Recent Cross Section Results from MicroBooNE

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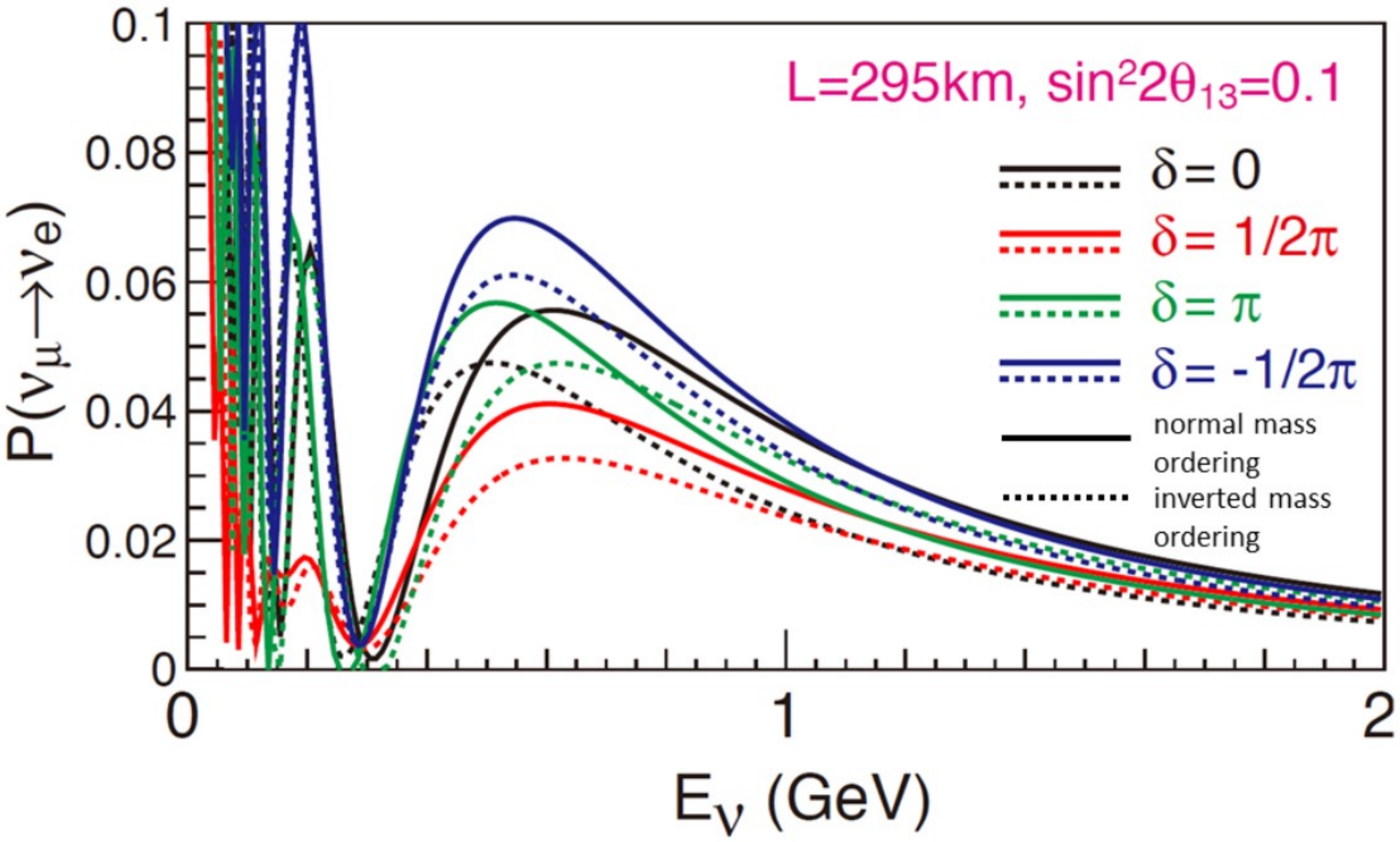
The Importance of Cross Sections

- To perform sensitive measurements of neutrino oscillation we must measure the flux as a function of neutrino energy:



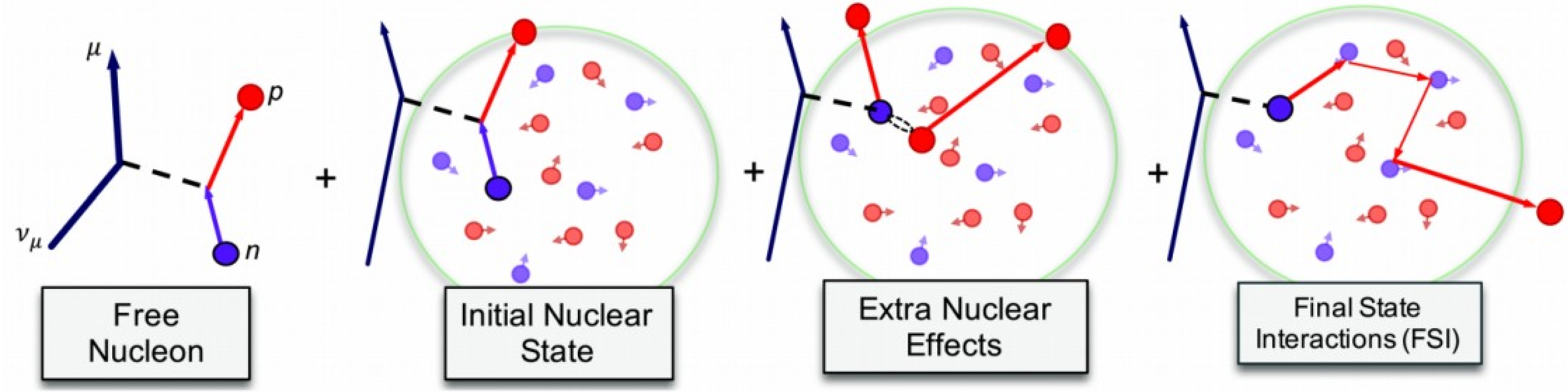
- Crux is that we can't control or observe the neutrino energy directly!

The Importance of Cross Sections

- We are forced to estimate the neutrino energy from other quantities that we can observe.
- For example, the momentum and direction of the outgoing charged lepton/hadrons.
- The relationship between these variables and the neutrino energy is **very** complicated...

Why Are Neutrino Cross Sections Hard?

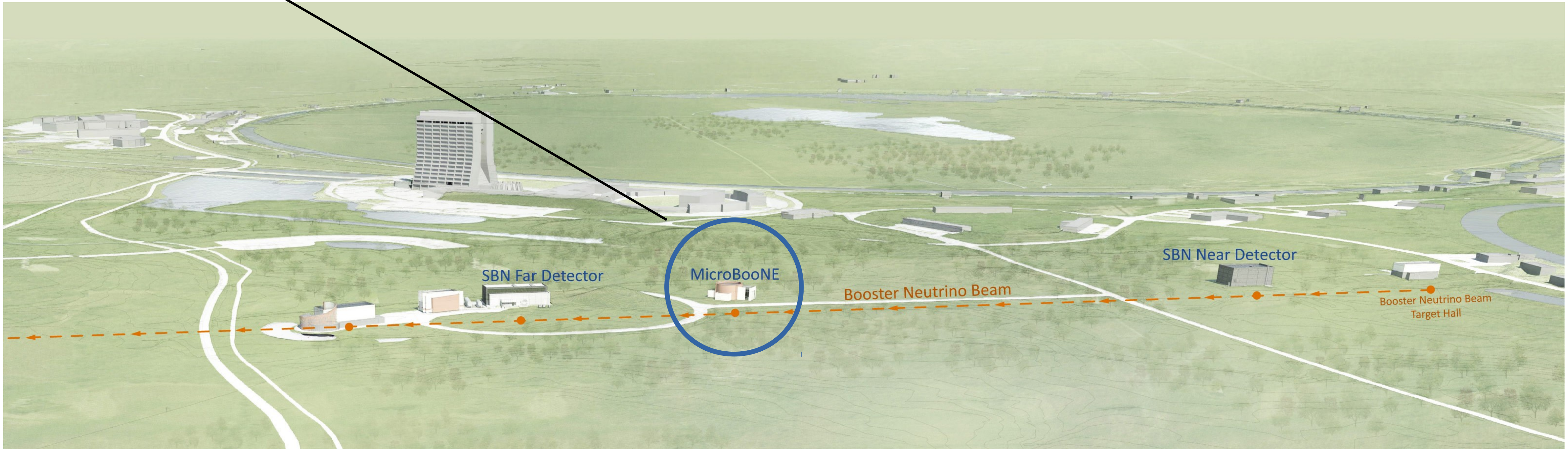
- *In principle*, if the target is a free, stationary nucleon, the energy of the neutrino can be determined exactly.



- Nuclear effects introduce lots of quantities we can't directly observe into the energy balance.
- We can't always observe all the final state particles.

MicroBooNE

- Located in the Booster Neutrino* beamline at Fermilab, Illinois.



- Approx. 450m from the BNB target.
- 85 ton active mass liquid argon time projection chamber (LArTPC).

*We don't just receive neutrinos from the BNB!

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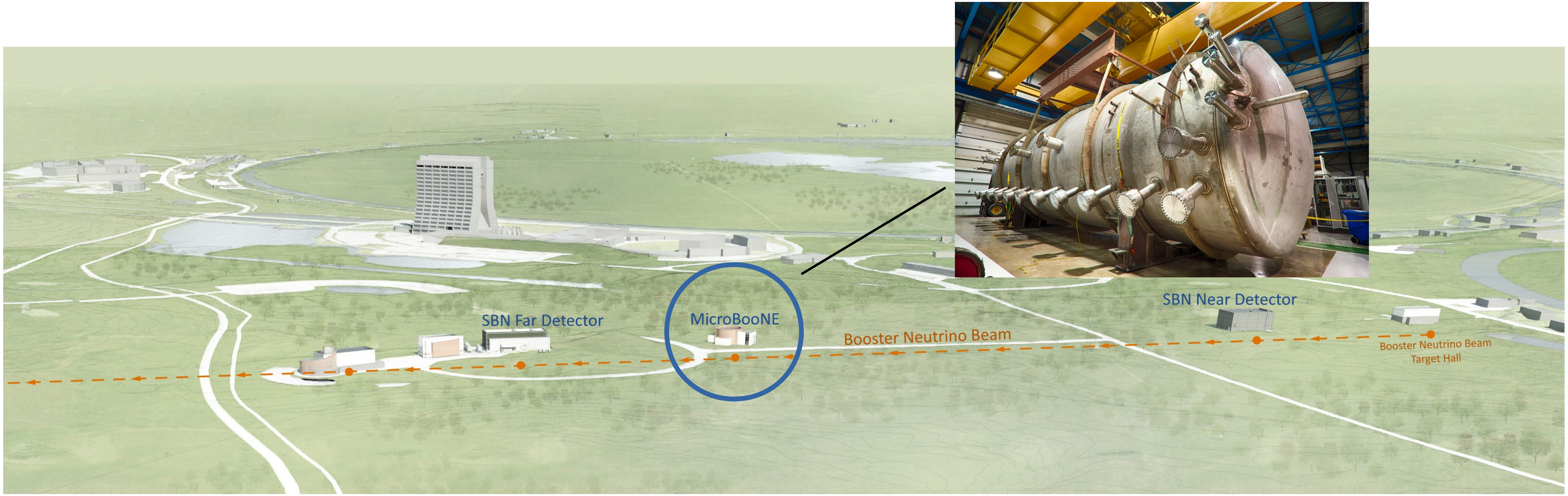

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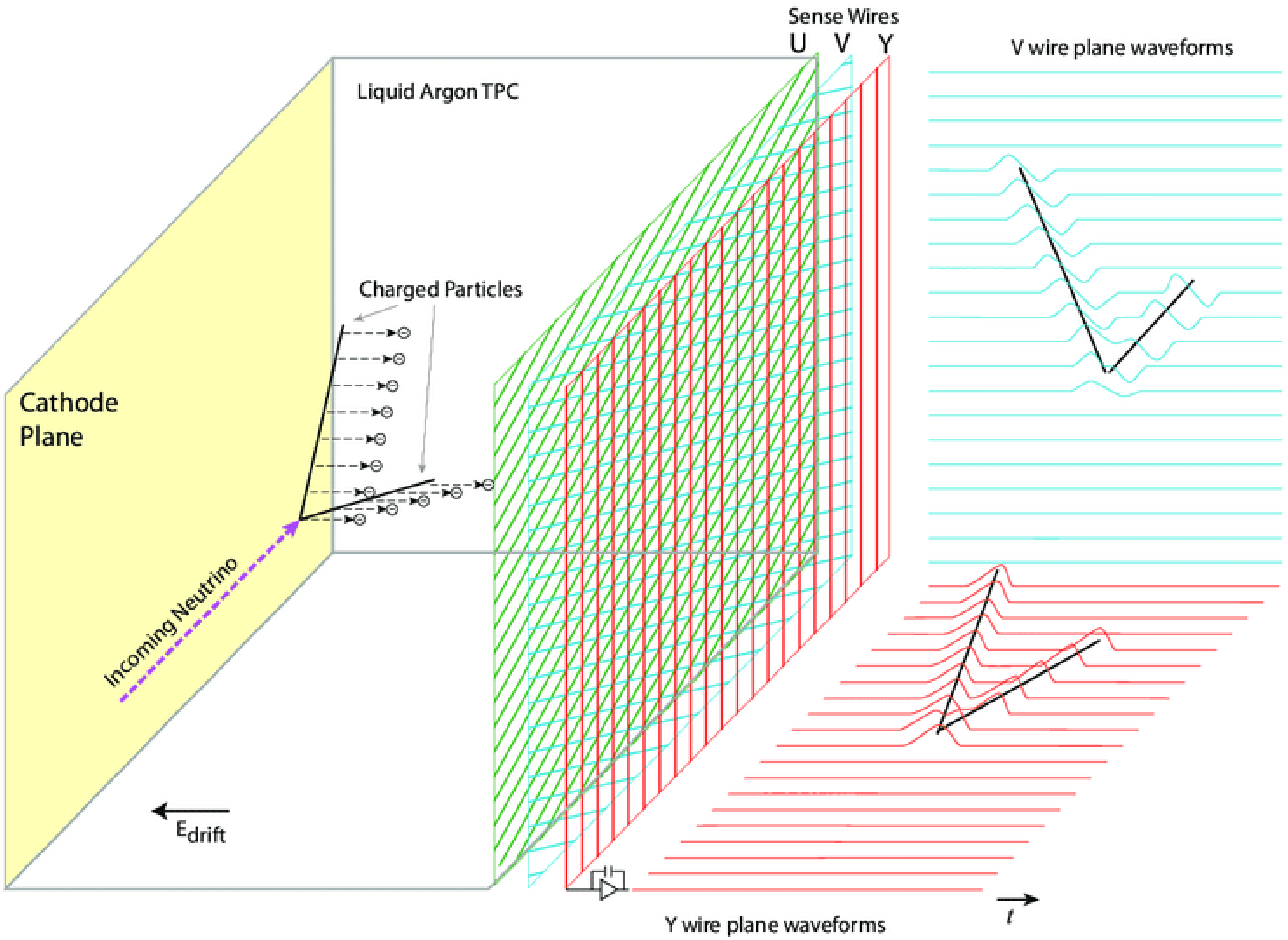
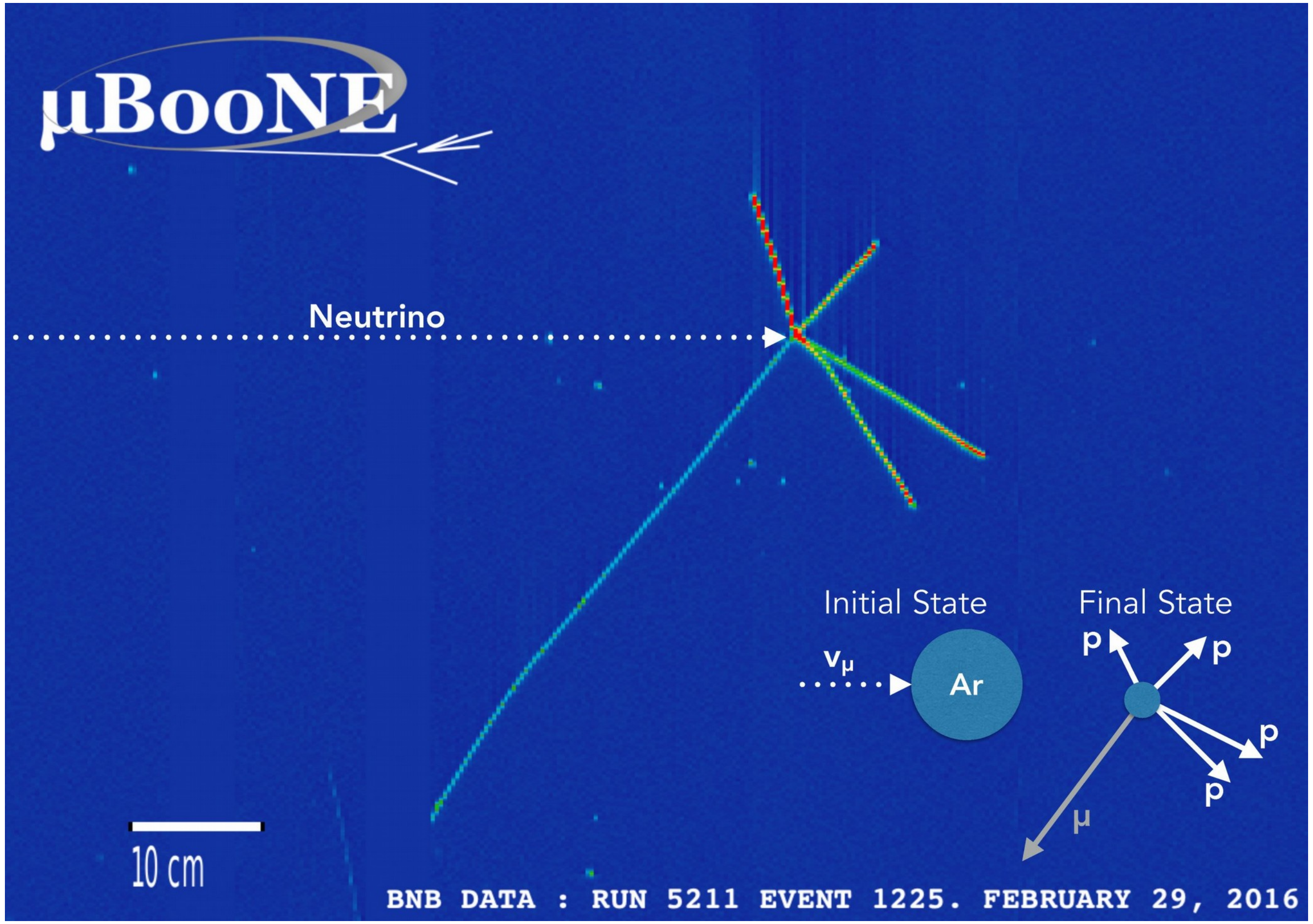
The LArTPC Principle

- Charged particles ionise the argon.
- E-field causes electrons/ions to drift towards wires.
- Induced currents in the wires reconstructed into particle trajectories.

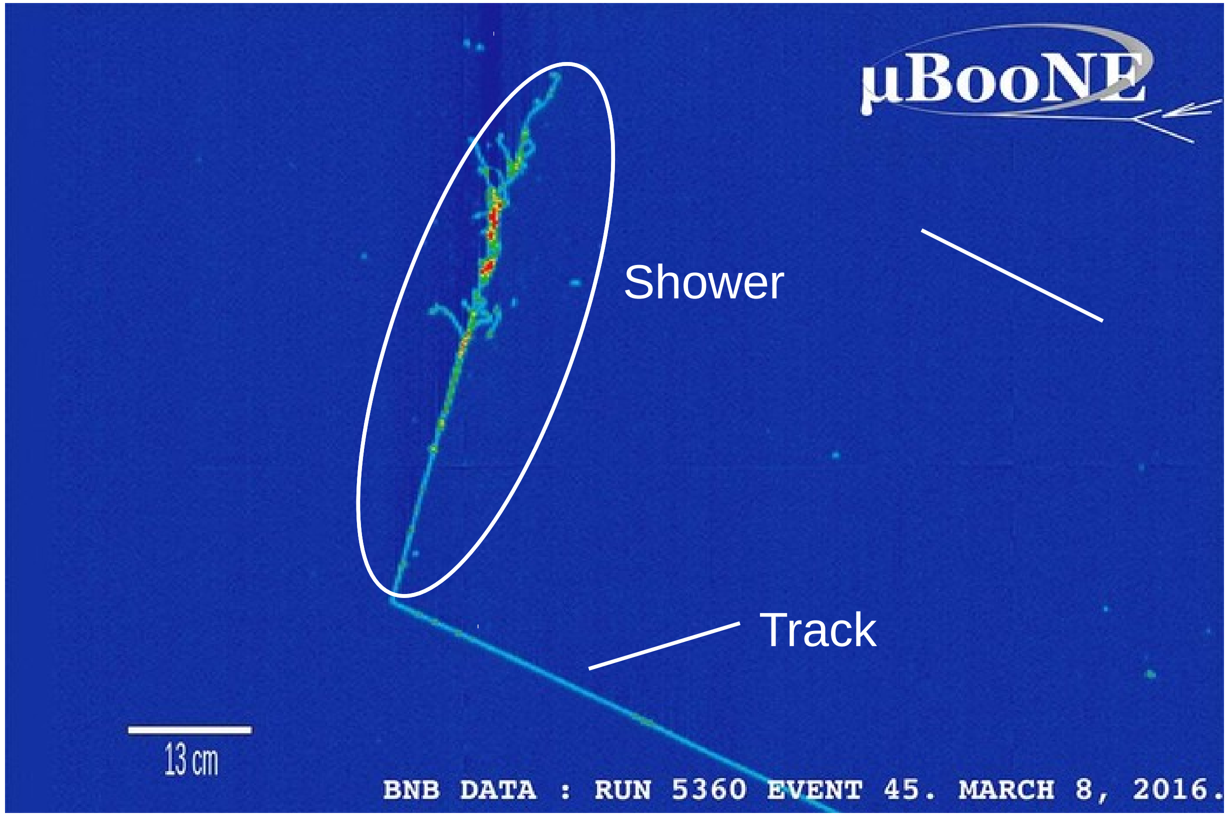


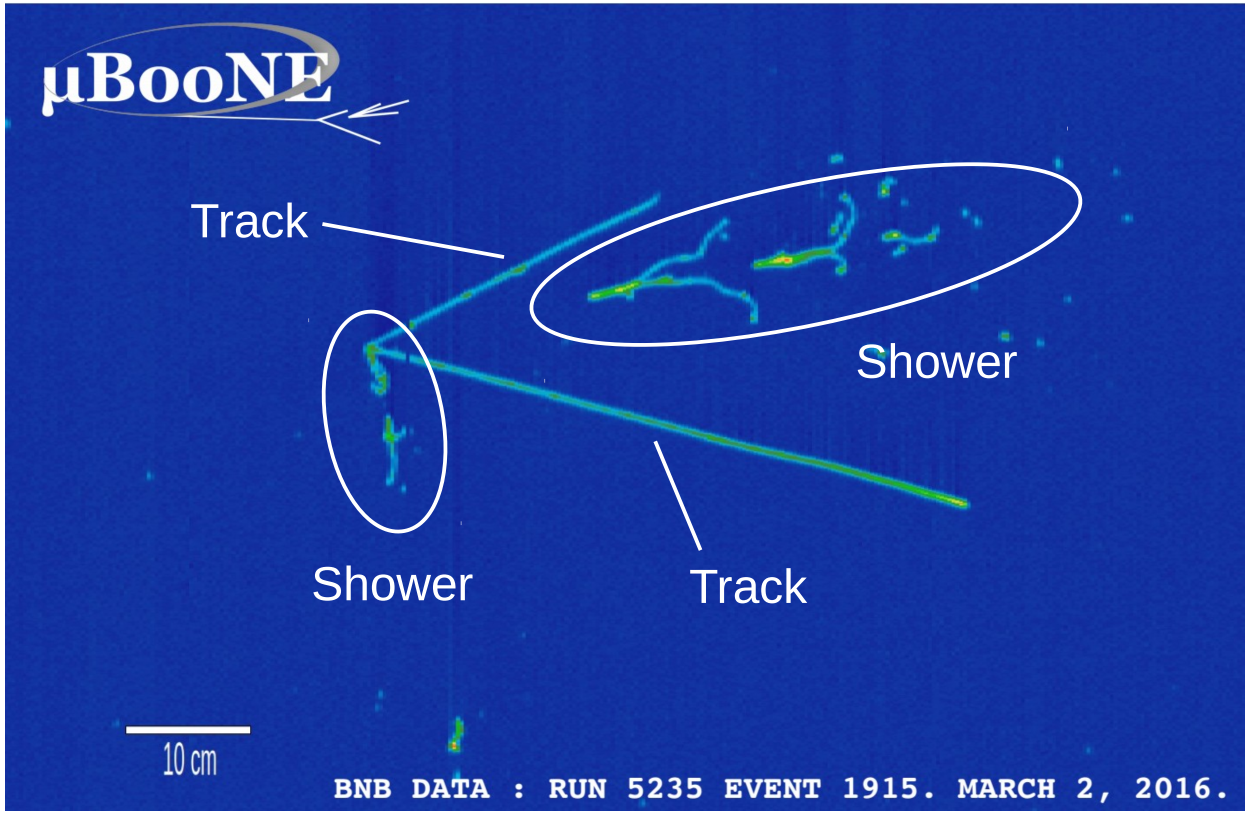
The LArTPC Principle



- Full tracking and calorimetric information with 4π acceptance.
- Energy loss along a particle's trajectory used for PID.

Particle Signatures and Selections

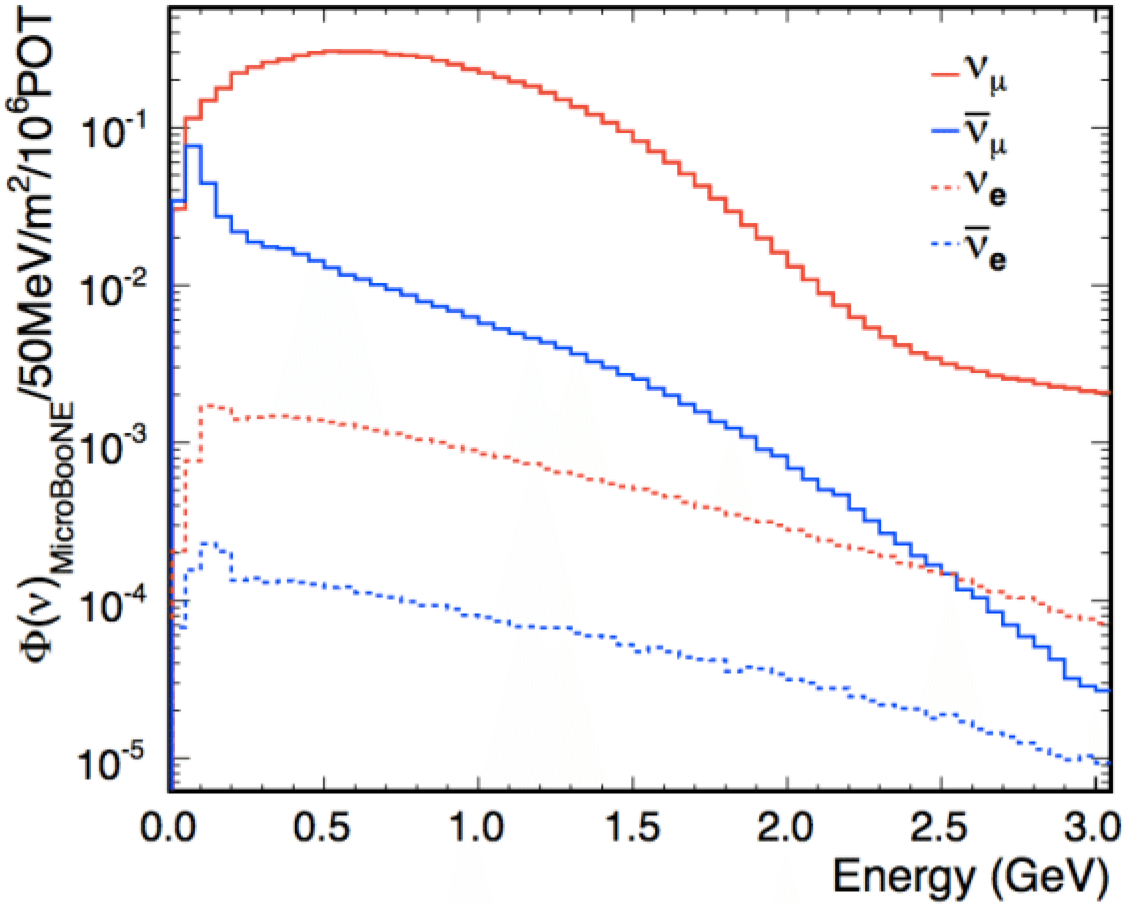




Showers = e, γ   Tracks = μ, $\pi^{\pm}$, $K^{\pm}$, p

- Basic approach is to search for these elements, then apply PID/quality/kinematic criteria.

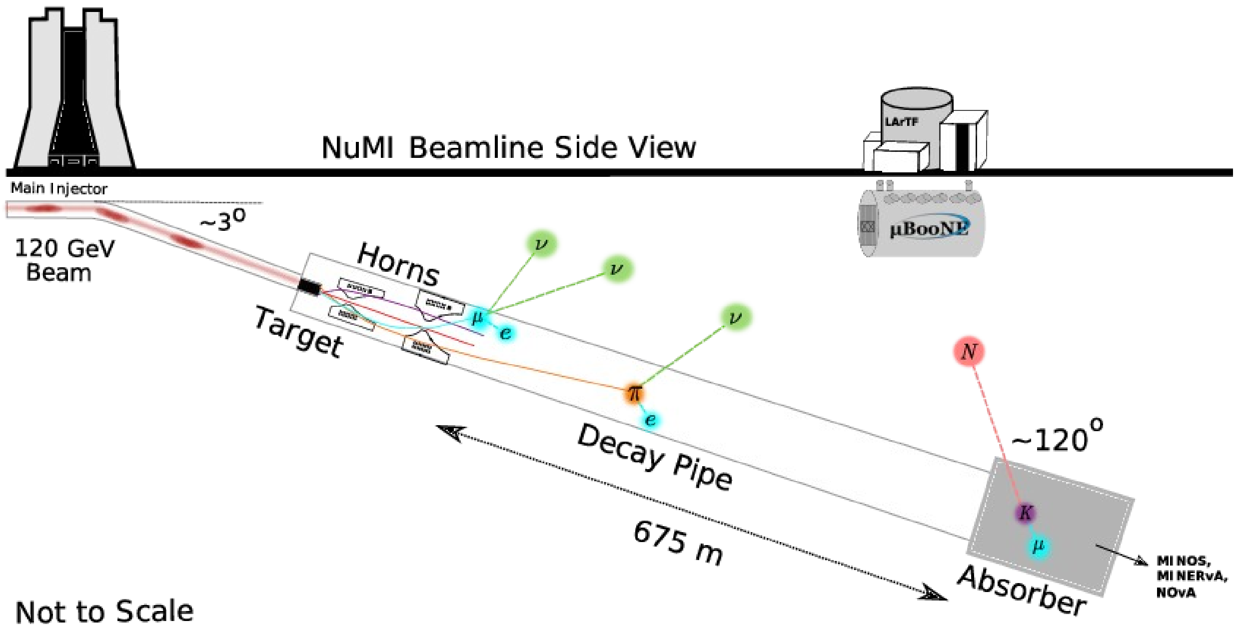
The Beams - BNB



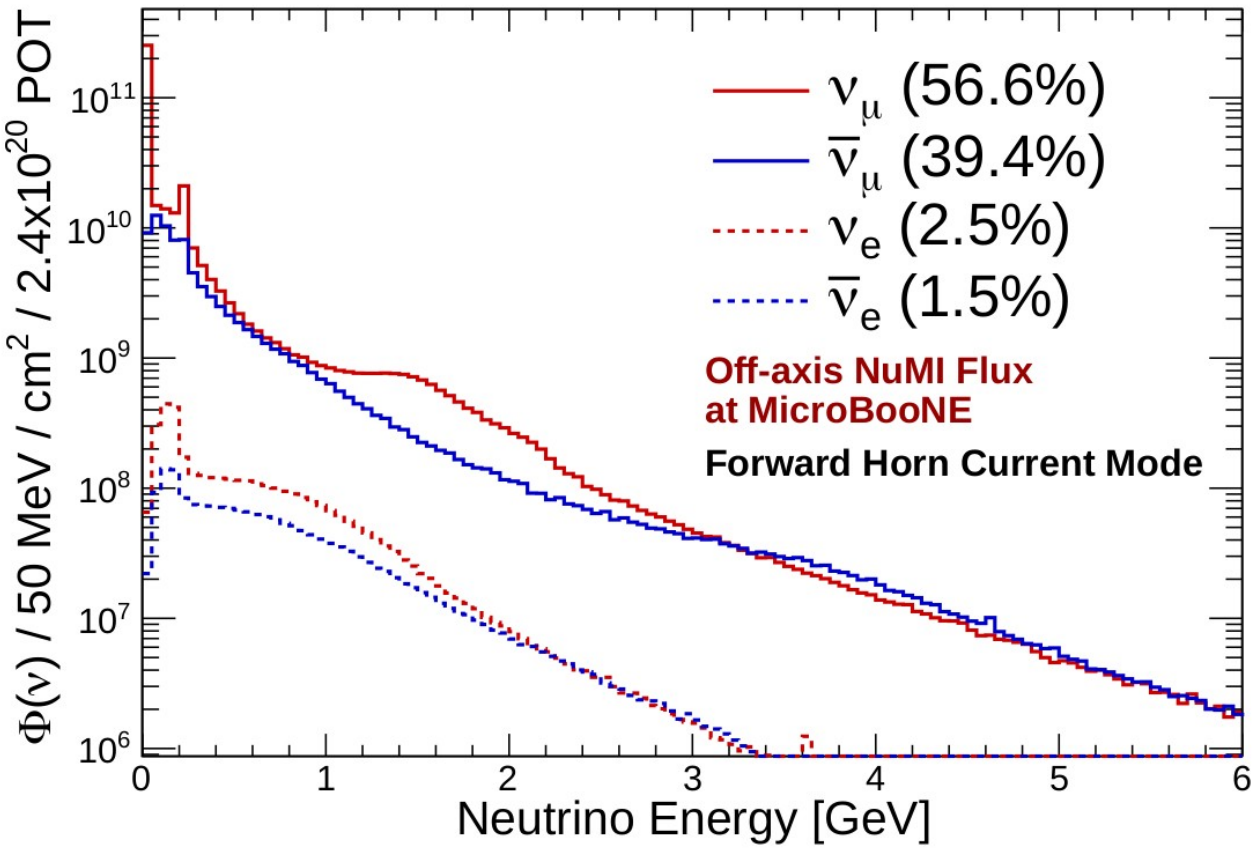
Flux is 99.3% $\nu_\mu/\bar{\nu}_\mu$.

Flux and simulation described in Phys. Rev. D 79, 072002

The Beams - NuMI



Off axis angles ranging from 8° to 120°
Enhances the wrong sign component.



Much larger $\nu_e/\bar{\nu}_e$ flux

Described in Nucl. Instrum. Meth. A806, 279–306 and Phys. Rev. D 104, 052002

Cross Sections – Published/Submitted

- Charged current:
  - ν_μ Inclusive: BNB, BNB energy dep.
  - ν_e Inclusive: NuMI total and NuMI differential.
  - ν_μ No Pions: BNB 1p, BNB 2p, BNB Np, BNB TKI.
  - ν_e No Pions: BNB 1p.
  - ν_μ neutral π with BNB.

Several pion production measurements in the works!!!

- Neutral current:
  - BNB neutral π.

- Rare processes:
  - Λ baryon production.
  - η meson production.

Cross Sections – Published/Submitted

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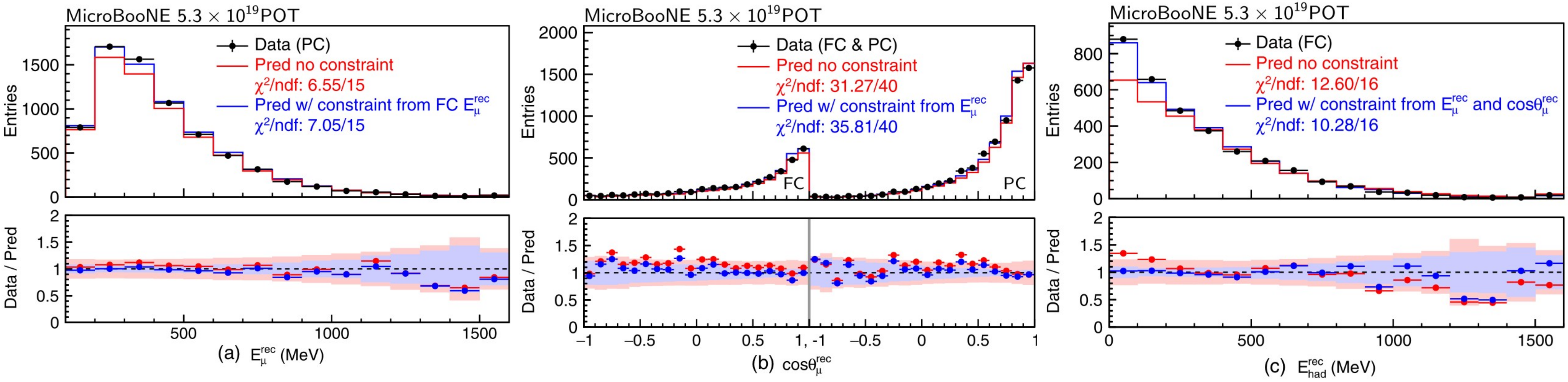
ν_μ CC Energy Dependence

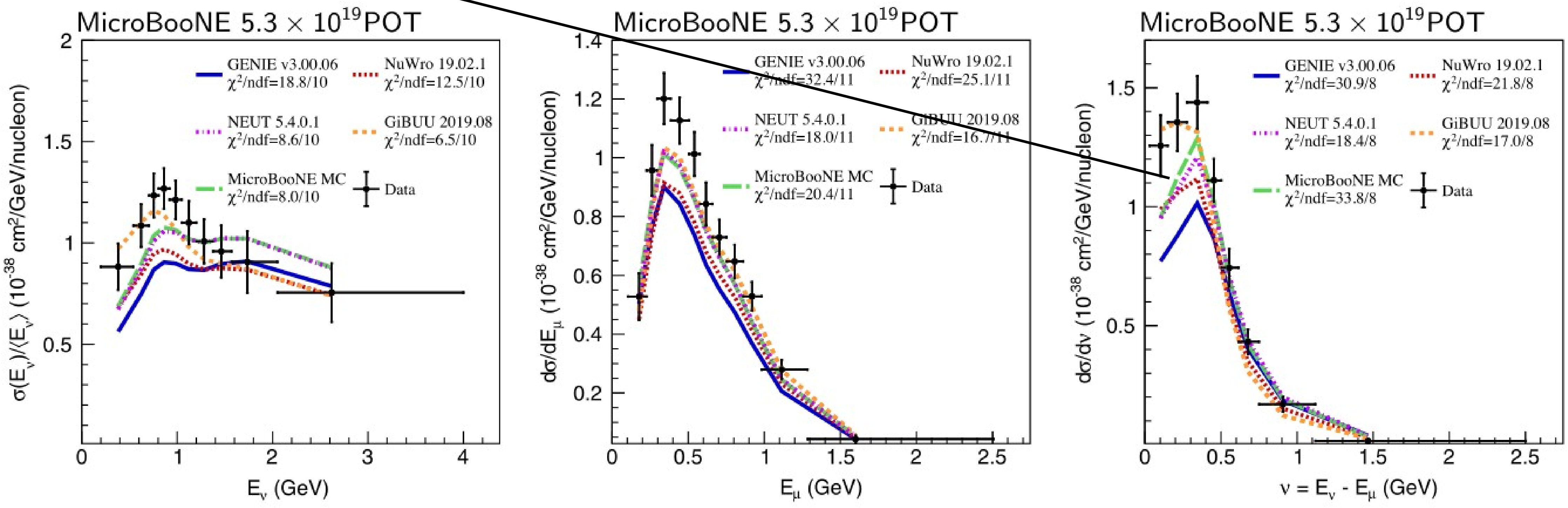
- Observe the visible hadronic energy, muon energy and direction.
- Use these to constrain uncertainties due to missing hadronic energy.



Phys. Rev. Lett. 128, 151801

ν_μ CC Energy Dependence

- Unfold into true neutrino energy*.
- First ever measurement of cross section as a function of energy transfer.

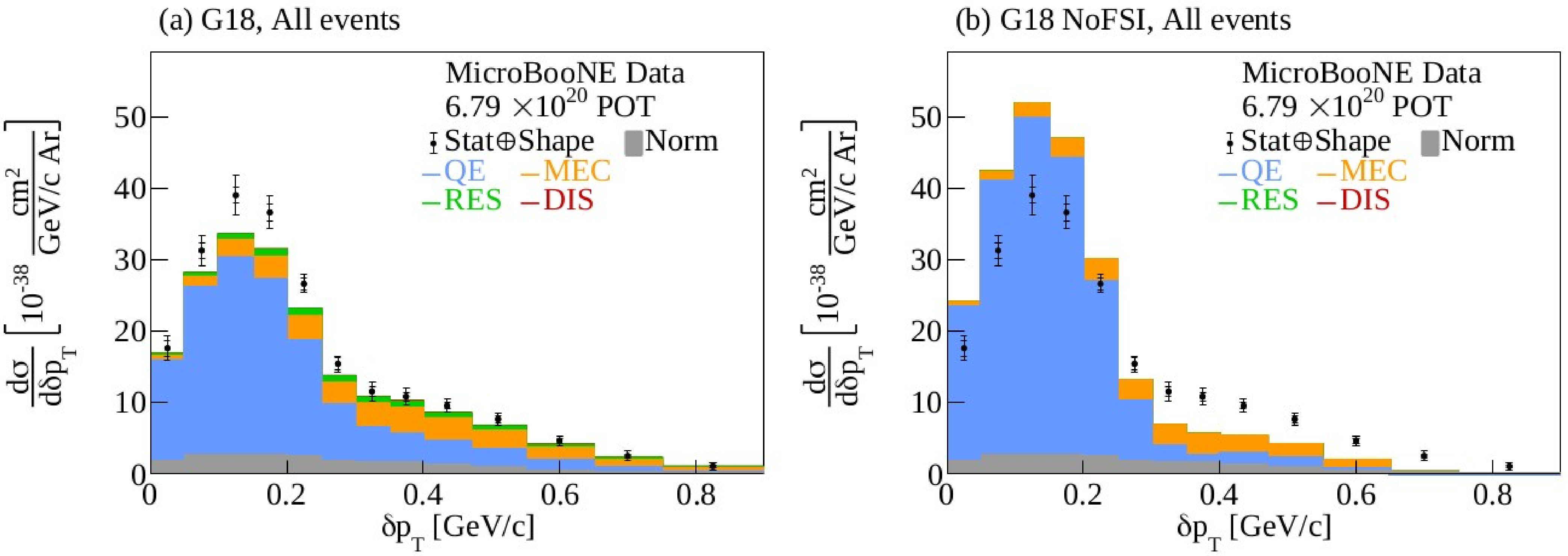


Phys. Rev. Lett. 128, 151801

*details in backup

ν_μCC 1P0π Kinematic Imbalance

- Certain variables are very sensitive to initial nucleon momentum and FSI*.

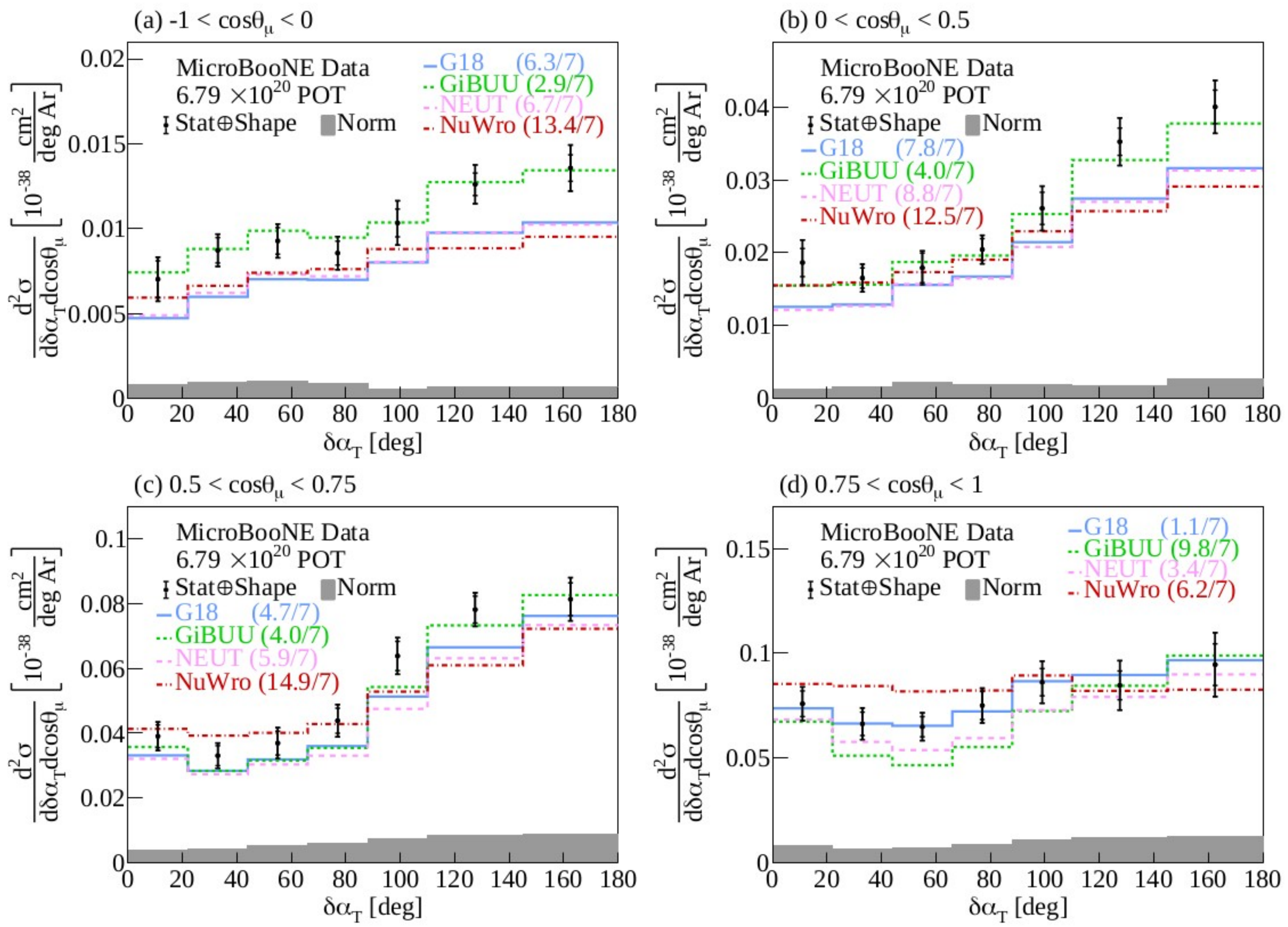


arXiv:2301.03700 and arXiv:2301.03706

*definitions in backup.

ν_μCC 1P0π Kinematic Imbalance

- Double differential cross sections in terms of TKI variables!

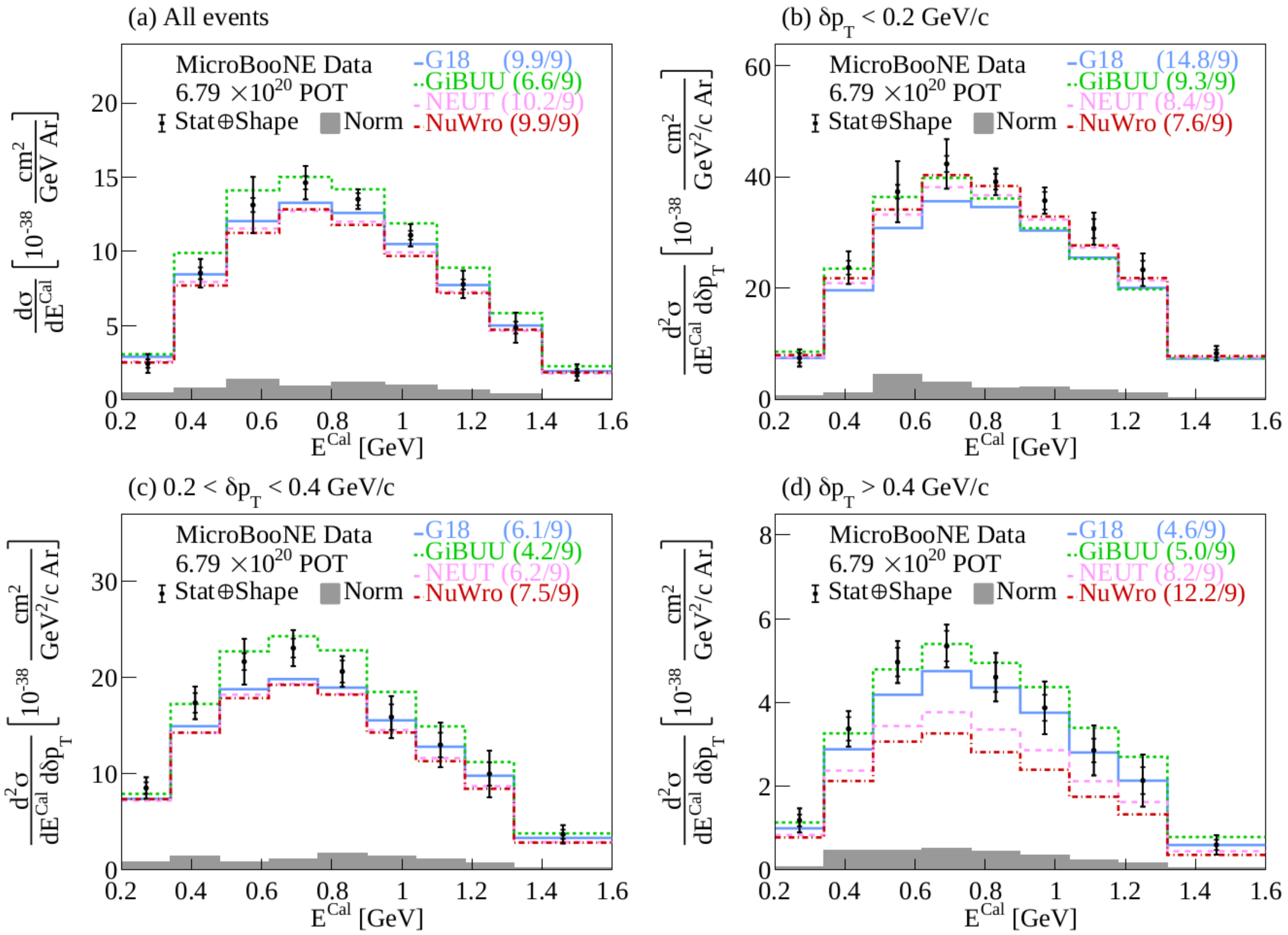


arXiv:2301.03700 and arXiv:2301.03706

ν_μCC 1P0π Kinematic Imbalance

- Double differential cross sections in terms of total visible energy and TKI variables.

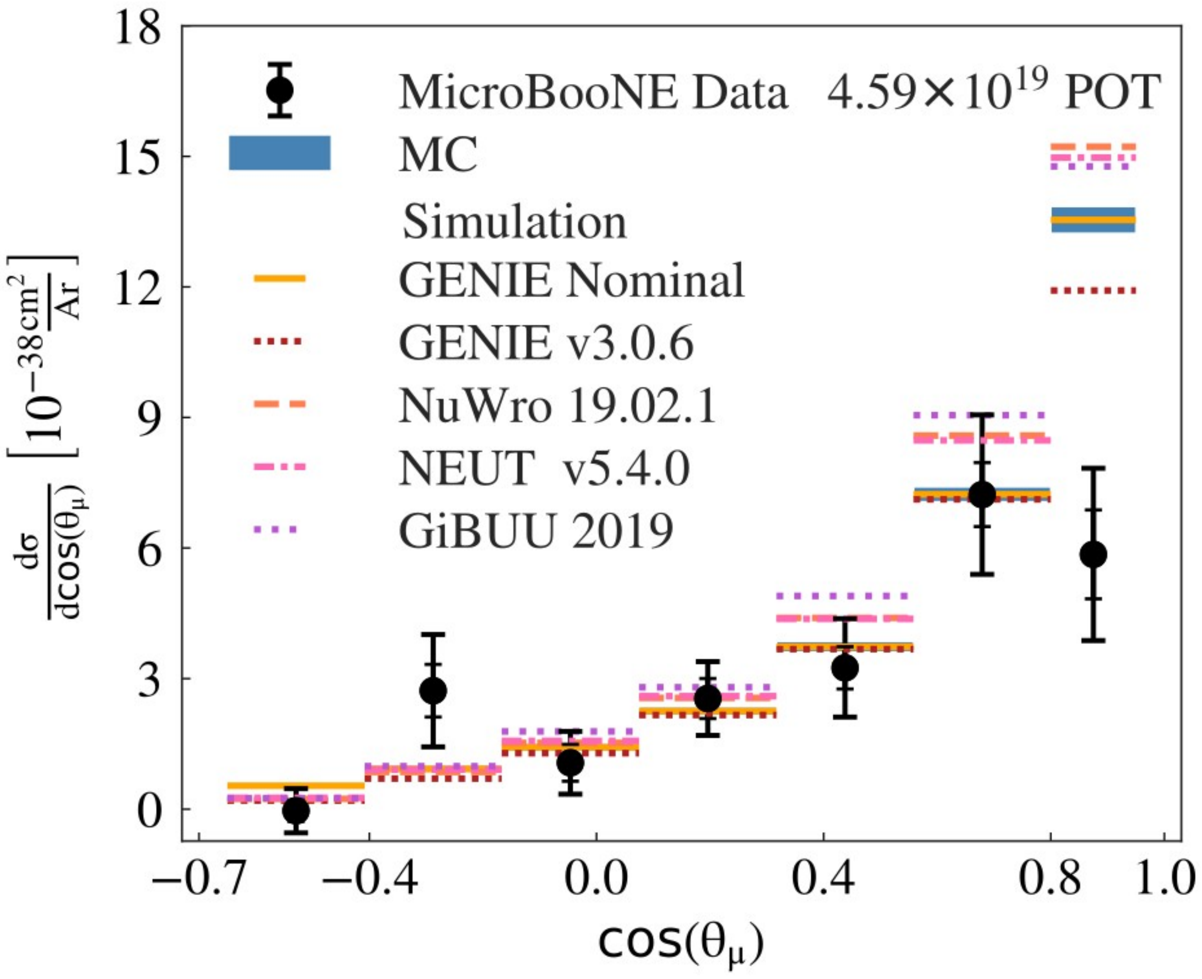
- Study the impact of nuclear effects on energy estimation.



arXiv:2301.03700 and arXiv:2301.03706

ν_μCC 1P0π

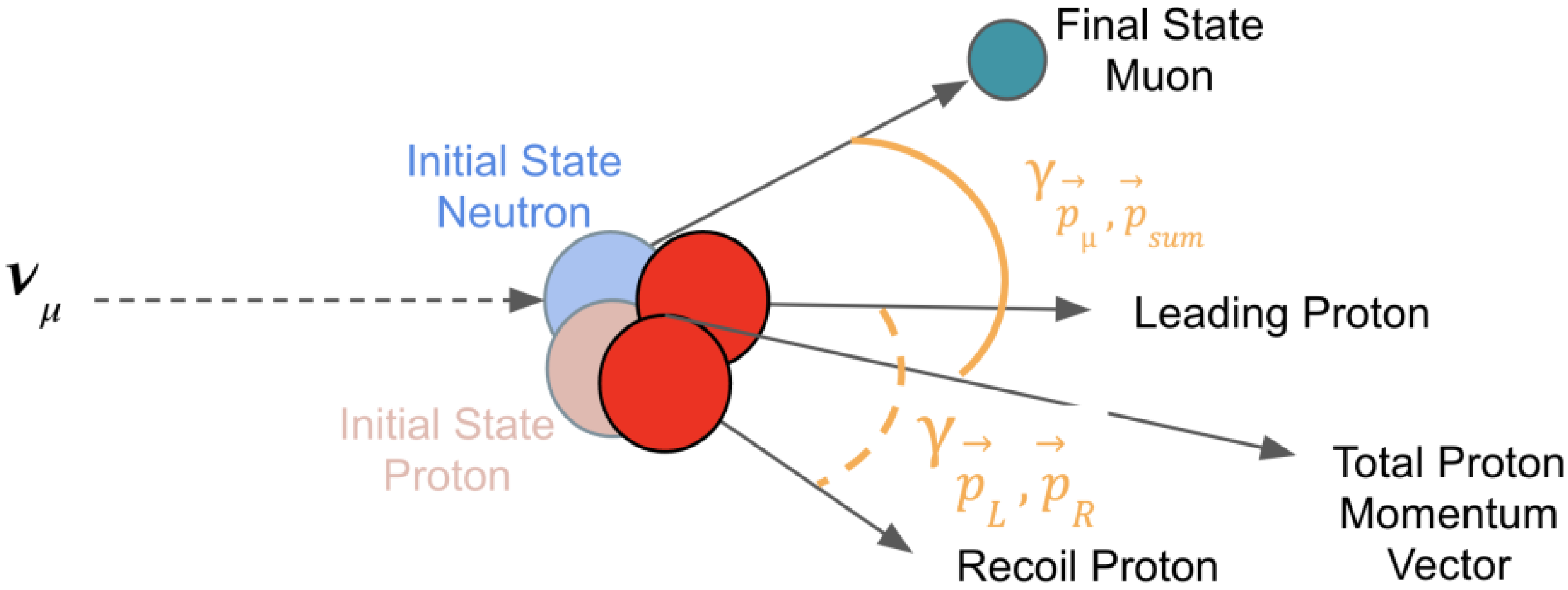
- Slightly older result in the same channel as TKI.
- Generators all overpredict in “soft scattering” region.
- One of the more difficult regions of phase space to model!



Phys. Rev. Lett. 125, 201803

ν_μCC 2P0π

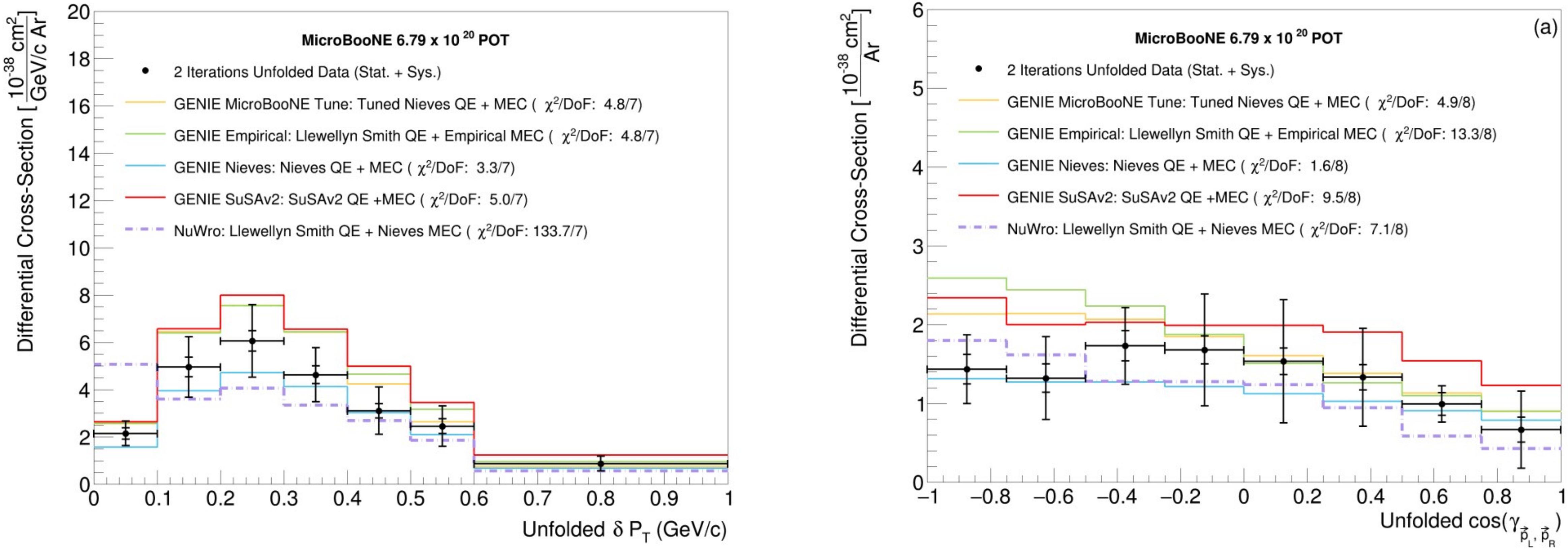
- Study the influence of multi-nucleon effects, eg. meson exchange current, short range correlations etc.



arXiv:2211.03734

ν_μCC 2P0π

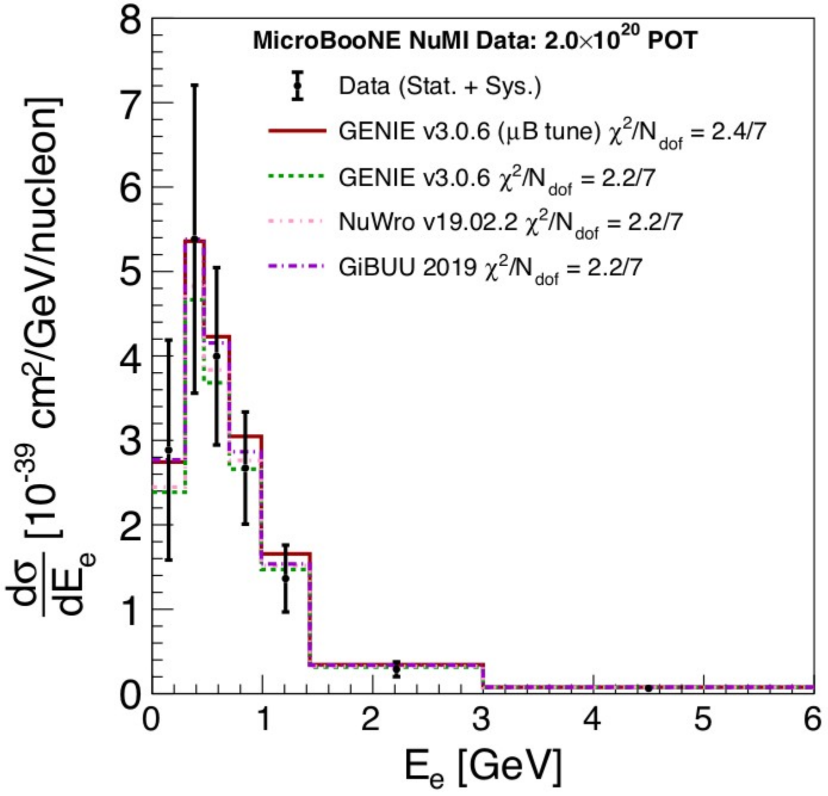
- Look at transverse momentum of final state particles and their opening angles.
- First high statistics analysis of its kind.

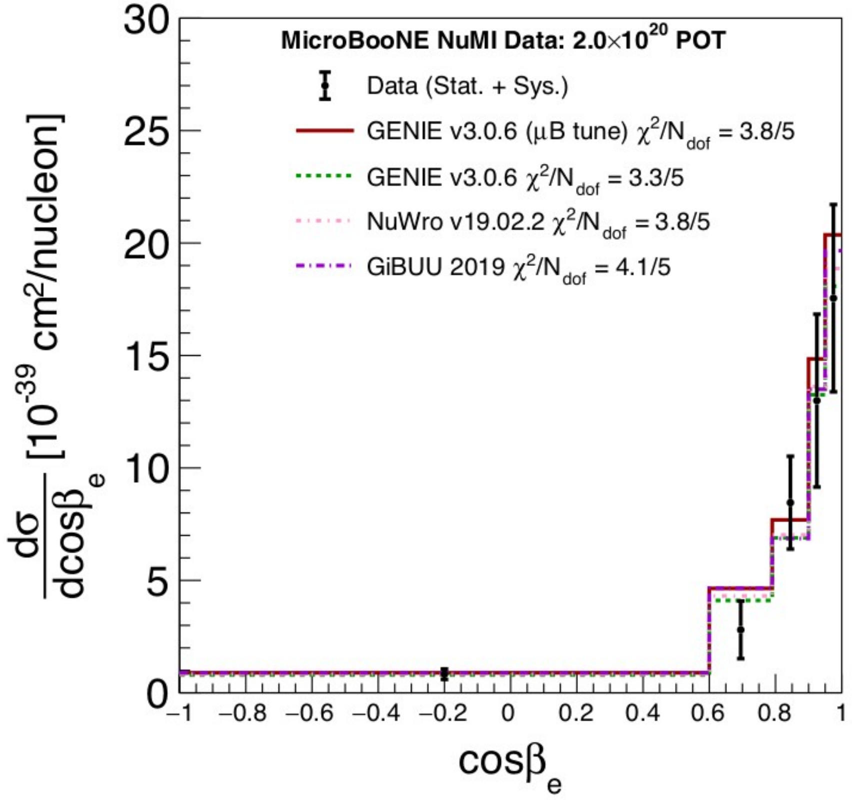


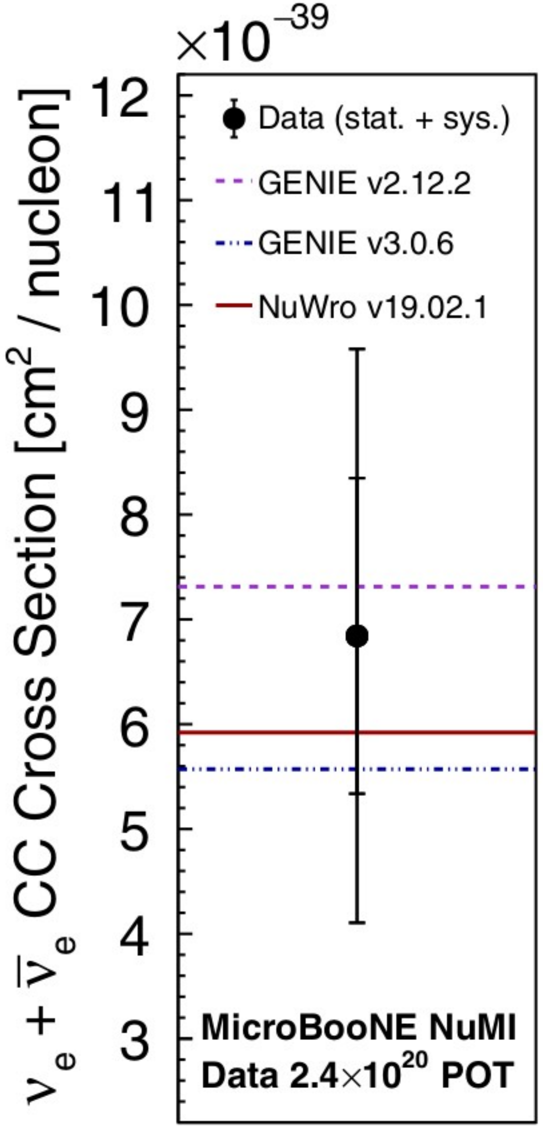
arXiv:2211.03734

ν_e CC with NuMI

- High ν_e content makes NuMI an excellent place to study ν_e interactions.





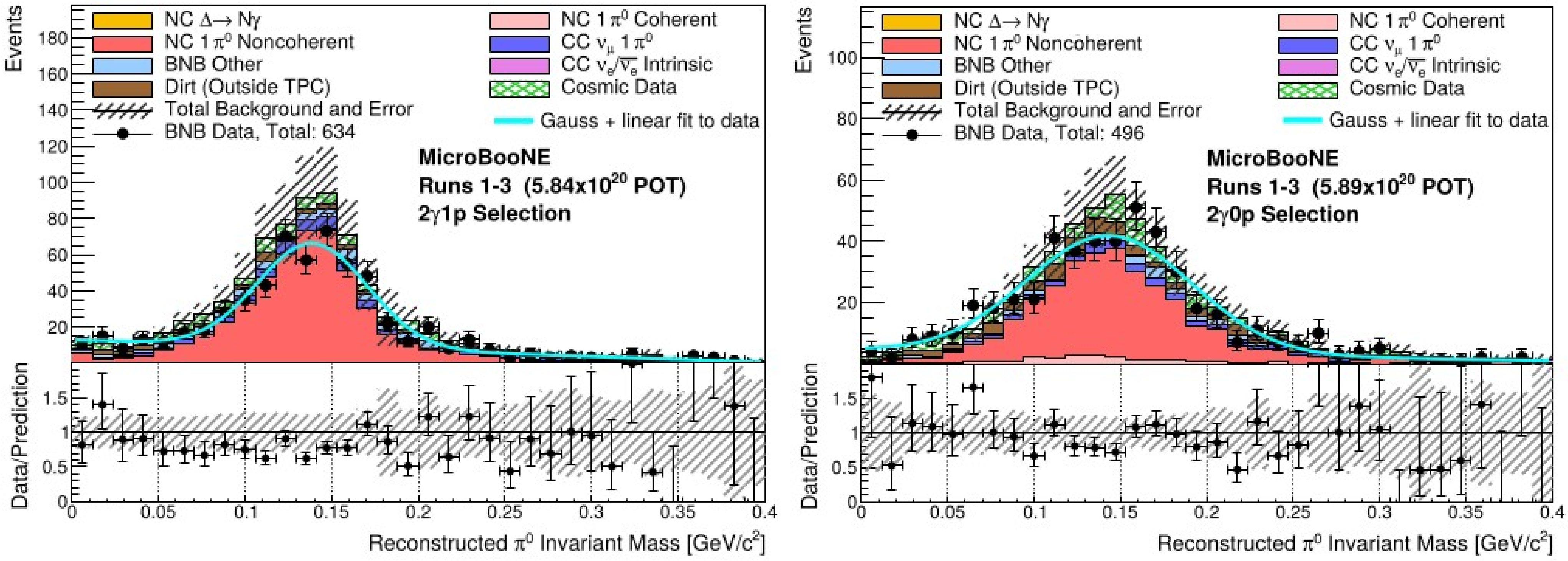


Phys. Rev. D 104, 052002 and Phys. Rev. D 105, L051102

NC π^0

Same channel with Wire-cell reconstruction in MicroBooNE Public Note 1111, and deep learning in Phys. Rev. D 105, 112003.

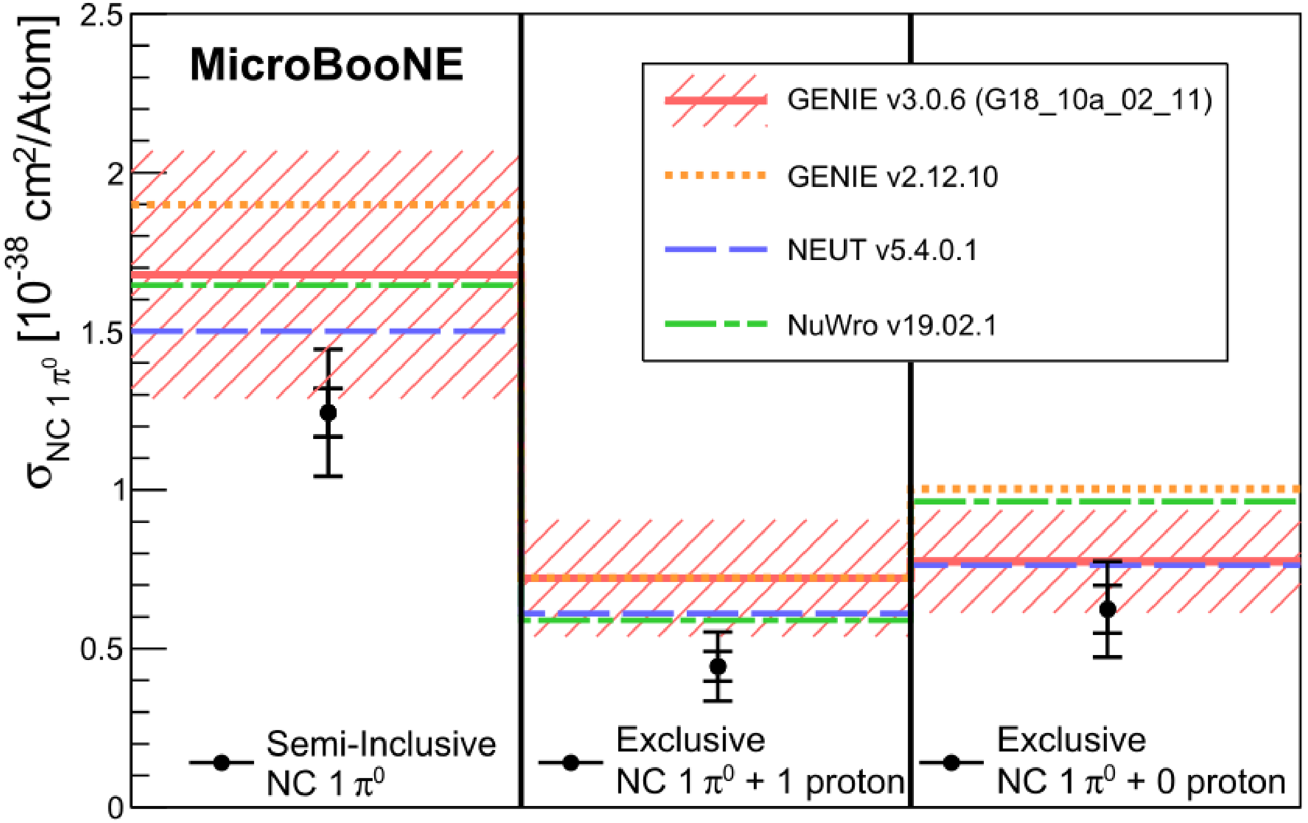
- Extensively studied as background to LEE.
- Identify neutral pions through their invariant mass.



Phys. Rev. D 107, 012004

NC π^0

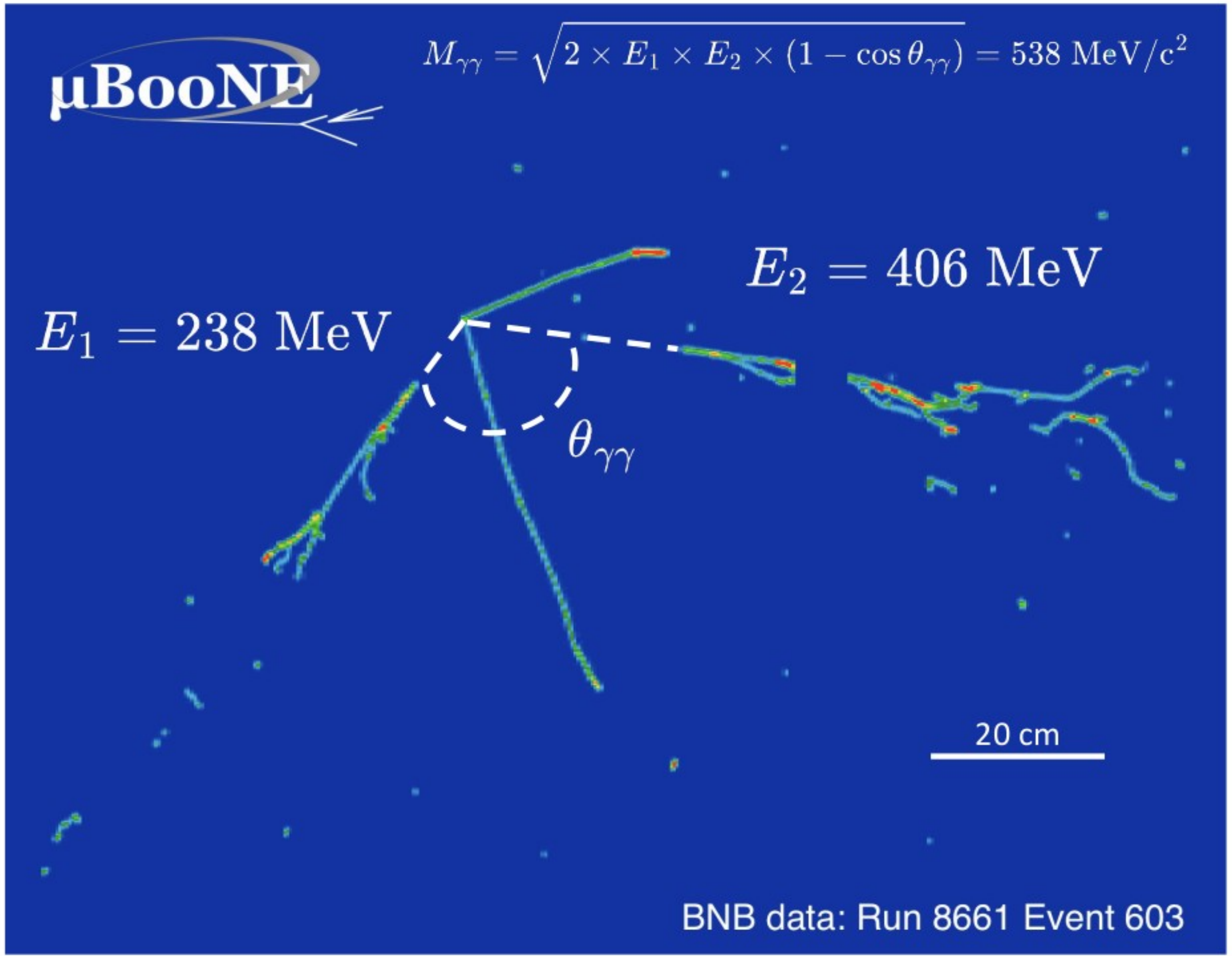
- Measure 0p and 1p channels (and their combination).



Phys. Rev. D 107, 012004

η Meson Production

- Unique probe of higher resonances such as N(1535), N(1650), and N(1710).
- Complimentary standard candle to π^0.
- Identified via decay to 2ɣ with invariant mass of 548 MeV.

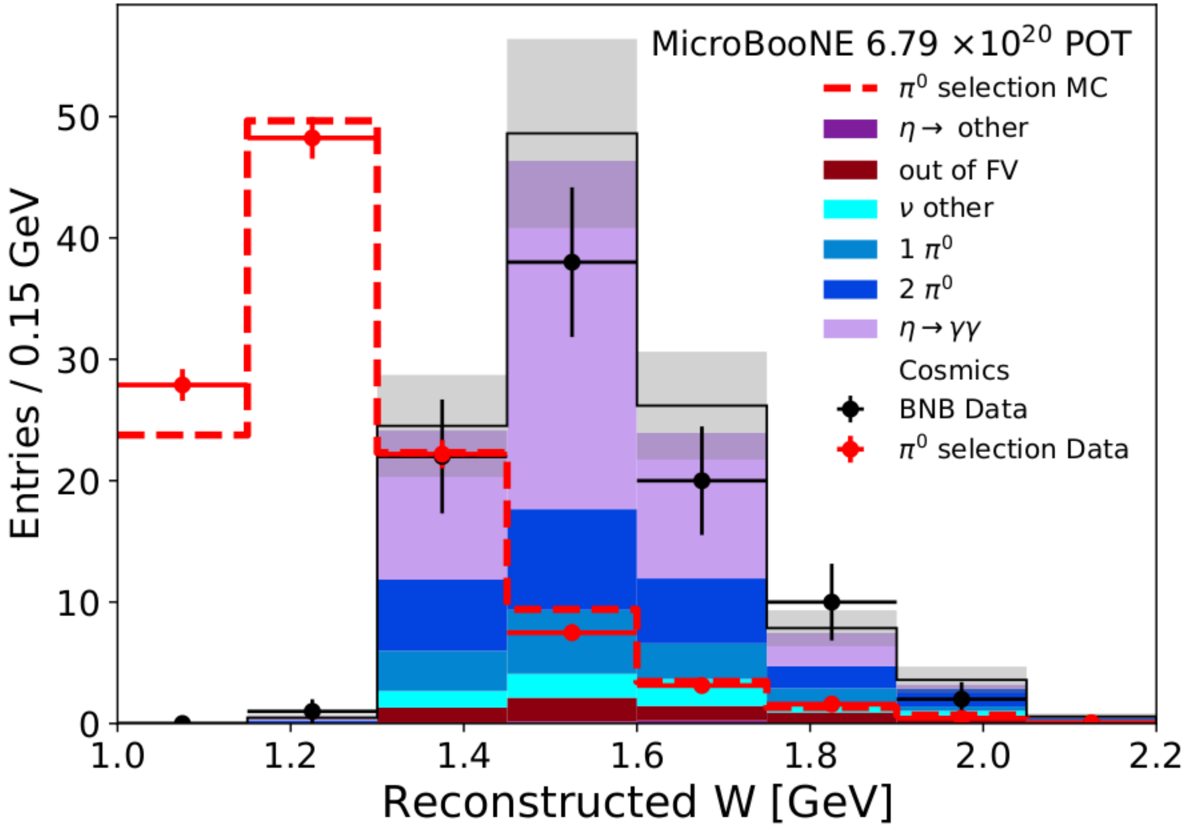


arXiv:2305.16249

η Meson Production

- Include protons to estimate reconstructed invariant mass of hadronic system.

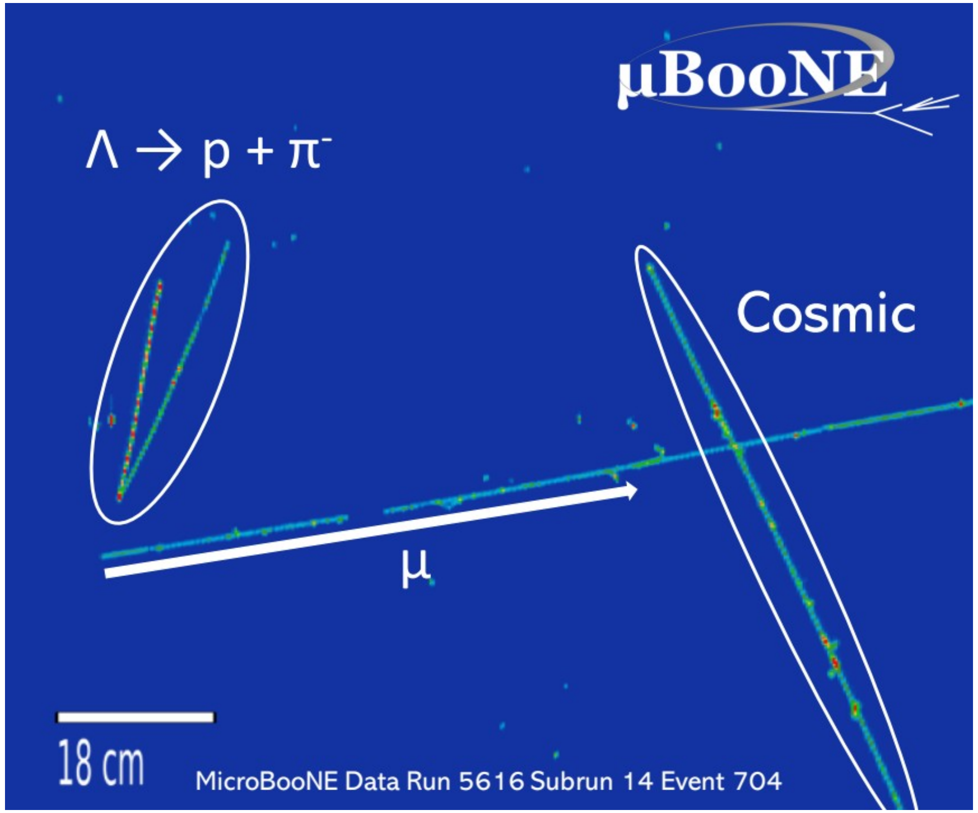
- Observe separate peak at 1.5 GeV!

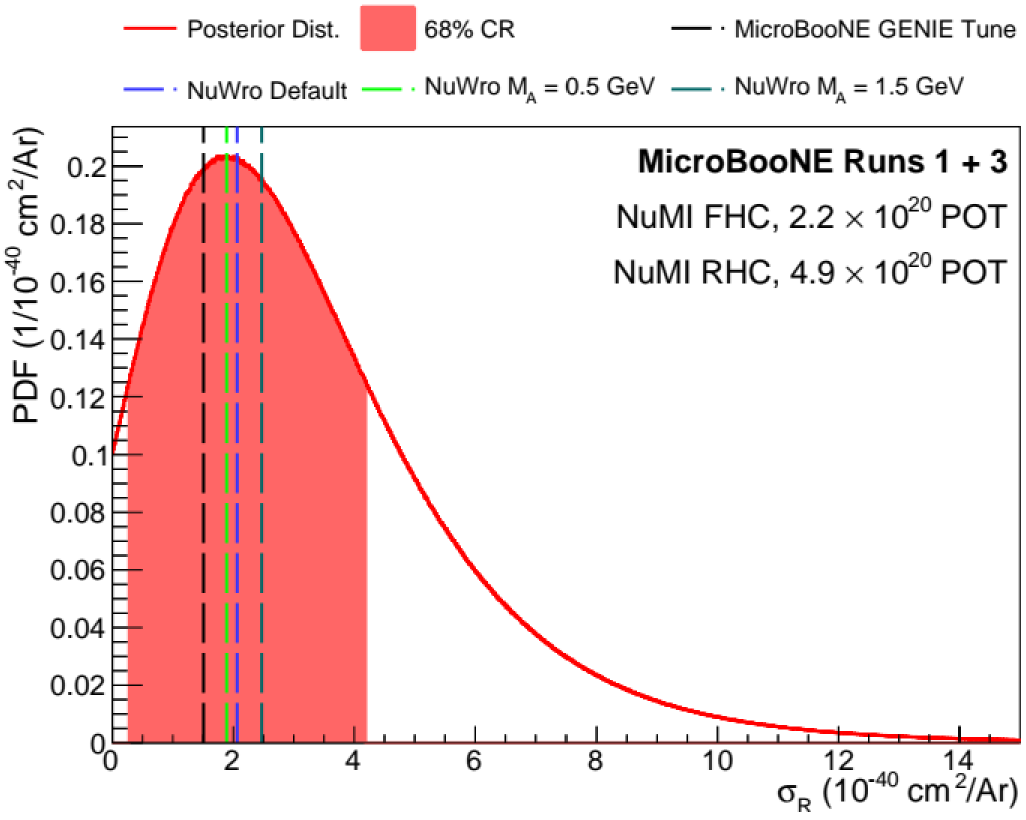


arXiv:2305.16249

Λ Baryon Production

- First measurement with a modern detector.
- **Very rare interaction** – observed 5 candidates.
- Identify Λ baryons through invariant mass and separated vertex.





Phys. Rev. Lett. 130, 231802

Cross Sections – In Progress

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

Summary

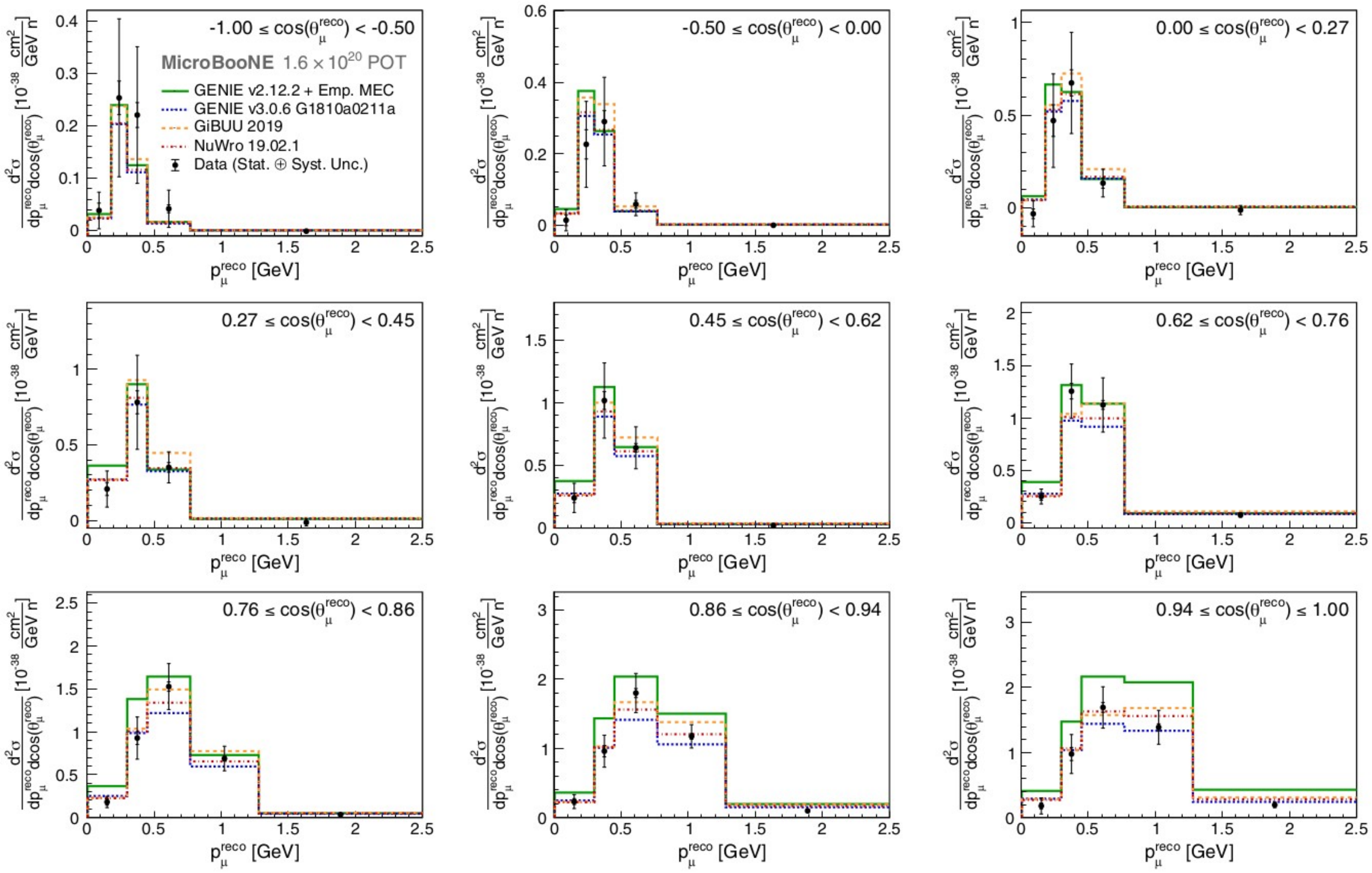
- Diverse and comprehensive cross section program.
- Exploring lots of different channels and variety of analysis techniques.
- Sensitive enough to expose inconsistencies between modeling approaches, list of interesting features in data continues to grow.
- **Haven’t yet analysed our full dataset** – runs 4 and 5 still to go.

Thank you for listening!

Backup Slides

ν_μCC Inclusive

- First ever double differential cross section with argon.

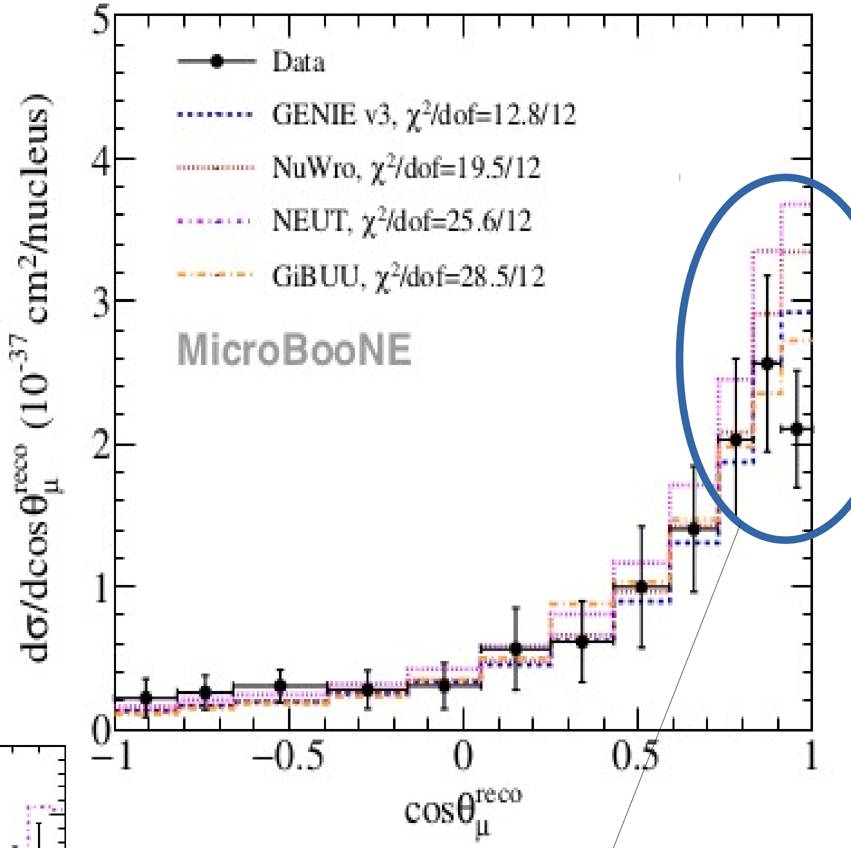


*See this paper.

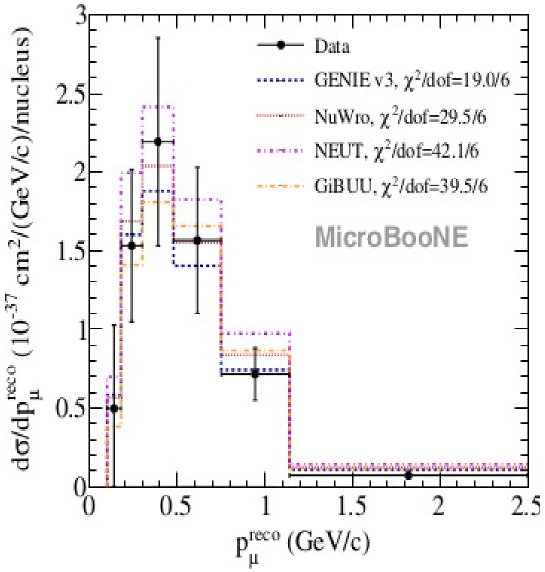
Phys. Rev. Lett. 123, 131801

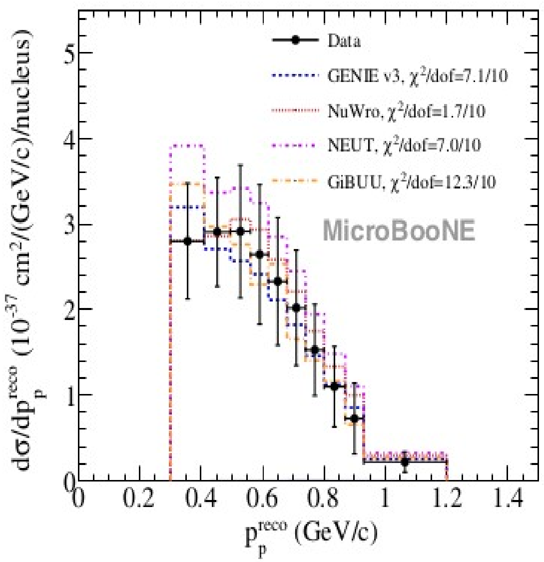
ν_μCC NP

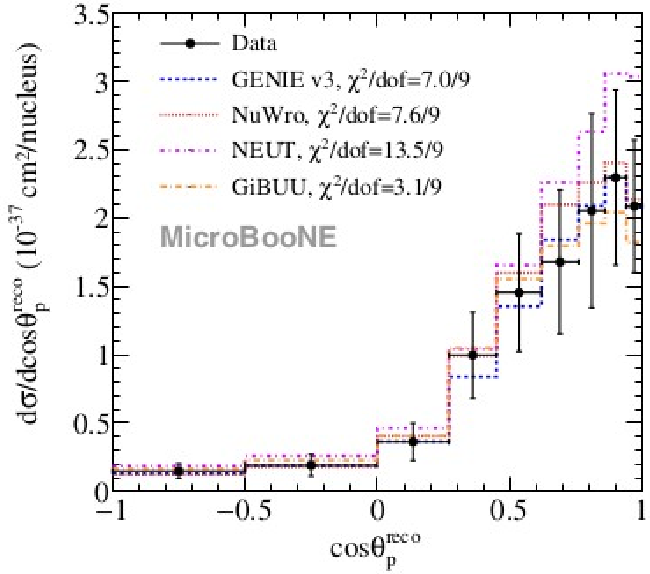
- Similar to the previous measurement with more inclusive selection.
- Observe similar overprediction at small muon angles.



Still see the deficit at small muon angles.



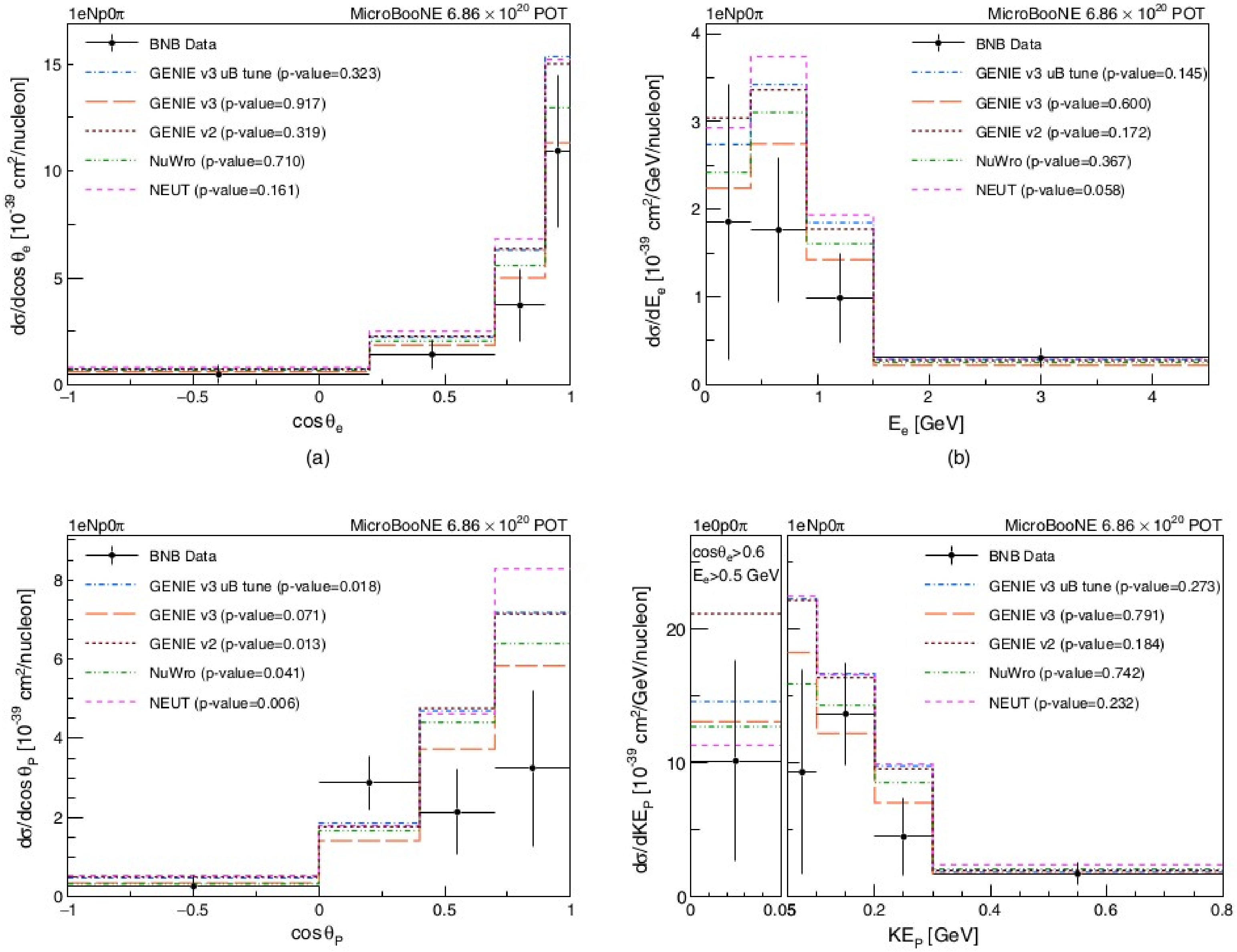




Phys. Rev. D 102, 112013

ν_e CC with BNB

- Reinterpreting the LEE ν_e search as a cross section.

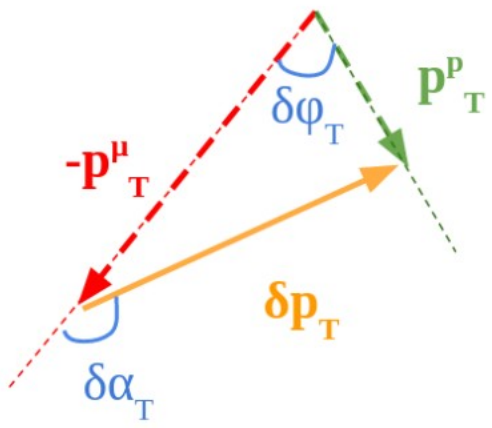


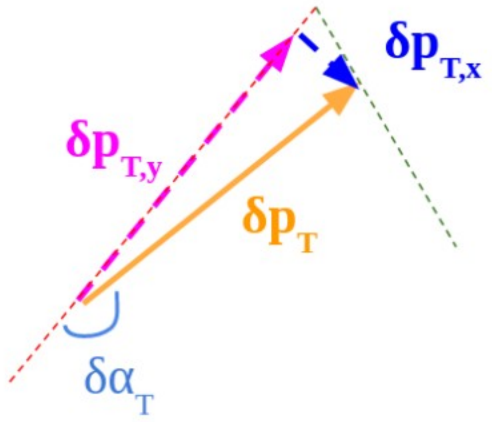
Phys. Rev. D 106, L051102

Neutrino Event Generators

- We make comparisons between our data and calculations made with several neutrino event generators:
  - GENIE – version 2 and version 3. We have our own tune of v3.
  - NuWro – more theory focused generator, developed by group of University of Wrocław.
  - NEUT – developed in-house by the SK/T2K collaboration.
  - GiBUU – more quantum mechanical, solves the Giessen-Boltzmann-Uehling-Uhlenbeck nuclear transport equations.

Kinematic Imbalance Variables



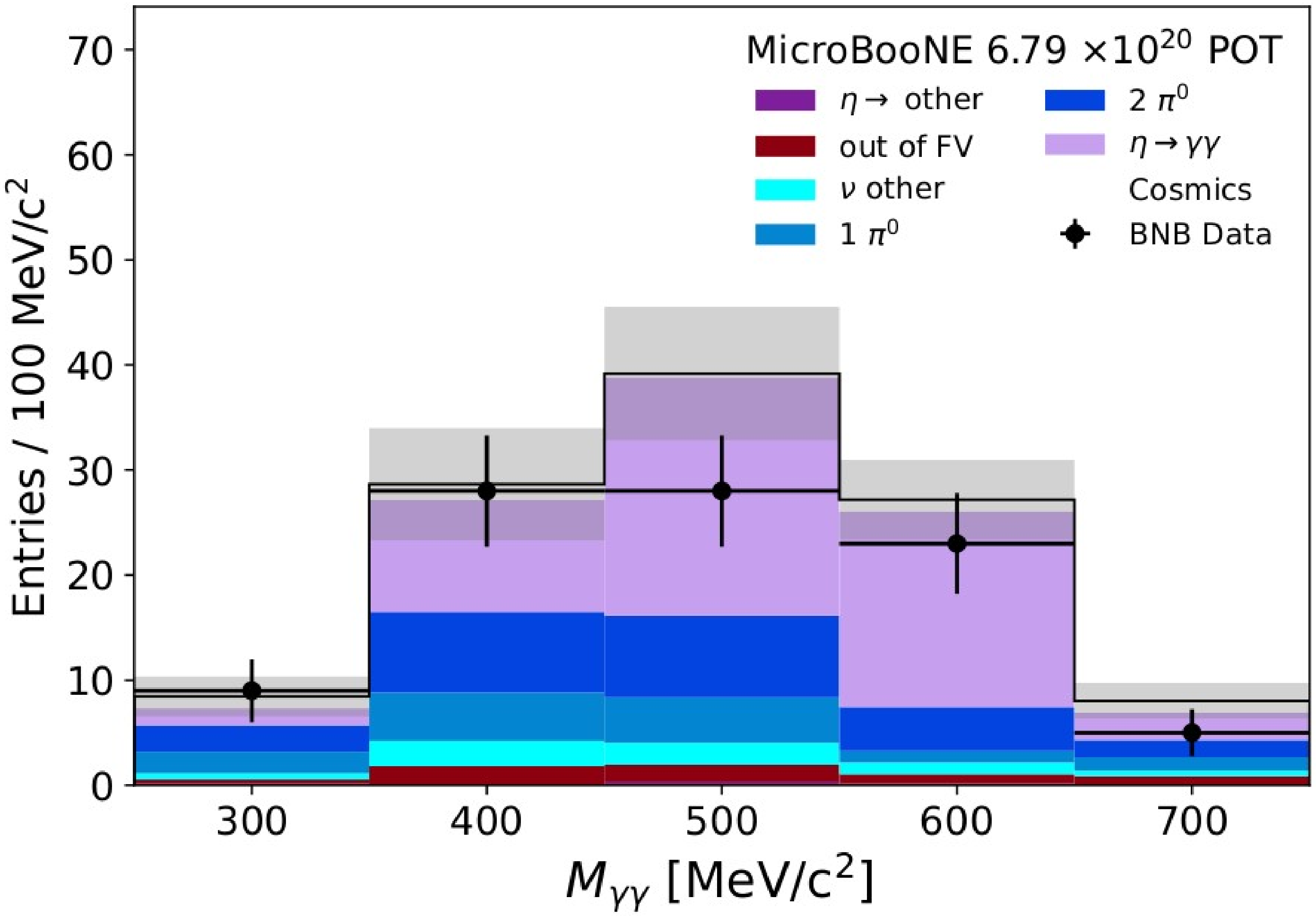


$$\delta\alpha_T = \arccos\left(\frac{-\vec{p}_T^{\,\mu}\cdot\delta\vec{p}_T}{p_T^{\,\mu}\,\delta p_T}\right) \qquad \delta\phi_T = \arccos\left(\frac{-\vec{p}_T^{\,\mu}\cdot\vec{p}_T^{\,p}}{p_T^{\,\mu}\,p_T^{\,p}}\right)$$

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

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

η Meson Production – π^0 Background



arXiv:2305.16249

Forward Folding vs Unfolding

- Forward folding:

$$q_j^{\text{obs}} = \sum_i M_{ij} q_i^{\text{true}}$$

Publish the data in reconstructed variables

Supply response matrix to enable theorists/generator builders to compare to reconstructed data

- Unfolding:

$$q_j^{\text{true}} = \sum_i M_{ij}^{-1} q_i^{\text{obs}}$$

Publish the data in true variables

Invert the response matrix

Wiener SVD unfolding: JINST 12 (2017) 10, P10002
d'Agostini unfolding: arXiv:1010.0632

q_i^{true} = true prediction in bin i q_j^{obs} = reconstructed data in bin j M_{ij} = response matrix