MicroBooNE's Recent Cross Section Results

Lee Hagaman (University of Chicago)
On behalf of the MicroBooNE Collaboration

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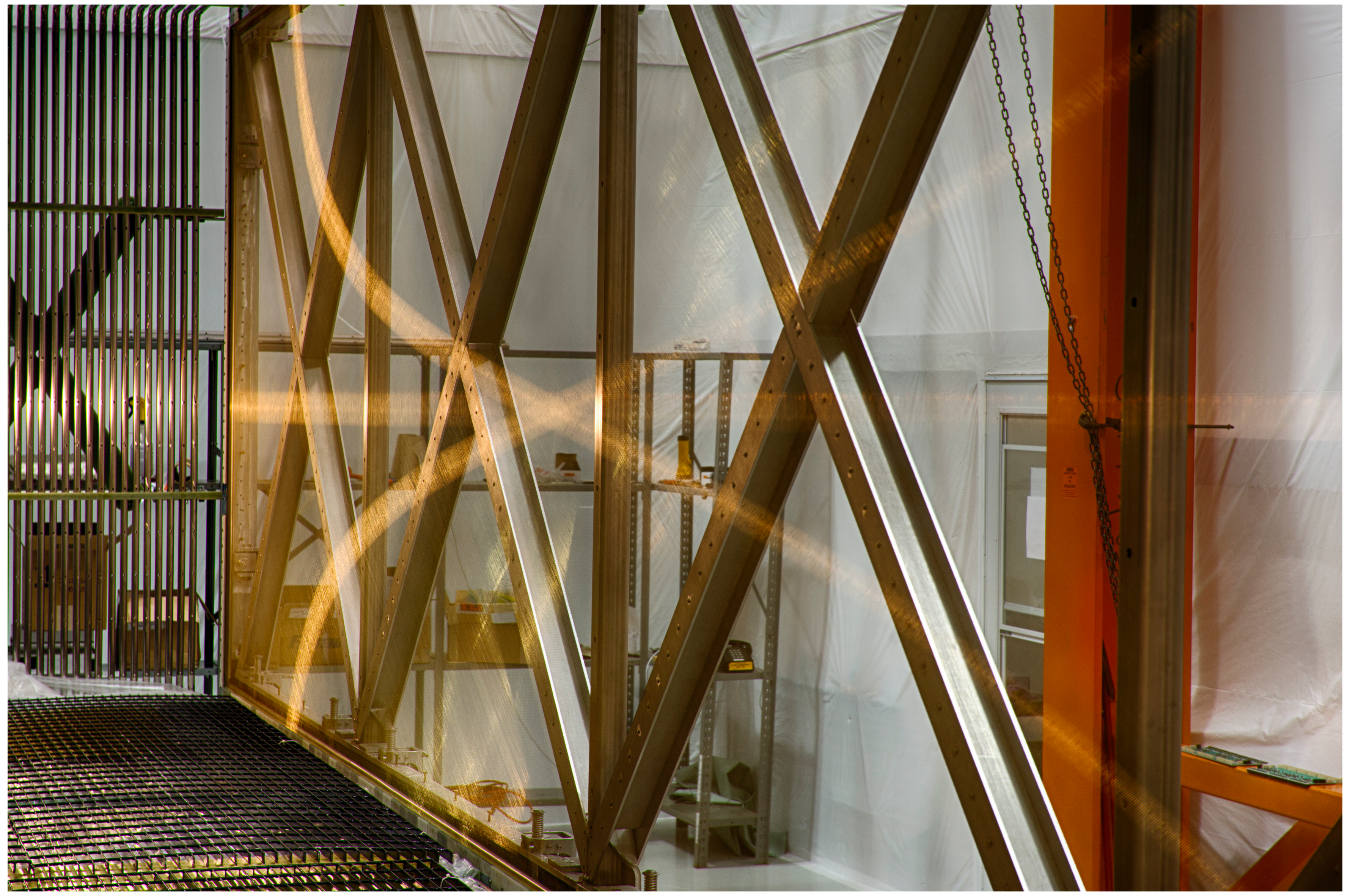
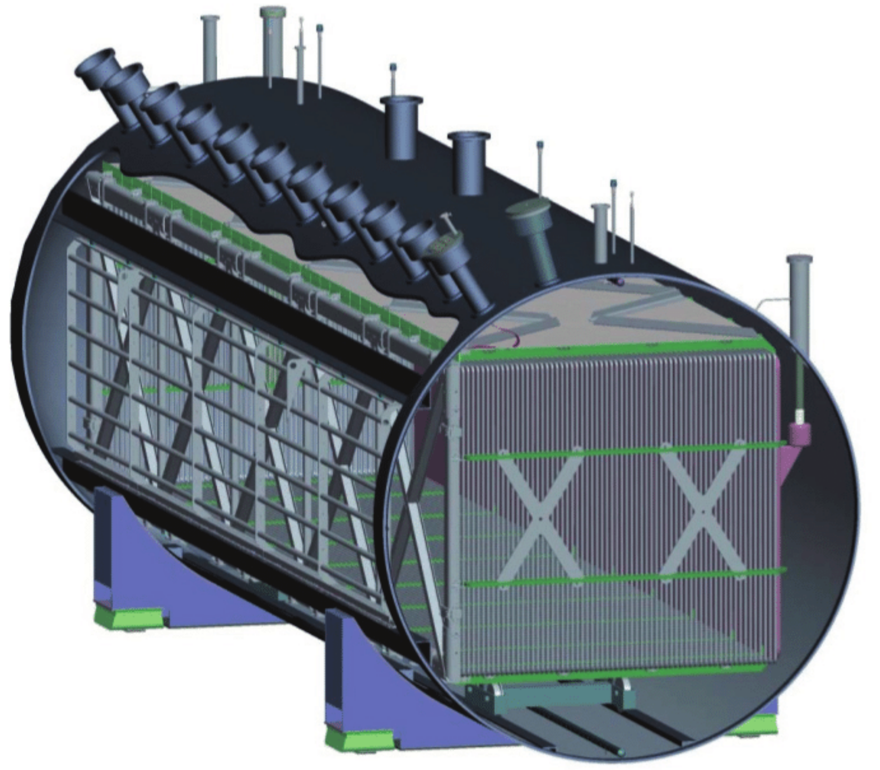
2nd Short-Baseline Experiment-Theory Workshop

MicroBooNE Data Run 5616 Subrun 14 Event 704

MicroBooNE

- MicroBooNE's more unique features among neutrino cross section experiments:
  - We use argon, and developing our understanding of neutrino-argon interactions is very important for DUNE oscillation searches
  - LArTPC technology allows low energy thresholds for individual particles in each event
  - We see two neutrino beams simultaneously, BNB on-axis and NuMI off-axis

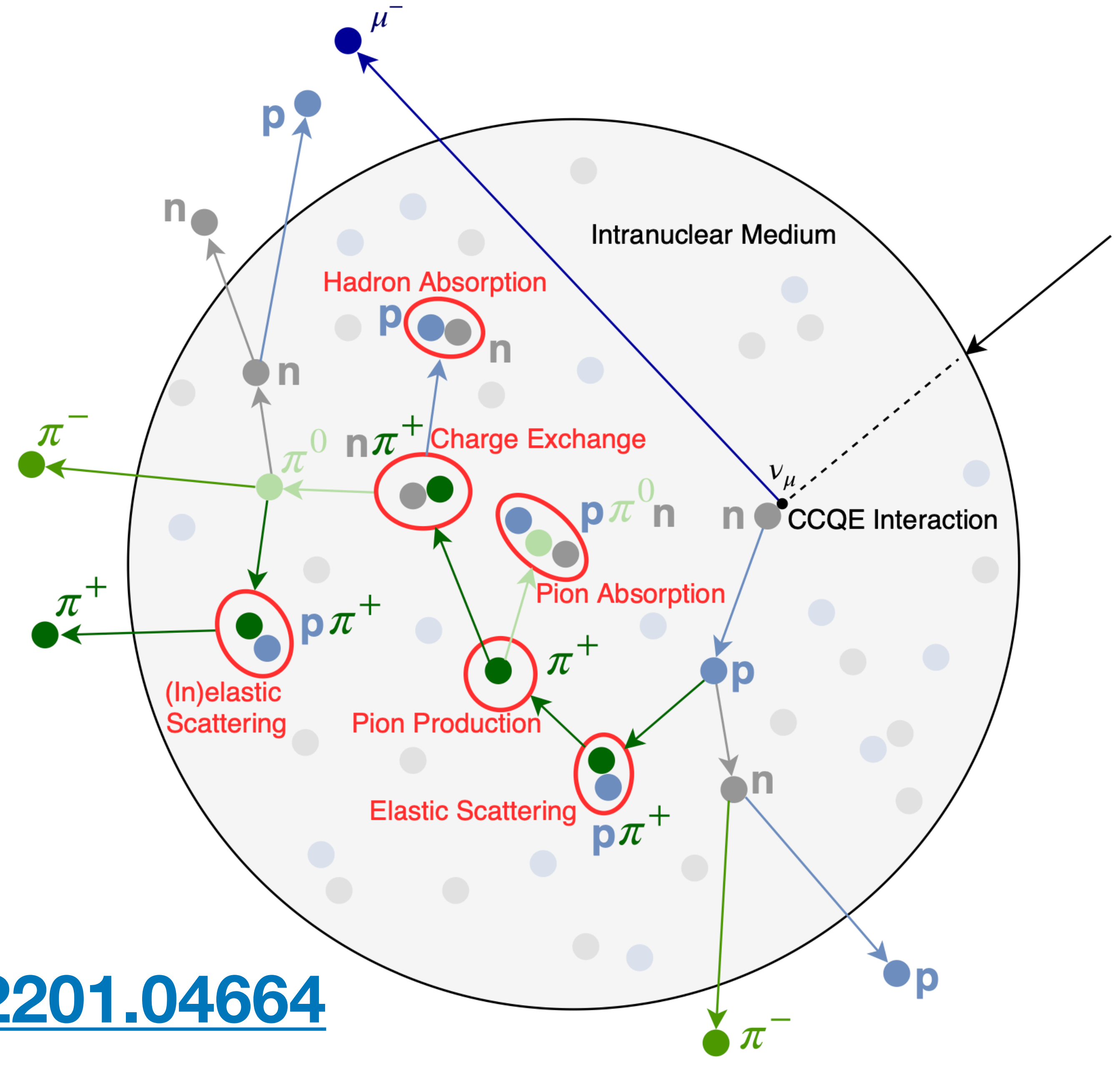




Fermilab Neutrino Beams

Different Interaction Mechanisms

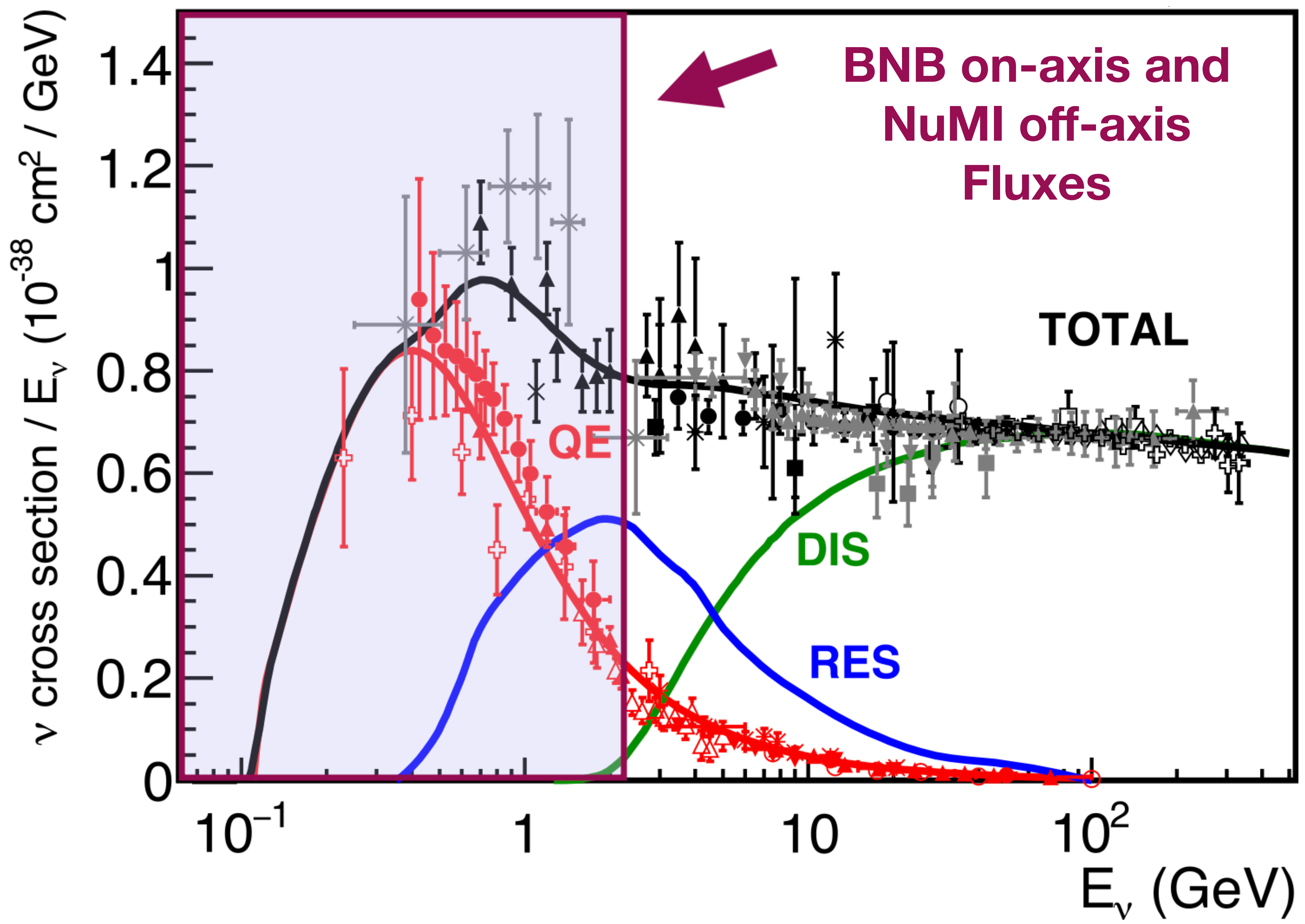
- Different neutrino energies cause different interaction mechanisms
- MicroBooNE sees many QE and RES events from the BNB and NuMI neutrino beams
- Final state interactions complicate this picture, changing the kinematics and topologies of events in complex ways

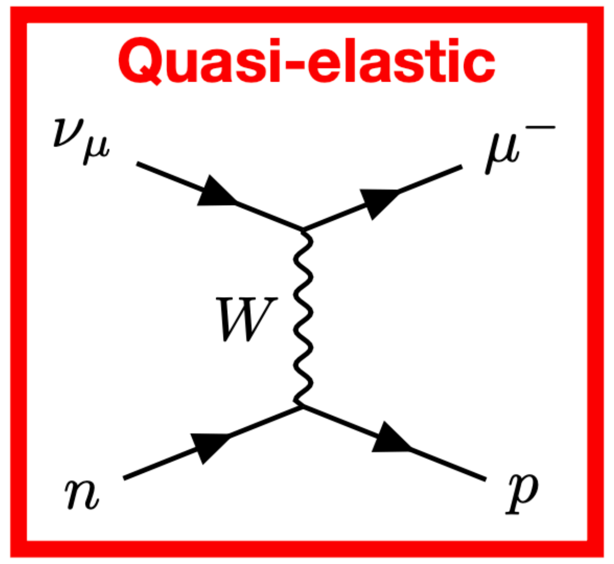


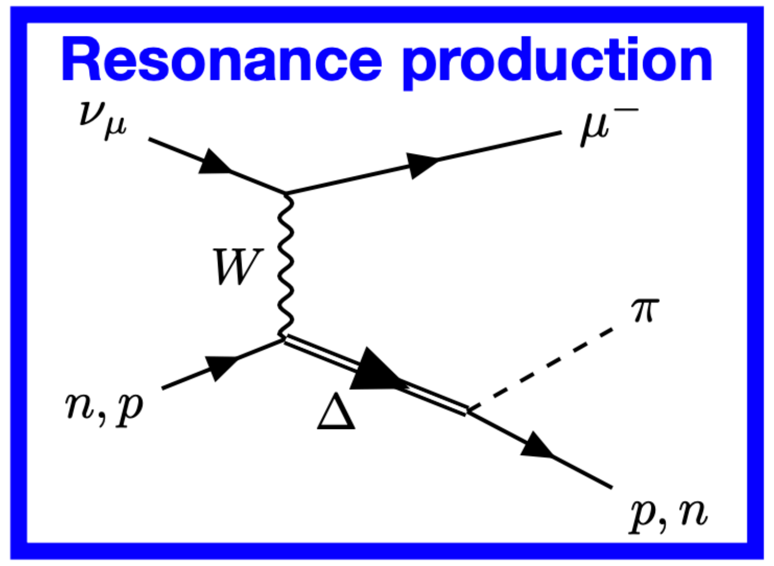
arXiv:2201.04664

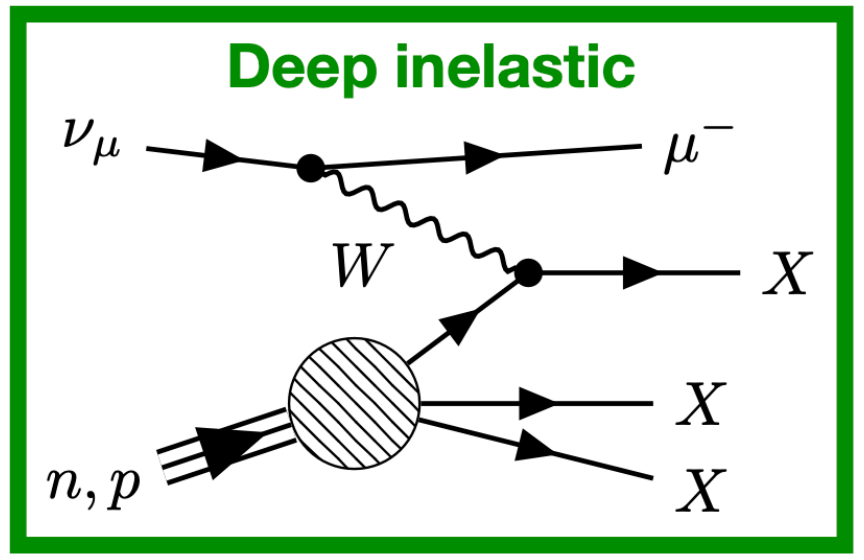
* Meson Exchange Current (MEC) is another interaction type that often expels two nucleons

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









Outline

- In this talk, I will discuss:
  - Our latest results on inclusive ν_μCC cross sections, including all these interaction types
  - Our latest results on exclusive ν_μCC 0π topologies, giving particular insight into QE interactions
  - Latest results on rare cross sections
    - A Cabibbo-suppressed version of QE: Λ production
    - A heavy version of RES interactions, producing an $N(1535)$ rather than a $\Delta(1232)$

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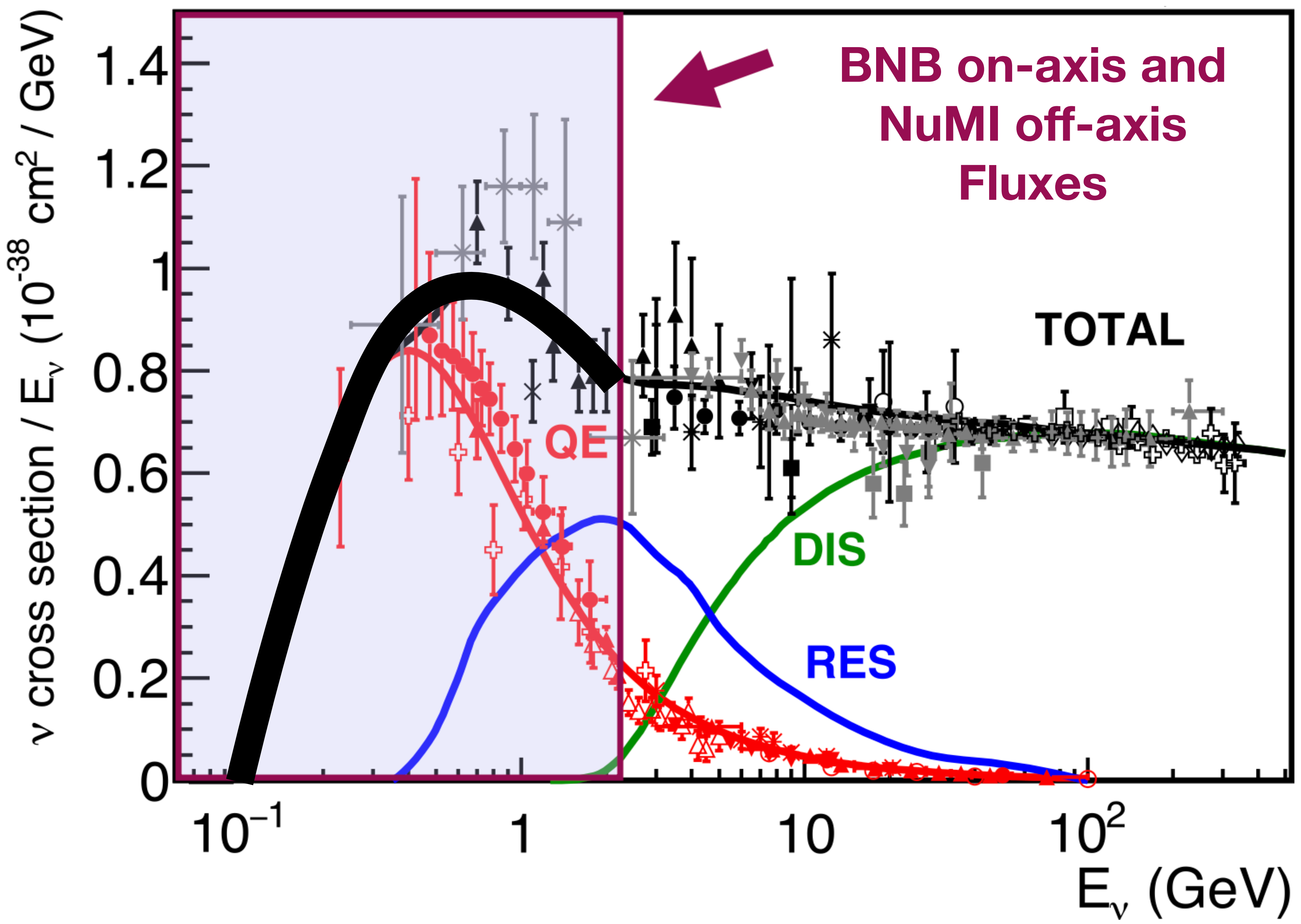

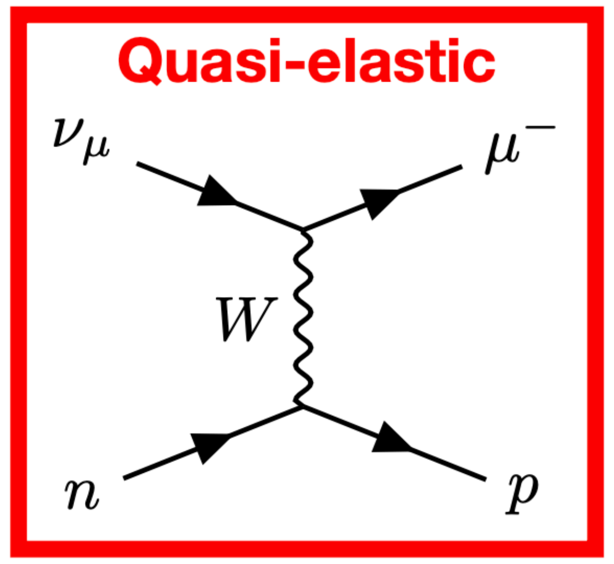

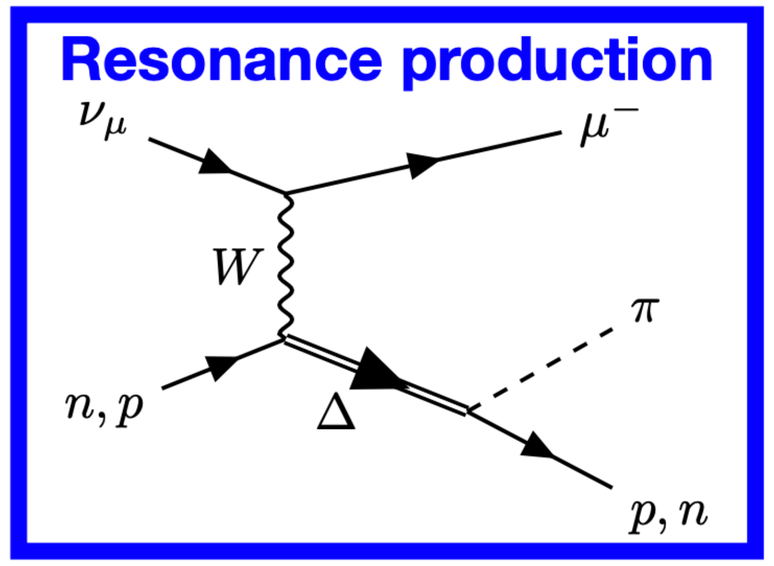

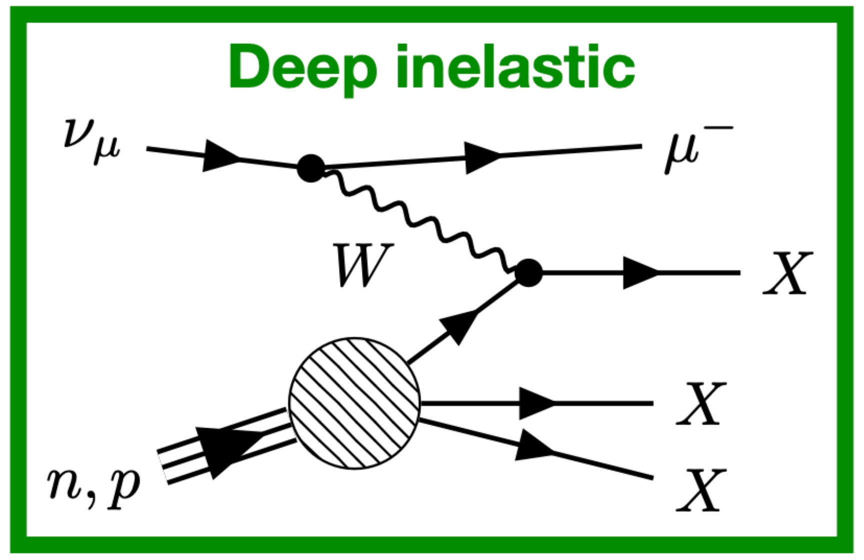

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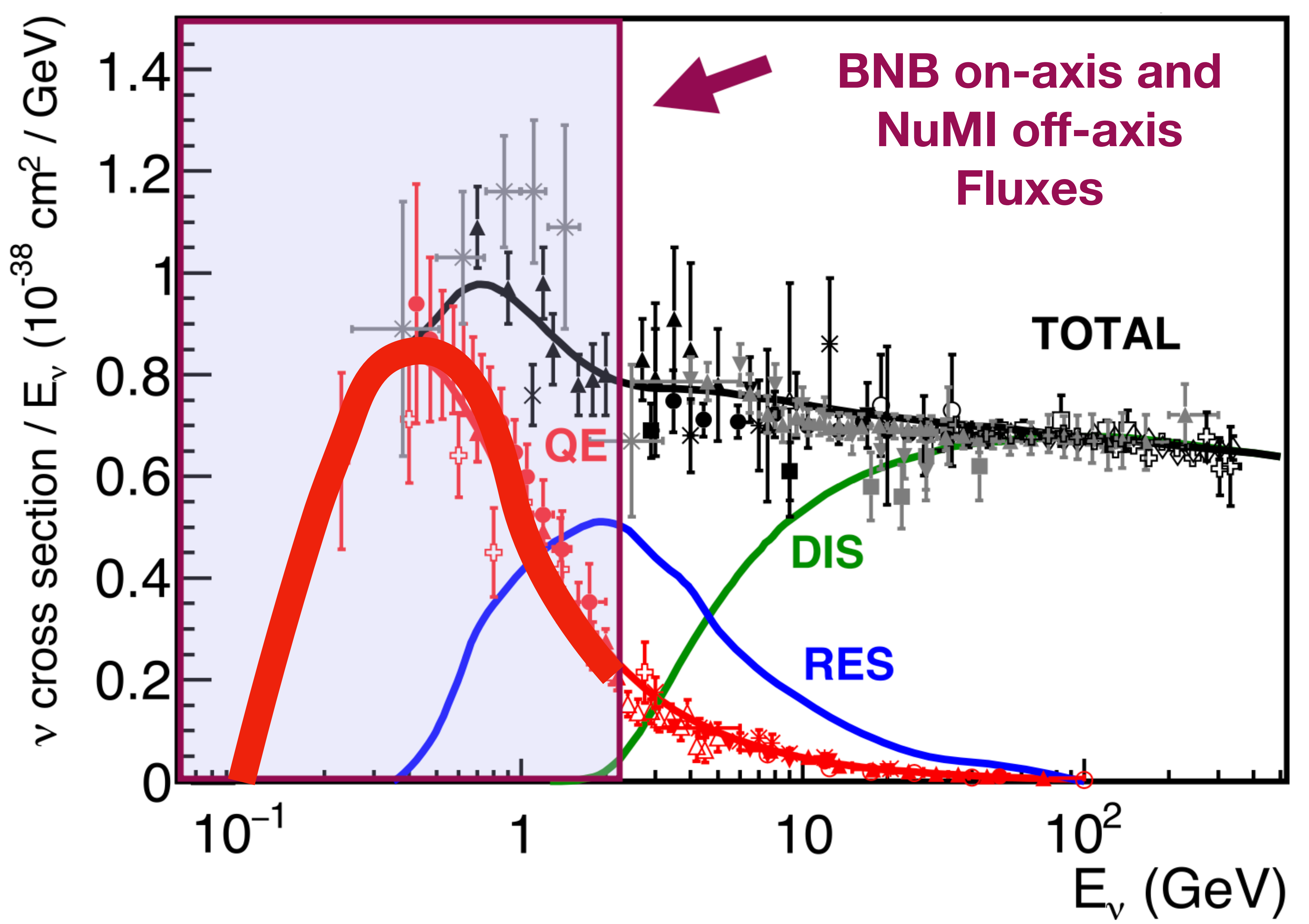

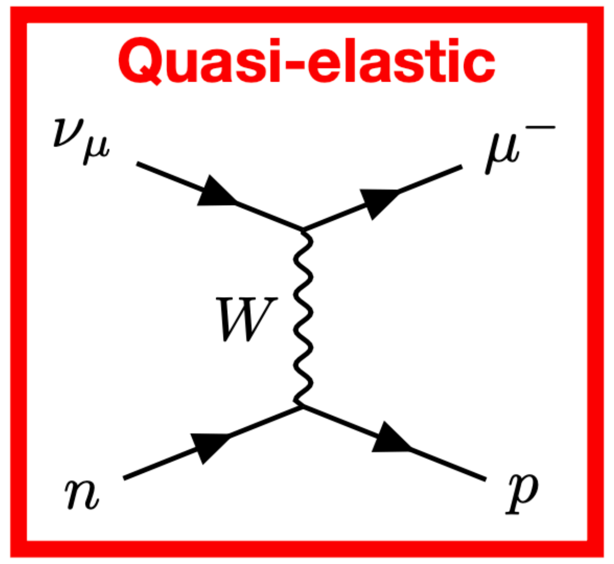

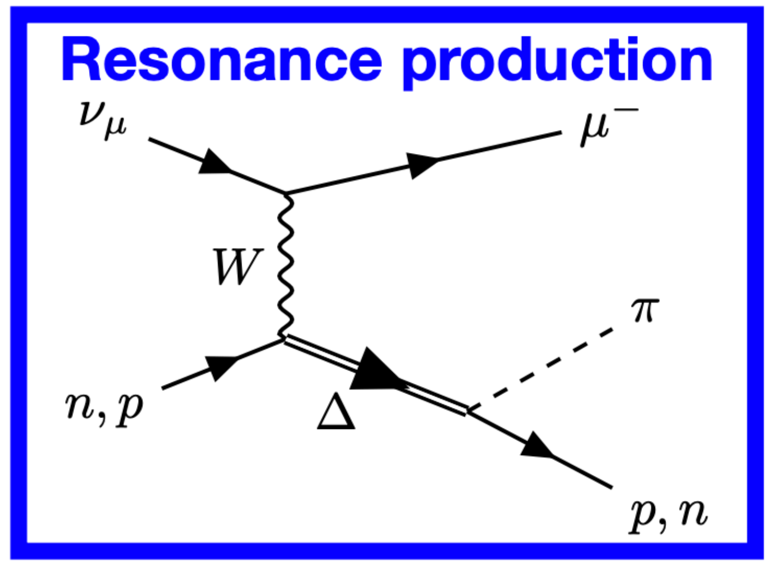

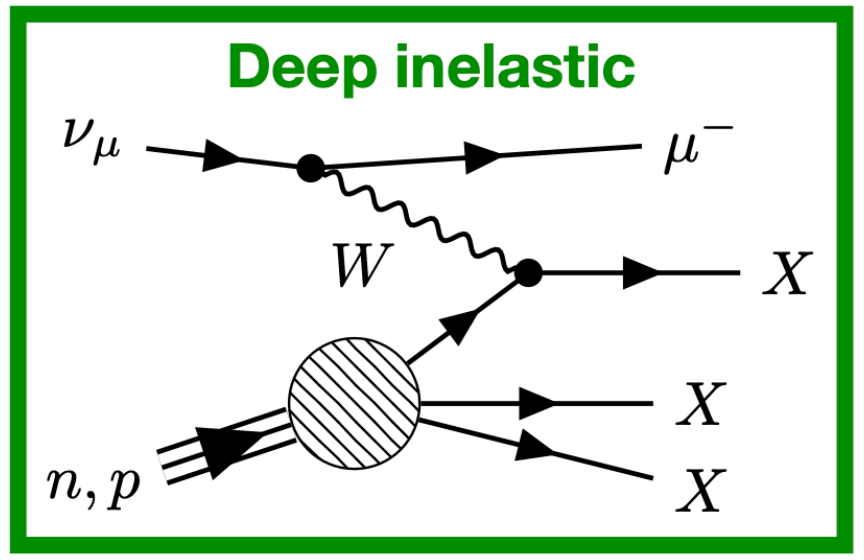

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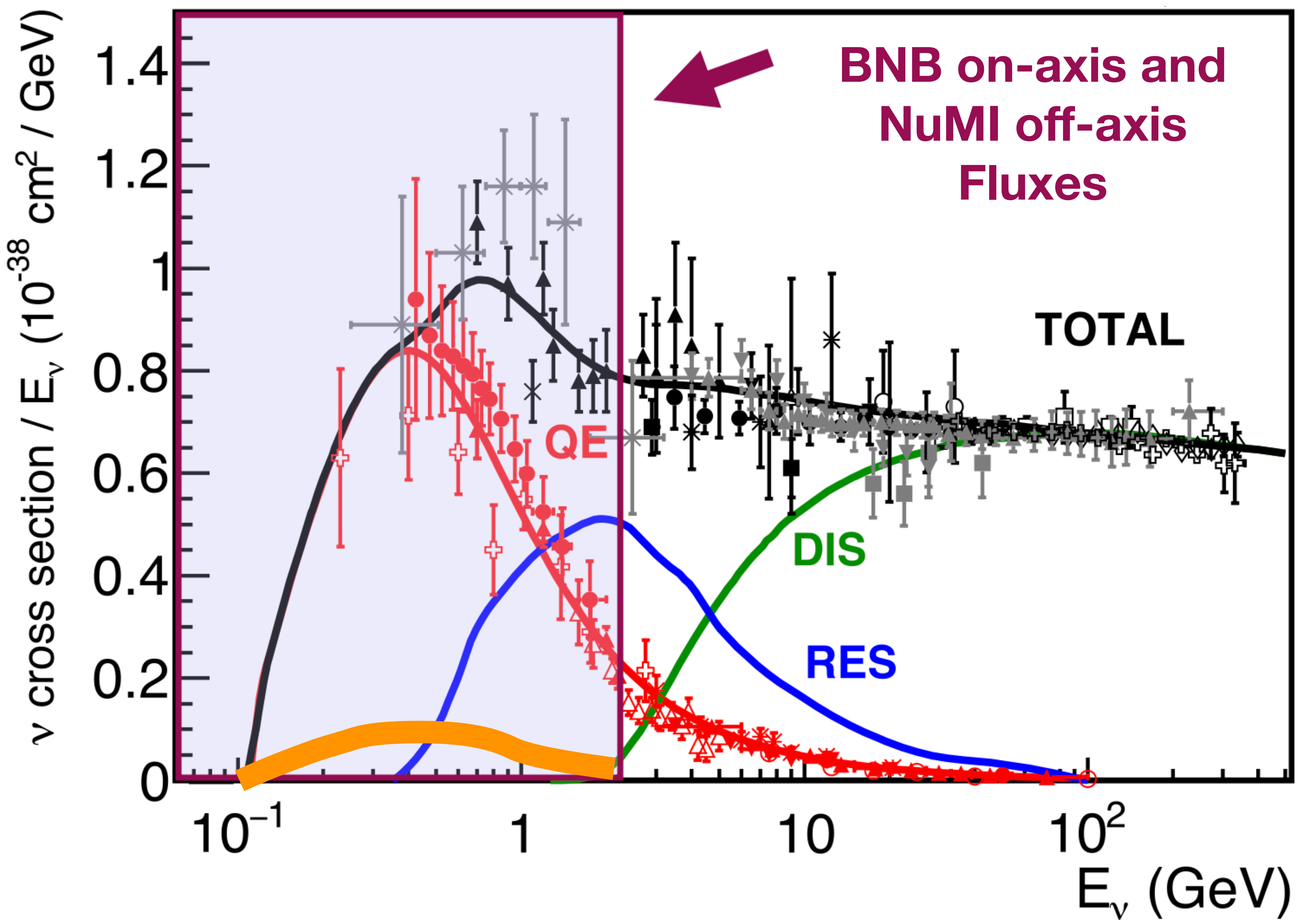

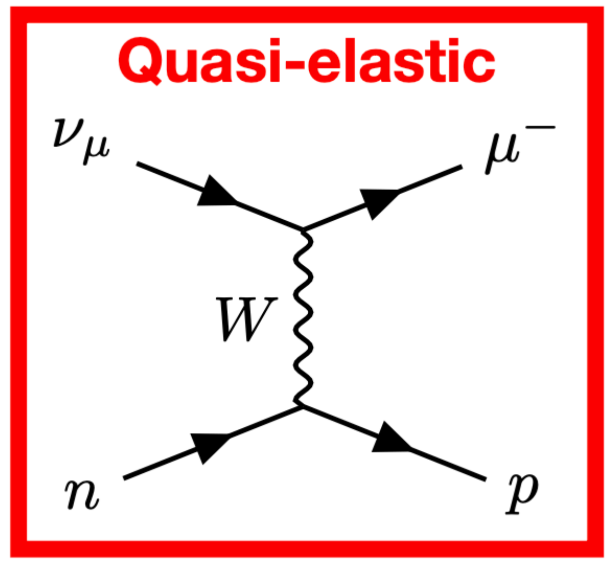

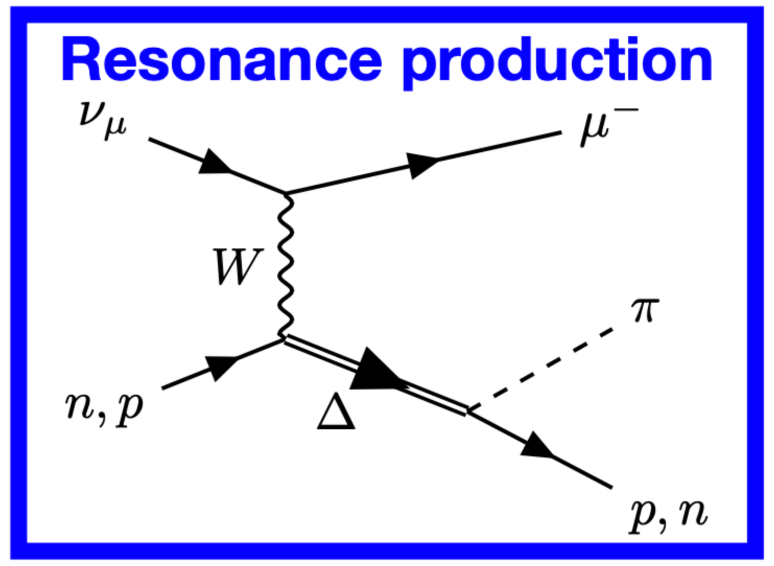

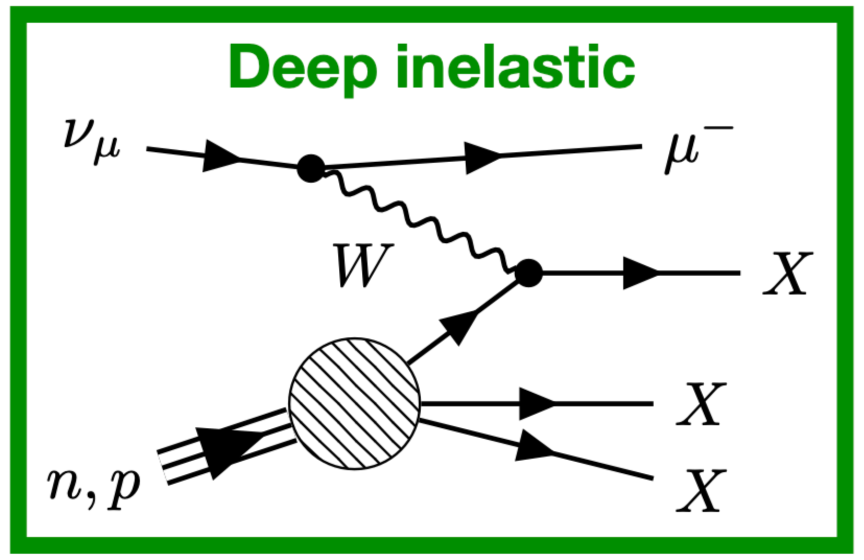

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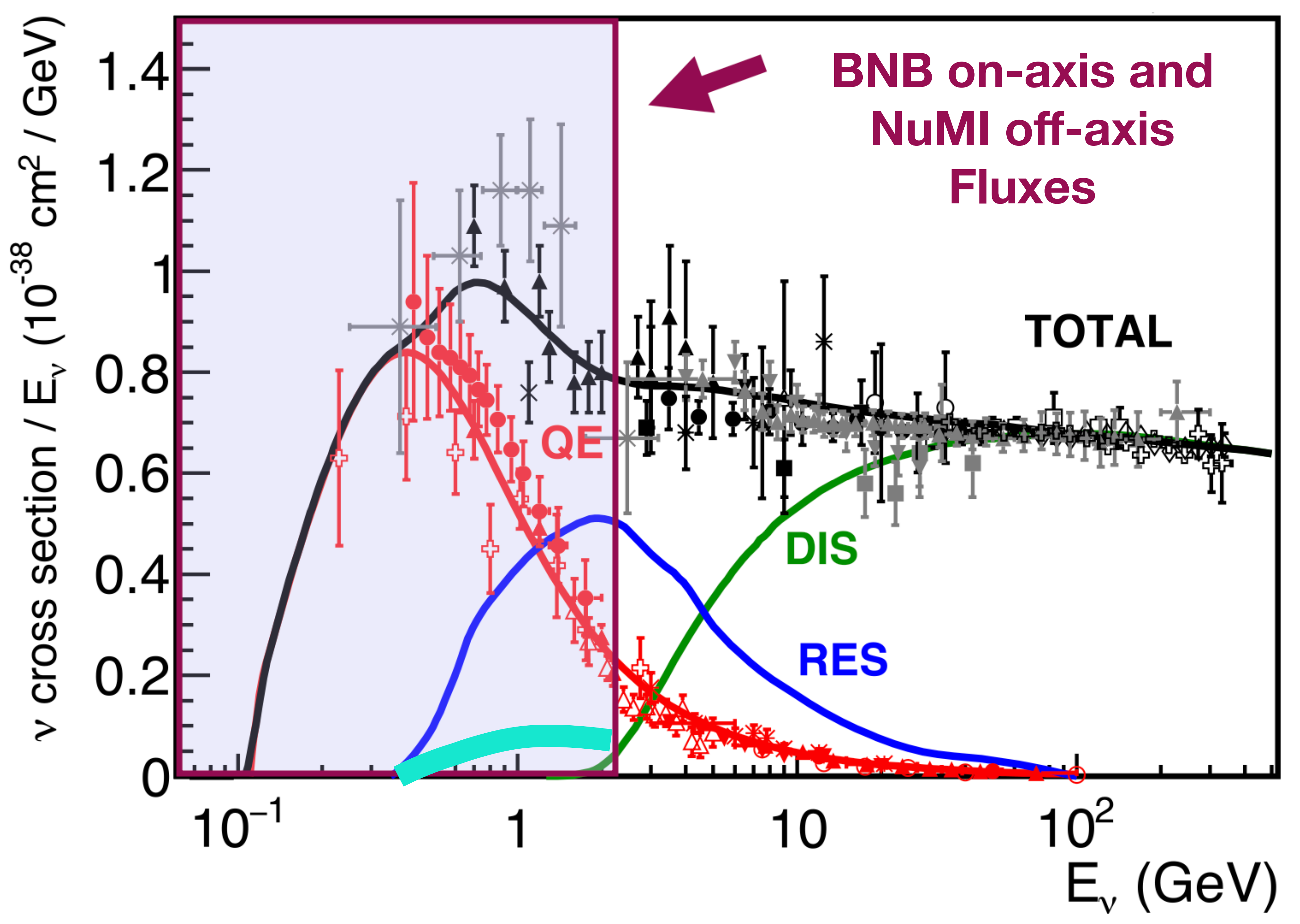
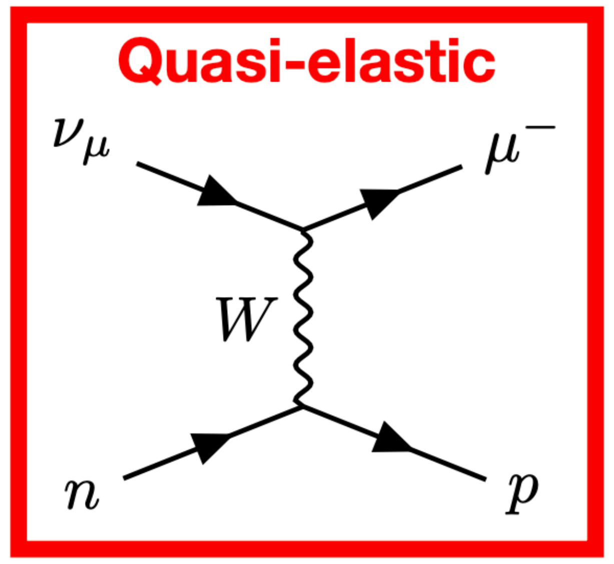
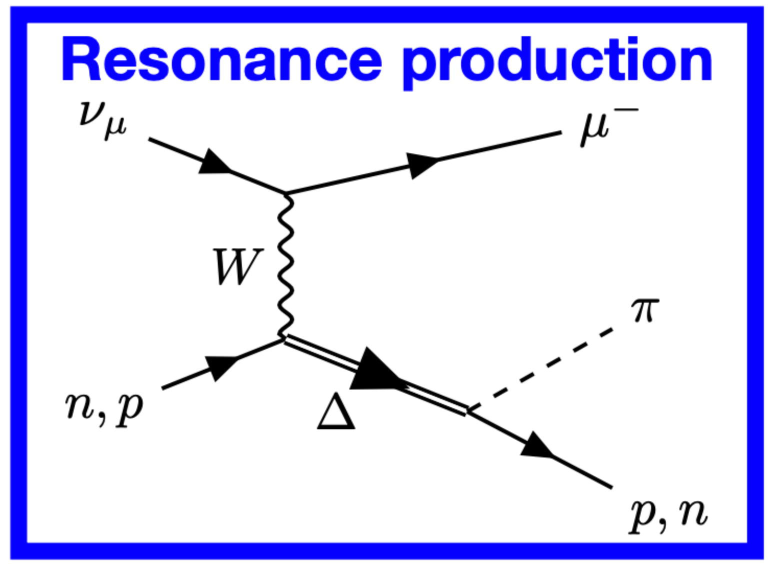
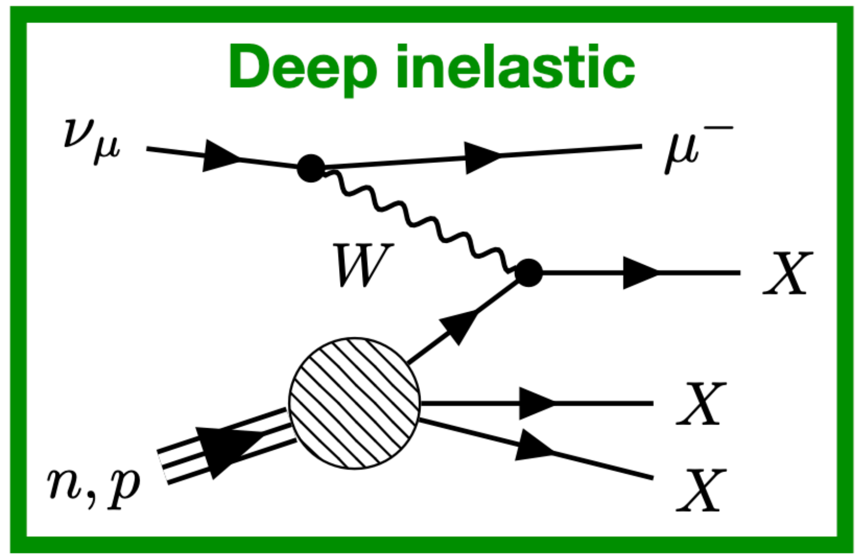




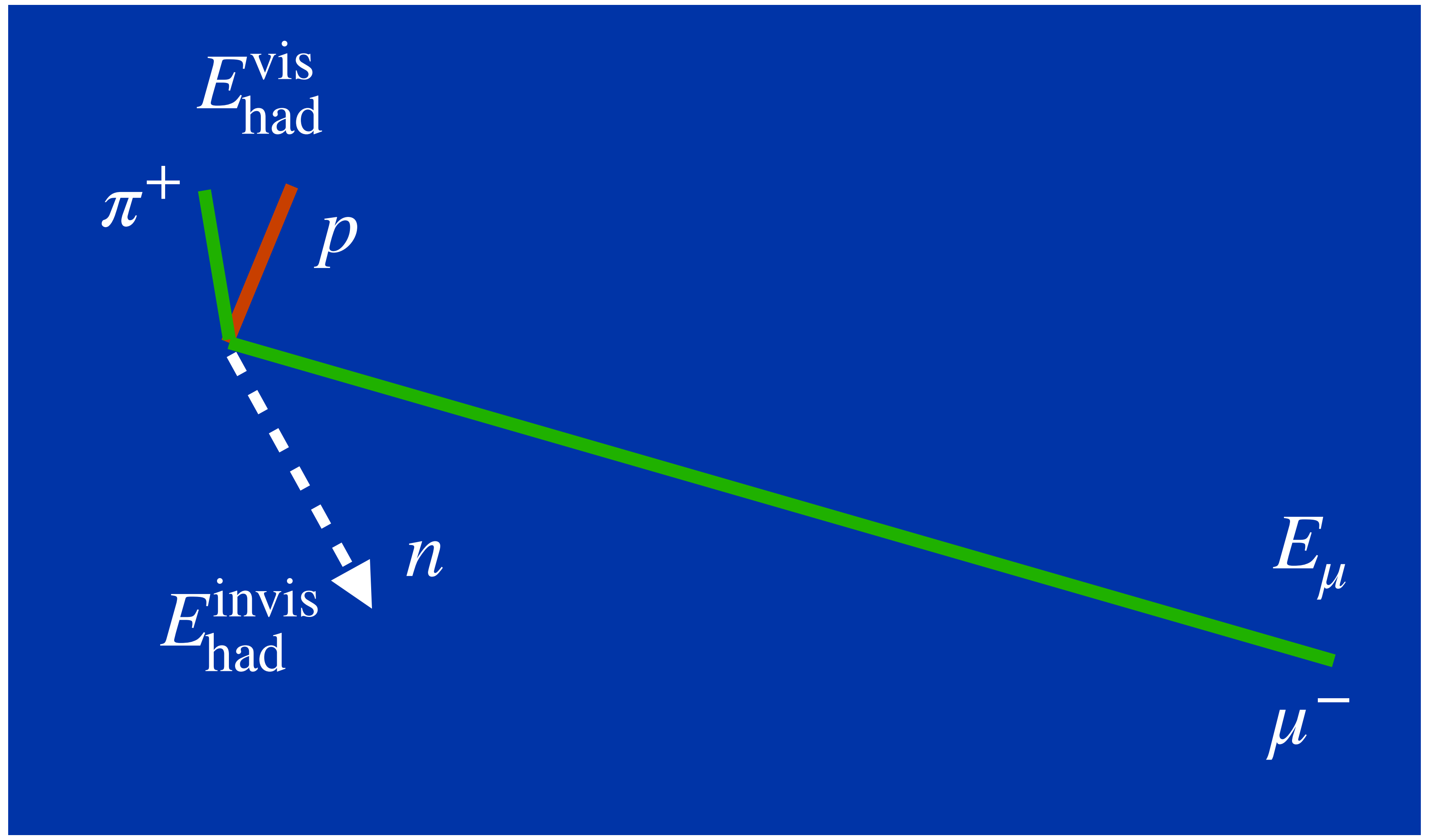




Invisible Neutrino Energy Modeling Validation

- Modeling the $E_\nu^{\text{true}} \to E_\nu^{\text{rec}}$ mapping is very important for oscillation analyses
- These quantities differ by $E_{\text{had}}^{\text{invis}}$
  - No direct measurement possible
  - Can we improve confidence in our modeling of this quantity within uncertainties (cross-section, flux, detector response, and statistical)?

Consider ν_μ CC interactions: $$E_\nu^{\text{true}} = E_\mu + E_{\text{had}}^{\text{vis}} + E_{\text{had}}^{\text{invis}}$$



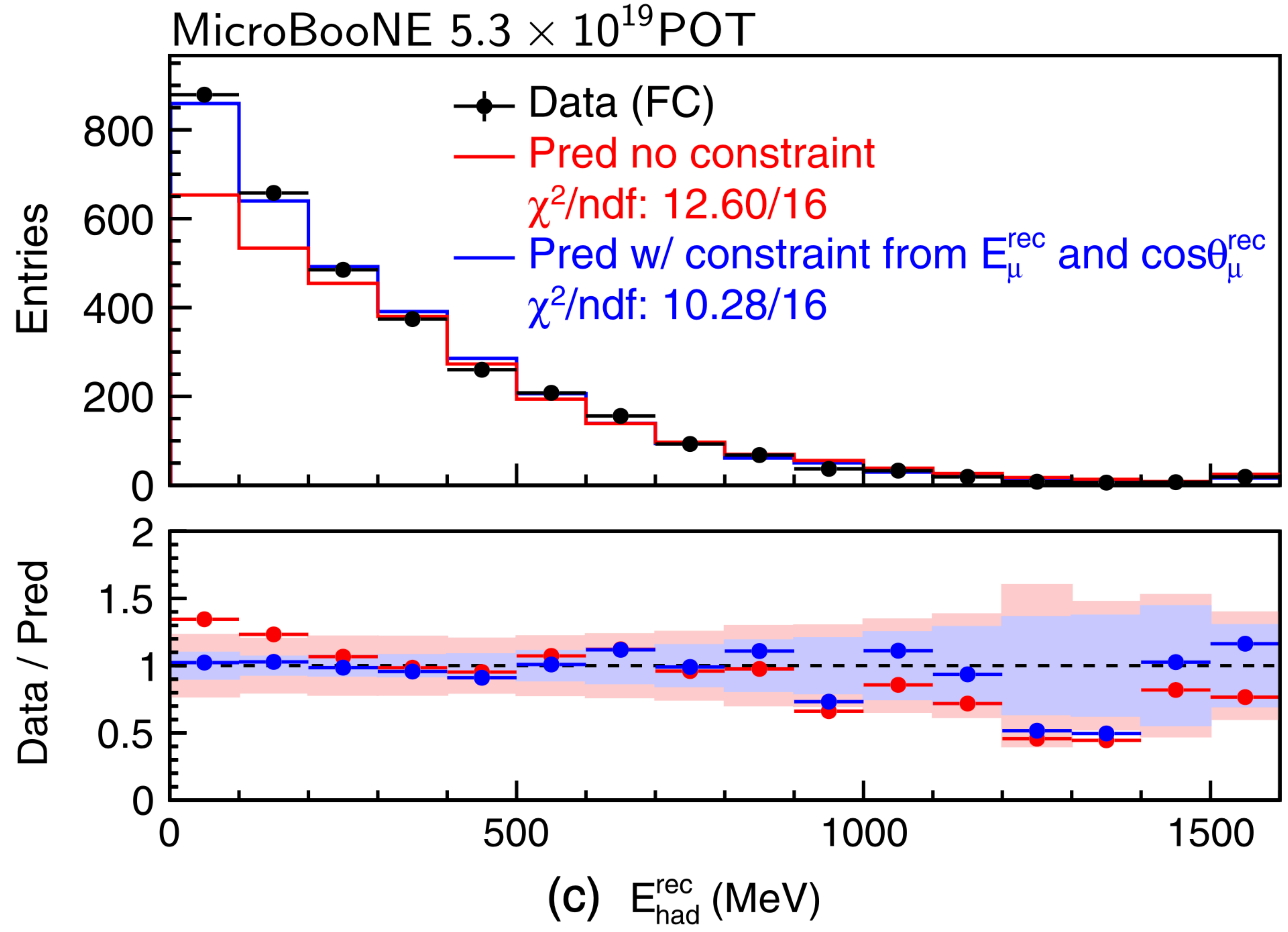
Phys. Rev. Lett. 128, 151801 (2022)

Invisible Neutrino Energy Modeling Validation

- Energy conservation: if modeling of $E_\nu^{true}, E_\mu, E_{had}^{vis}$ is correct, then our modeling of E_{had}^{invis} must be correct
- We can't test this event-by-event, but we can test this for a distribution of many events
- A conditional constraint test shows that E_{had}^{vis} data matches the prediction using E_ν^{true} (from our flux model) and E_μ (from our data measurement)
- So, three of these distributions tell a consistent story, so the energy conservation equation helps to validate our modeling of the E_{had}^{invis} distribution

Known from beam flux · Measured from muon range · Measured from hadronic ionization · Initially unknown (Neutrons, low energy photons, etc.)

Consider ν_μ CC interactions: $$E_\nu^{true} = E_\mu + E_{had}^{vis} + E_{had}^{invis}$$



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

Invisible Neutrino Energy Modeling Validation

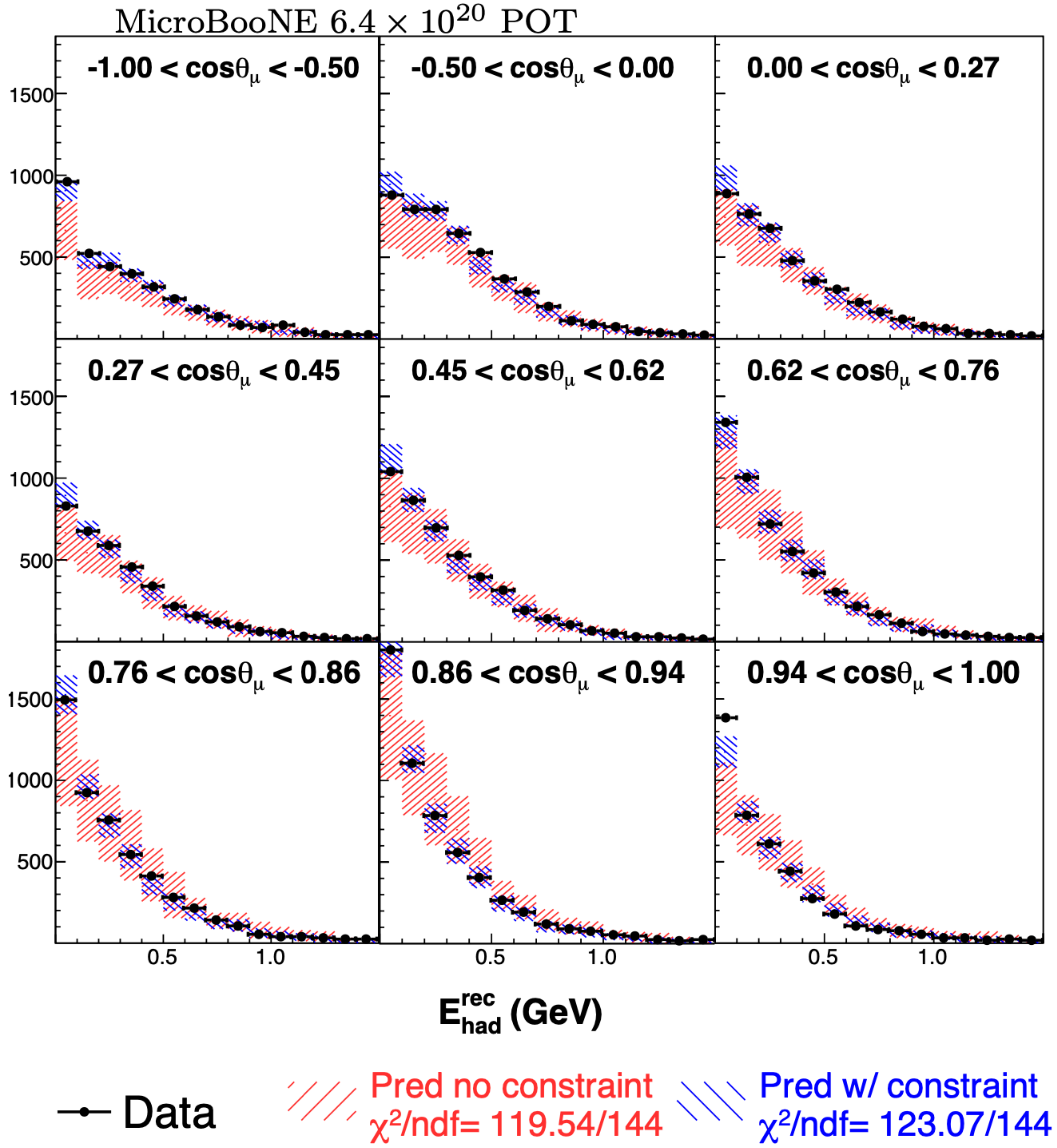
- We've performed many types of these constraint tests, and expanded to study more dimensions

- In fake data tests, this procedure is sensitive to ~15% shifts between E_{had}^{vis} and E_{had}^{invis}

  - Our resulting E_ν cross section results are significantly less sensitive to changes in the missing energy

- We have also tested this procedure with fake data from GENIE v2 and NuWro, and in all cases, we have found that when we pass model validation, we get the correct E_ν XS result within uncertainties

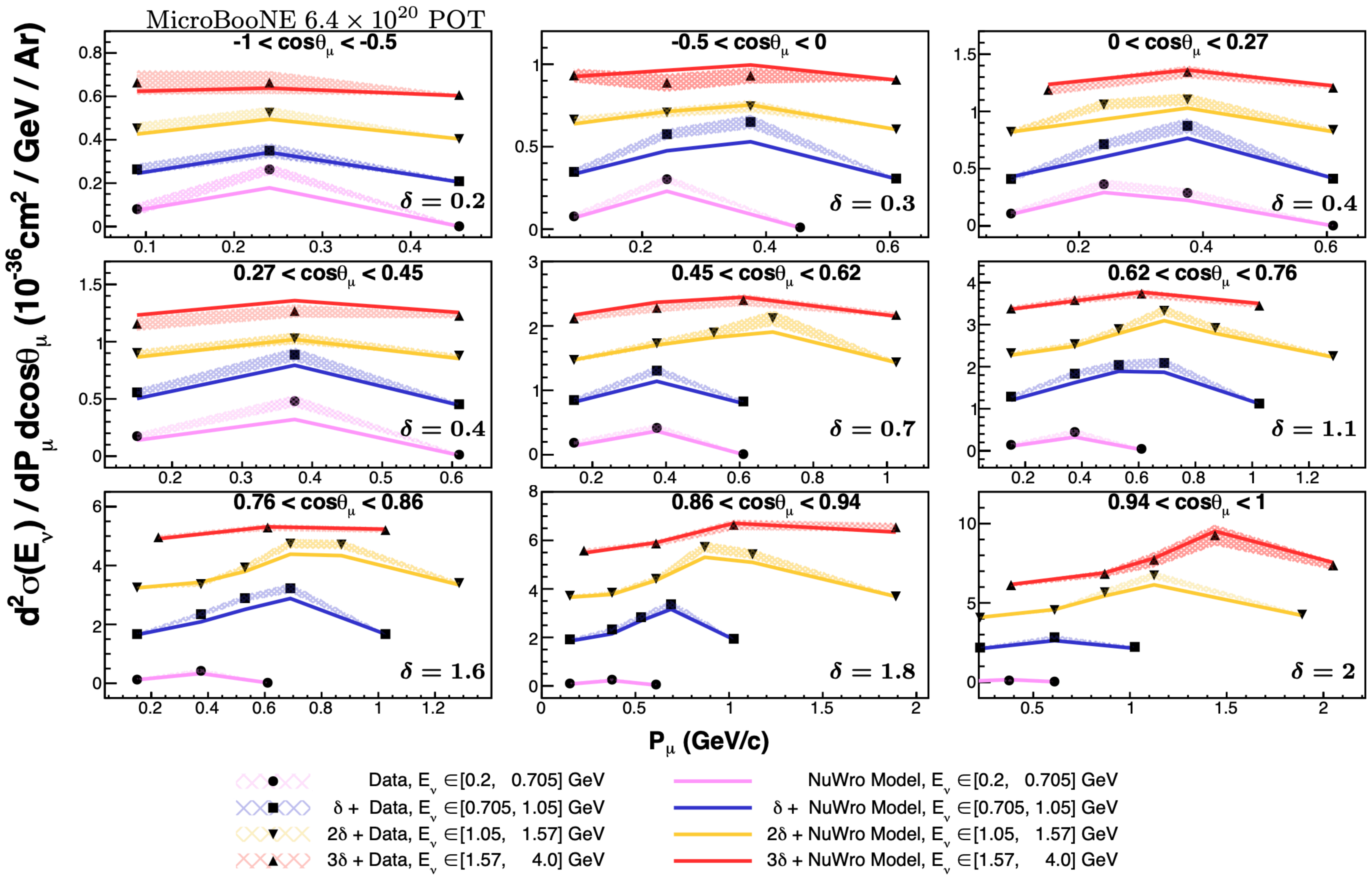
$\{E_{rec}^{had}, \cos\,\theta_\mu\}$ constrained by $\{P_\mu, \cos\,\theta_\mu\}$



arXiv:2307.06413

3D ν_μCC Inclusive Cross Section Results

- With this model validation giving us confidence in our modeling of the $E_\nu^{\text{true}} \rightarrow E_\nu^{\text{reco}}$ mapping within uncertainties, we can extract cross sections as a function of E_ν
- One of our latest results does this simultaneously in 3 dimensions:
  - E_ν, P_μ, and $\cos\,\theta_\mu$
- NuWro has the best agreement with our data, and GiBUU and NEUT do better in the lower E_ν region

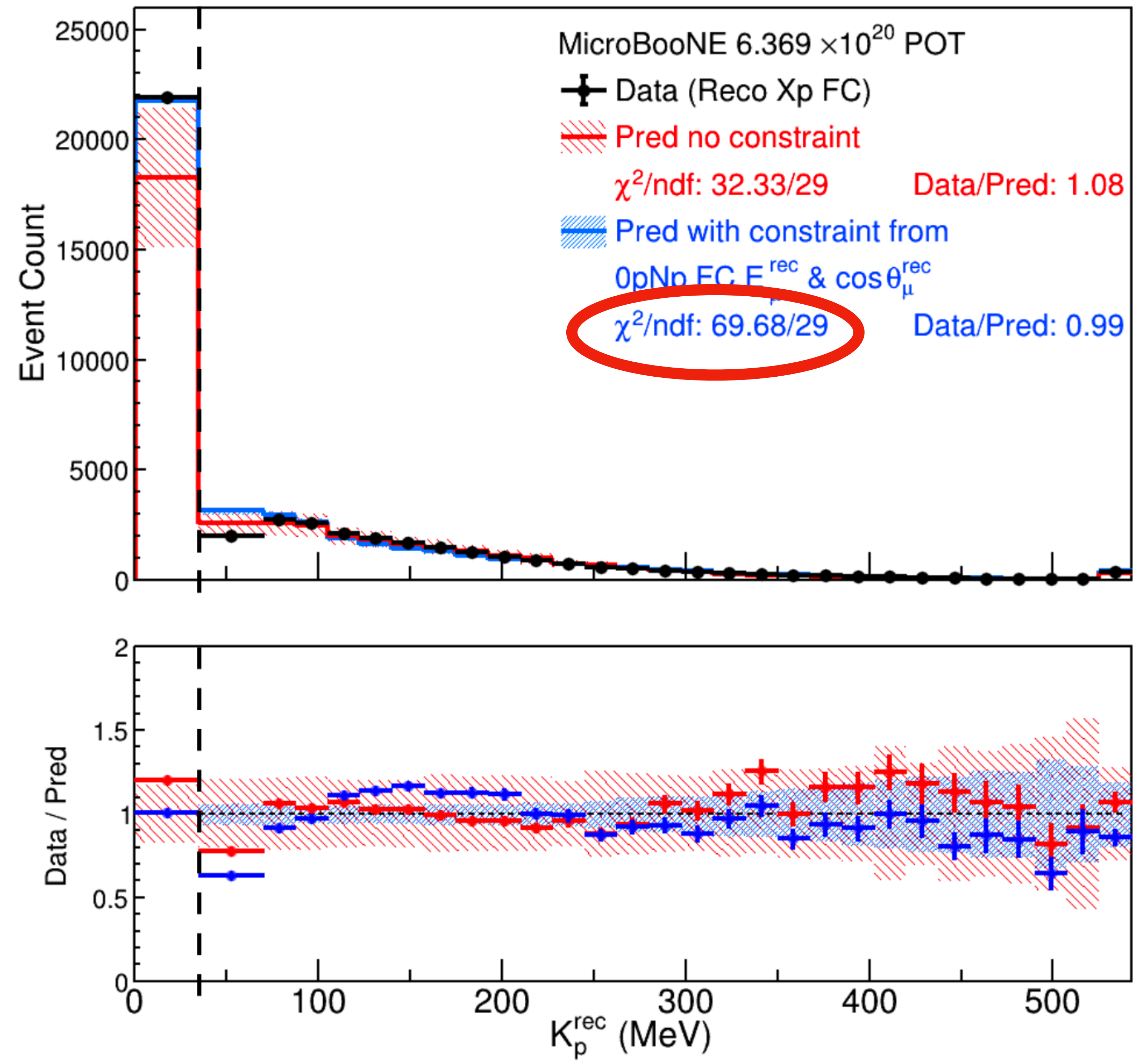


	Full 3D space	1D $\cos\,\theta_\mu$ 0.2-0.705 GeV
Model Name	χ^2/ndf	χ^2/ndf
GENIE v2	741.1/138	12.4/9
MicroBooNE model	326.1/138	31.2/9
GENIE v3 untuned	322.2/138	50.3/9
GiBUU	269.9/138	11.7/9
NEUT	243.4/138	27.6/9
NuWro	212.1/138	24.8/9

arXiv:2307.06413

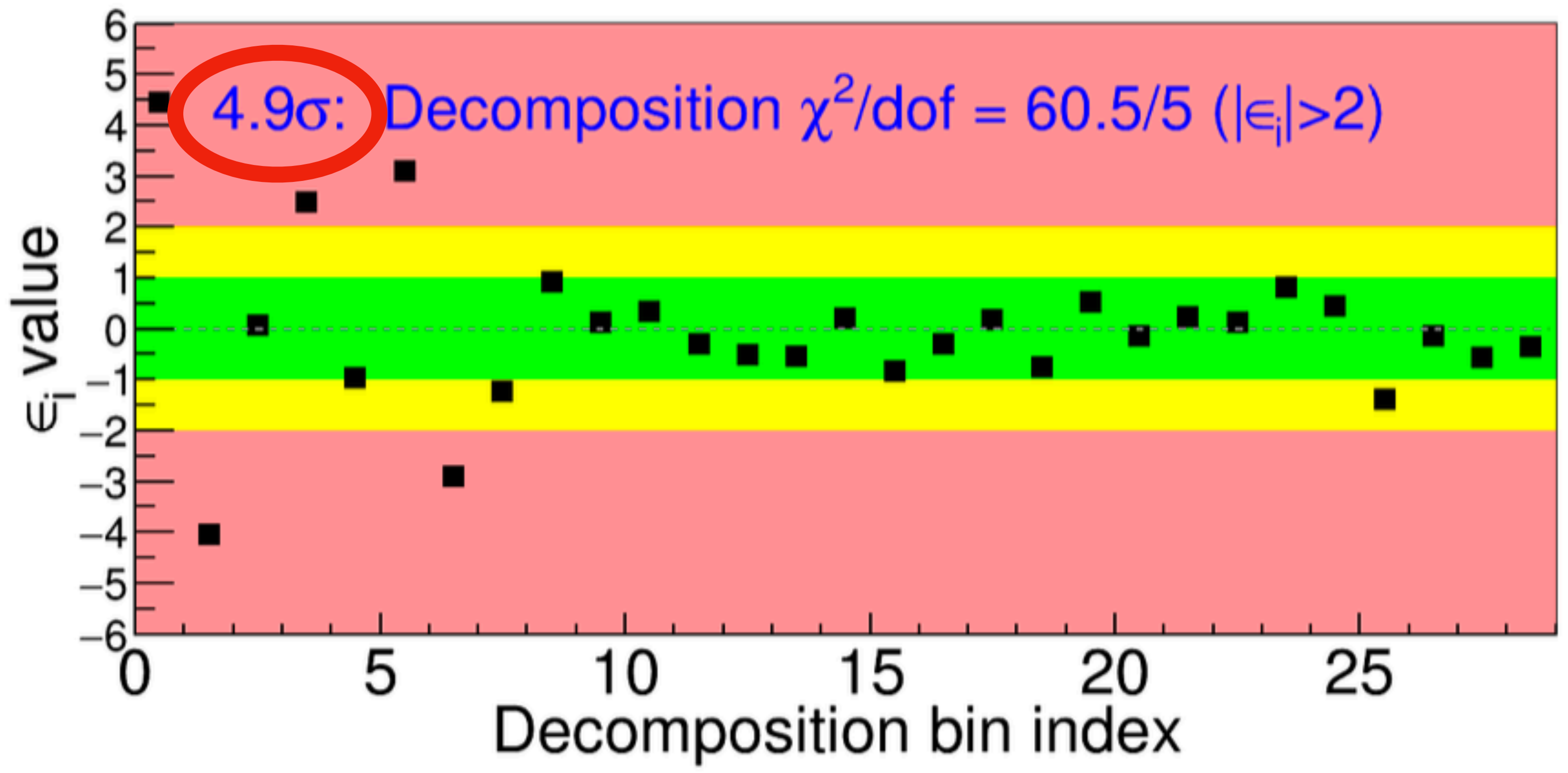
3D ν_μCC Inclusive 0p/Np: Failing Model Validation

- We also expanded this ν_μCC inclusive analysis to study detailed final states with and without protons
- We do a similar type of model validation for reconstructed proton kinetic energy, but it fails!
- Our data is incompatible with our cross section model when describing the distribution of proton energies
  - A low energy proton connected to a muon is the type of topology that LArTPCs can study much more precisely than some other technologies
- Low energy proton mis-modeling could potentially cause incorrect neutrino background estimates in searches for coherent interactions or BSM decay-in-flight events



This decomposition test transforms the covariance matrix and χ^2 calculation to a space where the bins are uncorrelated

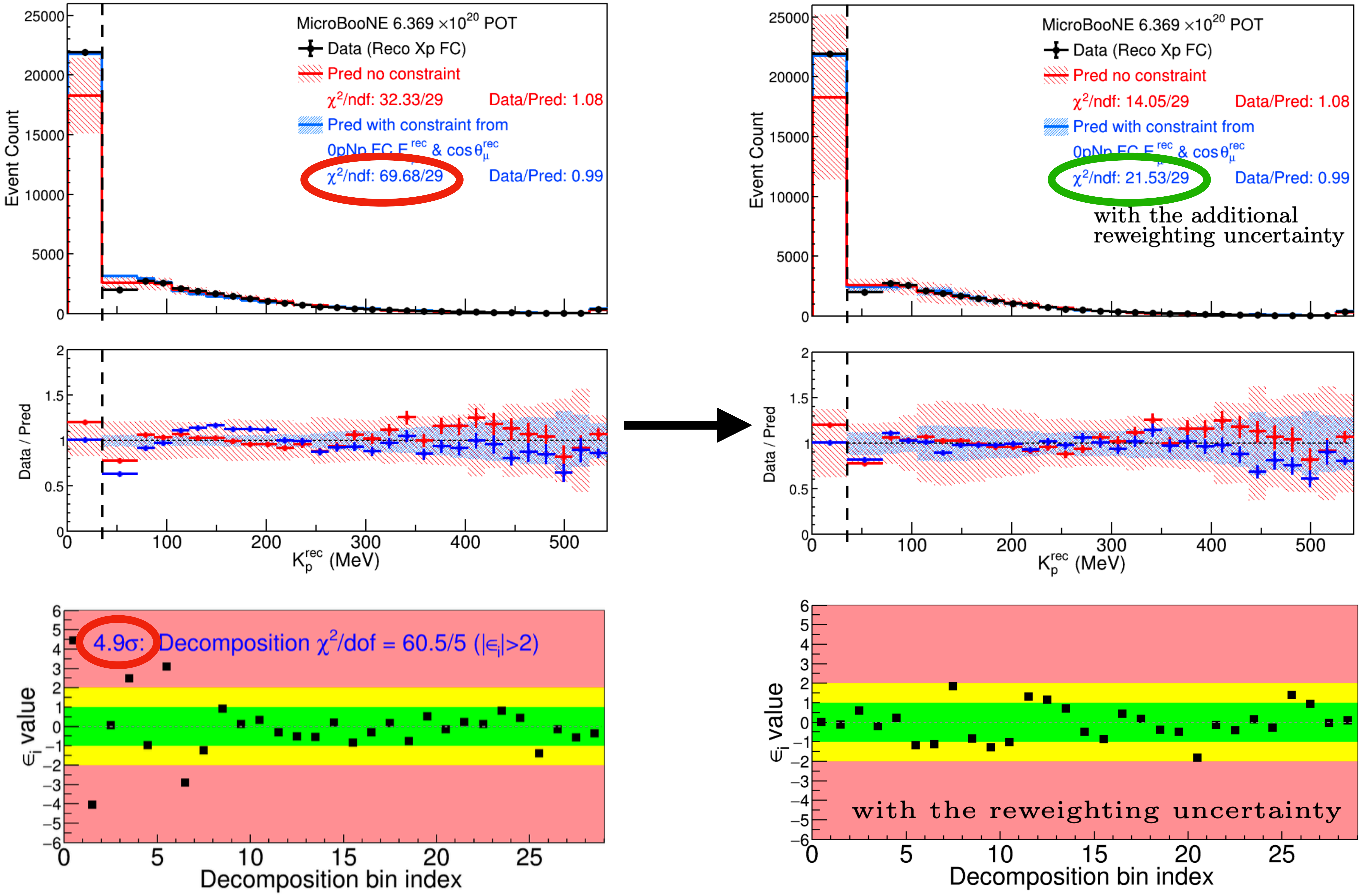
Lower bin indices correspond to larger eigenvalues, and typically represent broader details of the distribution (normalization, broad shape, etc.)

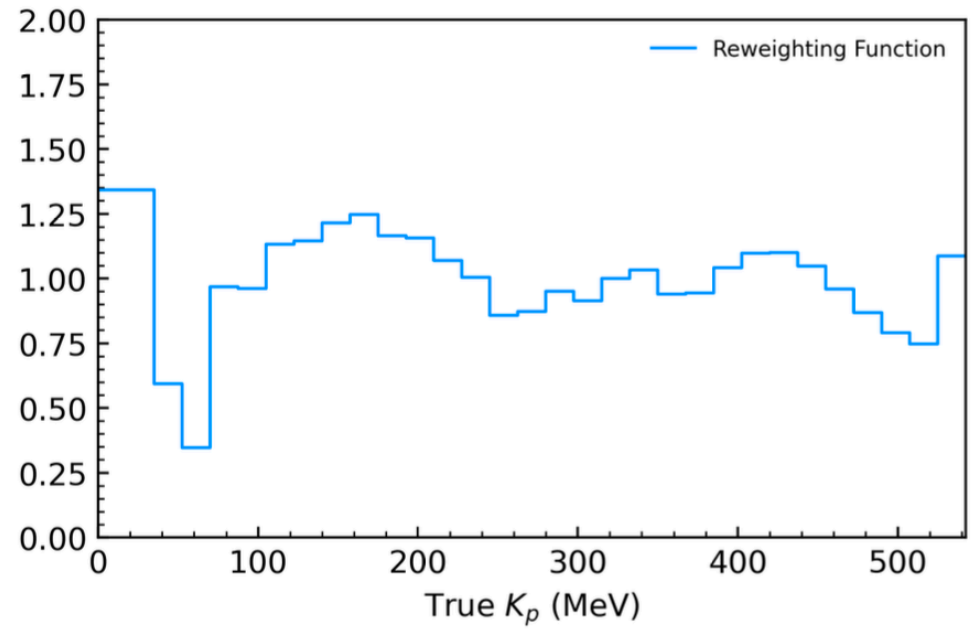


arXiv:2402.06413 arXiv:2402.19281

3D ν_μCC Inclusive 0p/Np: Passing Model Validation

- We use this data-simulation difference to create a new variation in our cross section model
- Unfold this distribution (statistical uncertainty only) to get a reweighting binned in true K_p
- We use this reweighting function to form a new covariance matrix describing this data/MC difference, including correlated and uncorrelated terms
- When we use this to expand our cross section uncertainty, we pass all model validation tests
- So, we can extract cross sections related to protons now

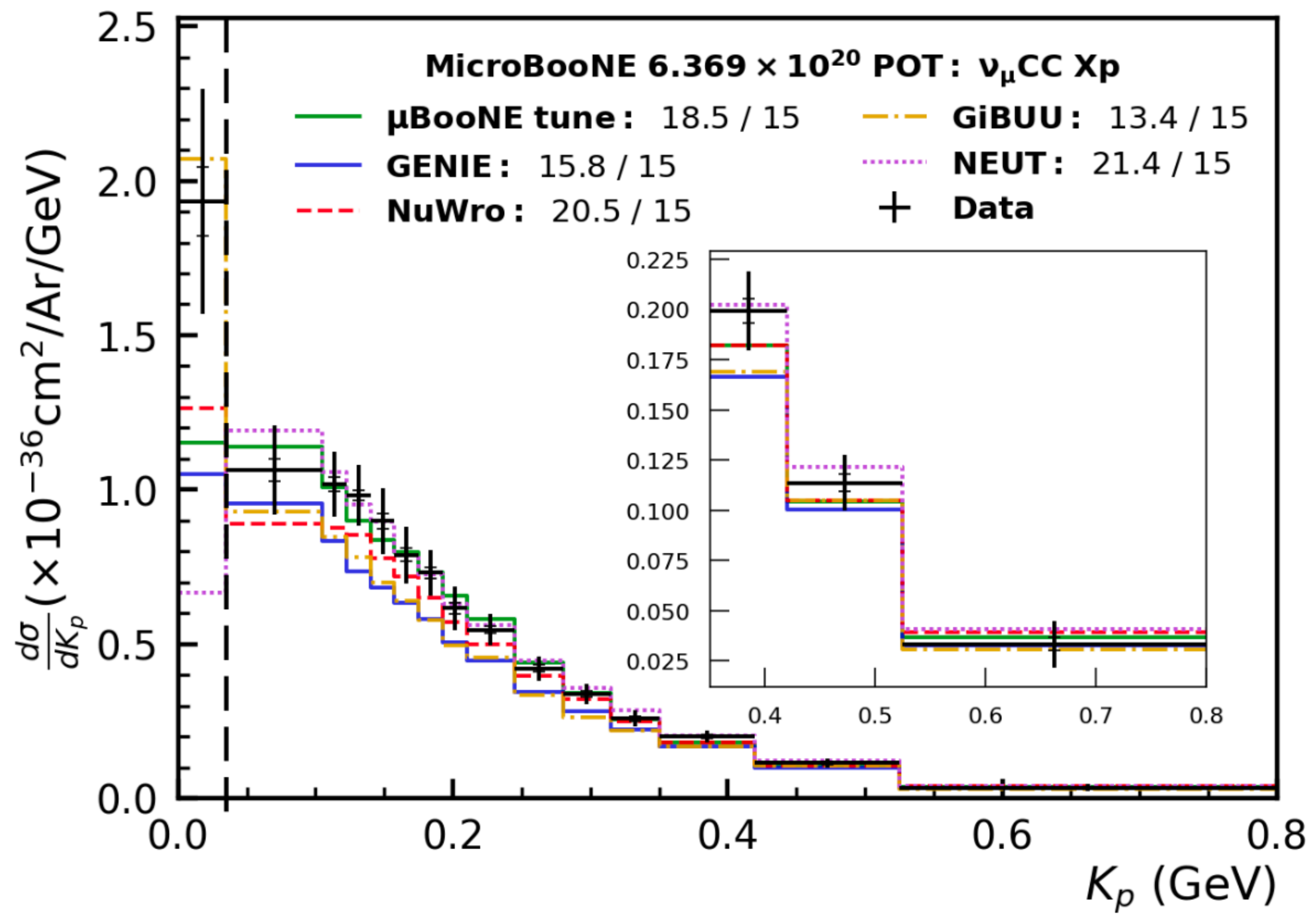


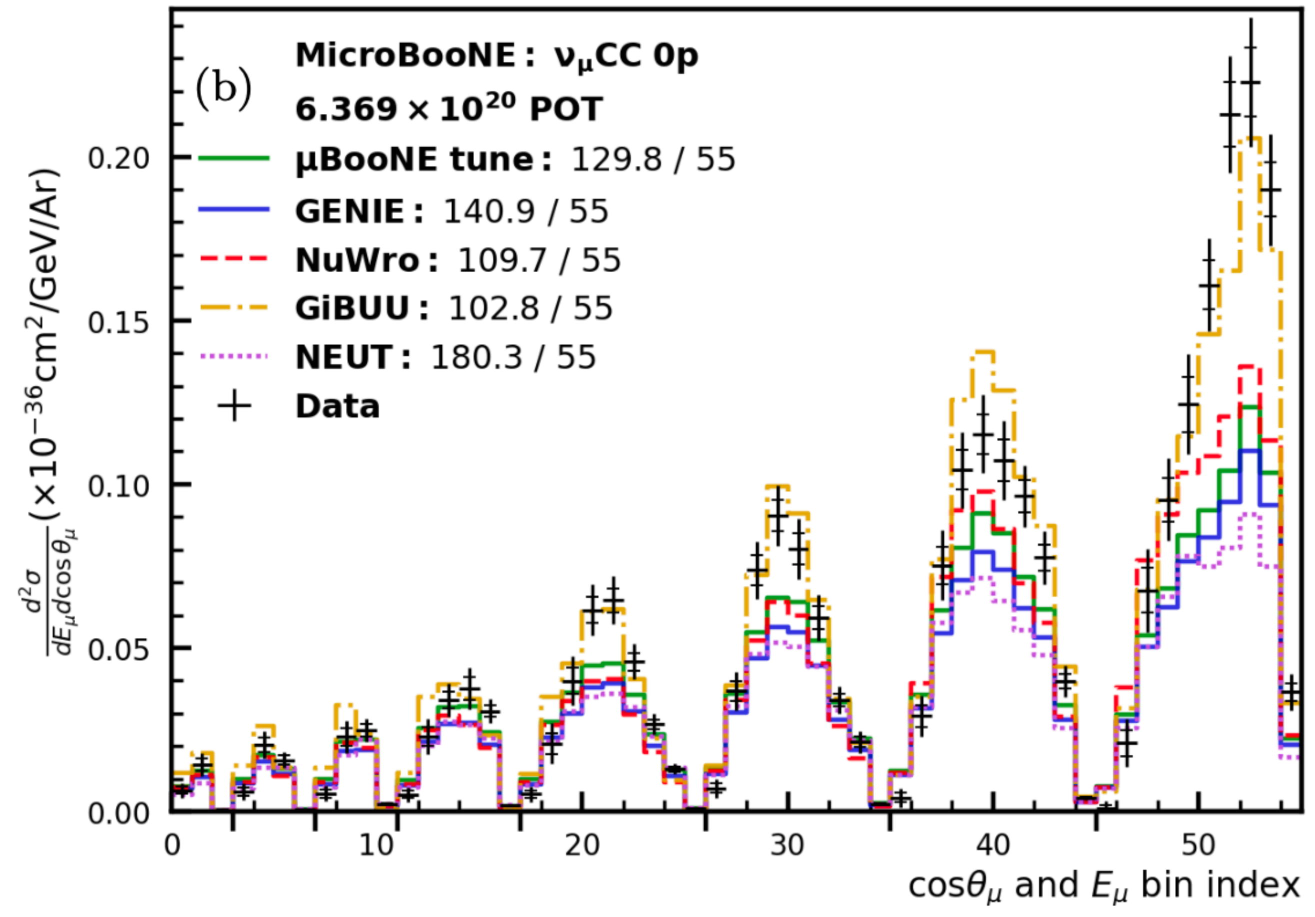


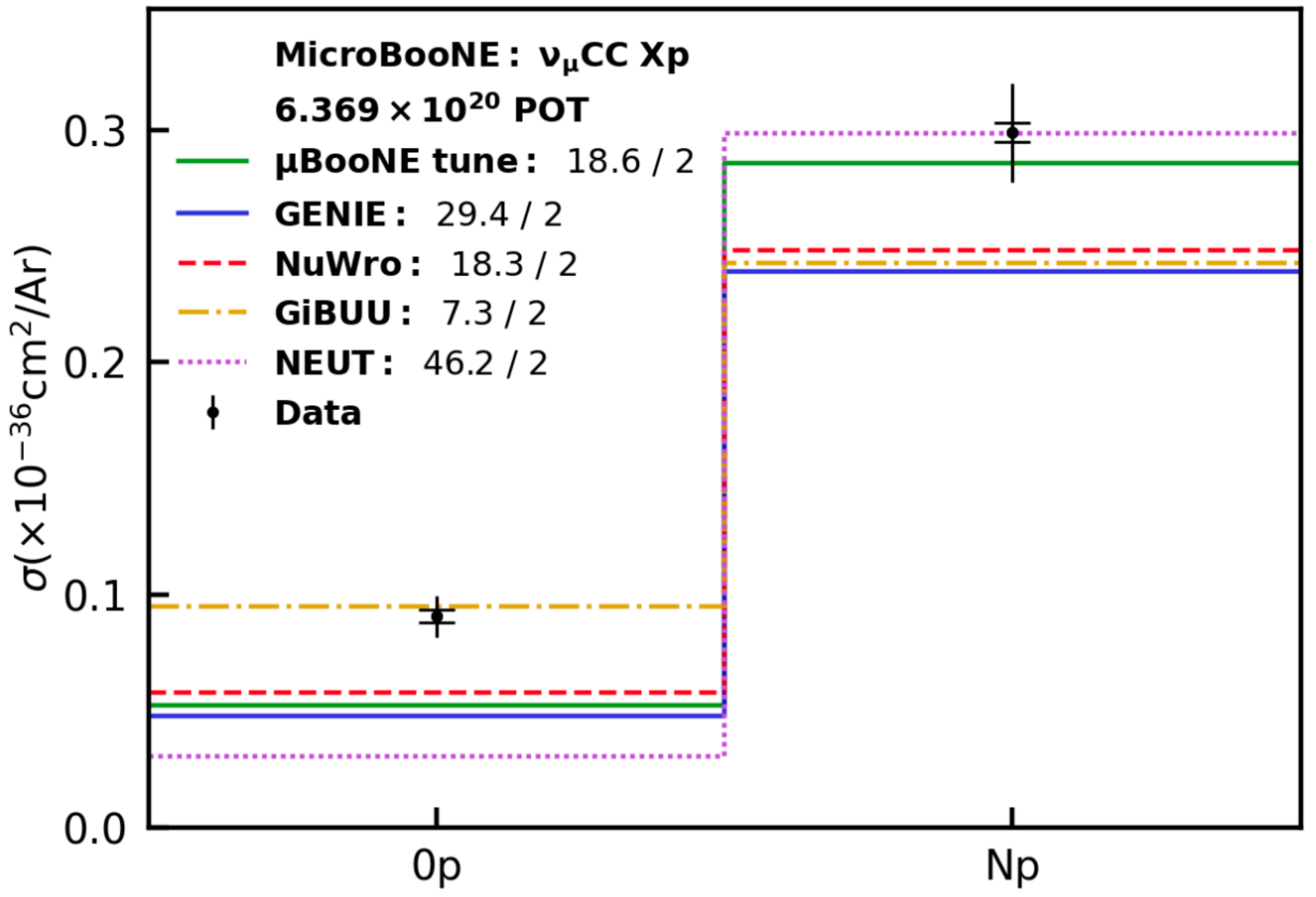
arXiv:2402.06413 arXiv:2402.19281

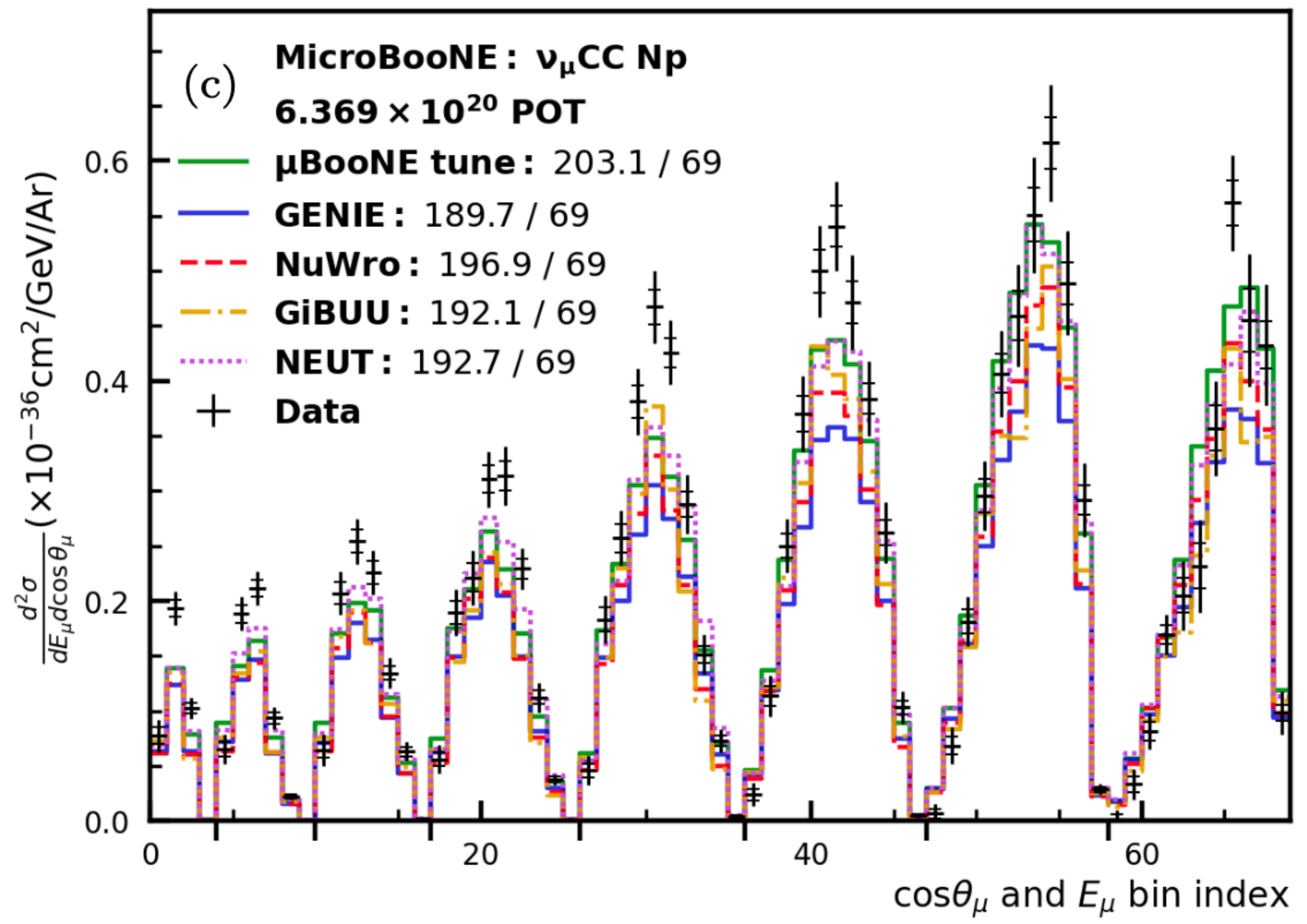
3D ν_μCC Inclusive 0p/Np Cross Section Results

- Many XS results extracted
  - E_μ, $\cos\,\theta_\mu$, E_ν, ν, E_{avail}, K_p, $\cos\,\theta_p$
  - 1D, 2D, and 3D
  - 0p, Np, and Xp
  - Proton multiplicity
- We also report correlations between all these cross section results simultaneously
- GiBUU does much better at describing low energy proton energies and the 0p/Np split, perhaps due to a better treatment of FSI









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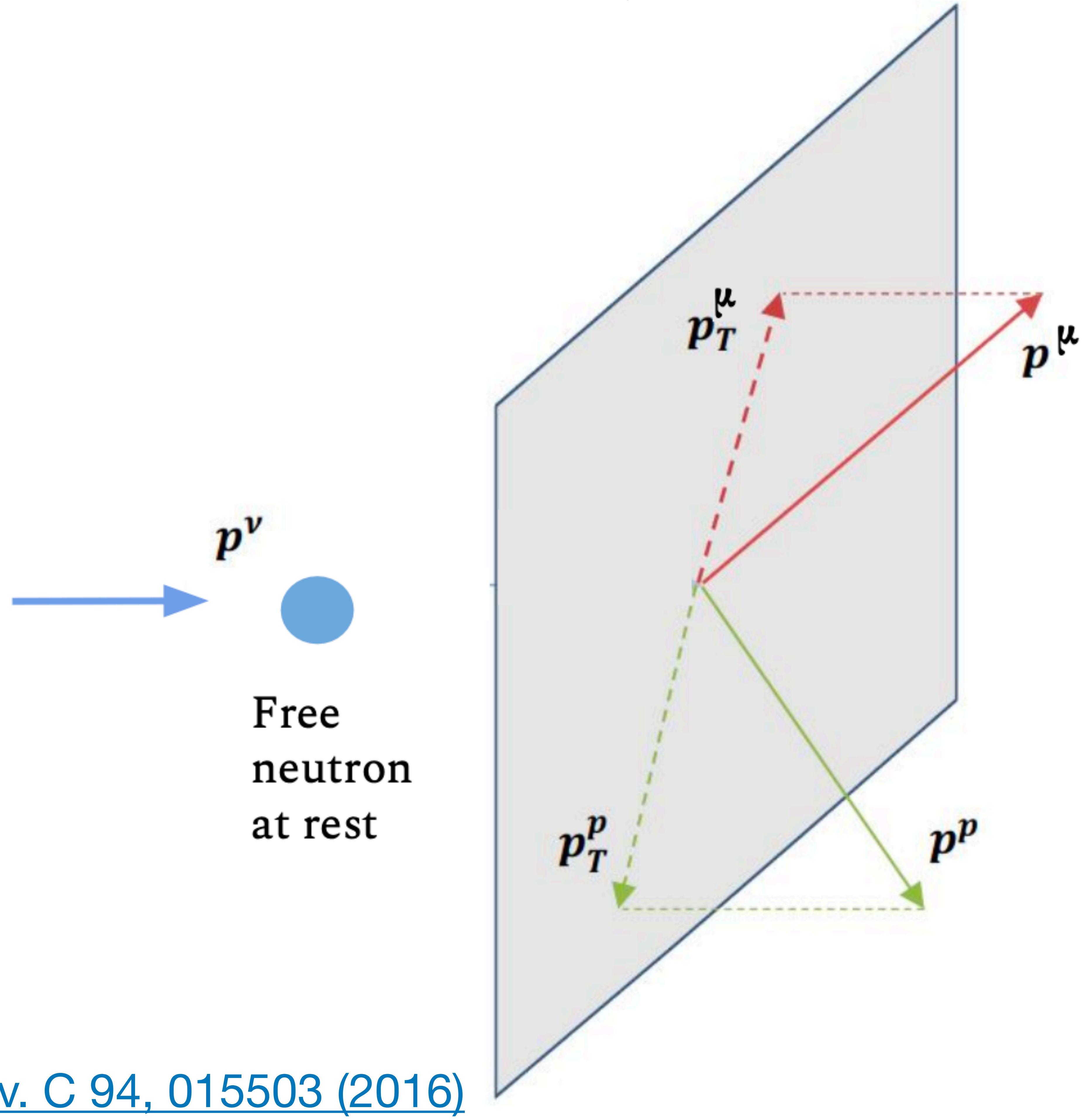
ν_μCC 1p0π

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

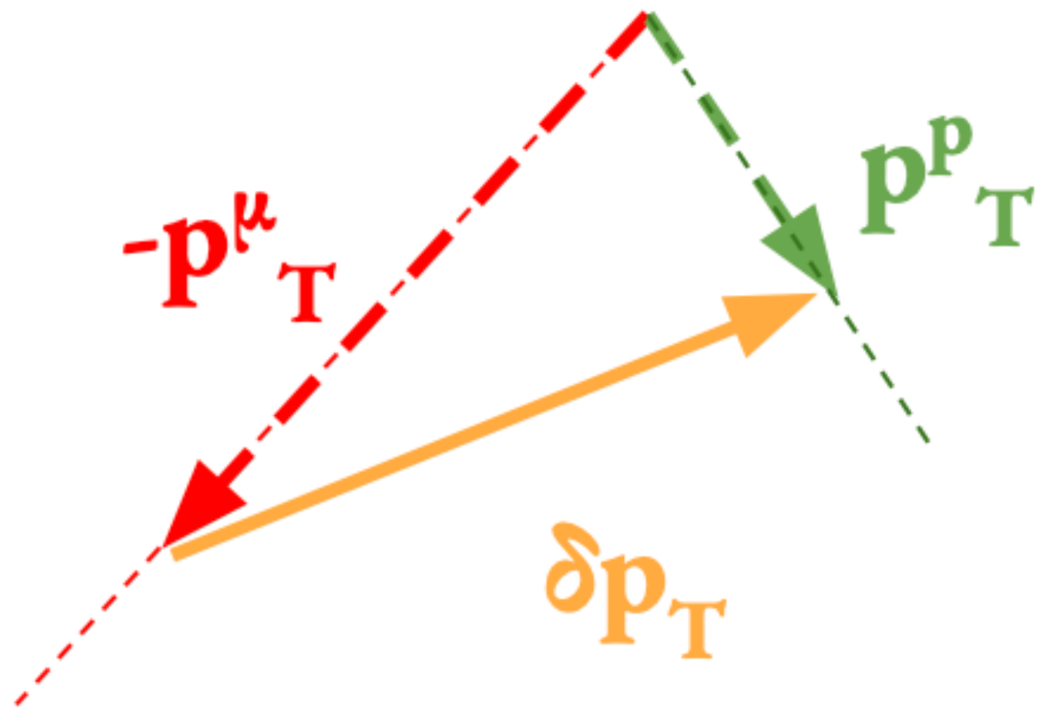
- If we model CCQE events as a neutrino striking a free neutron at rest, the system is very simple
- We get essentially 2 interesting degrees of freedom, which we can choose to be E_μ and θ_μ
  - In particular, given those, we know E_{tot}
  - This is how MiniBooNE and Super-K can calculate E_ν while only seeing the muon
- The transverse momentum of the muon and proton are exactly balanced, summing to zero

- 6 degrees of freedom
  - $\vec{p}_p$ and $\vec{p}_\mu$
- 4 constraints/symmetries
  - Incoming neutrino direction: $\vec{p}_{\text{tot}} \cdot \hat{x} = 0, \vec{p}_{\text{tot}} \cdot \hat{y} = 0$
  - Incoming neutrino kinematics: $|\vec{p}_{\text{tot}}|\ c = E_{\text{tot}}$
  - Azimuthal symmetry
- 6 - 4 = 2-dimensional resulting phase space

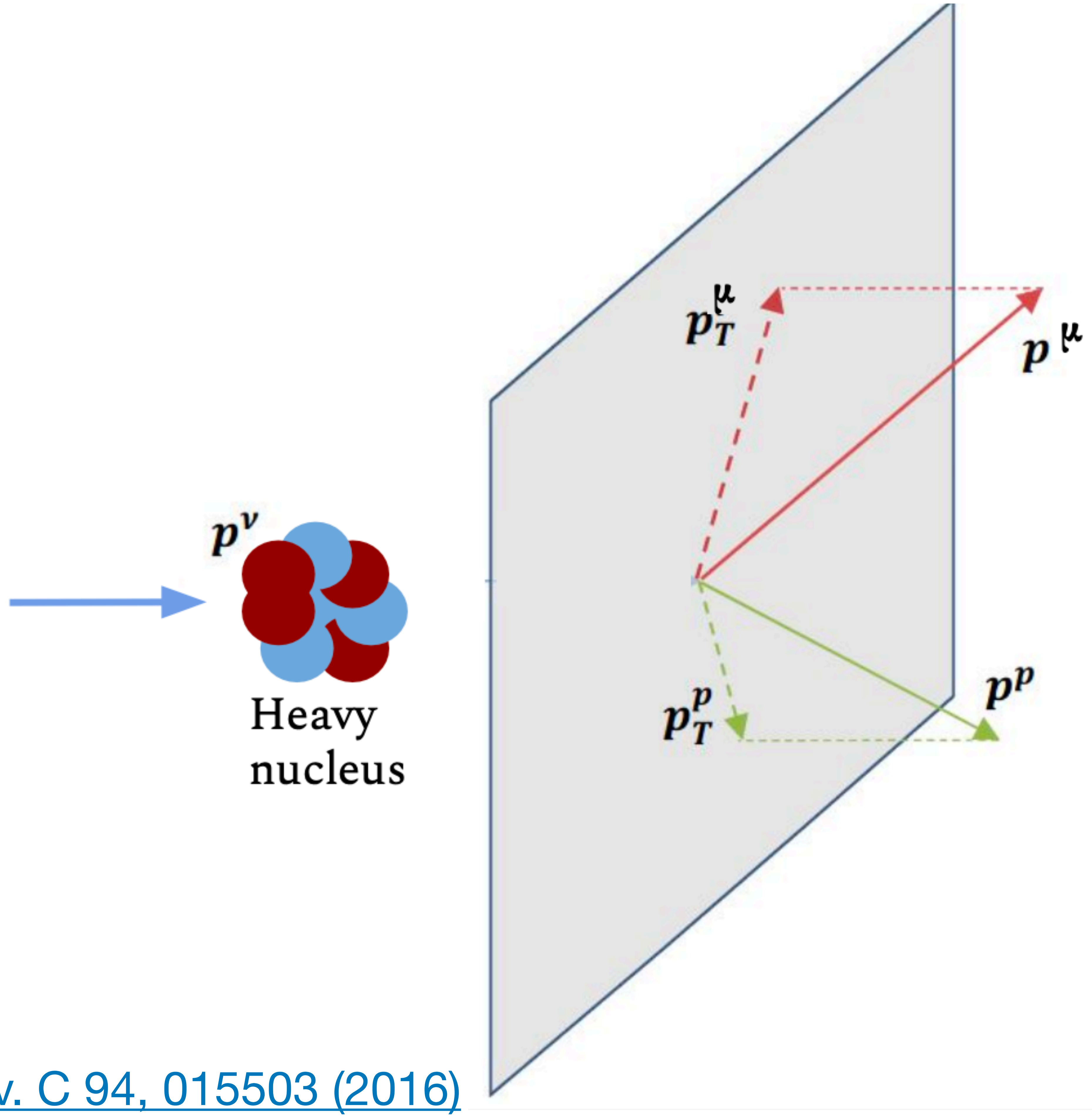


Phys. Rev. C 94, 015503 (2016)

ν_μCC 1p0π TKI



- But in reality, our CCQE events do not involve a free neutron at rest, they involve a complex heavy nucleus
    - The struck nucleon can have nonzero initial momentum
    - The outgoing proton can undergo final state interactions
    - Increasing our understanding of initial-nucleon states and final state interactions are very important for a wide variety of neutrino interactions beyond just ν_μCC 1p0π (for oscillation and other BSM searches)
- So, the total momentum of the muon-proton system can have a nonzero transverse component δp_T (Transverse Kinematic Imbalance, TKI)



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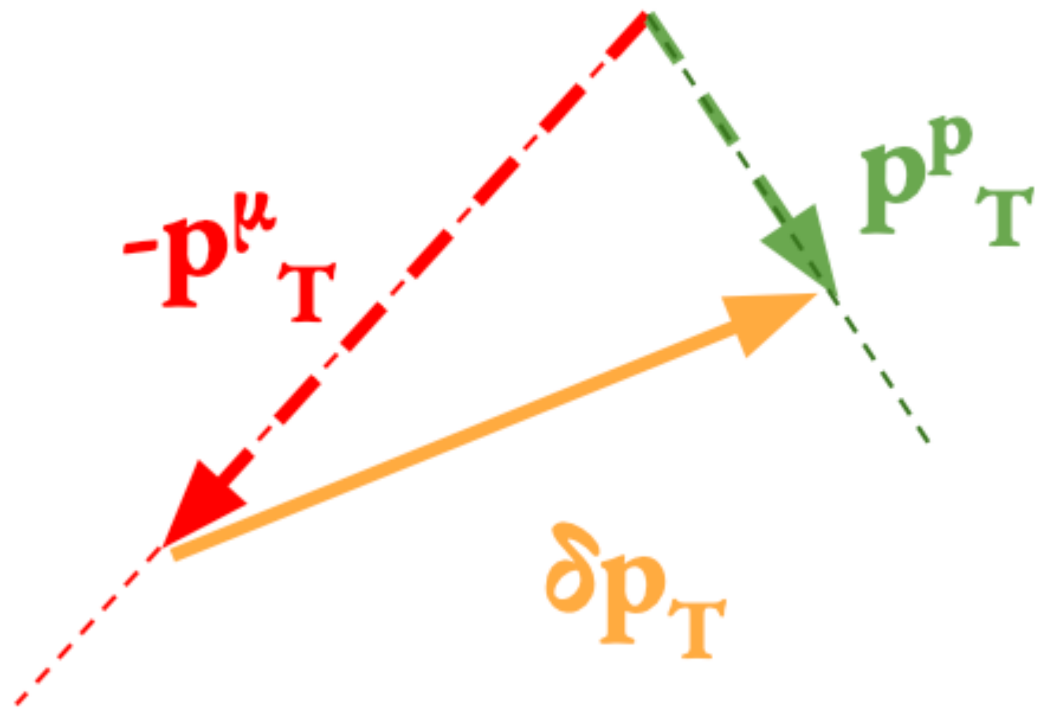
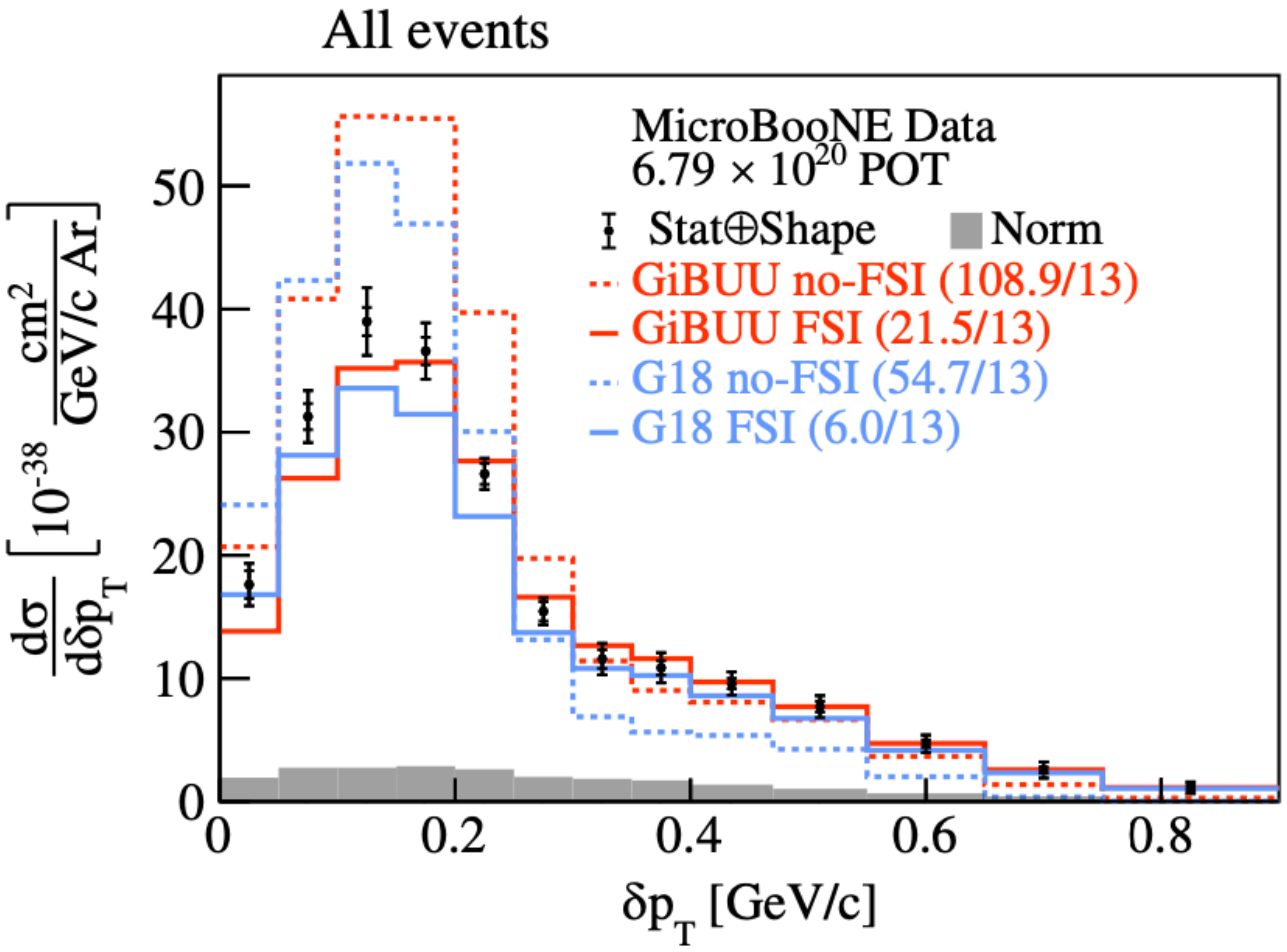
ν_μCC 1p0π TKI



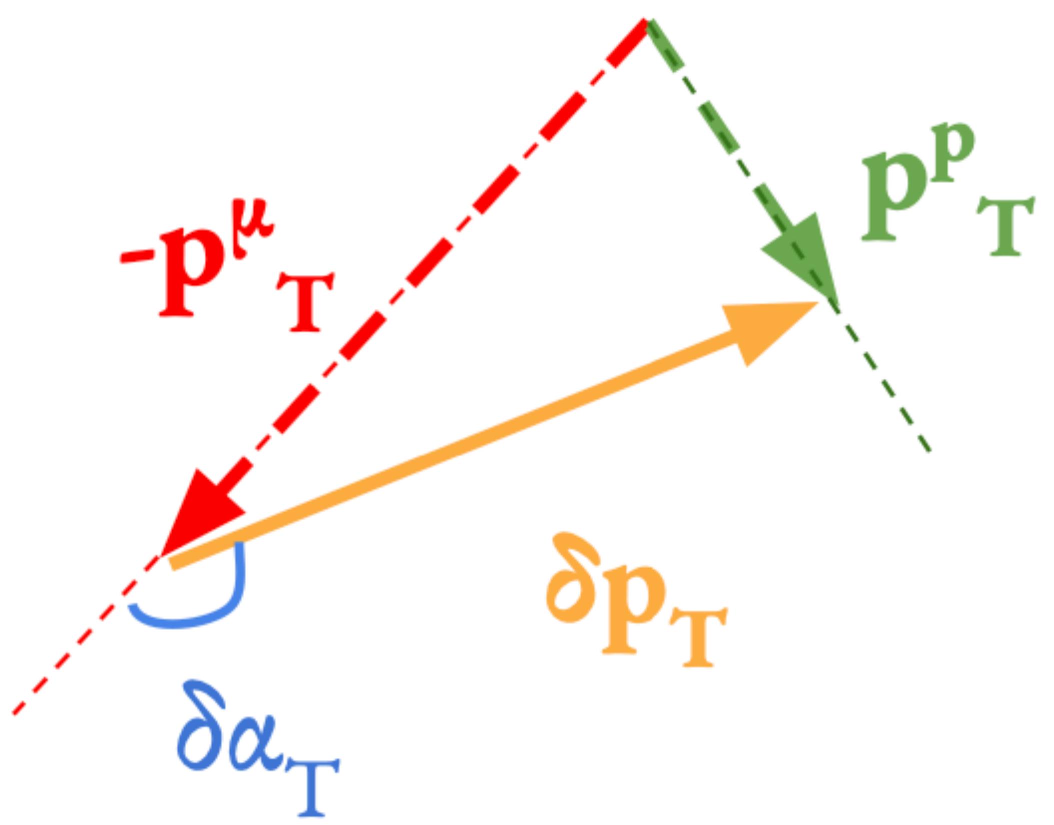
- We measure a cross section in this δp_T value, which has significant sensitivity to final state interactions

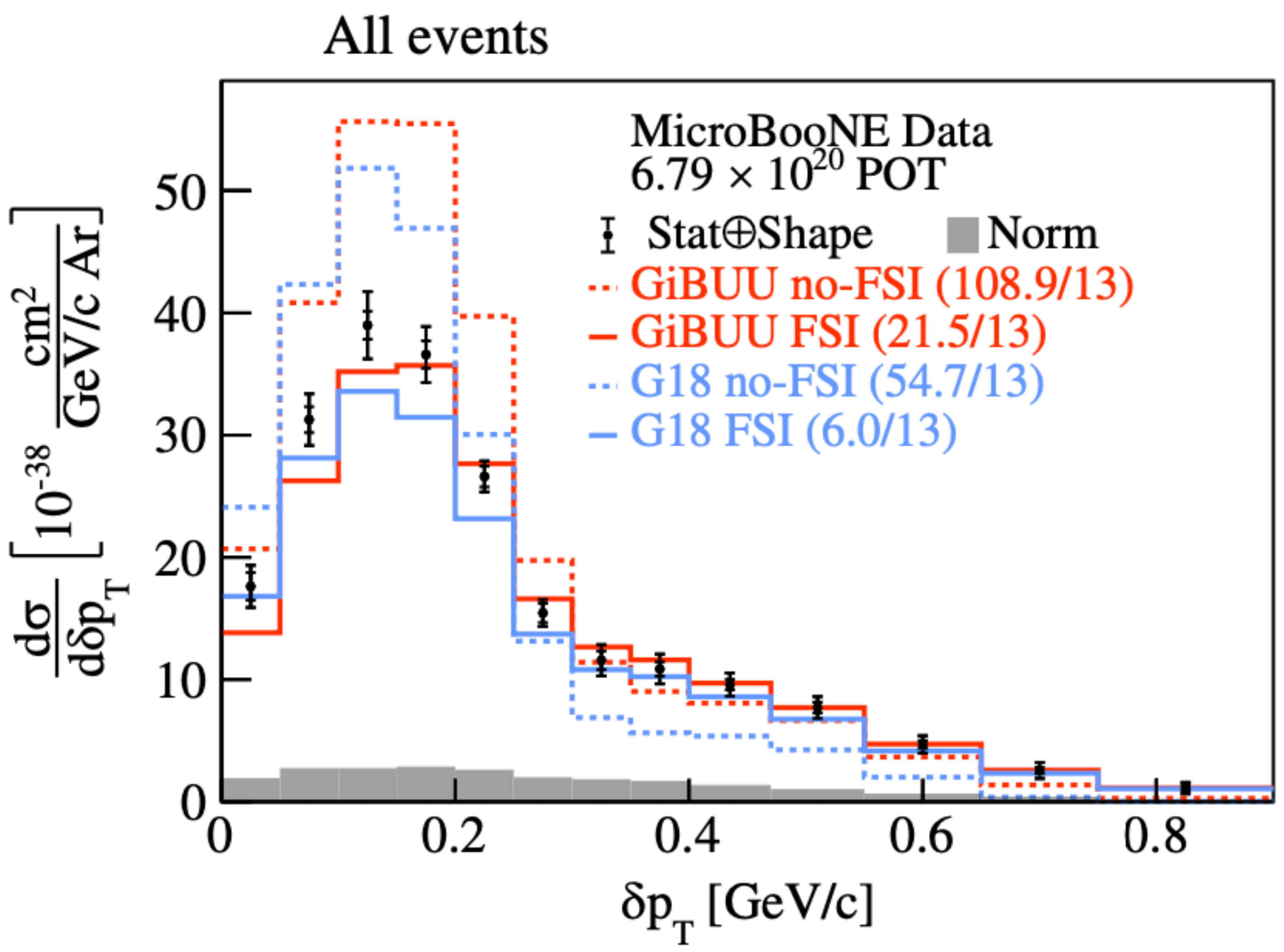


Phys. Rev. Lett. 131, 101802 (2023) Phys. Rev. D 108, 053002 (2023)

ν_μCC 1p0π TKI

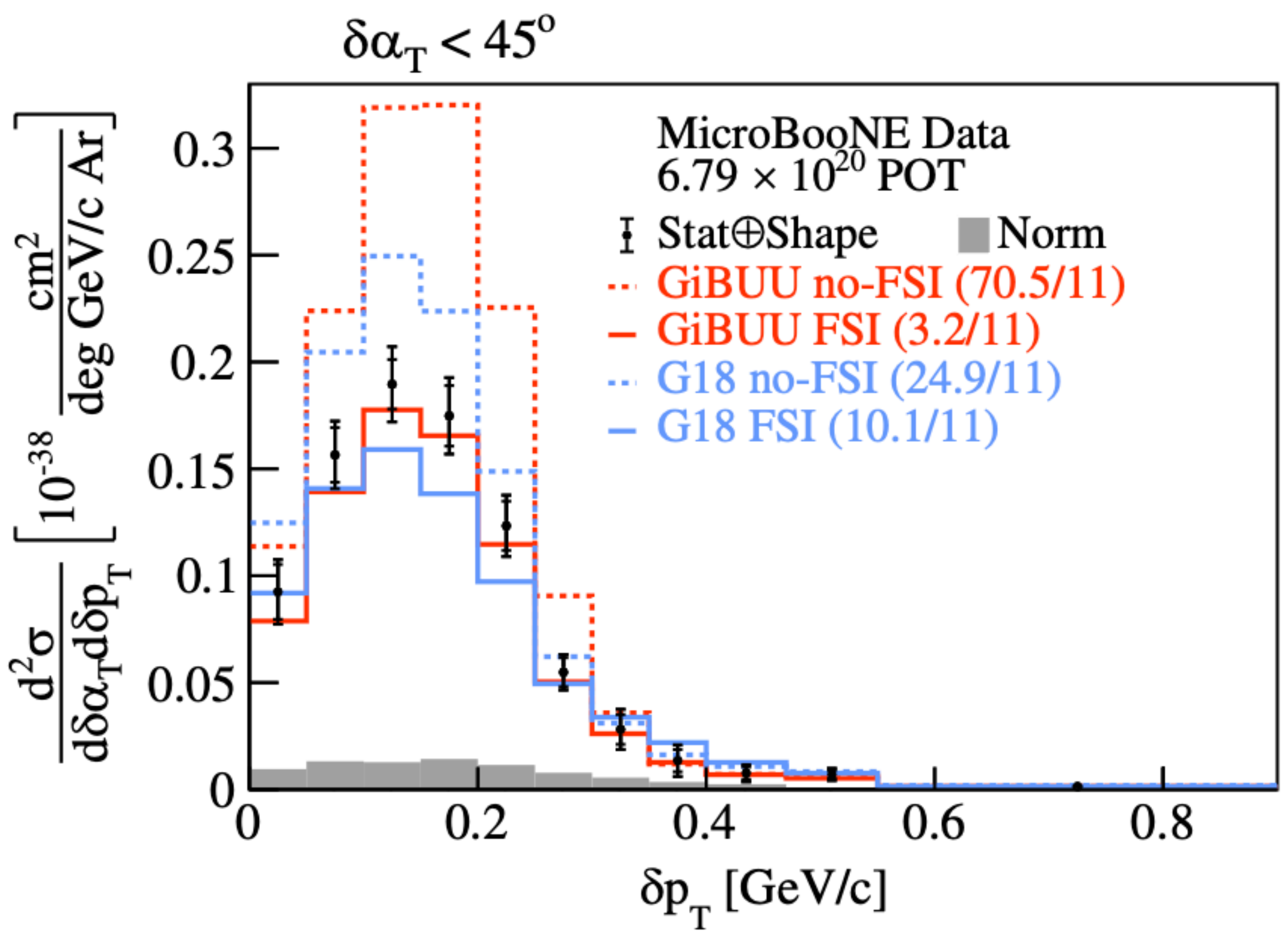
- We can expand this to multiple dimensions, looking at the angle between these transverse momentum vectors
- We get even more model discrimination power

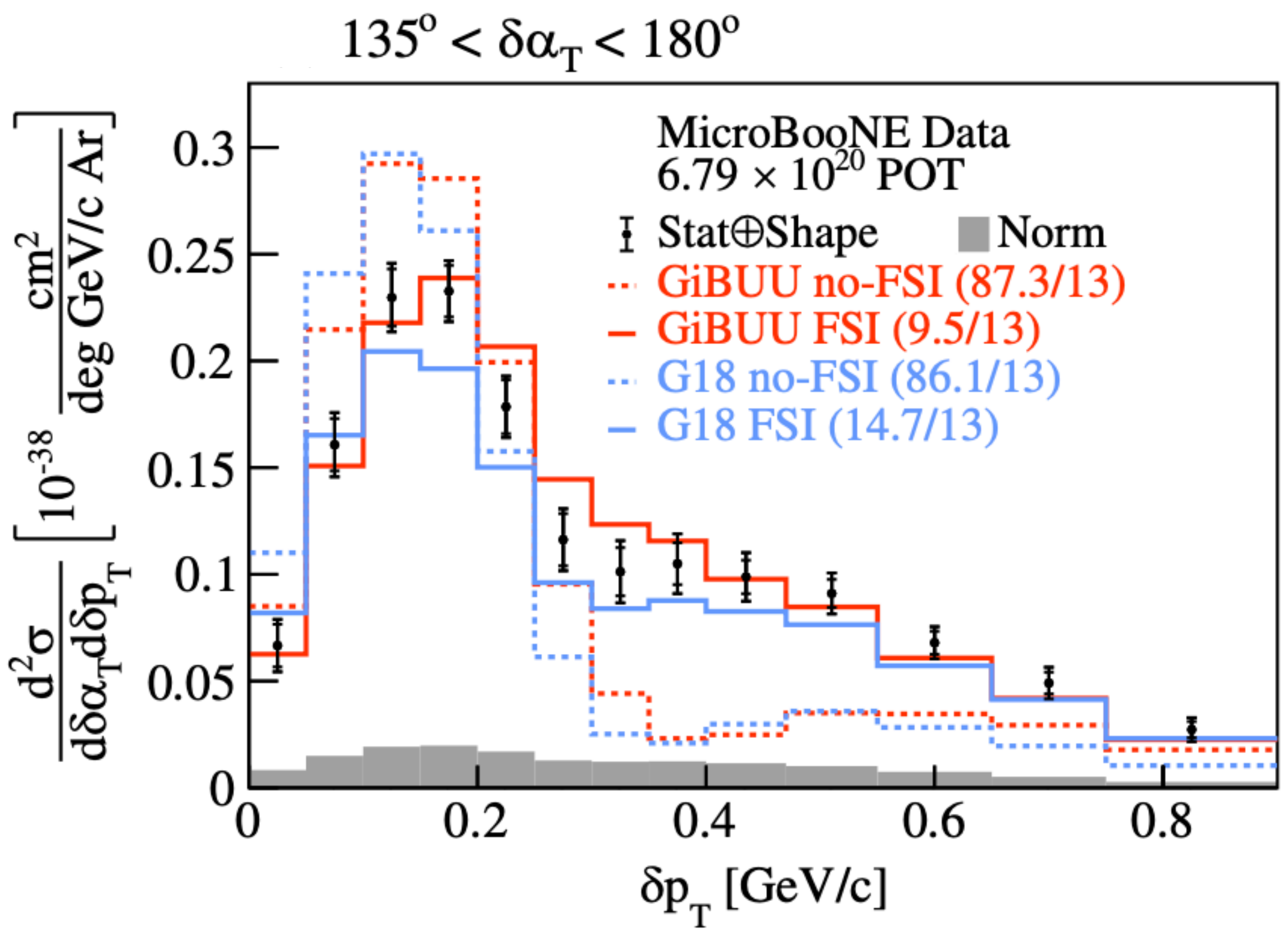




QE-dominated

MEC/RES/FSI-dominated



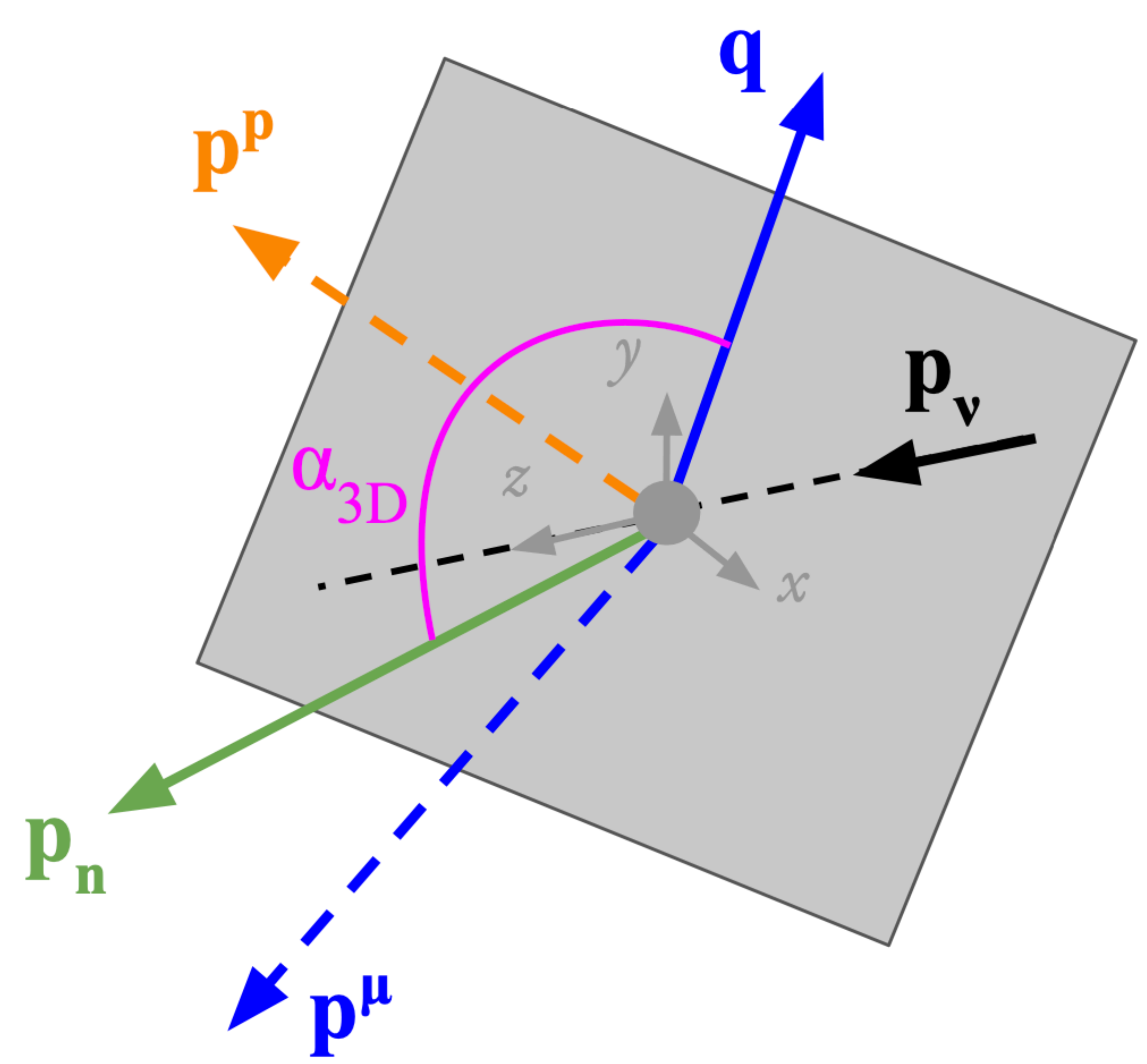


Phys. Rev. Lett. 131, 101802 (2023) Phys. Rev. D 108, 053002 (2023)

ν_μCC 1p0π GKI

$\vec{q}$: momentum transfer to the hadronic system

- That was considering the momentum in the transverse plane, where we would naively expect the momentum to be balanced with $\delta p_T = 0$
- However, we measure E_μ and E_p, so we know E_ν*, so we know the longitudinal momentum as well and can compare with a measured value
- We expand to 3D, out of the transverse plane, to consider the total momentum imbalance, p_n (Generalized Kinematic Imbalance, GKI)



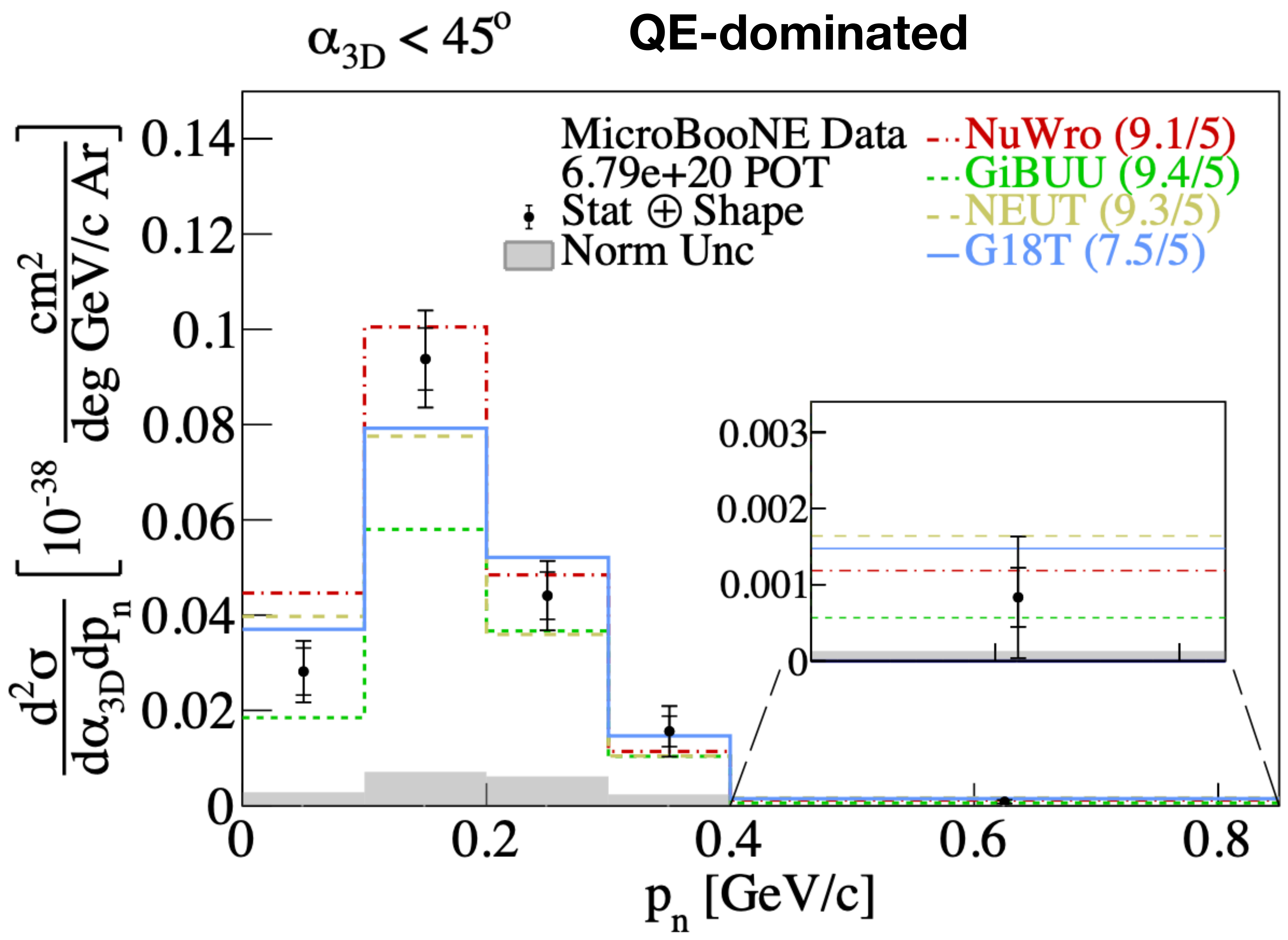
*(assuming not much $E_{\text{had}}^{\text{invis}}$ on average for this topology)

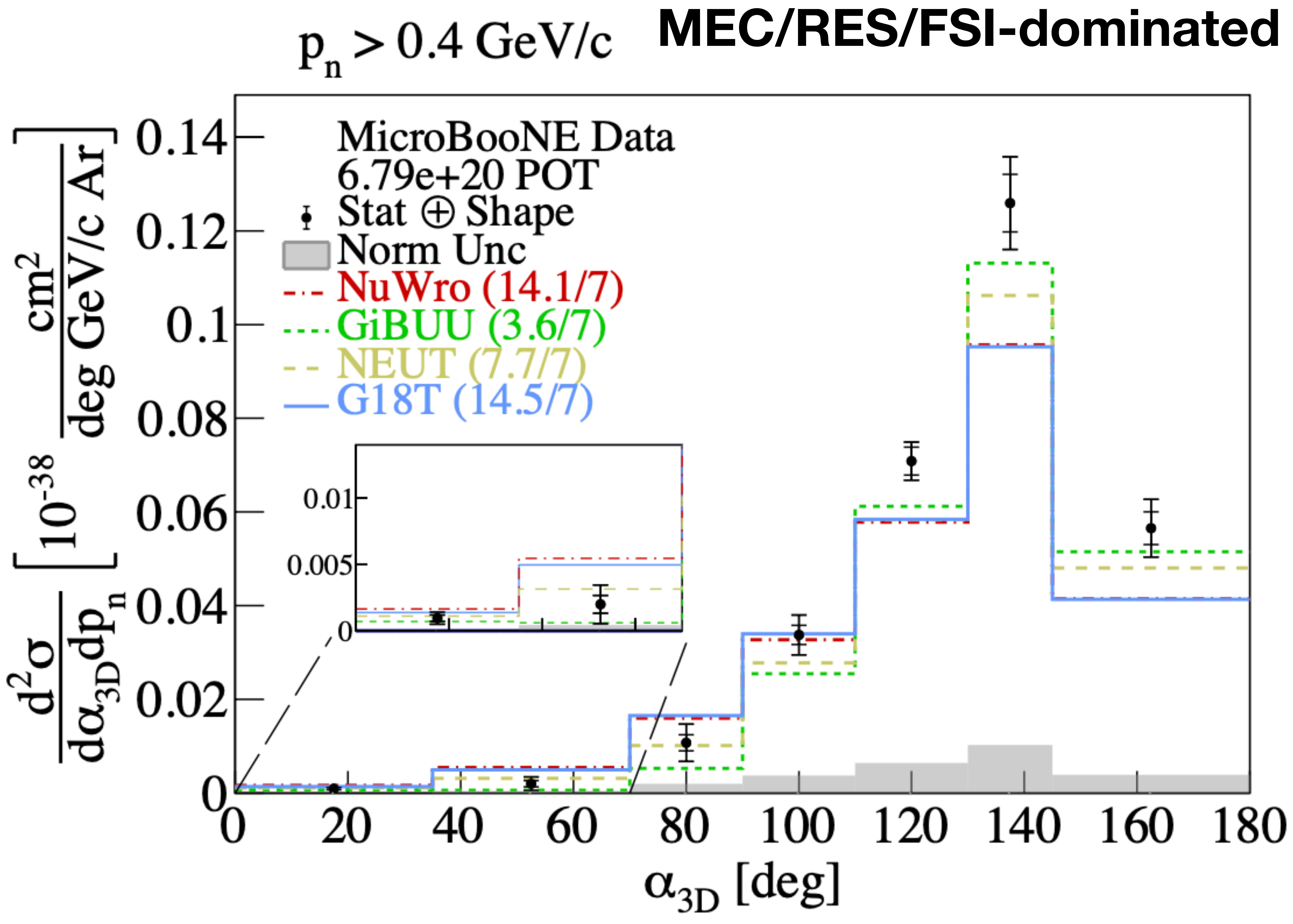
arXiv:2310.06082

ν_μCC 1p0π GKI

- We measure this 2D cross section, and can look at slices in p_n or α_{3D}, with large model discrimination power
- GENIE performs best in QE-dominated regions, while GiBUU performs best in FSI-dominated regions

Recall that there were also indications of better GiBUU FSI from the ν_μCC inclusive K_p cross section!

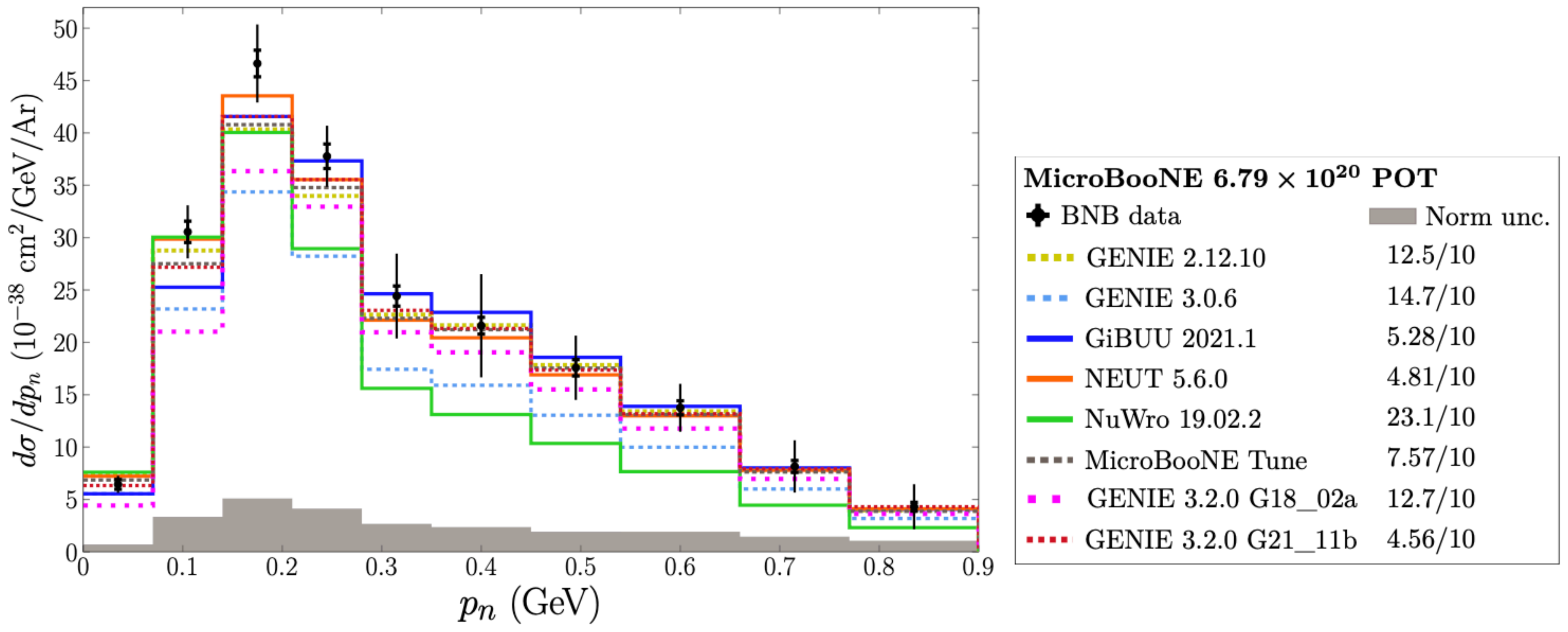


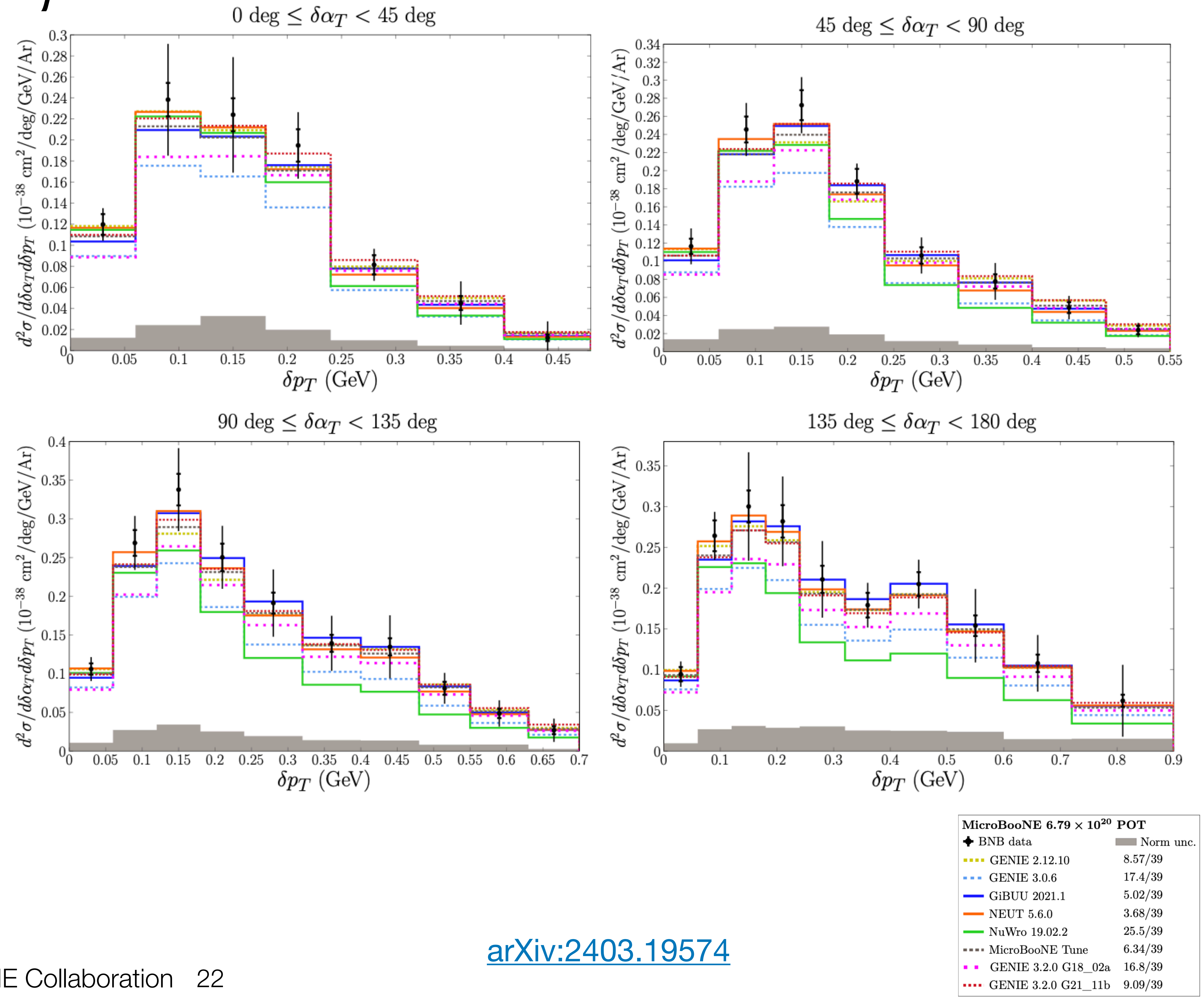


arXiv:2310.06082

ν_μCC Np0π

- Studied TKI and GKI variables for this topology as well, using the highest energy proton
- We report correlations between a large set of extracted cross sections

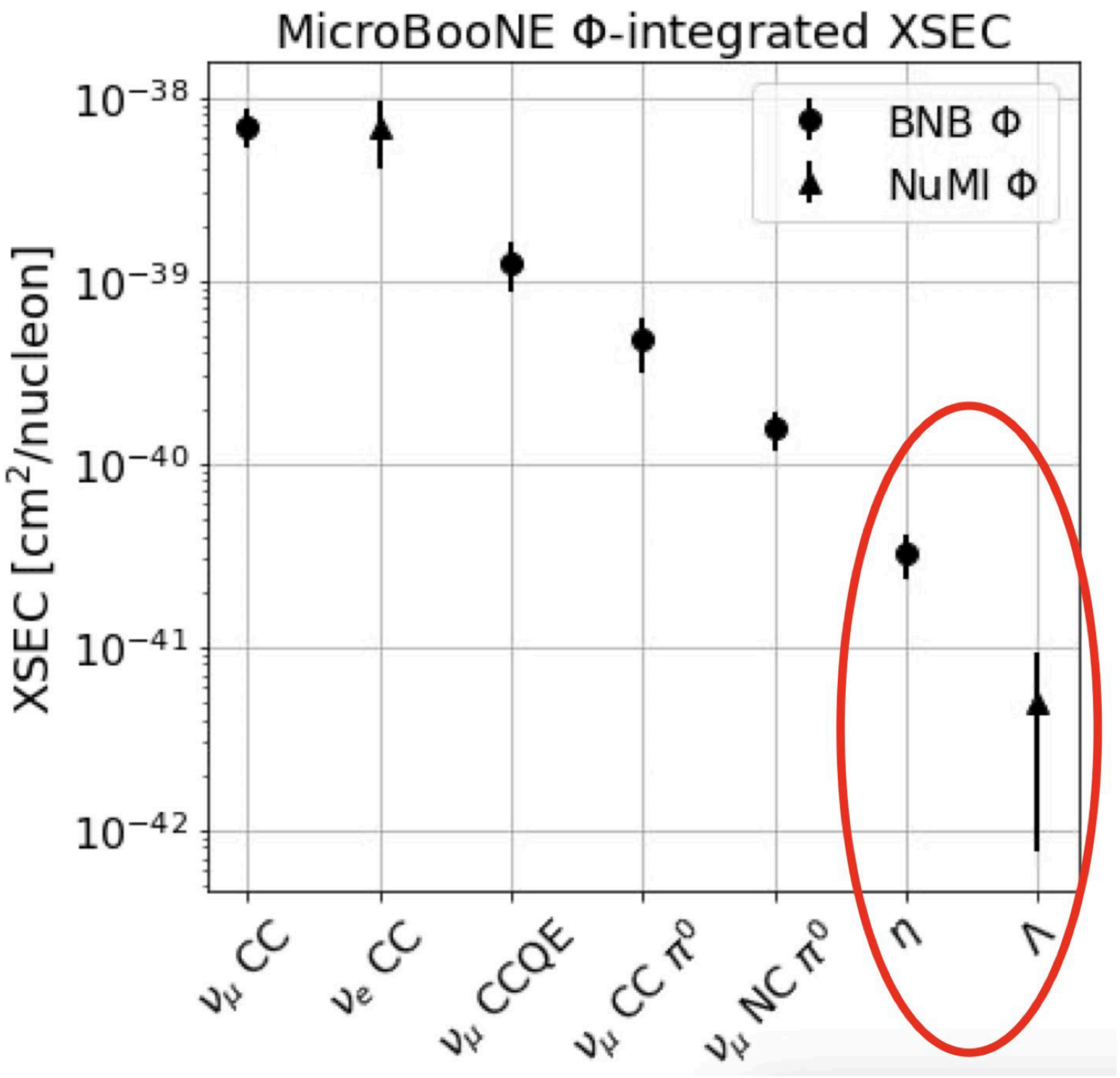




arXiv:2403.19574

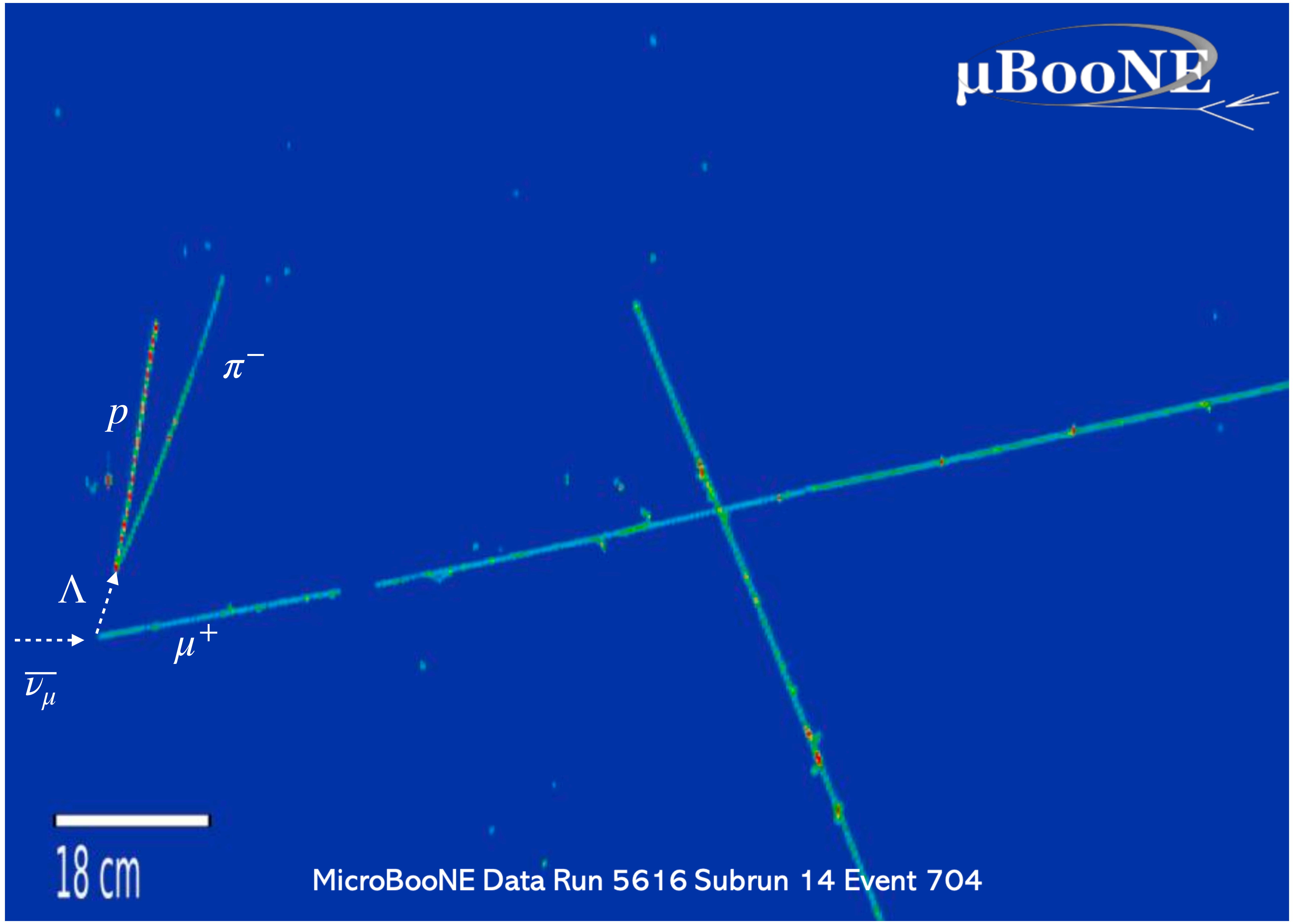
Rare Channels

- Neutrino interactions are famously rare in the first place
- Interactions producing these new final state particles have cross sections ~100-1000 times smaller than the inclusive cross section



Λ Production

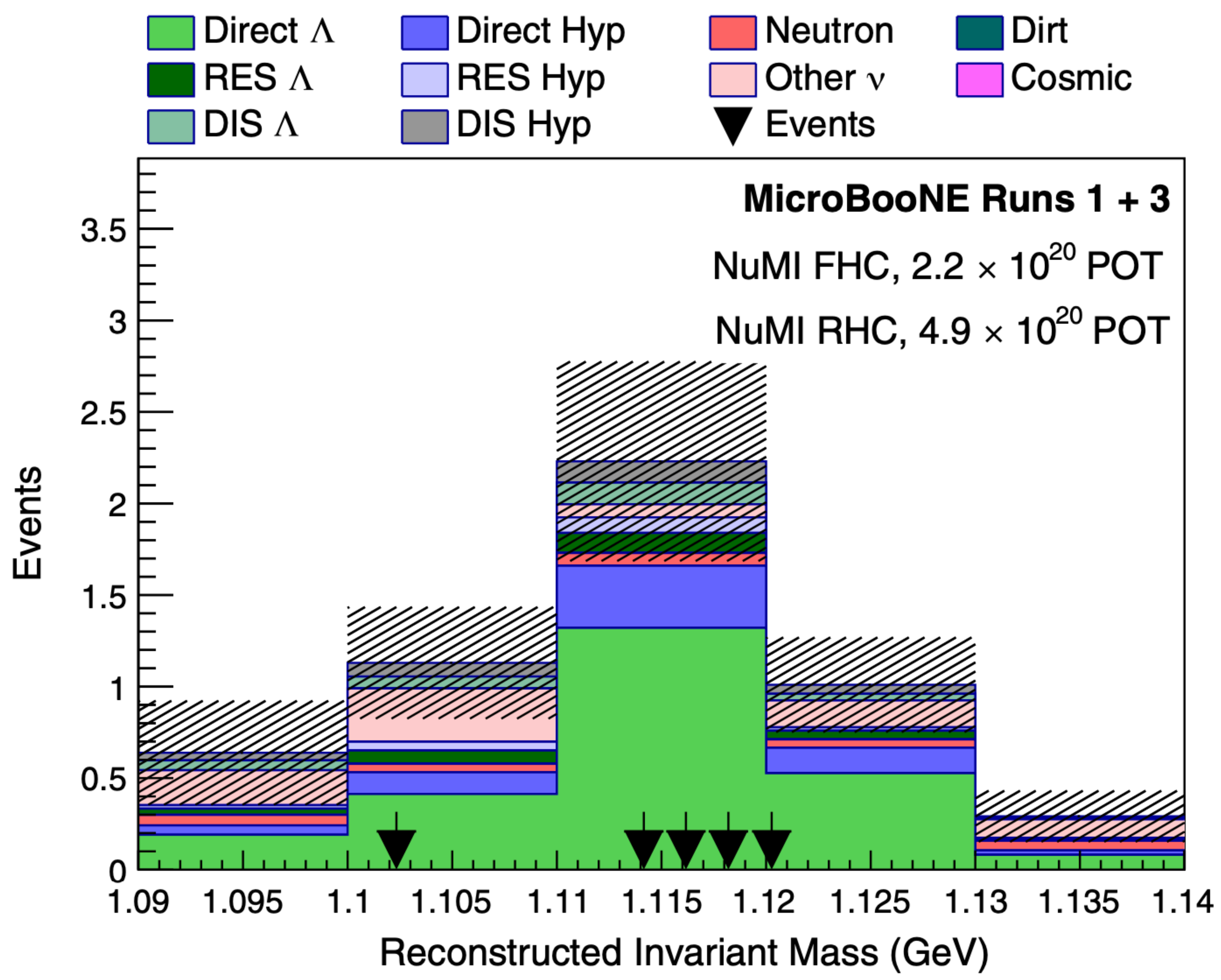
- Cabibbo-suppressed counterpart of CCQE interactions: $\overline{\nu}_\mu + \mathrm{Ar} \rightarrow \mu^+ + \Lambda + X$
  - Then $\Lambda \rightarrow p + \pi^-$
- "Hyperon puzzle", studying these particles could have consequences for neutron star populations
- Only a handful of old bubble chamber observations of this process
- Secondary $\Lambda + \mathrm{A}r \rightarrow K^+ + X$ is a potential background to $p \rightarrow K + \nu$ proton decay searches
- Sensitive to nucleon form factors, hyperon-nucleus potentials, and final state interactions
- Exclusively due to $\overline{\nu}$, can constrain antineutrino content in a neutrino beam

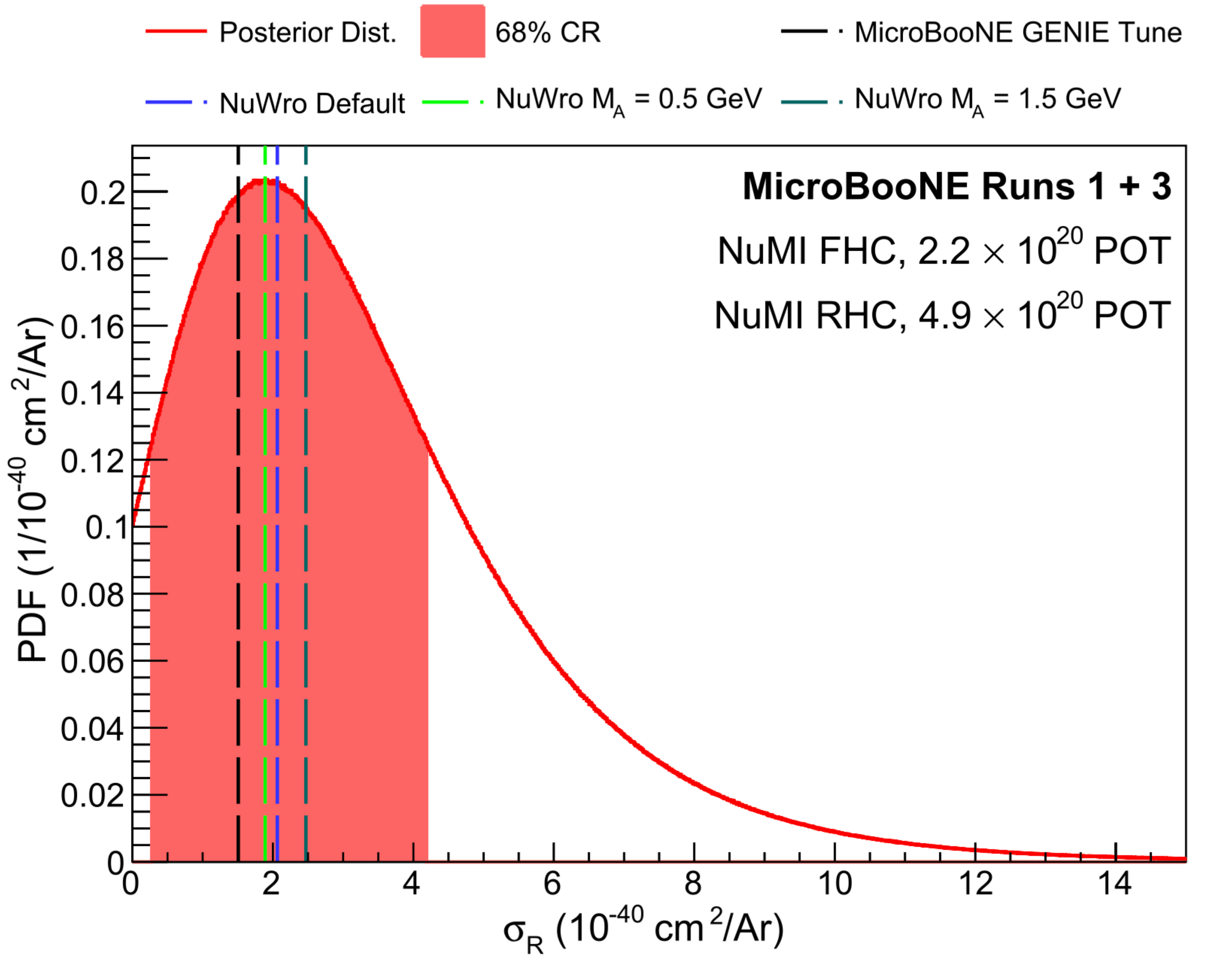


Phys. Rev. Lett. 130, 231802 (2023)

Λ Production

- We select five data events
- Invariant mass is consistent with the Λ mass of 1116 MeV
- Relatively low statistics, used about 1/4 of MicroBooNE NuMI data
- We report a measurement rather than an exclusion





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

η Production

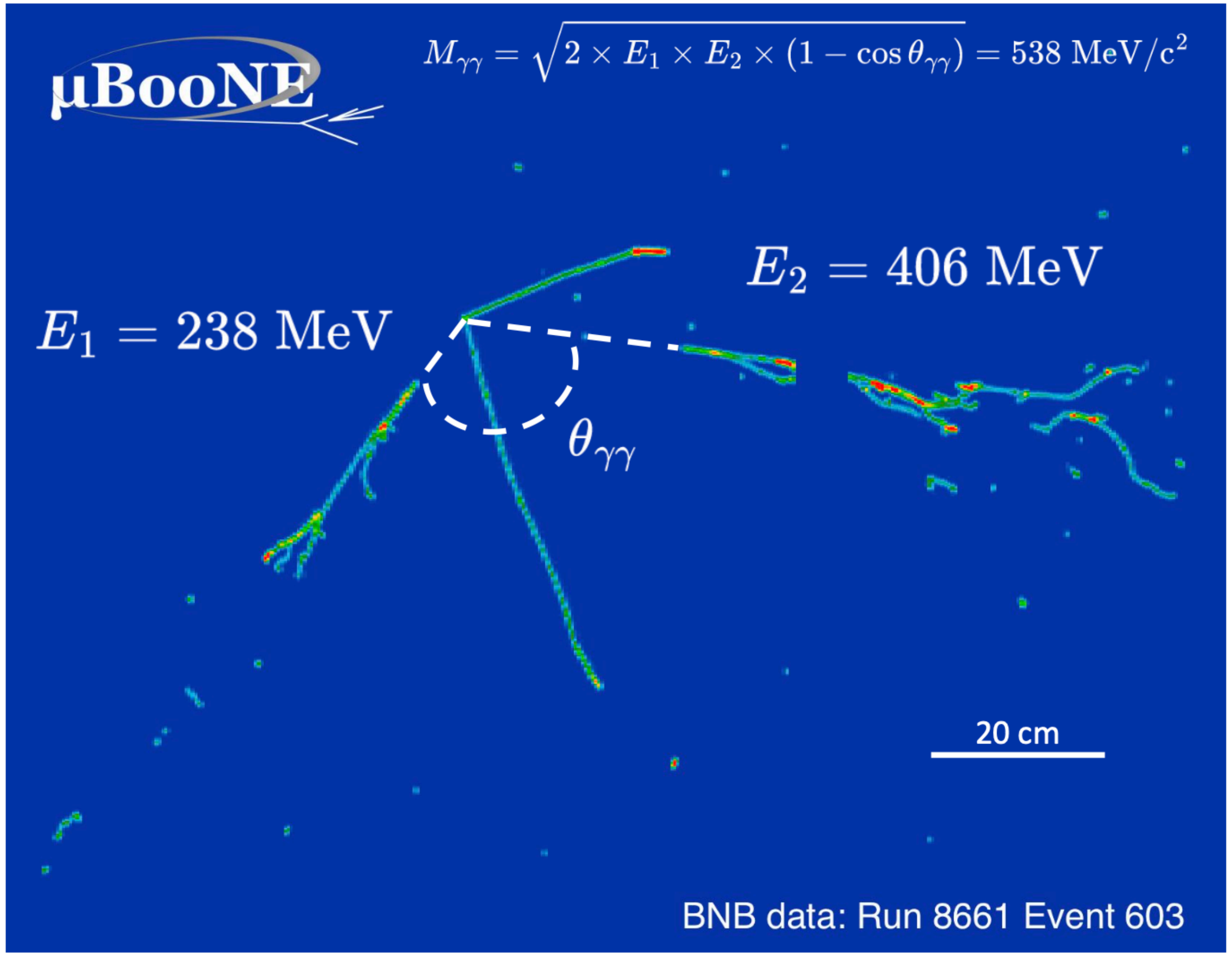
- By studying rarely produced η mesons which behave like a heavier π^0, we can get a unique handle on higher mass resonances and their decays
- $p \rightarrow e^+ + \eta$ is an important potential proton decay channel, which has already been studied in Super-K
- New shower energy calibration scale, with an invariant mass of 548 MeV (compared to 135 MeV π^0)

Typical resonant neutrino interaction:

$$\nu + p \rightarrow \Delta(1232) \rightarrow p + \pi^0 \rightarrow p + \gamma + \gamma$$

Possible higher mass resonant neutrino interaction:

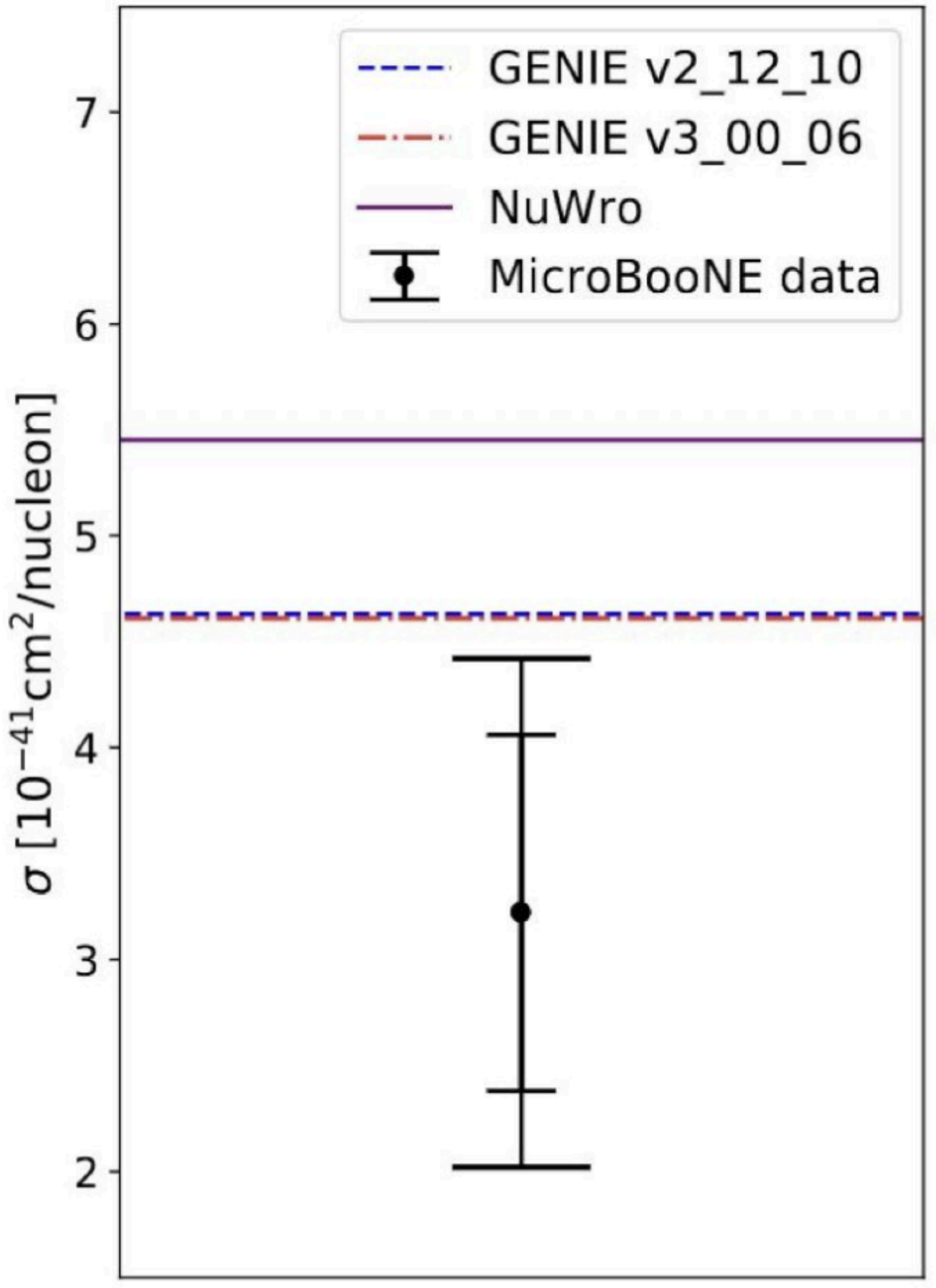
$$\nu + p \rightarrow N(1535) \rightarrow p + \eta \rightarrow p + \gamma + \gamma$$

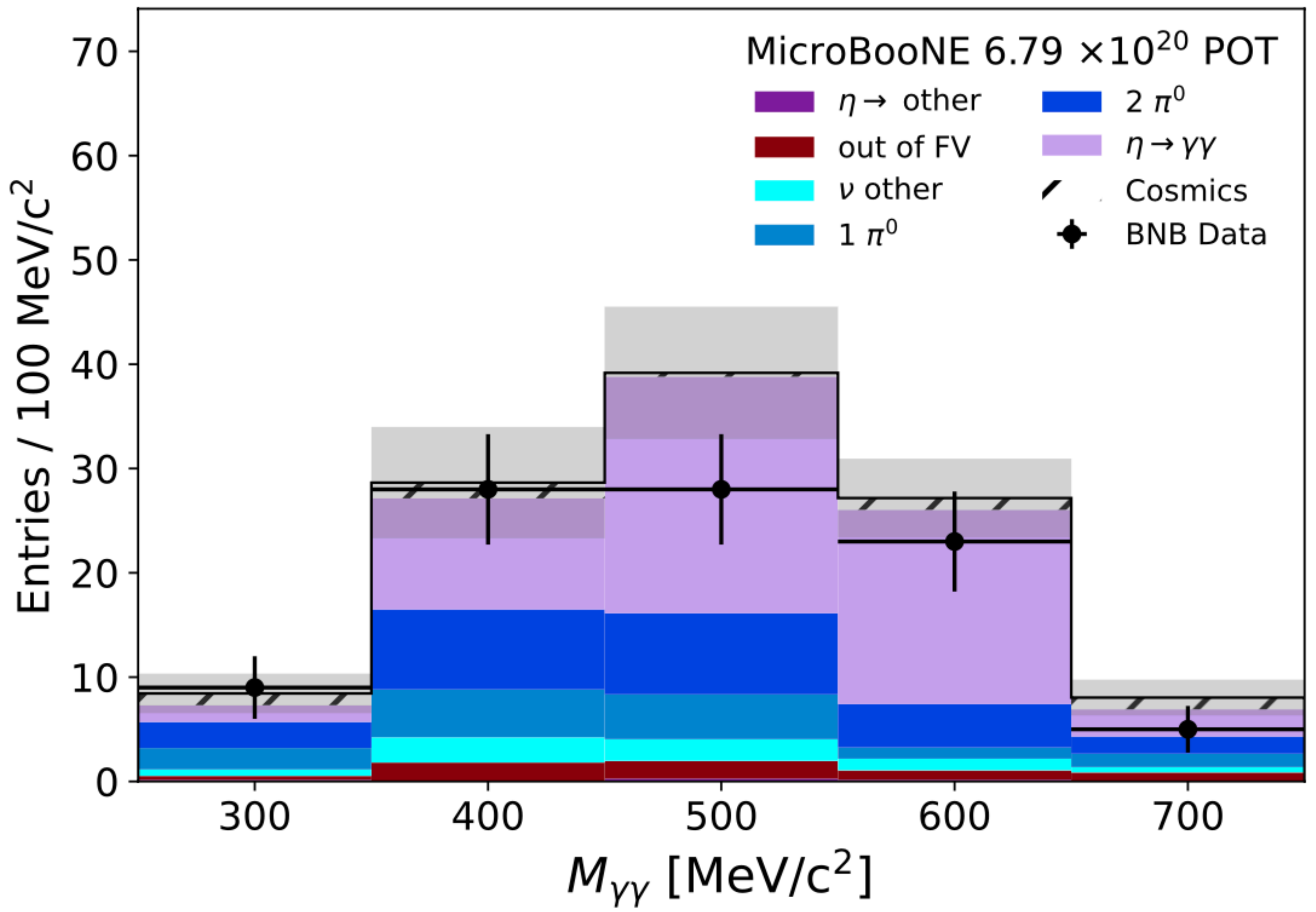


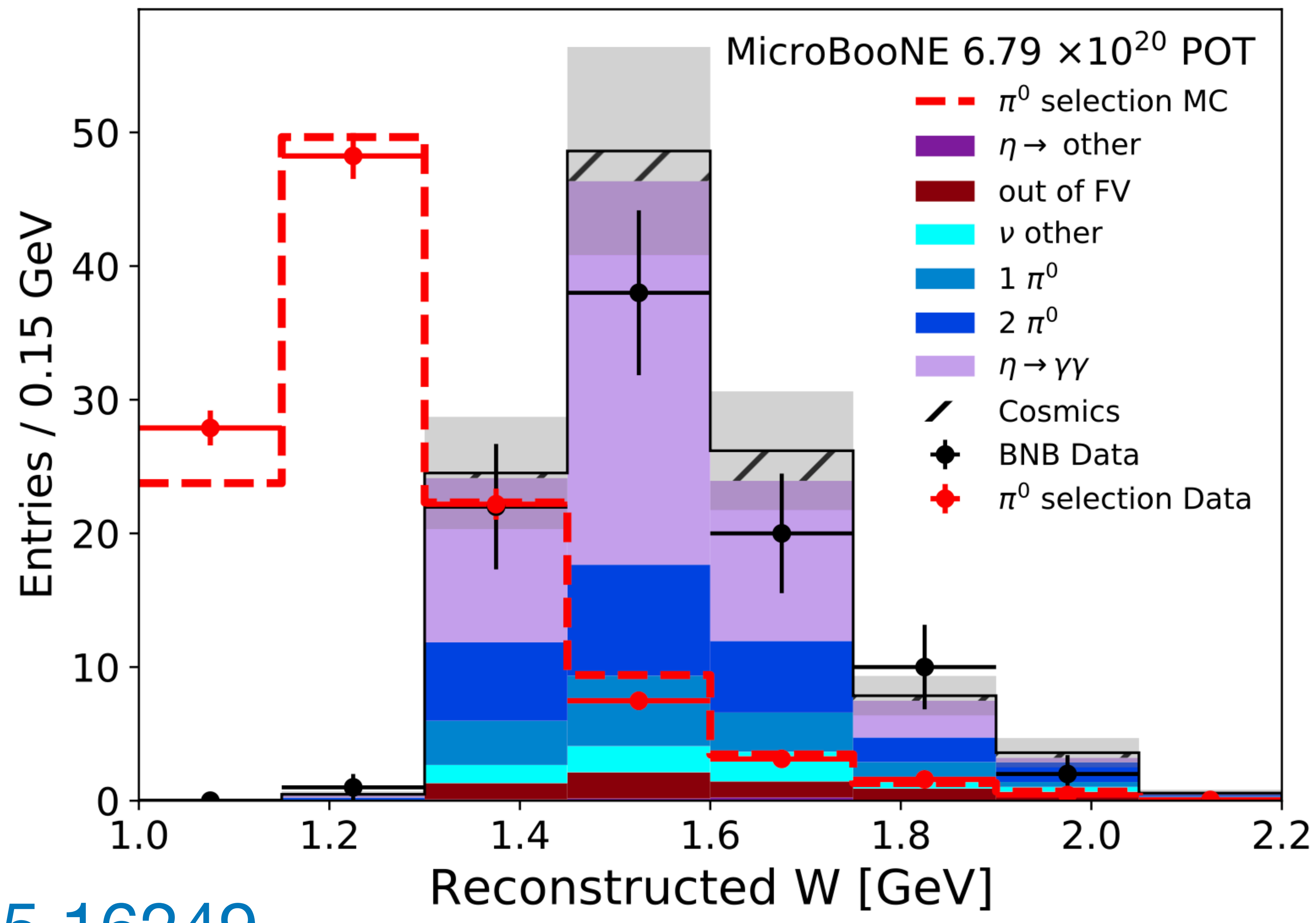
arXiv:2305.16249

η Production

- The two photon invariant mass $M_{\gamma\gamma}$ is consistent with the η mass, 548 MeV
- The hadronic system invariant mass W is consistent with the $N(1535)$ mass
- We report a measurement rather than an exclusion







arXiv:2305.16249

Conclusions

- MicroBooNE's recent cross section results have explored a lot of different directions
  - New ways to validate the $E_\nu^{\mathrm{true}} \rightarrow E_\nu^{\mathrm{rec}}$ mapping for oscillation experiments
  - Important generator deficiencies for low energy protons
  - New ways to explore initial nucleon momentum and final state interactions with simple topologies
  - Two first-time observations of rare particles in neutrino-argon interactions

- Looking to the future, we are actively working on lots of cross section analyses, including:
  - Studying more new final state particles
    - $K^{+/-}$, $\pi^{+/-}$, and neutron production
  - New methods to extract more information from our data
    - Separating neutrino and antineutrino cross sections
    - Reporting more correlations between different cross section measurements
    - Joint BNB/NuMI cross sections, reducing flux uncertainties

Thanks for your attention!

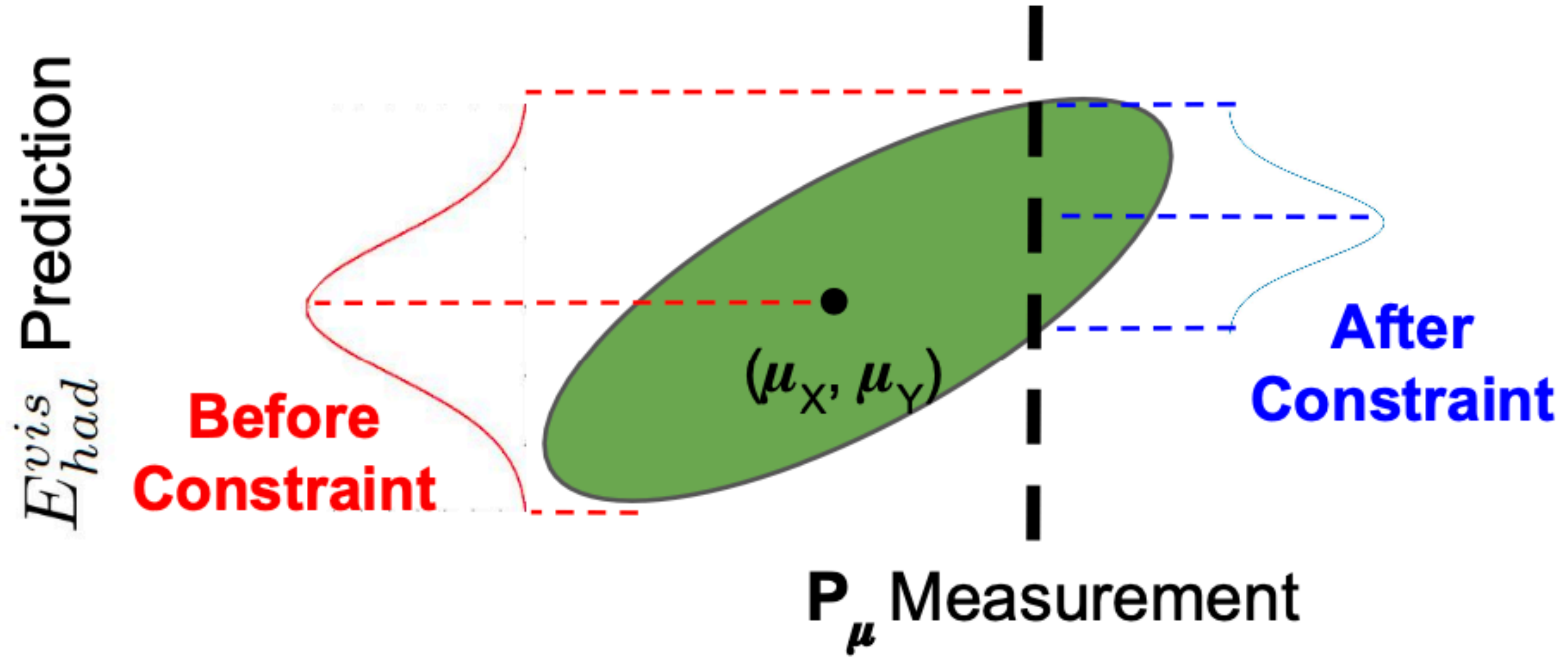
Backup Slides

All Public MicroBooNE XS Measurements

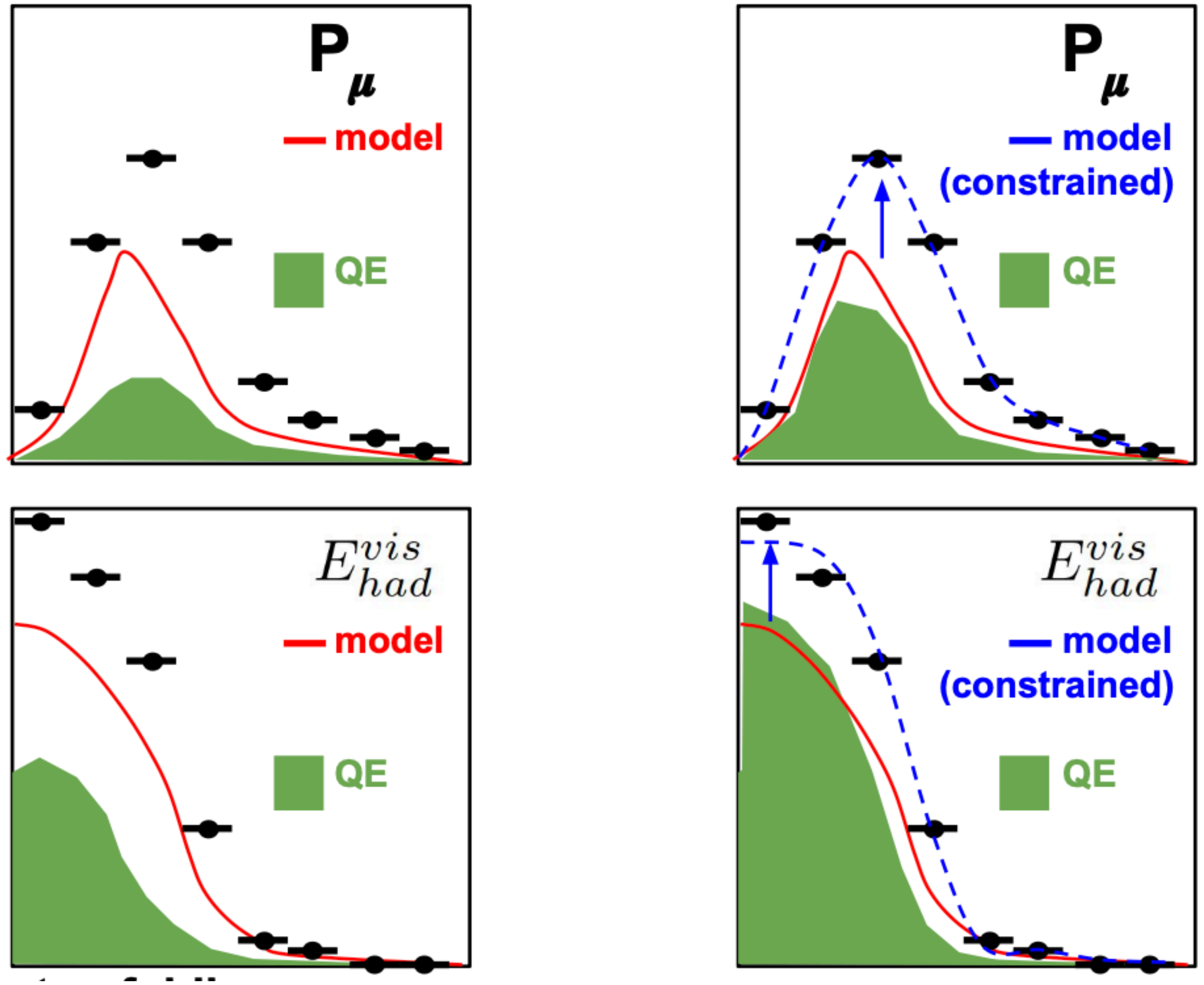
- CC inclusive
  - 3D ν_μCC inclusive 0p/Np, BNB, arXiv:2402.19281, arXiv:2402.19216
  - 3D ν_μCC inclusive, BNB, arXiv:2307.06413
  - 1D ν_μCC inclusive E_ν, BNB, Phys. Rev. Lett. 128, 151801 (2022)
  - 1D ν_eCC inclusive, NuMI, Phys. Rev. D105, L051102 (2022)
  - ν_eCC inclusive, NuMI, Phys. Rev. D104, 052002 (2021)
  - 2D ν_μCC inclusive, BNB, Phys. Rev. Lett. 123, 131801 (2019)
- Pion production
  - NC π^0, BNB, Phys. Rev. D 107, 012004 (2023)
  - CC π^0, BNB, Phys. Rev. D 99, 091102(R) (2019)
- Rare channels
  - η production, BNB, arXiv:2305.16249
  - Λ production, NuMI, Phys. Rev. Lett. 130, 231802 (2023)
  - NC $\Delta \to N\gamma$ (interpreted as a limit on the XS), BNB, Phys. Rev. Lett. 128, 111801 (2022)
- CC 0π
  - 2D ν_μ CC Np0π, BNB, arXiv:2403.19574
  - 1D & 2D ν_μ CC 1p0π Generalized Imbalance arXiv:2310.06082, BNB, accepted by PRD
  - 1D & 2D ν_μCC 1p0π Transverse Imbalance, BNB, Phys. Rev. Lett. 131, 101802 (2023), Phys. Rev. D 108, 053002 (2023)
  - 1D ν_eCC Np0π, BNB, Phys. Rev. D 106, L051102 (2022)
  - 1D ν_μ CC 2p0π, BNB, arXiv:2211.03734
  - 1D ν_μ CC Np0π, BNB, Phys. Rev. D102, 112013 (2020)
  - 1D ν_μ CC 1p0π, BNB, Phys. Rev. Lett. 125, 201803 (2020)

Conditional Constraint

Illustrative toy example:



For Illustrative Purposes Only:



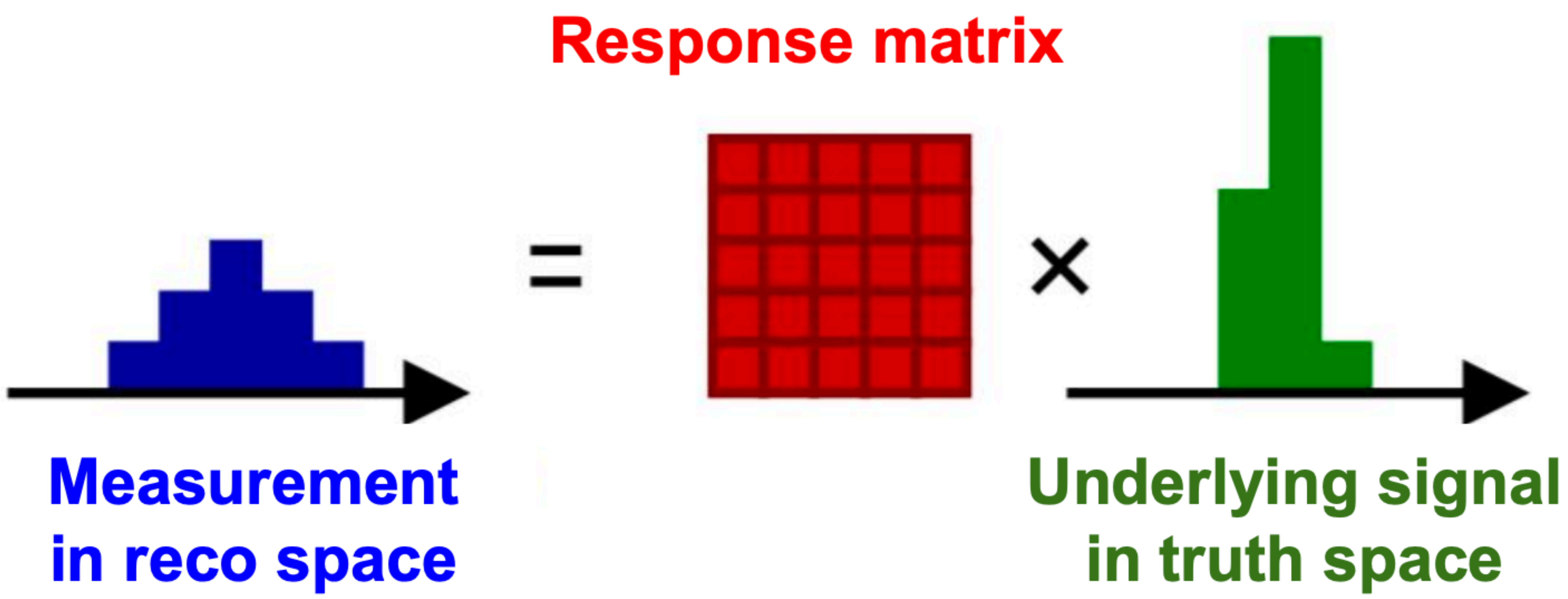
$$\Sigma = \begin{pmatrix} \Sigma^{XX} & \Sigma^{XY} \\ \Sigma^{YX} & \Sigma^{YY} \end{pmatrix}, \quad n: \text{measurement}, \quad \mu: \text{prediction}$$

$$\mu^{X,\text{const.}} = \mu^X + \Sigma^{XY} \cdot (\Sigma^{YY})^{-1} \cdot (n^Y - \mu^Y)$$

$$\Sigma^{XX,\text{const.}} = \Sigma^{XX} - \Sigma^{XY} \cdot (\Sigma^{YY})^{-1} \cdot \Sigma^{YX}$$

Unfolding

$$M_i = \Sigma_j R_{ij} \cdot S_j + B_i$$



We solve for S by inverting R_{ij}

We use a regularization technique to avoid large fluctuations after inversion

How We Unfold To Nominal Flux Using Data From The Real Flux

Protons on target → POT; **Number of targets** → T; **Beam flux** → $F(E_\nu)$; **Cross section** → $\sigma(E_\nu)$; **Detector response** → $D(E_\nu \to E_{rec})$; **Selection efficiency** → $\varepsilon(E_\nu, E_{rec})$; **Background** → $B(E_{rec})$

$$M(E_{rec}) = POT \cdot T \cdot \int F\left(E_\nu\right) \cdot \sigma\left(E_\nu\right) \cdot D\left(E_\nu \to E_{rec}\right) \cdot \varepsilon\left(E_\nu, E_{rec}\right) \cdot dE_\nu + B\left(E_{rec}\right)$$

All of these quantities must consider full flux, cross-section, detector, and statistical uncertainties!

Re-writing this same equation to be useful later (adding more terms that cancel each other out):

$$M(E_{rec}) = \underbrace{\frac{POT \cdot T \cdot \int_j F\left(E_{\nu\, j}\right) \cdot \sigma\left(E_{\nu\, j}\right) \cdot D\left(E_{\nu\, j} \to E_{rec\, i}\right) \cdot \varepsilon\left(E_{\nu\, j}, E_{rec\, i}\right) \cdot dE_{\nu\, j}}{POT \cdot T \cdot \int_j \overline{F}\left(E_{\nu\, j}\right) \cdot \sigma\left(E_{\nu\, j}\right) \cdot dE_{\nu\, j}}}_{\tilde{\Delta}_{ij}} \cdot \underbrace{POT \cdot T \cdot \int_j \overline{F}\left(E_{\nu\, j}\right) \cdot dE_{\nu\, j}}_{\tilde{F}_j} \cdot \underbrace{\frac{\int_j \overline{F}\left(E_{\nu\, j}\right) \cdot \sigma\left(E_{\nu\, j}\right) \cdot dE_{\nu\, j}}{\int_j \overline{F}\left(E_{\nu\, j}\right) \cdot dE_{\nu\, j}}}_{S_j} + B\left(E_{rec}\right)$$

$$M(E_{rec})_i = \tilde{\Delta}_{ij} \cdot \tilde{F}_j \cdot S_j + B\left(E_{rec}\right)_i$$

How We Unfold To Nominal Flux Using Data From The Real Flux

$$M(E_{rec})_i = \tilde{\Delta}_{ij} \cdot \tilde{F}_j \cdot S_j + B\left(E_{rec}\right)_i$$

$$\tilde{\Delta}_{ij} = \frac{POT \cdot T \cdot \int_j F\left(E_{\nu\, j}\right) \cdot \sigma\left(E_{\nu\, j}\right) \cdot D\left(E_{\nu\, j}, E_{rec\, i}\right) \cdot \varepsilon\left(E_{\nu\, j}, E_{rec\, i}\right) \cdot dE_{\nu\, j}}{POT \cdot T \cdot \int_j \overline{F}\left(E_{\nu\, j}\right) \cdot \sigma\left(E_{\nu\, j}\right) \cdot dE_{\nu\, j}}$$

Cross-section uncertainty largely (but not entirely) cancels

$$\tilde{F}_j = POT \cdot T \cdot \int_j \overline{F}\left(E_{\nu\, j}\right) \cdot dE_{\nu\, j}$$

Binned nominal flux

$$S_j = \frac{\int_j \overline{F}\left(E_{\nu\, j}\right) \cdot \sigma\left(E_{\nu\, j}\right) \cdot dE_{\nu\, j}}{\int_j \overline{F}\left(E_{\nu\, j}\right) \cdot dE_{\nu\, j}}$$

Nominal flux-binned cross-section signal

This is what we want to measure!