

Proton final-states and kinematic imbalance in neutrino cross sections with the MicroBooNE detector

[Phys. Rev. Lett. 131, 101802 \(2023\)](#), [Phys. Rev. D 108, 053002 \(2023\)](#), [arXiv:2310.06082](#)

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Warwick, 11/1/2024



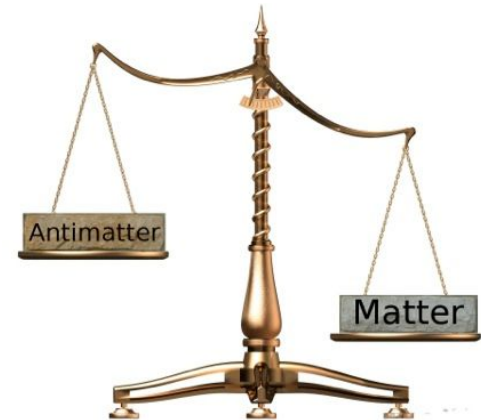
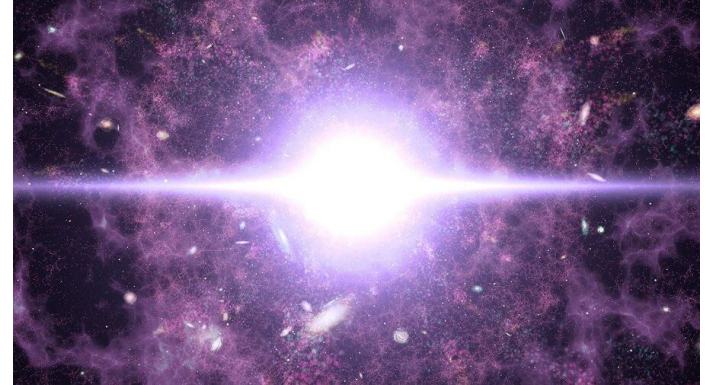
High-Precision Neutrino Measurements

Question: why matter dominated universe ?

(Potential) answer: Neutrino parameters lead to preferred matter production

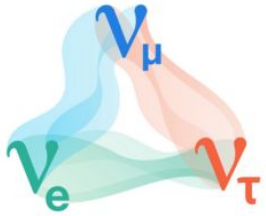
Experimental test: Forthcoming DUNE experiment will measure neutrino (matter) and anti-neutrino (anti-matter) interaction rates

Challenge: unprecedented understanding of neutrino-nucleus interactions



Neutrinos 101

Flavor eigenstates



$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = U_{\text{PMNS}} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

Mass eigenstates



Mixing
matrix

$$U_{\text{PMNS}} = \begin{bmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{bmatrix} \begin{bmatrix} c_{13} & 0 & s_{13}e^{-i\delta_{\text{CP}}} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta_{\text{CP}}} & 0 & c_{13} \end{bmatrix} \begin{bmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{bmatrix} \quad \begin{array}{l} c_{ij} = \cos\theta_{ij} \\ s_{ij} = \sin\theta_{ij} \\ \theta = \text{mixing angle} \end{array}$$

Experimental Overview

Two-neutrino approximation

$$P(\nu_\alpha \rightarrow \nu_\beta) \sim \sin^2(2\theta) \sin^2\left(\frac{\Delta m_{ij}^2 L}{4E}\right)$$

L: distance (baseline)

E: neutrino energy

Δm^2 : neutrino mass splitting

$$U_{\text{PMNS}} = \begin{bmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{bmatrix} \begin{bmatrix} c_{13} & 0 & s_{13} e^{-i\delta_{\text{CP}}} \\ 0 & 1 & 0 \\ -s_{13} e^{i\delta_{\text{CP}}} & 0 & c_{13} \end{bmatrix} \begin{bmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{bmatrix} \quad \begin{array}{l} c_{ij} = \cos\theta_{ij} \\ s_{ij} = \sin\theta_{ij} \\ \theta = \text{mixing angle} \end{array}$$

Experimental Overview

Optimizing baseline L for a given neutrino source of energy E
Mass eigenstate splitting Δm^2 and mixing angles θ known to few %-level

$$U_{\text{PMNS}} = \begin{bmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{bmatrix} \begin{bmatrix} c_{13} & 0 & s_{13}e^{-i\delta_{\text{CP}}} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta_{\text{CP}}} & 0 & c_{13} \end{bmatrix} \begin{bmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{bmatrix}$$



Atmospheric



Accelerator



Reactor



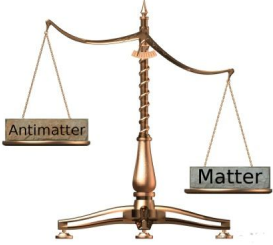
Solar

Open Questions

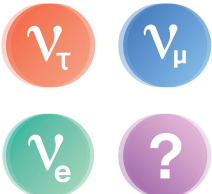
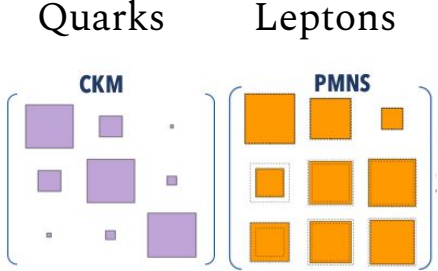


Neutrino nature

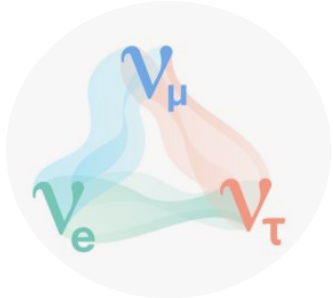
Charge parity violation



CKM vs PMNS matrix

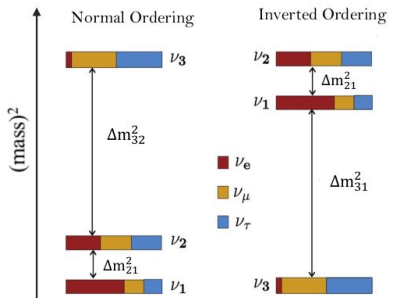


Sterile neutrinos & BSM



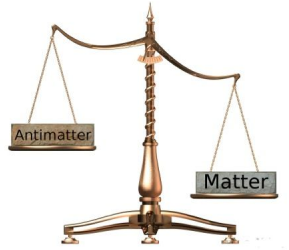
Mass mechanism

Mass ordering

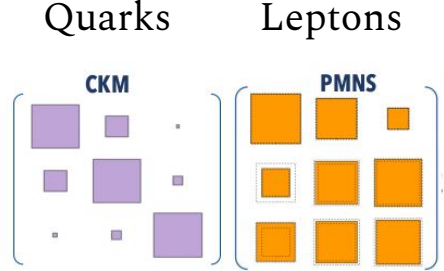


Open Questions

Charge parity violation

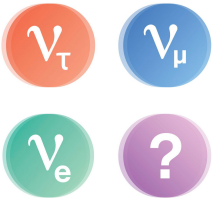


CKM vs PMNS matrix

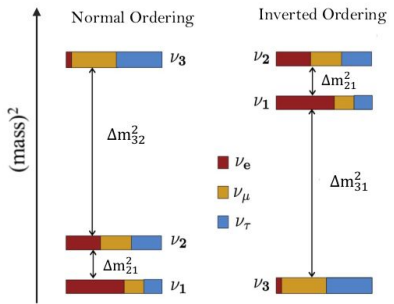


Investigated with high-precision short- and long-baseline neutrino oscillation experiments

Mass ordering



Sterile neutrinos & BSM



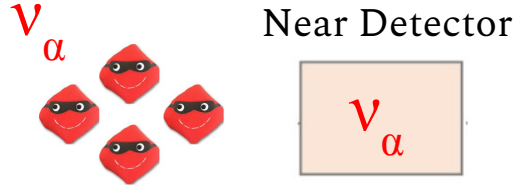
Neutrino Oscillation Experiments



$N_{ND}^\alpha(E_{rec})$: Number of
events of flavor α

E_{rec} = Reconstructed ν energy

Near Detector



Neutrino flux
prediction

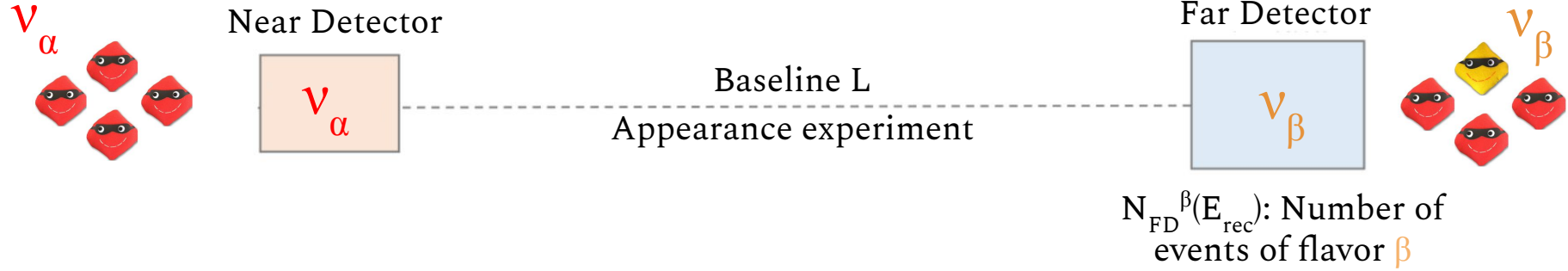
Near detector
selection efficiency

$$N_{\text{ND}}^{\alpha}(E_{\text{rec}}) \sim \Phi_{\text{ND}}(E_{\nu}) \sigma(E_{\nu}) \varepsilon_{\text{ND}}(E_{\nu})$$

Neutrino cross
section model

E_{ν} = True ν energy
Also dependence on detector observables

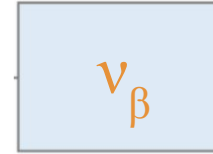
Neutrino Oscillation Experiments



E_{rec} = Reconstructed ν energy

Far Detector

Far Detector



$$N_{\text{FD}}^{\beta}(E_{\text{rec}}) \sim \Phi_{\text{FD}}(L, E_{\nu}) \sigma(E_{\nu}) \varepsilon_{\text{FD}}(E_{\nu}) \mathbf{P}(\nu_{\alpha} \rightarrow \nu_{\beta})$$

Neutrino flux prediction Far detector selection efficiency Oscillation probability

Neutrino cross section Model

$$P(\nu_{\alpha} \rightarrow \nu_{\beta}) \sim \sin^2(2\theta) \sin^2\left(\frac{\Delta m_{ij}^2 L}{4E}\right)$$

E_{ν} = True ν energy
 Also dependence on detector observables

Far Detector



Measured

$$N_{\text{FD}}^\beta(E_{\text{rec}})$$

Precise modeling input needed

$$\sim \Phi_{\text{FD}}(L, E_\nu) \sigma(E_\nu) \varepsilon_{\text{FD}}(E_\nu)$$

Want to measure with high-precision

$$P(\nu_\alpha \rightarrow \nu_\beta) \text{ Oscillation probability}$$

- Smearing relating E_ν to E_{rec}
- Neutrino signal topologies
- Neutrino backgrounds for BSM
- ...

Far Detector



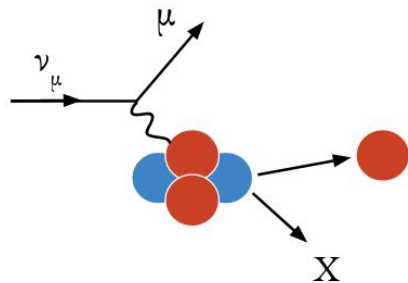
$$N_{\text{FD}}^{\beta}(E_{\text{rec}}) \sim \Phi_{\text{FD}}(L, E_{\nu}) \sigma(E_{\nu}) \epsilon_{\text{FD}}(E_{\nu}) \mathbf{P}(\nu_{\alpha} \rightarrow \nu_{\beta}) \quad \text{Oscillation probability}$$

Need for high precision
 ν cross section measurements

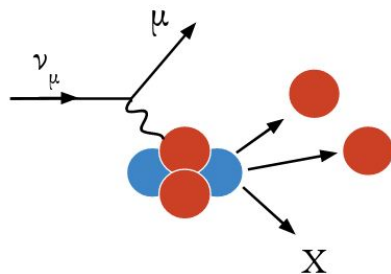
Challenging ...

- Broad neutrino spectra
- Various complex interaction mechanisms

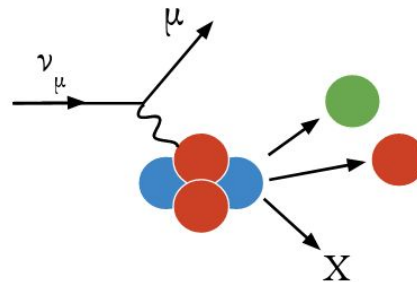
Any mismodeling in neutrino event generator simulation predictions can limit experimental sensitivity



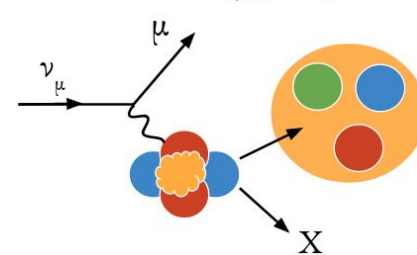
Quasi-elastic (QE)



Meson Exchange Current (MEC)

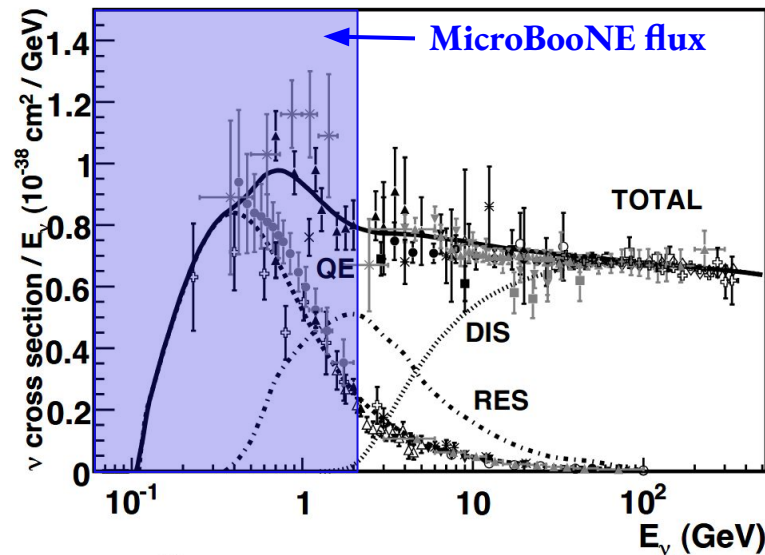


Resonance (RES)



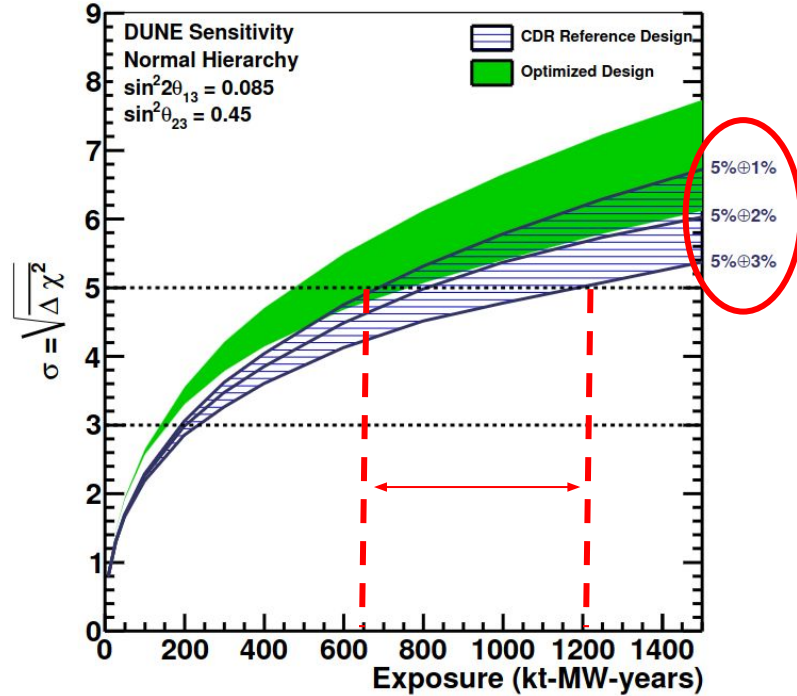
Deep Inelastic Scattering (DIS)

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



Future Experiments

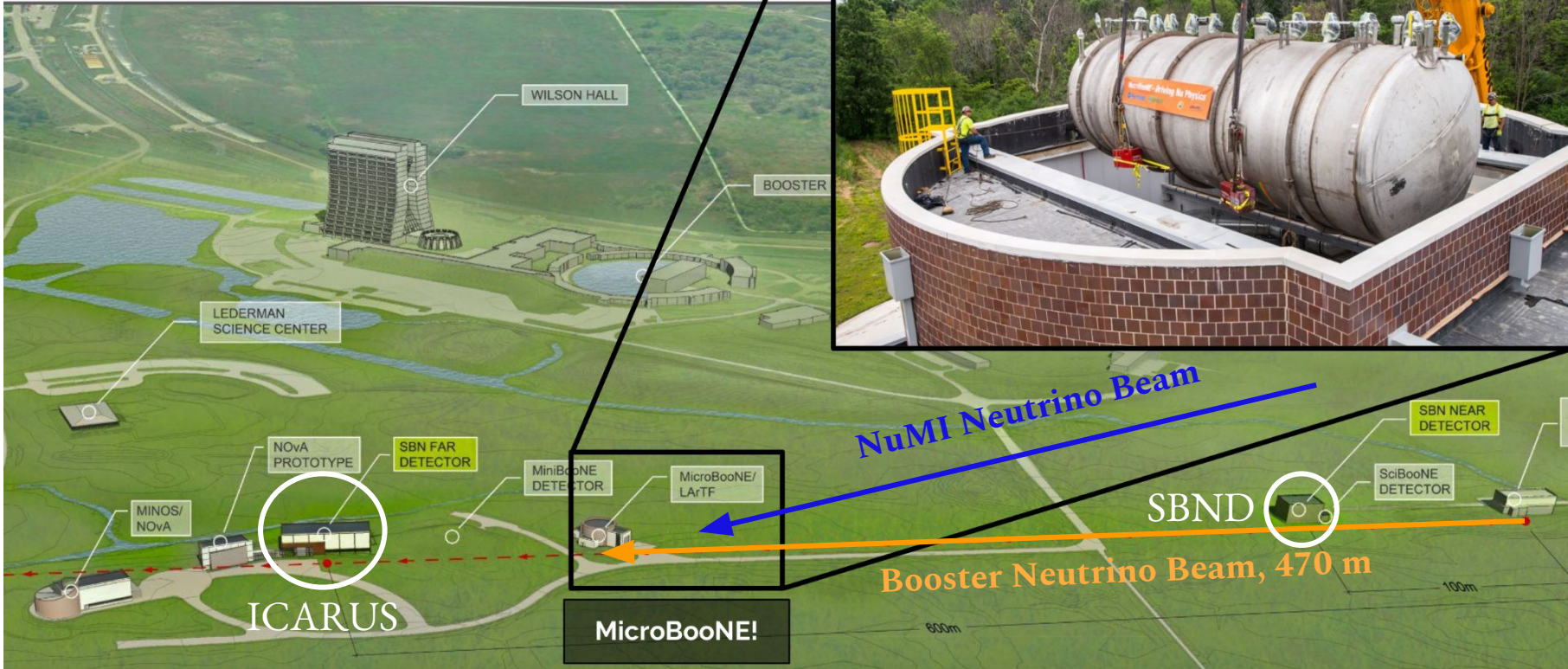
50% CP Violation Sensitivity



- Mismodeling can impact required run time of forthcoming flagship experiments
- But ... head start with Short-Baseline Neutrino (SBN) Program (MicroBooNE, SBND, ICARUS)

DUNE CDR, [arXiv:1512.06148](https://arxiv.org/abs/1512.06148)

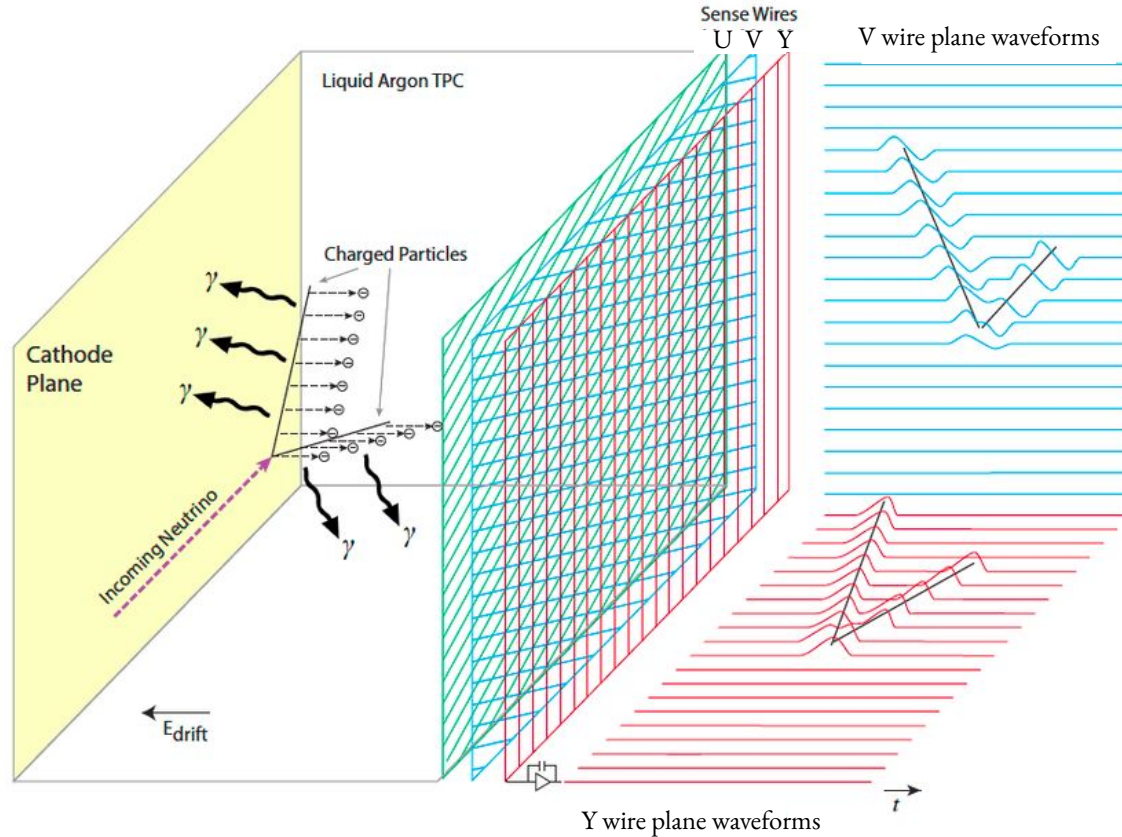
MicroBooNE@FNAL



85 tonne Liquid Argon Time Projection Chamber (LArTPC)

[JINST 12, P02017 \(2017\)](#)

LArTPC Operation Principle



MicroBooNE

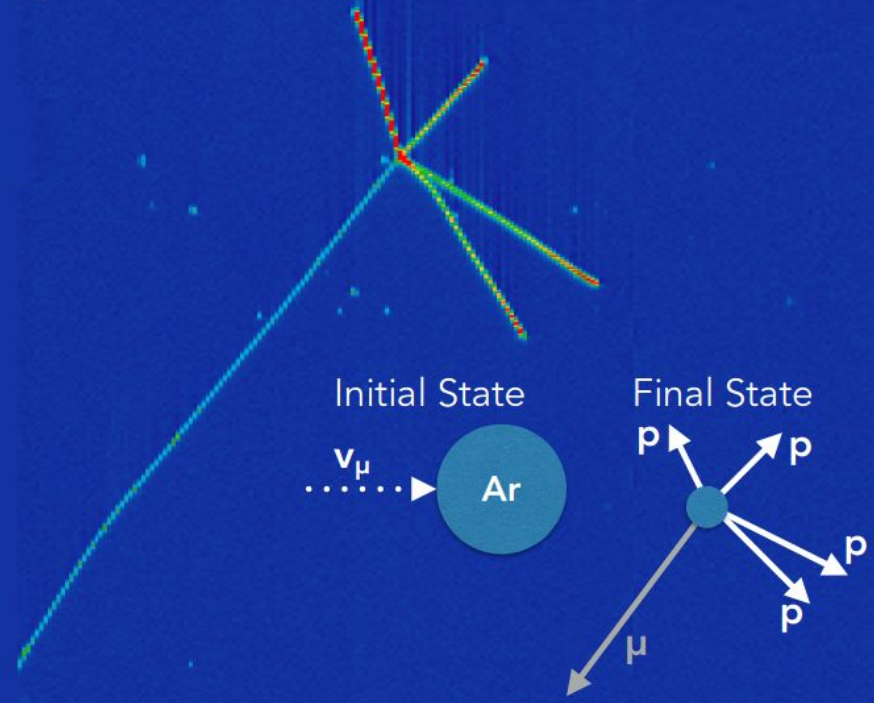
- 3 wire planes
- 8192 gold coated wires
- 3 mm wire spacing
- 32 PMTs

MicroBooNE Data Events



Color scale shows deposited charge

Time
Position in direction perpendicular to beam line
Position along beam direction
Wire



10 cm

BNB DATA : RUN 5211 EVENT 1225. FEBRUARY 29, 2016

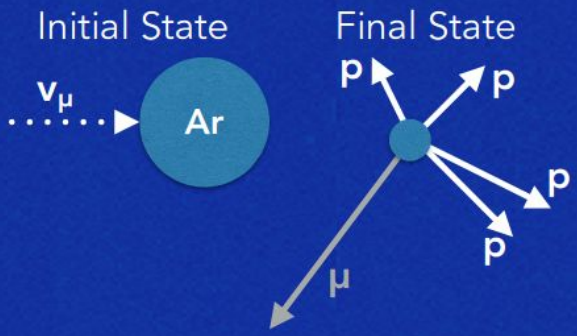
- Excellent spatial resolution
- Low detection thresholds
- Precise calorimetric information
- Powerful particle identification

MicroBooNE Data Events



Color scale shows deposited charge

Time
Position in direction perpendicular to beam line
Position along beam direction
Wire



10 cm

BNB DATA : RUN 5211 EVENT 1225. FEBRUARY 29, 2016

- Largest available neutrino-argon data set with ~500k recorded neutrino interactions
- 15 released and more than 30 active MicroBooNE cross section analyses
- Multiple topologies investigated

Already Public Results



CC inclusive

- $1D \nu_{\mu}$ CC inclusive @ BNB
[Phys. Rev. Lett. 123, 131801 \(2019\)](#)
- $1D \nu_{\mu}$ CC E_{ν} @ BNB
[Phys. Rev. Lett. 128, 151801 \(2022\)](#)
- $3D$ CC E_{ν} @ BNB
[arXiv:2307.06413](#), submitted to PRL
- $1D \nu_e$ CC inclusive @ NuMI
[Phys. Rev. D105, L051102 \(2022\)](#)
[Phys. Rev. D104, 052002 \(2021\)](#)

Pion production

- ν_{μ} NC π^0 @ BNB
[Phys. Rev. D 107, 012004 \(2023\)](#)

Rare channels

- η production @ BNB, submitted to PRL
[arXiv:2305.16249](#)
- Λ production @ NuMI
[Phys. Rev. Lett. 130, 231802 \(2023\)](#)

CC0 π

- $1D \nu_e$ CCNp0 π @ BNB
[Phys. Rev. D 106, L051102 \(2022\)](#)
- $1D$ & $2D \nu_{\mu}$ CC1p0 π Transverse Imbalance @ BNB
[Phys. Rev. Lett. 131, 101802 \(2023\)](#)
[Phys. Rev. D 108, 053002 \(2023\)](#)
- $1D$ & $2D \nu_{\mu}$ CC1p0 π Generalized Imbalance @ BNB
[arXiv:2310.06082](#), submitted to PRD
- $1D \nu_{\mu}$ CC1p0 π @ BNB
[Phys. Rev. Lett. 125, 201803 \(2020\)](#)
- $1D \nu_{\mu}$ CC2p @ BNB
[arXiv:2211.03734](#)
- $1D \nu_{\mu}$ CCNp0 π @ BNB
[Phys. Rev. D102, 112013 \(2020\)](#)

15 cross section publications
and way more to come!

Already Public Results



CC inclusive

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[Phys. Rev. D 108, 053002 \(2023\)](#)
- $1D$ & $2D \nu_{\mu}$ CC1p0 π Generalized Imbalance @ BNB
[arXiv:2310.06082](#), submitted to PRD
- $1D \nu_{\mu}$ CCNp0 π @ BNB
[Phys. Rev. D102, 112013 \(2020\)](#)
[arXiv:2211.03734](#)

Opportunity to extensively benchmark neutrino event generator predictions

15 cross section publications
and way more to come!

Nuclear Effects in Event Generators

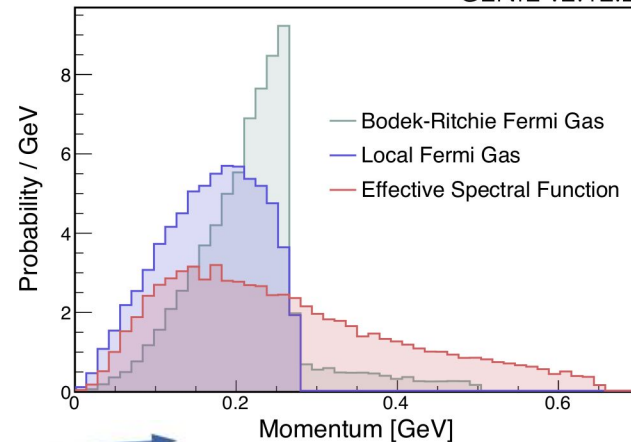
- Fermi motion
- Final state interactions
- Meson exchange currents
- ...

} Known unknowns that need to be accurately simulated

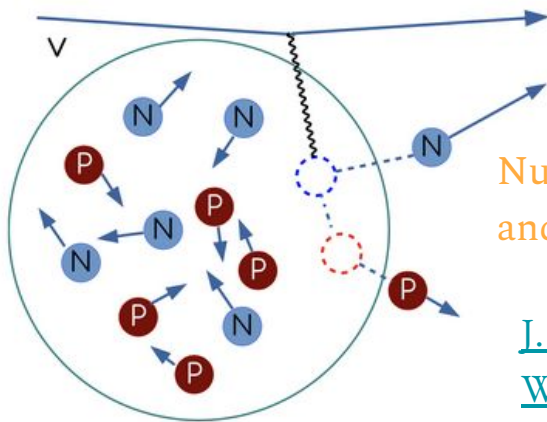
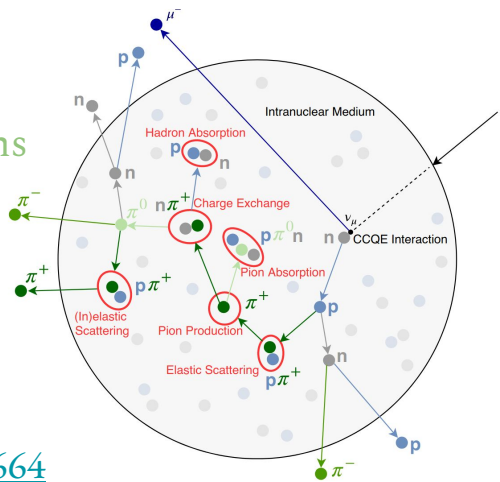
[Rev. Mod. Phys. 89, 045002 \(2017\)](#)

Struck nucleon motion in argon

GENIE v2.12.2



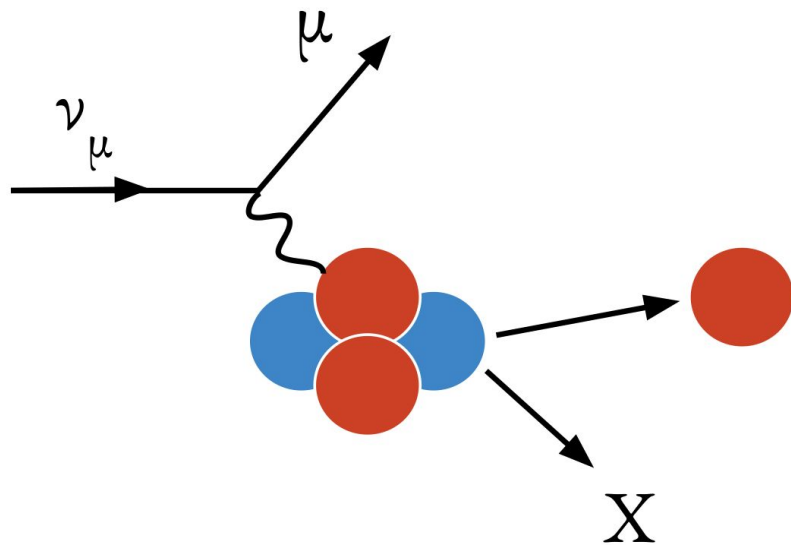
Hadron reinteractions



Nucleon-nucleon relative angle and momenta

[J. Wolcott](#)
[Wine & Cheese Seminar](#)

Double-Differential Single-Proton Knockout



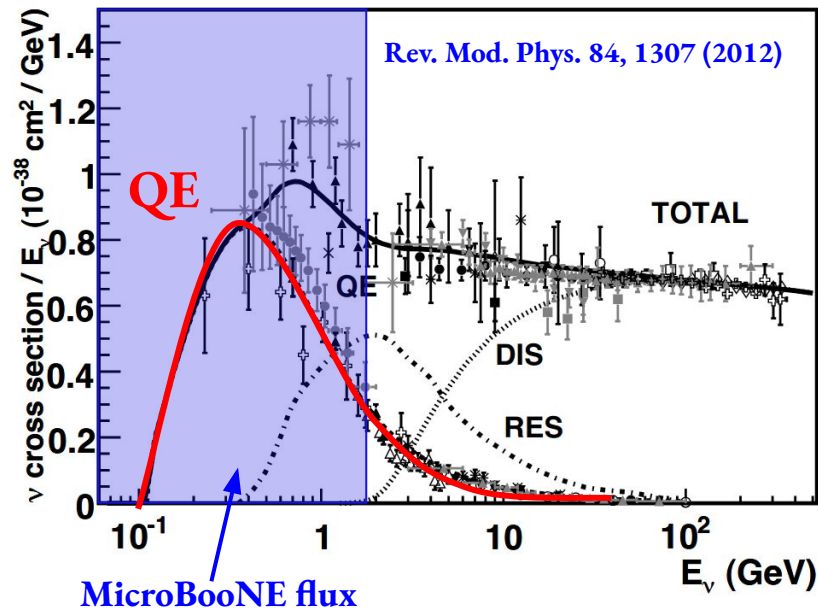
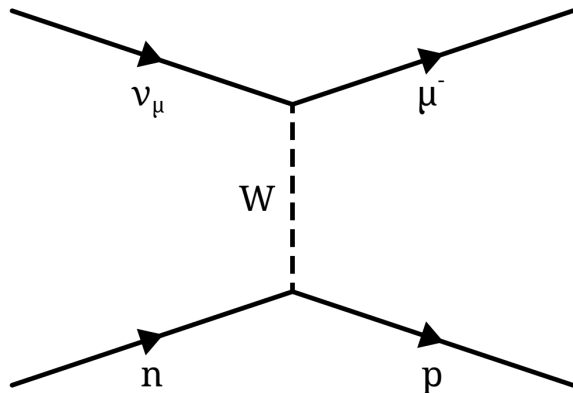
- First double-differential single-proton cross section measurement on argon
- Identified kinematic variables and phase-space regions with sensitivity to Fermi motion & final state interactions
- Uses ~50% of available MicroBooNE data sets & Booster Neutrino Beam (BNB)

[Phys. Rev. Lett. 131, 101802 \(2023\)](#)

[Phys. Rev. D 108, 053002 \(2023\)](#)

[arXiv:2310.06082](#)

Single-Proton Knockout



- Dominated by Charged Current Quasi-elastic (CCQE) interactions
- Simple single muon-proton events
- Dominant at MicroBooNE energies

CC1p0 π Quasielastic-like Signal Definition

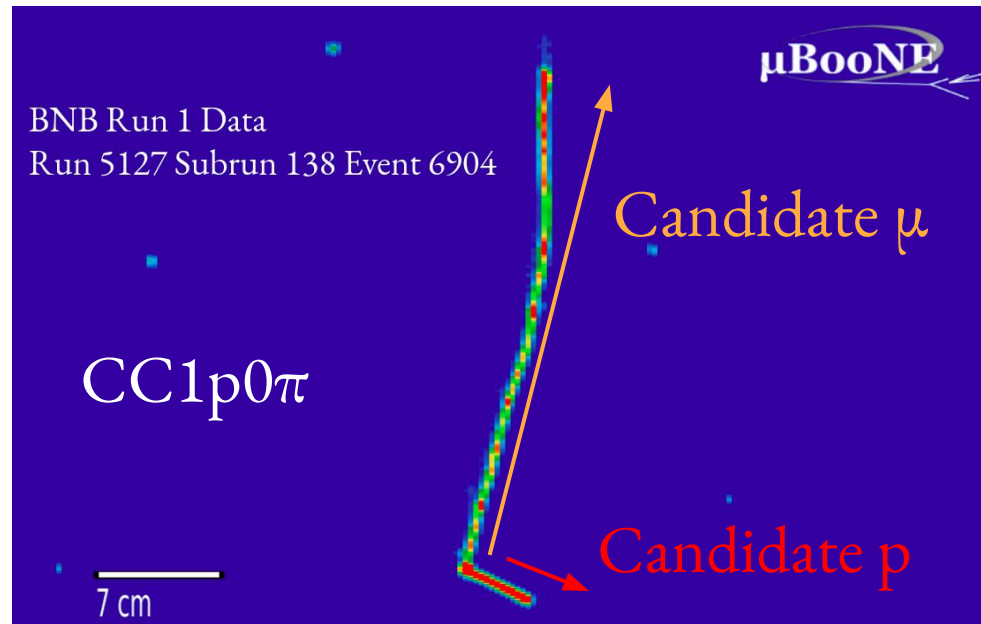
Ranges driven by minimum track length, track containment, hadronic reinteractions, and systematics

- 1 muon
 $100 < P_{\mu} < 1200$ MeV/c
- 1 proton
 $300 < P_p < 1000$ MeV/c
- No π^{\pm} with $P_{\pi} > 70$ MeV/c
- No π^0 or heavier mesons
- Any number of neutrons

9051 CC1p0 π candidate data events

CC1p0 π ~10% efficiency

~70% purity



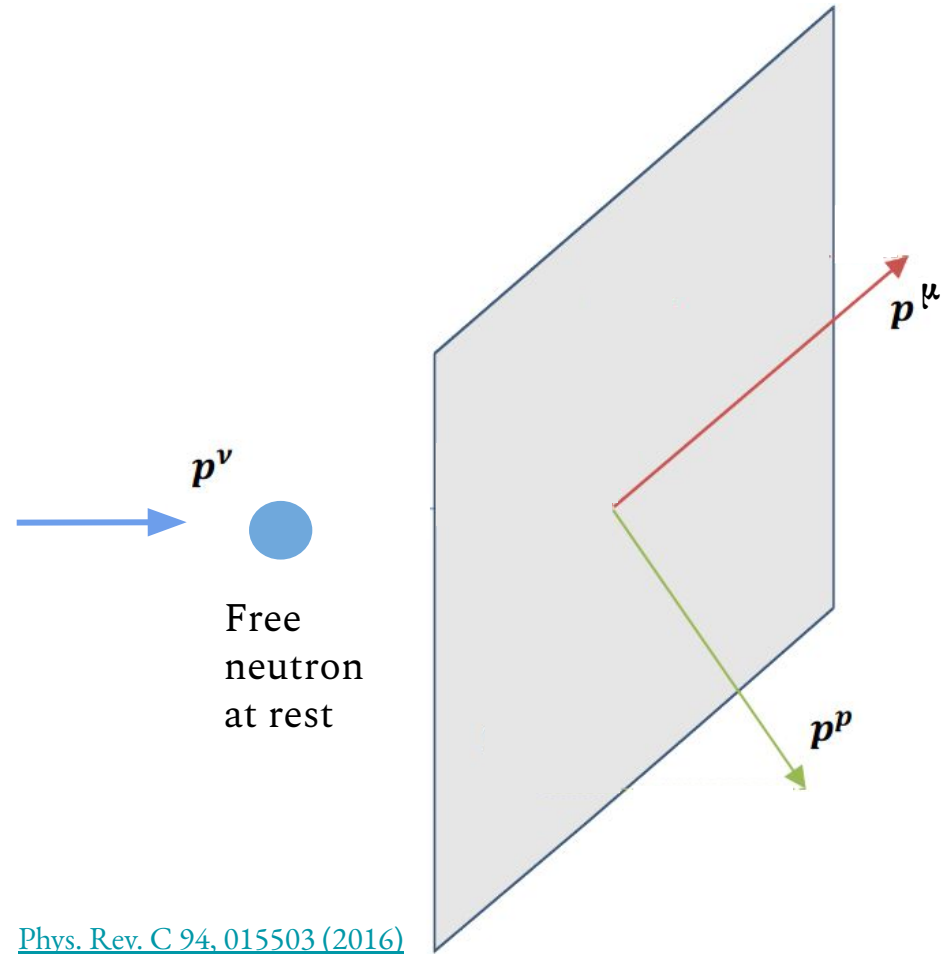
[Phys. Rev. Lett. 131, 101802 \(2023\)](#)

[Phys. Rev. D 108, 053002 \(2023\)](#)

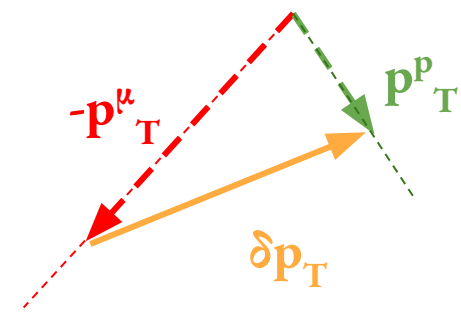
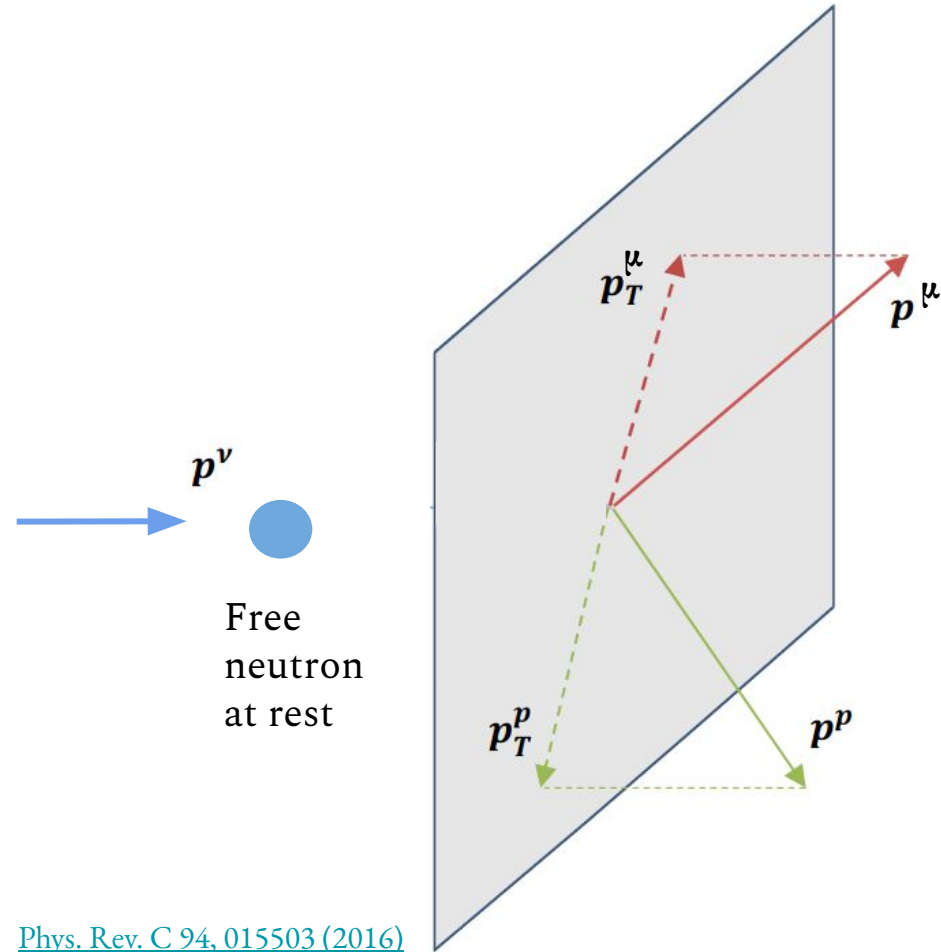
* [Phys. Rev. D 105, 072001 \(2022\)](#)

MC: GENIE v3.0.6 G18_10a_02_11b + tune*
Nieves QE & MEC, Berger Sehgal RES

Transverse Kinematic Imbalance (TKI)



Transverse Kinematic Imbalance (TKI)

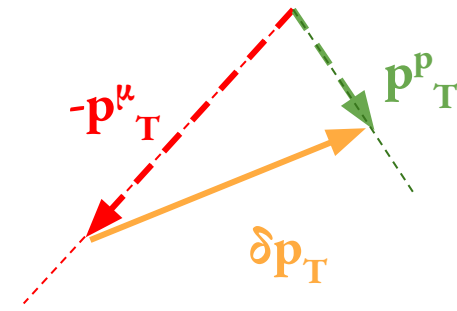
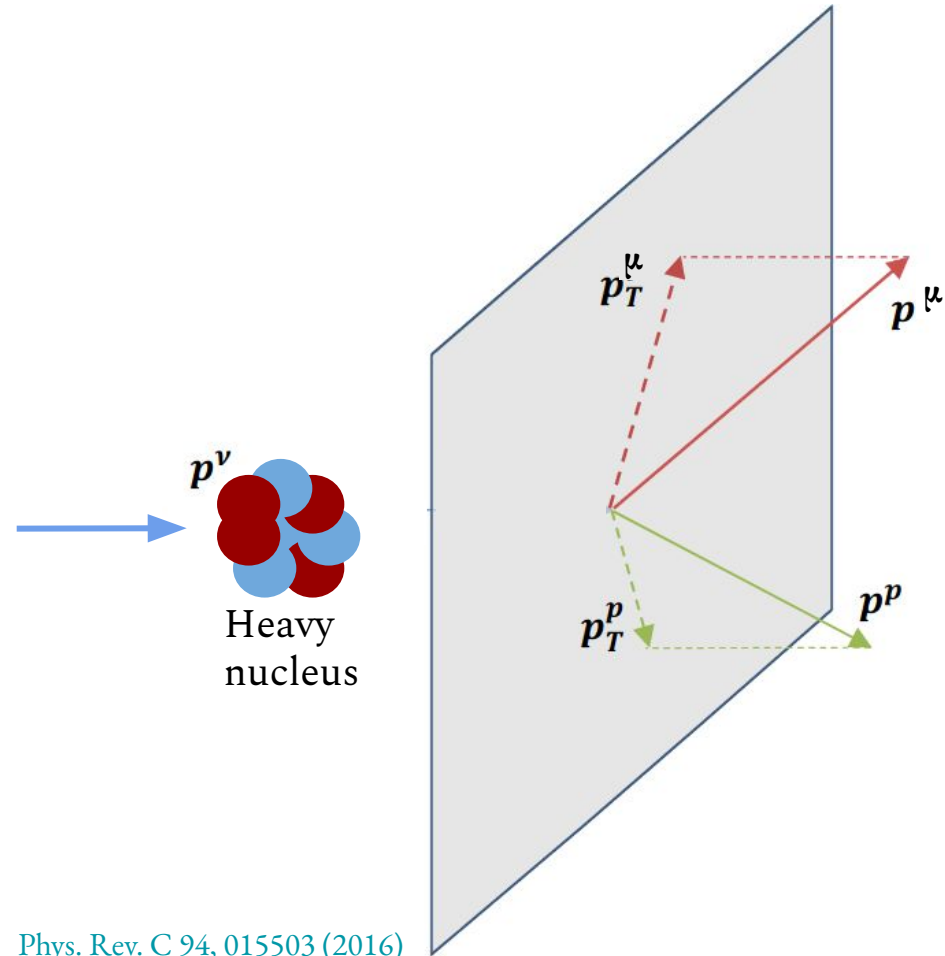


Transverse missing momentum

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

Transverse projections
equal and opposite due to
momentum conservation

Transverse Kinematic Imbalance (TKI)

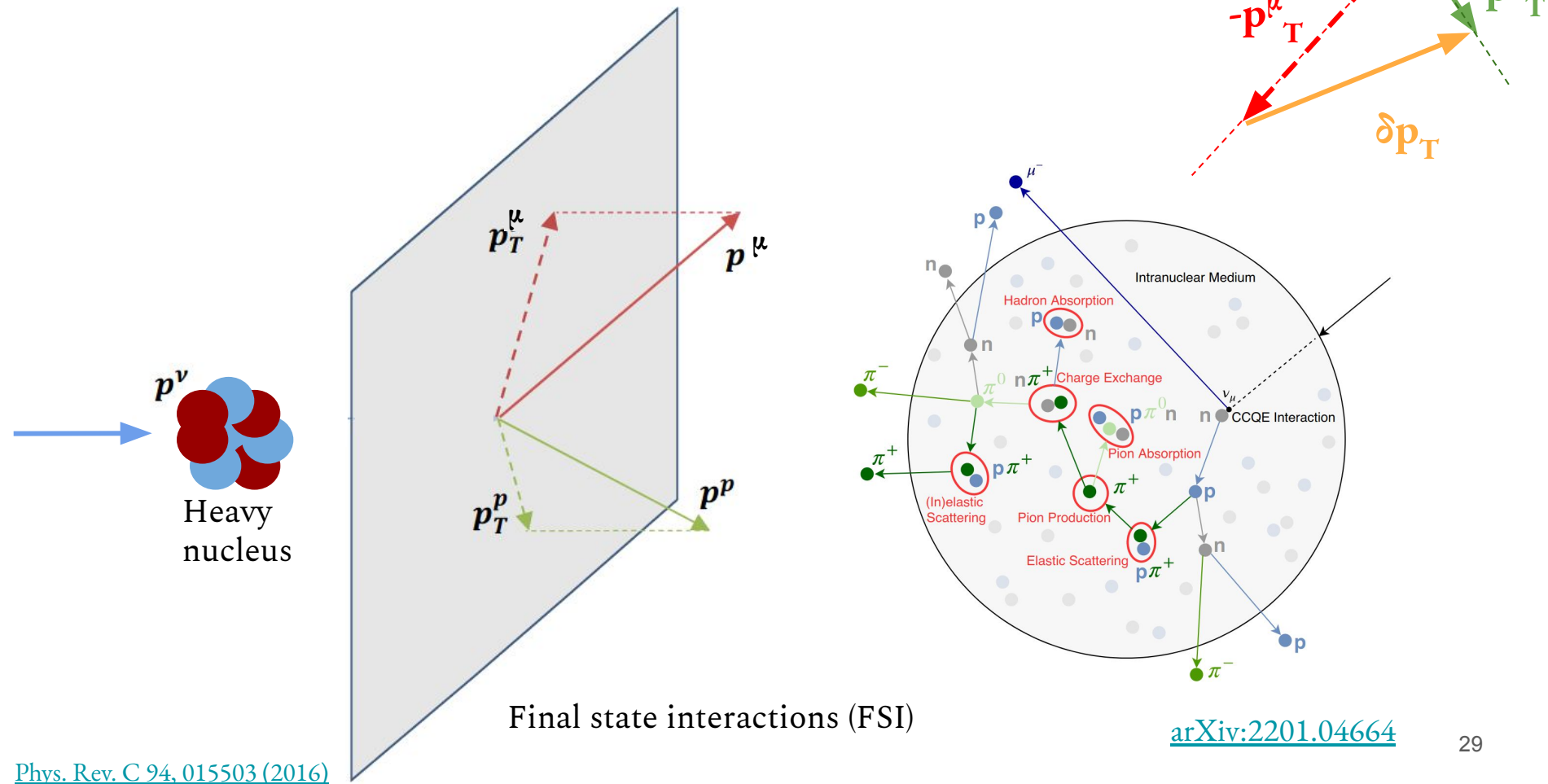


Transverse missing momentum

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

Broad distribution due to initial nucleon motion and other nuclear effects

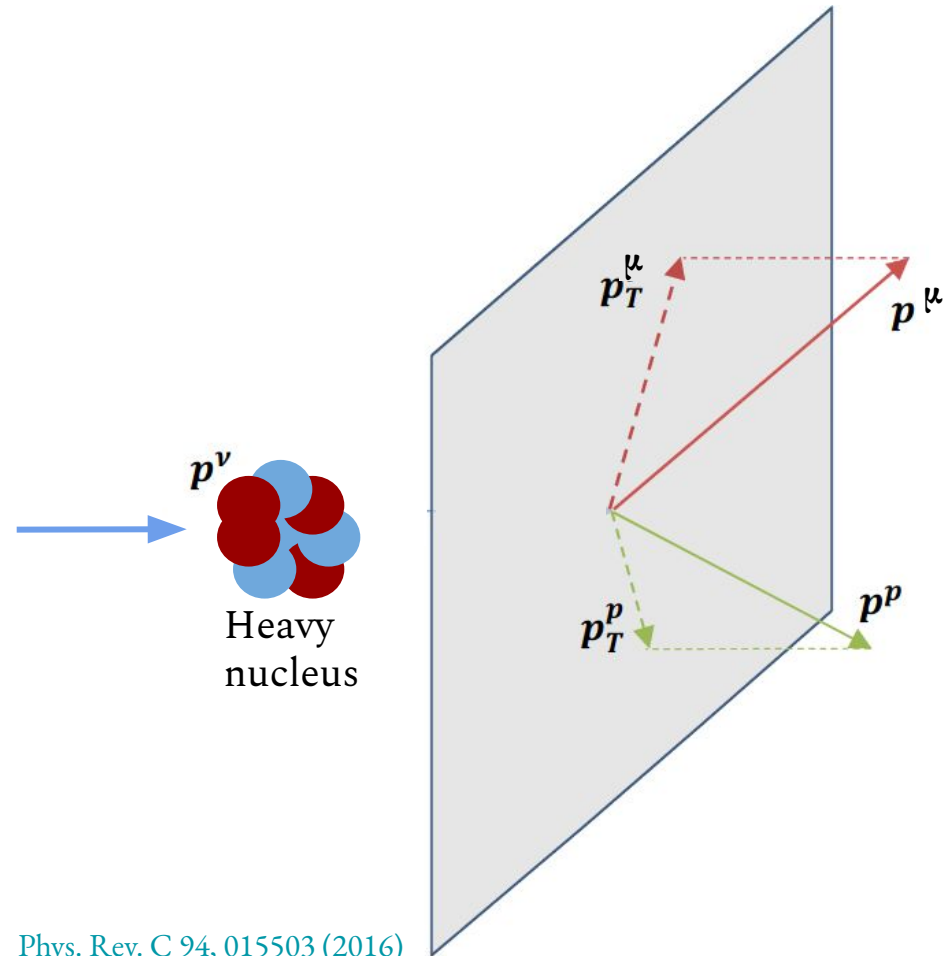
Transverse Kinematic Imbalance (TKI)



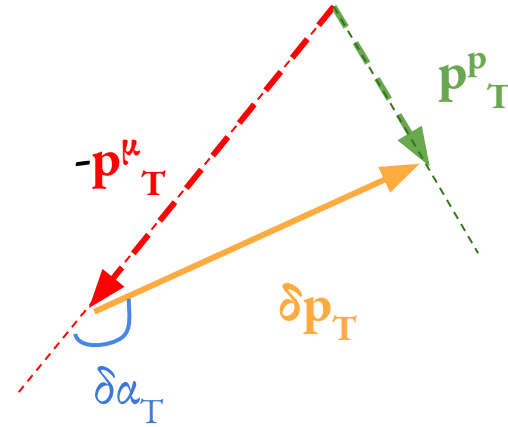
Final state interactions (FSI)

[arXiv:2201.04664](https://arxiv.org/abs/2201.04664)

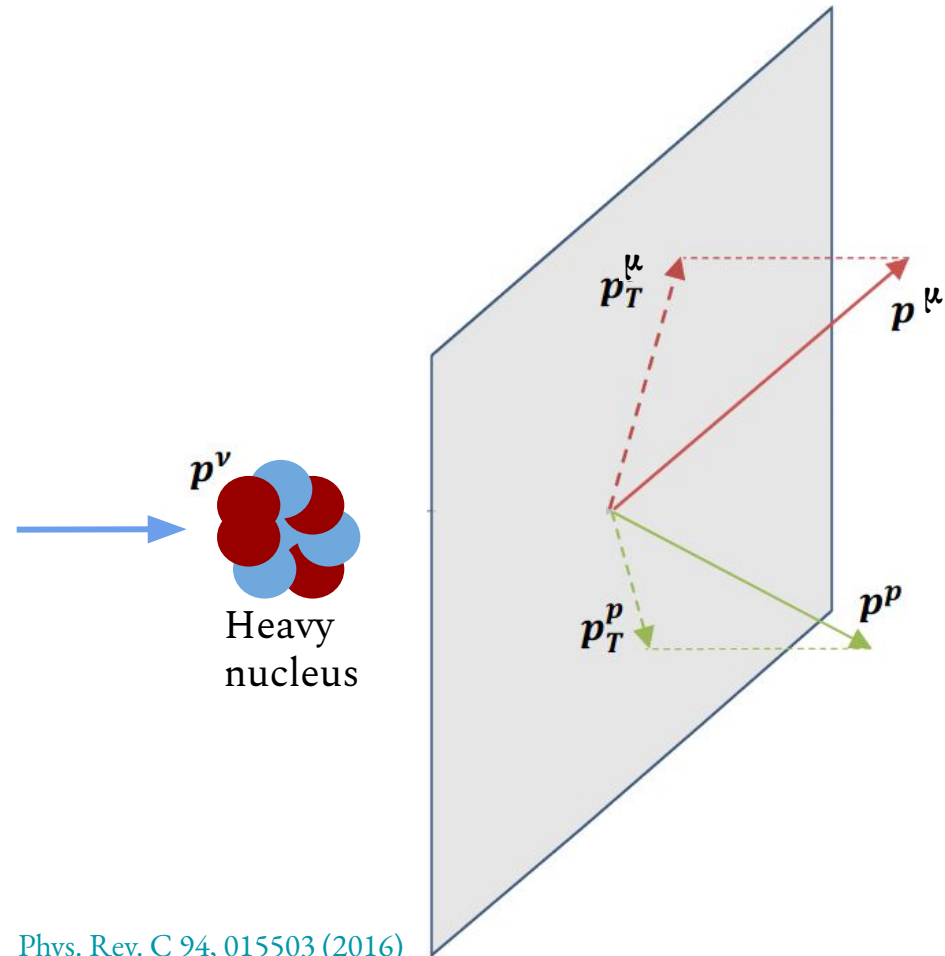
Transverse Kinematic Imbalance (TKI)



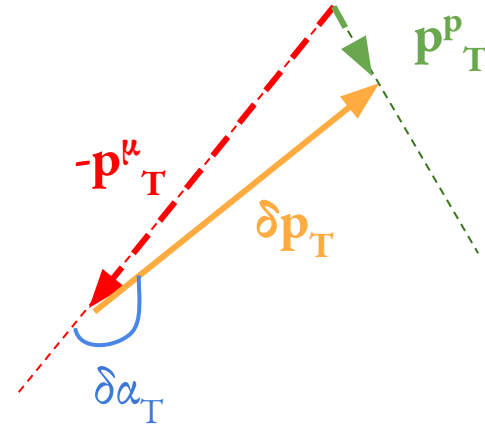
Orientation of the imbalance ($\delta\alpha_T$) also meaningful



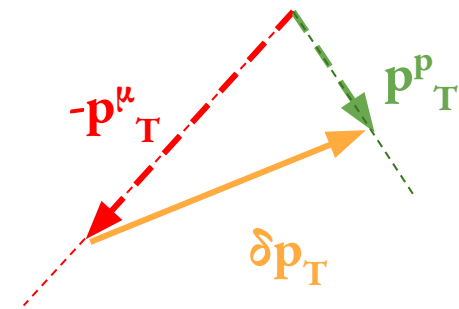
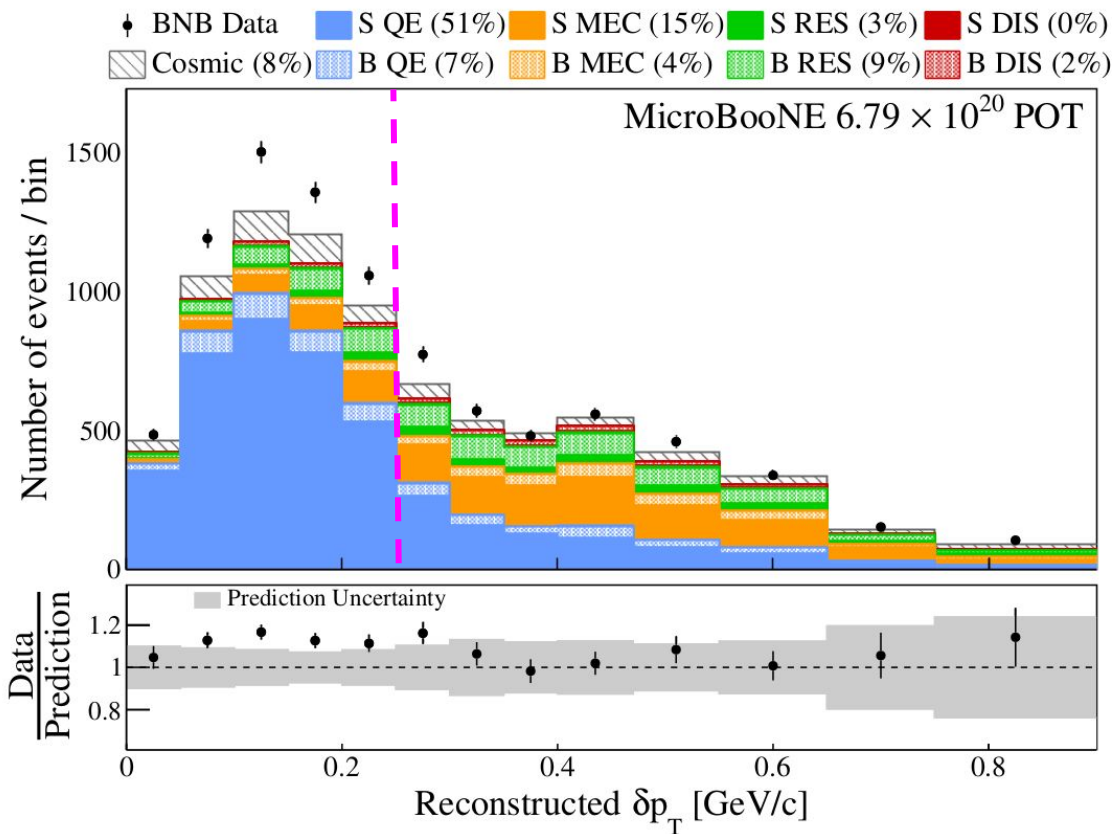
Transverse Kinematic Imbalance (TKI)



Lower proton momentum due to FSI leads to larger $\delta\alpha_T$ (closer to 180°)



Transverse Missing Momentum δp_T



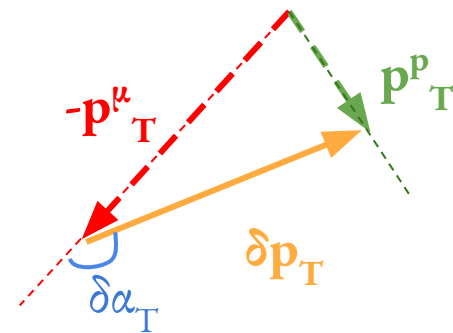
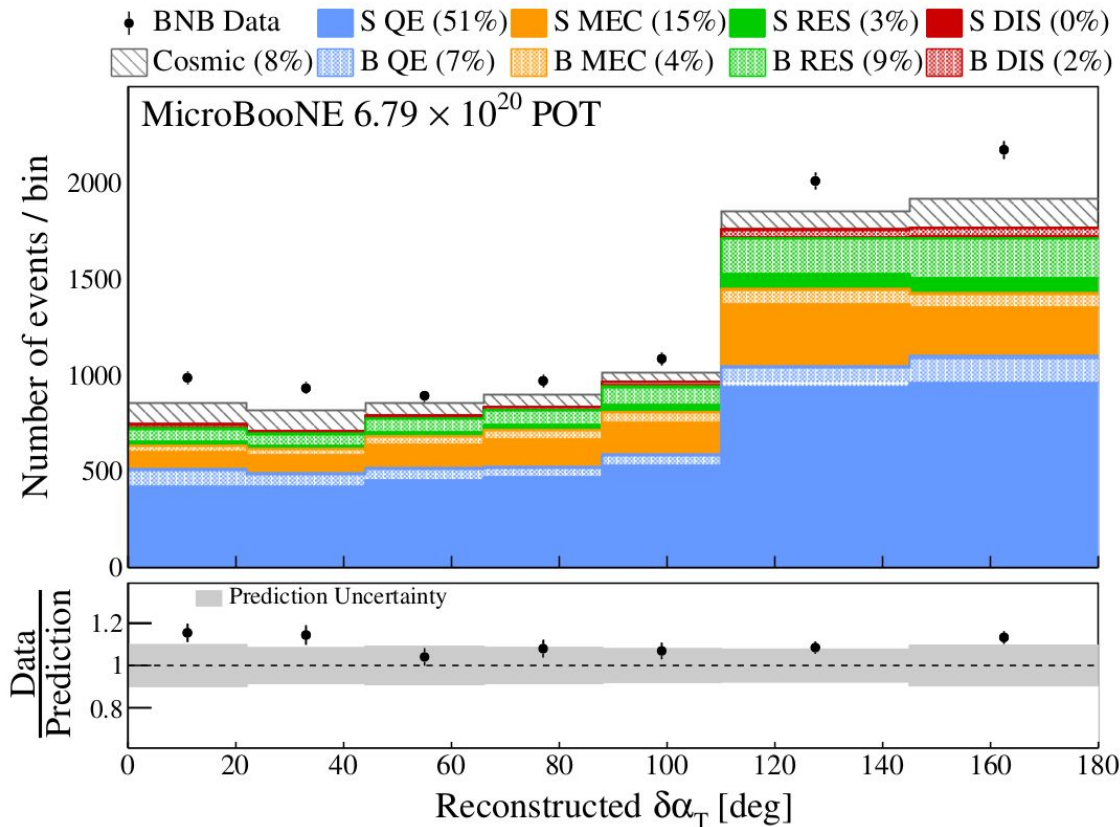
- S = Signal, B = Background
- **QE** dominance in peak below Fermi momentum (~ 250 MeV/c)
- **MEC/RES** mainly in high momentum tail

[Phys. Rev. D 108, 053002 \(2023\)](#)

* [Phys. Rev. D 105, 072001 \(2022\)](#)

GENIE v3.0.6 G18_10a_02_11b + tune*
Nieves QE & MEC, Berger Sehgal RES

Transverse Orientation $\delta\alpha_T$



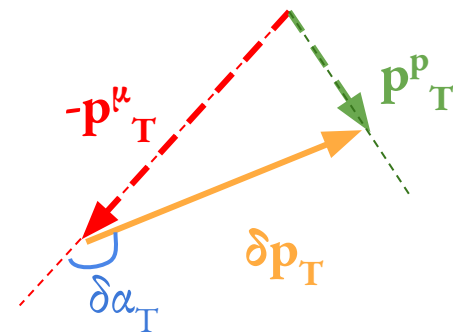
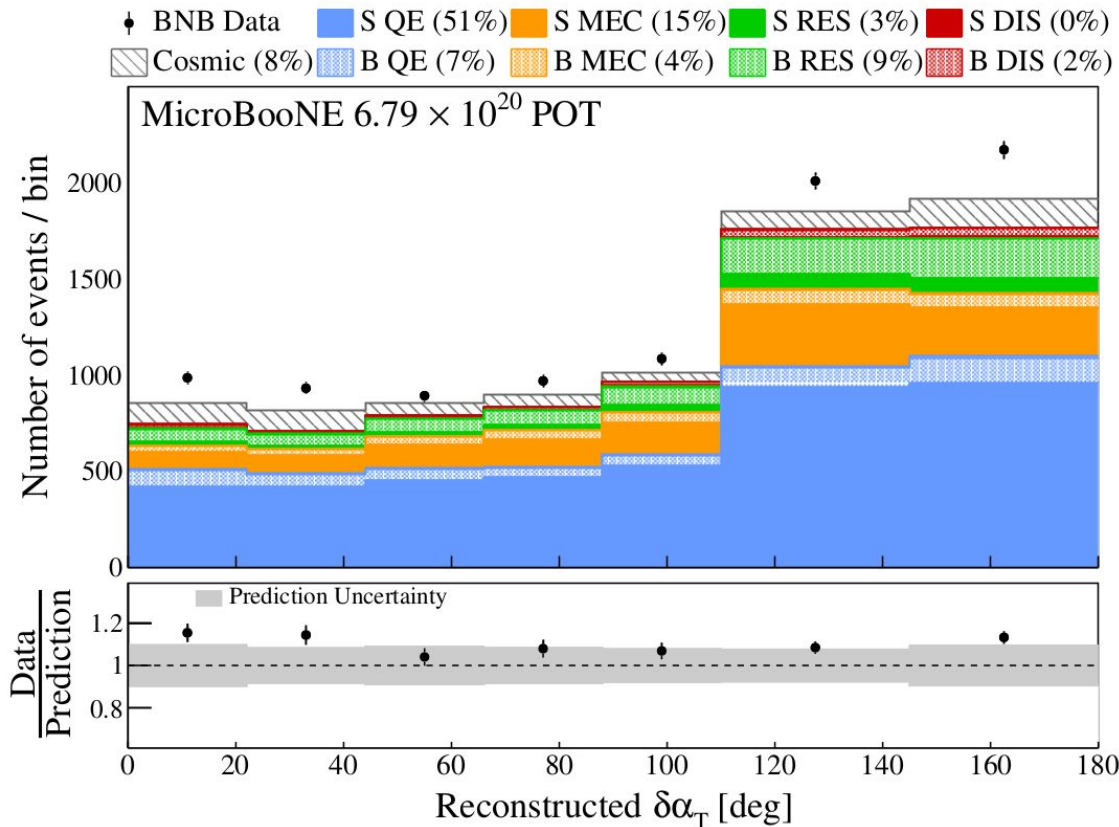
- $\delta\alpha_T$ asymmetry due to proton FSI
- **MEC/RES** fractional contribution enhanced in $\sim 180^\circ$ region

[Phys. Rev. D 108, 053002 \(2023\)](#)

* [Phys. Rev. D 105, 072001 \(2022\)](#)

GENIE v3.0.6 G18_10a_02_11b + tune*
Nieves QE & MEC, Berger Sehgal RES

Transverse Orientation $\delta\alpha_T$



Need to move from event distributions to cross sections \rightarrow *unfolding*

[Phys. Rev. D 108, 053002 \(2023\)](#)

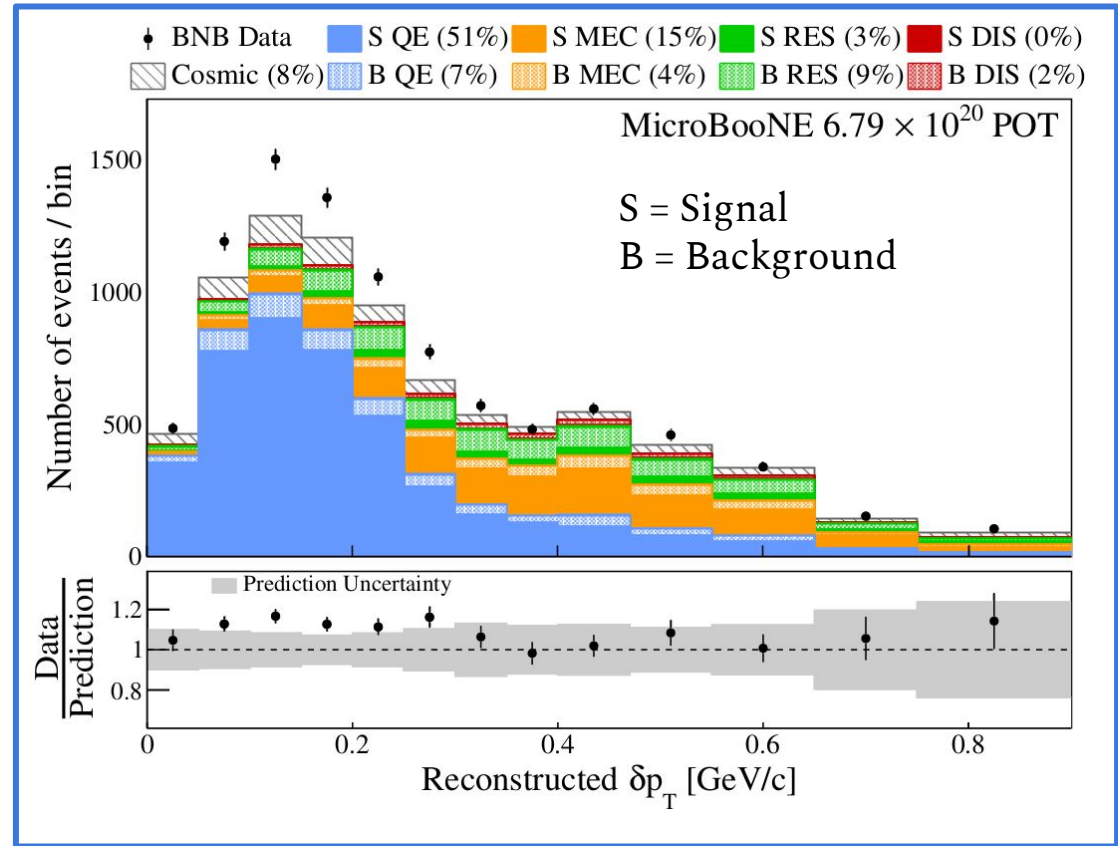
* [Phys. Rev. D 105, 072001 \(2022\)](#)

Cross Section Extraction with Wiener SVD Unfolding

[JINST 12 P10002 \(2017\)](#)

Input Quantities

- Measurement (Data)
- Background (Cosmics + MC)
- Response Matrix (MC)
- Total Covariance Matrix (MC)



Cross Section Extraction with Wiener SVD Unfolding

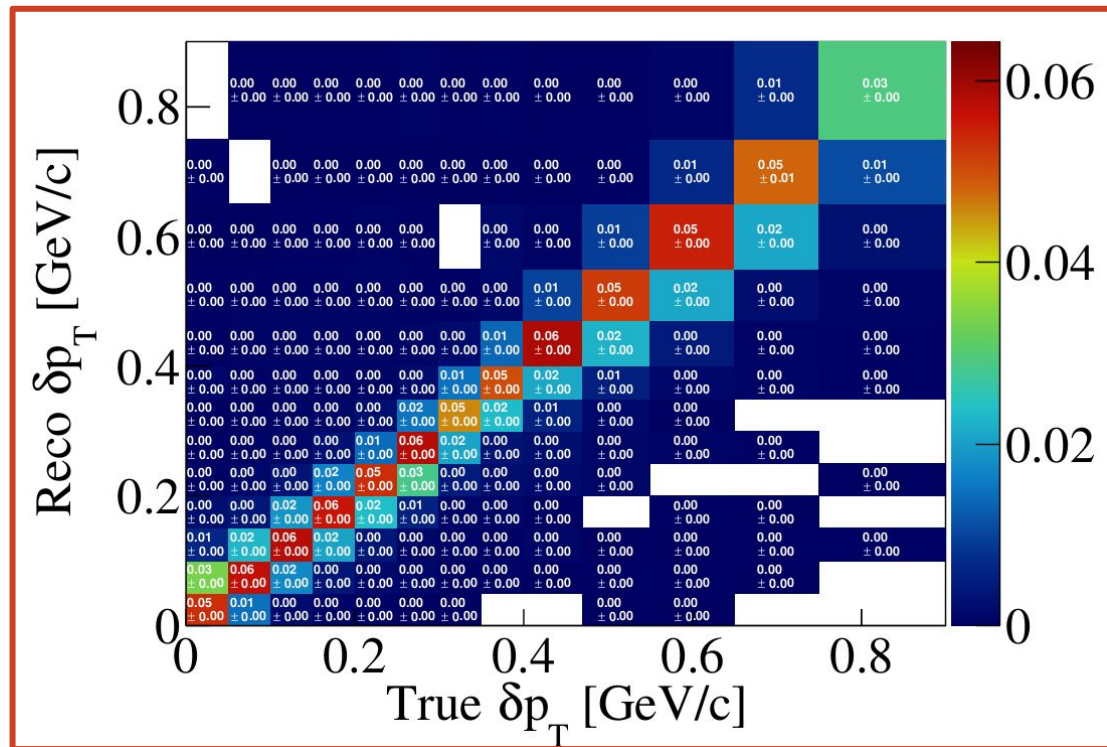
[JINST 12 P10002 \(2017\)](#)

Input Quantities

- Measurement (Data)
- Background (MC)
- Response Matrix (MC)
- Total Covariance Matrix (MC)

Probability that a generated event is reconstructed and selected

Diagonal matrix with flat ~6% efficiency



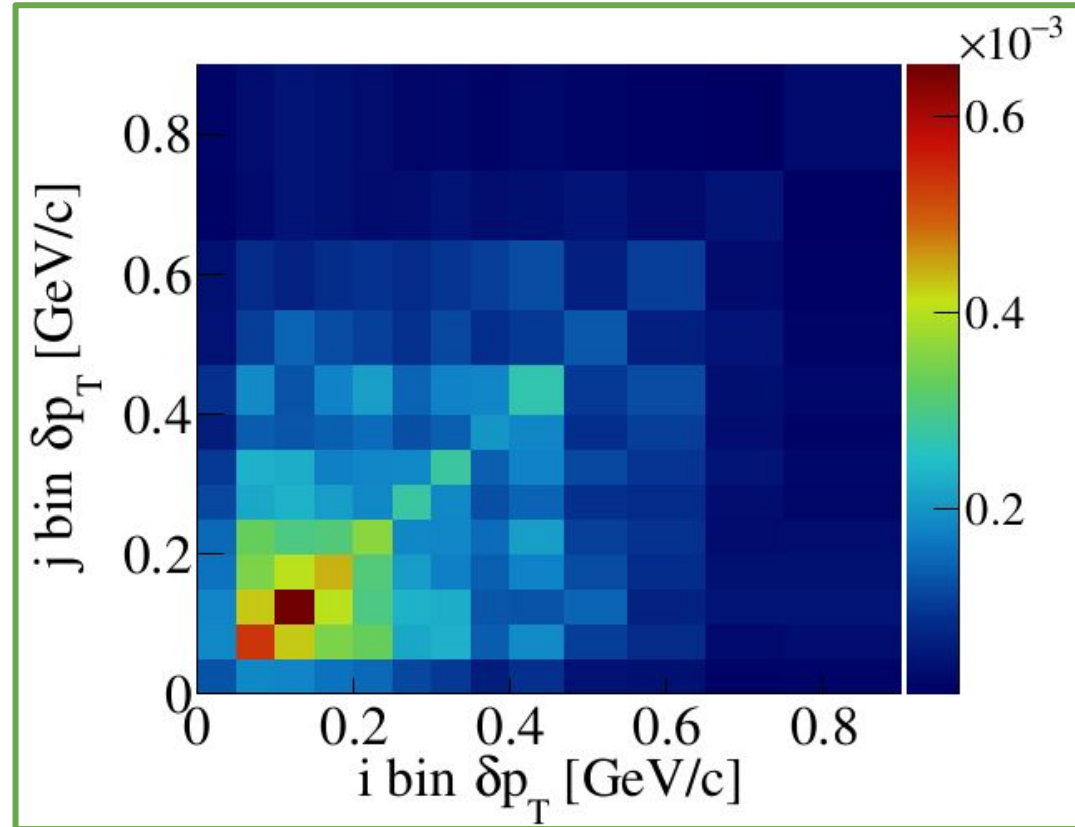
Cross Section Extraction with Wiener SVD Unfolding

[JINST 12 P10002 \(2017\)](#)

Input Quantities

- Measurement (Data)
- Background (MC)
- Response Matrix (MC)
- Total Covariance Matrix (MC)

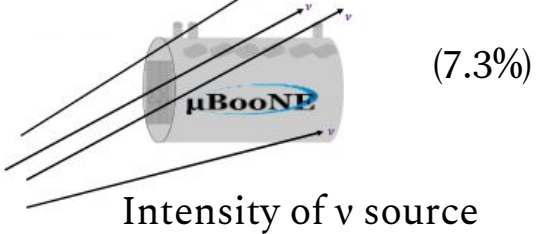
Includes information on statistical and systematic uncertainties



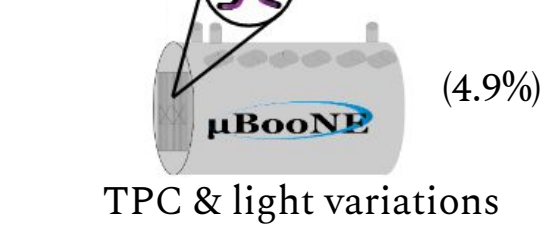
[Phys. Rev. D 108, 053002 \(2023\)](#)

Uncertainties

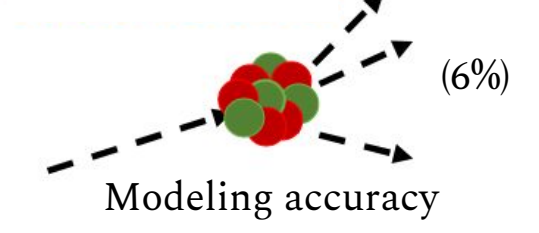
Flux



Detector



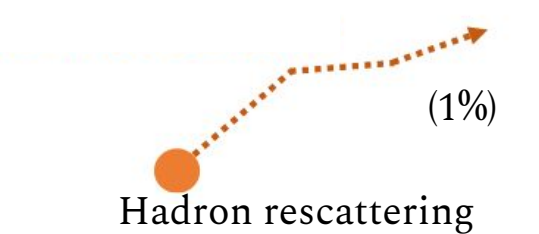
Cross section



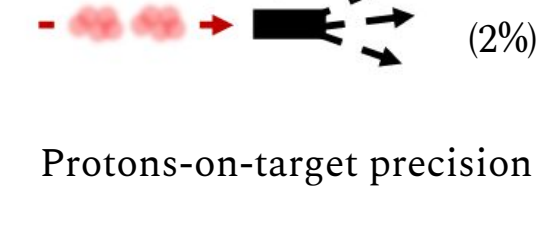
Dirt



Reinteractions



POT counting



- + Statistical (1.5%)
- + Number of argon targets (1%)

Total (11%)

Systematics-dominated analysis

Cross Section Extraction with Wiener SVD Unfolding

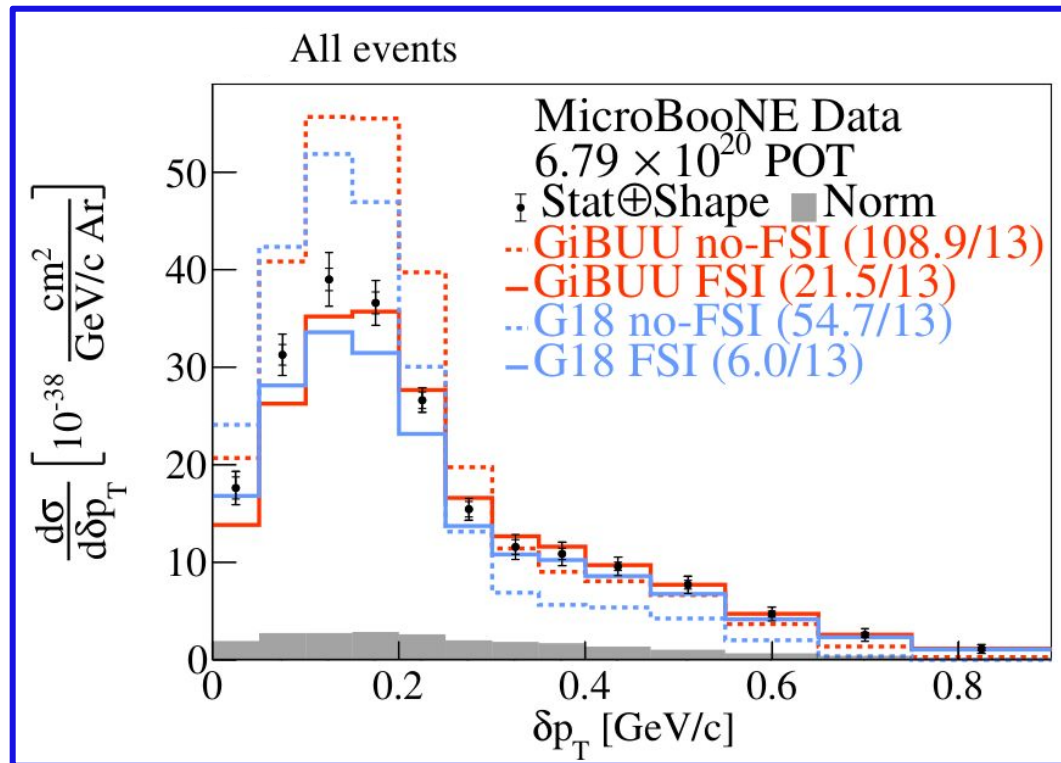
[JINST 12 P10002 \(2017\)](#)

Output quantities in regularized space

- Unfolded data spectrum

- Smearing Matrix A_C

*Applied on theory predictions and included in data release



Cross Section Extraction with Wiener SVD Unfolding

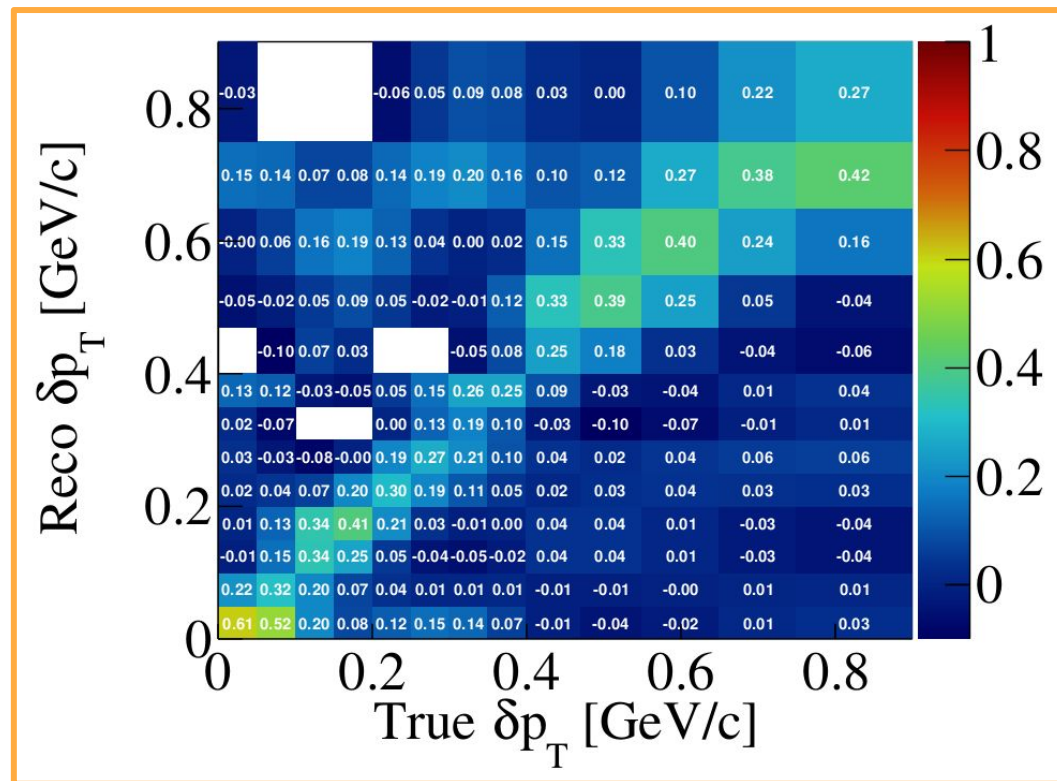
[JINST 12 P10002 \(2017\)](#)

Output quantities in regularized space

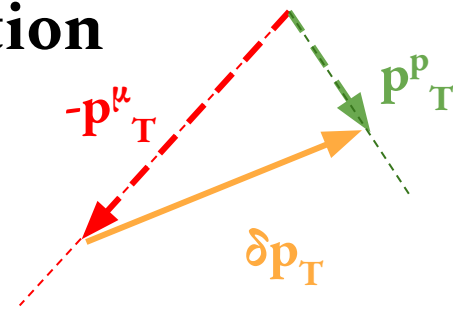
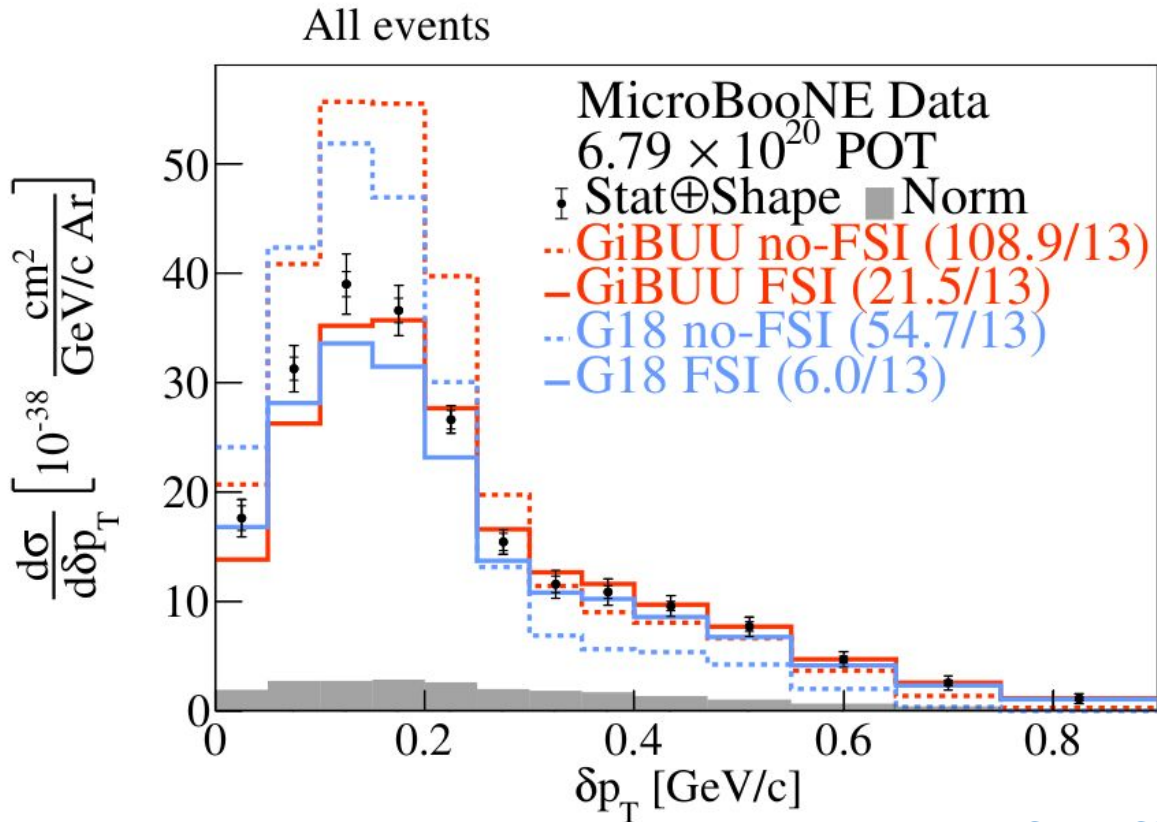
- Unfolded data spectrum

- Smearing Matrix A_C

*Applied on theory predictions and included in data release



Transverse Missing Momentum δp_T Cross Section



- First neutrino-argon differential cross section in δp_T
- FSI reduces strength of the peak
- Small changes in the tail
- Data favors FSI addition

[Phys. Rev. Lett. 131, 101802 \(2023\)](#)

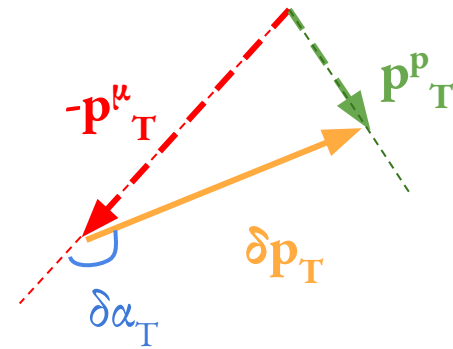
* [Phys. Rev. D 105, 072001 \(2022\)](#)

G18 = GENIE v3.0.6 G18_10a_02_11b + tune*

GiBUU = GiBUU 2021

High Statistics → Into the Multiverse!

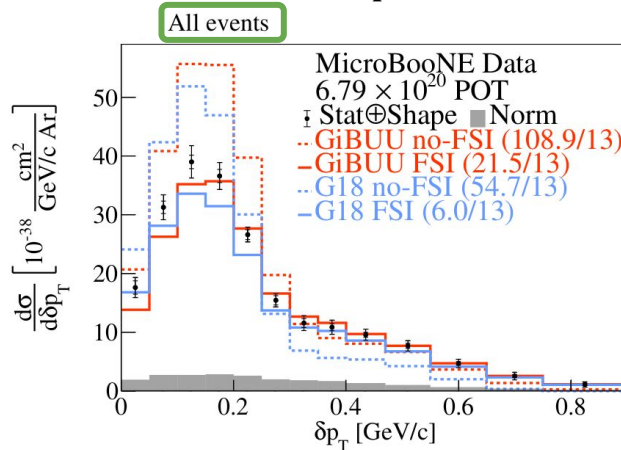
- **Extension to 2D** for the first time on argon
- Probe regions with greater model discrimination power



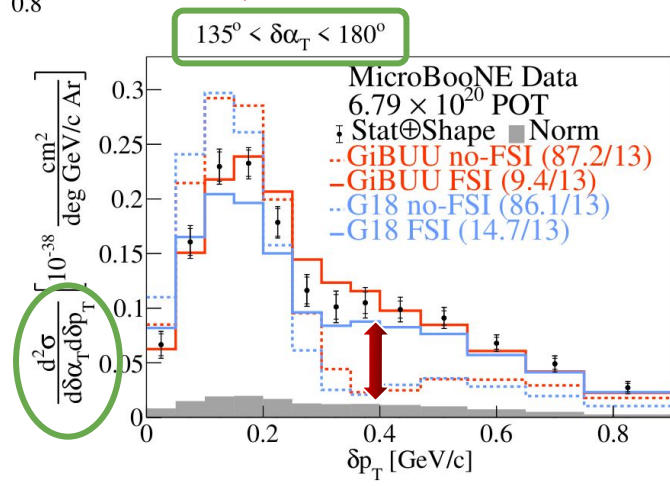
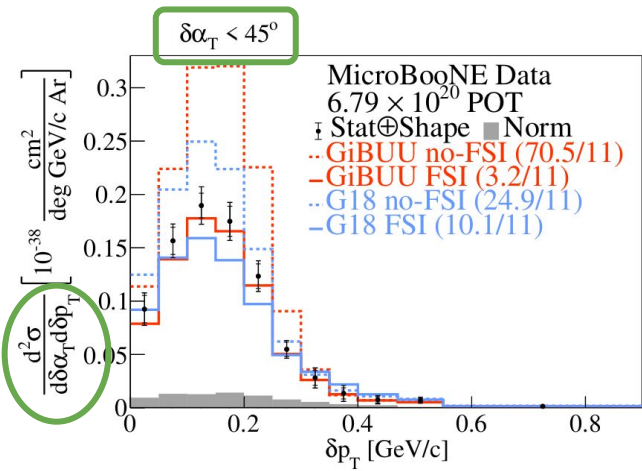
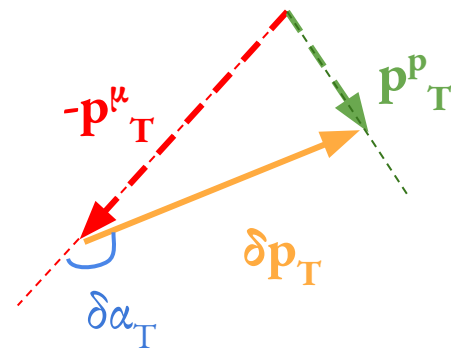
High Statistics → Into the Multiverse!

- **Extension to 2D** for the first time on argon
- Probe regions with greater model discrimination power

QE-dominated

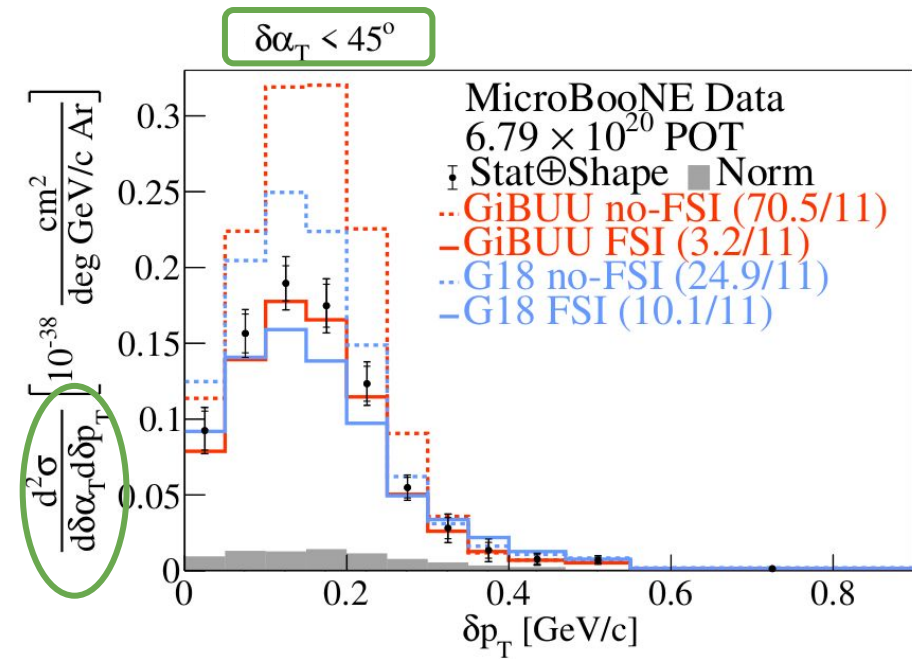
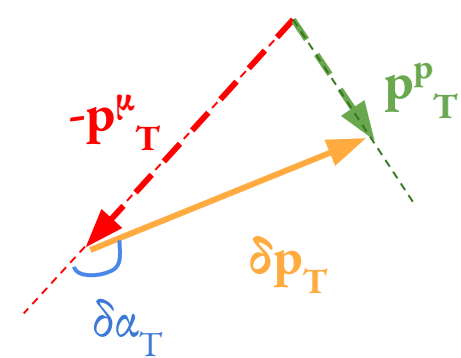


MEC/RES/FSI-dominated



High Statistics → Into the Multiverse!

QE-dominated region



- No high transverse missing momentum tail
- Ideal part of phase-space to study Fermi motion
- Results consistent with local Fermi gas distribution

[Phys. Rev. Lett. 131, 101802 \(2023\)](#)

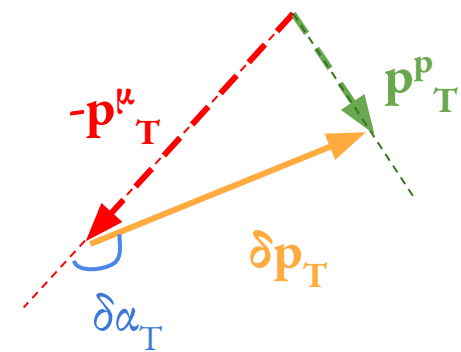
* [Phys. Rev. D 105, 072001 \(2022\)](#)

G18 = GENIE v3.0.6 G18_10a_02_11b + tune*

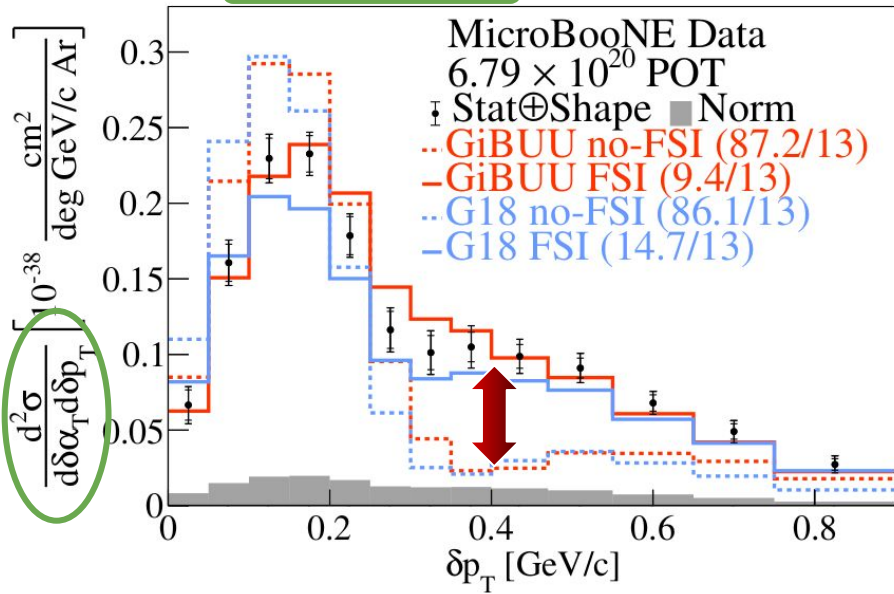
GiBUU = GiBUU 2021

High Statistics → Into the Multiverse!

MEC/RES/FSI-dominated



$135^\circ < \delta\alpha_T < 180^\circ$



- FSI predictions in good agreement with data
- Minimal no-FSI contributions at high δp_T
- High $\delta\alpha_T$ & high δp_T part of phase-space ideal to test FSI / multinucleon effects

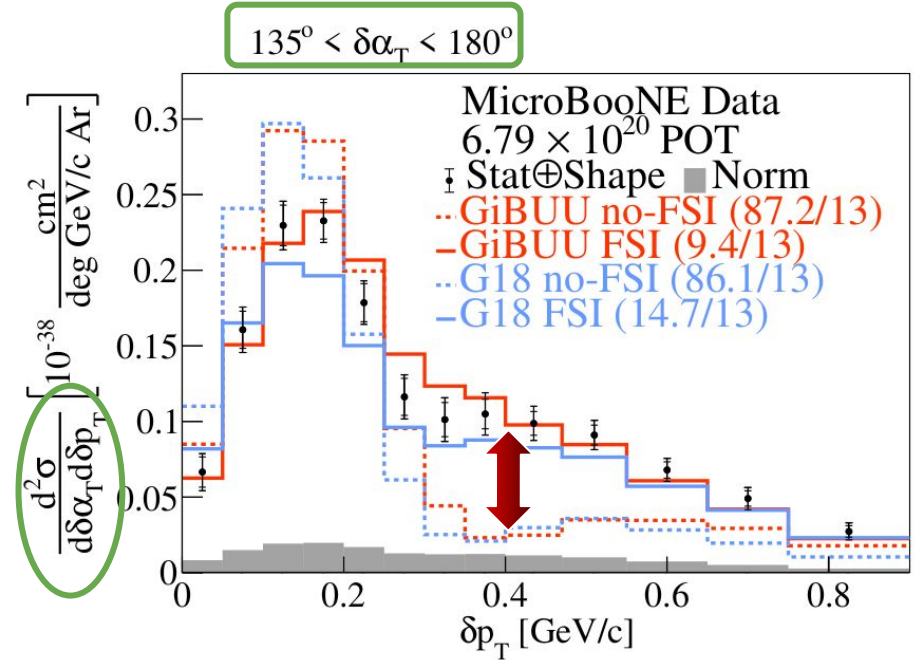
[Phys. Rev. Lett. 131, 101802 \(2023\)](#)

* [Phys. Rev. D 105, 072001 \(2022\)](#)

G18 = GENIE v3.0.6 G18_10a_02_11b + tune*
GiBUU = GiBUU 2021

CC1p0π TKI Summary

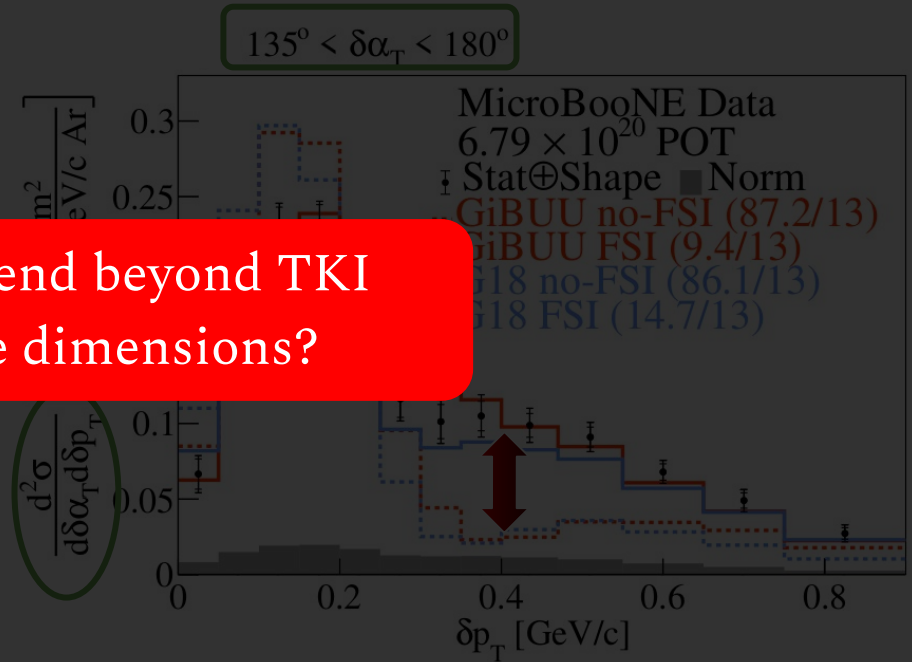
- First single- and double- differential neutrino-argon cross section measurements in TKI
- Fermi motion studied with 2D measurement in δp_T with $\delta\alpha_T < 45^\circ$
- FSI & multinucleon effects studied with 2D measurement in δp_T with $135^\circ < \delta\alpha_T < 180^\circ$
- Way more single- and double-differential results in [Phys. Rev. Lett. 131, 101802 \(2023\)](#) and [Phys. Rev. D 108, 053002 \(2023\)](#)!



CC1p0π TKI Summary

- First single- and double- differential neutrino-argon cross section measurements in TKI
- Fermi motion studied with 2D measurement in δp_T with $\delta\alpha_T < 45^\circ$
- FSI & multinucleon effects studied with 2D measurement in δp_T with $135^\circ < \delta\alpha_T < 180^\circ$
- Way more single- and double-differential results in [Phys. Rev. Lett. 131, 101802 \(2023\)](#) and [Phys. Rev. D 108, 053002 \(2023\)](#)!

But why not extend beyond TKI
by using three dimensions?



Generalized Kinematic Imbalance (GKI)

[Phys. Rev. C 95, 065501 \(2017\)](#)

[arXiv:2310.06082](#)

- Extension to 3D by considering longitudinal component of missing momentum and calorimetric assumption on the incoming energy

Generalized Kinematic Imbalance (GKI)

[Phys. Rev. C 95, 065501 \(2017\)](#)

[arXiv:2310.06082](#)

- Extension to 3D by considering longitudinal component of missing momentum and calorimetric assumption on the incoming energy

BE = 30.9 MeV

$$E_{\text{cal}} = E_{\mu} + K_p + B$$

$$\vec{q} = E_{\text{cal}} \hat{z} - \vec{p}_{\mu}$$

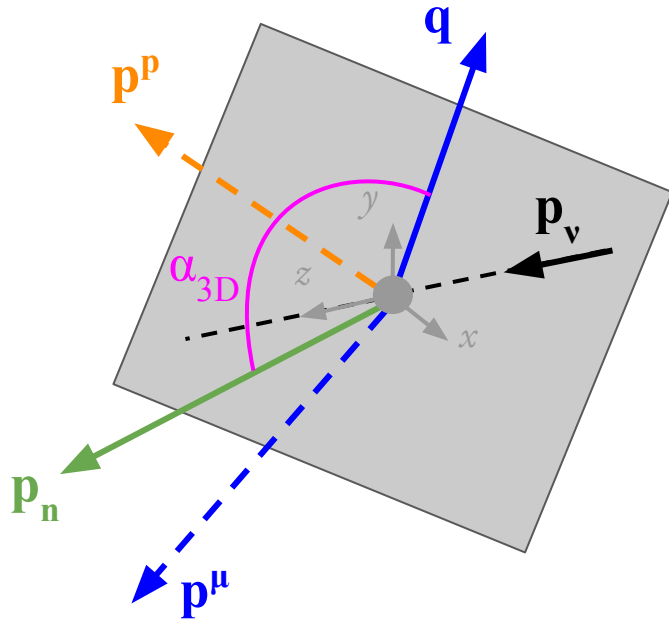
$$p_L = p_L^{\mu} + p_L^p - E_{\text{cal}}$$

Generalized Kinematic Imbalance (GKI)

[Phys. Rev. C 95, 065501 \(2017\)](#)

[arXiv:2310.06082](#)

- Extension to 3D by considering longitudinal component of missing momentum and calorimetric assumption on the incoming energy



$$p_n = |\vec{p}_n| = \sqrt{p_L^2 + \delta p_T^2}$$

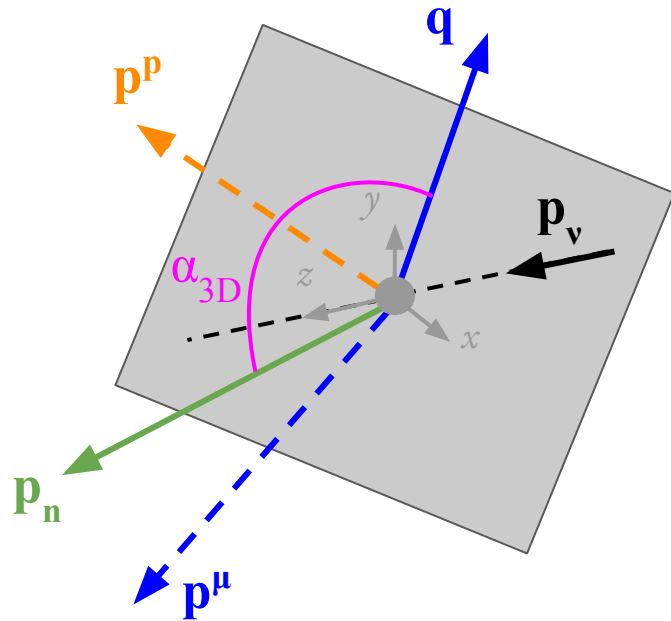
$$\alpha_{3D} = \cos^{-1} \left(\frac{\vec{q} \cdot \vec{p}_n}{|\vec{q}| |\vec{p}_n|} \right)$$

Generalized Kinematic Imbalance (GKI)

[Phys. Rev. C 95, 065501 \(2017\)](#)

[arXiv:2310.06082](#)

- Extension to 3D by considering longitudinal component of missing momentum and calorimetric assumption on the incoming energy
- Extensively tested against several event generators and model configurations



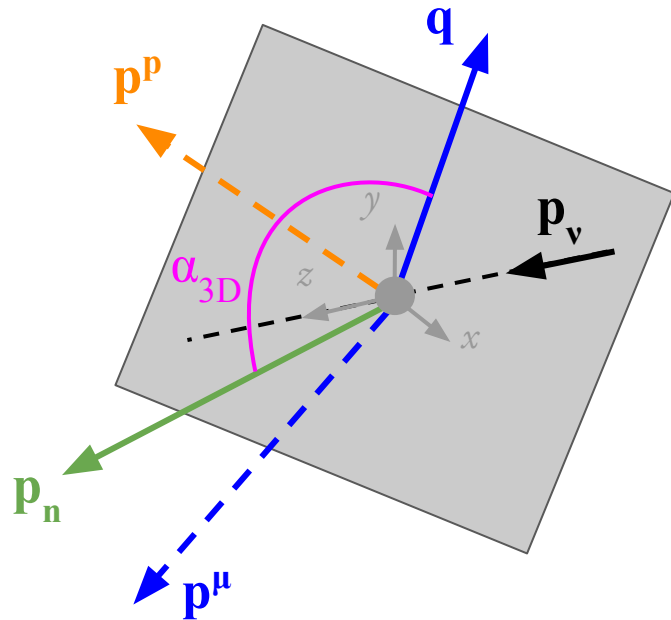
Name	Generator / Configuration
Gv2	GENIE v2.12.10
G18	GENIE v3.0.6 G18_10a_02_11a
G18T	G18 with tune
G21	GENIE v3.2.0 G21_11b_00_000
GiBUU	GiBUU 2021
NuWro	NuWro v19.02.1
NEUT	NEUT v5.4.0

Generalized Kinematic Imbalance (GKI)

[Phys. Rev. C 95, 065501 \(2017\)](#)

[arXiv:2310.06082](#)

- Extension to 3D by considering longitudinal component of missing moment and calorimetric assumption on the incoming energy
- Extensively tested against several event generators and model configurations

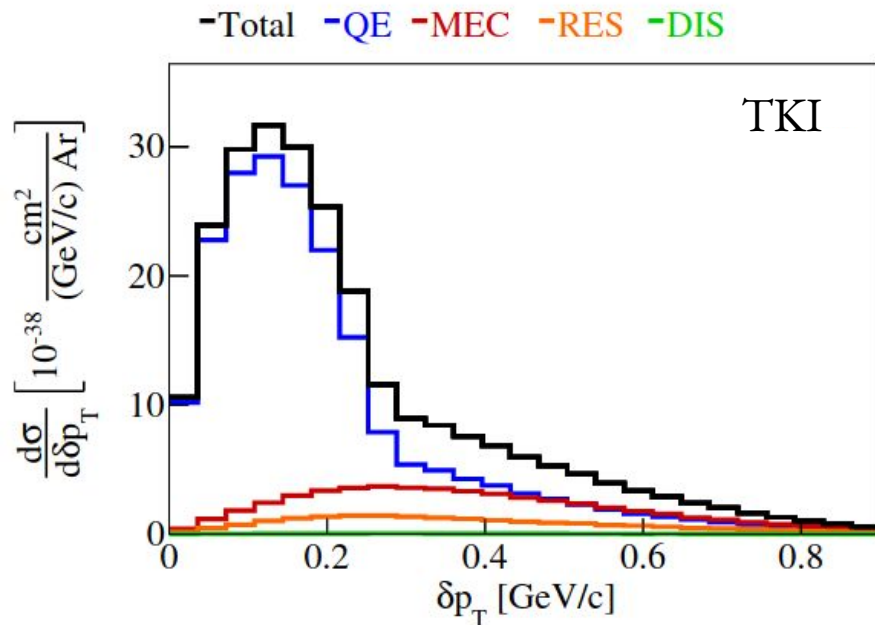
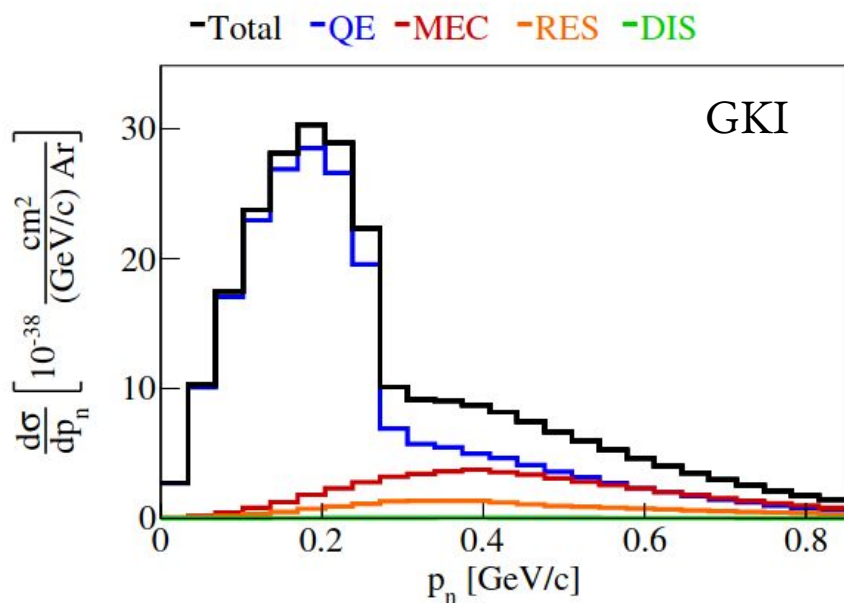


Name	Generator / Configuration
Gv2	GENIE v2.12.10
G18	GENIE v3.0.6 G18_10a_02_11a
G18T	G18 with tune
G21	GENIE v3.2.0 G21_11b_00_000
GiBUU	GiBUU 2021
NuWro	NuWro v19.02.1
NEUT	NEUT v5.4.0

Selected comparisons shown next
using same CC1p0 π selection

Missing momentum

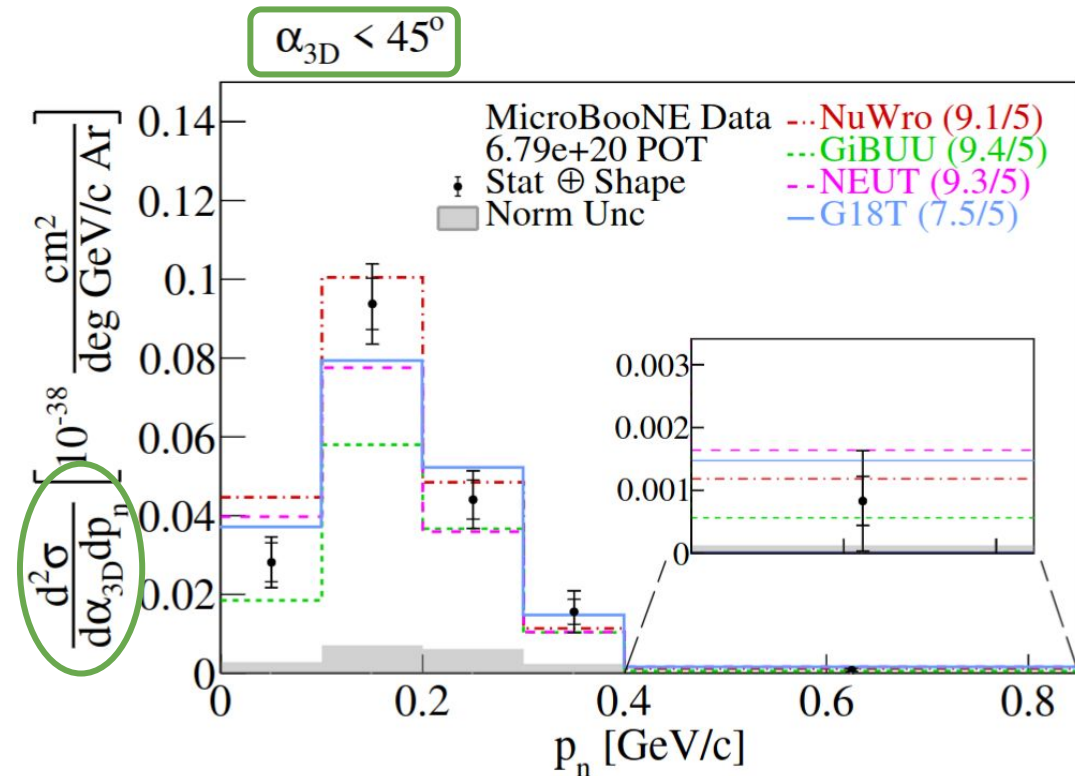
GENIE v3.0.6 G18_10a_02_11a (no tune)



- QE dominance due to CC1p0 π signal definition
- p_n pushes non-QE component to higher values

Into the GKI multiverse!

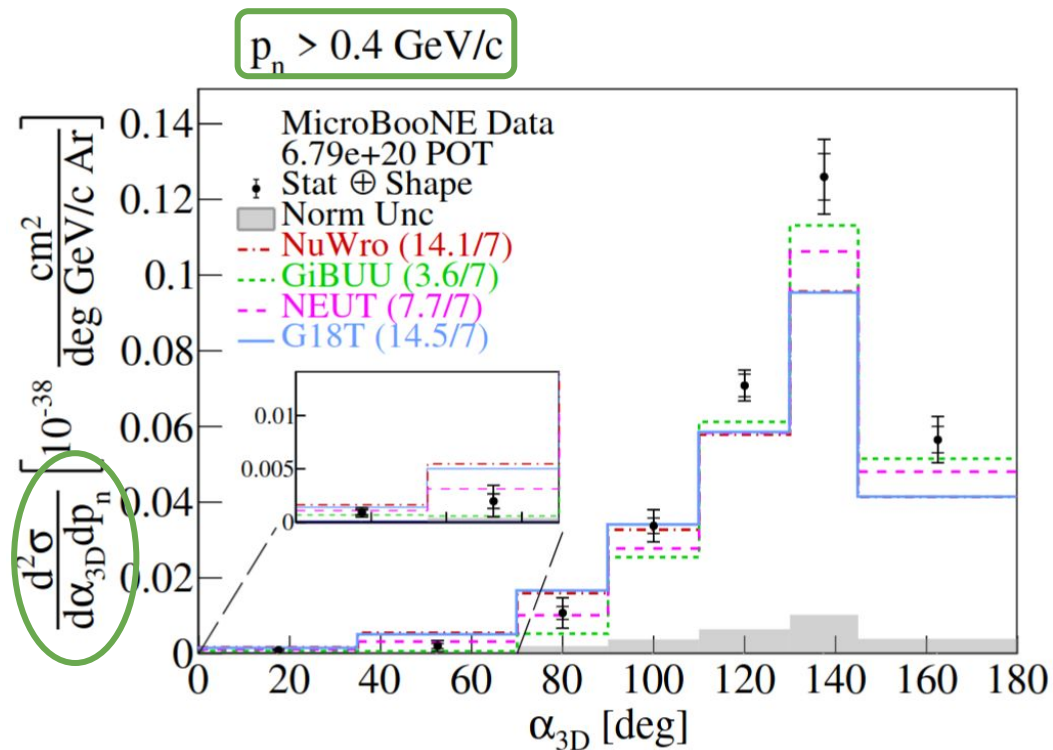
QE-dominated region



- Tail significantly suppressed
- Consistent with local Fermi gas
- G18T results in lowest χ^2

Into the GKI multiverse!

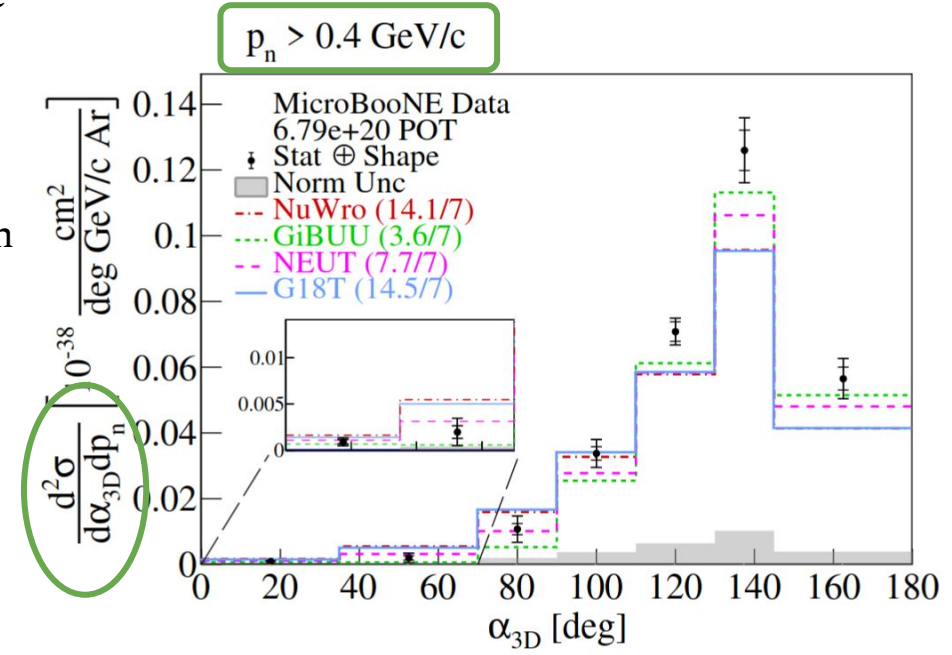
MEC/RES/FSI-dominated



- Sharply peaked distribution to the right
- Driven by FSI
- GiBUU yields best result

CC1p0π GKI Summary

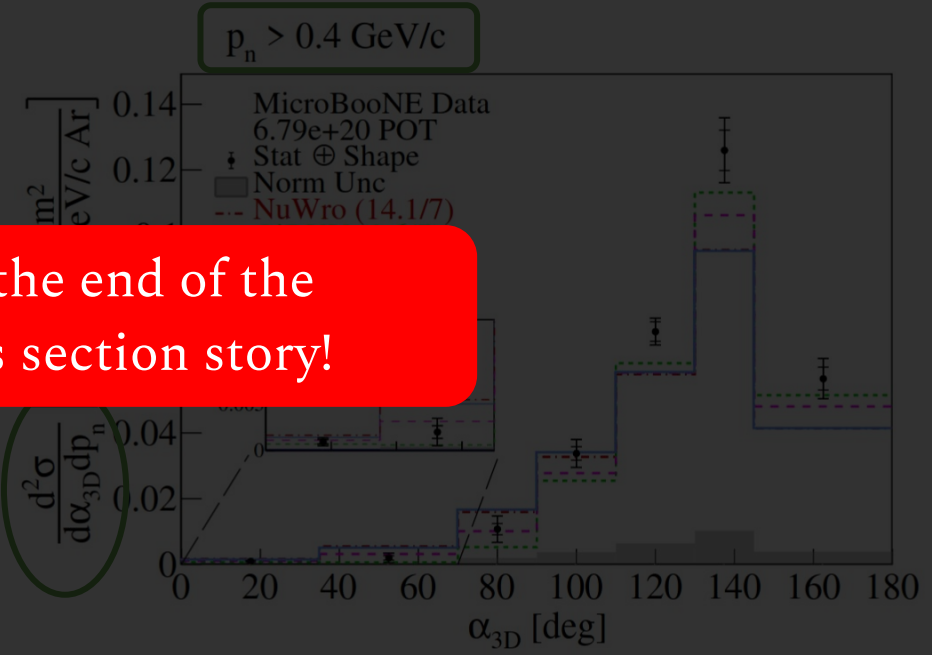
- Introduction of generalized kinematic imbalance (GKI) variables in 3D space
- Enhanced sensitivity to nuclear effects
- First single- and double-differential cross section GKI measurement ever with MicroBooNE
- **G18T** results in good description in QE-dominated regions
- **GiBUU** yields best performance in FSI-dominated regions
- Way more results in [arXiv:2310.06082!](https://arxiv.org/abs/2310.06082)



CC1p0π GKI Summary

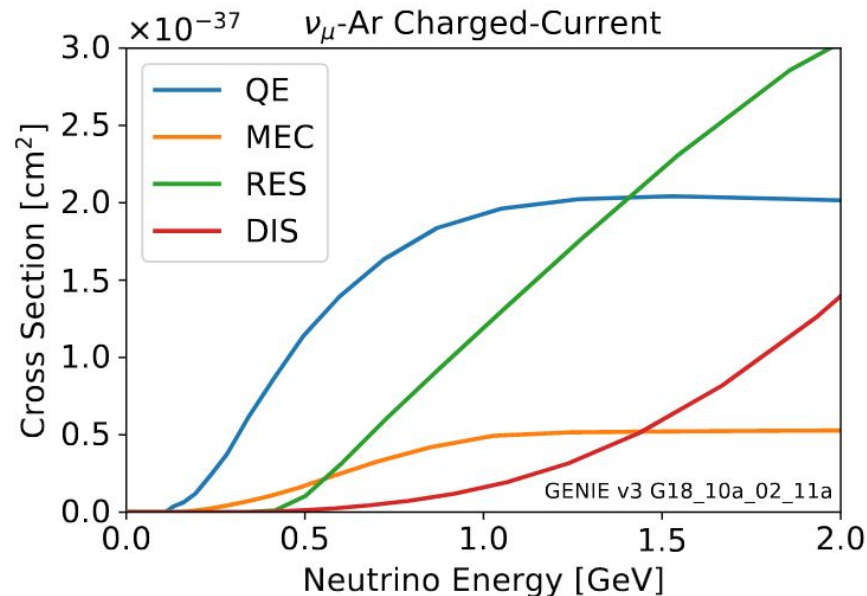
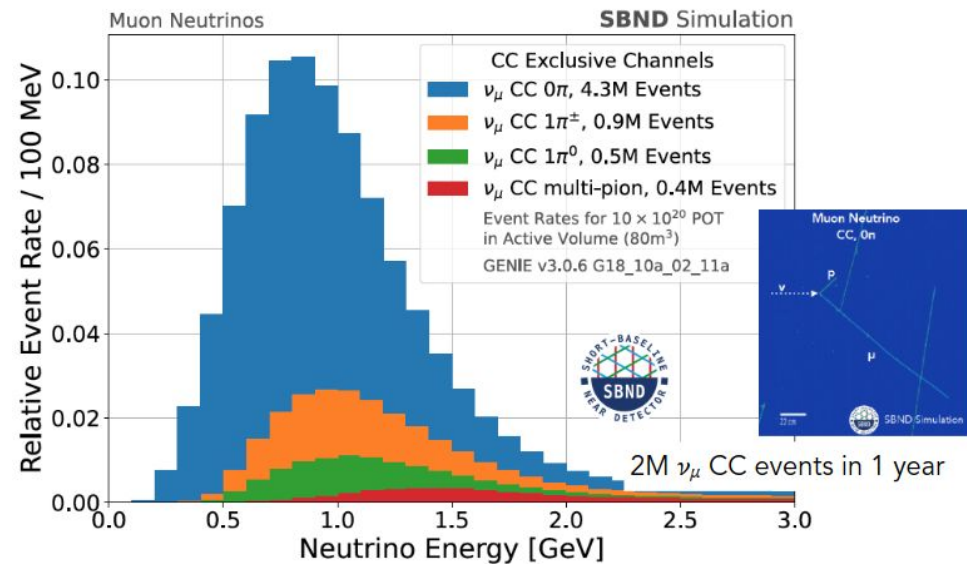
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- First single- and double-differential GKI measurement ever
- **G18T** results in good description in QE-dominated regions
- **GiBUU** yields best performance in FSI-dominated regions
- Way more results in [arXiv:2310.06082!](https://arxiv.org/abs/2310.06082)

But far from the end of the neutrino cross section story!



SBN Experiments (SBND & ICARUS)

Common model configuration used by both experiments, systematics under development
High statistics cross section measurements planned using both BNB & NuMI beamlines

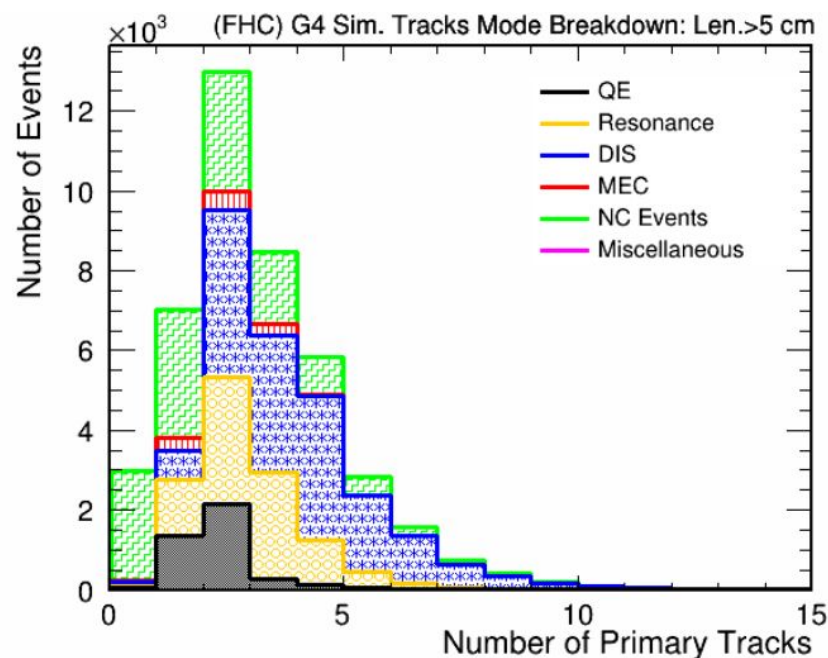
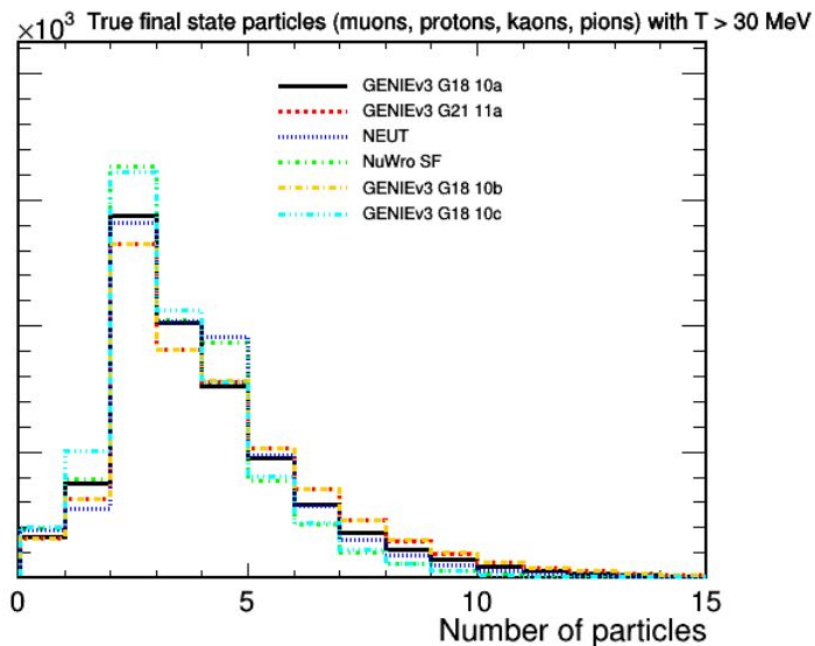


DUNE Near Detector

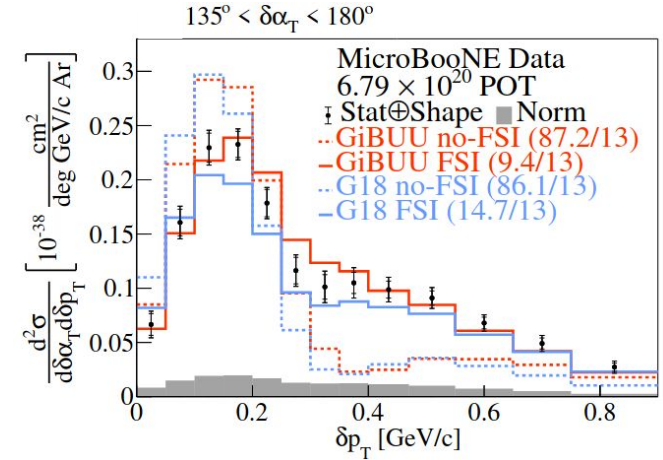
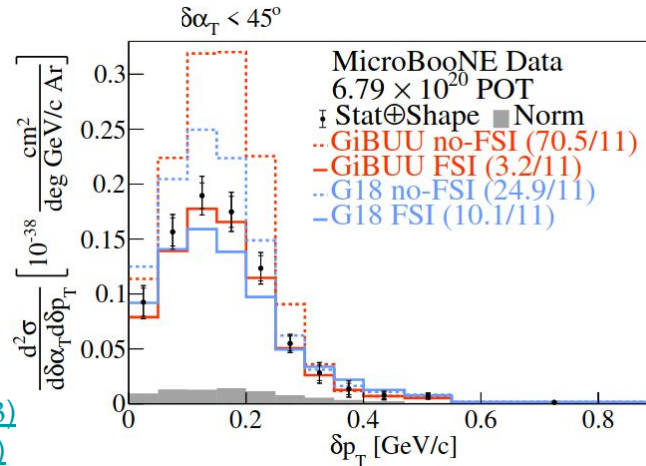
2x2 Near Detector prototype

Simulation studies on track multiplicity and inclusive selection

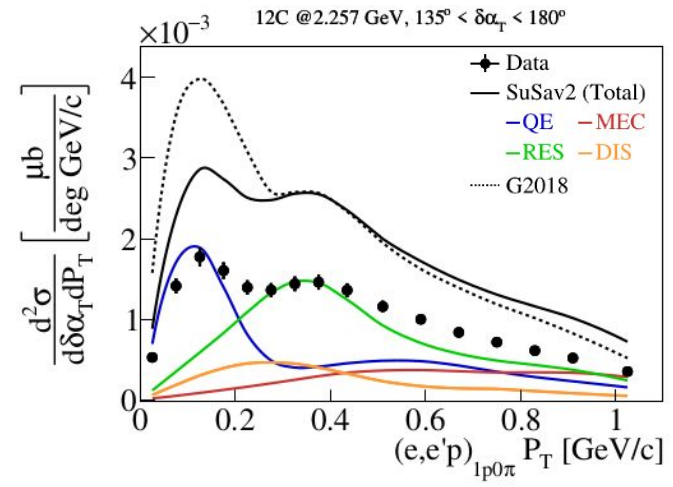
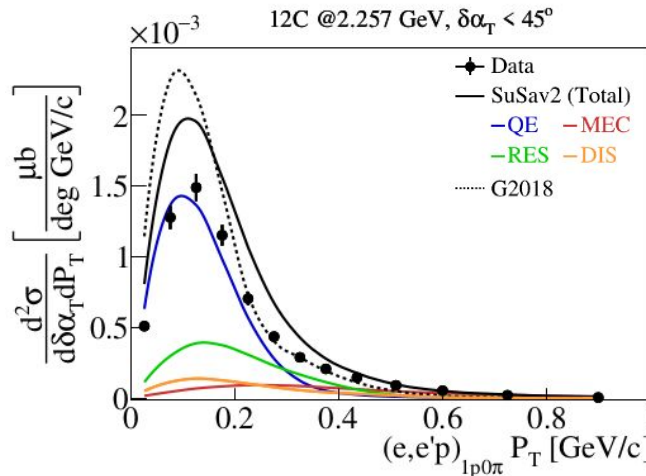
Cross section measurement targeting specific interactions



Electron Complementarity



[Phys. Rev. Lett. 131, 101802 \(2023\)](#)
[Phys. Rev. D 108, 053002 \(2023\)](#)



In preparation



Thank you!



Backup Slides

Backup Slides: Table of Contents

MicroBooNE / Unfolding: 66-77

TKI PRD: 78-127

TKI PRL: 128-159

GKI arxiv: 160-182

e4v: 183-280

3.6.3 Effect of Variation in Uncertainty

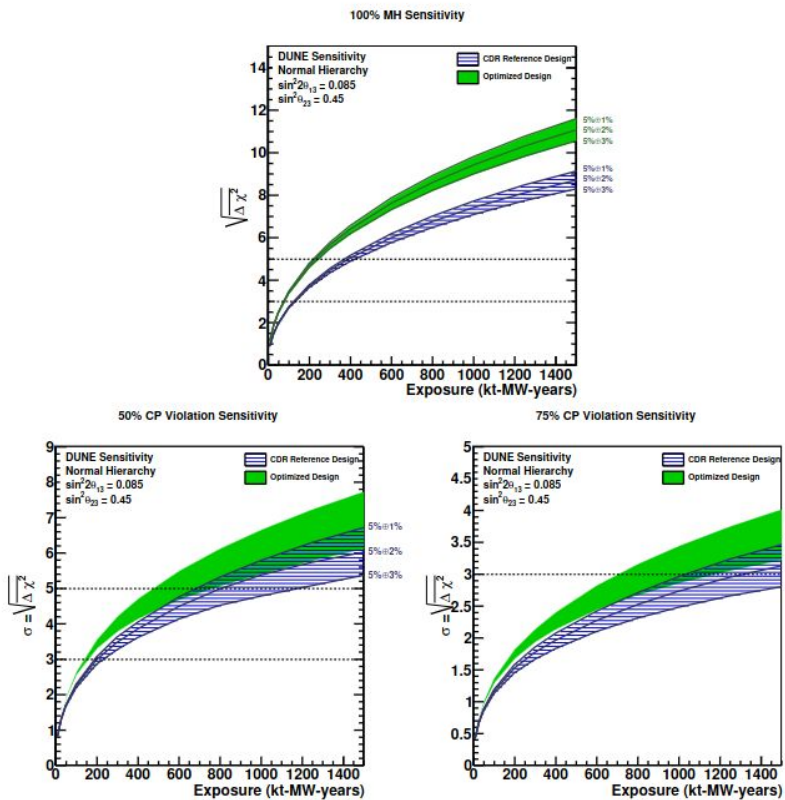
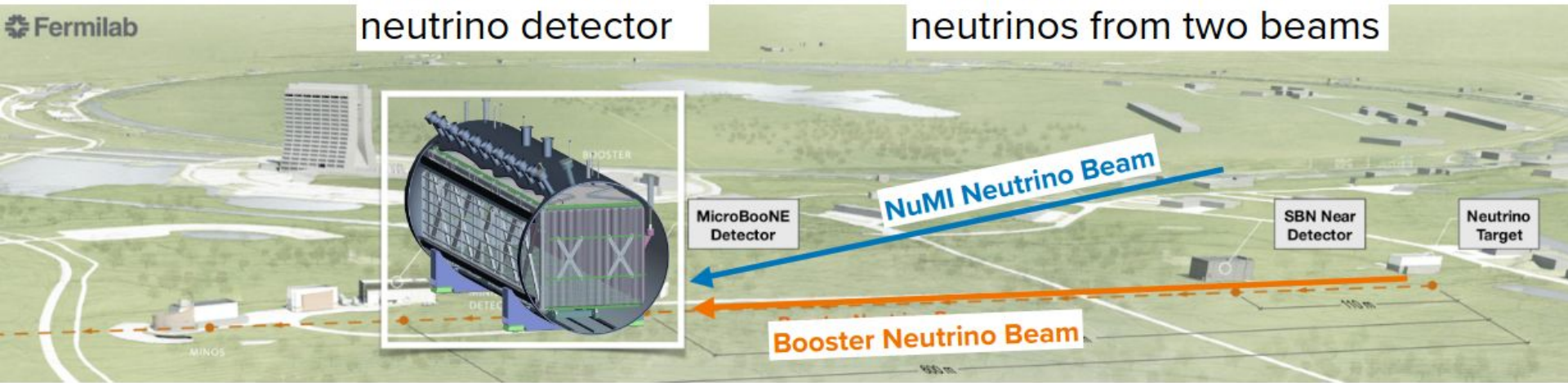


Figure 3.23 shows DUNE sensitivity to determination of neutrino mass hierarchy and discovery of CP violation as a function of exposure for several levels of signal normalization uncertainty. As seen in Figure 3.23, for early phases of DUNE with exposures less than 100 kt · MW · year, the experiment will be statistically limited. The impact of systematic uncertainty on the CP-violation sensitivity for large exposure is obvious in Figure 3.23; the ν_e signal normalization uncertainty must be understood at the level of $5\% \oplus 2\%$ in order to reach 5σ sensitivity for 75% of δ_{CP} values with exposures less than ~ 900 kt · MW · year in the case of the Optimized Design. Specifically, the absolute normalization of the ν_μ sample must be known to $\sim 5\%$ and the normalization of the ν_e sample, relative to the $\bar{\nu}_e$, ν_μ , and $\bar{\nu}_\mu$ samples after all constraints from external, near detector, and far detector data have been applied, must be determined at the few-percent level. This level of systematic uncertainty sets the capability and design requirements for all components of the experiment, including the beam design and the near and far detectors.

Figure 3.23: Expected sensitivity of DUNE to determination of the neutrino mass hierarchy (top) and discovery of CP violation, i.e., $\delta_{CP} \neq 0$ or π , (bottom) as a function of exposure in kt · MW · year, assuming equal running in neutrino and antineutrino mode, for a range of values for the ν_e and $\bar{\nu}_e$ signal normalization uncertainties from $5\% \oplus 3\%$ to $5\% \oplus 1\%$. The sensitivities quoted are the minimum sensitivity for 100% of δ_{CP} values in the case of mass hierarchy and 50% (bottom left) or 75% (bottom right) of δ_{CP} values in the case of CP violation. The two bands on each plot represent a range of potential beam designs: the blue hashed band is for the CDR Reference Design and the solid green band is for the Optimized Design. Sensitivities are for true normal hierarchy; neutrino mass hierarchy and θ_{23} octant are assumed to be unknown.

A short baseline
neutrino detector

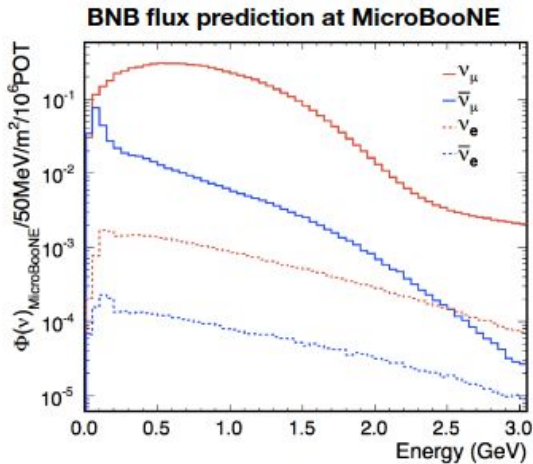
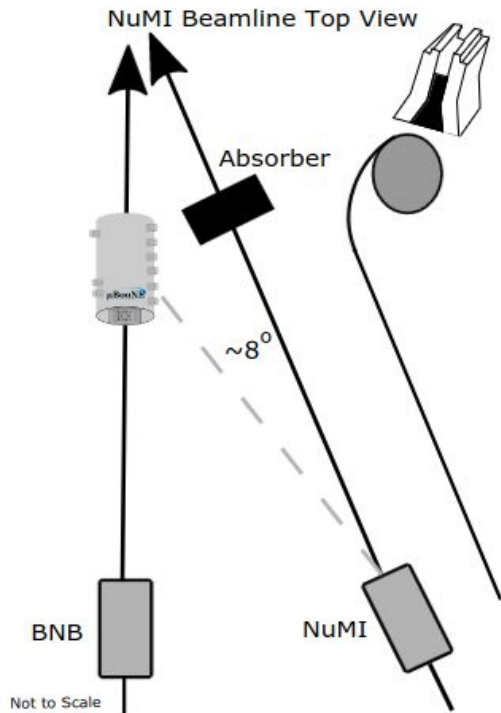
Studying accelerator
neutrinos from two beams



MicroBooNE's physics program

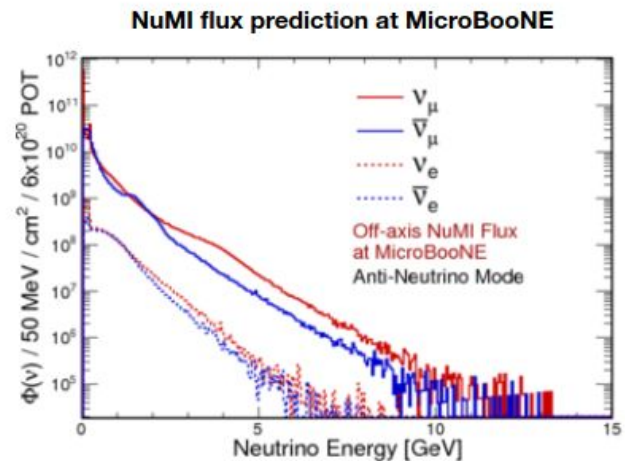
Non-standard neutrino oscillations	Cross-section measurements	Detector physics, R&D
---------------------------------------	-------------------------------	--------------------------

Beyond Standard Model physics!



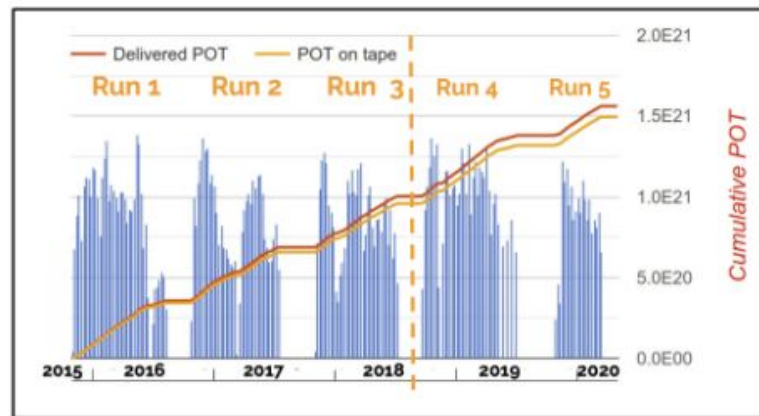
- 120 GeV protons
- ~ 680 m from MicroBooNE
- $\sim 8^\circ$ off-axis from MicroBooNE

- 8 GeV protons
- ~ 470 m from MicroBooNE
- On-axis



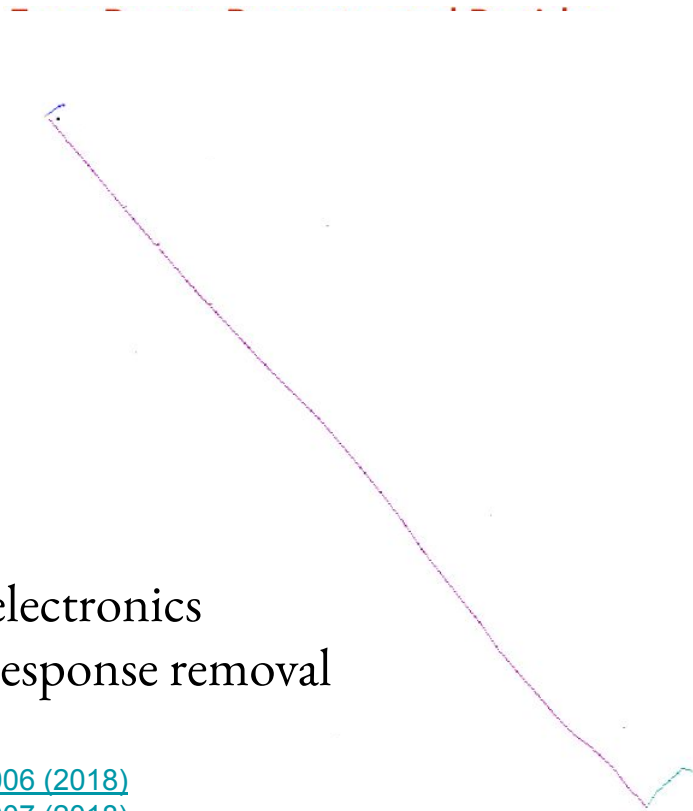
- MicroBooNE collected BNB and NuMI data between 2015 and 2020

- ~50% of the dataset (Runs 1-3) used in first wave of results



← First results →

POT: Protons on Target



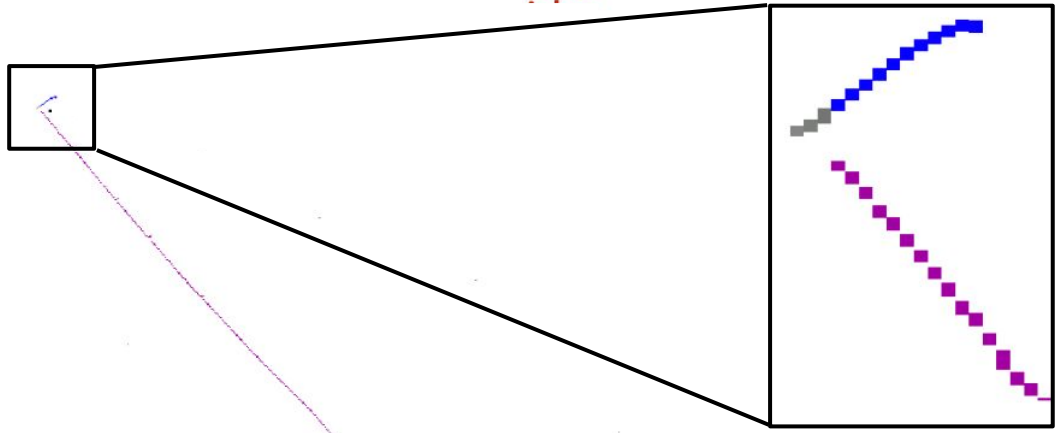
Readout electronics
and field response removal

[JINST 13, P07006 \(2018\)](#)
[JINST 13, P07007 \(2018\)](#)

From raw hits to
particle reconstruction

Pandora Pattern Recognition

- [Eur. Phys. J. C78, 1, 82 \(2018\)](#)

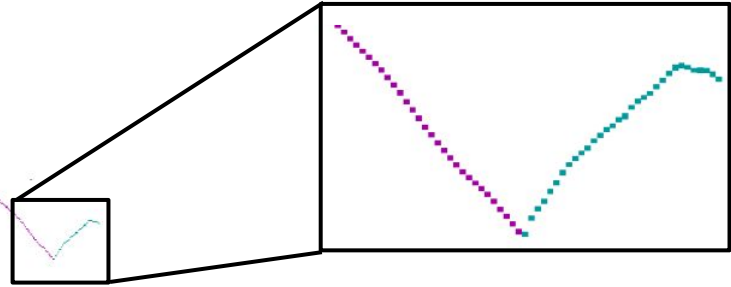


From raw hits to
particle reconstruction

Pandora Pattern Recognition

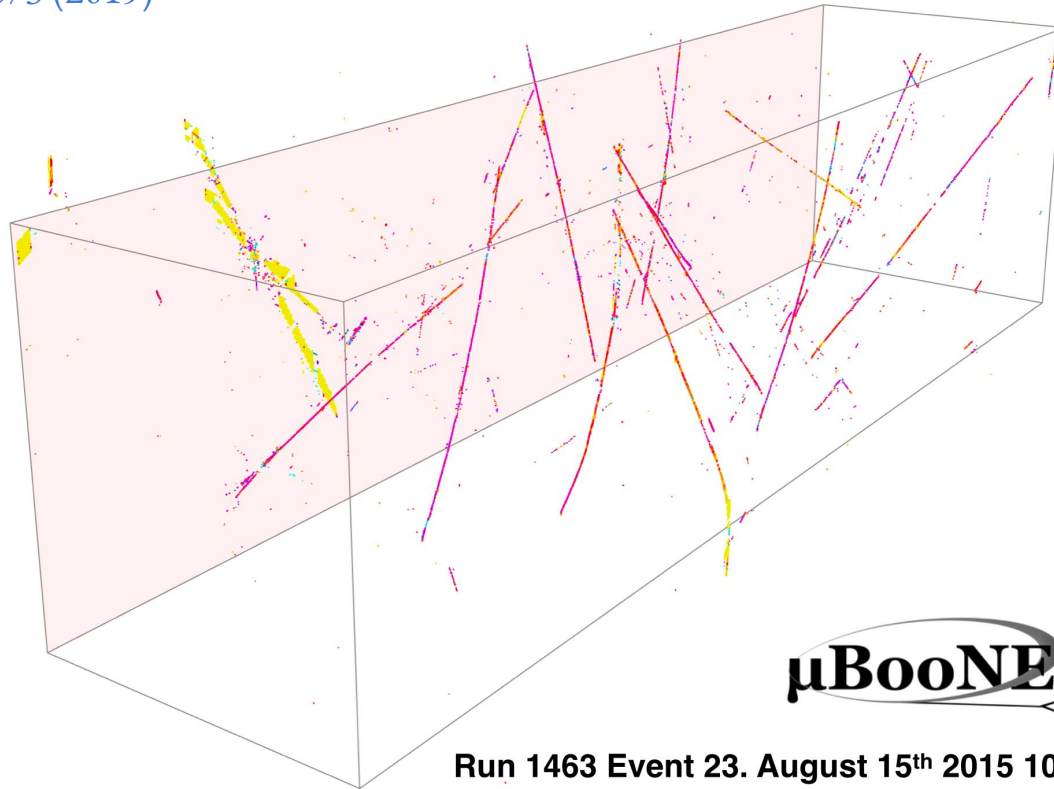
[Eur. Phys. J. C78, 1, 82 \(2018\)](#)

Readout electronics
and field response removal



[JINST 13, P07006 \(2018\)](#)
[JINST 13, P07007 \(2018\)](#)

Eur. Phys. J. C 79 673 (2019)



Run 1463 Event 23. August 15th 2015 10:37

Readout window of 2.3 ms

- ~20 cosmic interactions
- ~0.0017 ν interactions

Significant reduction using optical information
to 1 ν interaction in ~10 events

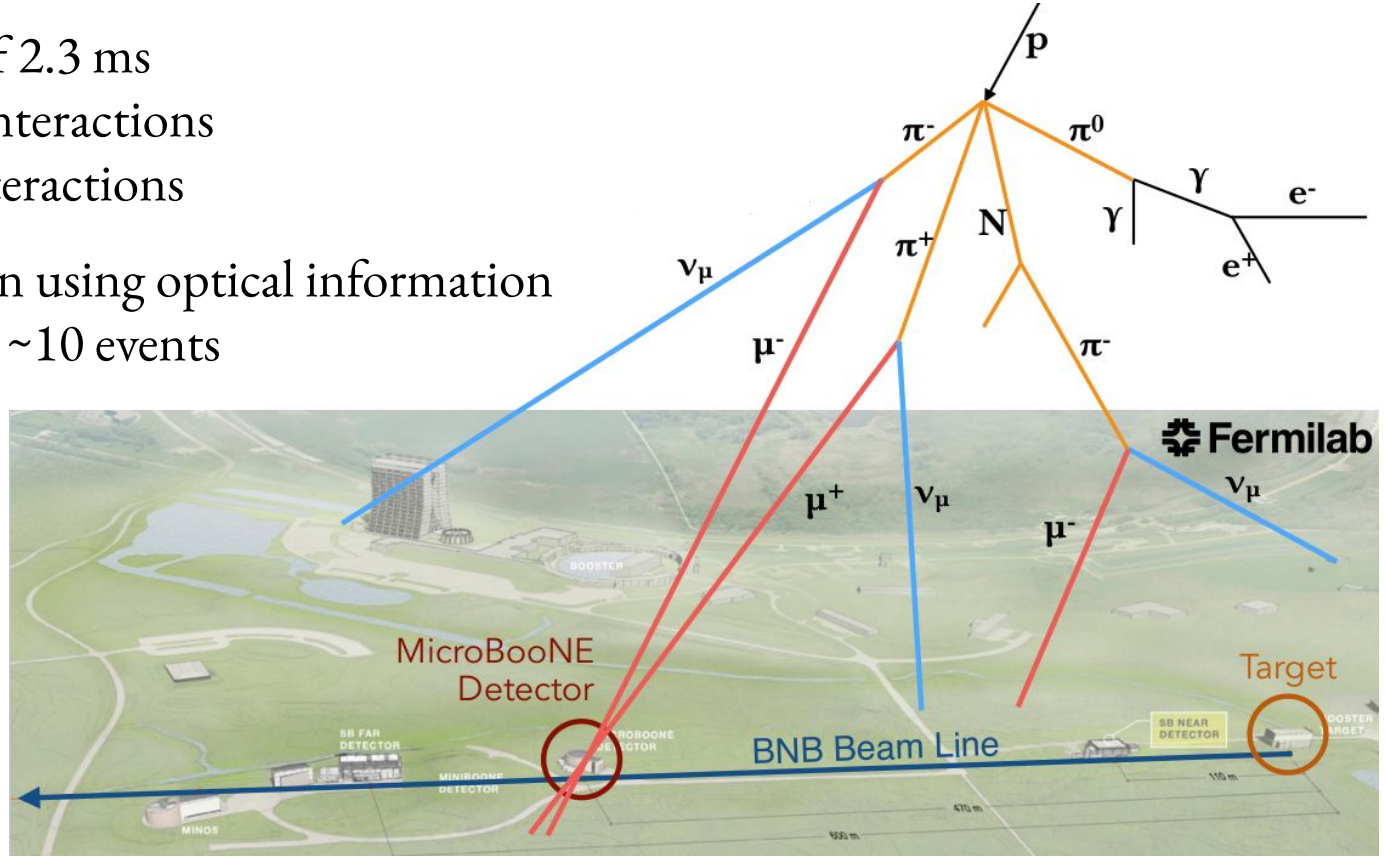


TABLE IV. Tuned parameter values and uncertainties after fitting to T2K $\text{CC}0\pi$ data for the nominal simulation and three tunes that build to the final four parameter tune. Note that postfit χ^2 values are quoted here only for the 58 bins included in the fit (excluding the highest muon momentum bin in each $\cos\theta$ bin), and using diagonal elements of the covariance matrix only. In the text and figures, pre- and postfit χ^2 comparisons are also quoted for the full T2K dataset of 67 bins. “Norm.” is an abbreviation for normalization.

	MaCCQE fitted value	CC2p2h Norm. fitted value	CCQE RPA Strength fitted value	CC2p2h Shape fitted value	T2K $\chi^2_{\text{diag}}/N_{\text{bins}}$
Nominal (untuned)	0.961242 GeV	1	100%	0	106.7/58
Fit MaCCQE + CC2p2h Norm.	1.14 ± 0.07 GeV	1.61 ± 0.19	100% (fixed)	0 (fixed)	71.8/58
Fit MaCCQE + CC2p2h Norm + CCQE RPA Strength	1.18 ± 0.08 GeV	1.12 ± 0.38	$(64 \pm 23)\%$	0 (fixed)	69.7/58
Fit MaCCQE + CC2p2h Norm + CCQE RPA Strength + CC2p2h Shape	1.10 ± 0.07 GeV	1.66 ± 0.19	$(85 \pm 20)\%$	$1^{+0}_{-0.74}$	52.5/58

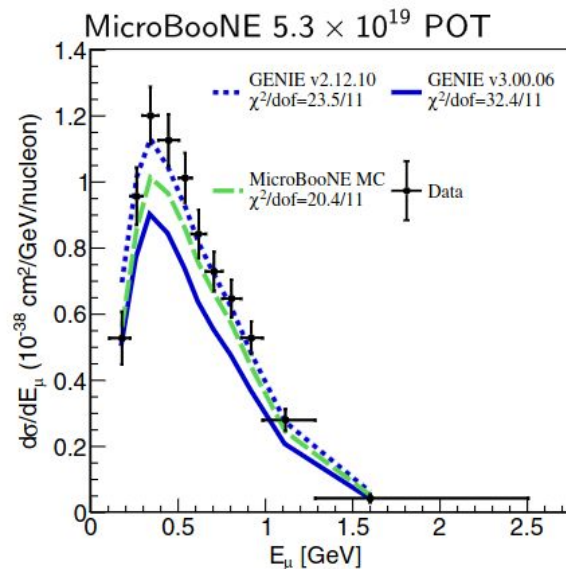
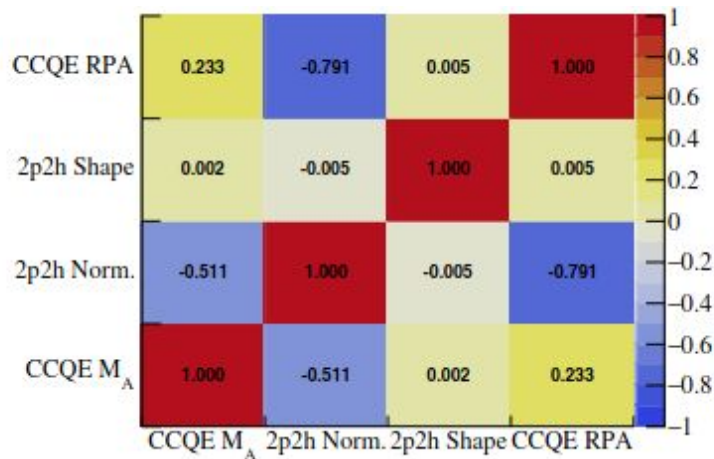


FIG. 7. Correlations between parameters after fitting to T2K $\text{CC}0\pi$ data.

Unfolding problem

- In practice, the data unfolding problem starts with

$$\chi^2(s) = (\mathbf{m} - \mathbf{r} \cdot \mathbf{s})^T \text{Cov}^{-1} (\mathbf{m} - \mathbf{r} \cdot \mathbf{s})$$

- \mathbf{m} : measured spectrum, m -dimensional vector
 - \mathbf{s} : unknown spectrum, to be unfolded, n -dimensional vector
 - \mathbf{r} : smearing (response) matrix, $m \times n$ and $m \geq n$
 - Cov : covariance matrix containing all statistical and systematic uncertainties associated with \mathbf{m} and \mathbf{r} .
- Cholesky decomposition: $\text{Cov}^{-1} = Q^T Q$, Q is a lower triangular matrix

$$\chi^2(s) = (M - R \cdot s)^T \cdot (M - R \cdot s)$$

Pre-scaling

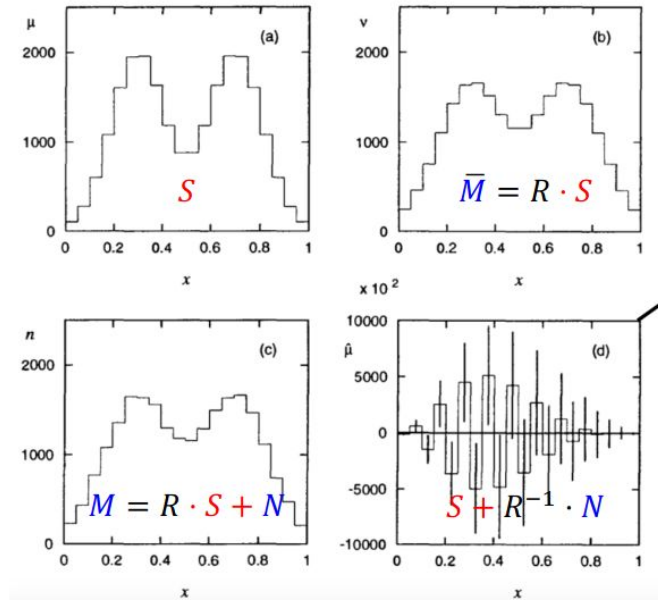
- $M := Q \cdot \mathbf{m}$
- $R := Q \cdot \mathbf{r}$

Solution (direct inversion)

$$\hat{s} = (R^T R)^{-1} R^T M$$
$$\hat{s} = (R^T R)^{-1} R^T (R \cdot s_{true} + N)$$

The response matrix R is unnecessary to be a square matrix

Unfolding problem



This is one unbiased solution (direct inversion) to an unfolding problem. However, it has catastrophic oscillations, i.e. huge variance, in the unfolded spectrum.

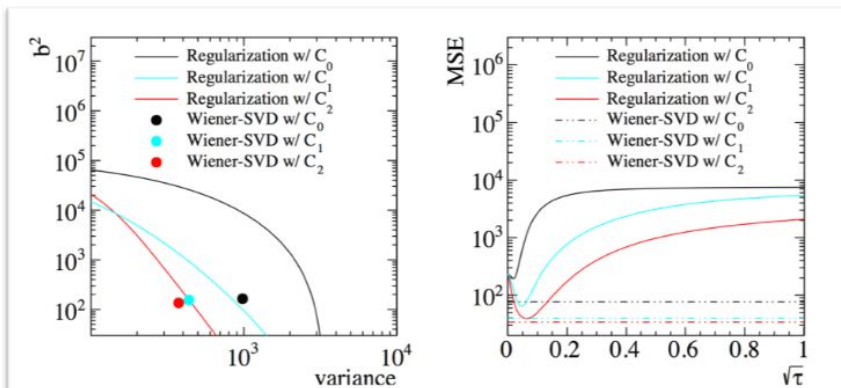
- Decrease the number of bins to suppress the “oscillation” --> Nyquist theorem
- Trade-off **bias** and **variance** to suppress the “oscillation” --> e.g. **regularization [unfolding method]**

Wiener-SVD unfolding

- To automatically minimize the Mean Square Error (MSE) given a model S

$$\begin{aligned}
 \text{MSE} &= E \left[(\hat{S} - S)^2 \right] = E \left[\left(F \cdot \frac{M}{R} - S \right)^2 \right] = E \left[\left(F \cdot S + F \cdot \frac{N}{R} - S \right)^2 \right] \\
 &= E \left[\underbrace{\left((F - I) \cdot S \right)^2}_{\text{Bias}} + \underbrace{\left(F \cdot \frac{N}{R} \right)^2}_{\text{Variance}} \right]
 \end{aligned}$$

F = “filter” = additional smearing matrix = regularization



Given one model S

- General regularization, e.g. Tikhonov regularization, needs to “tune” a regularization strength parameter [curve in the left plot]
- Wiener-SVD regularization corresponds to a fixed point in the phase space of bias versus variance with **minimum MSE**

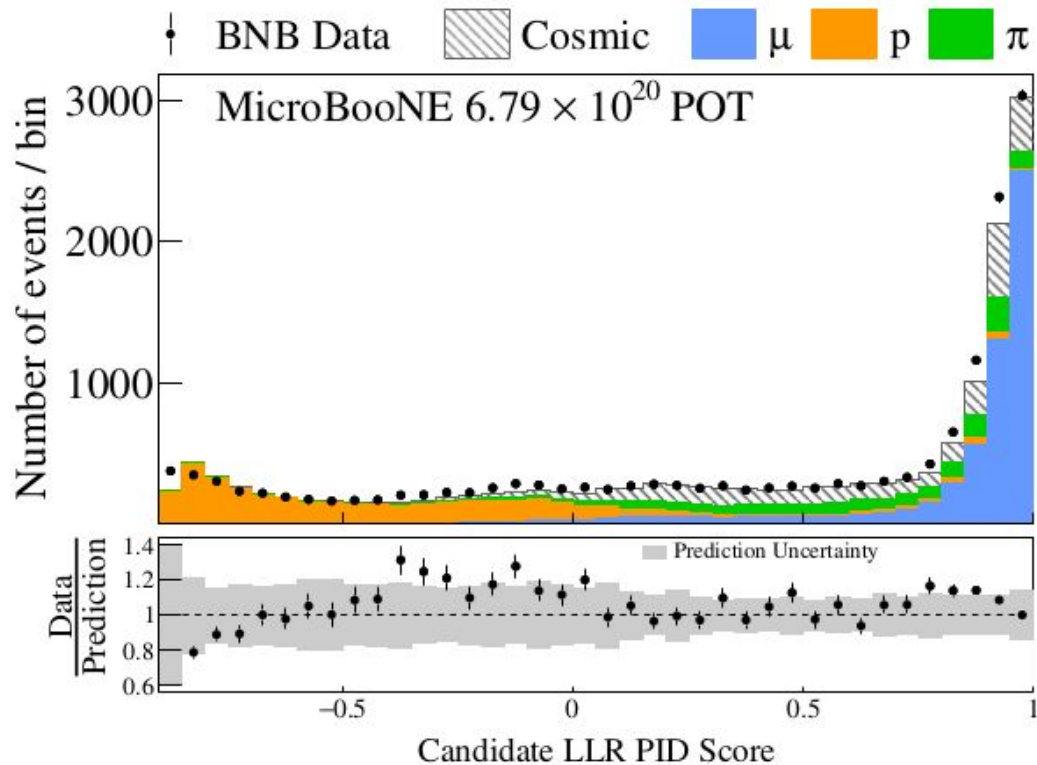


FIG. 1. The log-likelihood ratio (LLR) particle identification (PID) score distribution used to tag the muon and proton candidates.

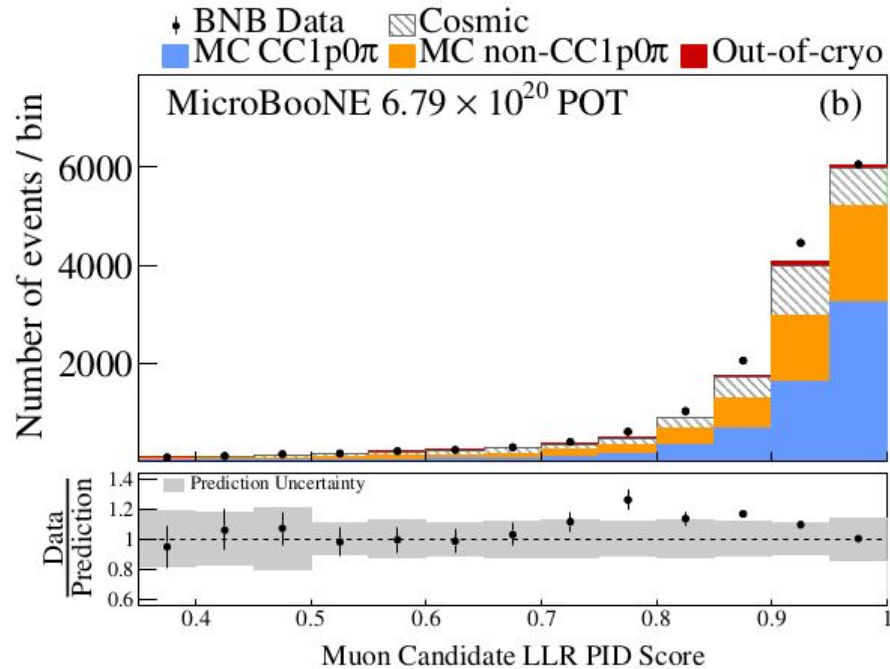
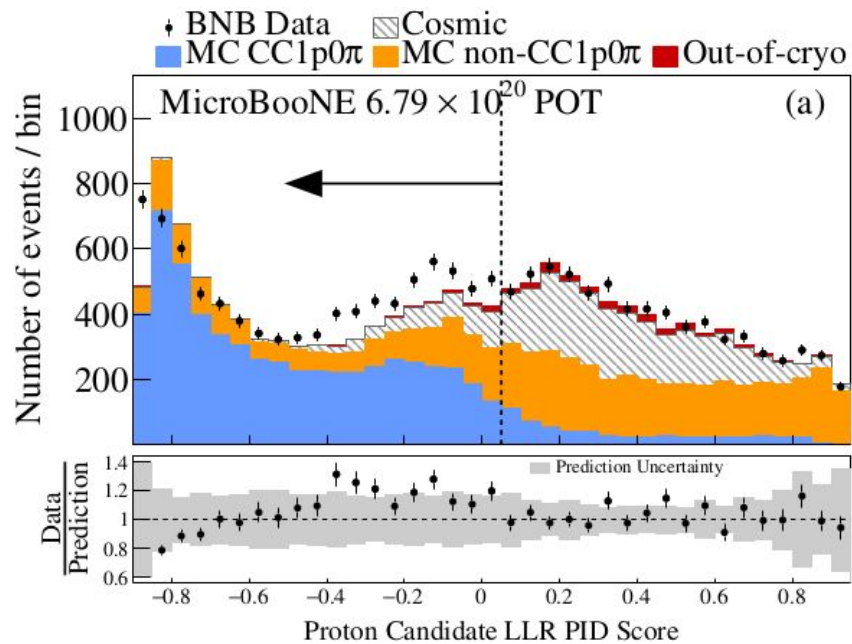


FIG. 2. (Top) the proton candidate LLR PID score distribution, illustrating the fitness of a cut at LLR PID < 0.05 to reject cosmic and non-CC1p0 π background events. (Bottom) the muon candidate LLR PID score distribution, illustrating a peak close to one. Only statistical uncertainties are shown on the data. The bottom panel shows the ratio of data to prediction.

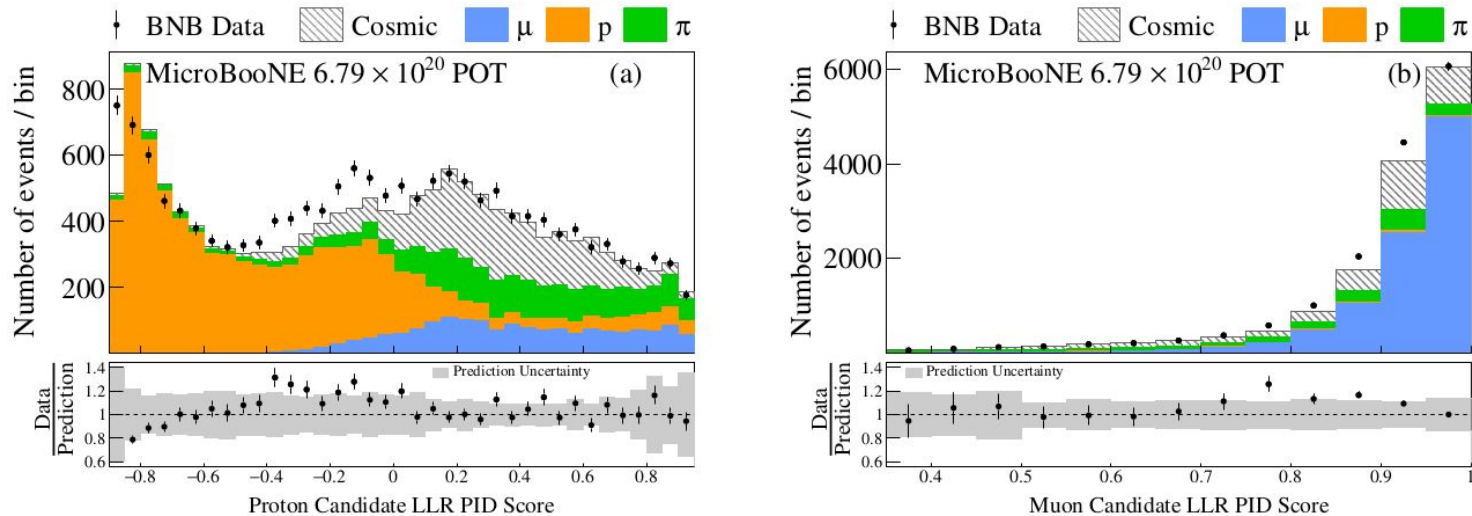


FIG. 1. (Left) the proton candidate LLR PID score distribution, illustrating the particle composition of the variable. (Right) the muon candidate LLR PID score distribution, illustrating a peak close to one. Only statistical uncertainties are shown on the data. The bottom panel shows the ratio of data to prediction.

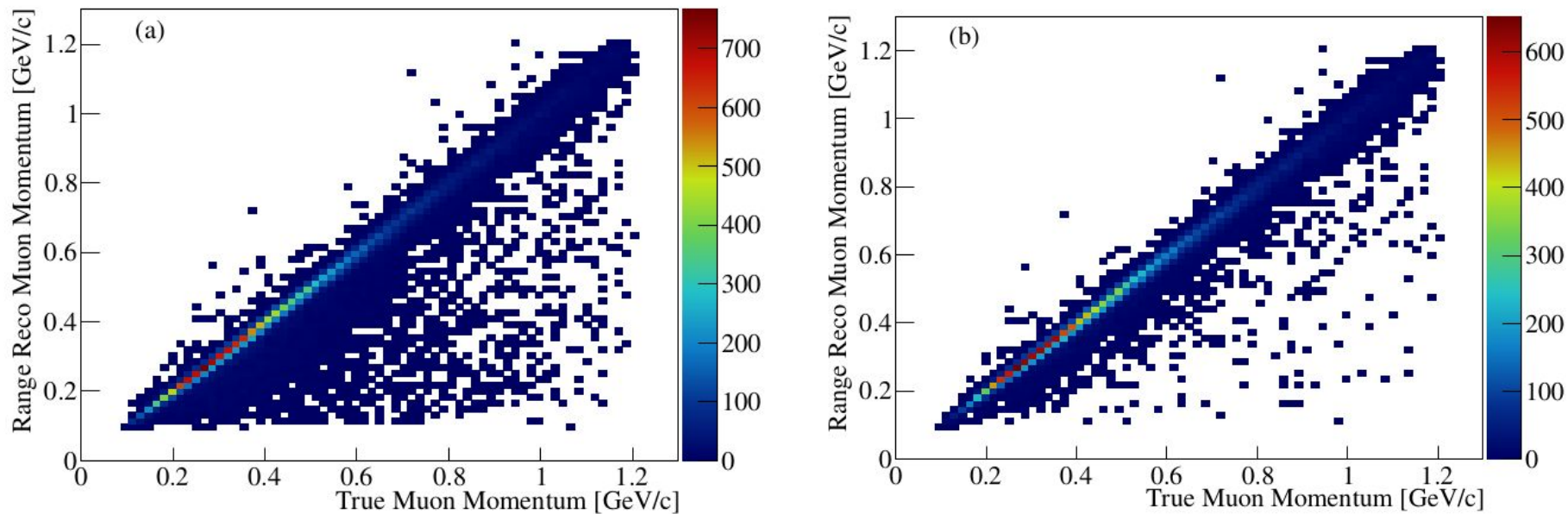
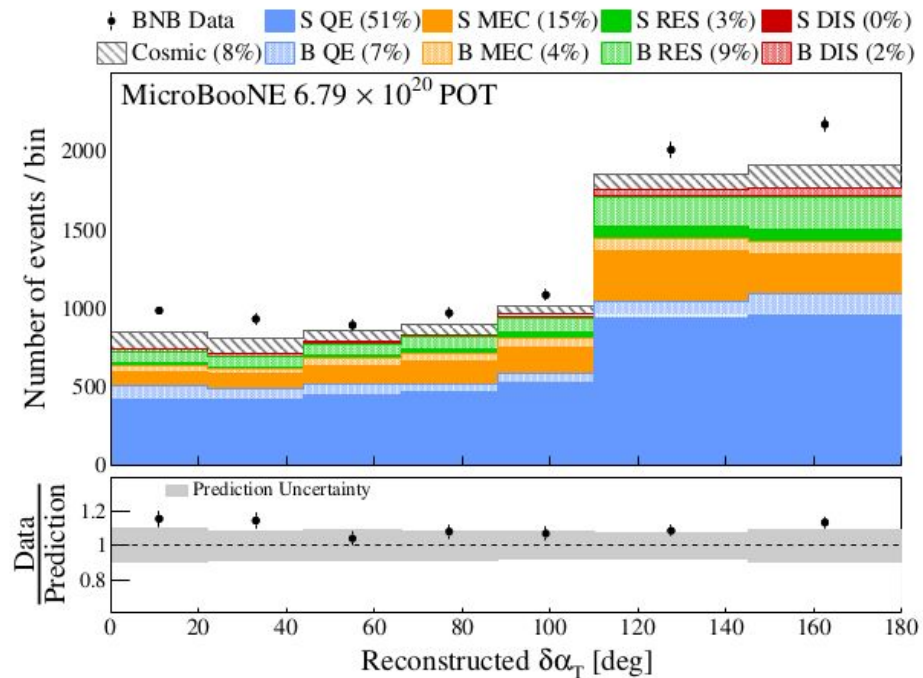
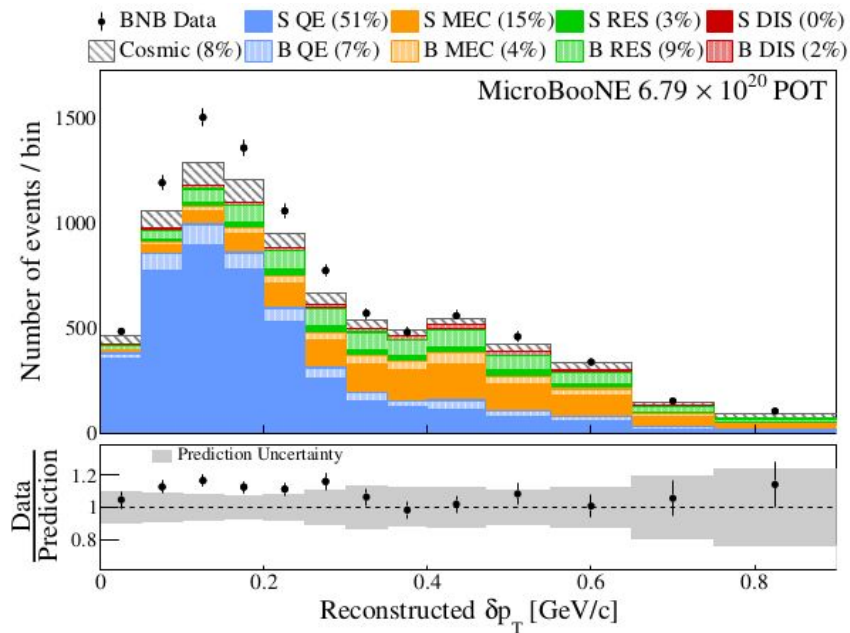
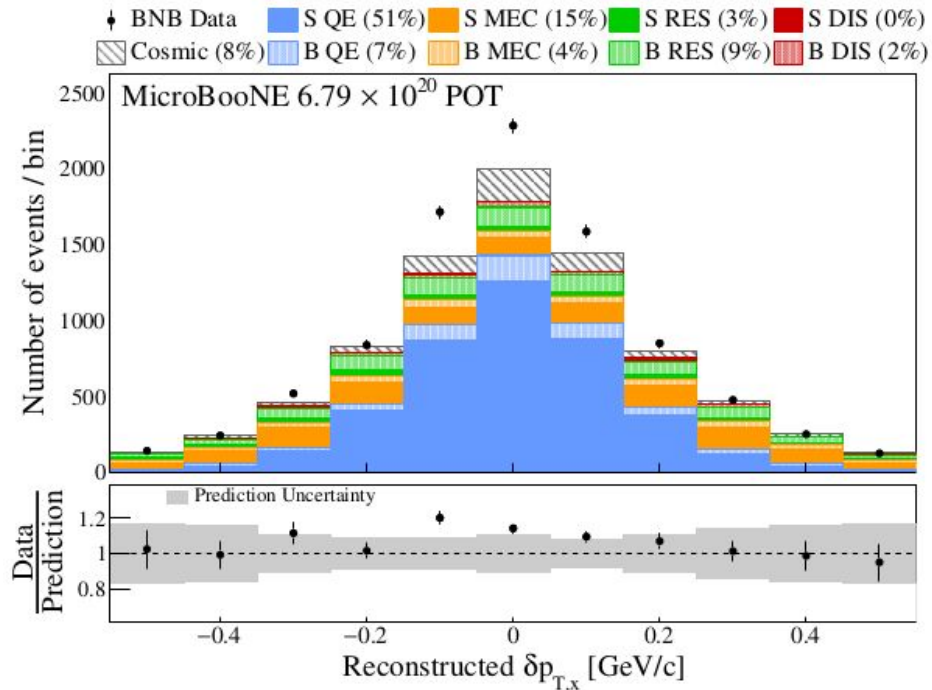
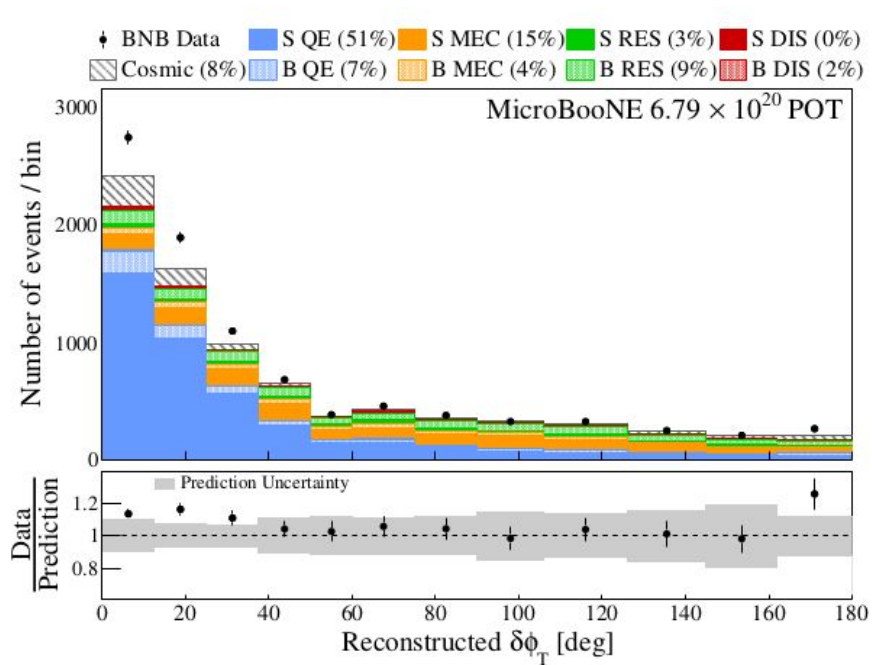
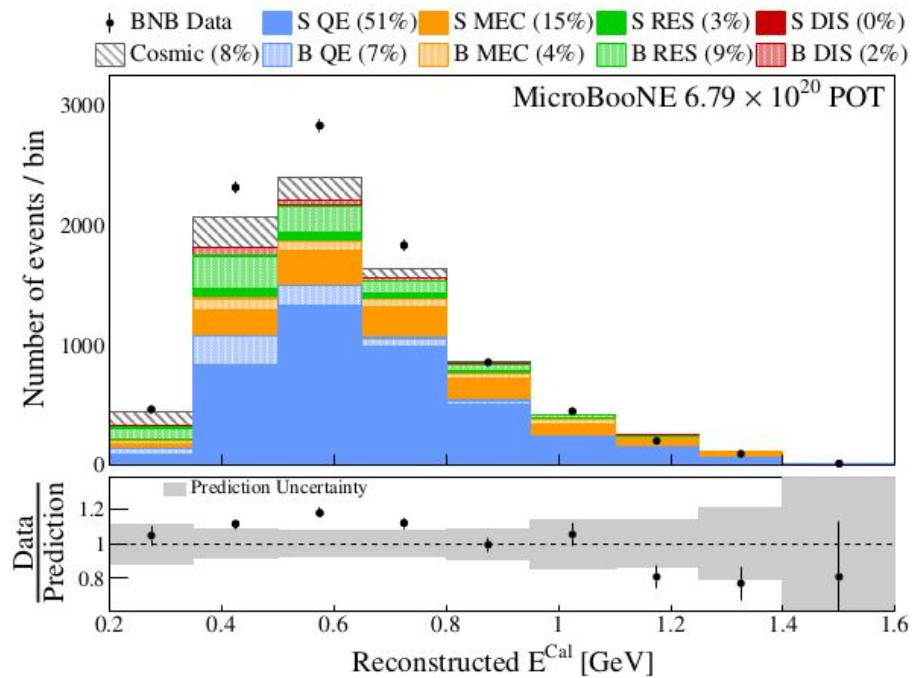
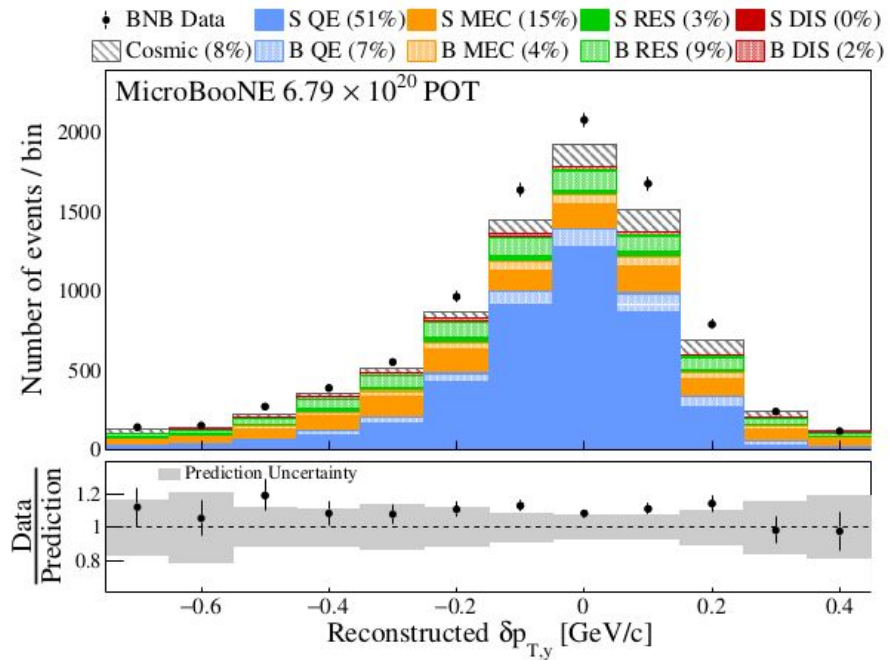
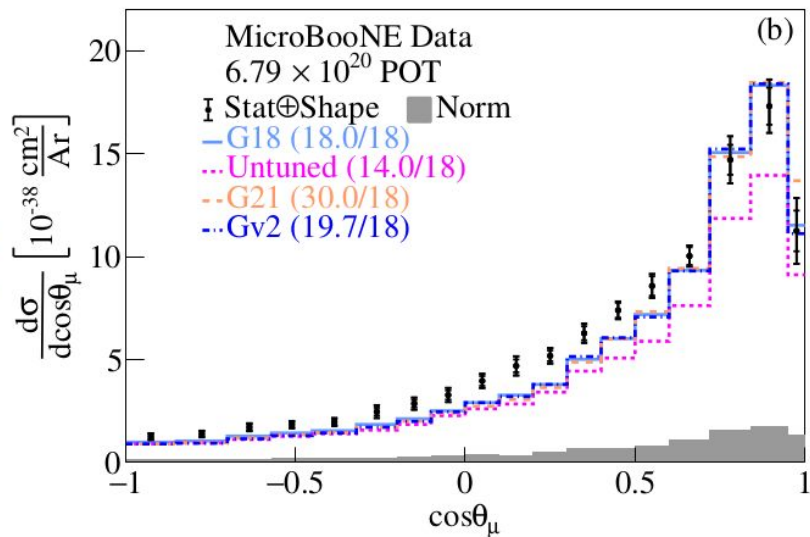
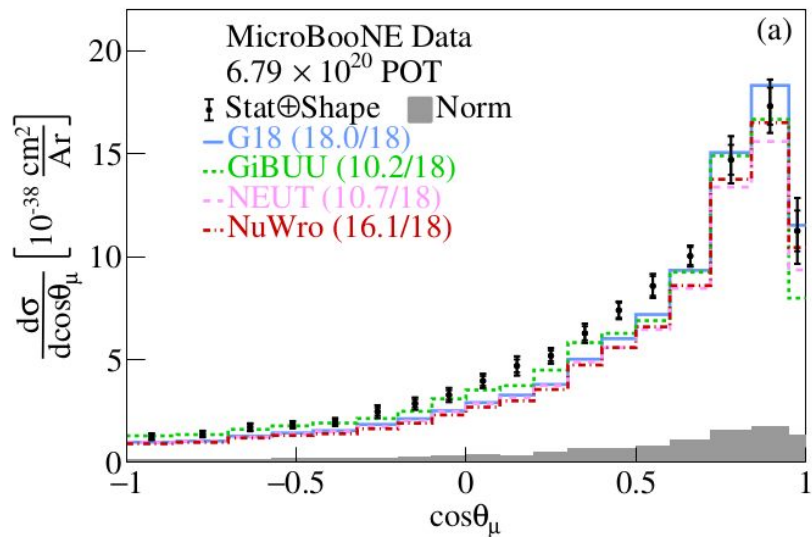


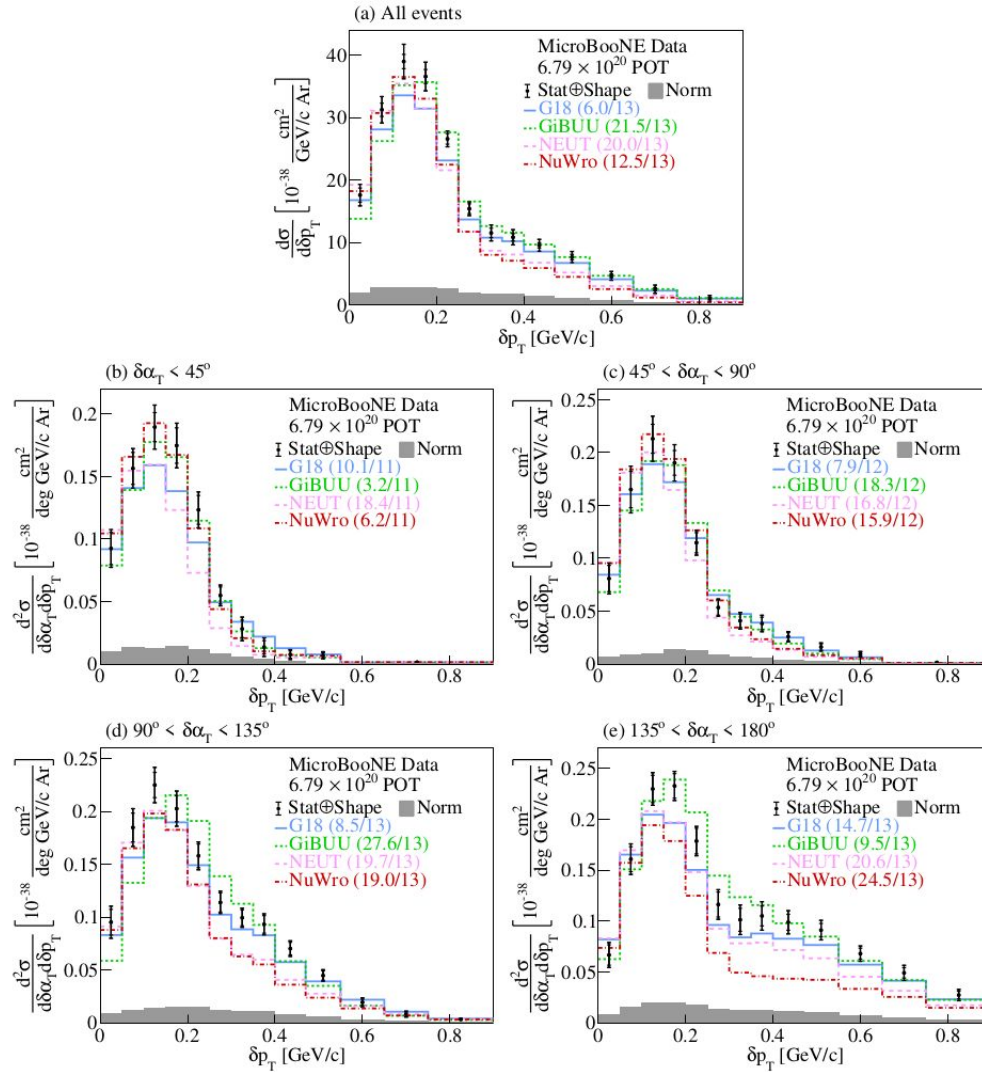
FIG. 3. Muon momentum reconstruction (top) before and (bottom) after the application of the muon momentum quality cut using contained muon tracks.

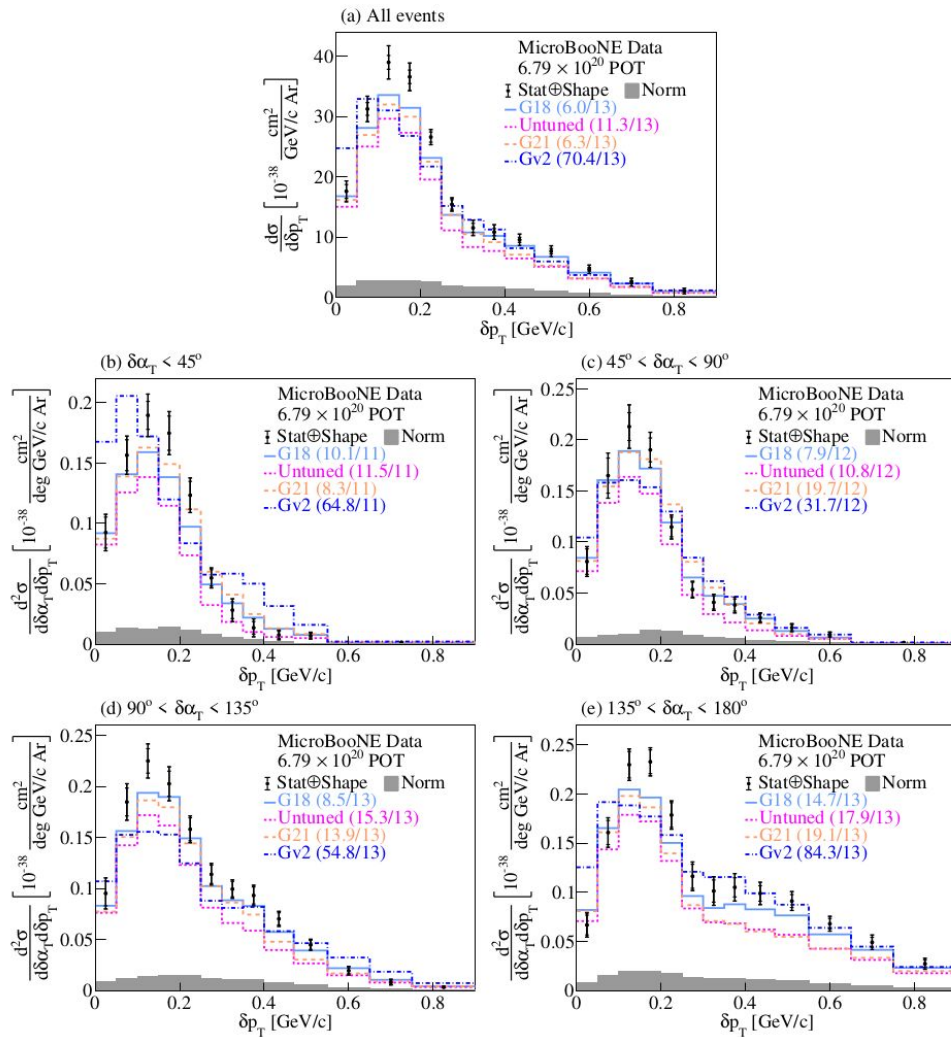




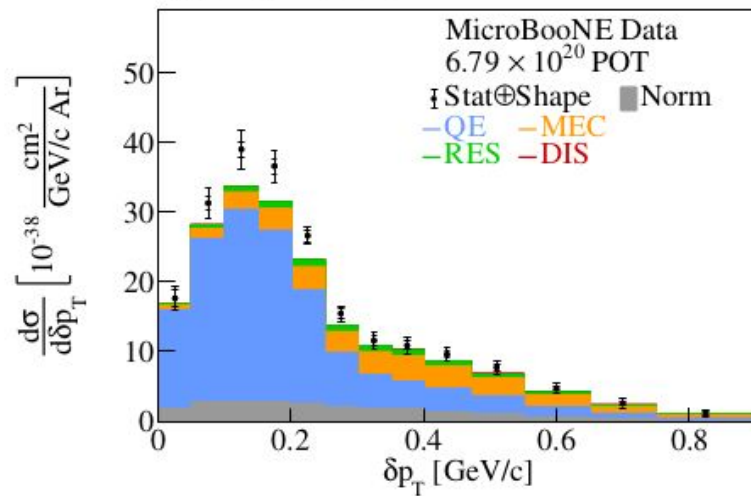




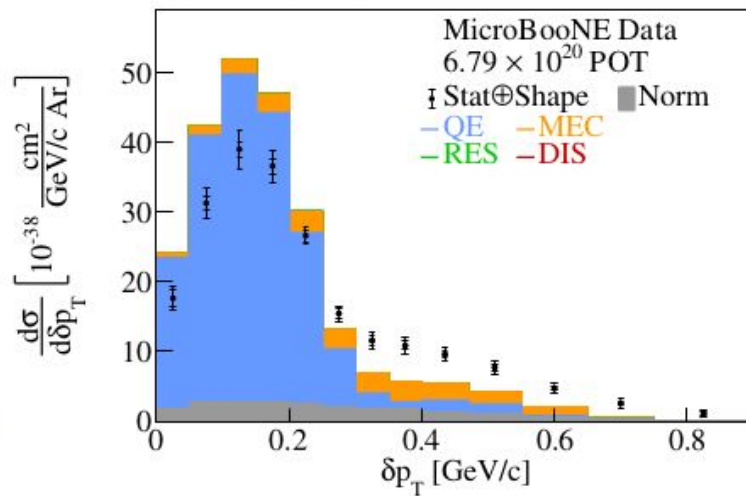


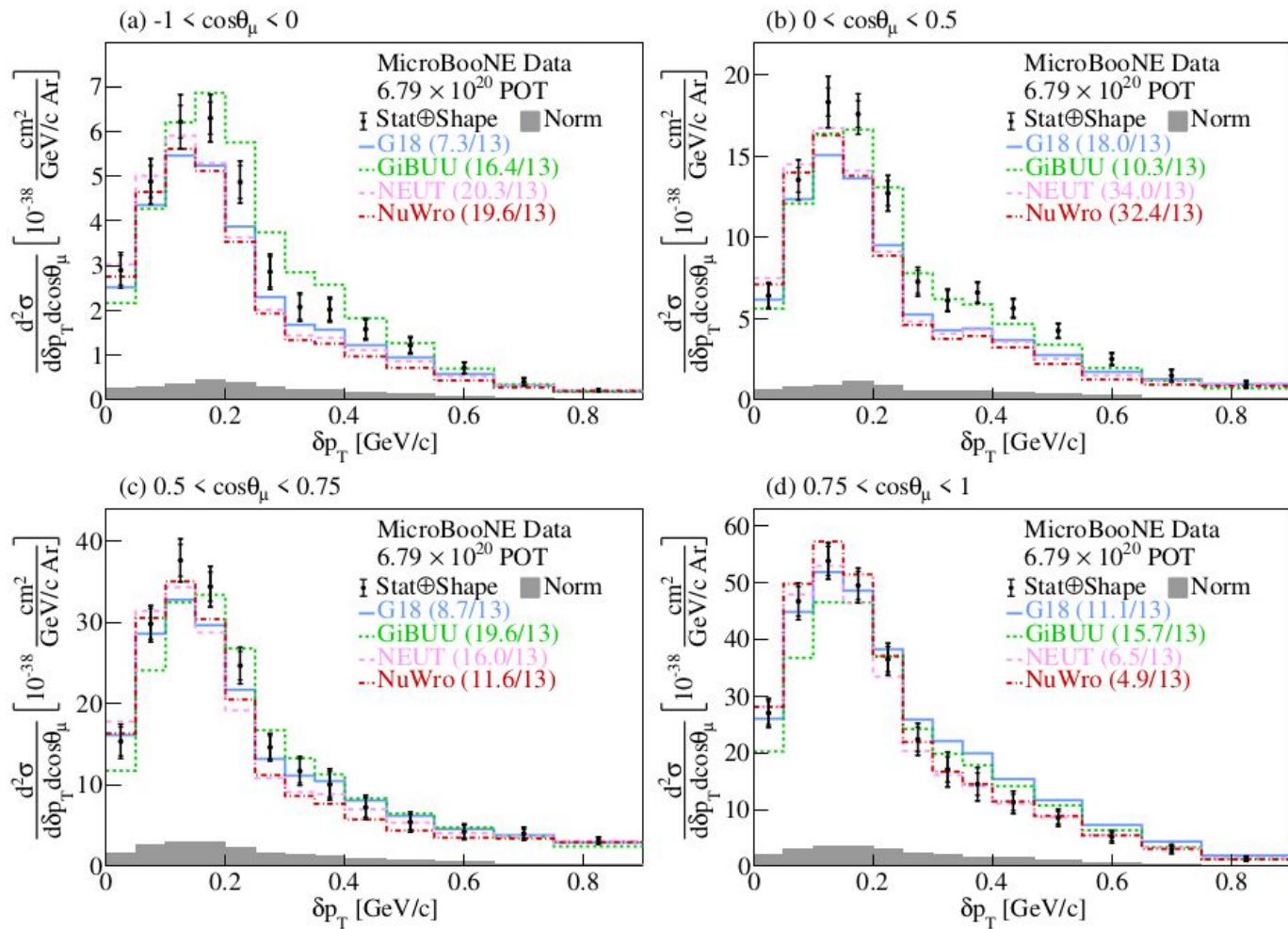


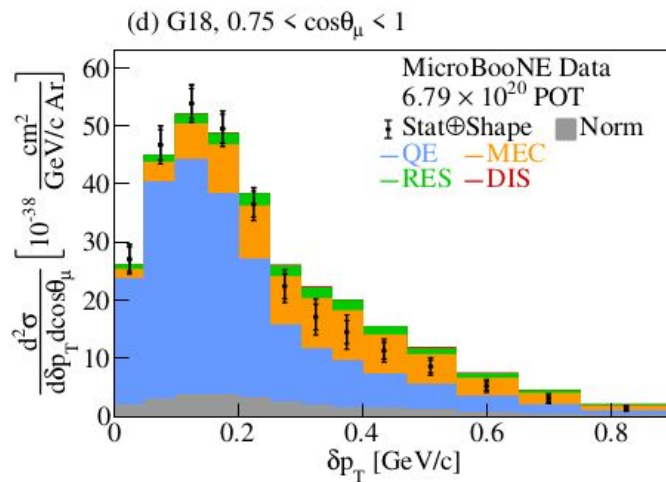
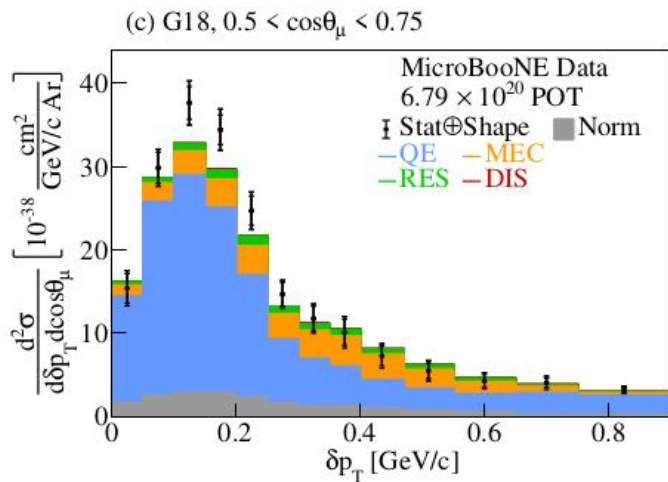
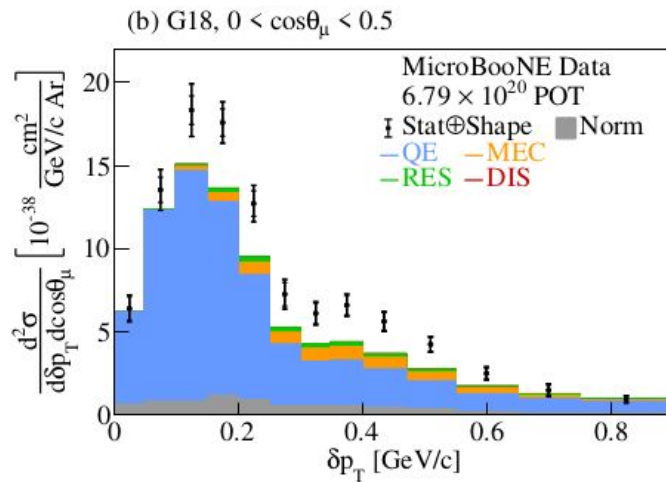
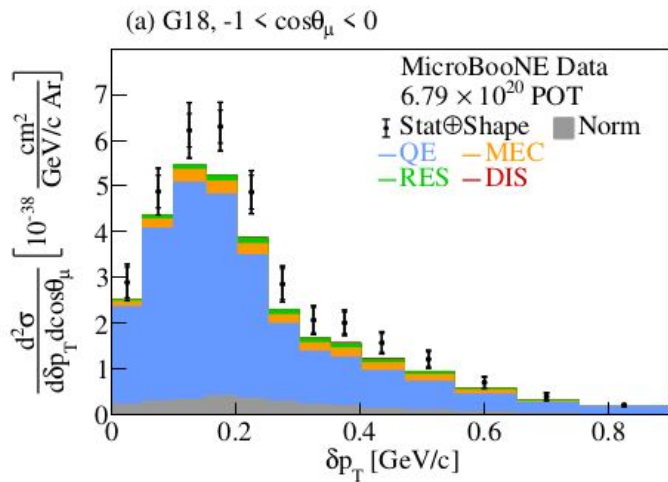
(a) G18, All events

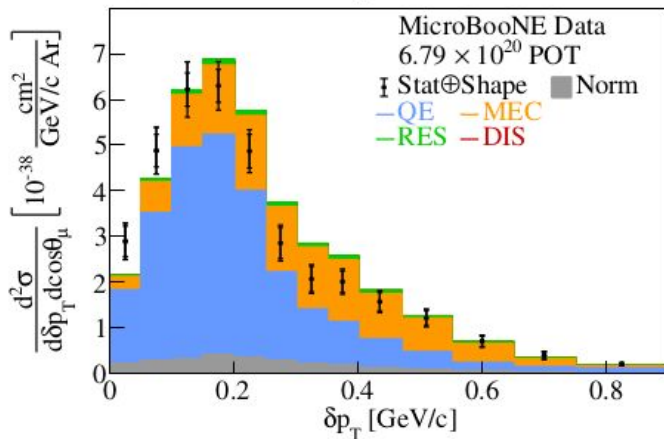
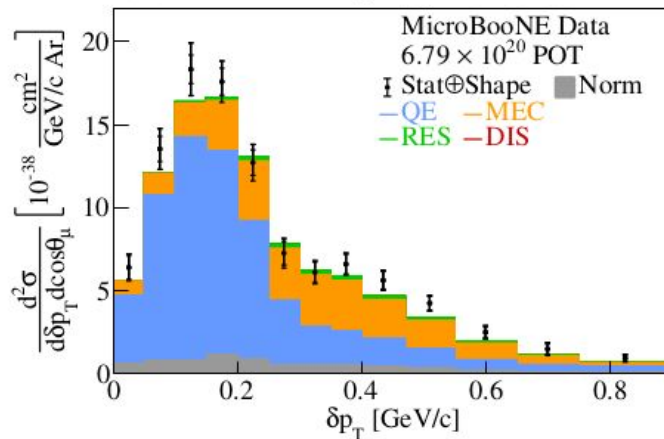
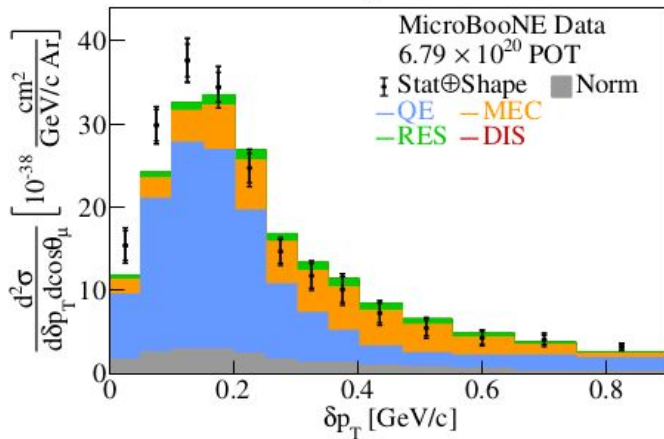
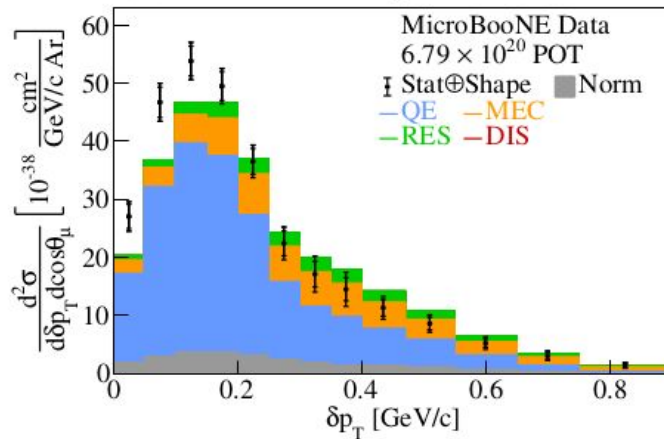


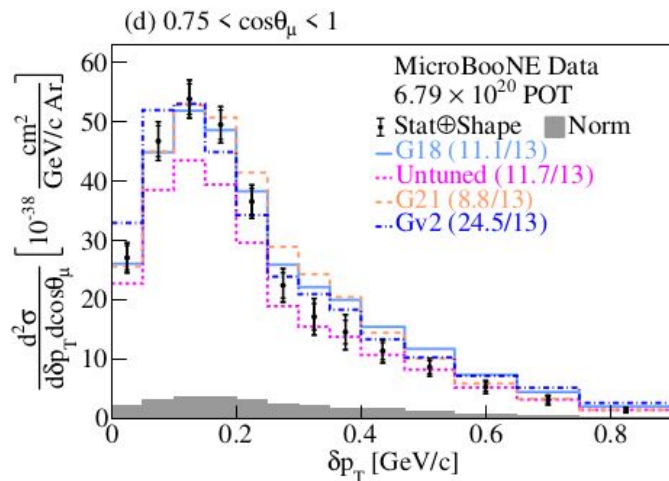
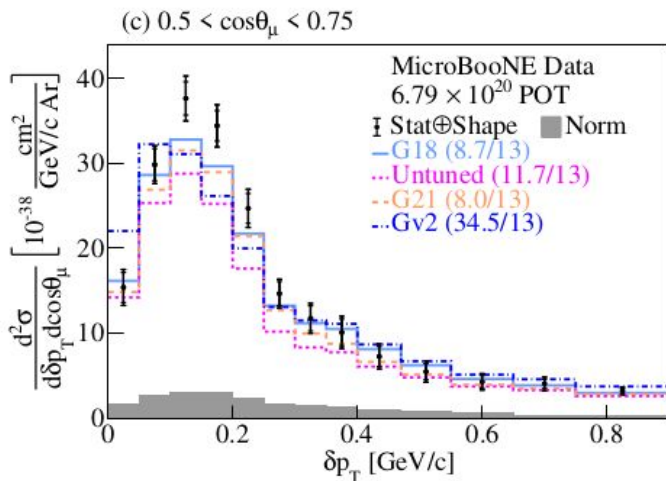
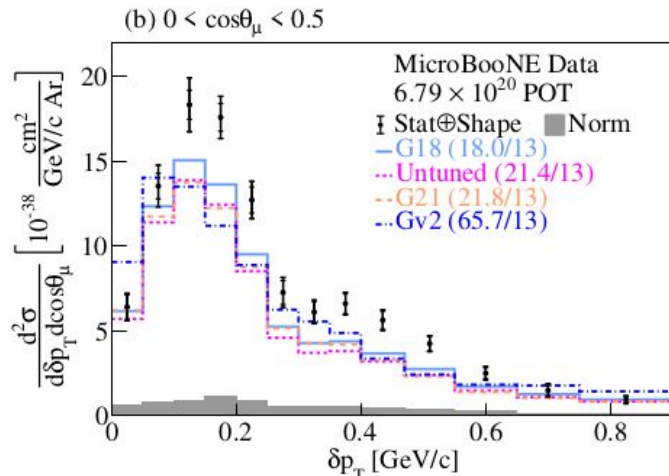
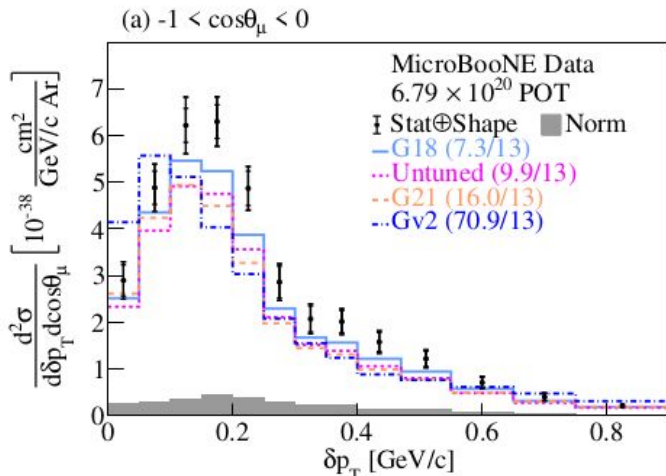
(b) G18 NoFSI, All events

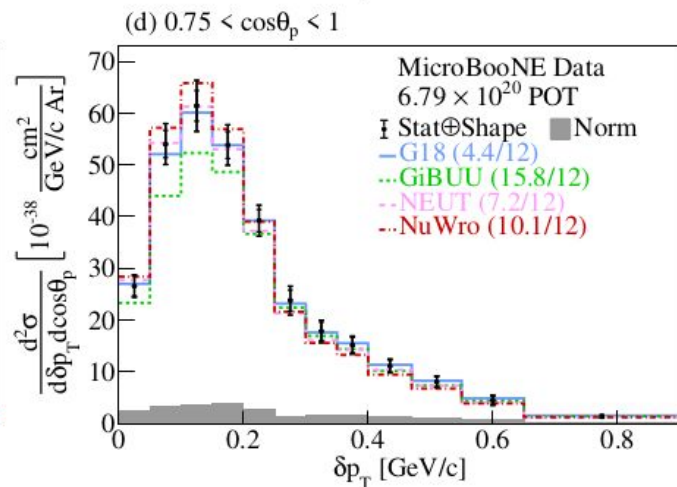
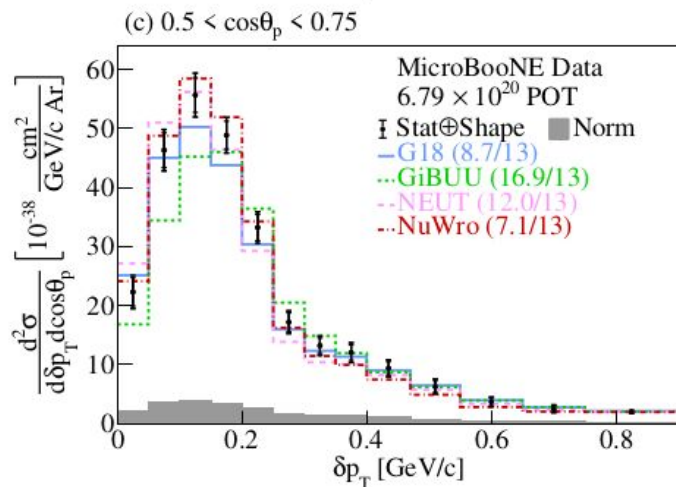
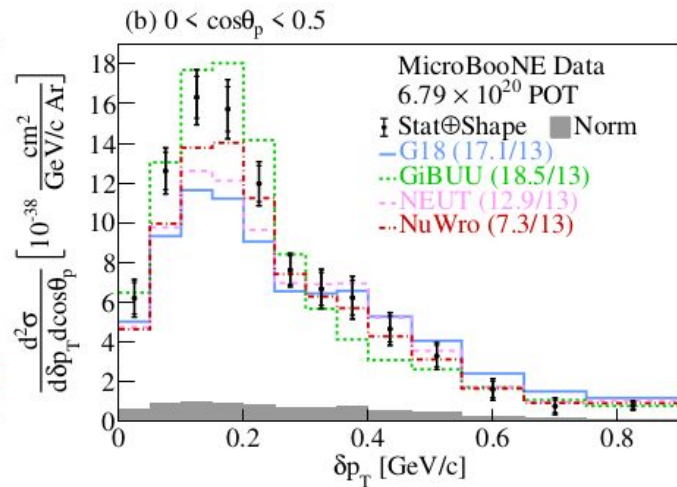
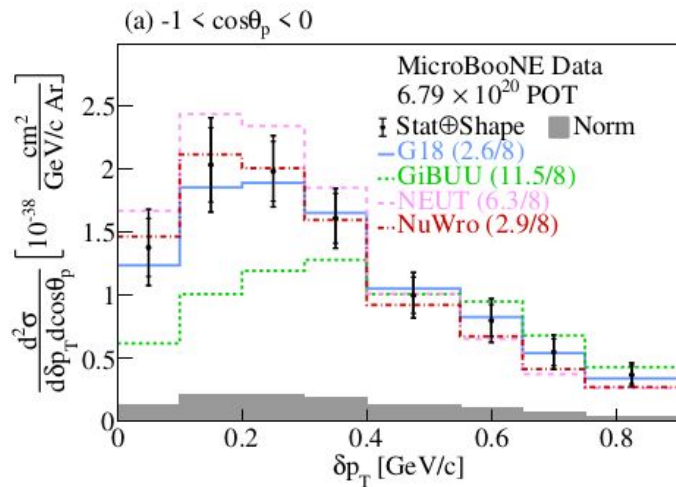


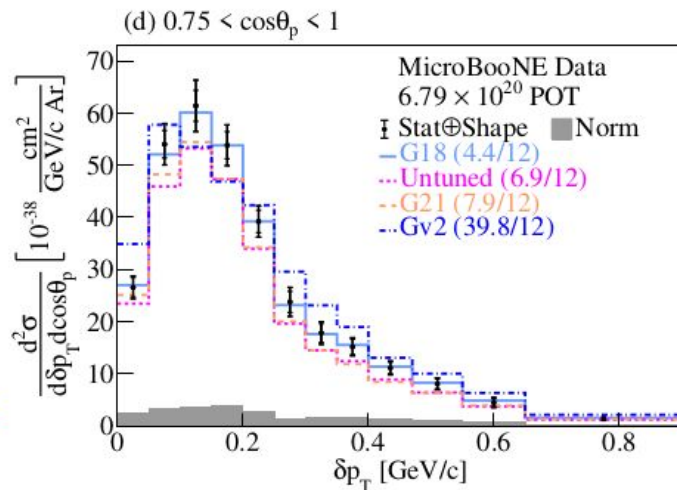
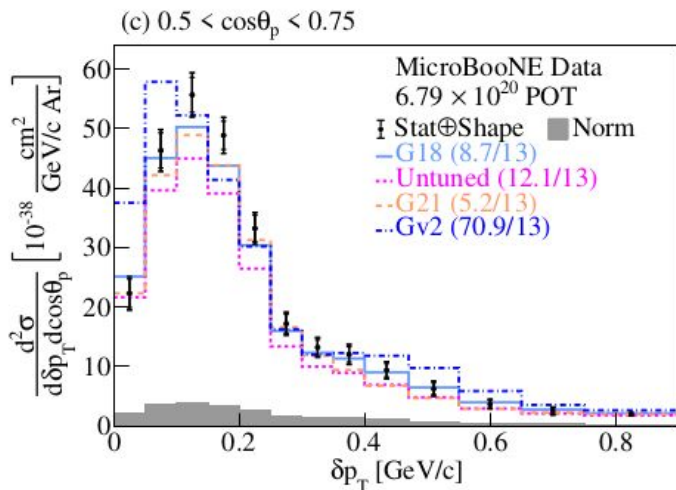
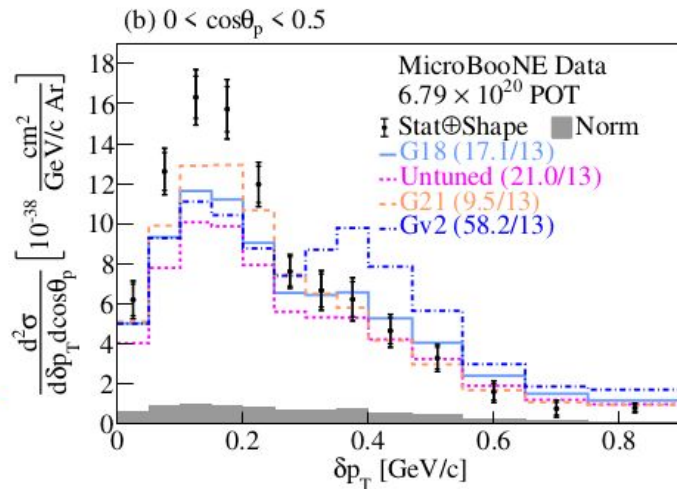
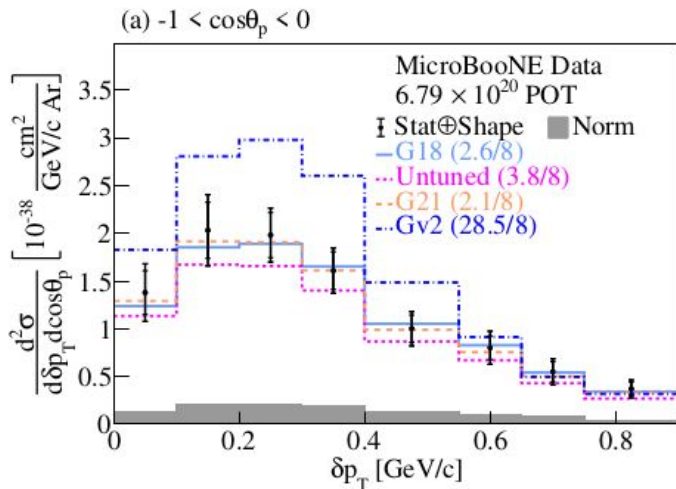


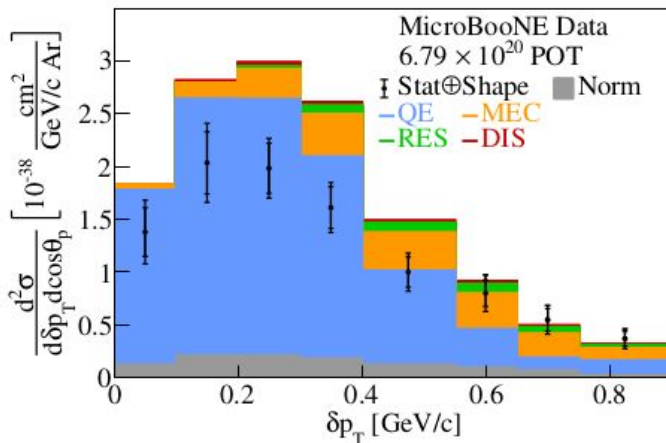
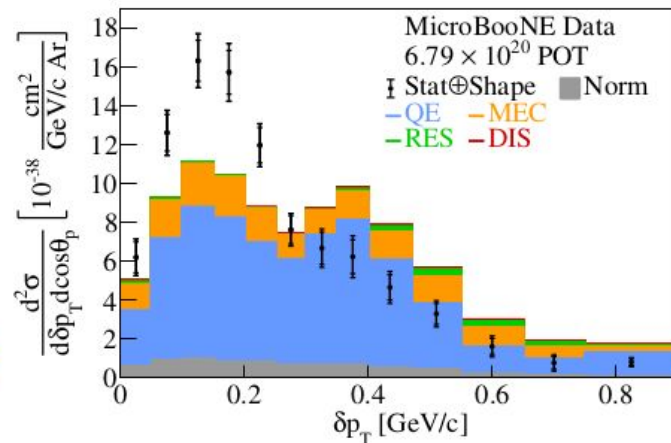
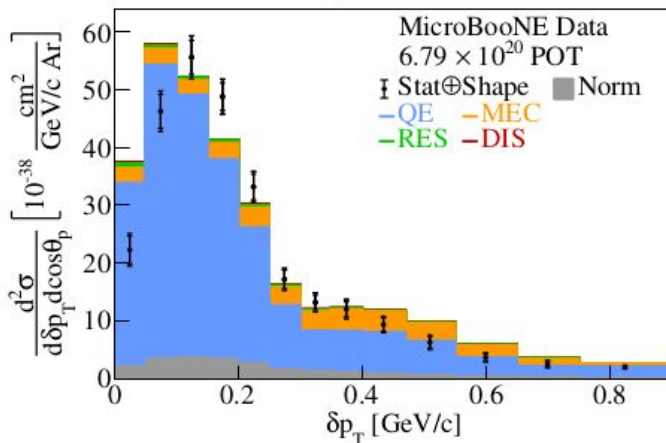
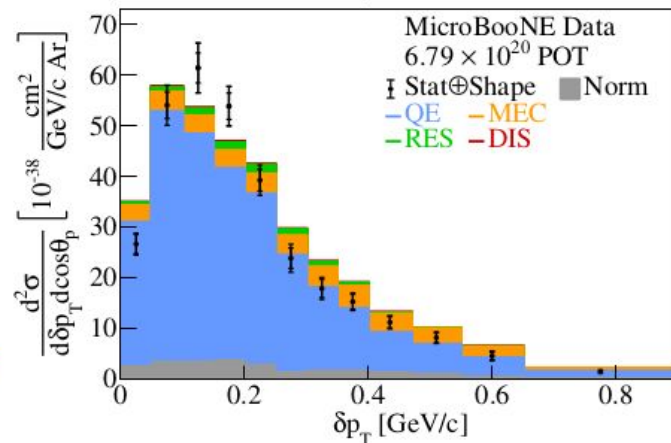


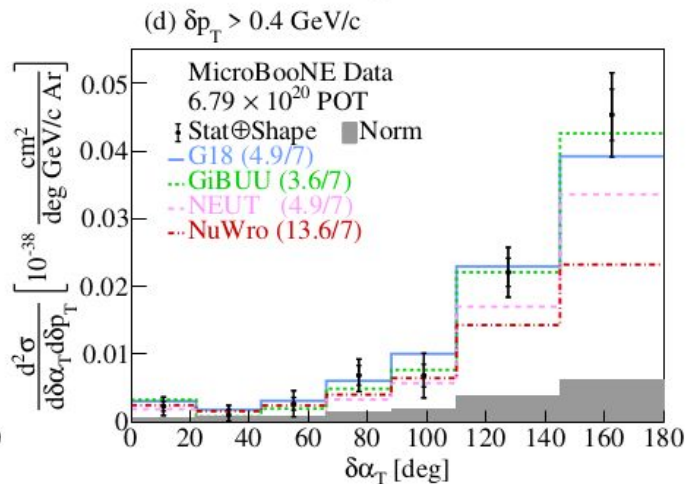
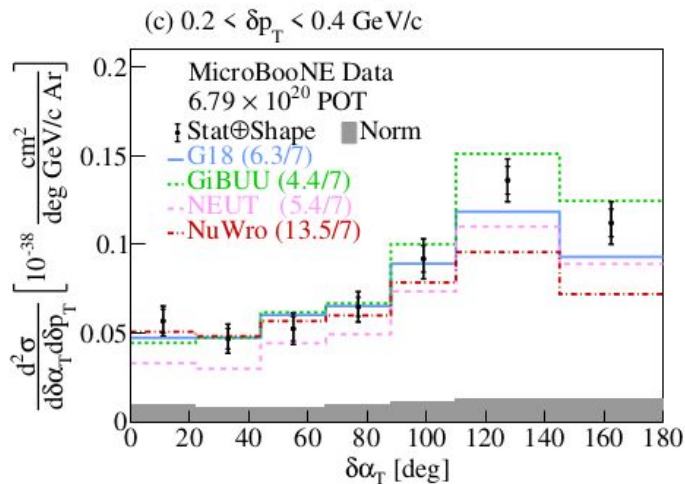
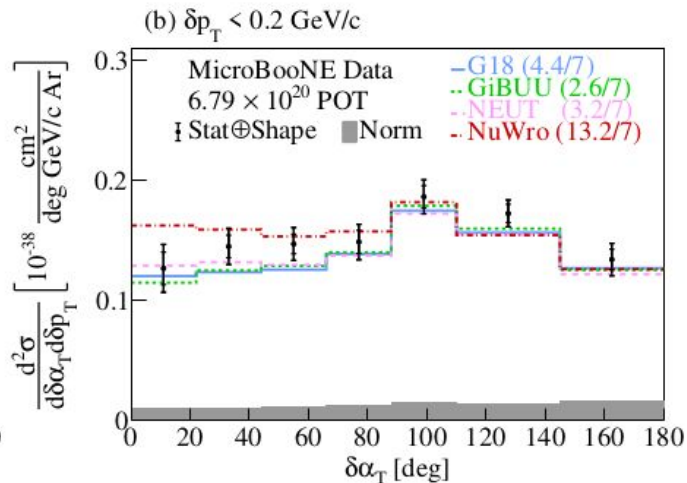
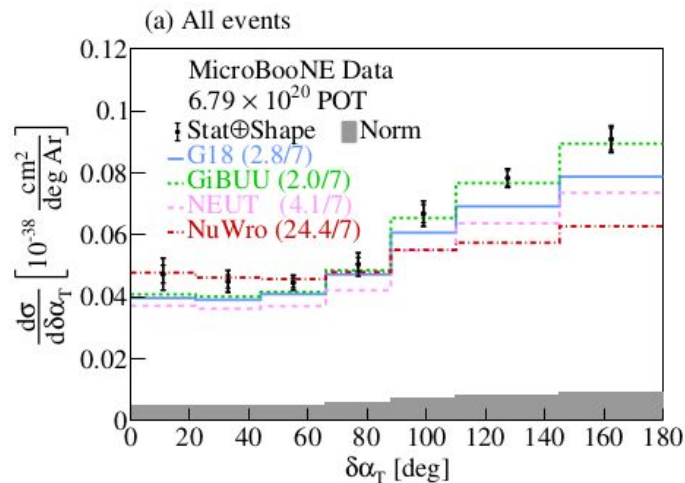
(a) GiBUU, $-1 < \cos\theta_\mu < 0$ (b) GiBUU, $0 < \cos\theta_\mu < 0.5$ (c) GiBUU, $0.5 < \cos\theta_\mu < 0.75$ (d) GiBUU, $0.75 < \cos\theta_\mu < 1$ 

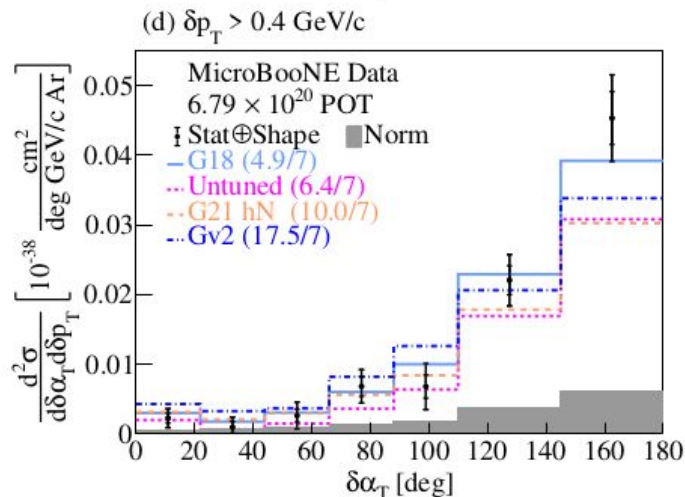
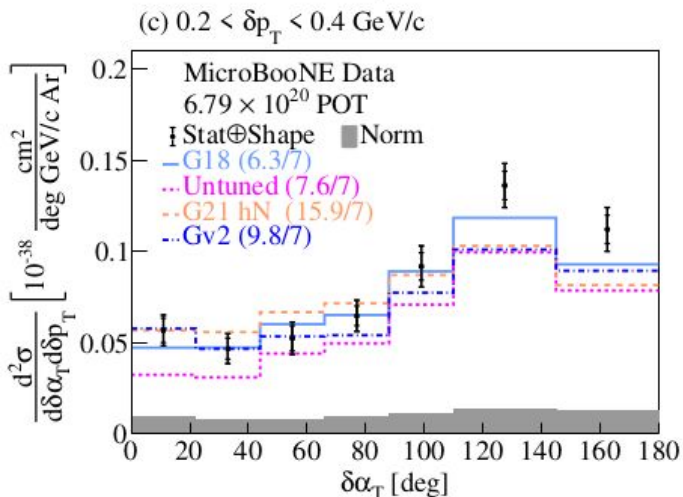
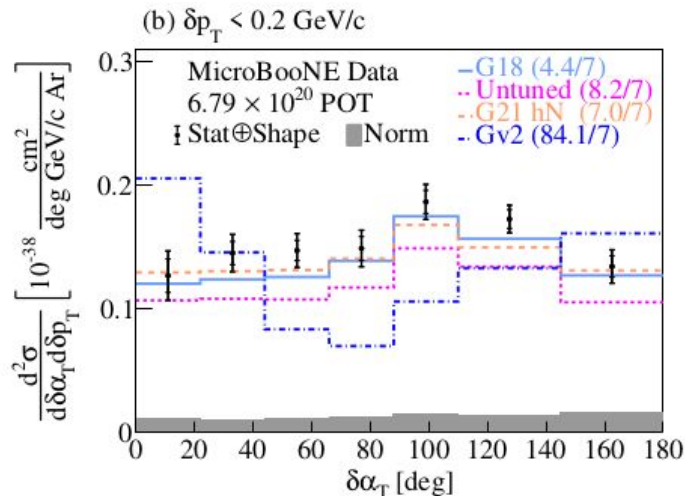
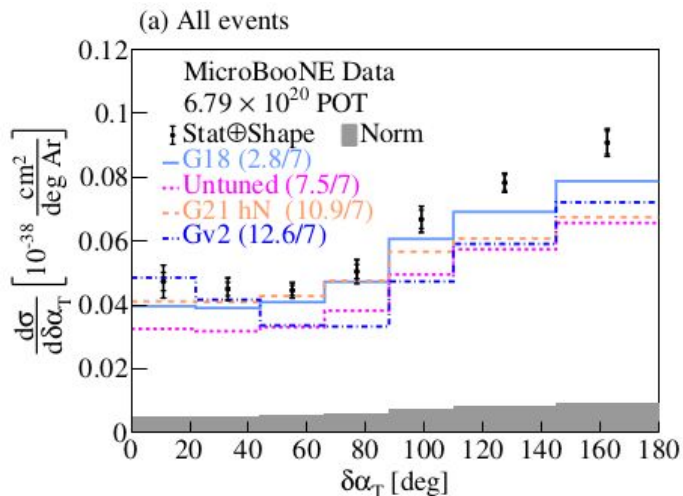


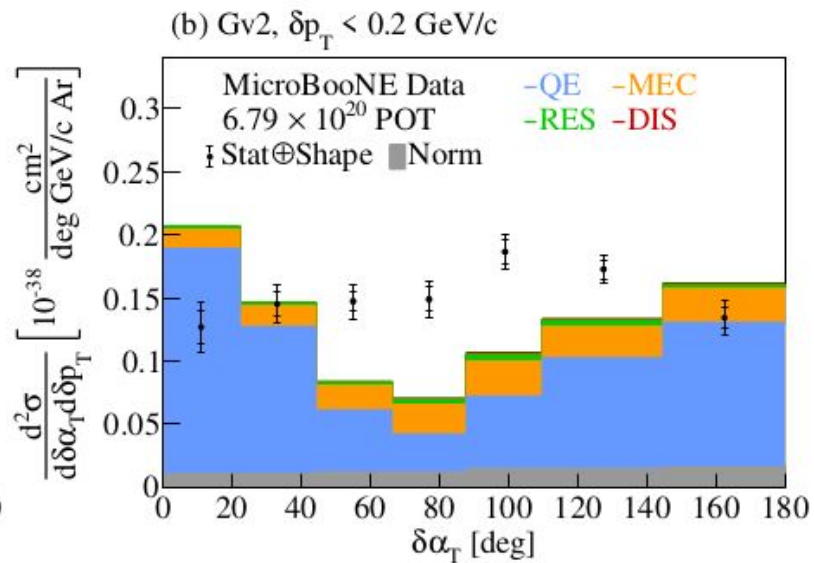
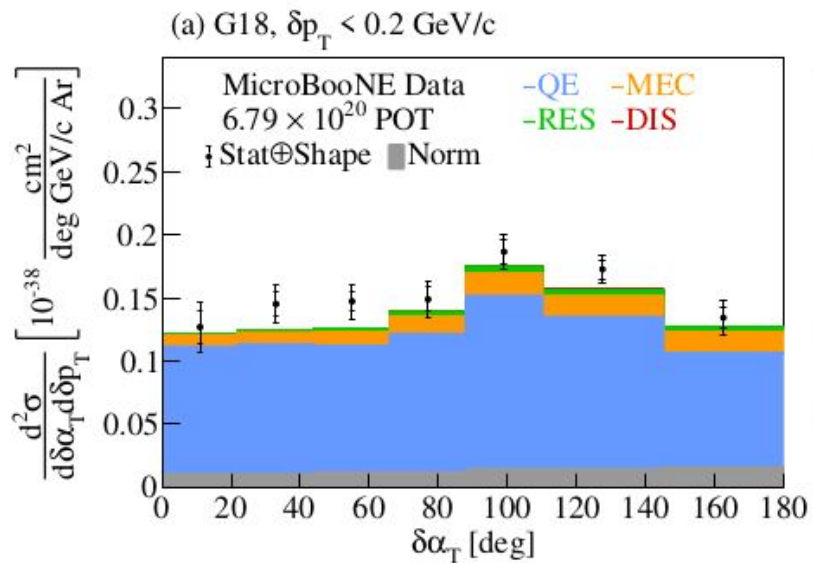


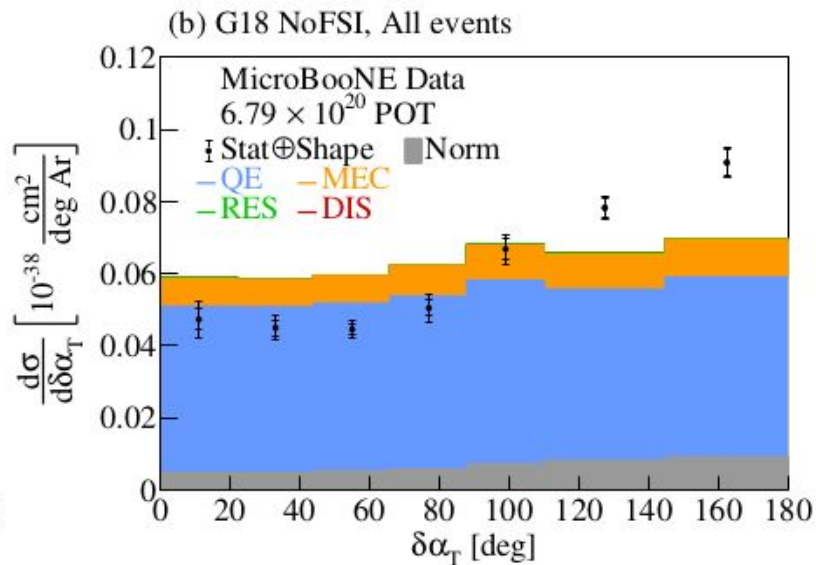
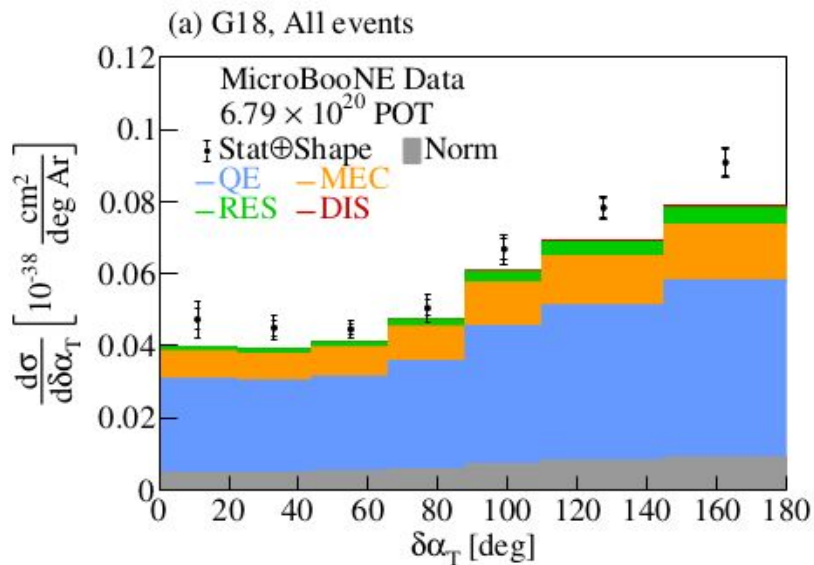


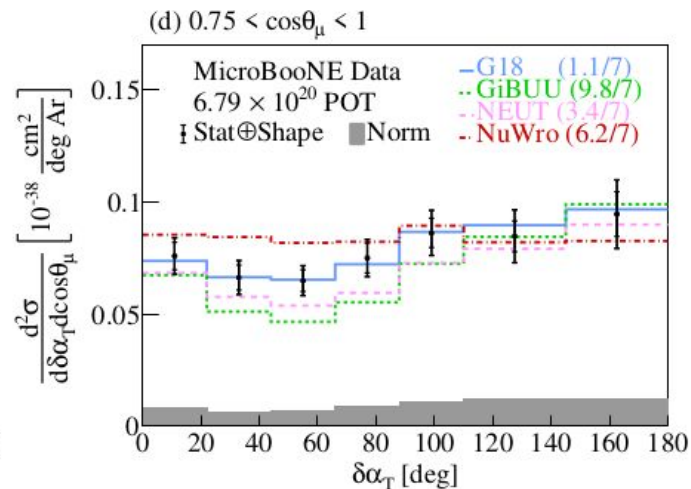
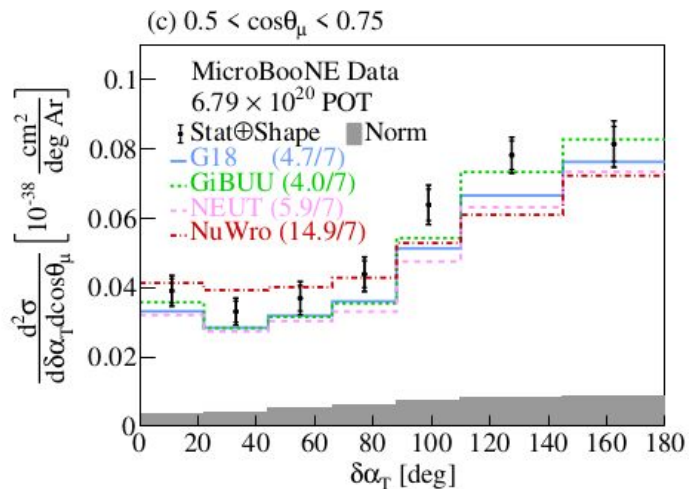
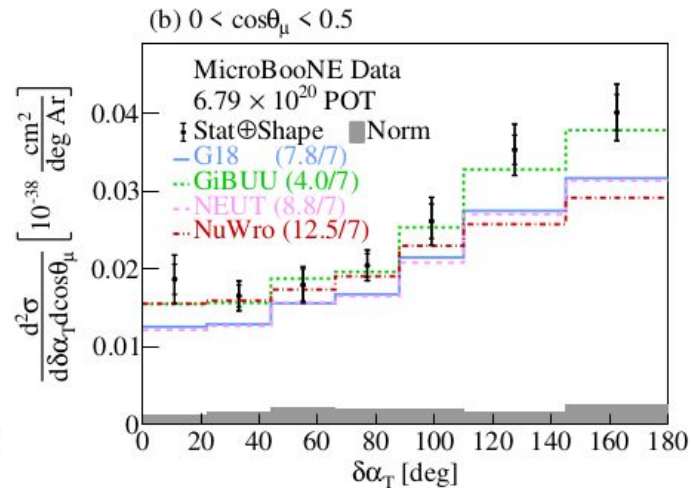
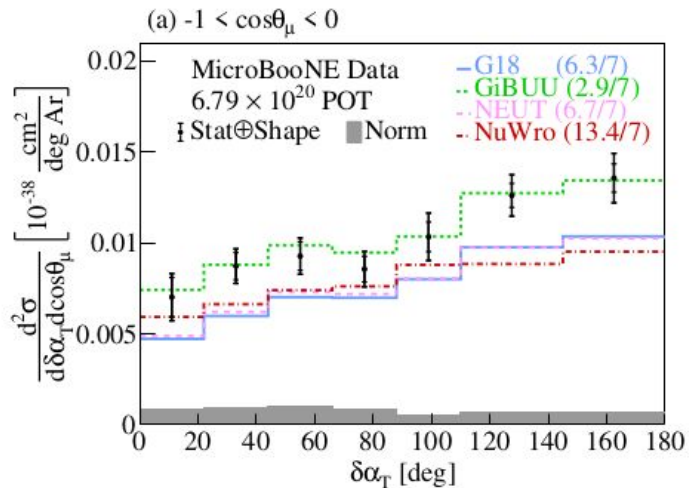
(a) Gv2, $-1 < \cos\theta_p < 0$ (b) Gv2, $0 < \cos\theta_p < 0.5$ (c) Gv2, $0.5 < \cos\theta_p < 0.75$ (d) Gv2, $0.75 < \cos\theta_p < 1$ 

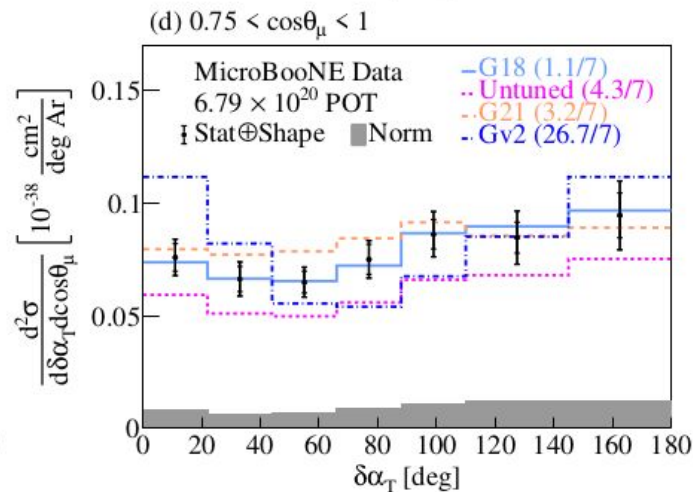
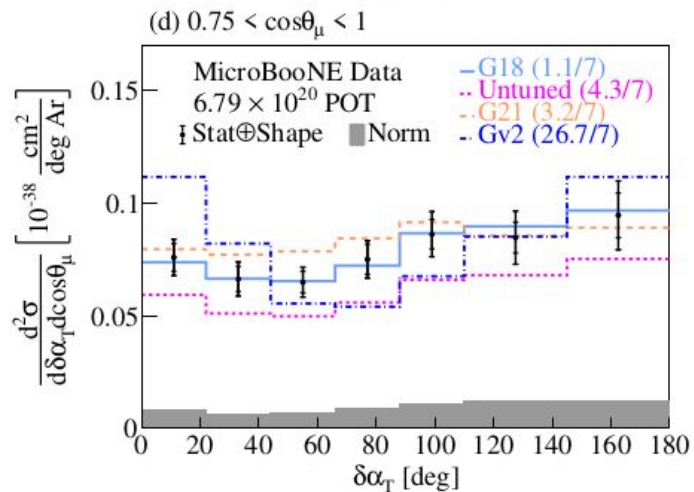
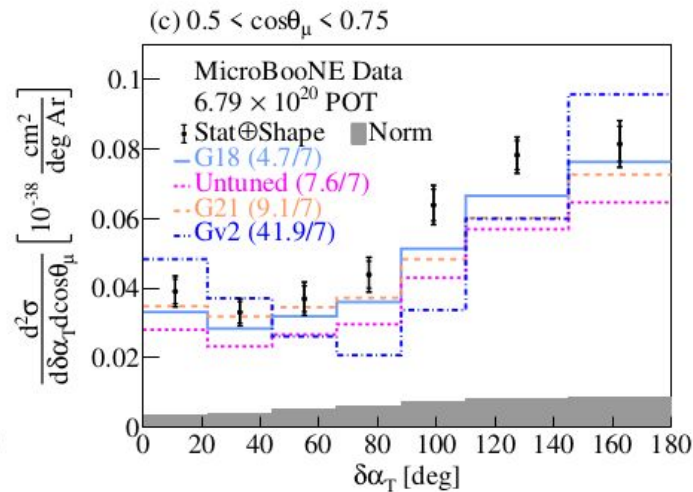
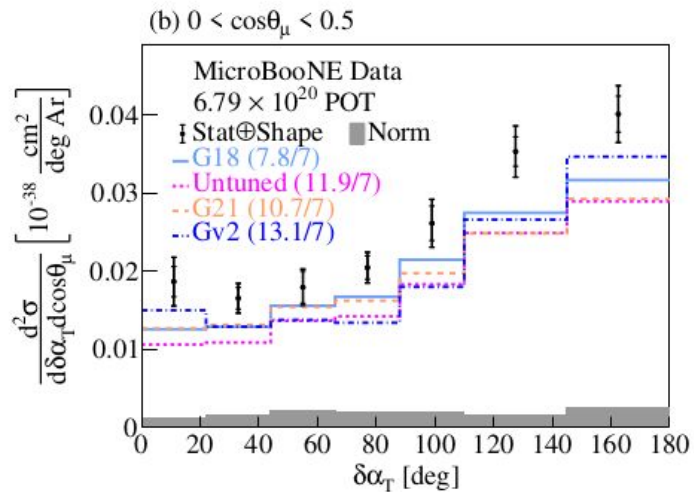


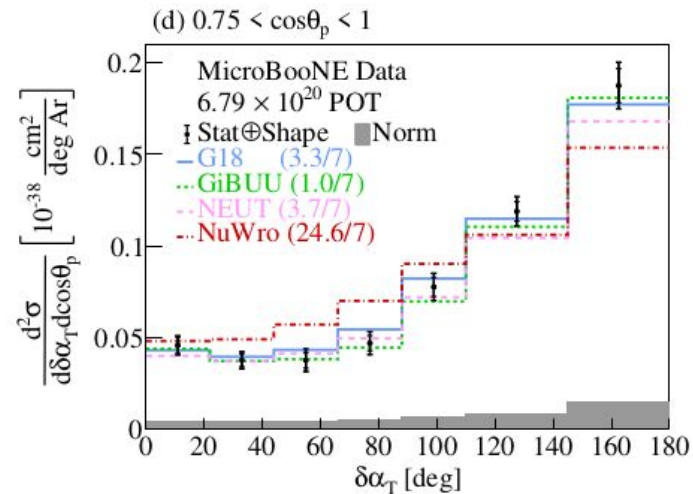
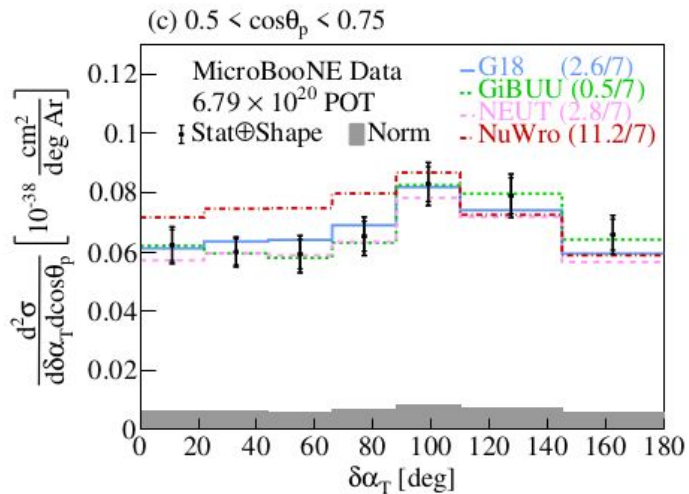
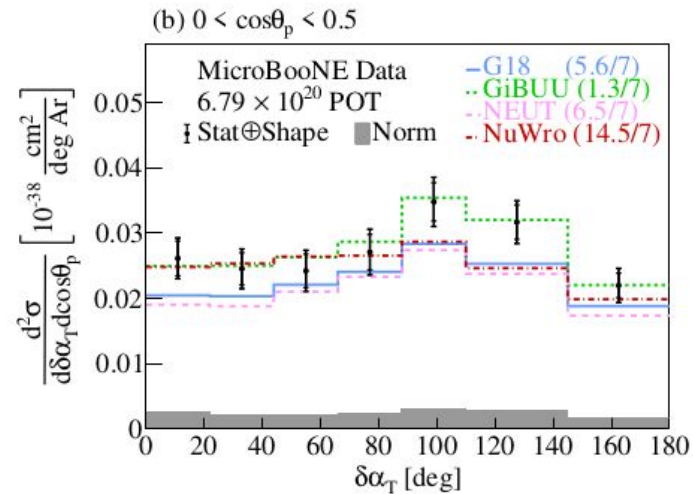
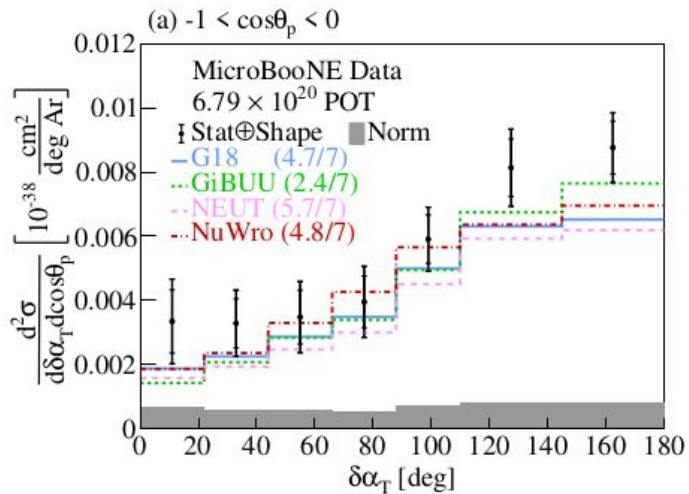


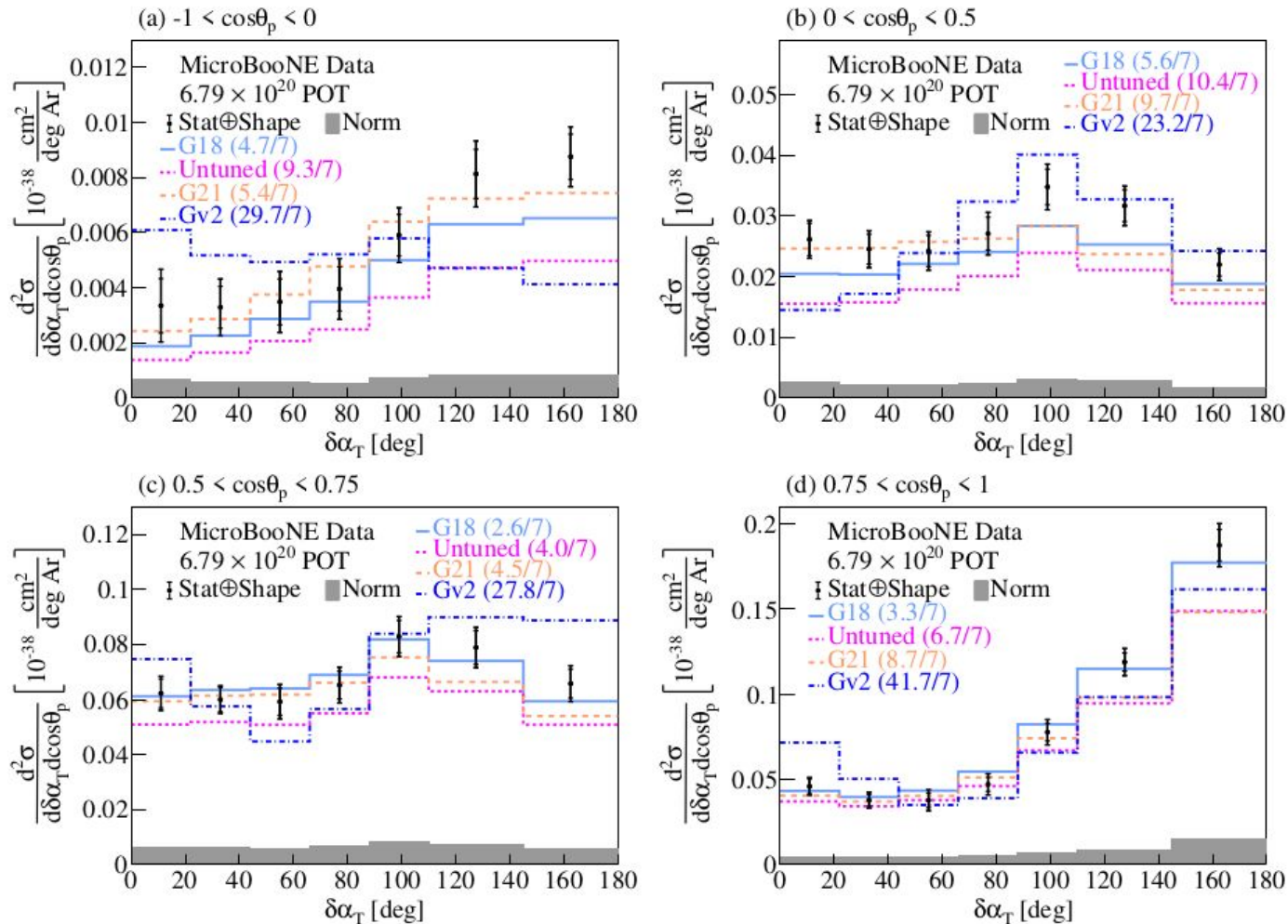


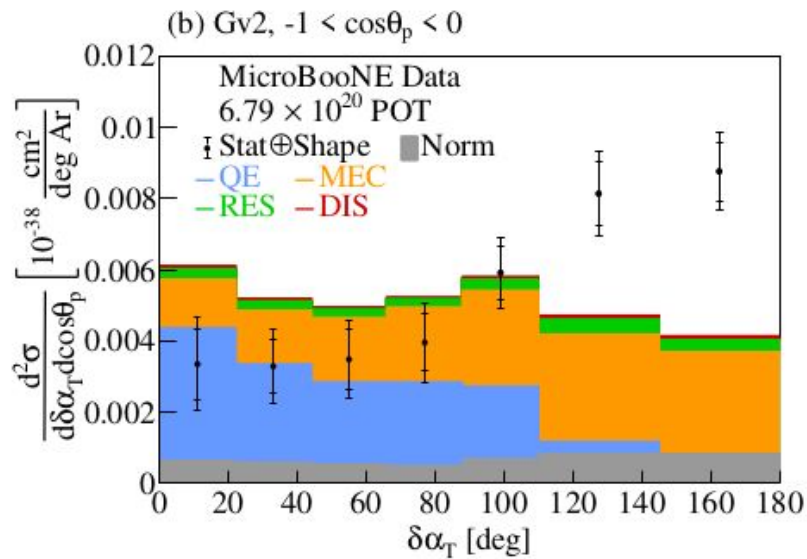
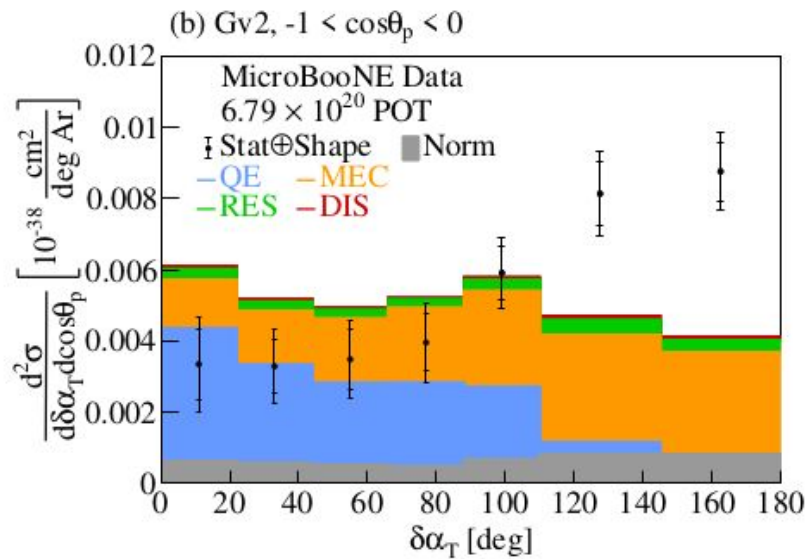


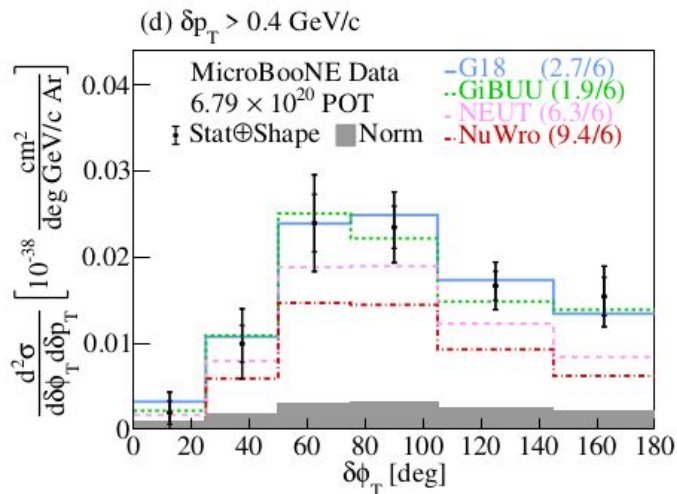
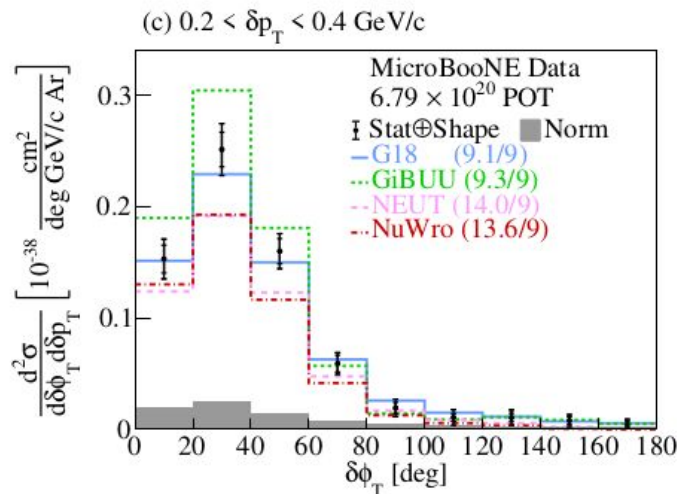
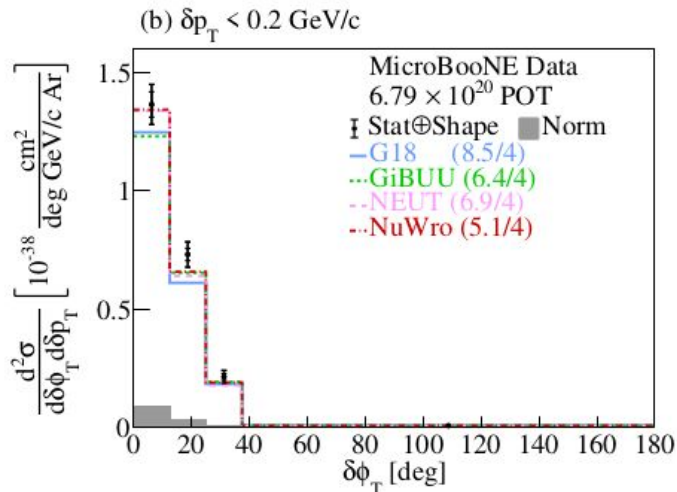
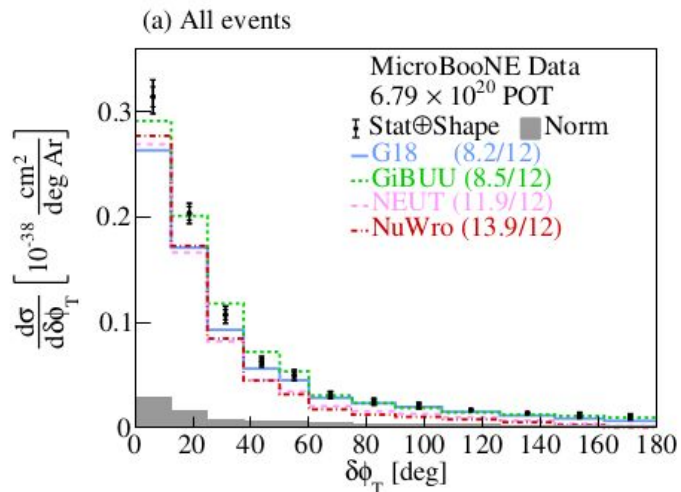


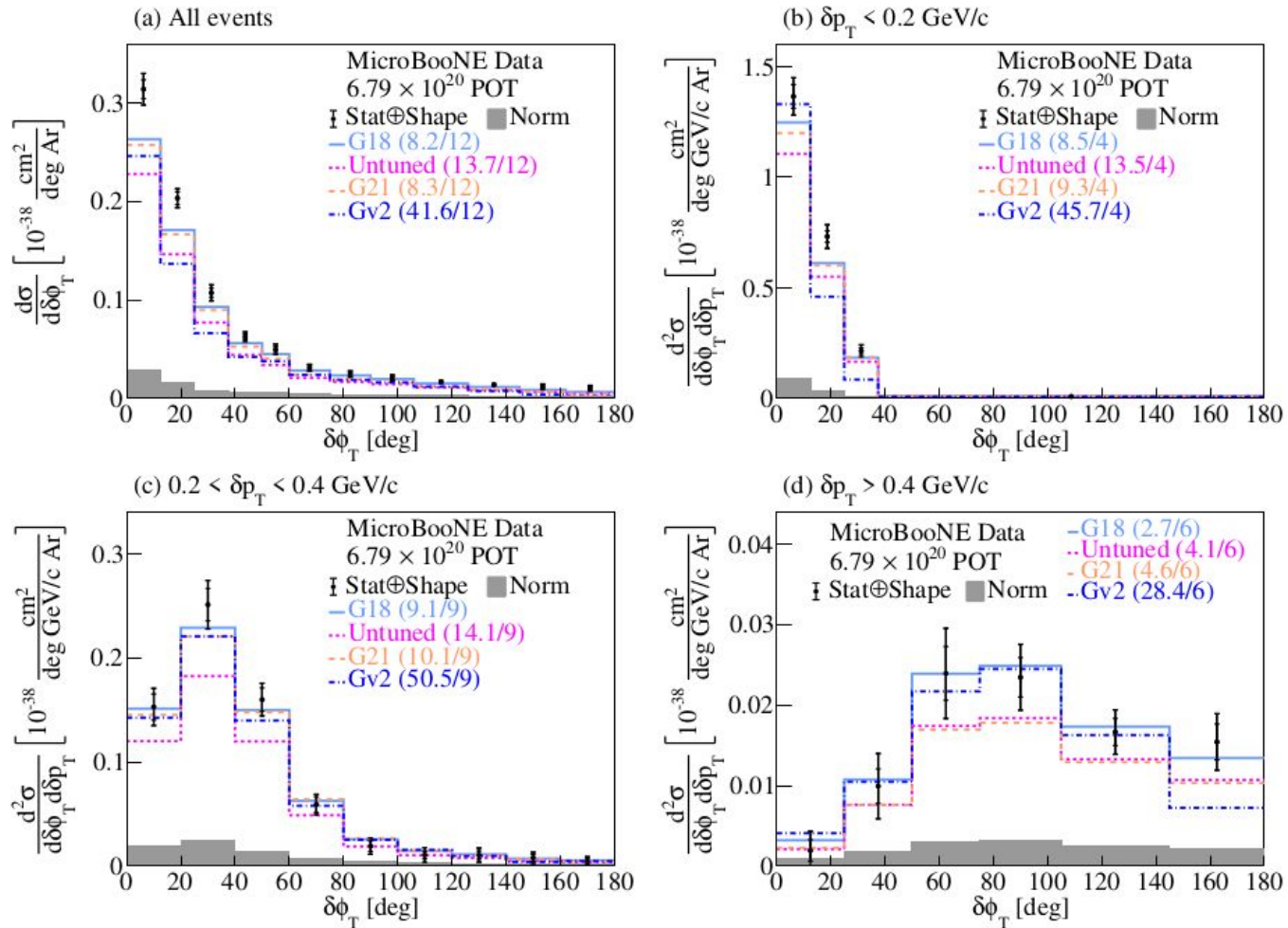


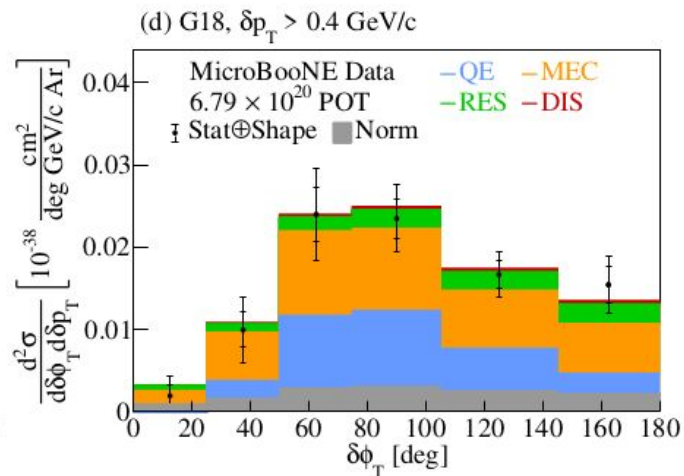
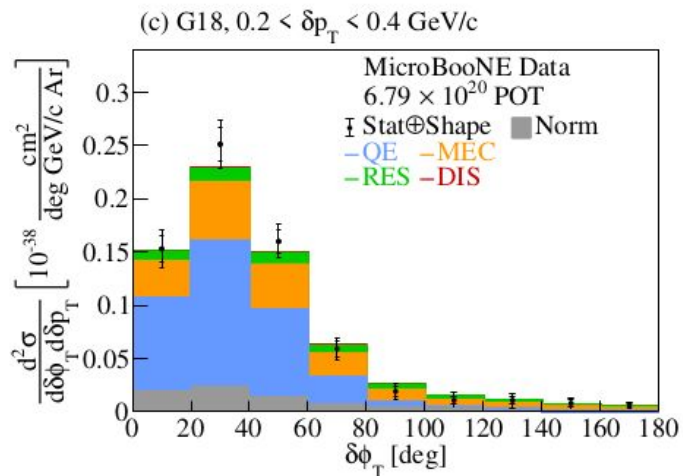
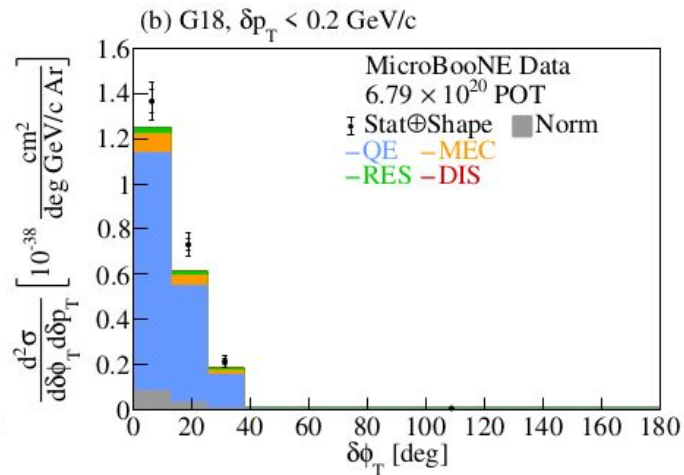
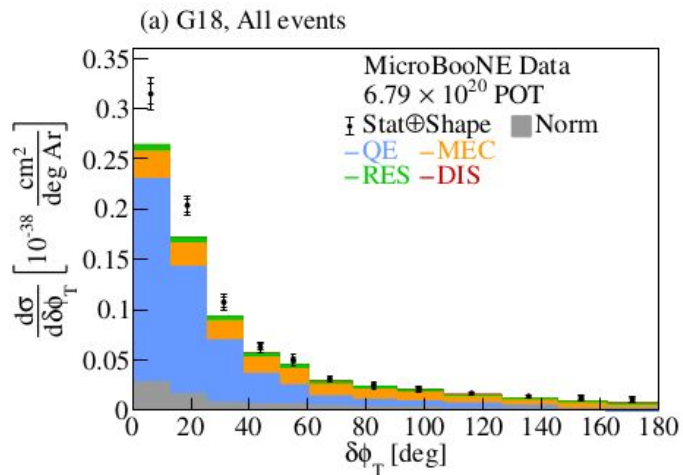


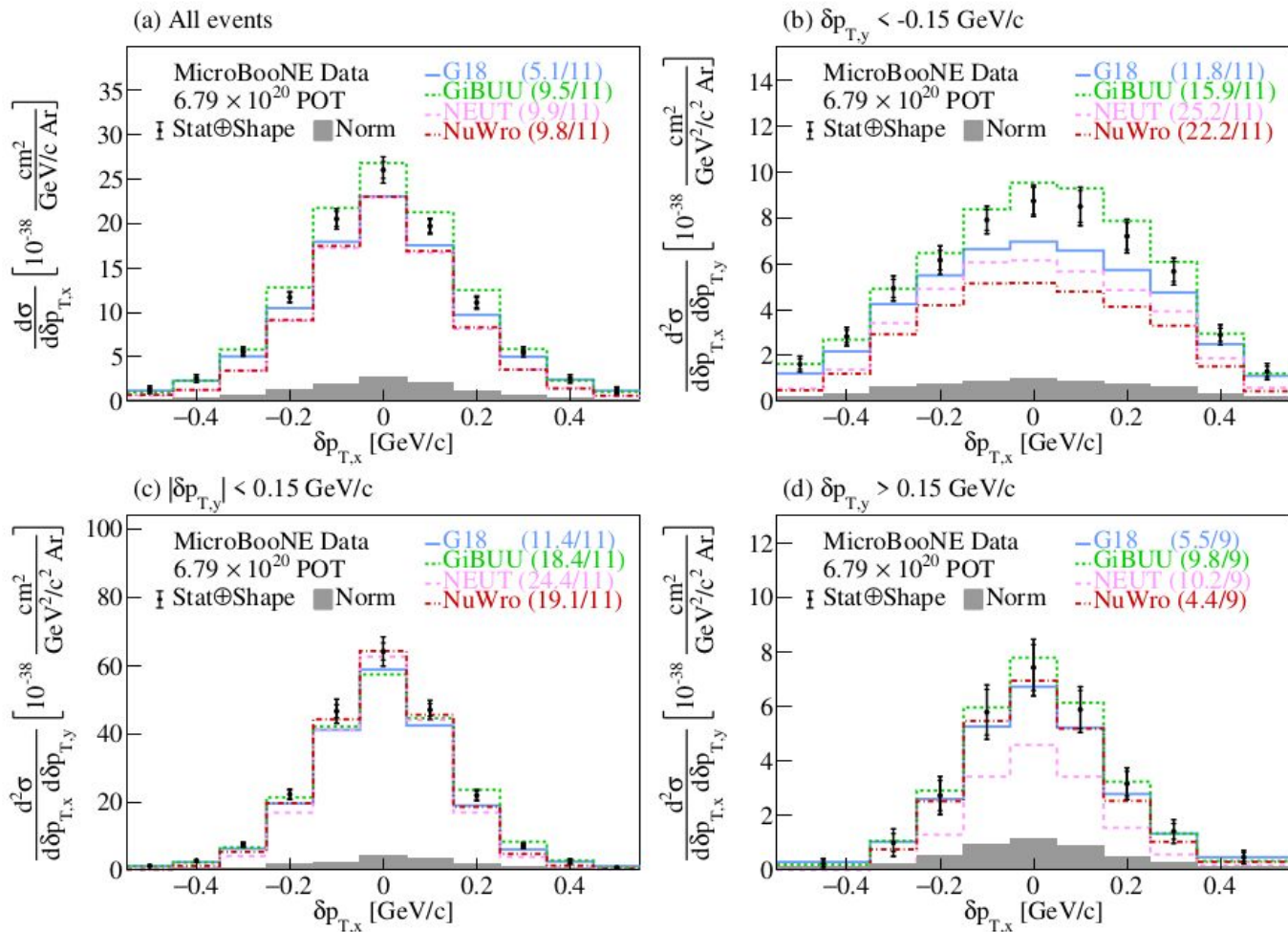


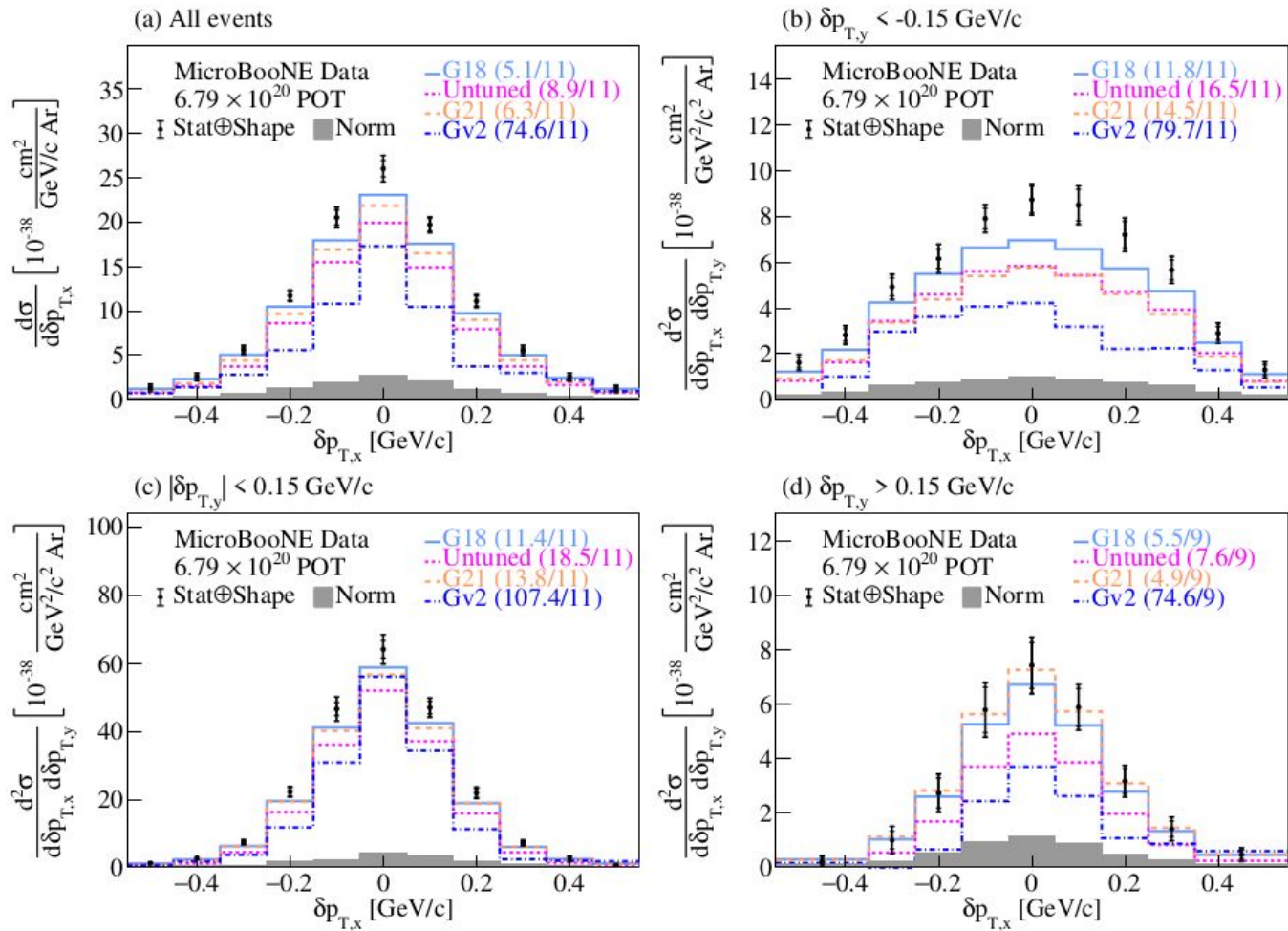


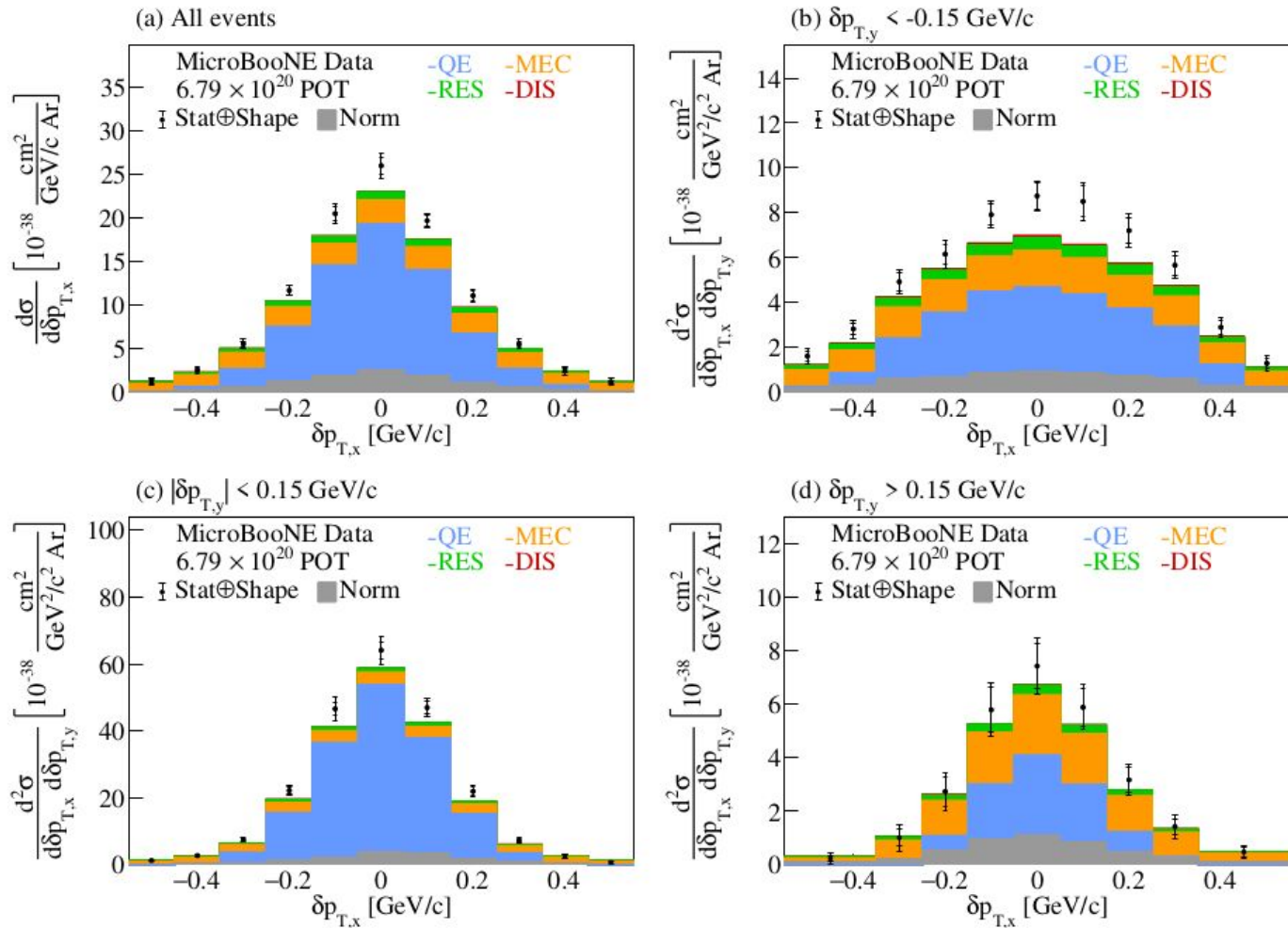


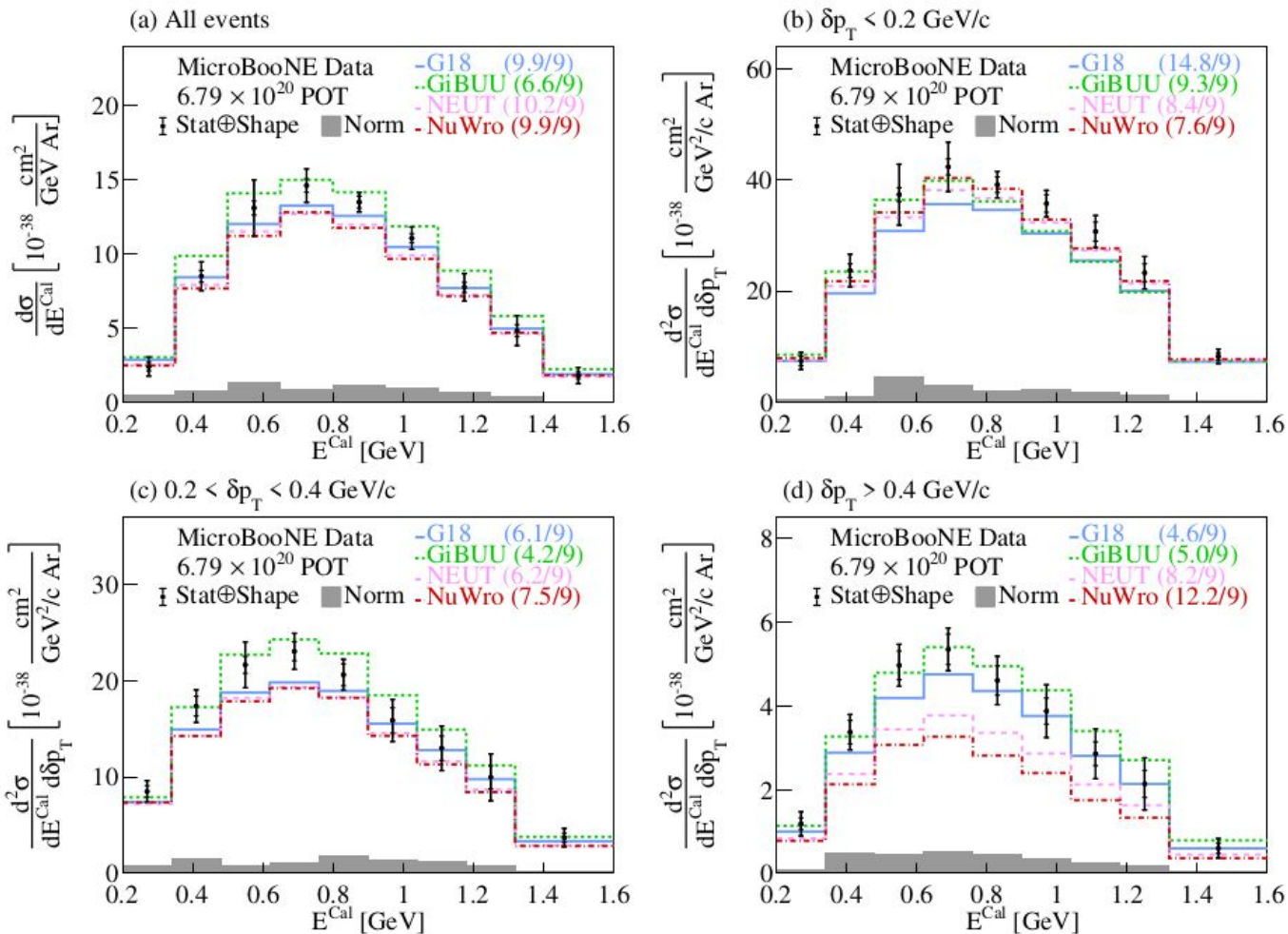


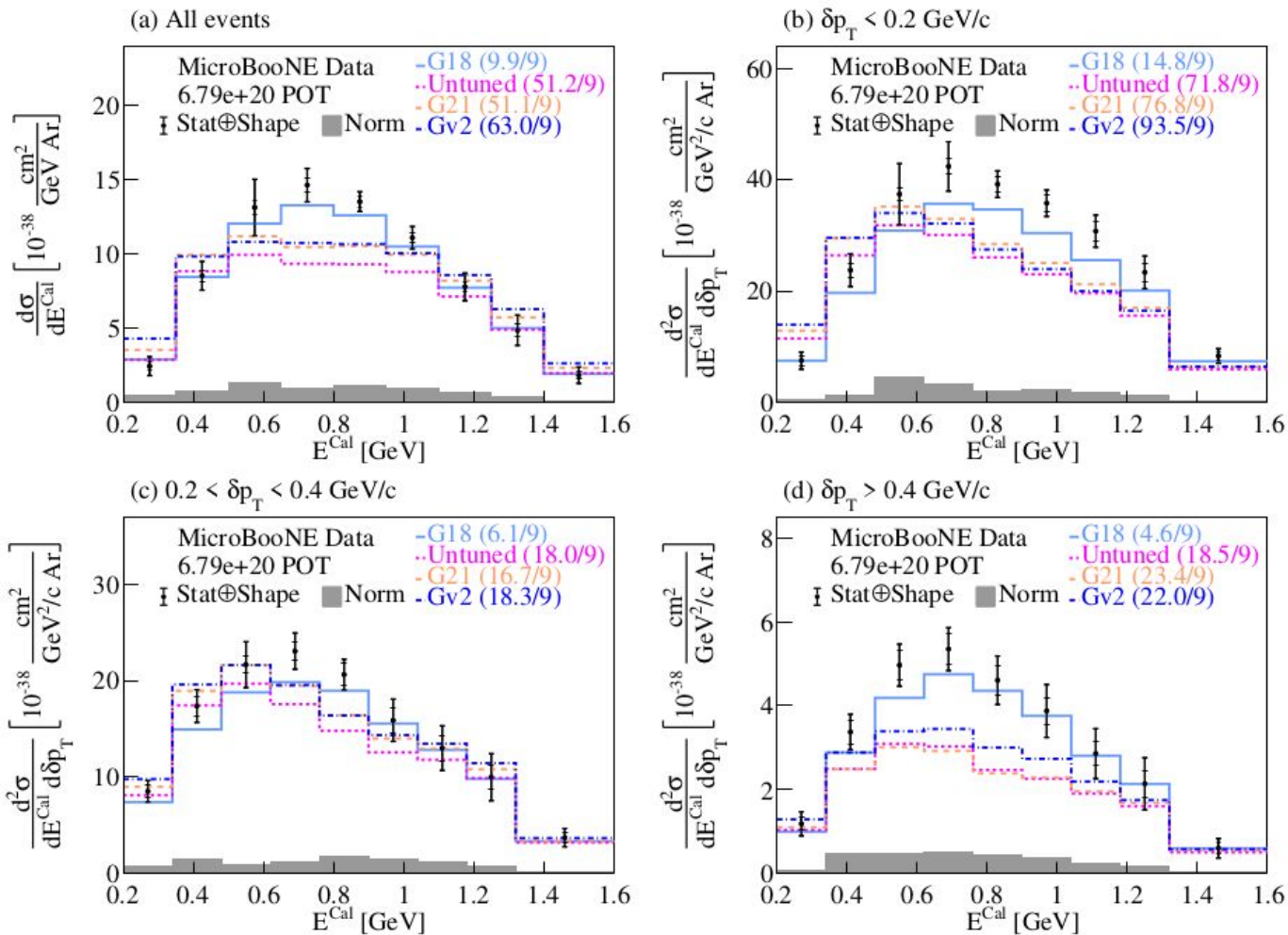


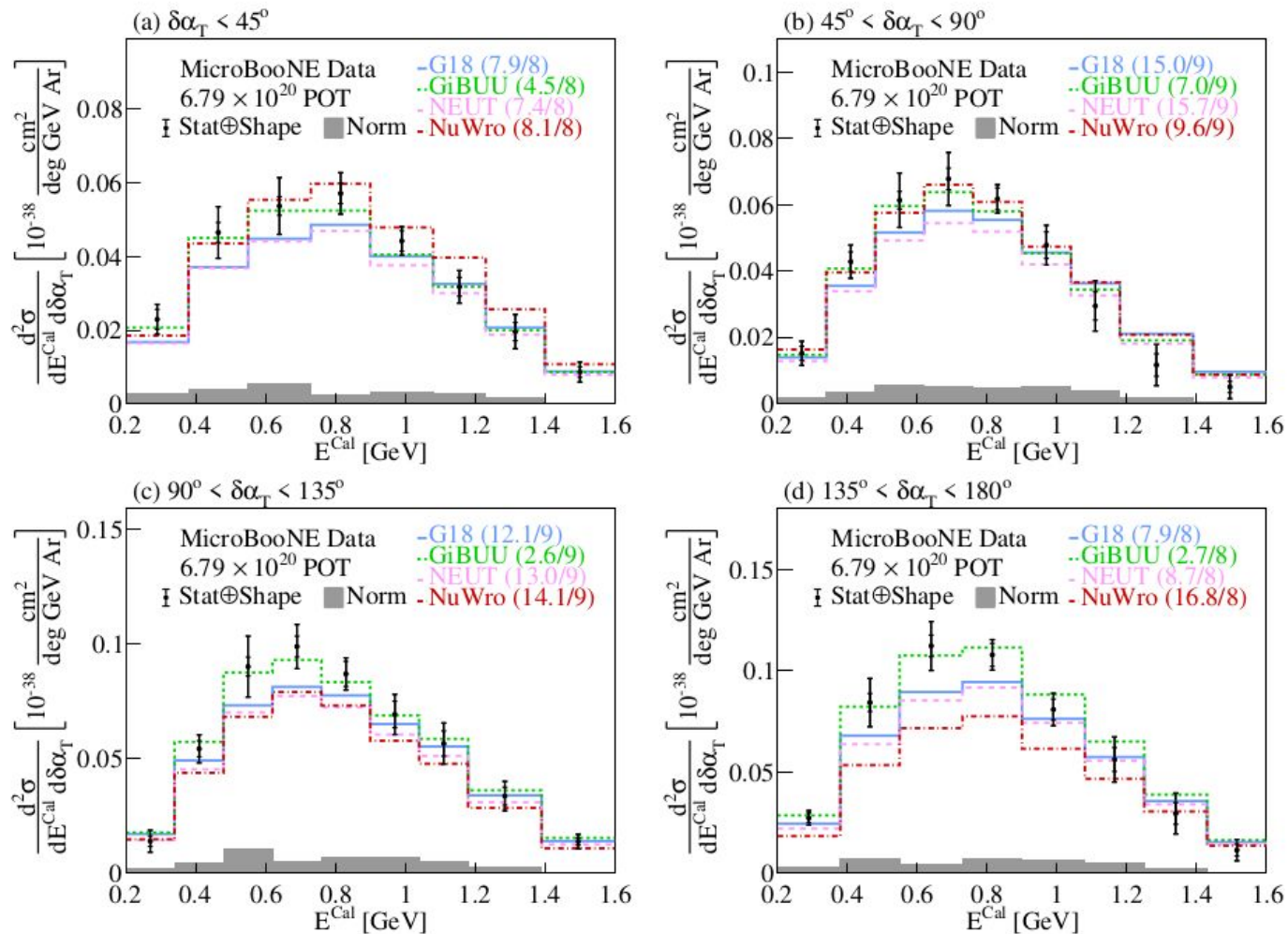


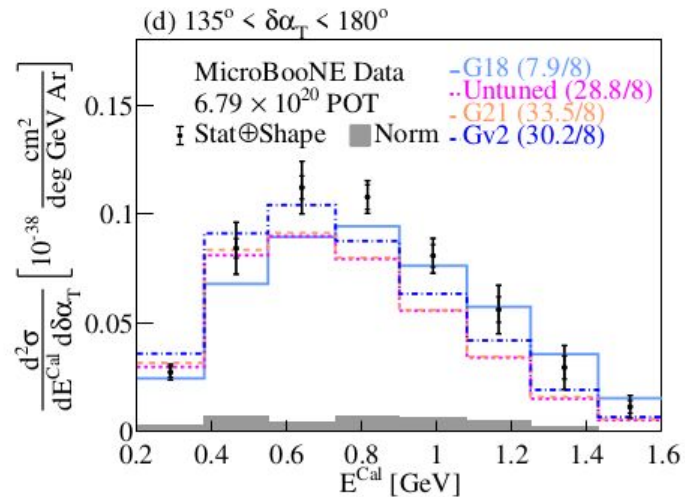
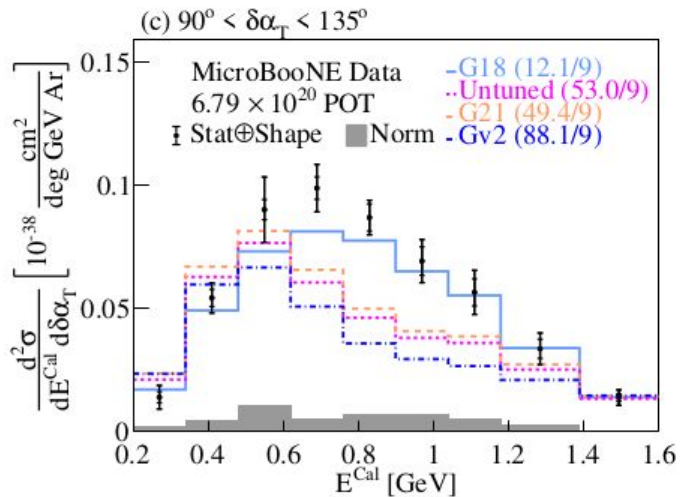
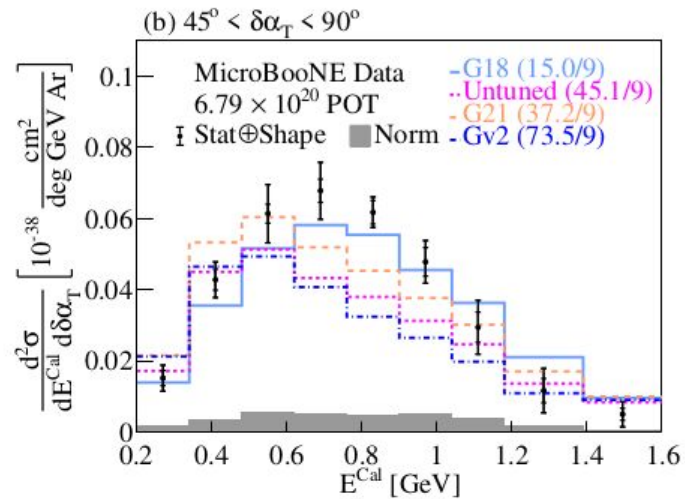
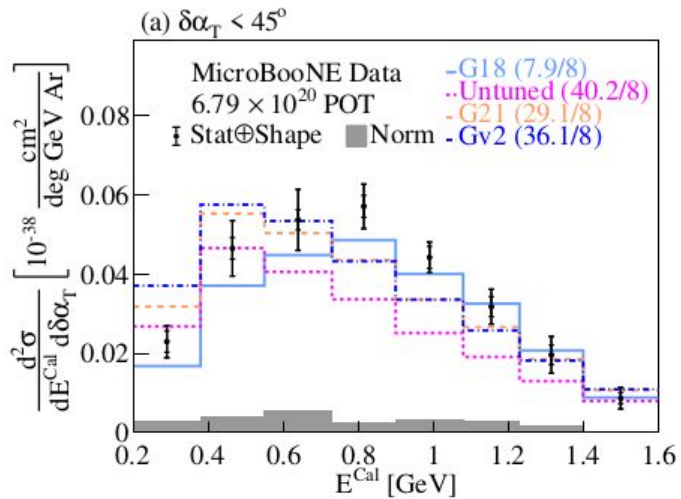


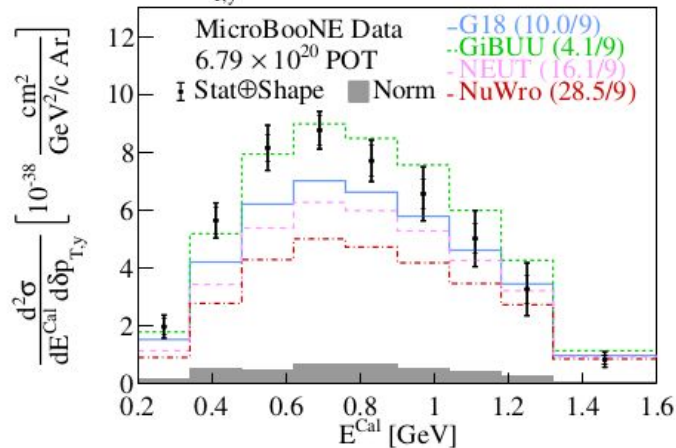
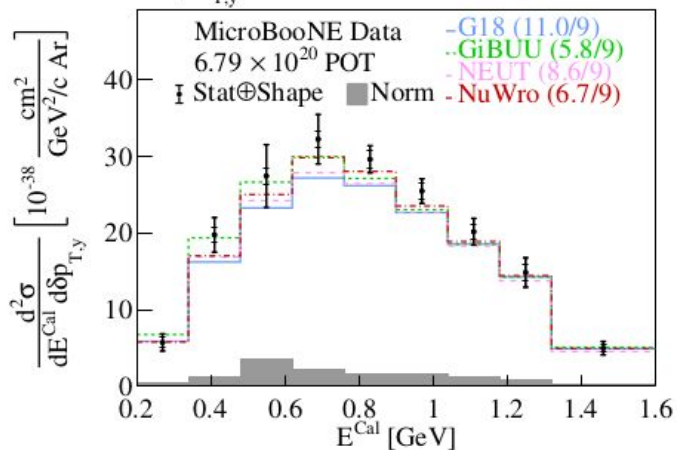
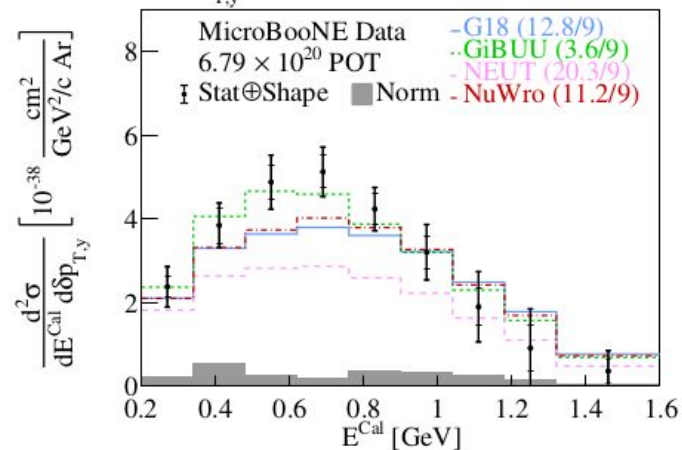


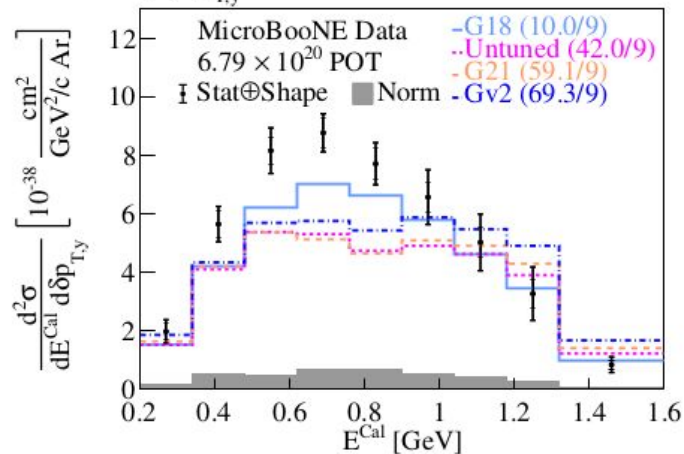
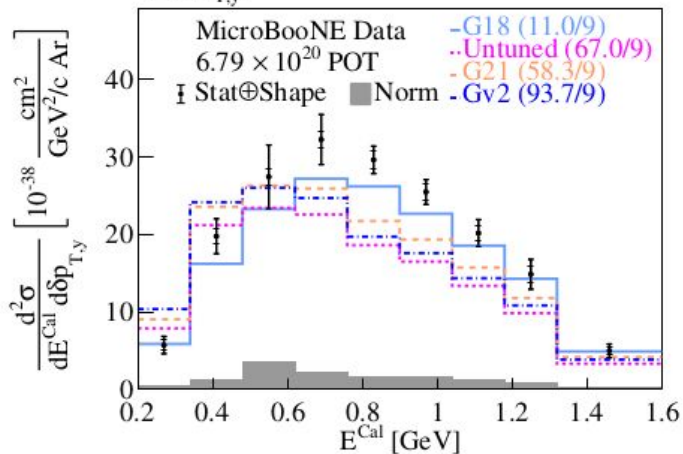
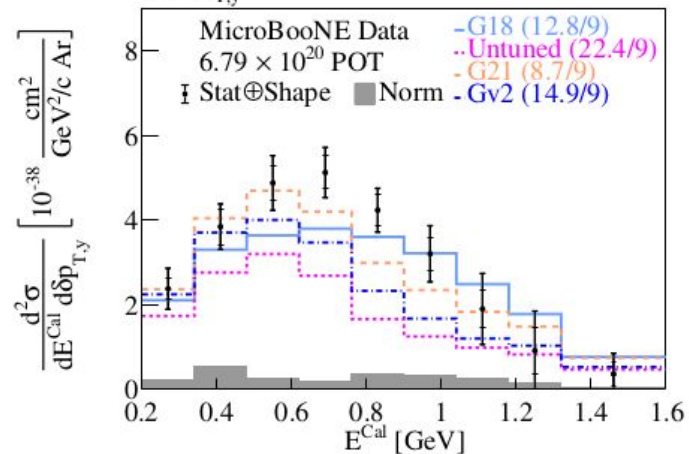




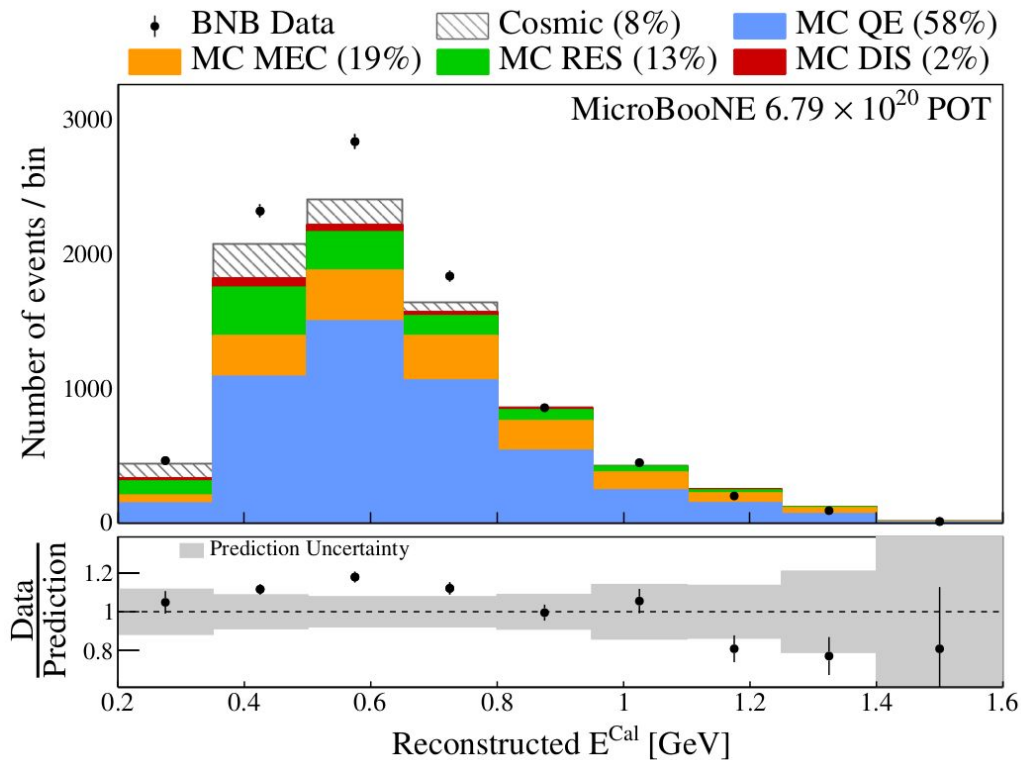




(b) $\delta p_{T,y} < -0.15$ GeV/c(a) $|\delta p_{T,y}| < 0.15$ GeV/c(c) $\delta p_{T,y} > 0.15$ GeV/c

(b) $\delta p_{T,y} < -0.15$ GeV/c(a) $|\delta p_{T,y}| < 0.15$ GeV/c(c) $\delta p_{T,y} > 0.15$ GeV/c

Calorimetric Energy



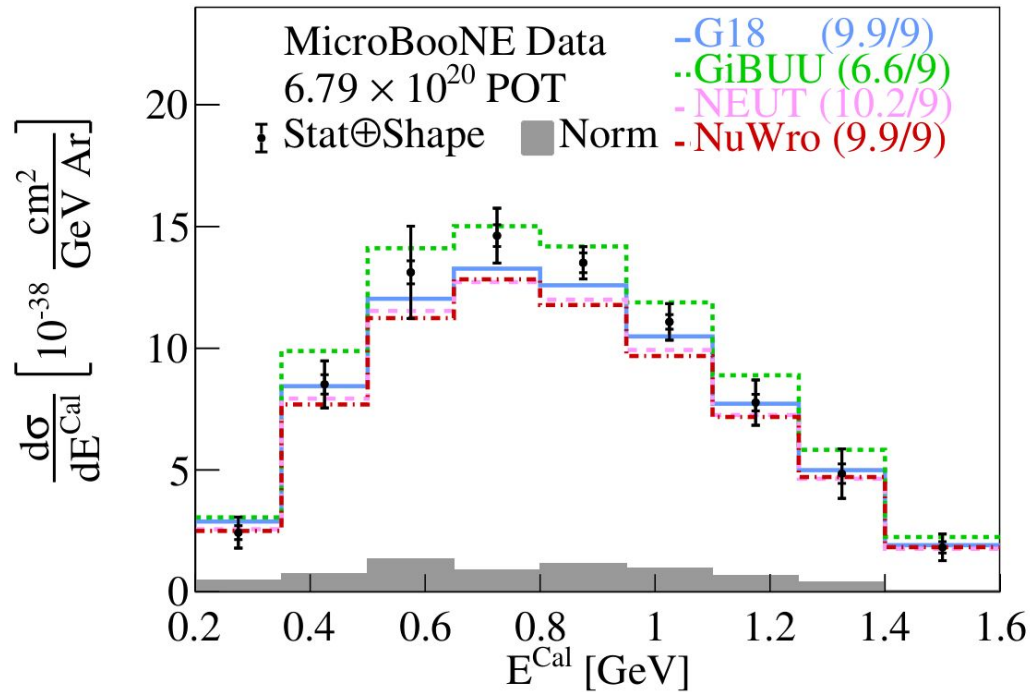
$$E^{\text{Cal}} = E_{\mu} + T_p + BE$$

- E_{μ} = muon energy
- T_p = proton kinetic energy
- $BE = 40$ MeV binding energy
- Peak at ~ 0.7 GeV

Calorimetric Energy Cross Section

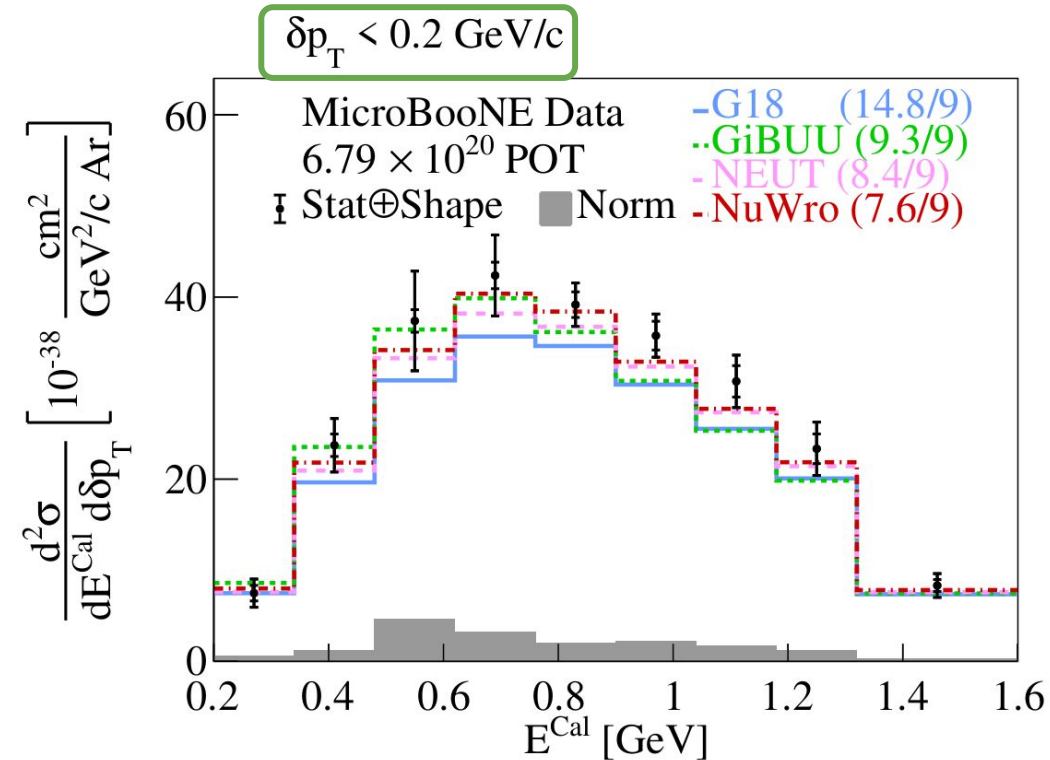
All events

$$E^{Cal} = E_{\mu} + T_p + BE$$



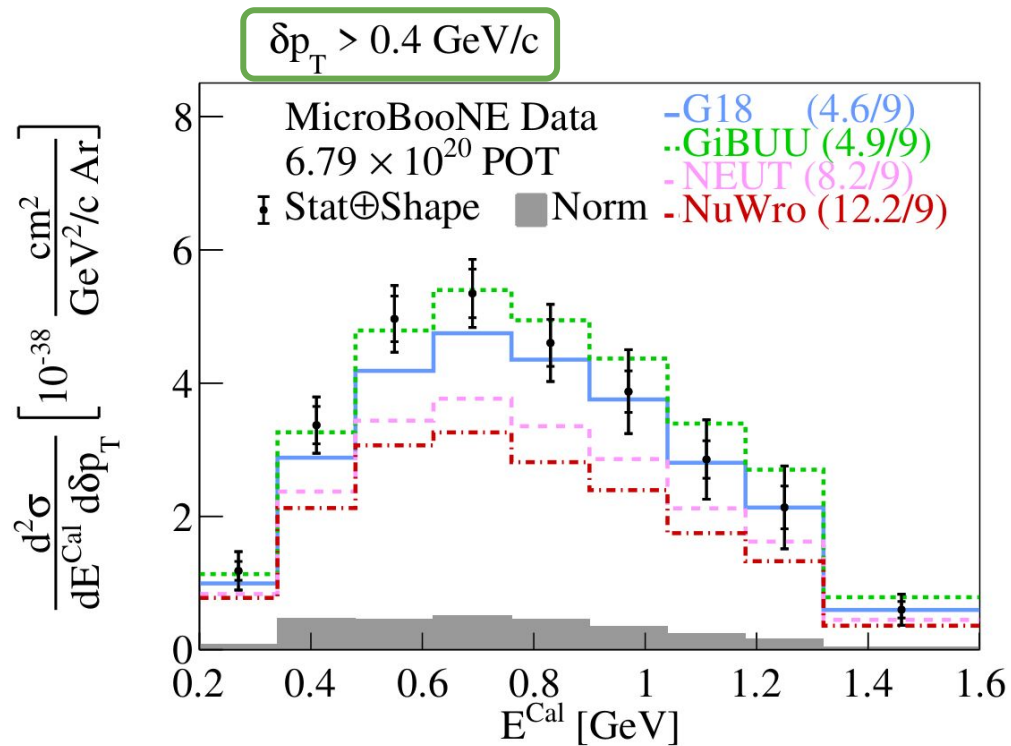
- E_{μ} = muon energy
- T_p = proton kinetic energy
- BE = 40 MeV binding energy
- All generators yield good agreement

High Statistics → Into the Multiverse!



- QE dominated region
- All generators yield good agreement

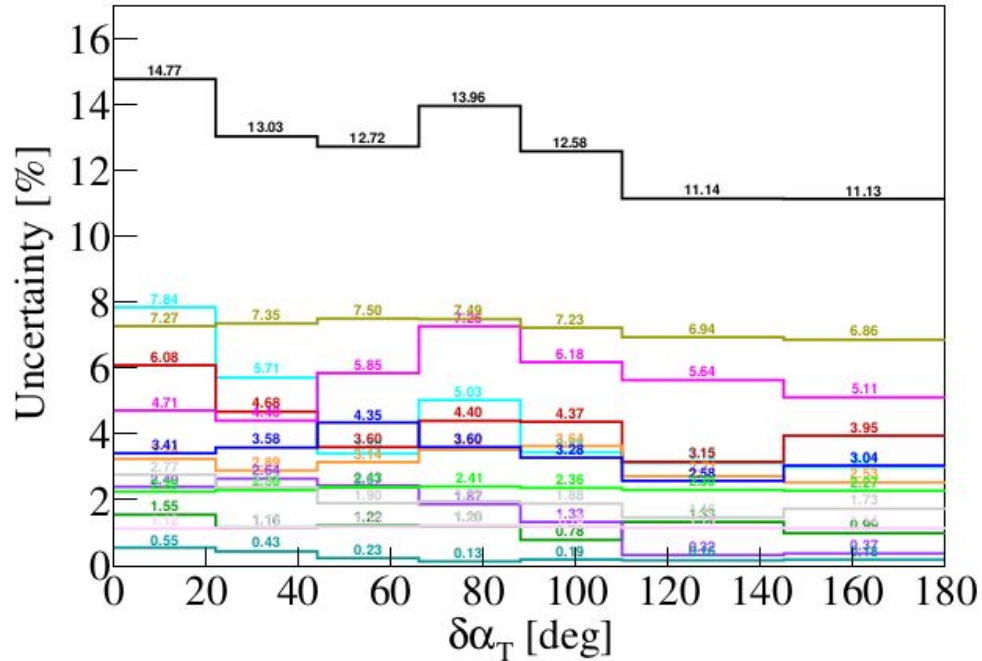
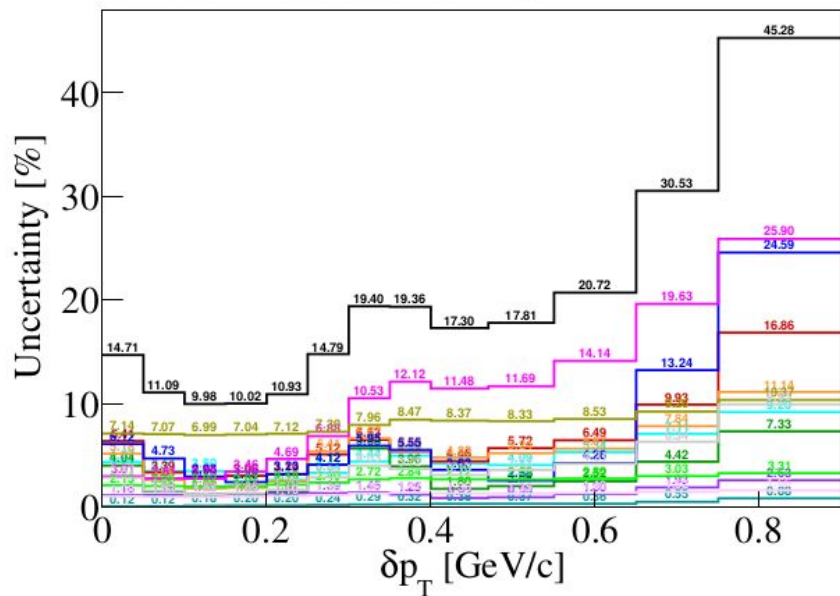
High Statistics → Into the Multiverse!

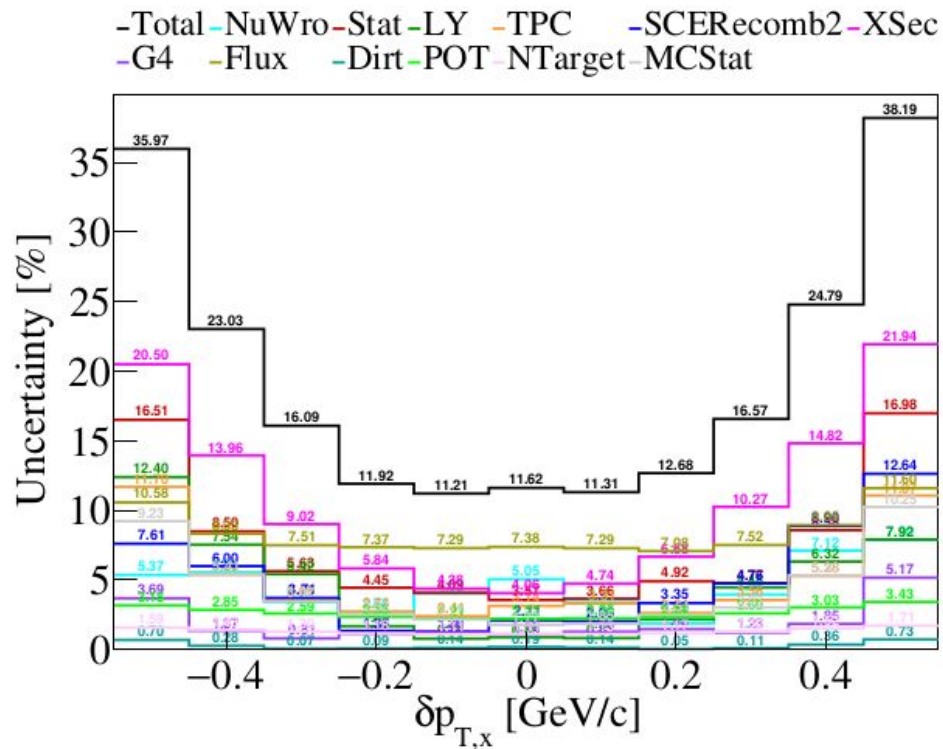
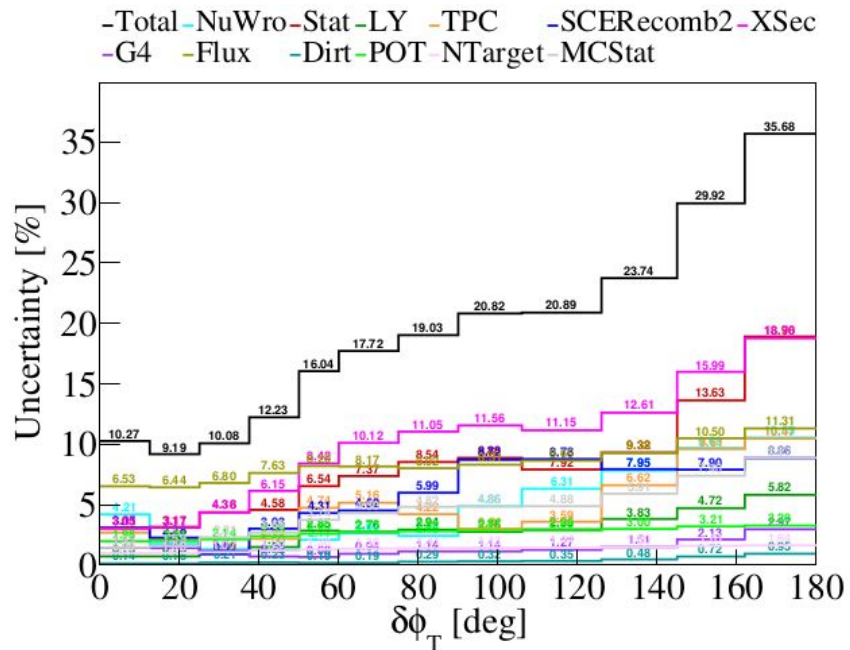


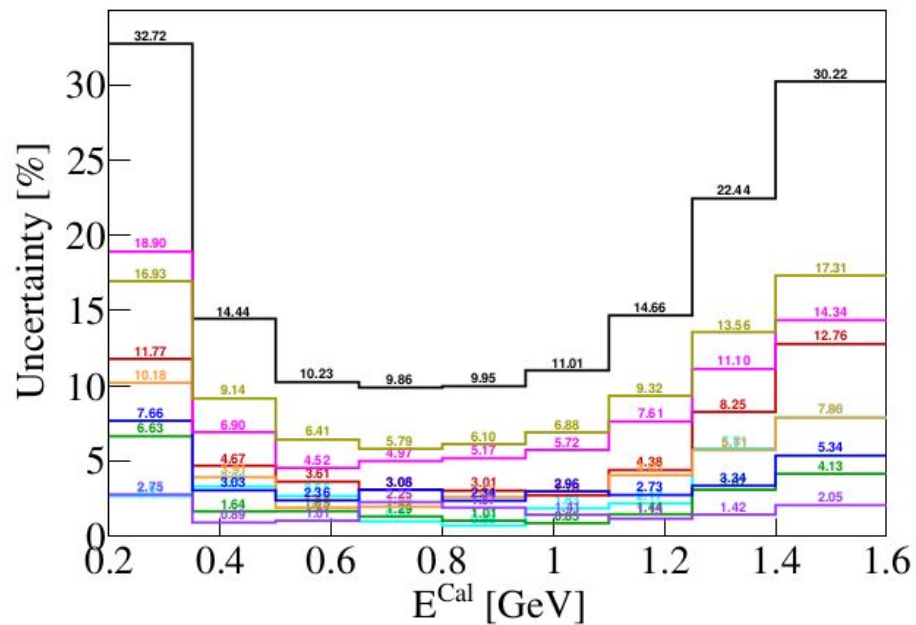
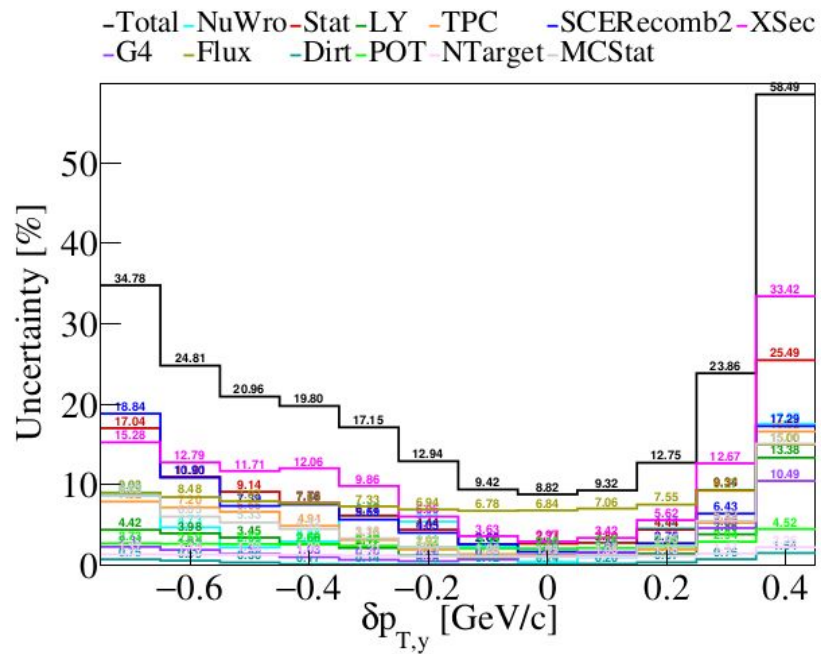
- MEC/RES dominated region
- Similar shapes
- Normalization differences
- Still reasonable χ^2 !

-Total -NuWro -Stat -LY -TPC -SCERcomb2 -XSec
 -G4 -Flux -Dirt -POT -NTarget -MCStat

-Total -NuWro -Stat -LY -TPC -SCERcomb2 -XSec
 -G4 -Flux -Dirt -POT -NTarget -MCStat







Parameter	Description	CV	1σ Uncertainty	Contributing Uncertainty (%)
Quasi-Elastic Parameters				
MaCCQE	CCQE axial mass	1.10 GeV	± 0.1 GeV	0.038
RPA CCQE	Strength of the RPA correction	0.151	± 0.4	2.094
MaNCEL	Axial mass for NCEL	0.961242 GeV	$\pm 25\%$	0.348
EtaNCEL	Empirical parameter used to account for sea quark contribution to NCEL form factor	0.12	$\pm 30\%$	0.010
AxFFCCQeshape	Parametrisation of the nucleon axial form factor	Dipole	z-expansion	0.022
VecFFCCQeshape	Parametrisation of the nucleon vector form factors	BBA07	Dipole	0.051
MEC Parameters				
NormCCMEC	Energy-independent normalization for CCMEC	1.66	± 0.5	1.832
NormNCMEC	Energy-independent normalization for NCMEC	1	$\pm 20\%$	0.129
FracPNCCMEC	Fraction of initial nucleon pairs that are pn (0 = Valencia)	0	$\pm 20\%$	0.041
FracDeltaCCMEC	Relative contribution of Δ diagrams to total MEC cross section (0 = Valencia)	0	$\pm 30\%$	0.124
XSecShape CCMEC	Changes shape of differential cross section	1.0	0.0	2.273
DecayAngMEC	Changes angular distribution of nucleon cluster	Isotropic	$\cos^2 \vartheta$ in rest frame	0.693
Resonant Parameters				
MaCCRES	CCRES axial mass	1.120 GeV	± 0.2	0.986
MvCCRES	Shape-only CCRES axial mass	0.840 GeV	± 0.1	0.775
MaNCRES	NCRES axial mass	1.120 GeV	± 0.2	0.969
MvNCRES	NCRES vector mass.	0.840 GeV	± 0.1	0.395
ThetaDelta2Npi	Interpolates angular distribution for $\Delta \rightarrow N + \pi$	Rein-Sehgal	Isotropic	1.533
ThetaDelta2NRad	Interpolates angular distribution for $\Delta \rightarrow N + \gamma$	Rein-Sehgal	$\cos^2 \vartheta$	0.016

Parameter	Description	CV	1σ Uncertainty	Contributing Uncertainty (%)
Non-Resonant Parameters				
NonRESBGvpNC1pi	Non-resonant background normalization for ν_p NC1 π	0.1	± 0.5	0.041
NonRESBGvpNC2pi	Non-resonant background normalization for ν_p NC2 π	1	± 0.5	0.096
NonRESBGvnNC1pi	Non-resonant background normalization for ν_n NC1 π	0.3	± 0.5	0.390
NonRESBGvnNC2pi	Non-resonant background normalization for ν_n NC2 π	1	± 0.5	0.022
NonRESBGvbarpNC1pi	Non-resonant background normalization for $\bar{\nu}_p$ NC1 π	0.3	± 0.5	0.010
NonRESBGvbarpNC2pi	Non-resonant background normalization for $\bar{\nu}_p$ NC2 π	1	± 0.5	0.010
NonRESBGvbarnNC1pi	Non-resonant background normalization for $\bar{\nu}_n$ NC1 π	0.1	± 0.5	0.010
NonRESBGvbarnNC2pi	Non-resonant background normalization for $\bar{\nu}_n$ NC2 π	1	± 0.5	0.010
NonRESBGvpCC1pi	Non-resonant background normalization for ν_p CC1 π	0.007713	± 0.5	0.014
NonRESBGvpCC2pi	Non-resonant background normalization for ν_p CC2 π	0.787999	± 0.5	0.059
NonRESBGvnCC1pi	Non-resonant background normalization for ν_n CC1 π	0.127858	± 0.5	0.217
NonRESBGvnCC2pi	Non-resonant background normalization for ν_n CC2 π	2.11523	± 0.5	0.079
NonRESBGvbarpCC1pi	Non-resonant background normalization for $\bar{\nu}_p$ CC1 π	0.127858	± 0.5	0.013
NonRESBGvbarpCC2pi	Non-resonant background normalization for $\bar{\nu}_p$ CC2 π	2.11523	± 0.5	0.010
NonRESBGvbarnCC1pi	Non-resonant background normalization for $\bar{\nu}_n$ CC1 π	0.007713	± 0.5	0.010
NonRESBGvbarnCC2pi	Non-resonant background normalization for $\bar{\nu}_n$ CC2 π	0.787999	± 0.5	0.010
AhtBY	A _{HT} higher-twist parameter in the Bodek-Yang model scaling variable ξ_w	0.538	± 0.25	0.010
BhtBY	B _{HT} higher-twist parameter in the Bodek-Yang model scaling variable ξ_w	0.305	± 0.25	0.010
CV1uBY	CV1u valence GRV98 PDF correction parameter in the Bodek-Yang model	0.291	± 0.3	0.010
CV2uBY	CV2u valence GRV98 PDF correction parameter in the Bodek-Yang model	0.189	± 0.4	0.010

Hadronisation Parameters

AGKYxF1pi	Hadronization parameter, applicable to true DIS interactions only	-0.385	± 0.2	0.108
AGKYpT1pi	Hadronization parameter, applicable to true DIS interactions only	1/6.625	± 0.03	0.034

Final State Interaction Parameters

MFP $_{\pi}$	π mean free path	0	± 0.2	0.032
MFP $_N$	Nucleon mean free path	0	± 0.2	1.212
FrCEx $_{\pi}$	Fractional cross section for π charge exchange	0	± 0.5	0.159
FrInel $_{\pi}$	Fractional cross section for π inelastic scattering	0	± 0.4	0.133
FrAbs $_{\pi}$	Fractional cross section for π absorption	0	± 0.3	0.906
FrCEx $_N$	Fractional cross section for nucleon charge exchange	0	± 0.2	0.953
FrInel $_N$	Fractional cross section for nucleon inelastic scattering	0	± 0.5	0.289
FrAbs $_N$	Fractional cross section for nucleon absorption	0	± 0.4	0.906

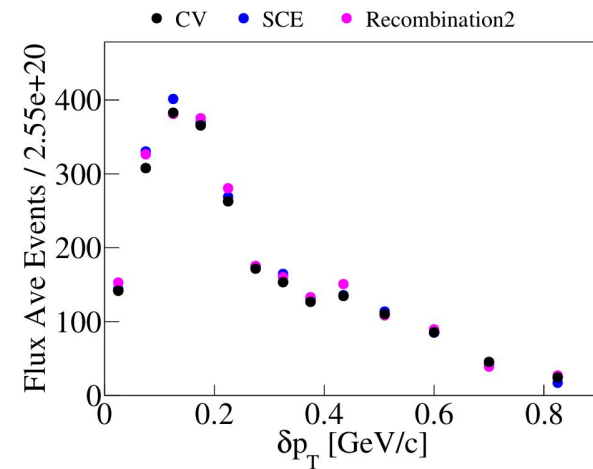
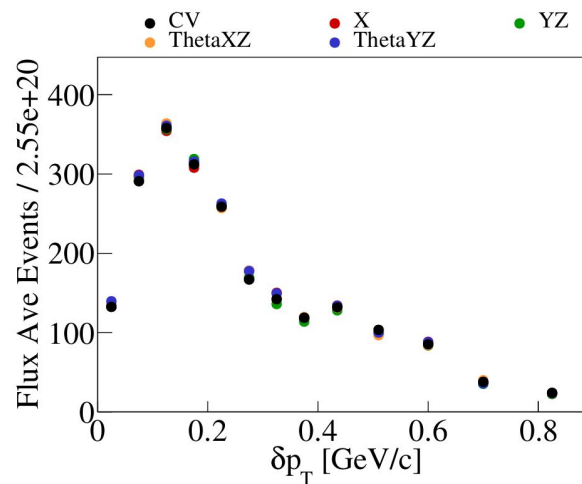
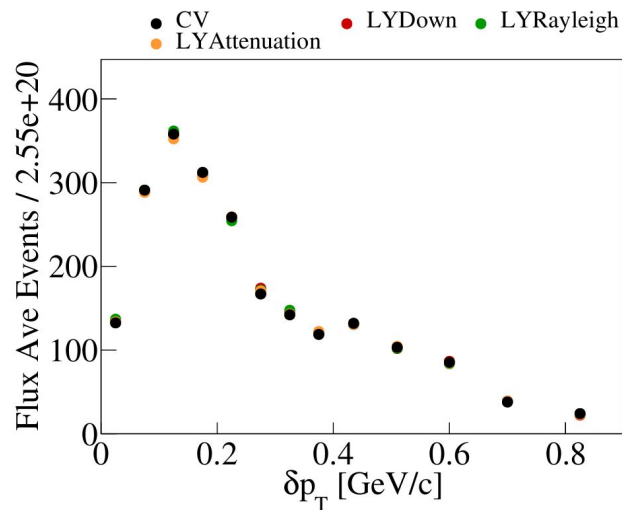
Delta Resonant Decay Parameters

RDecBR1gamma	Normalization for $\Delta \rightarrow \gamma$ decays	Nominal BR	± 0.5	0.042
RDecBR1eta	Normalization for $\Delta \rightarrow \eta$ decays	Nominal BR	± 0.5	0.513

Coherent Parameters

NormCCCOH	Scaling factor for CCCOH π production total cross section	Nominal	100% increase	0.027
NormNCCOH	Scaling factor for NCCOH π production total cross section	Nominal	100% increase	0.016

Variation	Description
Wire Mod x position	Wire modification of x position
Wire Mod (y,z) position	Wire modification of (y,z) position
Wire Mod θ_{XZ}	Wire modification of angle in XZ plane
Wire Mod θ_{YZ}	Wire modification of angle in YZ plane
Light Yield Attenuation	Attenuation of LY response in detector over time
Light Yield Down	Turn down the light yield in the detector by 25%
Light Yield Rayleigh	Increase Rayleigh scattering length from 60 cm to 90 cm
Recombination	Reduce value of β' in the Modified Box Model
SCE	Use an alternative Space Charge Map



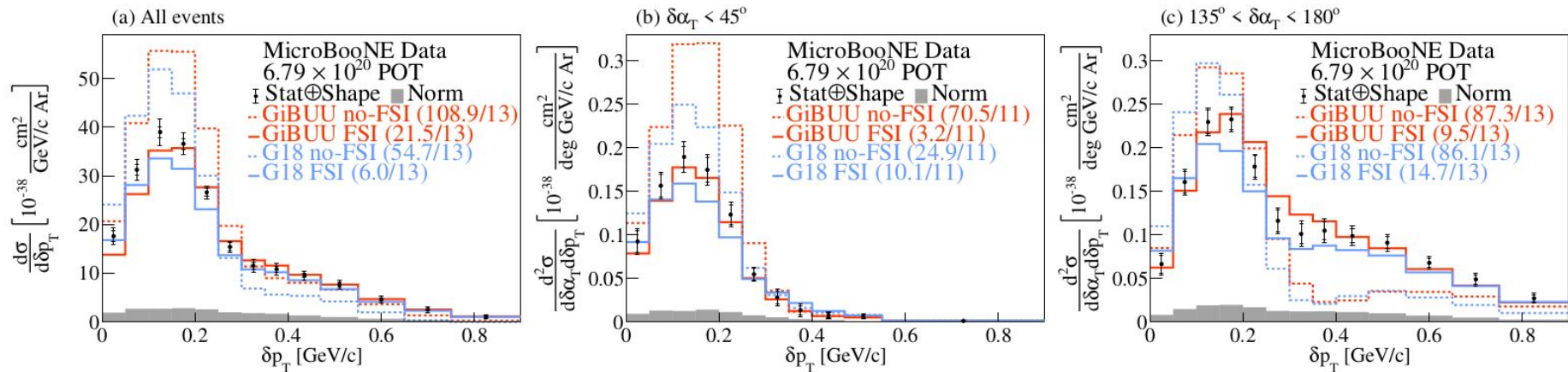


FIG. 1. The flux-integrated (a) single- and (b-c) double- (in $\delta\alpha_T$ bins) differential CC1p0 π cross sections as a function of the transverse missing momentum δp_T . Inner and outer error bars show the statistical and total (statistical and shape systematic) uncertainty at the 1σ , or 68%, confidence level. The gray band shows the separate normalization systematic uncertainty. Colored lines show the results of theoretical cross section calculations with (solid line) and without (dashed line) FSI based on the GENIE (blue) and GiBUU (orange) event generators.

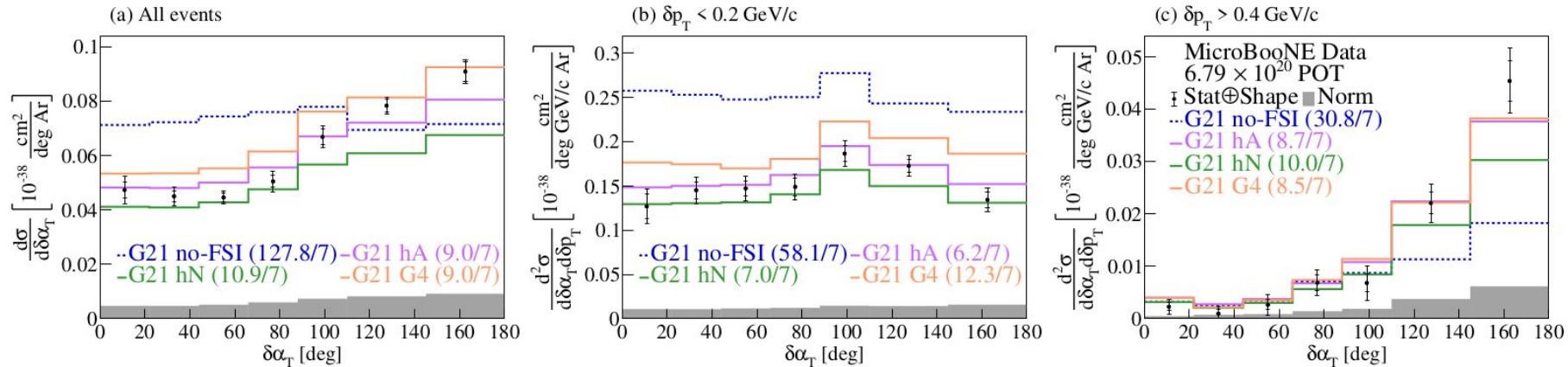


FIG. 2. The flux-integrated (a) single- and (b-c) double- (in δp_T bins) differential CC1p0 π cross sections as a function of the angle $\delta\alpha_T$. Inner and outer error bars show the statistical and total (statistical and shape systematic) uncertainty at the 1σ , or 68%, confidence level. The gray band shows the separate normalization systematic uncertainty. Colored lines show the results of theoretical cross section calculations with a number of FSI-modeling choices based on the GENIE event generator.

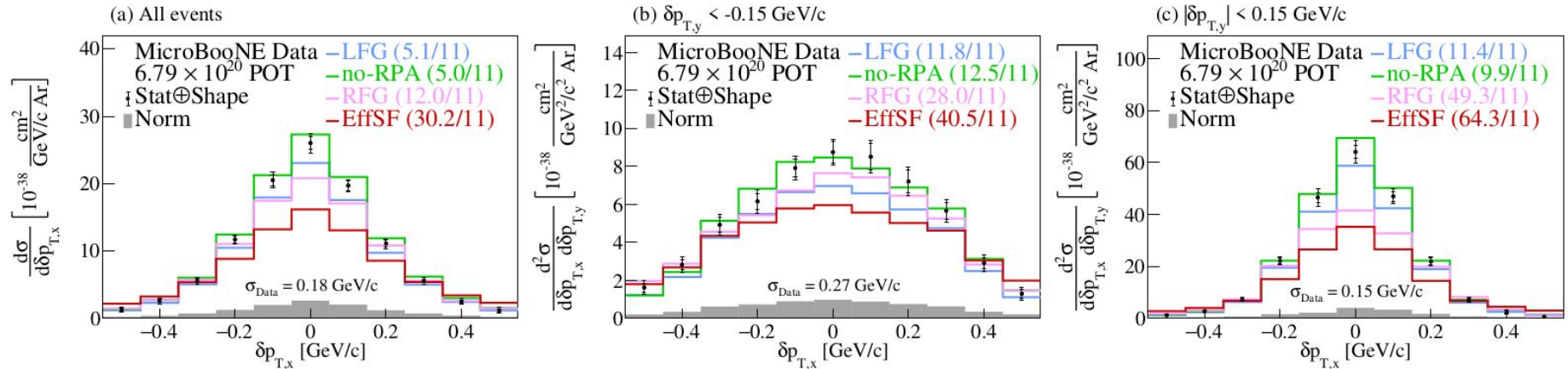
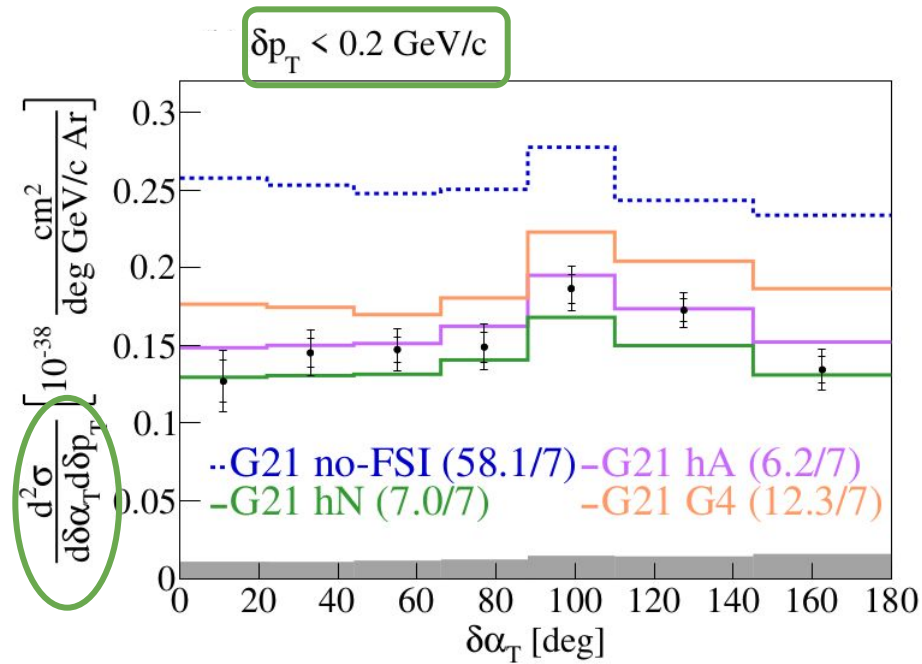
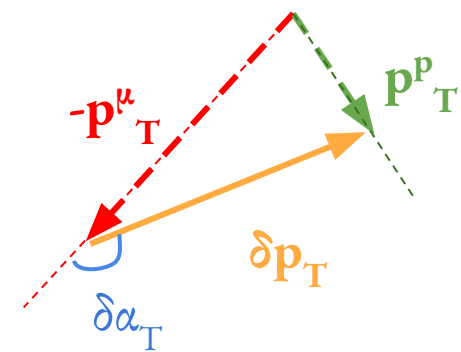


FIG. 3. The flux-integrated (a) single- and (b-c) double- (in $\delta p_{T,y}$ bins) differential CC1p0 π cross sections as a function of the transverse three-momentum transfer component, $\delta p_{T,x}$. Inner and outer error bars show the statistical and total (statistical and shape systematic) uncertainty at the 1σ , or 68%, confidence level. The gray band shows the separate normalization systematic uncertainty. Colored lines show the results of theoretical cross section calculations with a number of event generators. The standard deviation (σ_{Data}) of a Gaussian fit to the data is shown on each panel.

High Statistics → Into the Multiverse!

QE-dominated region



- Flat distribution indicative of absence of proton FSI
- Shape and normalization differences across FSI models

G21 = GENIE v3.0.6 G21_11b_00_000

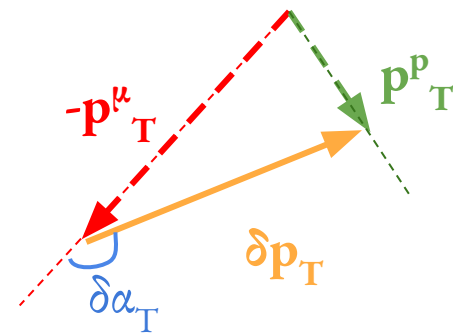
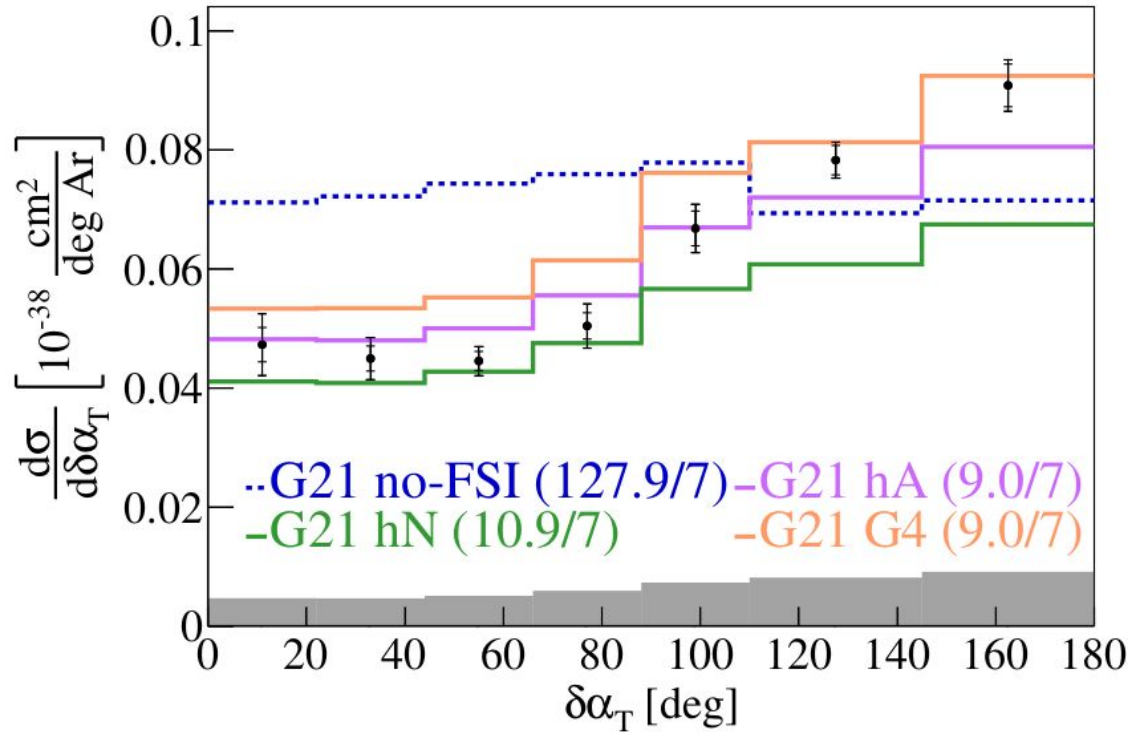
SuSAv2 QE & MEC*, hA/hN/G4 = FSI modeling options 129

[Phys. Rev. Lett. 131, 101802 \(2023\)](#)

* [Phys. Rev. D 101, 033003 \(2020\)](#)

Transverse Orientation $\delta\alpha_T$ Cross Section

All events



- First neutrino-argon differential cross section in $\delta\alpha_T$
- Sensitive to proton FSI modeling
- Data favors FSI addition
- Shape differences observed

[arXiv:2301.03706](https://arxiv.org/abs/2301.03706)

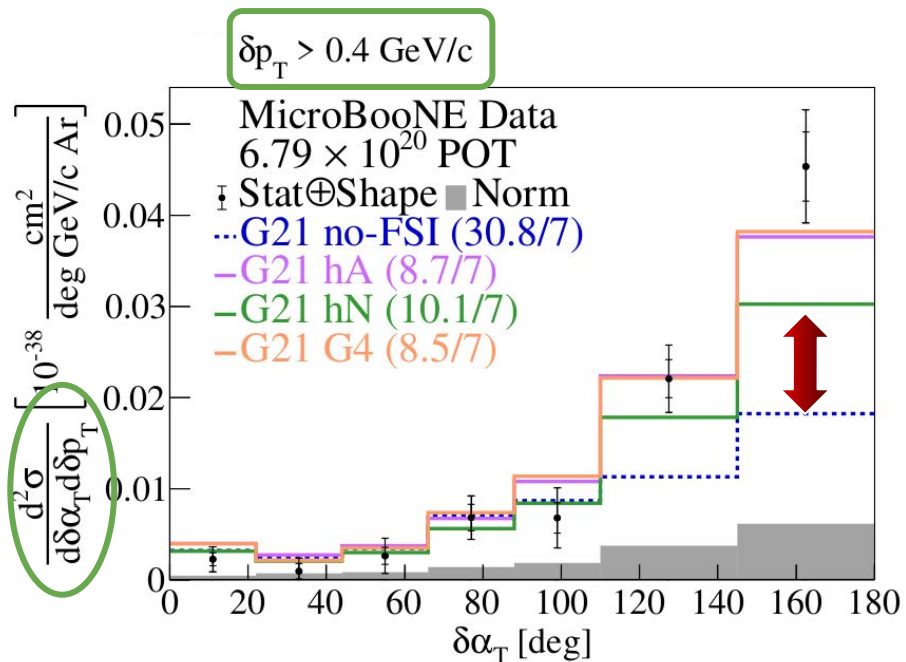
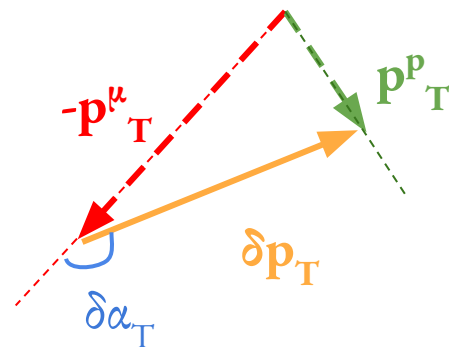
* [Phys. Rev. D 101, 033003 \(2020\)](https://arxiv.org/abs/1903.03303)

G21 = GENIE v3.0.6 G21_11b_00_000

SuSv2 QE & MEC*, hA/hN/G4 = FSI modeling options 130

High Statistics → Into the Multiverse!

- **Extension to 2D** for the first time on argon
- Probe regions with greater model discrimination power



- Primarily contributions from MEC/RES & QE events undergoing FSI
- More asymmetric behavior compared to 1D result
- No-FSI contribution lower than FSI ones
- High $\delta \alpha_T$ & high δp_T part of phase-space ideal to test FSI / multinucleon effect sensitivity

G21 = GENIE v3.0.6 G21_11b_00_000

SuSAv2 QE & MEC*, hA/hN/G4 = FSI modeling options 131

The nominal MC neutrino interaction prediction (G18) uses the local Fermi gas (LFG) model [50], the Nieves CCQE scattering prescription [51] which includes Coulomb corrections for the outgoing muon [52] and random phase approximation (RPA) corrections [53]. Additionally, it uses the Nieves MEC model [54], the KLN-BS RES [55–58] and Berger-Sehgal coherent (COH) [59] scattering models, the hA2018 FSI model [60], and MicroBooNE-specific tuning of model parameters [38].

Our results are also compared to a number of alternative event generators. GiBUU 2021 (GiBUU) uses similar models, but they are implemented in a coherent way by solving the Boltzmann-Uehling-Uhlenbeck transport equation [61]. The modeling includes the LFG model [50], a standard CCQE expression [62], an empirical MEC model and a dedicated spin dependent resonance amplitude calculation following the MAID analysis [61]. The DIS model is from PYTHIA [63]. GiBUU’s FSI treatment propagates the hadrons through the residual nucleus in a nuclear potential which is consistent with the initial state. NuWro v19.02.2 (NuWro) uses the LFG model [50], the Llewellyn Smith model for QE events [64], the Nieves model for MEC events [65], the Adler-Rarita-Schwinger formalism to calculate the Δ resonance explicitly [58], the BS COH [59] scattering model and an intranuclear cascade model for FSI [65]. NEUT v5.4.0 (NEUT) uses the LFG model [50], the Nieves CCQE scattering prescription [51], the Nieves MEC model [54], the BS RES [55–58] and BS COH [59] scattering models, and FSI with Oset medium corrections for pions [35, 36].

In addition to the alternative event generators, our results are compared to a number of different GENIE configurations. These include an older version, GENIE v2.12.10 (Gv2) [35, 36], which uses the Bodek-Ritchie Fermi Gas model, the Llewellyn Smith CCQE scattering prescription [64], the empirical MEC model [66], a Rein-Sehgal RES and COH scattering model [67], and a data driven FSI model denoted as “hA” [68]. Another model, “Untuned”, uses the GENIE v3.0.6 G18_10a_02_11a configuration without additional MicroBooNE-specific tuning. Finally, the newly added theory-driven GENIE v3.2.0 G21_11b_00_000 configuration (G21) is shown. This includes the SuSAv2 prediction for the QE and MEC scattering parts [69] and the hN2018 FSI model [70]. The modeling options for RES, DIS, and COH interactions are the same as for G18.

To quantify the data-simulation agreement, the χ^2/bins ratio data comparison for each generator is shown on all the figures and is calculated by taking into account the total covariance matrix. Ratios close to unity are indicative of a sufficiently accurate modeling performance. Theoretical uncertainties on the models themselves are not included.

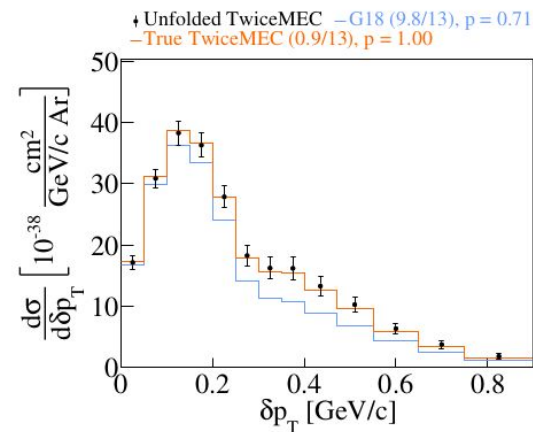
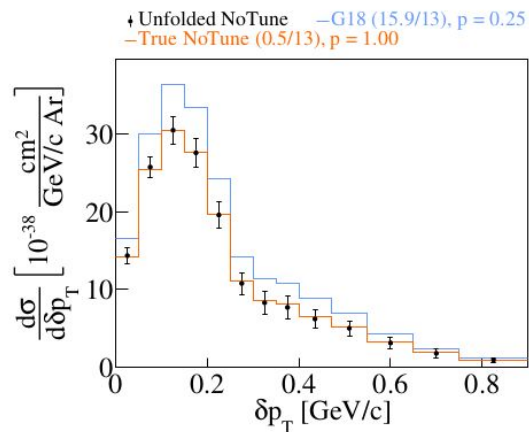
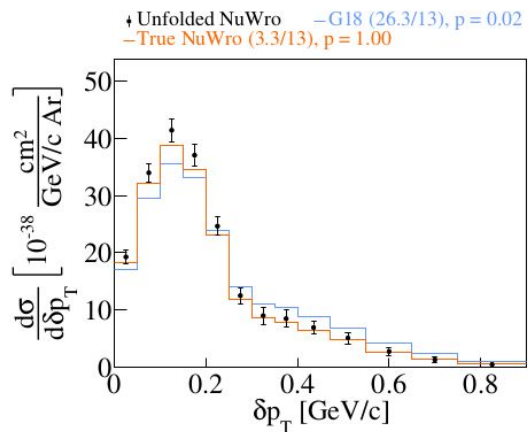


FIG. 1. Fake data studies for δp_T using (left) NuWro, (center) GENIE without the MicroBooNE tune (NoTune), and (right) twice the weights for MEC events (TwiceMEC) as fake data samples.

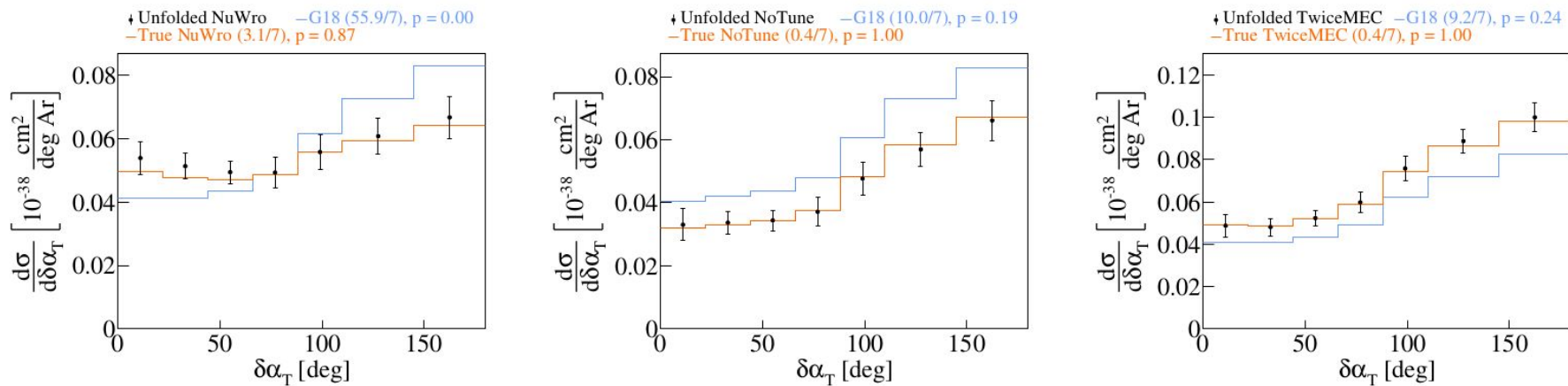


FIG. 2. Fake data studies for $\delta\alpha_T$ using (left) NuWro, (center) GENIE without the MicroBooNE tune (NoTune), and (right) twice the weights for MEC events (TwiceMEC) as fake data samples.

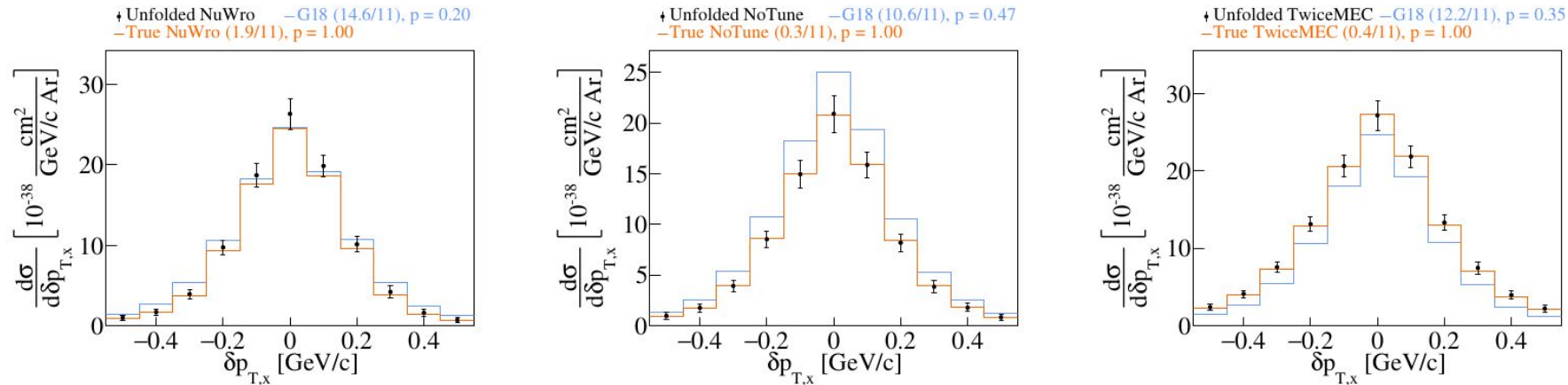


FIG. 3. Fake data studies for $\delta p_{T,x}$ using (left) NuWro, (center) GENIE without the MicroBooNE tune (NoTune), and (right) twice the weights for MEC events (TwiceMEC) as fake data samples.

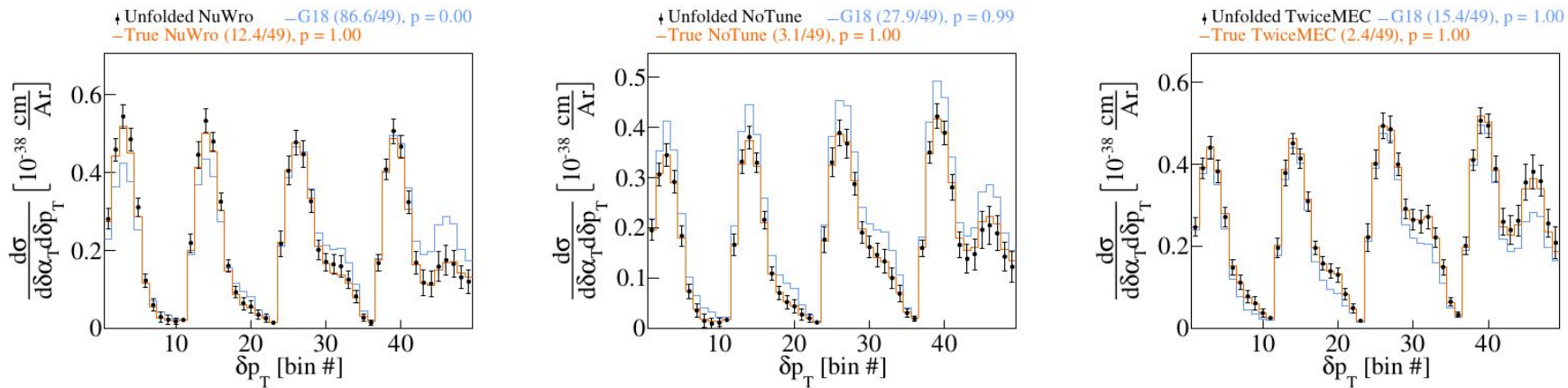


FIG. 4. Fake data studies for δp_T in $\delta\alpha_T$ bins using (left) NuWro, (center) GENIE without the MicroBooNE tune (NoTune), and (right) twice the weights for MEC events (TwiceMEC) as fake data samples.

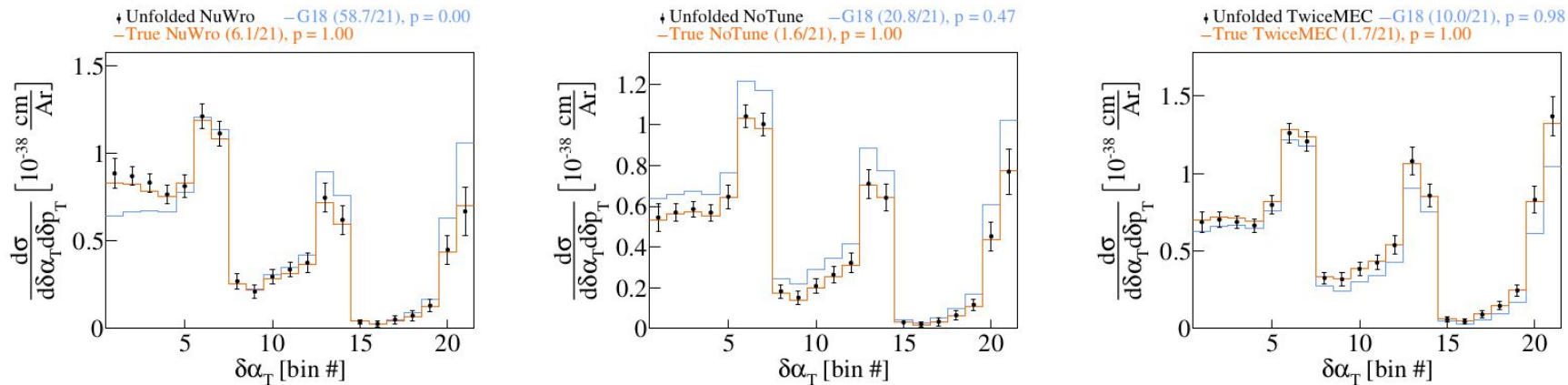


FIG. 5. Fake data studies for $\delta\alpha_T$ in δp_T bins using (left) NuWro, (center) GENIE without the MicroBooNE tune (NoTune), and (right) twice the weights for MEC events (TwiceMEC) as fake data samples.

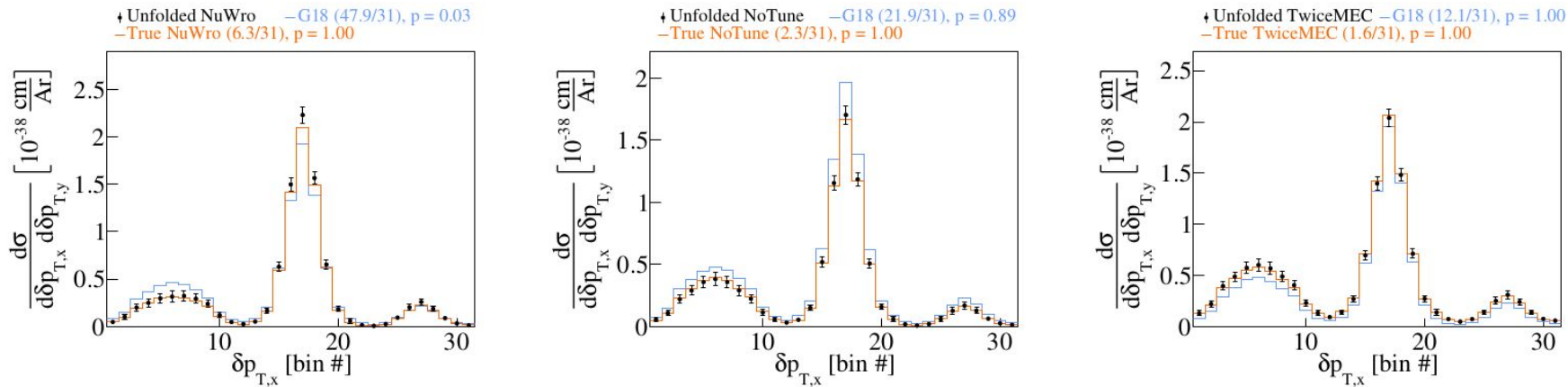


FIG. 6. Fake data studies for $\delta p_{T,x}$ in $\delta p_{T,y}$ bins using (left) NuWro, (center) GENIE without the MicroBooNE tune (NoTune), and (right) twice the weights for MEC events (TwiceMEC) as fake data samples.

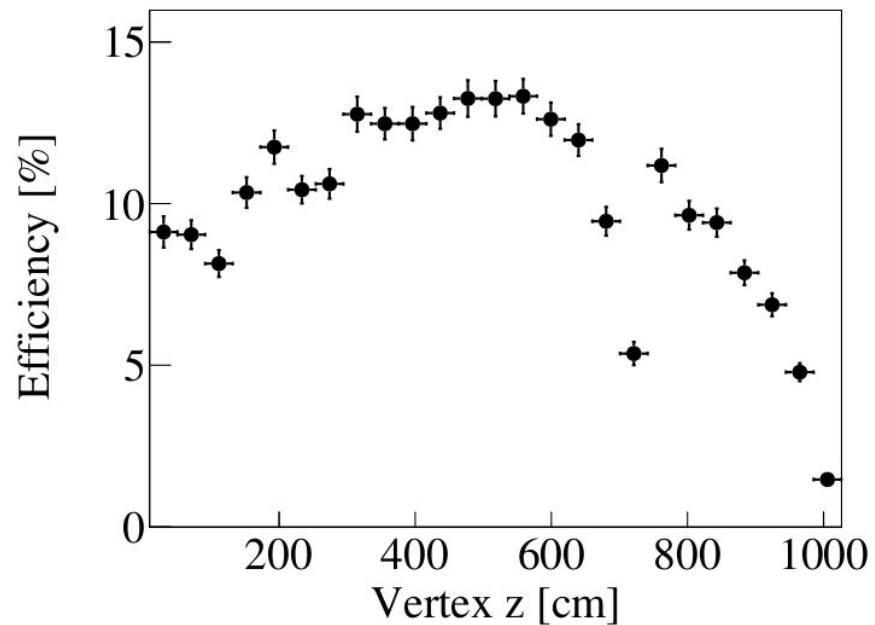
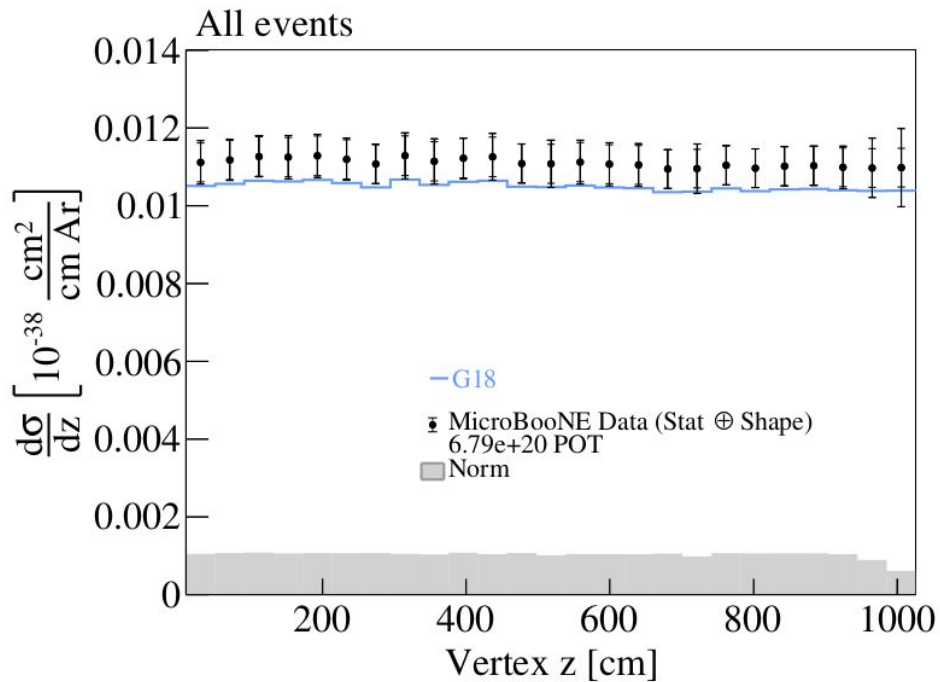


FIG. 7. (Left) extracted cross section as a function of the vertex z distribution. (Right) vertex z efficiency function.

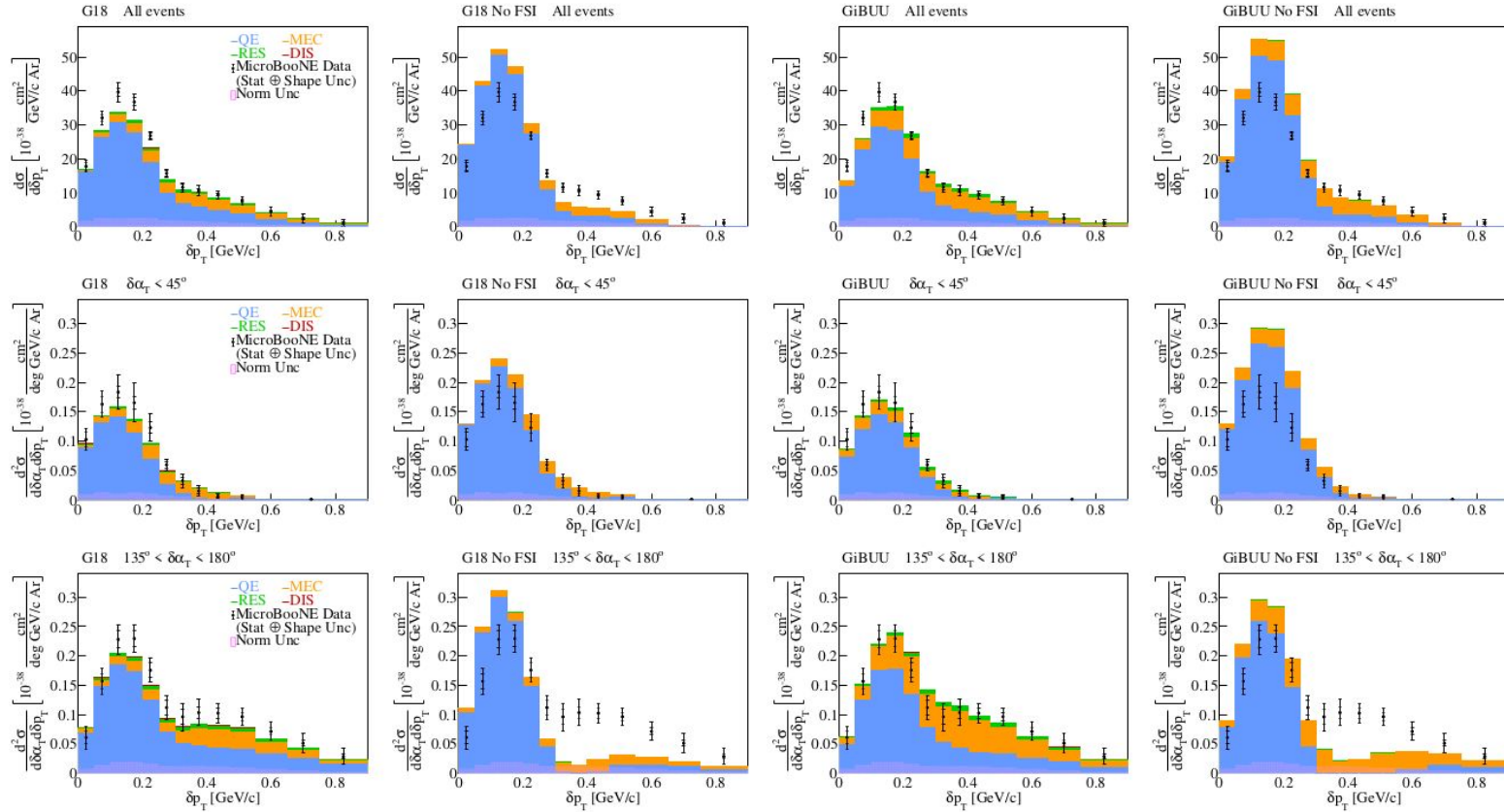


FIG. 8. Cross section interaction breakdown for (top) all the selected events, (middle) events with $\delta\alpha_T < 45^\circ$, and (bottom) events with $135^\circ < \delta\alpha_T < 180^\circ$. The breakdown is shown for (first column) the G18 configuration with FSI effects, (second column) the G18 configuration without FSI effects, (third column) GiB with FSI effects, and (fourth column) GiB without FSI effects.

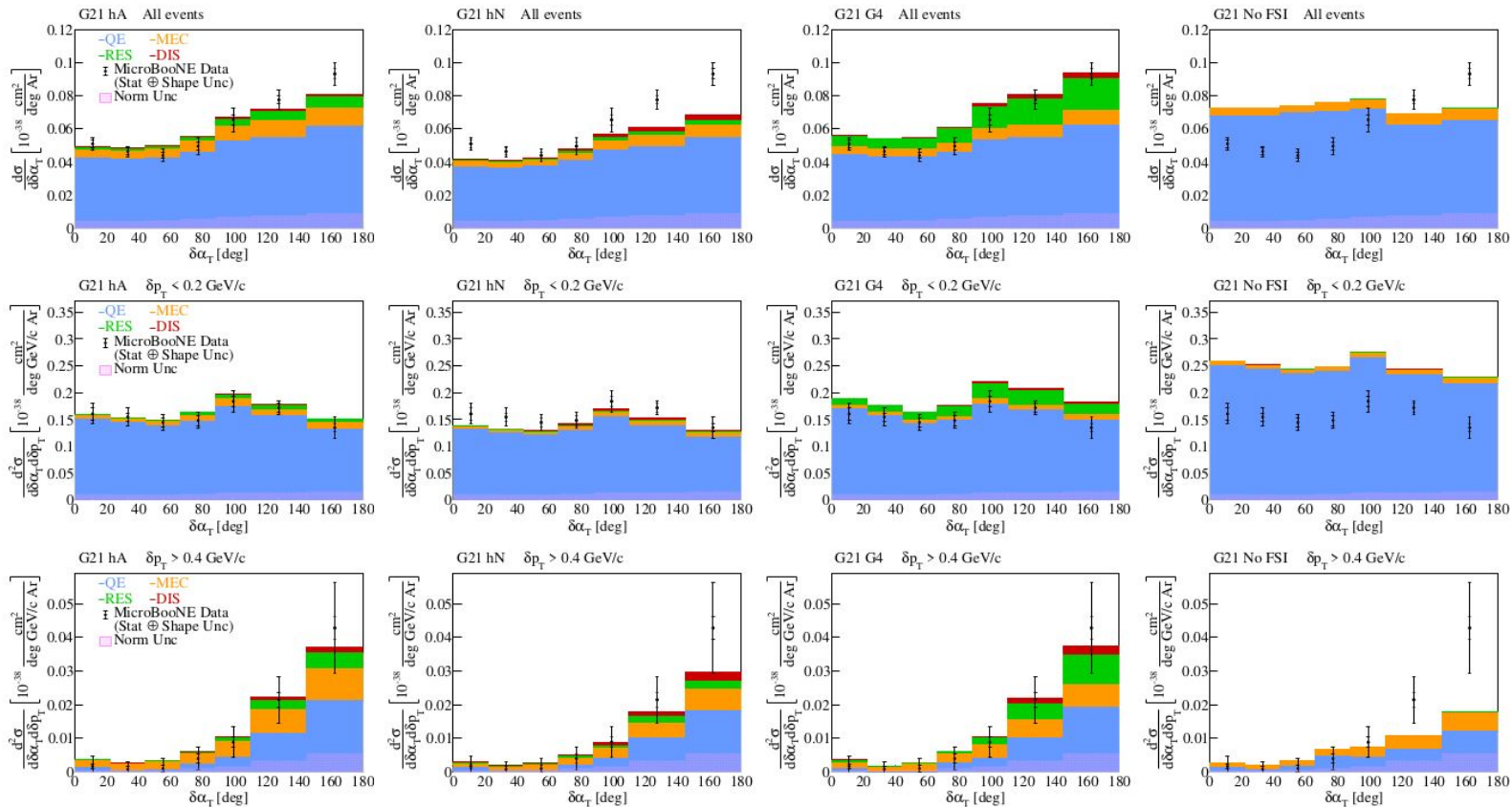


FIG. 9. Cross section interaction breakdown for (top) all the selected events, (middle) events with $\delta p_T < 0.2 \text{ GeV}/c$, and (bottom) events with $\delta p_T > 0.4 \text{ GeV}/c$. The breakdown is shown for (first column) the G21 hA configuration with the hA2018 FSI model, (second column) the G21 hN configuration with the hN FSI model, (third column) the G21 G4 configuration with the G4 FSI model, and (forth column) the G21 No FSI configuration without FSI effects.

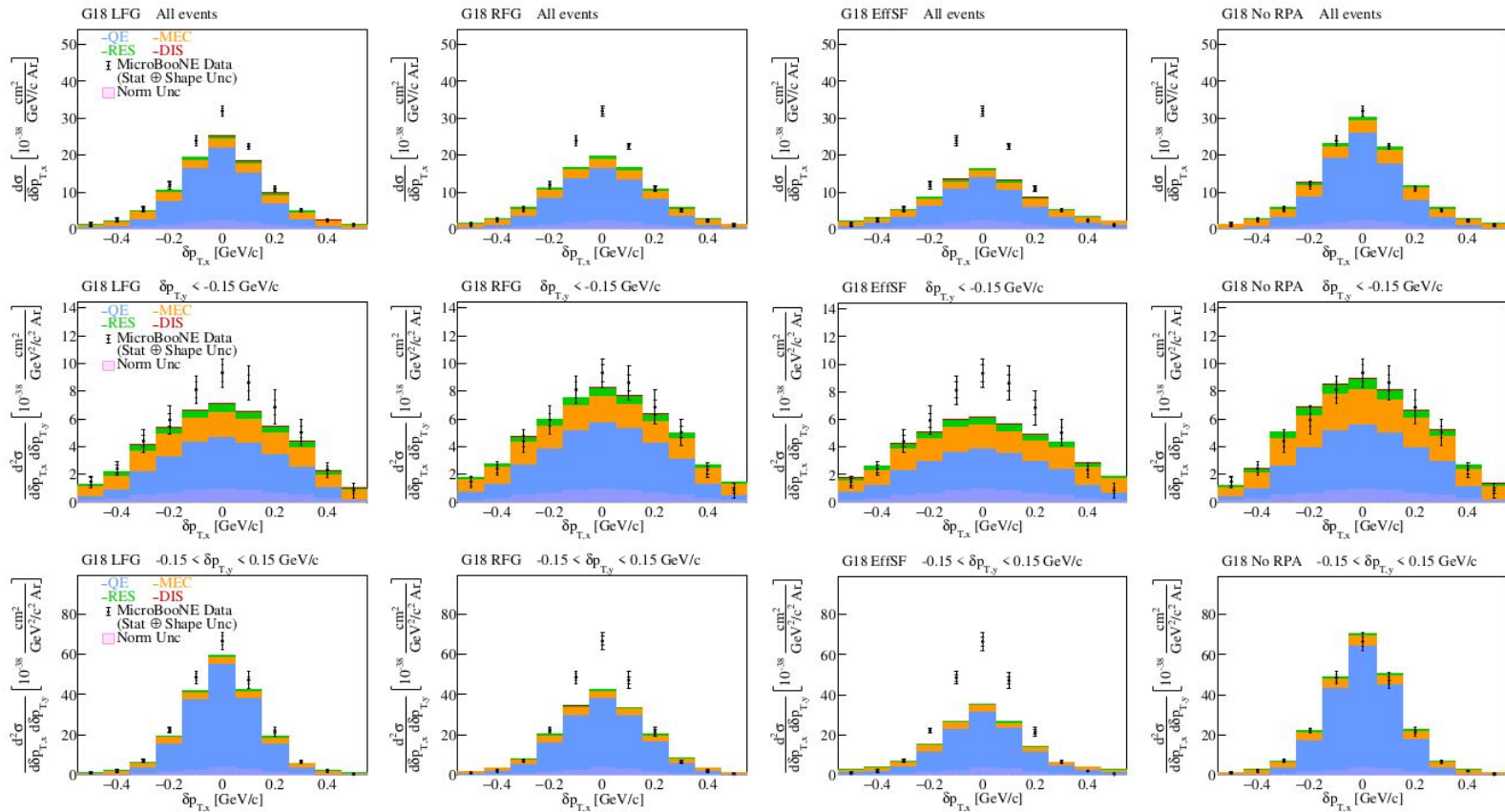


FIG. 10. Cross section interaction breakdown for (top) all the selected events, (middle) events with $\delta p_{T,y} < -0.15$ GeV/c, and (bottom) events with $-0.15 < \delta p_{T,y} < 0.15$ GeV/c. The breakdown is shown for (first column) the G18 LFG configuration, (second column) the G18 RFG configuration, (third column) the G18 EffSF configuration, and (forth column) the G18 No RPA configuration.

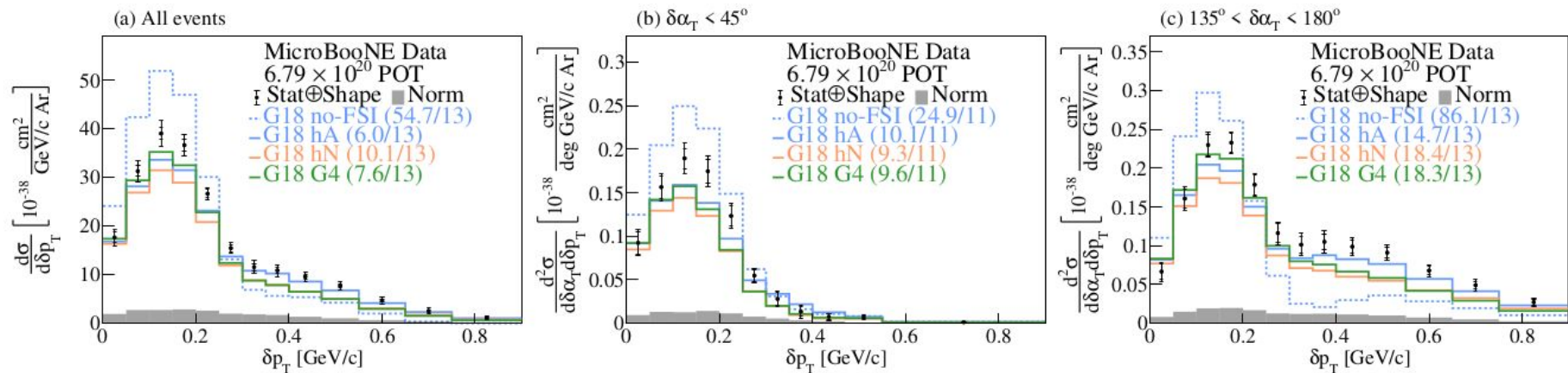


FIG. 11. The flux-integrated (a) single- and (b-c) double- (in $\delta\alpha_T$ bins) differential CC1p0 π cross sections as a function of the transverse missing momentum, δp_T . Inner and outer error bars show the statistical and total (statistical and shape systematic) uncertainty at the 1σ , or 68%, confidence level. The gray band shows the separate normalization systematic uncertainty. Colored lines show the results of theoretical cross section calculations with a number of G21 FSI modeling variations.

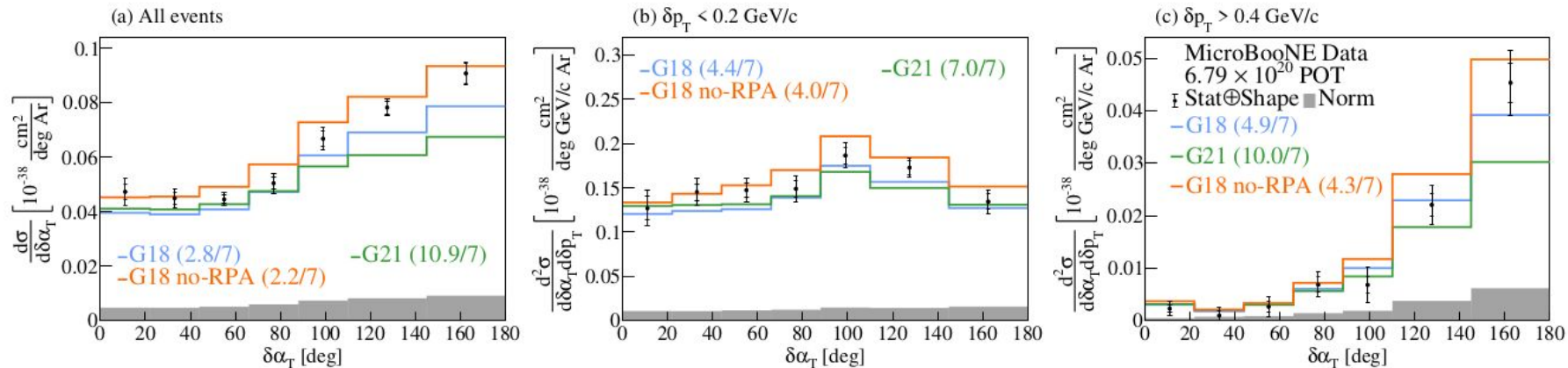


FIG. 12. The flux-integrated (a) single- and (b-c) double- (in δp_T bins) differential CC1p0 π cross sections as a function of the angle $\delta\alpha_T$. Inner and outer error bars show the statistical and total (statistical and shape systematic) uncertainty at the 1σ , or 68%, confidence level. The gray band shows the separate normalization systematic uncertainty. Colored lines show the results of theoretical cross section calculations with a number of QE-modeling choices based on the GENIE event generator.

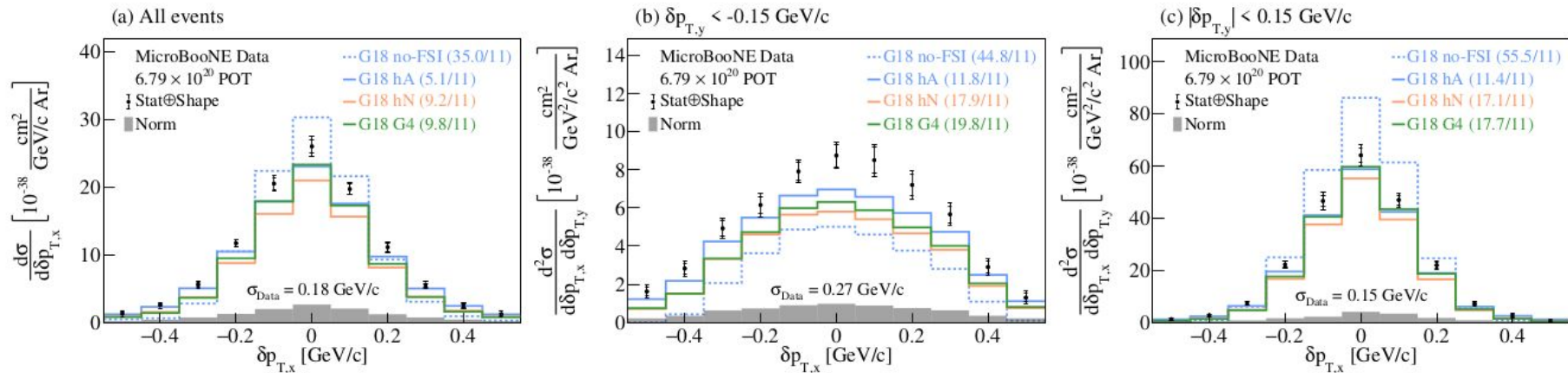
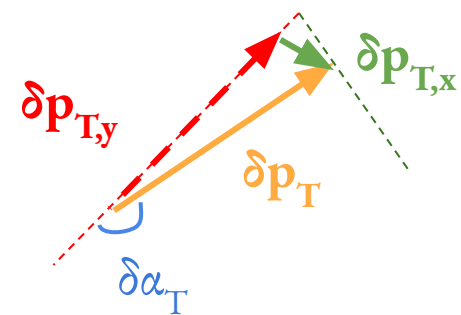


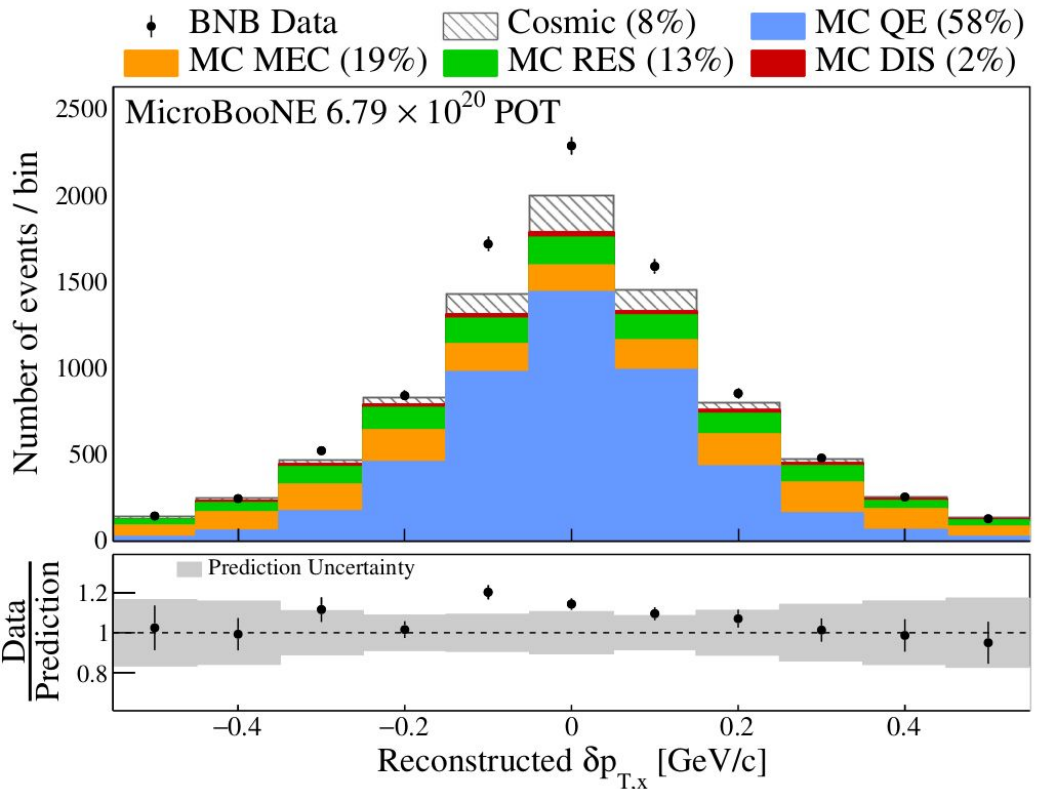
FIG. 13. The flux-integrated (a) single- and (b-c) double- (in $\delta p_{T,y}$ bins) differential CC1p0 π cross sections as a function of the transverse three-momentum transfer component, $\delta p_{T,x}$. Inner and outer error bars show the statistical and total (statistical and shape systematic) uncertainty at the 1σ , or 68%, confidence level. The gray band shows the separate normalization systematic uncertainty. Colored lines show the results of theoretical cross section calculations with a number of G18 FSI modeling variations. The standard deviation (σ_{Data}) of a Gaussian fit to the data is shown on each panel.

Transverse Component $\delta p_{T,x}$

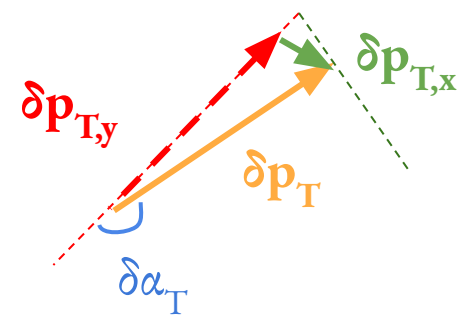
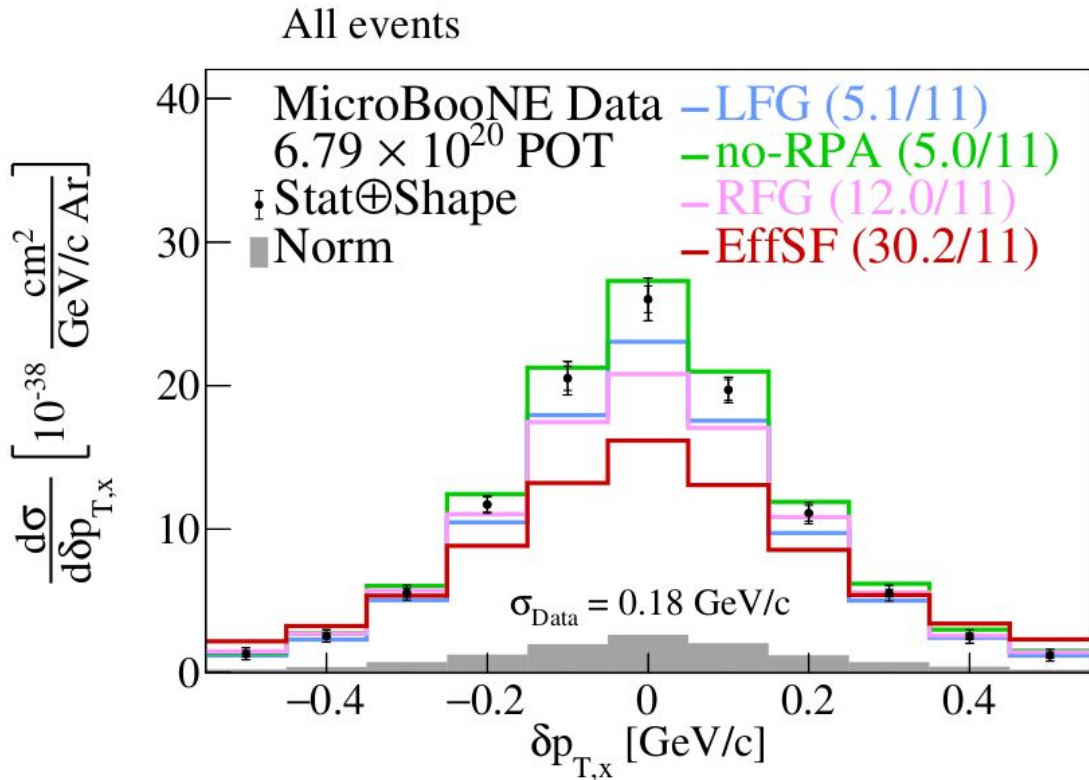


$$\delta p_{T,x} = \delta p_T \cdot \sin \delta \alpha_T$$

- Symmetric around 0 GeV/c
- **QE** dominance in central region
- **MEC/RES** events primarily in the tail



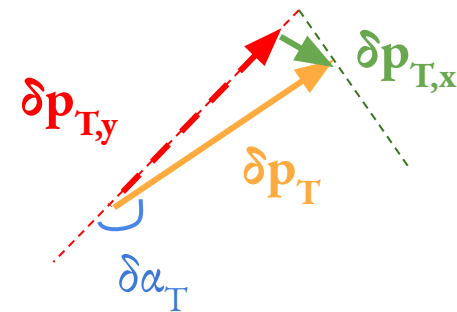
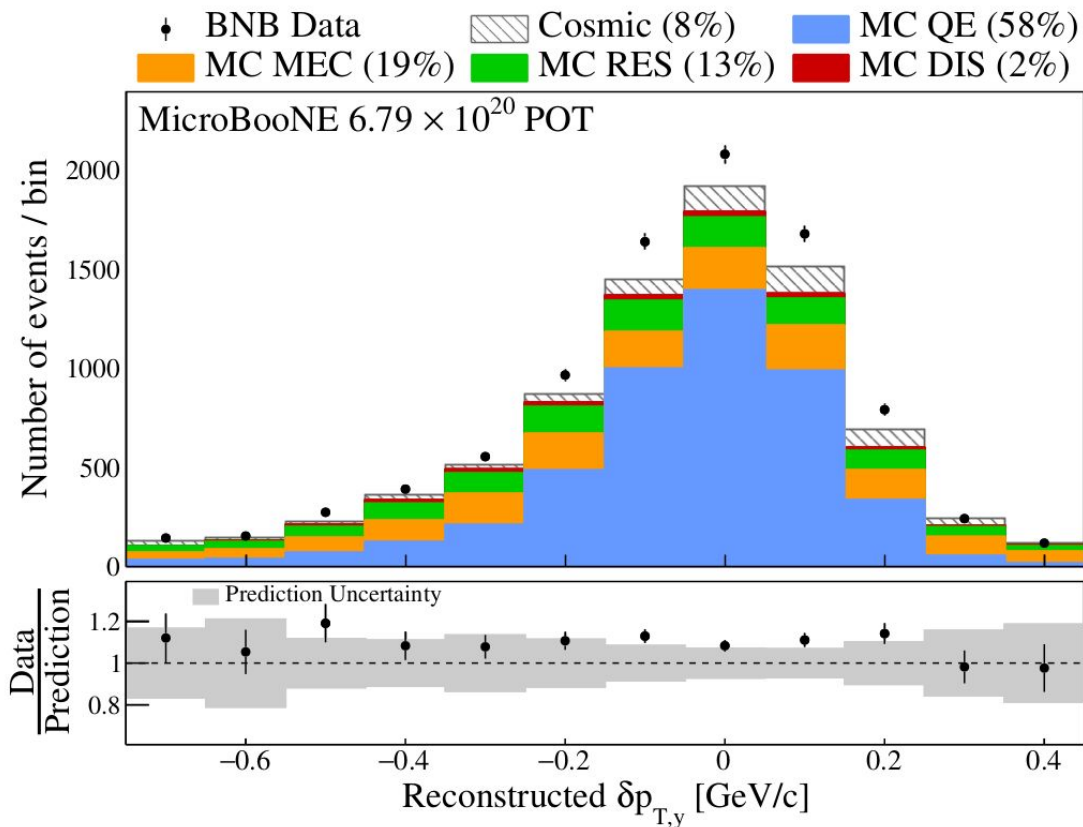
Transverse Component $\delta p_{T,x}$ Cross Section



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

- **G18 LFG** = GENIE v3.0.6
G18_10a_02_11a (G18) + uB Tune
with local Fermi gas
- **G18 no-RPA** = G18 w/o RPA effects
- **G18 RFG** = G18 with relativistic
Fermi gas (RFG)
- **G18 EffSF** = G18 with spectral
function (EffSF)

Longitudinal Component $\delta p_{T,y}$

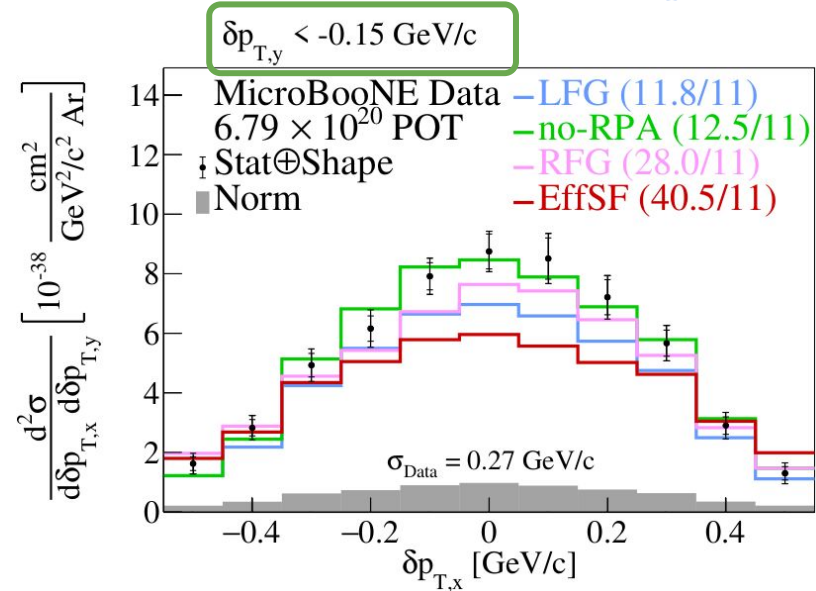
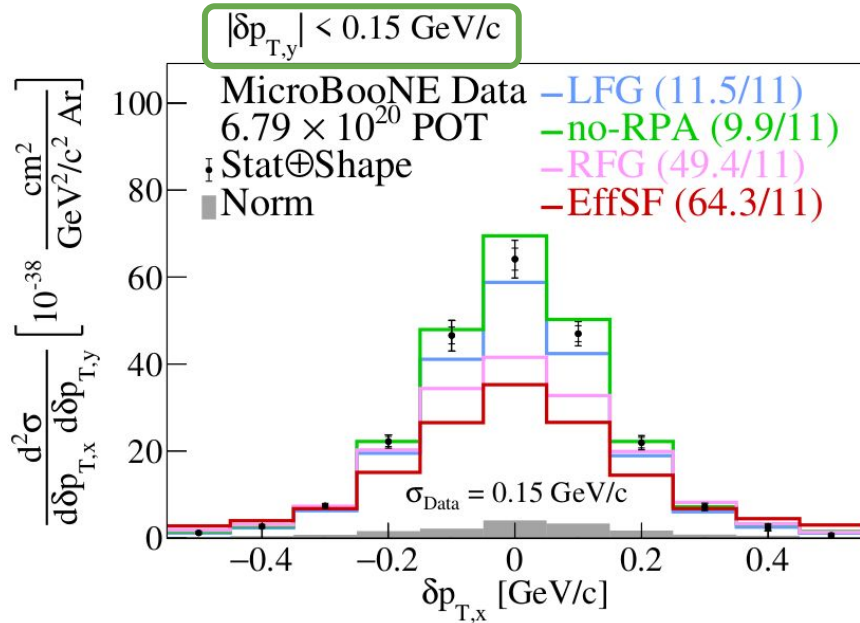
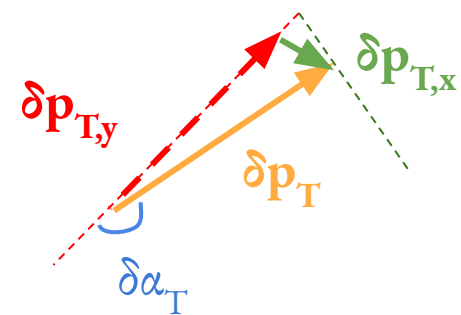


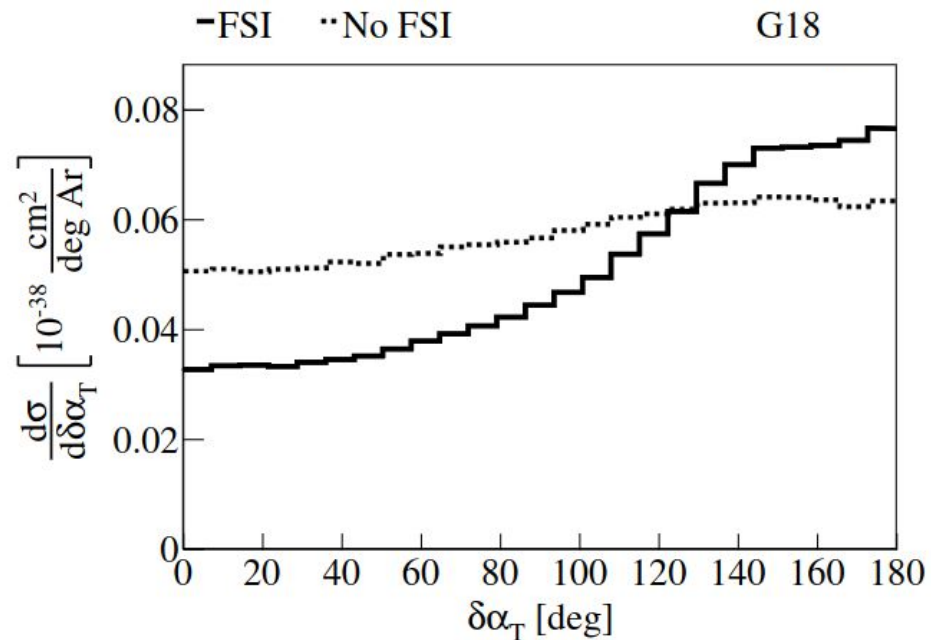
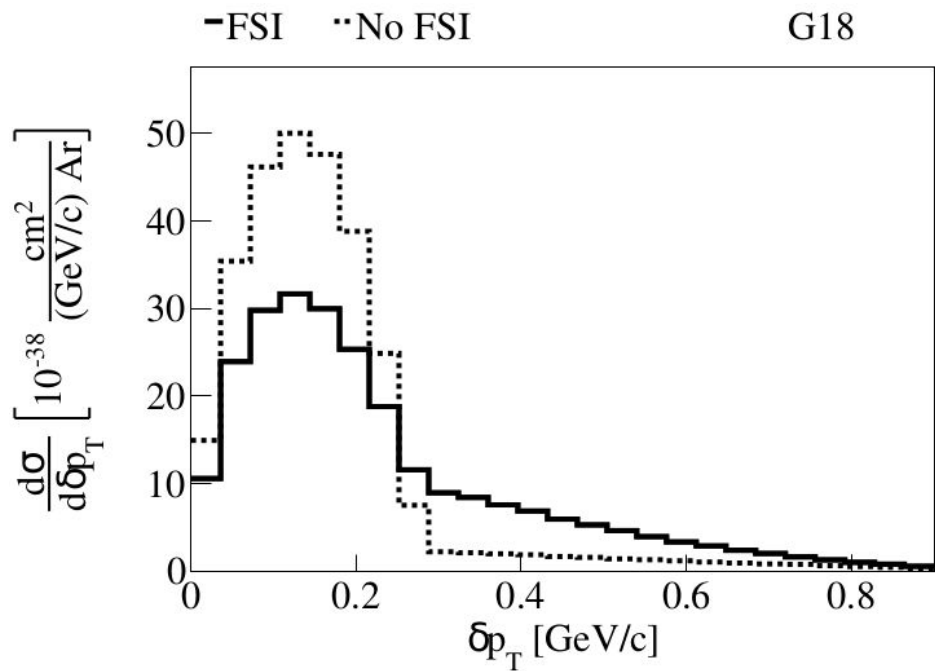
$$\delta p_{T,y} = \delta p_T \cdot \cos \delta \alpha_T$$

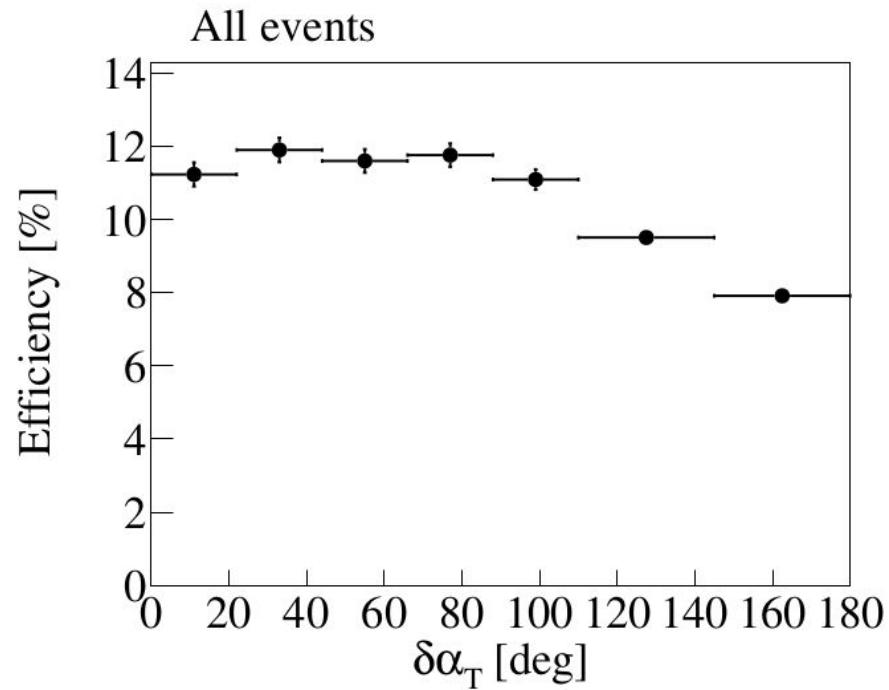
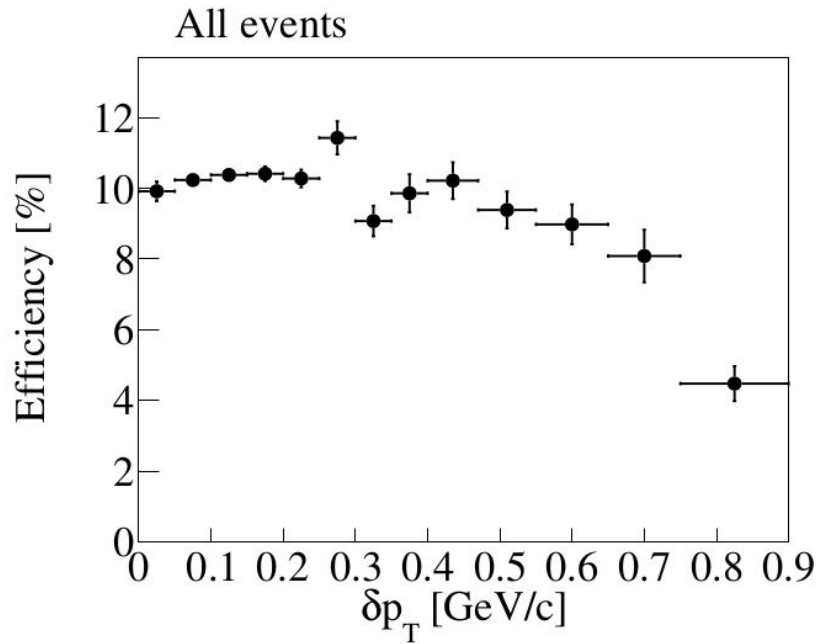
- Asymmetric due to $\delta \alpha_T$ enhancement at $\sim 180^\circ$
- **QE** dominance in central region
- Spread of tail sensitive to FSI strength & **MEC/RES**

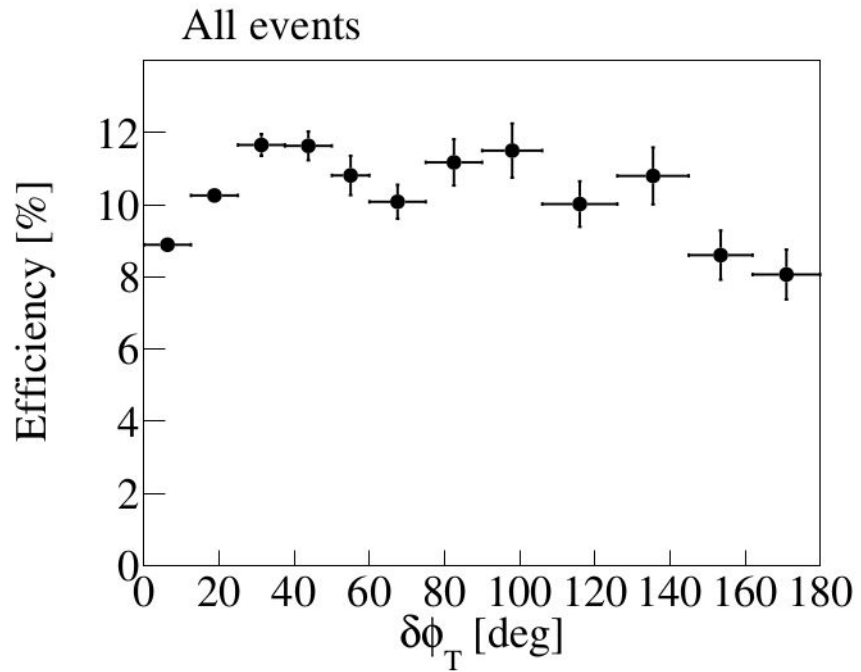
High Statistics → Into the Multiverse!

- First neutrino-argon differential cross section in TKI variables
- Sensitive to initial nucleon motion & proton FSI modeling

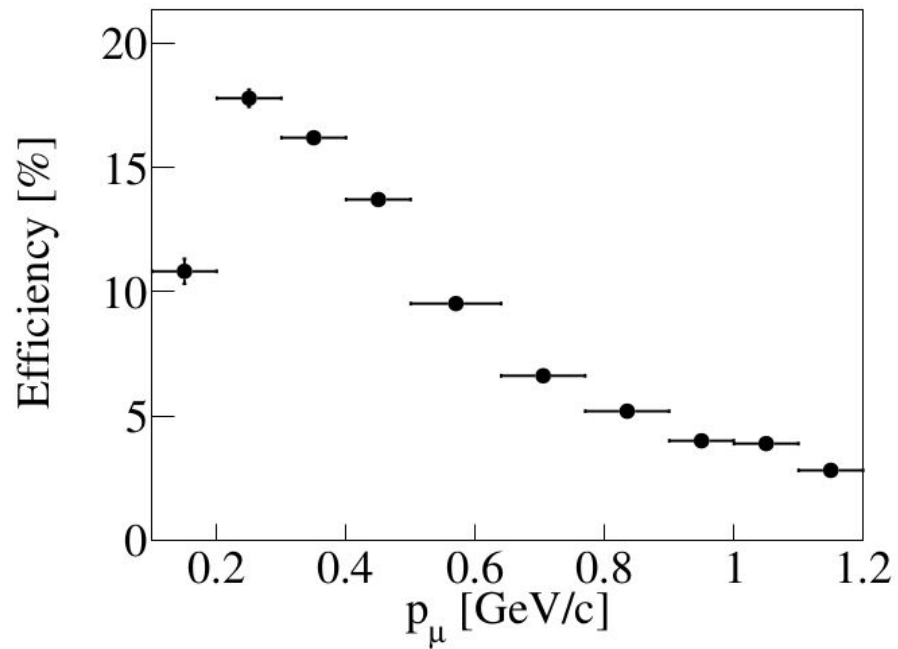




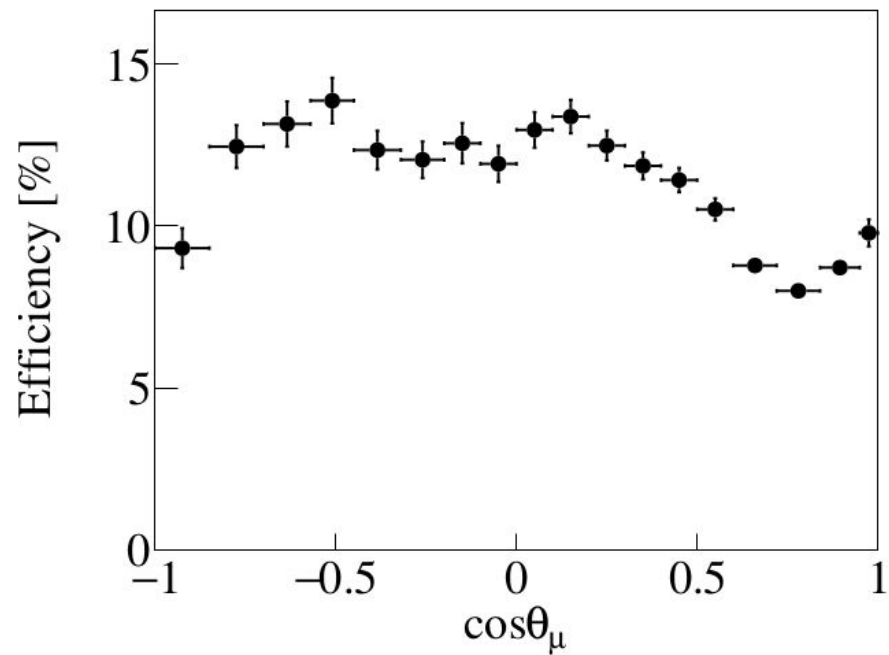


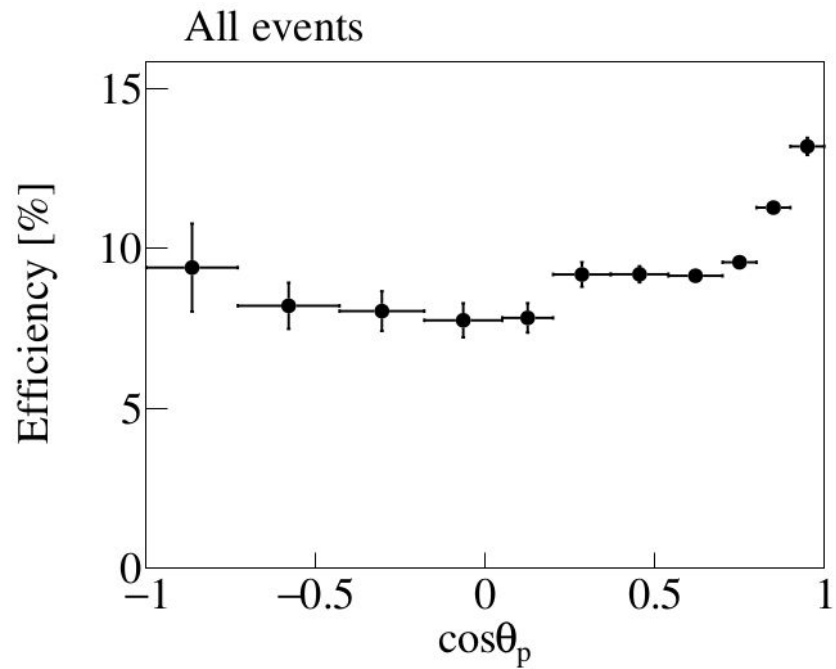
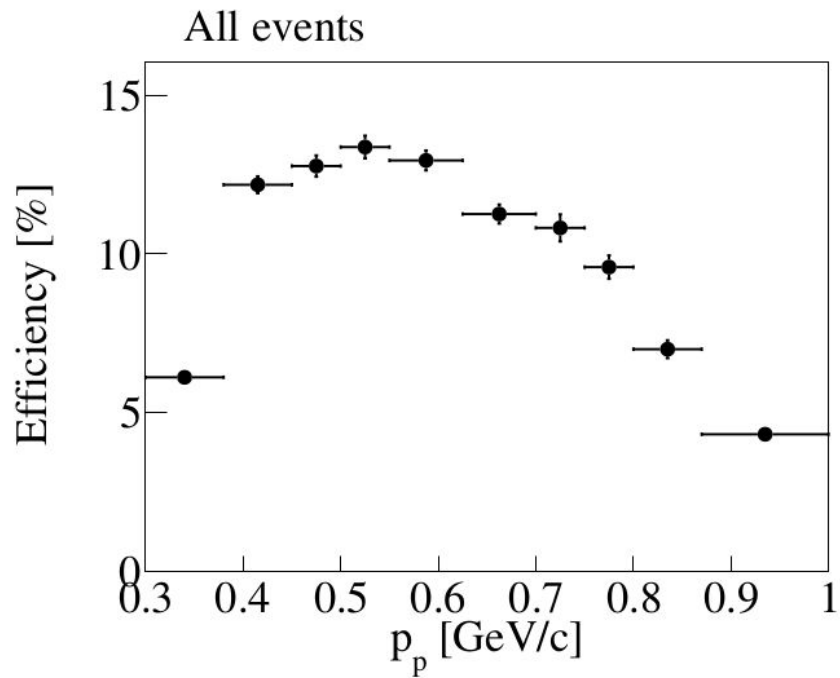


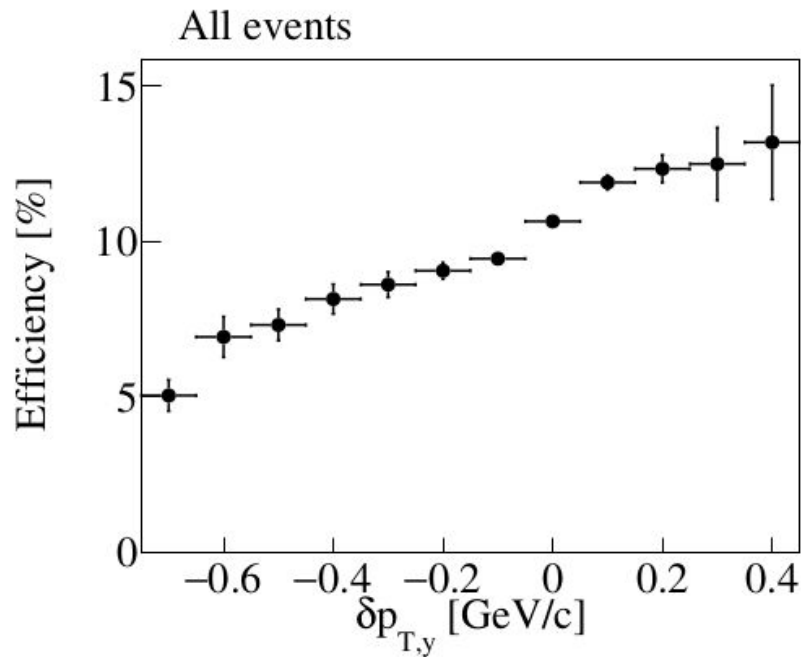
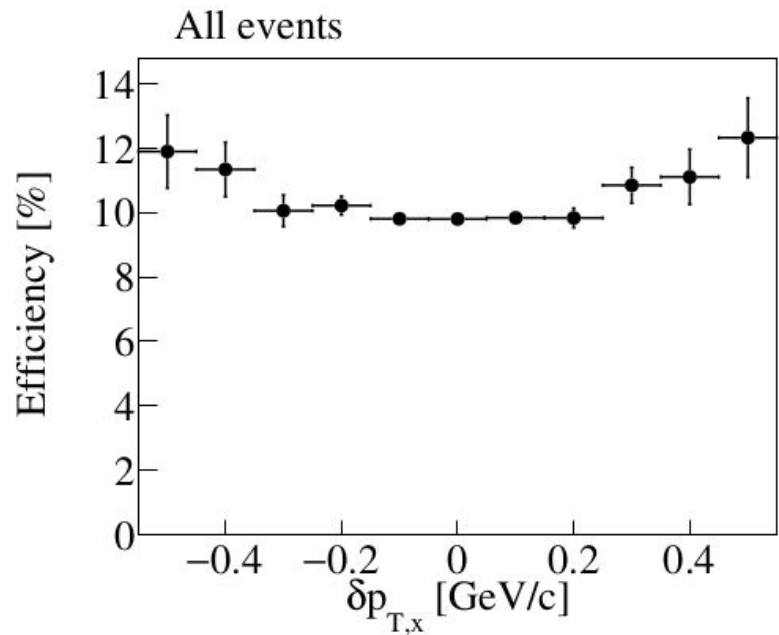
All events



All events







† MicroBooNE Data 6.79e+20 POT
— MC uB Tune

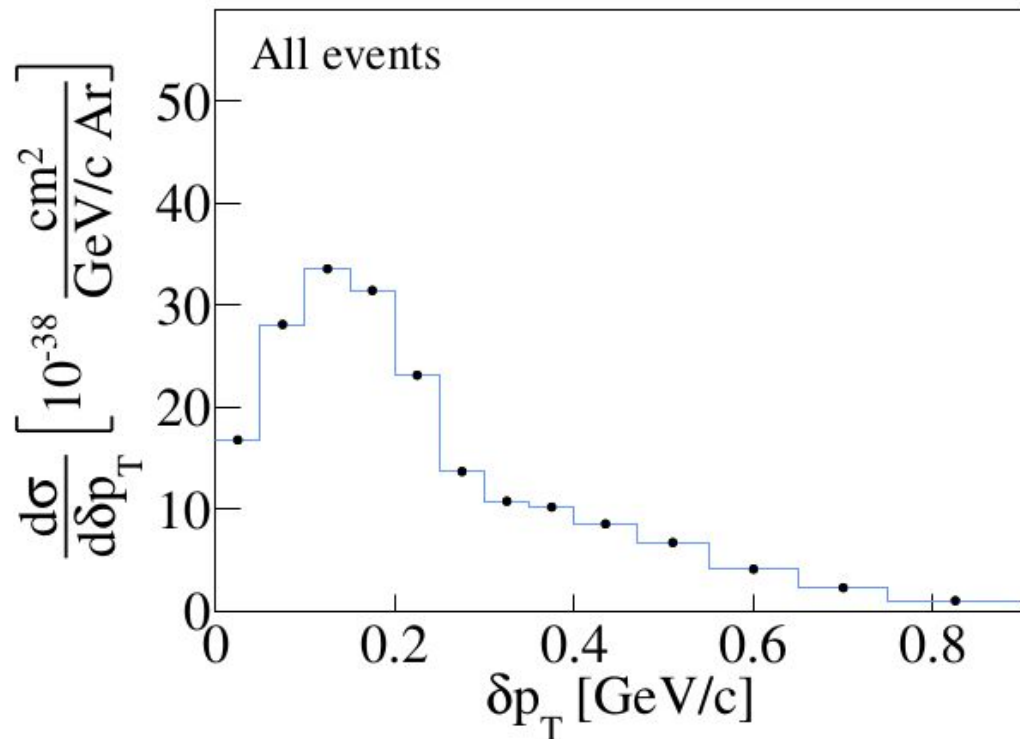
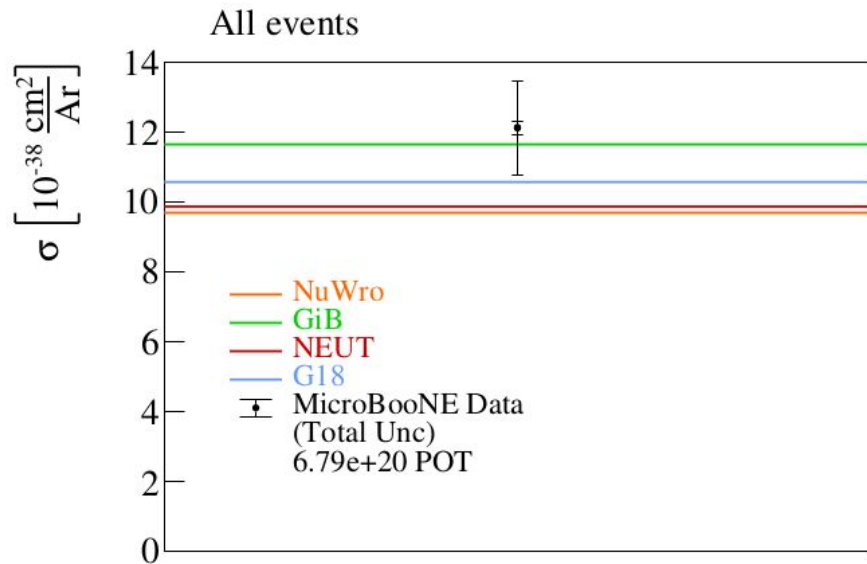
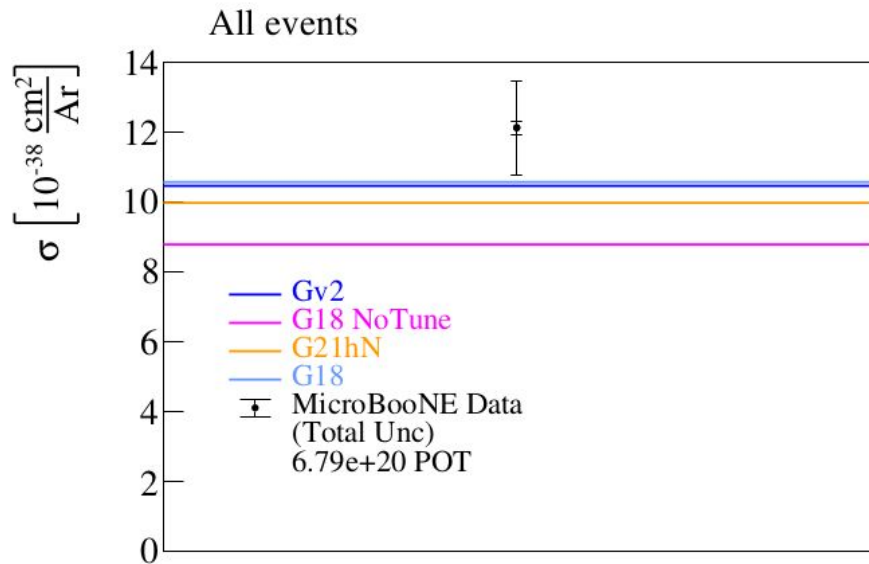


Figure 56: Closure test for δp_T .



Generalized Kinematic Imbalance (GKI)

Straightforward extension to 3D by considering longitudinal component of missing moment

However, an assumption on the incoming energy has to be made

First attempt in [Phys. Rev. C 95, 065501 \(2017\)](#) using CCQE interactions off a bound stationary neutron

Leveraging calorimetric energy estimator definition

$$E_{\text{cal}} = E_{\mu} + K_p + B$$

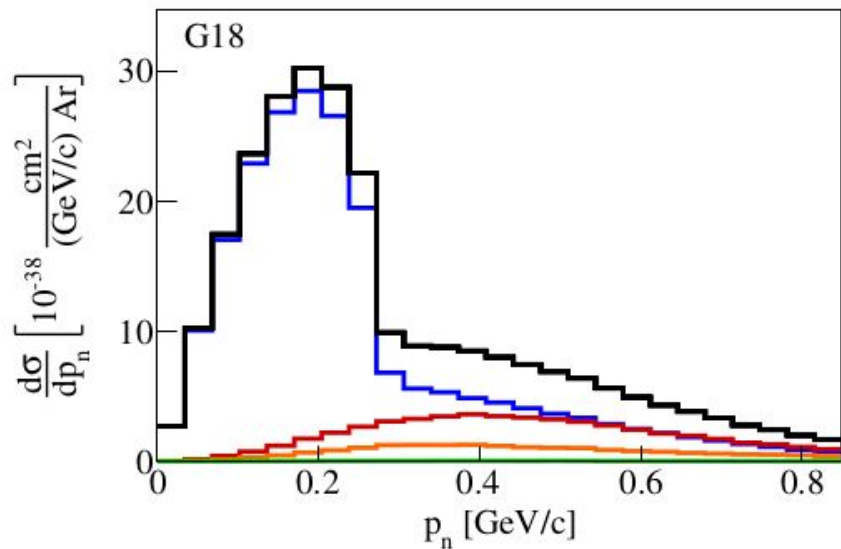
to obtain the longitudinal component of missing momentum

$$p_L = p_L^{\mu} + p_L^p - E_{\text{cal}}$$

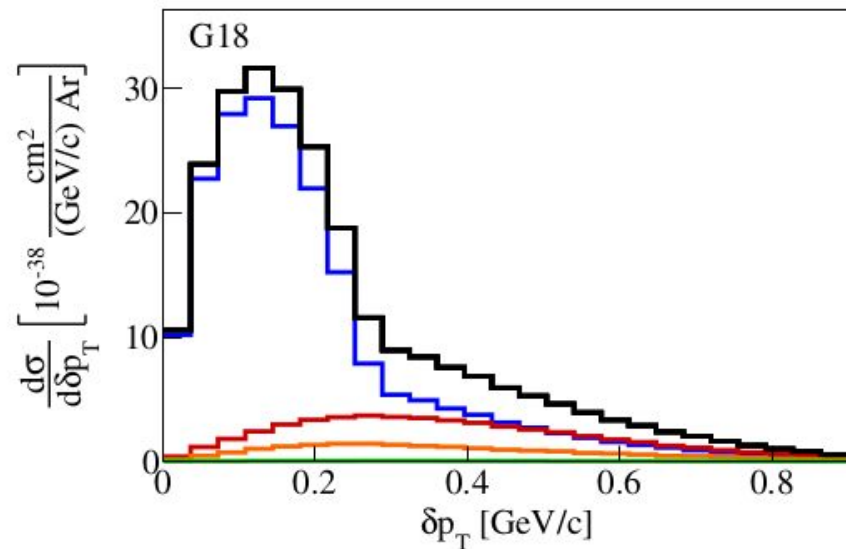
and the energy transfer vector

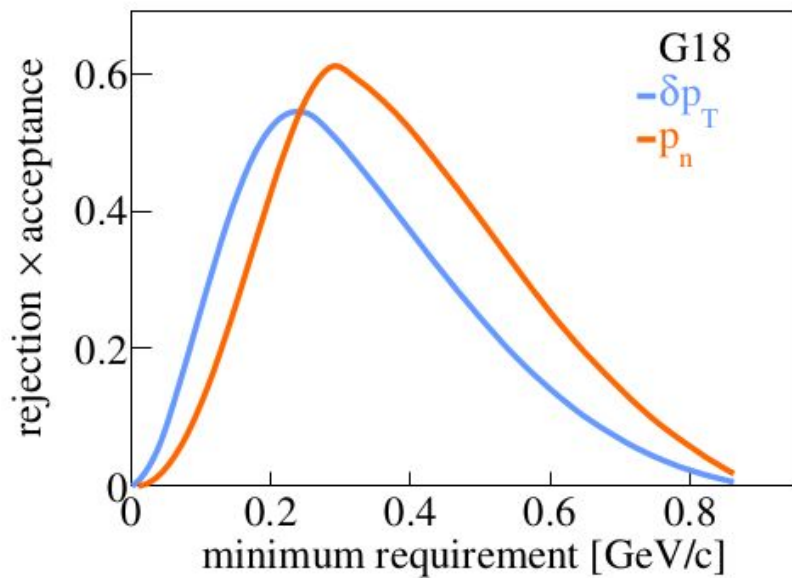
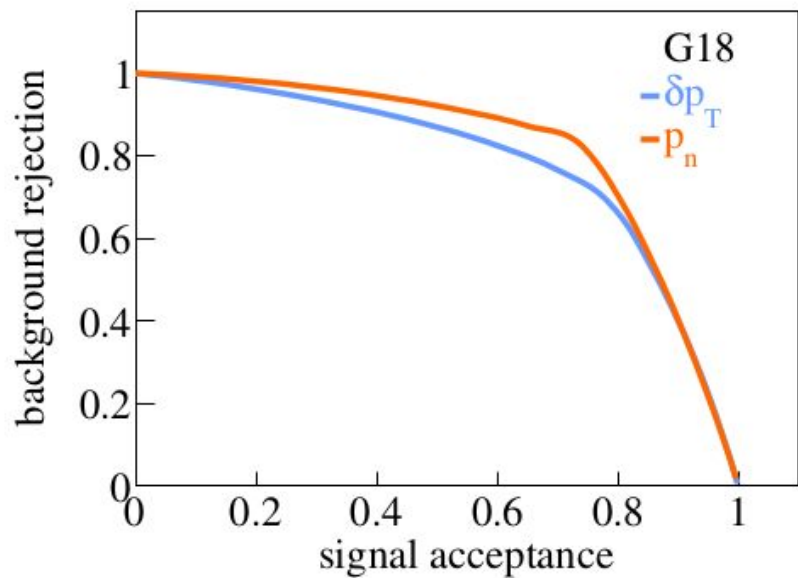
$$\vec{q} = E_{\text{cal}} \hat{z} - \vec{p}_{\mu}$$

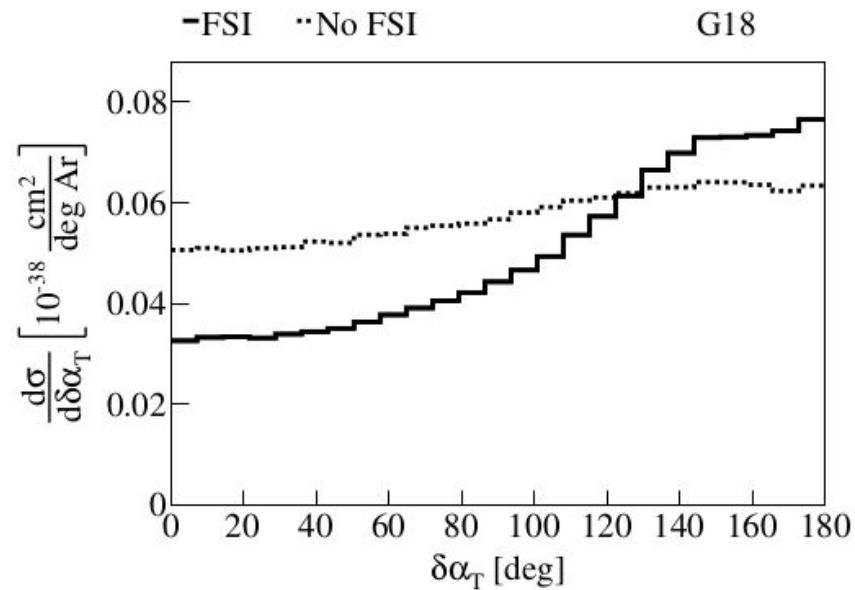
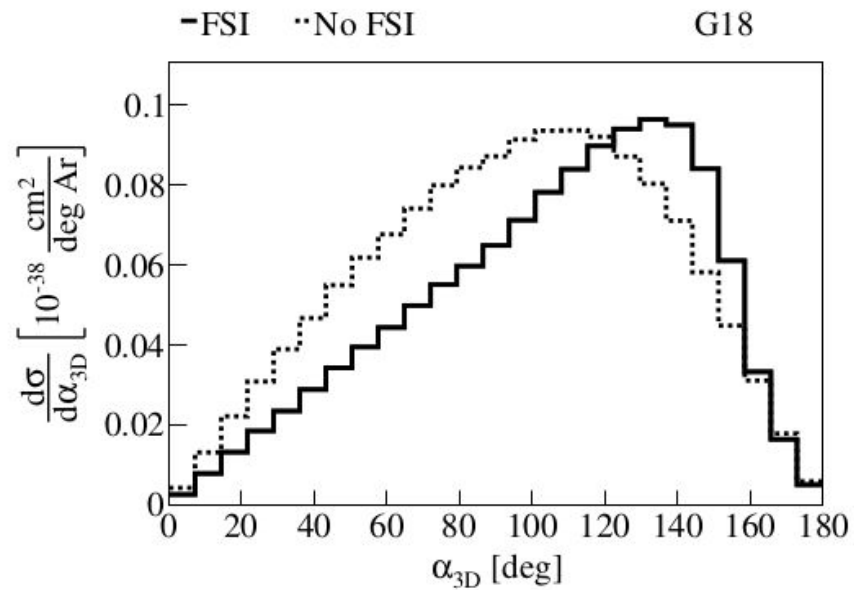
-Total -QE -MEC -RES -DIS

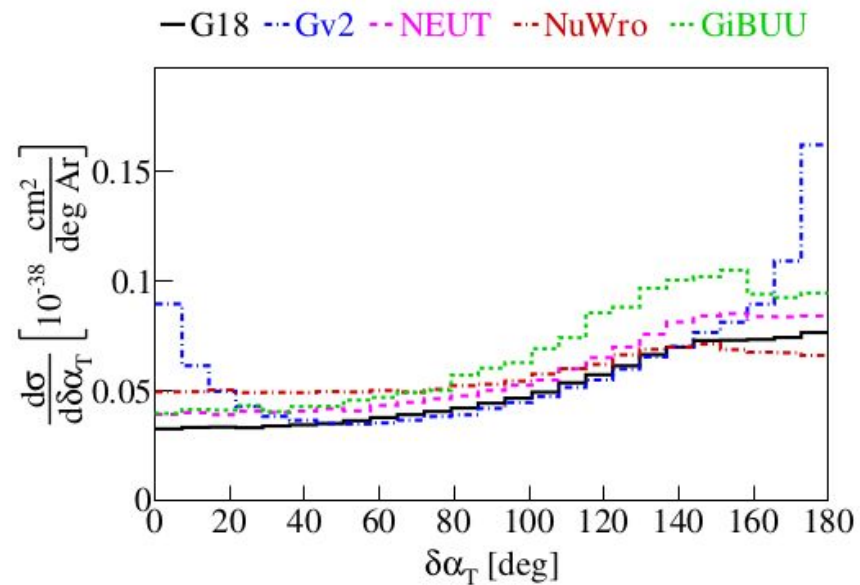
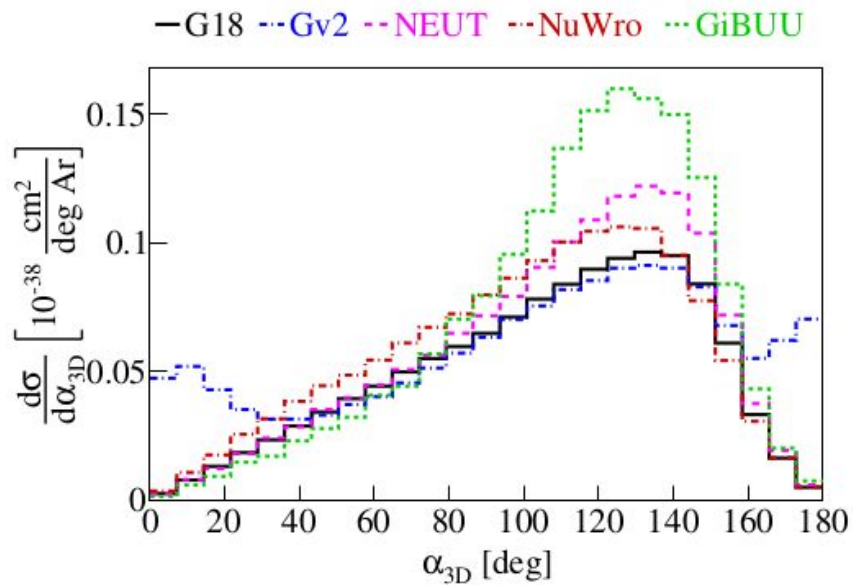


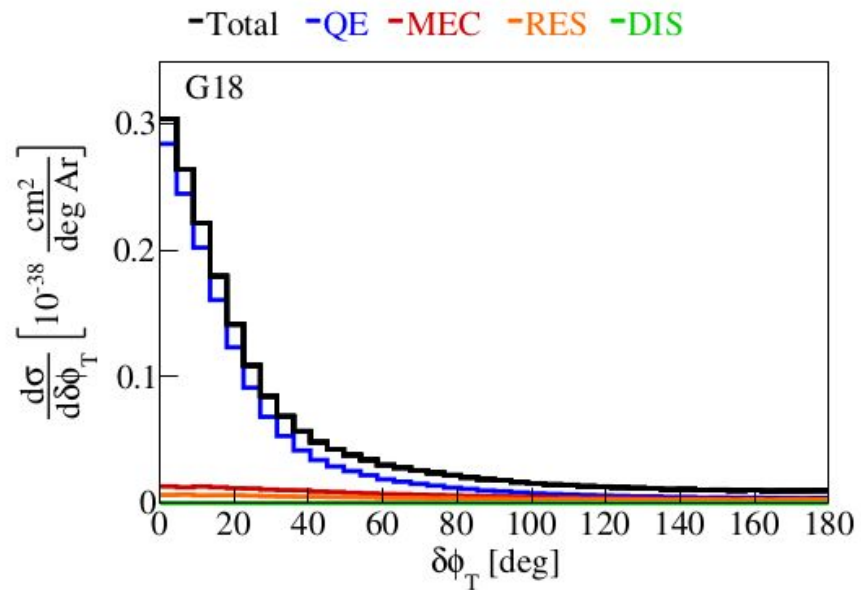
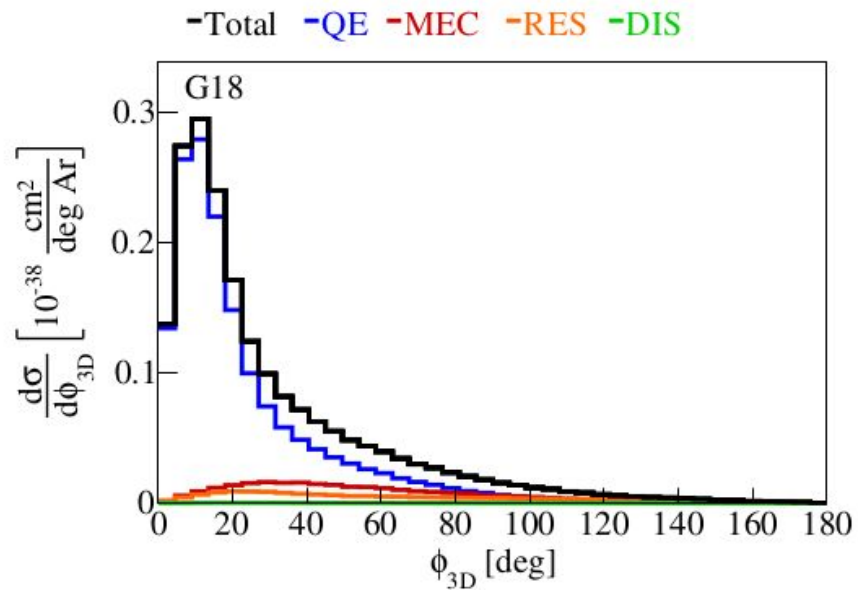
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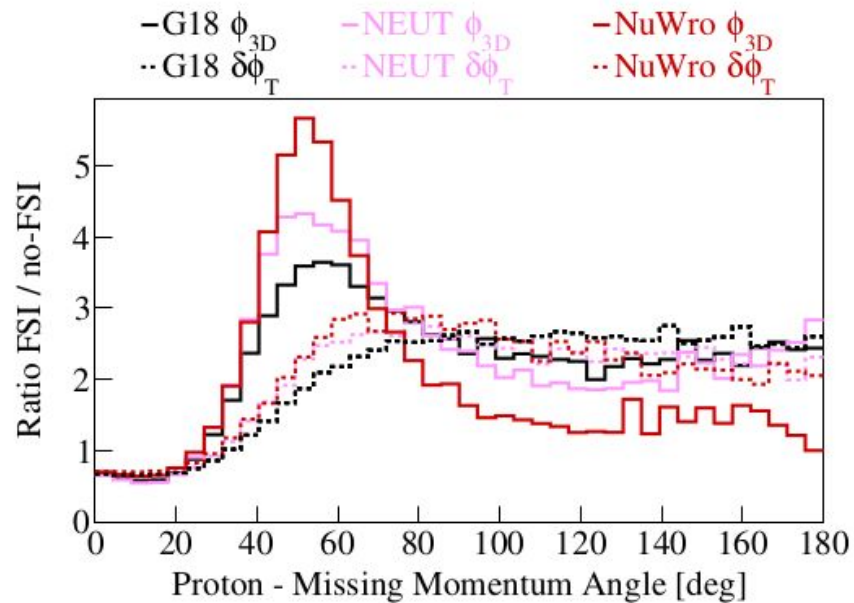
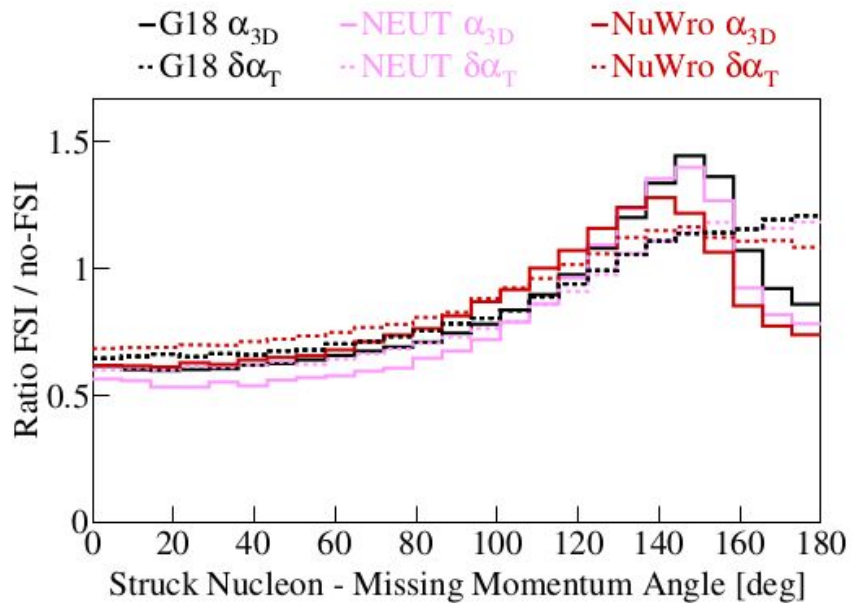


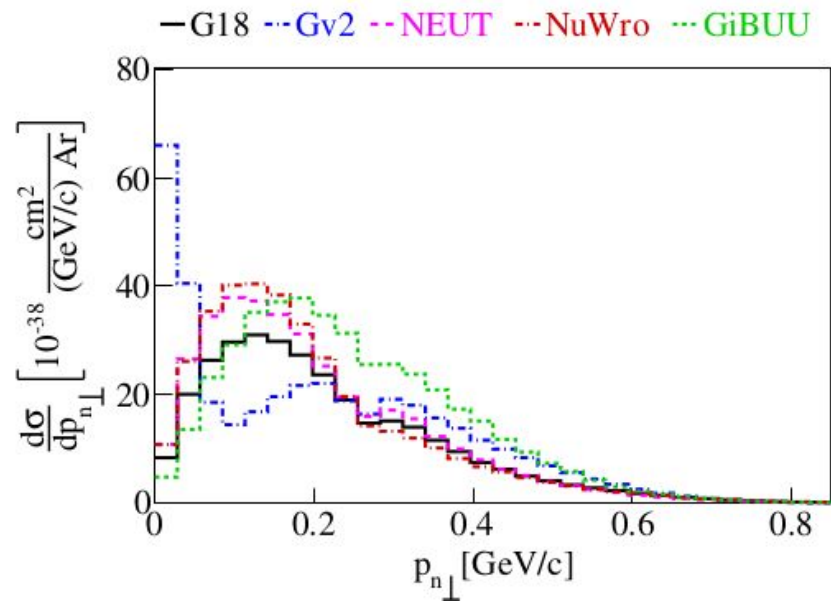
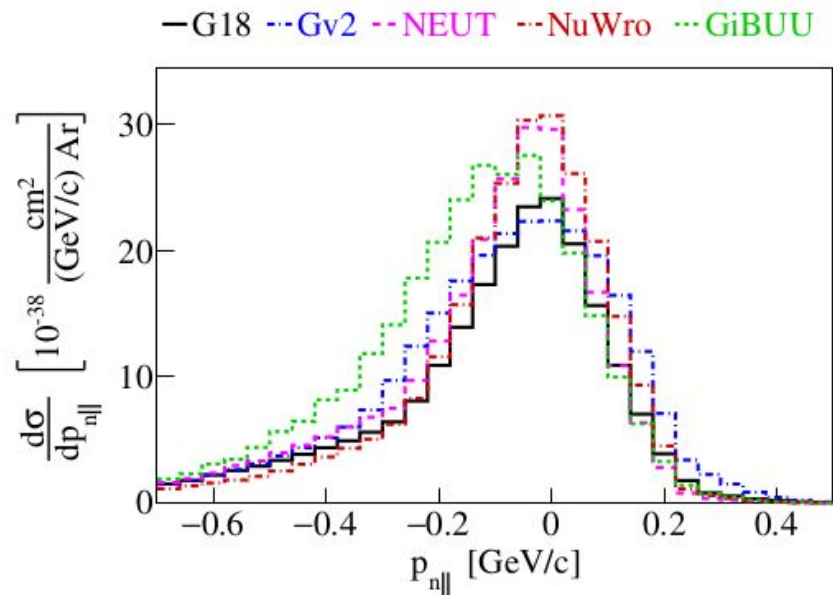




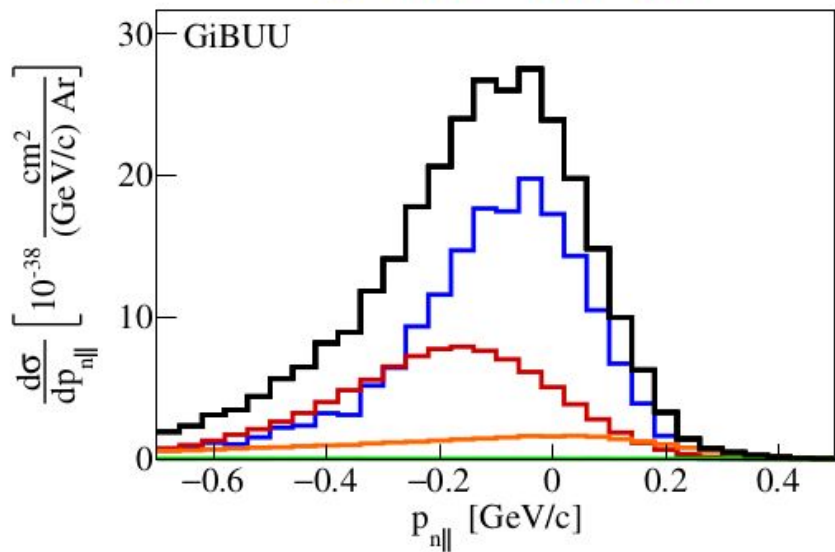




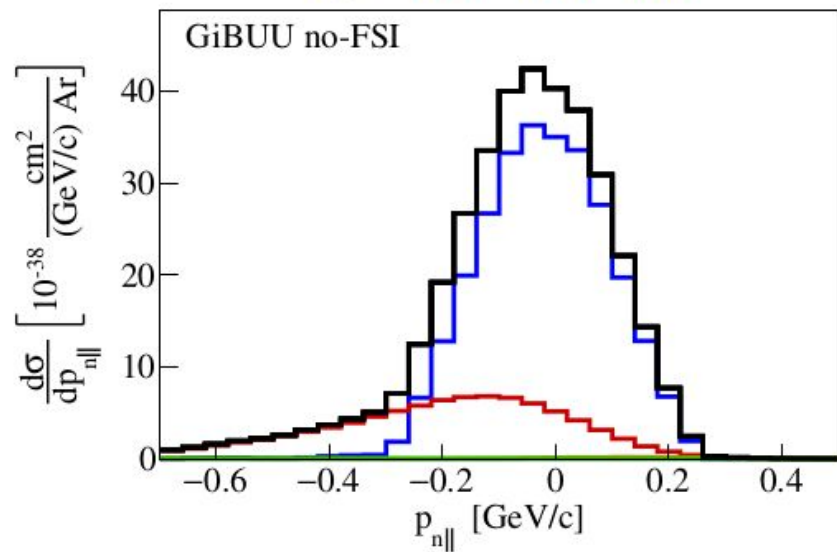


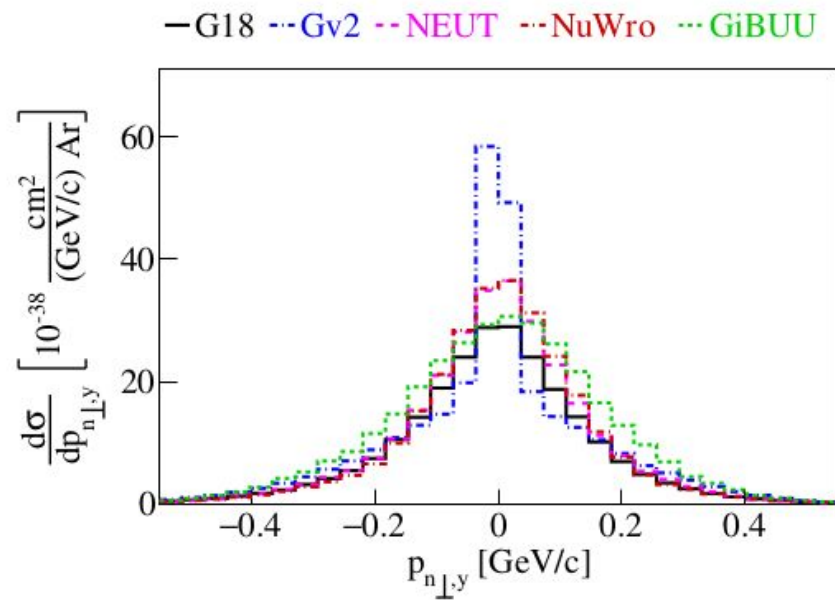
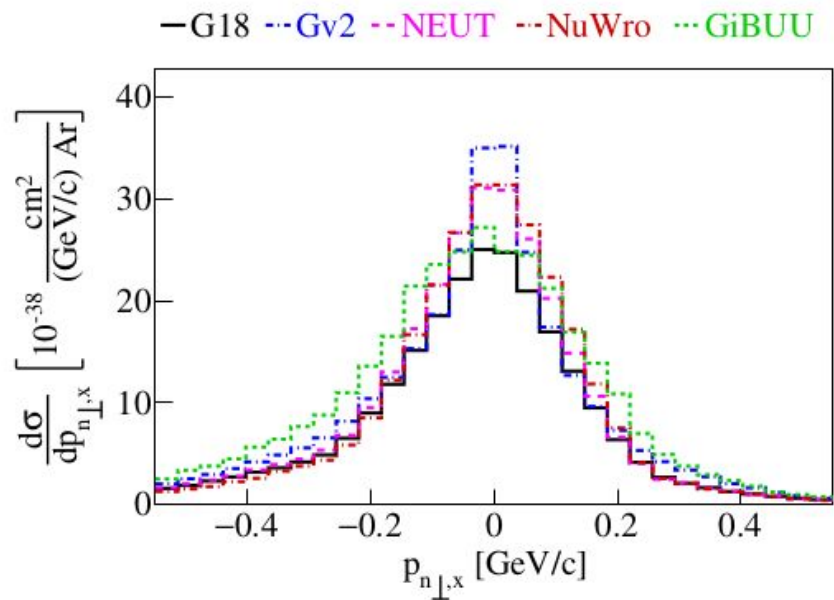


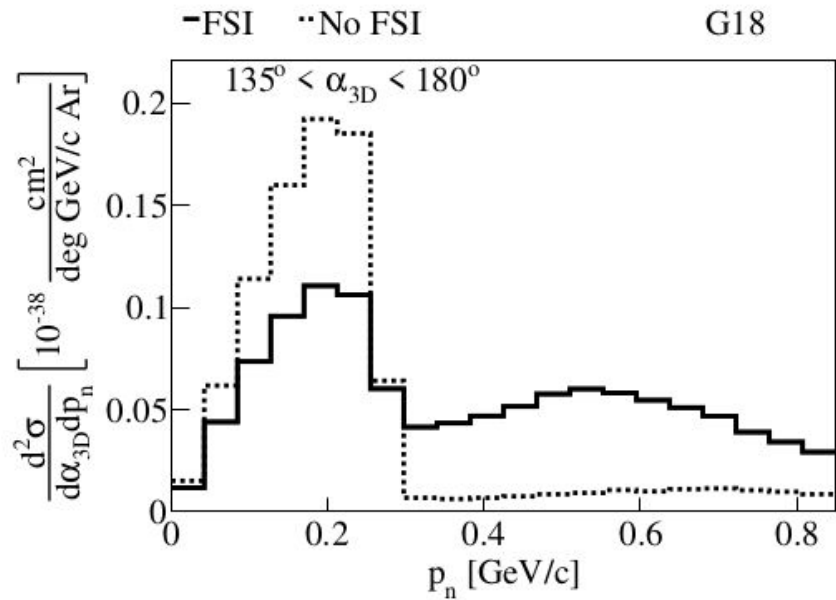
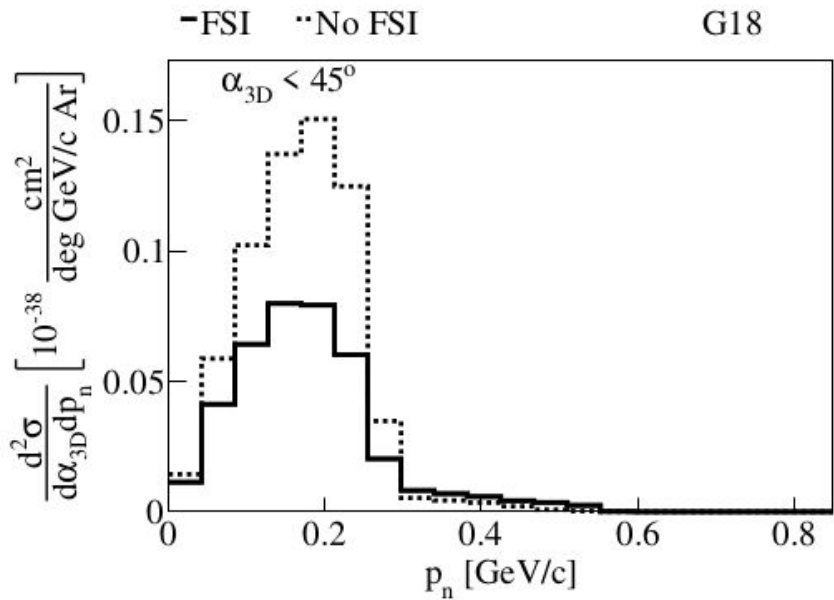
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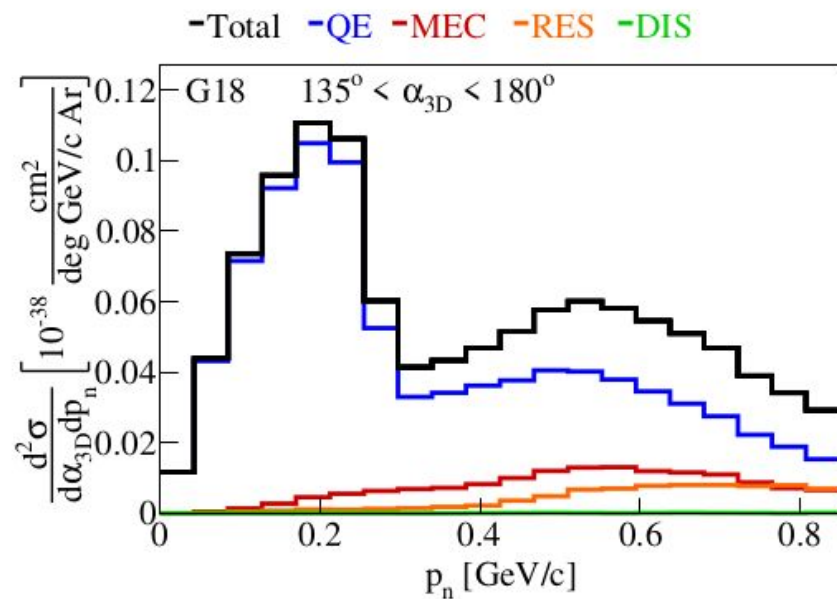
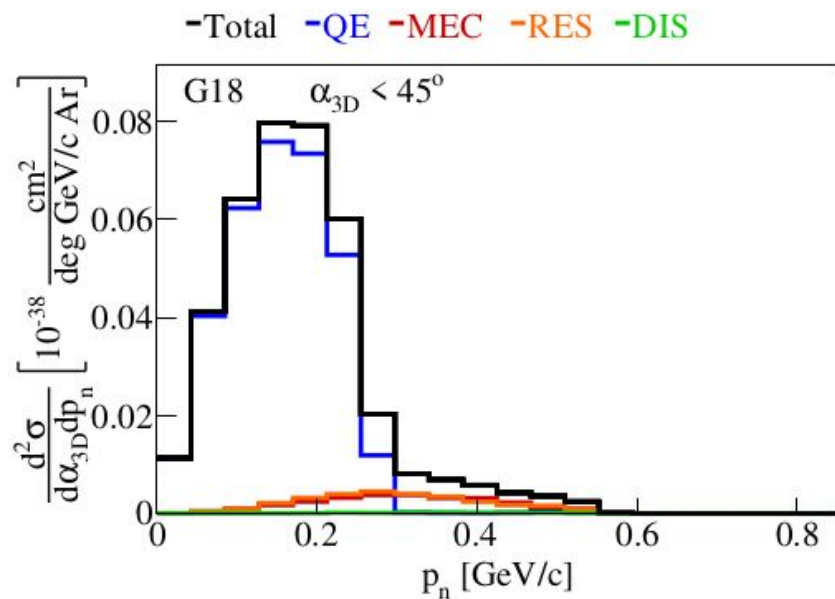


-Total -QE -MEC -RES -DIS

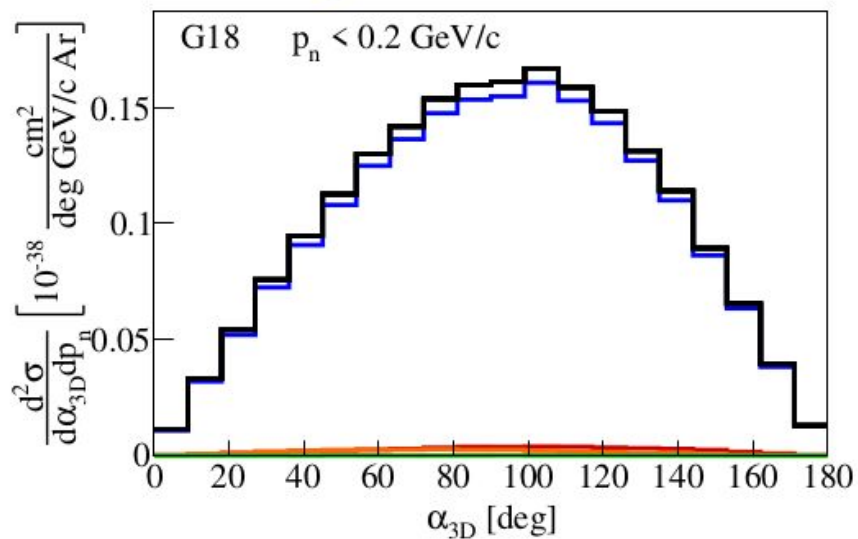




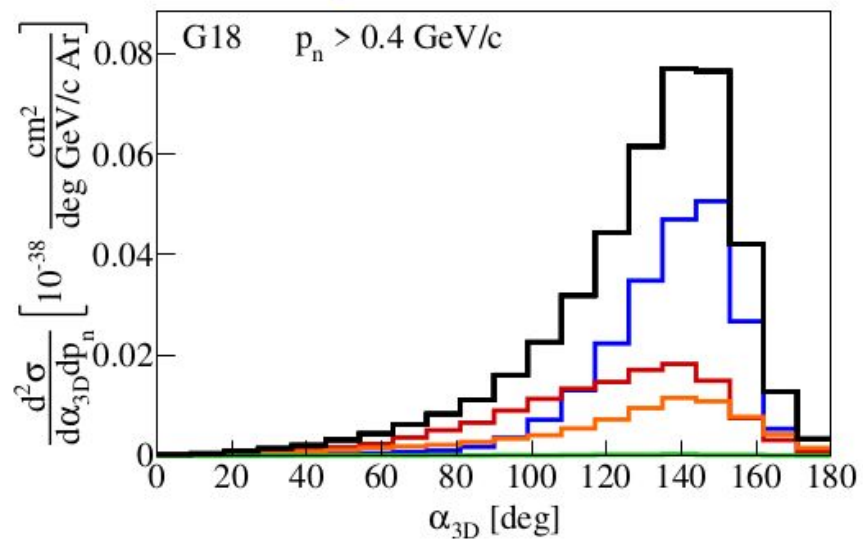


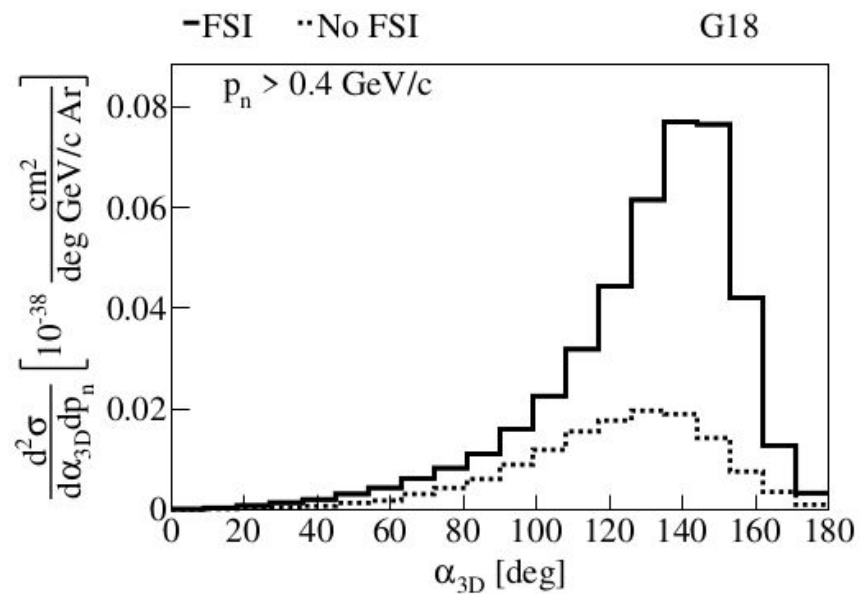
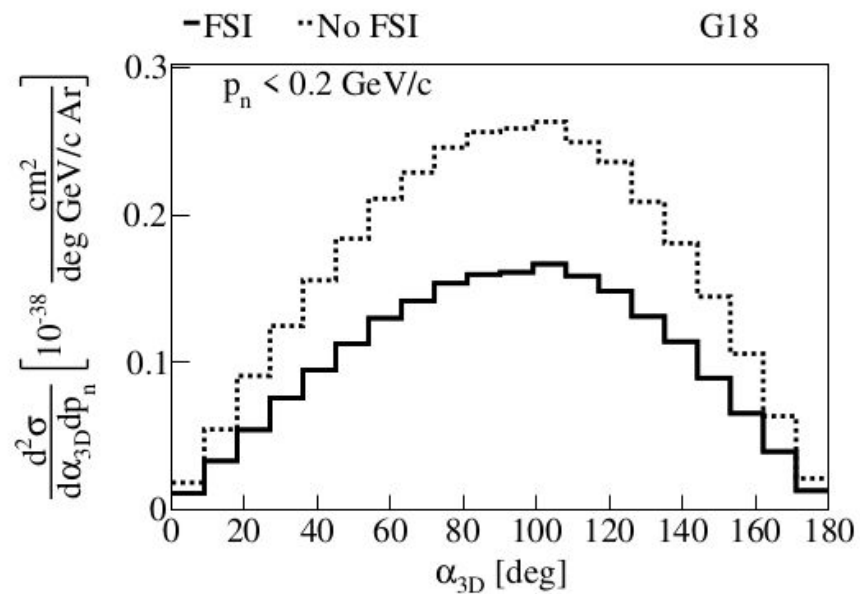


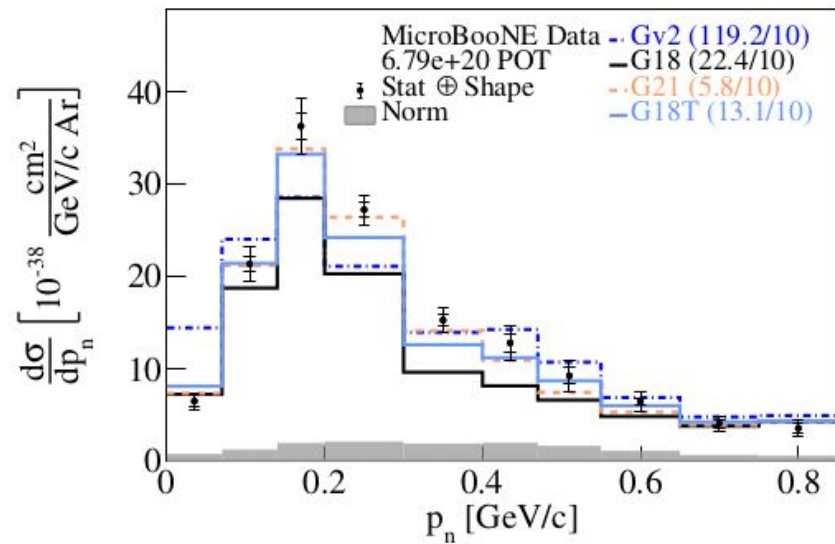
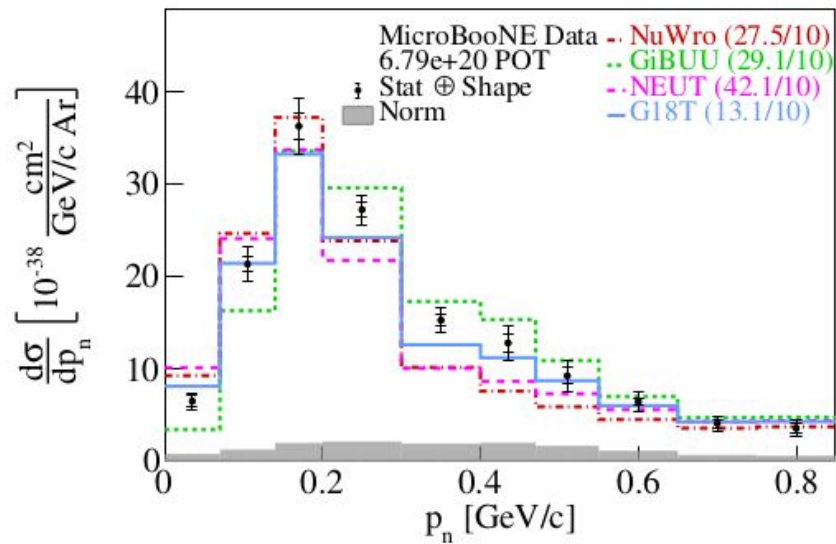
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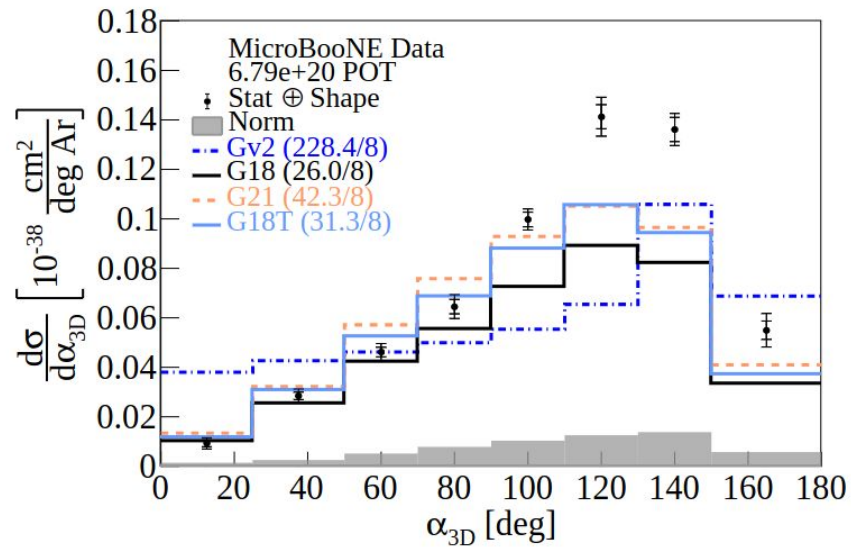
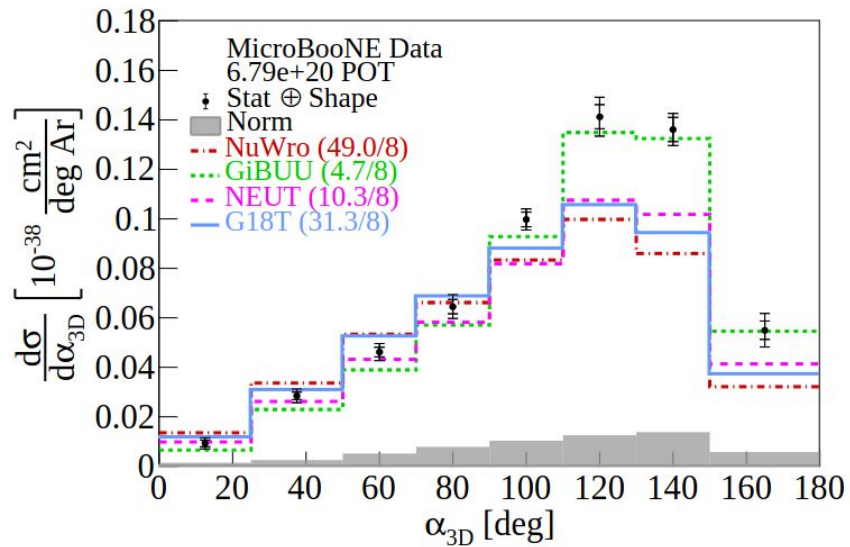


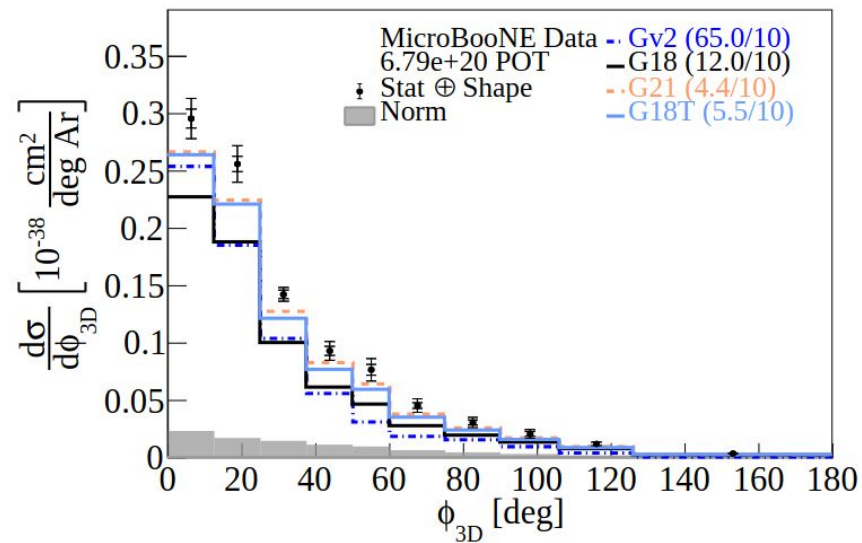
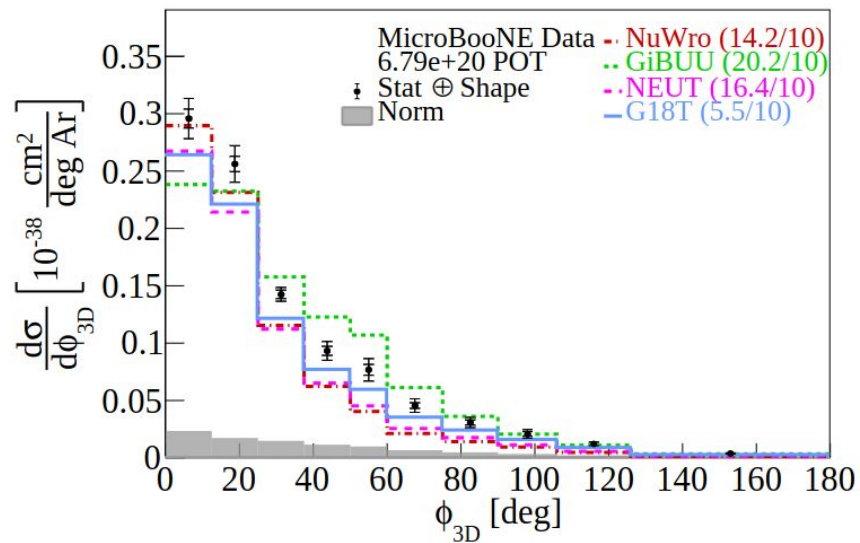
-Total -QE -MEC -RES -DIS

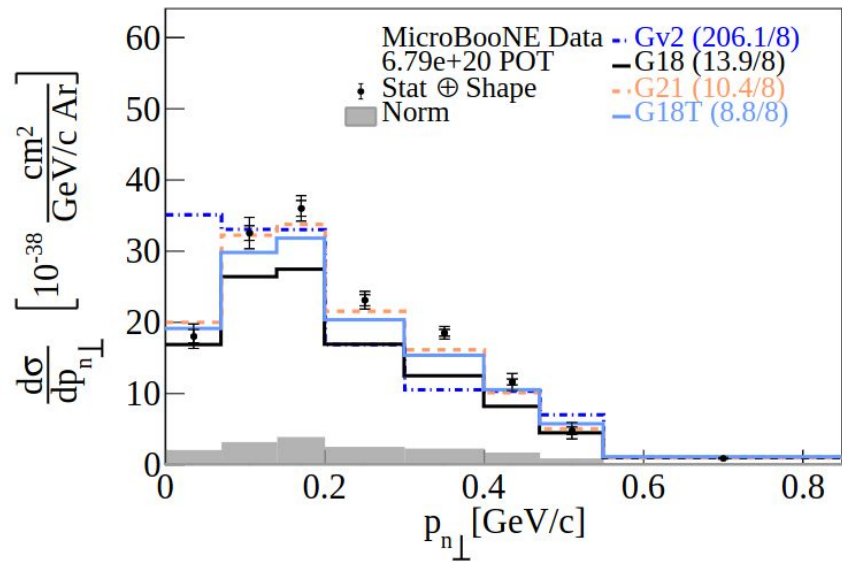
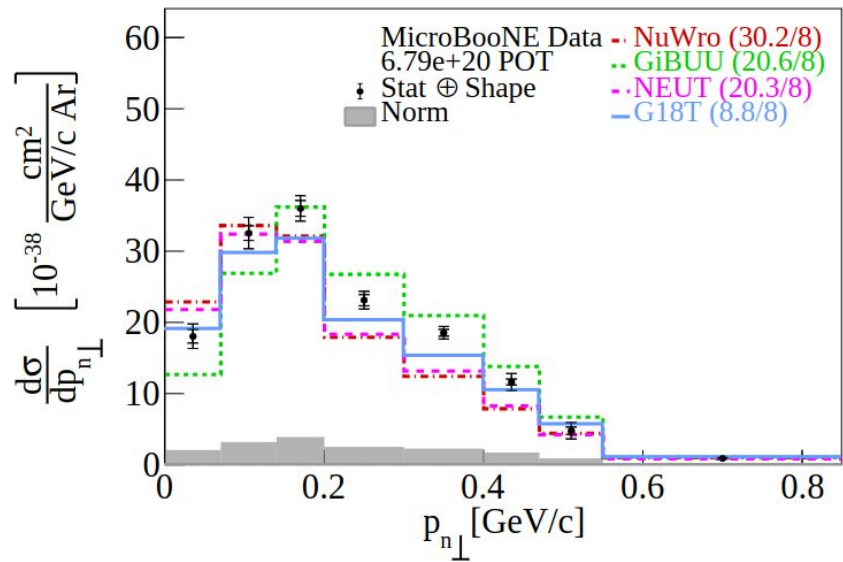


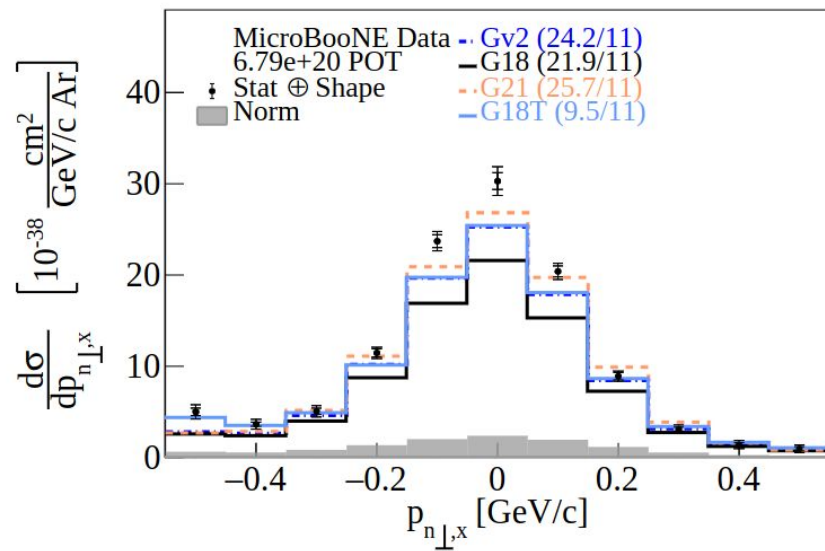
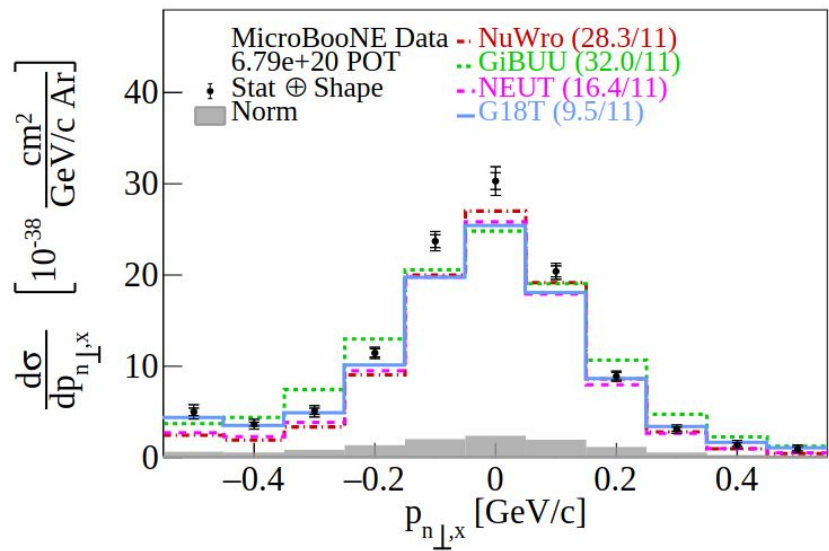


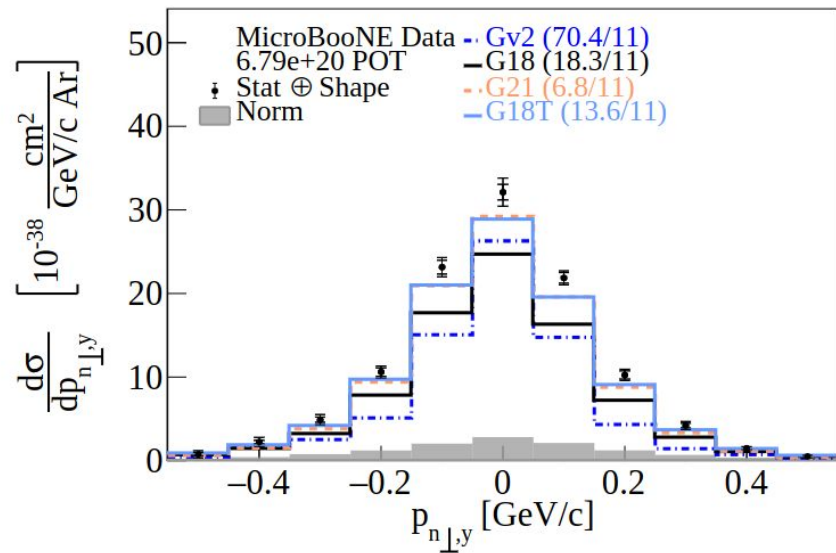
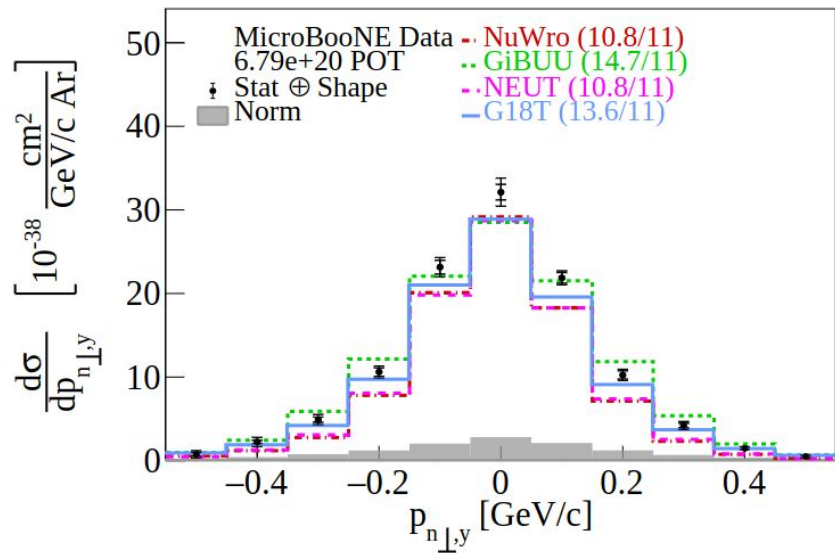


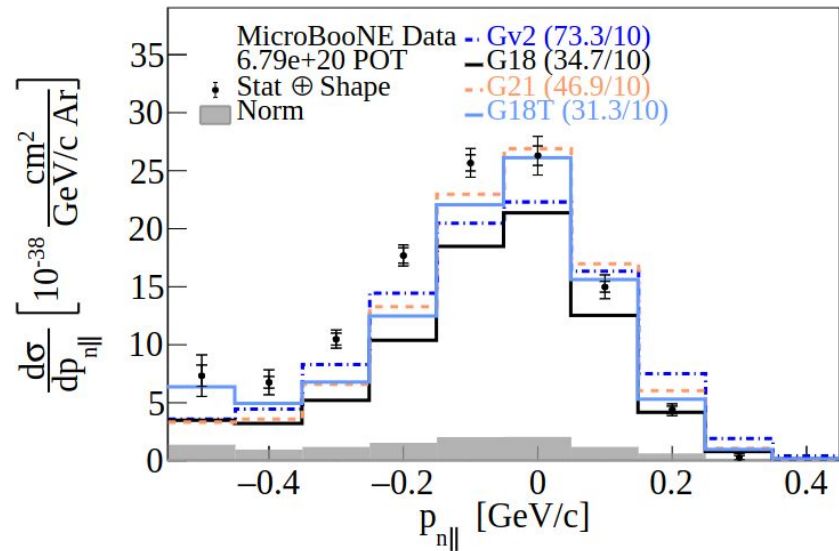
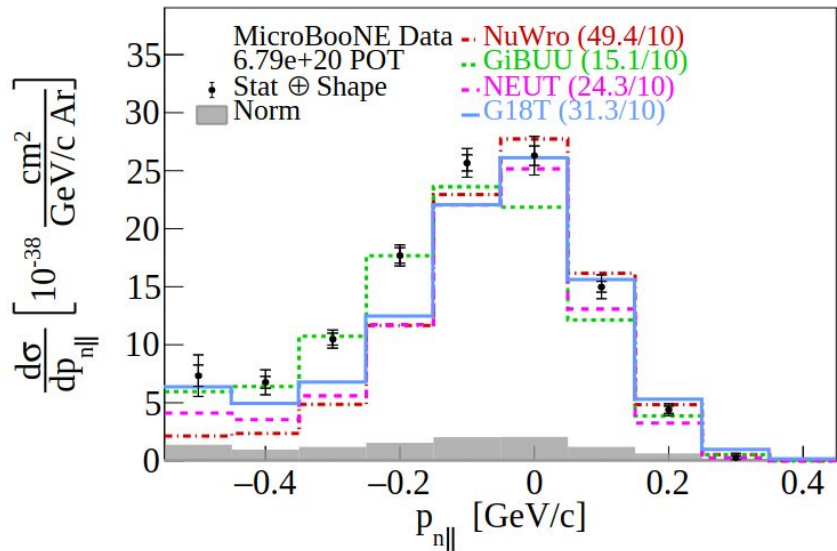






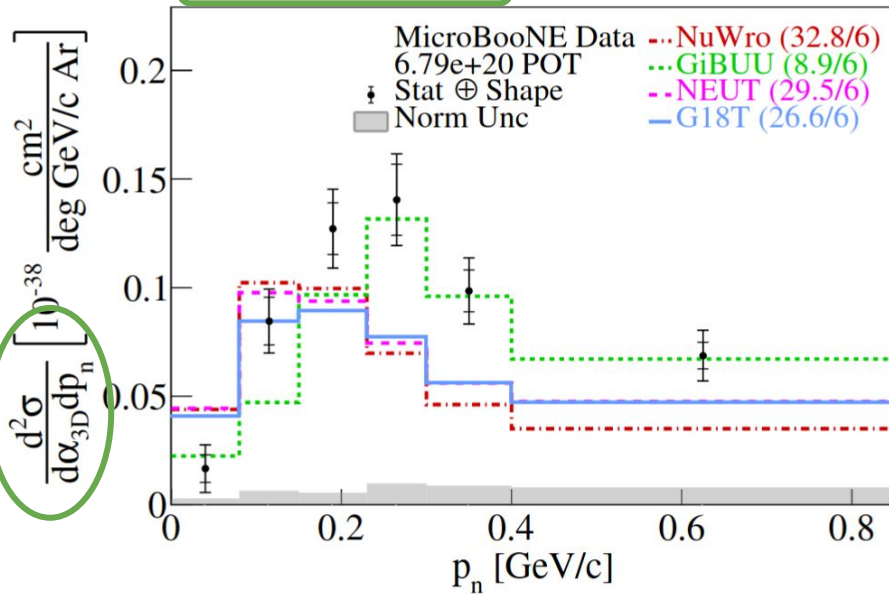






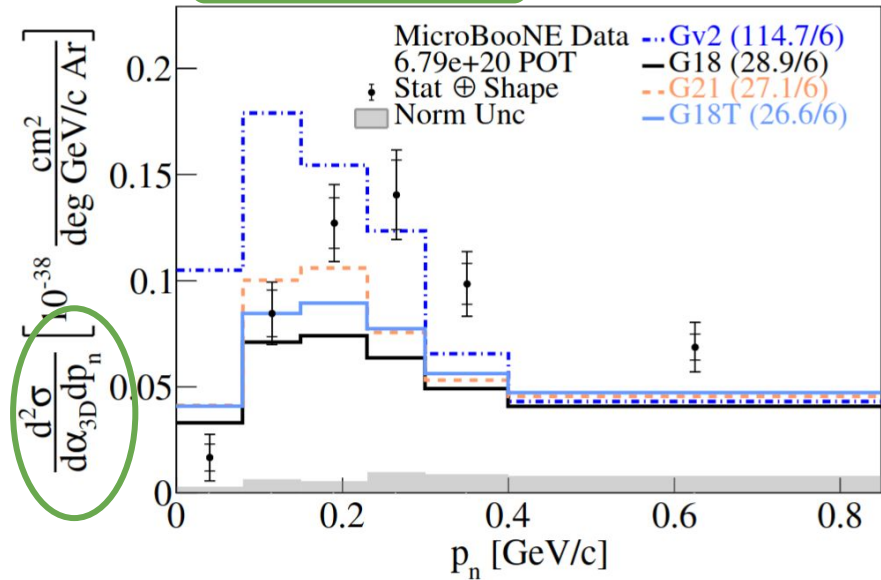
Into the GKI multiverse!

$135^\circ < \alpha_{3D} < 180^\circ$



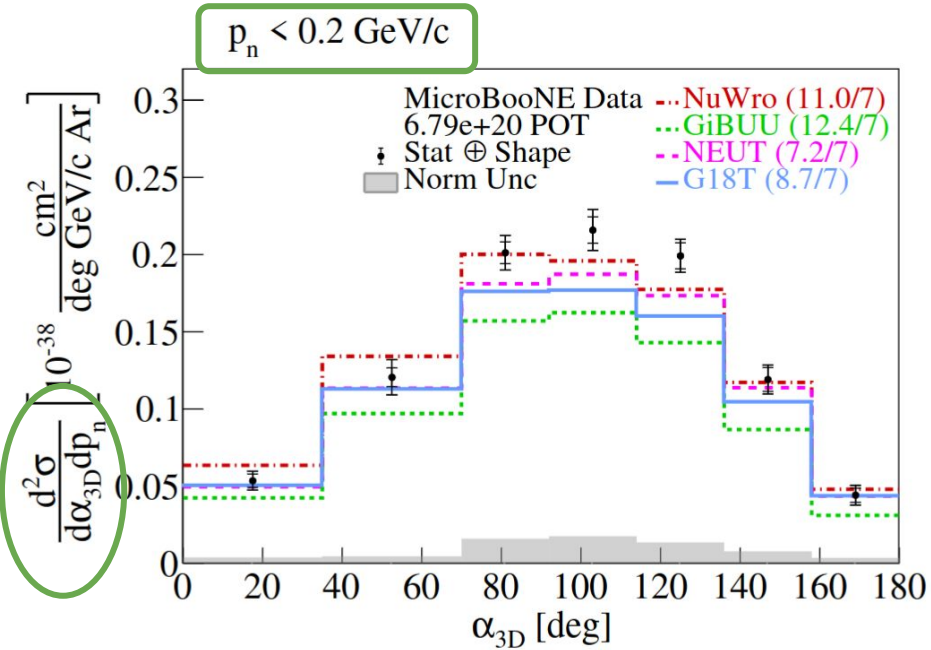
- Extended tail to higher values
- FSI-dominated region

$135^\circ < \alpha_{3D} < 180^\circ$

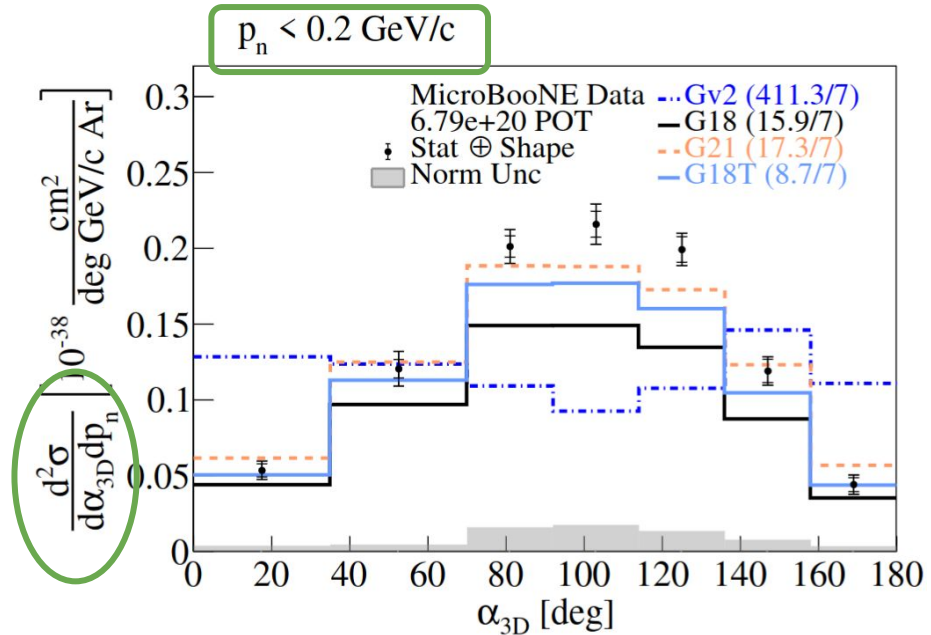


- GiBUU shift to the right, yet lowest χ^2
- Gv2 yields worst agreement
- Other generators yield comparable ratios

Into the GKI multiverse!



- QE-dominated region
- Most generators result in comparable results

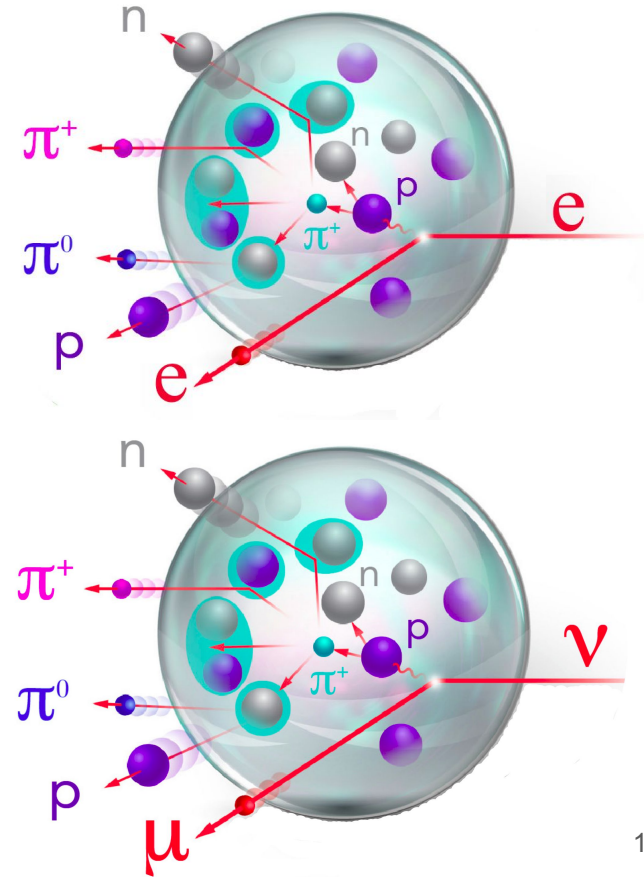


- Gv2 yields worst agreement
- G18T results in good agreement

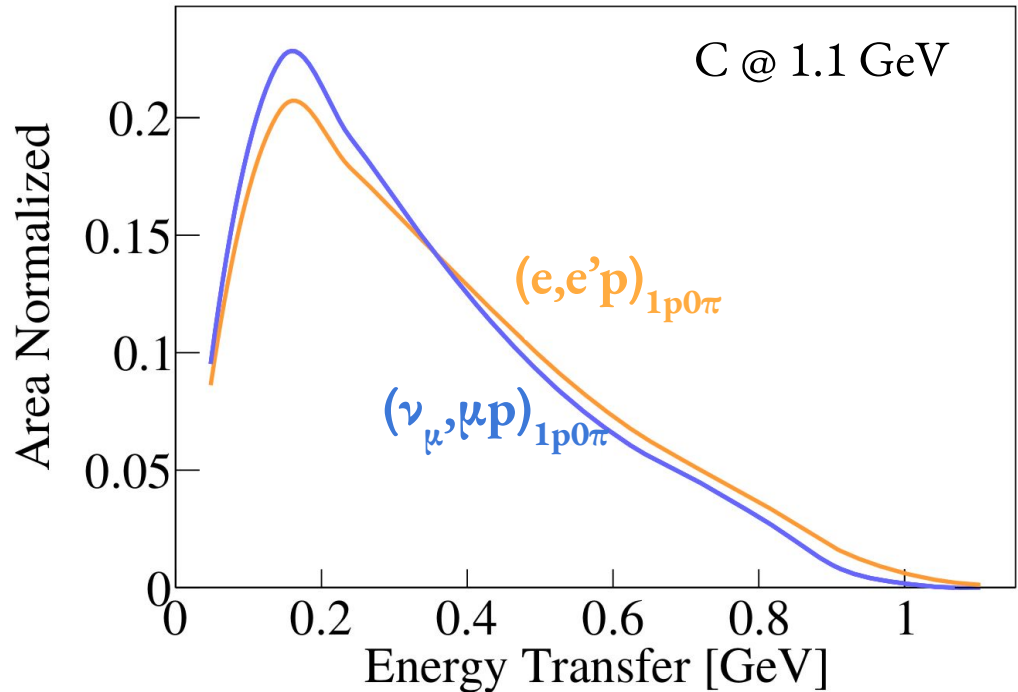
Why electrons?

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 - Precision measurements

Any model must work for electrons,
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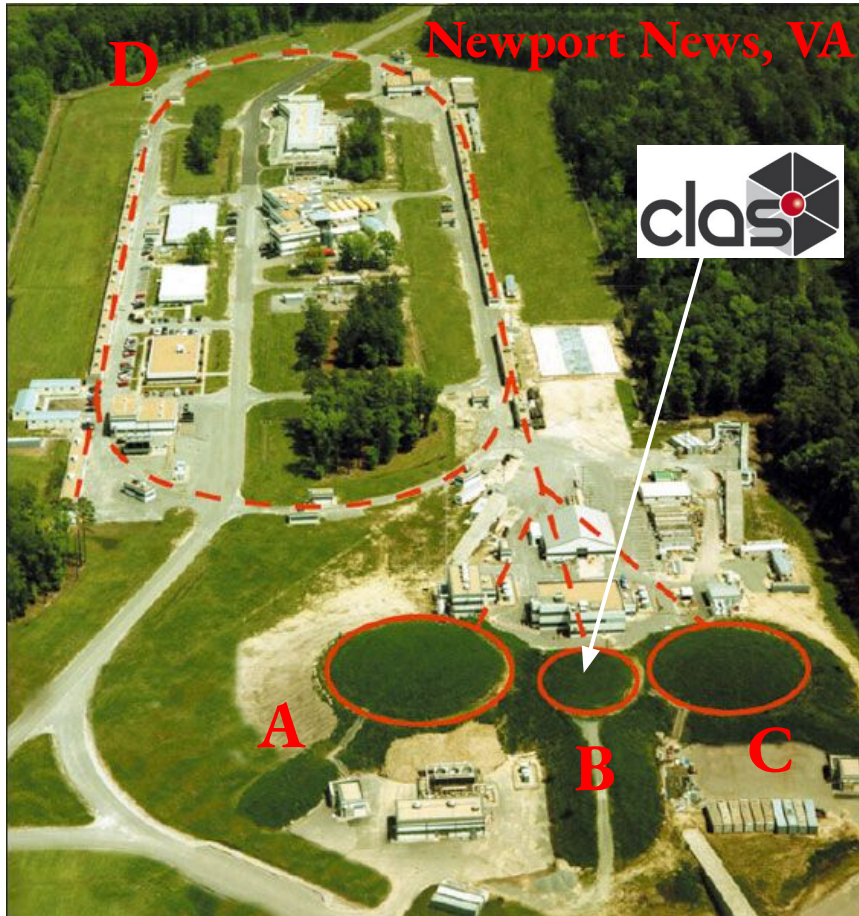


Similar ν & e Distributions

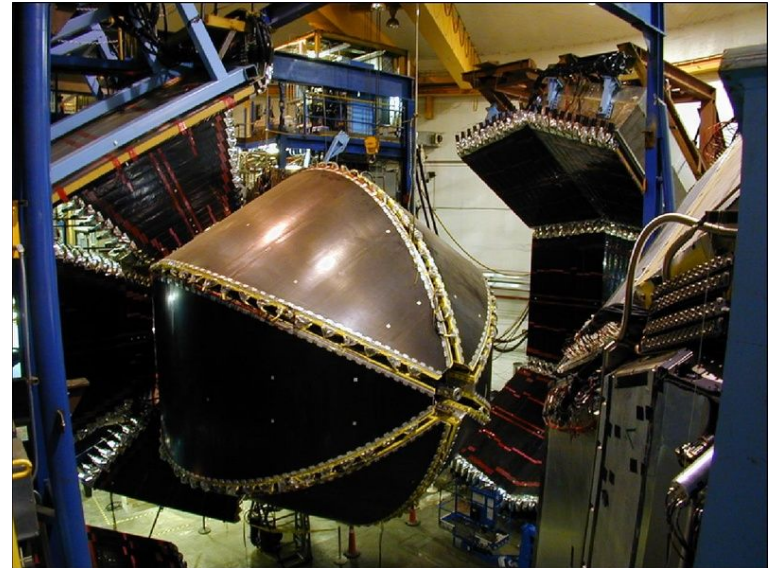


Accounting for propagator mass (γ vs W) via Q^4 scaling of the electron side

Jefferson Laboratory

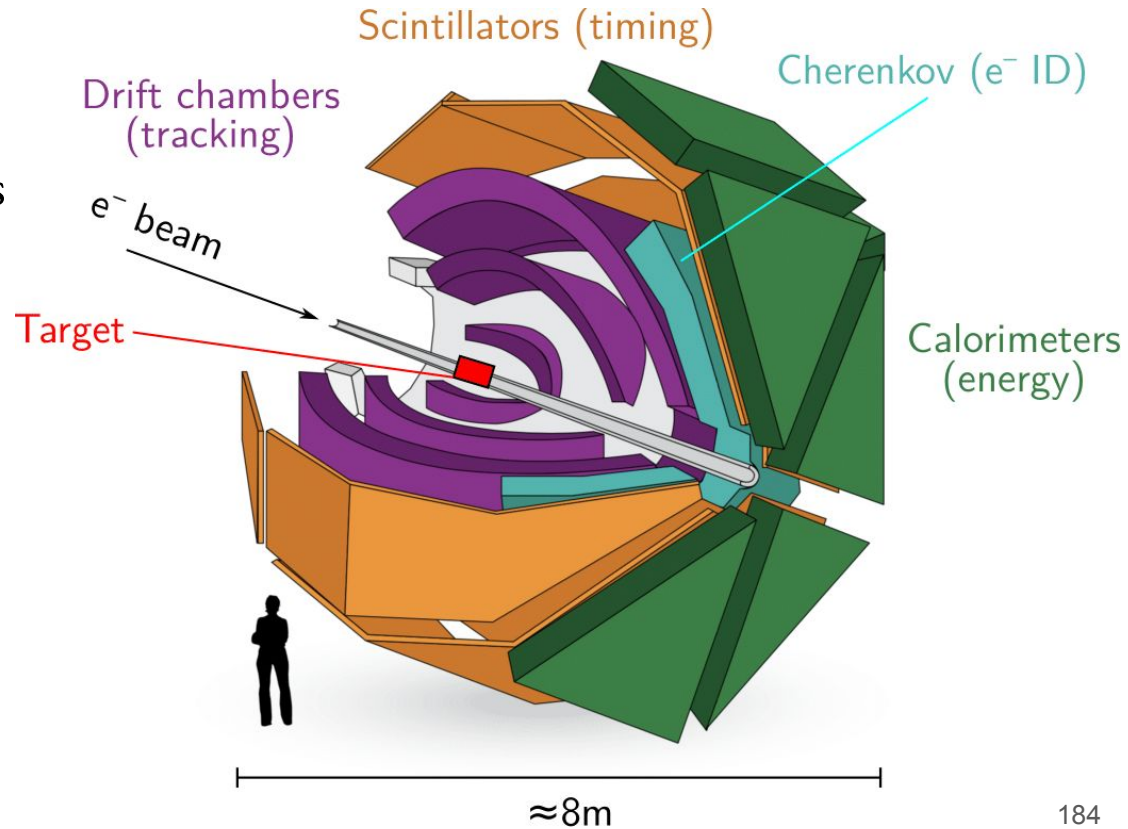


- Electron beam accelerator facility
- Energies up to 12 GeV
- Using Hall B & CLAS detector



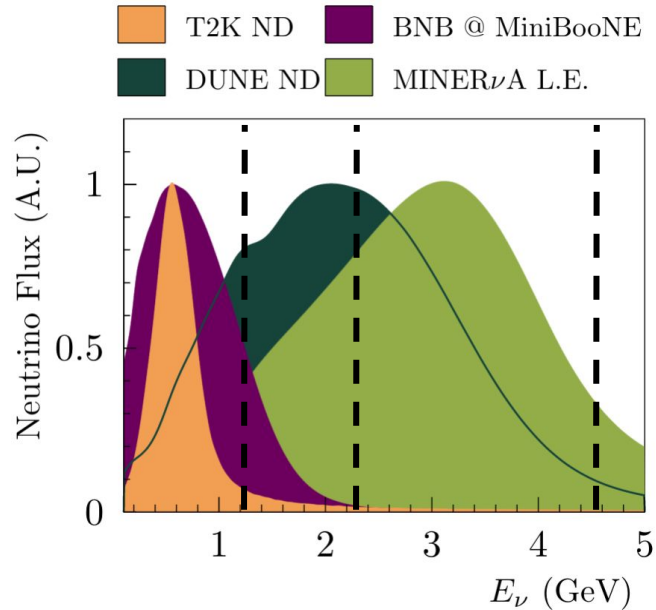
$e_4\nu$ Data-Mining With CLAS

- Charged particle threshold similar to ν tracking detectors
- $\sim 50\%$ of “ 4π ” coverage



$e4\nu$ Data-Mining With CLAS

- Charged particle threshold similar to ν tracking detectors
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- Energies: 1, 2 & 4 GeV
- Targets: ${}^4\text{He}$, ${}^{12}\text{C}$, ${}^{56}\text{Fe}$



T2K

H₂O

NOVA

MINERvA

CH

SBN Program
DUNE

Ar

Playing The QE-like Neutrino Game



- 1 proton (> 300 MeV/c)
- No π^\pm (> 70 MeV/c)

[Phys. Rev. Lett. 125, 201803 \(2020\)](#)

[arXiv:2301.03706](#)

[arXiv:2301.03700](#)



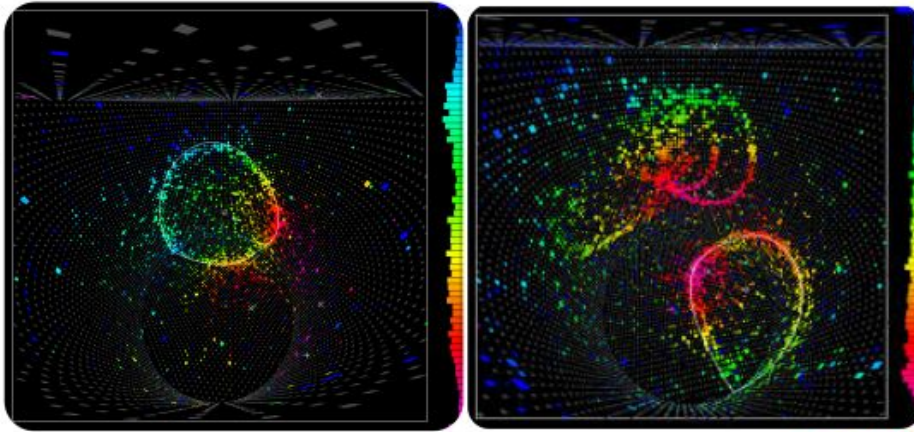
- 1 proton (> 300 MeV/c)
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- Scale by $\sigma_{\nu N} / \sigma_{eN} \propto Q^4$

[Nature 599, 565–570 \(2021\)](#)

- Study energy reconstruction
- Test against GENIE event generator

QE Energy Reconstruction

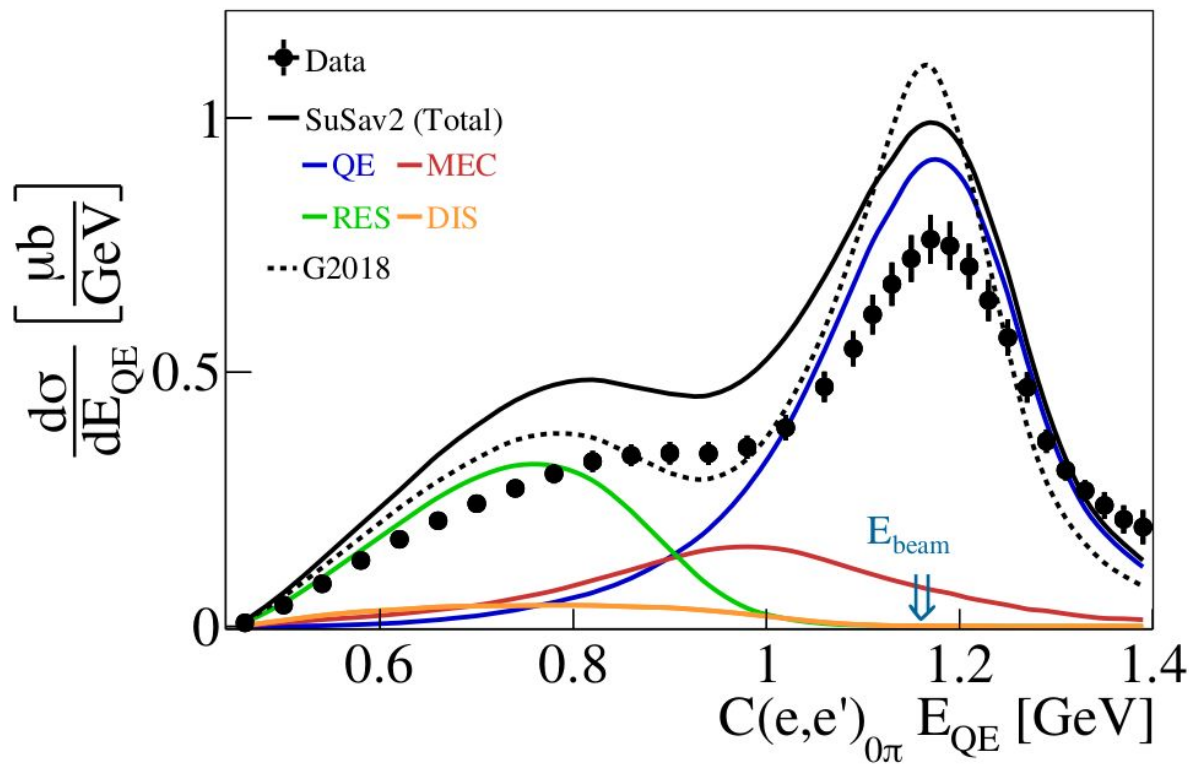


Cherenkov detectors
Assuming QE interaction
Using lepton kinematics

$$E_{QE} = \frac{2M\epsilon + 2ME_l - m_l^2}{2(M - E_l + |k_l|\cos\theta_l)}$$

QE Energy Reconstruction

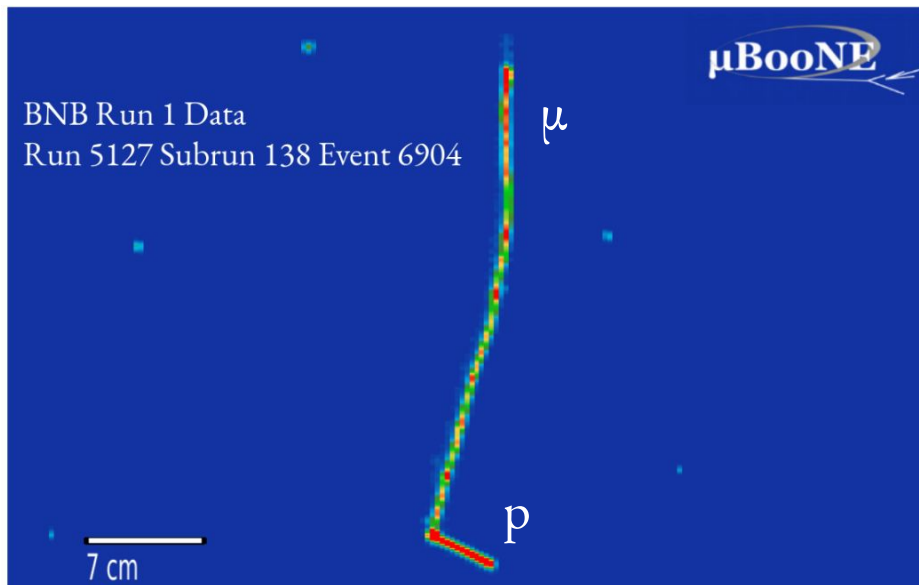
C @ 1.16 GeV



- Relevant for T2K
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Calorimetric Energy Reconstruction



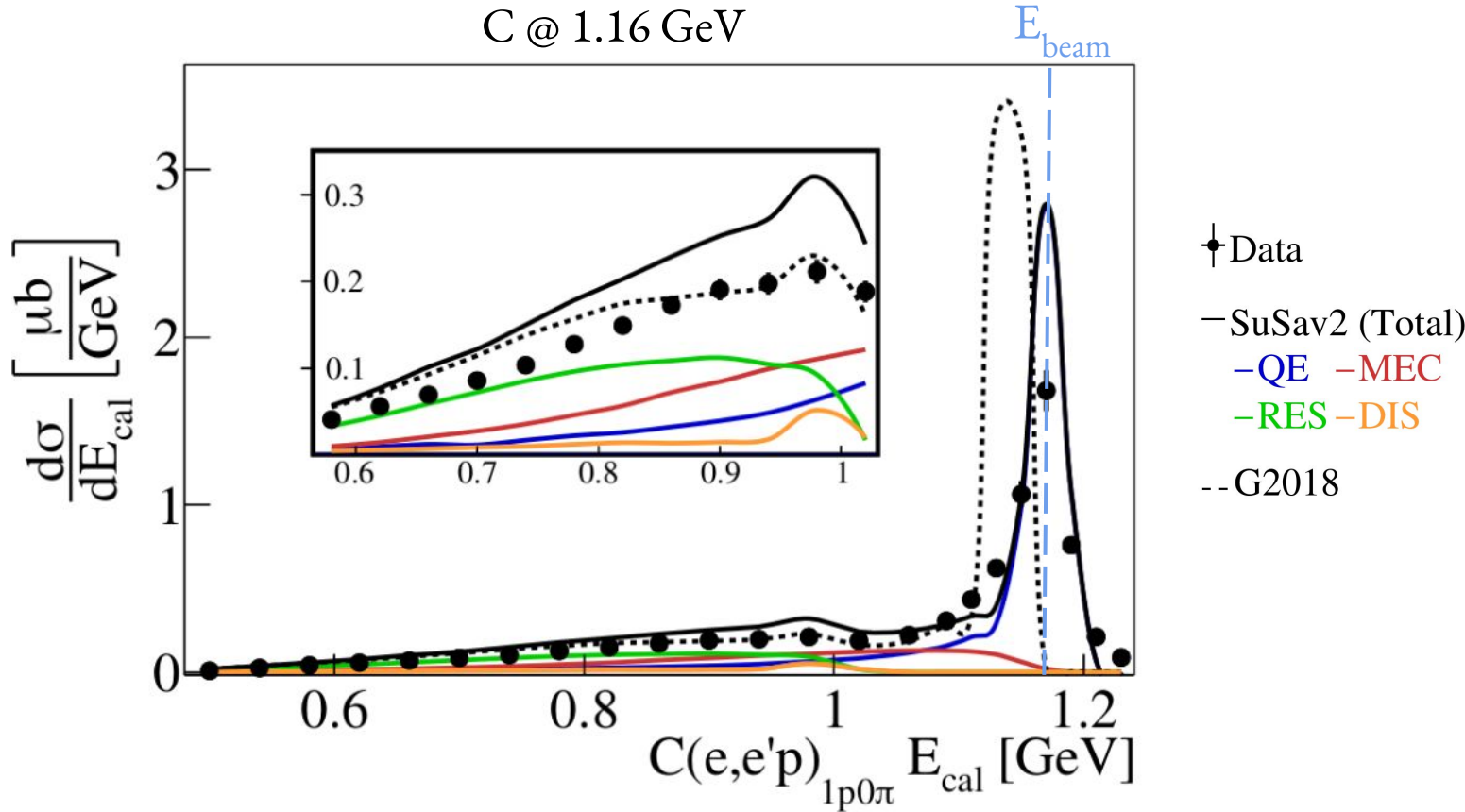
Tracking detectors

Calorimetric sum

Using all detected particles

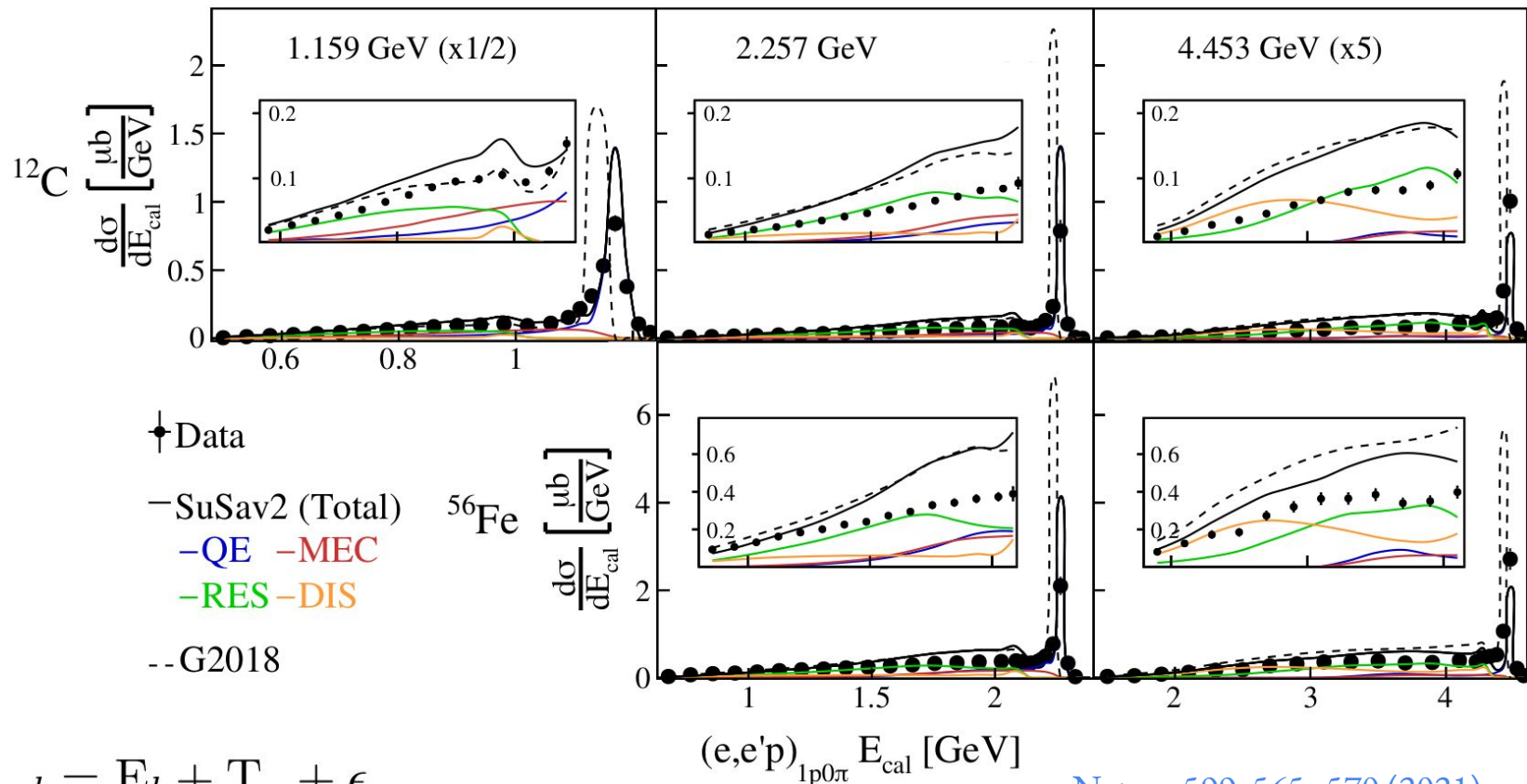
$$E_{cal} = E_l + T_p + \epsilon_B$$

Calorimetric Energy Reconstruction



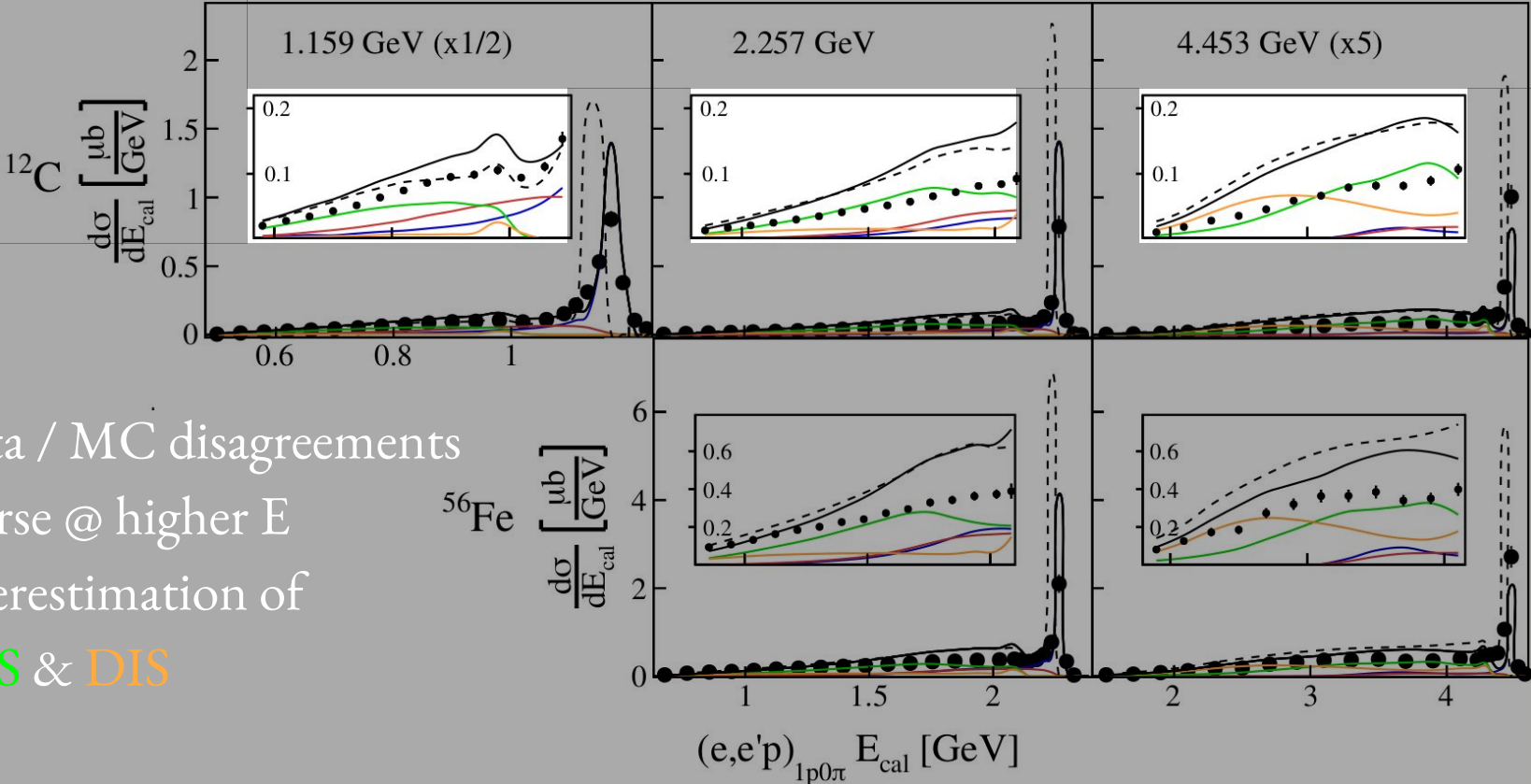
$$E_{cal} = E_l + T_p + \epsilon$$

E_{cal} Nucleus & Energy Dependence



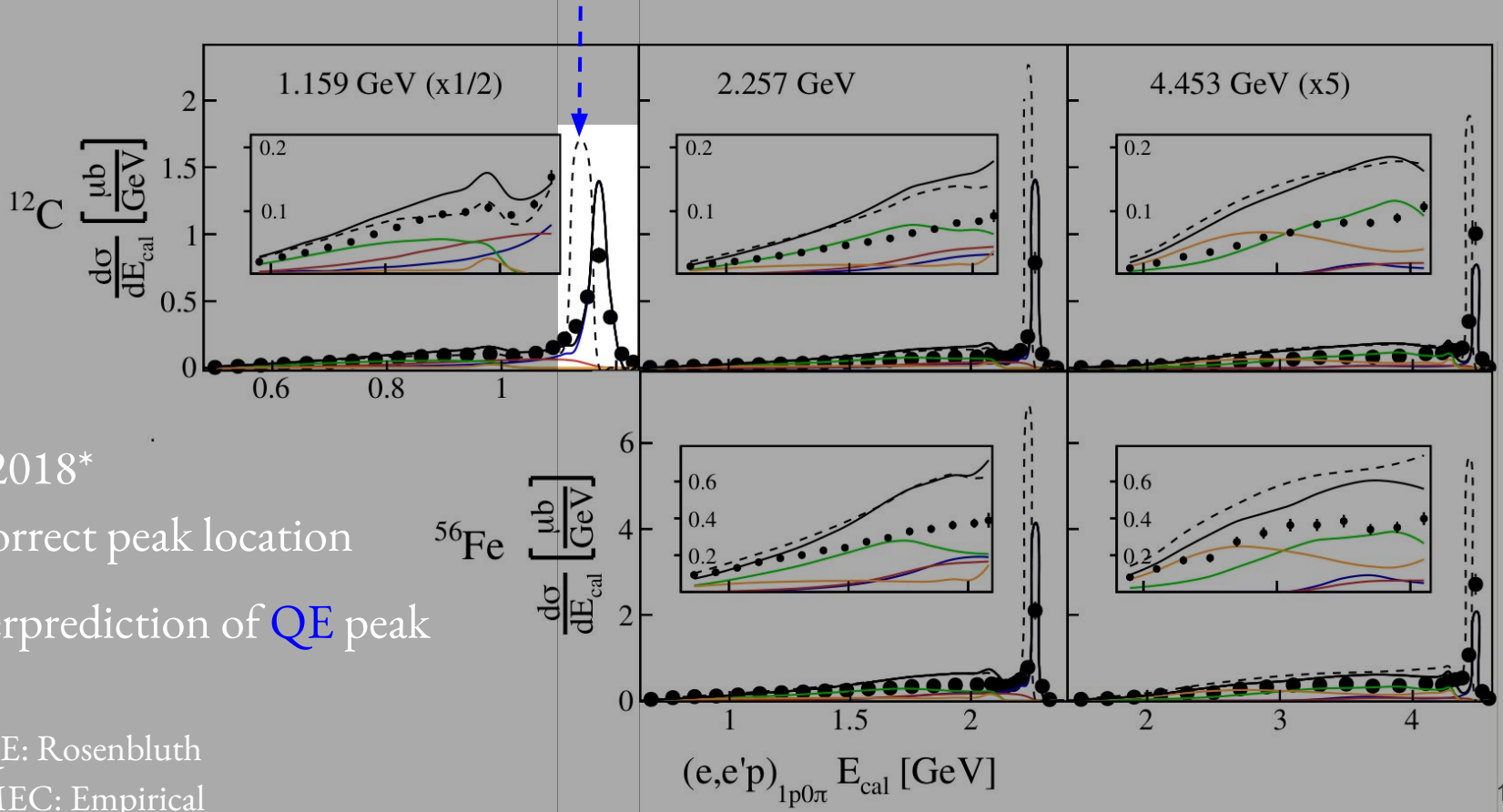
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Nucleus & Energy Dependence



- Data / MC disagreements
- Worse @ higher E
- Overestimation of
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Nucleus & Energy Dependence

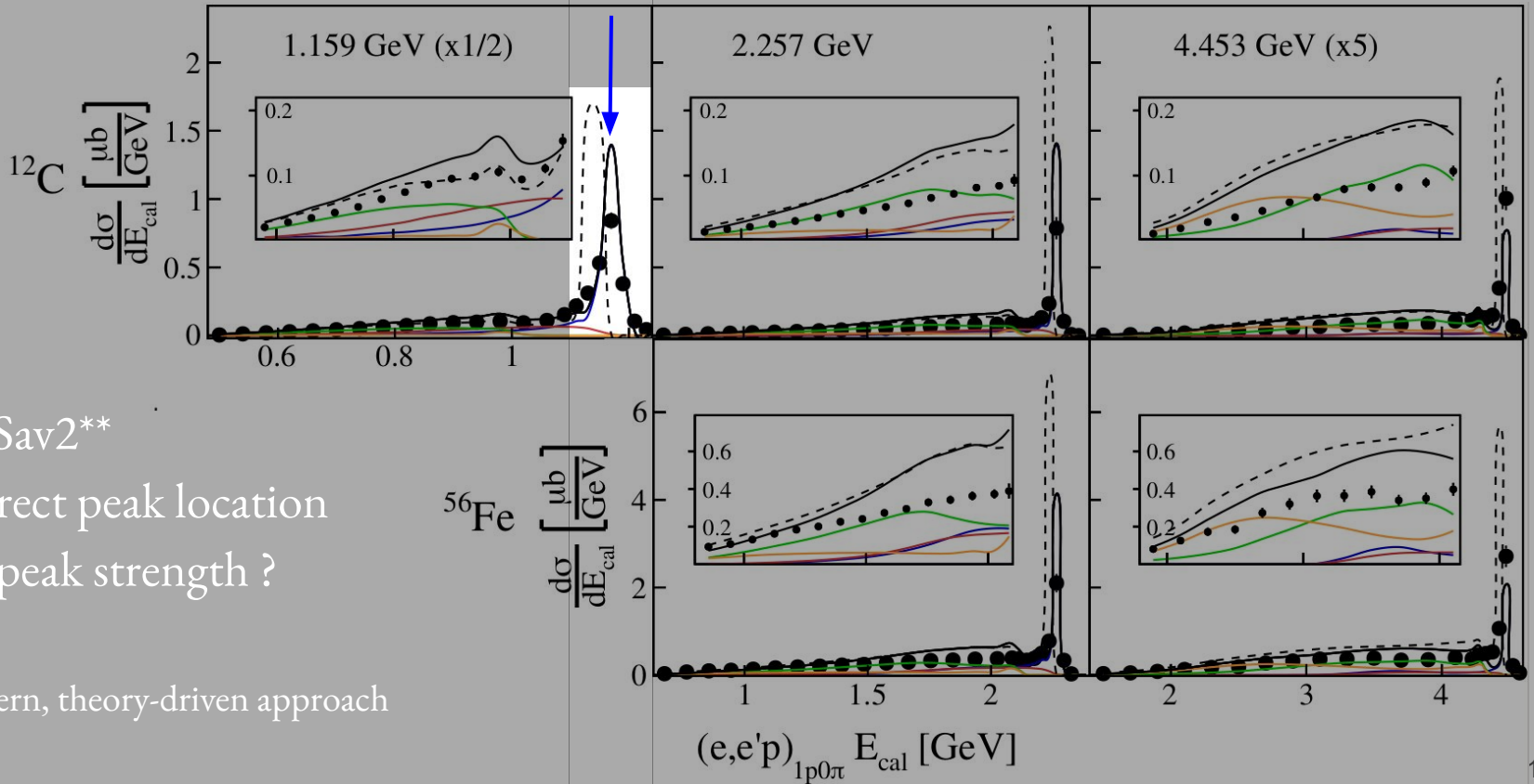


--- G2018*

- Incorrect peak location
- Overprediction of QE peak

* EMQE: Rosenbluth
EMMEC: Empirical

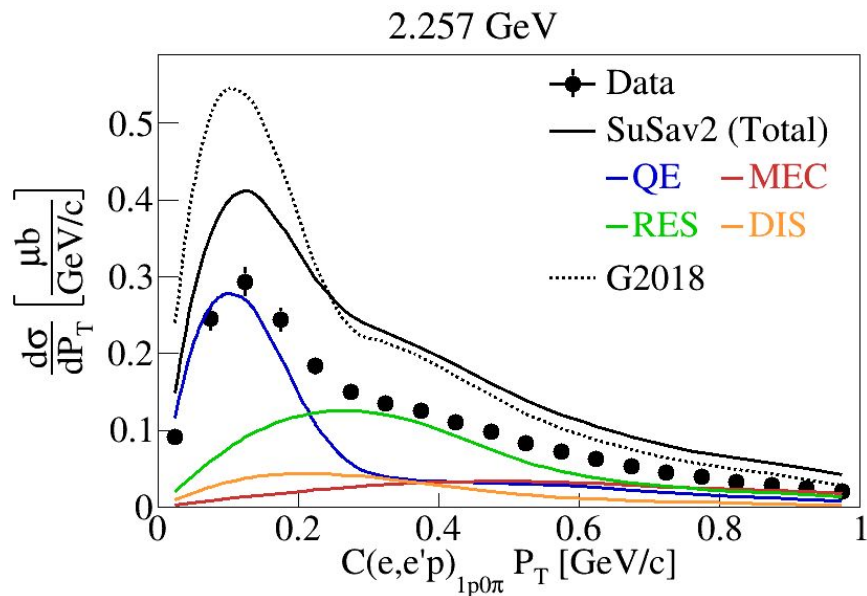
Nucleus & Energy Dependence



- SuSav2**
- Correct peak location
- QE peak strength ?

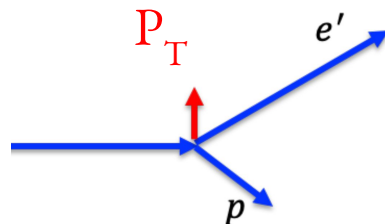
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Transverse Momentum



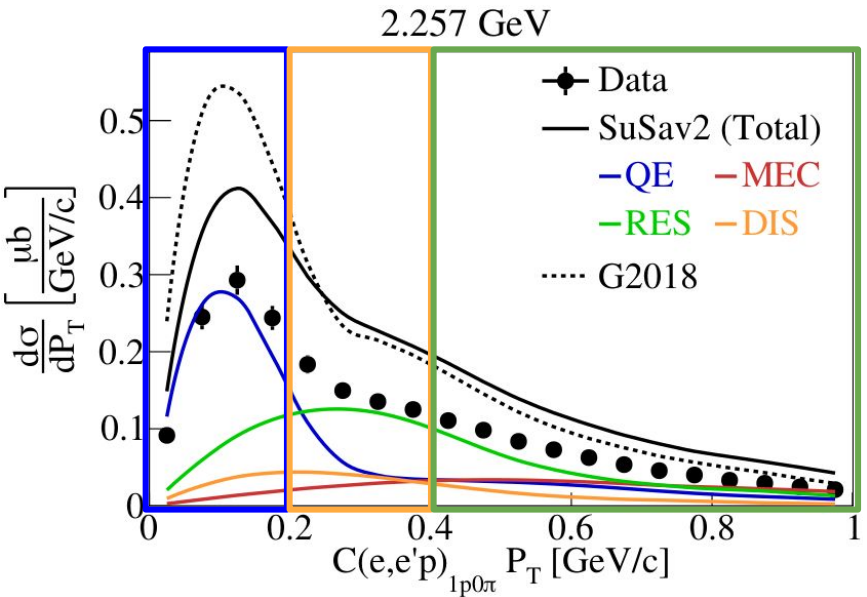
Nature 599, 565–570 (2021)

$$P_T = | \mathbf{P}_T^{e'} + \mathbf{P}_T^p |$$

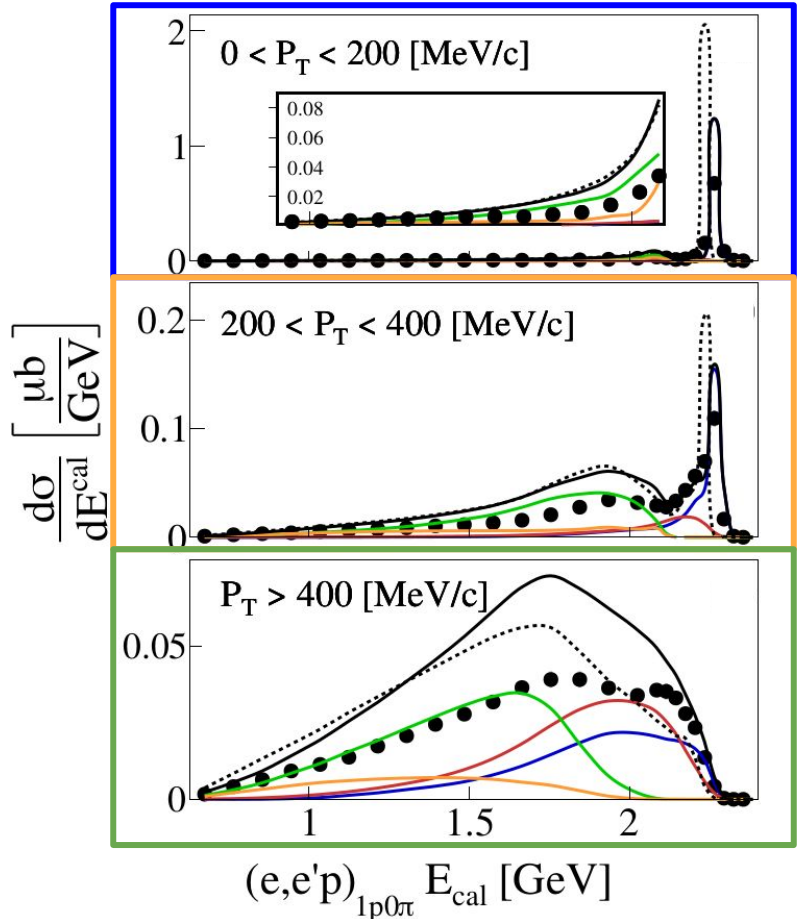


- P_T sensitivity to nuclear effects (fermi motion, final-state interactions, ...)
- Overestimation of **QE** peak & **RES** tail

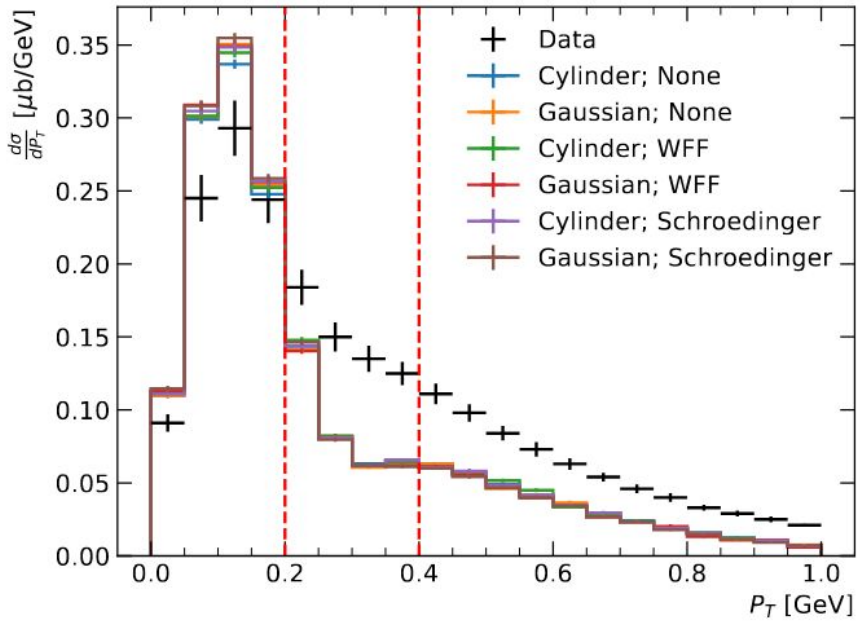
Energy Reconstruction In P_T Slices



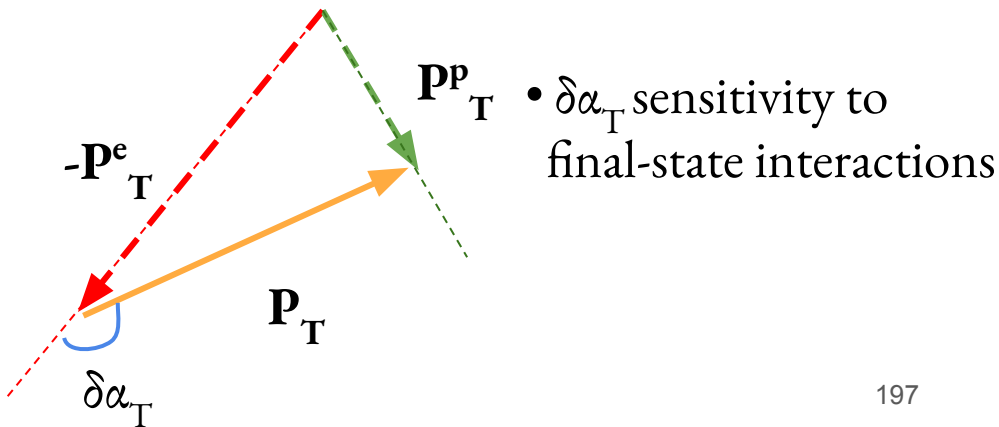
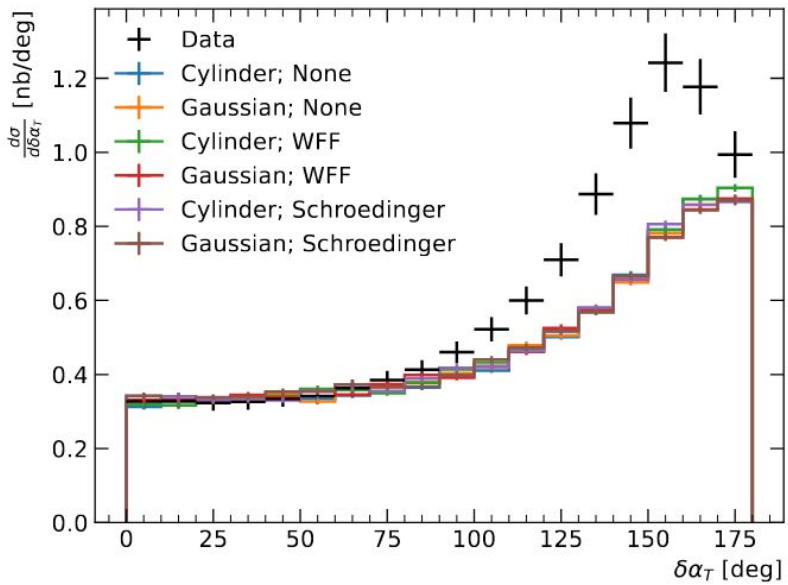
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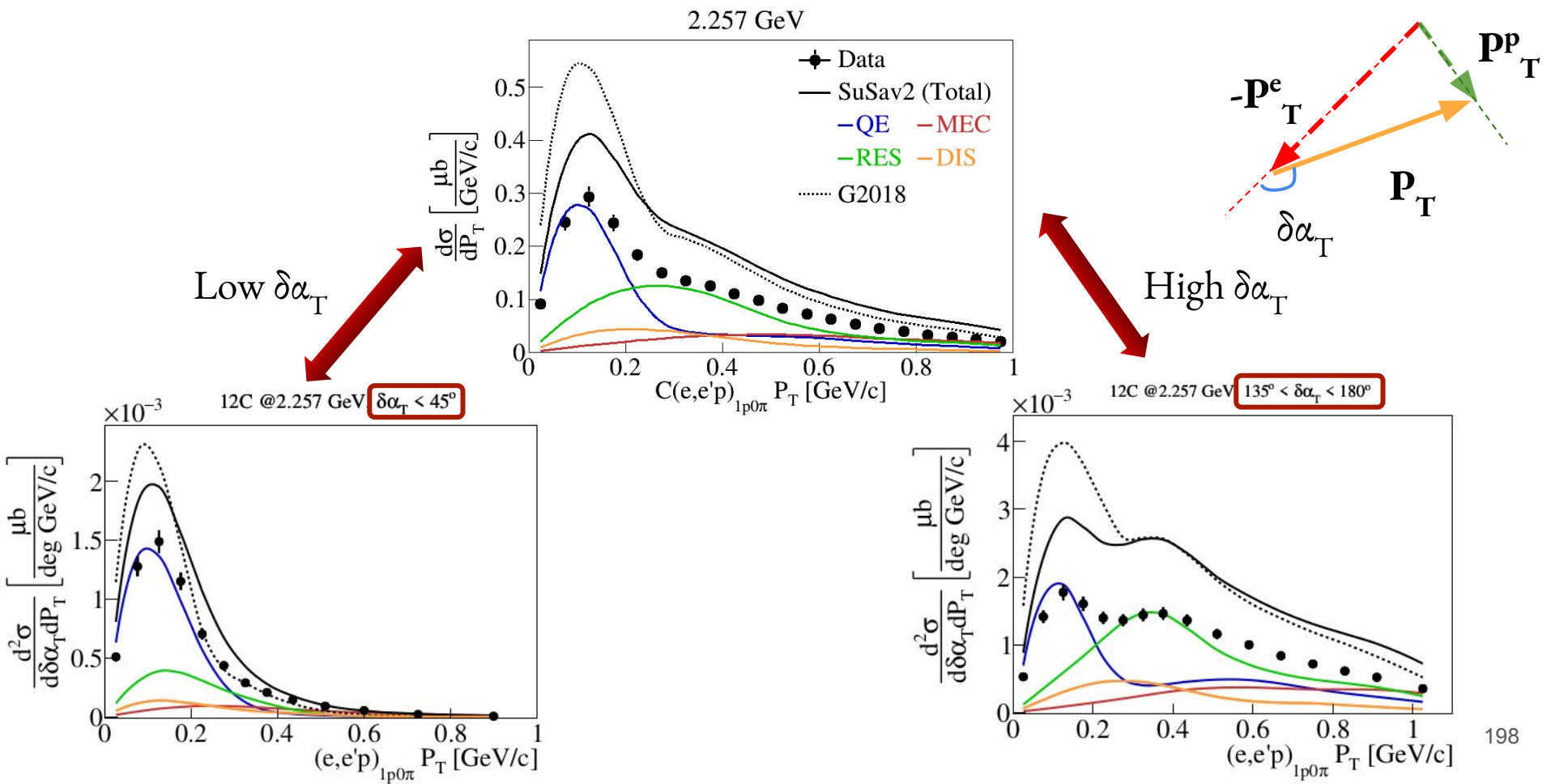
Example: Benchmarking New Generators & Kinematic Variables!



First step: only QE & FSI
 ACHILLES arXiv: 2205.06378



Example: 2D Kinematic Imbalance

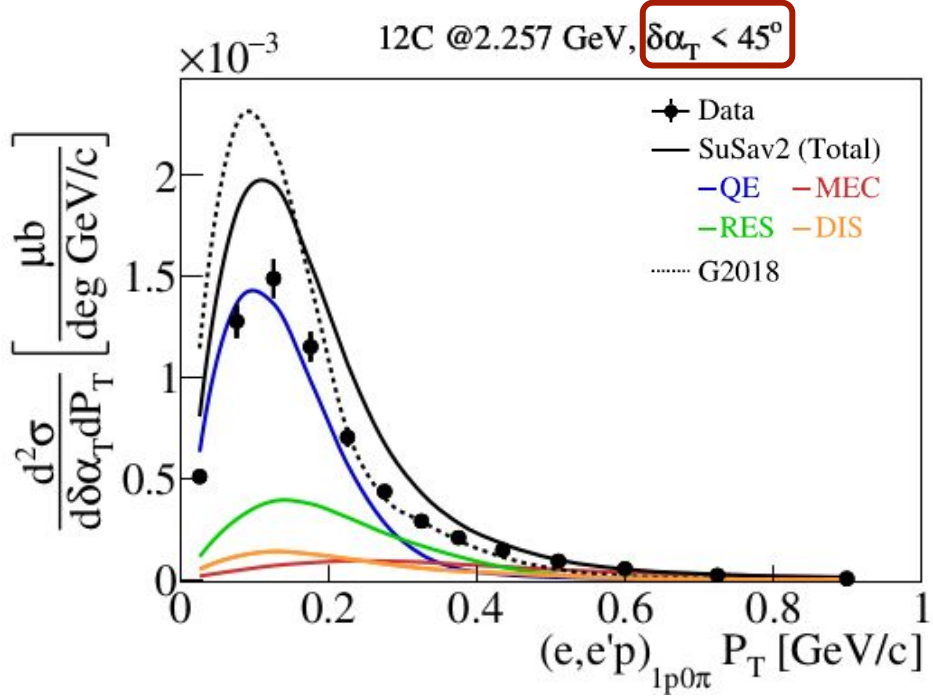


Example: 2D Kinematic Imbalance

Low $\delta\alpha_T$

QE-enhanced region

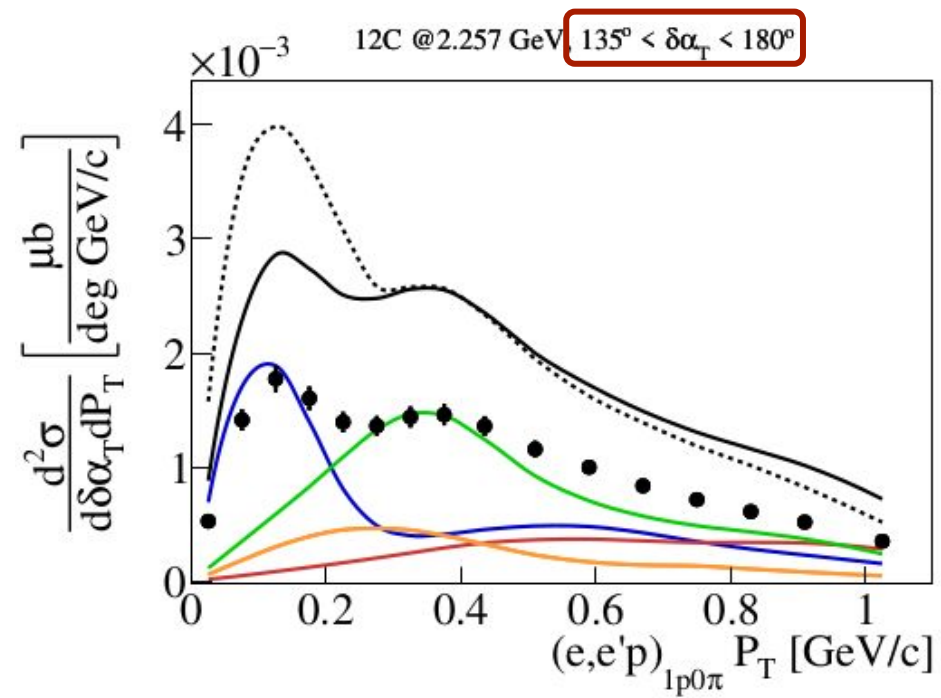
Sensitive to ground-state modeling



High $\delta\alpha_T$

Large non-QE contributions

Strong final-state interaction effects



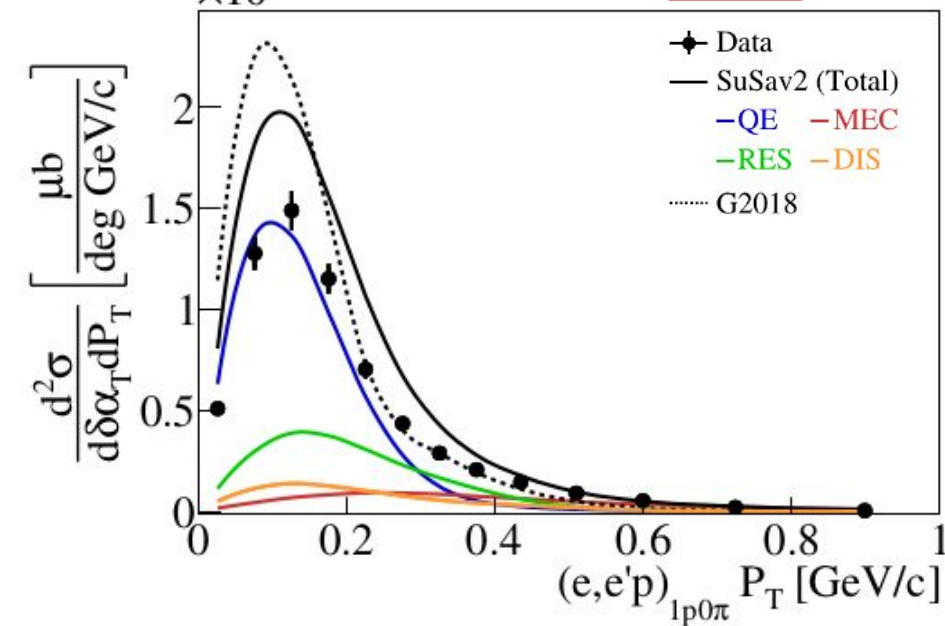
Example: 2D Kinematic Imbalance

Low $\delta\alpha_T$

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Sensitive to ground-state modeling

12C @ 2.257 GeV, $\delta\alpha_T < 45^\circ$

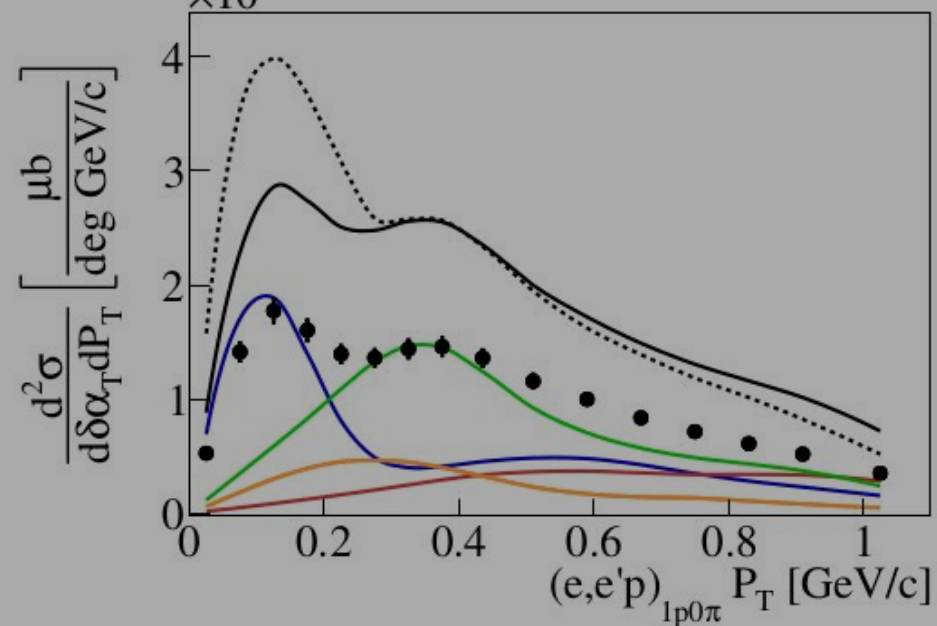


High $\delta\alpha_T$

Large non-QE contributions

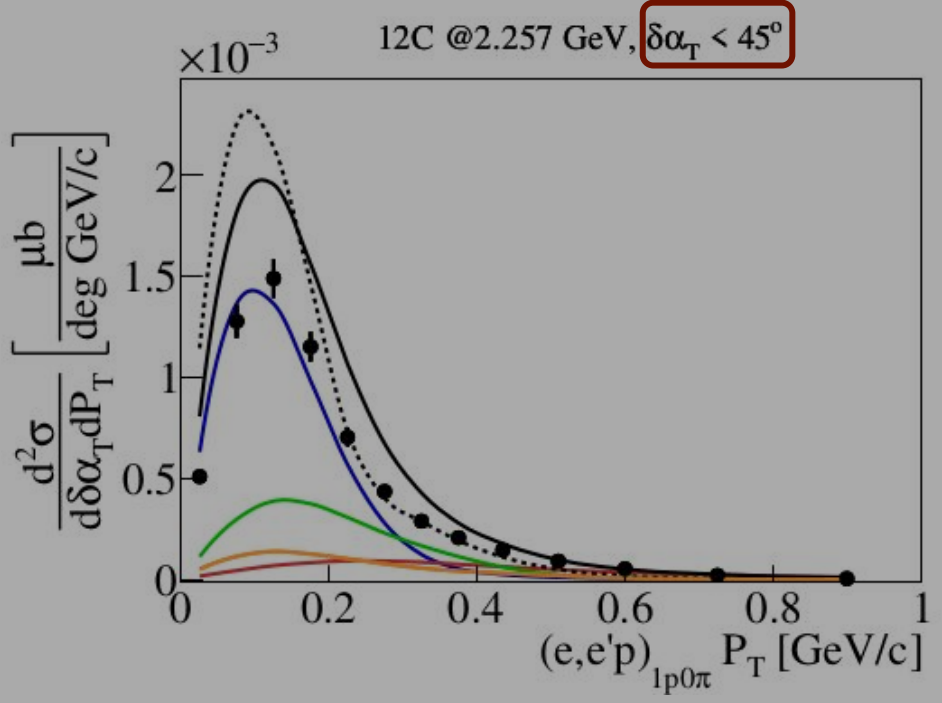
Strong final-state interaction effects

12C @ 2.257 GeV, $135^\circ < \delta\alpha_T < 180^\circ$

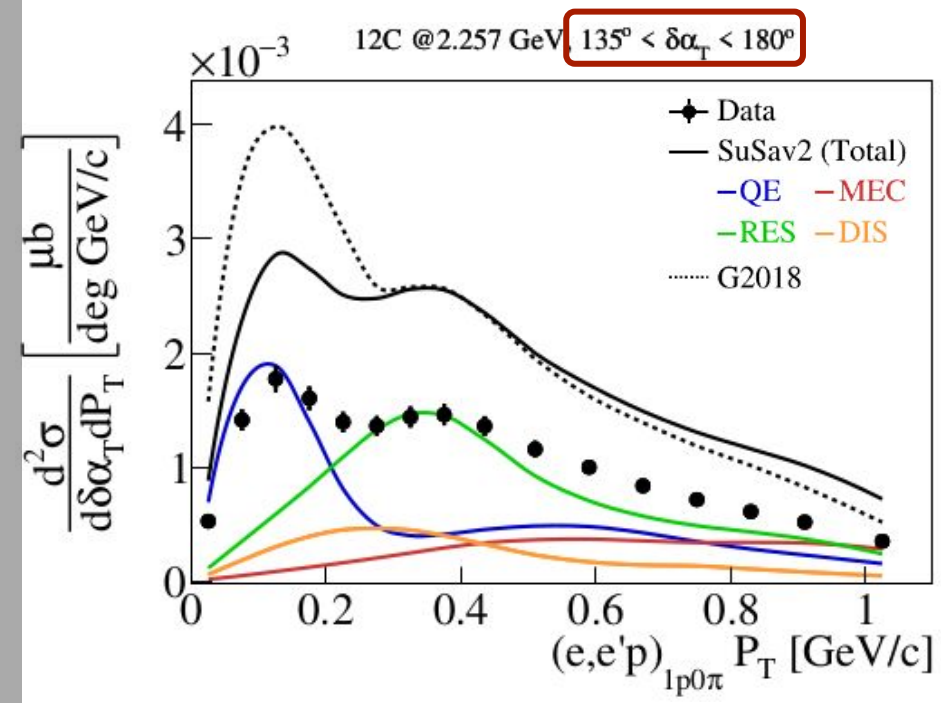


Example: 2D Kinematic Imbalance

Low $\delta\alpha_T$
 QE-enhanced region
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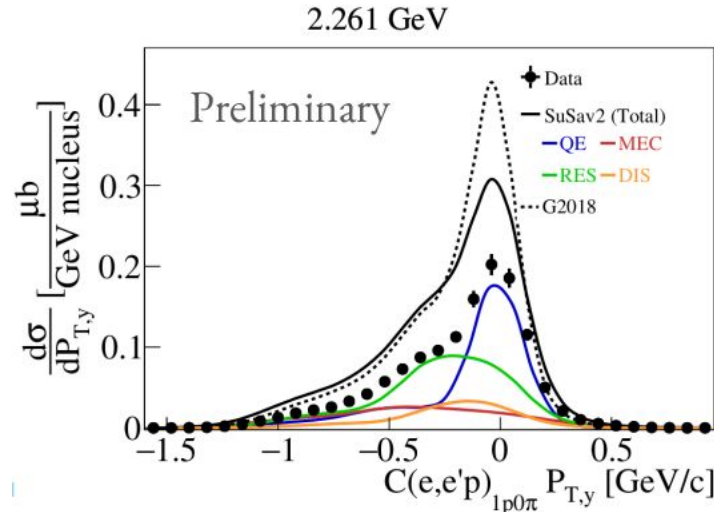
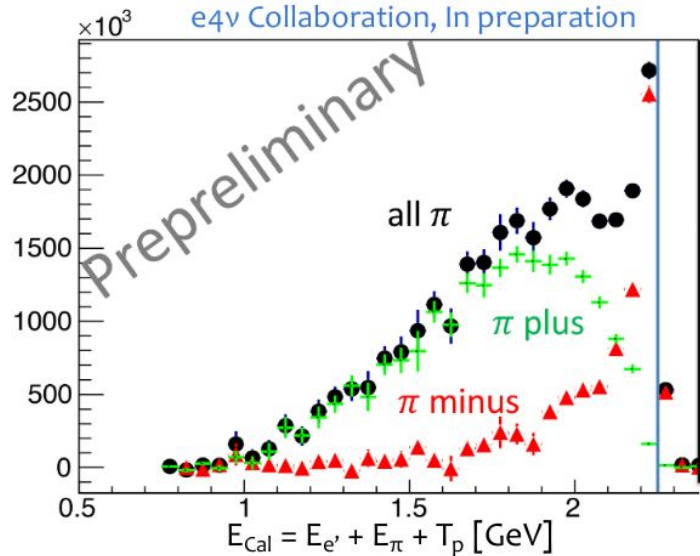
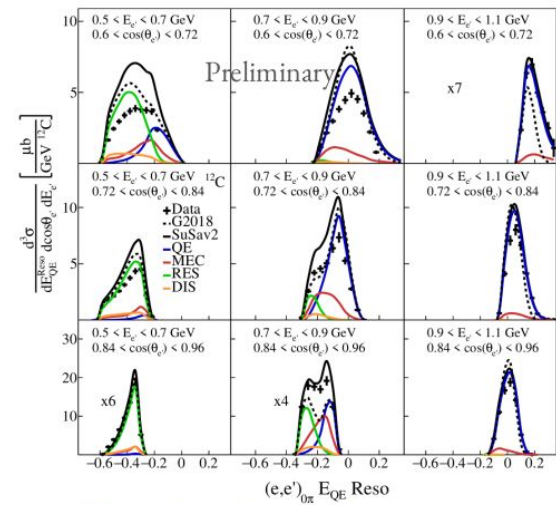


High $\delta\alpha_T$
 Large non-QE contributions
 Strong final-state interaction effects



Next Steps

- Even more differential! Into the 3D multiverse
Taking advantage of massive statistics
- More nuclear sensitivity variables
Help decide what to tune
- $1p1\pi$ exclusive cross sections

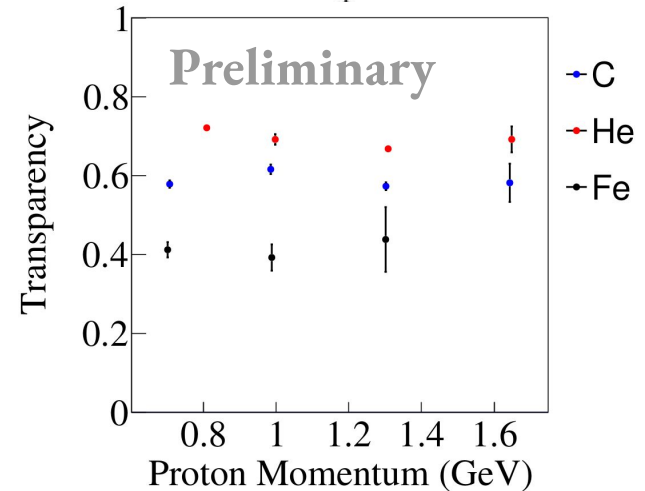
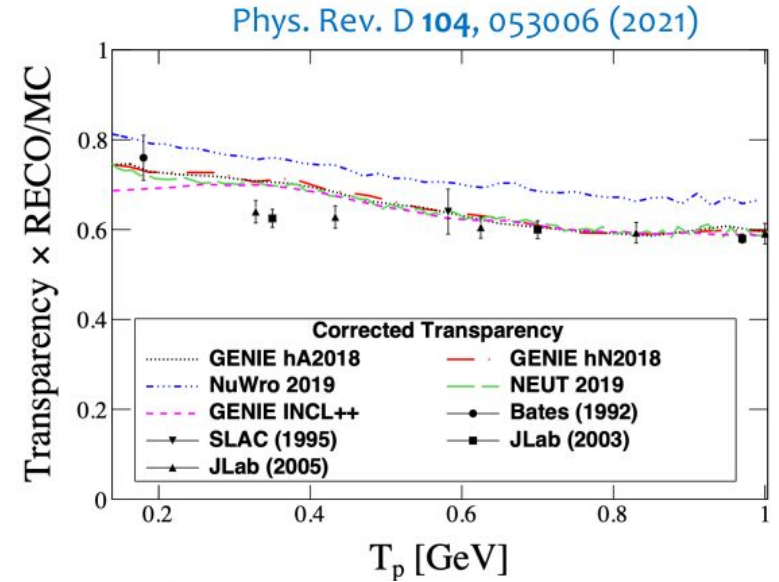


Next Steps

- More with CLAS6

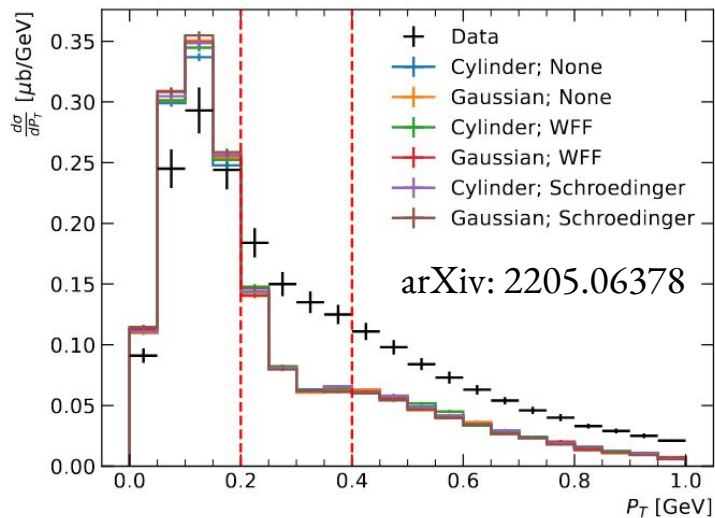
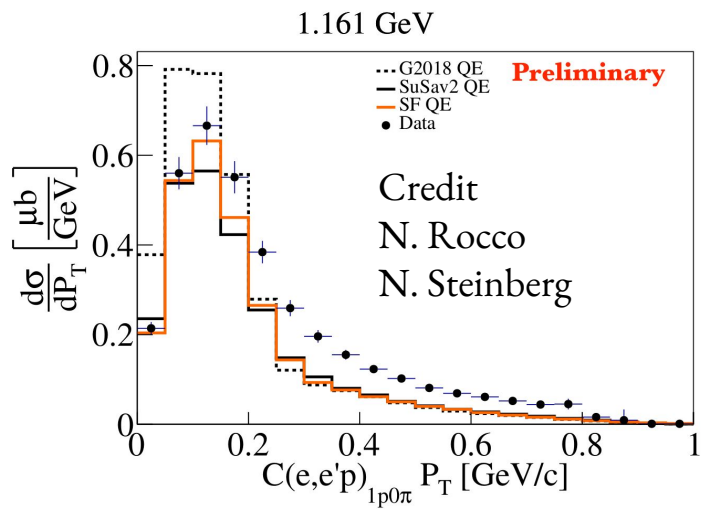
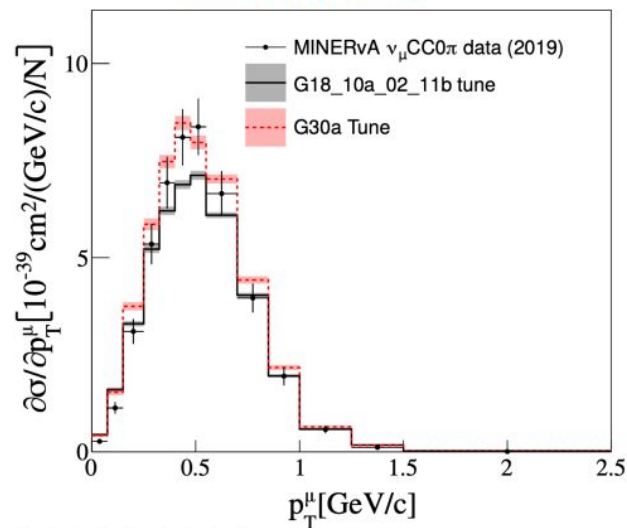
□ Proton transparency studies

- Observable that summarizes strength of intranuclear rescattering
- Measurement study
$$T = N_{\text{prot}}^{\text{detected}} / N_{\text{prot}}^{\text{PWIA}}$$
- Test event generator FSI models in GENIE across multiple nuclear targets
- Testing dependency of transparency calculations on PWIA normalization



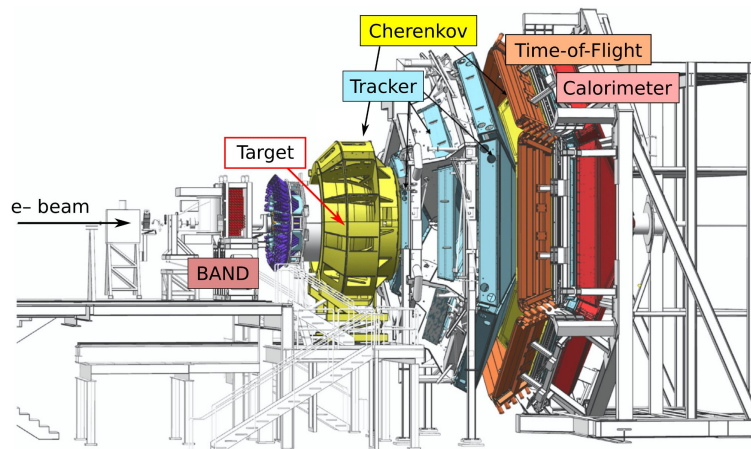
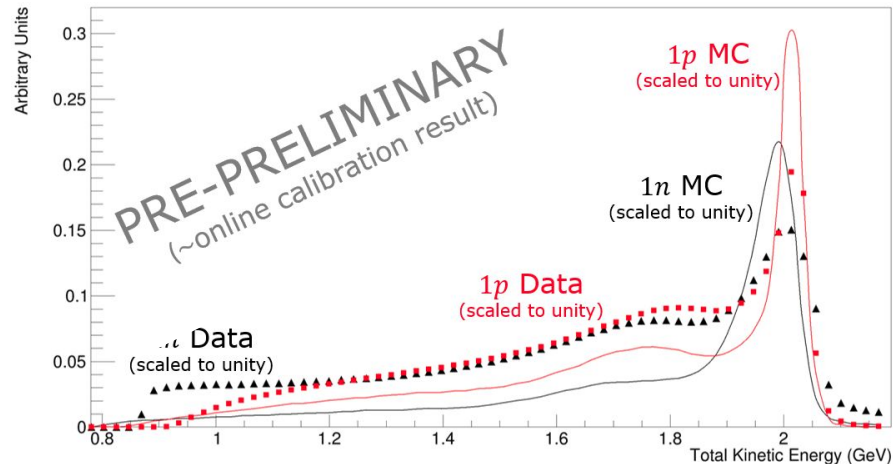
Next Steps

- More with CLAS6
- ☐ Prepare suite of cross sections in same variables as neutrinos for first e-GENIE tune
 - Compare with neutrino CC0 π tune
- $e4\nu$ data already being used to validate event generators



Next Steps

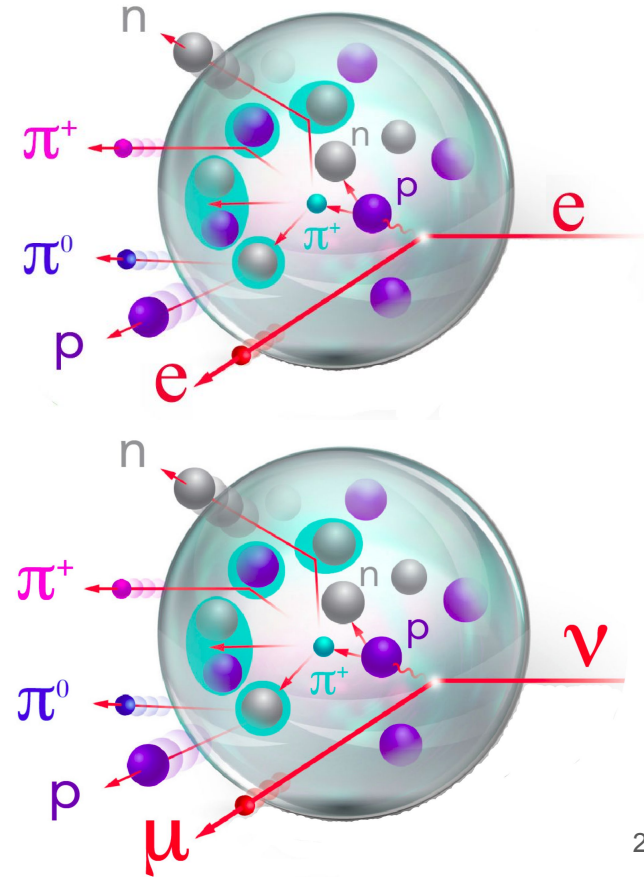
- New data with CLAS12
Targets: ^4He , ^{12}C , ^{40}Ar , ^{120}Sn
- 2 - 6 GeV beam energies
- More phase-space coverage ($\theta_e > 5^\circ$)
- Neutrons!



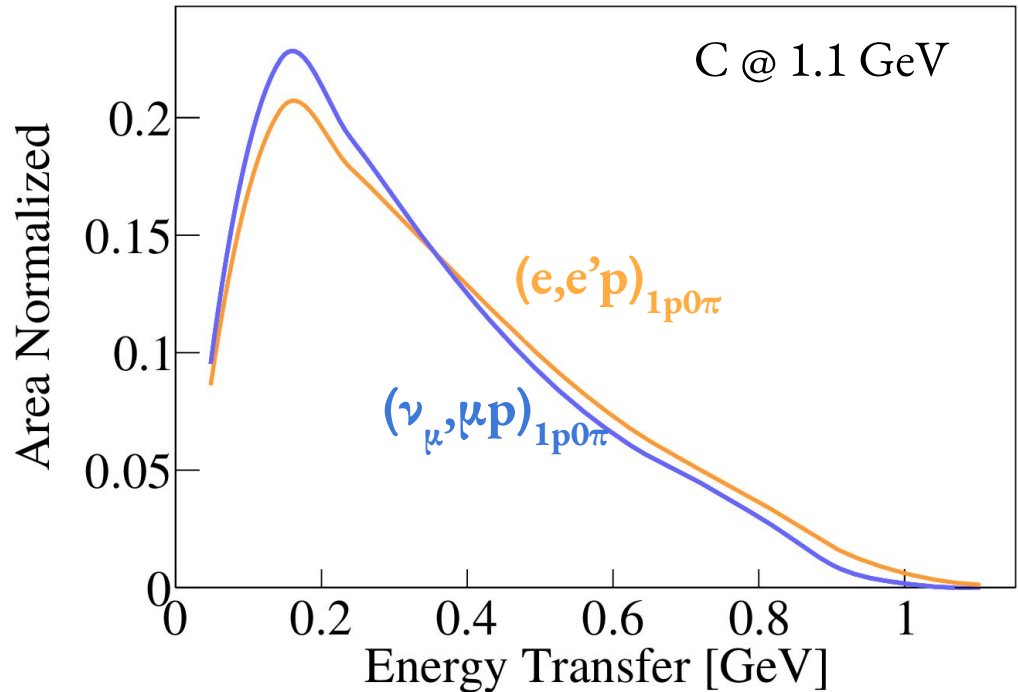
Why electrons?

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Any model must work for electrons,
or it won't work for neutrinos !

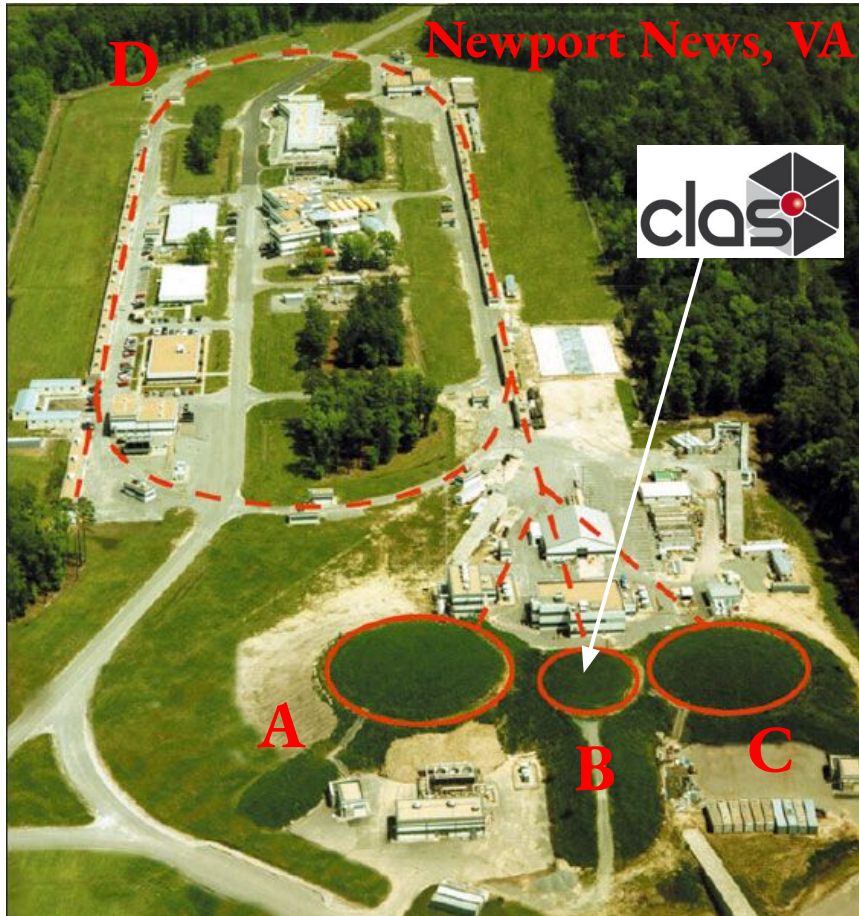


Similar ν & e Distributions

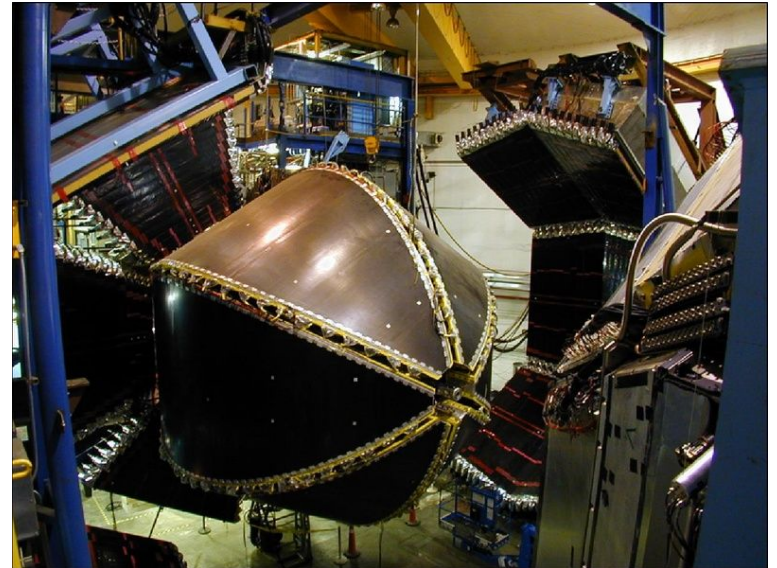


Accounting for propagator mass (γ vs W) via Q^4 scaling of the electron side

Jefferson Laboratory

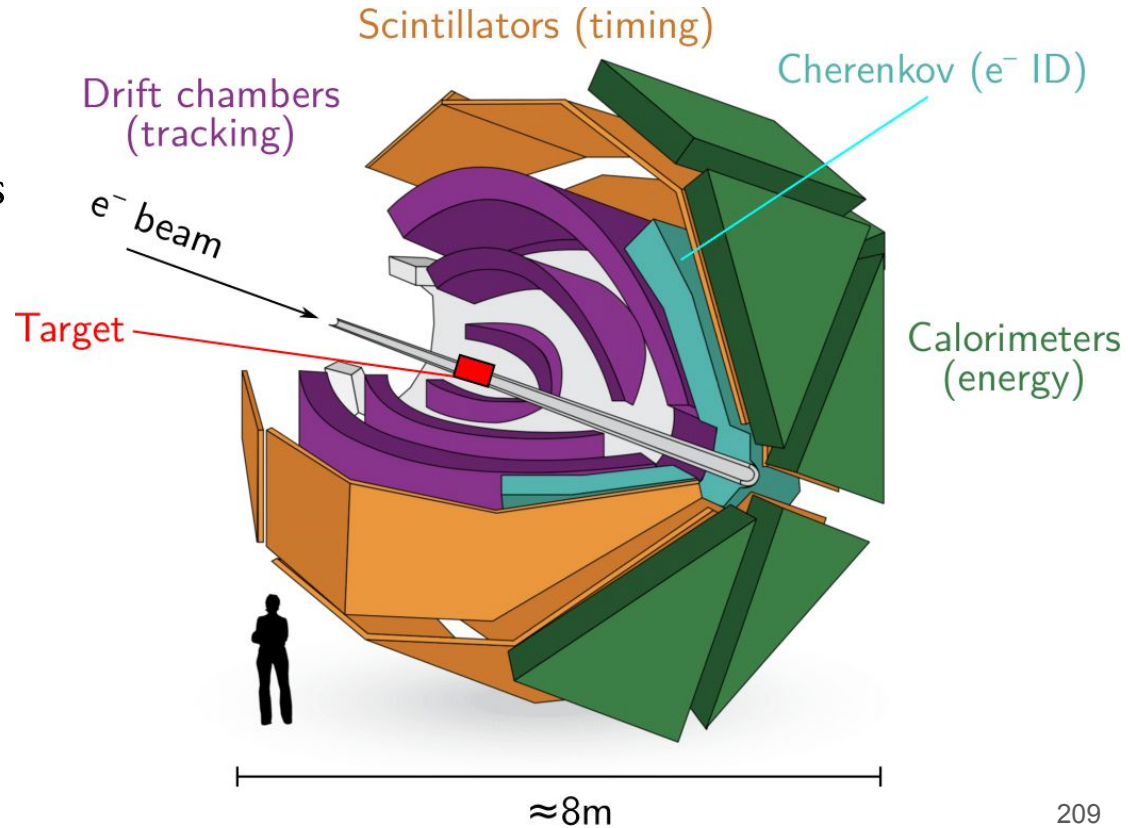


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- Energies up to 12 GeV
- Using Hall B & CLAS detector



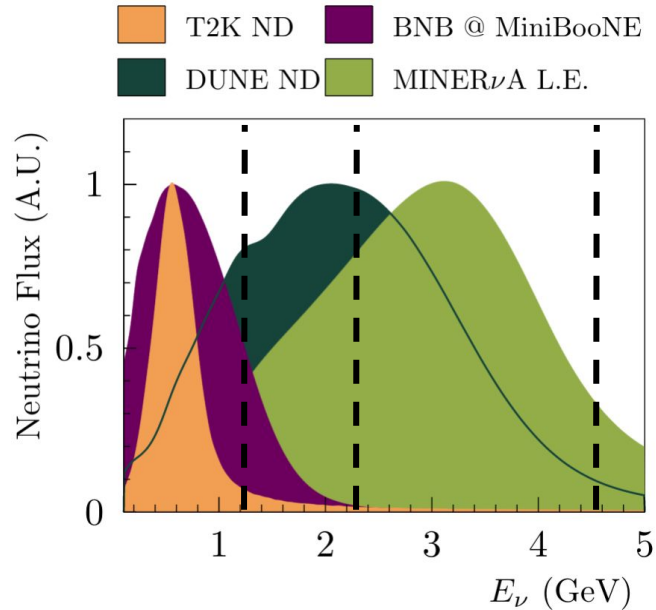
$e4\nu$ Data-Mining With CLAS

- Charged particle threshold similar to ν tracking detectors
- $\sim 50\%$ of “ 4π ” coverage



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- 1 proton (> 300 MeV/c)
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[Phys. Rev. Lett. 125, 201803 \(2020\)](#)

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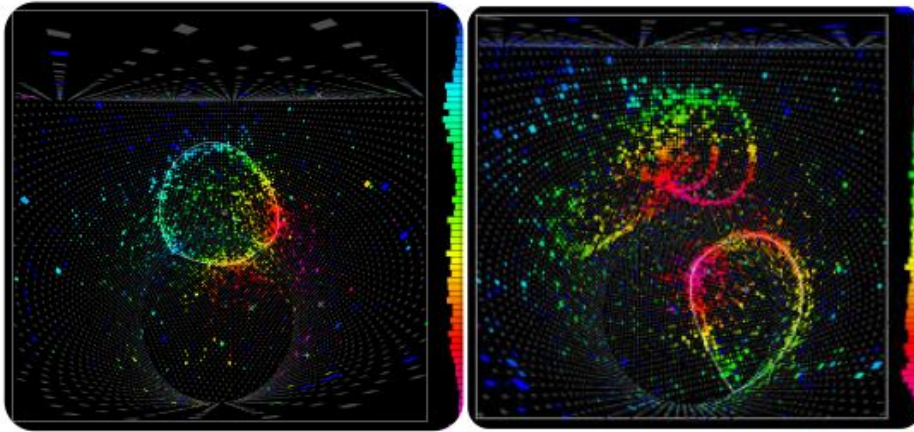


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[Nature 599, 565–570 \(2021\)](#)

- Study energy reconstruction
- Test against GENIE event generator

QE Energy Reconstruction

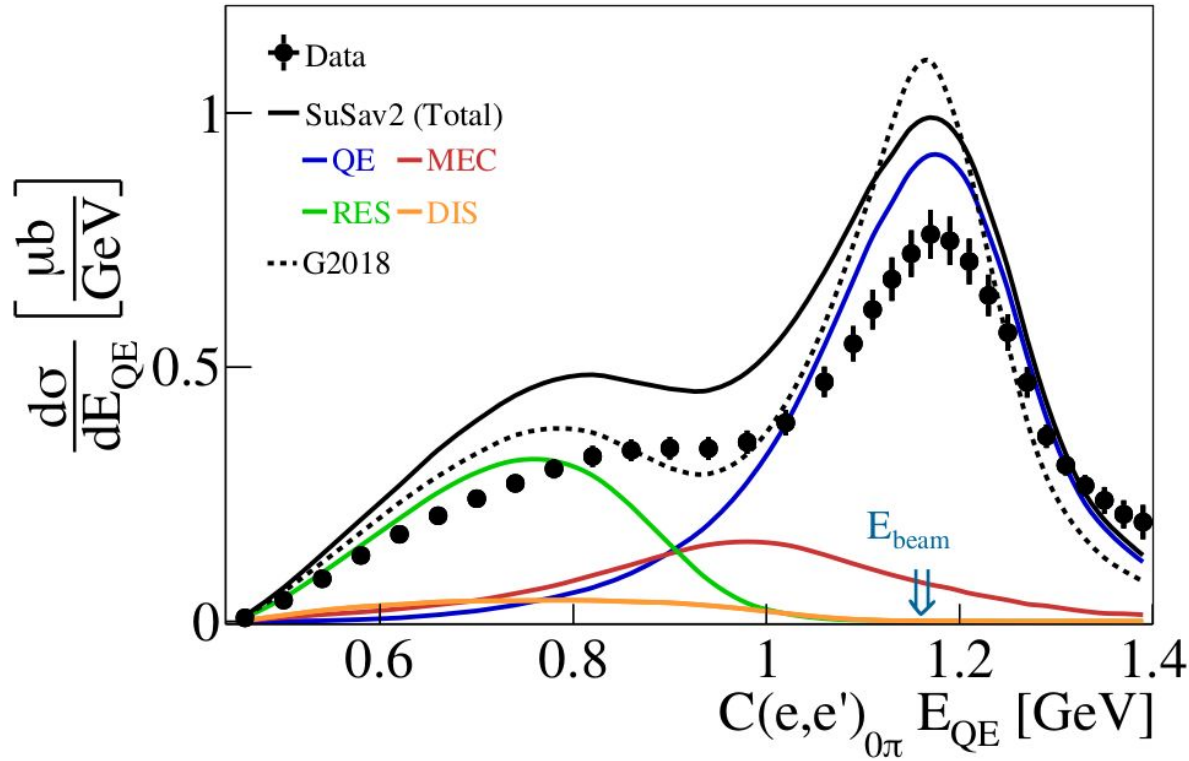


Cherenkov detectors
Assuming QE interaction
Using lepton kinematics

$$E_{QE} = \frac{2M\epsilon + 2ME_l - m_l^2}{2(M - E_l + |k_l|\cos\theta_l)}$$

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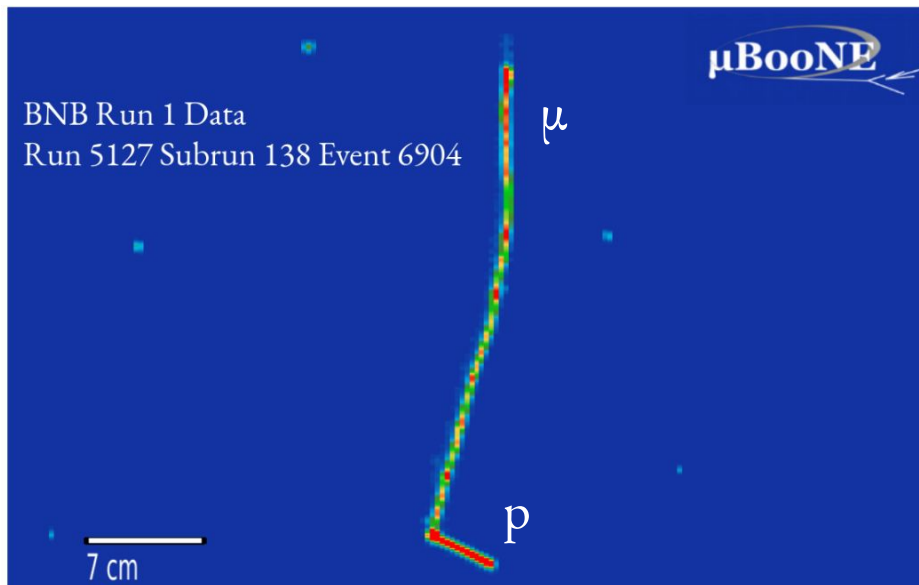
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- Relevant for T2K
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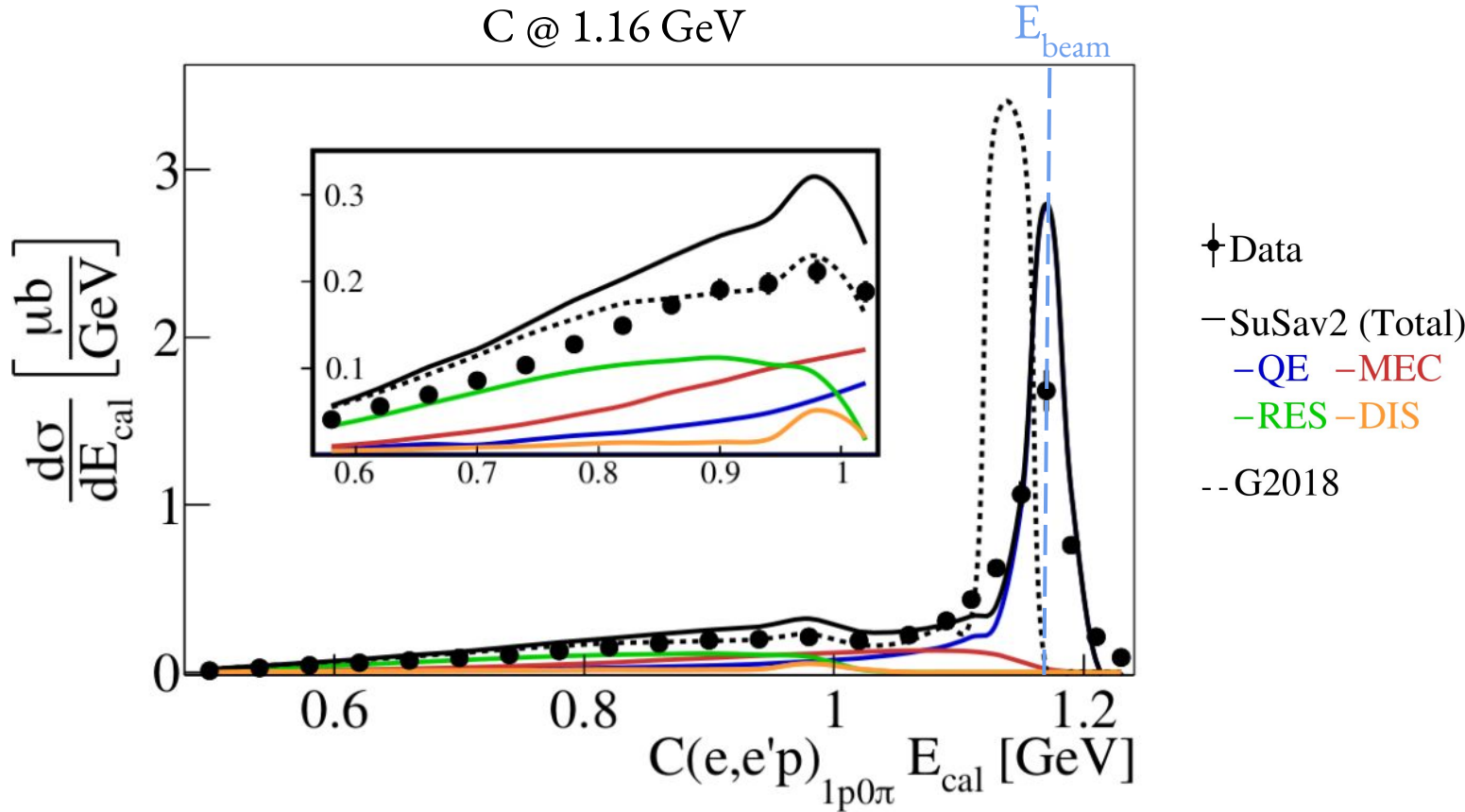
Calorimetric Energy Reconstruction



Tracking detectors
Calorimetric sum
Using all detected particles

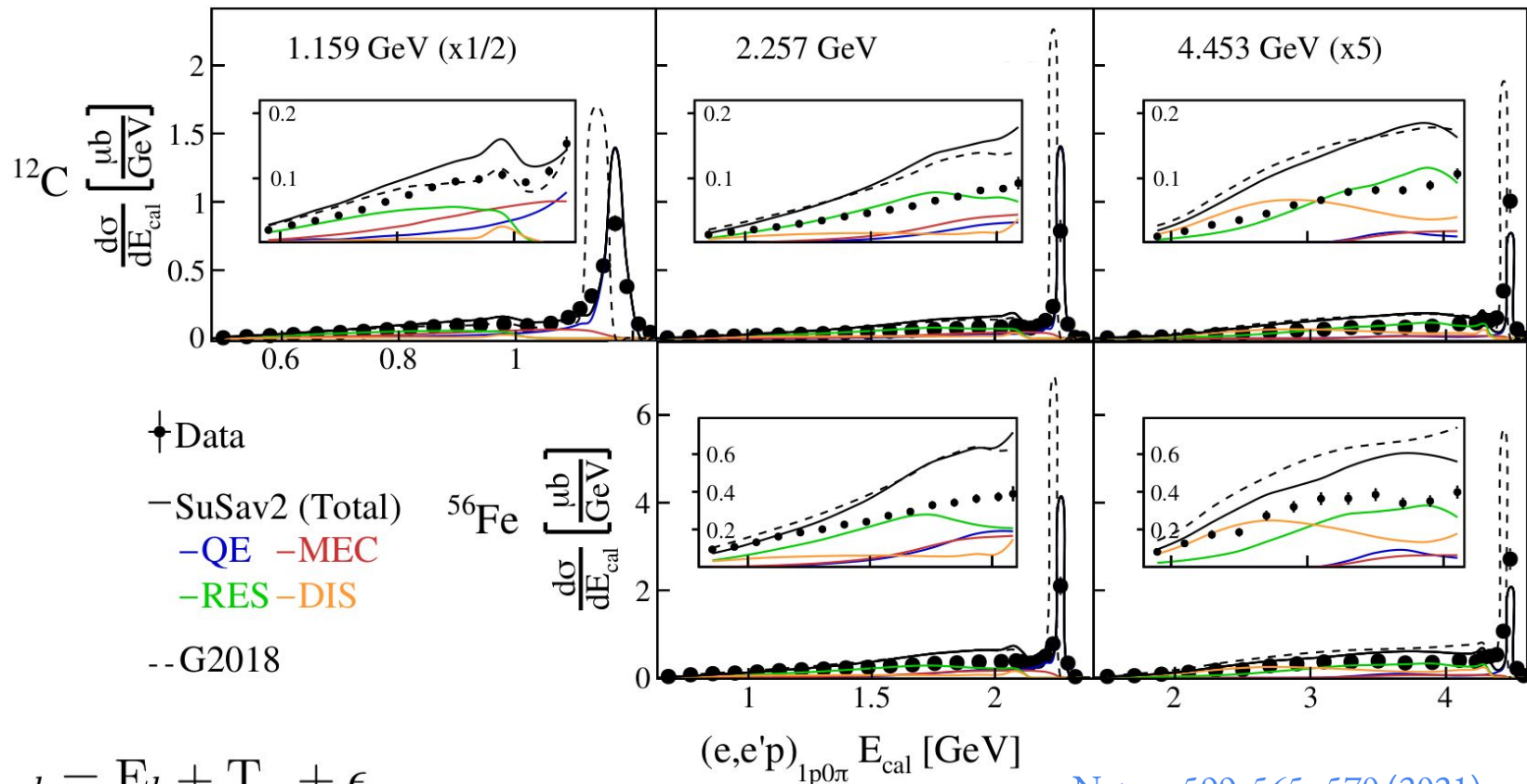
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Calorimetric Energy Reconstruction



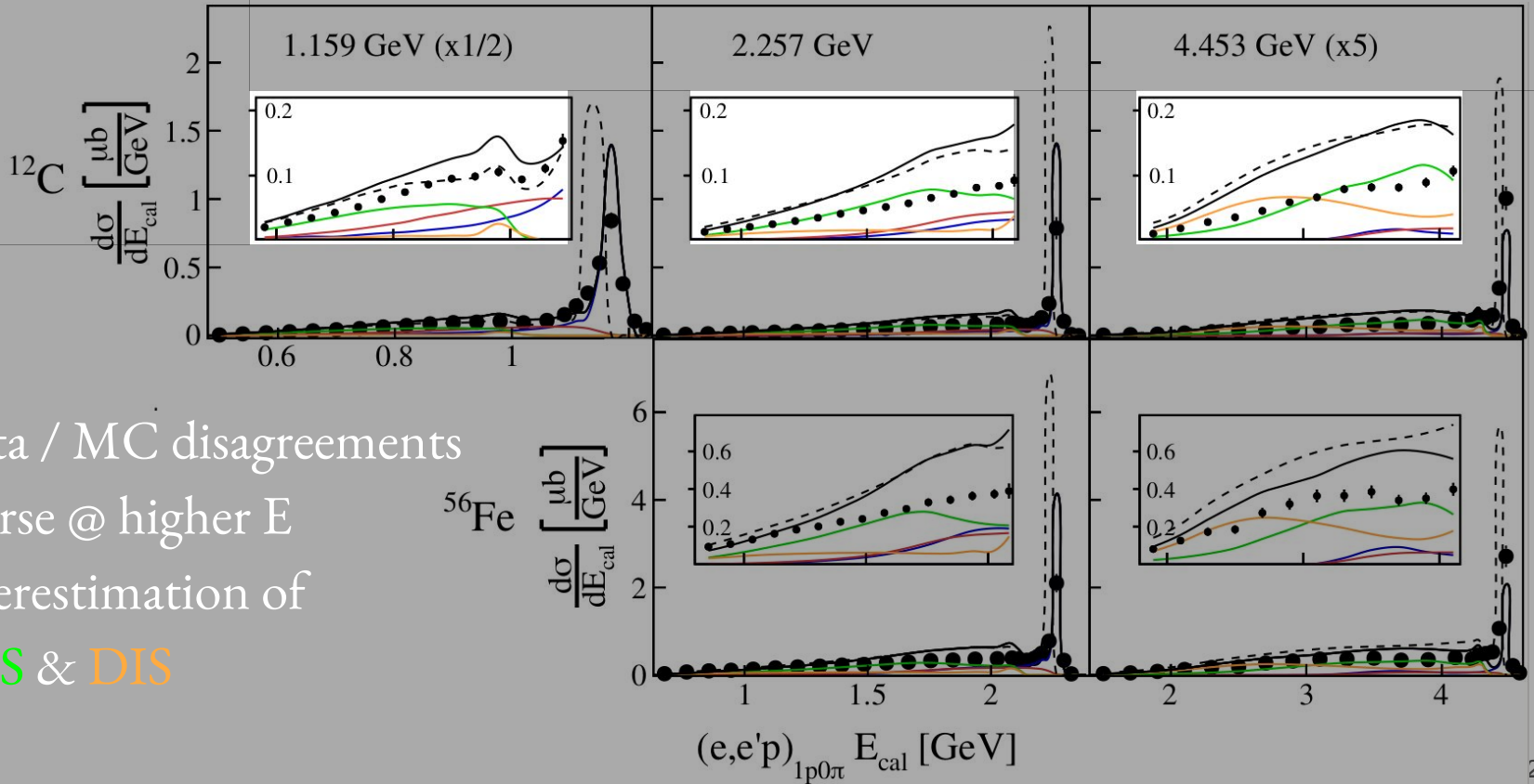
$$E_{cal} = E_l + T_p + \epsilon$$

E_{cal} Nucleus & Energy Dependence



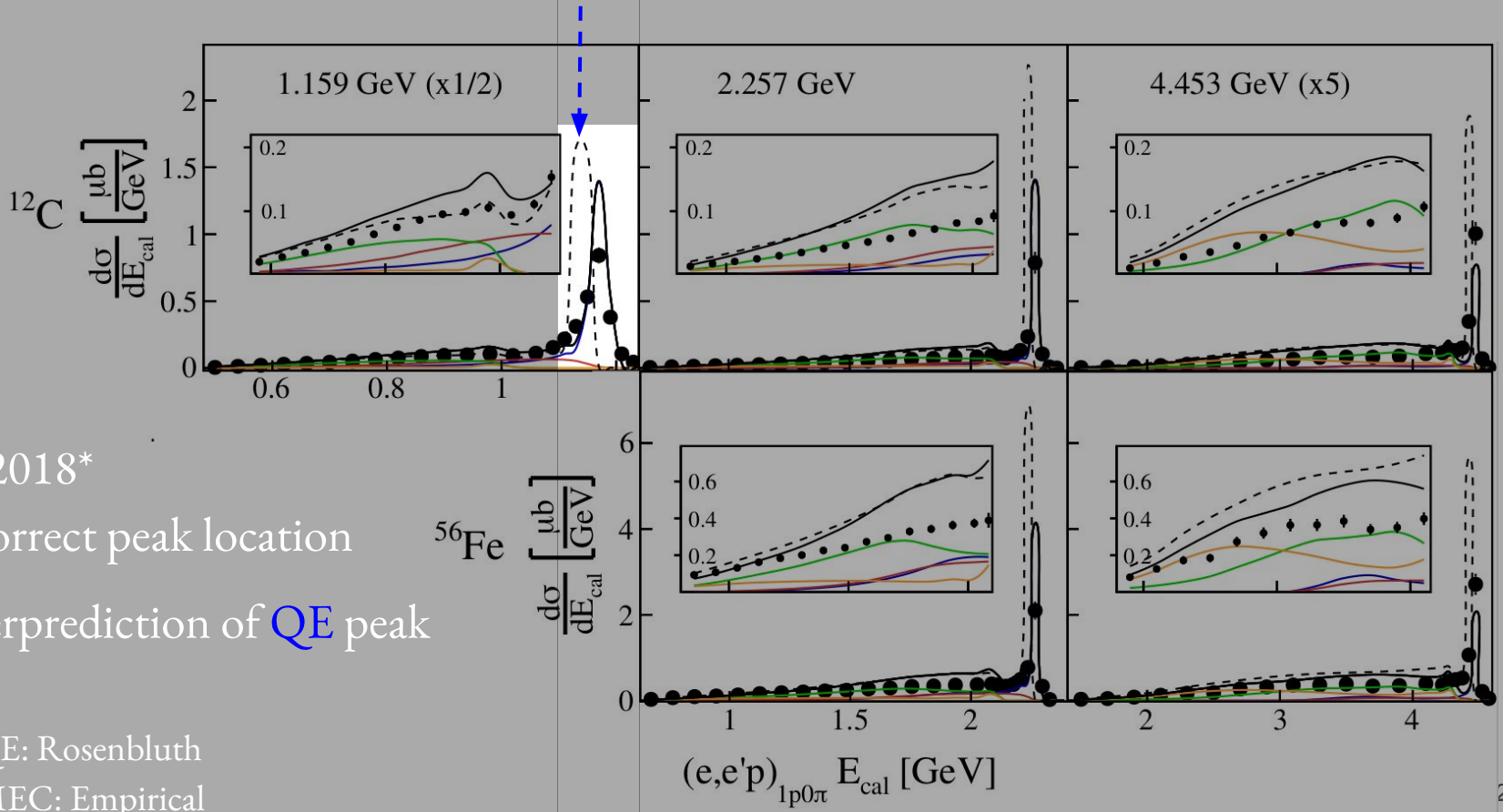
$$E_{cal} = E_l + T_p + \epsilon$$

Nucleus & Energy Dependence



- Data / MC disagreements
- Worse @ higher E
- Overestimation of
RES & DIS

Nucleus & Energy Dependence

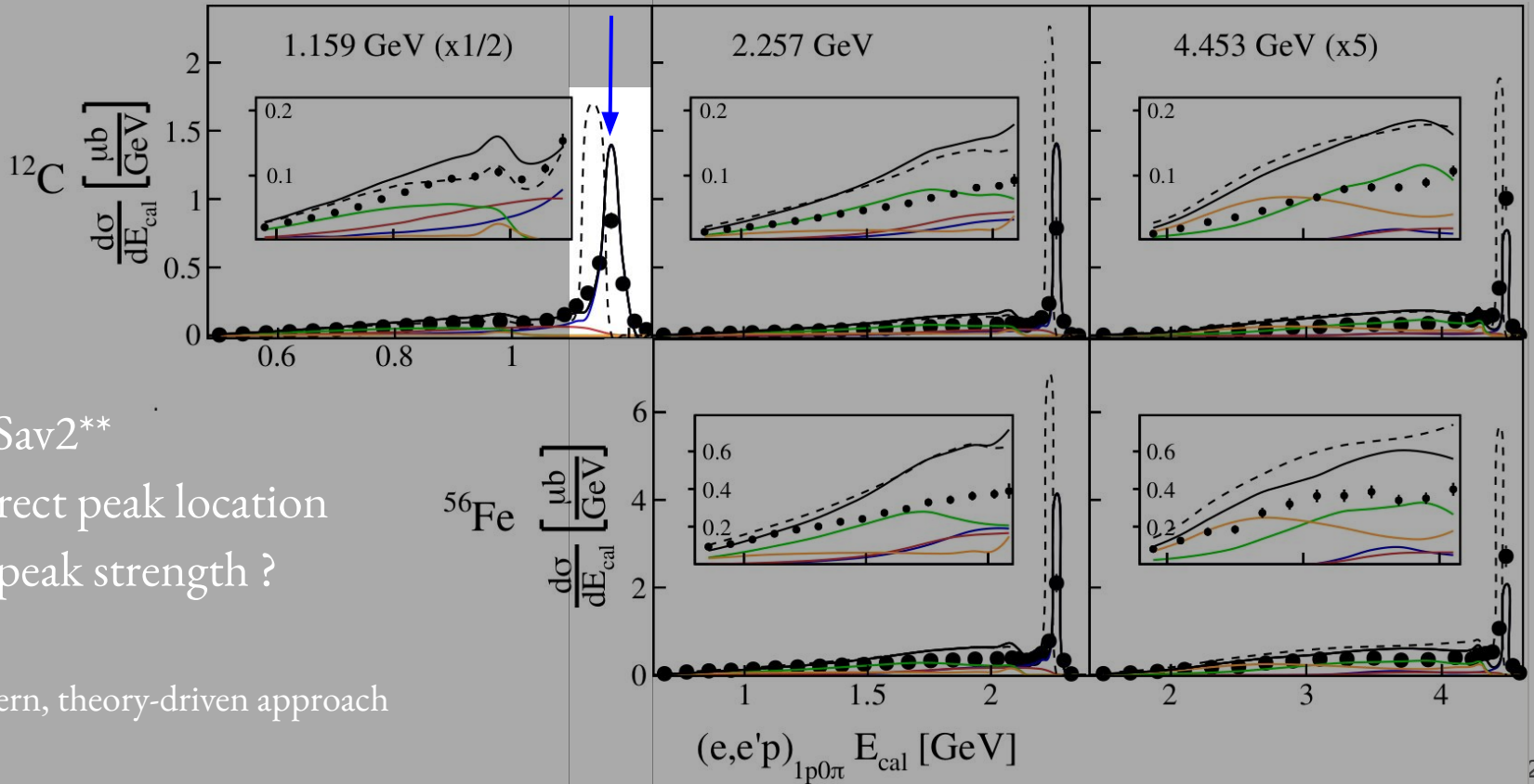


--- G2018*

- Incorrect peak location
- Overprediction of QE peak

* EMQE: Rosenbluth
EMMEC: Empirical

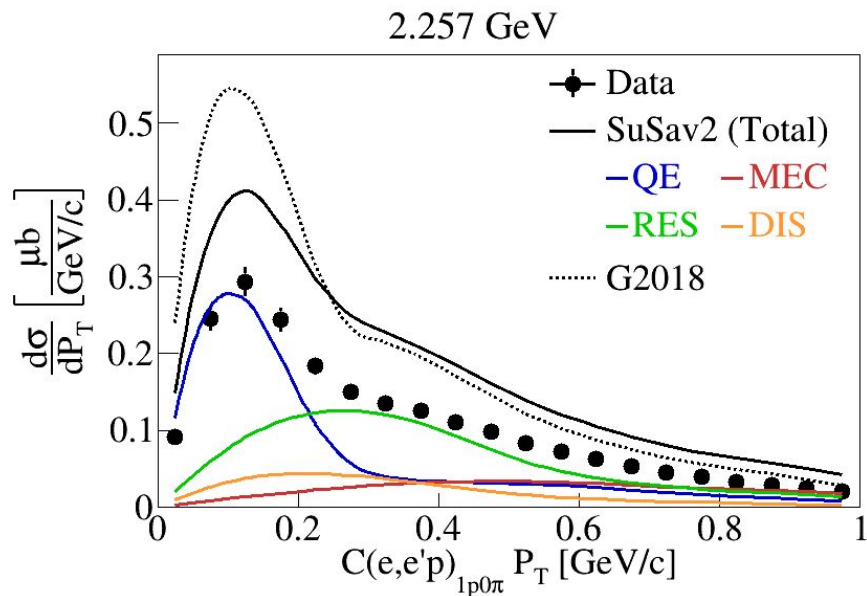
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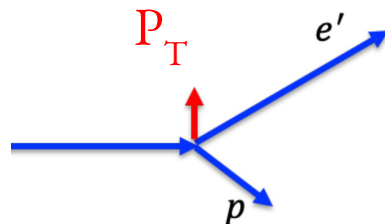
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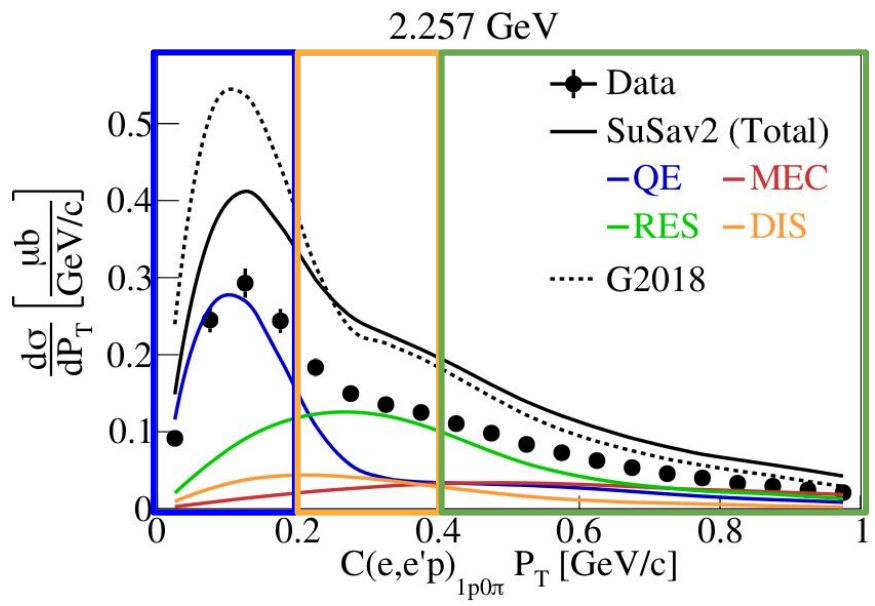
Nature 599, 565–570 (2021)

$$P_T = | \mathbf{P}_T^{e'} + \mathbf{P}_T^p |$$

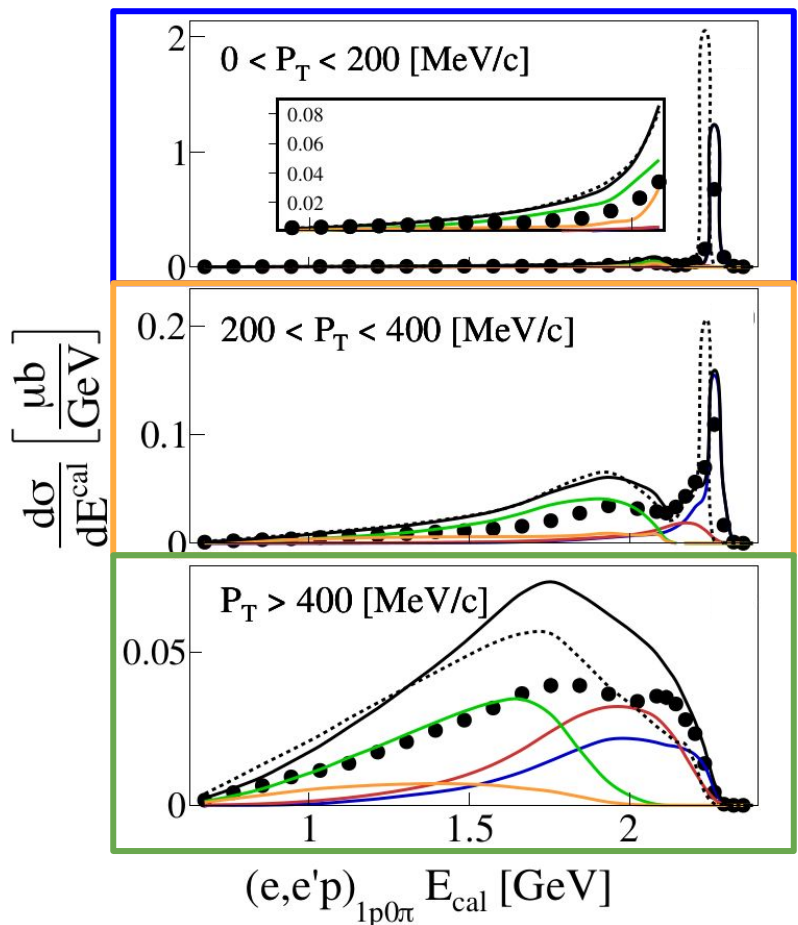


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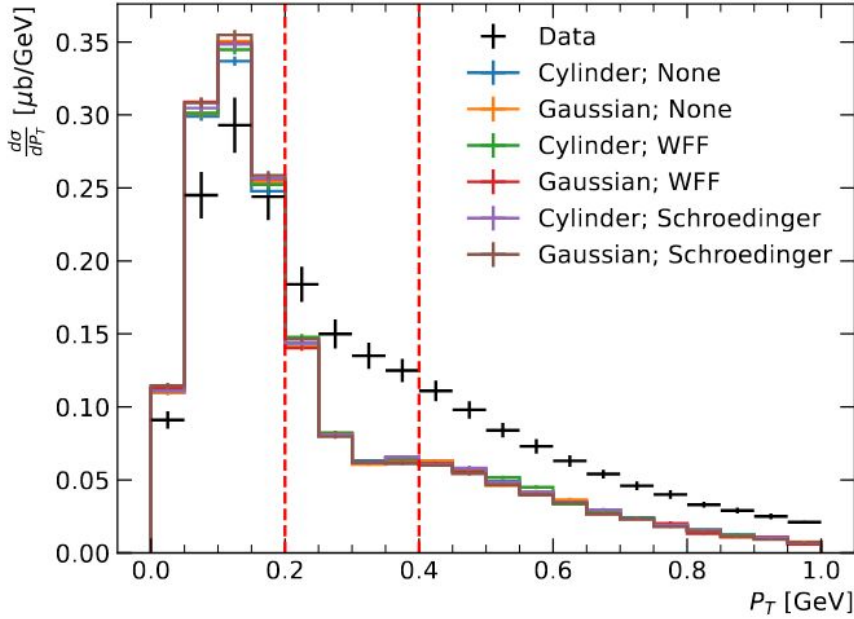
Energy Reconstruction In P_T Slices



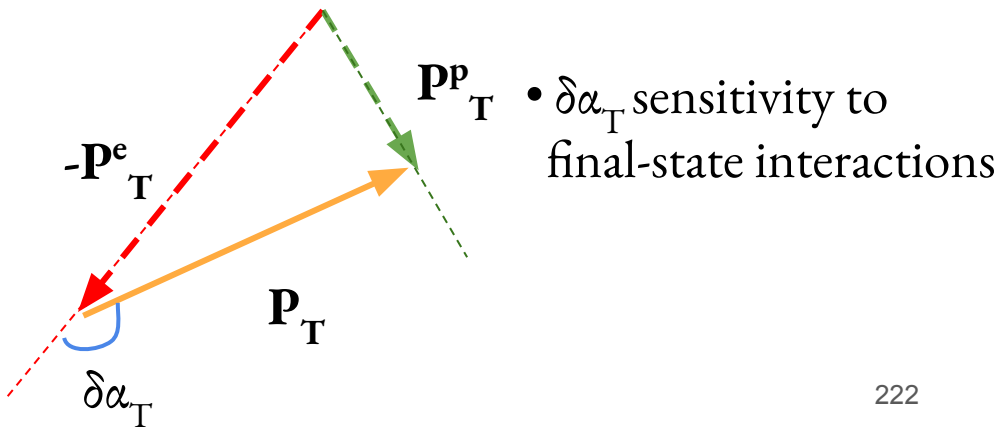
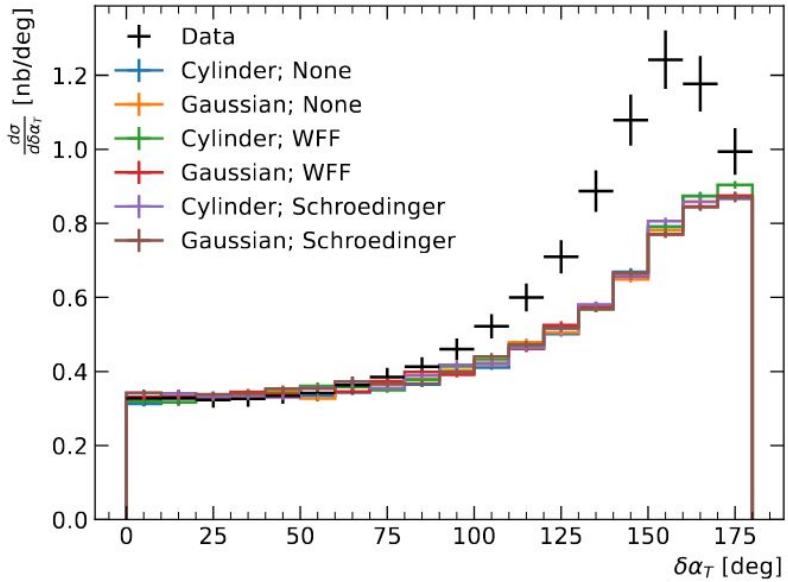
Nature 599, 565–570 (2021)



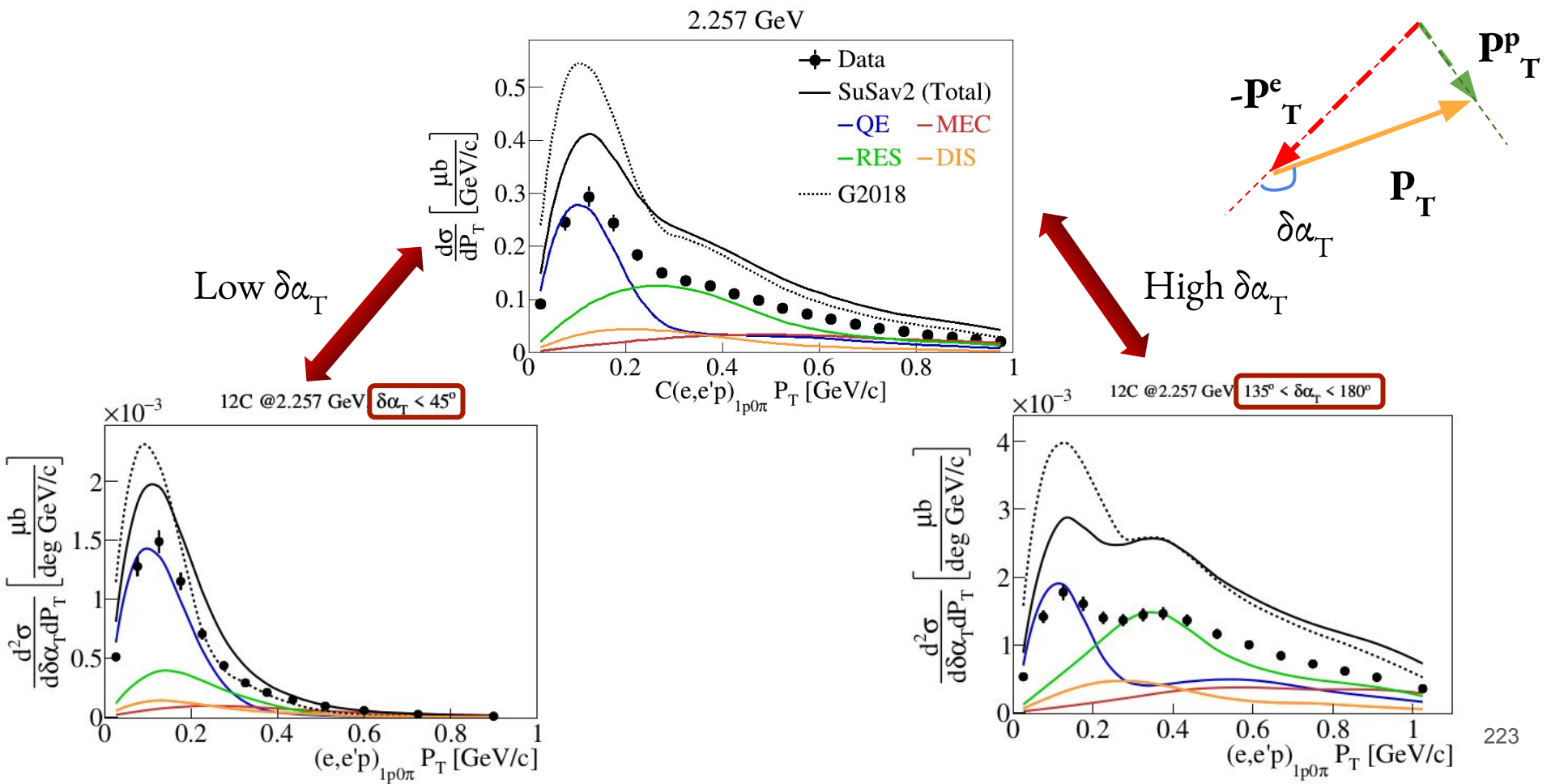
Example: Benchmarking New Generators & Kinematic Variables!



First step: only QE & FSI
 ACHILLES arXiv: 2205.06378



Example: 2D Kinematic Imbalance

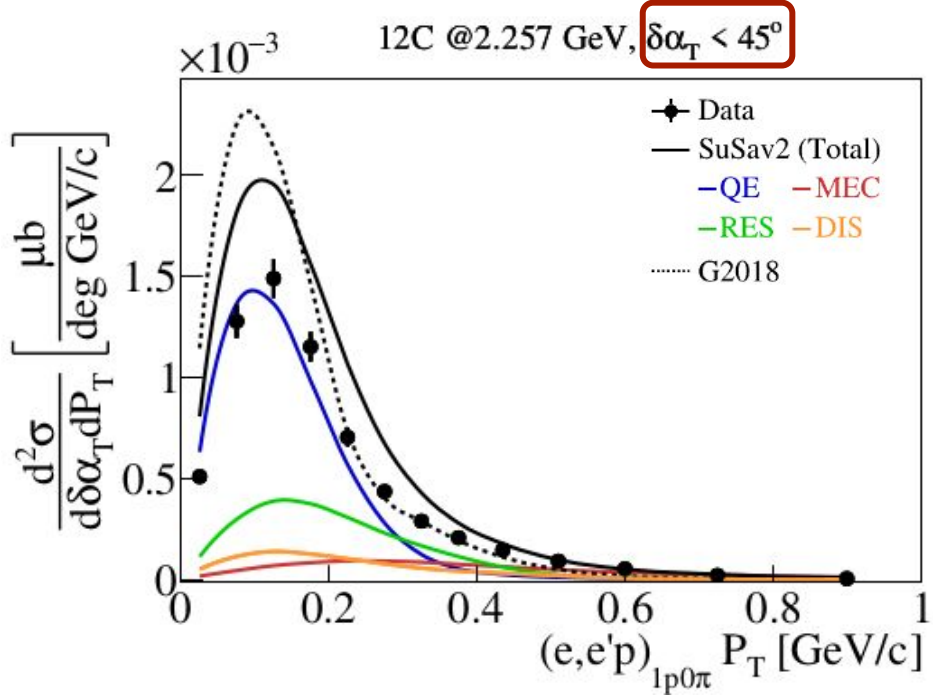


Example: 2D Kinematic Imbalance

Low $\delta\alpha_T$

QE-enhanced region

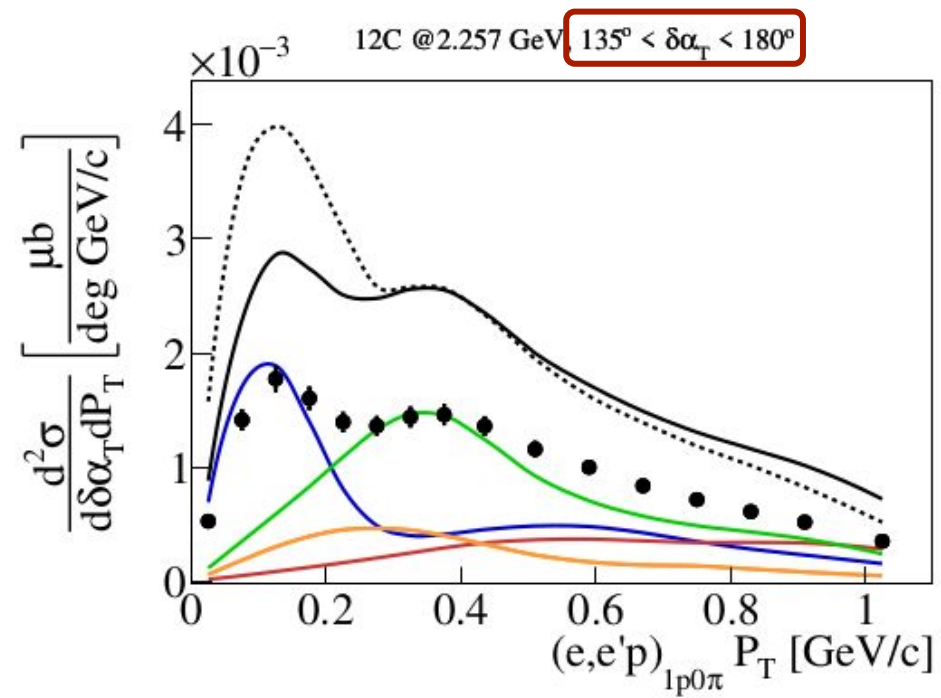
Sensitive to ground-state modeling



High $\delta\alpha_T$

Large non-QE contributions

Strong final-state interaction effects

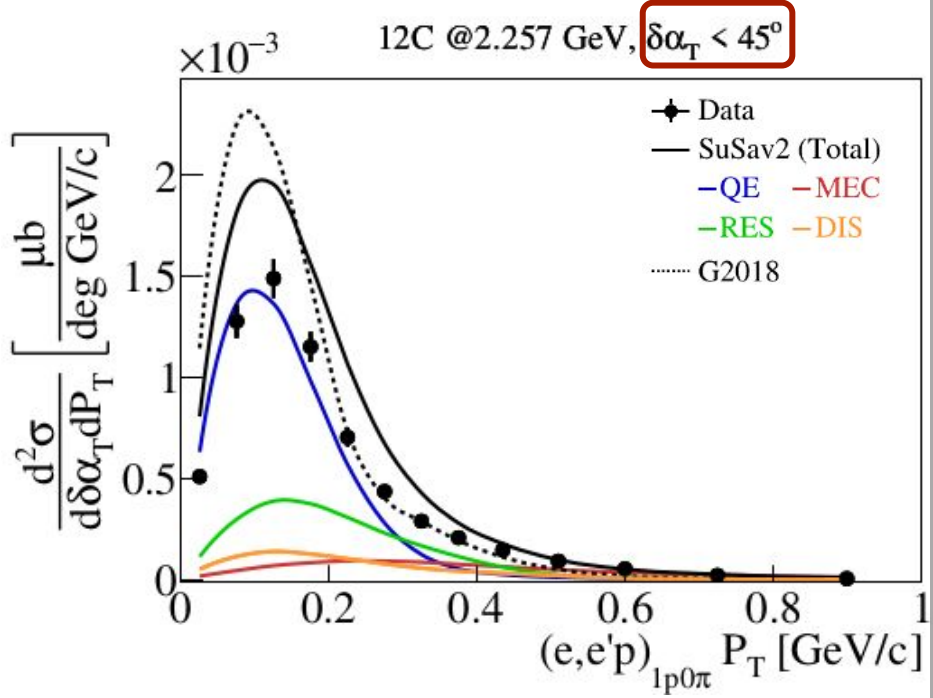


Example: 2D Kinematic Imbalance

Low $\delta\alpha_T$

QE-enhanced region

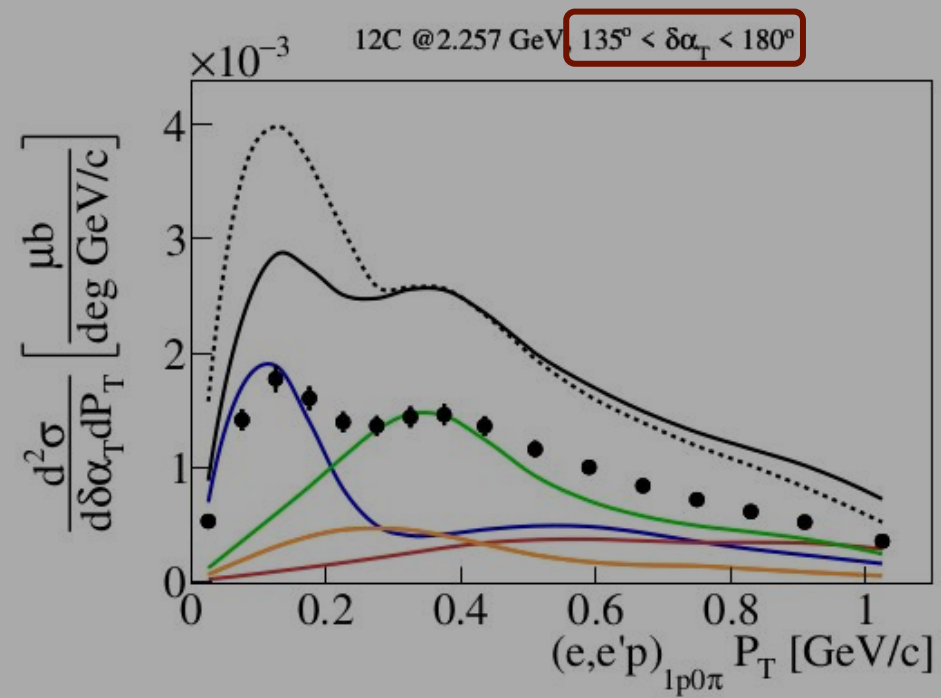
Sensitive to ground-state modeling



High $\delta\alpha_T$

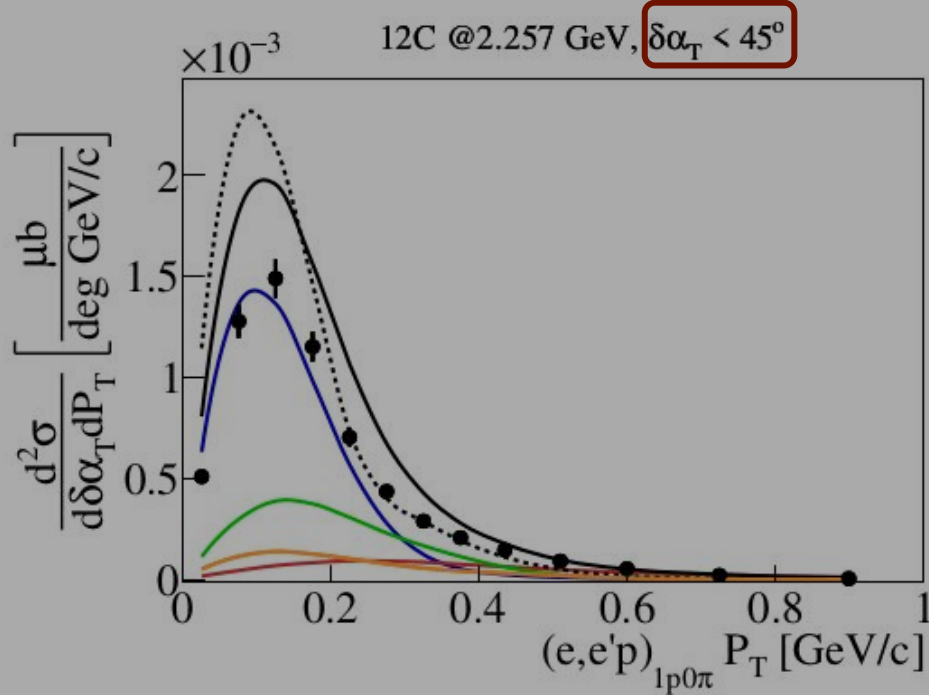
Large non-QE contributions

Strong final-state interaction effects

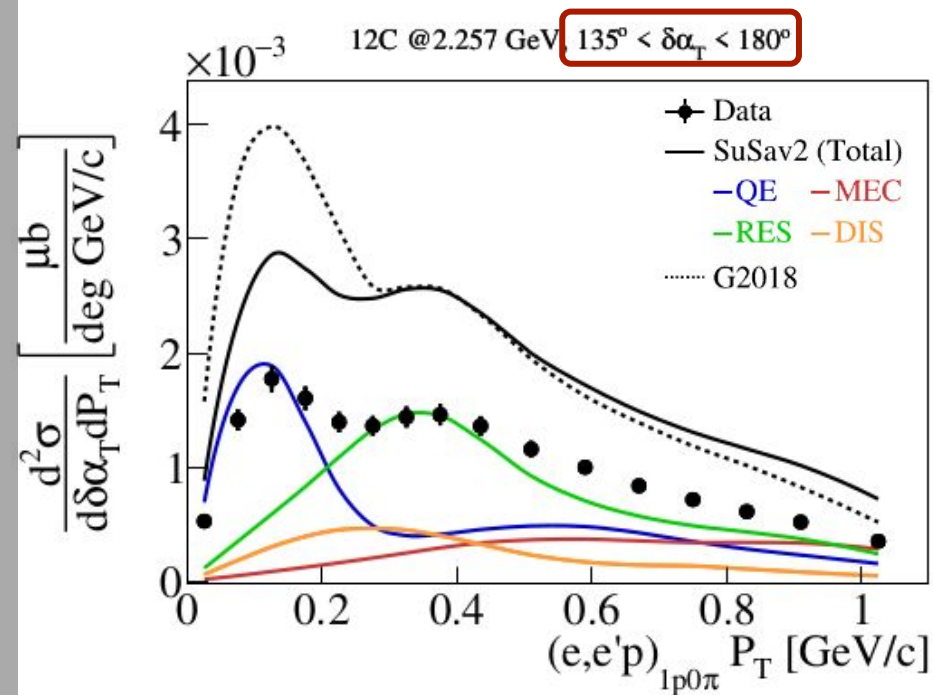


Example: 2D Kinematic Imbalance

Low $\delta\alpha_T$
QE-enhanced region
Sensitive to ground-state modeling

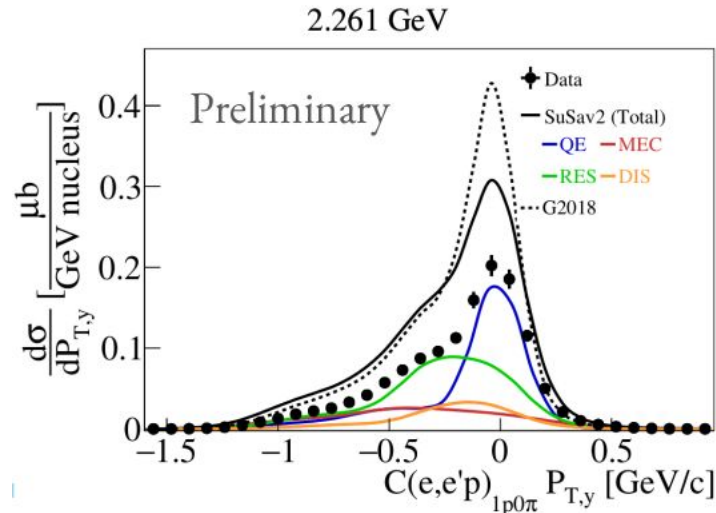
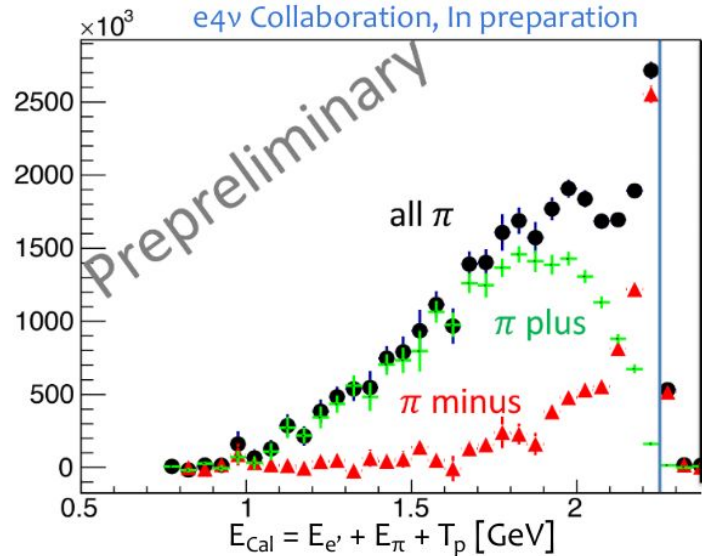
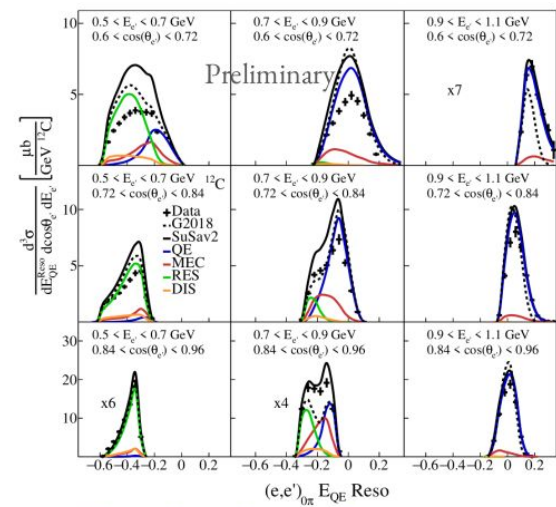


High $\delta\alpha_T$
Large non-QE contributions
Strong final-state interaction effects



Next Steps

- Even more differential! Into the 3D multiverse
Taking advantage of massive statistics
- More nuclear sensitivity variables
Help decide what to tune
- $1p1\pi$ exclusive cross sections

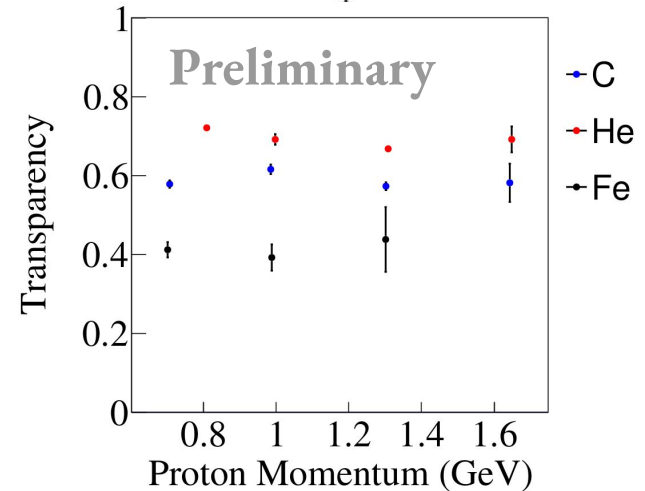
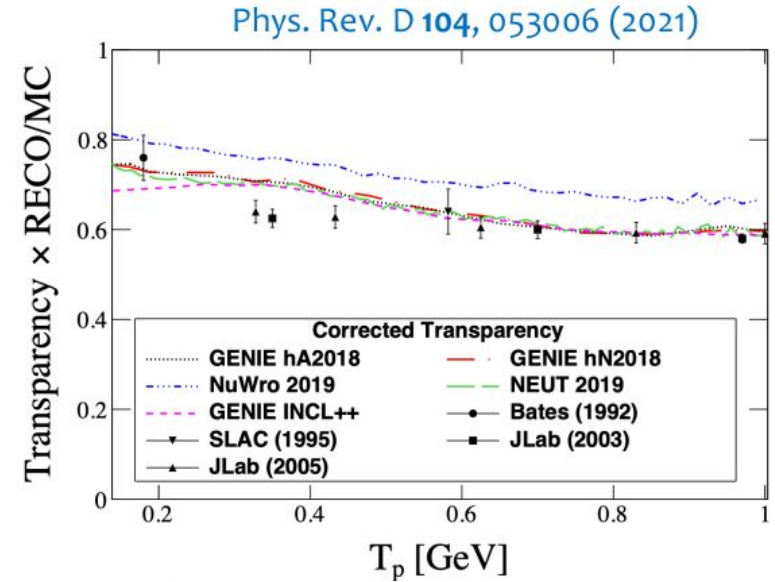


Next Steps

- More with CLAS6

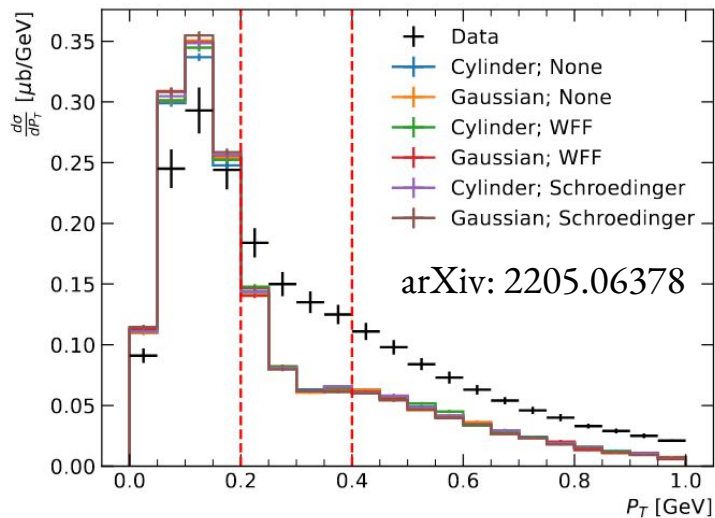
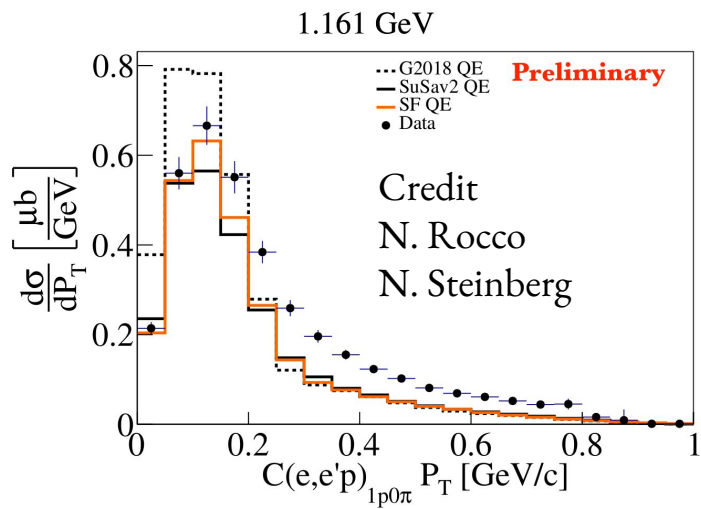
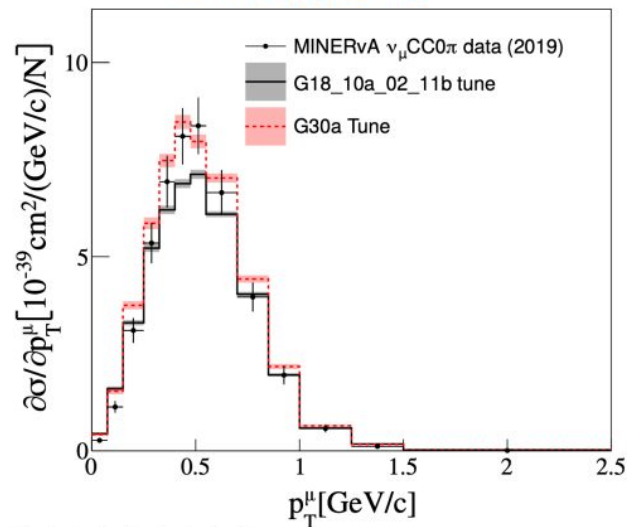
□ Proton transparency studies

- Observable that summarizes strength of intranuclear rescattering
- Measurement study
$$T = N_{\text{prot}}^{\text{detected}} / N_{\text{prot}}^{\text{PWIA}}$$
- Test event generator FSI models in GENIE across multiple nuclear targets
- Testing dependency of transparency calculations on PWIA normalization



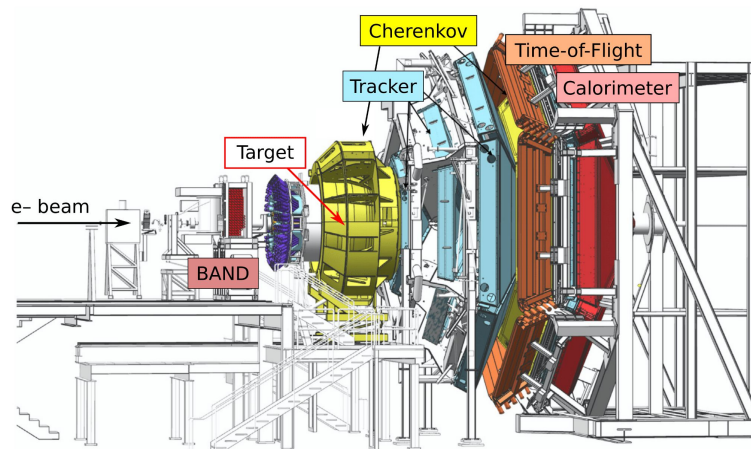
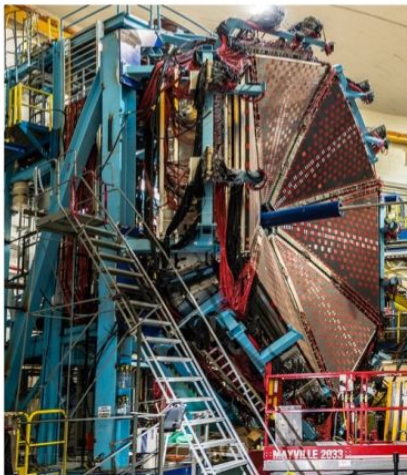
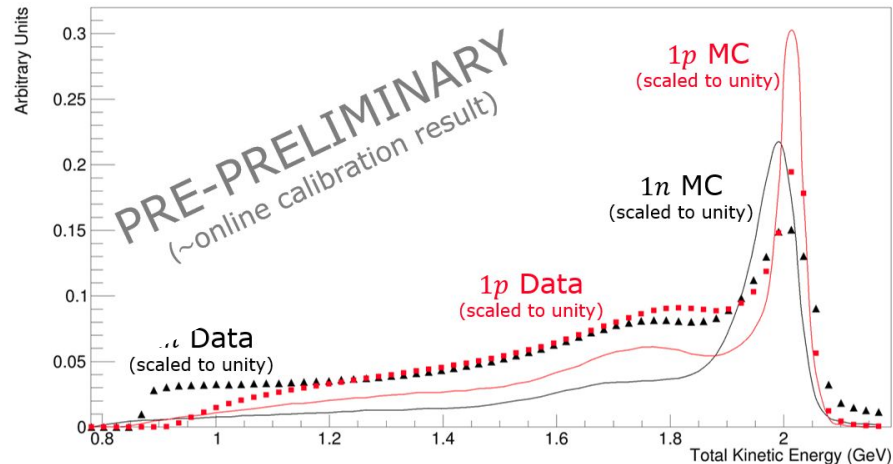
Next Steps

- More with CLAS6
- ☐ Prepare suite of cross sections in same variables as neutrinos for first e-GENIE tune
 - Compare with neutrino CC0 π tune
- $e4\nu$ data already being used to validate event generators



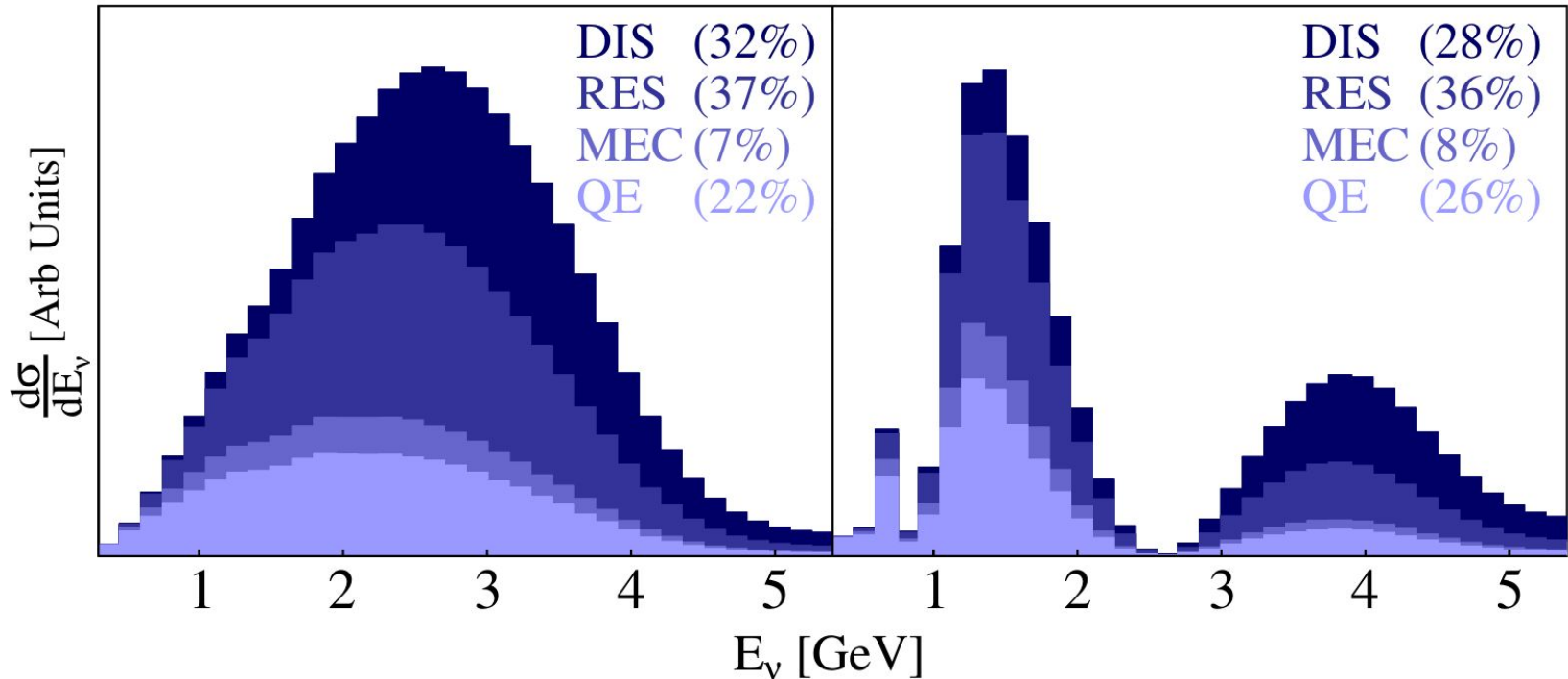
Next Steps

- New data with CLAS12
Targets: ^4He , ^{12}C , ^{40}Ar , ^{120}Sn
- 2 - 6 GeV beam energies
- More phase-space coverage ($\theta_e > 5^\circ$)
- Neutrons!

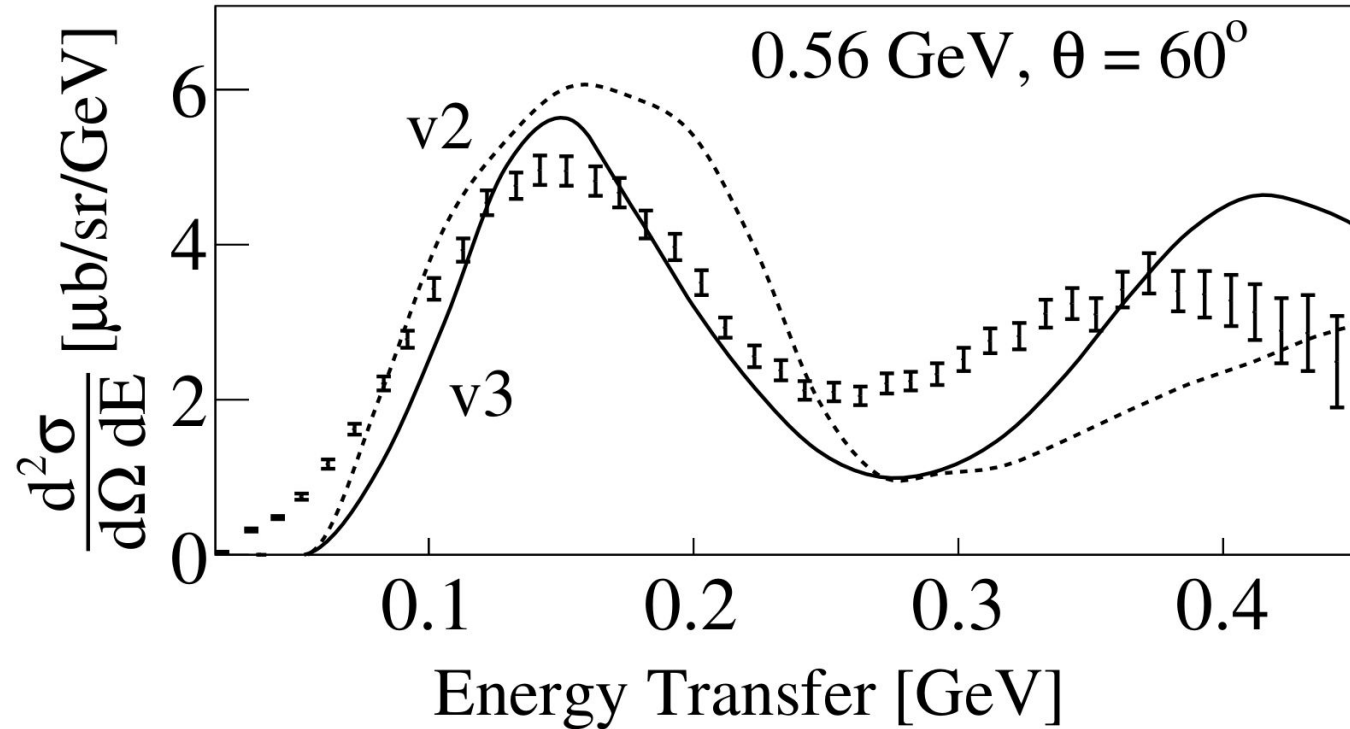


Mismodelling Impact On Mixing Parameters

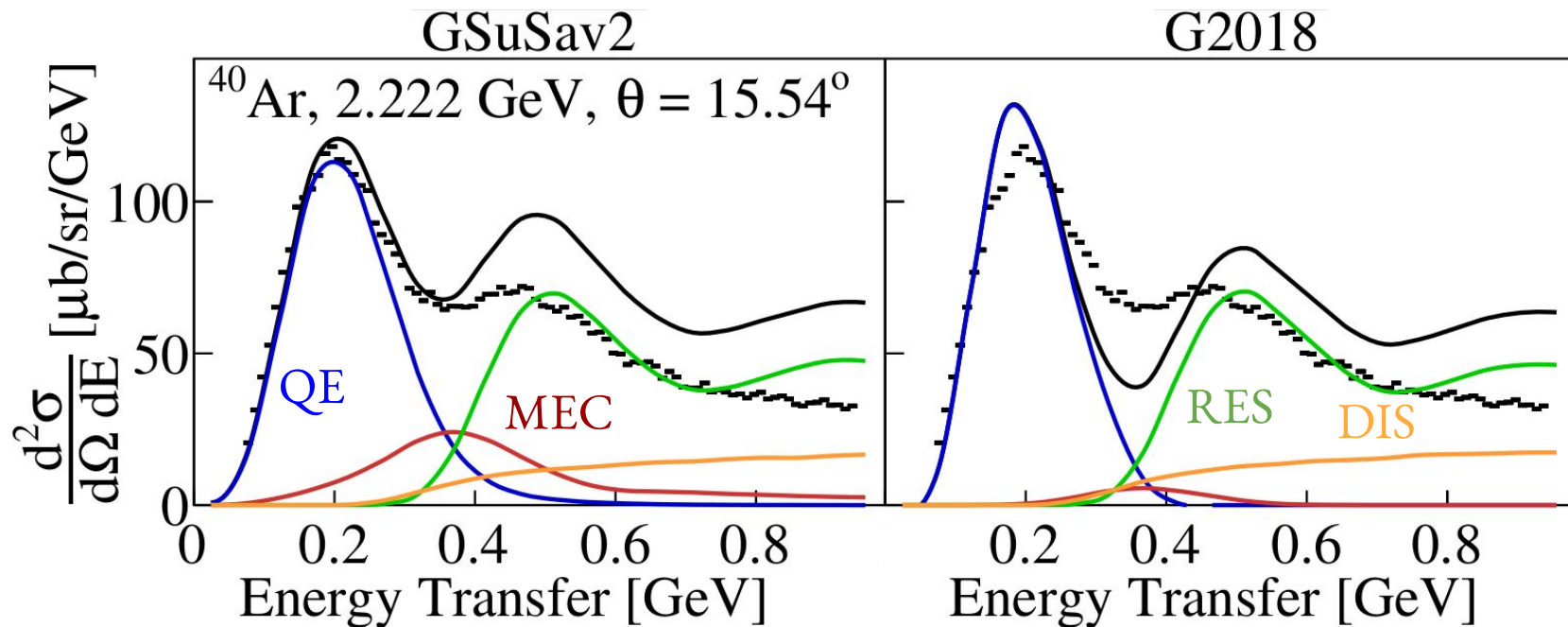
Charged current cross sections obtained using GENIE for the DUNE near detector (left) and far detector (right) oscillated fluxes



(e,e') ^{12}C with G2018

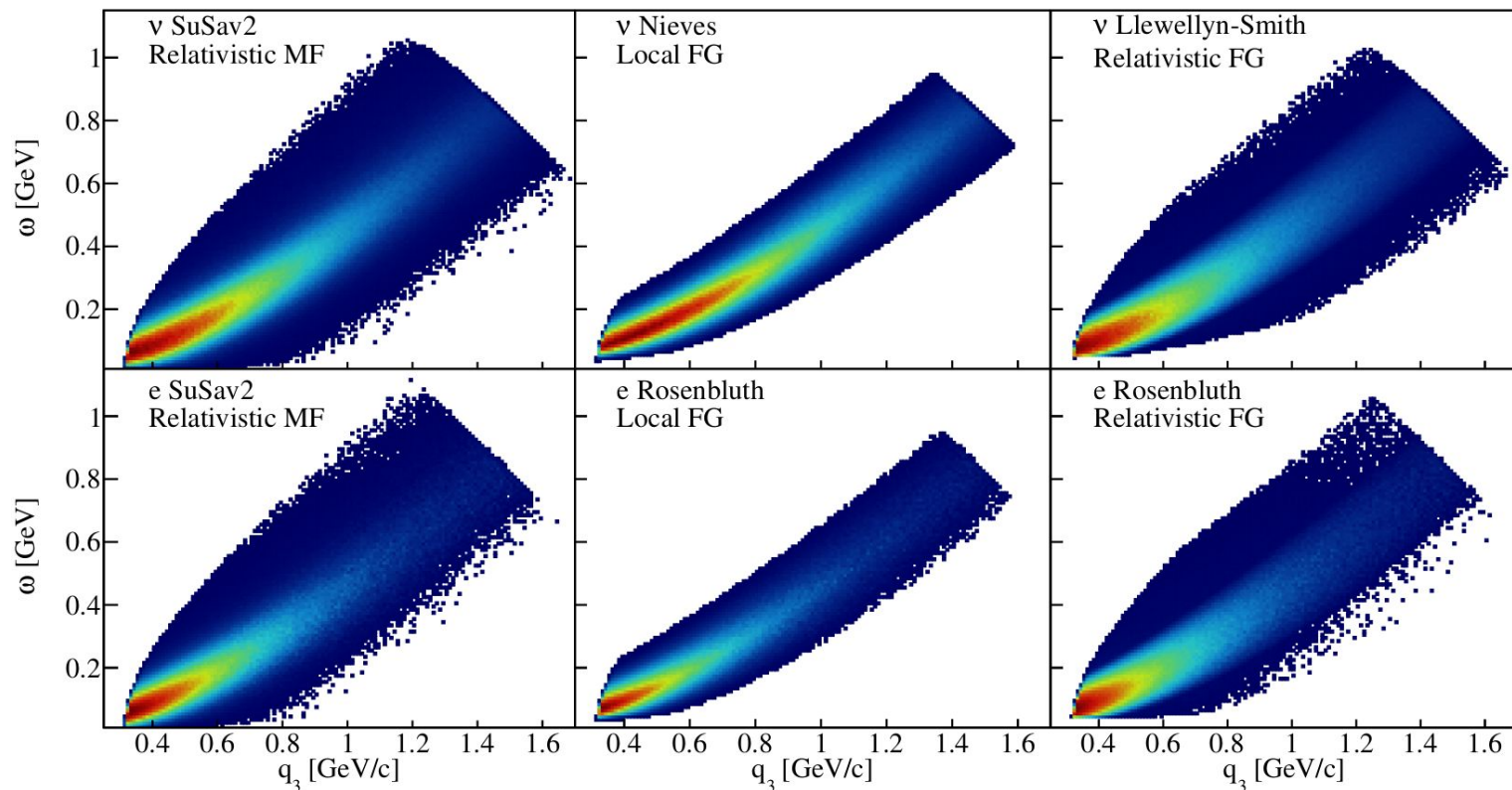


SuSav2 Offers More Accurate Prediction



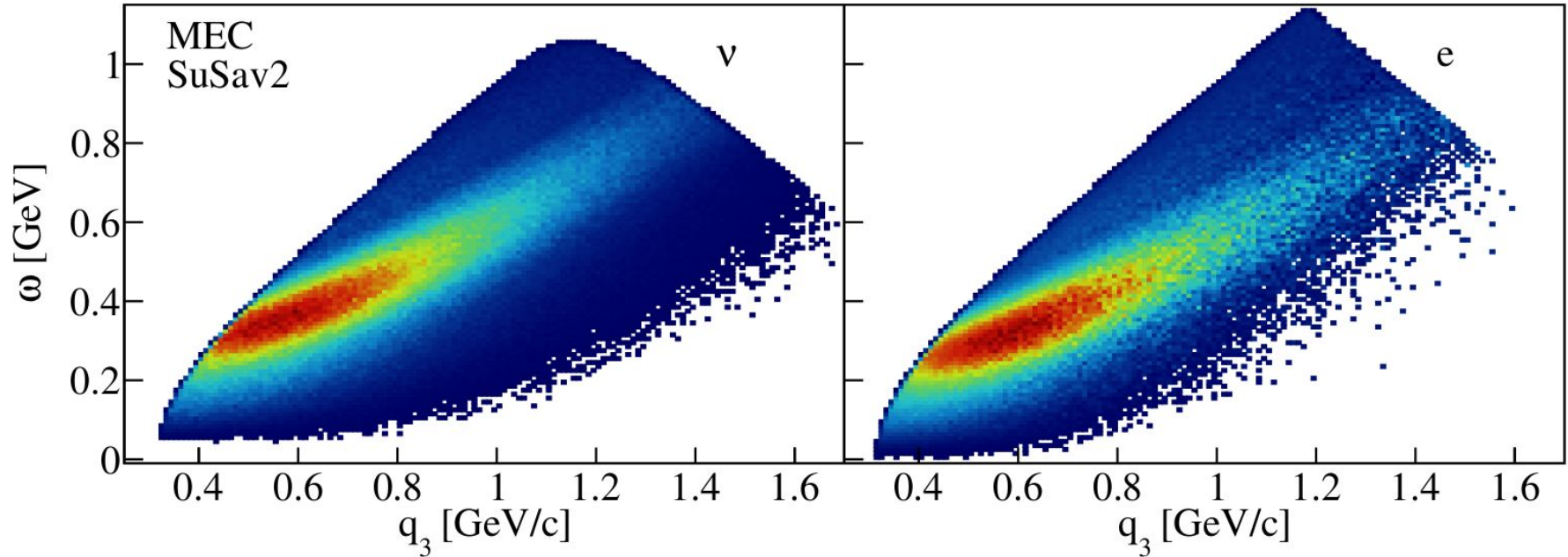
Probing The Neutrino Phase-Space With Electrons

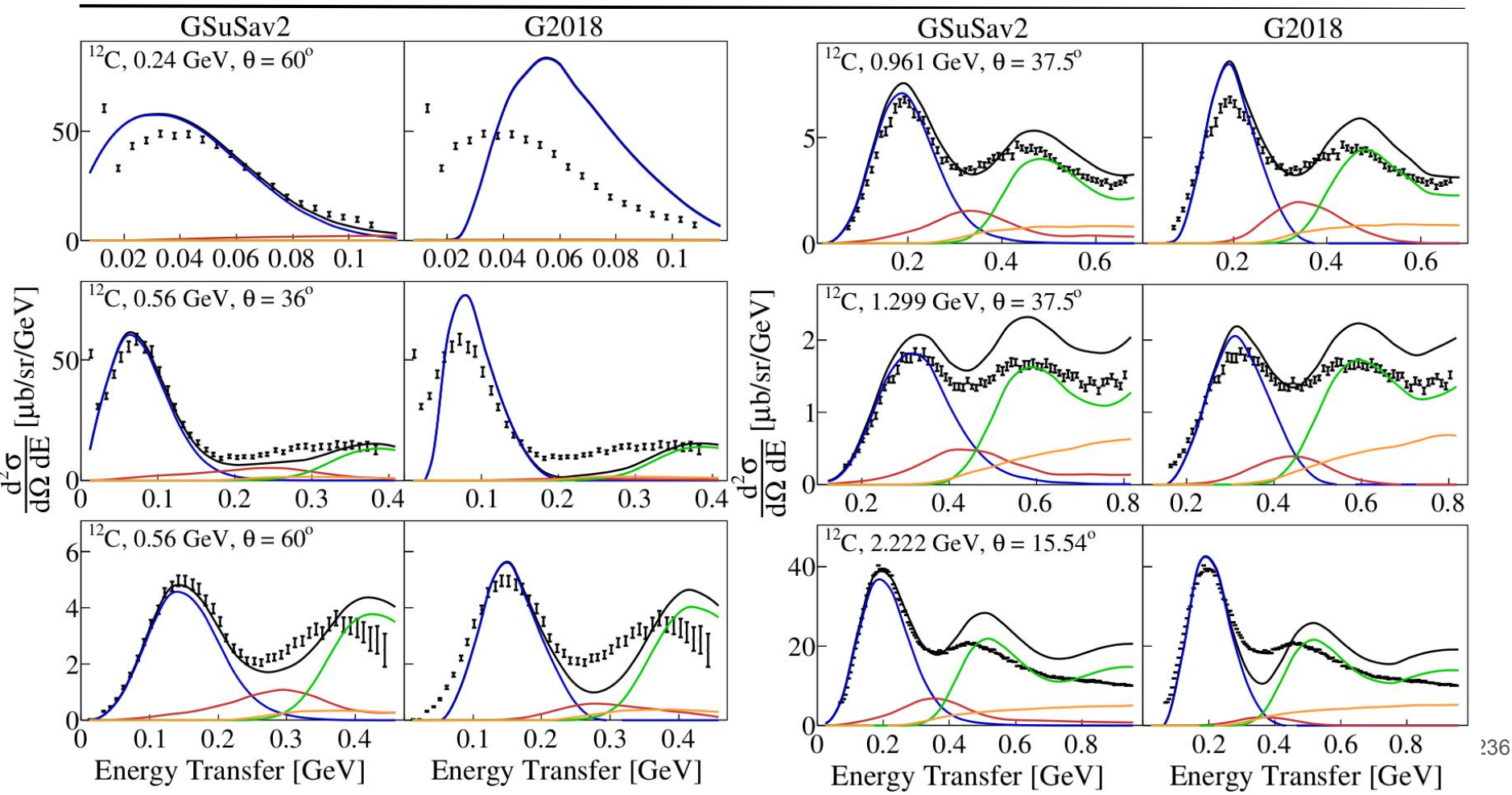
QE Events

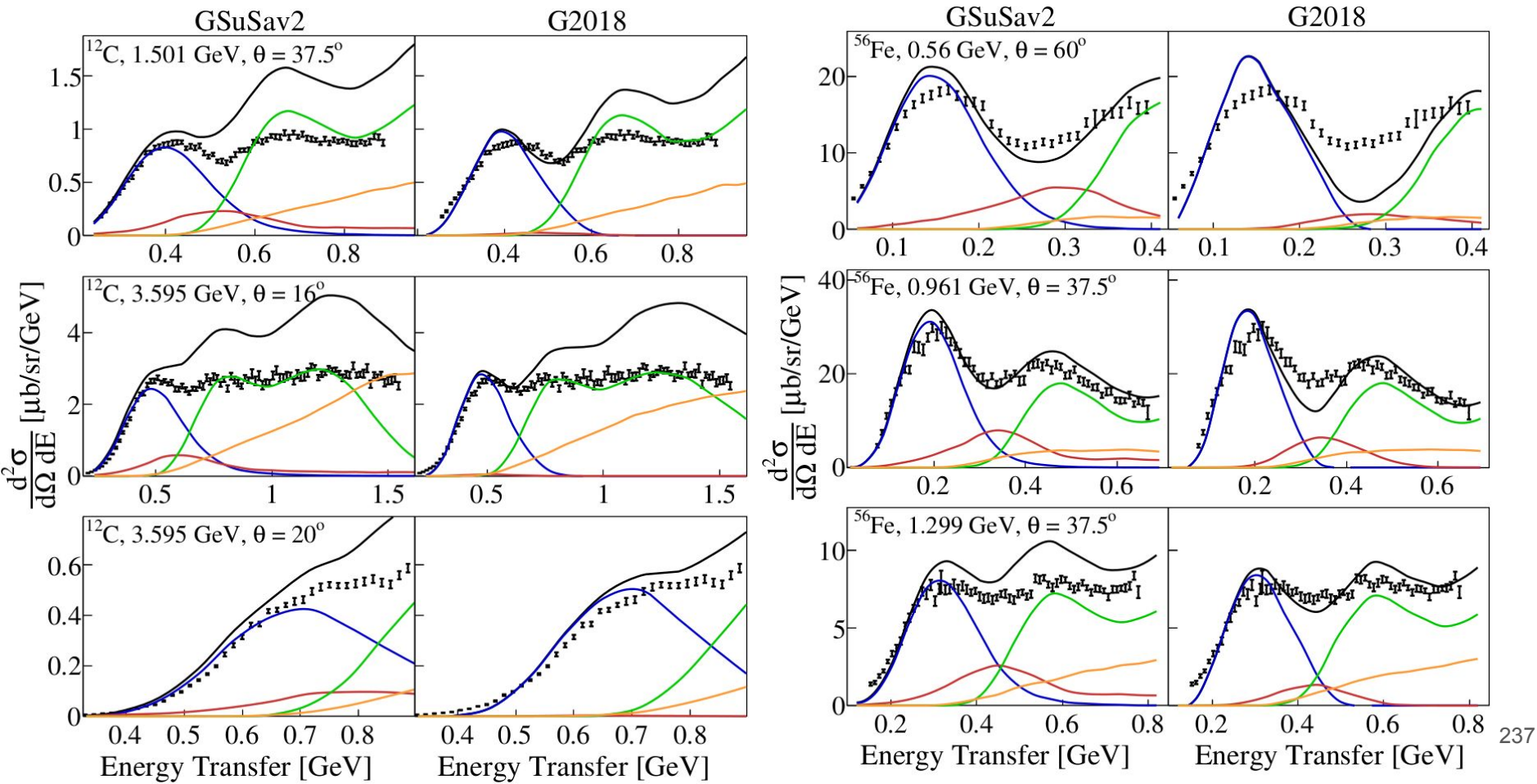


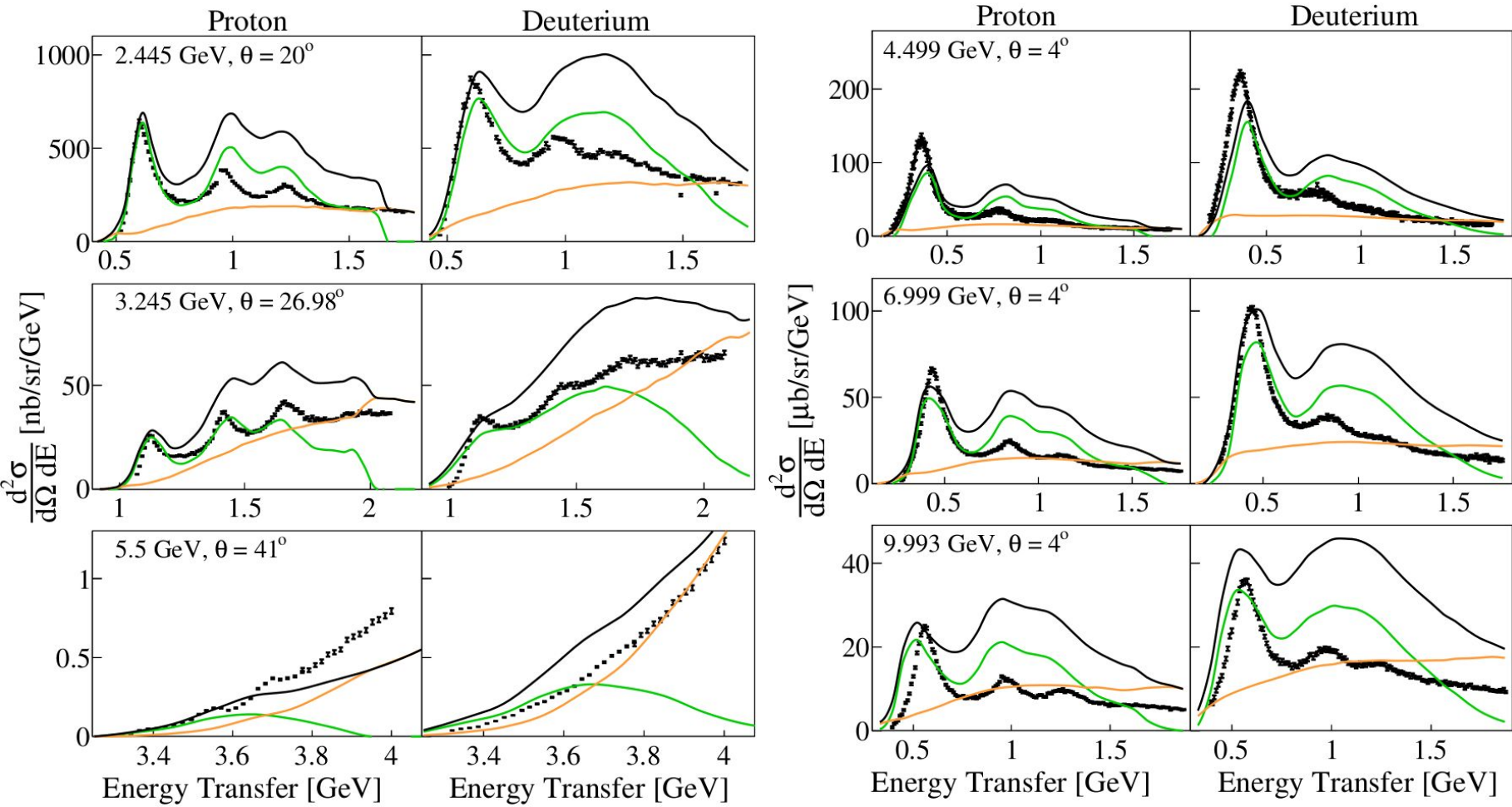
Consistent Treatment Of MEC Events With SuSav2

Unique chance to constraint one of least understood interaction channels

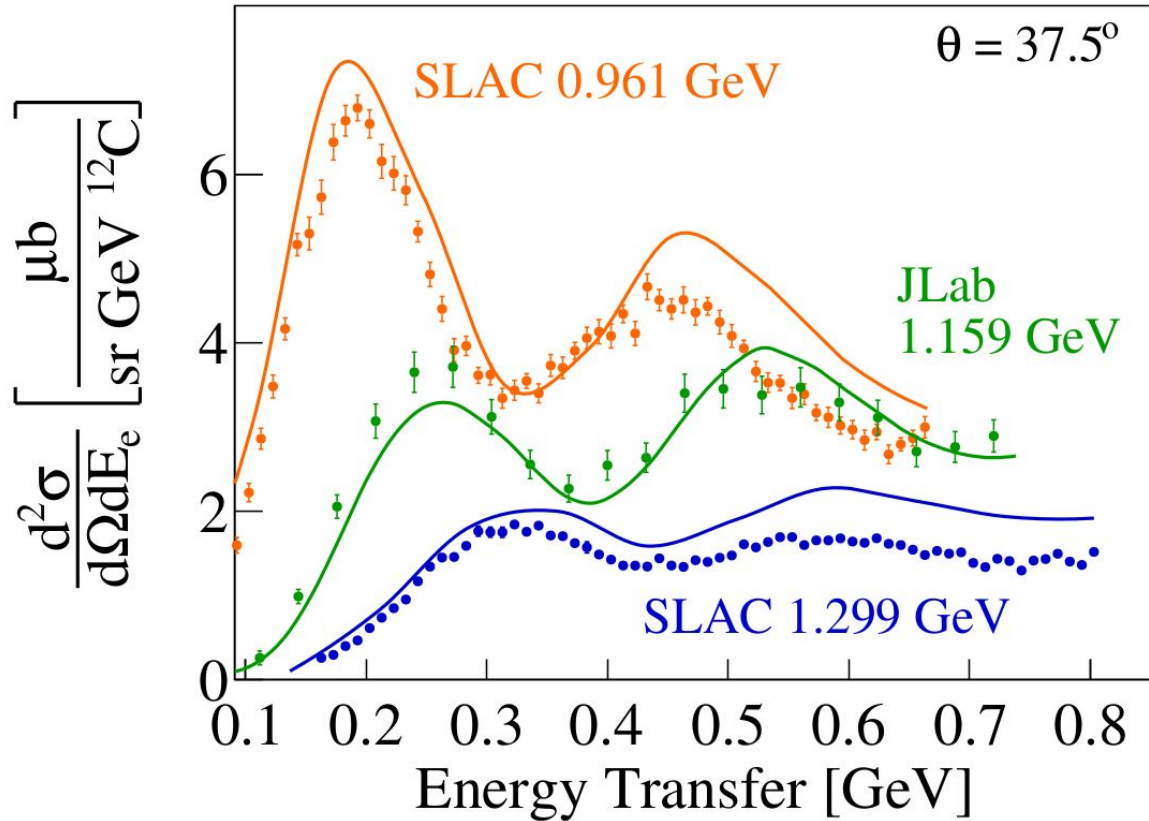




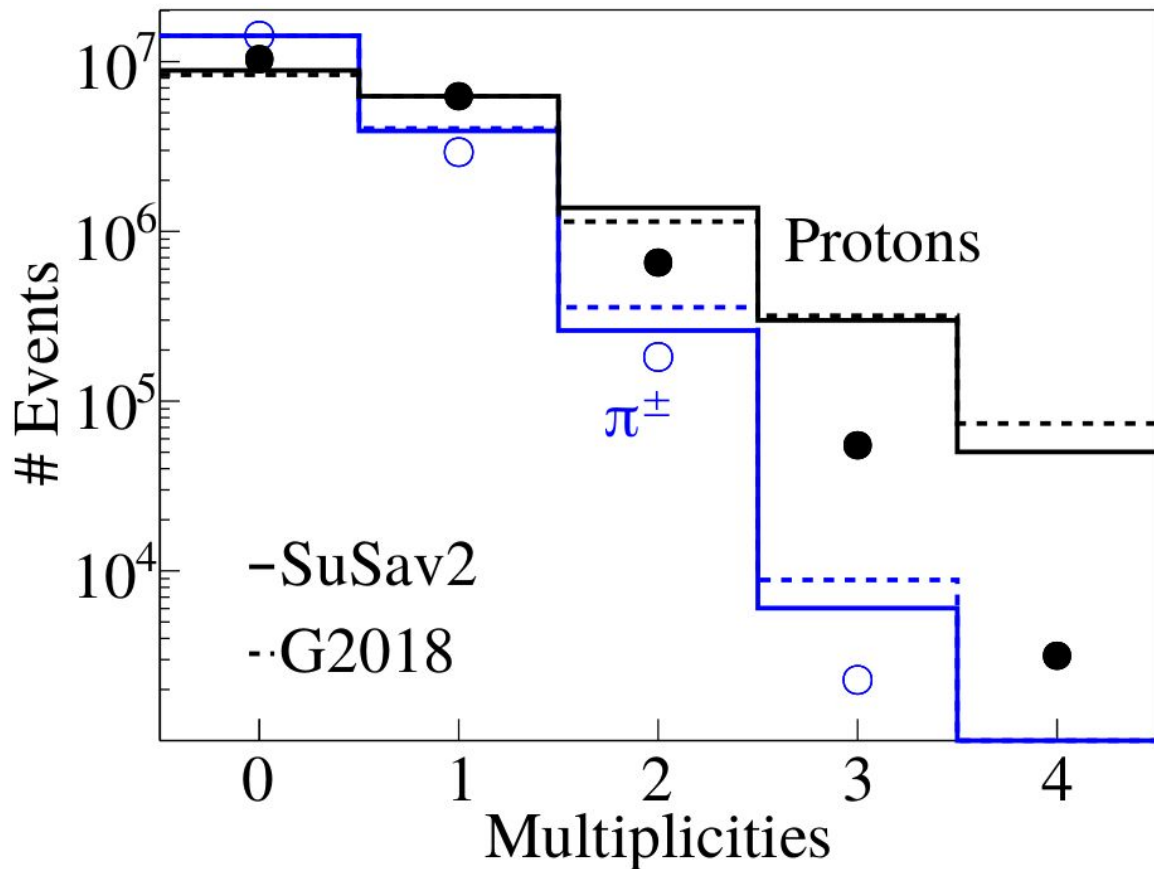




Sanity Check With Inclusive Cross Sections



Detected Hadron Multiplicities



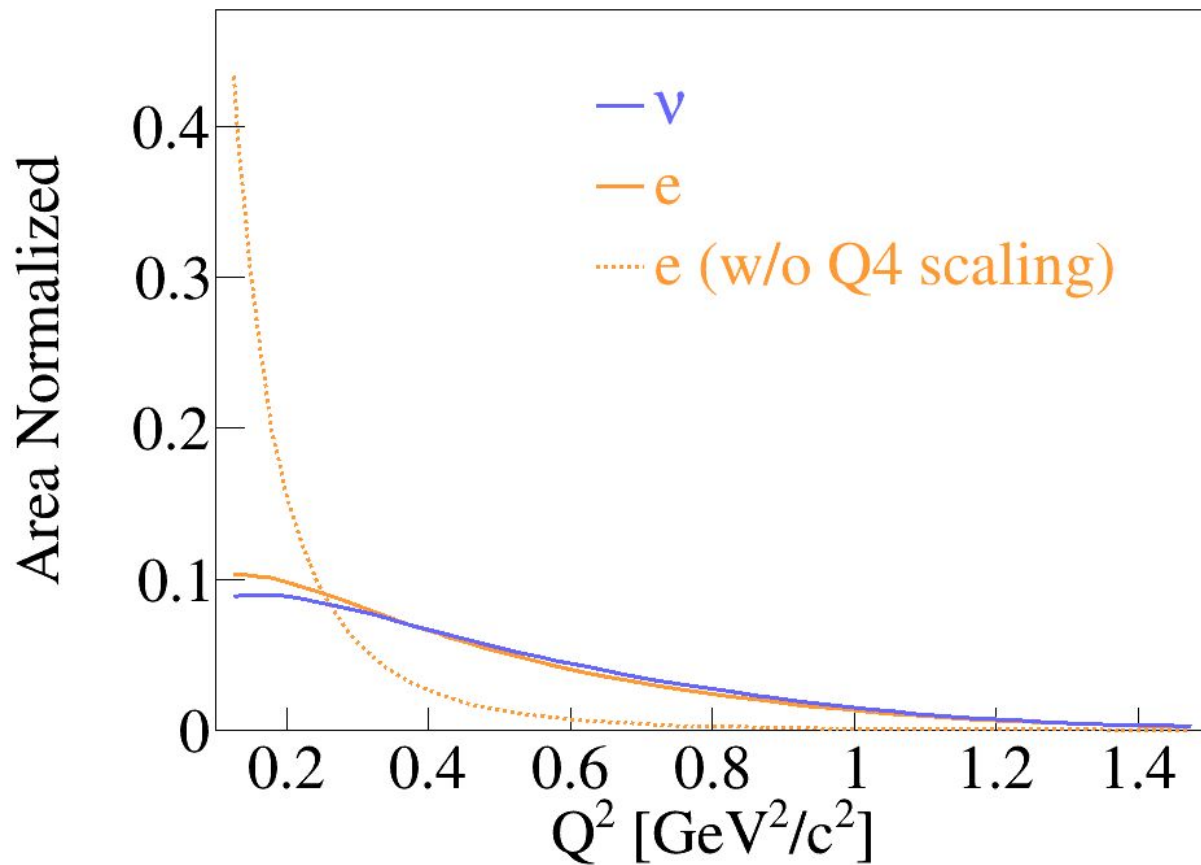
^{12}C @ 2.2 GeV

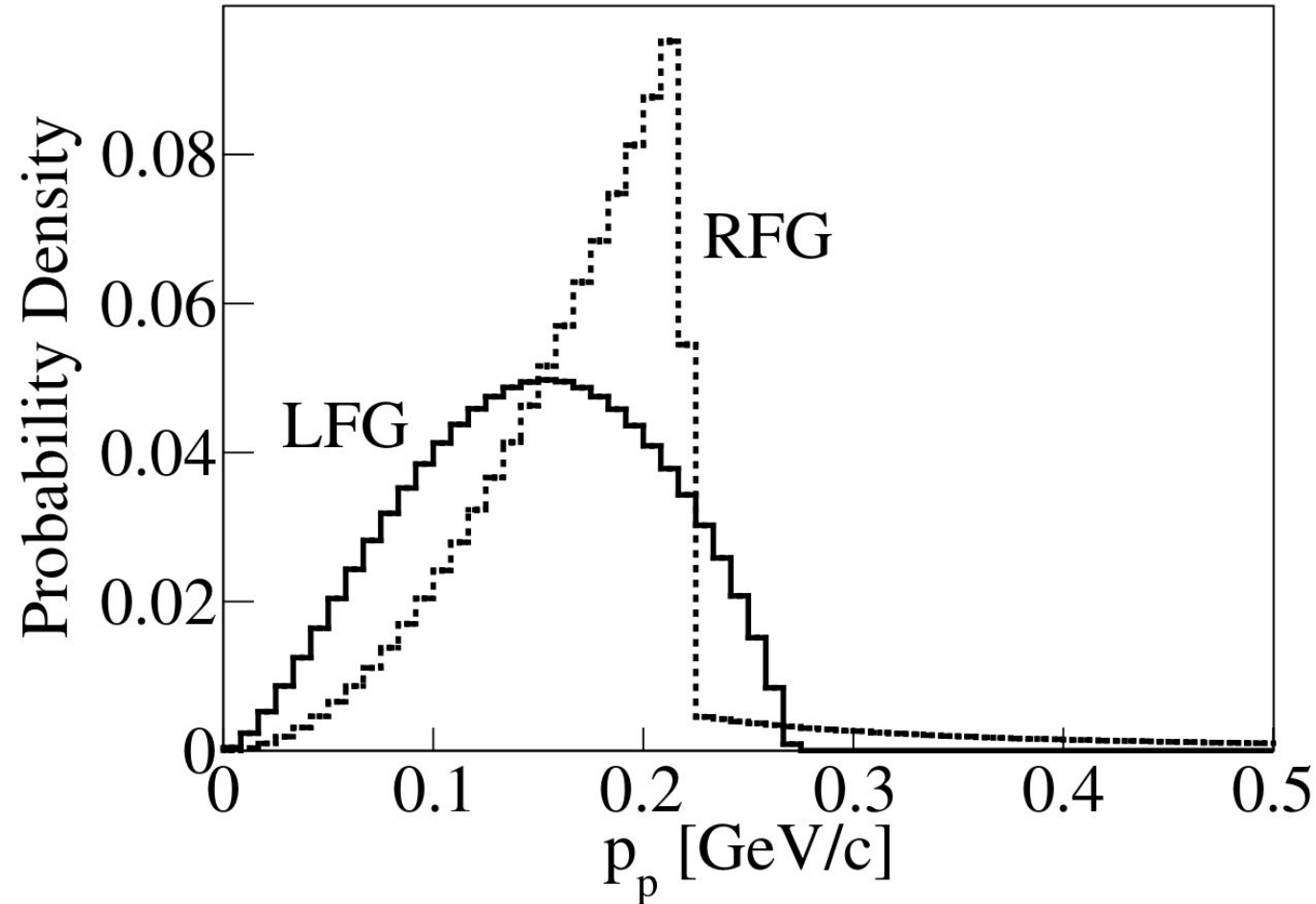
$P_p > 300 \text{ MeV}/c$
 $P_\pi > 150 \text{ MeV}/c$

Simulation overpredicts
hadron multiplicities

M.Khachatryan, A.Papadopoulou, et al.
Nature 599, 565–570 (2021)

Q^4 Scaling Effect





SuSav2 Configuration / GEM21_11b_00_000

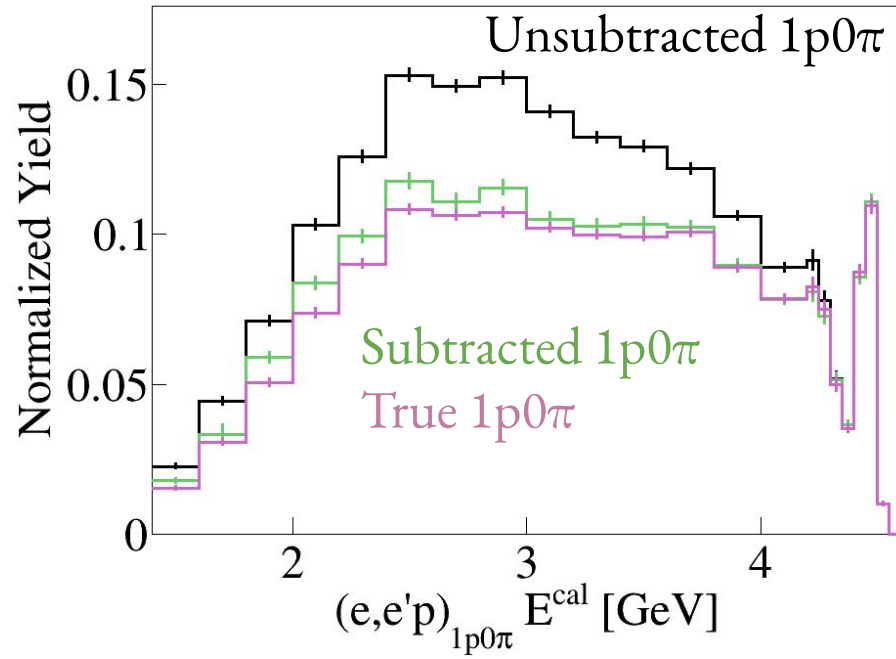
	Electrons	Neutrinos
QE	SuSav2	SuSav2
MEC	SuSav2	SuSav2
RES	Berger-Sehgal	Berger-Sehgal
DIS	AGKY	AGKY
FSI	hN2018	hN2018
Nuclear Model	Relativistic Mean Field	Relativistic Mean Field

G2018 Model Configuration

	Electrons	Neutrinos
QE	Rosenbluth	Nieves
MEC	Empirical	Nieves
RES	Berger-Sehgal	Berger-Sehgal
DIS	AGKY	AGKY
FSI	hA2018	hA2018
Nuclear Model	Local Fermi Gas	Local Fermi Gas

Closure Test

- Use GENIE files
- Filter specific topologies (e.g. $1p0\pi p + 1p1\pi$)
- **Subtracted** & **True** $1p0\pi$ are in good agreement



Well defined signal definition: Min θ_e Cut

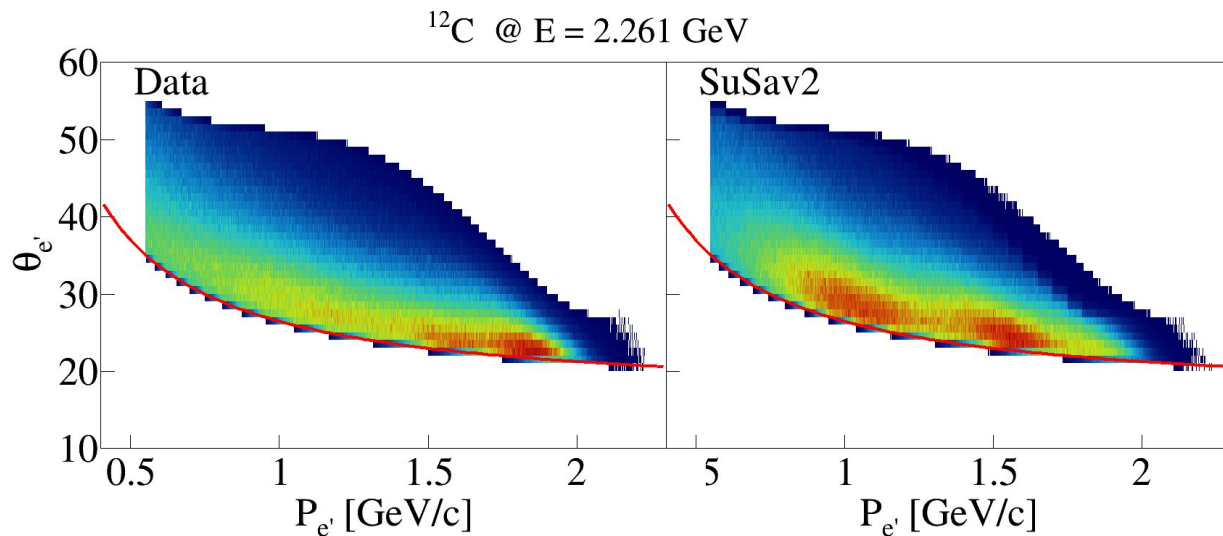
@ 1.1 GeV: $\theta = 17 + 7 / P$

@ 2.2 GeV: $\theta = 16 + 10.5 / P$

@ 4.4 GeV: $\theta = 13.5 + 15 / P$

See backup for p / $\pi^{+/-}$ definitions

- We do not acceptance correct below min θ



Well defined signal definition: Min θ_e Cut

@ 1.1 GeV: $\theta = 17 + 7 / P$

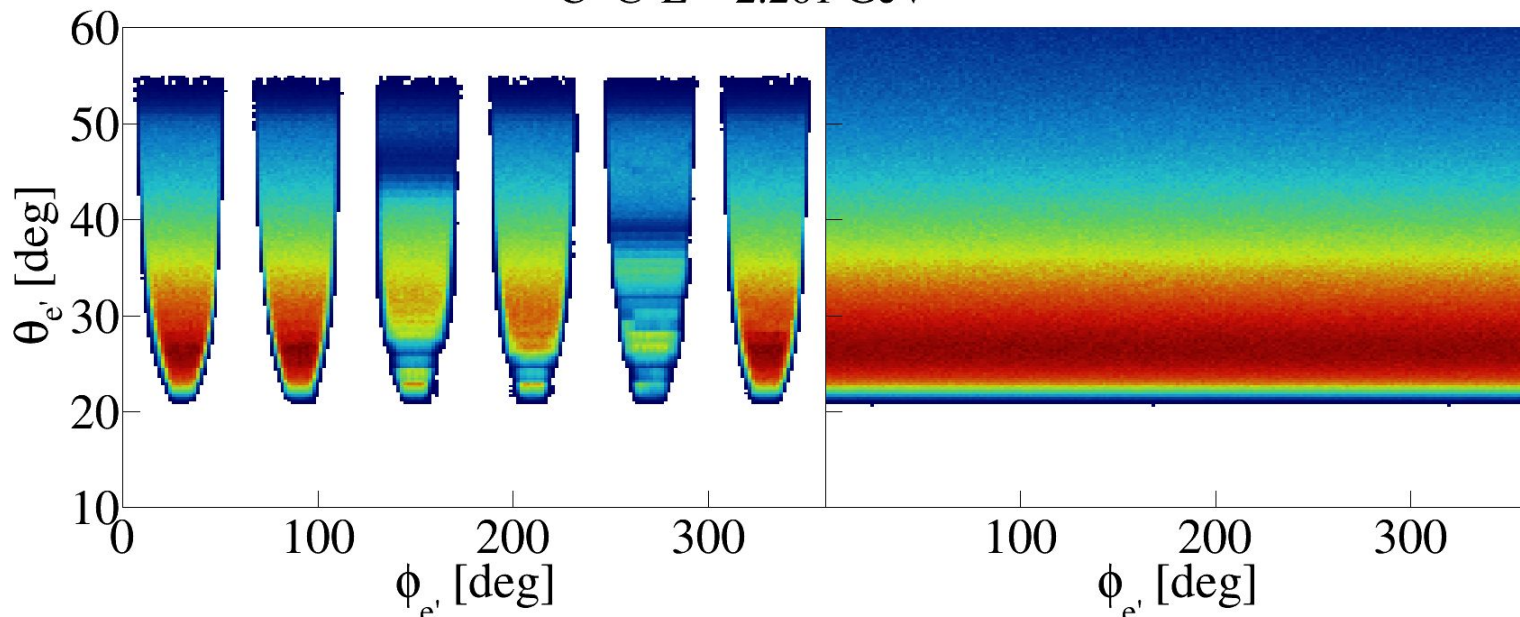
@ 2.2 GeV: $\theta = 16 + 10.5 / P$

@ 4.4 GeV: $\theta = 13.5 + 15 / P$

See backup for $p / \pi^{+/-}$ definitions

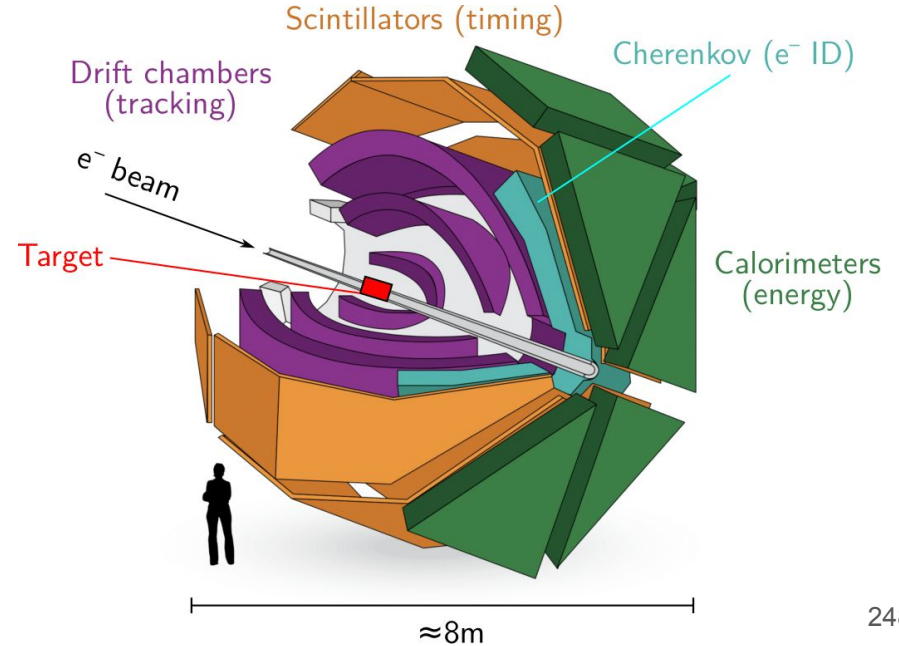
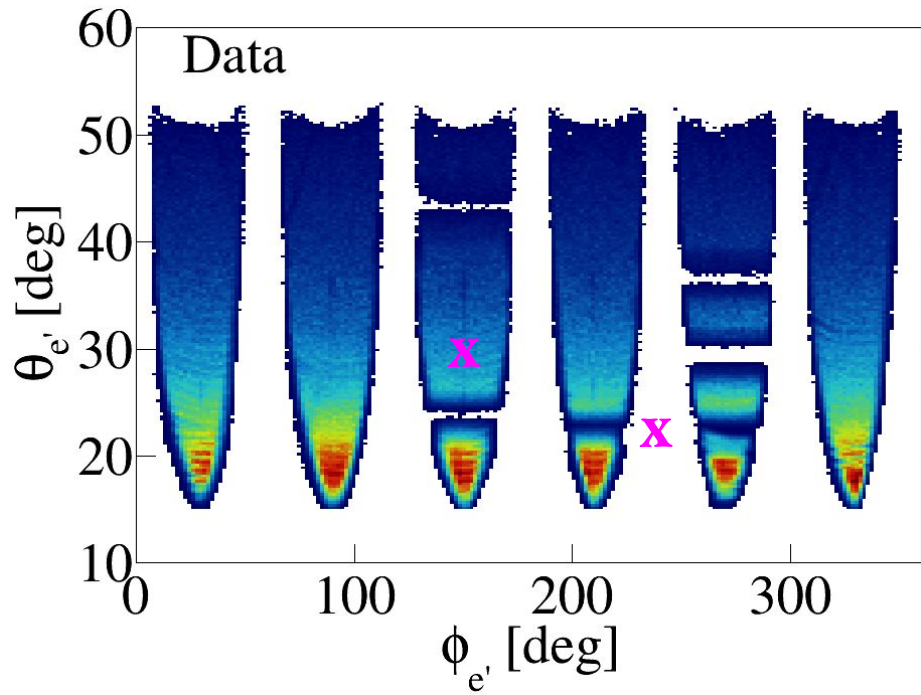
- We do not acceptance correct below min θ

^{12}C @ $E = 2.261$ GeV



Background Subtraction

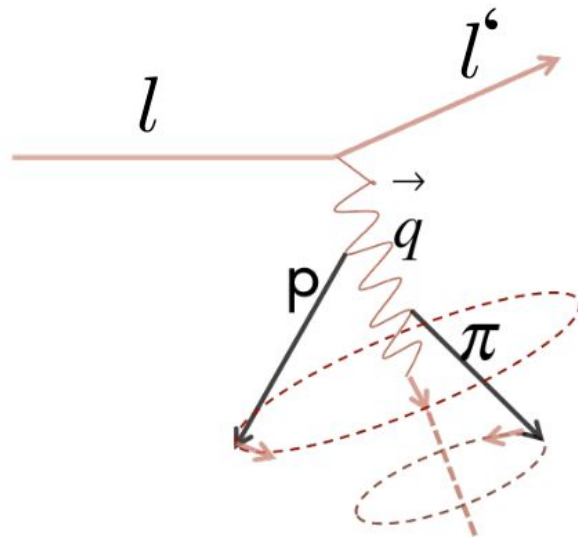
Non-($e,e'p$) interactions lead to multi-hadron final states
Gaps can make them look like ($e,e'p$) events



Data Driven Correction

Non-($e,e'p$) interactions lead to multi-hadron final states
Gaps make them look like ($e,e'p$) events

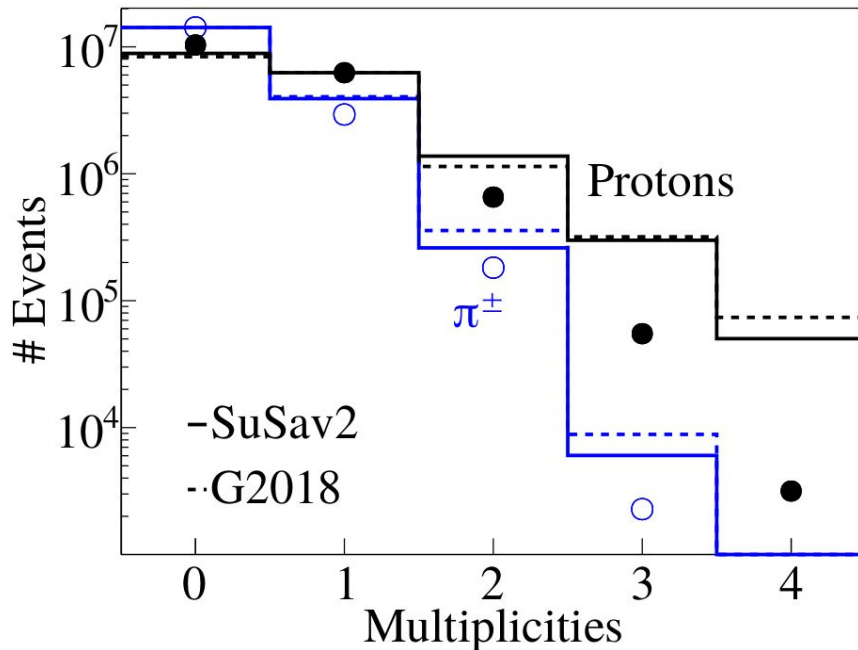
- Use measured ($e,e'p\pi$) events
- Rotate p , π around q to determine π detection efficiency
- Subtract undetected ($e,e'p\pi$)
- Repeat for higher hadron multiplicities



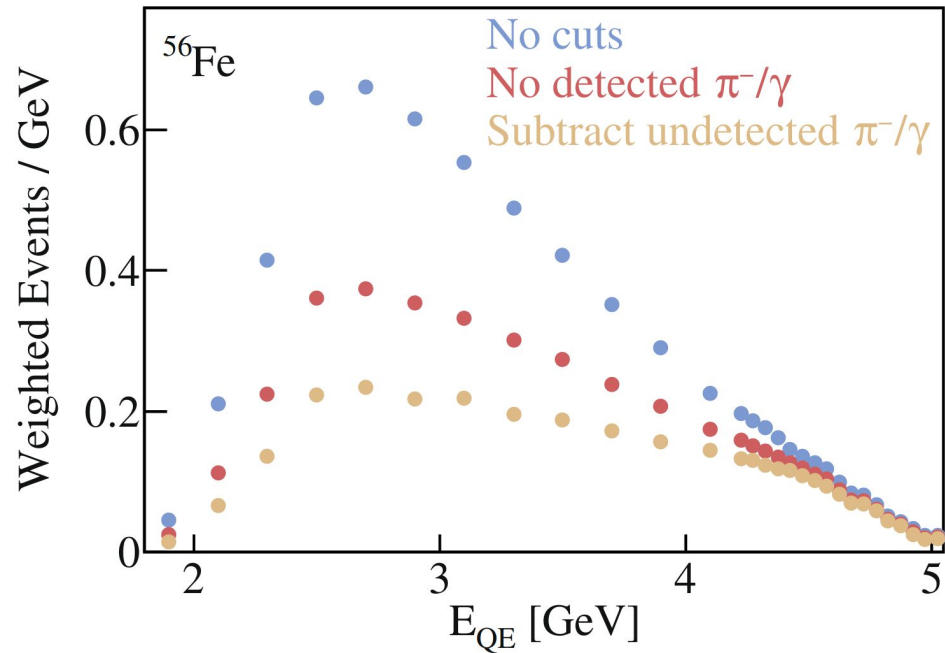
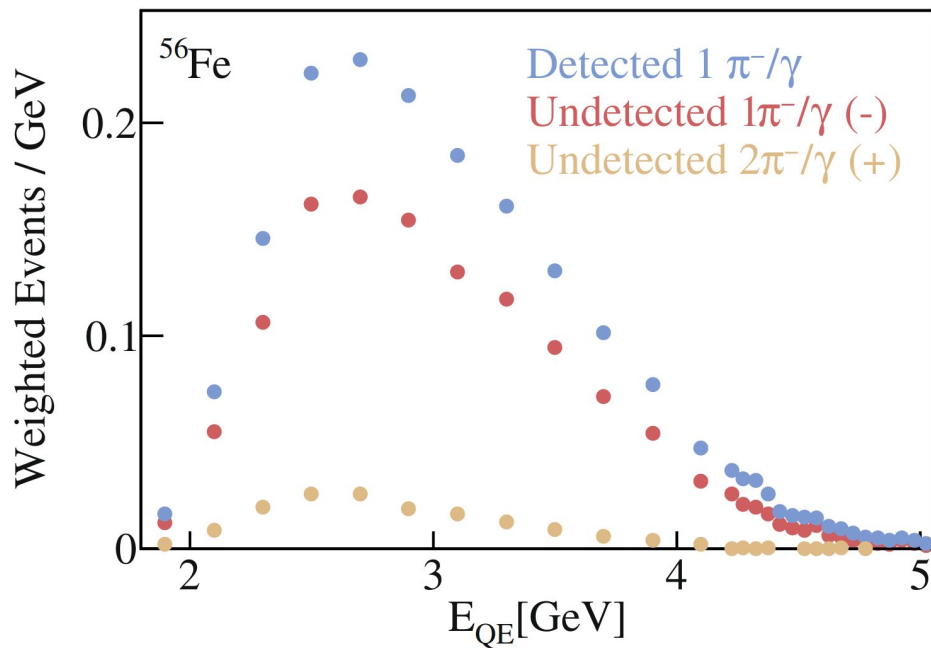
Data Driven Correction

Non-($e,e'p$) interactions lead to multi-hadron final states
Gaps can make them look like ($e,e'p$) events

- Use measured ($e,e'p\pi$) events
- Rotate p , π around q to determine π detection efficiency
- Subtract for undetected ($e,e'p\pi$)
- Repeat for higher hadron multiplicities
($2p$, $3p$, $2p+1\pi$, ...)

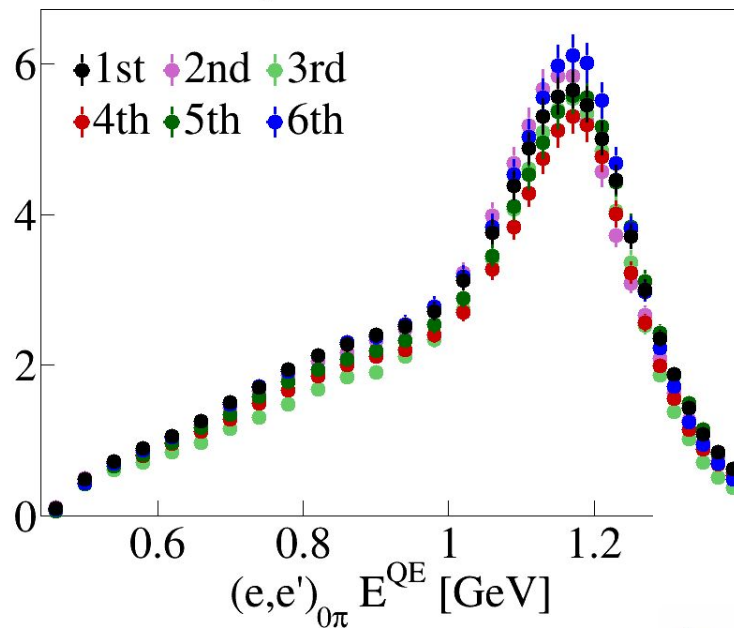


Subtraction Effect

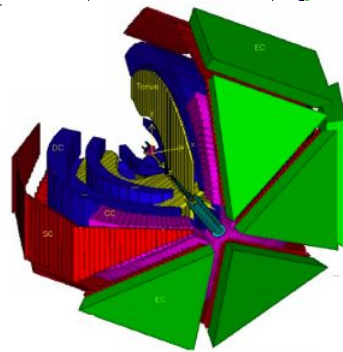
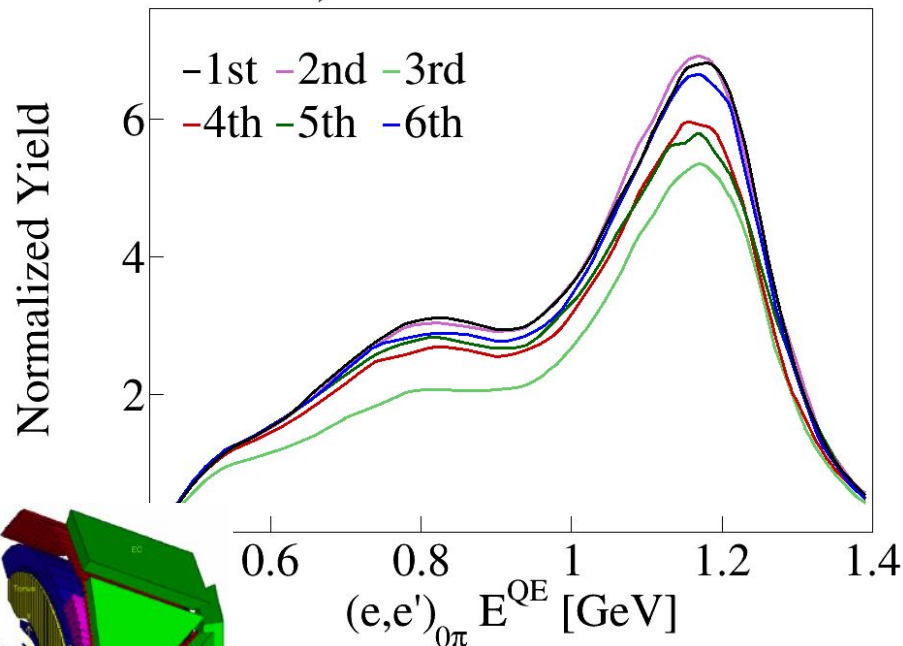


Systematics: Sector Dependence

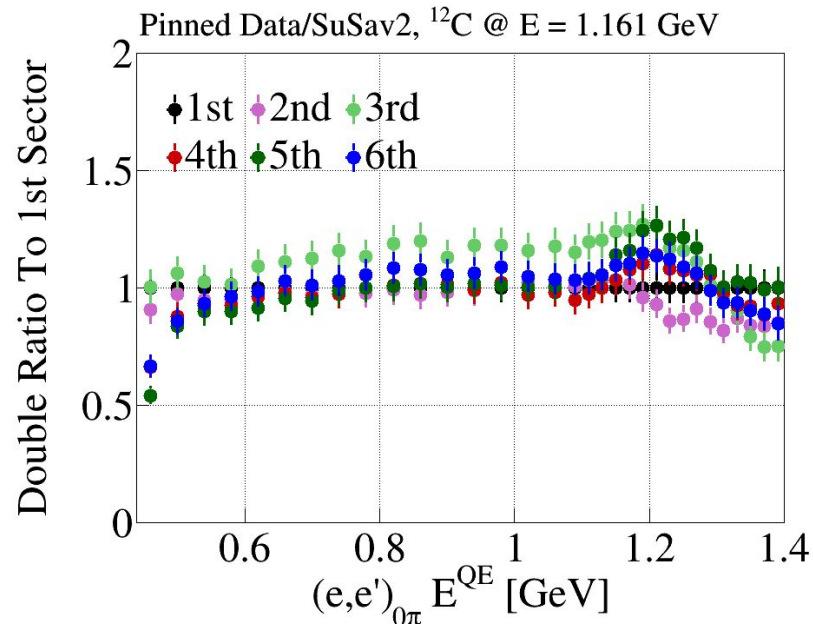
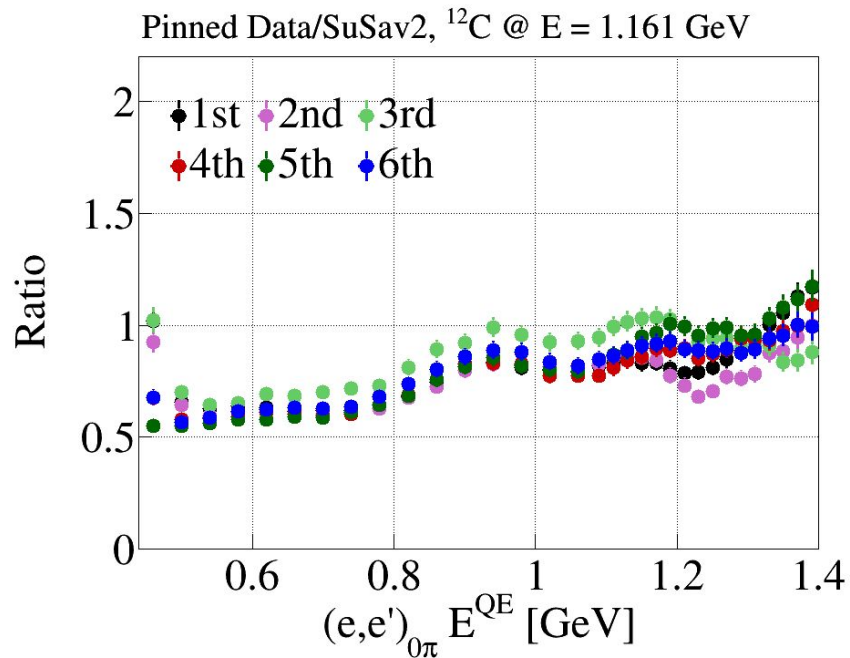
Pinned Data, ^{12}C @ $E = 1.161$ GeV



SuSav2, ^{12}C @ $E = 1.161$ GeV

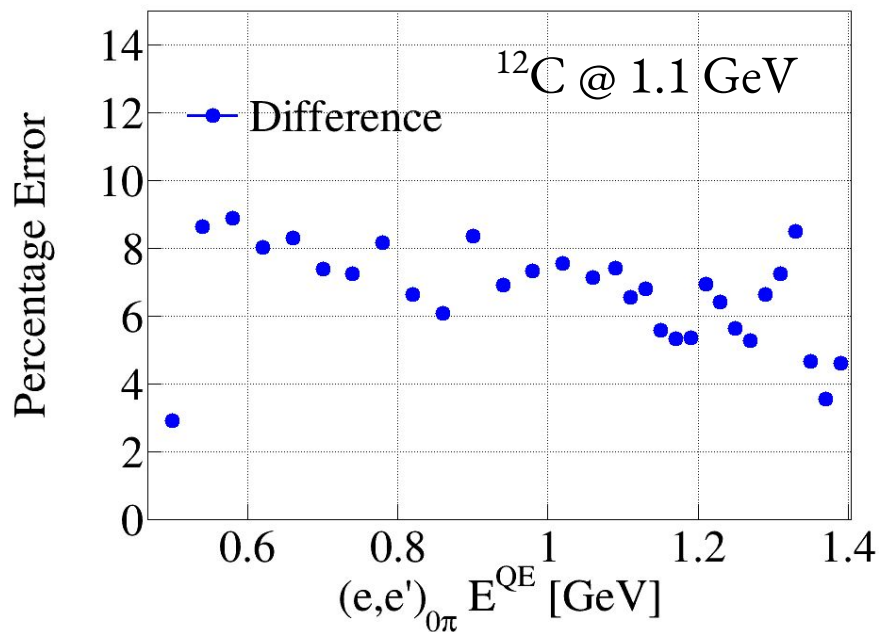


Systematics: Sector Dependence



Systematics: Sector Dependence

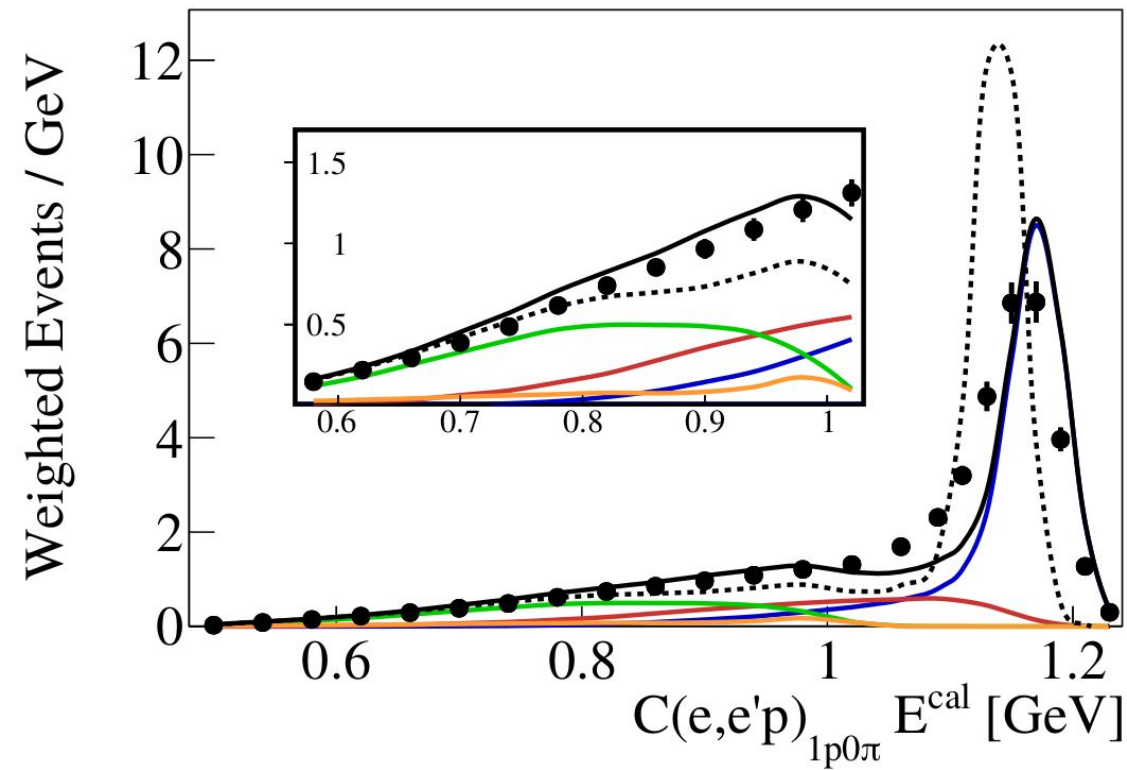
Quantifying uncertainty by using unweighted variance & by subtracting variance from statistical uncertainty



- Playing this game across all nuclei & energies
- Division by $\sqrt{N}_{\text{sectors}}$
- Flat uncertainty of 6%

1st $e4\nu$ Submission

Calorimetric energy reconstruction using the $1p0\pi$ channel



- Area normalized results
- No information with respect to absolute scale
- G2018 offset potentially due to binding energy issue

• Data

— SuSav2 (Total)

— QE — MEC

— RES — DIS

-- G2018

Step #2: Normalized Yield

Data

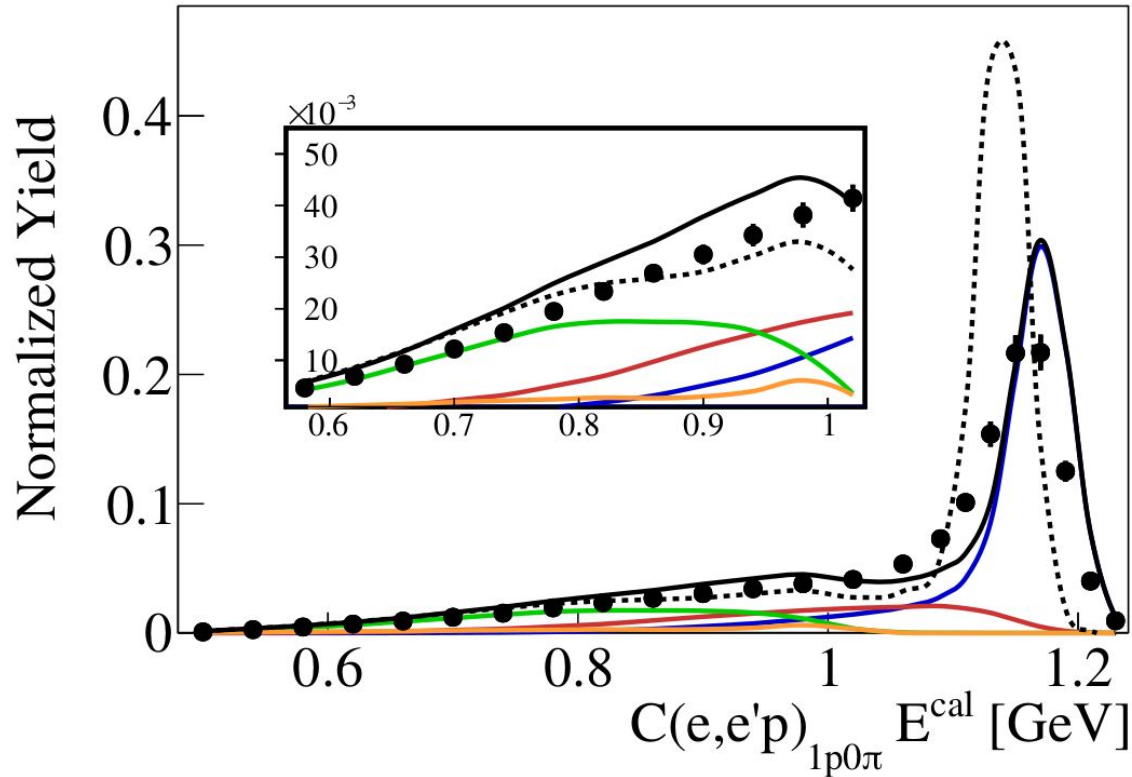
- Divide # events by integrated charge & target thickness to get xsec in μb
- Divide by bin width to get $\mu\text{b}/\text{GeV}$

Simulation

- Get GENIE total cross section for E_e / target A & $Q_2 > Q_{2\text{min}}$
- $\text{xsec} = (\text{Selected detected events} / \text{all generated events}) * \text{total xsec} / \text{bin width}$

No corrections for CLAS acceptance or for bremsstrahlung radiation

Step #2: Normalized Yield



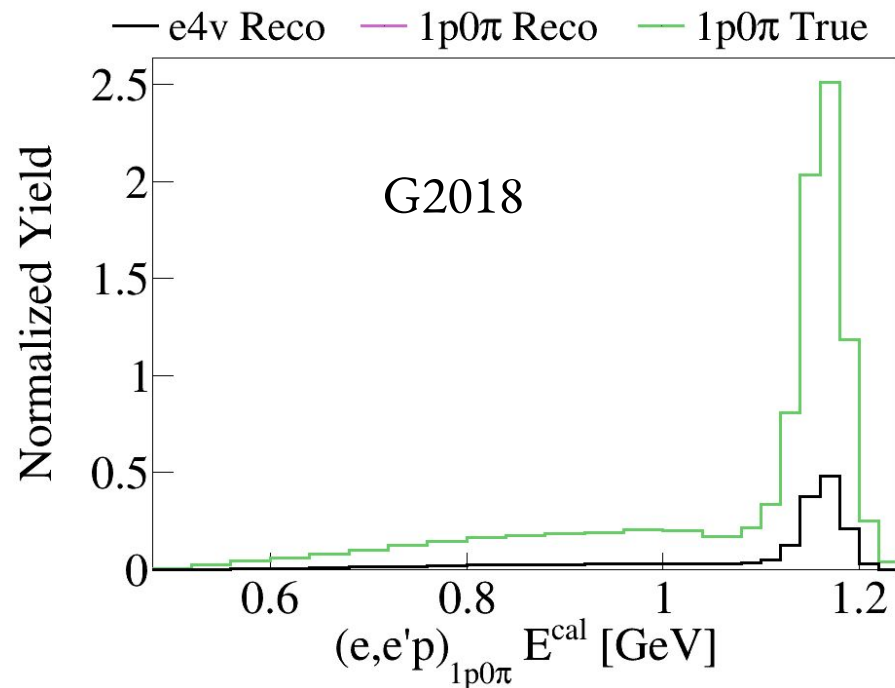
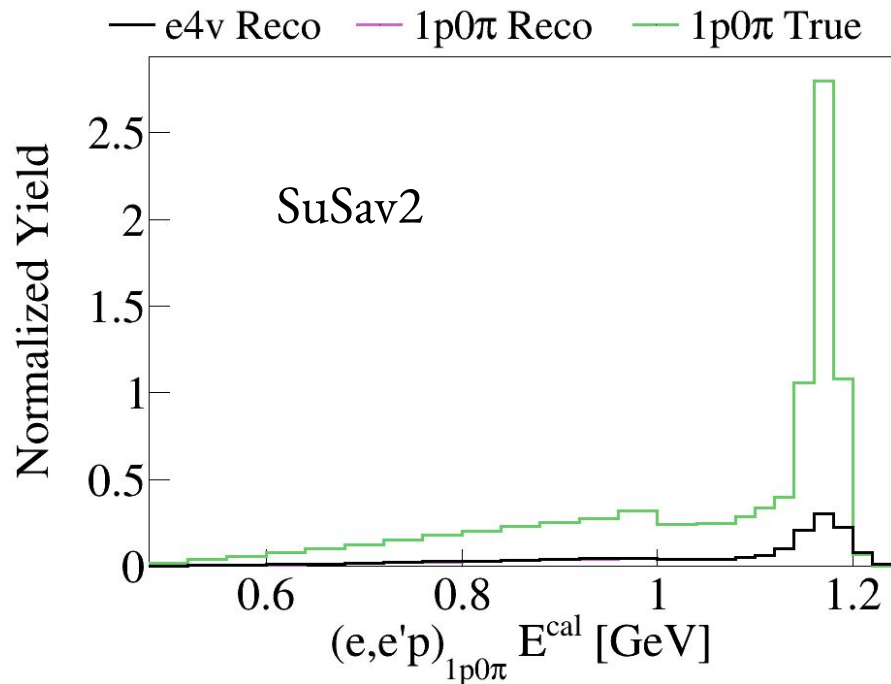
- Absolute scale comparison
- Small effect @ 1GeV

• Data
— SuSav2 (Total)
— QE — MEC
— RES — DIS
-- G2018

Step #3a: Acceptance Correction

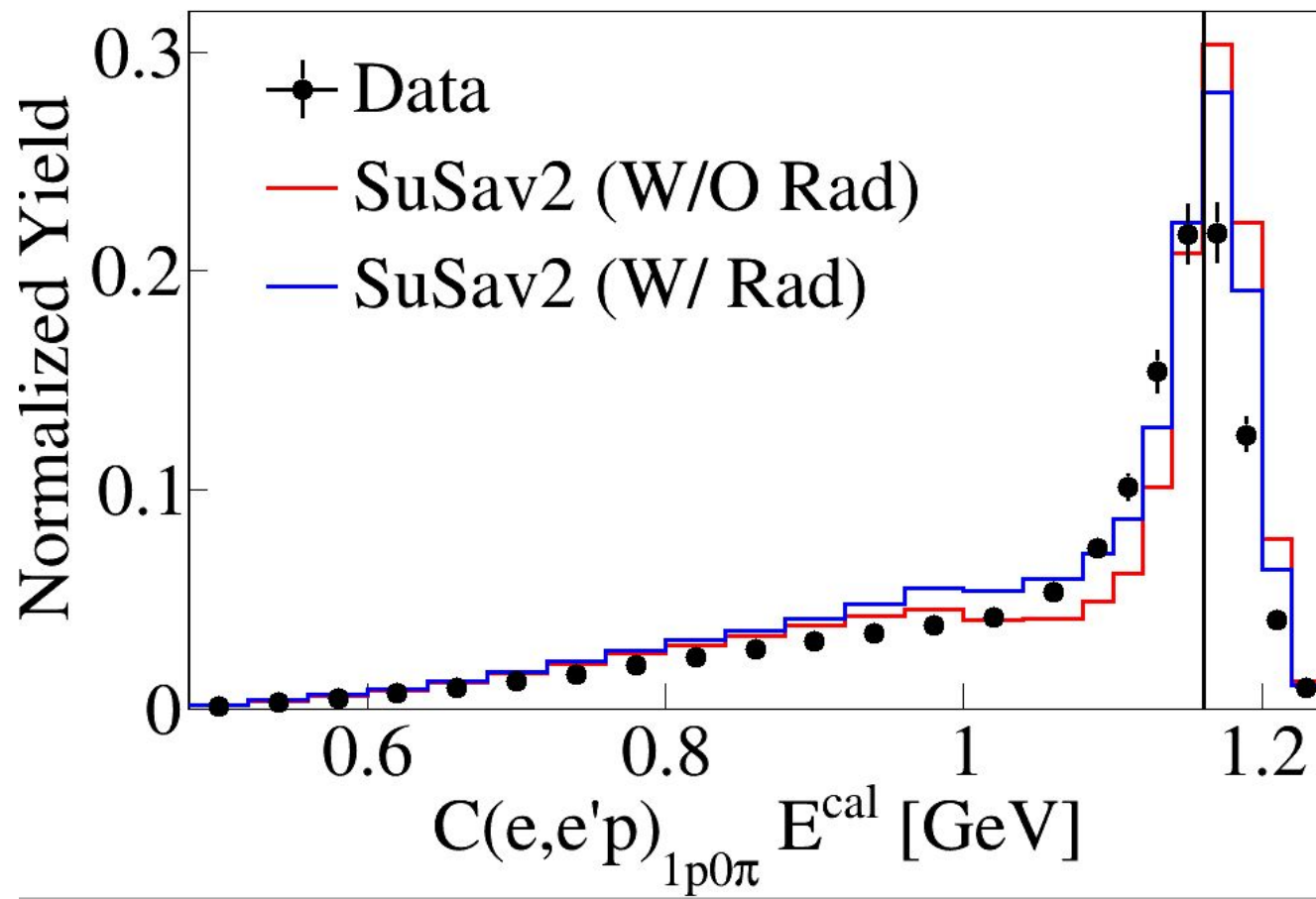
- Start from reco / true ratio w/o radiation to obtain acceptance correction
- Average on a bin-by-bin basis $x = |\text{SuSav2} + \text{G2018}| / 2$
- Due to offset, G2018 Ecal predictions have been shifted by
10/25/36 MeV for $^4\text{He}/^{12}\text{C}/^{56}\text{Fe}$ respectively

Step #3a: Example 12C @ 1.1 GeV



Use reco / true ratio to obtain acceptance correction

Step #3b: Radiation Correction



Use ratio of red / blue
to correct for radiation

Averaged Acceptance Correction Uncertainty Over True Beam Energy

On a bin-by-bin basis

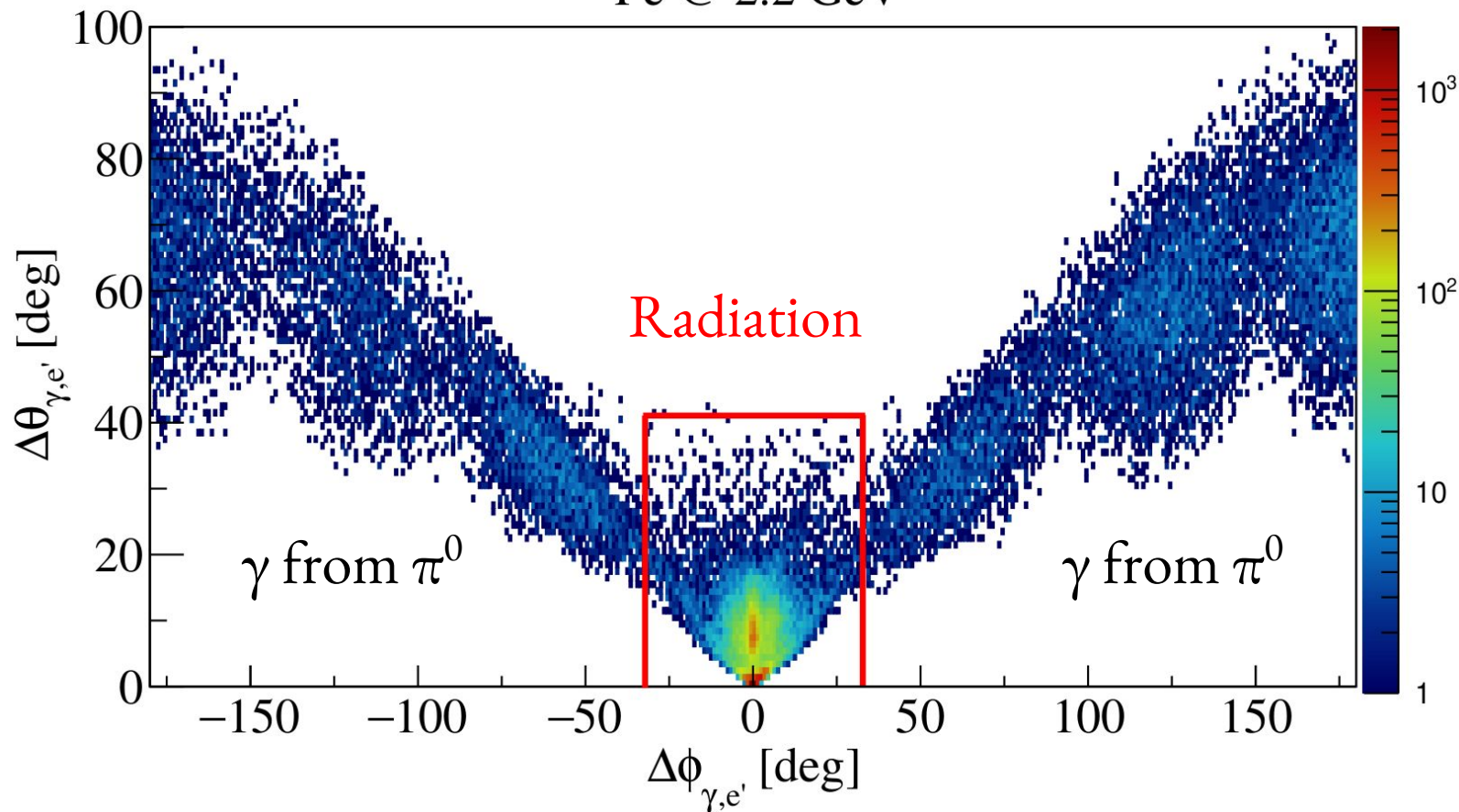
$$x = |\text{SuSav2} - \text{G2018}| / \text{Sqrt}(12)$$

$$\text{Bin Entry} = x / \text{Average} * 100 \%$$

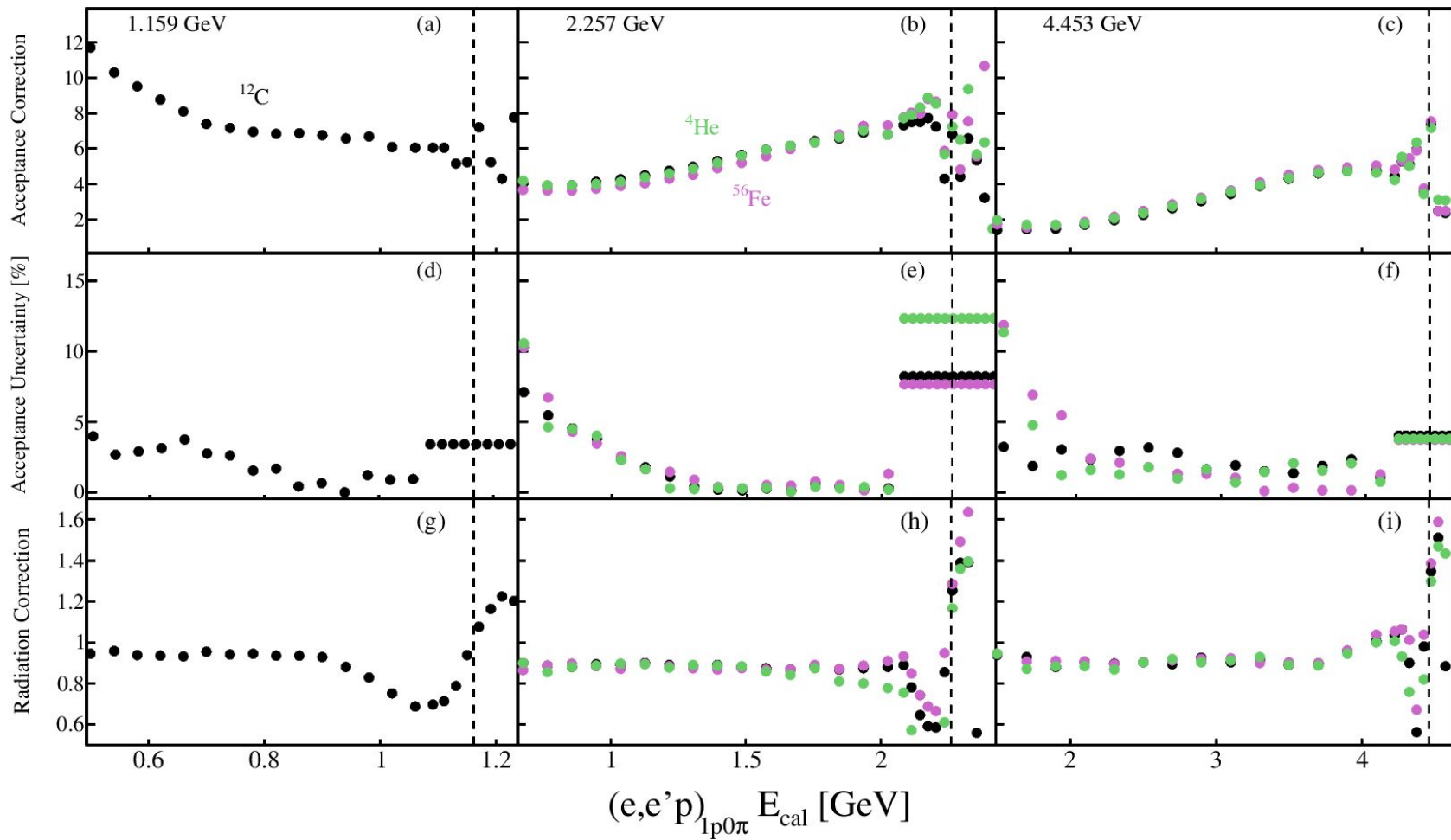
Same recipe as for acceptance correction but,
to avoid infinities, will use average (1 bin) around the peak and
 $\text{average}(\text{reco}) / \text{average}(\text{true})$ for correction factor

Excluding Radiation

^{56}Fe @ 2.2 GeV

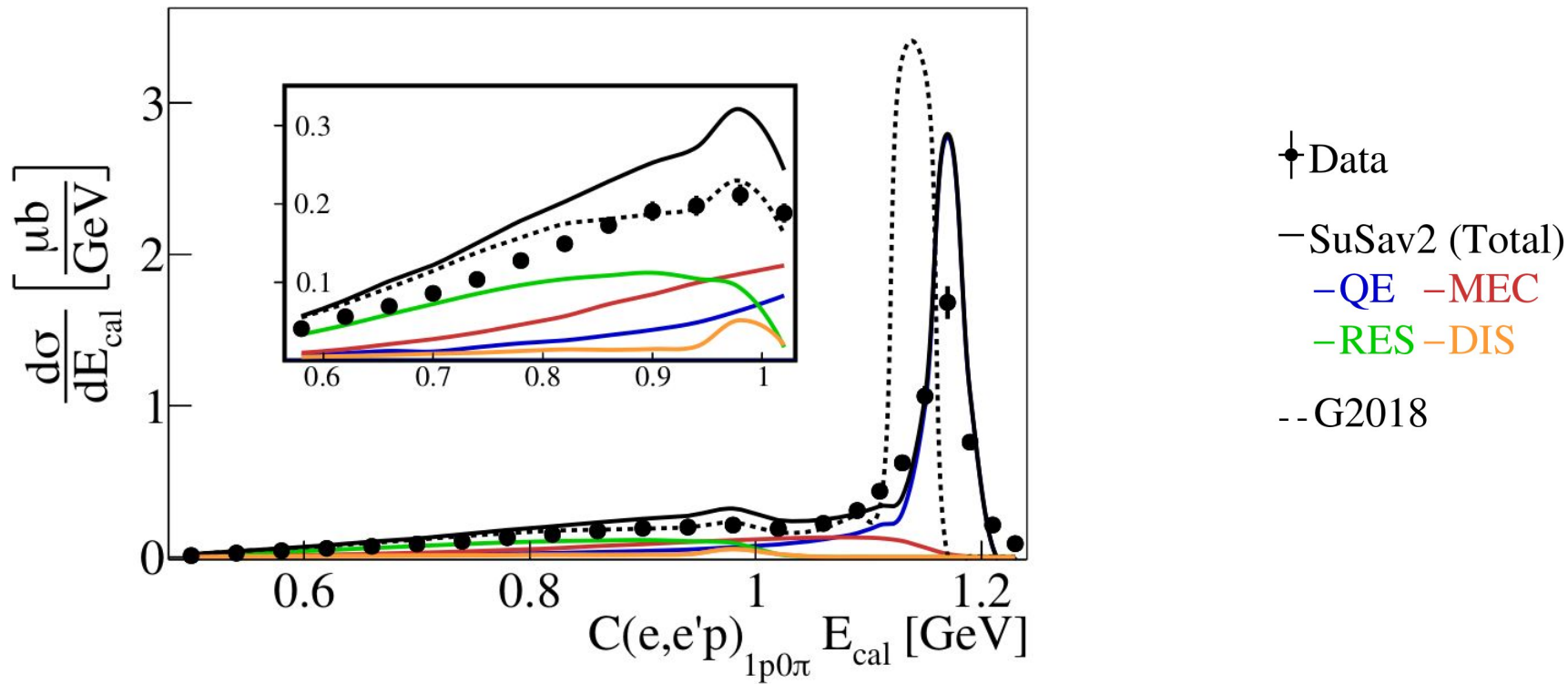


Correction Factors



Step #4: Absolute Cross Sections

After both acceptance & radiation corrections, without systematics yet



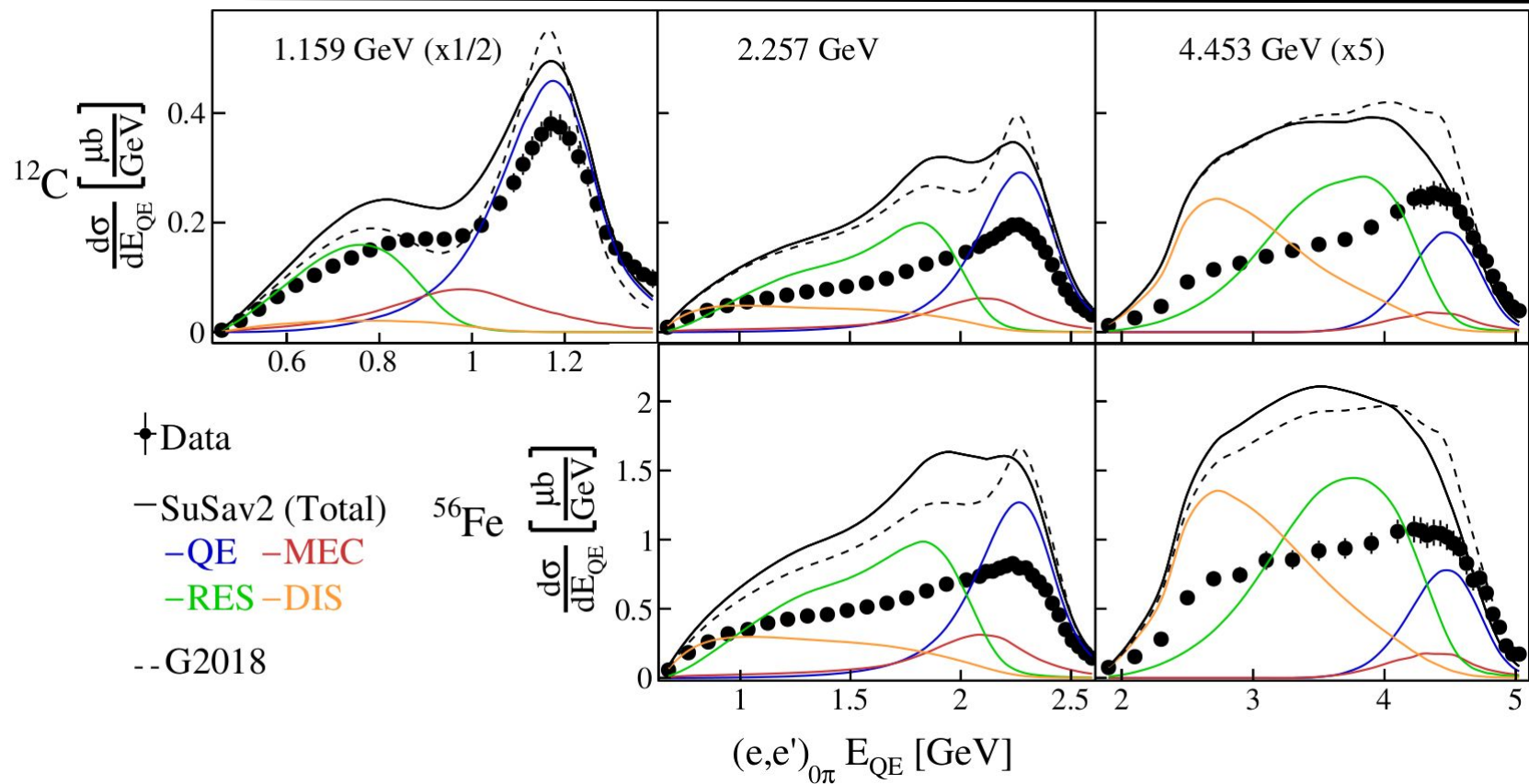
Systematics

Source	Uncertainty (%)
Detector acceptance Identification cuts $\phi_{q\pi}$ cross section dependence Number of rotations	2,2.1,4.7 (@ 1.1,2.2,4.4 GeV)
Sector dependence	6
Acceptance correction	2-15
Overall normalization	3
Electron inefficiency	2

Energy Reconstruction Accuracy

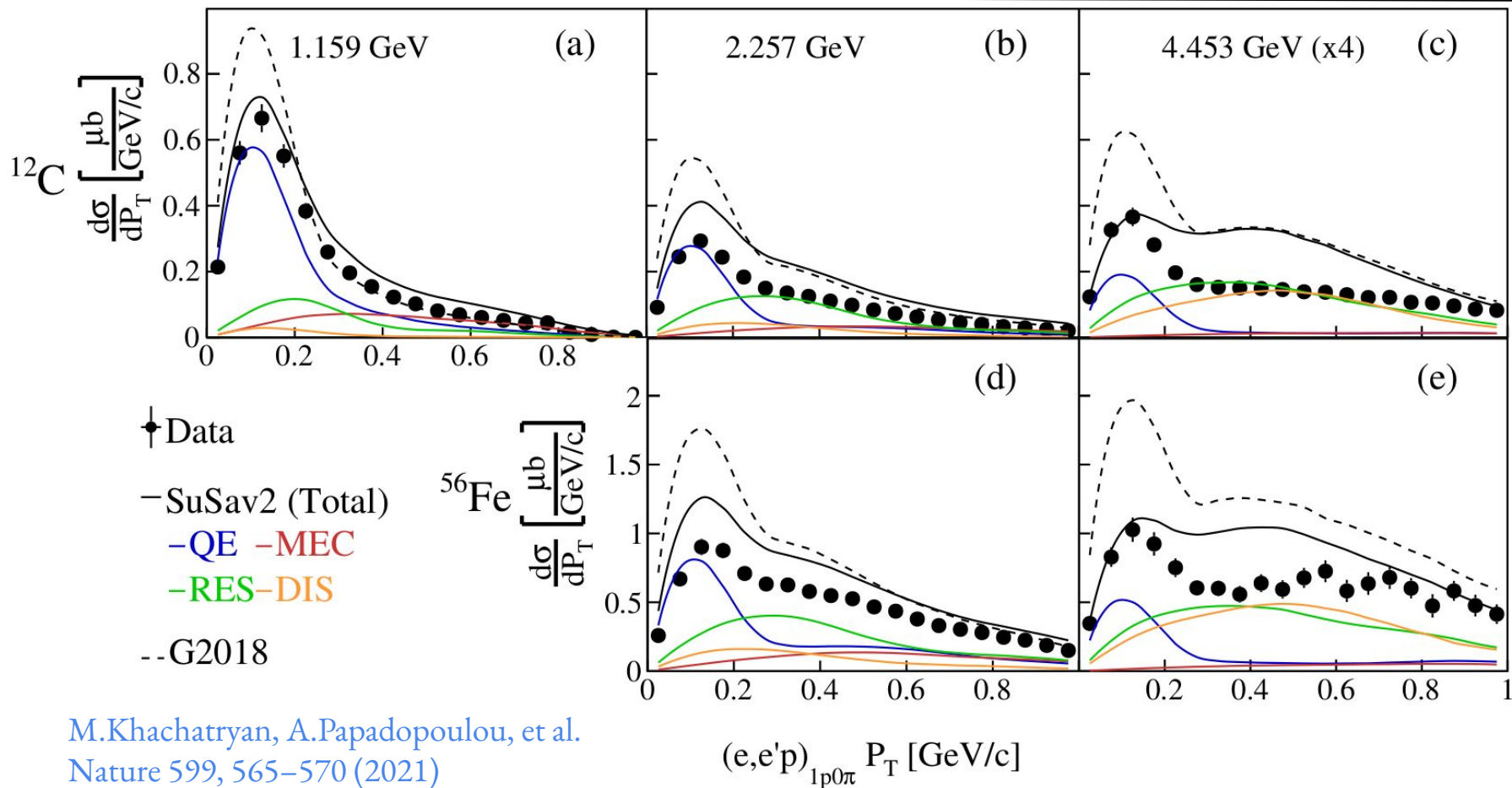
		1.159 GeV		2.257 GeV		4.453 GeV	
		Peak	Peak	Peak	Peak	Peak	Peak
		Fraction	Sum [μb]	Fraction	Sum [μb]	Fraction	Sum [μb]
^4He	Data	-	-	41	0.48	38	0.15
	SuSAv2	-	-	45	1.31	22	0.14
	G2018	-	-	39	0.93	24	0.16
^{12}C	Data	39	4.13	31	1.26	32	0.34
	SuSAv2	44	5.33	27	1.76	12	0.20
	G2018	51	6.53	37	2.44	23	0.43
^{56}Fe	Data	-	-	20	3.73	23	1.01
	SuSAv2	-	-	21	5.28	10	0.58
	G2018	-	-	30	8.22	19	1.48

E_{QE} Nucleus & Energy Dependence



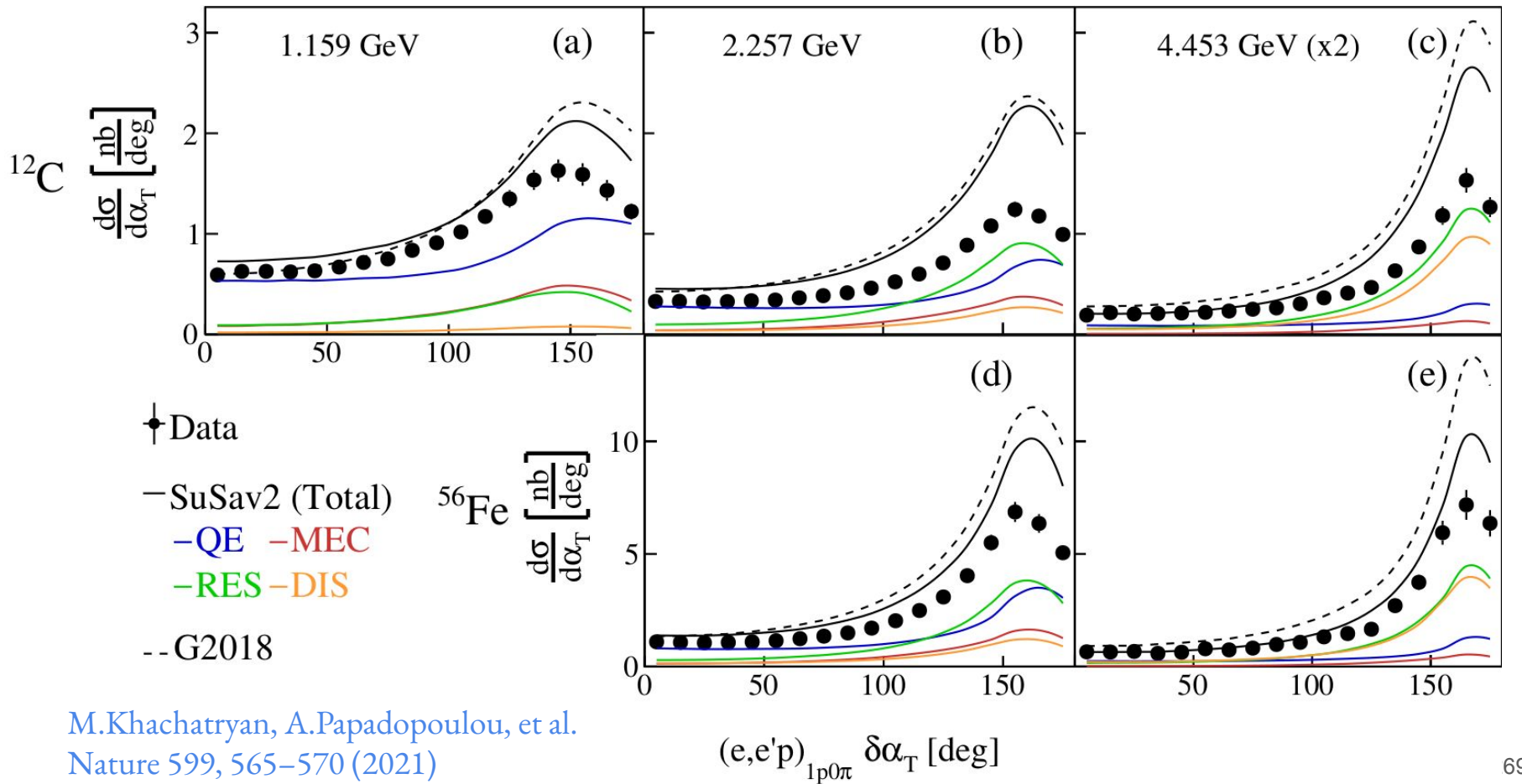
$$E_{QE} = \frac{2M\epsilon + 2ME_l - m_l^2}{2(M - E_l + |k_l|\cos\theta_l)}$$

P_T Nucleus & Energy Dependence



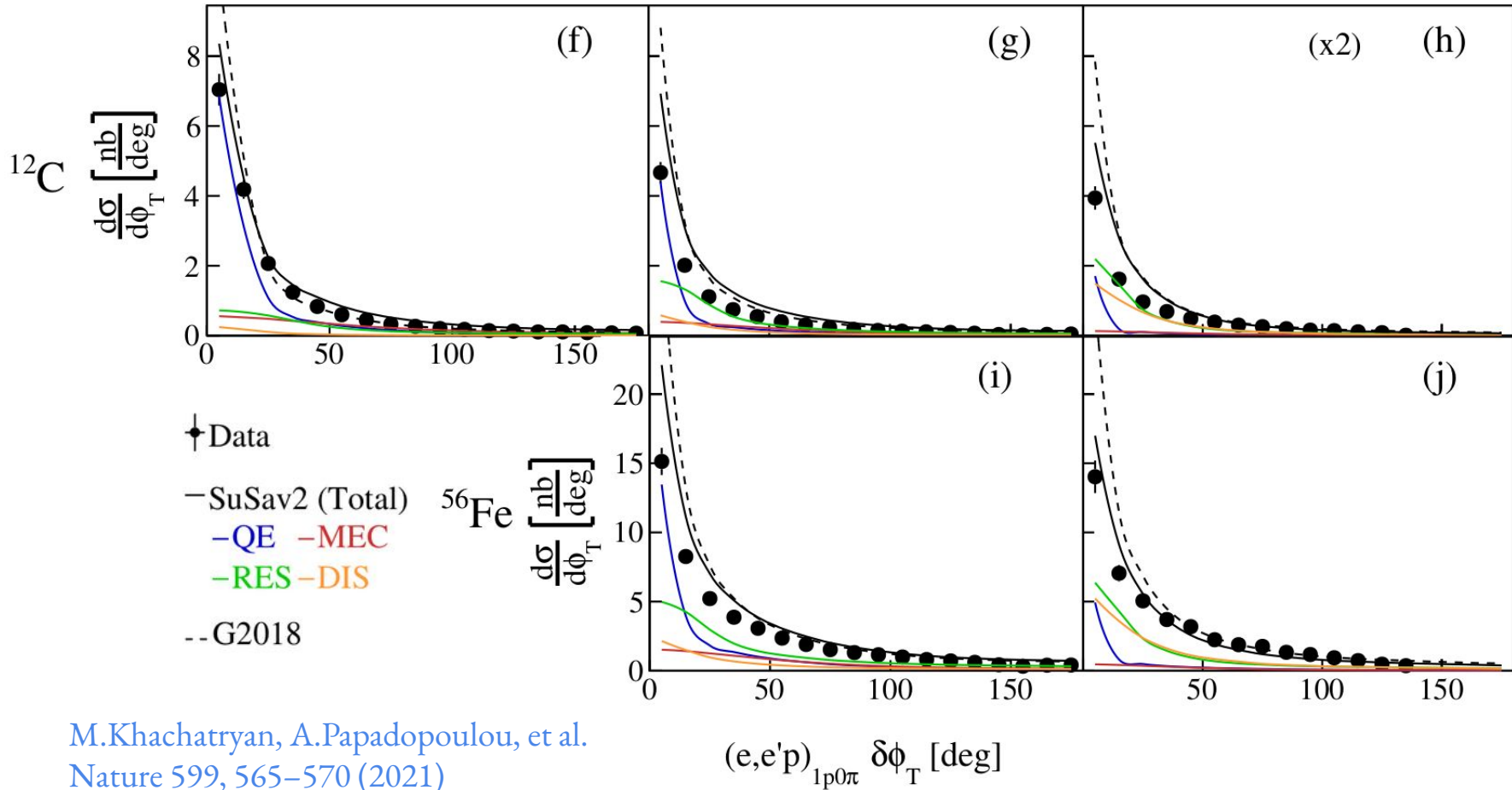
M.Khachatryan, A.Papadopoulou, et al.
 Nature 599, 565–570 (2021)

$\delta\alpha_T$ Nucleus & Energy Dependence



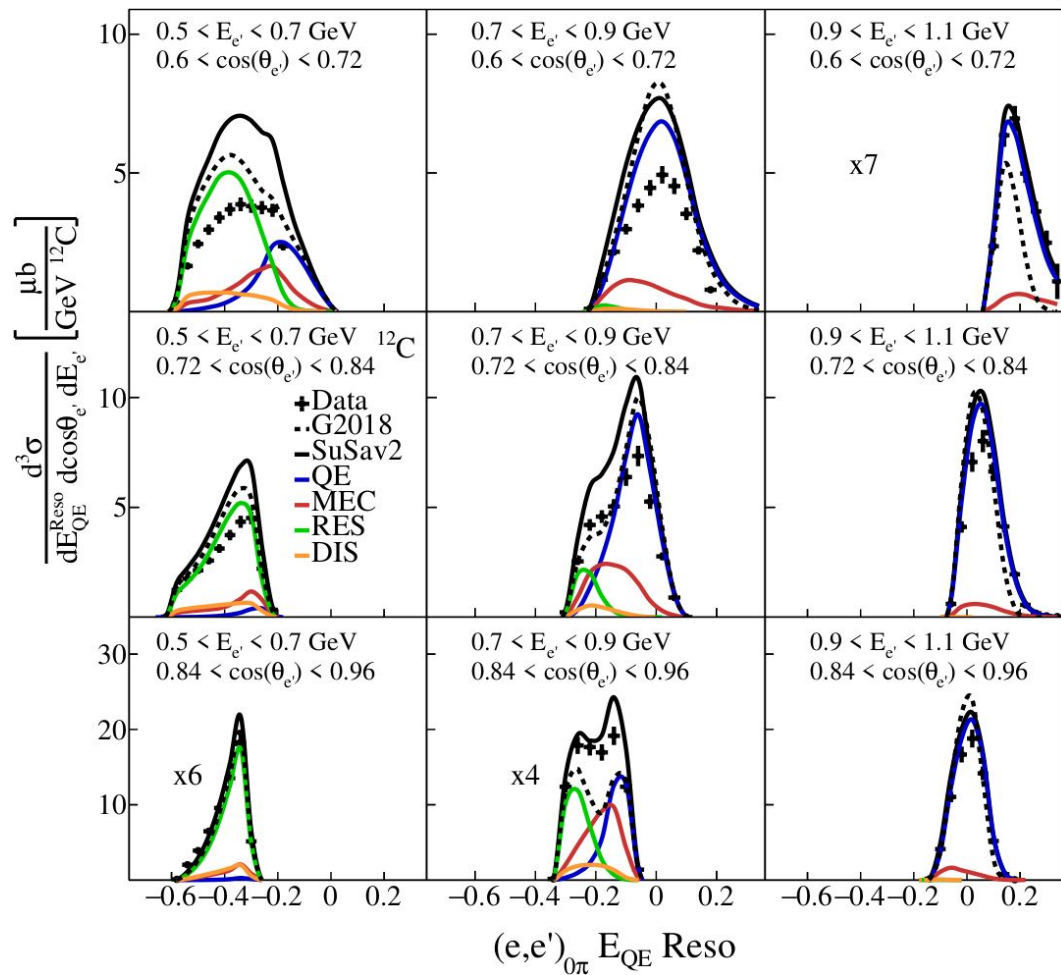
M.Khachatryan, A.Papadopoulou, et al.
 Nature 599, 565–570 (2021)

$\delta\phi_T$ Nucleus & Energy Dependence



M.Khachatryan, A.Papadopoulou, et al.
 Nature 599, 565–570 (2021)

Into The 3D $e4\nu$ Multiverse!

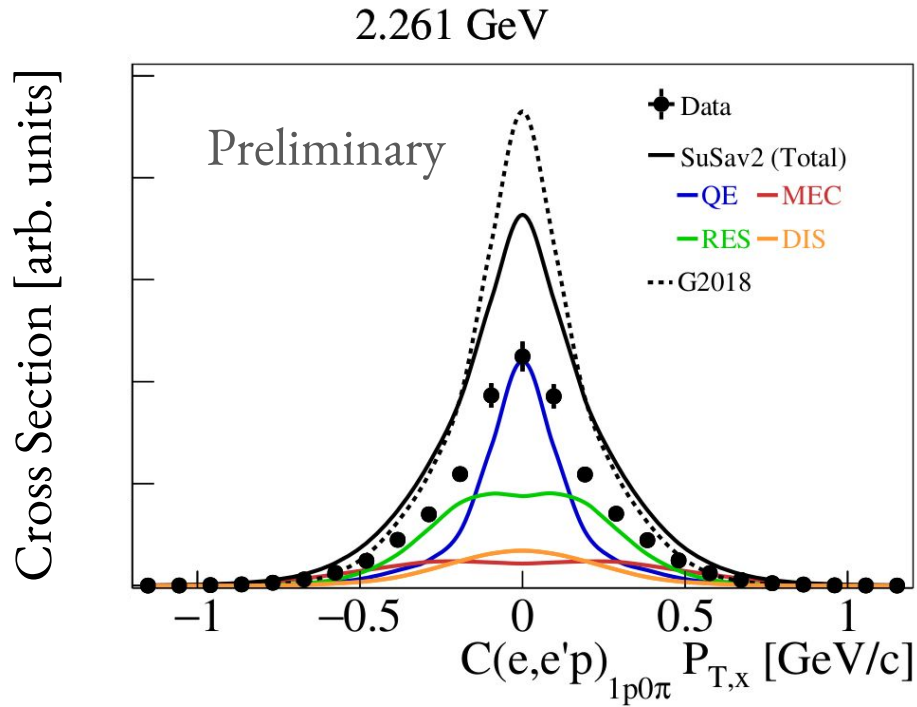


A.Papadopoulou, et al,
In preparation

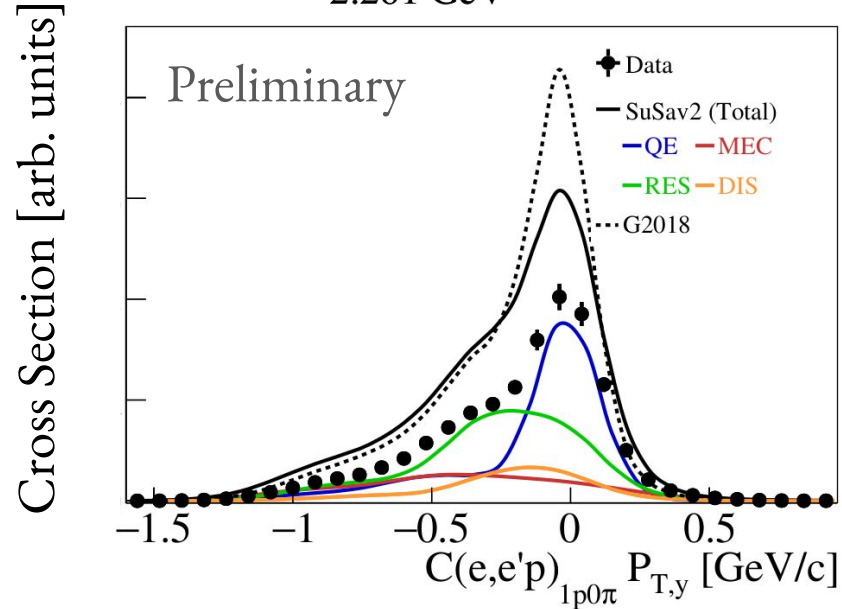
Nuclear Sensitivity Variables

$$\delta p_{T_x} = (\hat{p}_v \times \hat{p}_T^l) \cdot \delta \vec{p}_T = |\delta \vec{p}_T| \sin(\delta \alpha_T)$$

Sensitivity to Fermi motion



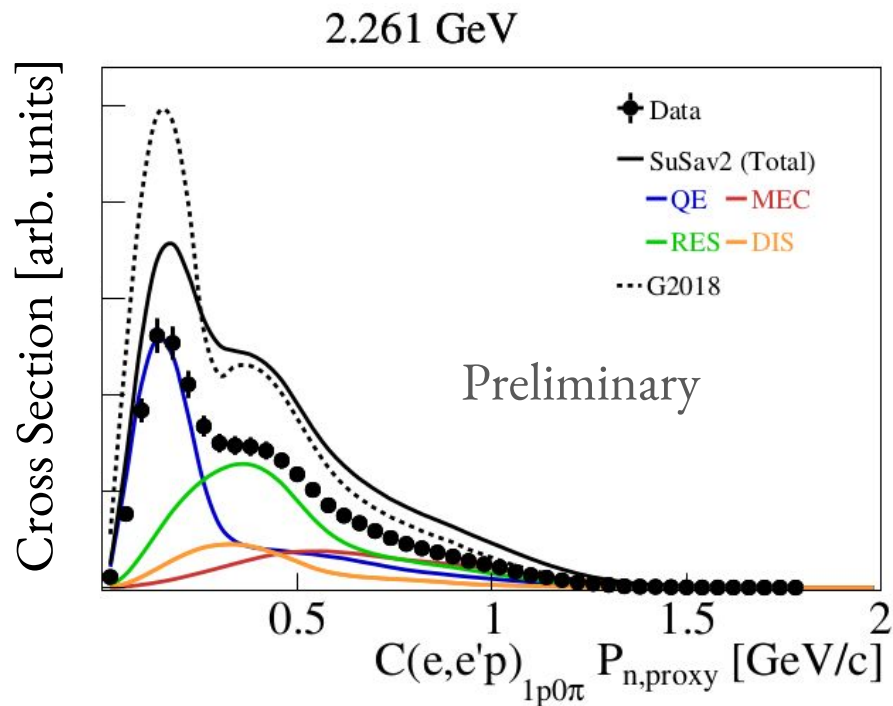
2.261 GeV



$$\delta p_{T_y} = -\hat{p}_T^l \cdot \delta \vec{p}_T = |\delta \vec{p}_T| \cos(\delta \alpha_T)$$

Sensitivity to final state interactions

Missing Momentum Approximation



$$P_{n,proxy} = \sqrt{\delta p_L^2 + \delta p_T^2}$$

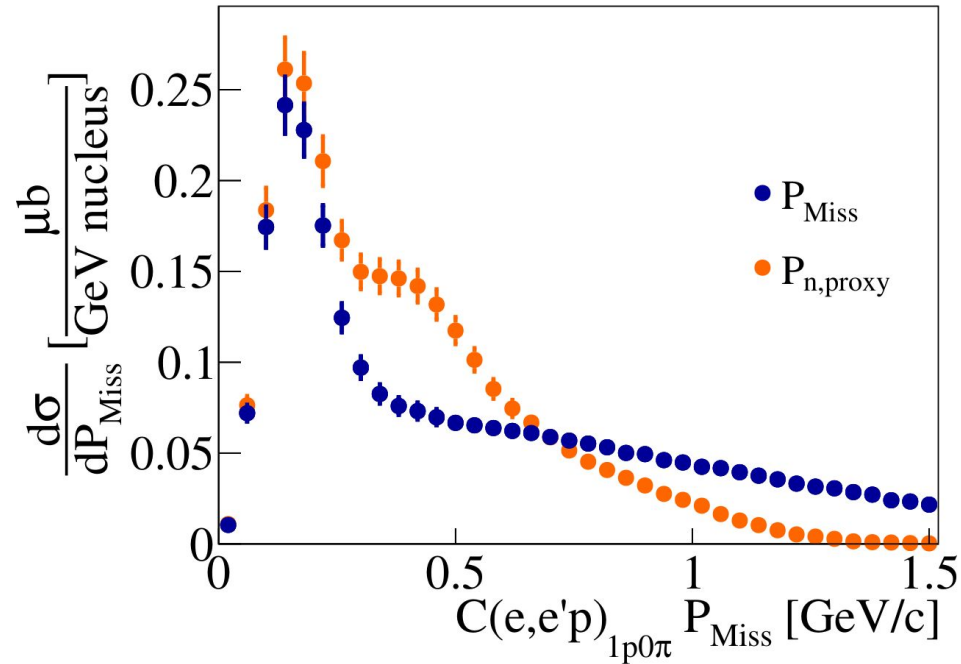
Under QE assumption

[Phys. Rev. Lett. 121, 022504 \(2018\)](#)

[A.Papadopoulou, et al, In preparation](#)

Fails To Reproduce True Missing Momentum

2.261 GeV



A.Papadopoulou, et al, In preparation

$$P_{\text{n,proxy}} = \sqrt{\delta p_{\text{L}}^2 + \delta p_{\text{T}}^2}$$

Under QE assumption

[Phys. Rev. Lett. 121, 022504 \(2018\)](#)

True missing momentum

$$P_{\text{miss}} = |p - q|$$

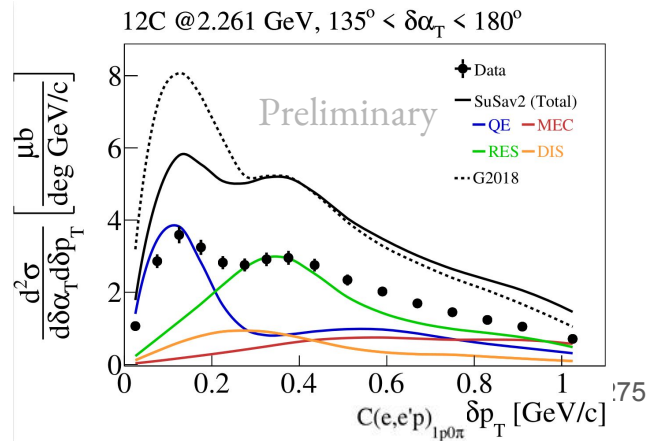
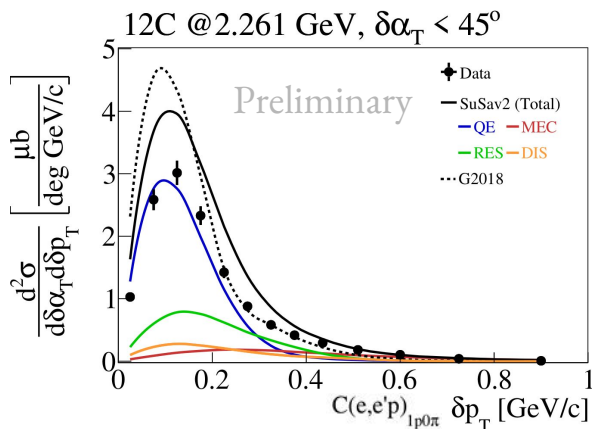
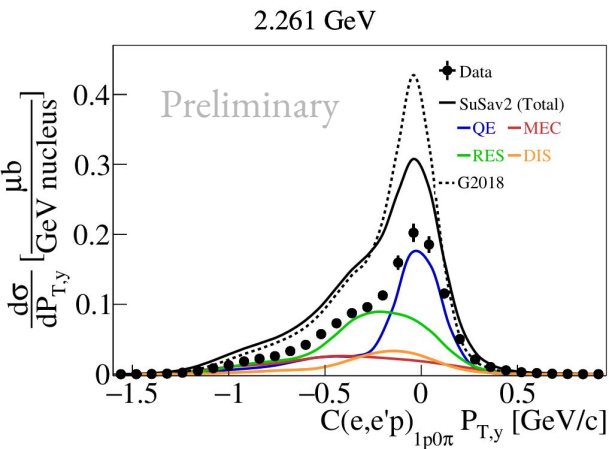
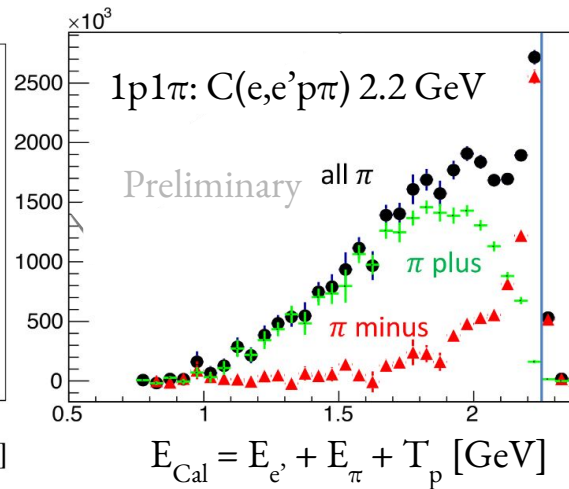
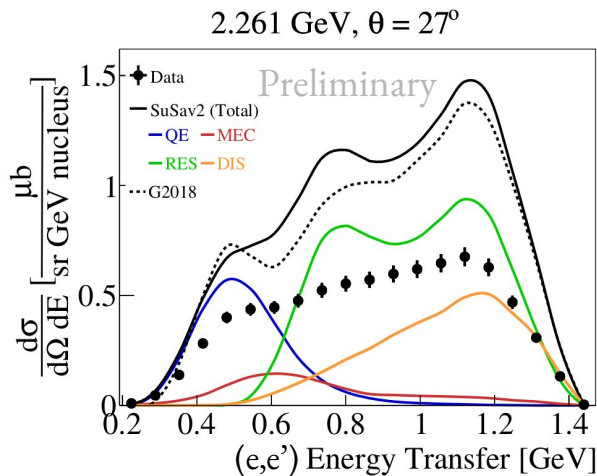
p = proton 3-vector

q = momentum transfer

The $e4\nu$ Result Factory Continued!

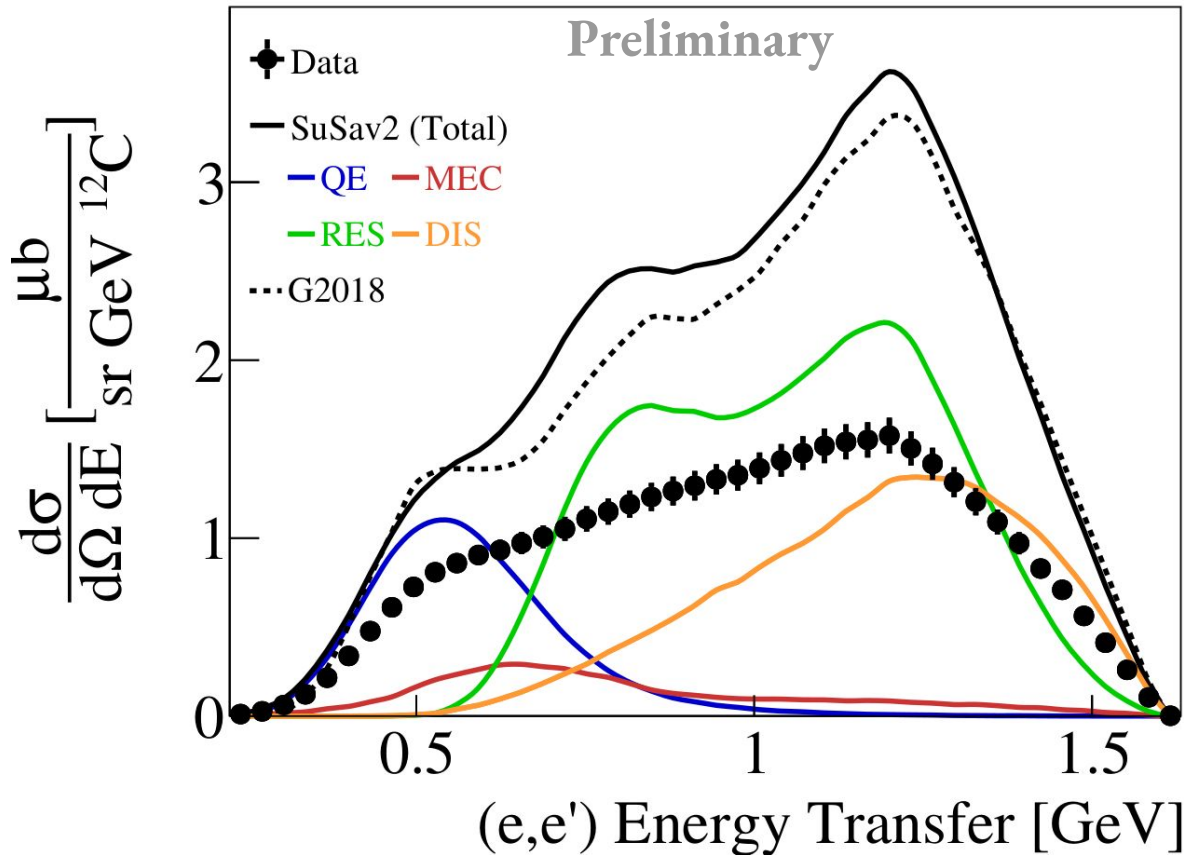
- More inclusive results
- More complex channels
- Nuclear sensitivity variables
- Multi-differential results

$e4\nu$ Collaboration, In preparation



Inclusive Results

2.261 GeV, $\theta = 28^\circ$



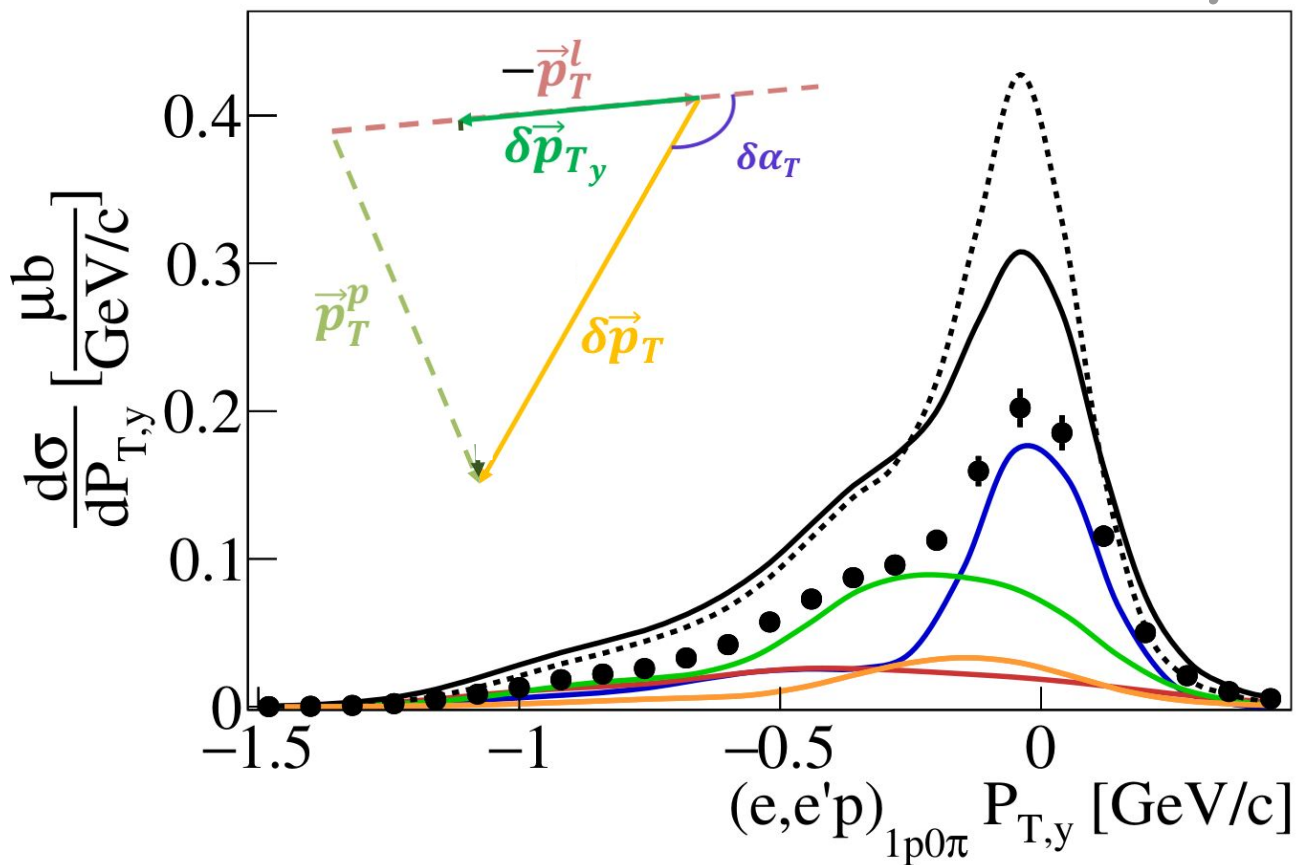
The $e4\nu$ Result Factory
Continued!

- Scan over multiple angles
- Results on Argon soon

$e4\nu$ Collaboration
In preparation

Nuclear Sensitivity Variables

12C @ 2.261 GeV Preliminary



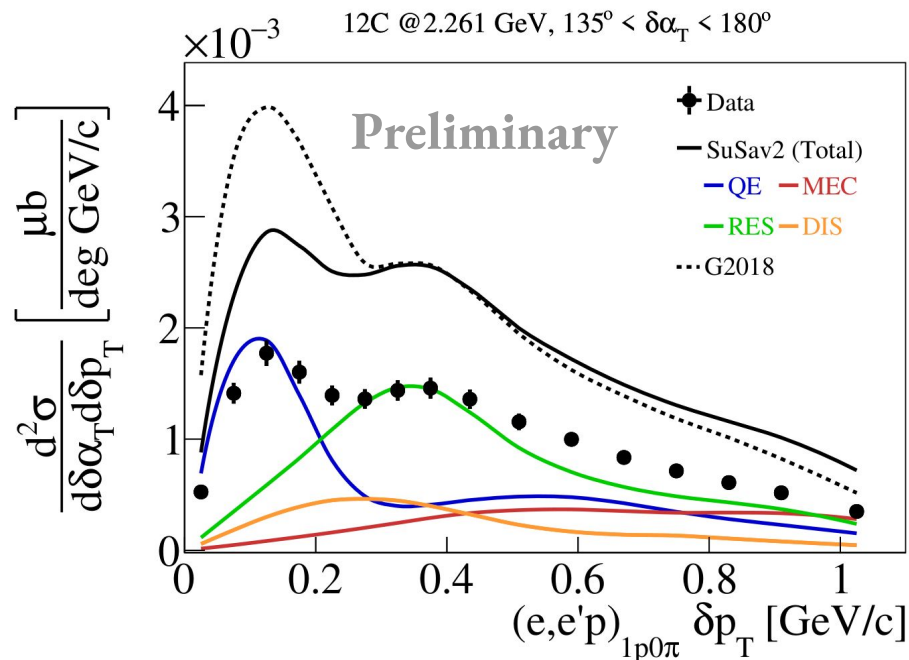
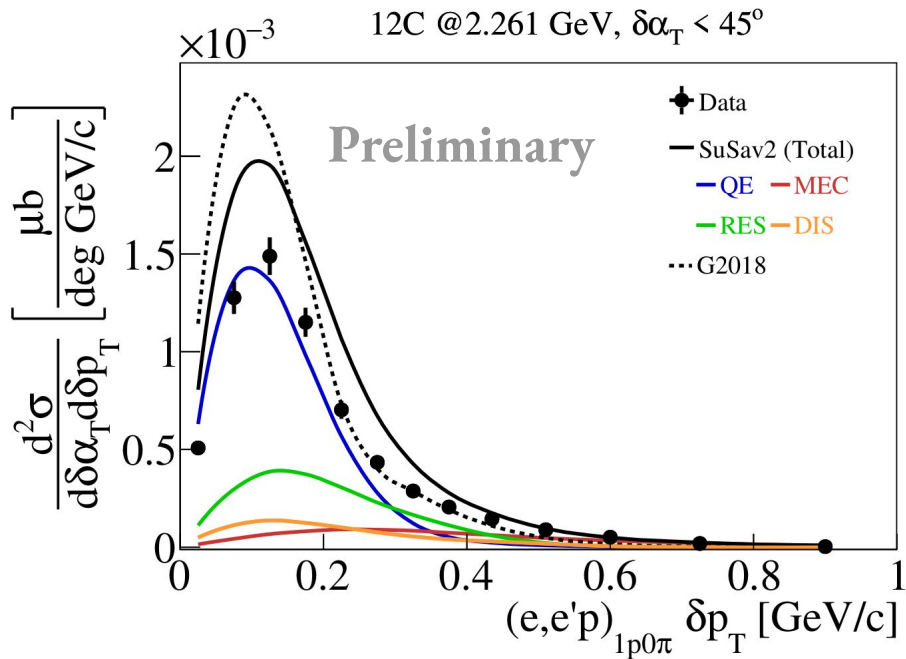
$$\delta p_{T,y} = -\hat{p}_T^l \cdot \delta \vec{p}_T = |\delta \vec{p}_T| \cos(\delta \alpha_T)$$

The $e4\nu$ Result Factory
Continued!

- Fermi motion
- Final state interactions (FSI)

e4ν Collaboration
In preparation

Double Differential Results



The $e4\nu$ Result Factory
Continued!

[e4ν Collaboration](#)
In preparation

- Handle over FSI / initial state effects
- Tuning potential