Recent MicroBooNE Neutrino Cross-Section Results

Marina Reggiani-Guzzo
on behalf of the MicroBooNE collaboration

EPS-HEP Conference, 21-25 August 2023

Outline

Neutrino cross sections

MicroBooNE and LArTPCs

Cross section results

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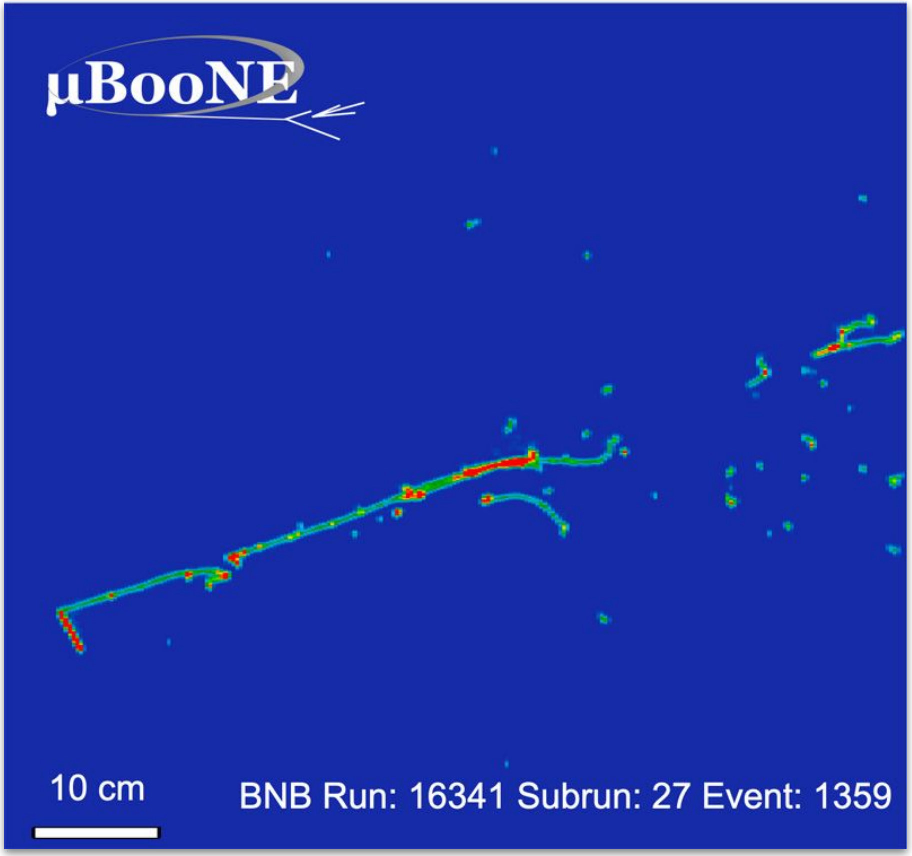
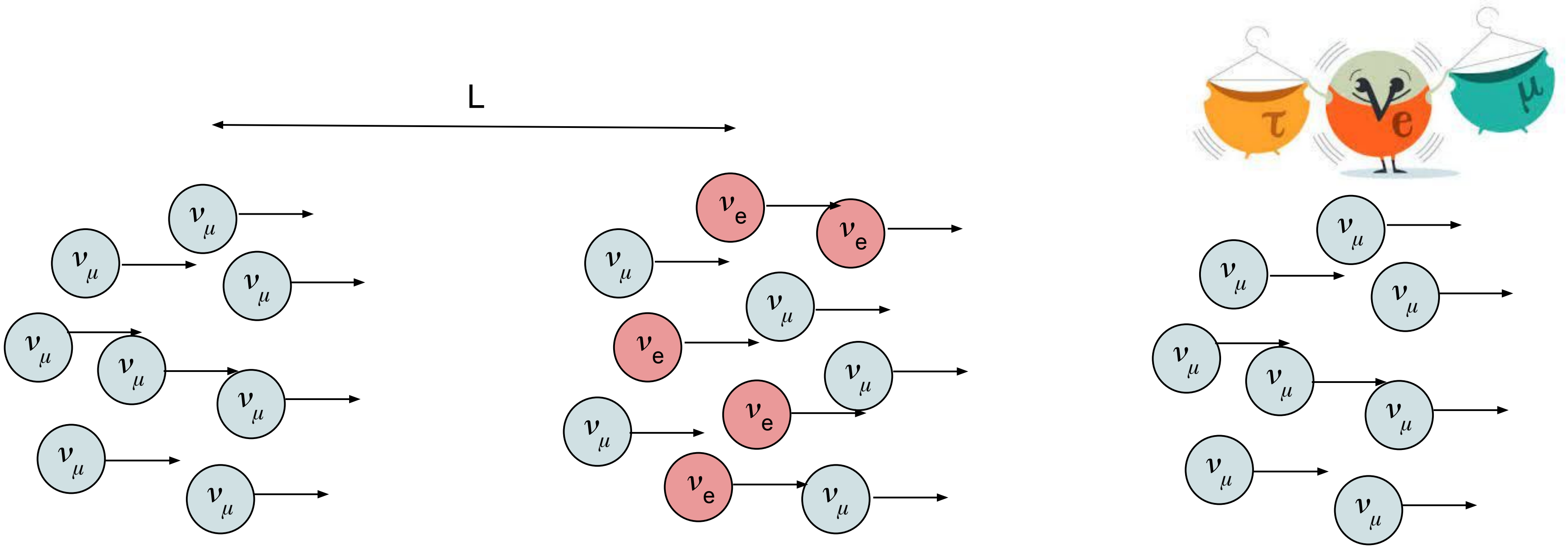
Cross section results



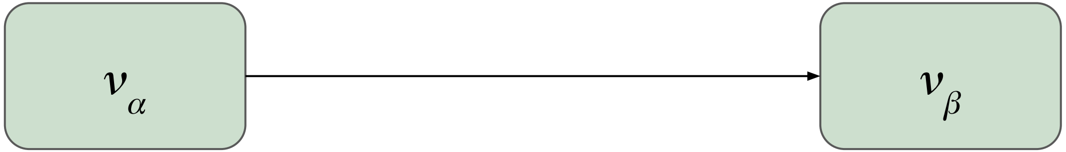
Why do we measure neutrino cross sections?

Neutrino oscillation, where neutrinos change flavour as they travel.



Why do we measure neutrino cross sections?

Oscillation probability is a function of the neutrino cross section.



Neutrino flux

Detection efficiency

$$N^\beta(E_{rec}) \sim \Phi(L, E_\nu)\sigma(E_\nu)\epsilon(E_\nu)P(\nu_\alpha \rightarrow \nu_\beta)$$

Measured

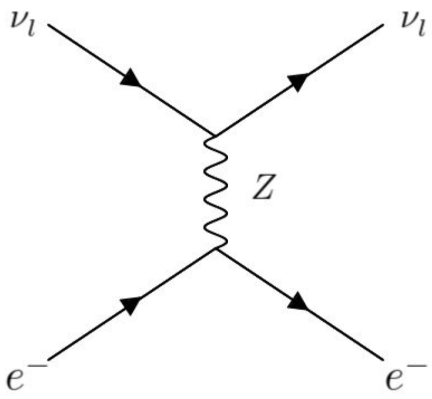
Neutrino cross section

Oscillation probability

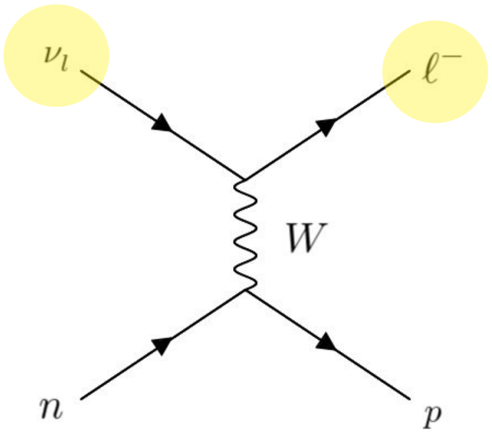
Neutrino Interactions

Neutrinos undergo weak interactions.

Neutral current: Same process for all neutrino flavours

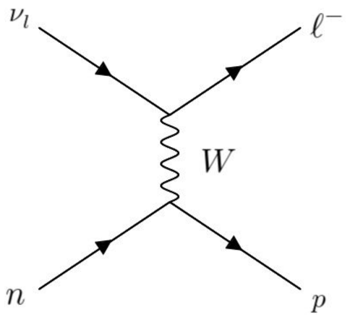


Charged current: Produced lepton flavour in agreement with incoming neutrino flavour

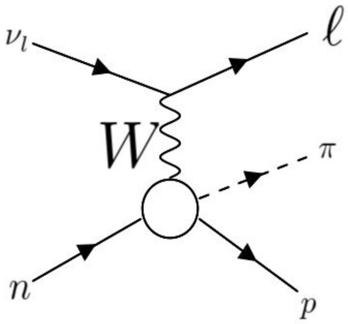


Neutrino Interactions

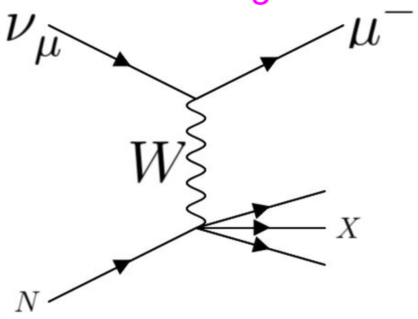
Quasi-elastic scattering

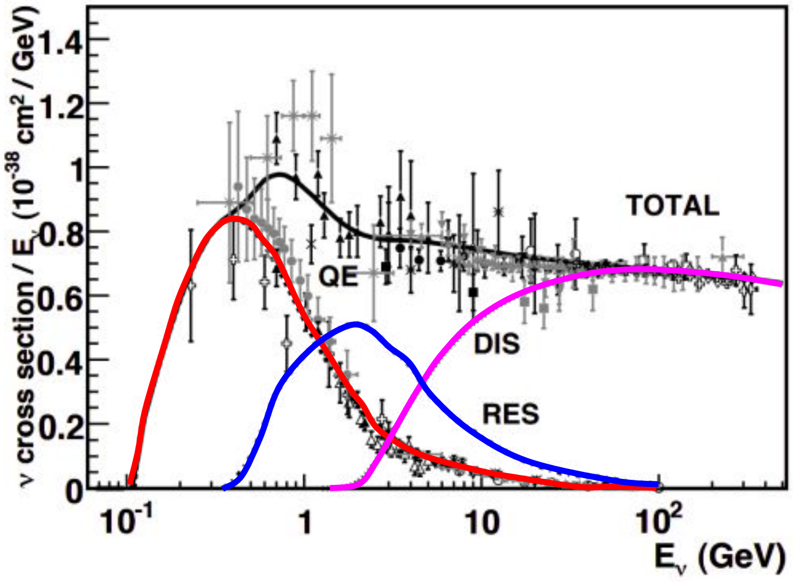


Resonant



Deep Inelastic Scattering



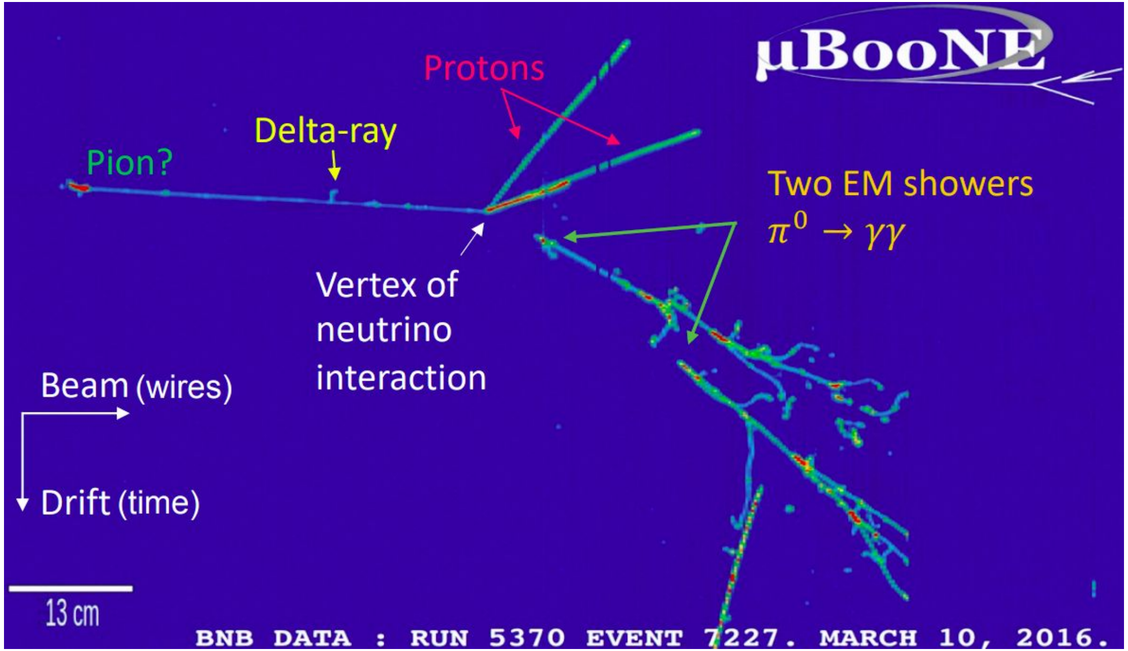


Rev. Mod. Phys. 84.1307

What are the challenges?

Our detector can only observe charged particles, neutrinos are not directly detected.

We are forced to estimate the neutrino energy through other quantities.

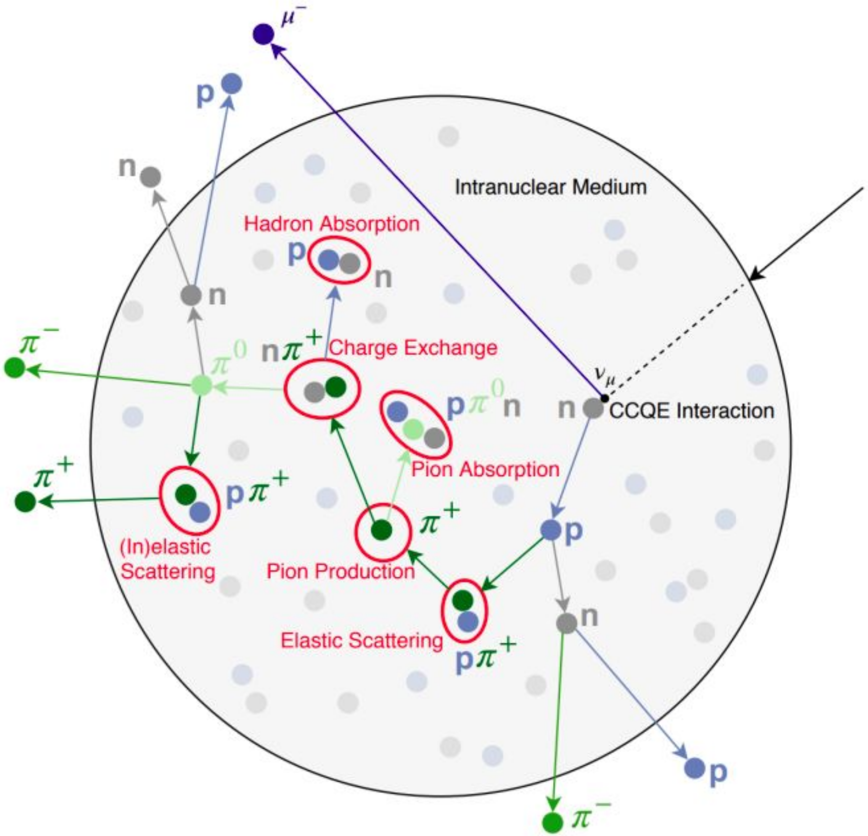


However… complicated neutrino interactions

Observed particles might not be the primary daughter particles.

Effects become larger the heavier the nucleus.

Nuclear effects introduce quantities we cannot directly observe.



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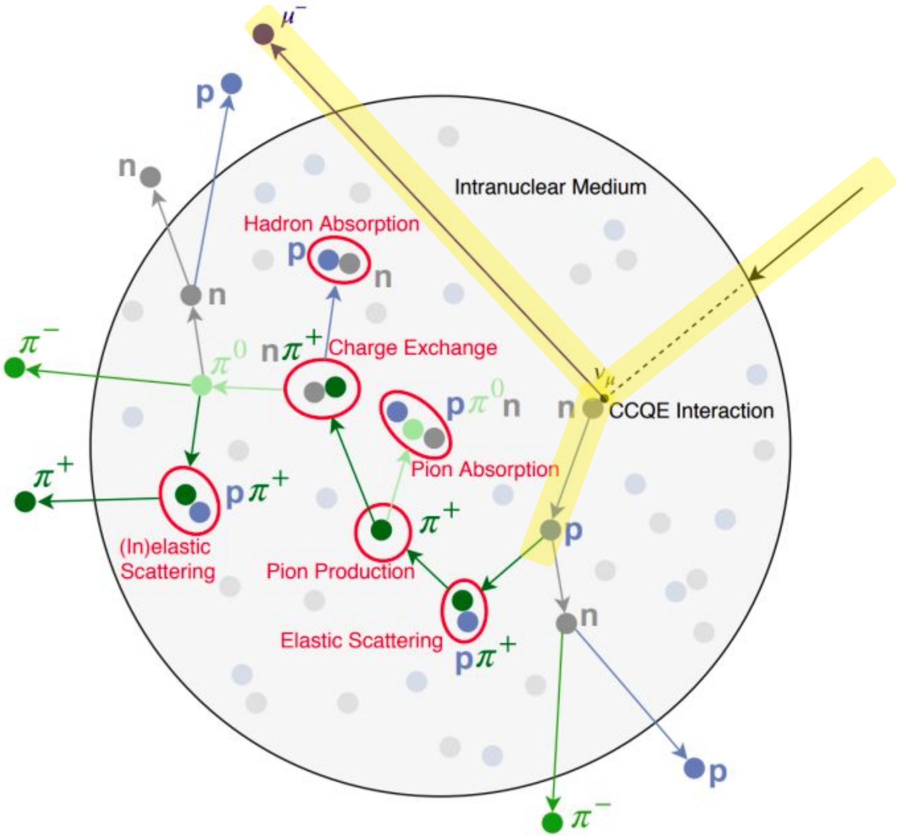

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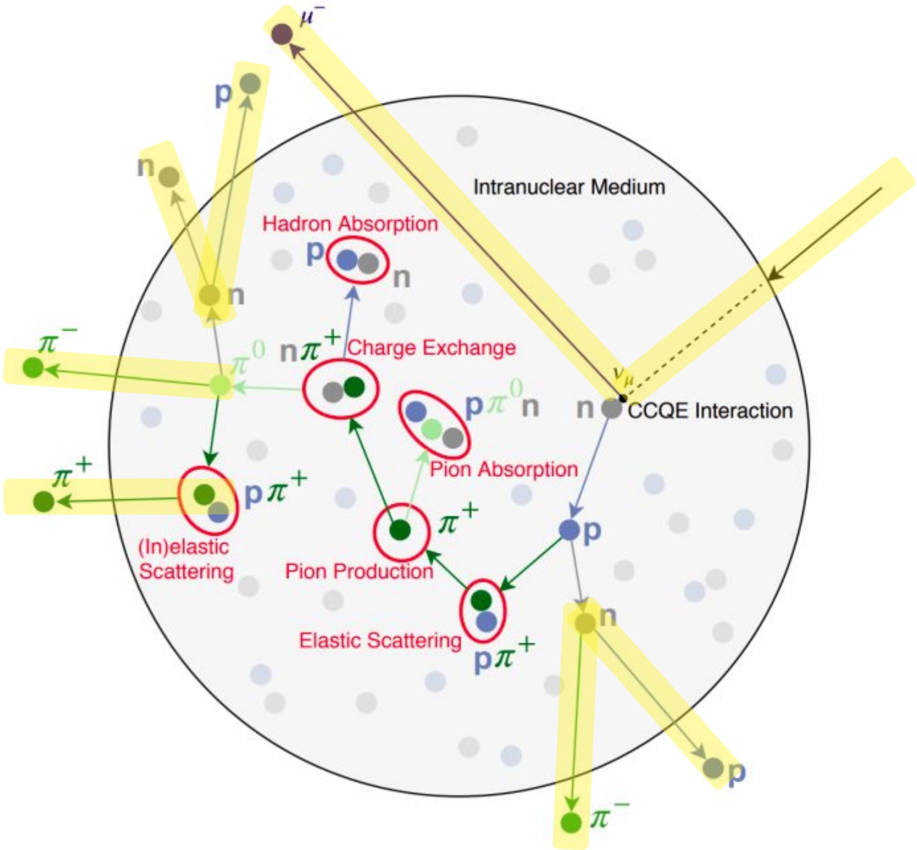

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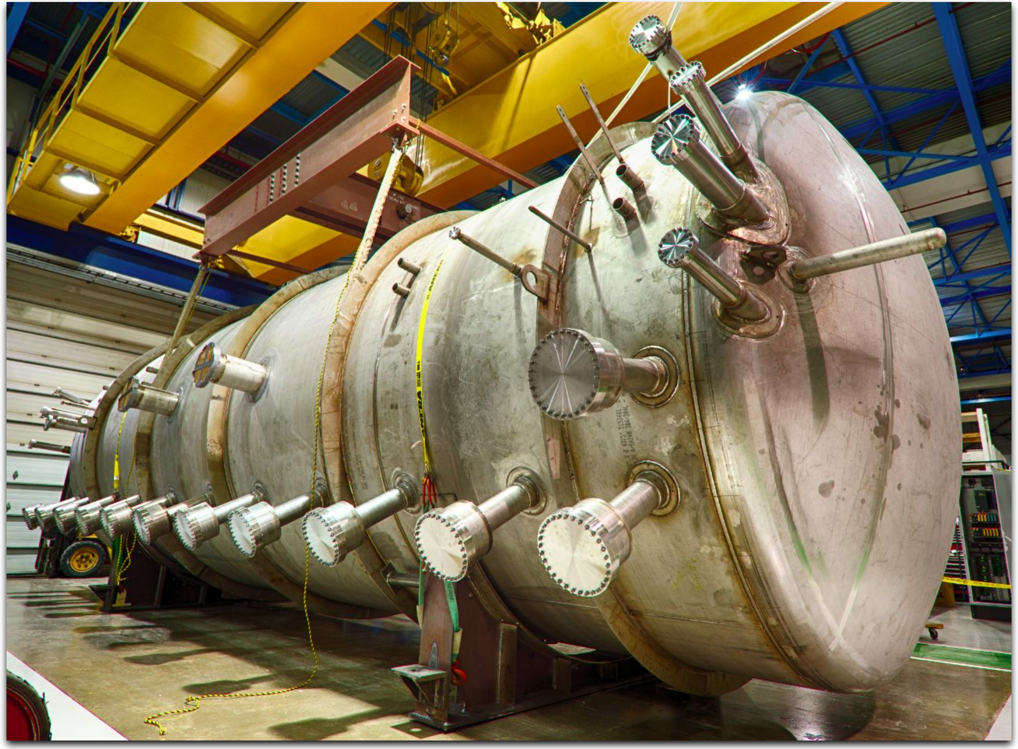
The MicroBooNE Experiment

A precise detector is needed to measure and unravel these complicated interactions.

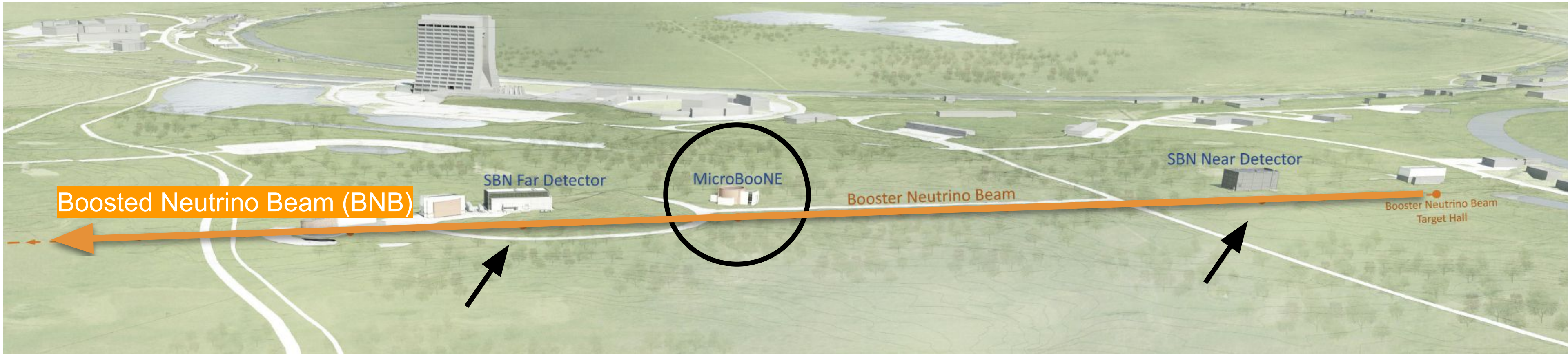
A Liquid Argon Time Projection Chamber (LArTPC) is a great solution!

MicroBooNE:
10.36 x 2.56 x 2.32 m^3
85 tonnes of active mass of LAr



The MicroBooNE Experiment

SBN program

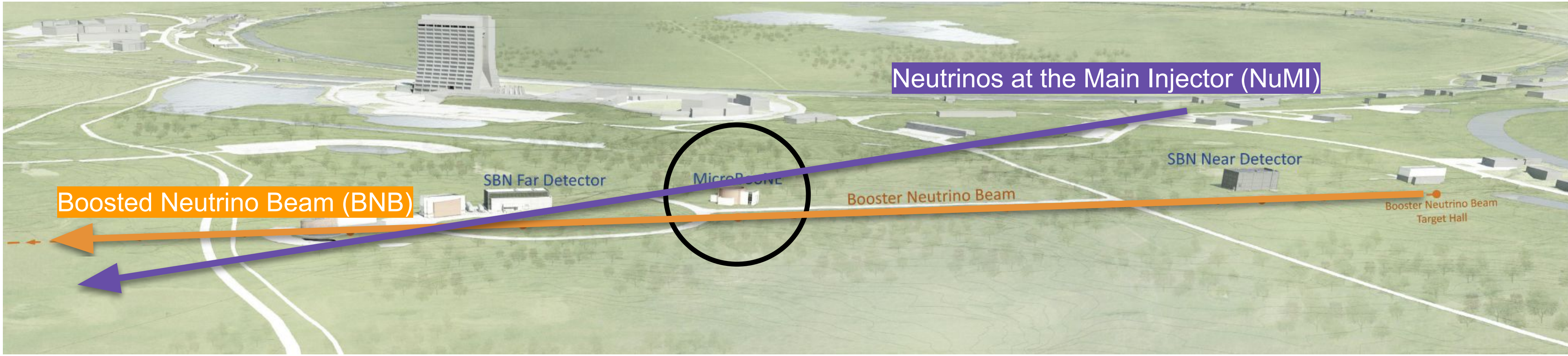


Physics goals covered in this conference:

- Low-energy excess (LEE) anomaly — See Benjamin Bogart's talk tomorrow
- Beyond standard model program — See Luis Mora's talk on Friday

The MicroBooNE Experiment

SBN program



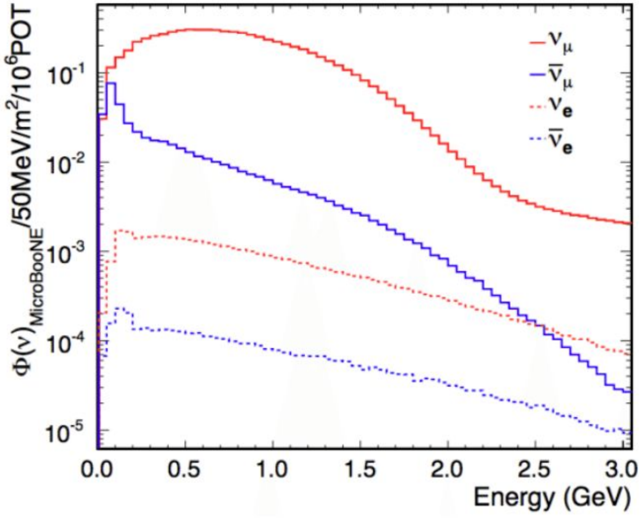
MicroBooNE's off-axis to the NuMI beam → more data available!

Neutrino fluxes

BNB beam Phys. Rev. D 79, 072002

8 GeV protons

Flux is 99.3% $\nu_\mu/\bar{\nu}_\mu$

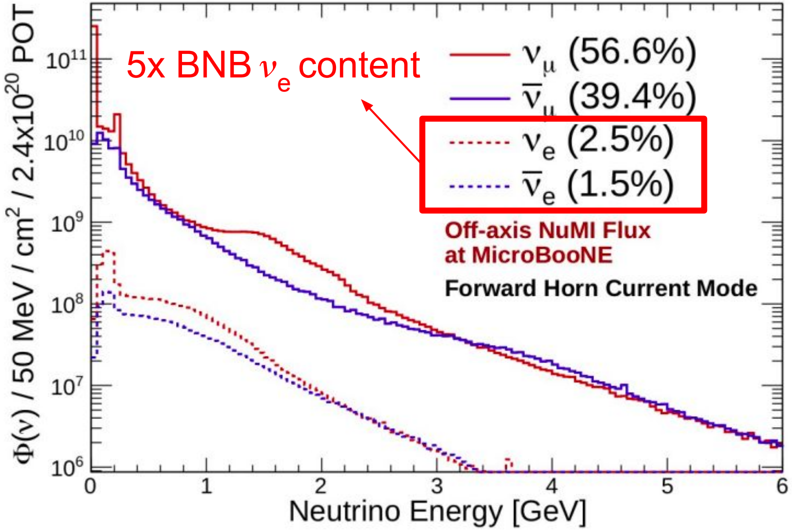


NuMI beam Nucl. Instrum. Meth. A806, 276-306
Phys. Rev. D 104, 052002

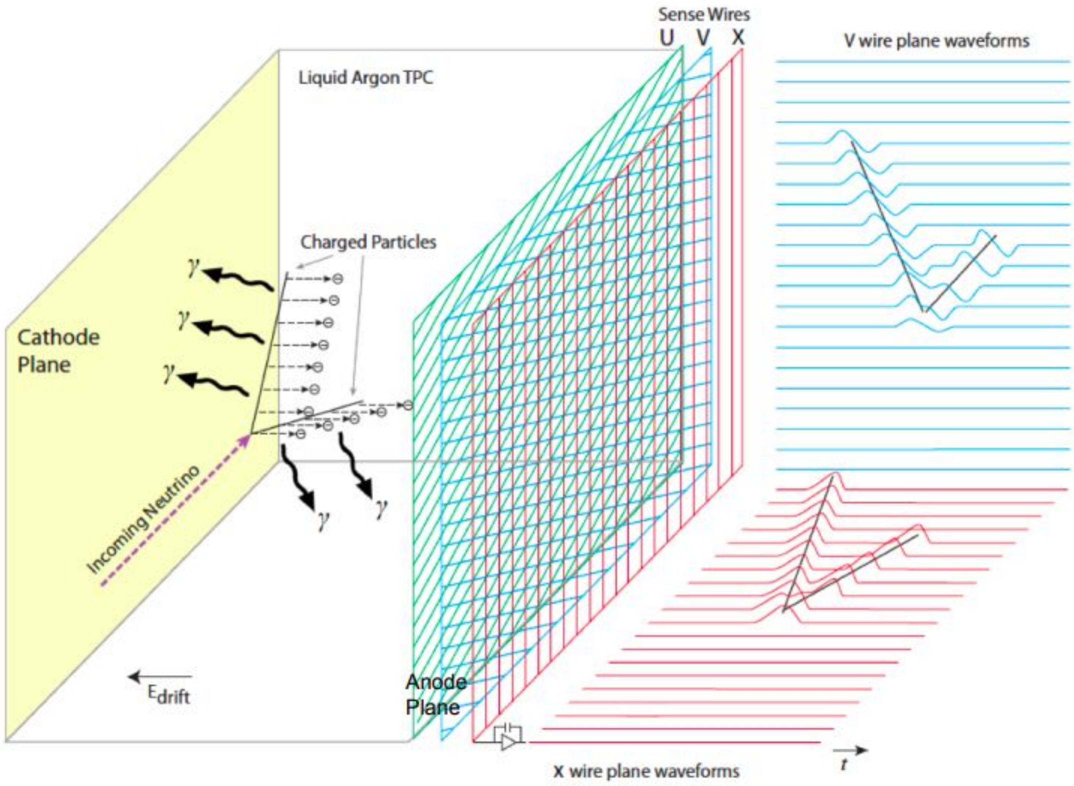
120 GeV protons

Off-axis: enhances wrong sign component

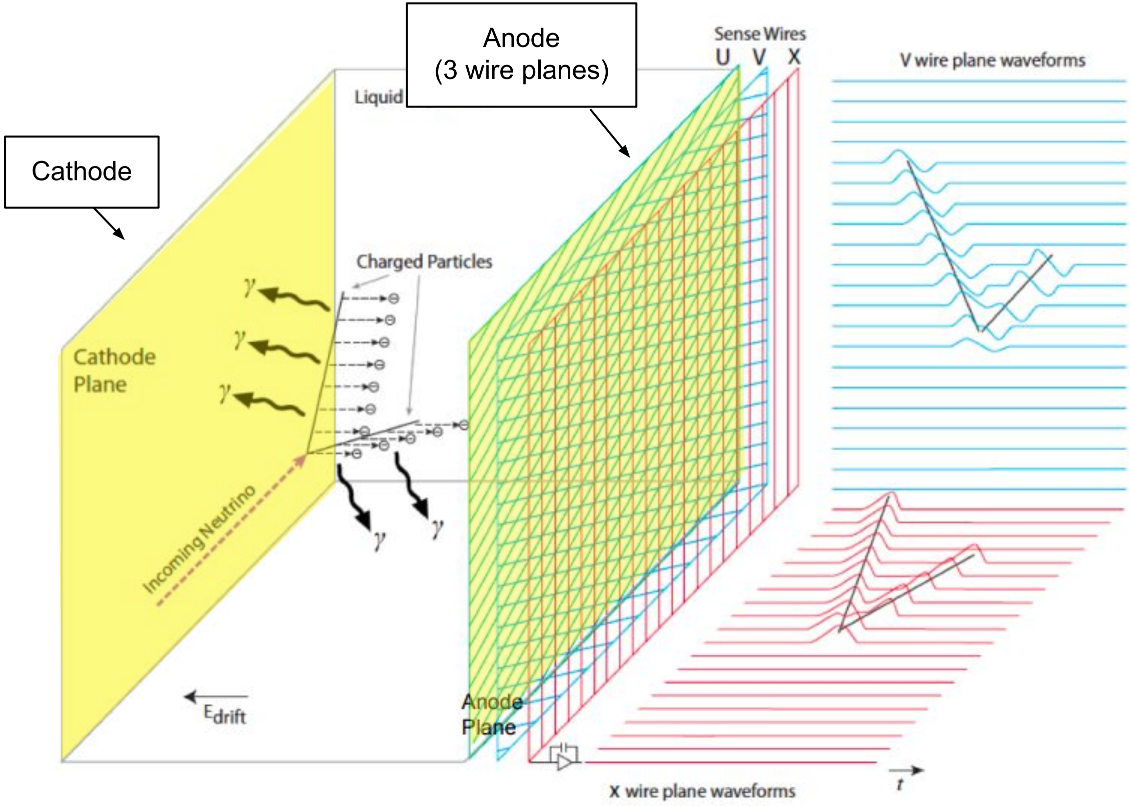
→ larger $\nu_e/\bar{\nu}_e$ flux



Liquid Argon Time Projection Chambers



Liquid Argon Time Projection Chambers



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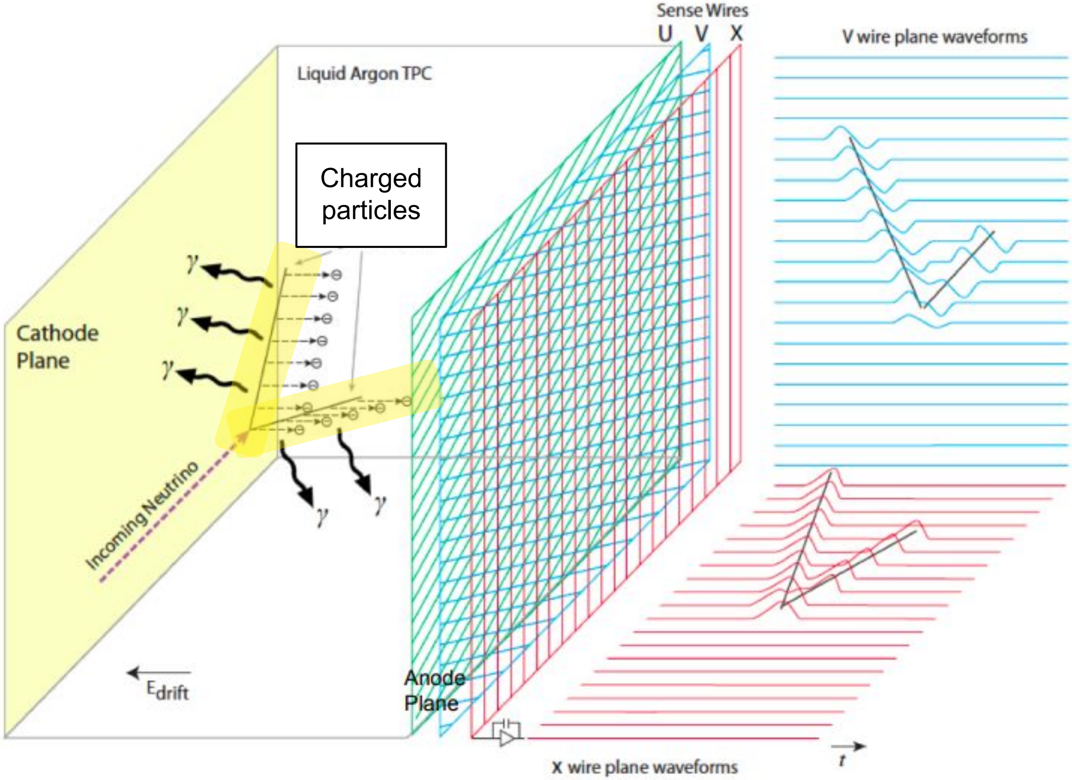
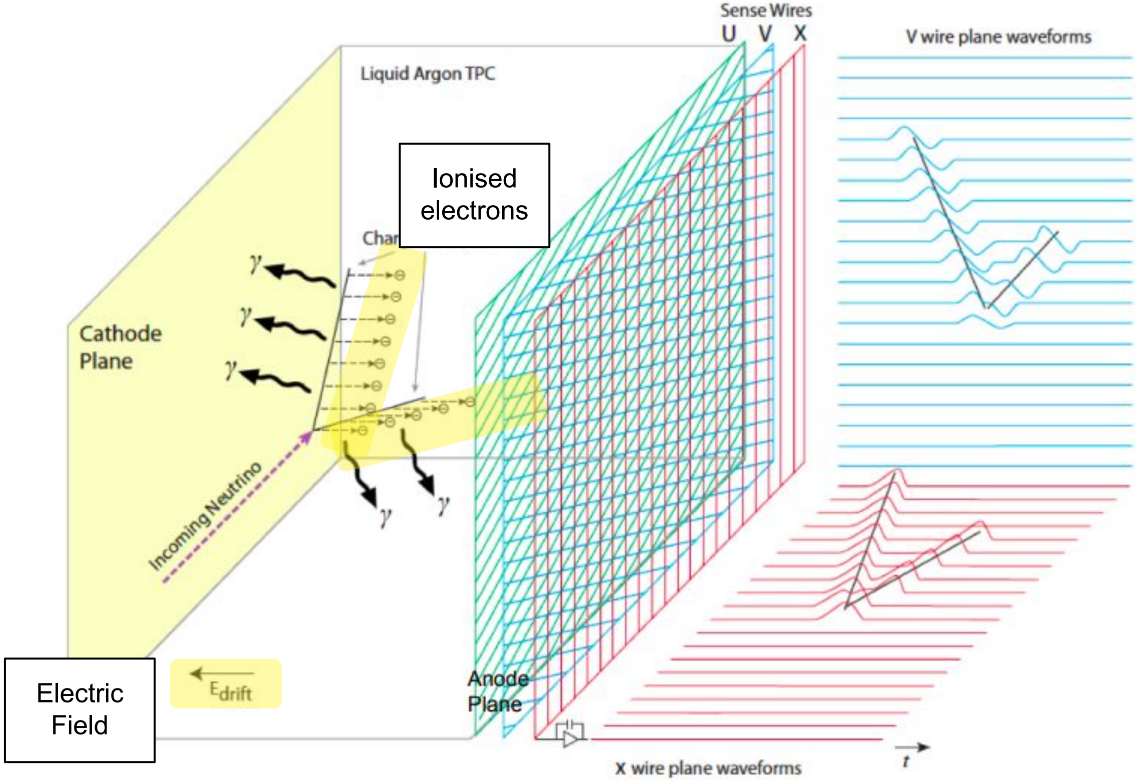
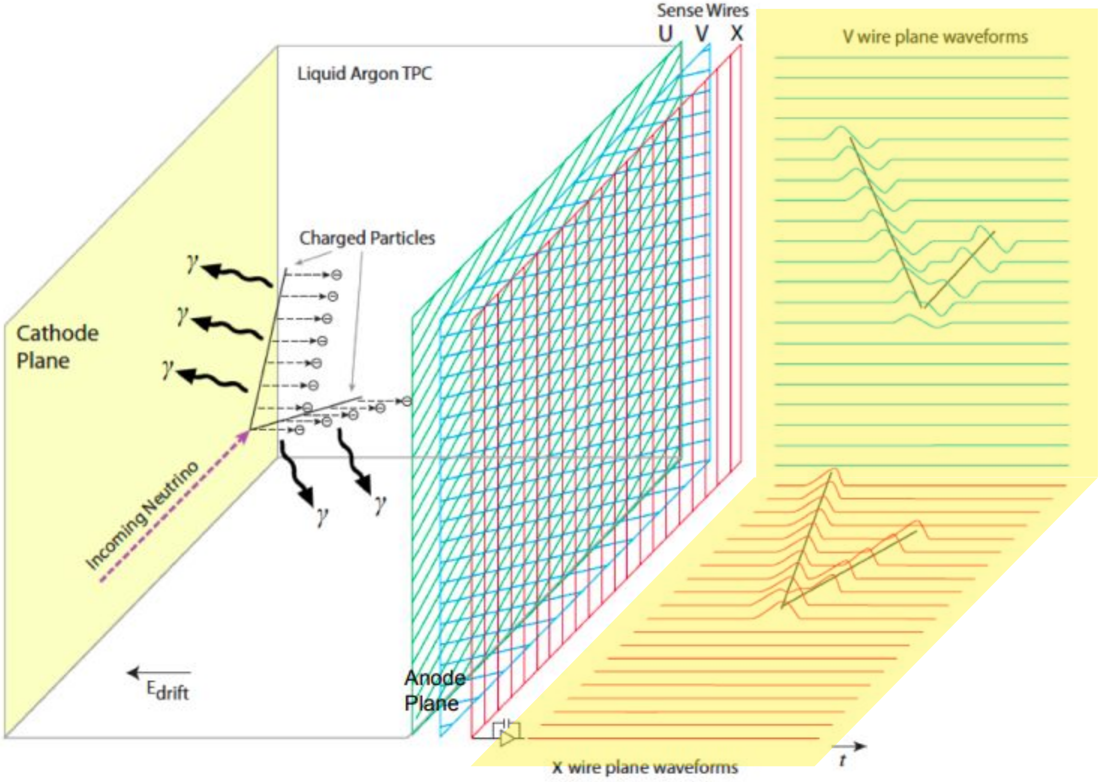


Liquid Argon Time Projection Chambers



Liquid Argon Time Projection Chambers

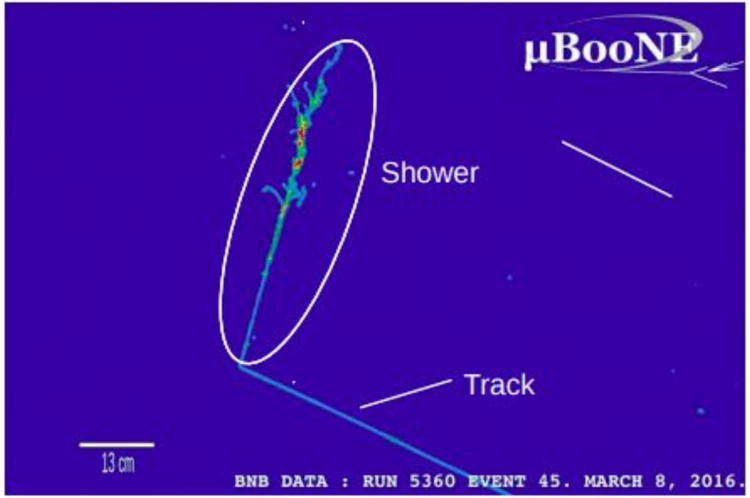


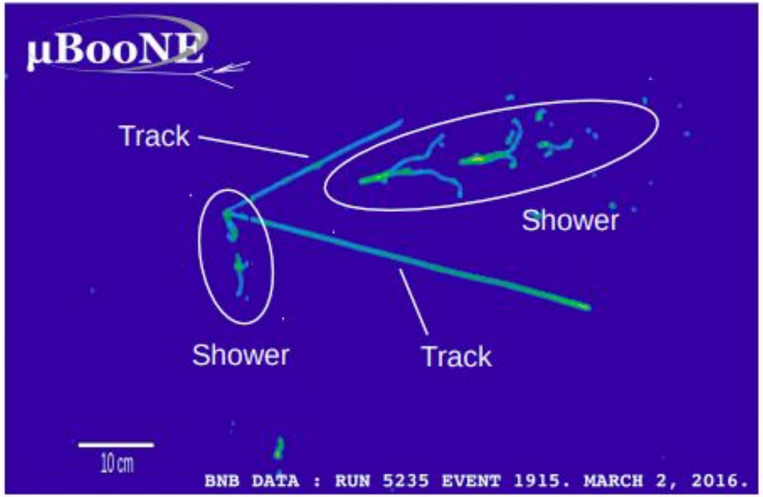
Induced currents in the wires are reconstructed into particle trajectories

Particle Signatures

Colours: amount of deposited energy

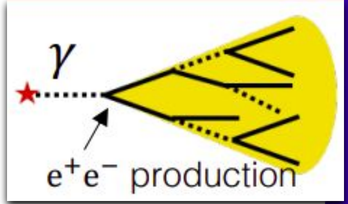
Signatures: shower ($e^{\pm}$, γ, π^0…) or track ($\mu^{\pm}$, p…)

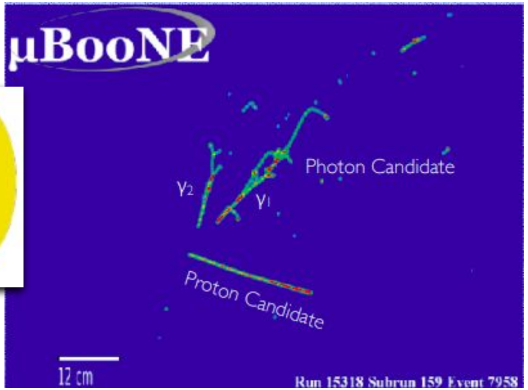


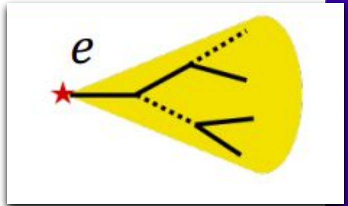


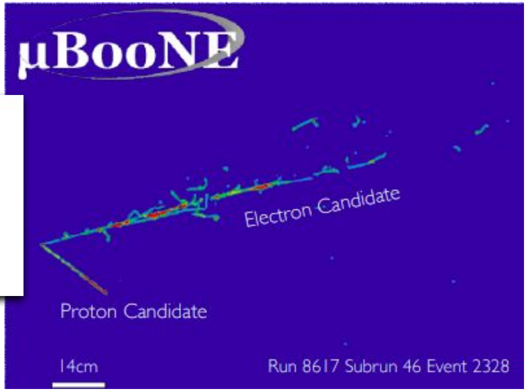
Quality and kinematic criteria → particle identification!

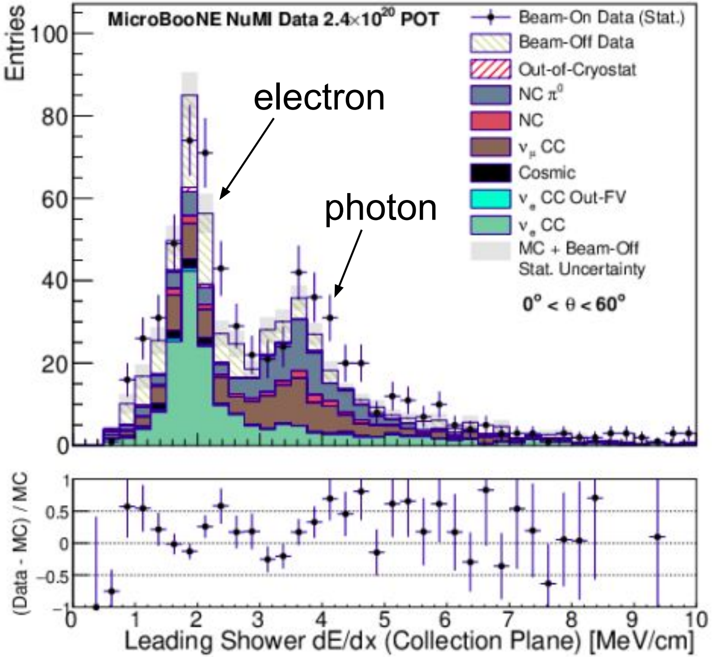
Electron/Photon Separation











Phys. Rev. D 104, 052002 (2021)

Important for electron-neutrino CC measurements:

- CC interactions → electrons
- NC interactions → photons (background)

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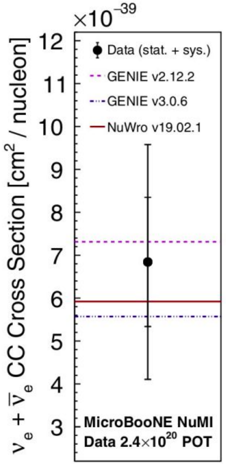
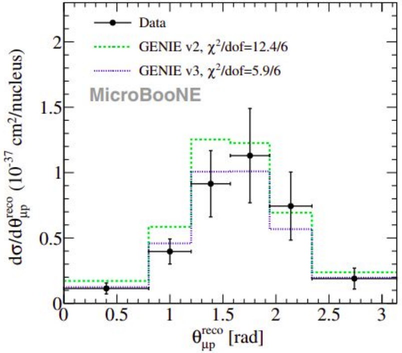
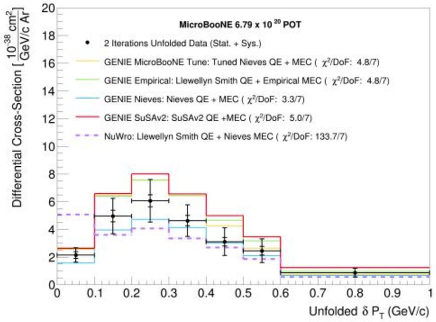
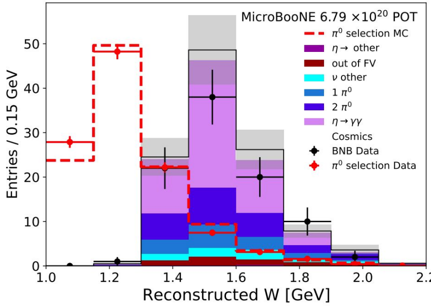
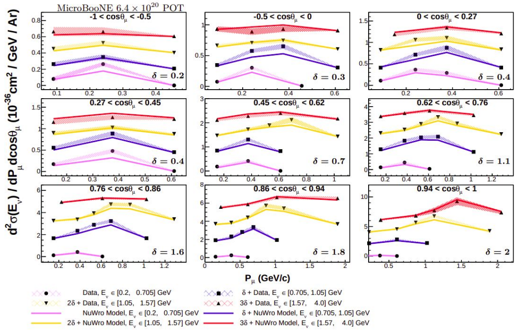
Cross section results



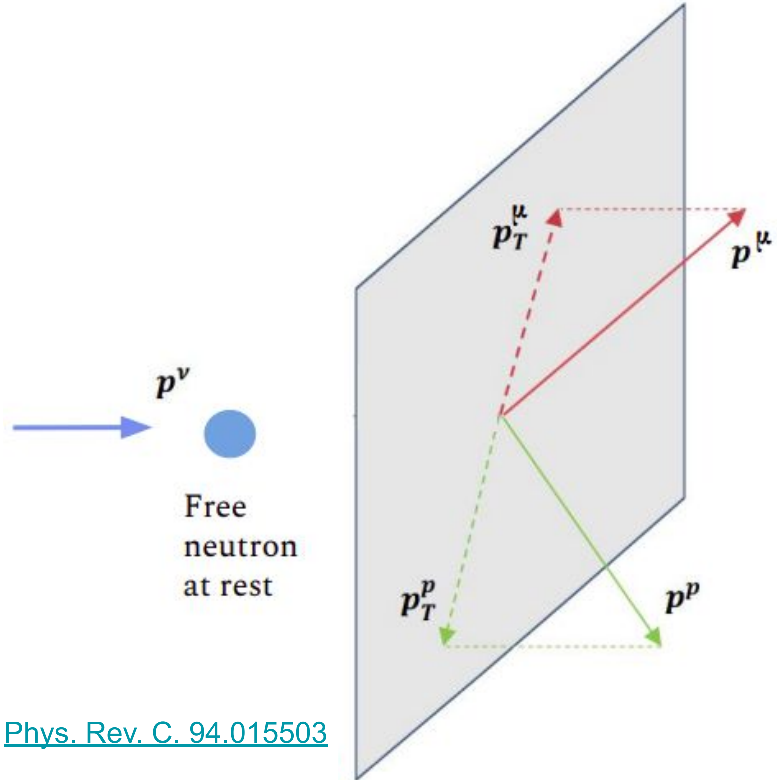








Transverse Kinematic Imbalance (TKI) Variables



[Phys. Rev. C. 94.015503]

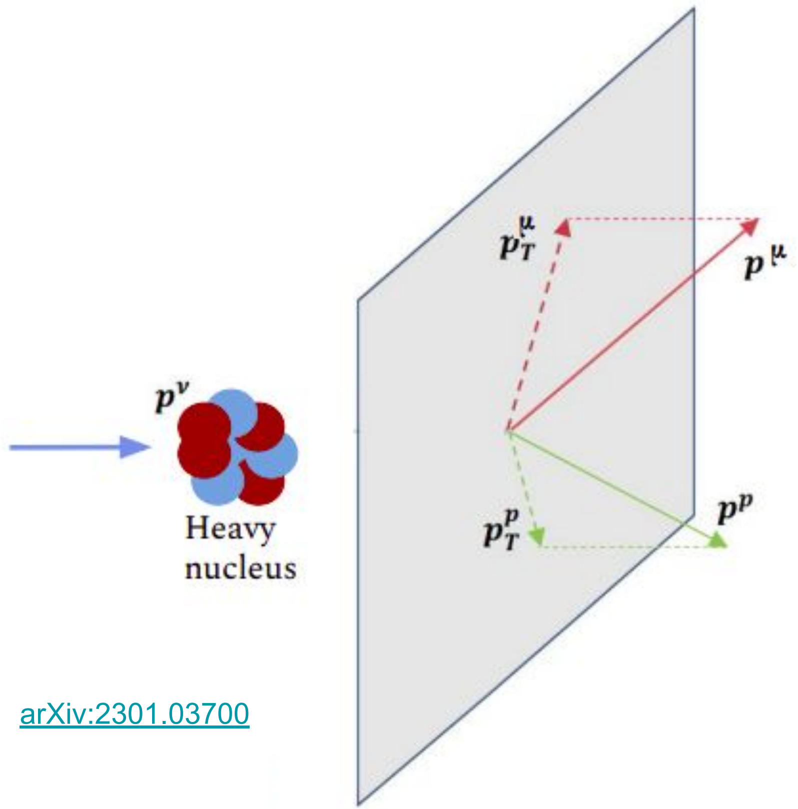
Nuclear effects impact the output of neutrino interactions.

Understanding nuclear effects is crucial, and excellent progress has been made towards this.

Transverse missing momentum
$\delta p_T = | \mathbf{p}_T^\mu + \mathbf{p}_T^p | = 0$

Pure neutrino interaction → transverse projections equal and opposite due to momentum conservation.

Transverse Kinematic Imbalance (TKI) Variables

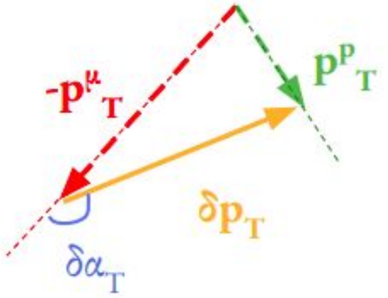


arXiv:2301.03700

Transverse missing momentum
$\delta p_T = | \mathbf{p}_T^{\mu} + \mathbf{p}_T^{p} | > 0$

TKI variables were found to be sensitive to nuclear effects → powerful descriminators of interaction models.

Transverse kinematic imbalance variables:

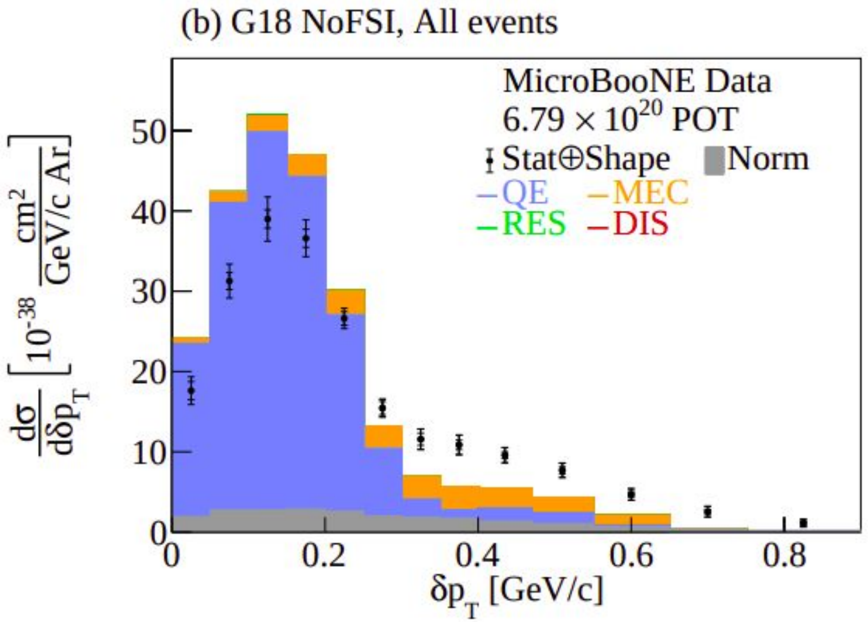


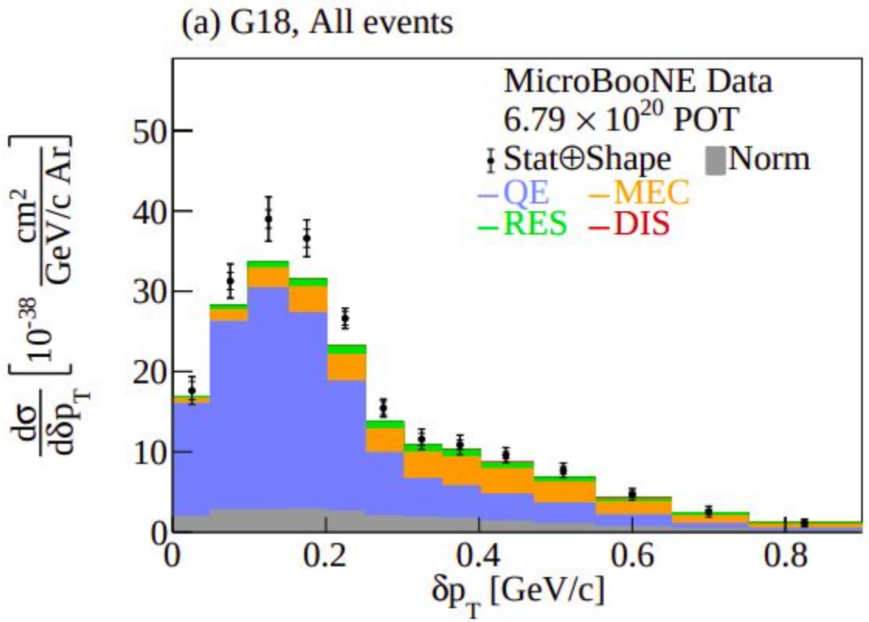
Transverse Kinematic Imbalance (TKI) Variables

No nuclear effects.
No proton reinteraction.

Include nuclear effects →

Nuclear effects considered.
Proton reinteracts in the nucleus.



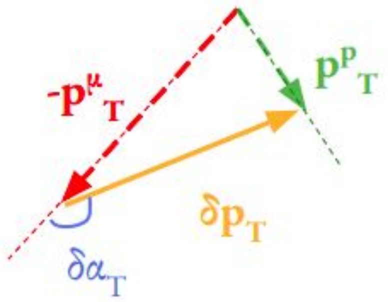


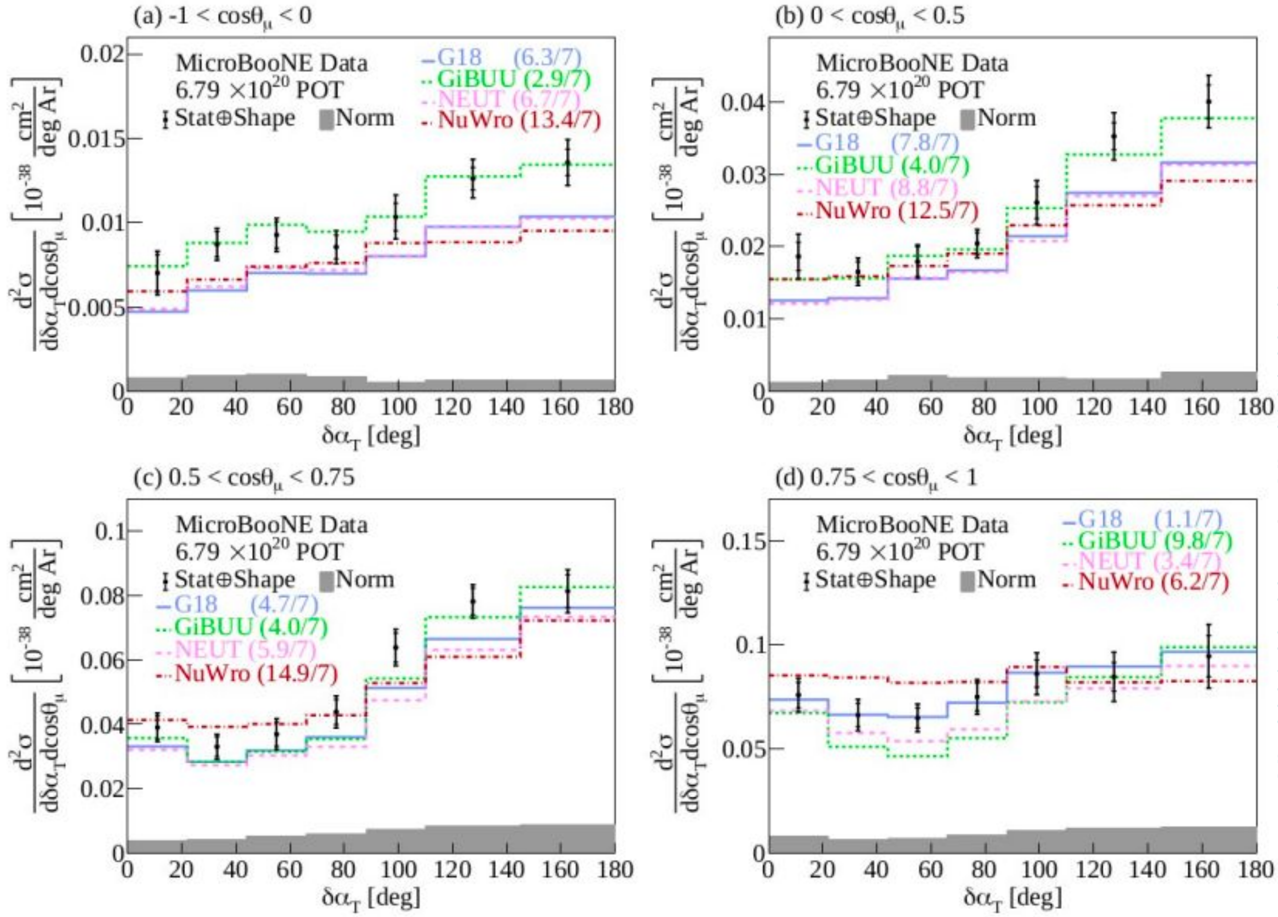
arXiv:2301.03700

Transverse Kinematic Imbalance (TKI) Variables

Necessary study to tune the nuclear effects of our neutrino generators.

The agreement varies for different scattering angles.

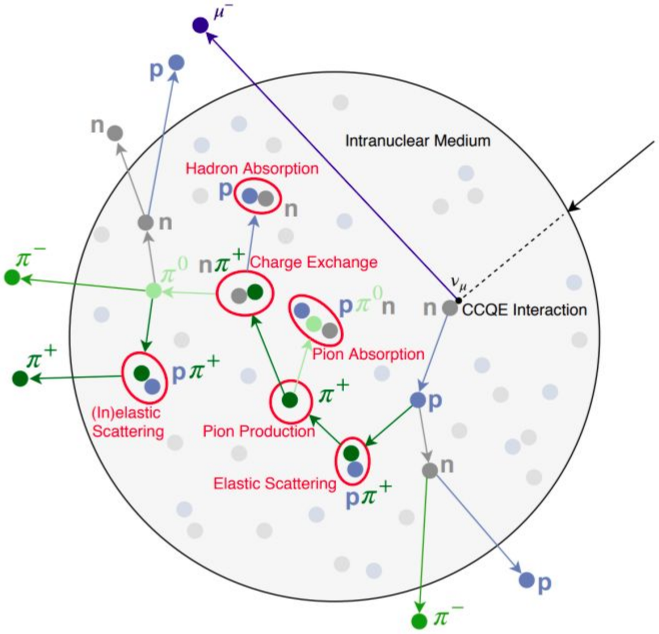


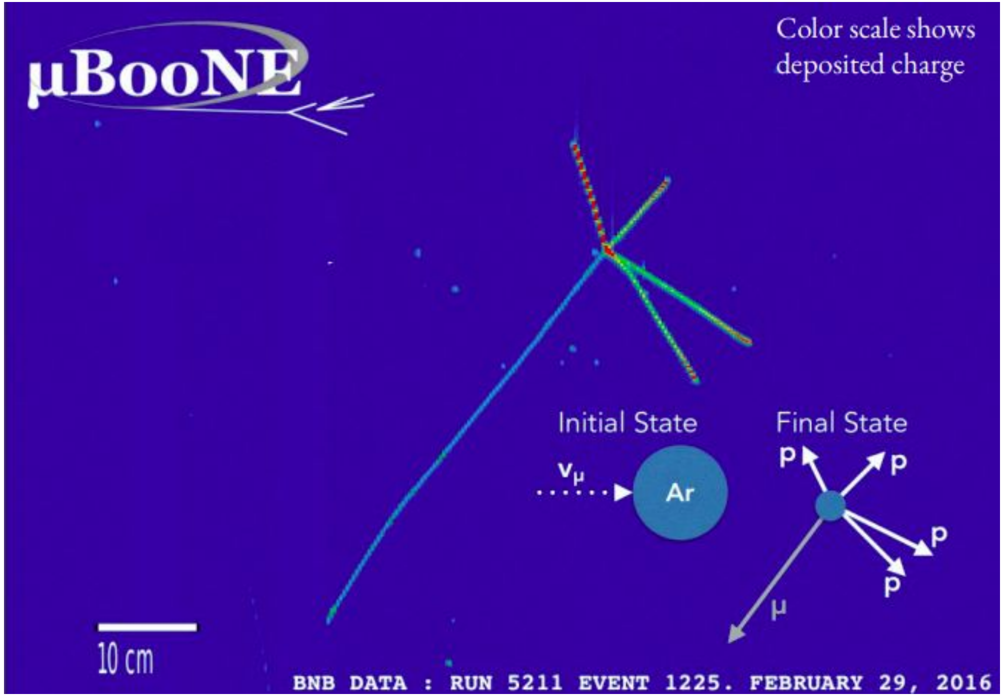


arXiv:2301.03700 and arXiv:2301.03706

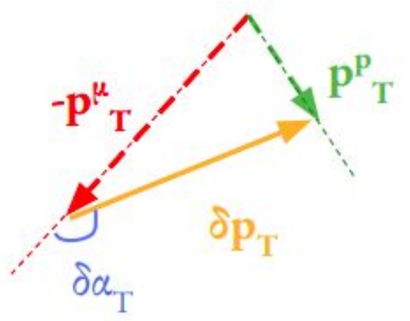
ν_μ CC multiple-proton interactions

Clear sign of final state interactions and nuclear effects.





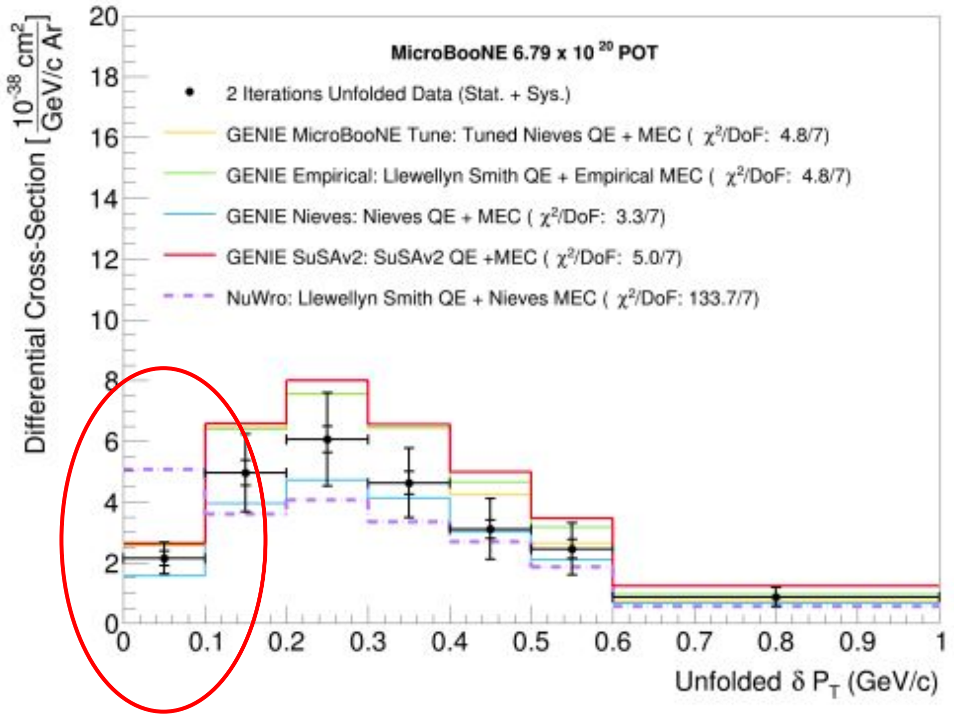
ν_μ CC multiple-proton interactions, 2p0π



Cross section as a function of the transverse momentum.

NuWro overpredicts at low values due to back-to-back proton orientation.

GENIE predictions in better agreement.



arXiv:2211.03734

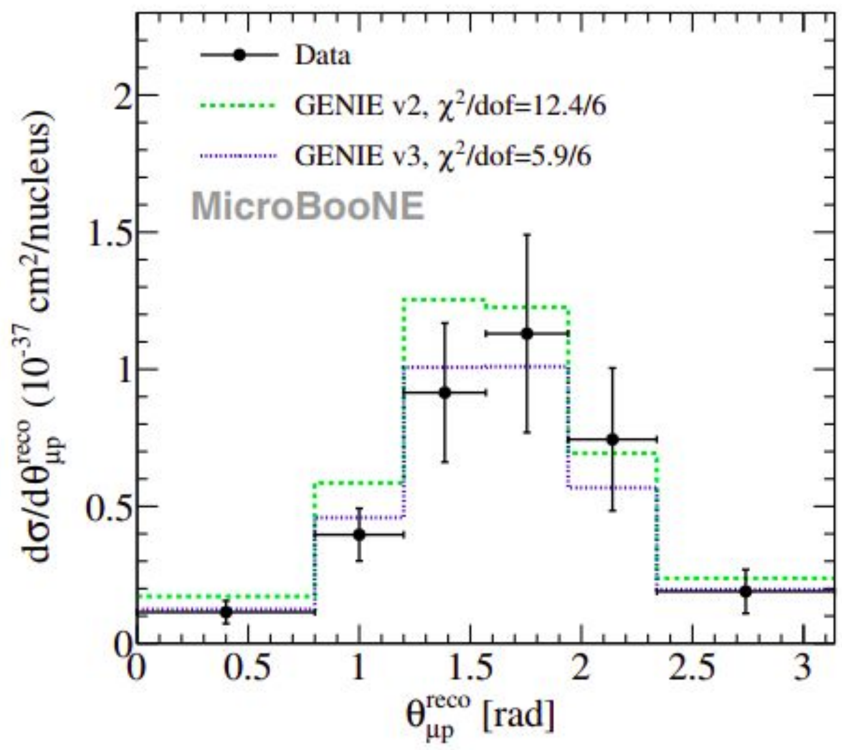
ν_μ CC multiple-proton interactions, Np0π

First differential cross-section of the signature 1μNp0π on argon.

Cross section in five reconstructed variables:

- the muon momentum and polar angle
- the leading proton momentum and polar angle
- and the muon-proton opening angle

Data modelling improved with GENIE v3.

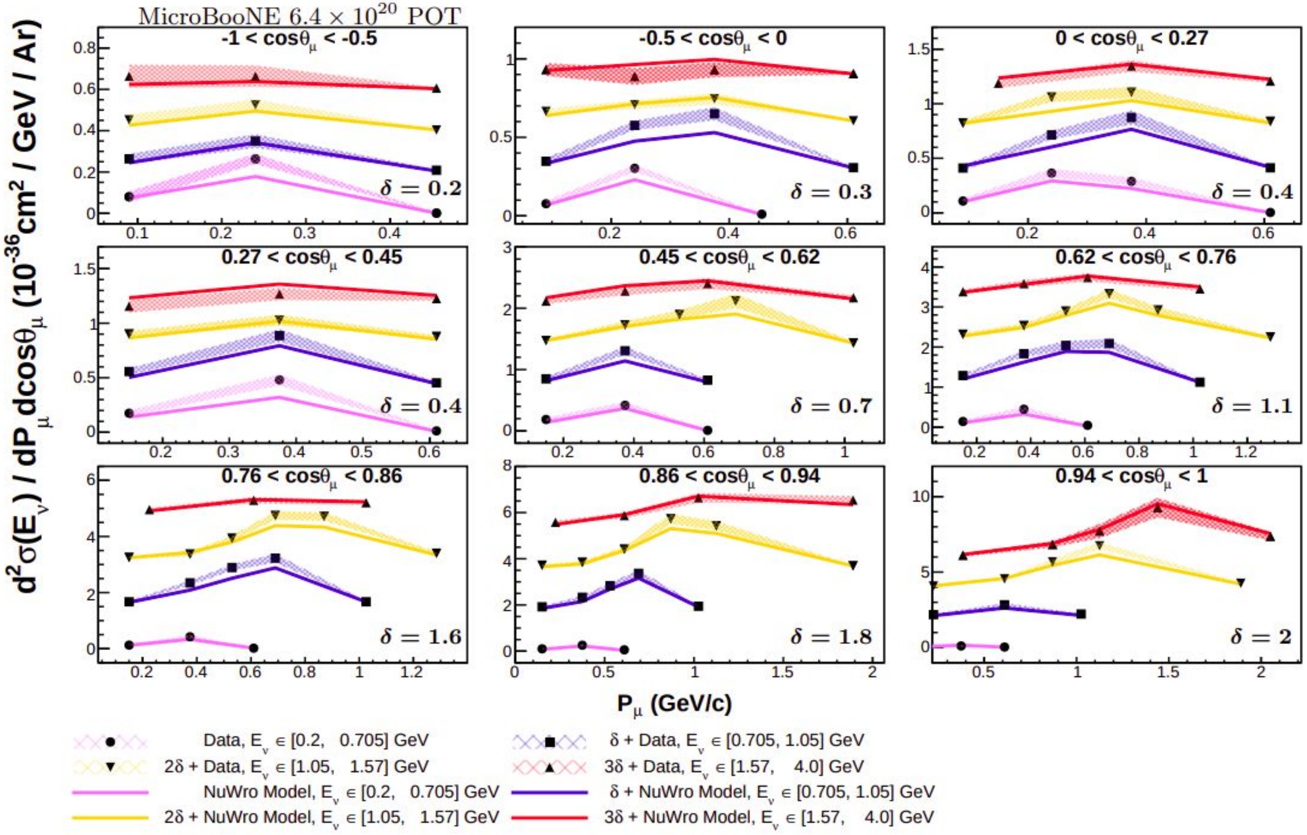


Phys. Rev. D 102,112013

3D ν_μ CC inclusive cross section

First 3D cross section over E_ν, P_ν and $\cos(\theta_\mu)$ on argon.

Better understanding of neutrino event generator performance across a broad phase space.



arXiv:2307.06413

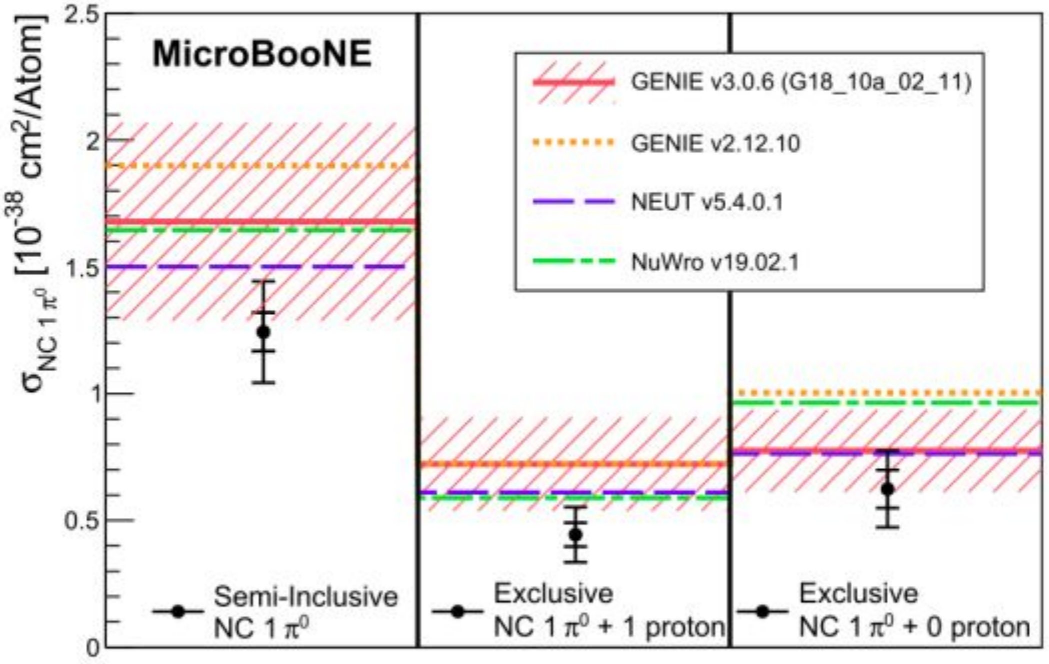
NC π^0 production

See Ben's talk tomorrow and Luis' talk on Friday

Extensively studied as background to BSM studies that search for electron-positron pairs.

Most precise measurement of π^0 production on argon.

Cross section measured in two exclusive topologies 1p and 0p, and their combination.



Phys. Rev. D 107, 012004 (2023)

ν_eCC with NuMI

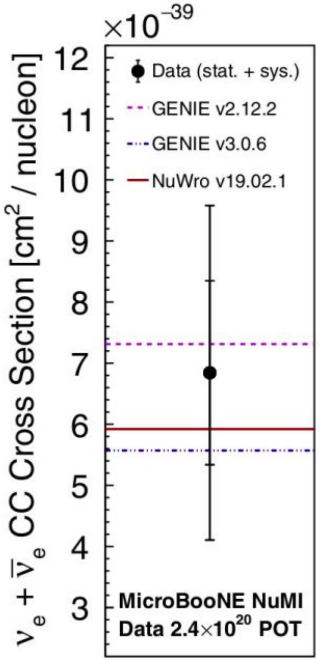
NuMI has a higher ν_e component, excellent to study ν_e interactions.

<u>Bottom-left</u>:

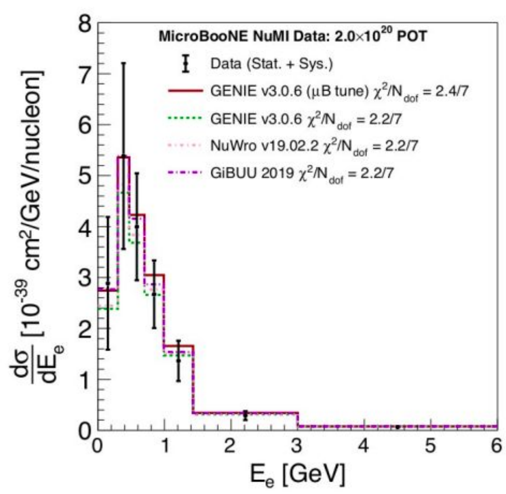
- Flux-averaged total cross section with 214 selected events

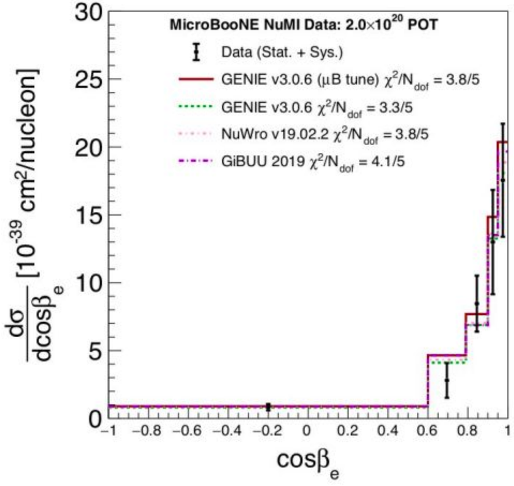
<u>Right (top/bottom)</u>:

- First measurement of Inclusive $\nu_e + \bar{\nu}_e$ CC differential in lepton energy and angle
- Largest sample of selected ν_eCC interactions on argon to date: 243 selected events



Phys. Rev. D. 104.052002





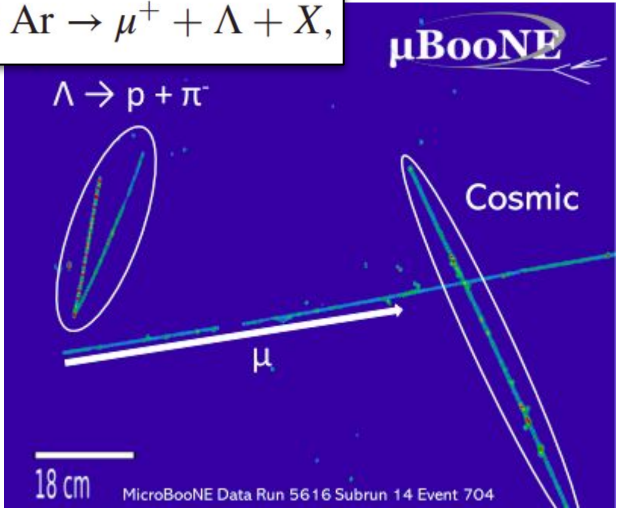
Phys. Rev. D. 105.L051102

Rare channels - Λ production

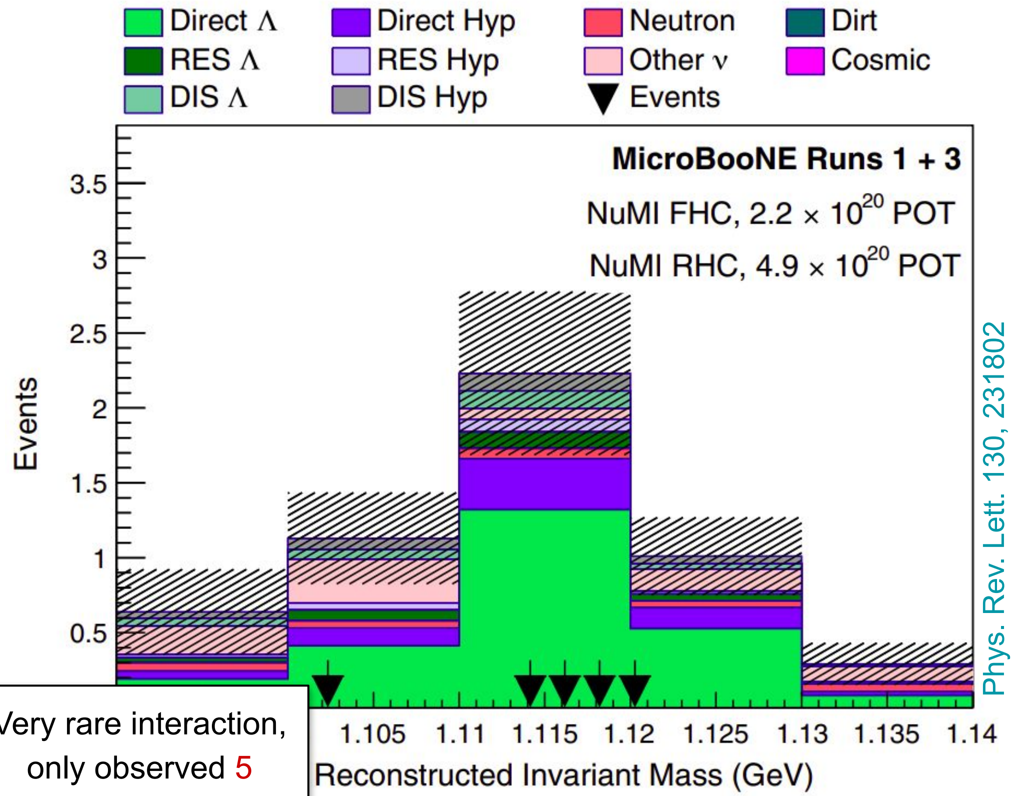
First measurement of Λ baryon production.

Identify Λ baryons through invariant mass and separation vertex.

$$\bar{\nu}_\mu + \text{Ar} \rightarrow \mu^+ + \Lambda + X,$$



Phys. Rev. Lett. 130, 231802



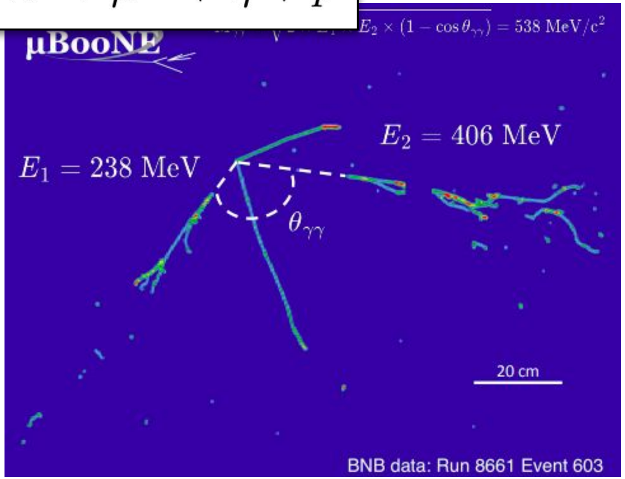
Very rare interaction, only observed 5 candidates.

Phys. Rev. Lett. 130, 231802

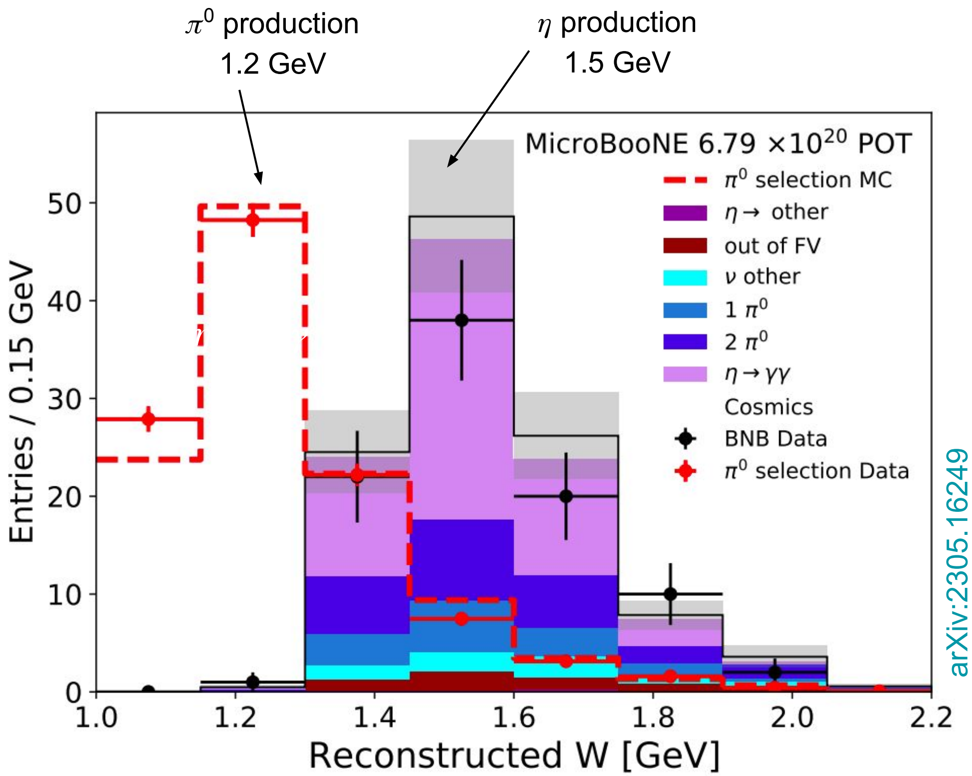
Rare channels - η production

First demonstration of the ability to identify higher-order resonances, crucial for future rare channel cross section measurements.

$$\nu_\mu + n \rightarrow \mu^- + \eta + p$$



arXiv:2305.16249



arXiv:2305.16249

Cross Section (Already Public) Results

CC inclusive:

- 1D & 3D ν_μ CC inclusive @ BNB Phys. Rev. Lett. 123, 131801 (2019) and arXiv:2307.06413 (2023)
- 1D ν_μ CC energy-dependent @ BNB Phys. Rev. Lett. 128, 151801 (2022)
- 1D ν_e CC inclusive @ NuMI Phys. Rev. D 104, 052002 (2021) and Phys. Rev. D 105, L051102 (2022)

CC0π:

- 1D ν_e CCNp0π @ BNB Phys. Rev. D 106, L051102 (2022)
- 1D & 2D ν_μ CC1p0π Kinematic Imbalance @ BNB arXiv:2301.03700 (2023) and arXiv:2301.03706 (2023) (submitted to PRL & PRD)
- 1D ν_μ CC1p0π @ BNB Phys. Rev. Lett. 125, 201803 (2020)
- 1D ν_μ CC2p @ BNB arXiv:2211.03734 (2023) (submitted to PRL)
- 1D ν_μ CCNp0π @ BNB Phys. Rev. D 102, 112013 (2020)

Rare channels:

- η production arXiv:2305.16249 (2023) (submitted to PRL)
- Λ production Phys. Rev. Lett.130, 231802 (2023)

Pion production:

- NC π^0 production (BNB) Phys. Rev. D 107, 012004 (2023)

Ongoing MicroBooNE cross section program

In progress cross-section studies:

- ν_μ inclusive with NuMI, ν_μ/ν_e ratio, hadronic energy
- Charged pions with BNB and NuMI
- Coherent pion production
- $\bar{\nu}_e$ with NuMI
- Neutrons, kaons, Σ baryons
- MeV scale physics
- Much more to come with kinematic imbalance variables

Conclusion

The MicroBooNE cross section program is very broad.

Recent studies show the potential of also using NuMI beam data.

TKI variables show powerful discrimination of interaction models.

Haven't yet analysed our full dataset -- more statistics available!

Stay tuned for more exciting results soon!


Lancaster University
Thank you!

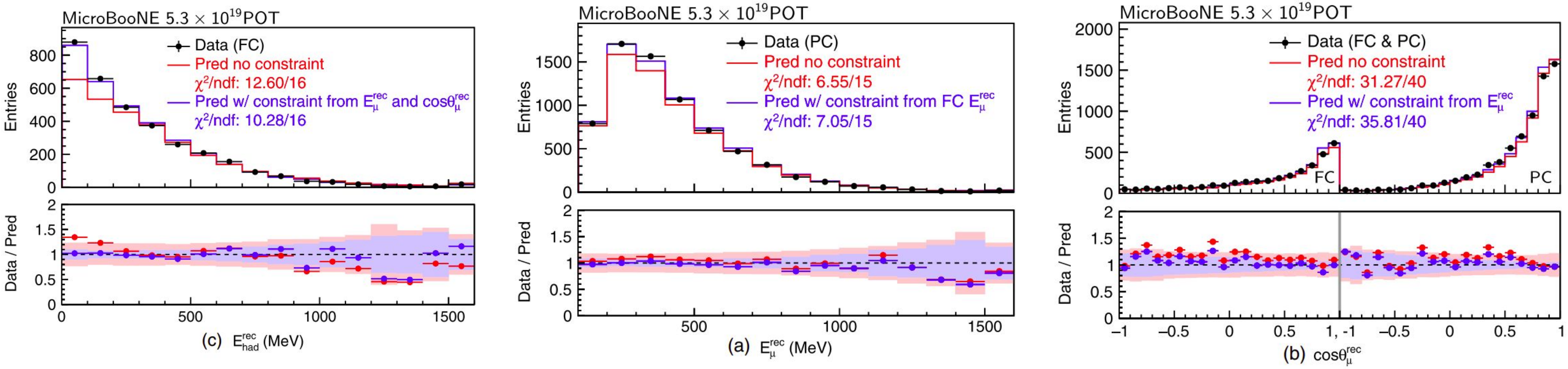
Back-up slides

Charged-Current Measurements

Energy-dependent inclusive ν_μCC cross section (1)

Missing hadronic energy model validated with visible hadronic energy.

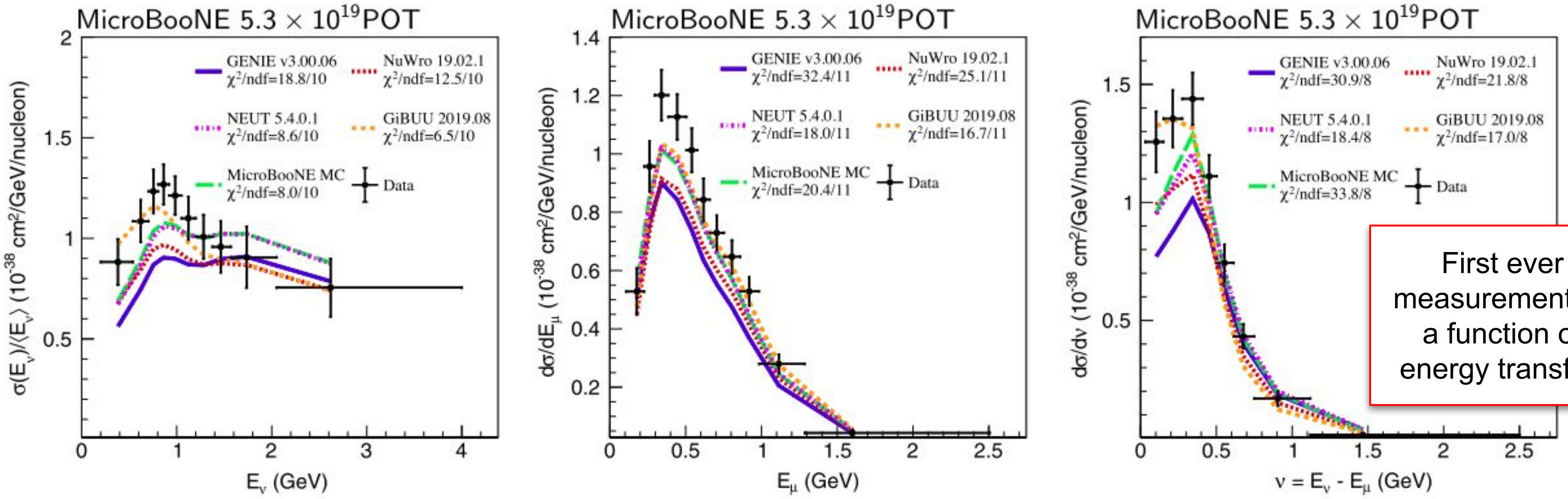
Muon energy and direction used to constrain uncertainties on the missing hadronic energy, mostly caused by undetected neutral particles.



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

Energy-dependent inclusive ν_μCC cross section (2)

Cross section extracted through the unfolding procedure.



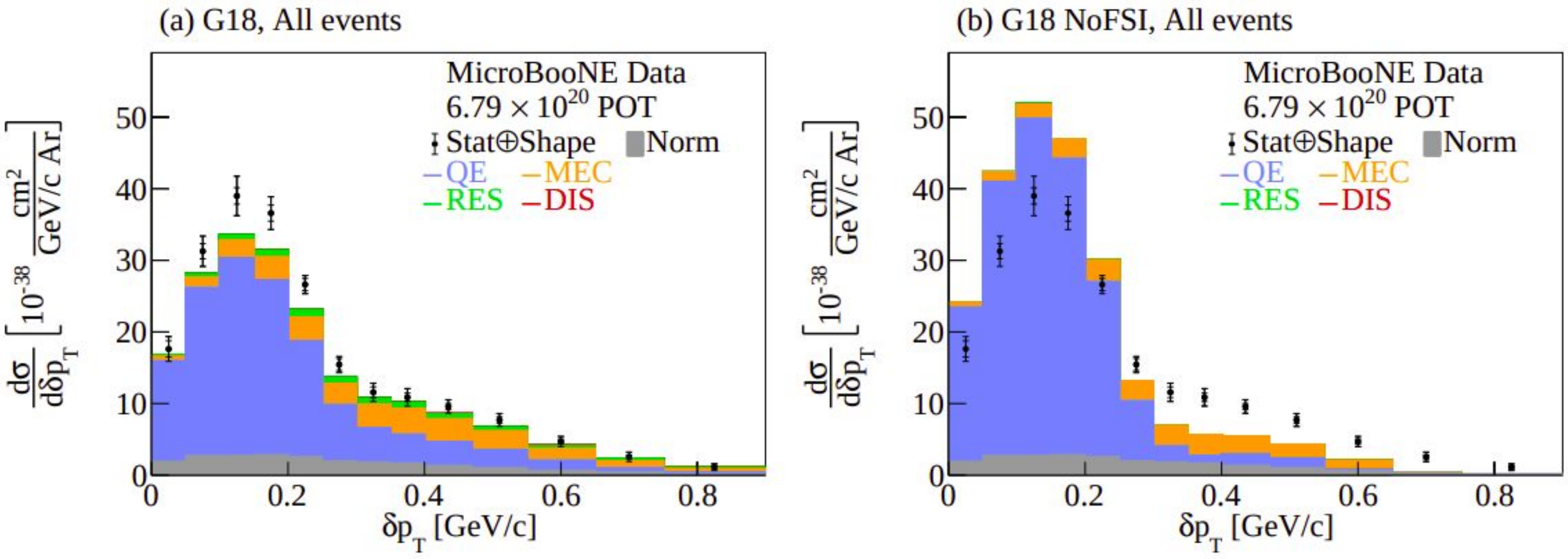
First ever measurement as a function of energy transfer!

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

ν_μ CC traverse kinematic imbalance (1)

Simulation very sensitive to FSI effects for certain variables.

Example: the missing momentum in the plane traverse to the beam, δp_T

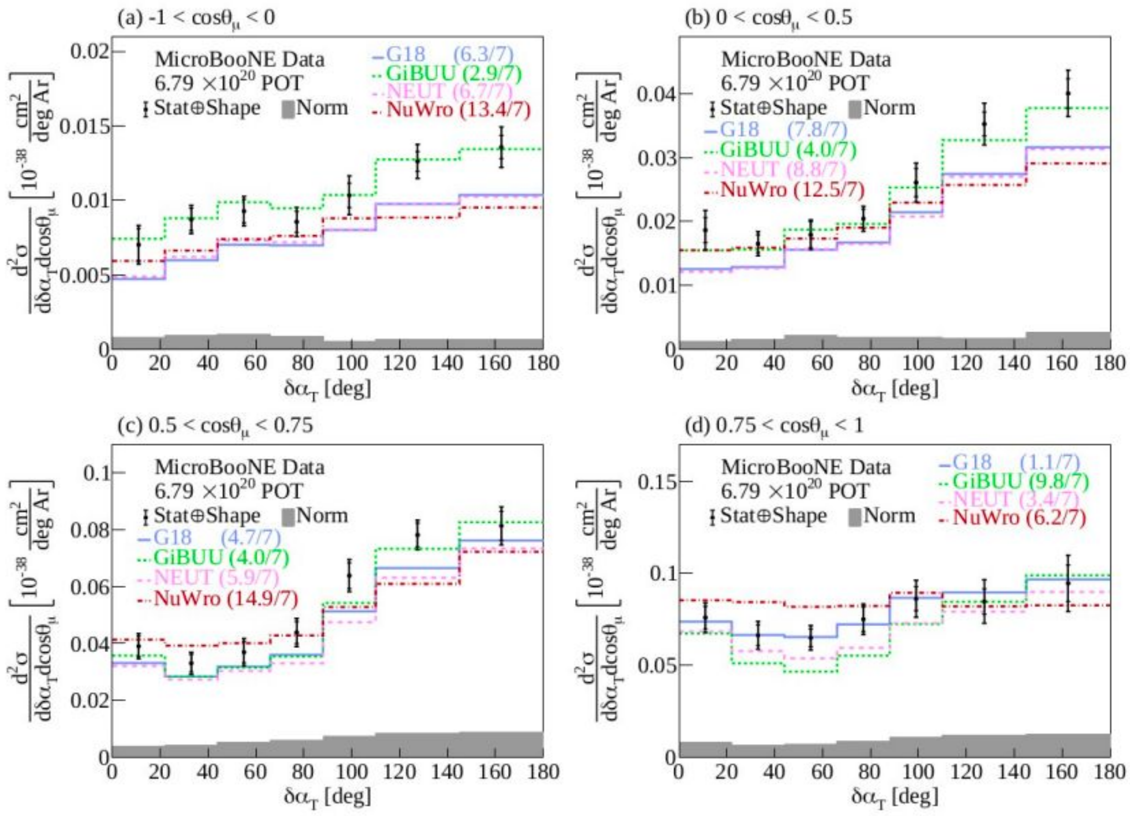


arXiv:2301.03700 (2023)

arXiv:2301.03706 (2023)

ν_μ CC traverse kinematic imbalance (2)

First ever 2D cross section as a function of TKI variables.

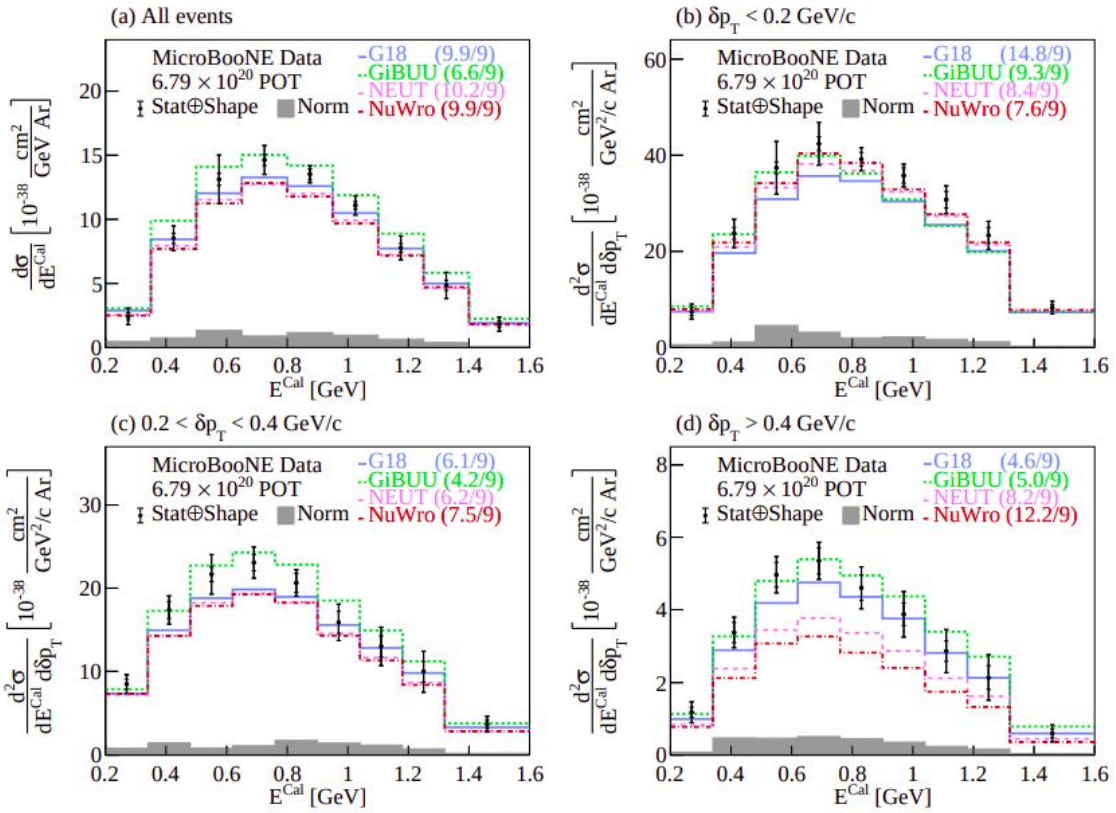


arXiv:2301.03700 (2023)
arXiv:2301.03706 (2023)

ν_μ CC traverse kinematic imbalance (3)

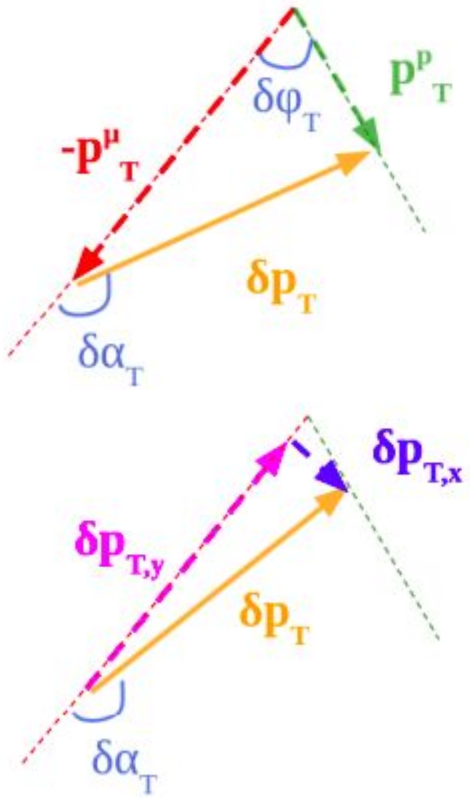
2D cross section in terms of total visible energy and TKI variables.

Nuclear effects impact on the estimation of neutrino energy.



arXiv:2301.03700 (2023)
arXiv:2301.03706 (2023)

Kinematic Imbalance Variables



$$\delta p_T = |\vec{p}_T{}^{\mu} + \vec{p}_T{}^{p}|,$$

$$\delta\alpha_T = \arccos\left(\frac{-\vec{p}_T{}^{\mu}\cdot\delta\vec{p}_T}{p_T{}^{\mu}\,\delta p_T}\right)$$

$$\delta\phi_T = \arccos\left(\frac{-\vec{p}_T{}^{\mu}\cdot\vec{p}_T{}^{p}}{p_T{}^{\mu}\,p_T{}^{p}}\right)$$

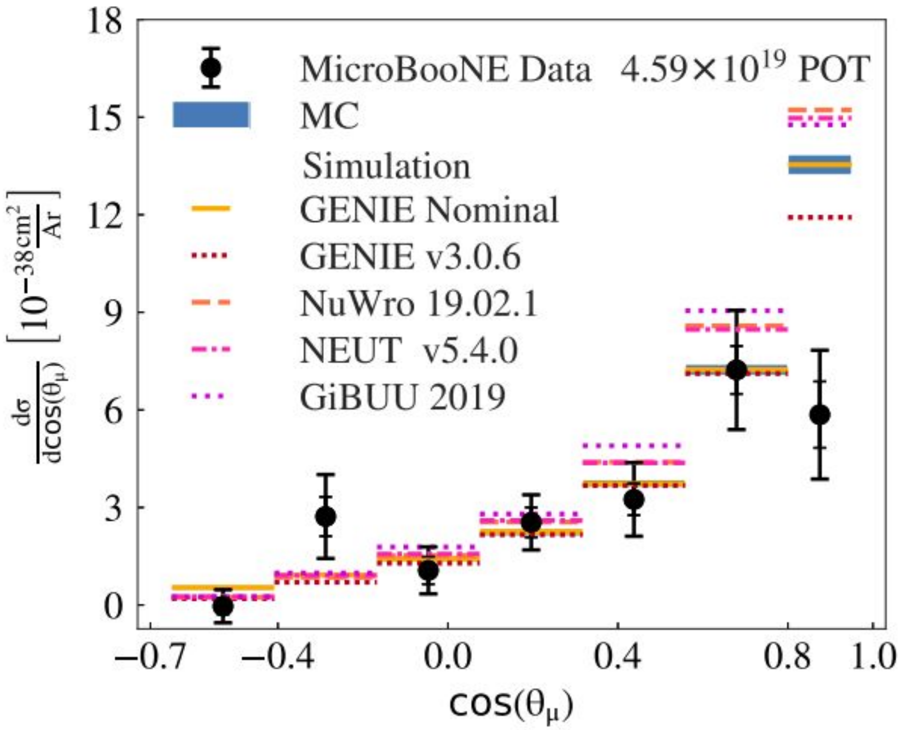
$$\delta p_{T,x} = \delta p_T \cdot \sin\delta\alpha_T$$
$$\delta p_{T,y} = \delta p_T \cdot \cos\delta\alpha_T.$$

arXiv:2301.03700 (2023)
arXiv:2301.03706 (2023)

Differential ν_μ CC 1p0π cross section

The cross section is given as a function of the muon scattering angle

Generators all overpredict in “soft scattering” region.

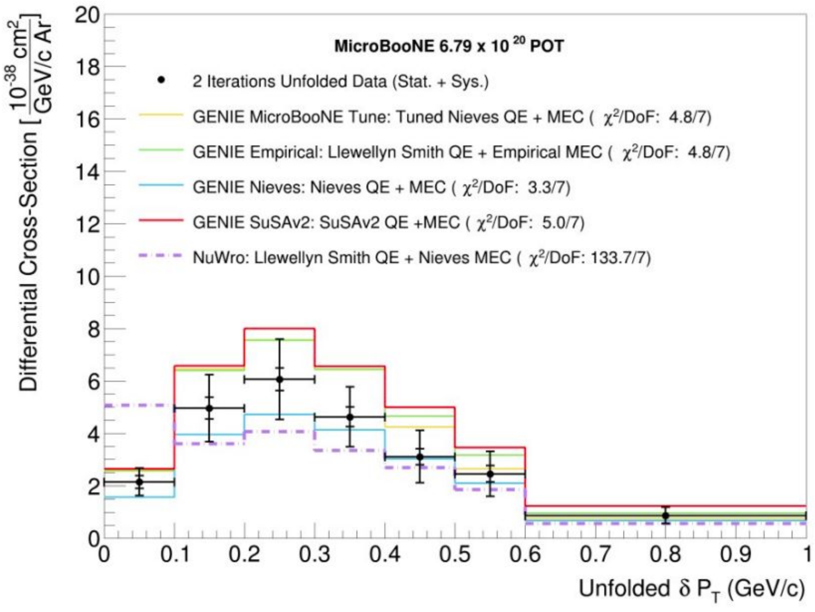


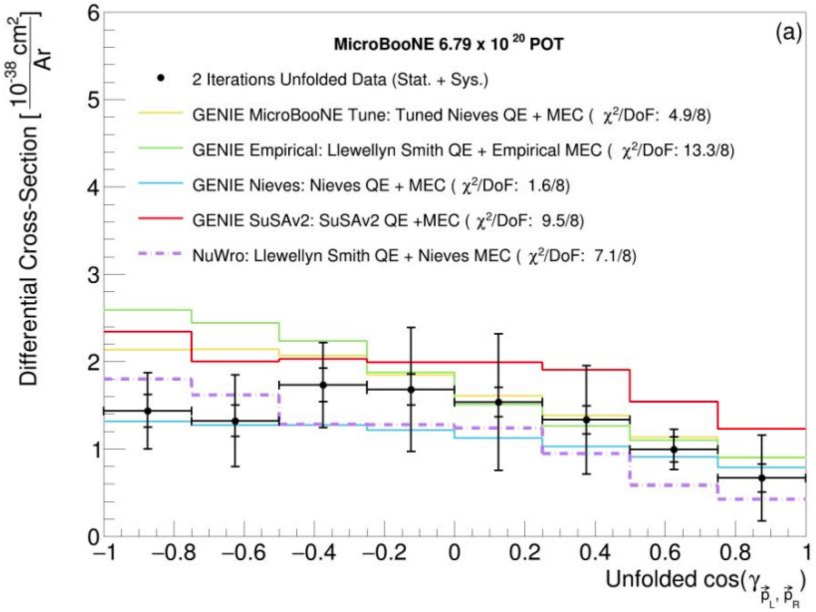
Phys. Rev. Lett. 125, 201803 (2020)

Differential ν_μCC 2p0π cross section

First high statistics ν_μCC2p0π analysis with cross section.

Transverse momentum and opening angles of final state particles.





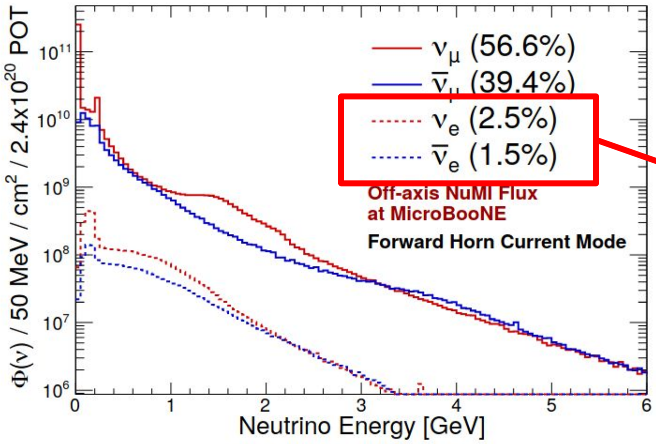
arXiv:2211.03734 (2022)

ν_eCC with NuMI (1)

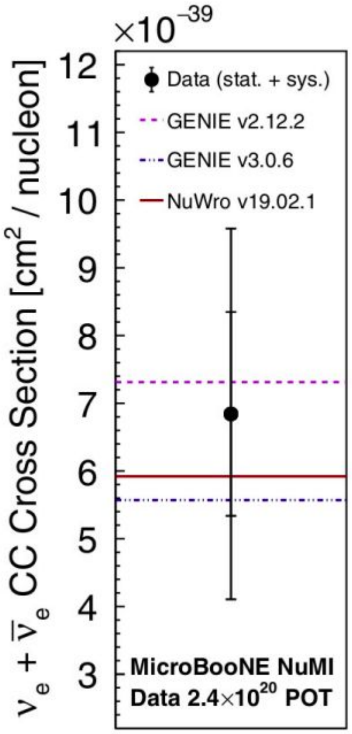
First cross section measurements using the NuMI beam.

NuMI has a high ν_e component, excellent to study ν_e interactions.

Flux-averaged total cross section with 214 selected events.



5x BNB ν_e content

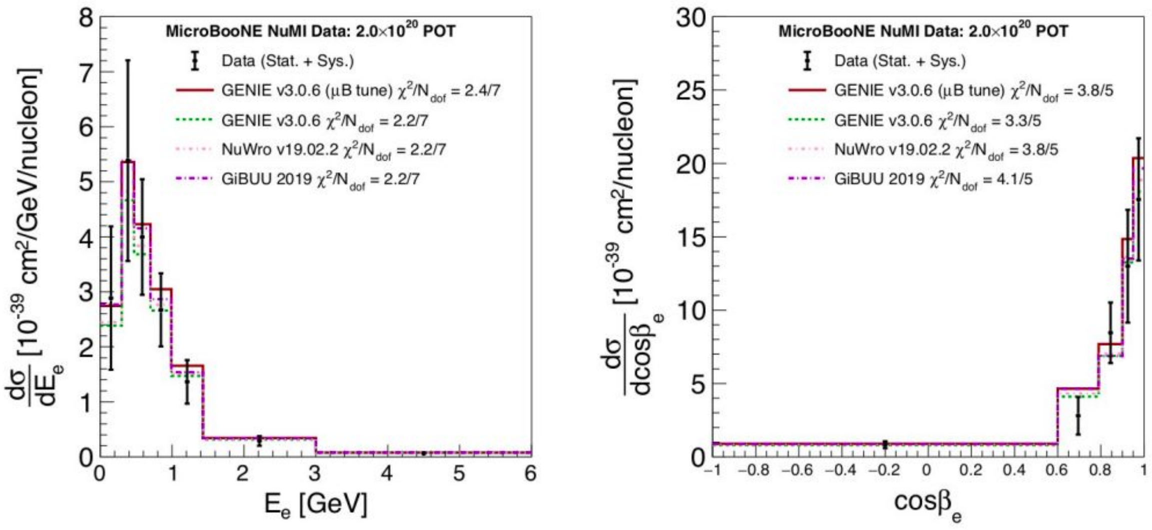


Phys. Rev. D 104, 052002 (2021)
Phys. Rev. D 105, L05110 (2022)

ν_eCC with NuMI (2)

First measurement of Inclusive $\nu_e + \bar{\nu}_e$ CC differential in lepton energy and angle

Largest sample of selected ν_eCC interactions on argon to date: 243 events.

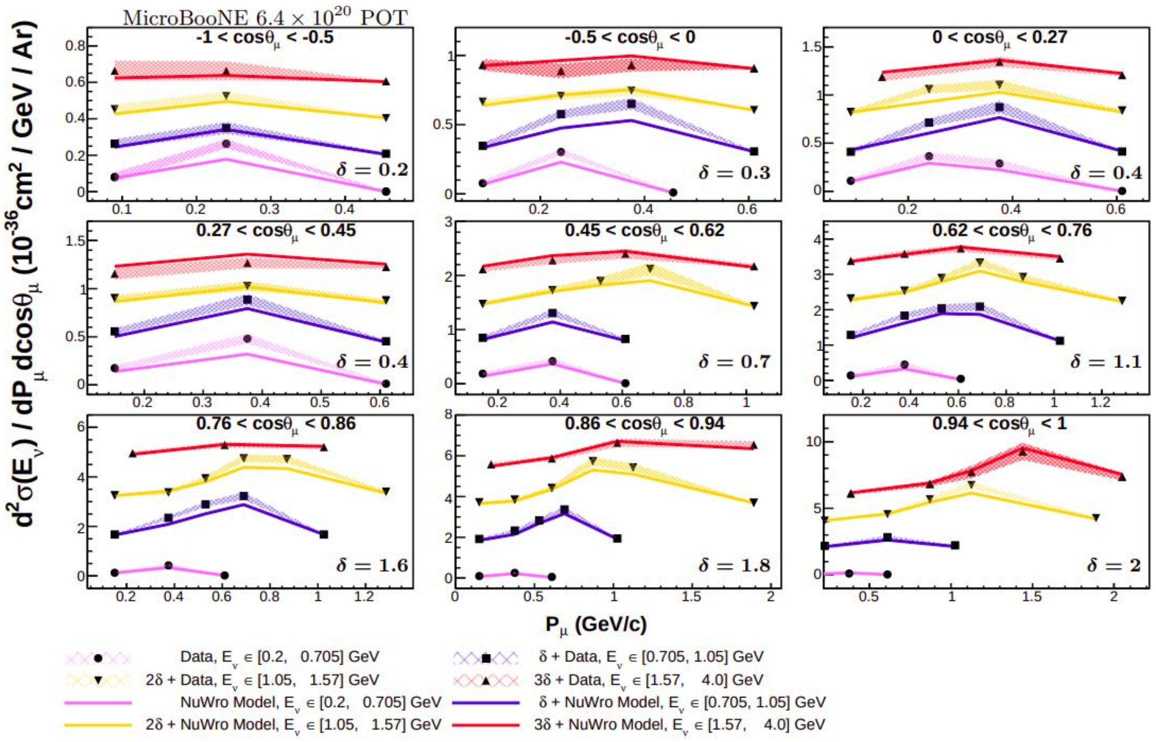


Phys. Rev. D 104, 052002 (2021)
Phys. Rev. D 105, L05110 (2022)

3D ν_μ CC inclusive cross section

First 3D cross section over E_ν, P_ν and $\cos(\theta_\mu)$.

Better understanding of neutrino event generator performance across a broad phase space.



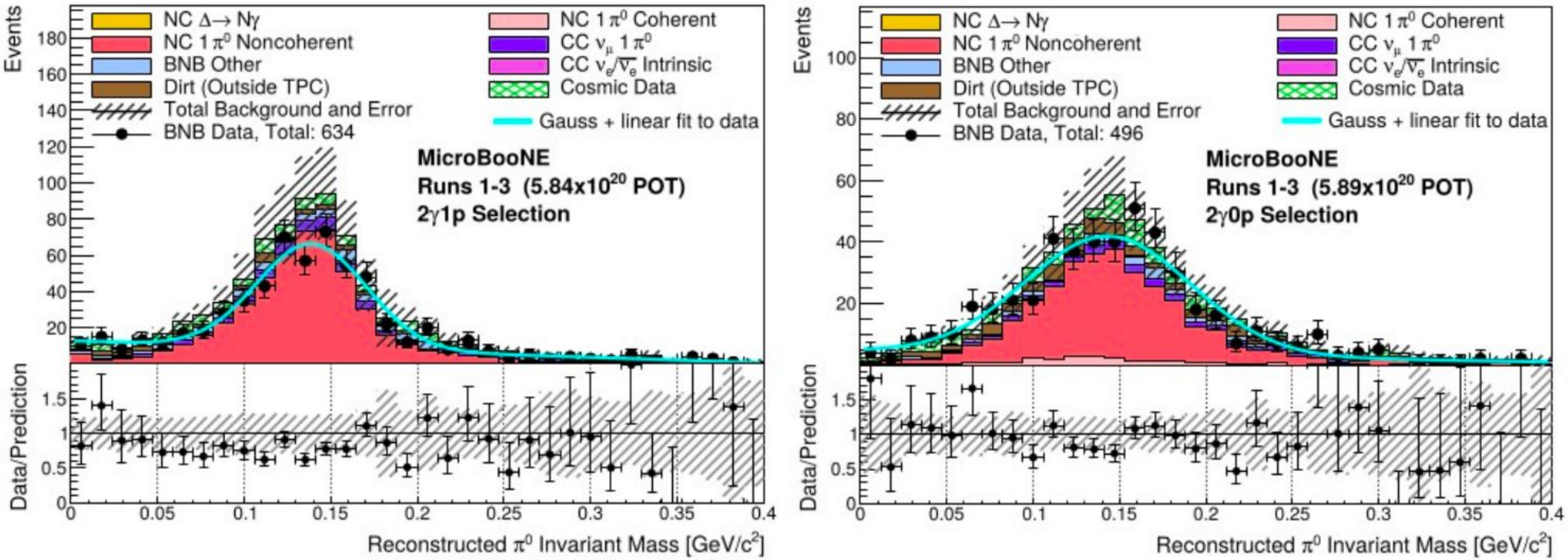
arXiv:2307.06413 (2023)

Pion production

NC π^0 production (1)

Extensively studied as background to LEE - Phys. Rev. D 105, 112003 (2022).

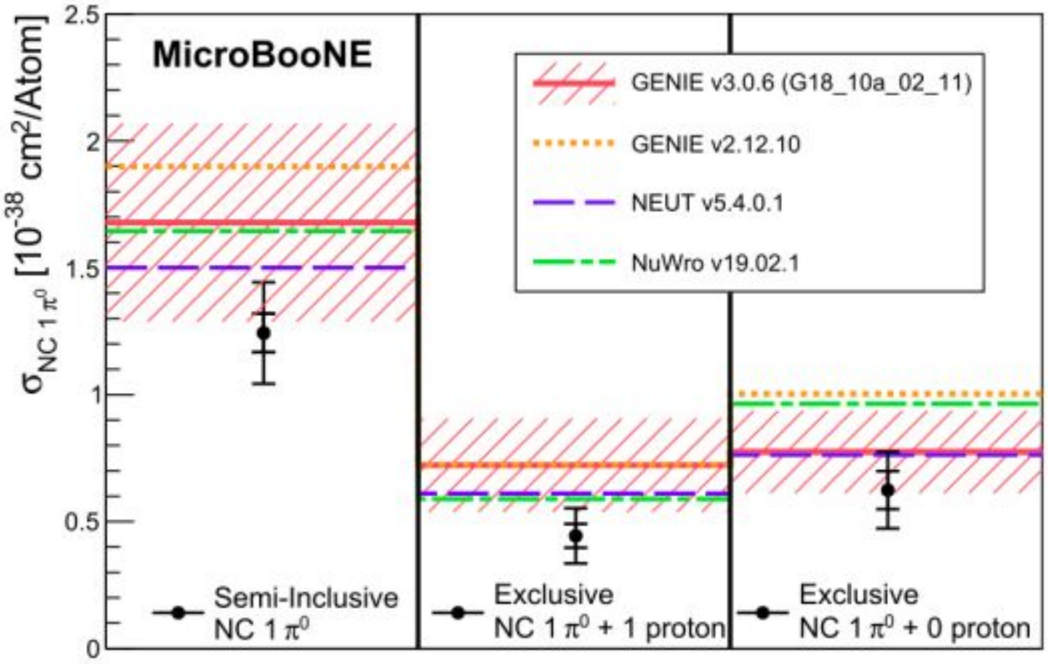
Identify π^0 through their invariant mass.



Phys. Rev. D 107, 012004 (2023)

NC π^0 production (2)

Measure 0p and 1p channels.



Phys. Rev. D 107, 012004 (2023)

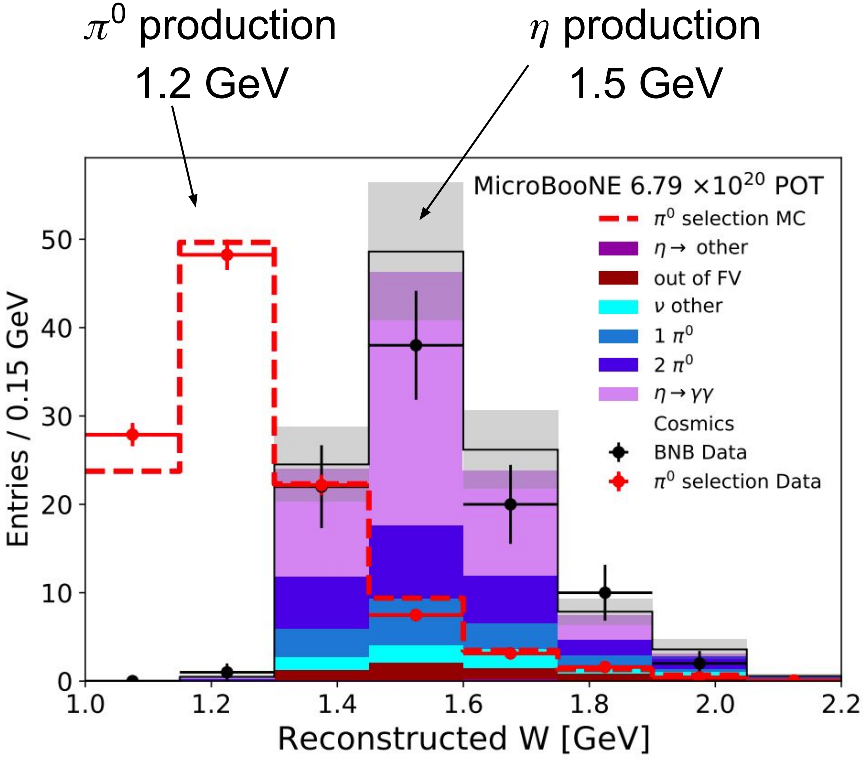
Rare channels

η meson production

Resonances such as N(1535), N(1650) and N(1710) with large branching fractions to η production.

The dominant decay has a 2γ signature with an invariant mass of 548 MeV/c^2.

First demonstration of the ability to identify higher-order resonances.



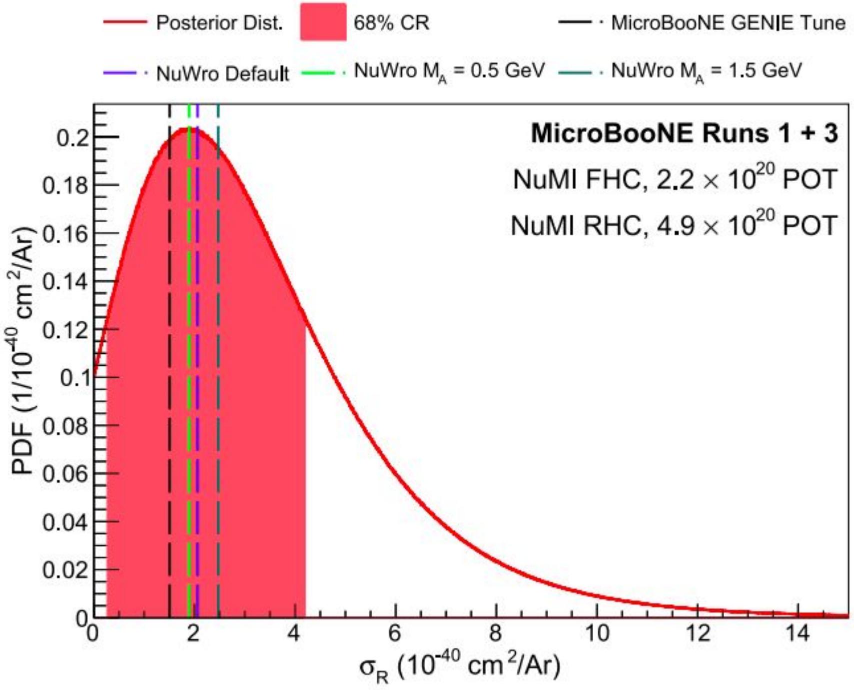
arXiv:2305.16249 (2023)

Λ baryon production

First measurement of Λ baryon production.

Identify Λ baryons through invariant mass and angular deviation.

Very rare interaction, full NuMI dataset observed 5 candidates.



Phys. Rev. Lett. 130, 231802 (2023)