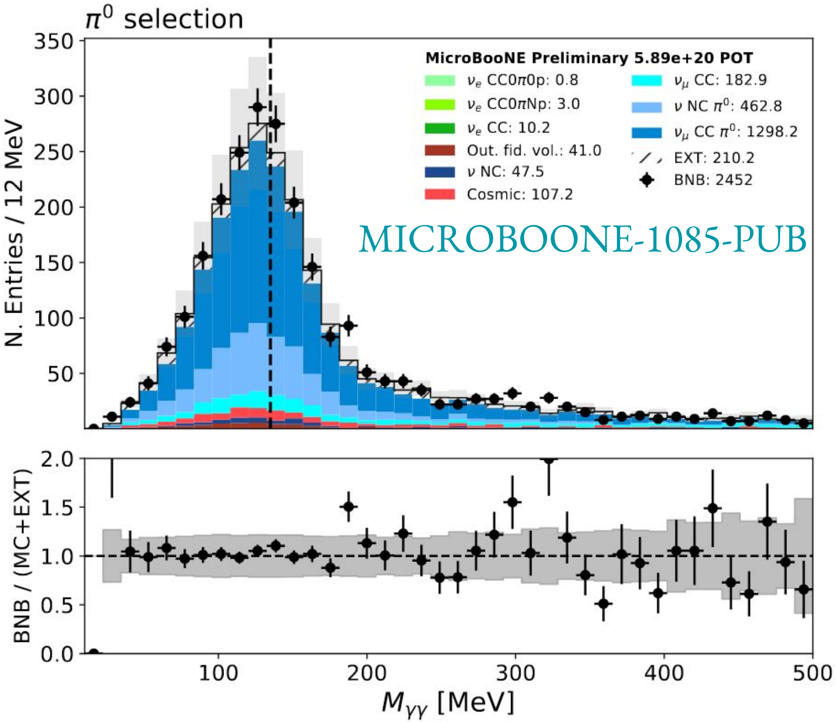
Neutral Pions!

With the update described



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



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Notes on results:

Energy dependent CC cross section.

Selection: neutrino vertex in fiducial volume (3 cm from detector boundaries)
Background rejection via muon directionality, NC rejection via muon length (5+ cm). Some charged pion rejection is achieved by detecting large-angle scattering in reconstructed track trajectories.

BDT from the background taggers —> 92% purity and 68% efficiency. 11528 ν_μCC candidates . 1/3 of the events are fully contained (FC) and 2/3 are partially contained (PC)

Energy Reco: Energy of stopping tracks via length (4+ cm), via calorimetry. Energy of EM shower by calibrated reconstructed charged.

The reconstructed neutrino energy Erec per event is estimated by summing the kinetic energies of each reconstructed (visible) final-state particle + their mass. If protons: 8.6 MeV of binding energy. The predicted energy resolution according to MC: Muon: ~10% Neutrino: ~20% Hadronic :~30- 50%

Unfolding: Wiener-SVD unfolding is used. Covariance matrix formalism to includes systematic uncertainties: flux 5-15%, XS ~20%, G4 ~1.5%, Detector same level as XS?

Constraint: the MC prediction is constrained using the FC events in muon energy and angle, then Erechad is compared distribution for the FC .
Binning: of the unfolded results is chosen by considering the energy resolution and the number of samples in the true space.