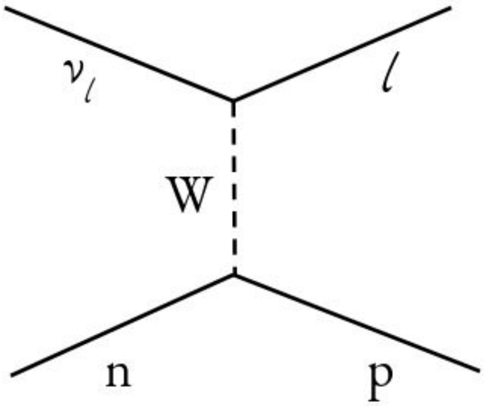
Lepton-Nucleus Scattering Measurements For Neutrino Interactions And Oscillations



Afroditi Papadopoulou

NOW 2022, Ostuni, Italy

Argonne NATIONAL LABORATORY

Attacking The Modeling Monster

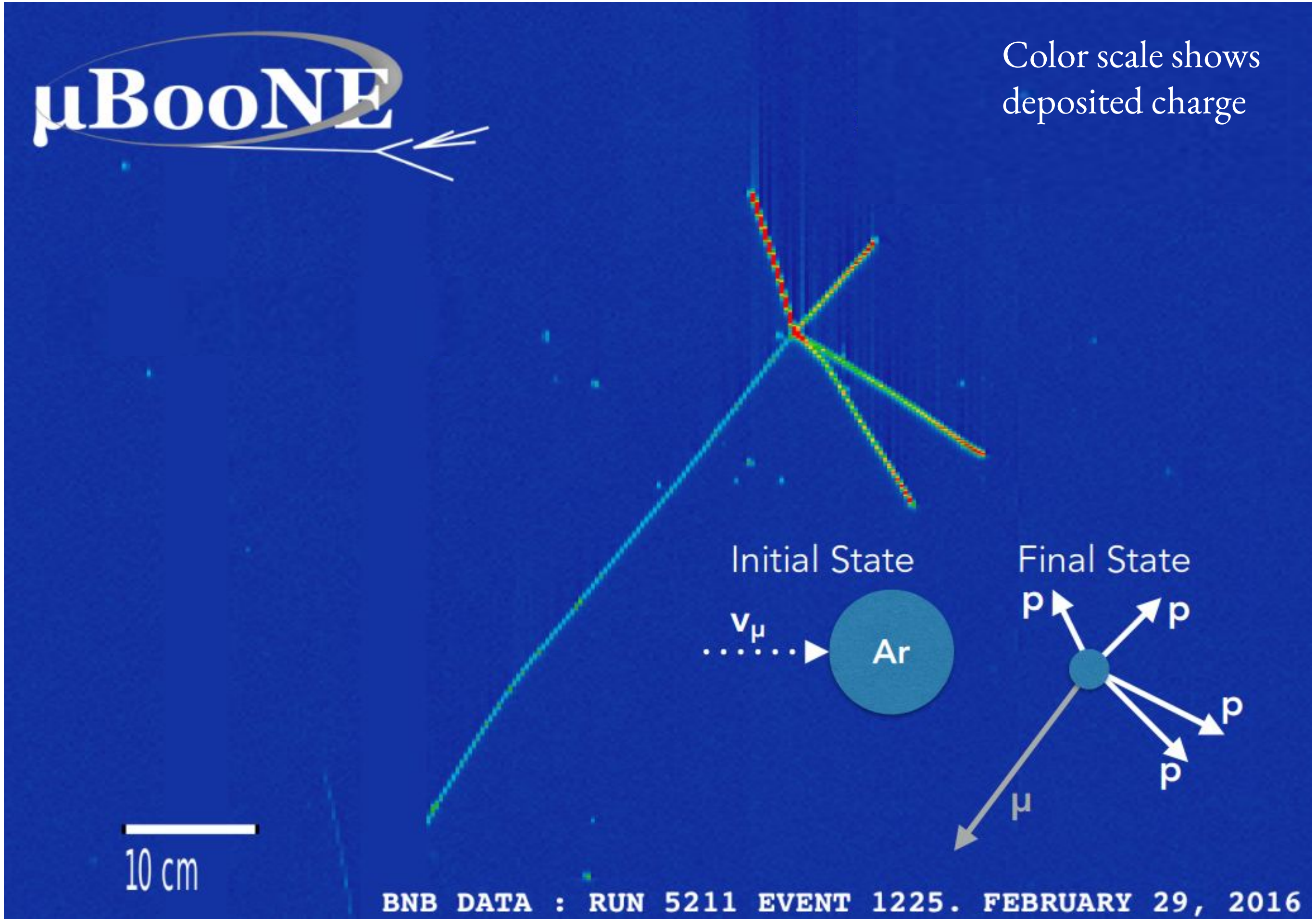
- Neutrino Cross Sections

- Event Generator Modeling

- Electron Cross Sections

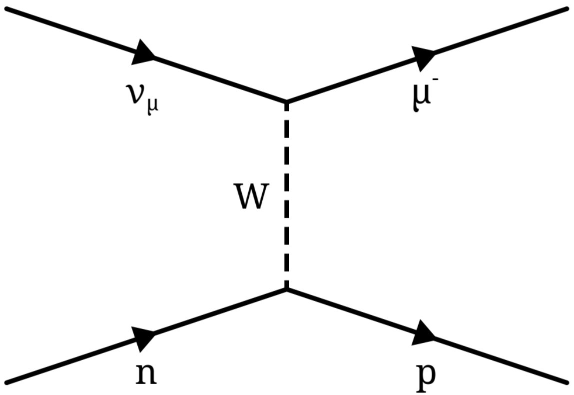
Also see Steven's talk

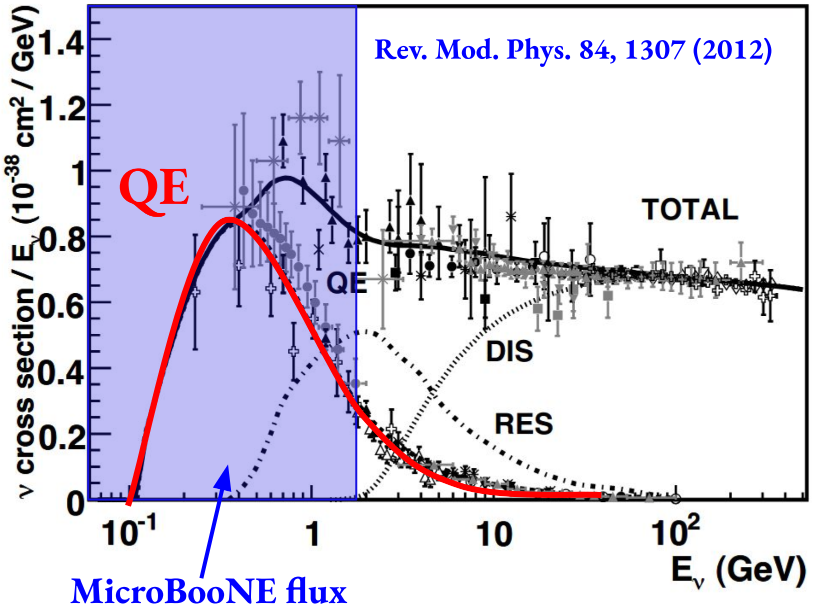
Neutrino Cross Sections



- Liquid Argon Time Projection Chamber (LArTPC)
  Also see Georgia's [talk]
- Low detection thresholds
- Precise calorimetric information
- Largest available neutrino-argon scattering data set to-date

Charged Current Quasi-elastic (CCQE) Interactions

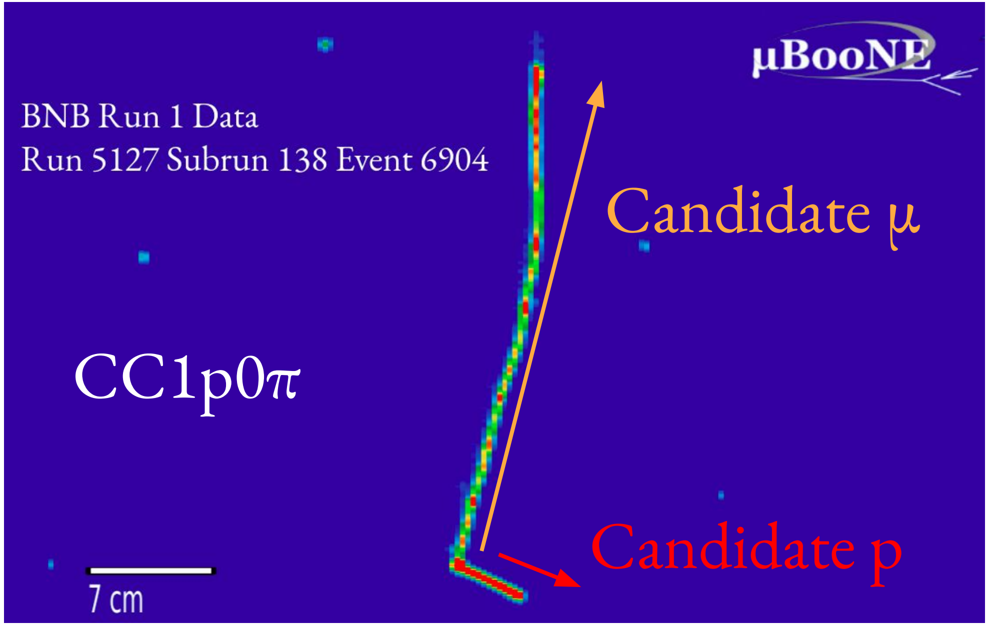




- Simple single muon-proton events
- Dominant at MicroBooNE energies

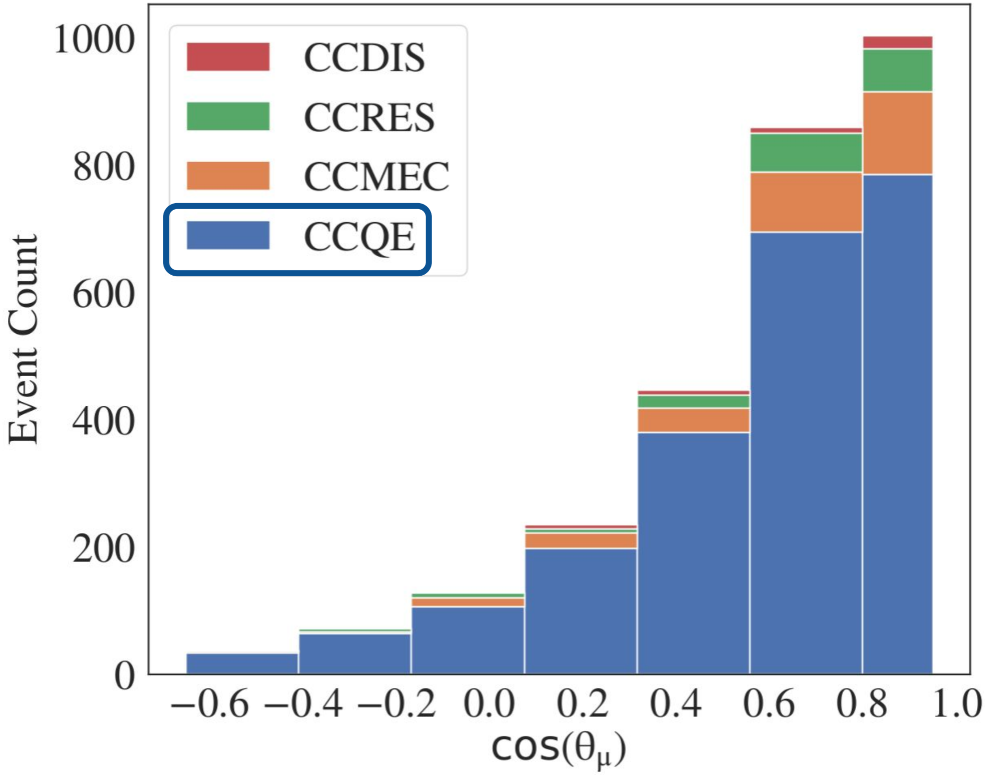
Quasielastic-like Signal Definition

- 1 muon ($P_\mu > 100$ MeV/c)
- 1 proton ($P_p >$ **300 MeV/c !!!**)
- No $\pi^\pm$ ($P_\pi > 70$ MeV/c)
- No π^0



CCQE Dominance

MicroBooNE Simulation



410 candidate 1p0π events

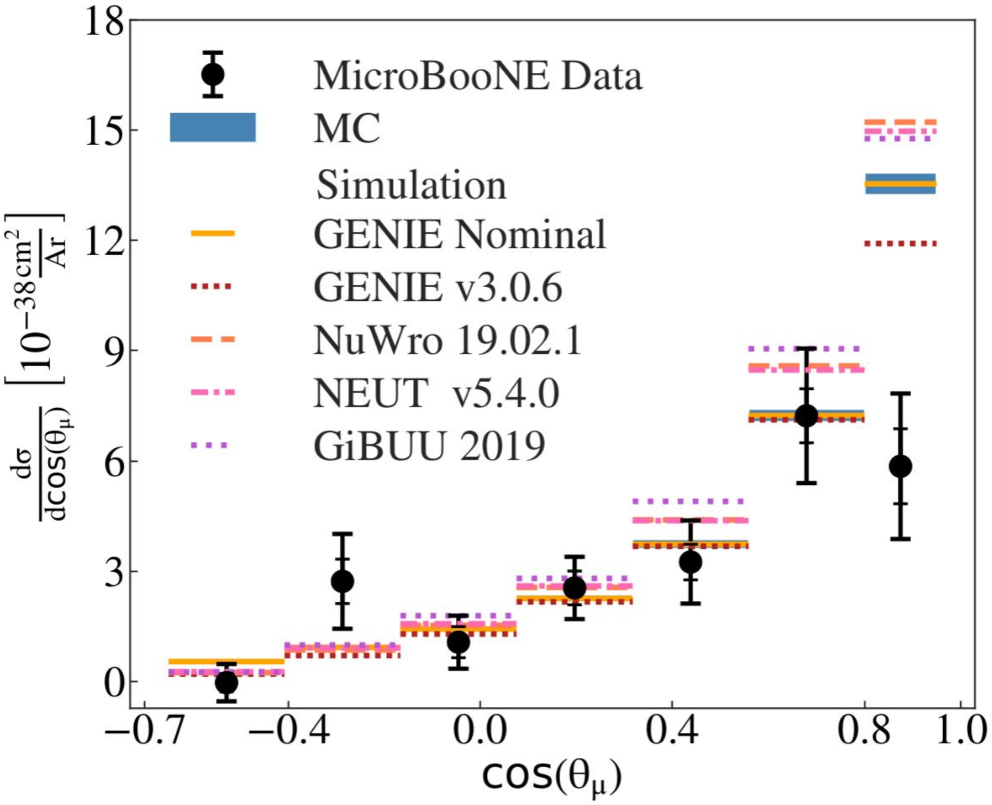
- **84%** CC1p0π*

Interaction Mode	Fractional Contribution (%)
CCQE	81.1
CCMEC	10.9
CCRES	6.6
CCDIS	1.4

Eur. Phys. J. C 79, 673 (2019)
Phys. Rev. Lett. 125, 201803 (2020)

*GENIE v2.12.10

Cross section vs Muon Angle



Good agreement with models, except at small angles

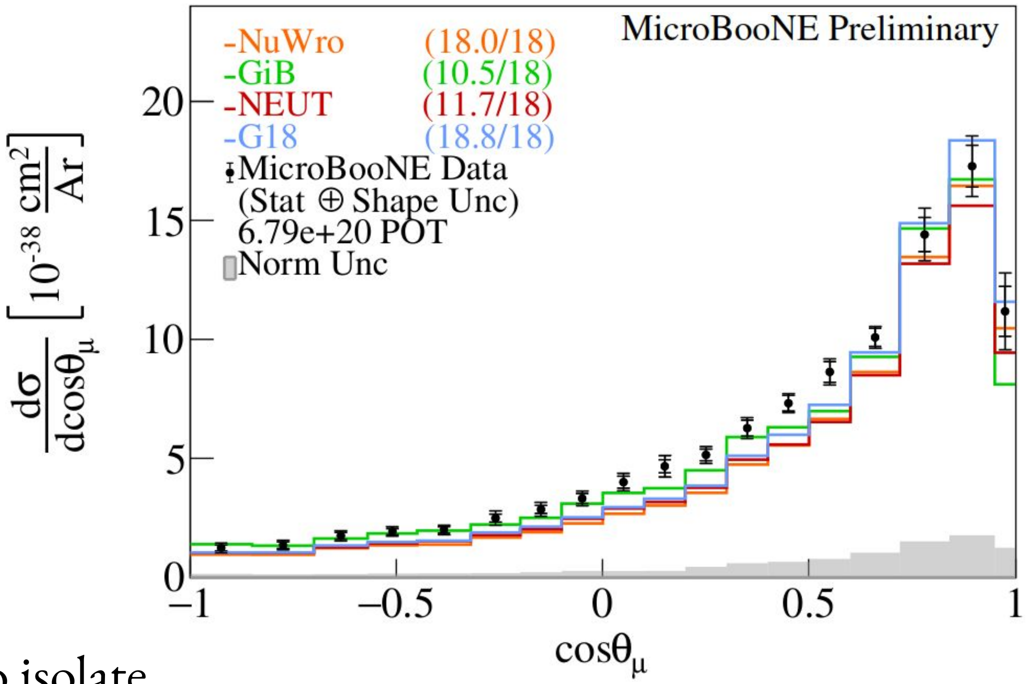
Phys. Rev. Lett. 125, 201803 (2020)

New MicroBooNE Results

- Higher statistics (x30)
  Phys. Rev. Lett. 128, 241801 (2022)
  Phys. Rev. Lett. 128, 111801 (2022)
- Improved signal processing
  JINST 13 P07007 (2018)
- Reduced systematics
  Eur. Phys. Journal C 82, 454 (2022)

- Improved modeling*
  Phys. Rev. D 105, 072001 (2022)
  EPJ Special Topics vol. 230, p. 4449–4467 (2021)

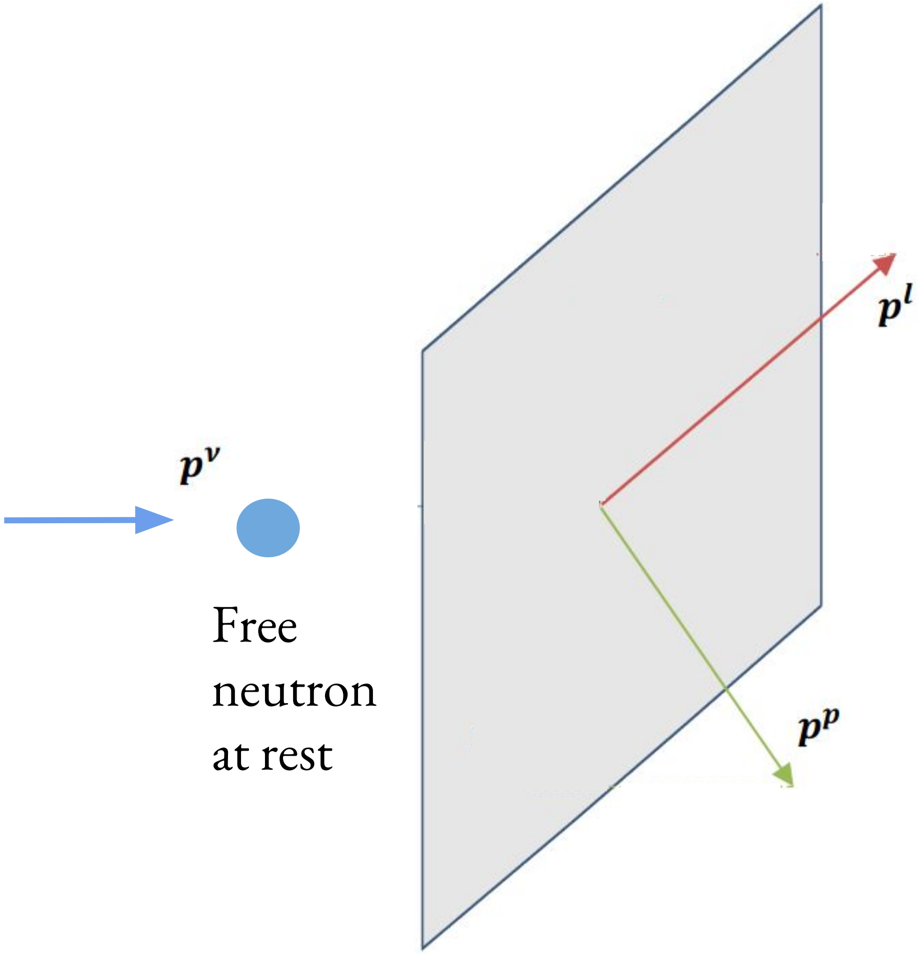
All events



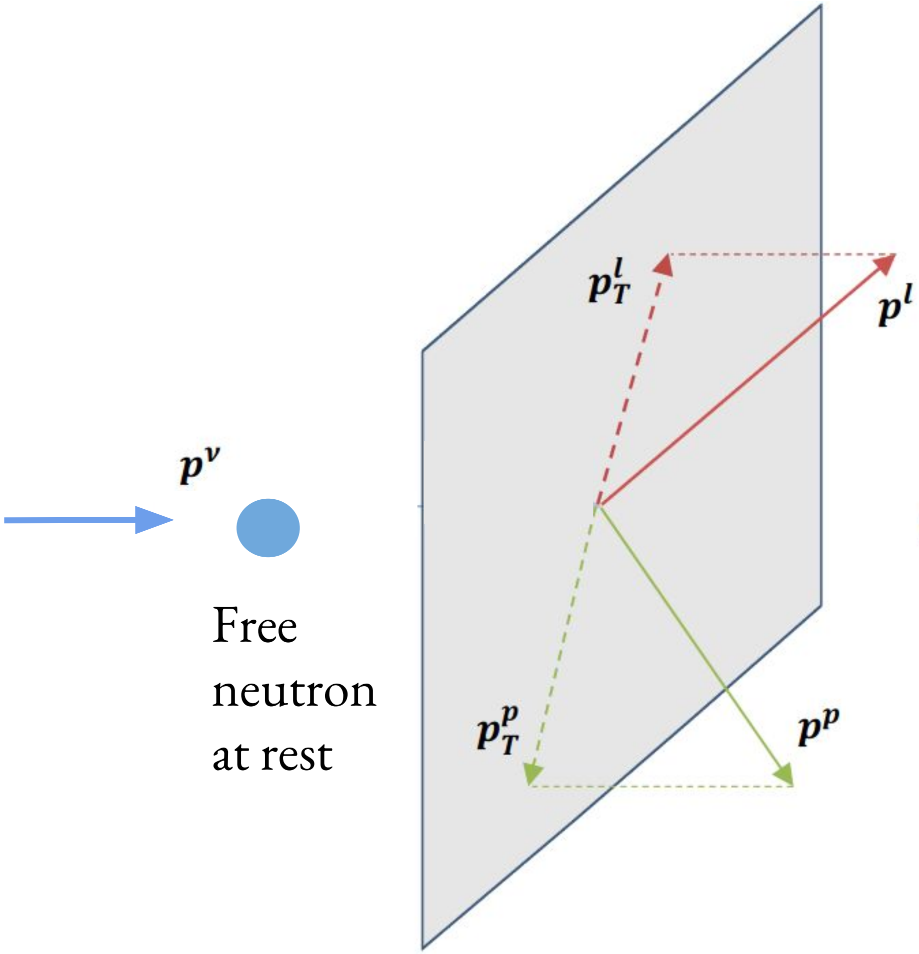
Now look at kinematic variables to isolate specific nuclear effects!

*GENIE v3.0.6

Scattering Off Free Nucleon



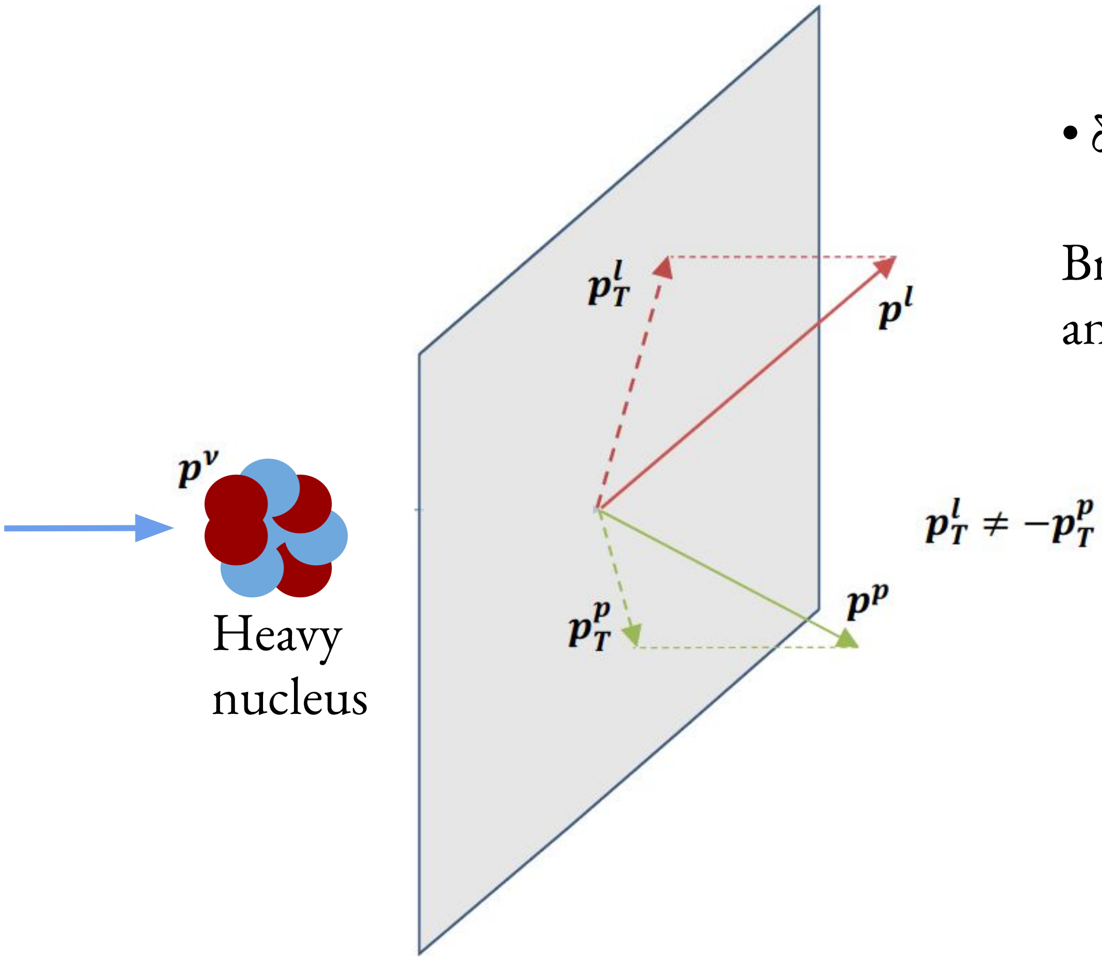
Cancelation In Absence Of Nuclear Effects



- $\delta p_T = |\,\mathbf{p_T}^l + \mathbf{p_T}^p\,| = 0$

$p^l_T = -p^p_T$

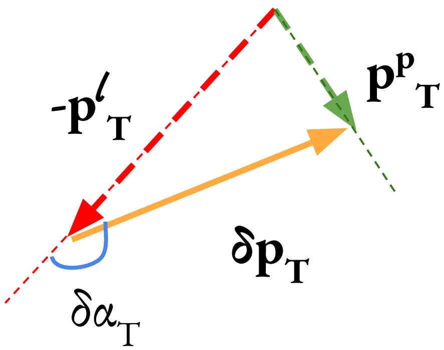
Transverse Momentum

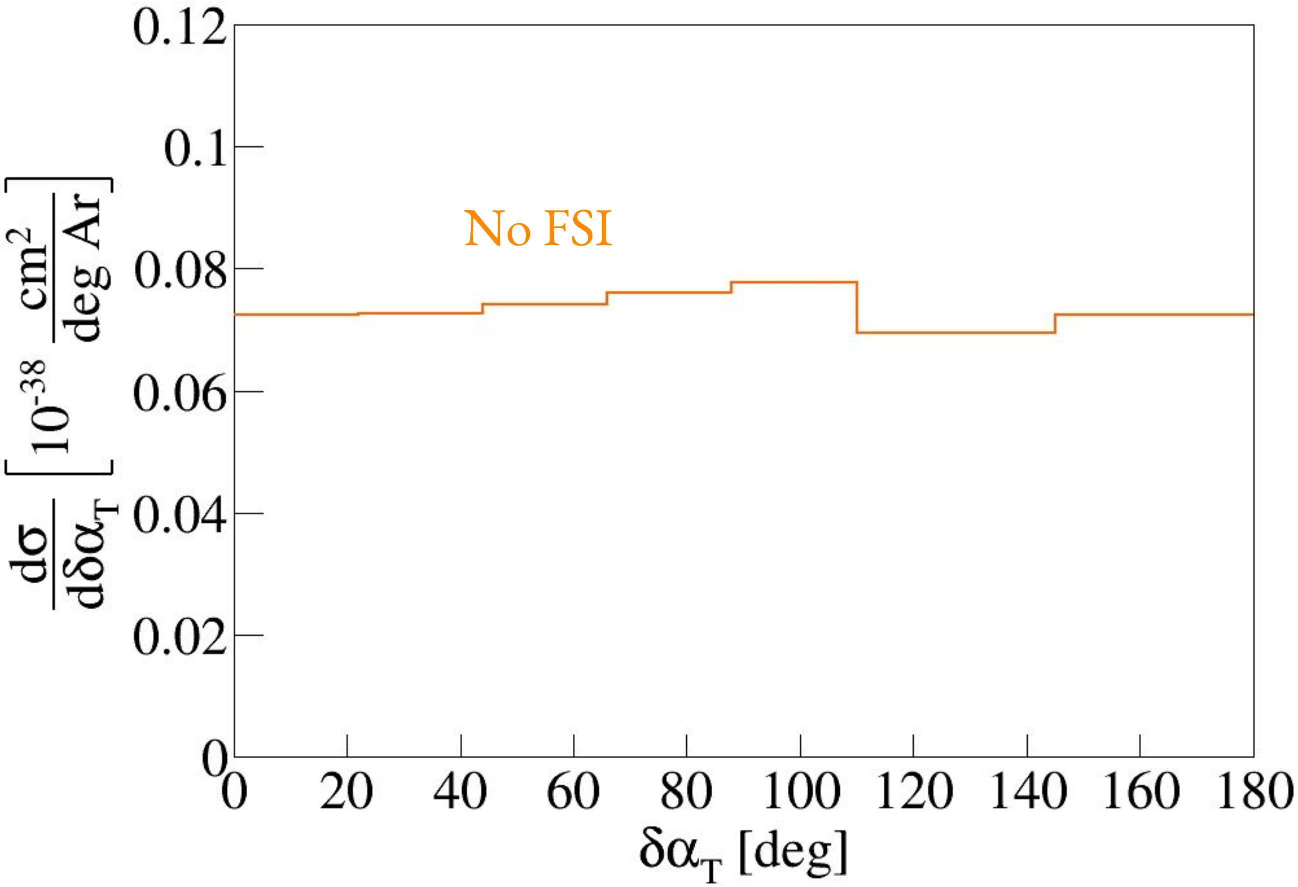


- $\delta p_T = |\,\mathbf{p_T}^{\ell} + \mathbf{p_T}^{\mathbf{p}}\,| > 0$

Broadened by initial nucleon motion and final-state interactions (FSI)

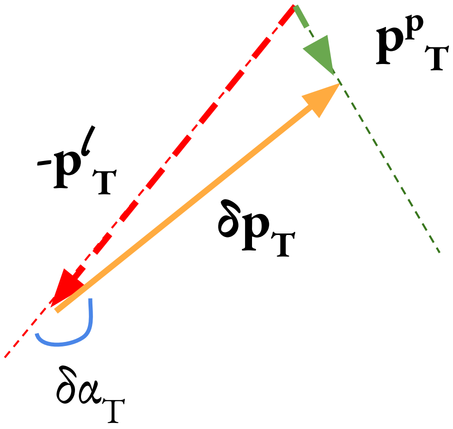
Transverse Angular Orientation ($\delta\alpha_T$)

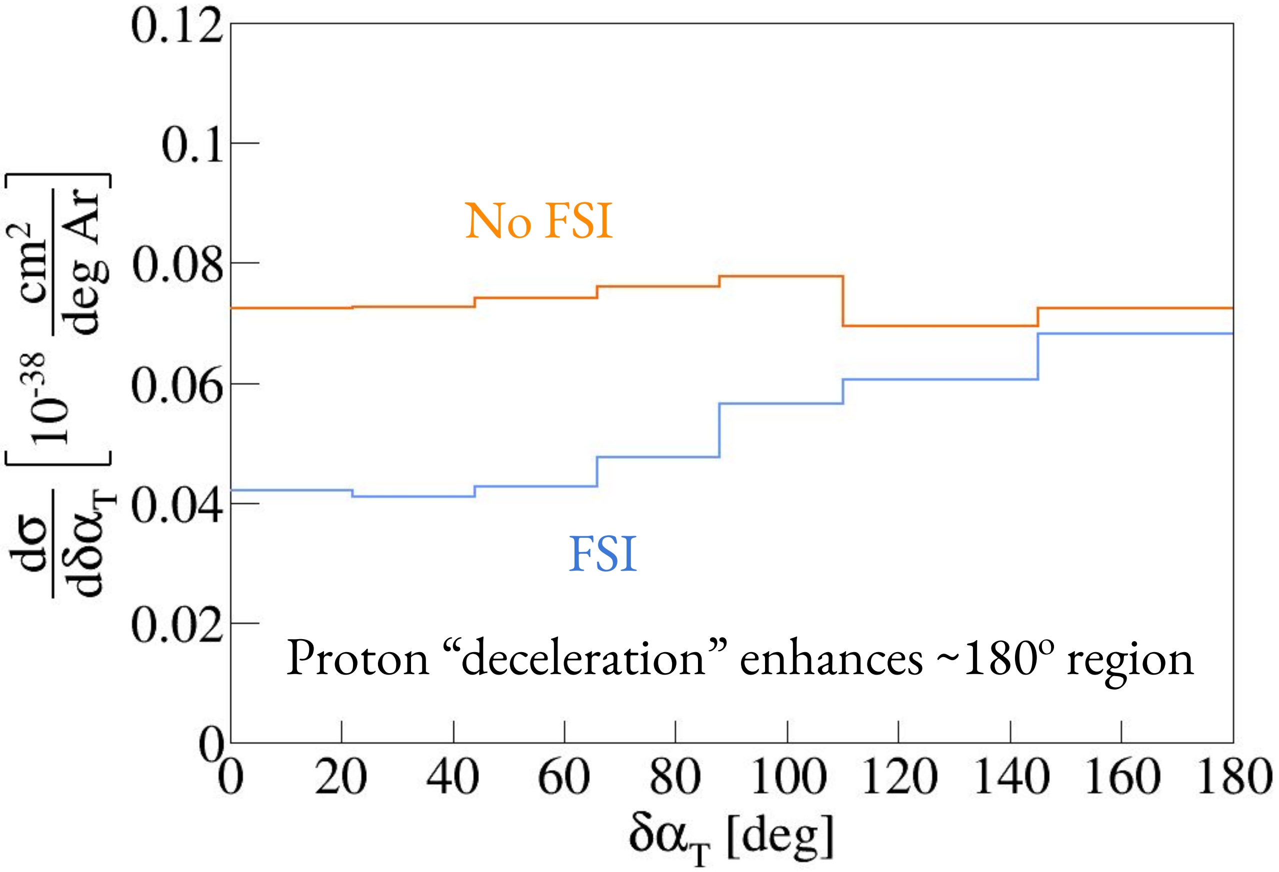




FSI = Final State Interactions

Transverse Angular Orientation ($\delta\alpha_T$)

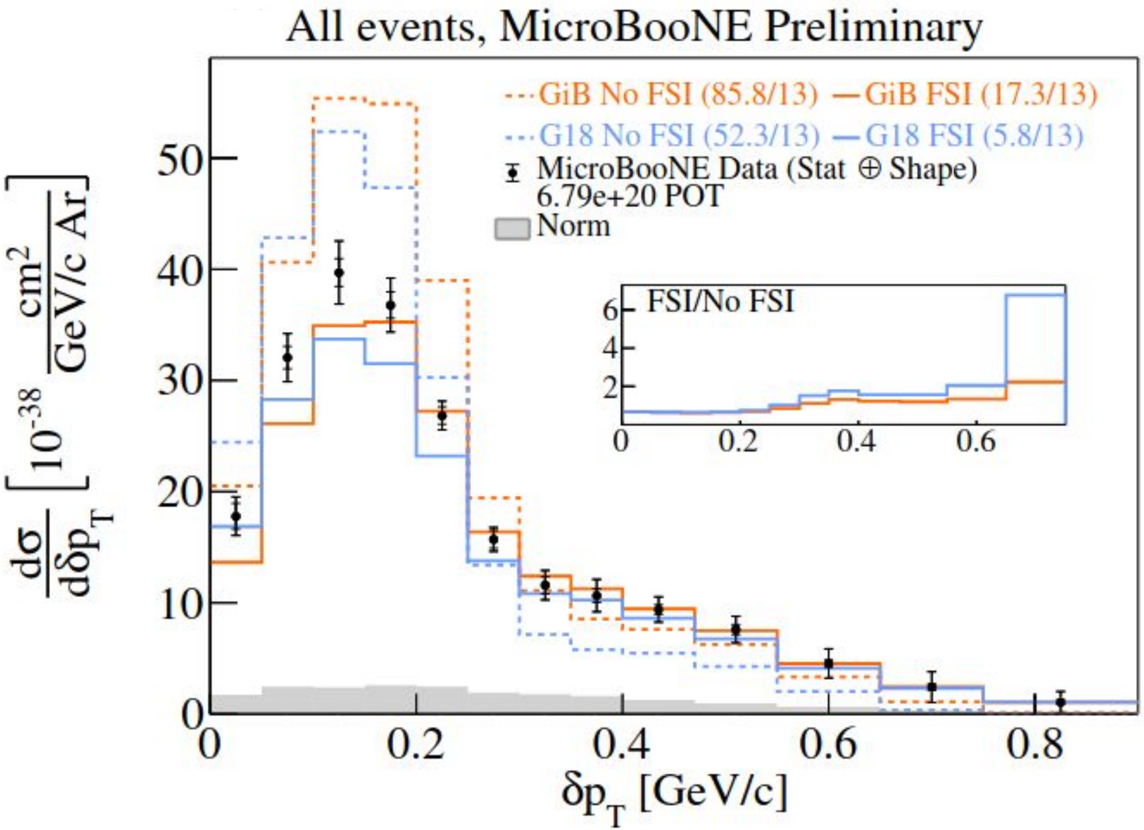


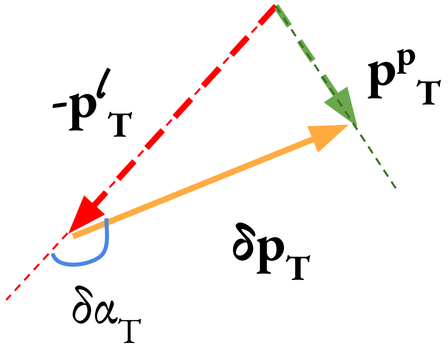


FSI = Final State Interactions

Transverse Kinematic Imbalance (TKI)

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

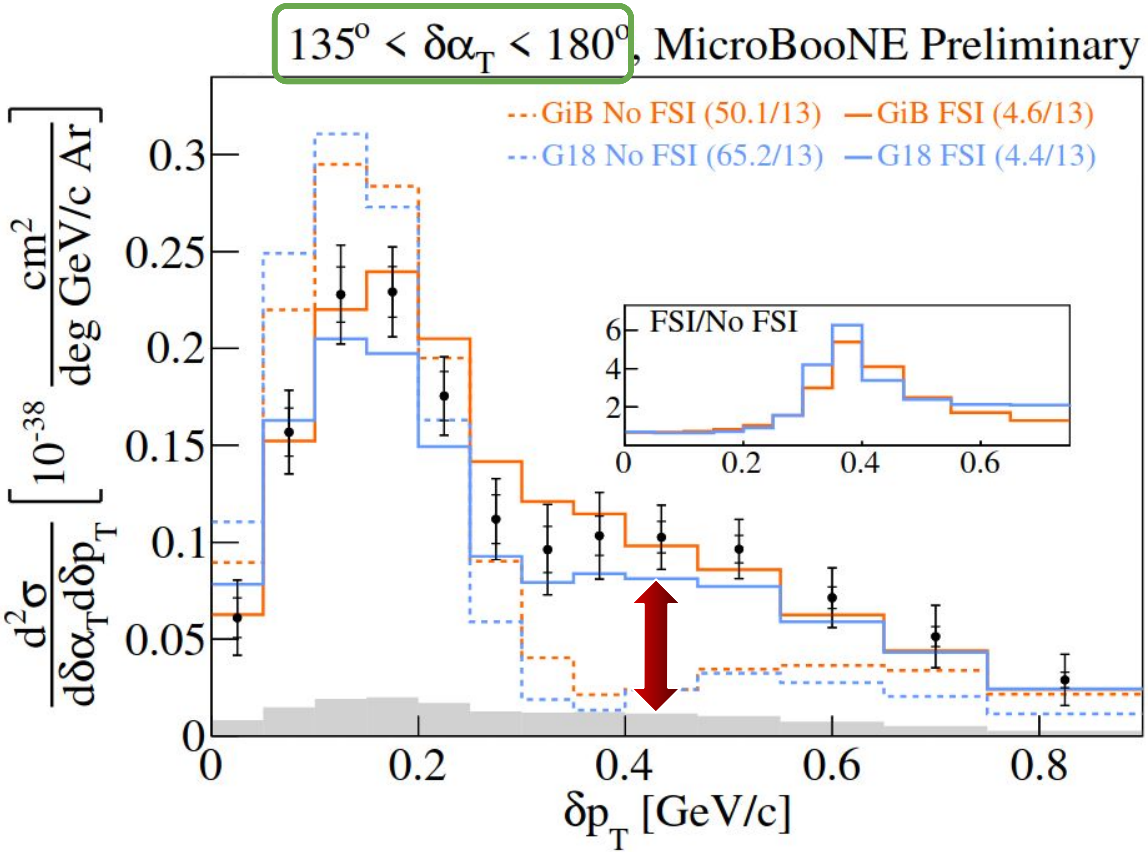


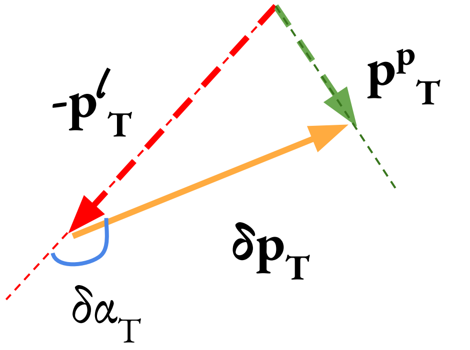


Transverse Kinematic Imbalance (TKI)

MICROBOONE-NOTE-1108-PUB

- Extension to 2D for the first time on any neutrino target
- Probe regions with greater model discrimination power





Connections To Electron Scattering

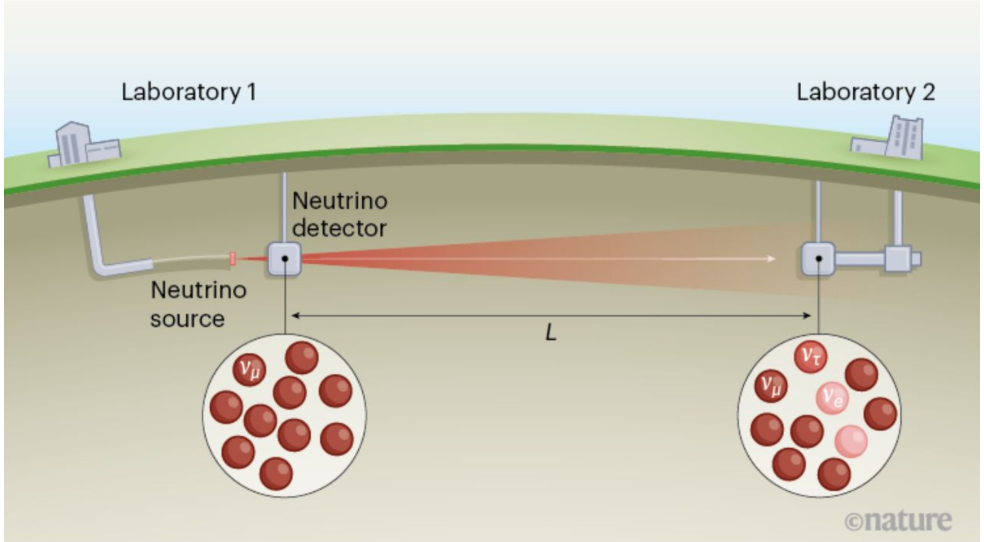
nature

NEWS AND VIEWS | 24 November 2021

Electrons reveal the need for improved neutrino models

Experiments on electrons interacting with atomic nuclei have shown that the models used to measure neutrino oscillations – and thereby possibly to understand the formation of the Universe – are less accurate than we thought.

Noemi Rocco

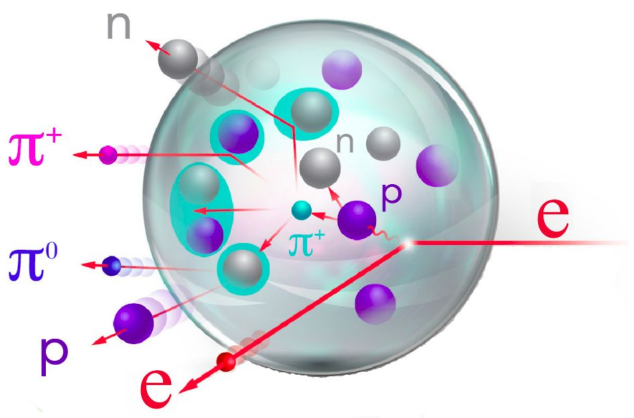


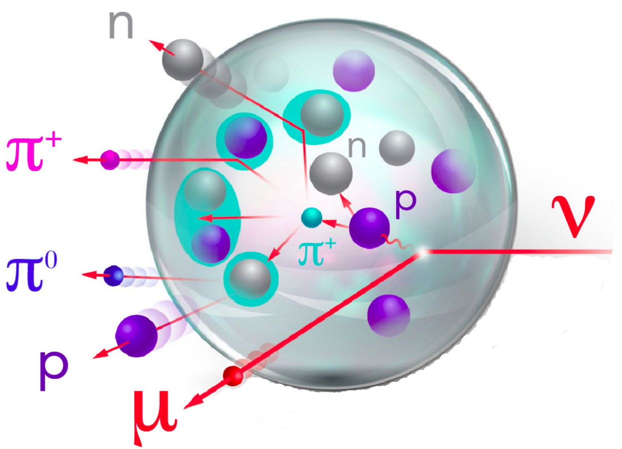
Why electrons?

- Common vector current
- Identical nuclear effects

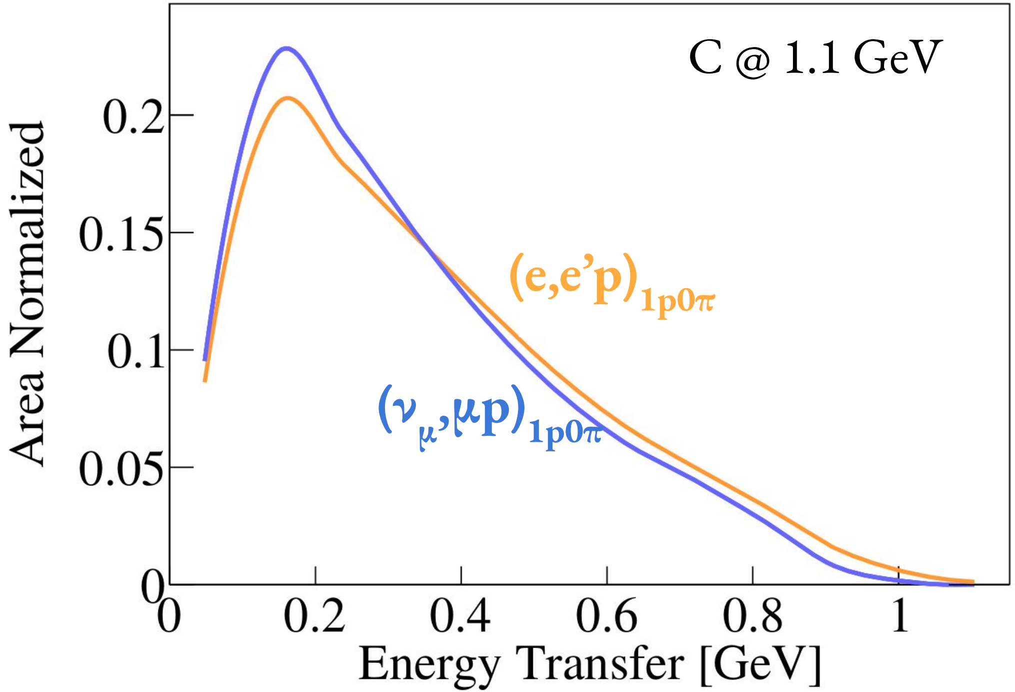
- Monoenergetic beams
- High statistics
  - Precision measurements

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





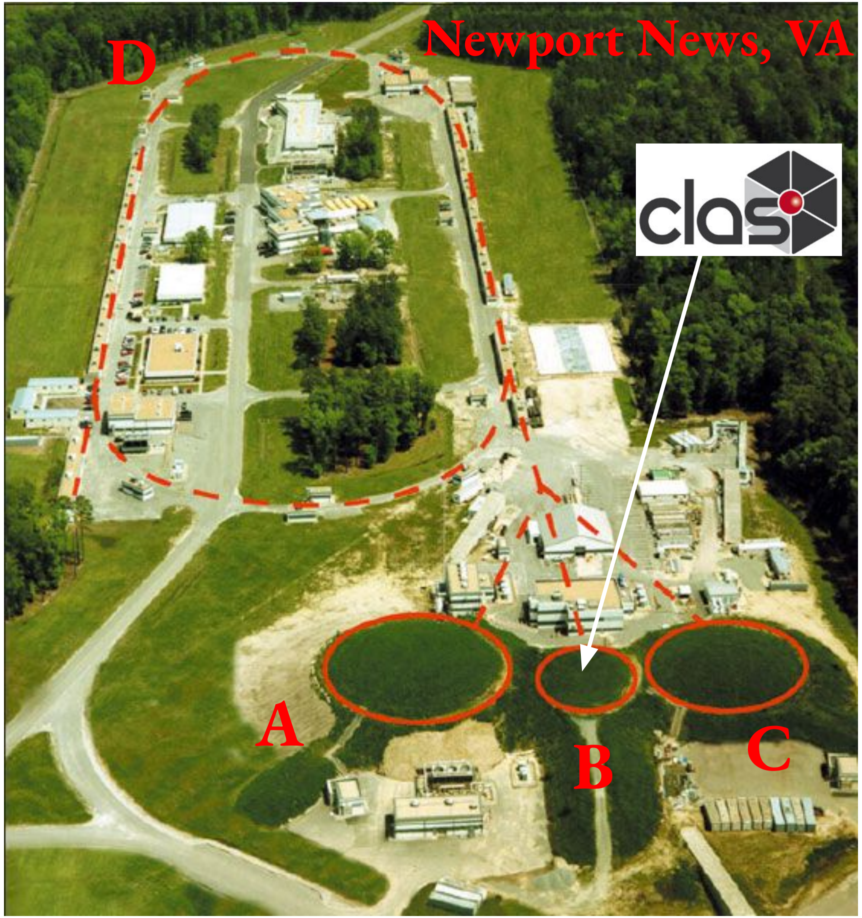
Similar ν & e Distributions



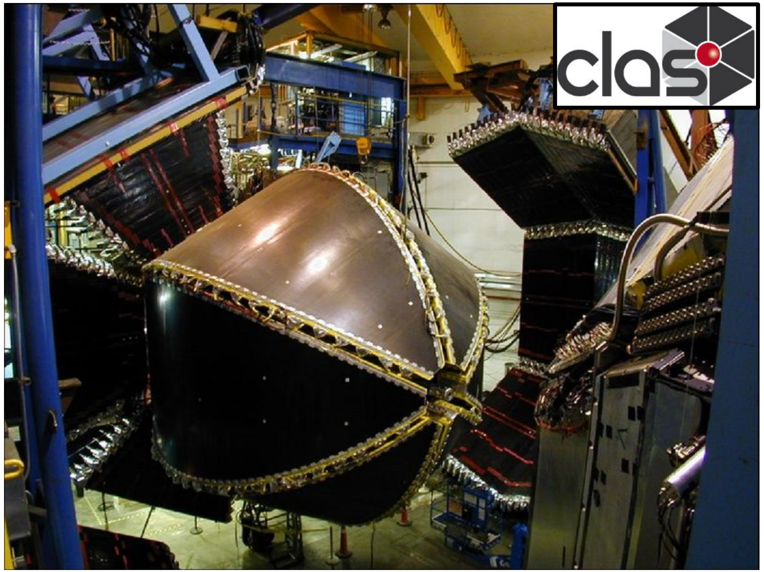
Accounting for propagator mass (γ vs W) via Q^4 scaling of the electron side

Phys. Rev. D 103, 113003 (2021)

Jefferson Laboratory

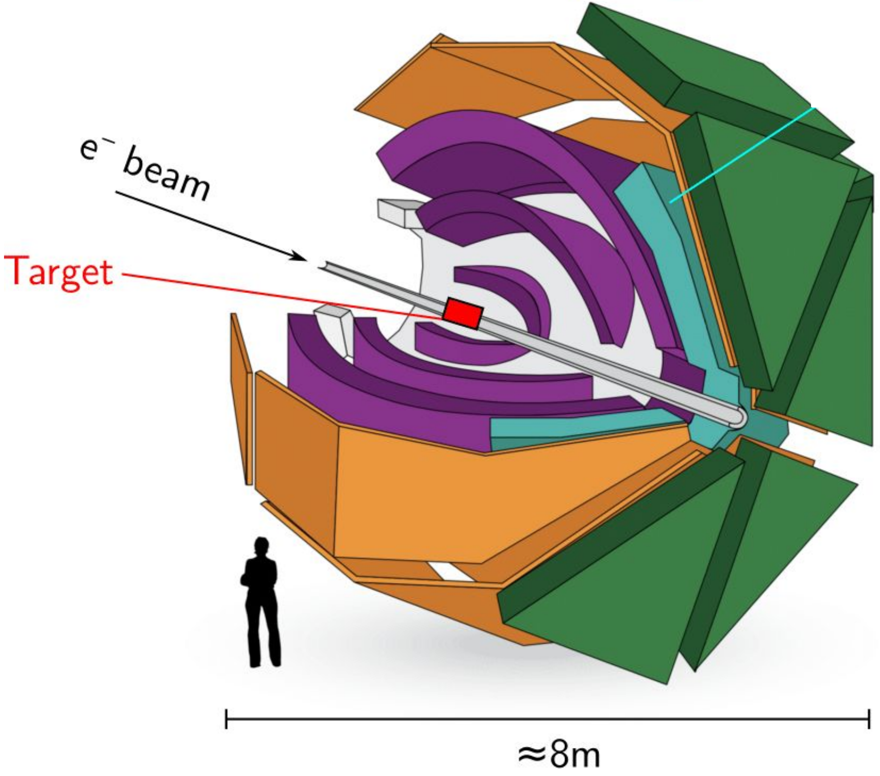


- Electron beam accelerator facility
- Energies up to 12 GeV
- Using Hall B & CLAS detector



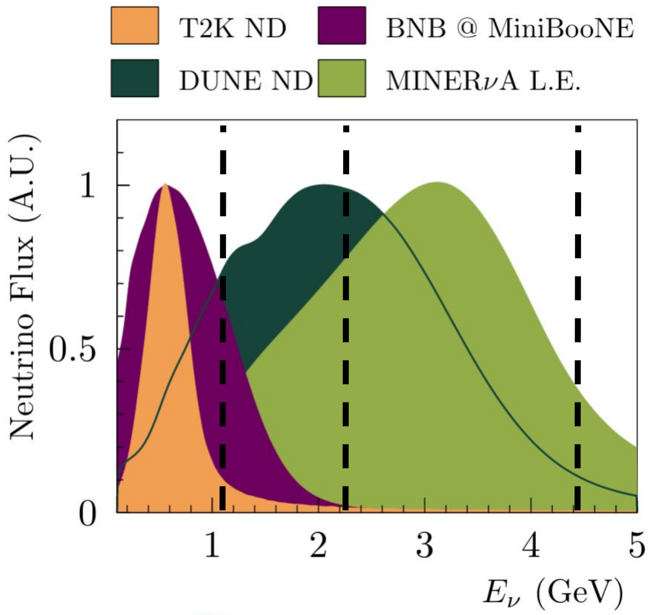
e4ν Data-Mining With CLAS

- Charged particle threshold similar to ν tracking detectors
- ~50% of "4π" coverage



e4ν Data-Mining With CLAS

- Charged particle threshold similar to ν tracking detectors
- ~50% of "4π" coverage
- Energies: 1, 2 & 4 GeV
- Targets: ^{4}He, ^{12}C, ^{56}Fe



T2K — H_2O

NOvA — CH

SBN Program, DUNE — Ar

Playing The QE-like Neutrino Game

μBooNE

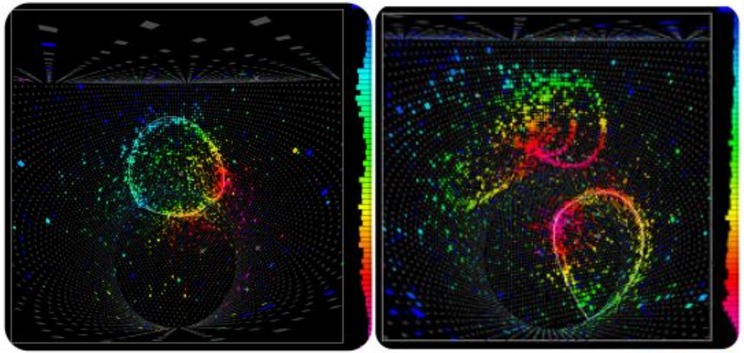
- 1 proton ($P_p > 300$ MeV/c)
- No $\pi^{\pm}$ ($P_\pi > 70$ MeV/c)

e4ν

- 1 proton ($P_p > 300$ MeV/c)
- No $\pi^{\pm}$ ($P_\pi > 150$ MeV/c)
- Scale by $\sigma_{\nu N} / \sigma_{eN} \propto Q^4$

- Study energy reconstruction
- Test Genie event generator

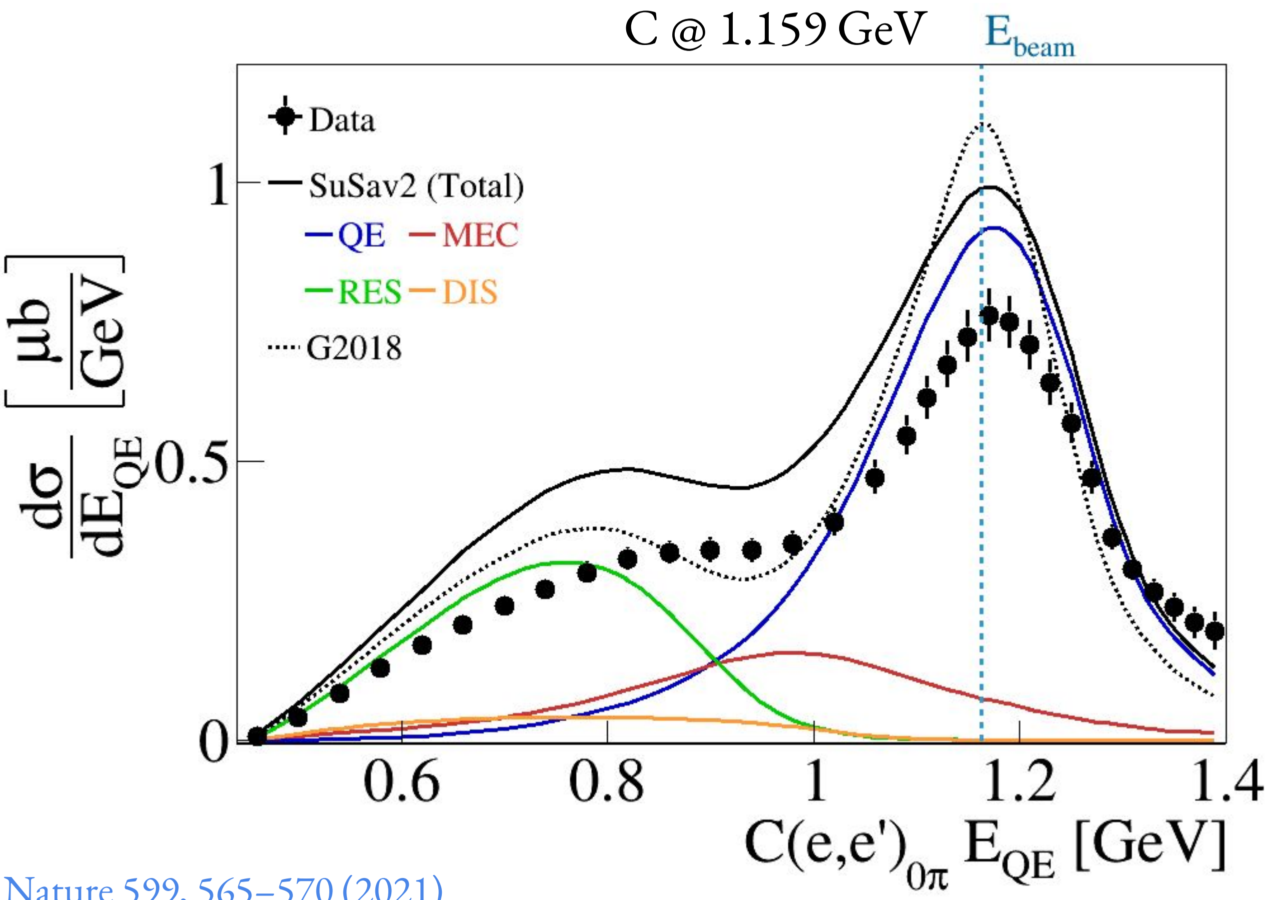
QE Energy Reconstruction



Cherenkov detectors
Assuming QE interaction
Using lepton kinematics

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

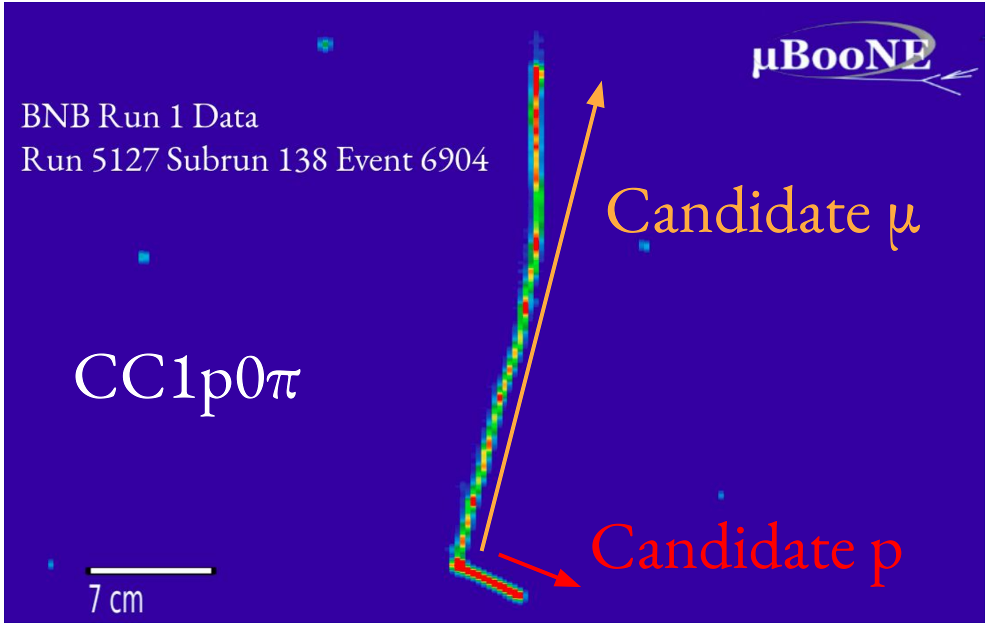
QE Energy Reconstruction



- Relevant for T2K
- Overestimation of QE peak & RES tail

Nature 599, 565–570 (2021)

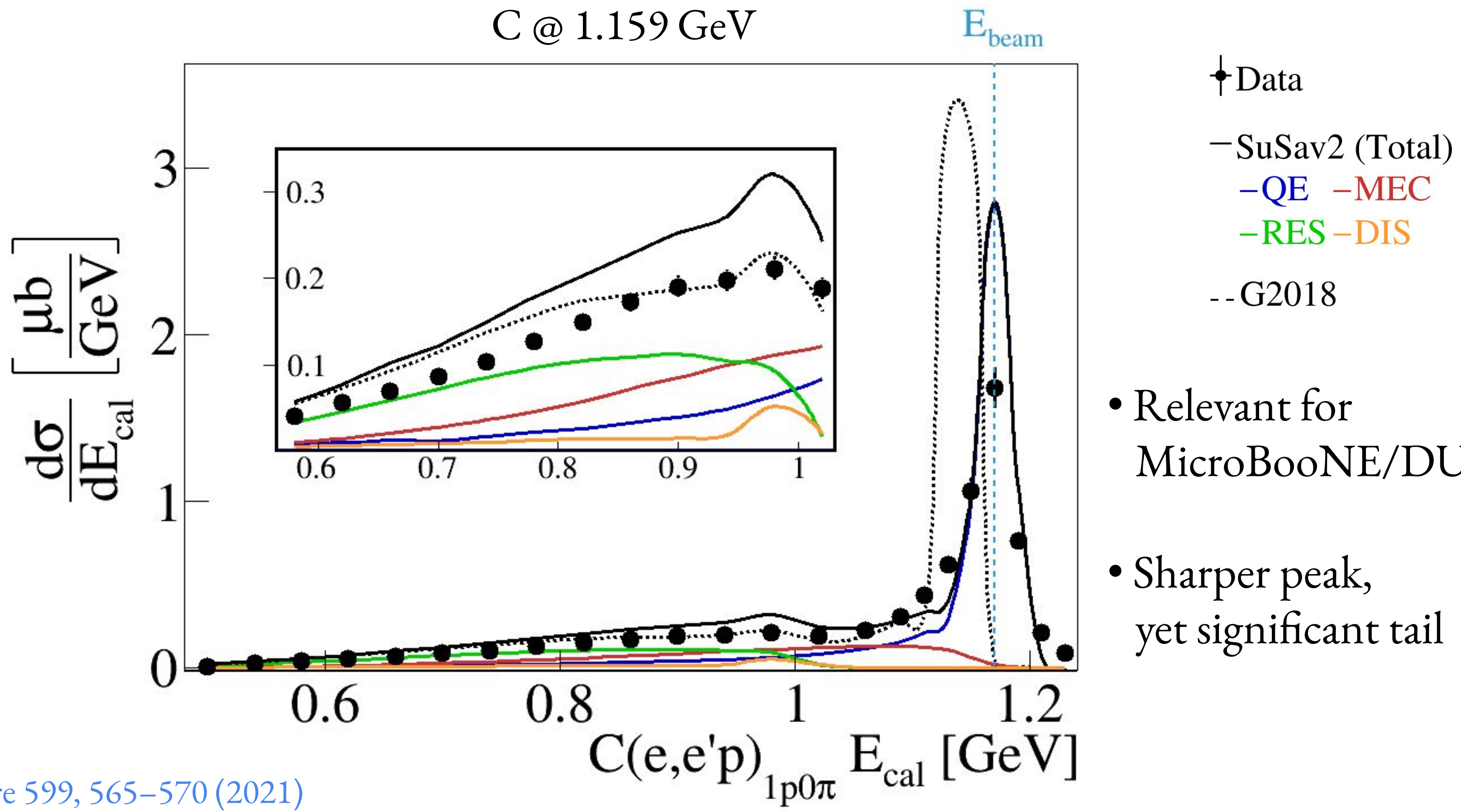
Calorimetric Energy Reconstruction



Tracking detectors
Calorimetric sum
Using all detected particles

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

Calorimetric Energy Reconstruction

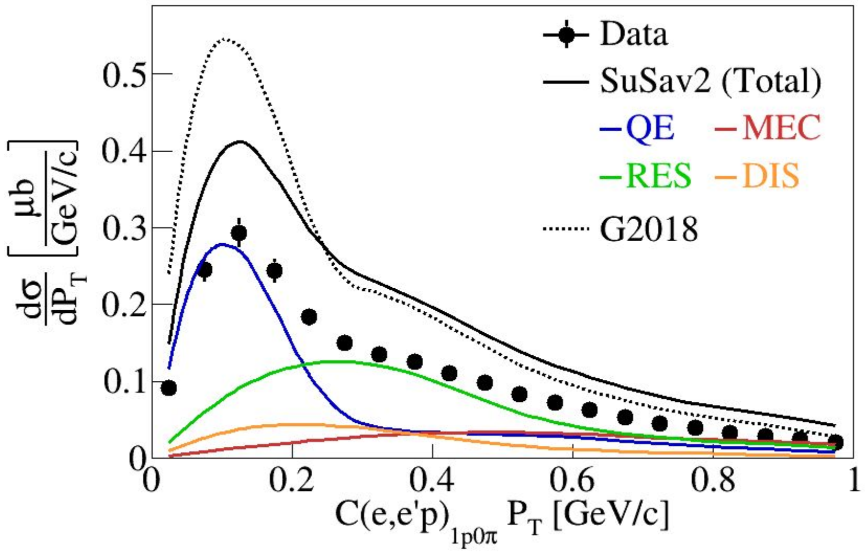


- Relevant for MicroBooNE/DUNE
- Sharper peak, yet significant tail

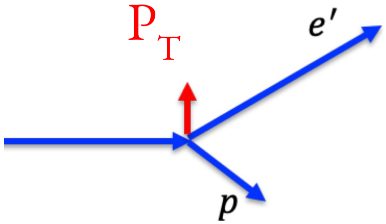
Nature 599, 565–570 (2021)

Transverse Momentum

C @ 2.257 GeV



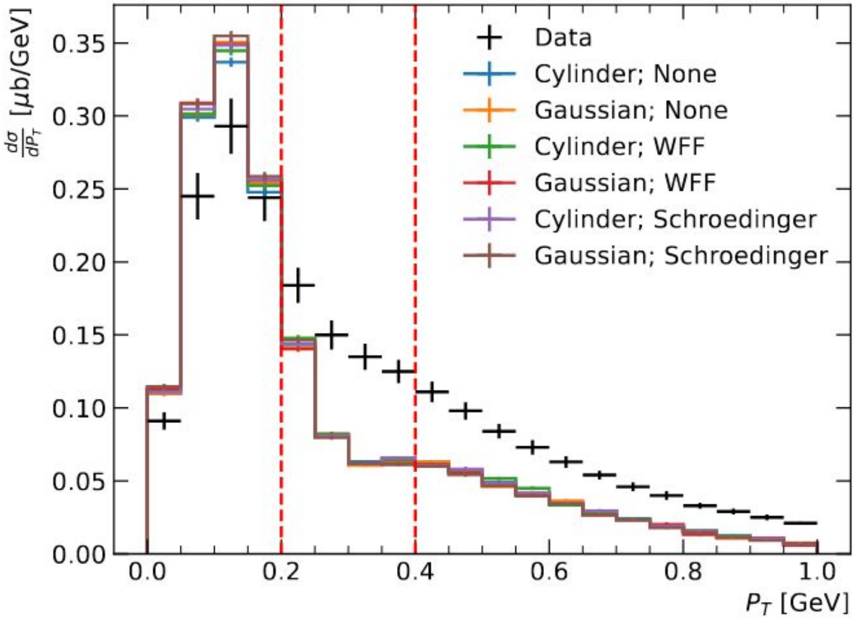
$$P_T = |\mathbf{P_T}^{e'} + \mathbf{P_T}^{p}|$$

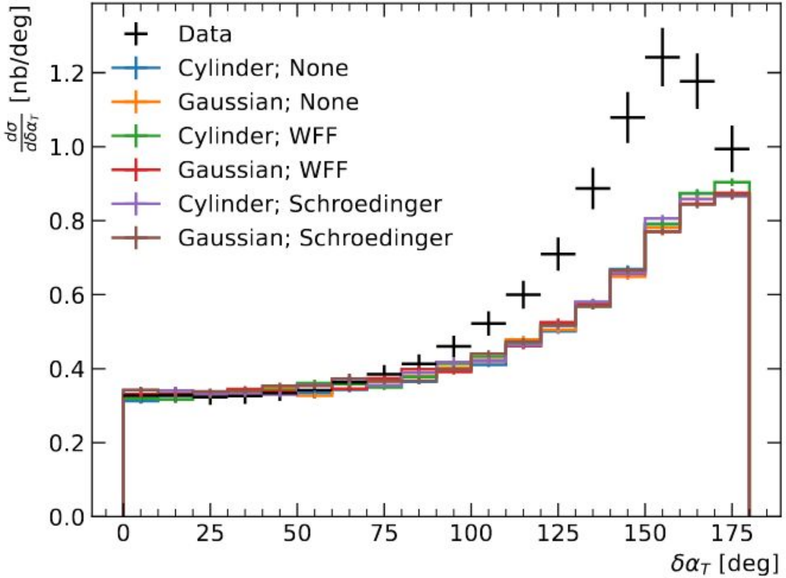


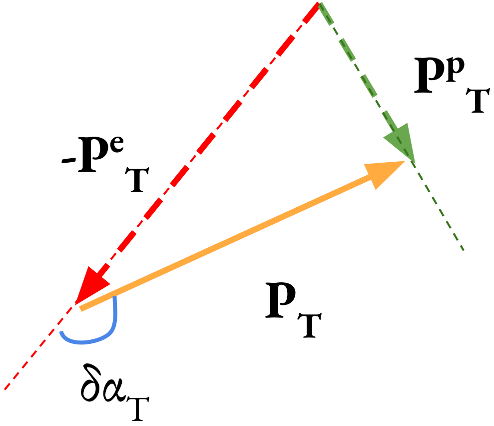
- Overestimation of QE peak & RES tail

Nature 599, 565–570 (2021)

Example: Benchmarking New Generators & Kinematic Variables!

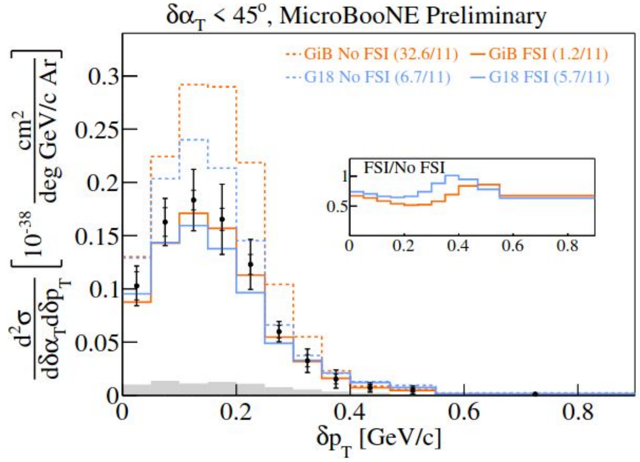


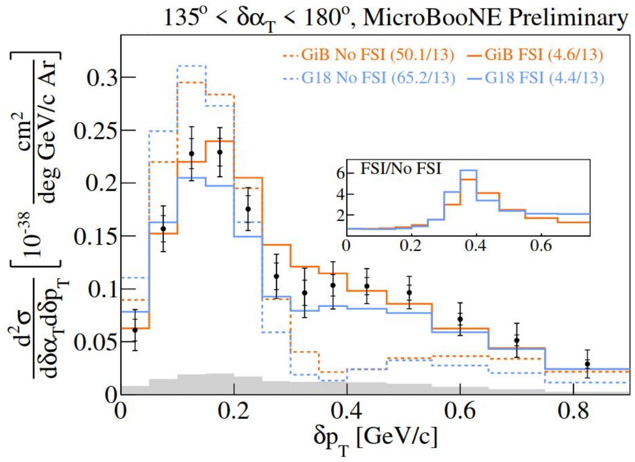




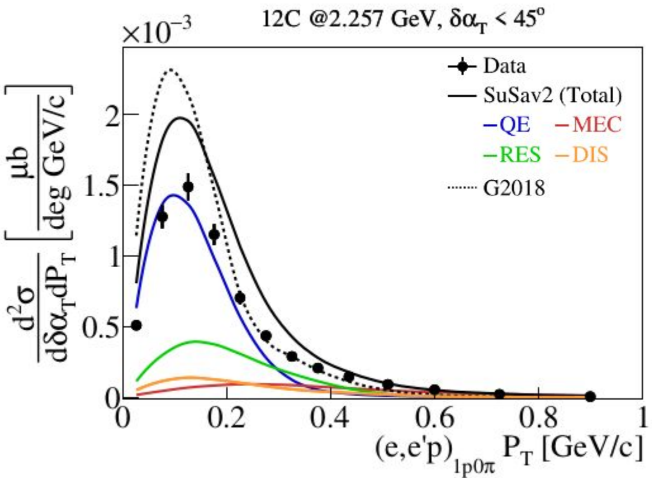
First step: only QE & FSI
ACHILLES arXiv: 2205.06378

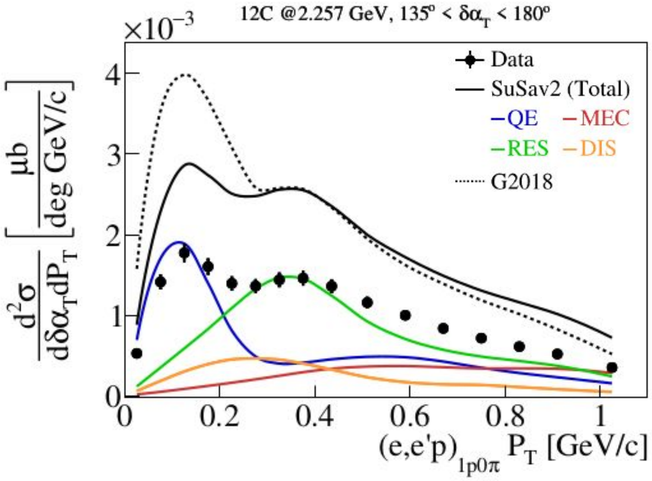
Complementarity To "Sister" Neutrino Analysis





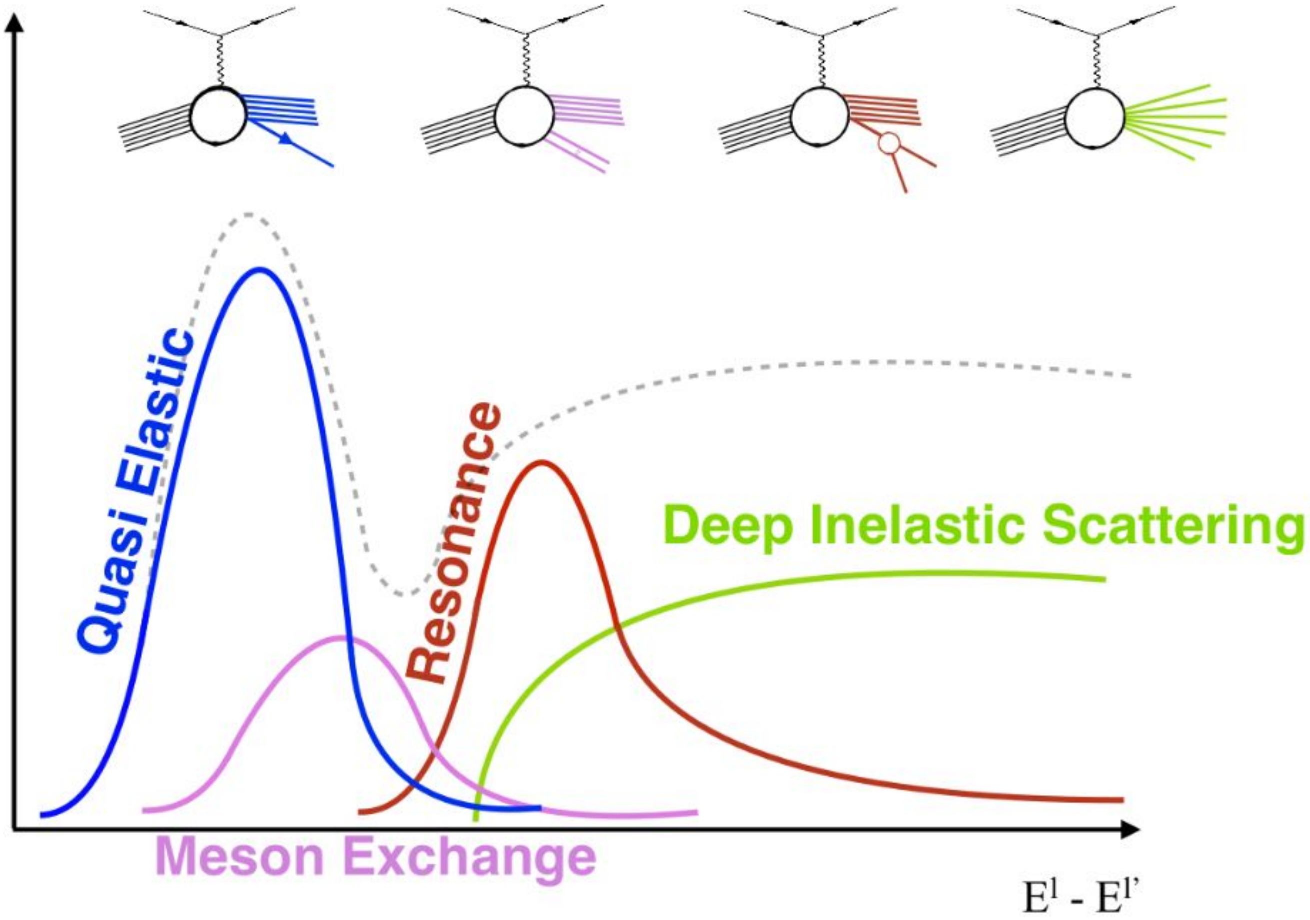
Papers in preparation





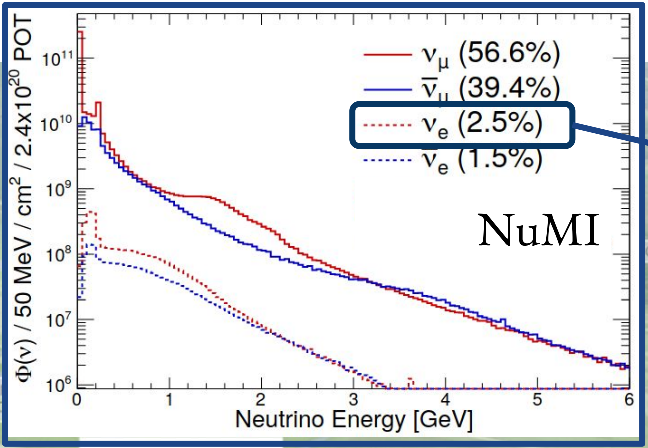
Thank you !

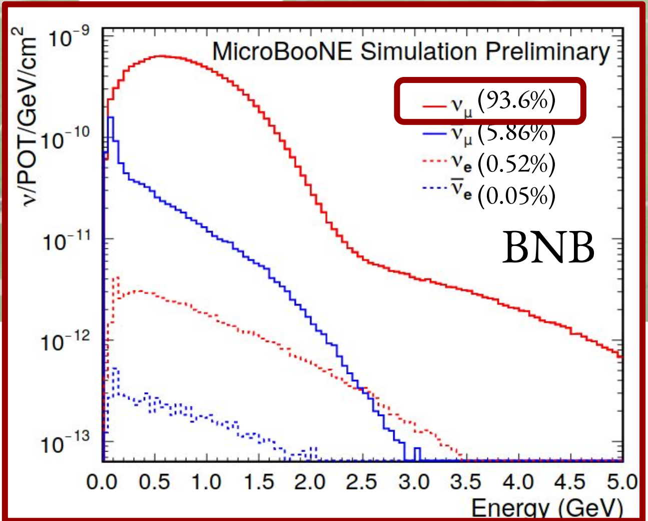
Backup Slides



$$|\Phi_a + \Phi_b|^2 \neq |\Phi_a|^2 + |\Phi_b|^2$$

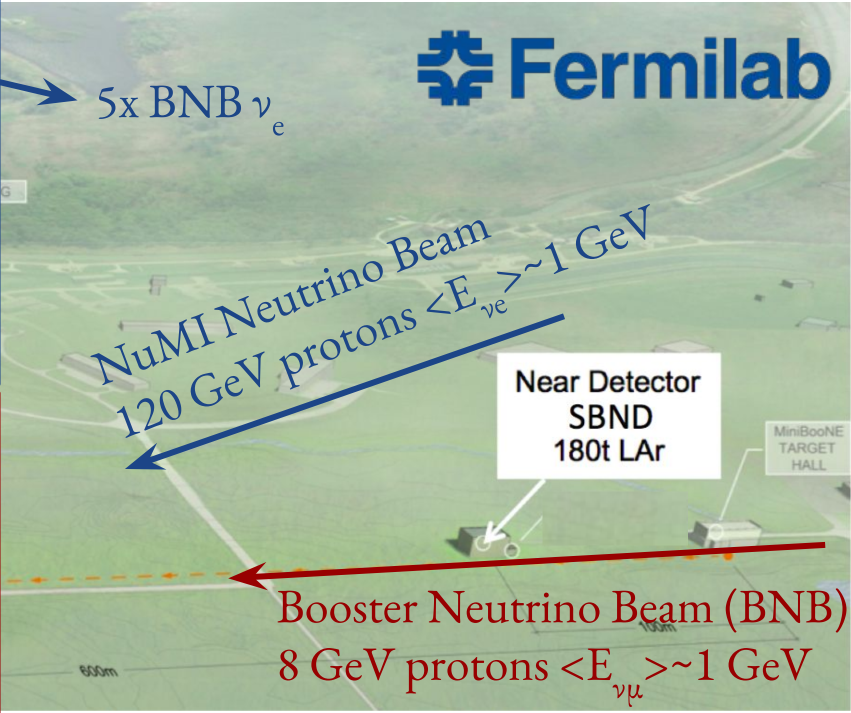
MicroBooNE Beams





Off axis [arXiv:2101.04228]

5x BNB ν_e

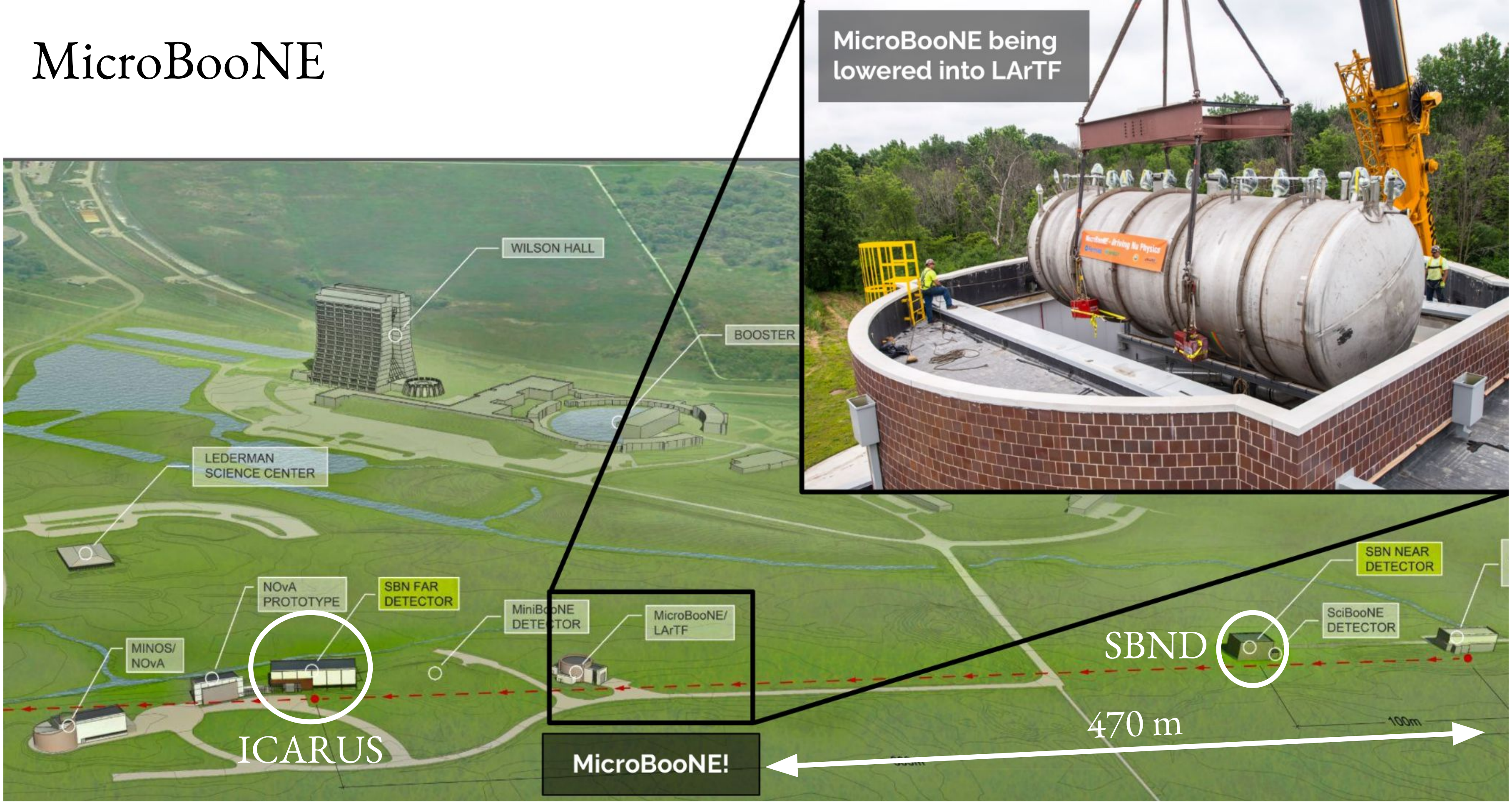


NuMI Neutrino Beam
120 GeV protons $\langle E_{\nu e}\rangle$~1 GeV

Booster Neutrino Beam (BNB)
8 GeV protons $\langle E_{\nu\mu}\rangle$~1 GeV

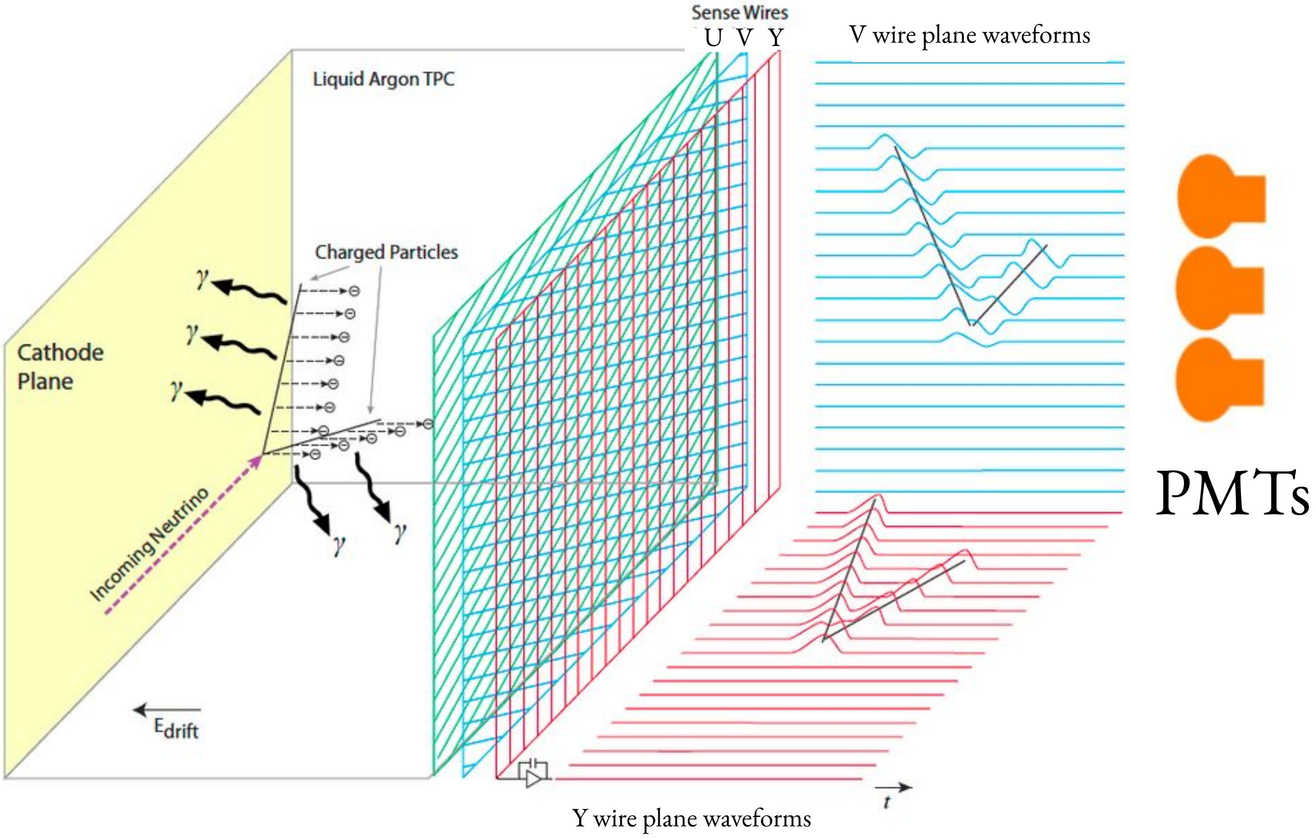
On axis [MICROBOONE-NOTE-1031-PUB]

MicroBooNE



85 ton Liquid Argon Time Projection Chamber (LArTPC)
JINST 12, P02017 (2017)

Time Projection Chambers



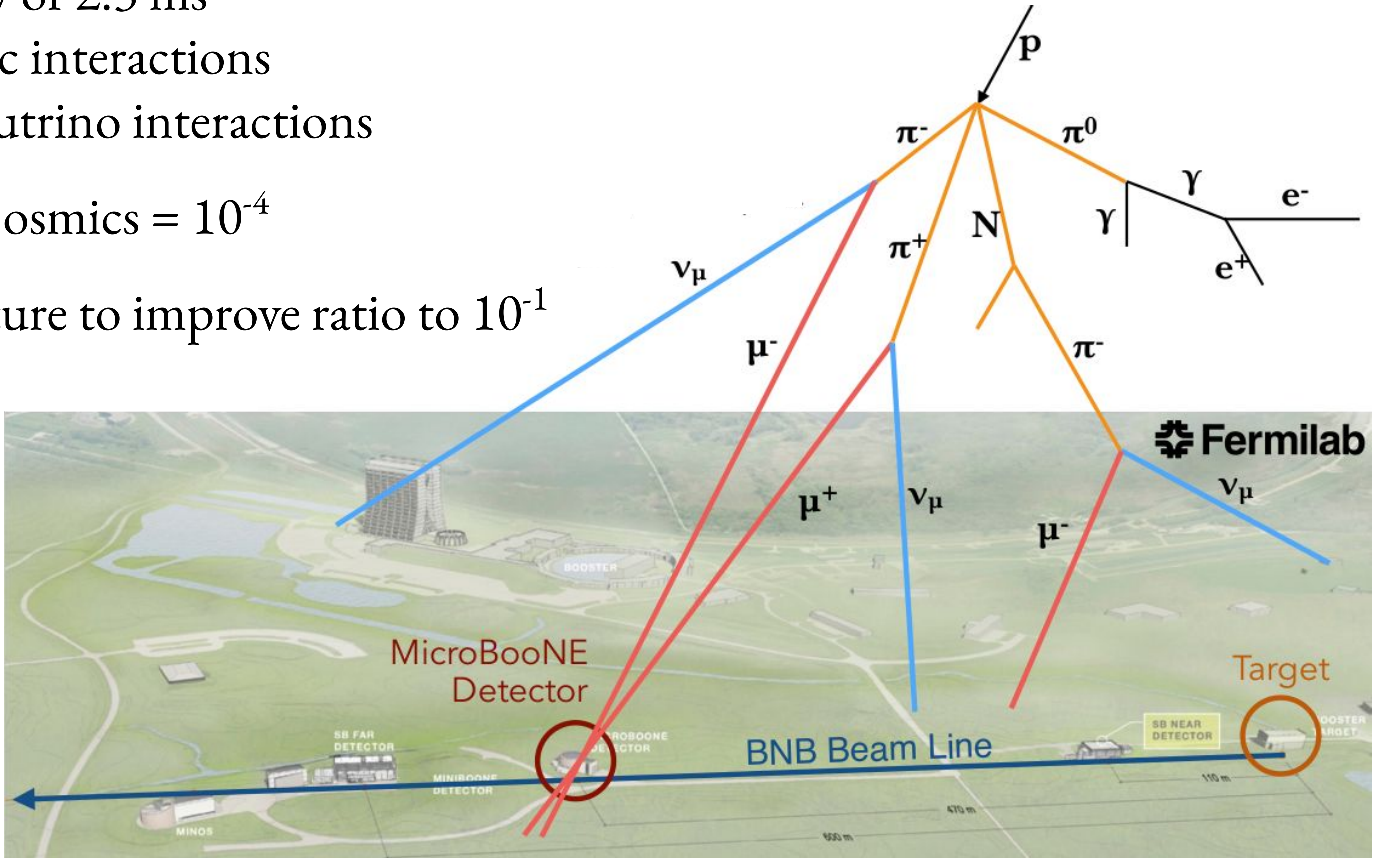
Cosmic Events Dominate

Readout window of 2.3 ms

- ~20 cosmic interactions
- ~0.002 neutrino interactions

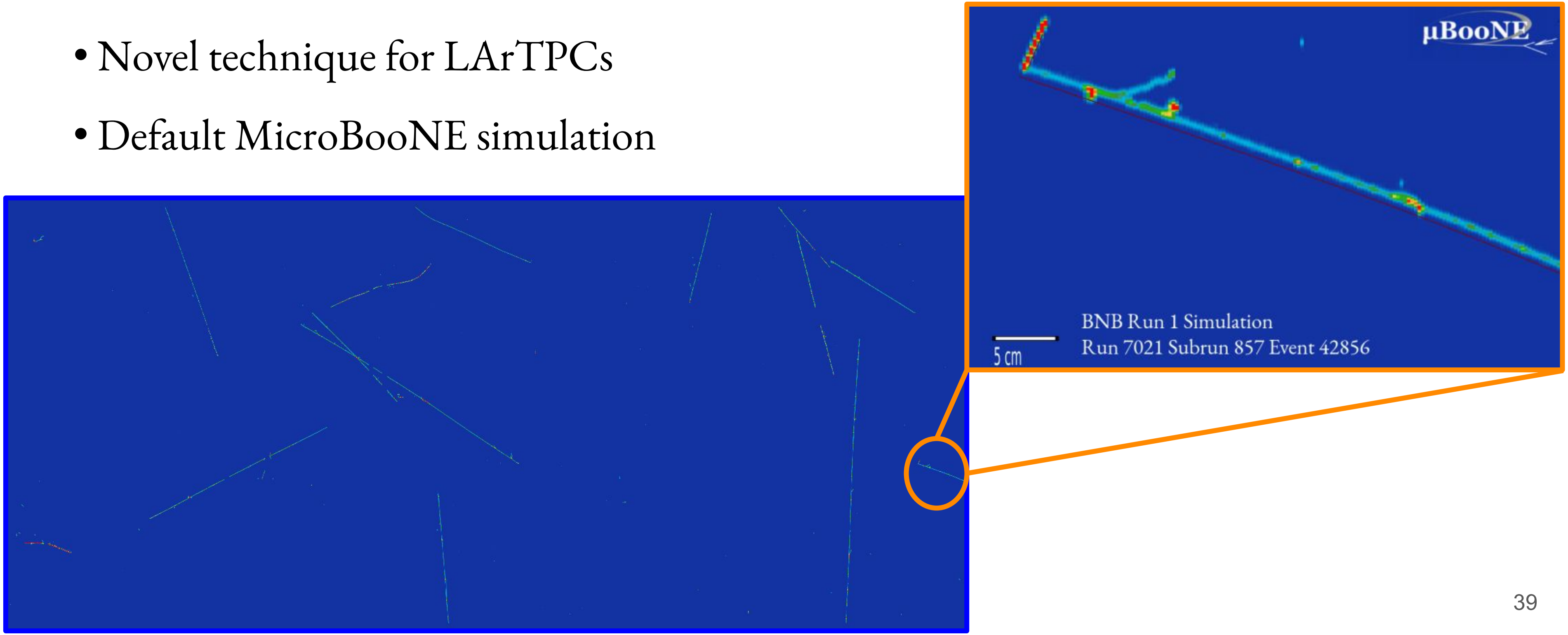
Neutrino/Cosmics = 10^{-4}

Beam time structure to improve ratio to 10^{-1}

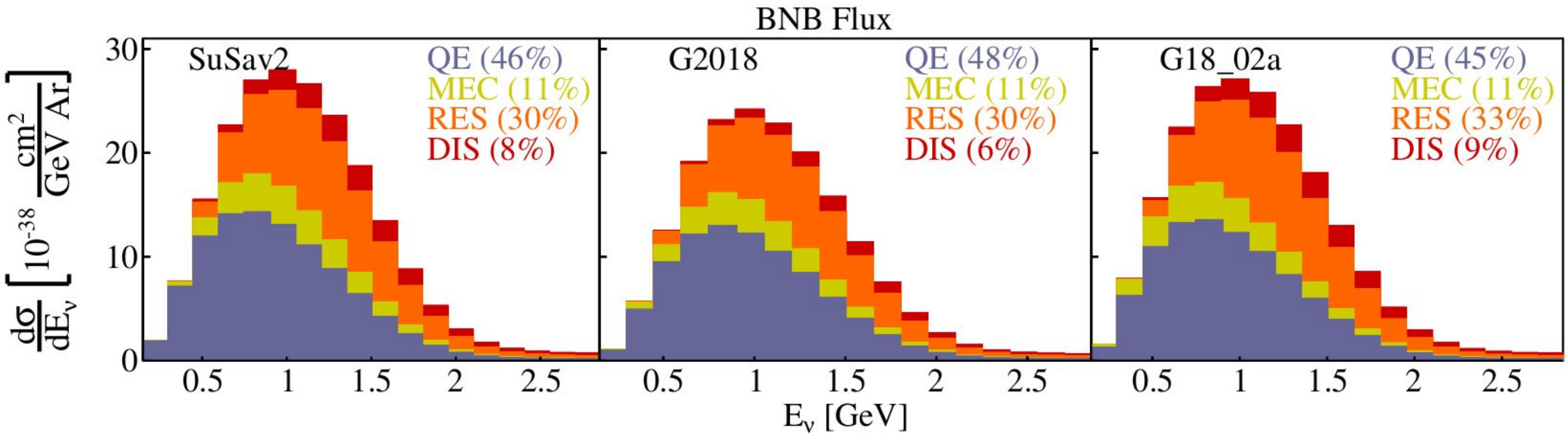


Isolating Neutrino Events In A Cosmic Sea

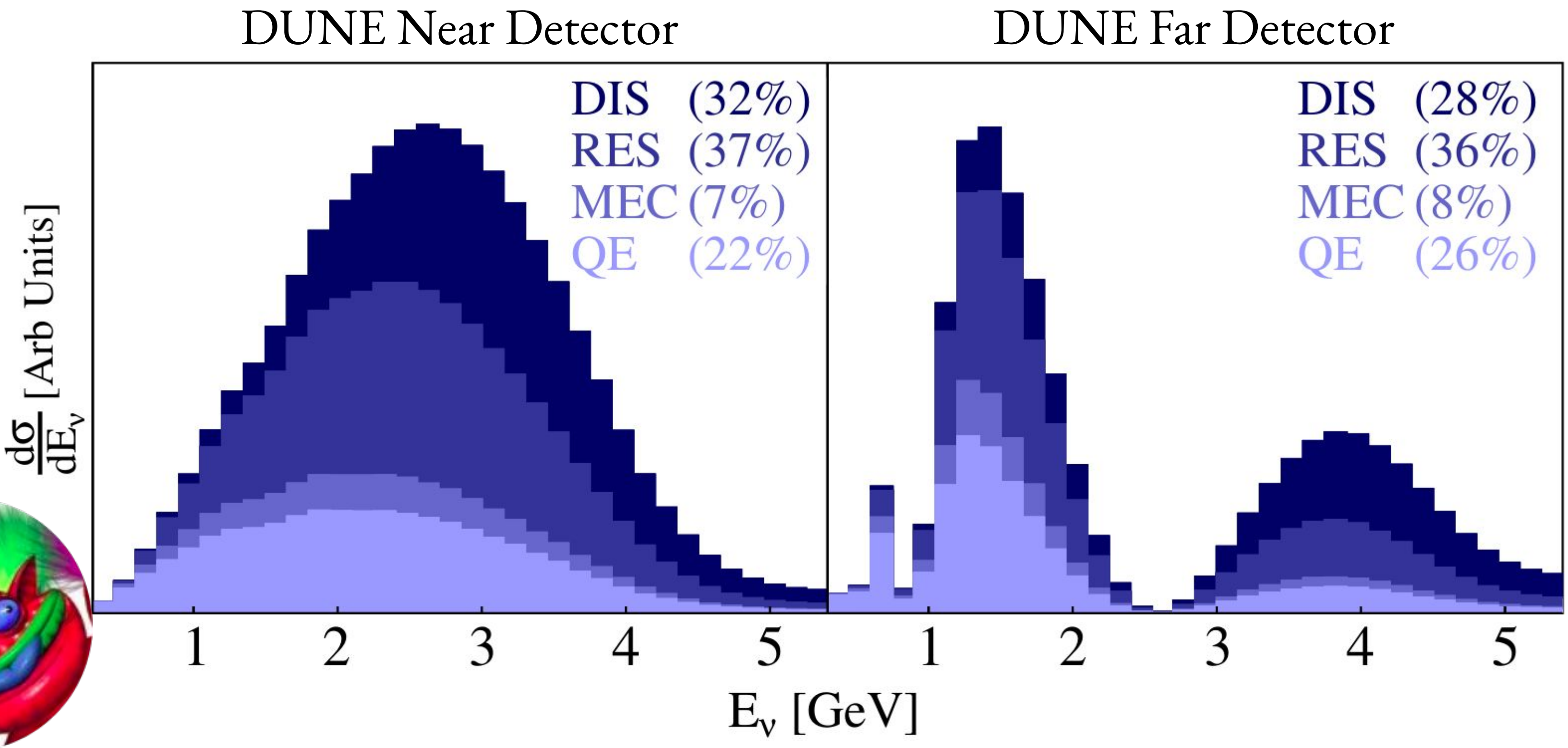
- Development of technique to combine simulated neutrino events and real cosmic events
- Novel technique for LArTPCs
- Default MicroBooNE simulation



MicroBooNE Flux

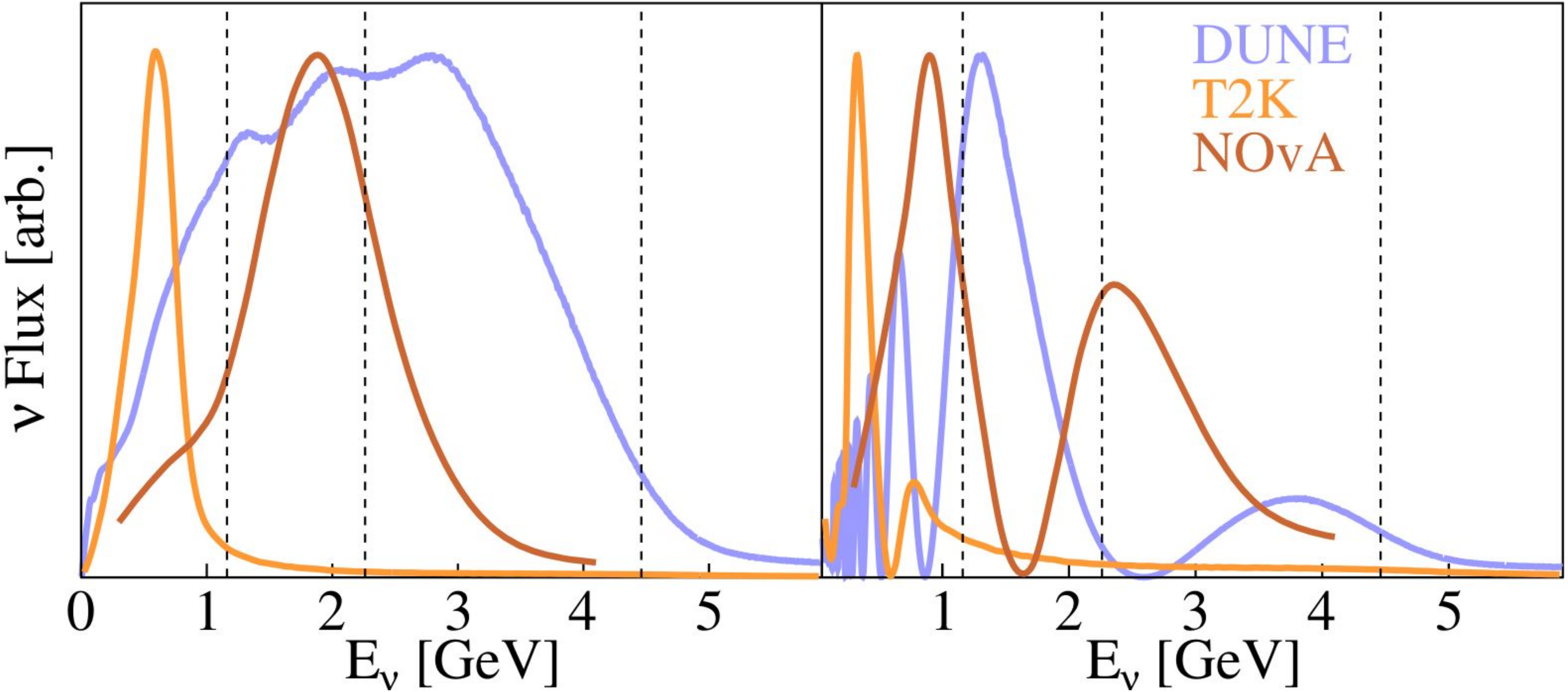


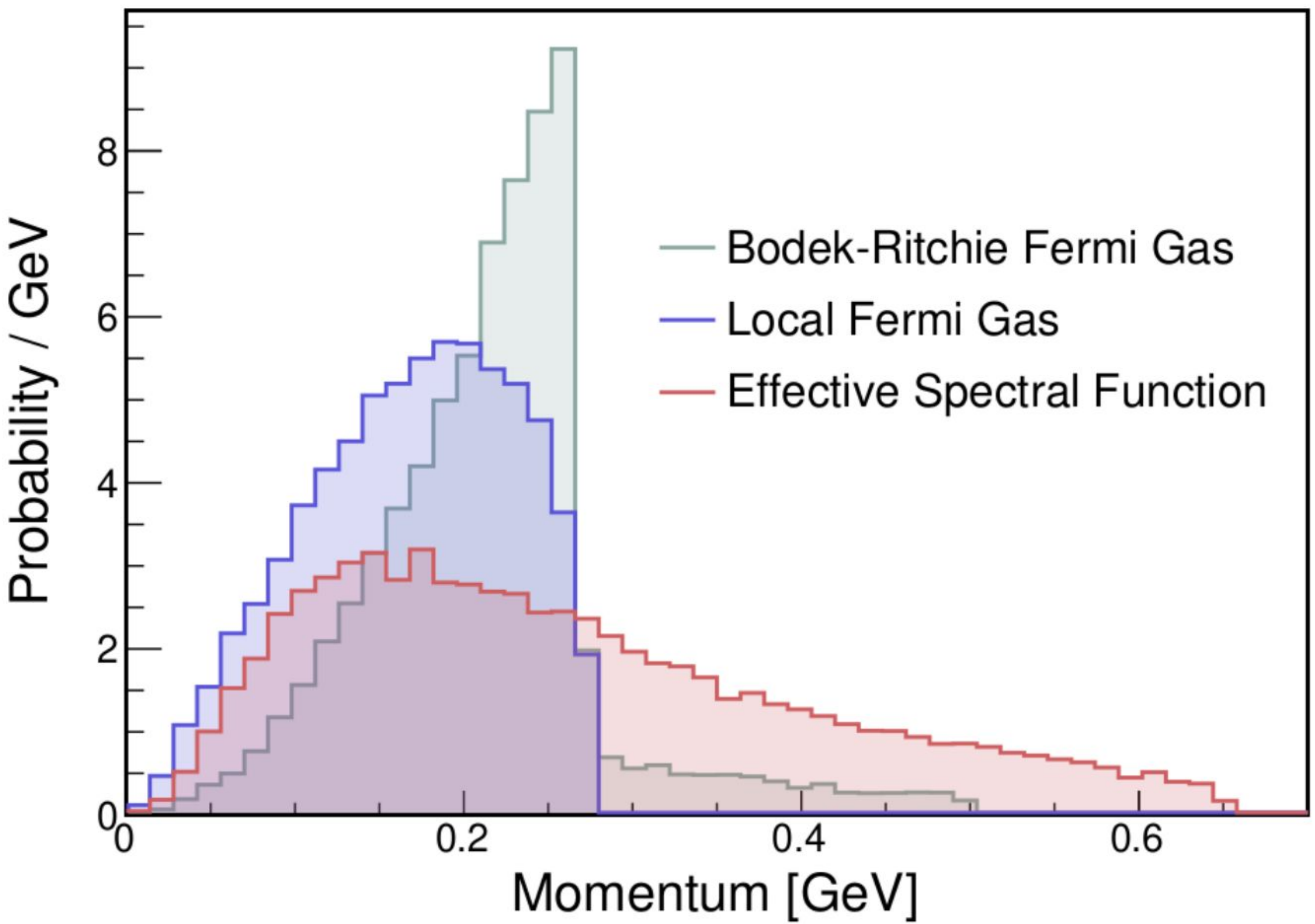
Nuclear Effects Smeared Due To Wide Neutrino Fluxes



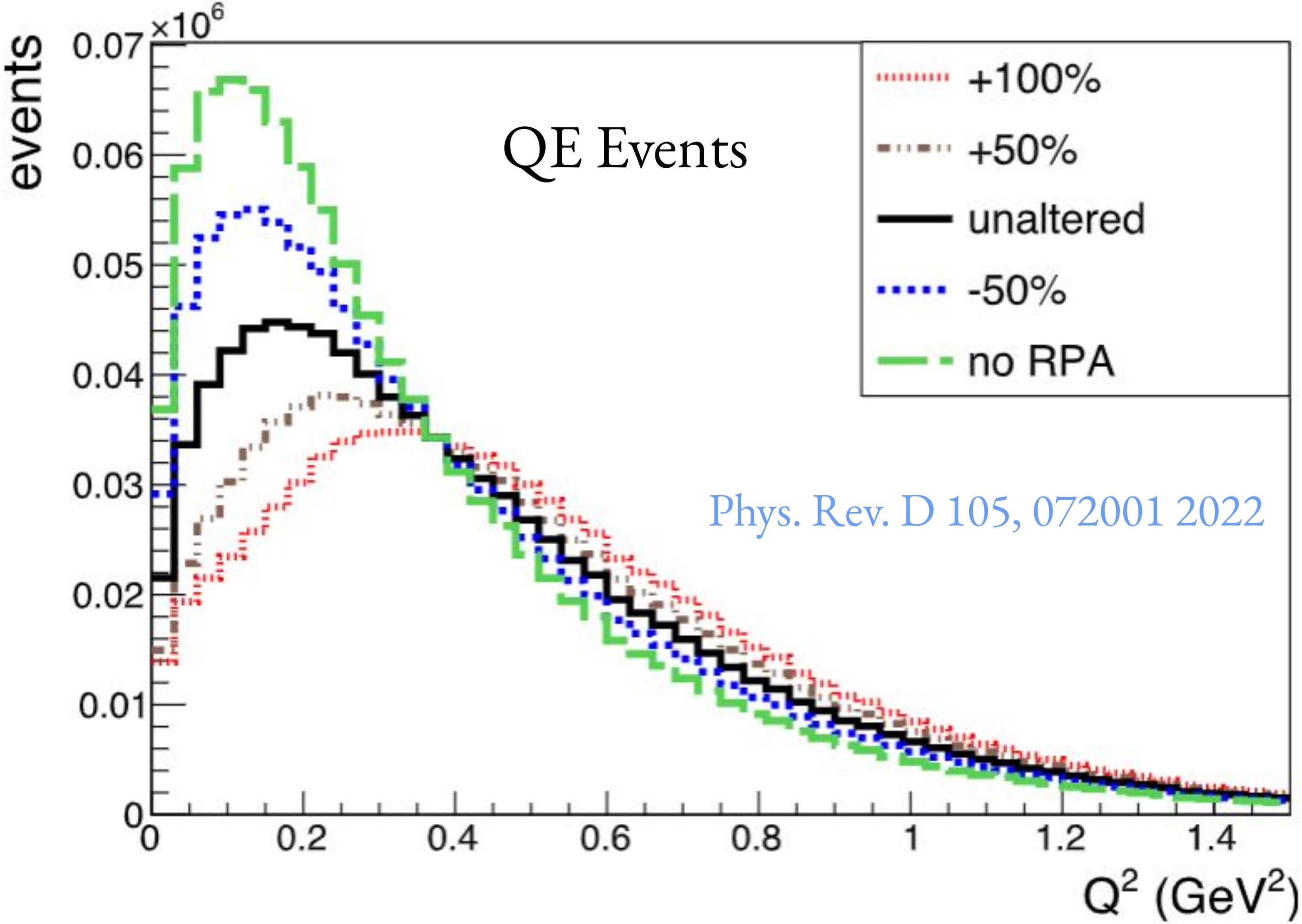
A.Papadopoulou, et al. Phys. Rev. D 103, 113003 (2021)

Wide Neutrino Beams



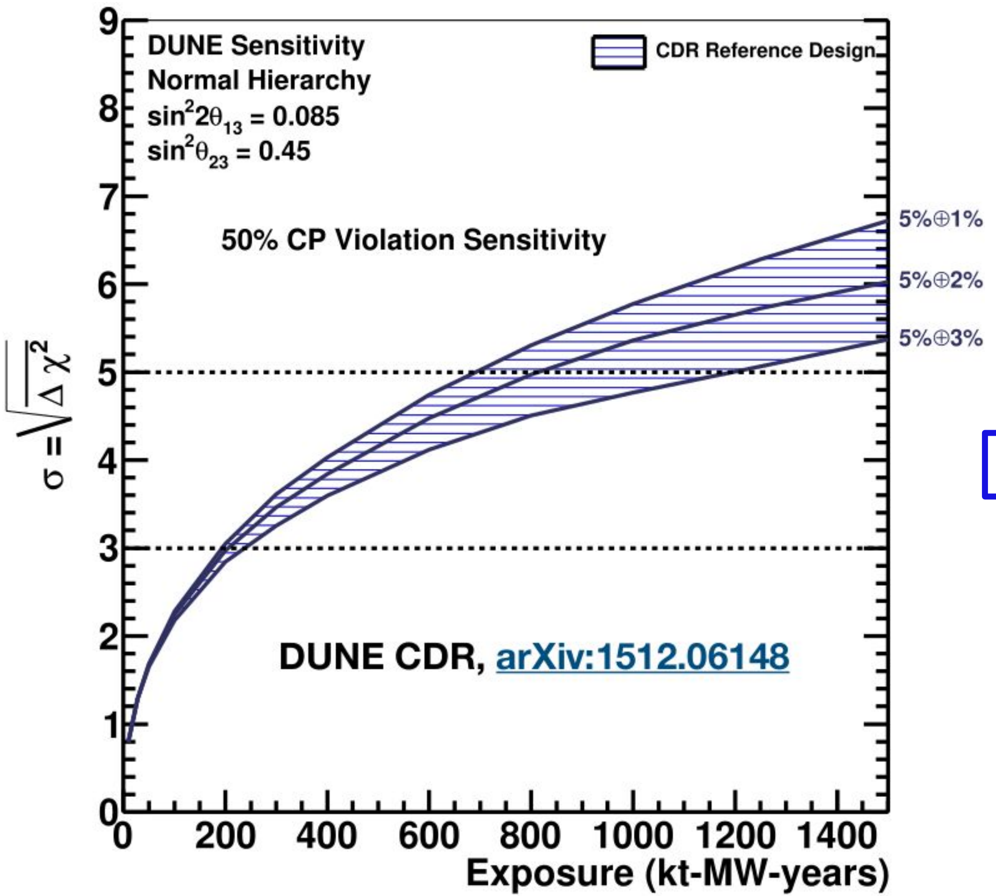


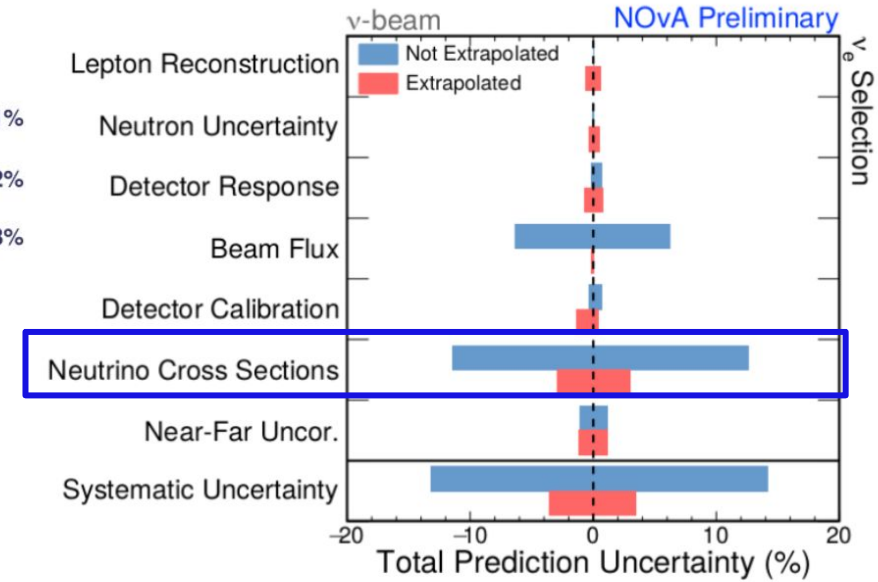
Bodek-Ritchie Fermi Gas
Local Fermi Gas
Effective Spectral Function
Probability / GeV
Momentum [GeV]
0
2
4
6
8
0
0.2
0.4
0.6



Phys. Rev. D 105, 072001 2022

What If The Interaction Modeling Is Wrong?





3 Flavor Case

$\boxed{a[\mathrm{eV}^2/c^4] = 7.56 \times 10^{-5} \rho[\mathrm{g/cm}^3] E_\nu[GeV]}$

[For antineutrino oscillation probabilities: $\delta \to -\delta, a \to -a$]

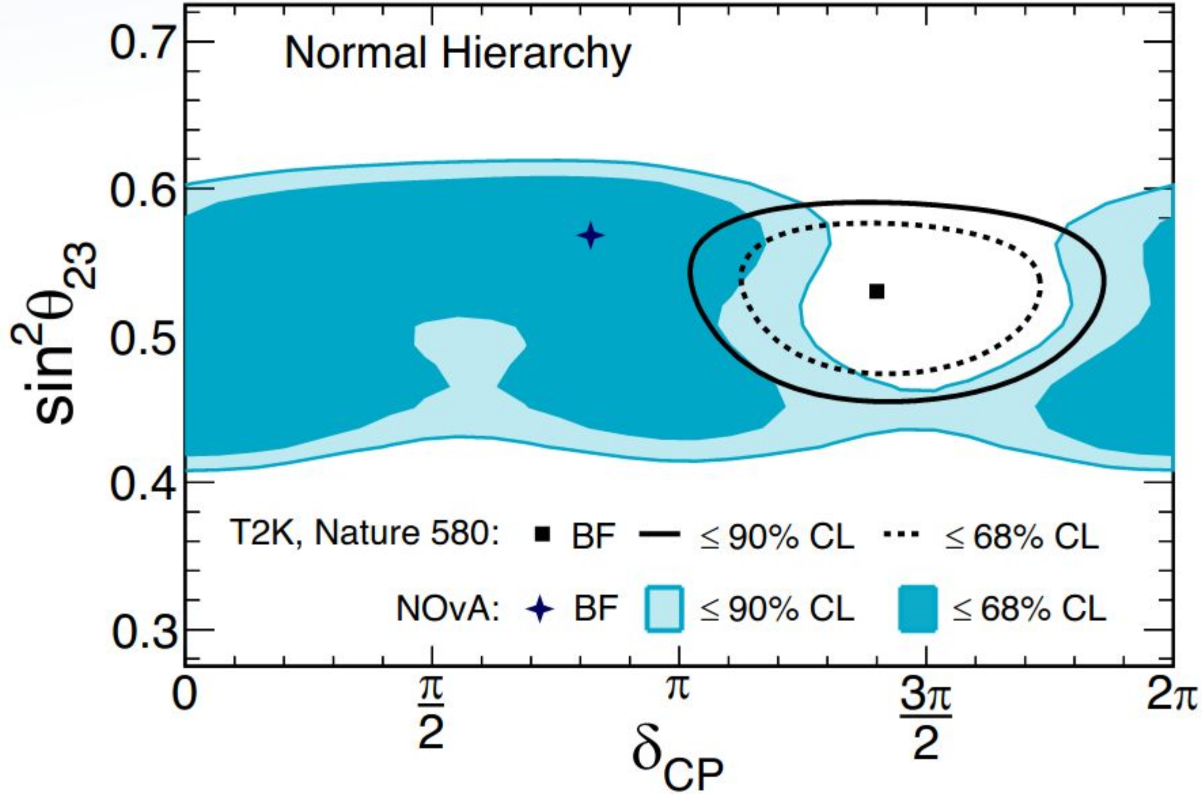
$\boxed{\phi_{ij} \equiv \frac{\Delta m^2_{ij} L}{4E}}$

$$
\begin{aligned}
P(\nu_\mu \to \nu_e) = & \; 4c_{13}^2 s_{13}^2 s_{23}^2 \sin^2 \phi_{31} \left(1 + \frac{2a}{\Delta m^2_{31}}(1 - 2s_{13}^2)\right) \\
& + 8c_{13}^2 s_{12} s_{13} s_{23}(c_{12}c_{23}\cos\delta - s_{12}s_{13}s_{23}) \cos\phi_{23} \sin\phi_{31} \sin\phi_{21} \\
& \boxed{- 8c_{13}^2 c_{12} c_{23} s_{12} s_{13} s_{23} \sin\delta \sin\phi_{32} \sin\phi_{31} \sin\phi_{21}} \\
& + 4s_{12}^2 c_{12}^2 (c_{12}^2 c_{23}^2 + s_{12}^2 s_{23}^2 s_{13}^2 - 2c_{12}c_{23}s_{12}s_{23}s_{13}\cos\delta) \sin^2\phi_{21} \\
& - 8c_{13}^2 s_{13}^2 s_{23}^2 (1 - 2s_{13}^2) \frac{aL}{4E_\nu} \cos\phi_{32} \sin\phi_{31}
\end{aligned}
$$

subleading,
CP-odd

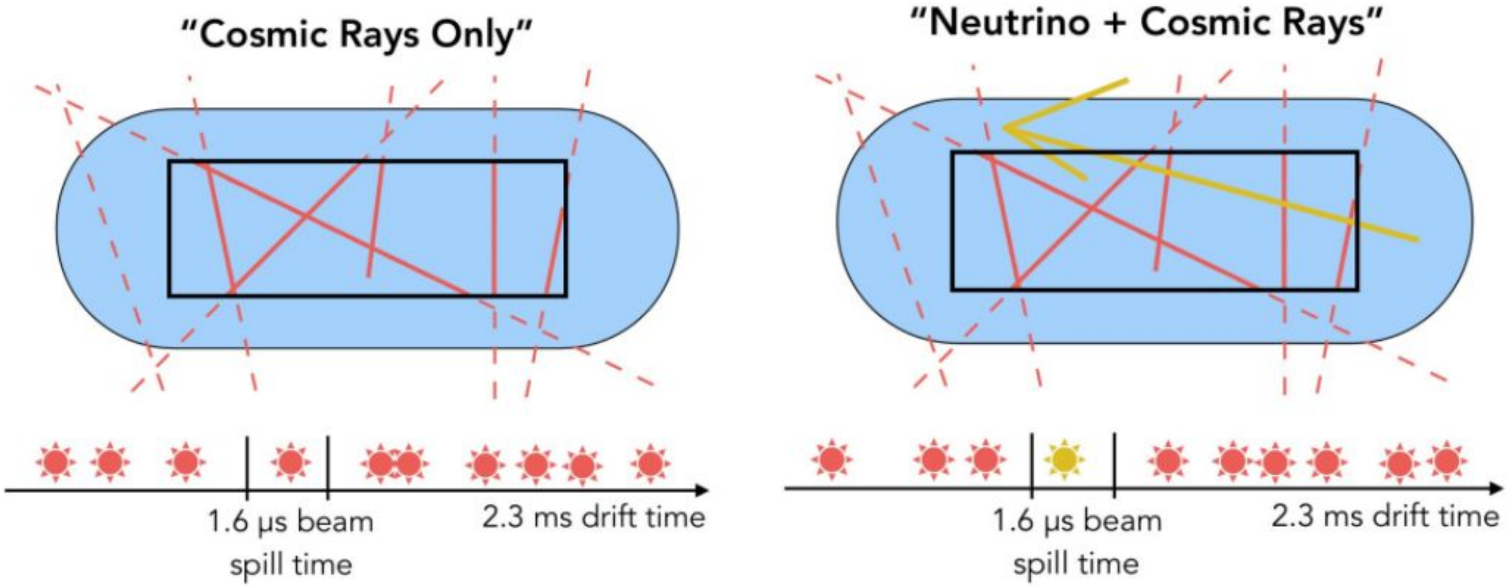
$$
\begin{aligned}
P(\nu_\mu \to \nu_\mu) = & \; 1 - 4(s_{12}^2 c_{23}^2 + s_{13}^2 s_{23}^2 c_{12}^2 + 2s_{12}s_{13}s_{23}c_{12}c_{23}\cos\delta) s_{23}^2 c_{13}^2 \sin^2\phi_{31} \\
& - 4(c_{12}^2 c_{23}^2 + s_{13}^2 s_{23}^2 s_{12}^2 - 2s_{12}s_{13}s_{23}c_{12}c_{23}\cos\delta) s_{23}^2 c_{13}^2 \sin^2\phi_{32} \\
& - 4(s_{12}^2 c_{23}^2 + s_{13}^2 s_{23}^2 c_{12}^2 + 2s_{12}s_{13}s_{23}c_{12}c_{23}\cos\delta) \\
& \times (c_{12}^2 c_{23}^2 + s_{13}^2 s_{23}^2 s_{12}^2 - 2s_{12}s_{13}s_{23}c_{12}c_{23} cos\delta) \sin^2\phi_{21}
\end{aligned}
$$

Comparison to T2K



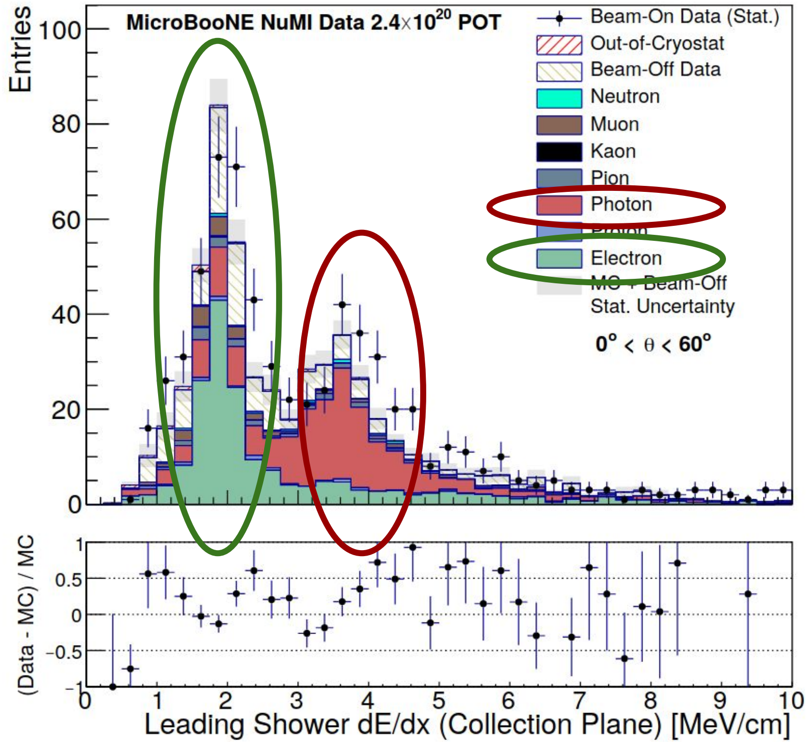
Alex Himmel's Neutrino 2020 Talk

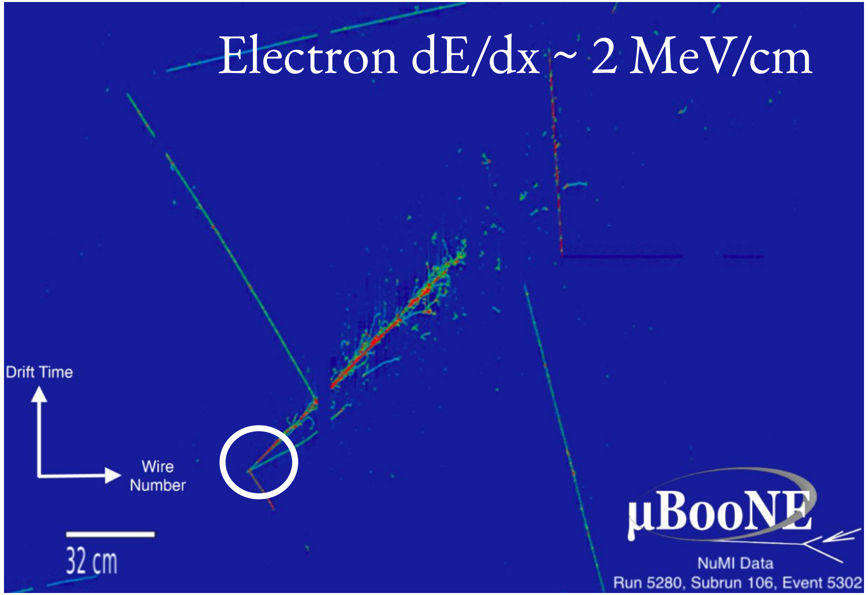
- Clear tension with T2K's preferred region.
- Quantifying consistency requires a joint fit of the data from the two experiments, which is already in the works.


"Cosmic Rays Only"
1.6 µs beam spill time
2.3 ms drift time
"Neutrino + Cosmic Rays"
1.6 µs beam spill time
2.3 ms drift time

LArTPC Strength: Electrons vs Photons

- Electrons deposit half the energy compared to photons
- Shower start attached to interaction vertex



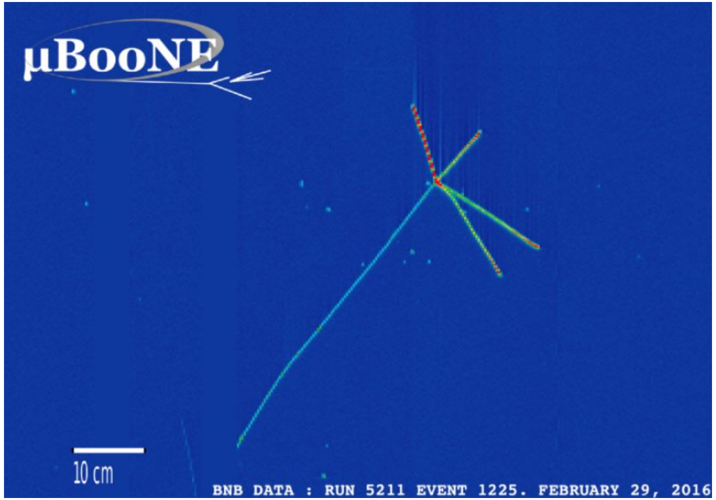


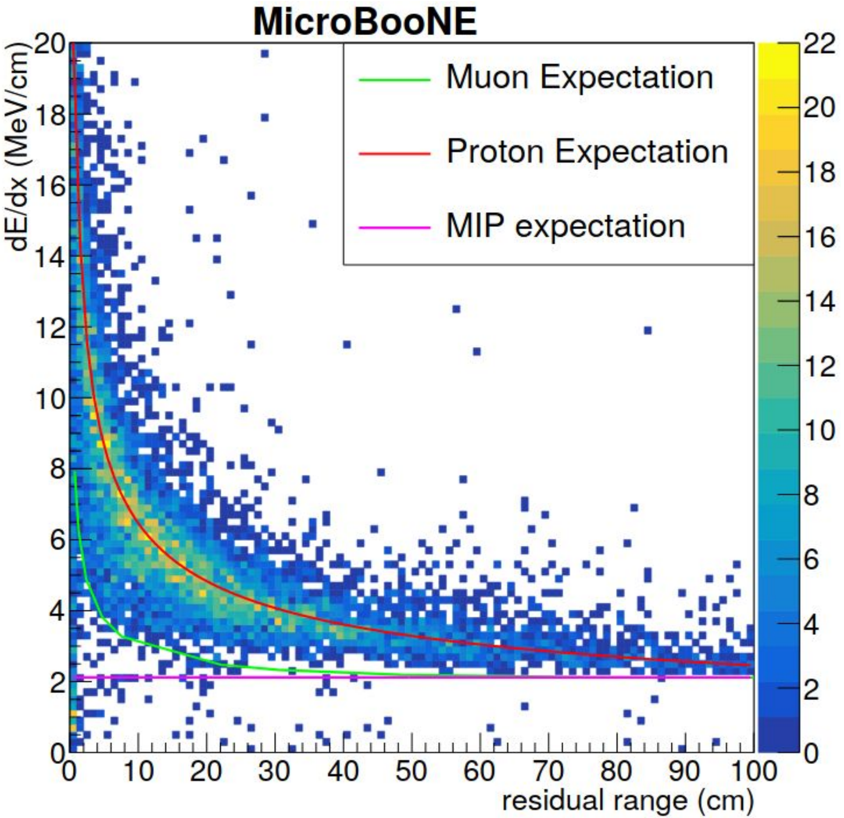
arXiv:2101.04228

Energy Deposition Profile

Protons identified by Bragg peak in last 30 cm of track

Low proton threshold @ **300 MeV/c**

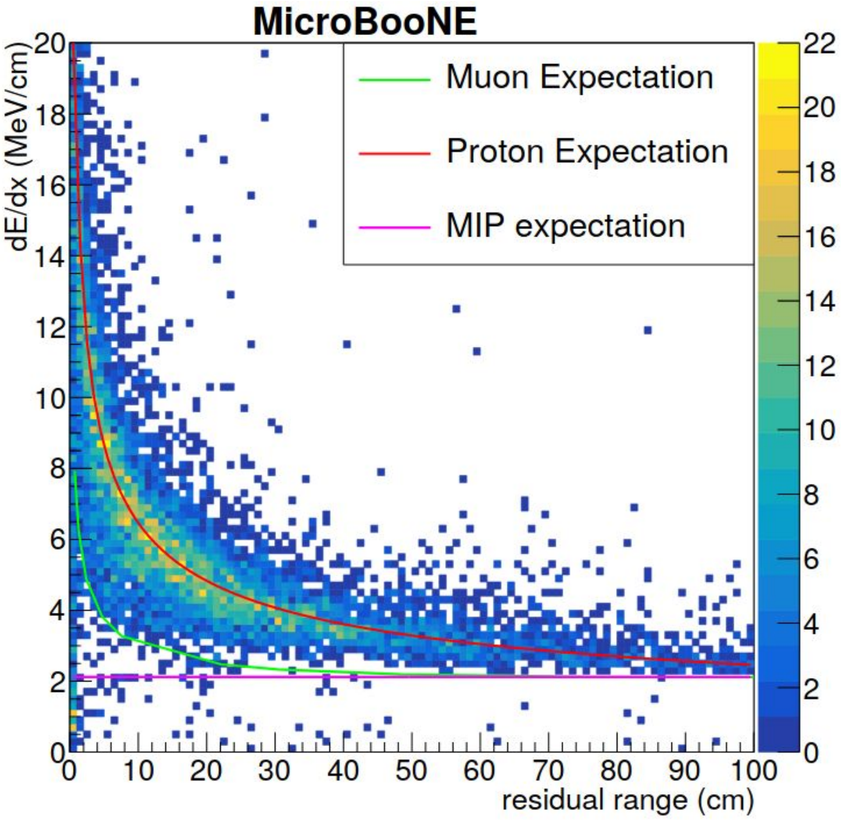




JINST 15, P03022 (2020)

Energy Deposition Profile

$$\text{PID} = \chi^2_{\text{proton}}/\text{d.o.f.} = \sum_{\text{Track hits}} \left(\frac{(dE/dx_{\text{measured}} - dE/dx_{\text{theory}})}{\sigma_{dE/dx}} \right)^2 \Bigg/ \text{d.o.f.},$$



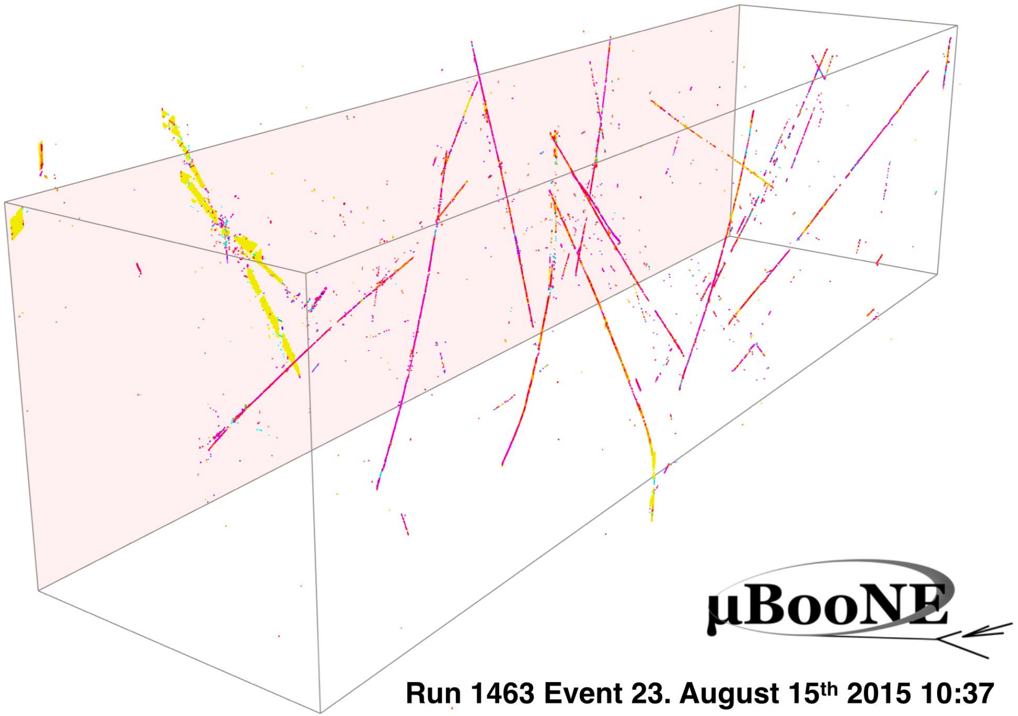
JINST 15, P03022 (2020)

Cosmic Rejection

- Energy deposition profile
- Track length
- Scintillation light at vertex
- Non-collinearity

$$|\Delta\theta_{\mu p} - 90^o| < 55^o$$

- Charge deposition at vertex

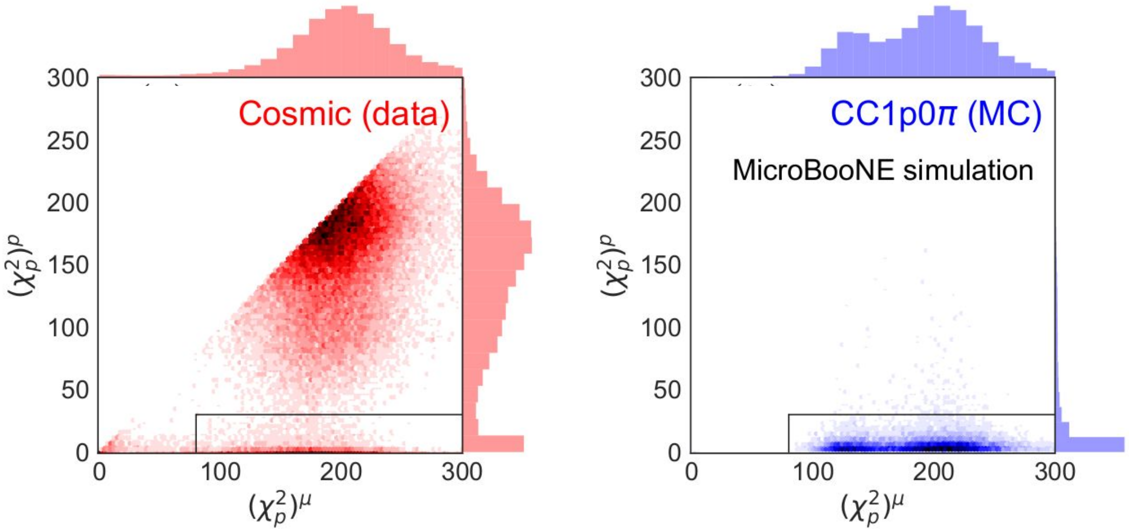


E.Cohen, A.Papadopoulou, et al,
Eur. Phys. J. C 79, 673 (2019)

Energy Deposition Profile

$$\chi^2_{\mu} > \chi^2_{p}$$

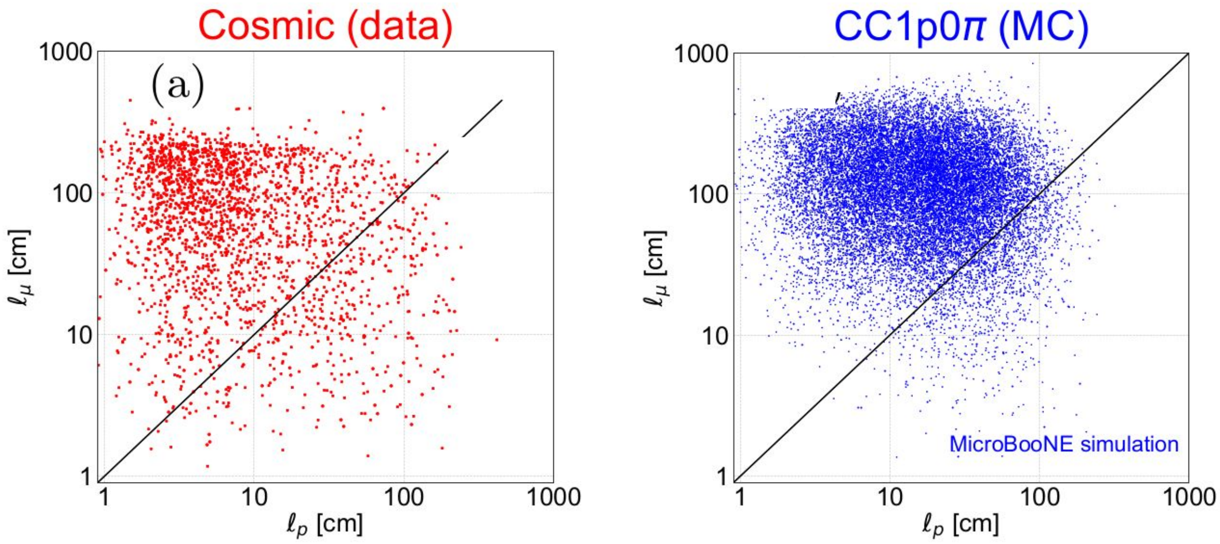
$$\chi^2_{\mu} > 80 \ \& \ \chi^2_{p} < 30$$



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

Track Length

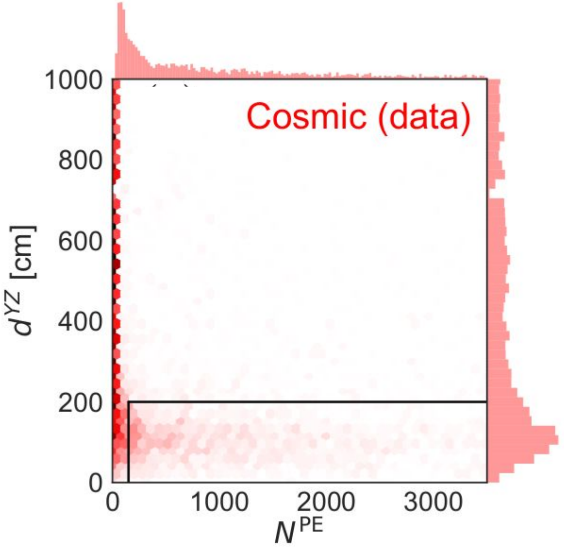
$$\ell_\mu > \ell_p$$

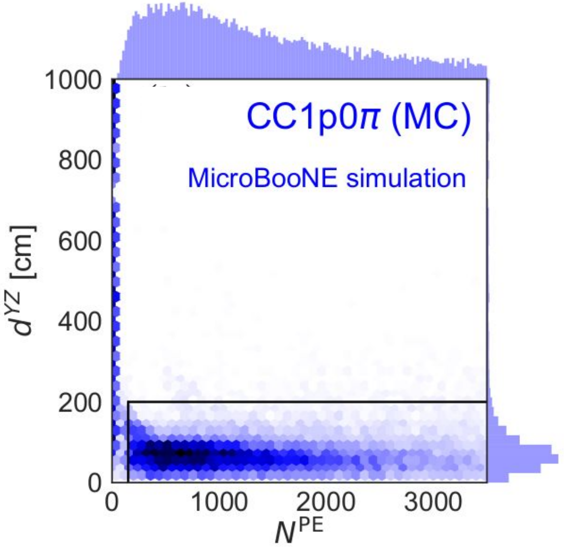


Eur. Phys. J. C 79 673 (2019)

Scintillation Light

photoelectrons > 200
YZ vertex-flash distance < 2 m

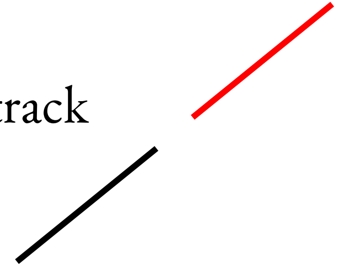


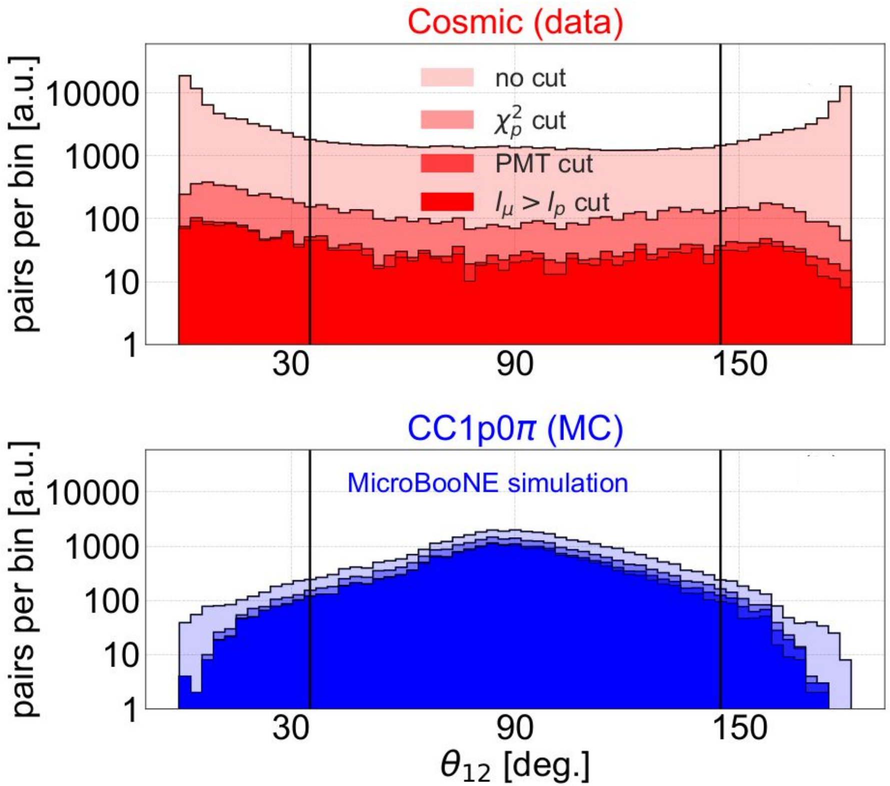


Eur. Phys. J. C 79 673 (2019)

$|\Delta\theta_{\mu p} - 90^o| < 55^o$

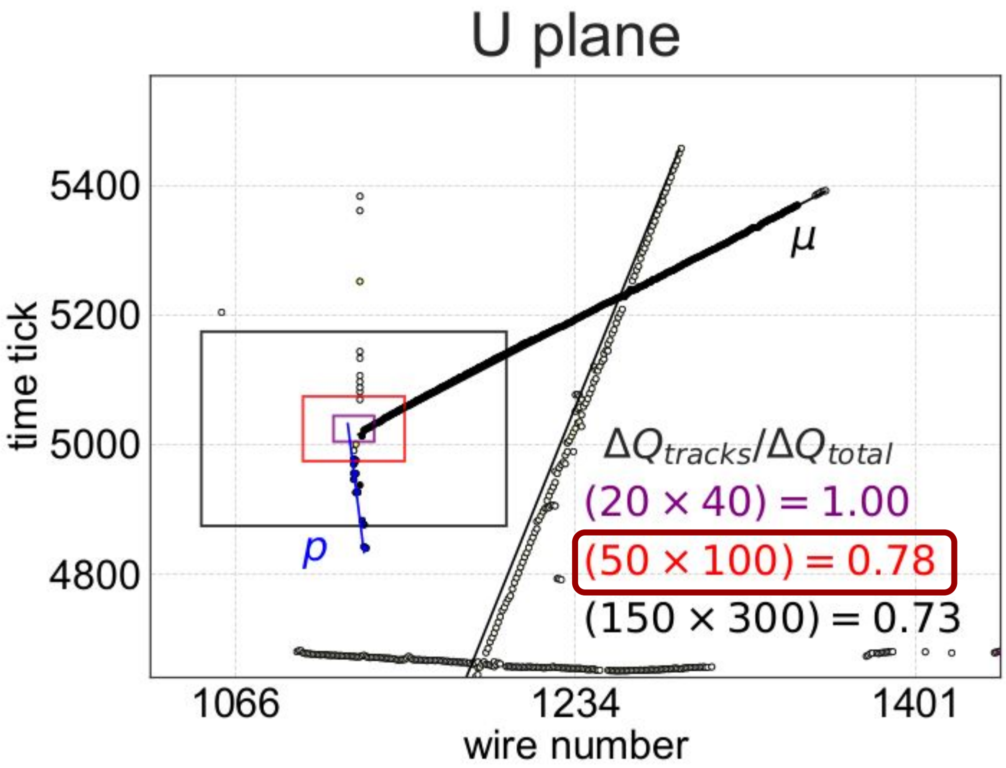
Broken track





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

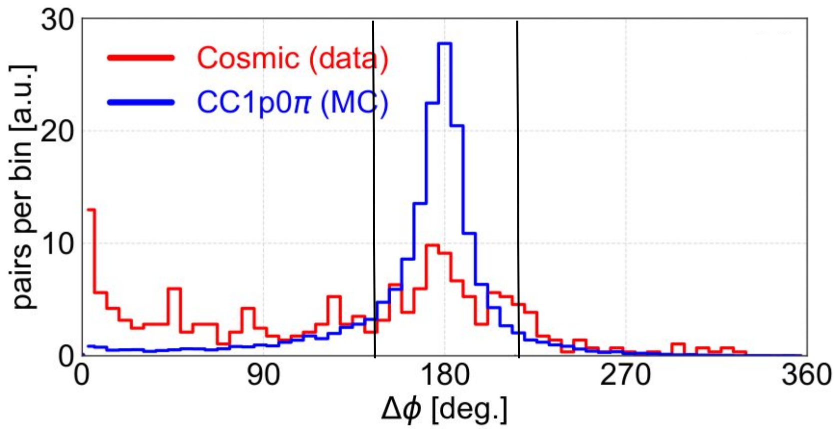
Vertex Activity



CCQE Enhancement

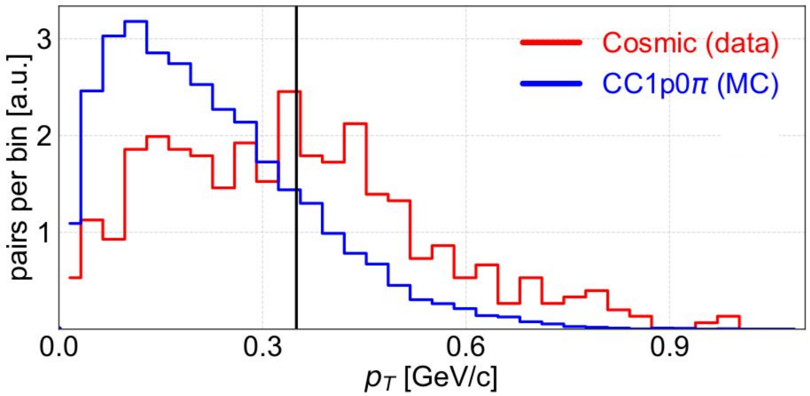
Coplanarity

$$|\Delta\phi_{\mu p} - 180^o| < 35^o$$



Transverse imbalance

$$P_T = |\vec{P}_\mu + \vec{P}_p|_T < 0.35\, GeV/c$$



E.Cohen, A.Papadopoulou, et al,
Eur. Phys. J. C 79, 673 (2019)

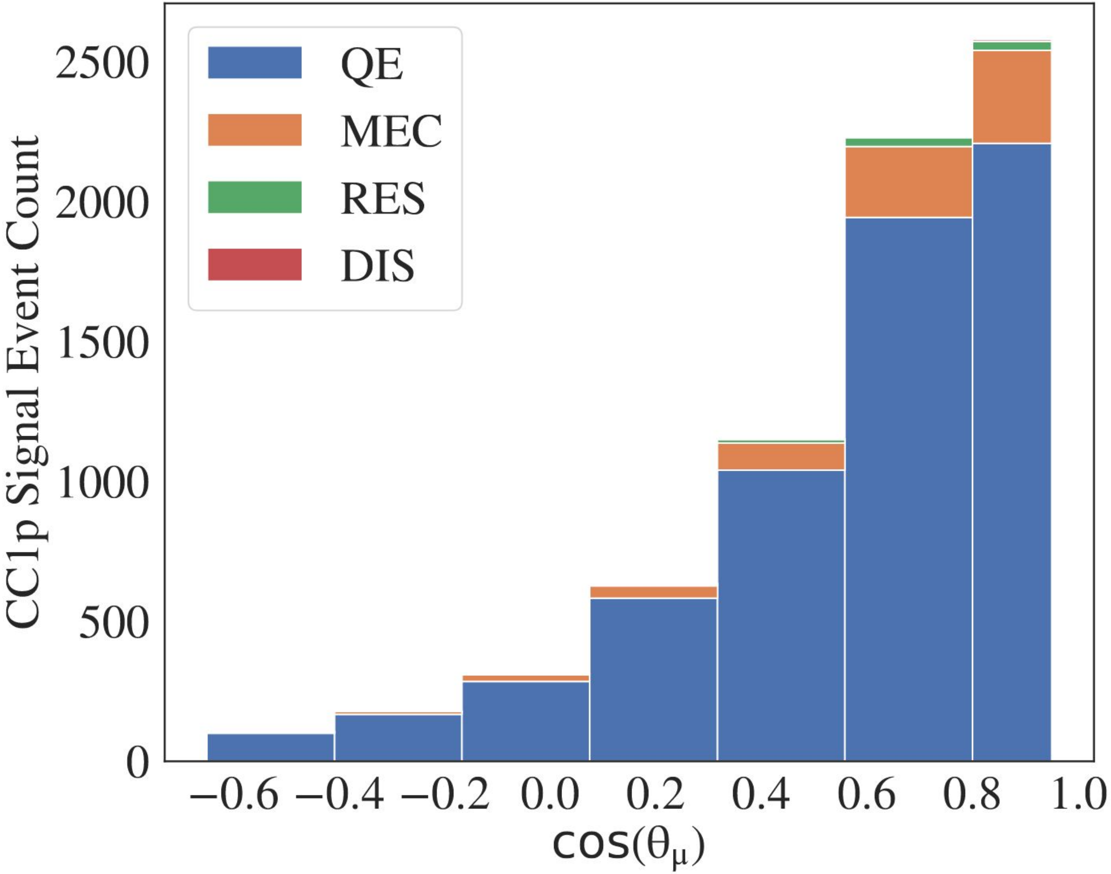
Cross Section Extraction

- Event selection in data sample
- Cosmic background subtraction
- Beam related MC background subtraction
- Detection efficiency correction

$$\frac{\mathrm{d}\sigma}{\mathrm{dX}_n} = \frac{\mathrm{N}_n^{\mathrm{on}} - \mathrm{N}_n^{\mathrm{off}} - \mathrm{B}_n}{\epsilon_n \cdot \Phi_\nu \cdot \mathrm{N}_{\mathrm{target}} \cdot \Delta_n}$$

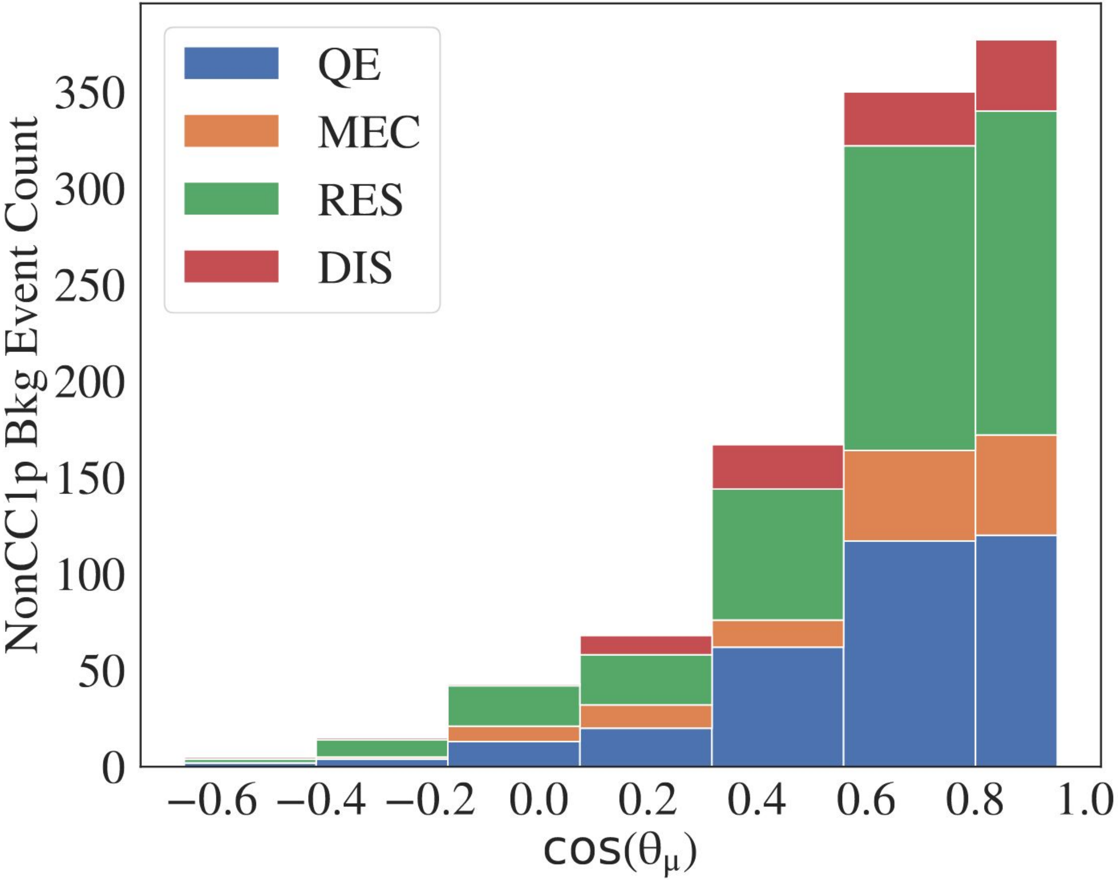
X = kinematic variable of interest

CC1p0π Breakdown



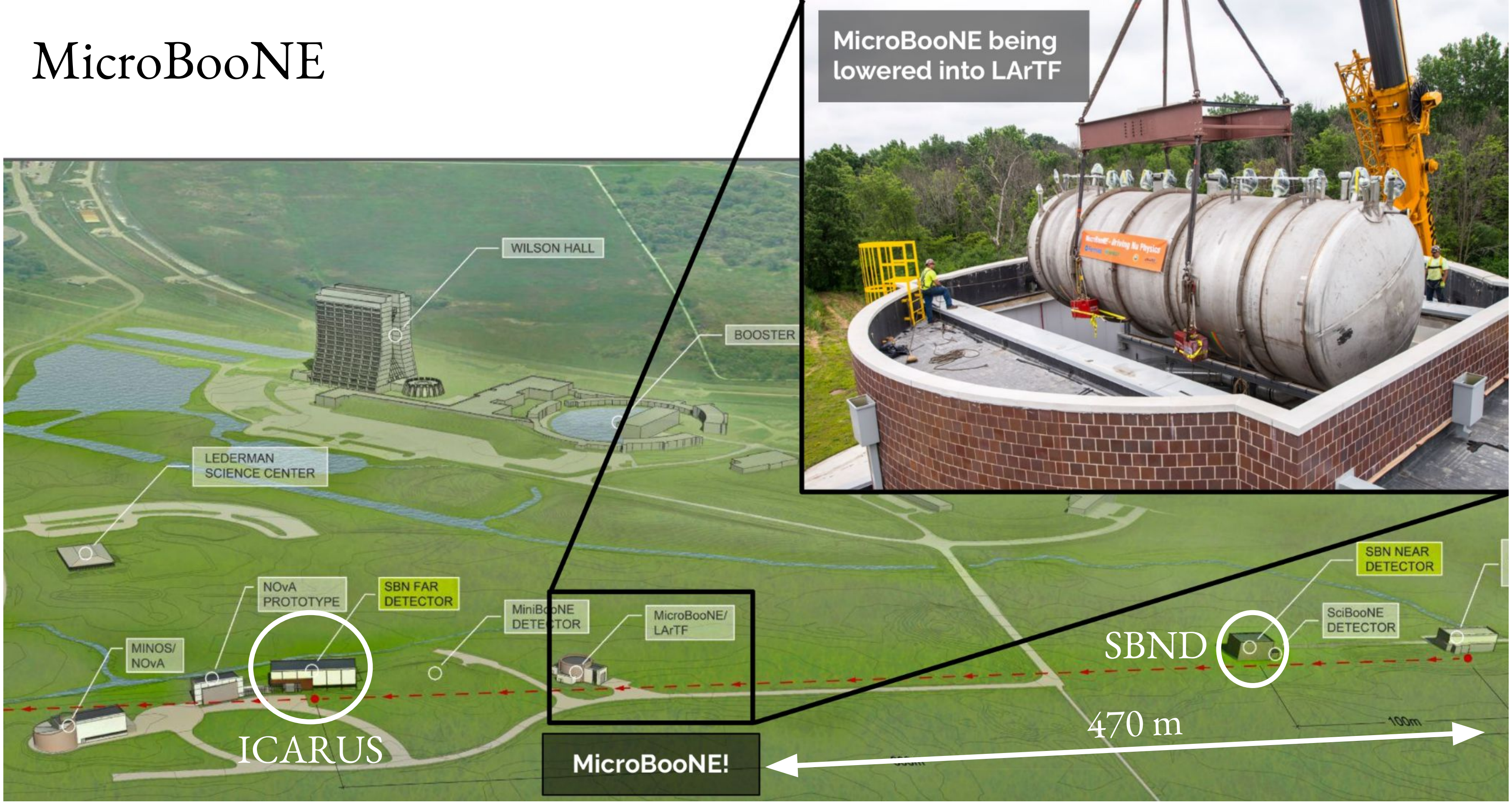
Interaction Mode	Fractional Contribution (%)
QE	87.9
MEC	10.6
RES	1.2
DIS	0.2

Non CC1p0π Breakdown



Interaction Mode	Fractional Contribution (%)
QE	33.0
MEC	13.1
RES	44.1
DIS	9.9

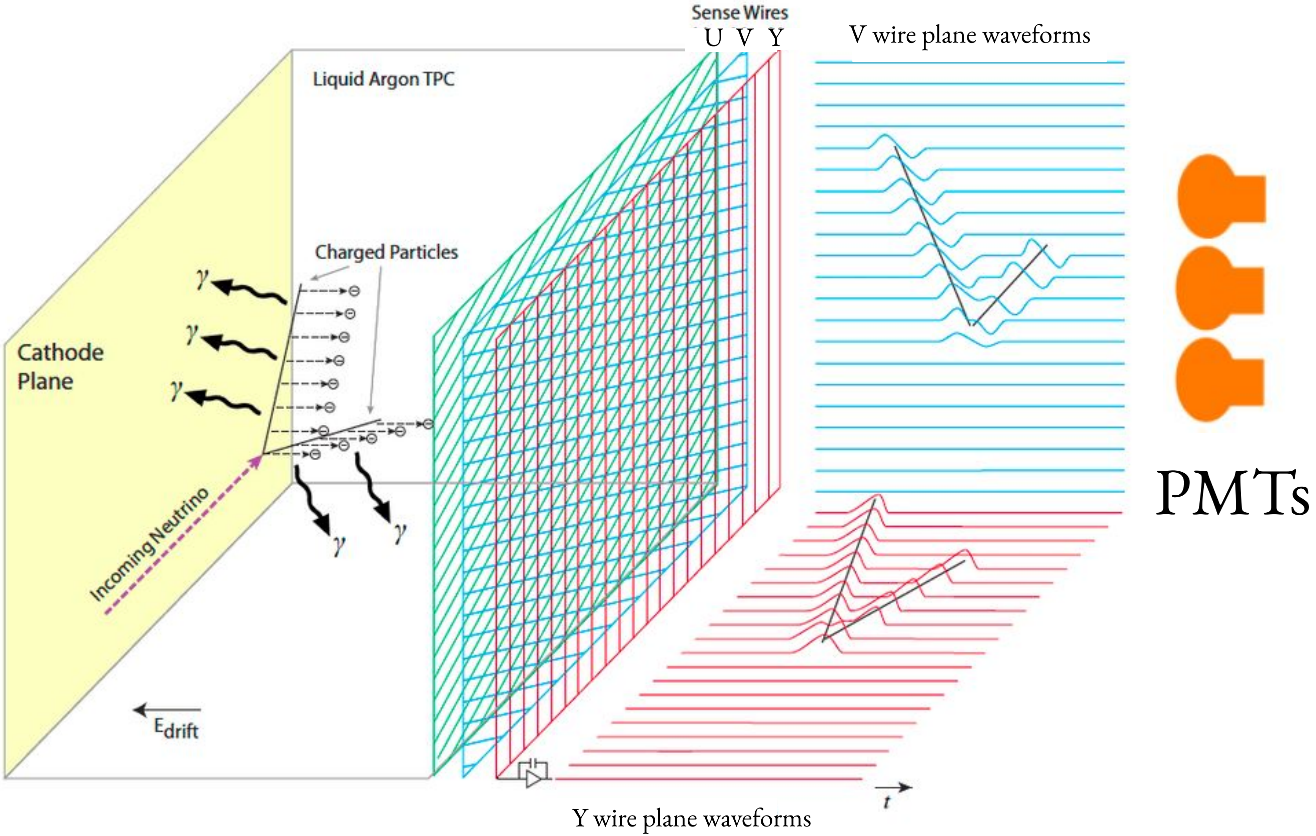
MicroBooNE



85 ton Liquid Argon Time Projection Chamber (LArTPC)

JINST 12, P02017 (2017)

Time Projection Chambers



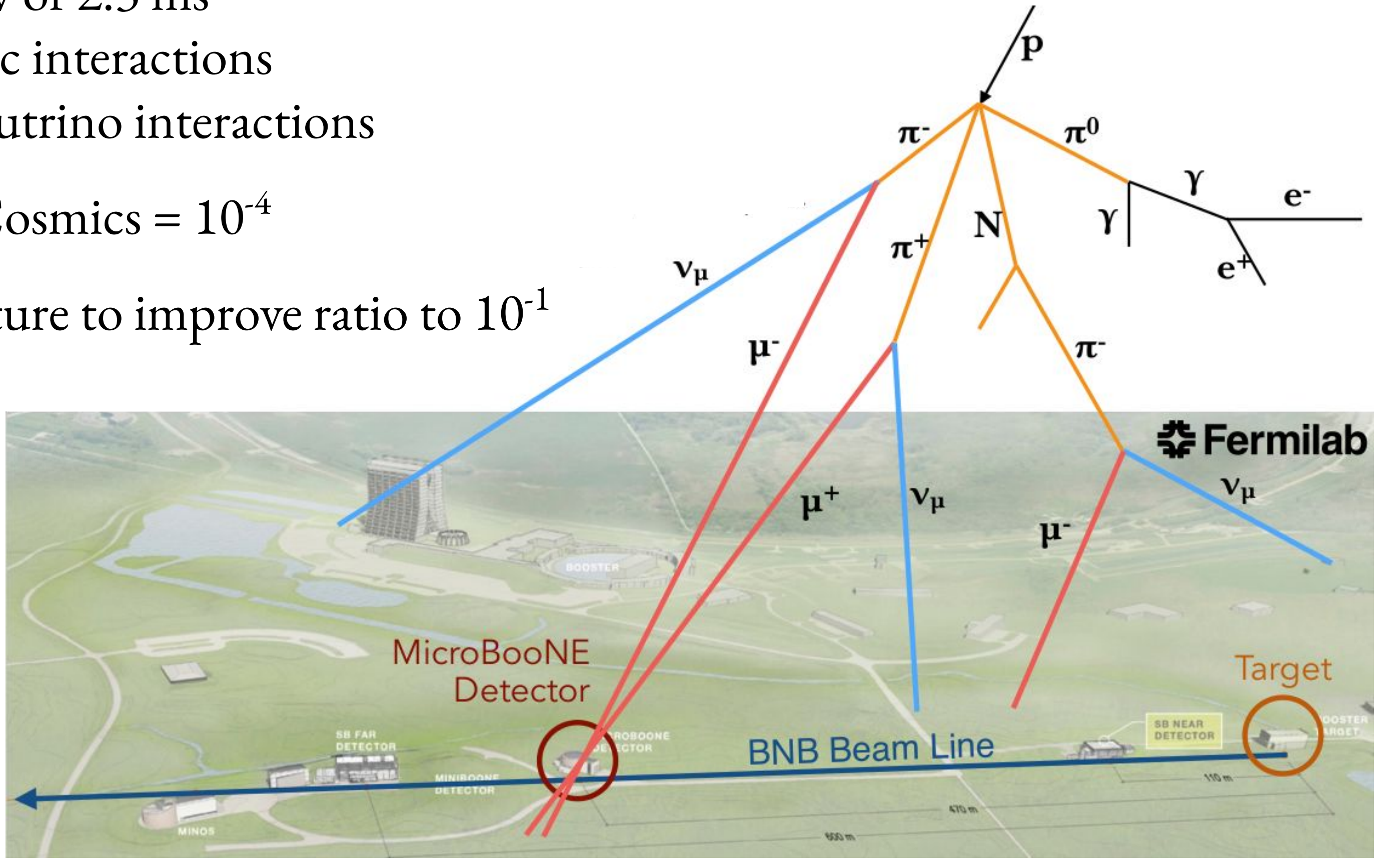
Cosmic Events Dominate

Readout window of 2.3 ms

- ~20 cosmic interactions
- ~0.002 neutrino interactions

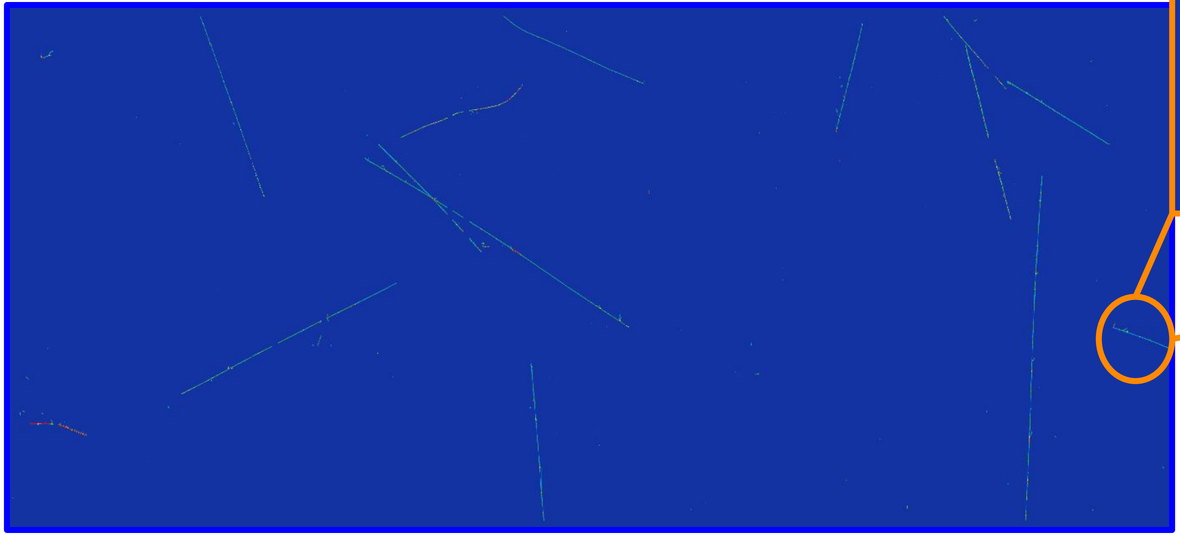
Neutrino/Cosmics = 10^{-4}

Beam time structure to improve ratio to 10^{-1}



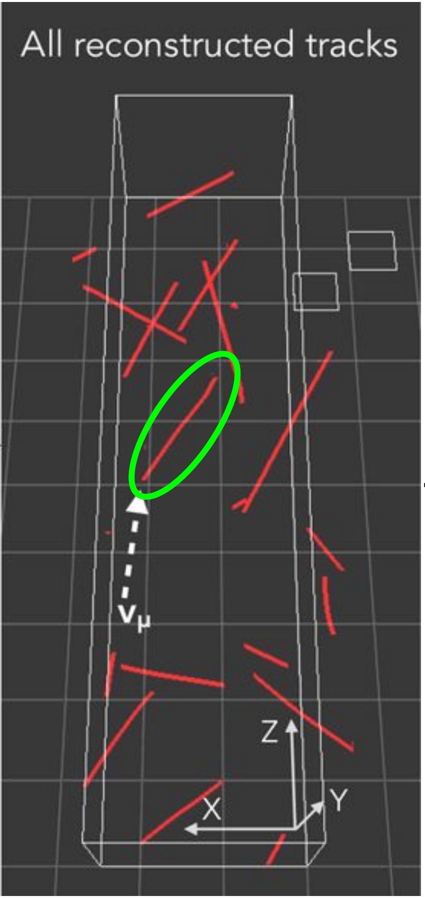
Isolating Neutrino Events In A Cosmic Sea

- Development of technique to combine simulated neutrino events and real cosmic events
- Novel technique for LArTPCs
- Default MicroBooNE simulation

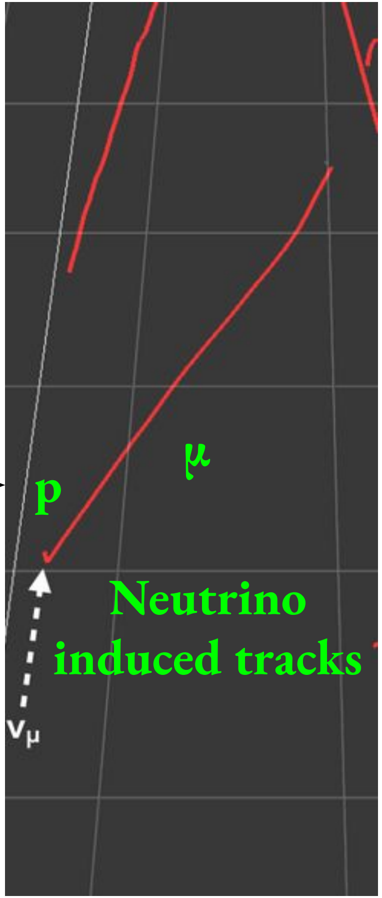


CC1p0π Event Selection

CC1p0π Event Selection



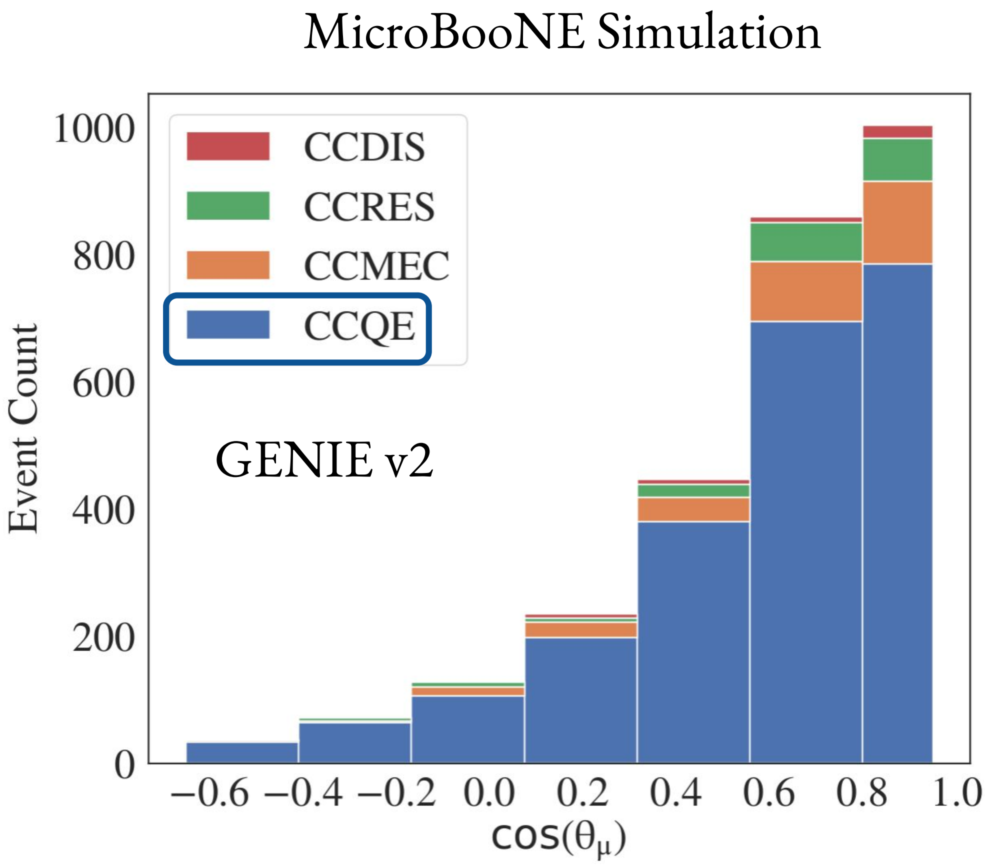
Zoom
In



Detector and kinematics–based cuts to reject cosmics & to enhance CC1p0π signal

E.Cohen, **A.Papadopoulou**, et al.
Eur. Phys. J. C 79, 673 (2019)

CCQE Dominance



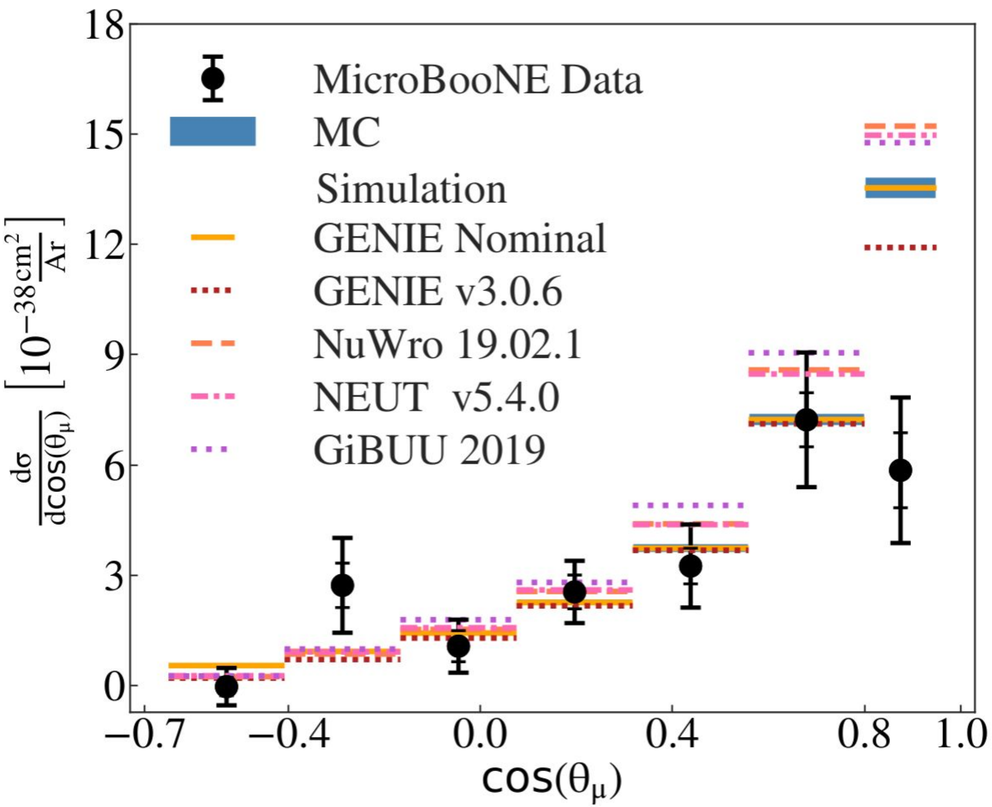
410 candidate 1p0π events

- **84%** CC1p0π

Interaction Mode	Fractional Contribution (%)
CCQE	81.1
CCMEC	10.9
CCRES	6.6
CCDIS	1.4

A.Papadopoulou, et al.
Phys. Rev. Lett. 125, 201803 (2020)

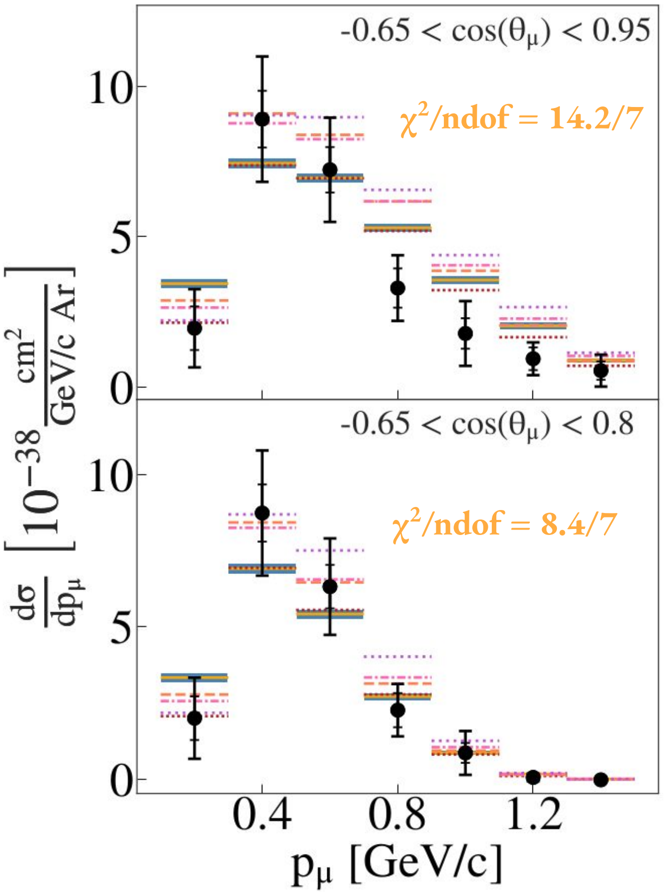
Cross section vs Muon Angle



Good agreement with models, except at small angles

A.Papadopoulou, et al.
Phys. Rev. Lett. 125, 201803 (2020)

Cross section vs Muon Momentum



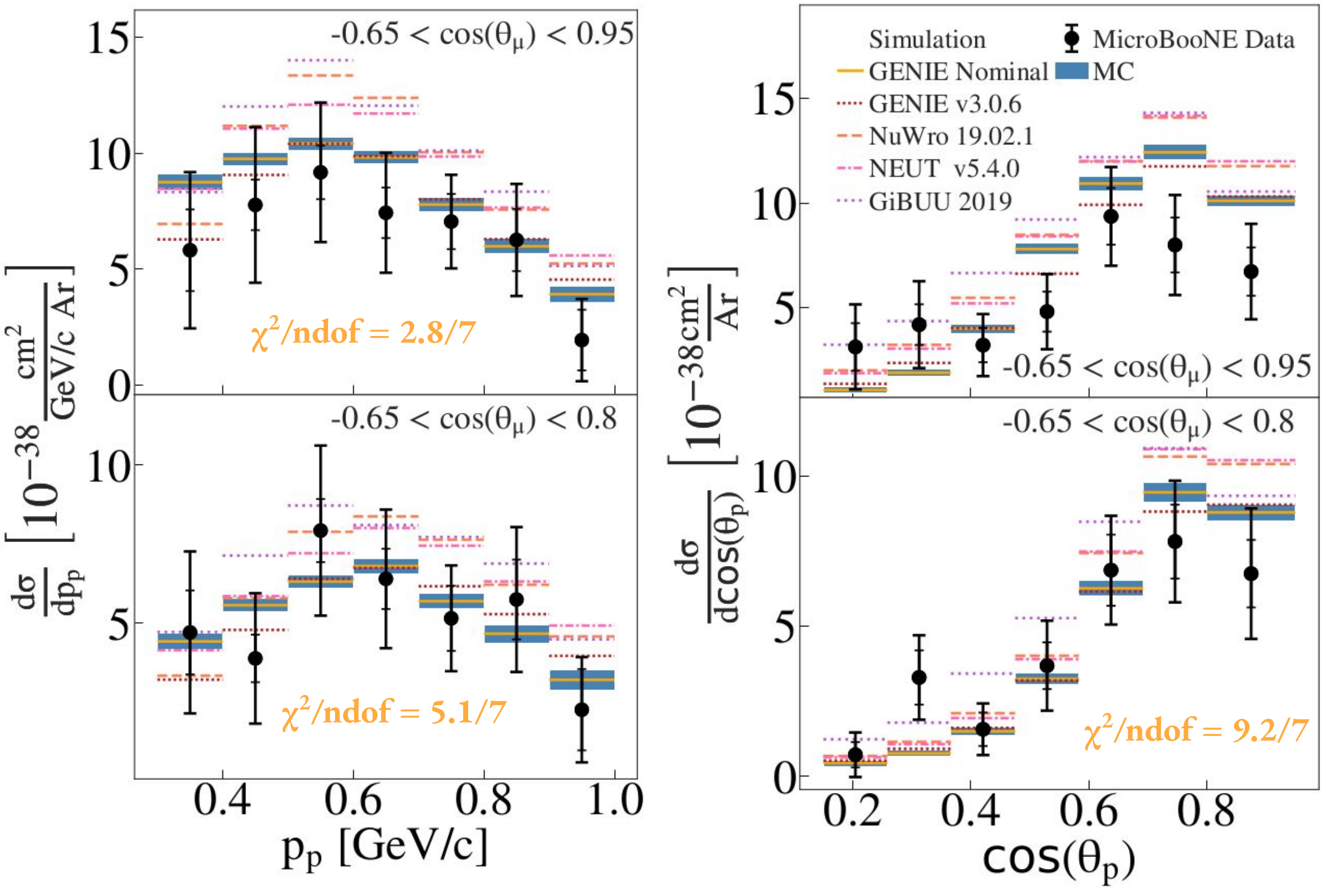
All muon angles

Improved agreement if small angles are excluded

Excluding small angles

A.Papadopoulou, et al.
Phys. Rev. Lett. 125, 201803 (2020)

Cross section vs Proton Variables



All muon angles

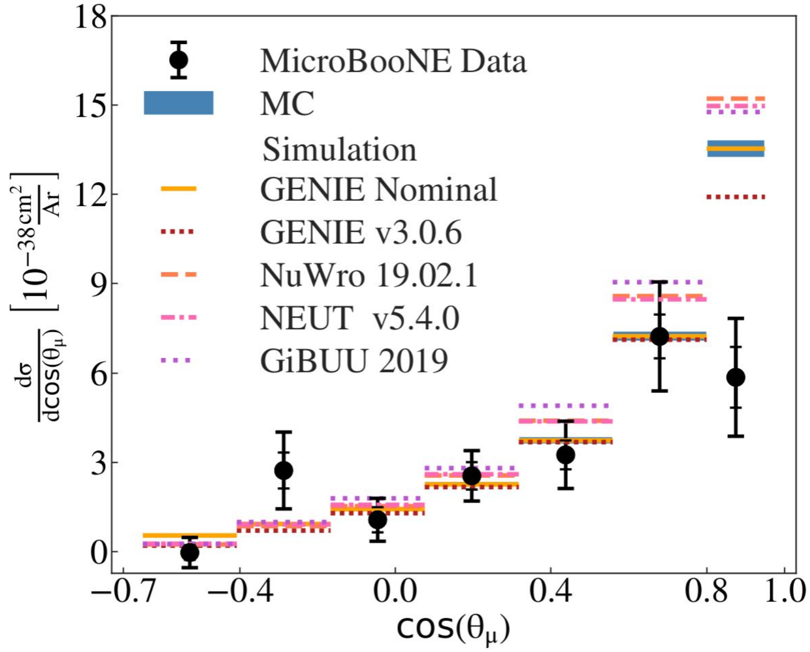
χ^2/ndof = 12.4/7

Excluding small angles

A.Papadopoulou, et al.
Phys. Rev. Lett. 125, 201803 (2020)

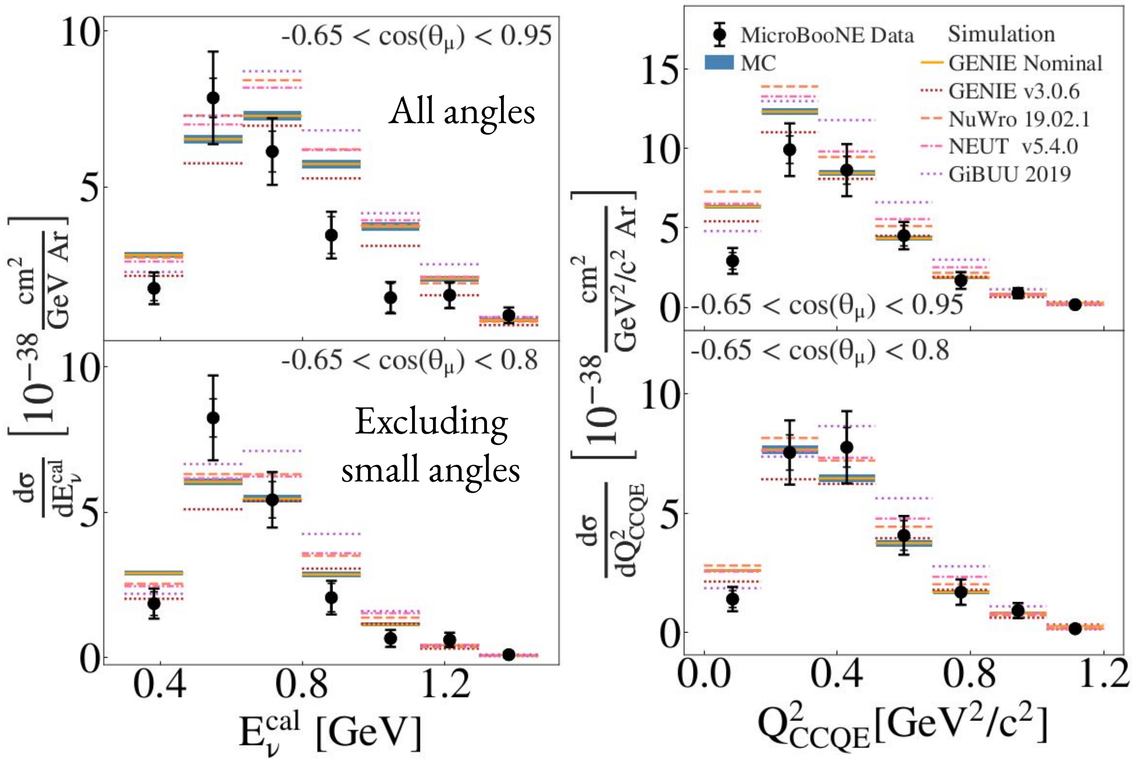
MicroBooNE CCQE-like Wrap Up

- First measurement of neutrino-argon CCQE-like cross sections
- Powerful cosmic background rejection and high CC1p0π signal purity
- Need for improved modeling!



A.Papadopoulou, et al.
Phys. Rev. Lett. 125, 201803 (2020)

More Cross Sections



$$E_\nu^{cal} = E_\mu + T_p + 40\,\mathrm{MeV}$$

$$\vec{p_\nu} = (0, 0, E_\nu^{cal})$$

$$Q^2_{CCQE} = (E_\nu^{cal} - E_\mu)^2 - (\vec{p_\nu} - \vec{p_\mu})^2$$

Under QE assumption

A.Papadopoulou, et al,
Phys. Rev. Lett. 125, 201803 (2020)

Integrated Cross Sections & χ^2

TABLE I. Integrated cross section values and χ^2 values for the agreement between the measured cross sections and various event generators. Results are listed for the full measured phase space and for a limited one of $\cos(\theta_\mu) < 0.8$.

		Integrated cross section (10^{-38} cm^2) (Differential cross section χ^2/d.o.f) $-0.65 < \cos(\theta_\mu) < 0.95$	Integrated cross section (10^{-38} cm^2) (Differential cross section χ^2/d.o.f) $-0.65 < \cos(\theta_\mu) < 0.8$
Data CC1$p0\pi$ integrated		4.93 ± 1.55	4.05 ± 1.40
Generators	GENIE nominal	6.18 (63.2/28)	4.04 (30.1/27)
	GENIE v3.0.6	5.45 (34.6/28)	3.66 (21.4/27)
	NuWro 19.02.1	6.67 (76.7/28)	4.39 (29.9/27)
	NEUT v5.4.0	6.64 (78.5/28)	4.39 (32.2/27)
	GiBUU 2019	7.00 (82.2./28)	4.78 (40.0/27)

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

Nominal χ^2

TABLE XXX: Extracted χ^2/d.o.f for the data–nominal GENIE simulation comparison using both the full available phase space as well as the limited one with $\cos(\theta_\mu) < 0.8$.

Kinematic Variable	$-0.65 < \cos(\theta_\mu) < 0.95$	$-0.65 < \cos(\theta_\mu) < 0.8$
P_μ	14.2/7	8.4/7
$\cos(\theta_\mu)$	33.8/7	7.3/6
P_p	2.8/7	5.1/7
$\cos(\theta_p)$	12.4/7	9.2/7

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

Systematic Uncertainties

$$\text{Syst} = \text{Flux} \oplus \text{XSec} \oplus \text{Detector}$$

Framework from MiniBooNE collaboration
PRD 79, 072002, 2009

More than 40 reweightable GENIE parameters
MICROBOONE-NOTE-1074-PUB

- Longitudinal & transverse diffusion
- Light yield outside the TPC
- Electron lifetime
- Recombination model
- Space charge map
- Electronic response

MICROBOONE-NOTE-1045-PUB

MICROBOONE-NOTE-1032-PUB

Integrated Cross Section Uncertainty Breakdown

Source Of Uncertainty	Relative Uncertainty (%)
Beam Flux & POT	19
Cross Section Modelling	7
Detector Response	18
Efficiency μ-p decoupling	6
Statistical	16
Total	32

Already significant improvements for future analyses on MicroBooNE to reduce detector & cross section systematic uncertainties

MICROBOONE-NOTE-1075-PUB K.Duffy Neutrino 2020 MICROBOONE-NOTE-1074-PUB

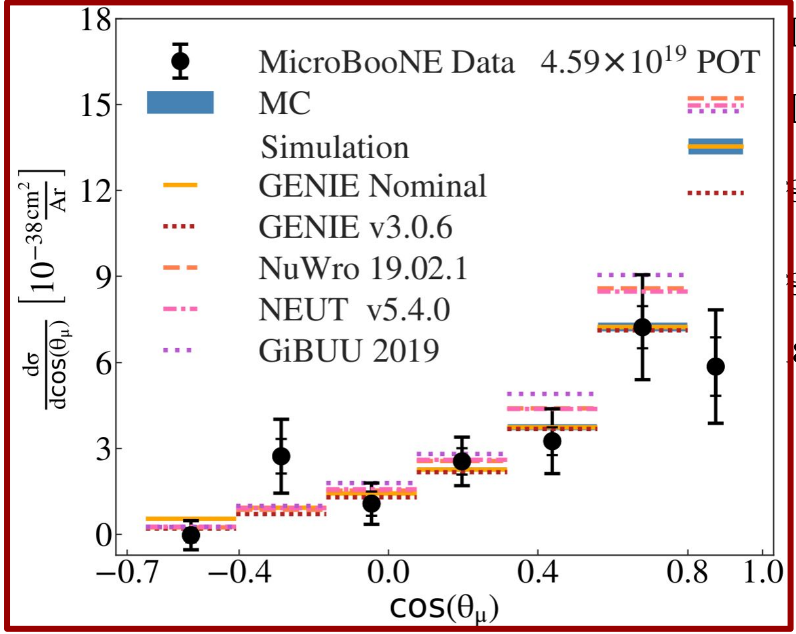
Model Comparisons

Model Component	GENIE Nominal v2.12.2 This work	GENIE v3.0.6 G18_10a_02_11a Future analyses	NuWro (19.02.1)	NEUT (v5.4.0)	GiBUU (2019)
Nuclear Model	Bodek-Ritchie Fermi Gas [1]	Local Fermi Gas [2, 3]	Local Fermi Gas [2, 3]	Local Fermi Gas [2, 3]	Consistent nuclear medium corrections
Quasi-elastic	Llewellyn-Smith [4]	Nieves [2, 3]	Nieves [2, 3]	Nieves [2, 3]	LFG model for nucleon momenta
MEC	Empirical [5]	Nieves [2, 3]	Nieves [2, 3]	Nieves [2, 3]	Separate MEC model [11]
Resonant	Rein-Seghal [6]	Berger-Seghal [7]	Berger-Seghal [7]	Berger-Seghal [7]	
Coherent	Rein-Seghal [6]	Berger-Seghal [7]	Berger-Seghal [7]	Rein-Seghal [6]	
FSI	hA [8]	hA2018 [8]	Oset [10]	Oset [10]	Propagates final state particles according to the BUU equations [11]

Significant differences in model components used in GENIE Nominal and other generators

Model Comparisons

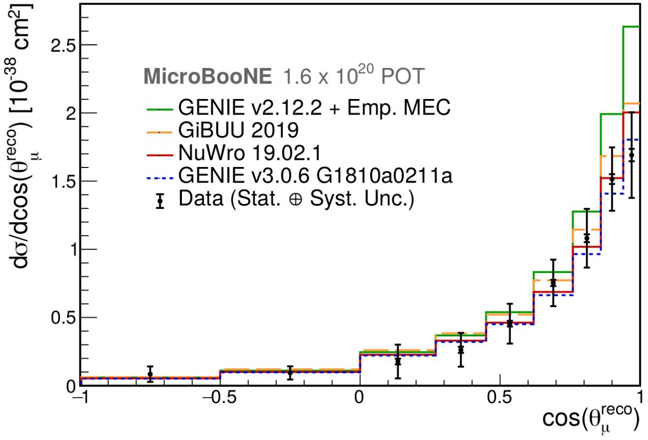
Model Component	GENIE Nominal v2.12.2 This work	GENIE v3.0.6 G18_10a_02_11a Future analyses	NuWro (19.02.1)	NEUT (v5.4.0)	GiBUU (2019)
Nuclear Model	Bodek-Ritchie Fermi Gas [1]	Local Fermi Gas [2, 3]	Local Fermi Gas [2, 3]	Local Fermi Gas [2, 3]	Consistent nuclear medium corrections
		[2, 3]	Nieves [2, 3]	Nieves [2, 3]	LFG model for nucleon momenta
		[2, 3]	Nieves [2, 3]	Nieves [2, 3]	Separate MEC model [11]
		ghal [7]	Berger-Seghal [7]	Berger-Seghal [7]	
		ghal [7]	Berger-Seghal [7]	Rein-Seghal [6]	Propagates final state particles according to the BUU equations [11]
		8 [8]	Oset [10]	Oset [10]	



But none of them reproduces the deficit in the forward direction ...

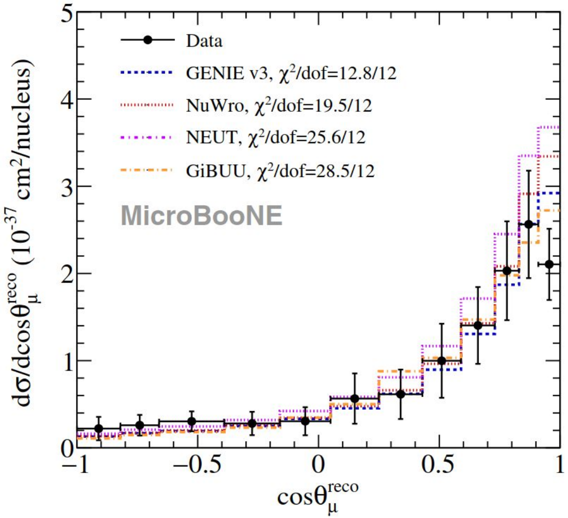
Consistent Picture

ν_μ CC Inclusive
MC excess in forward bin



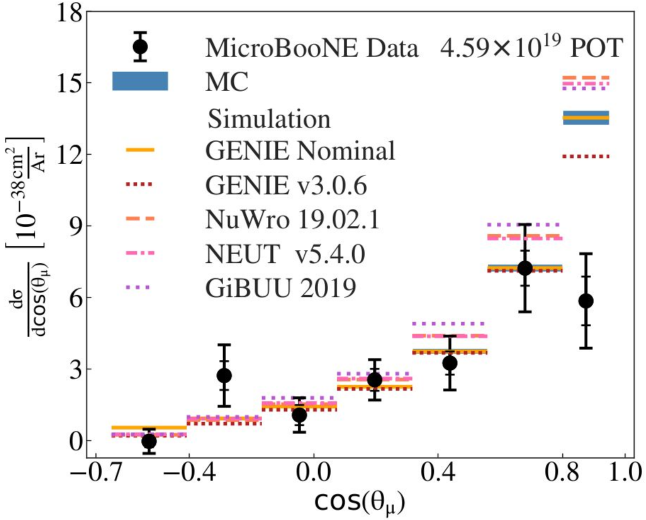
Phys. Rev. Lett. 123, 131801 (2019)

ν_μ CCNp
Data turnover in forward bin



Phys. Rev. D102, 112013 (2020)

ν_μ CCQE-like
Biggest deficit in forward bin



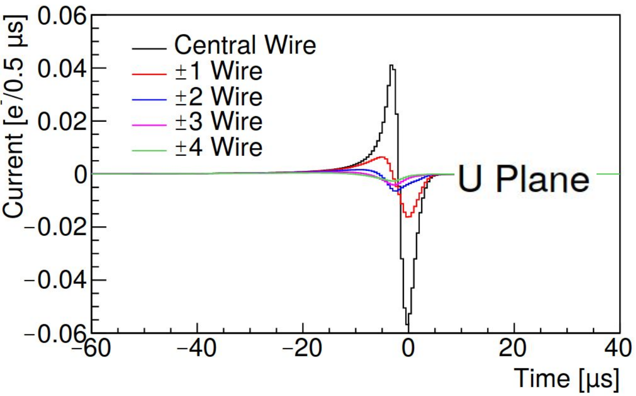
Phys. Rev. Lett. 125, 201803 (2020)

But far from the end of our cross section story!

Getting Even More Out Of LArTPCs

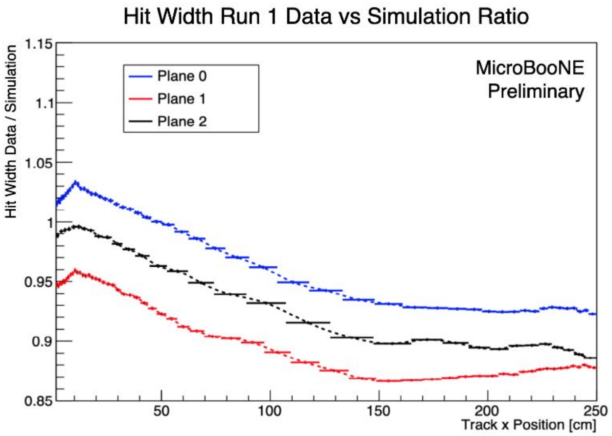
Better detector understanding
- Signal processing from all planes
- Improved calorimetry
- Better reconstruction efficiency

JINST 13, P07006 (2018)
JINST 13, P07007 (2018)



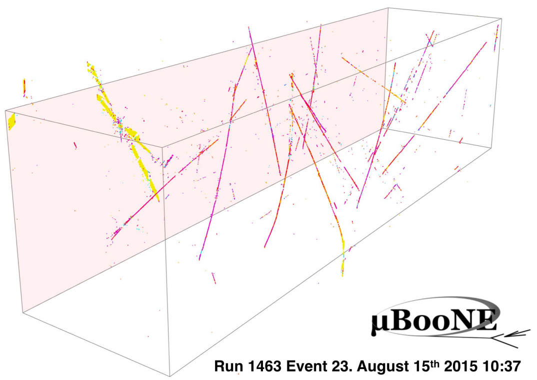
Reduced systematic uncertainties
- Data driven method for vastly improved detector uncertainties

MICROBOONE-NOTE-1075-PUB



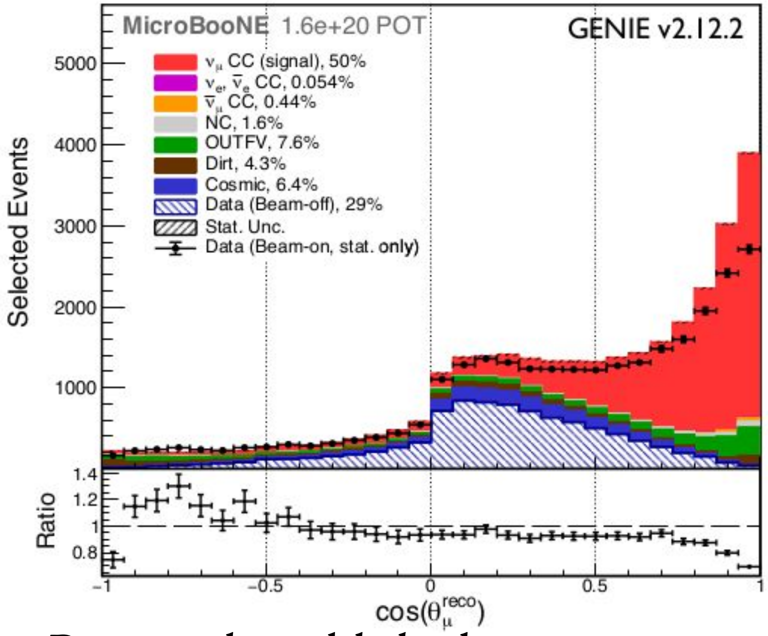
Reduced cosmic contamination uncertainty
- Cosmic Ray Tagger installed in 2018
- Cosmic data as background to simulation

JINST 14, P04004 (2019)



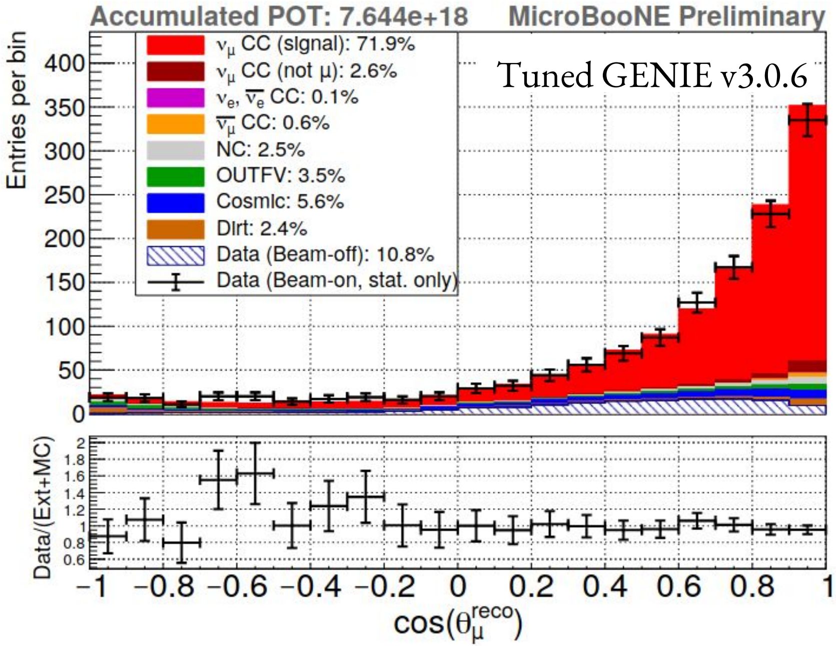
Improved Detector Understanding Enables Precision Measurements

- Improved ν_μ CC inclusive purity from 50% to 71.9%
- Reduction of cosmic contamination by a factor of ~3
- Reduced detector uncertainties from 16.2 % to 3.3 %



Previously published measurement

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



Current measurement

MICROBOONE-NOTE-1069-PUB

CCQE-like vs TKI

- 1 muon $100 < P_\mu < 1500$ MeV/c
- 1 proton $300 < P_p < 1000$ MeV/c
- No $\pi^\pm$ (> 70 MeV/c)
- No π^0 of any momenta

- $-0.65 < \cos\theta_\mu < 0.95$
- $\cos\theta_p > 0.15$

- $|\Delta\theta_{\mu,p} - 90^\circ| < 55^\circ$
- $|\Delta\varphi_{\mu,p} - 180^\circ| < 35^\circ$
- $\mathbf{p}_T = |\mathbf{p}_T^\mu + \mathbf{p}_T^p| < 350$ MeV/c

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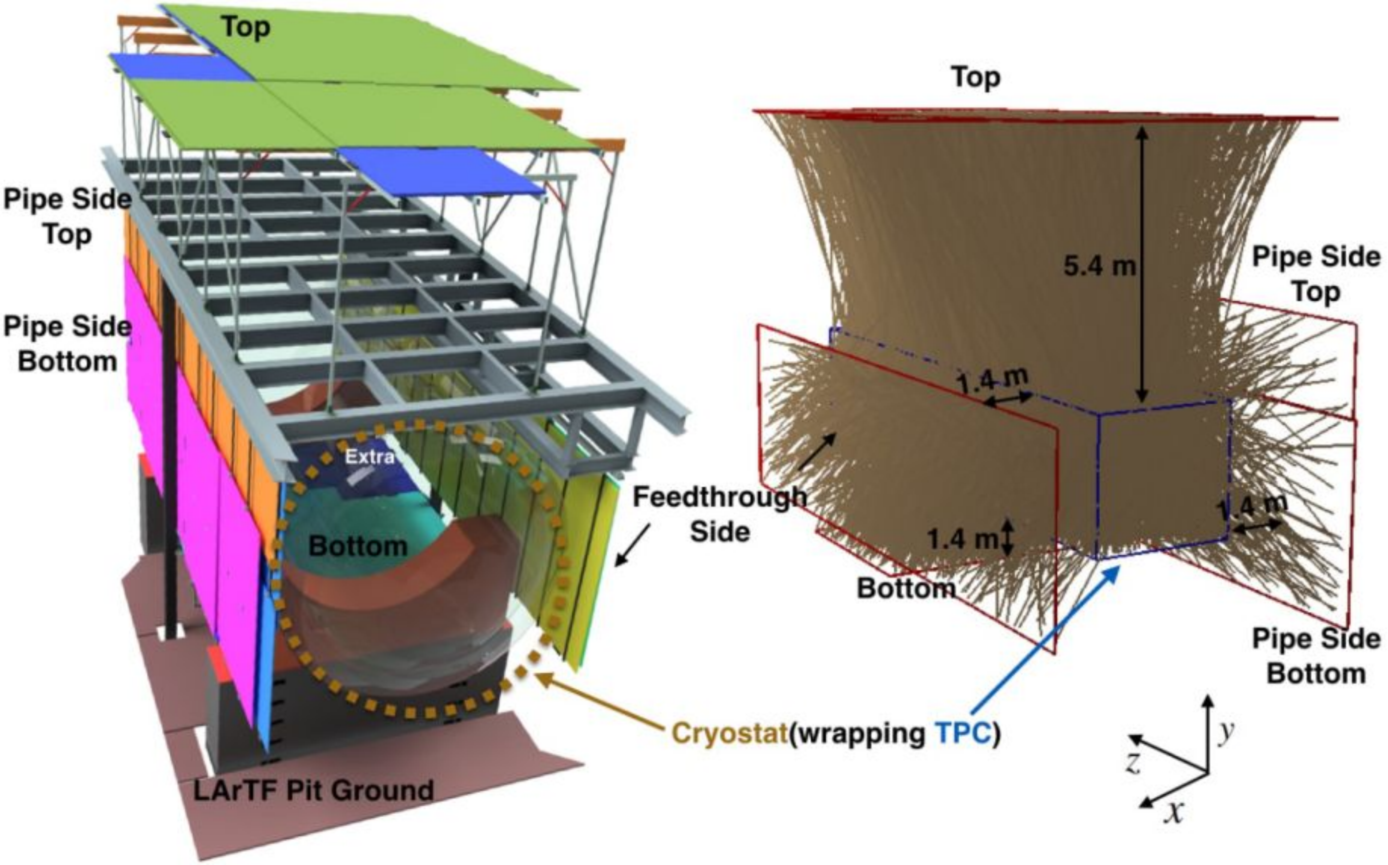
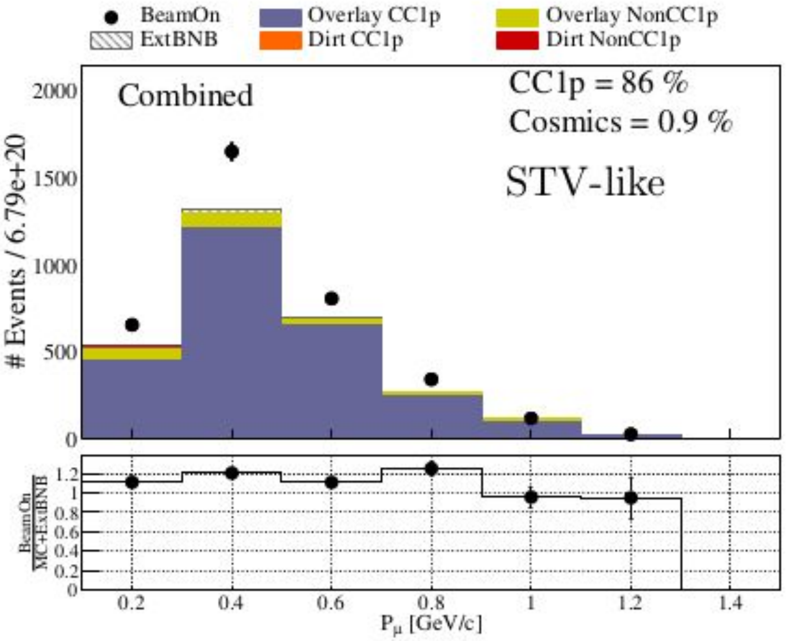
- 1 muon $100 < P_\mu < 1200$ MeV/c
- 1 proton $300 < P_p < 1000$ MeV/c
- No $\pi^\pm$ (> 70 MeV/c)
- No π^0 of any momenta

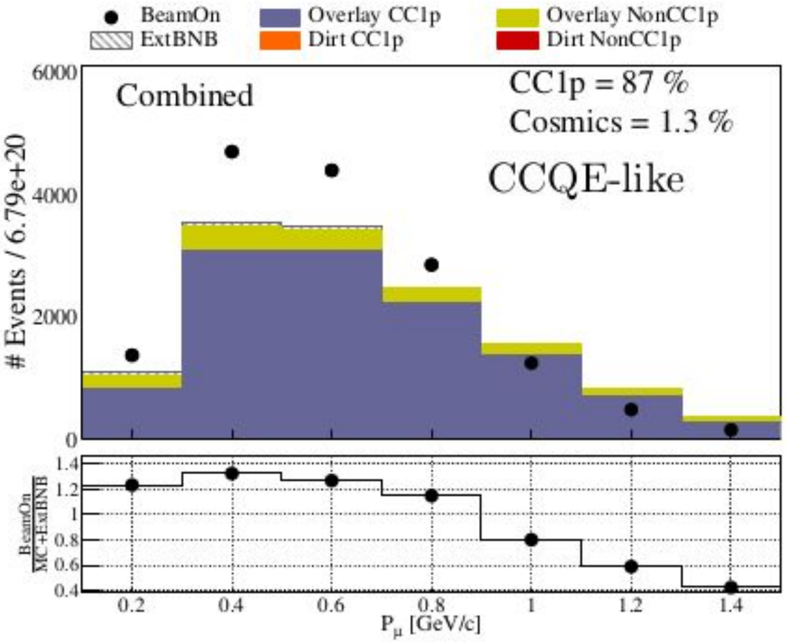
- $-1 < \cos\theta_\mu < 1$
- $-1 < \cos\theta_p < 1$

CRT


Top
Pipe Side Top
Pipe Side Bottom
Extra
Bottom
Feedthrough Side
LArTF Pit Ground
Cryostat(wrapping TPC)
Top
5.4 m
Pipe Side Top
1.4 m
1.4 m
1.4 m
Bottom
Pipe Side Bottom
y
z
x

CCQE-like vs TKI





Cross Section Extraction Via Wiener SVD Unfolding

- Measurement M (Data)
- Background B (MC)
- Response Matrix R (MC)
- Signal S (MC)
- Total Covariance Matrix C (Data Event Rate)
- Test statistic $T = (M\text{-}B\text{-}R\cdot S)^T \cdot C^{-1} \cdot (M\text{-}B\text{-}R\cdot S)$

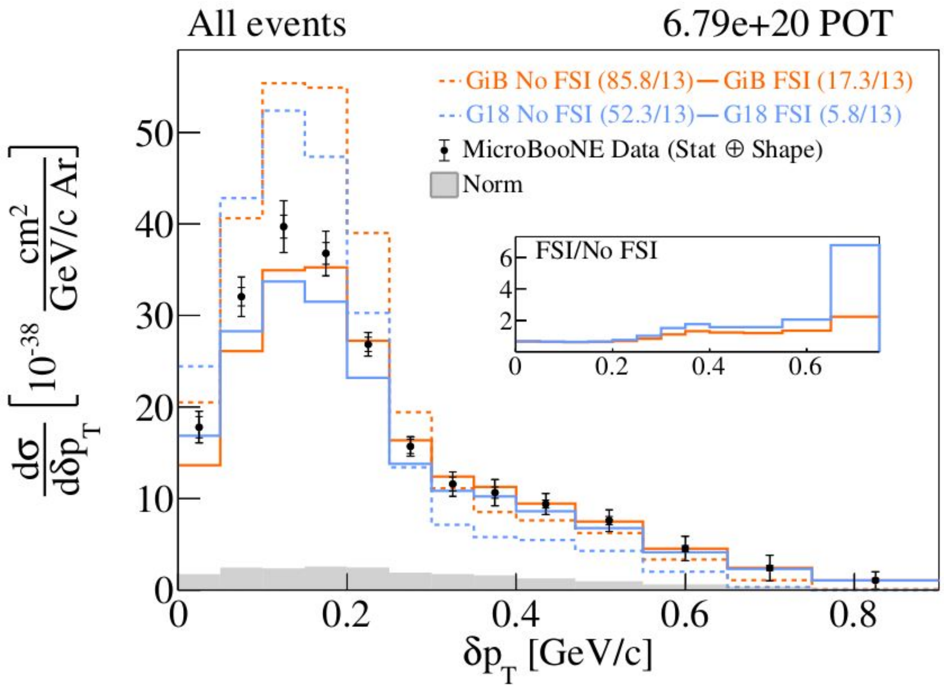
$$M\text{-}B = R\cdot S$$

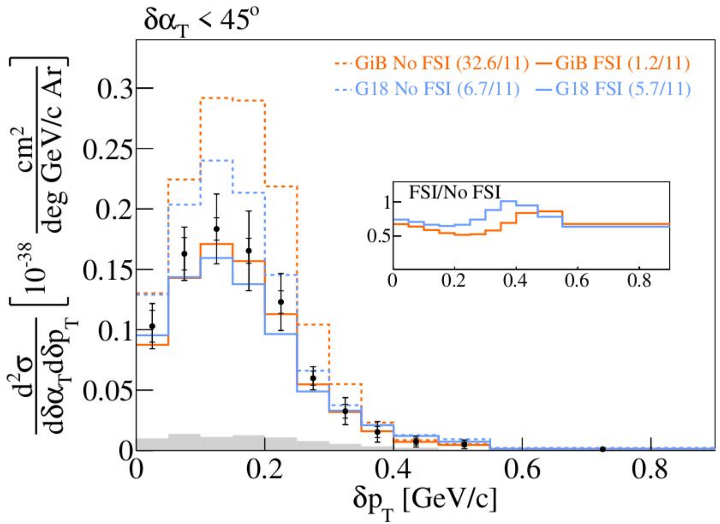
$$\Big\downarrow \text{ Minimize T}$$

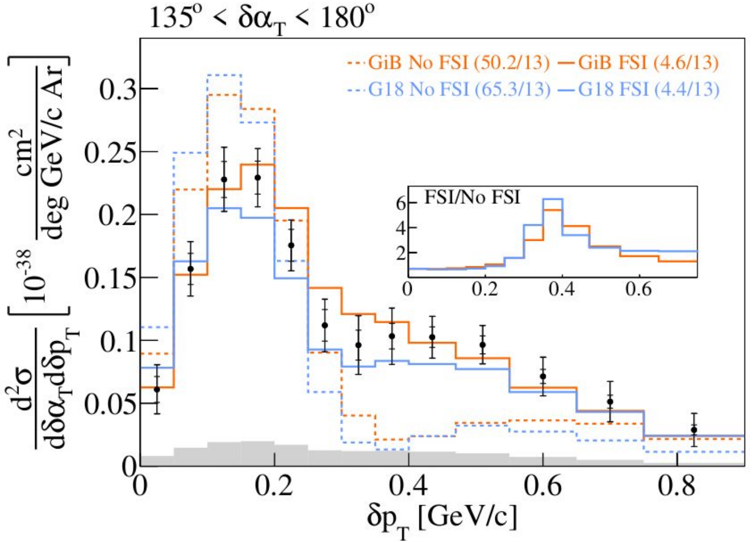
$$S = (R^T \cdot C^{-1} \cdot R)^{-1} \cdot R^T \cdot C^{-1} (M\text{-}B)$$
$$C_S = (R^T \cdot C^{-1} \cdot R)^{-1}$$

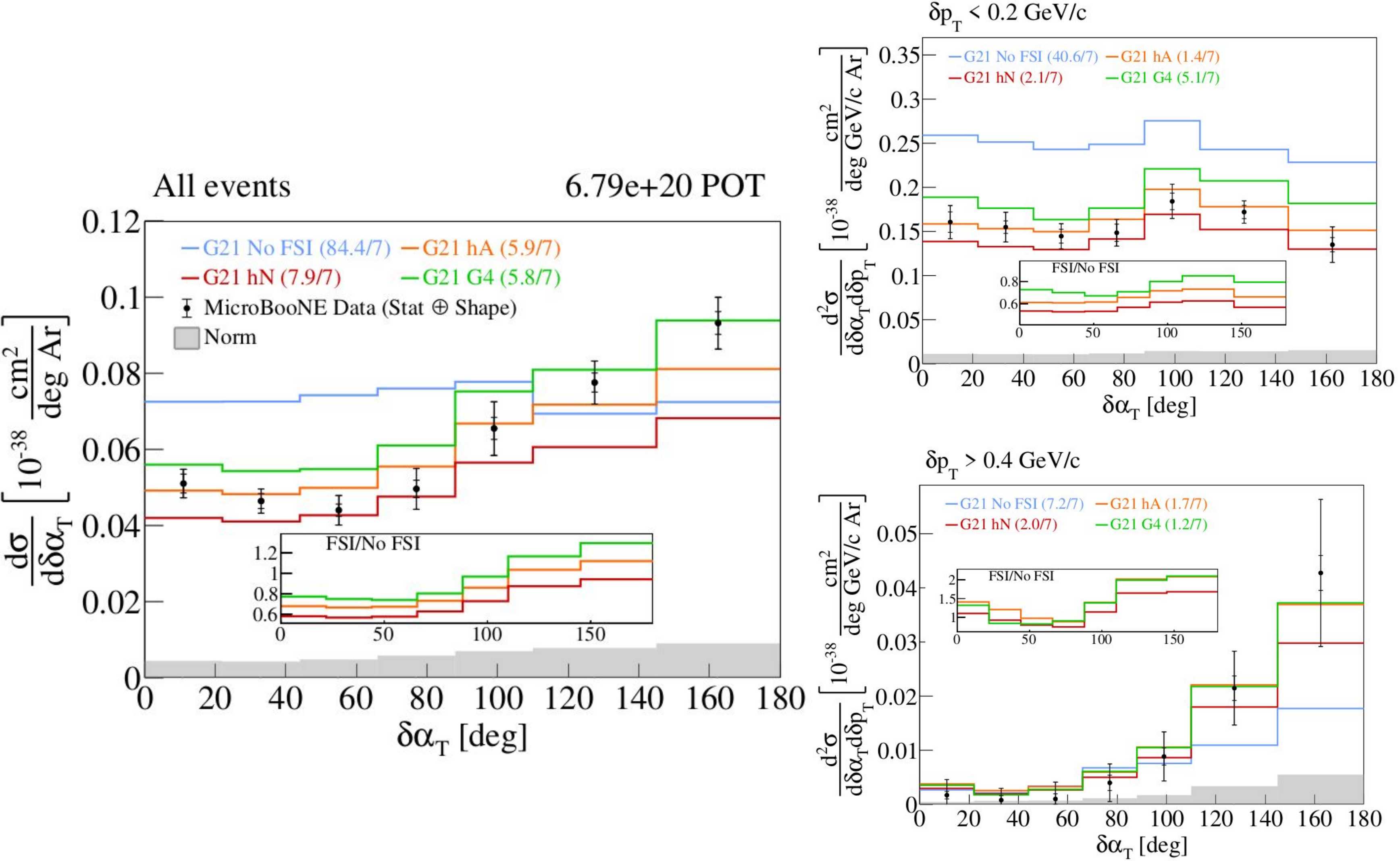
Cross sections computed as a function of truth variables

W. Tang, X. Li, X. Qian, H. Wei, and C. Zhang. Data unfolding with wiener-svd method. *Journal of Instrumentation*, 12(10):P10002–P10002, Oct 2017.

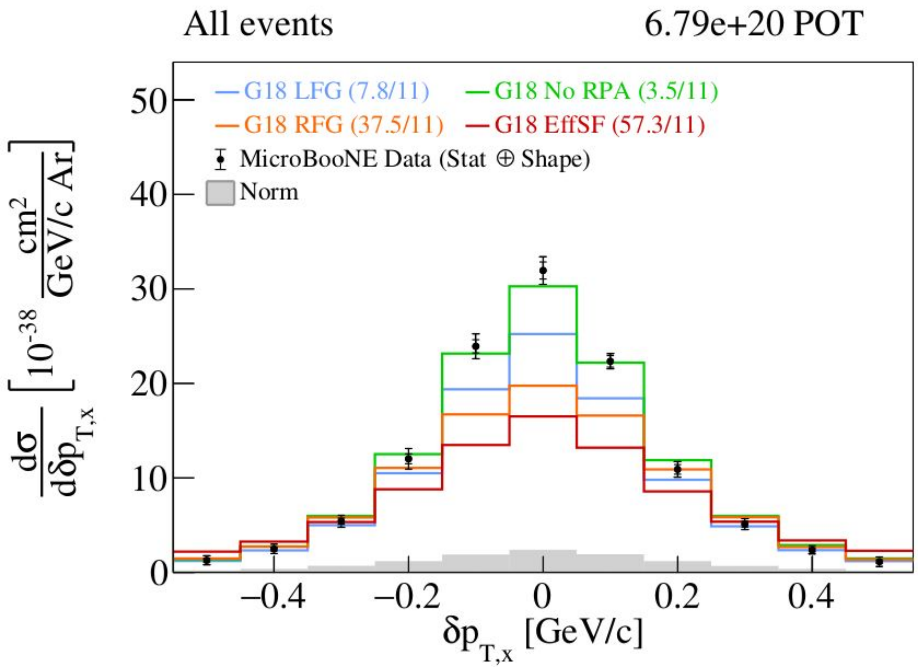

All events
6.79e+20 POT
GiB No FSI (85.8/13)
GiB FSI (17.3/13)
G18 No FSI (52.3/13)
G18 FSI (5.8/13)
MicroBooNE Data (Stat ⊕ Shape)
Norm
FSI/No FSI
$\frac{d\sigma}{d\delta p_T}$ $\left[10^{-38}\frac{cm^2}{GeV/c\ Ar}\right]$
δp_T [GeV/c]

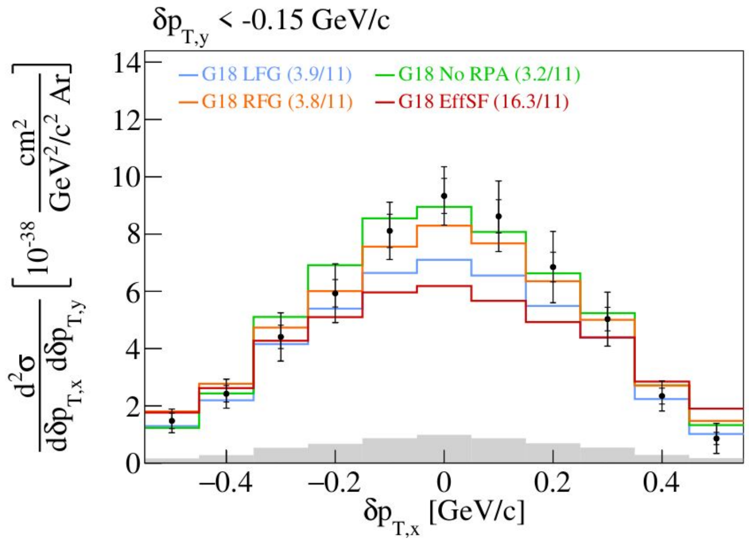

$\delta\alpha_T$ < 45°
GiB No FSI (32.6/11)
GiB FSI (1.2/11)
G18 No FSI (6.7/11)
G18 FSI (5.7/11)
FSI/No FSI
$\frac{d^2\sigma}{d\delta\alpha_T d\delta p_T}$ $\left[10^{-38}\frac{cm^2}{deg\ GeV/c\ Ar}\right]$
δp_T [GeV/c]

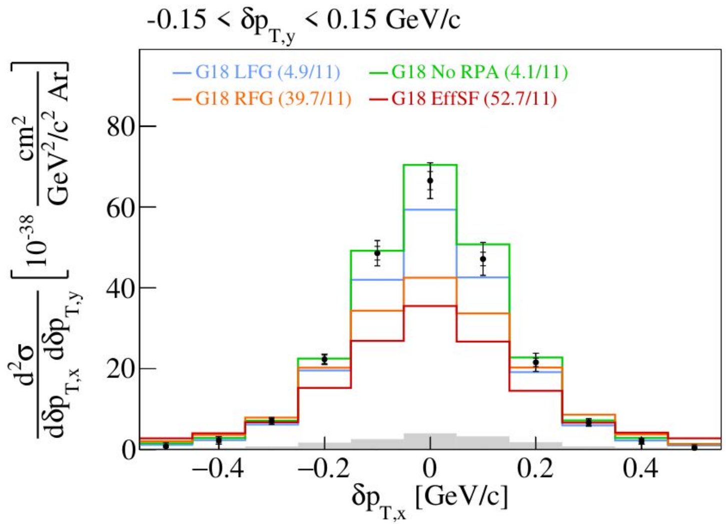

135° < $\delta\alpha_T$ < 180°
GiB No FSI (50.2/13)
GiB FSI (4.6/13)
G18 No FSI (65.3/13)
G18 FSI (4.4/13)
FSI/No FSI
$\frac{d^2\sigma}{d\delta\alpha_T d\delta p_T}$ $\left[10^{-38}\frac{cm^2}{deg\ GeV/c\ Ar}\right]$
δp_T [GeV/c]

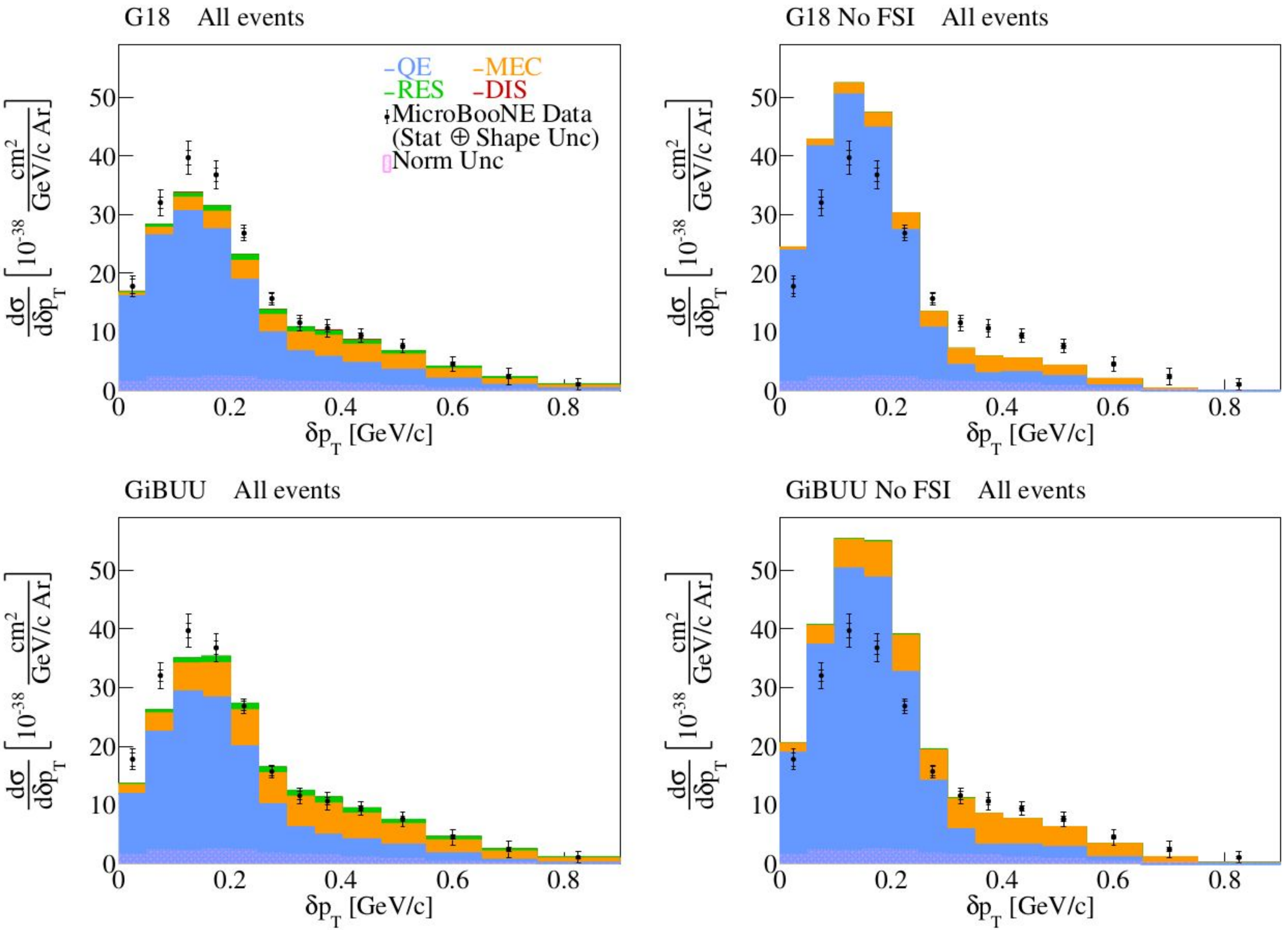


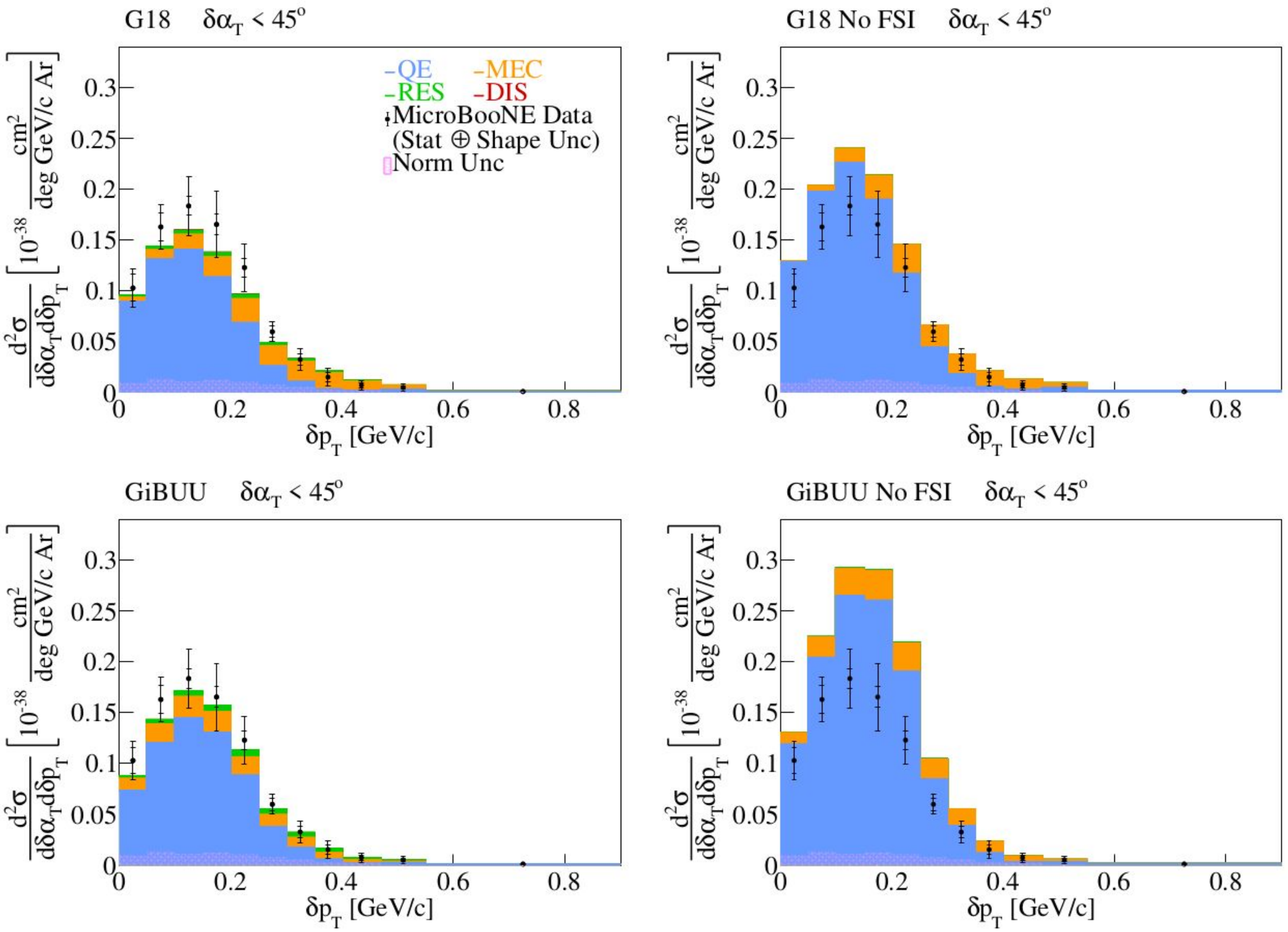
All events
6.79e+20 POT
G21 No FSI (84.4/7)
G21 hA (5.9/7)
G21 hN (7.9/7)
G21 G4 (5.8/7)
MicroBooNE Data (Stat ⊕ Shape)
Norm
FSI/No FSI
$\frac{d\sigma}{d\delta\alpha_T}\left[10^{-38}\frac{cm^2}{deg\ Ar}\right]$
$\delta\alpha_T$ [deg]
δp_T < 0.2 GeV/c
G21 No FSI (40.6/7)
G21 hA (1.4/7)
G21 hN (2.1/7)
G21 G4 (5.1/7)
FSI/No FSI
$\frac{d^2\sigma}{d\delta\alpha_T d\delta p_T}\left[10^{-38}\frac{cm^2}{deg\ GeV/c\ Ar}\right]$
$\delta\alpha_T$ [deg]
δp_T > 0.4 GeV/c
G21 No FSI (7.2/7)
G21 hA (1.7/7)
G21 hN (2.0/7)
G21 G4 (1.2/7)
FSI/No FSI
$\frac{d^2\sigma}{d\delta\alpha_T d\delta p_T}\left[10^{-38}\frac{cm^2}{deg\ GeV/c\ Ar}\right]$
$\delta\alpha_T$ [deg]


All events
6.79e+20 POT
G18 LFG (7.8/11)
G18 No RPA (3.5/11)
G18 RFG (37.5/11)
G18 EffSF (57.3/11)
MicroBooNE Data (Stat ⊕ Shape)
Norm
$\frac{d\sigma}{d\delta p_{T,x}}$ $\left[10^{-38}\ \frac{cm^2}{GeV/c\ Ar}\right]$
$\delta p_{T,x}$ [GeV/c]

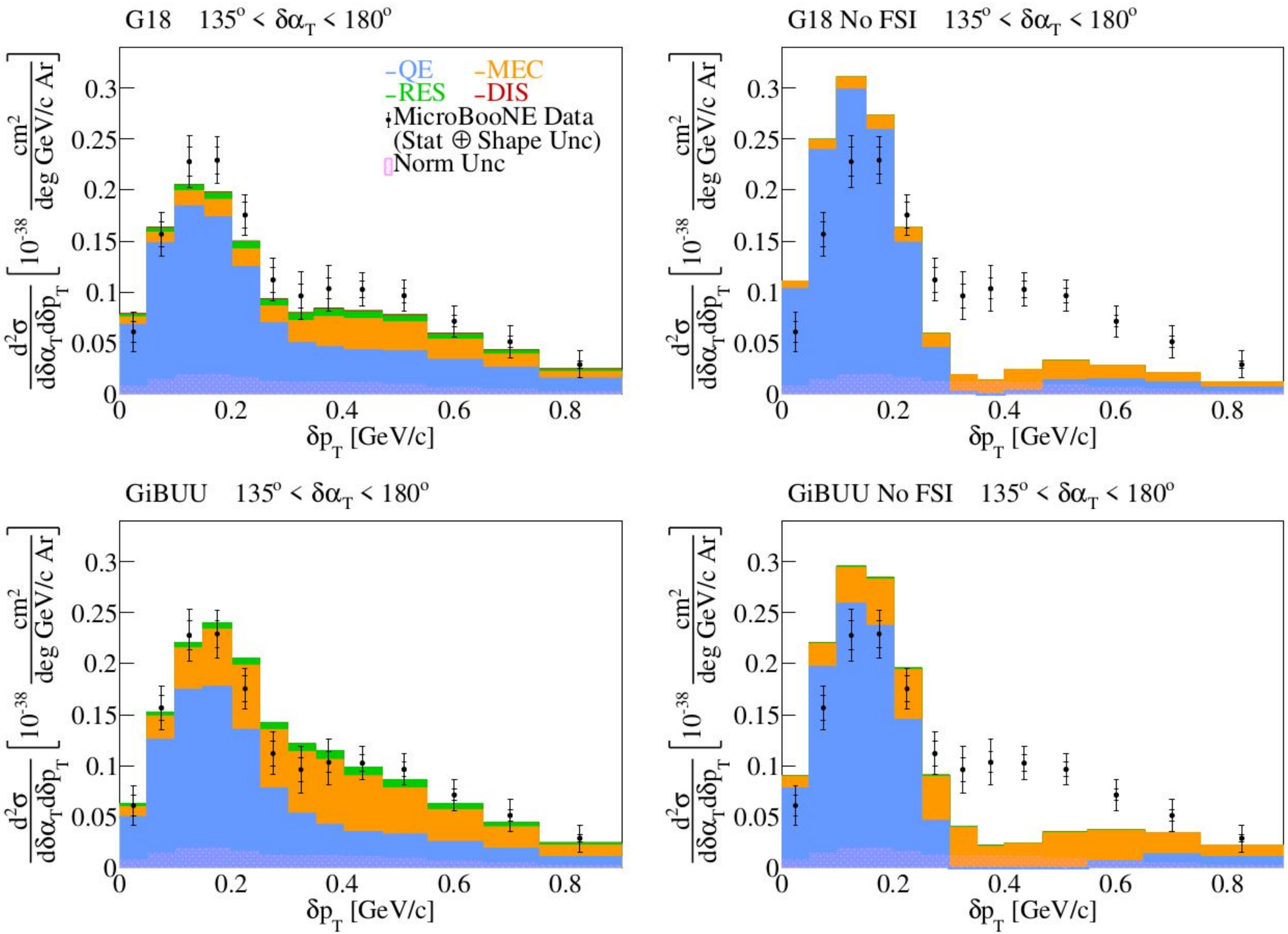

$\delta p_{T,y}$ < -0.15 GeV/c
G18 LFG (3.9/11)
G18 No RPA (3.2/11)
G18 RFG (3.8/11)
G18 EffSF (16.3/11)
$\frac{d^2\sigma}{d\delta p_{T,x}\, d\delta p_{T,y}}$ $\left[10^{-38}\ \frac{cm^2}{GeV^2/c^2\ Ar}\right]$
$\delta p_{T,x}$ [GeV/c]

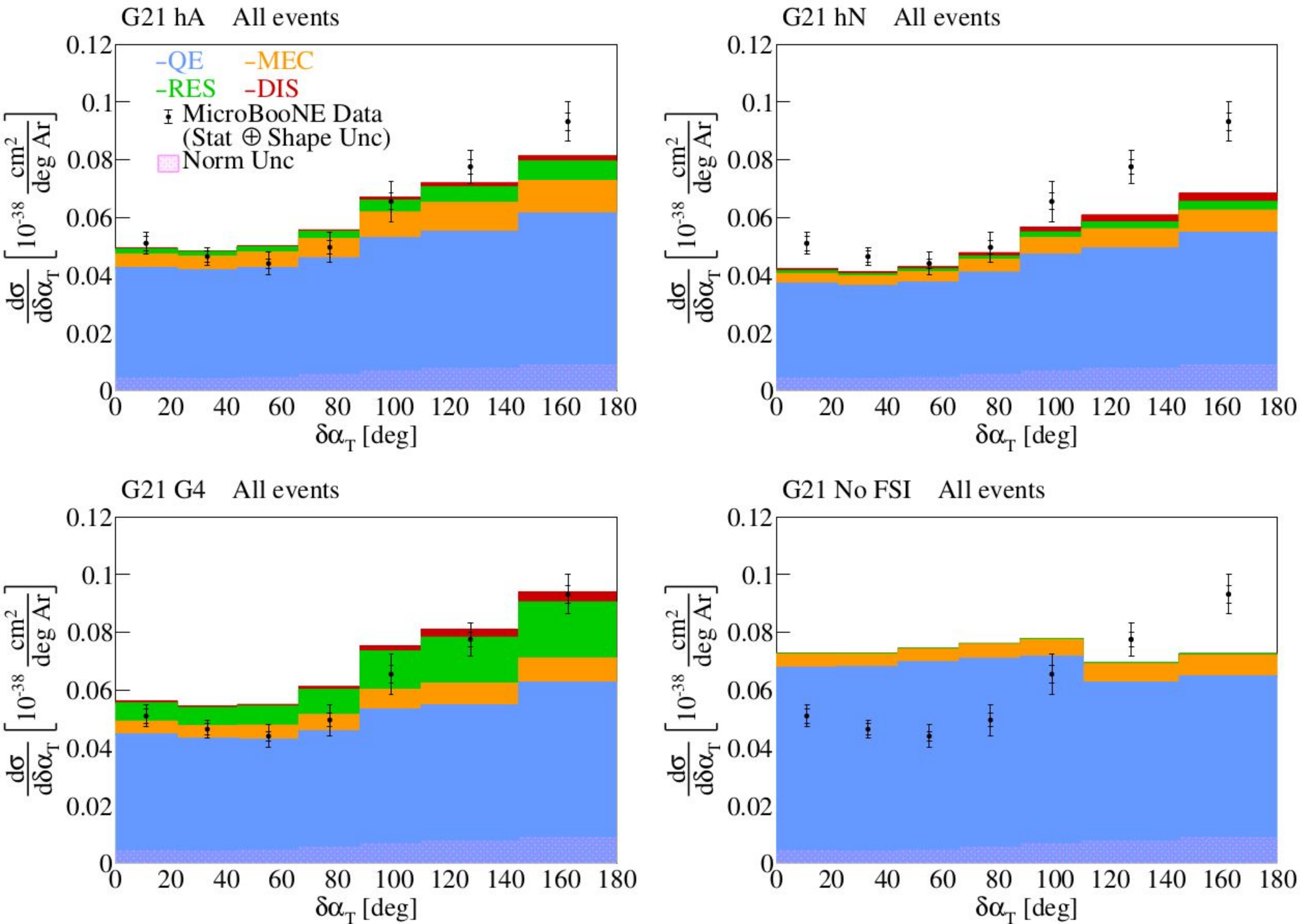

-0.15 < $\delta p_{T,y}$ < 0.15 GeV/c
G18 LFG (4.9/11)
G18 No RPA (4.1/11)
G18 RFG (39.7/11)
G18 EffSF (52.7/11)
$\frac{d^2\sigma}{d\delta p_{T,x}\, d\delta p_{T,y}}$ $\left[10^{-38}\ \frac{cm^2}{GeV^2/c^2\ Ar}\right]$
$\delta p_{T,x}$ [GeV/c]

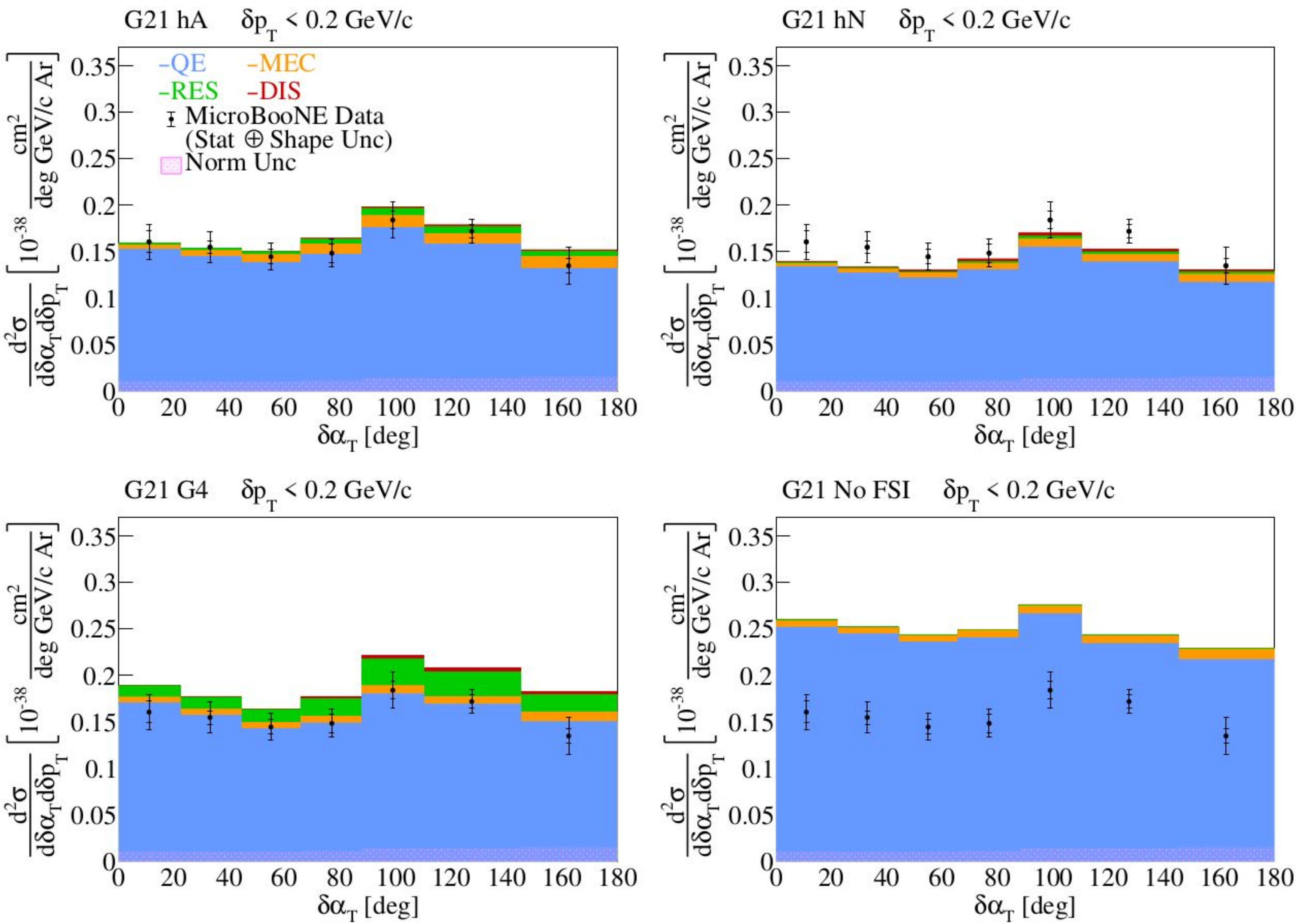

G18 All events
G18 No FSI All events
GiBUU All events
GiBUU No FSI All events
-QE
-MEC
-RES
-DIS
MicroBooNE Data
(Stat ⊕ Shape Unc)
Norm Unc
$\frac{d\sigma}{d\delta p_T}$ $\left[10^{-38} \frac{cm^2}{GeV/c\ Ar}\right]$
δp_T [GeV/c]



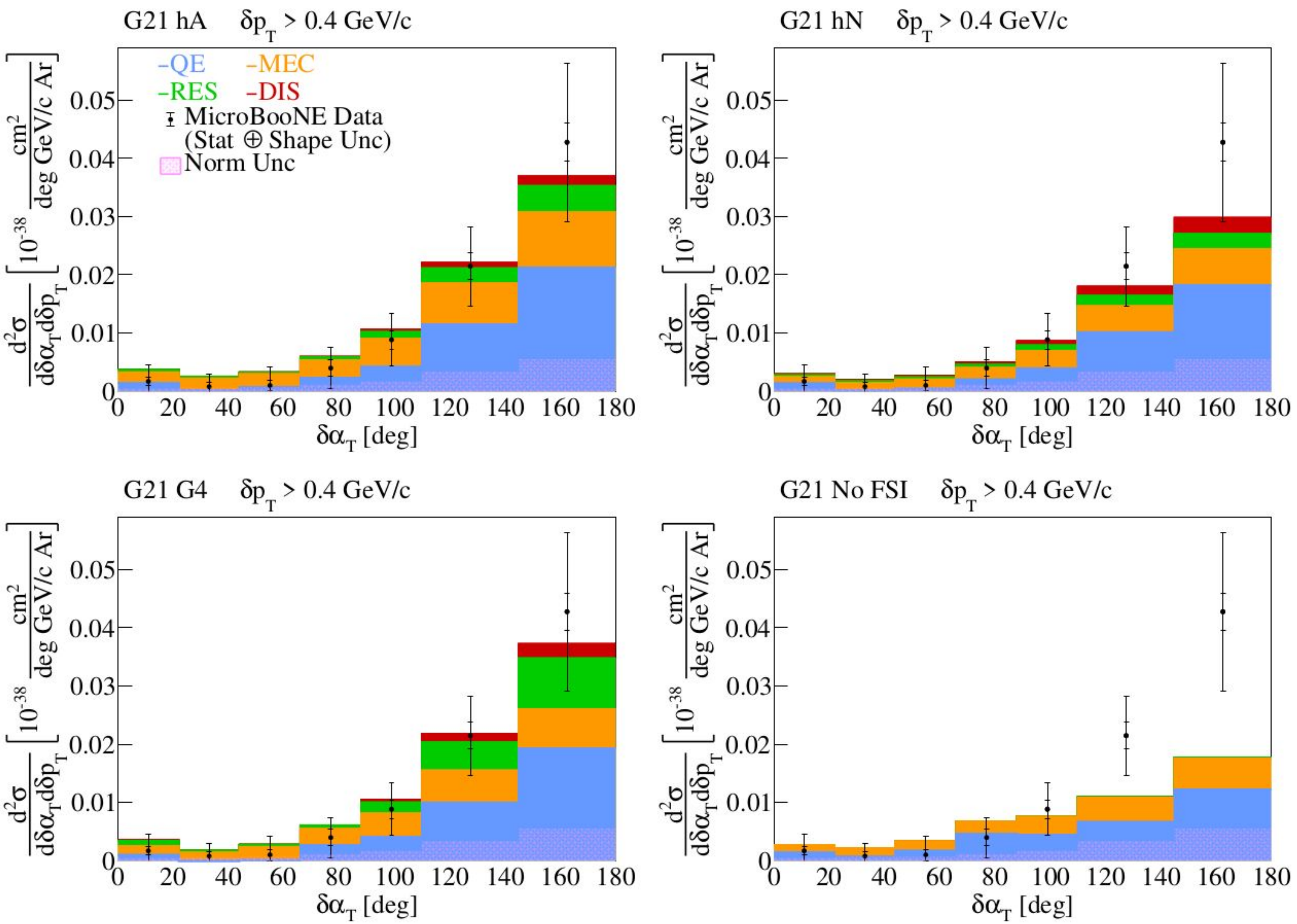
G18 δα_T < 45°
–QE –MEC
–RES –DIS
MicroBooNE Data
(Stat ⊕ Shape Unc)
Norm Unc
G18 No FSI δα_T < 45°
GiBUU δα_T < 45°
GiBUU No FSI δα_T < 45°
d²σ/dδα_T dδp_T [10^-38 cm²/deg GeV/c Ar]
δp_T [GeV/c]

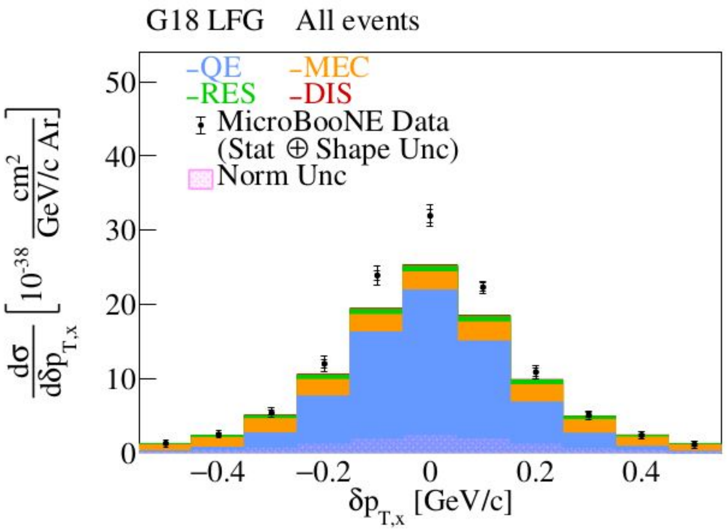

G18 135° < δα_T < 180°
G18 No FSI 135° < δα_T < 180°
GiBUU 135° < δα_T < 180°
GiBUU No FSI 135° < δα_T < 180°
QE
MEC
RES
DIS
MicroBooNE Data
(Stat ⊕ Shape Unc)
Norm Unc
d²σ/dδα_T dδp_T [10⁻³⁸ cm²/deg GeV/c Ar]
δp_T [GeV/c]
0
0.05
0.1
0.15
0.2
0.25
0.3
0.4
0.6
0.8

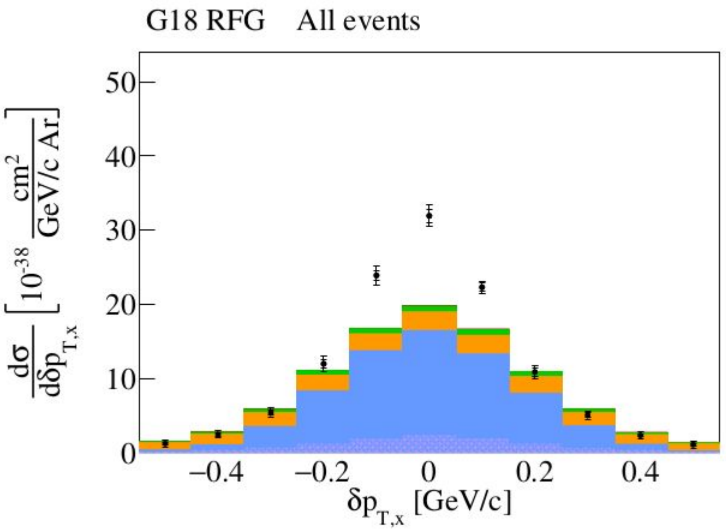

G21 hA All events
G21 hN All events
G21 G4 All events
G21 No FSI All events
-QE
-MEC
-RES
-DIS
MicroBooNE Data
(Stat ⊕ Shape Unc)
Norm Unc
$\frac{d\sigma}{d\delta\alpha_T}\left[10^{-38}\ \frac{cm^2}{deg\ Ar}\right]$
$\delta\alpha_T$ [deg]
0
0.02
0.04
0.06
0.08
0.1
0.12
0
20
40
60
80
100
120
140
160
180

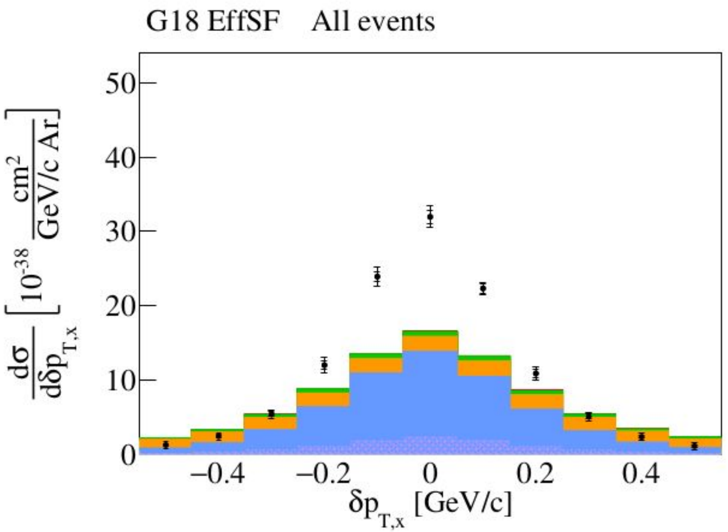


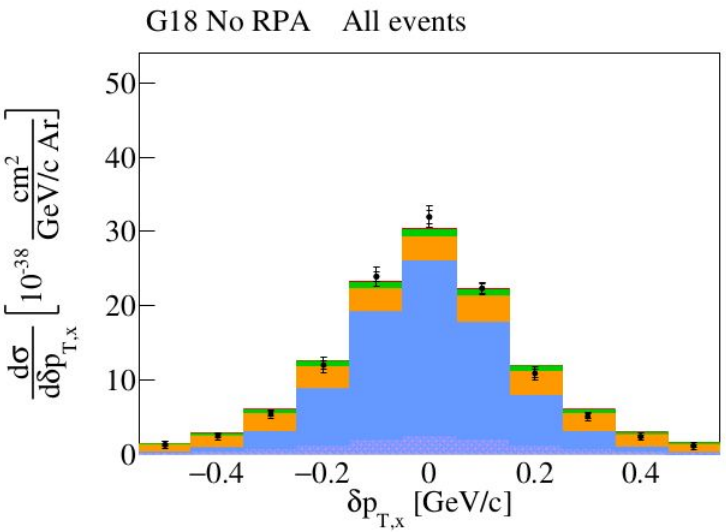
G21 hA δp_T < 0.2 GeV/c
G21 hN δp_T < 0.2 GeV/c
G21 G4 δp_T < 0.2 GeV/c
G21 No FSI δp_T < 0.2 GeV/c
-QE
-MEC
-RES
-DIS
MicroBooNE Data
(Stat ⊕ Shape Unc)
Norm Unc
d²σ/dδα_T dδp_T [10⁻³⁸ cm²/deg GeV/c Ar]
δα_T [deg]
0 20 40 60 80 100 120 140 160 180
0 0.05 0.1 0.15 0.2 0.25 0.3 0.35

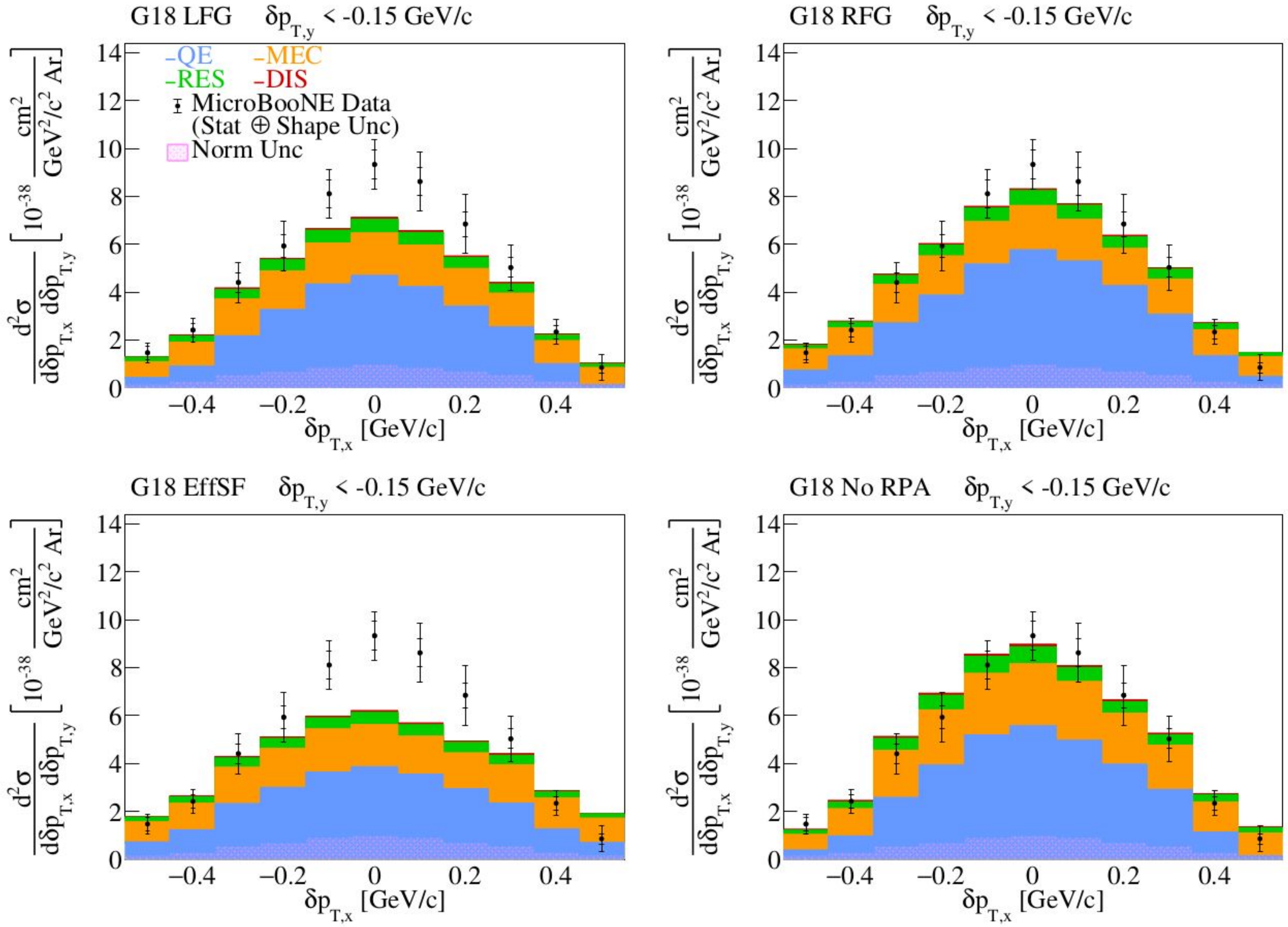

G21 hA δp_T > 0.4 GeV/c
G21 hN δp_T > 0.4 GeV/c
G21 G4 δp_T > 0.4 GeV/c
G21 No FSI δp_T > 0.4 GeV/c
QE
MEC
RES
DIS
MicroBooNE Data
(Stat ⊕ Shape Unc)
Norm Unc
d²σ/dδα_T dδp_T [10⁻³⁸ cm²/(deg GeV/c Ar)]
δα_T [deg]
0
0.01
0.02
0.03
0.04
0.05
0
20
40
60
80
100
120
140
160
180


G18 LFG All events
-QE
-MEC
-RES
-DIS
MicroBooNE Data
(Stat ⊕ Shape Unc)
Norm Unc
$\frac{d\sigma}{d\delta p_{T,x}} \left[10^{-38} \frac{cm^2}{GeV/c\ Ar}\right]$
$\delta p_{T,x}$ [GeV/c]

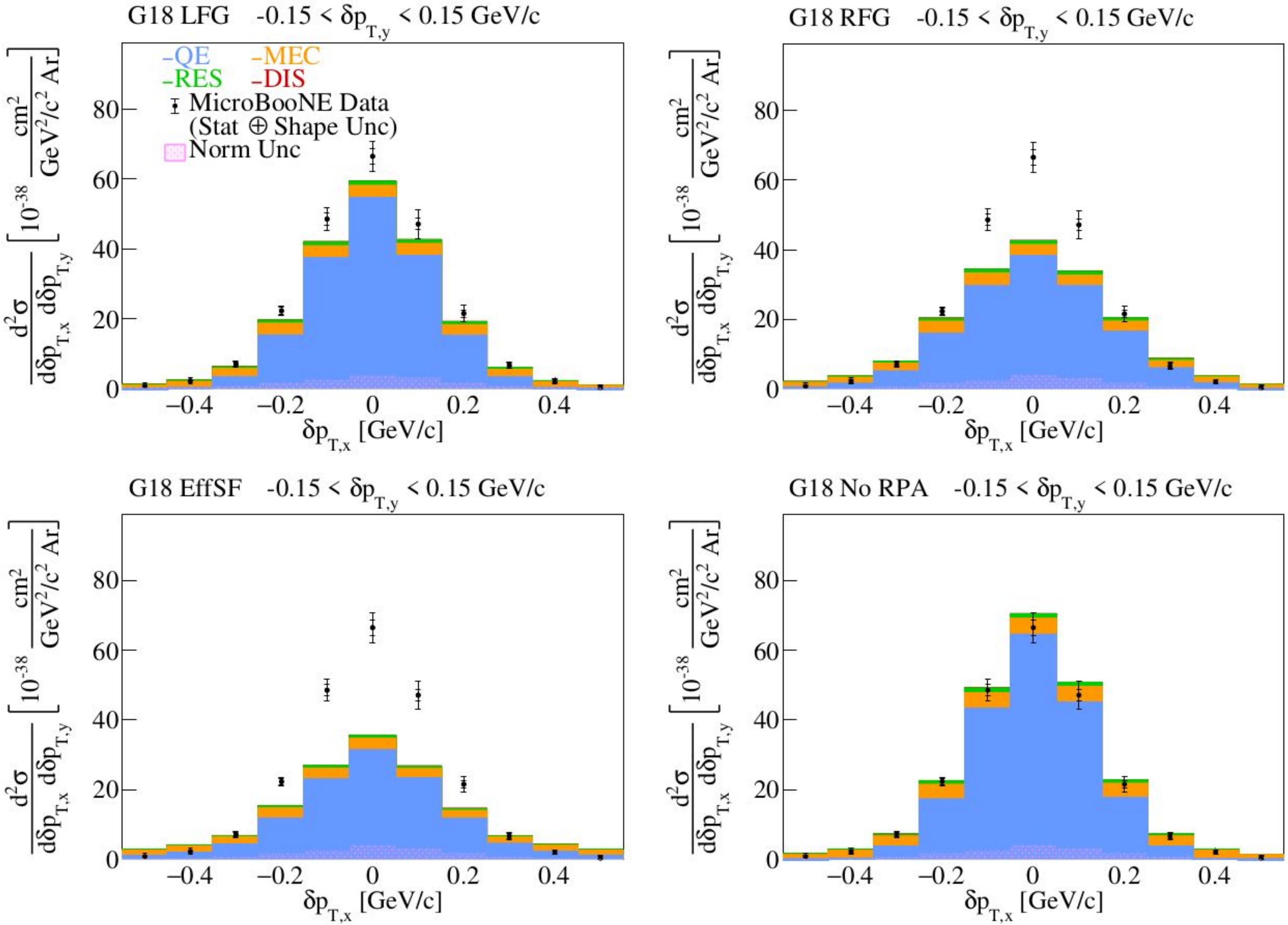

G18 RFG All events
$\frac{d\sigma}{d\delta p_{T,x}} \left[10^{-38} \frac{cm^2}{GeV/c\ Ar}\right]$
$\delta p_{T,x}$ [GeV/c]

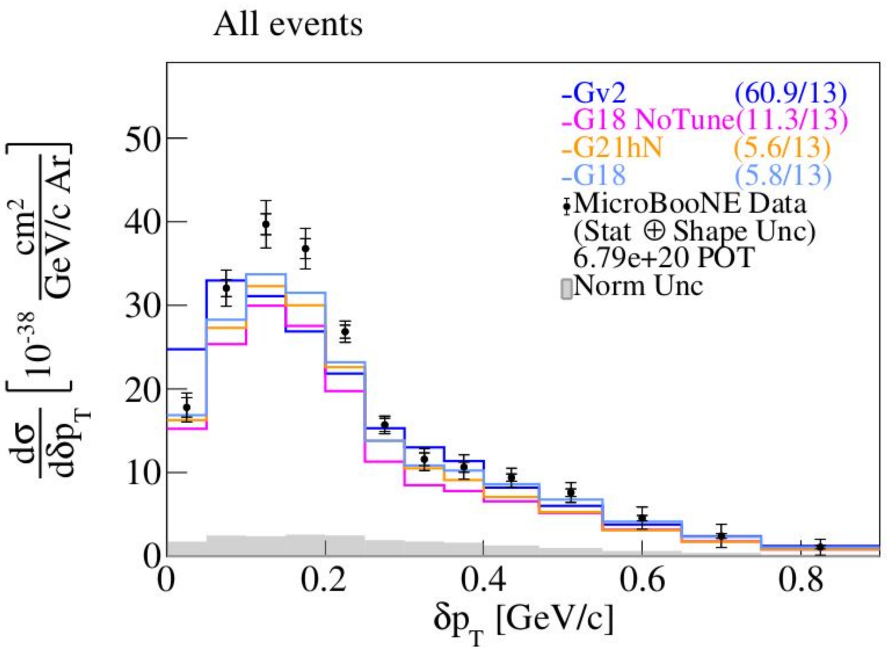

G18 EffSF All events
$\frac{d\sigma}{d\delta p_{T,x}} \left[10^{-38} \frac{cm^2}{GeV/c\ Ar}\right]$
$\delta p_{T,x}$ [GeV/c]

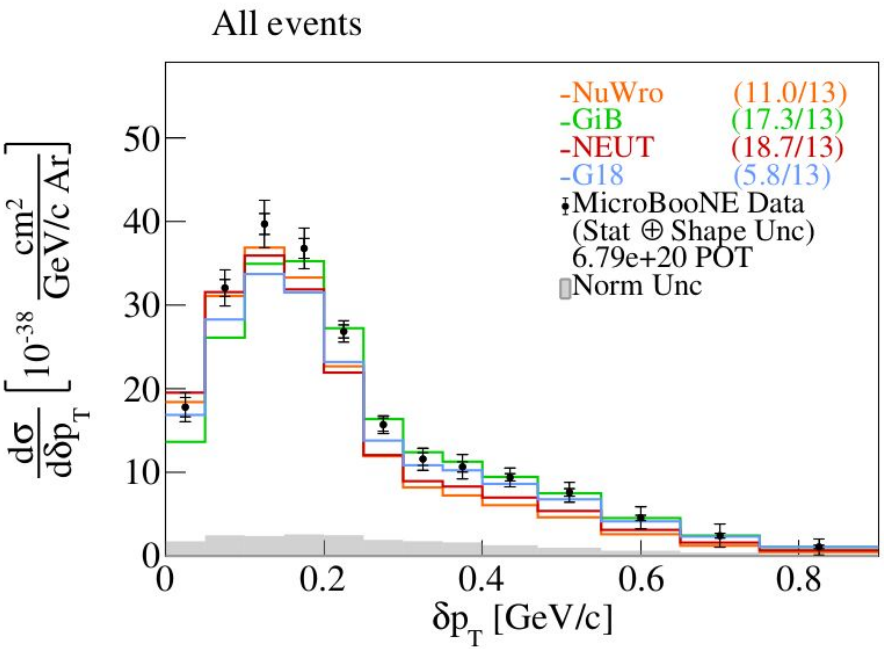

G18 No RPA All events
$\frac{d\sigma}{d\delta p_{T,x}} \left[10^{-38} \frac{cm^2}{GeV/c\ Ar}\right]$
$\delta p_{T,x}$ [GeV/c]

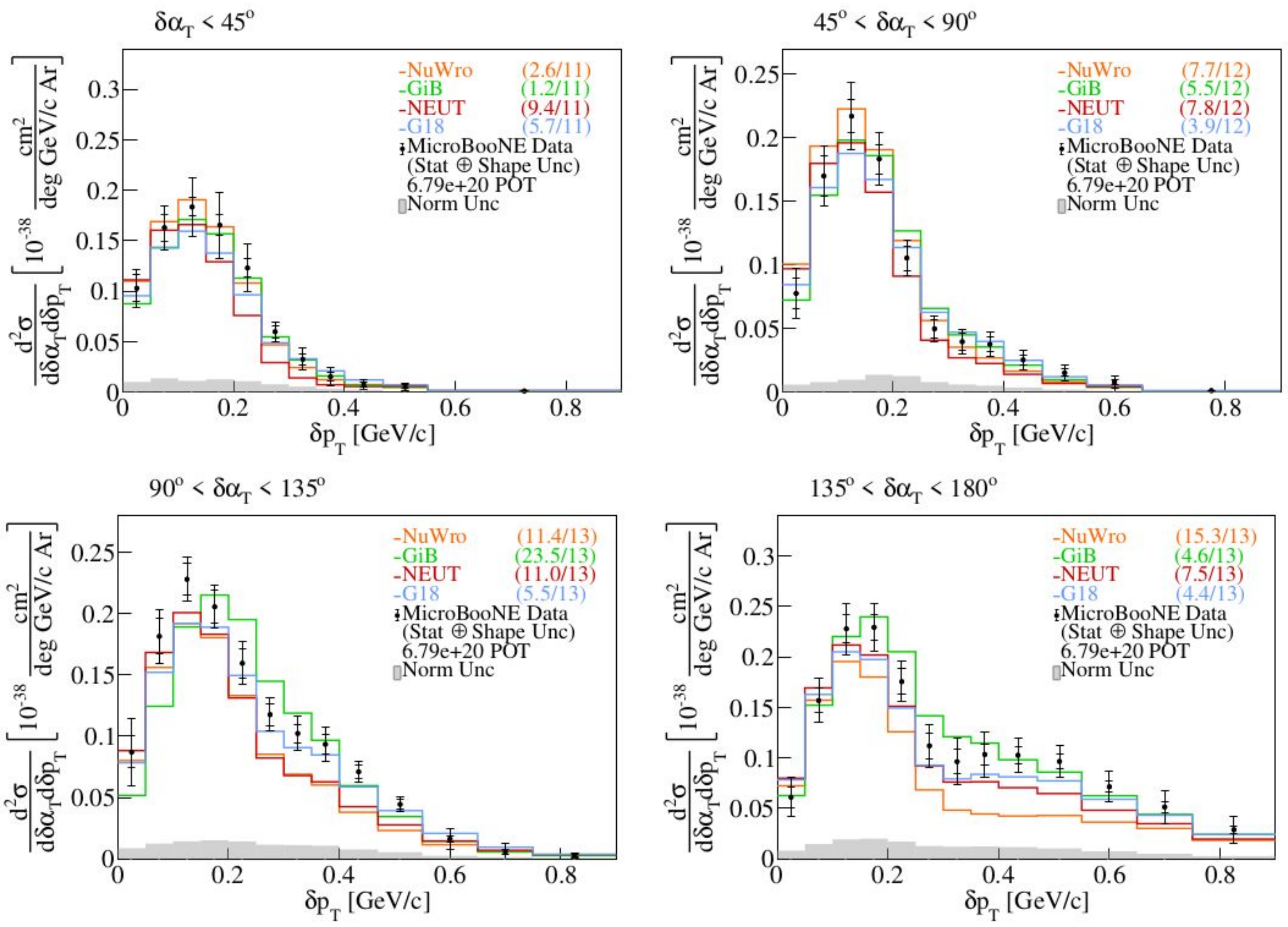


G18 LFG δp_{T,y} < -0.15 GeV/c
G18 RFG δp_{T,y} < -0.15 GeV/c
G18 EffSF δp_{T,y} < -0.15 GeV/c
G18 No RPA δp_{T,y} < -0.15 GeV/c
QE
MEC
RES
DIS
MicroBooNE Data
(Stat ⊕ Shape Unc)
Norm Unc
$\frac{d^2\sigma}{d\delta p_{T,x}\, d\delta p_{T,y}}$ $\left[10^{-38} \frac{cm^2}{GeV^2/c^2\, Ar}\right]$
δp_{T,x} [GeV/c]

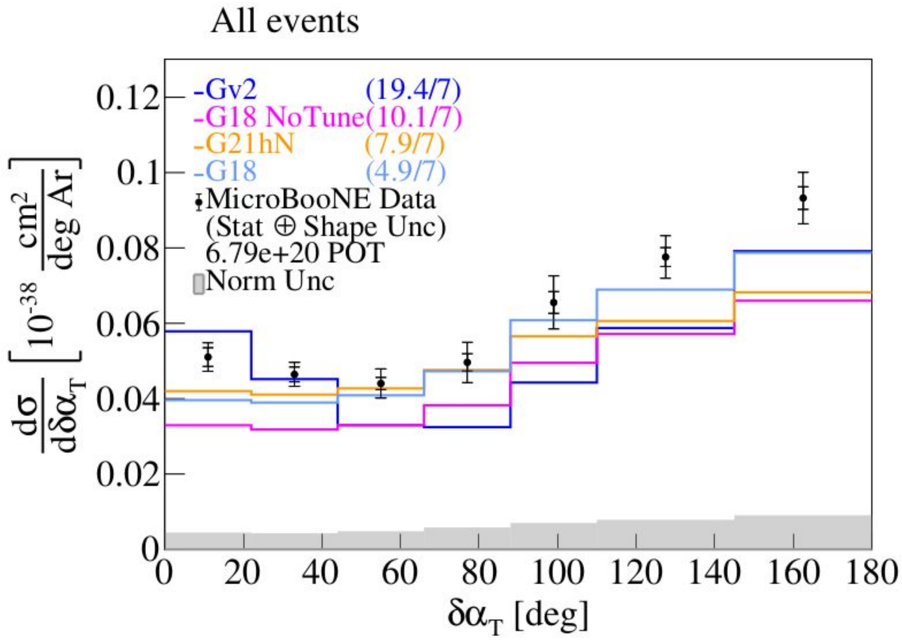

G18 LFG -0.15 < δp_T,y < 0.15 GeV/c
G18 RFG -0.15 < δp_T,y < 0.15 GeV/c
G18 EffSF -0.15 < δp_T,y < 0.15 GeV/c
G18 No RPA -0.15 < δp_T,y < 0.15 GeV/c
QE
MEC
RES
DIS
MicroBooNE Data
(Stat ⊕ Shape Unc)
Norm Unc
d²σ / dδp_T,x dδp_T,y [10^-38 cm² / GeV²/c² Ar]
δp_T,x [GeV/c]
0
20
40
60
80
−0.4
−0.2
0
0.2
0.4

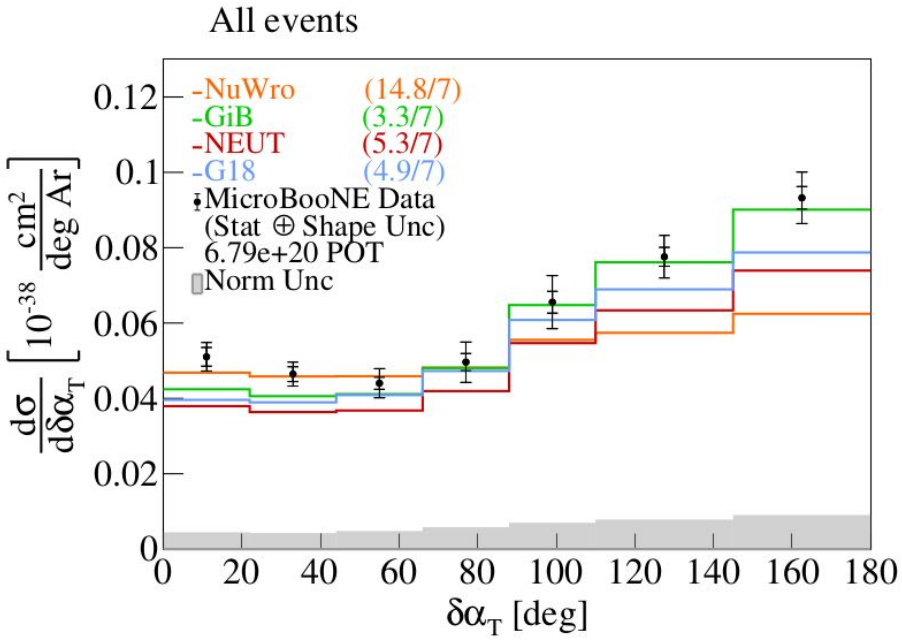

All events
-Gv2 (60.9/13)
-G18 NoTune(11.3/13)
-G21hN (5.6/13)
-G18 (5.8/13)
MicroBooNE Data
(Stat ⊕ Shape Unc)
6.79e+20 POT
Norm Unc
$\frac{d\sigma}{d\delta p_T}$ $\left[10^{-38} \frac{cm^2}{GeV/c\ Ar}\right]$
δp_T [GeV/c]

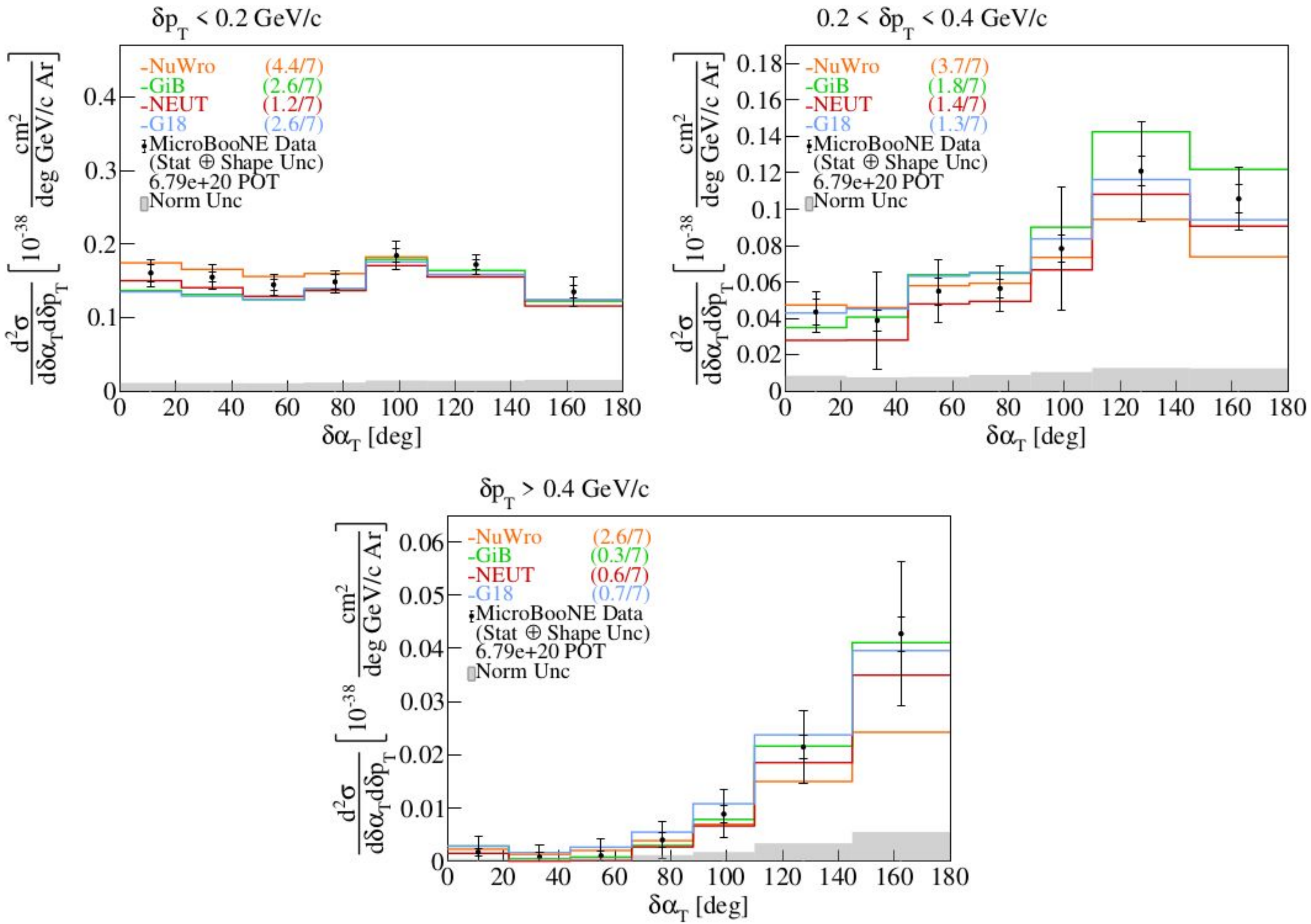

All events
-NuWro (11.0/13)
-GiB (17.3/13)
-NEUT (18.7/13)
-G18 (5.8/13)
MicroBooNE Data
(Stat ⊕ Shape Unc)
6.79e+20 POT
Norm Unc
$\frac{d\sigma}{d\delta p_T}$ $\left[10^{-38} \frac{cm^2}{GeV/c\ Ar}\right]$
δp_T [GeV/c]



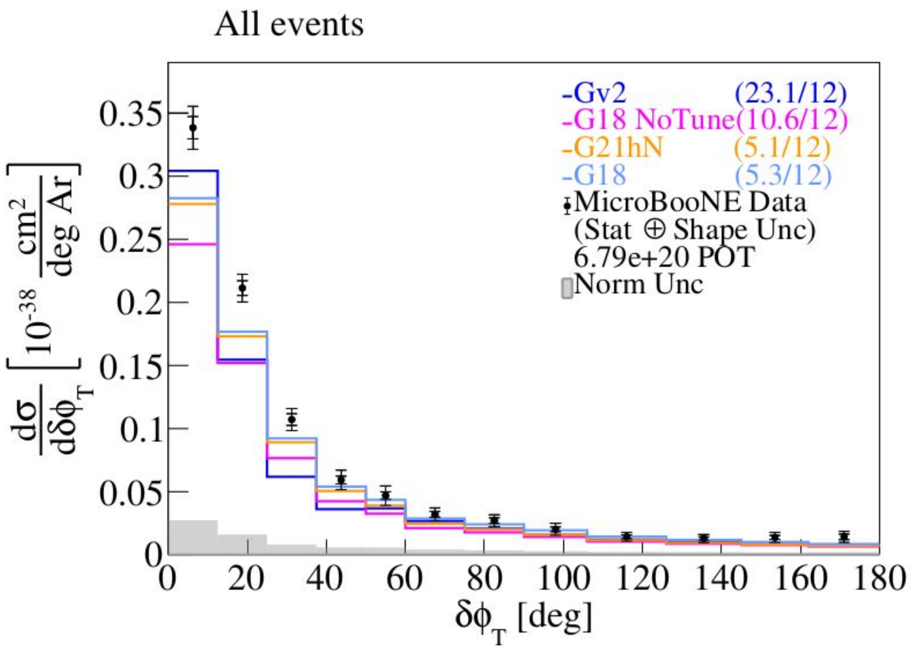
$\delta\alpha_T < 45^o$
-NuWro (2.6/11)
-GiB (1.2/11)
-NEUT (9.4/11)
-G18 (5.7/11)
MicroBooNE Data (Stat ⊕ Shape Unc)
6.79e+20 POT
Norm Unc
$45^o < \delta\alpha_T < 90^o$
-NuWro (7.7/12)
-GiB (5.5/12)
-NEUT (7.8/12)
-G18 (3.9/12)
$90^o < \delta\alpha_T < 135^o$
-NuWro (11.4/13)
-GiB (23.5/13)
-NEUT (11.0/13)
-G18 (5.5/13)
$135^o < \delta\alpha_T < 180^o$
-NuWro (15.3/13)
-GiB (4.6/13)
-NEUT (7.5/13)
-G18 (4.4/13)
$\frac{d^2\sigma}{d\delta\alpha_T d\delta p_T} \left[10^{-38} \frac{cm^2}{deg\ GeV/c\ Ar}\right]$
δp_T [GeV/c]

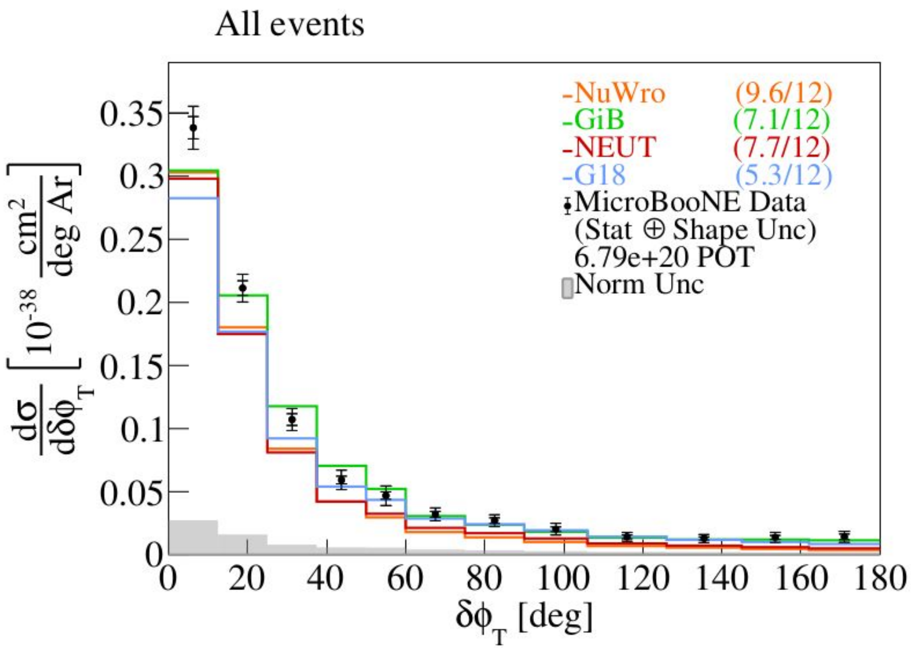

All events
-Gv2 (19.4/7)
-G18 NoTune(10.1/7)
-G21hN (7.9/7)
-G18 (4.9/7)
MicroBooNE Data
(Stat ⊕ Shape Unc)
6.79e+20 POT
Norm Unc
$\frac{d\sigma}{d\delta\alpha_T}\left[10^{-38}\frac{cm^2}{deg\ Ar}\right]$
$\delta\alpha_T$ [deg]

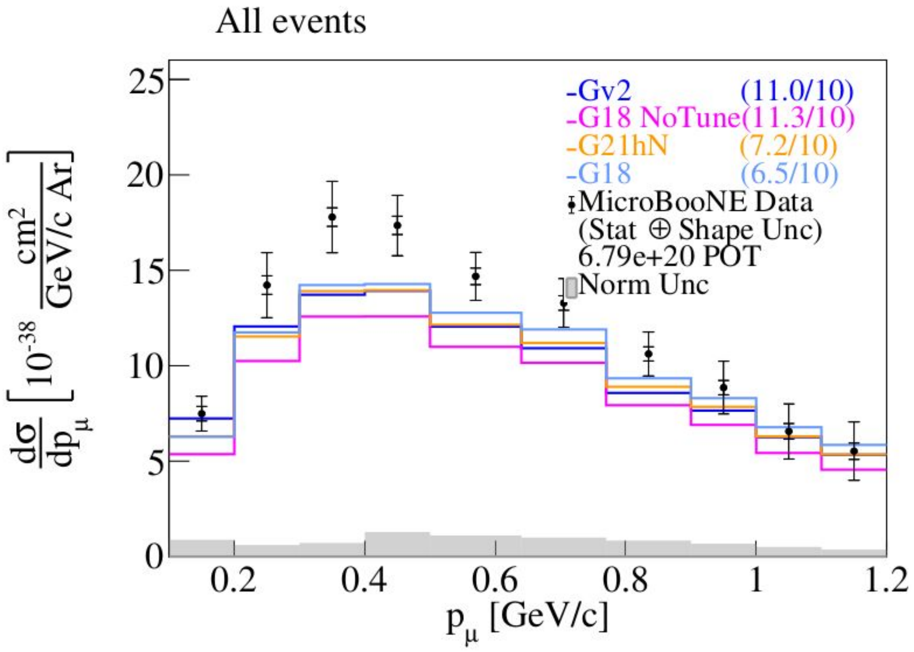

All events
-NuWro (14.8/7)
-GiB (3.3/7)
-NEUT (5.3/7)
-G18 (4.9/7)
MicroBooNE Data
(Stat ⊕ Shape Unc)
6.79e+20 POT
Norm Unc
$\frac{d\sigma}{d\delta\alpha_T}\left[10^{-38}\frac{cm^2}{deg\ Ar}\right]$
$\delta\alpha_T$ [deg]

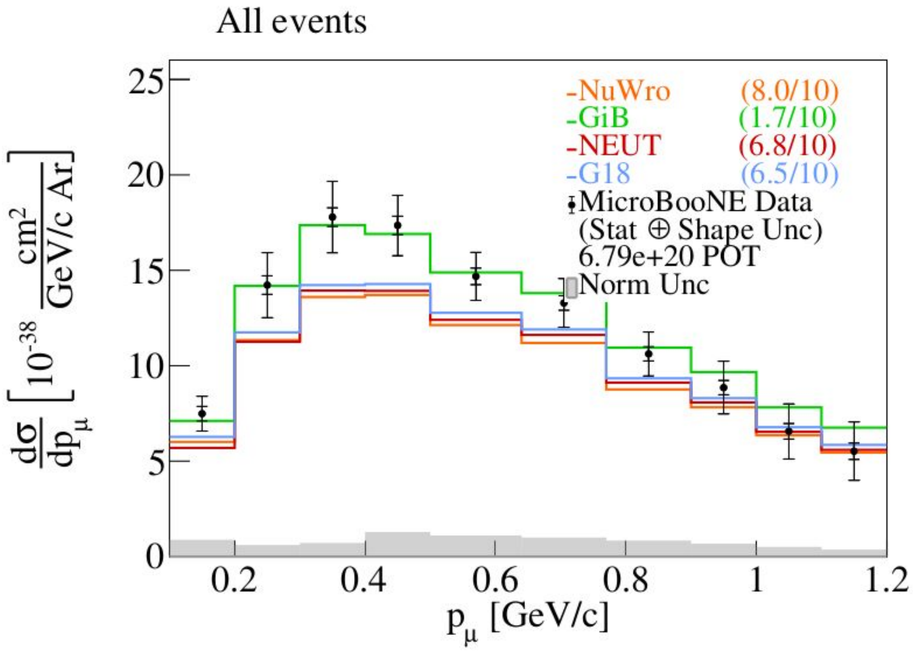


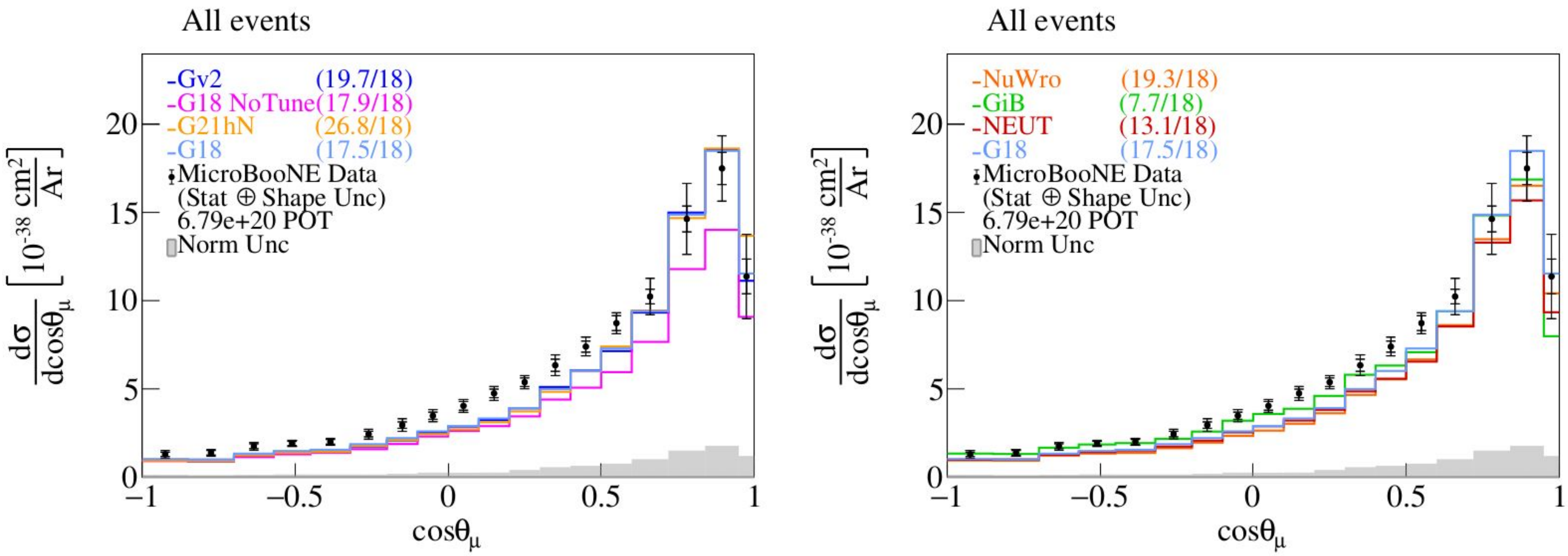
δp_T < 0.2 GeV/c
-NuWro (4.4/7)
-GiB (2.6/7)
-NEUT (1.2/7)
-G18 (2.6/7)
MicroBooNE Data
(Stat ⊕ Shape Unc)
6.79e+20 POT
Norm Unc
δα_T [deg]
0.2 < δp_T < 0.4 GeV/c
-NuWro (3.7/7)
-GiB (1.8/7)
-NEUT (1.4/7)
-G18 (1.3/7)
MicroBooNE Data
(Stat ⊕ Shape Unc)
6.79e+20 POT
Norm Unc
δα_T [deg]
δp_T > 0.4 GeV/c
-NuWro (2.6/7)
-GiB (0.3/7)
-NEUT (0.6/7)
-G18 (0.7/7)
MicroBooNE Data
(Stat ⊕ Shape Unc)
6.79e+20 POT
Norm Unc
δα_T [deg]


All events
-Gv2 (23.1/12)
-G18 NoTune(10.6/12)
-G21hN (5.1/12)
-G18 (5.3/12)
MicroBooNE Data
(Stat ⊕ Shape Unc)
6.79e+20 POT
Norm Unc
$\frac{d\sigma}{d\delta\phi_T}\left[10^{-38}\frac{cm^2}{deg\ Ar}\right]$
$\delta\phi_T$ [deg]

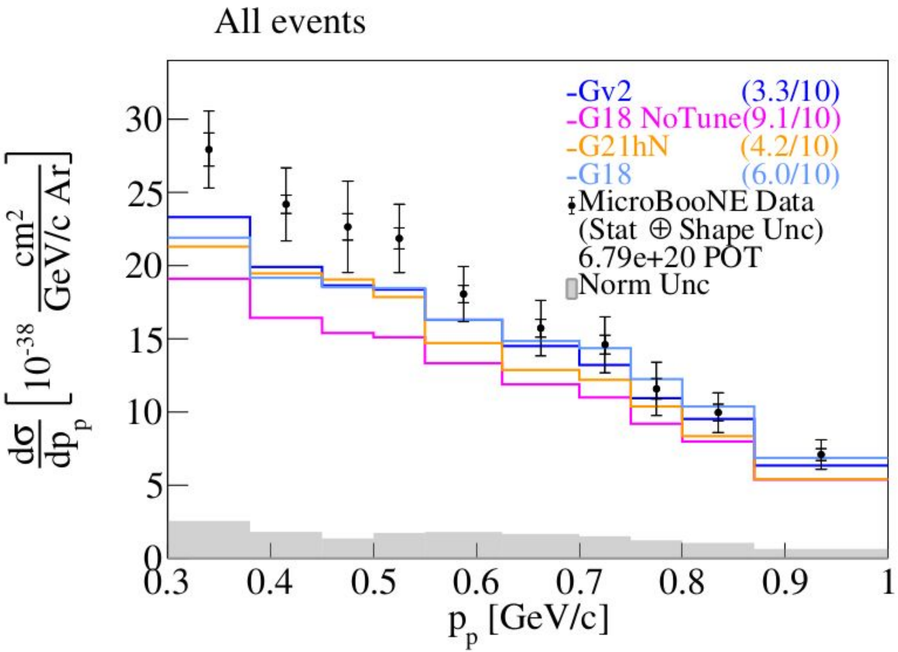

All events
-NuWro (9.6/12)
-GiB (7.1/12)
-NEUT (7.7/12)
-G18 (5.3/12)
MicroBooNE Data
(Stat ⊕ Shape Unc)
6.79e+20 POT
Norm Unc
$\frac{d\sigma}{d\delta\phi_T}\left[10^{-38}\frac{cm^2}{deg\ Ar}\right]$
$\delta\phi_T$ [deg]

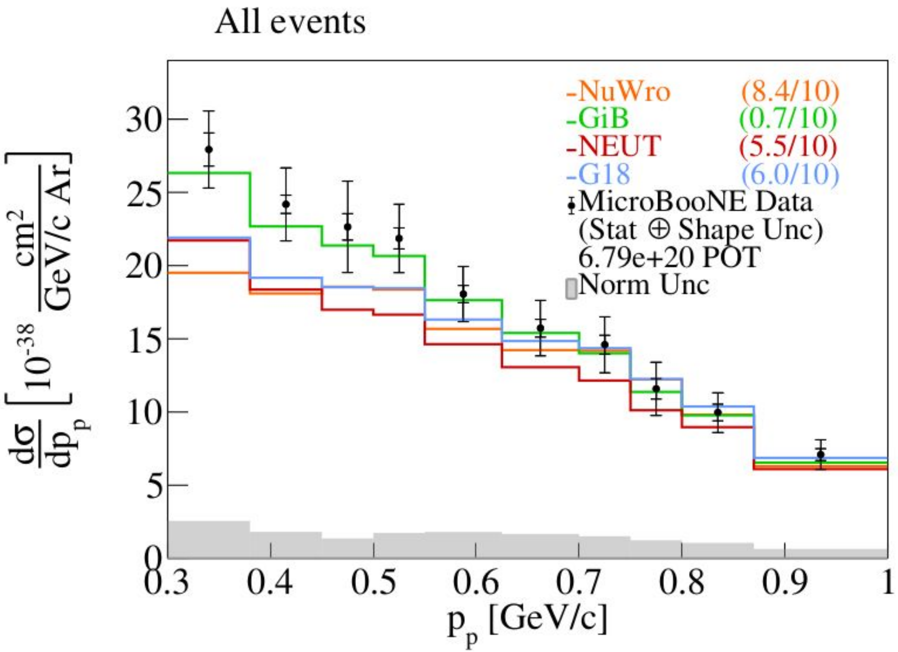

All events
-Gv2 (11.0/10)
-G18 NoTune(11.3/10)
-G21hN (7.2/10)
-G18 (6.5/10)
MicroBooNE Data
(Stat ⊕ Shape Unc)
6.79e+20 POT
Norm Unc
$\frac{d\sigma}{dp_{\mu}} \left[10^{-38} \frac{cm^2}{GeV/c\ Ar}\right]$
p_{μ} [GeV/c]

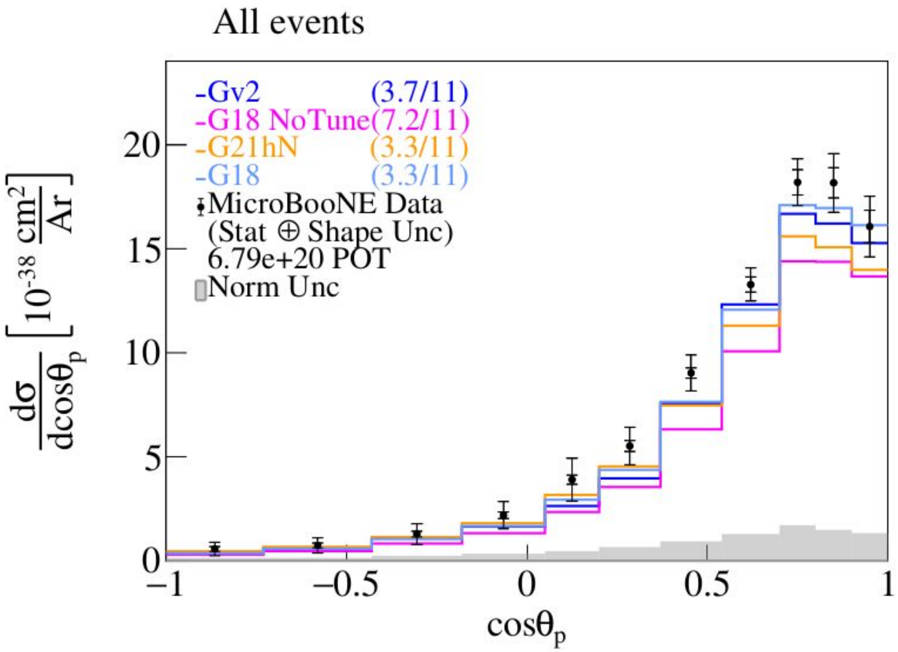

All events
-NuWro (8.0/10)
-GiB (1.7/10)
-NEUT (6.8/10)
-G18 (6.5/10)
MicroBooNE Data
(Stat ⊕ Shape Unc)
6.79e+20 POT
Norm Unc
$\frac{d\sigma}{dp_{\mu}} \left[10^{-38} \frac{cm^2}{GeV/c\ Ar}\right]$
p_{μ} [GeV/c]



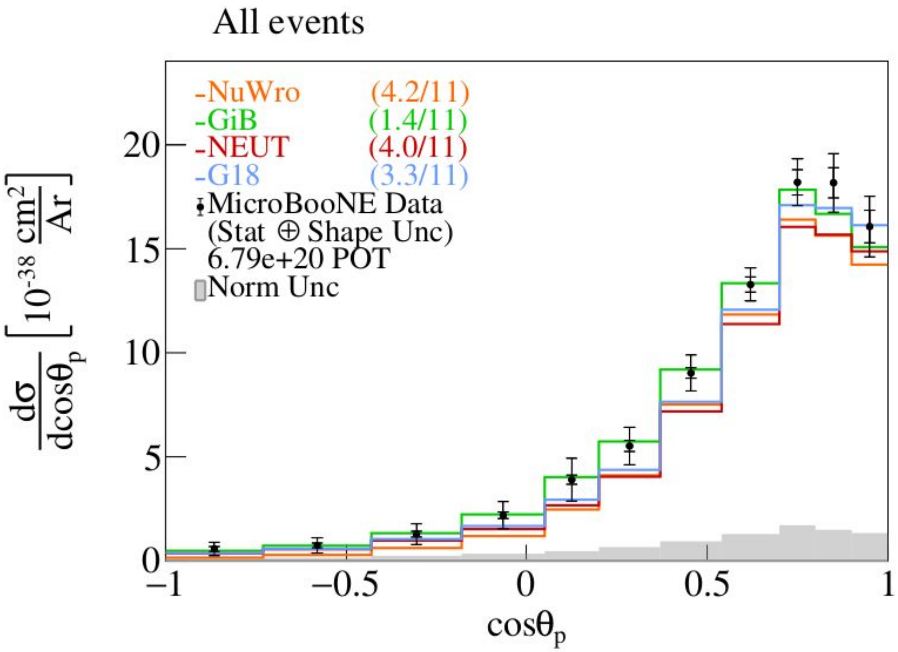
All events
-Gv2 (19.7/18)
-G18 NoTune(17.9/18)
-G21hN (26.8/18)
-G18 (17.5/18)
MicroBooNE Data
(Stat ⊕ Shape Unc)
6.79e+20 POT
Norm Unc
$\frac{d\sigma}{d\cos\theta_\mu}\left[10^{-38}\frac{cm^2}{Ar}\right]$
$\cos\theta_\mu$
All events
-NuWro (19.3/18)
-GiB (7.7/18)
-NEUT (13.1/18)
-G18 (17.5/18)
MicroBooNE Data
(Stat ⊕ Shape Unc)
6.79e+20 POT
Norm Unc
$\frac{d\sigma}{d\cos\theta_\mu}\left[10^{-38}\frac{cm^2}{Ar}\right]$
$\cos\theta_\mu$


All events
-Gv2 (3.3/10)
-G18 NoTune(9.1/10)
-G21hN (4.2/10)
-G18 (6.0/10)
MicroBooNE Data
(Stat ⊕ Shape Unc)
6.79e+20 POT
Norm Unc
$\frac{d\sigma}{dp_p}\left[10^{-38}\frac{cm^2}{GeV/c\ Ar}\right]$
p_p [GeV/c]


All events
-NuWro (8.4/10)
-GiB (0.7/10)
-NEUT (5.5/10)
-G18 (6.0/10)
MicroBooNE Data
(Stat ⊕ Shape Unc)
6.79e+20 POT
Norm Unc
$\frac{d\sigma}{dp_p}\left[10^{-38}\frac{cm^2}{GeV/c\ Ar}\right]$
p_p [GeV/c]



All events
-Gv2 (3.7/11)
-G18 NoTune(7.2/11)
-G21hN (3.3/11)
-G18 (3.3/11)
MicroBooNE Data
(Stat ⊕ Shape Unc)
6.79e+20 POT
Norm Unc
$\frac{d\sigma}{d\cos\theta_p}\left[10^{-38}\frac{cm^2}{Ar}\right]$
$\cos\theta_p$

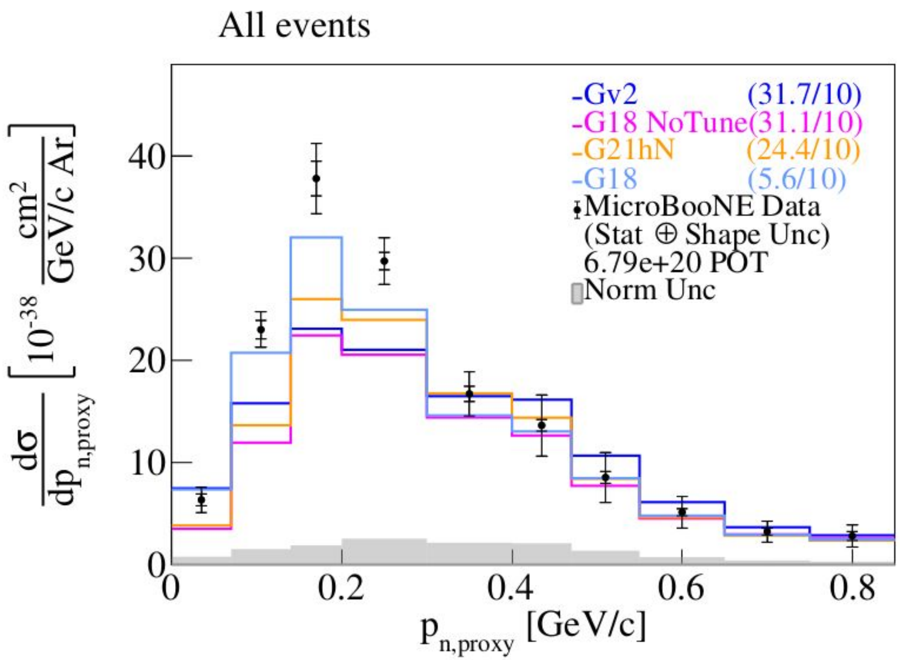


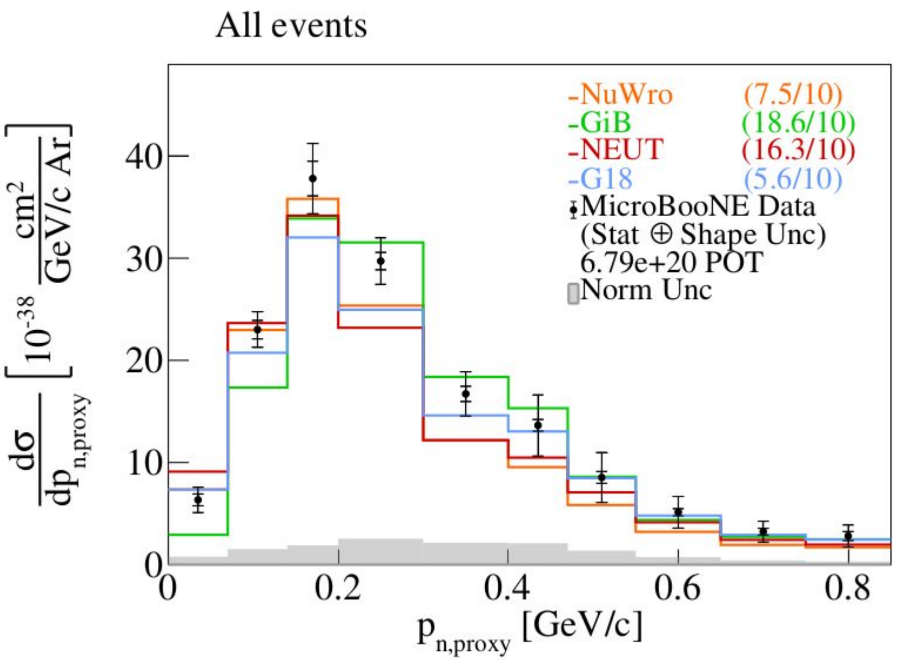
All events
-NuWro (4.2/11)
-GiB (1.4/11)
-NEUT (4.0/11)
-G18 (3.3/11)
MicroBooNE Data
(Stat ⊕ Shape Unc)
6.79e+20 POT
Norm Unc
$\frac{d\sigma}{d\cos\theta_p}\left[10^{-38}\frac{cm^2}{Ar}\right]$
$\cos\theta_p$

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

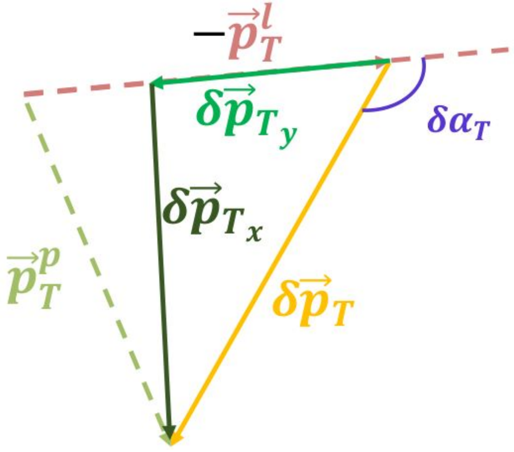
Under QE assumption

Phys. Rev. Lett. 121, 022504 (2018)





More Complex Nuclear Sensitivity Variables



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

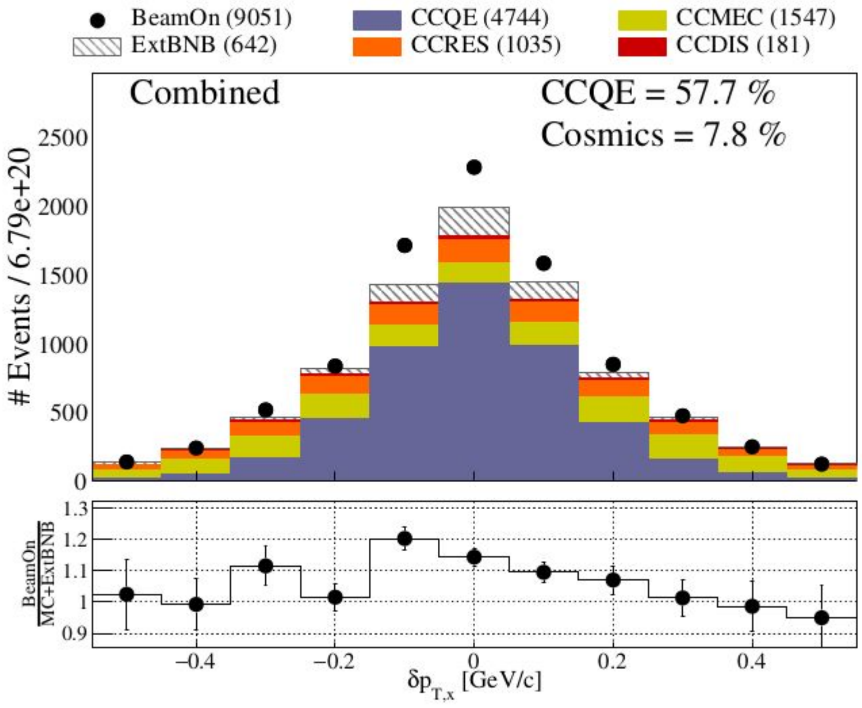
Sensitivity to Fermi motion

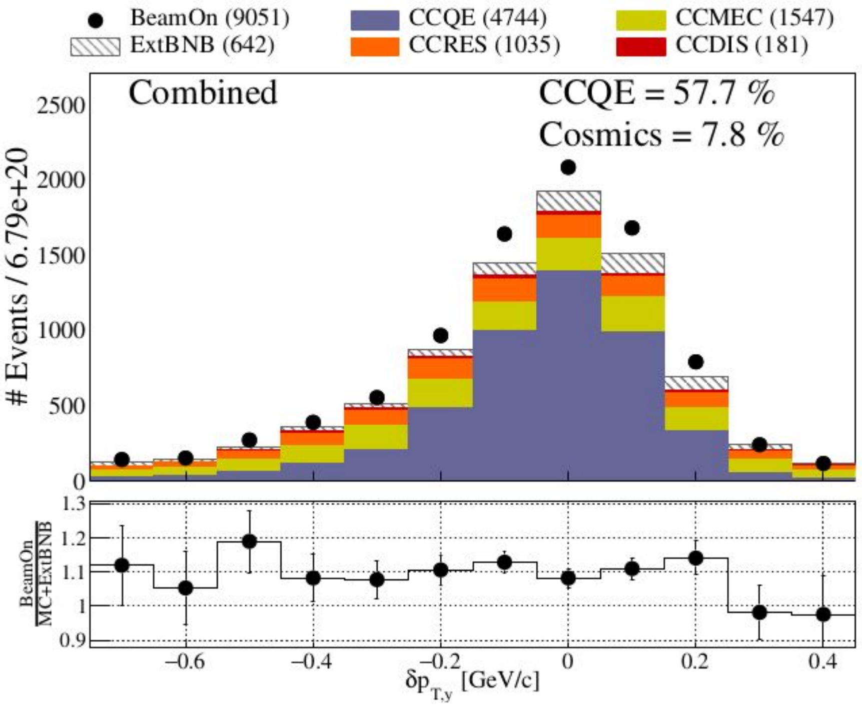
$$\delta p_{T_y} = -\hat{p}_T^l \cdot \delta\vec{p}_T = |\delta\vec{p}_T| \cos(\delta\alpha_T)$$

Sensitivity to removal energy

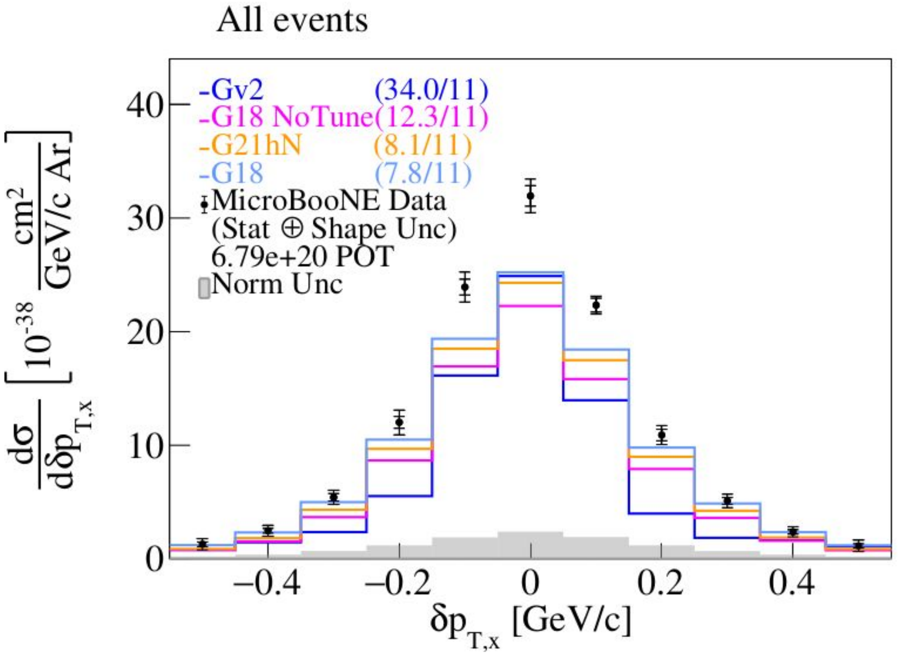
Phys.Rev. D 101, 092001 (2020)

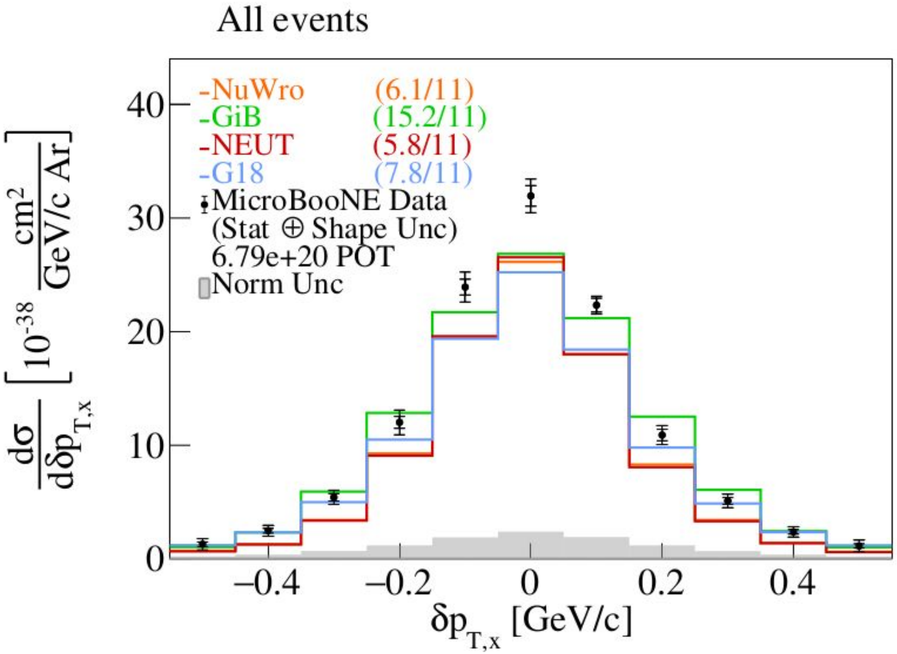
$$\delta p_{Tx} = \delta p_T \cdot sin\delta\alpha_T$$
$$\delta p_{Ty} = \delta p_T \cdot cos\delta\alpha_T.$$

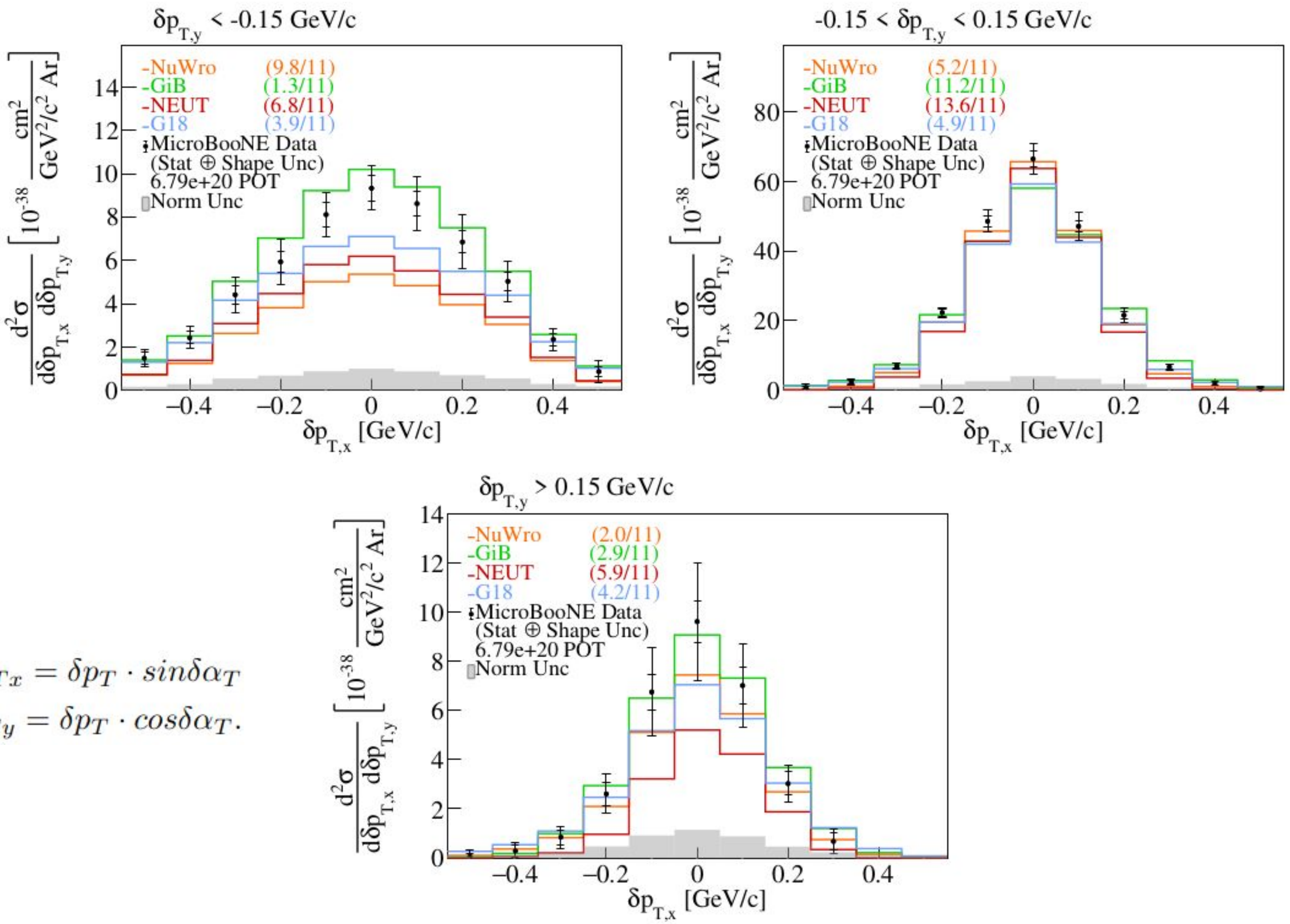




$$\delta p_{Tx} = \delta p_T \cdot sin\delta\alpha_T$$
$$\delta p_{Ty} = \delta p_T \cdot cos\delta\alpha_T.$$

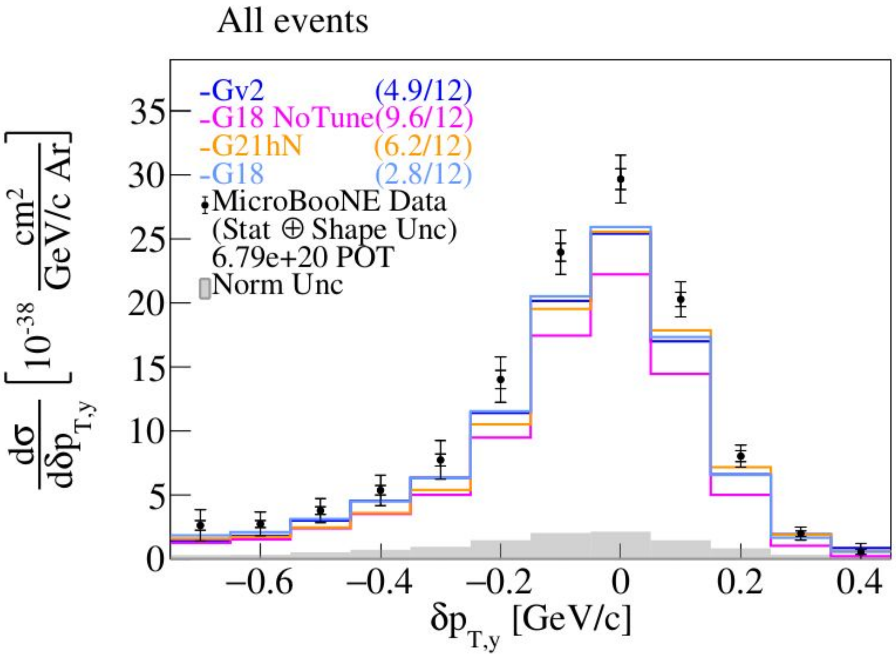


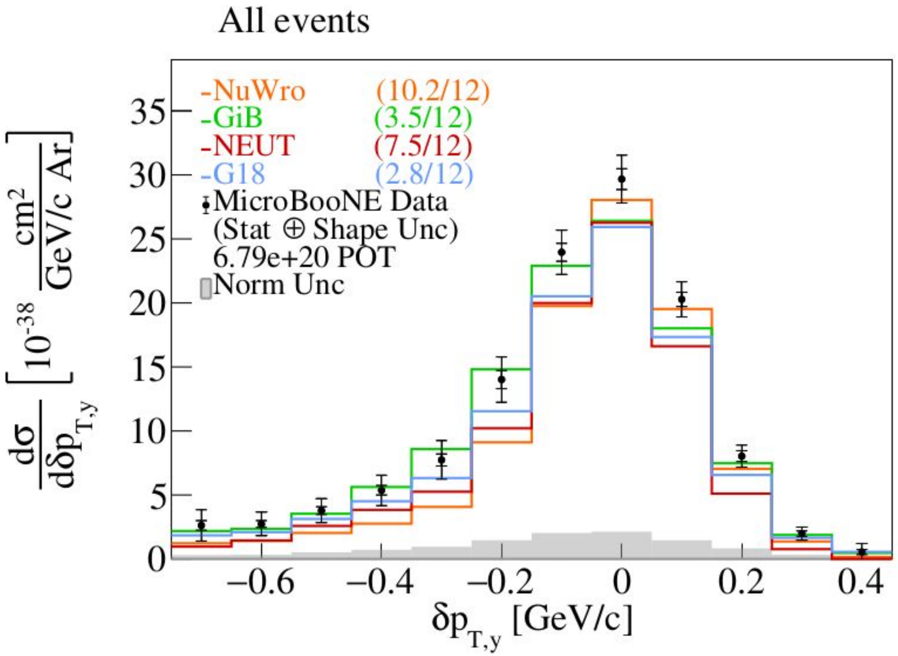




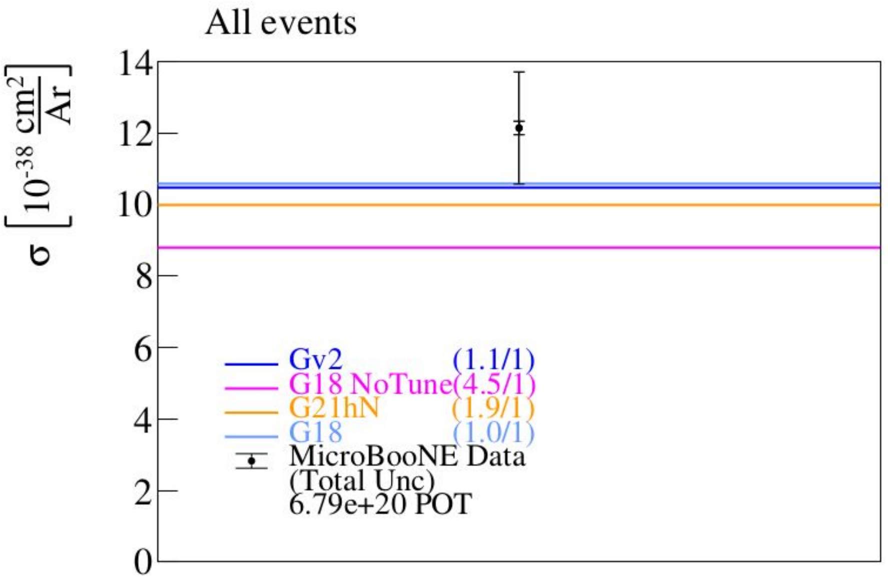
$$\delta p_{Tx} = \delta p_T \cdot sin\delta\alpha_T$$
$$\delta p_{Ty} = \delta p_T \cdot cos\delta\alpha_T.$$

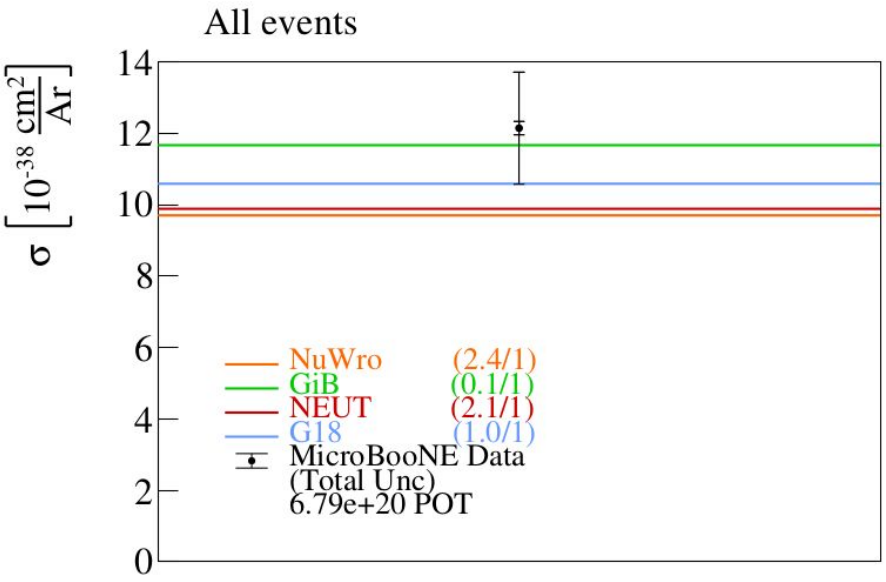
$$\delta p_{Tx} = \delta p_T \cdot sin\delta\alpha_T$$
$$\delta p_{Ty} = \delta p_T \cdot cos\delta\alpha_T.$$

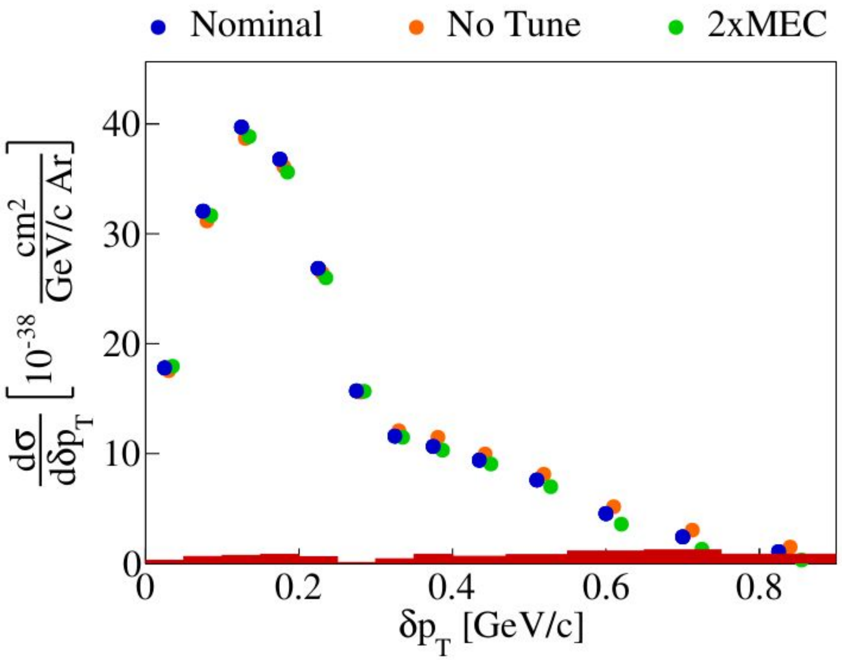




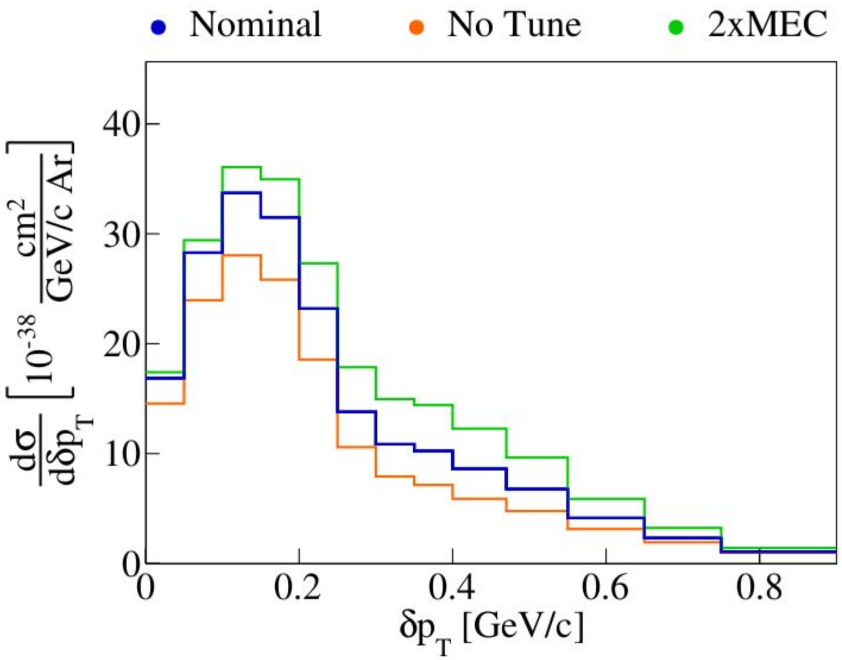
Integrated Cross Sections



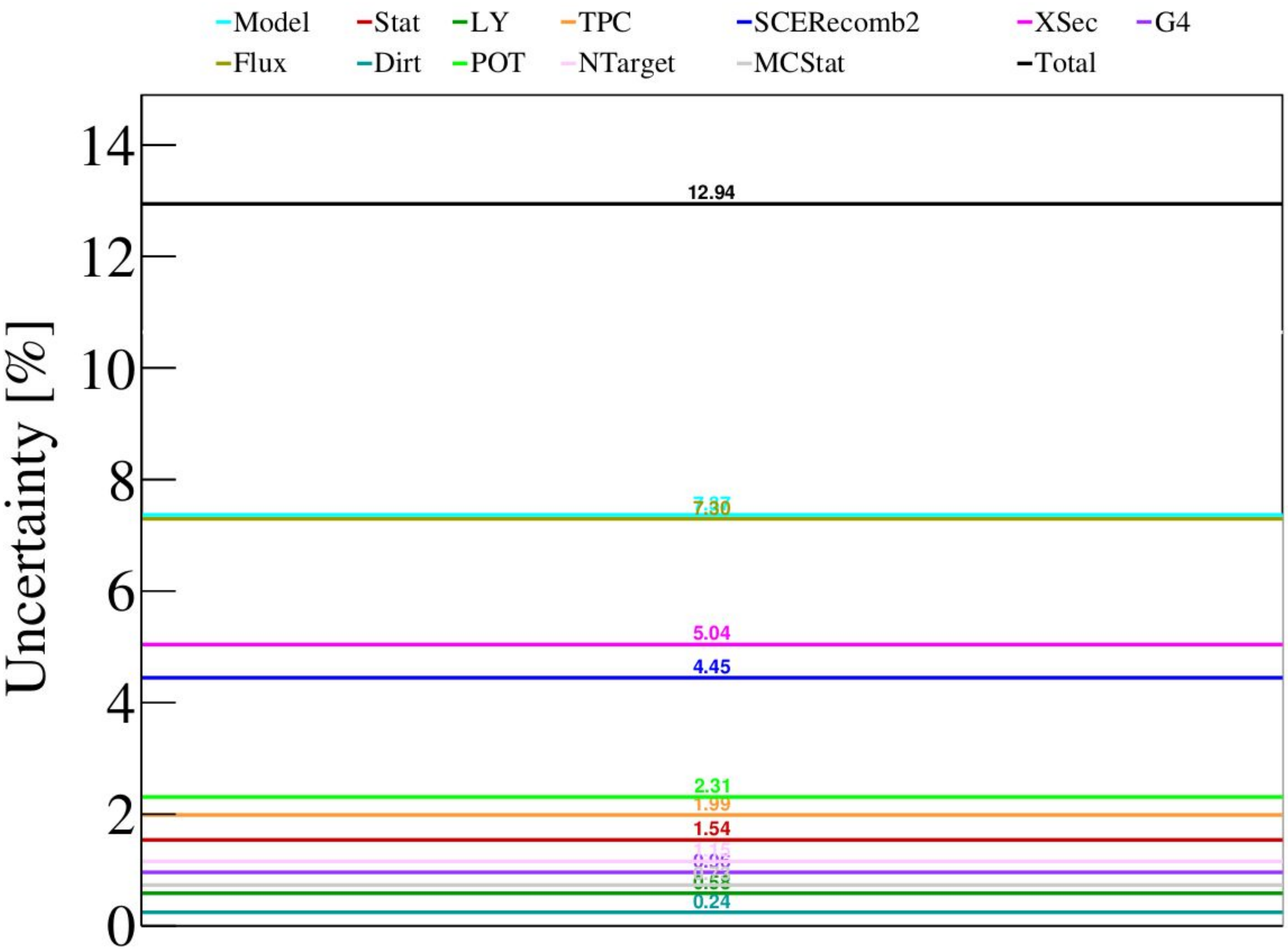




Nominal
No Tune
2xMEC
$\frac{d\sigma}{d\delta p_T}$ $\left[10^{-38} \frac{cm^2}{GeV/c\ Ar}\right]$
δp_T [GeV/c]



Nominal
No Tune
2xMEC
$\frac{d\sigma}{d\delta p_T}$ $\left[10^{-38} \frac{cm^2}{GeV/c\ Ar}\right]$
δp_T [GeV/c]

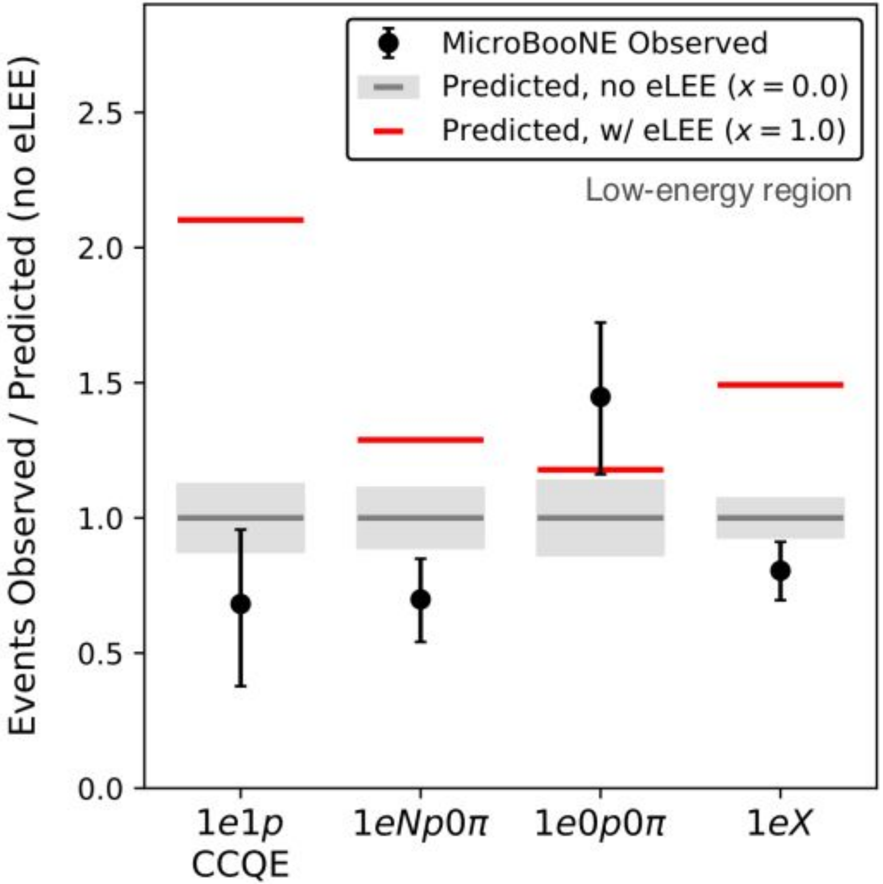

Model
Stat
LY
TPC
SCERecomb2
XSec
G4
Flux
Dirt
POT
NTarget
MCStat
Total
Uncertainty [%]
14
12
10
8
6
4
2
0
12.94
7.30
5.04
4.45
2.31
1.99
1.54
0.24

MicroBooNE LEE Results

- ν_e prediction adequately describes the data across many different kinematic quantities

- Constrained ν_e energy spectra for the CCQE 1e1p, 1eNp0π, 1e0p0π, and 1eX selections yield χ^2 goodness-of-fit p-values of 1.4×10^{-2}, 0.18, 0.13, and 0.85, respectively
  - Note that reconstructed neutrino energy definition differs between analyses

- Observe ν_e candidate event rates in general agreement with or below the predicted rates

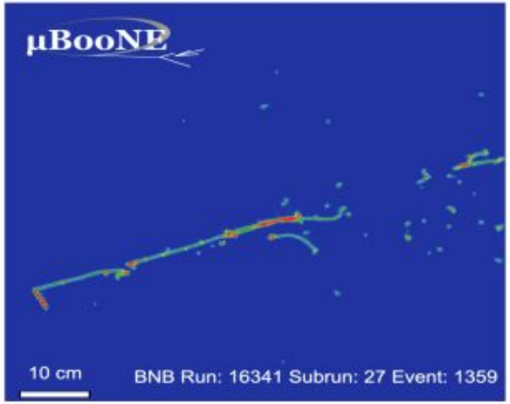


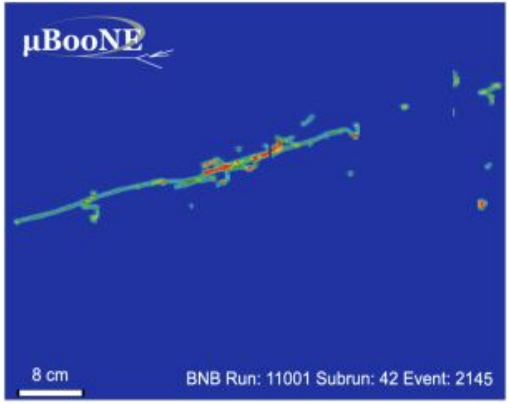
MicroBooNE LEE Summary

- Today's results are found to be consistent with the nominal ν_e rate expectations from the Booster Neutrino Beam
  - No excess of ν_e events is observed
  - Disfavor generic ν_e interactions as the primary contributor to the excess, with a 1σ (2σ) upper limit on the inclusive ν_e CC contribution to the excess of 22% (51%)
  - Reject simple eLEE model of the MiniBooNE low energy excess at >97% for both exclusive and inclusive event classes

- Previously reported that we disfavor the interpretation of MiniBooNE LEE as a x3.18 enhancement of NC $\Delta \rightarrow N\gamma$ rate at 94.8% CL (arXiv:2110.00409)

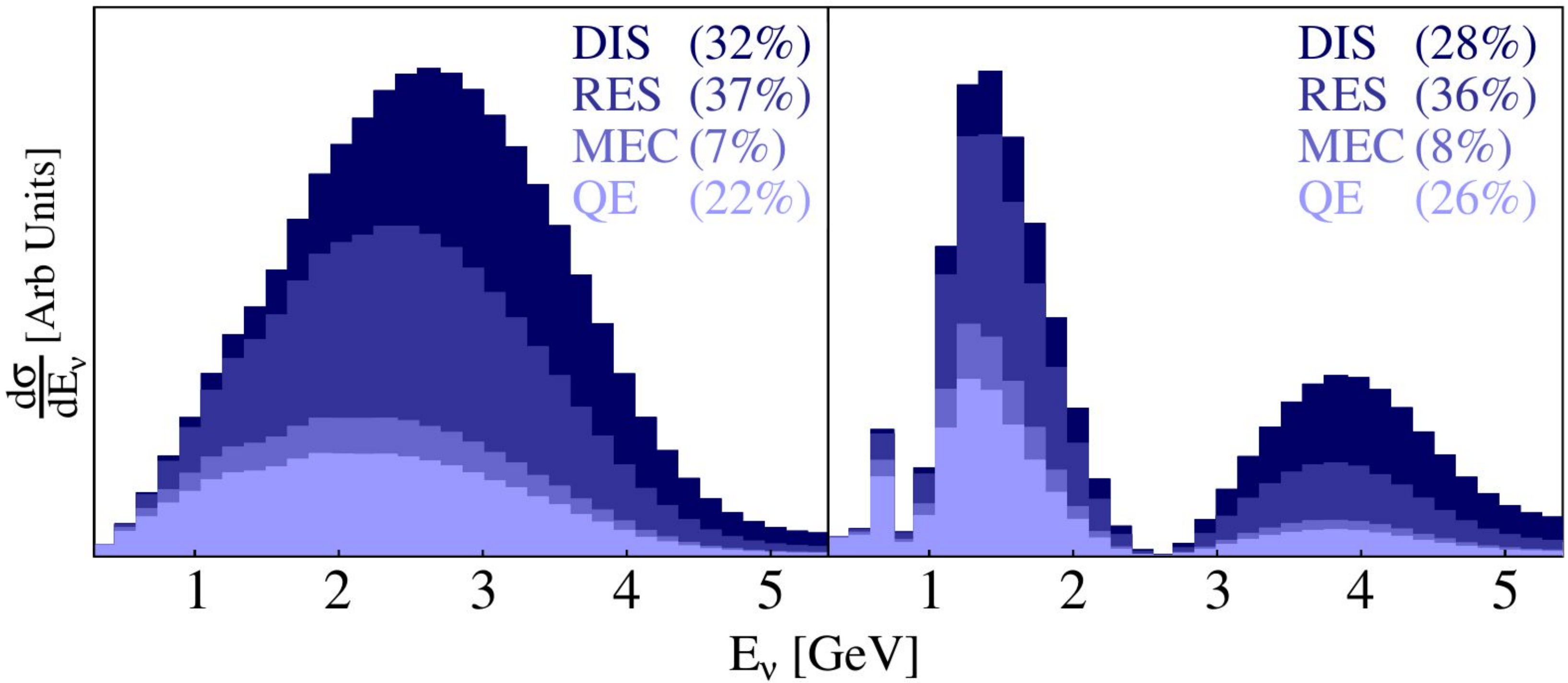
- Together, these are the first detailed study of the MiniBooNE low energy excess that first appeared in 2007





Mismodelling Impact On Mixing Parameters

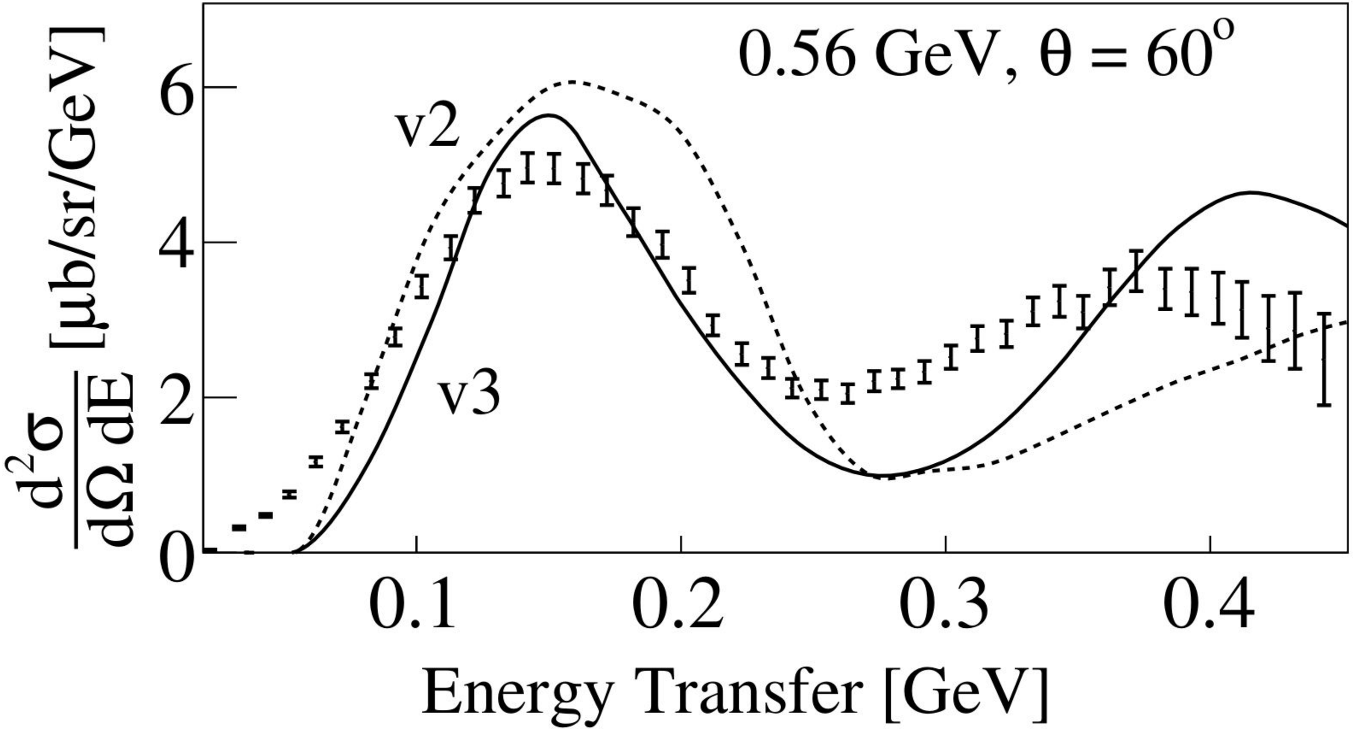
Charged current cross sections obtained using GENIE for the DUNE near detector (left) and far detector (right) oscillated fluxes



Phys. Rev. D 103, 113003 (2021)

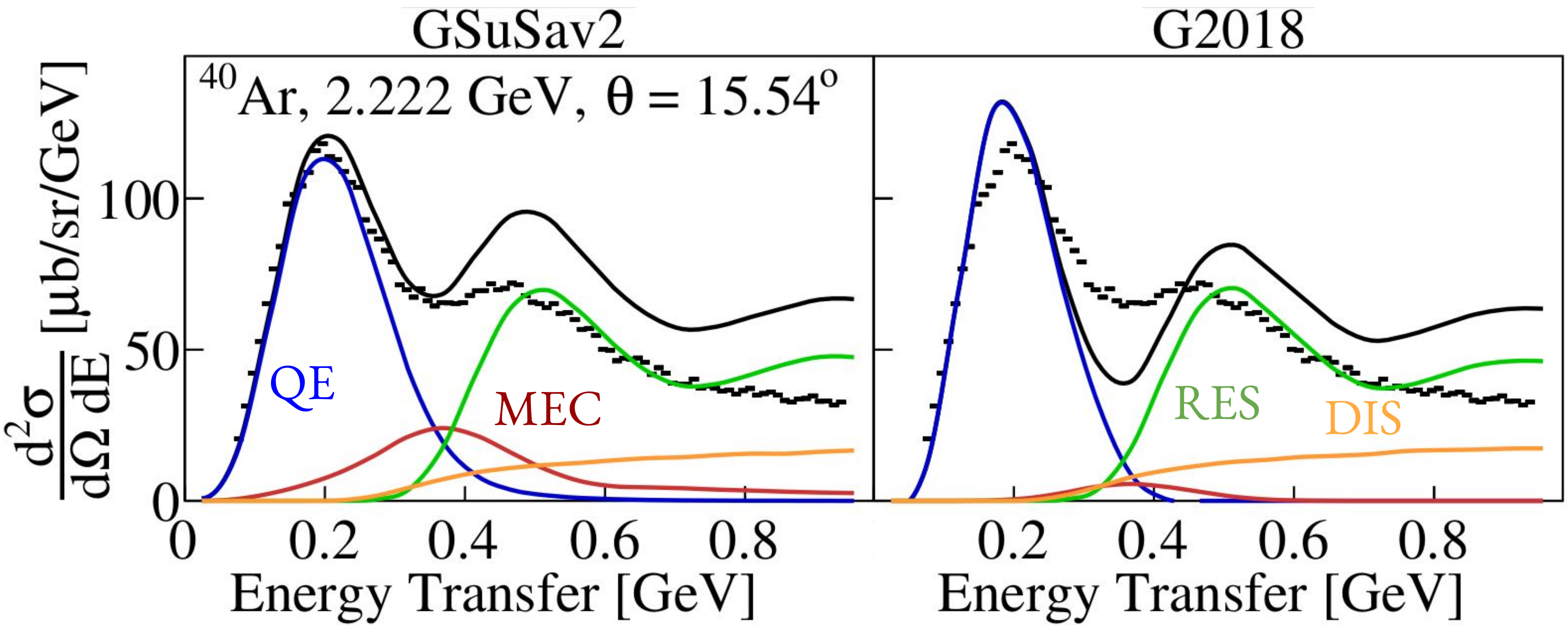
Issues Identified & Fixed In G2018

(e,e’) ^{12}C with G2018



Phys. Rev. D 103, 113003 (2021)

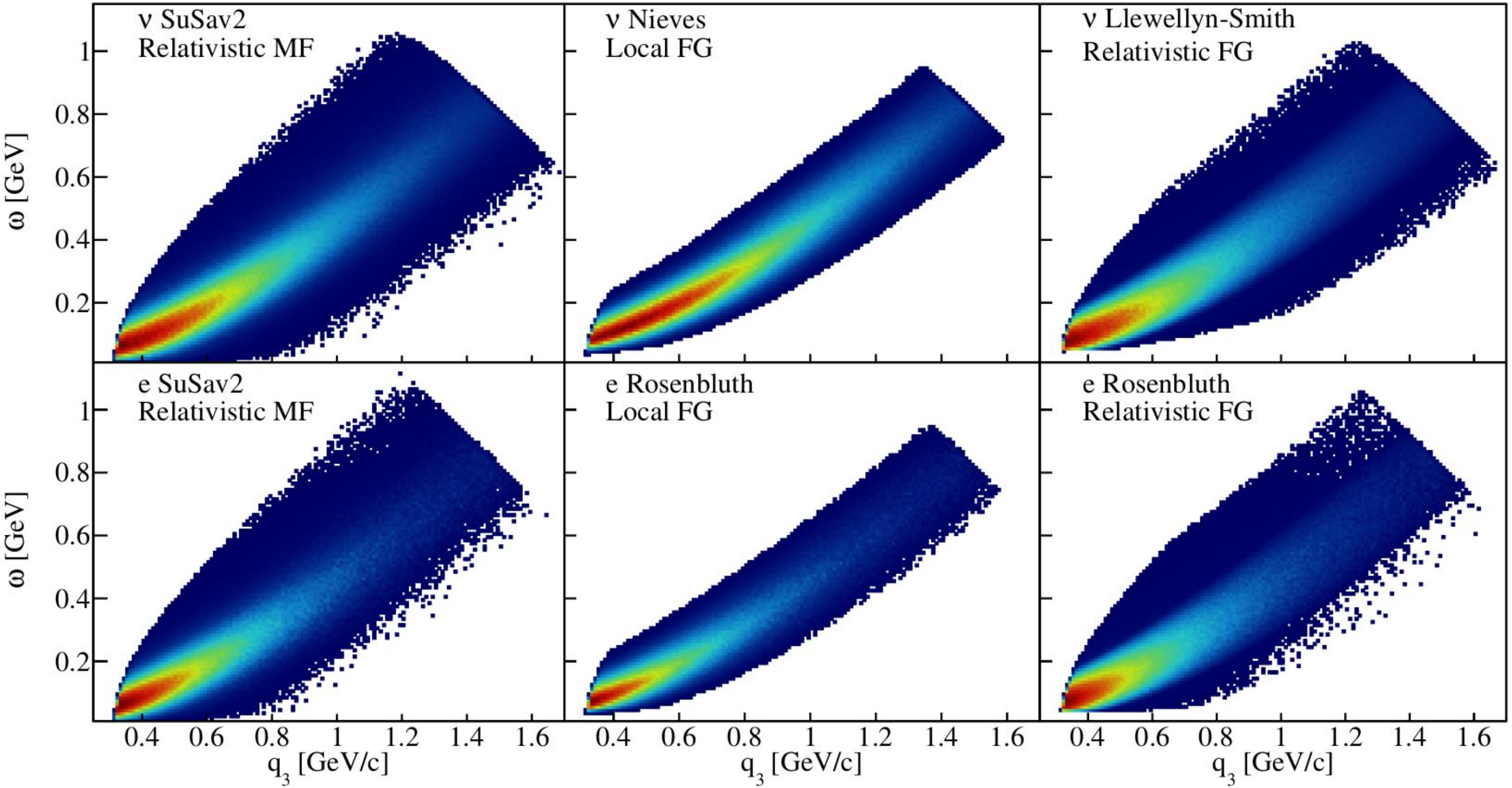
SuSav2 Offers More Accurate Prediction



Phys. Rev. D 103, 113003 (2021)

Impact Of Nuclear Model Choice On Phase-Space

QE Events

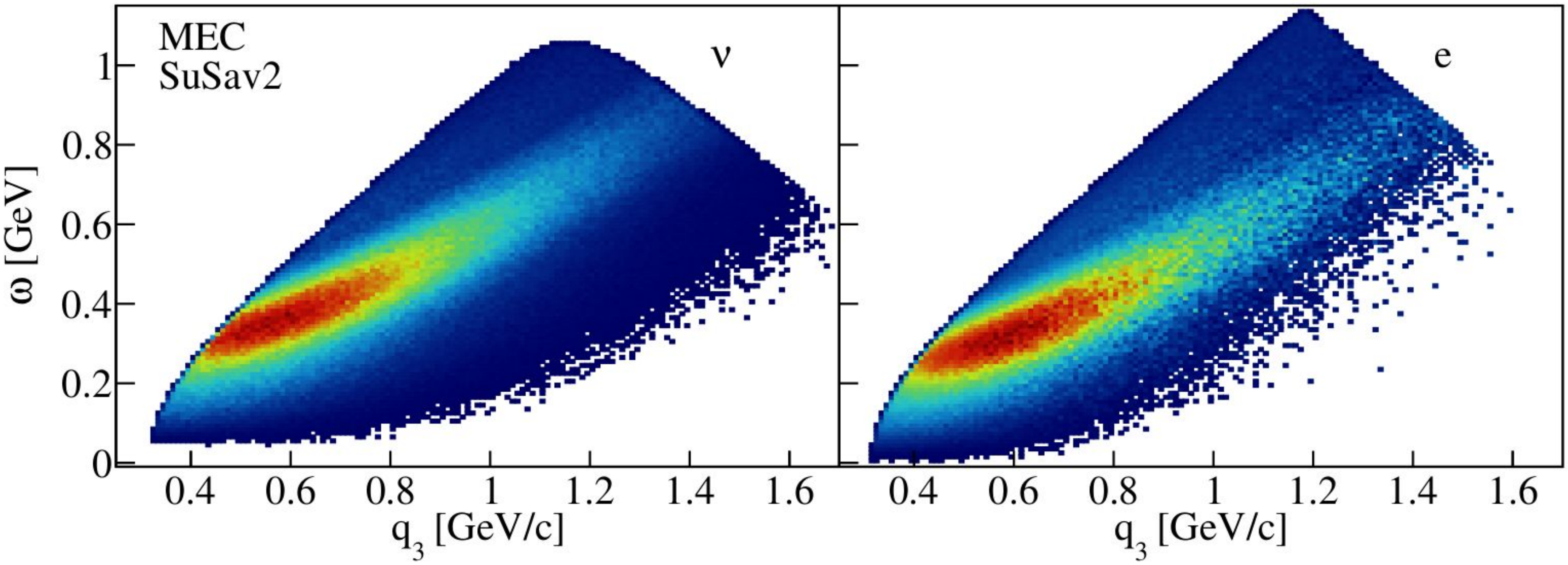


Phys. Rev. D 103, 113003 (2021)

Electron results scaled by Q^4

Consistent Treatment Of MEC Events With SuSav2

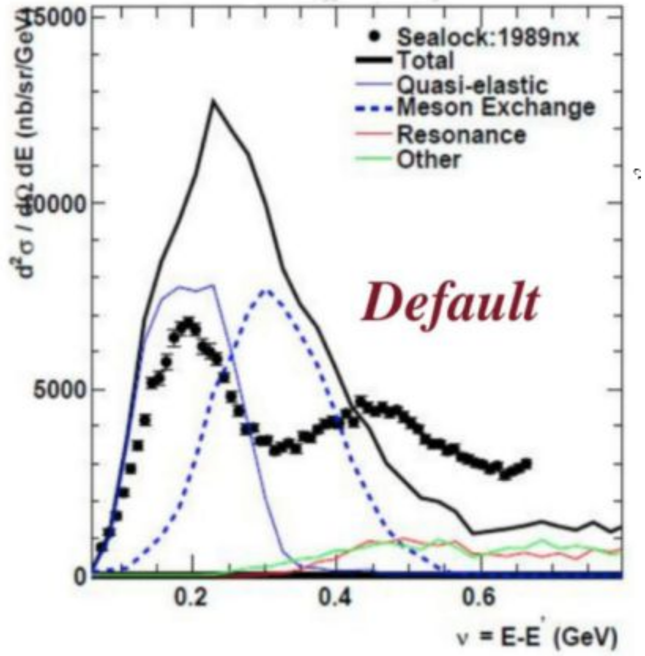
Unique chance to constraint one of least understood interaction channels

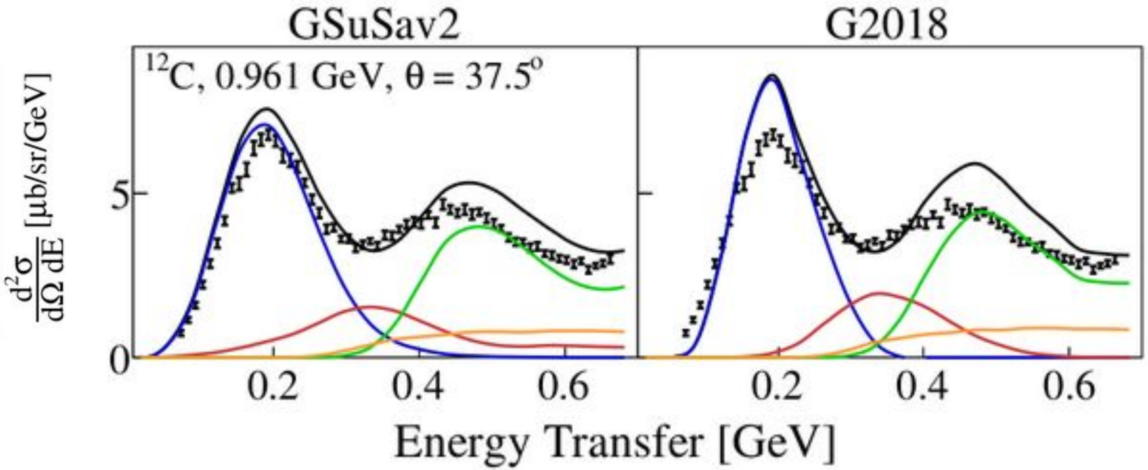


Phys. Rev. D 103, 113003 (2021)

Electron results scaled by Q^4

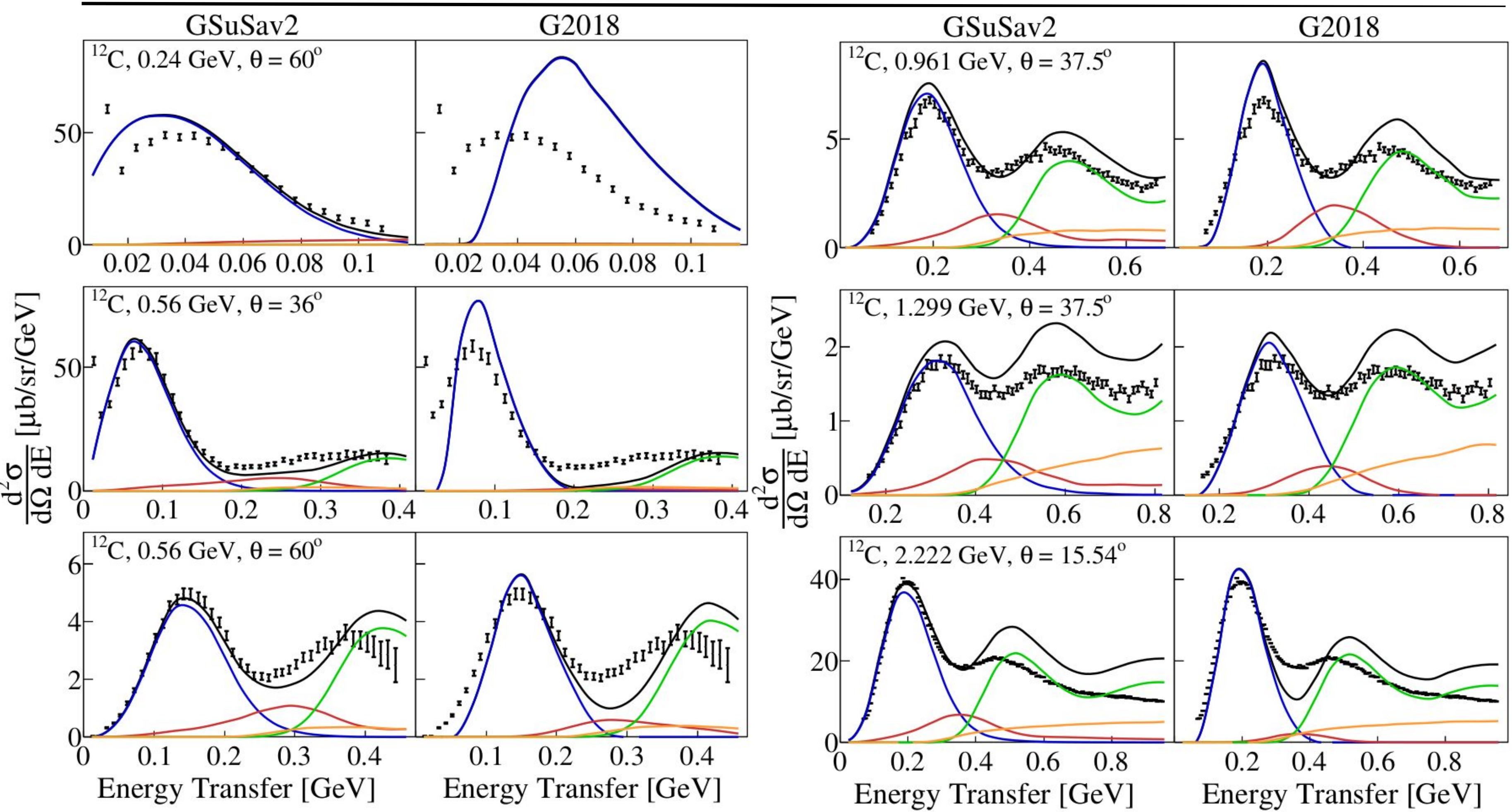
When Started vs Today





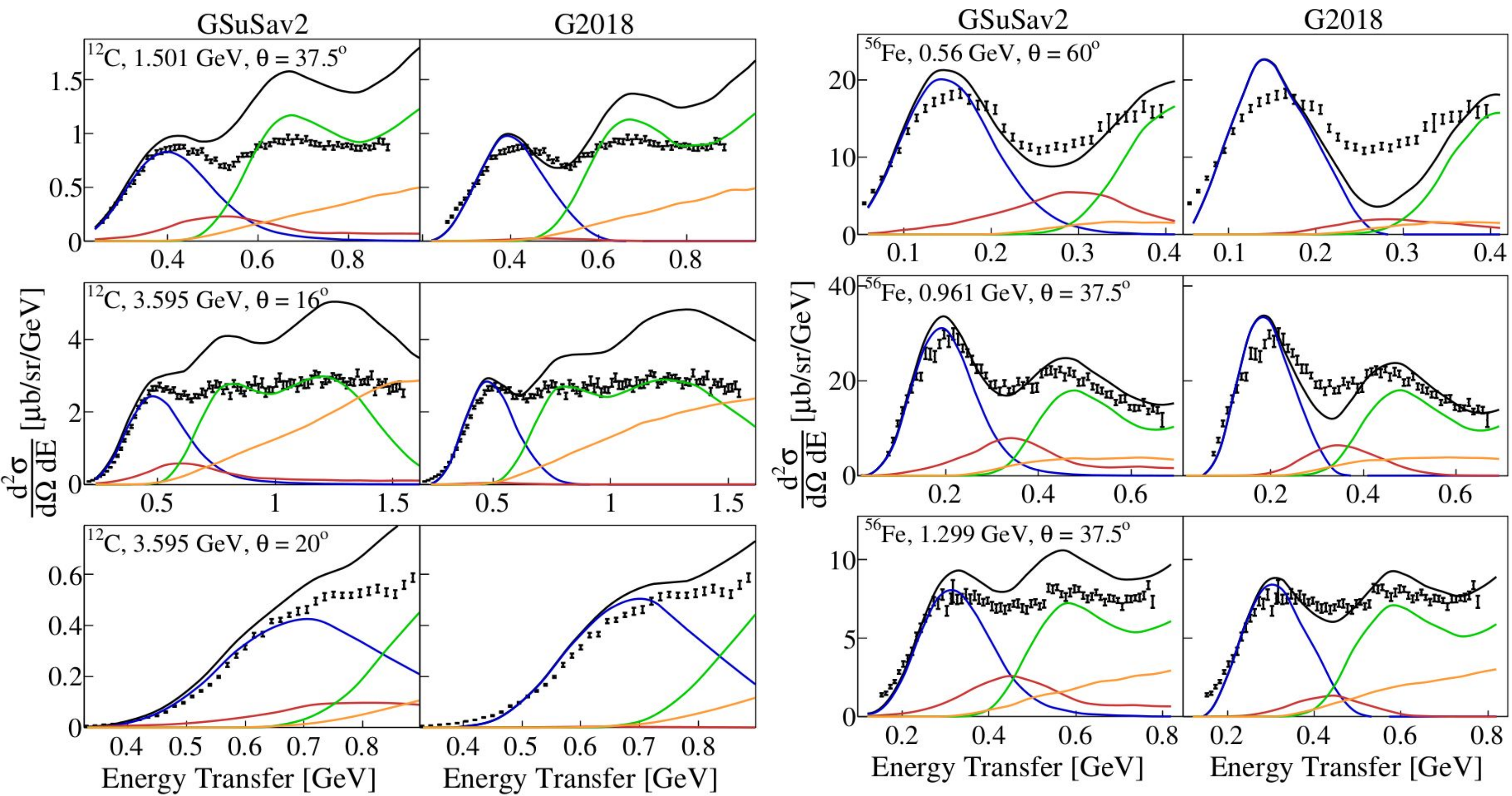
Inclusive C cross sections

Phys. Rev. D 103, 113003 (2021)



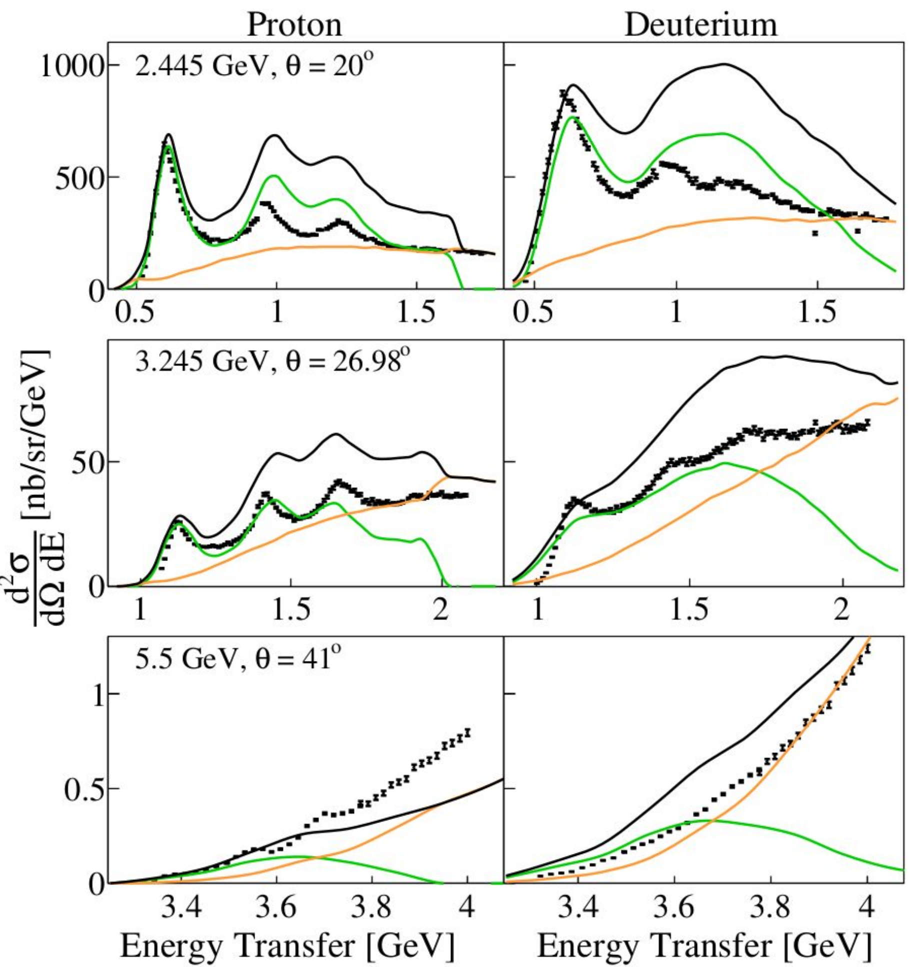
Inclusive C/Fe cross sections

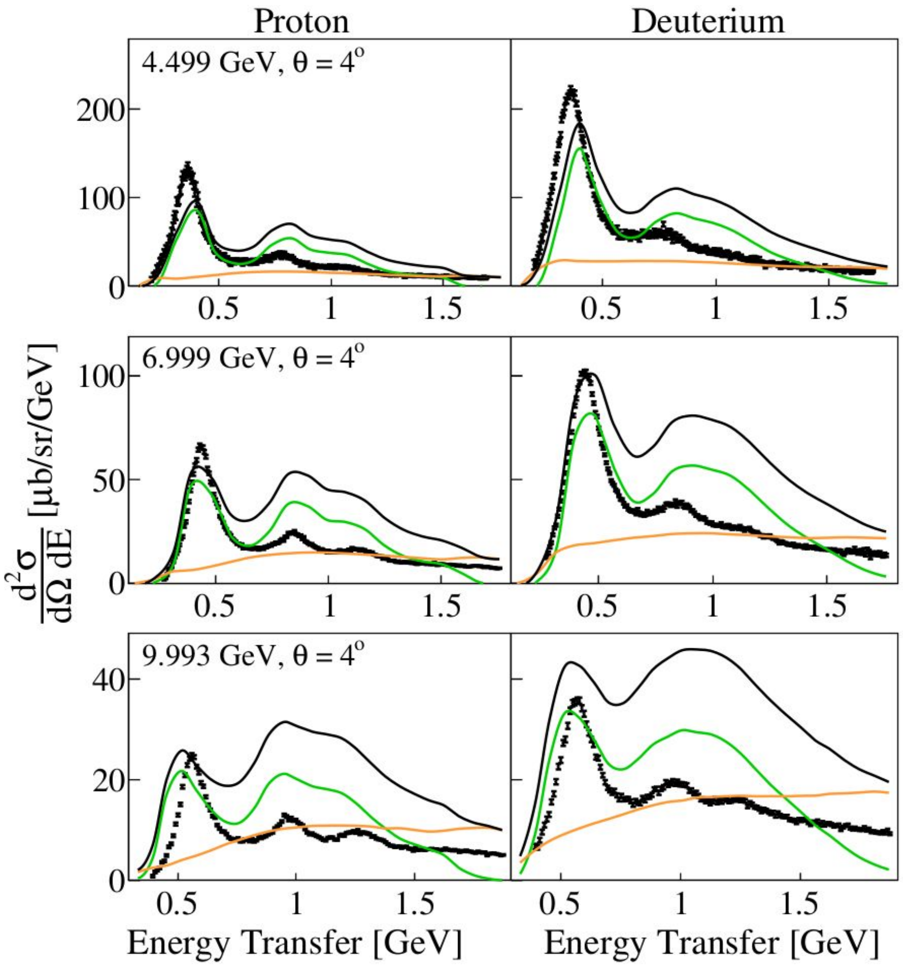
Phys. Rev. D 103, 113003 (2021)



Inclusive H cross sections

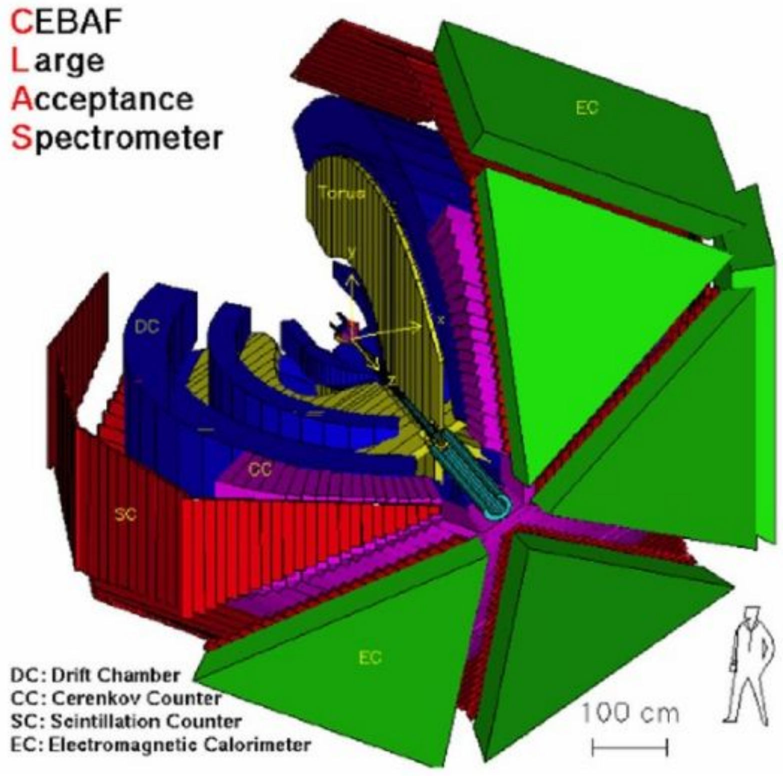
Phys. Rev. D 103, 113003 (2021)



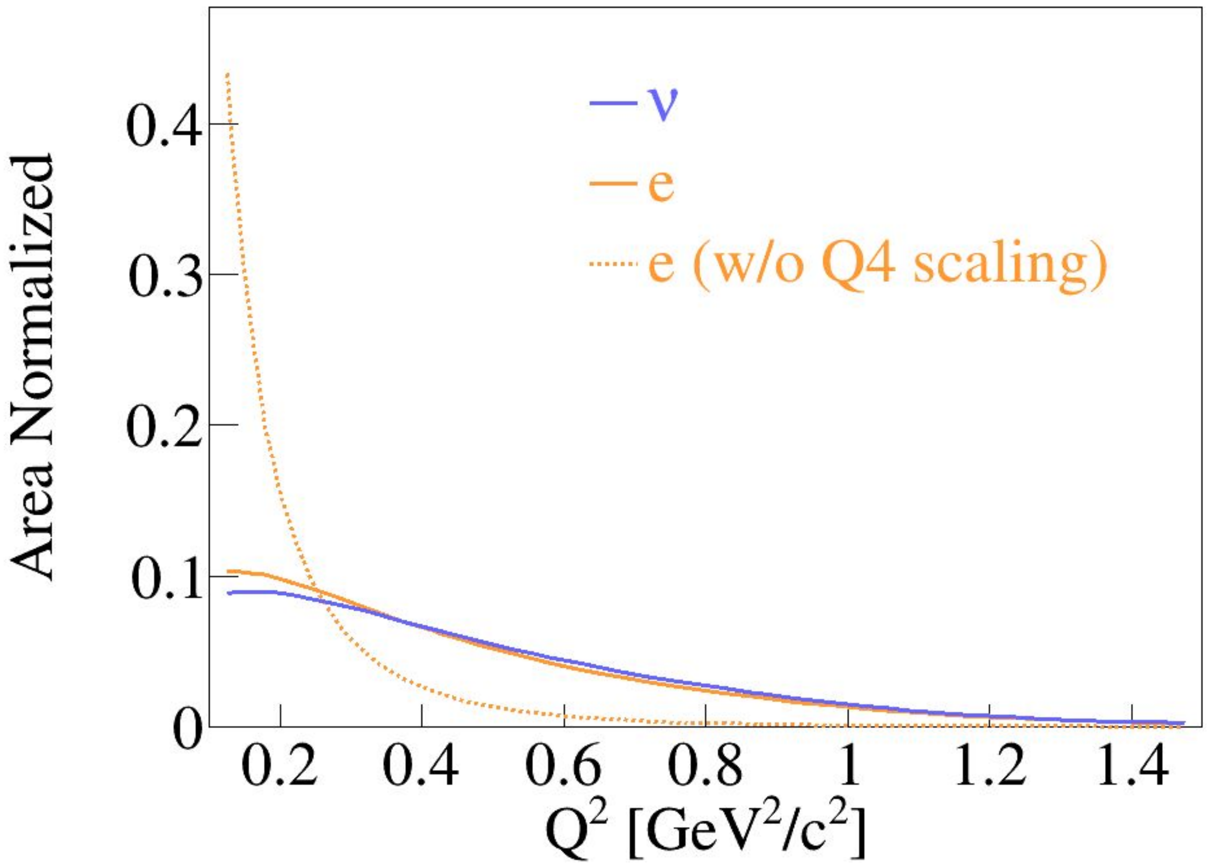


CLAS Angular Coverage

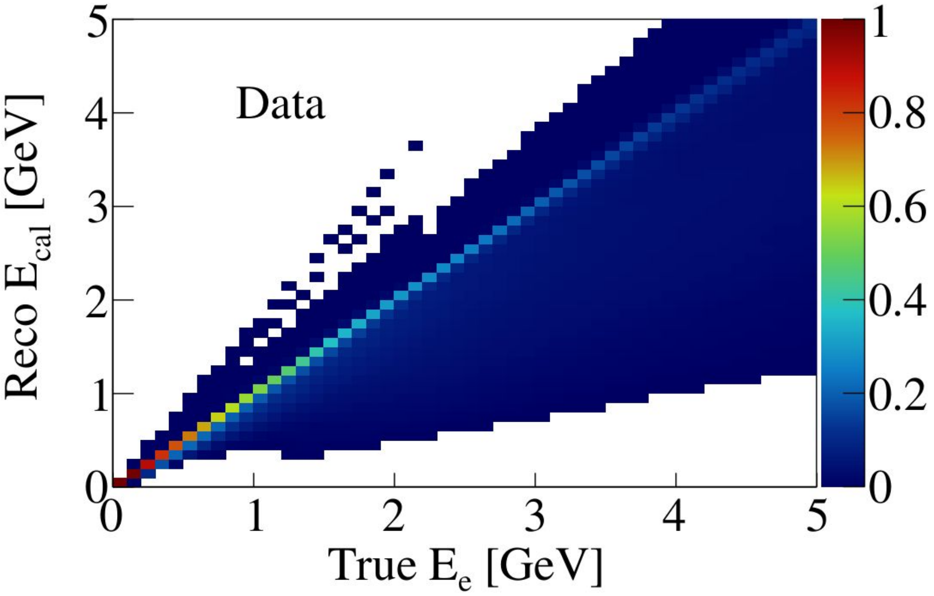
- Almost 4π acceptance
- Charged particles (8-143^o):
  P_p > 300 MeV/c
  P_π > 150 MeV/c
- Neutral particles:
  EM calorimeter (8-75^o)
  and TOF (8-143^o)

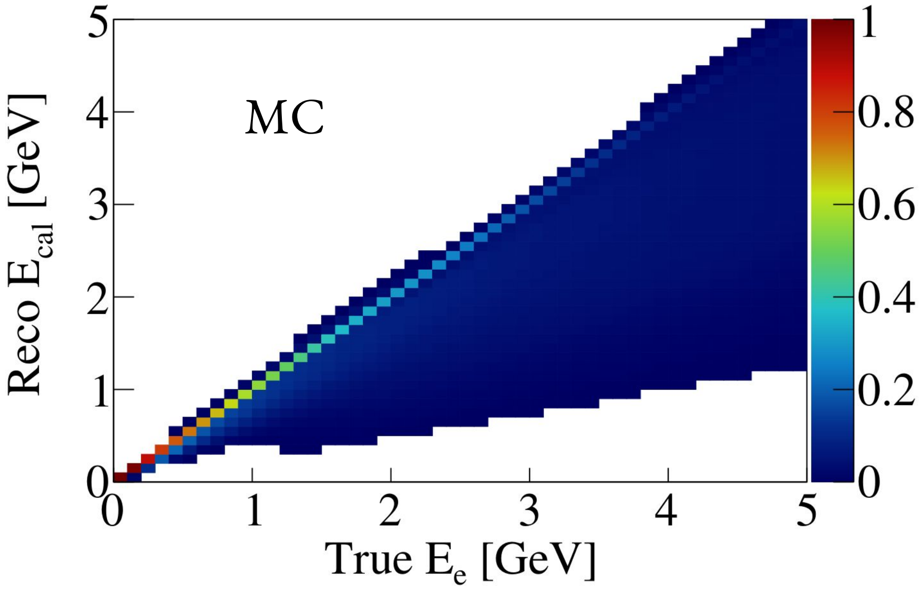


Q^4 Scaling Effect

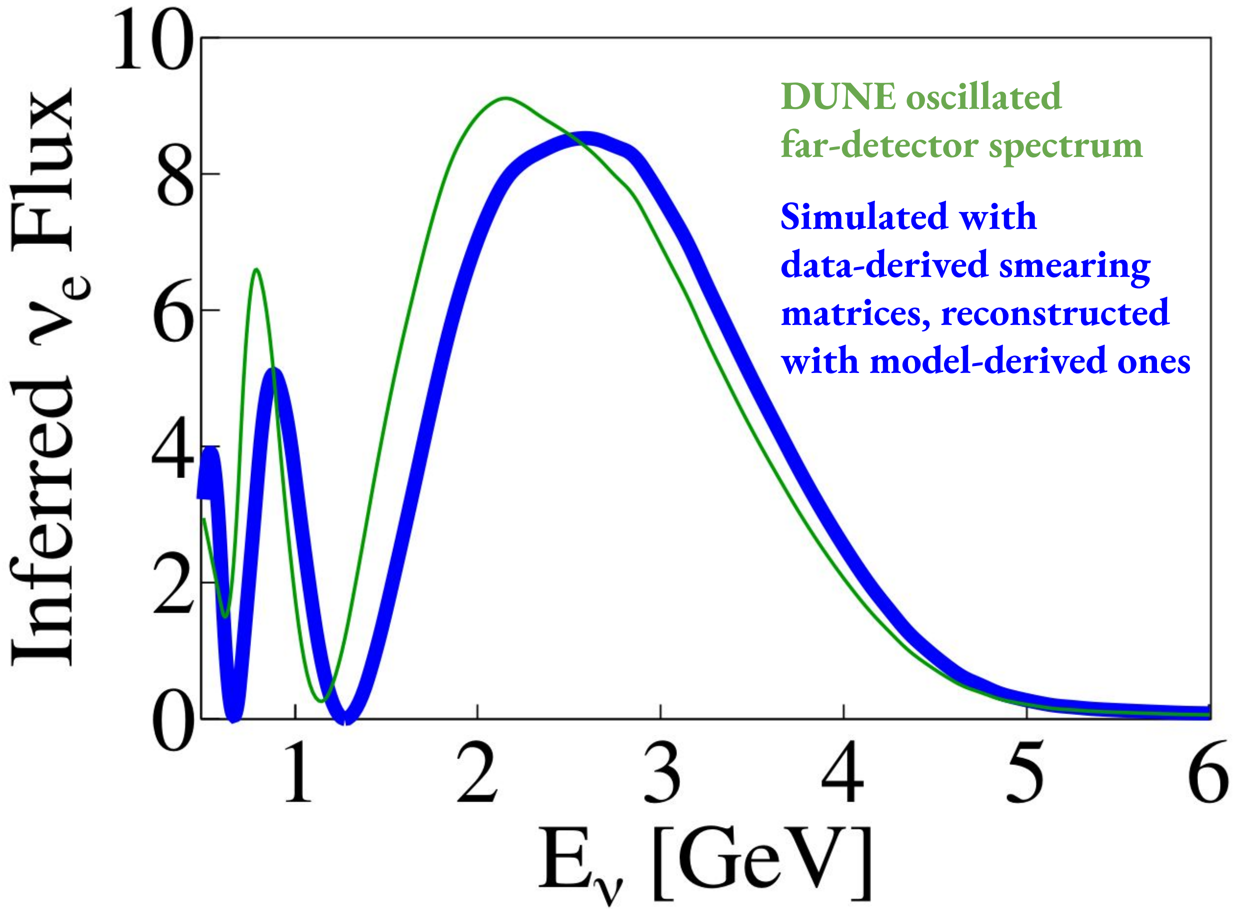


Data & MC Smearing Matrices





Mismodelling Impact On Mixing Parameters



SuSav2 Configuration / GEM21_11b_00_000

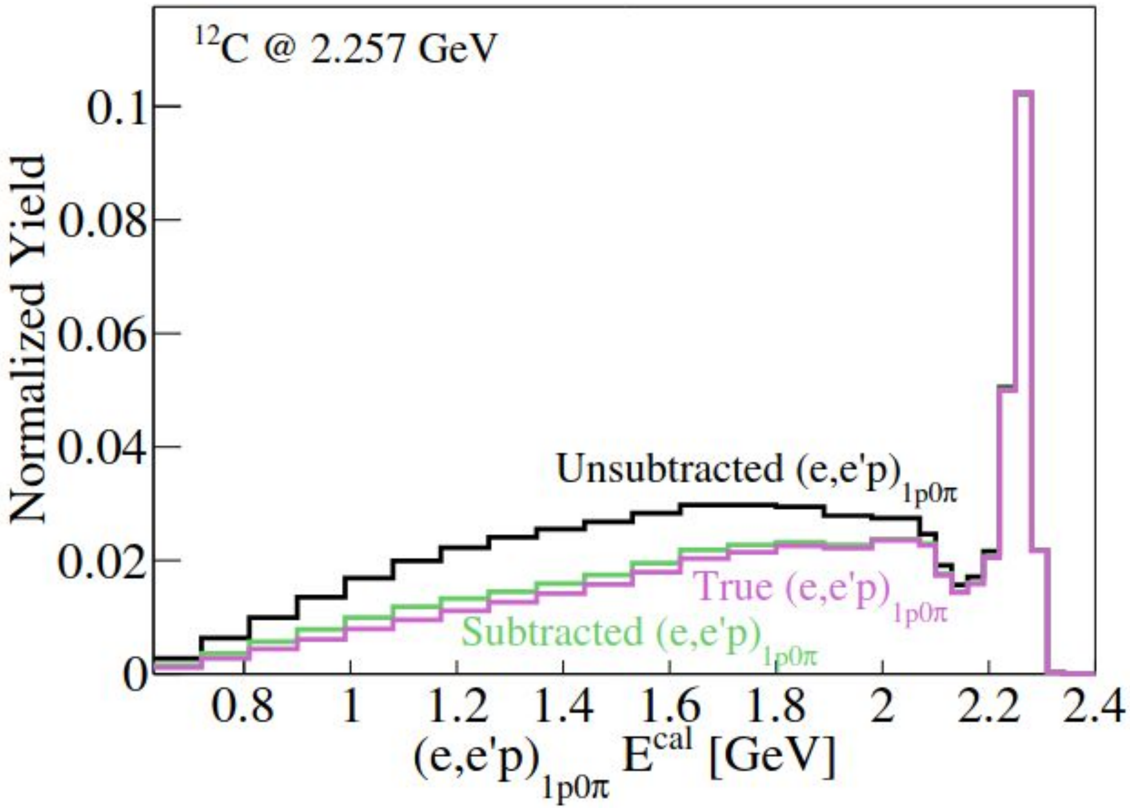
	Electrons	Neutrinos
QE	SuSav2	SuSav2
MEC	SuSav2	SuSav2
RES	Berger-Sehgal	Berger-Sehgal
DIS	AGKY	AGKY
FSI	hN2018	hN2018
Nuclear Model	Relativistic Mean Field	Relativistic Mean Field

G2018 Model Configuration / G18_10a_02_11a

	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

Data Driven Correction Closure Test

- Use eGENIE files
  - Subtracted & True 1p0π are in good agreement



Well defined signal definition: Min θ_e Cut

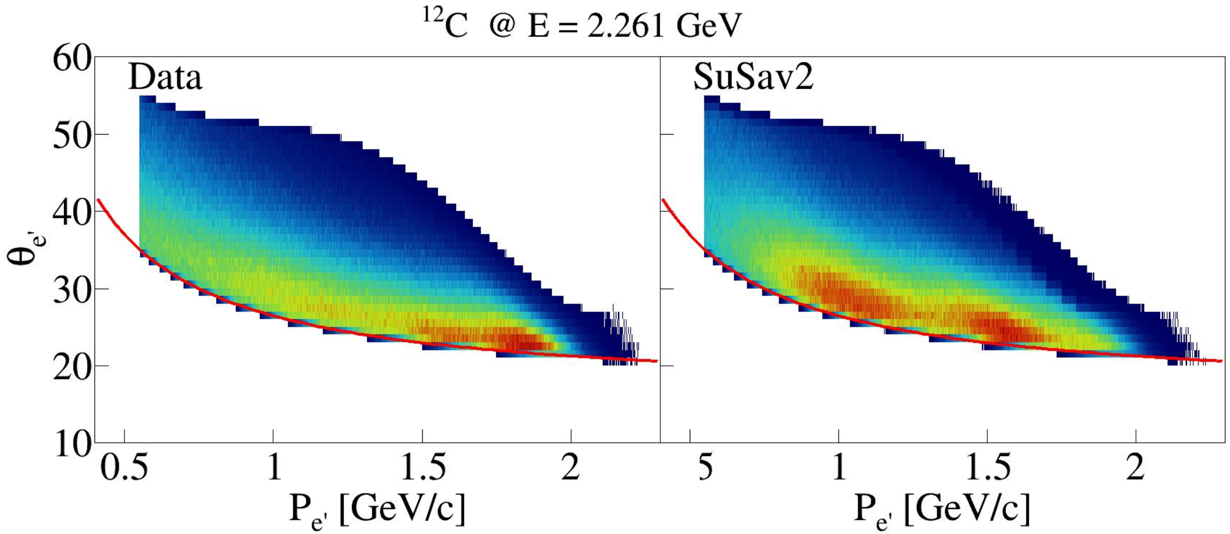
@ 1.1 GeV: $\theta = 17 + 7 / P$

@ 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

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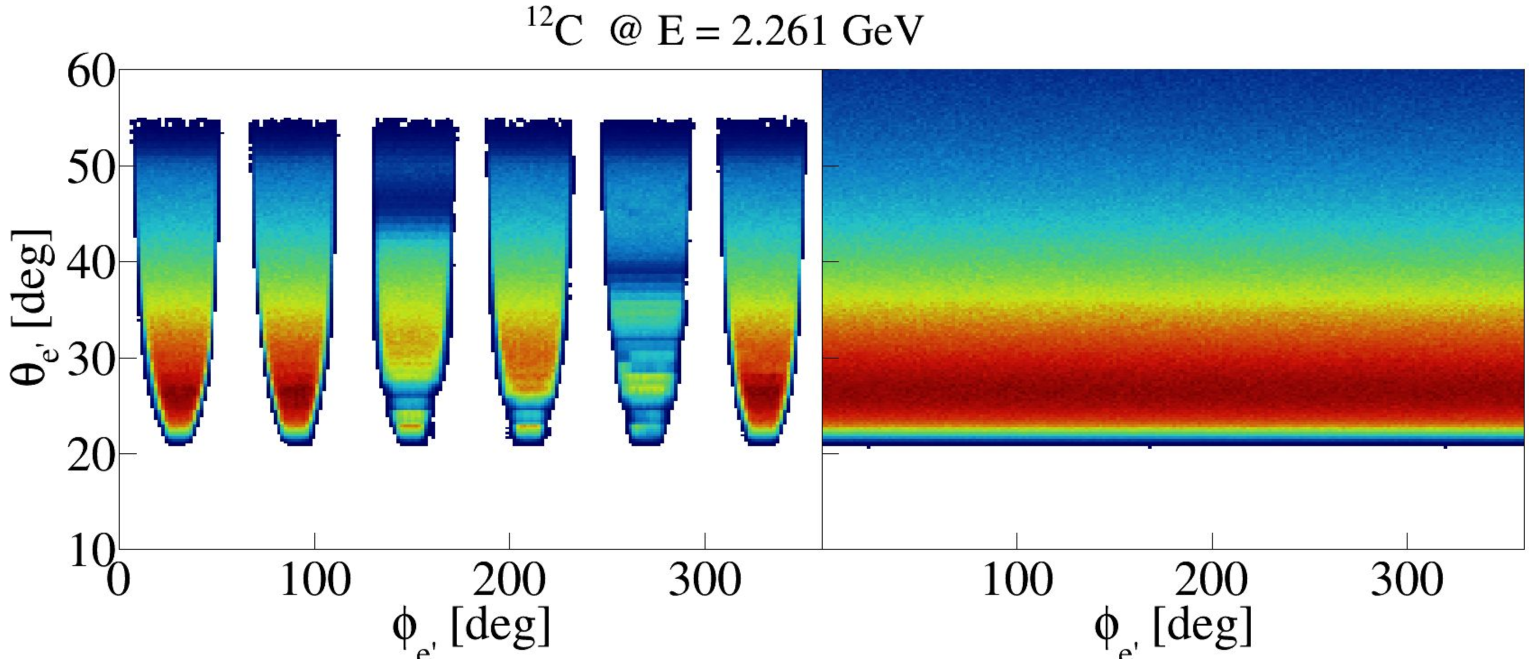
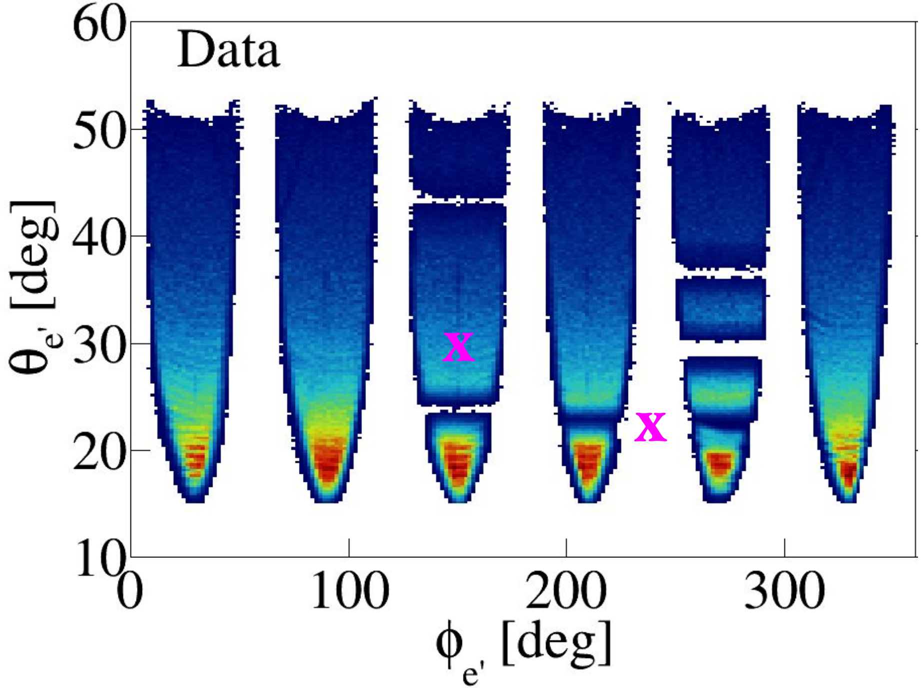
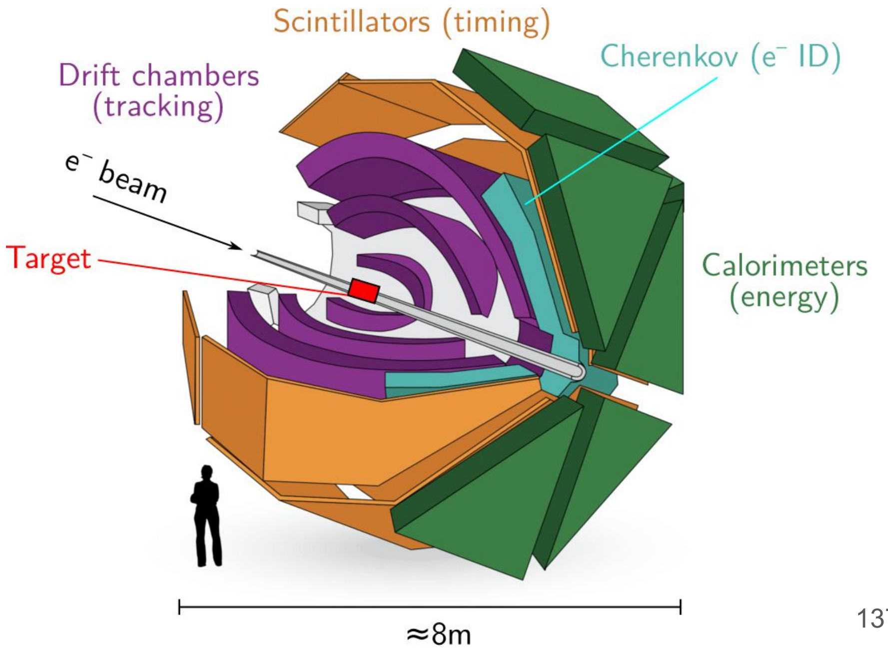


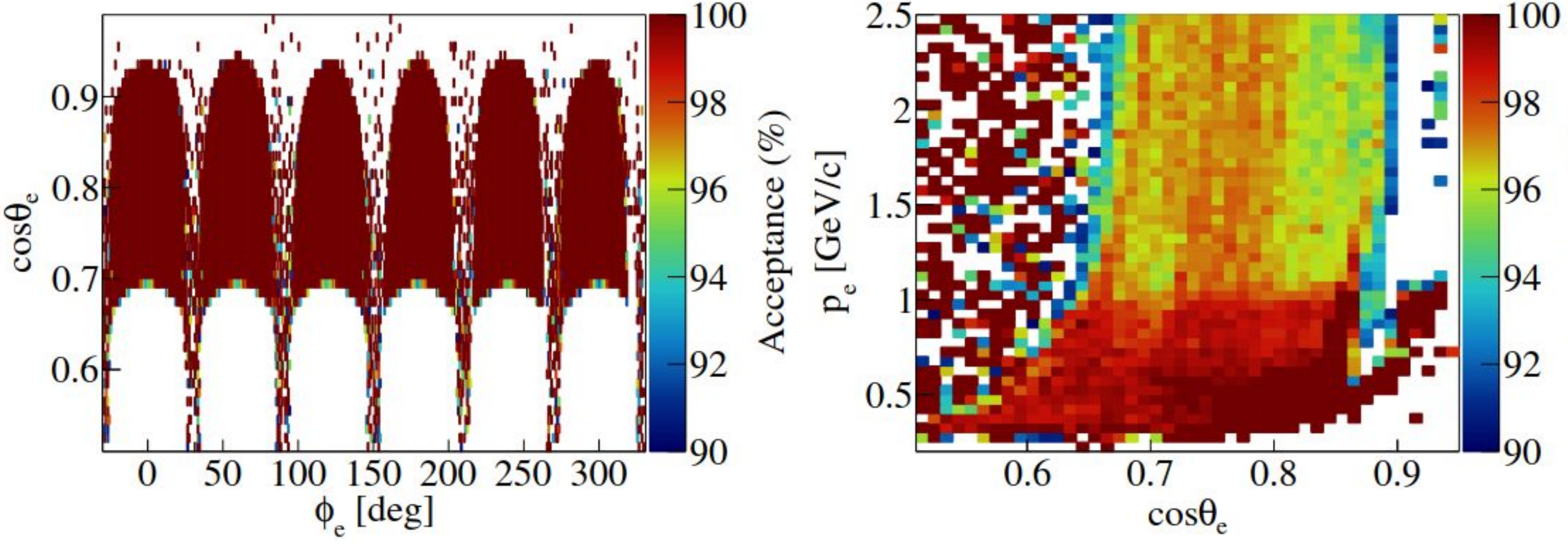
Background Subtraction

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





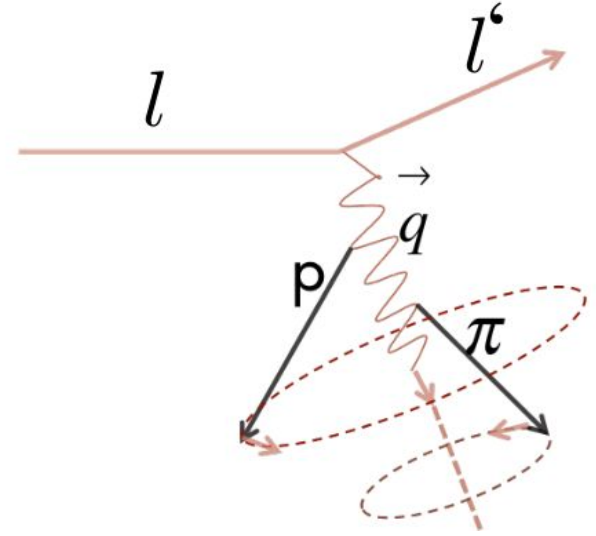
Acceptance Maps



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'pπ) events
- Rotate p, π around q to determine π detection efficiency
- Subtract undetected (e,e'pπ)
- Repeat for higher hadron multiplicities

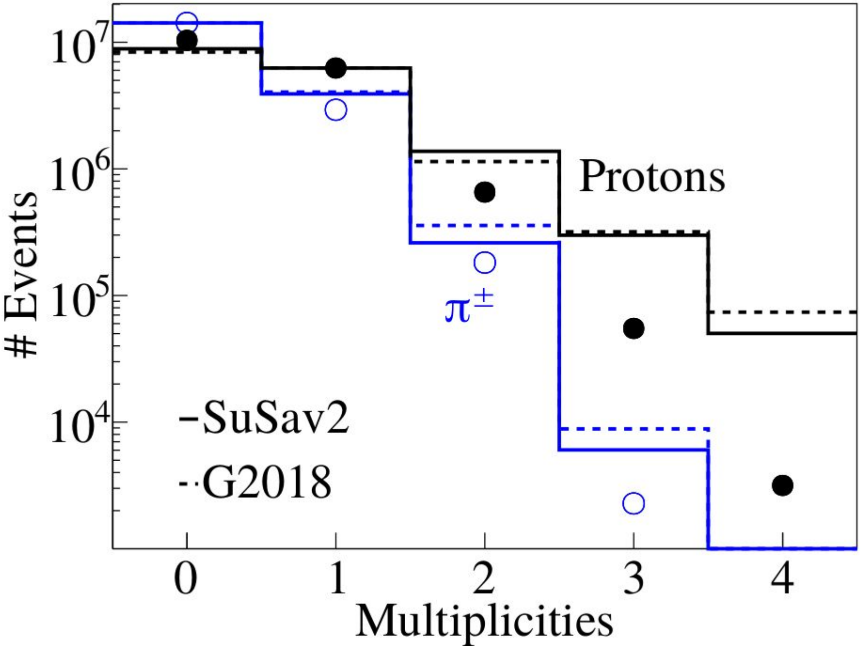


Data Driven Correction

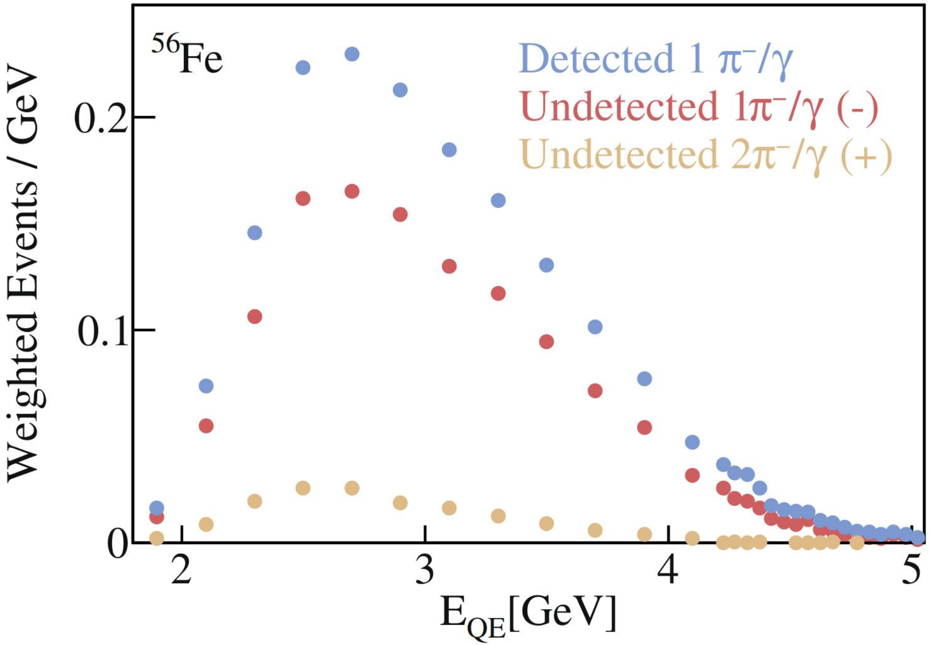
Non-(e,e'p) interactions lead to multi-hadron final states
Gaps can make them look like (e,e'p) events

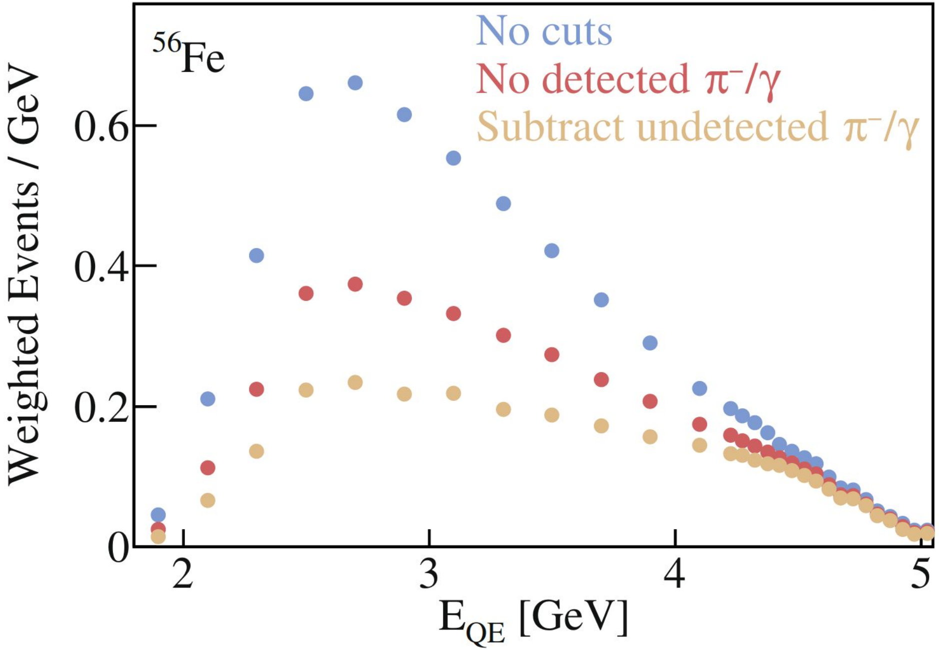
- Use measured (e,e'pπ) events
- Rotate p, π around q to determine π detection efficiency
- Subtract for undetected (e,e'pπ)
- Repeat for higher hadron multiplicities

(2p, 3p, 2p+1π, ...)



Subtraction Effect

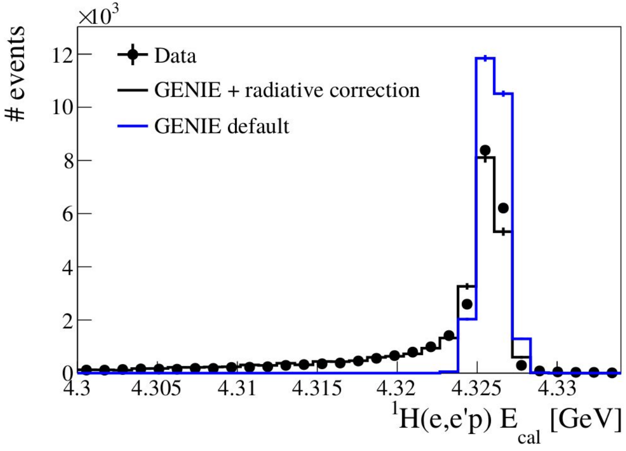




Cross-Section Extraction

- Subtract non-(e,e’p) backgrounds
- Scale counts by luminosity
- Correct for (e,e’p) acceptance & radiation

Systematic uncertainties on each correction plus variation among 6 CLAS detector sectors

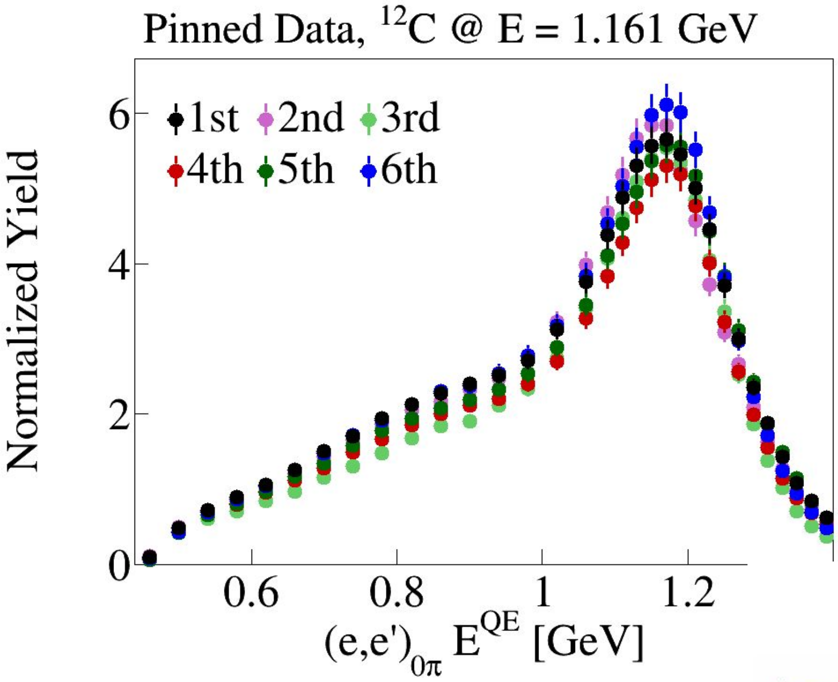


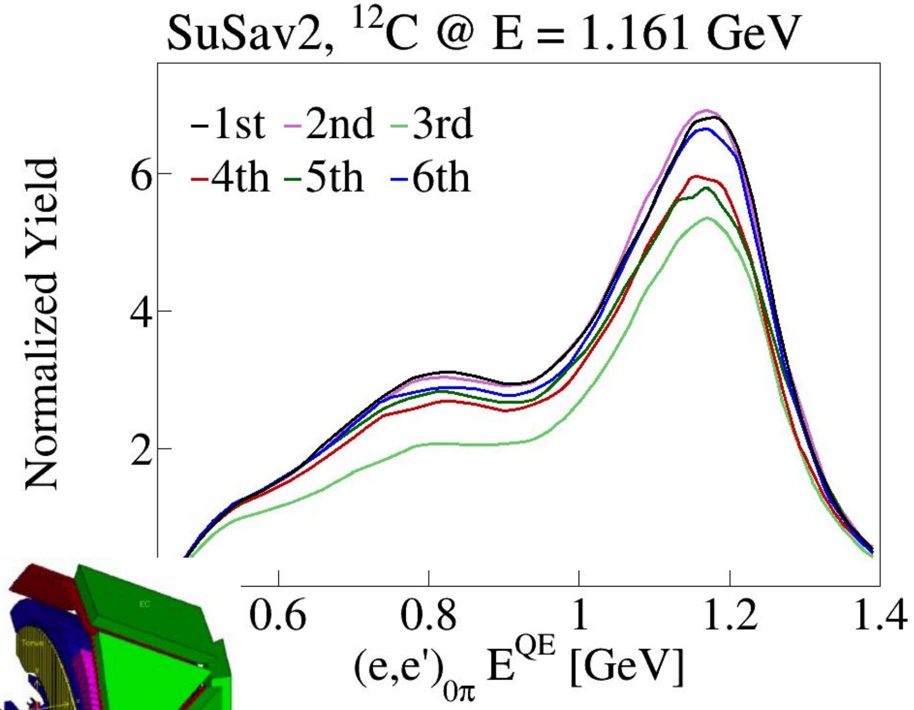
Hall A@ JLab

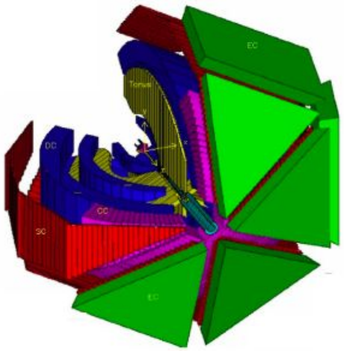
H(e,e’p) @ 4.32 GeV

A.Papadopoulou, et al, Phys. Rev. D 103, 113003 (2021)

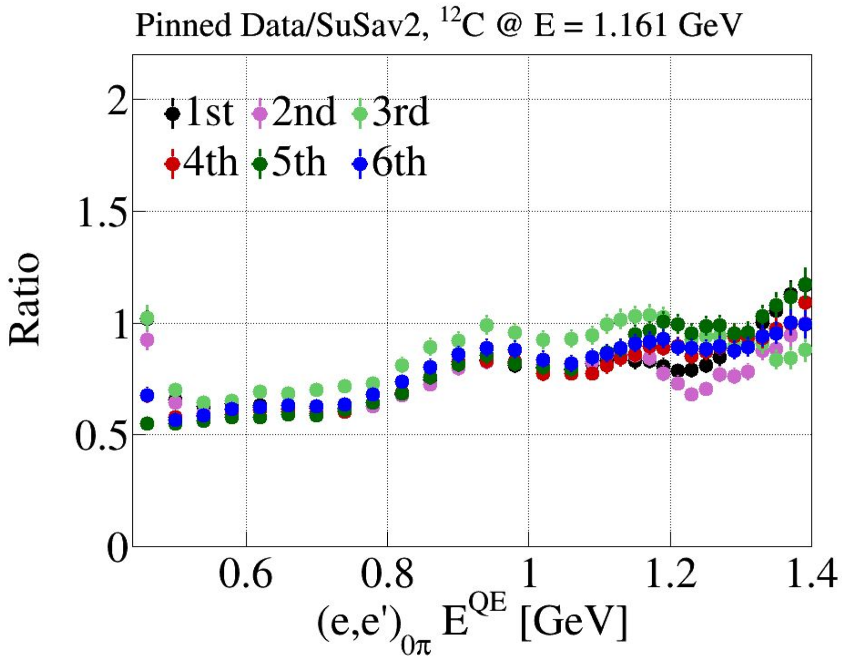
Systematics: Sector Dependence

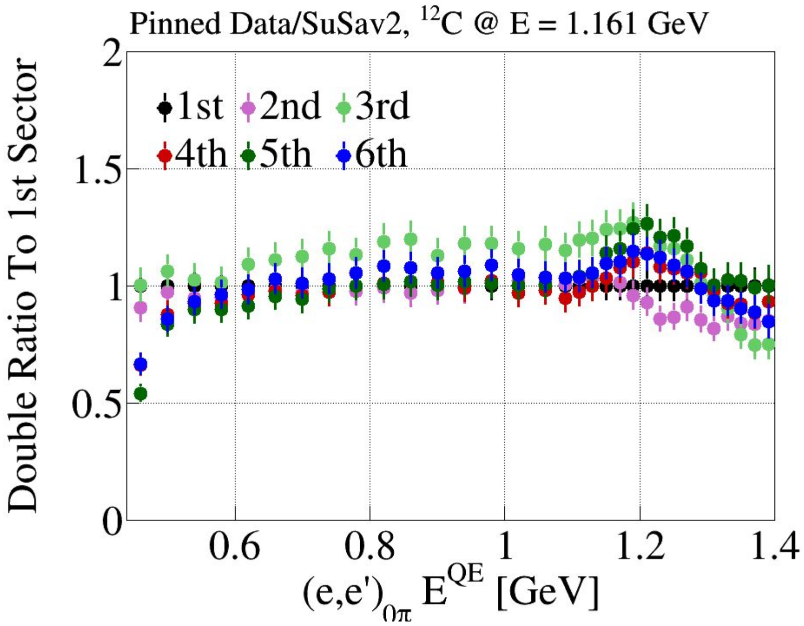






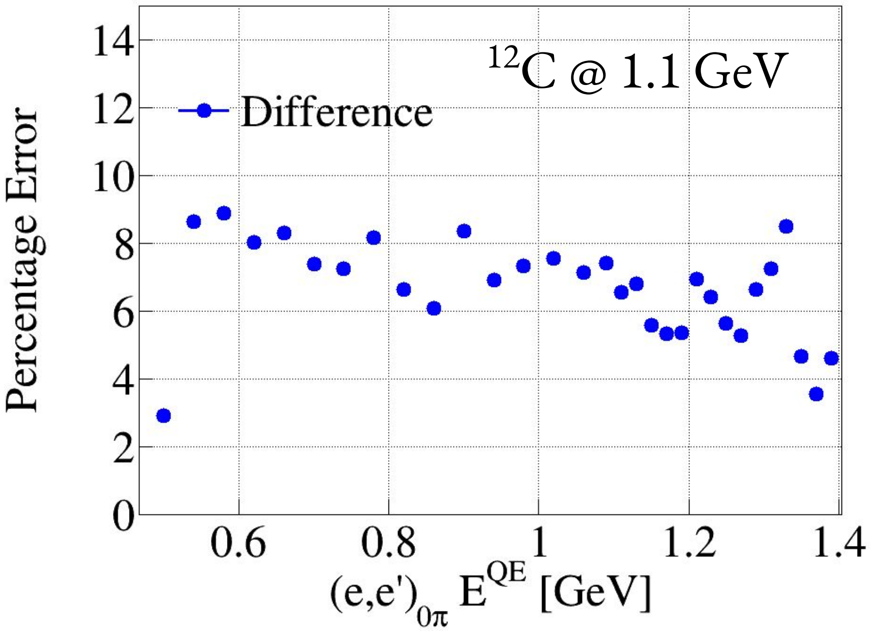
Systematics: Sector Dependence





Systematics: Sector Dependence

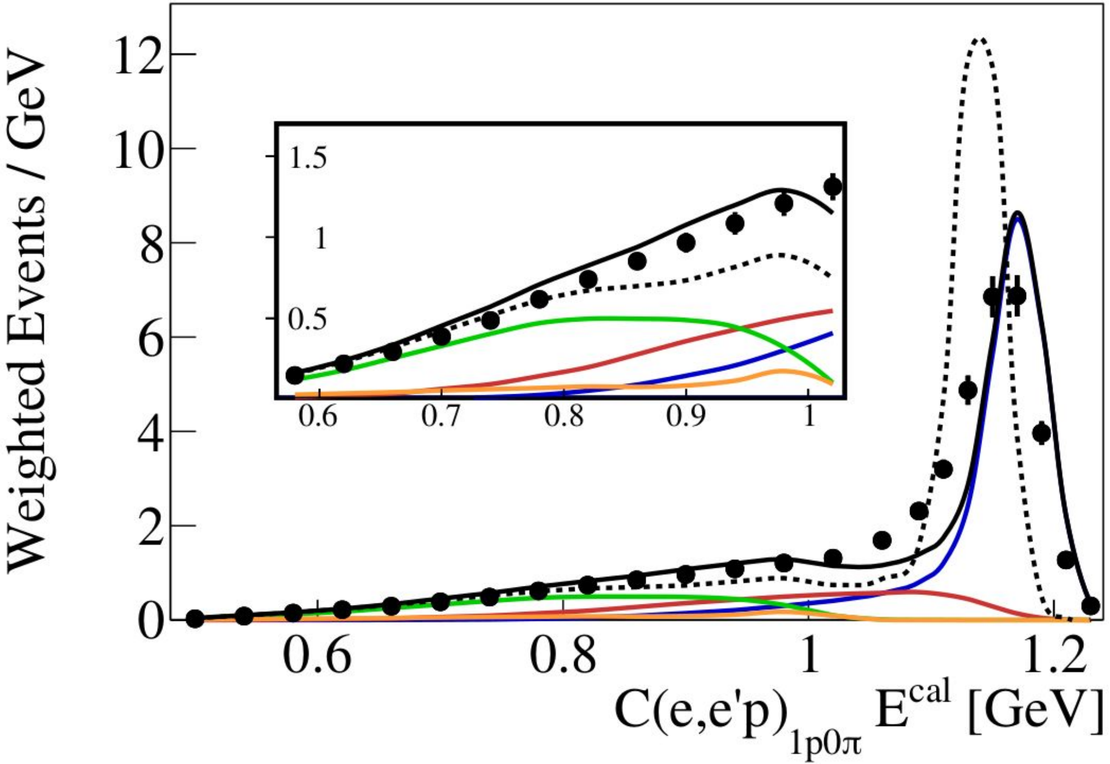
Quantifying uncertainty by using
unweighted variance & by subtracting variance from statistical uncertainty



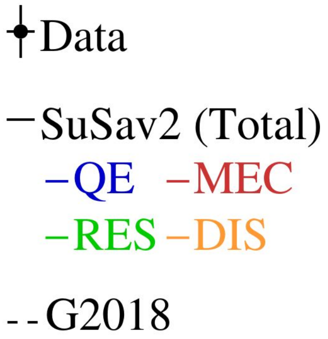
- Playing this game across all nuclei & energies
- Division by $\sqrt{N_{sectors}}$
- Flat uncertainty of 6%

1st e4ν Submission

Calorimetric energy reconstruction using the 1p0π channel



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



Step #2: Normalized Yield

Data

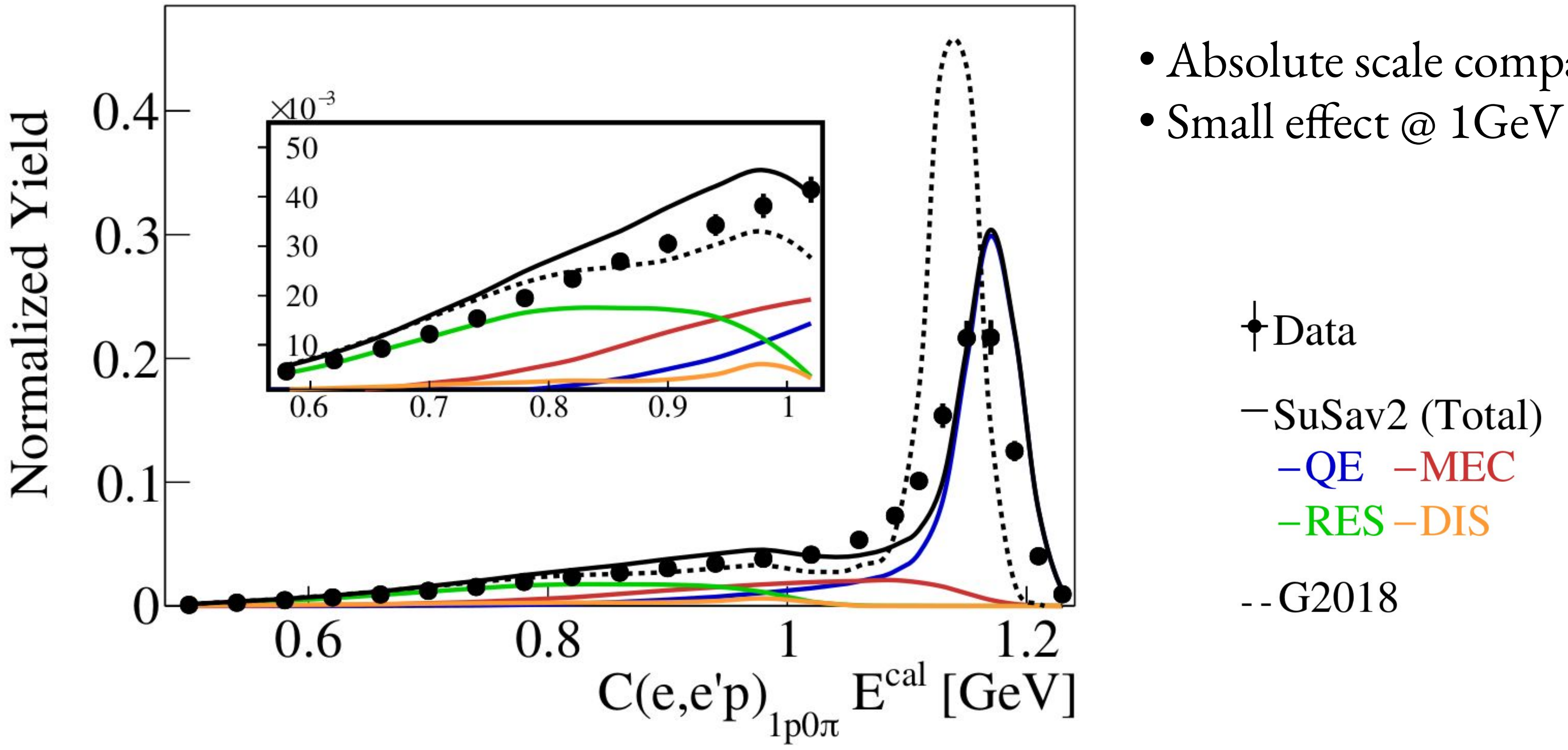
- Divide # events by integrated charge & target thickness to get xsec in μb
- Divide by bin width to get μb/GeV

Simulation

- Get GENIE total cross section for E_e / target A & Q2 > $Q2_{min}$
- xsec = (Selected detected events / all generated events) * total xsec / bin width

No corrections for CLAS acceptance or for bremsstrahlung radiation

Step #2: Normalized Yield

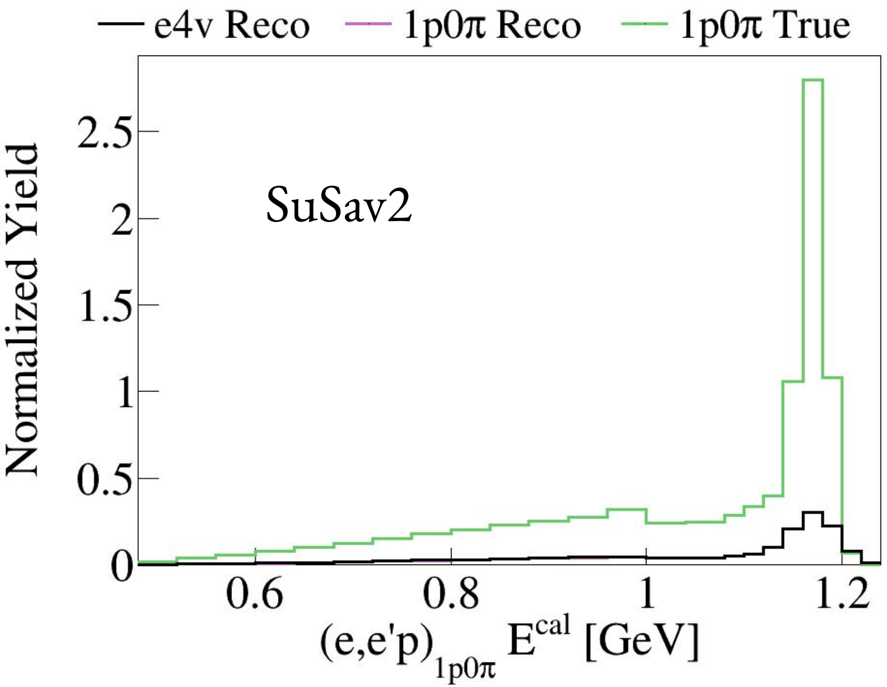


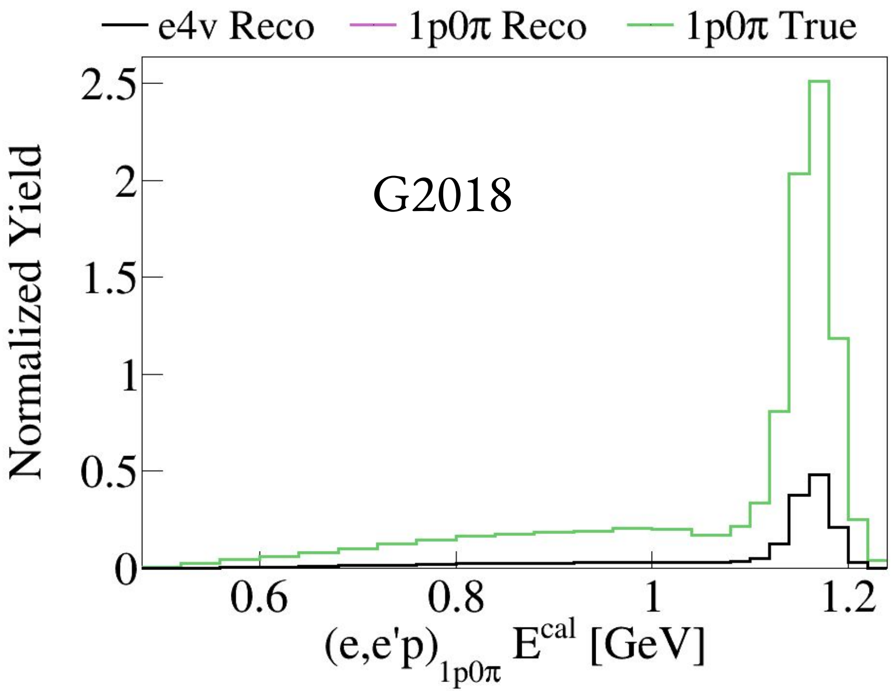
- Absolute scale comparison
- Small effect @ 1GeV

Step #3a: Acceptance Correction

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

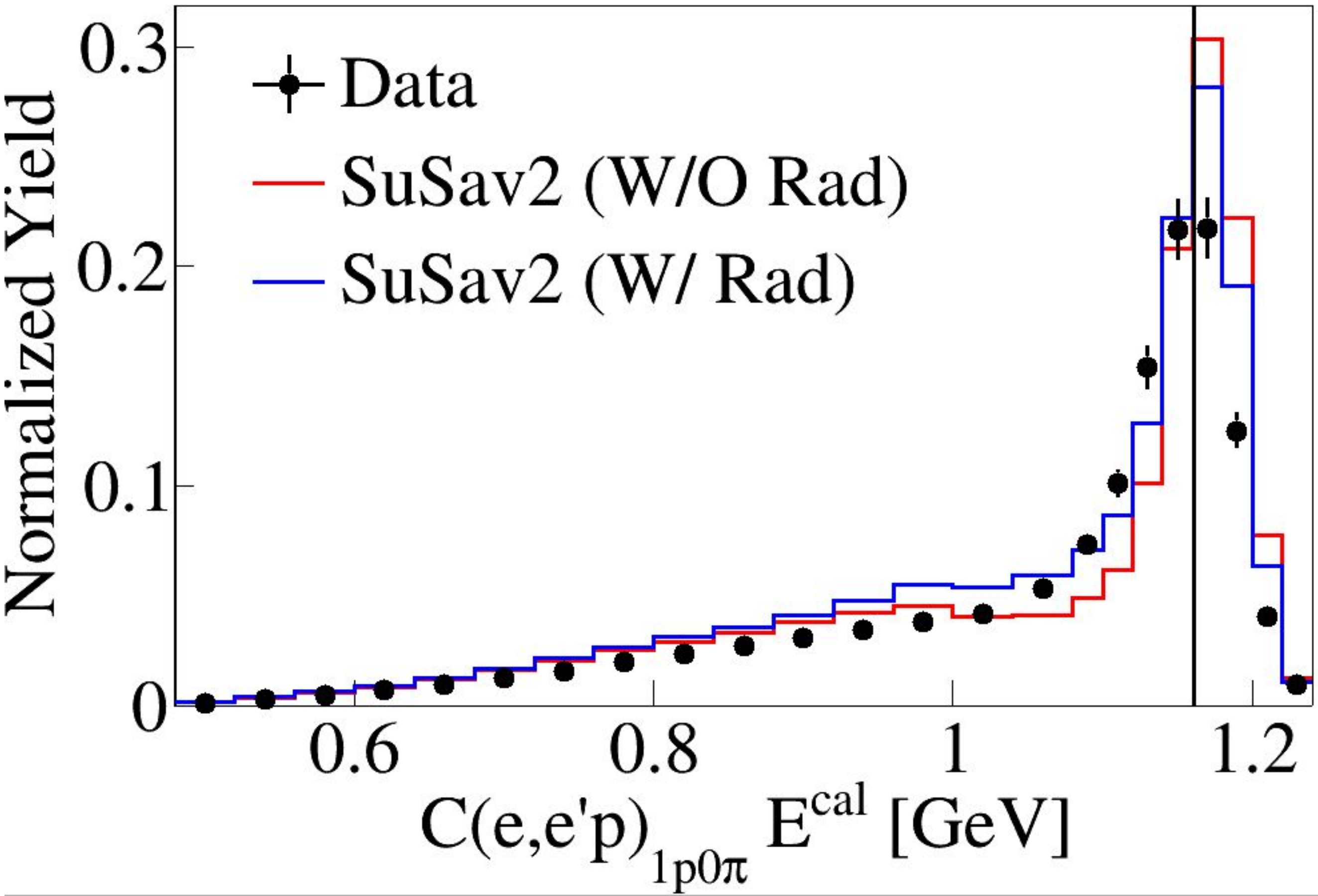
Step #3a: Example 12C @ 1.1 GeV





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

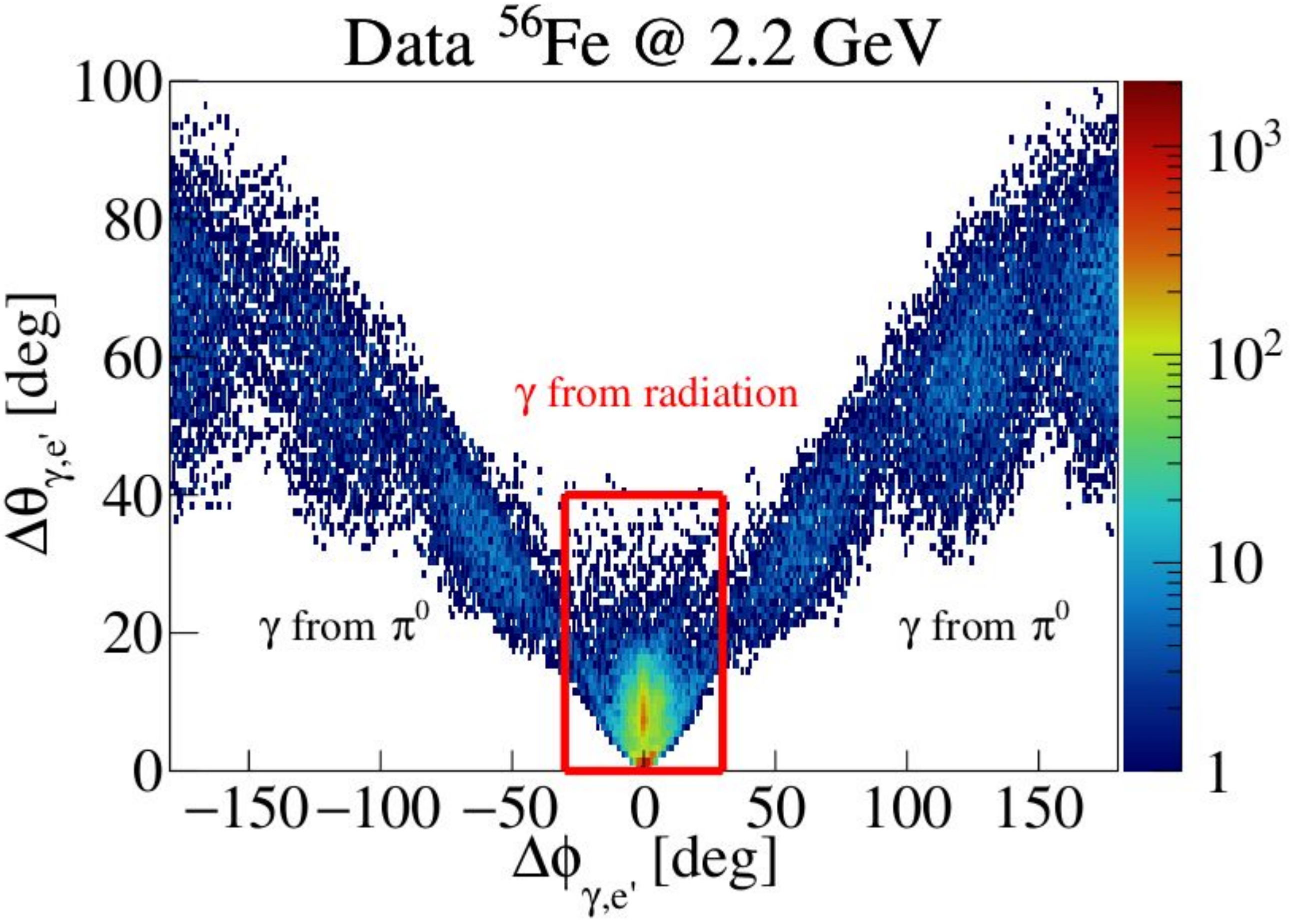
On a bin-by-bin basis

x = |SuSav2 - G2018| / Sqrt(12)

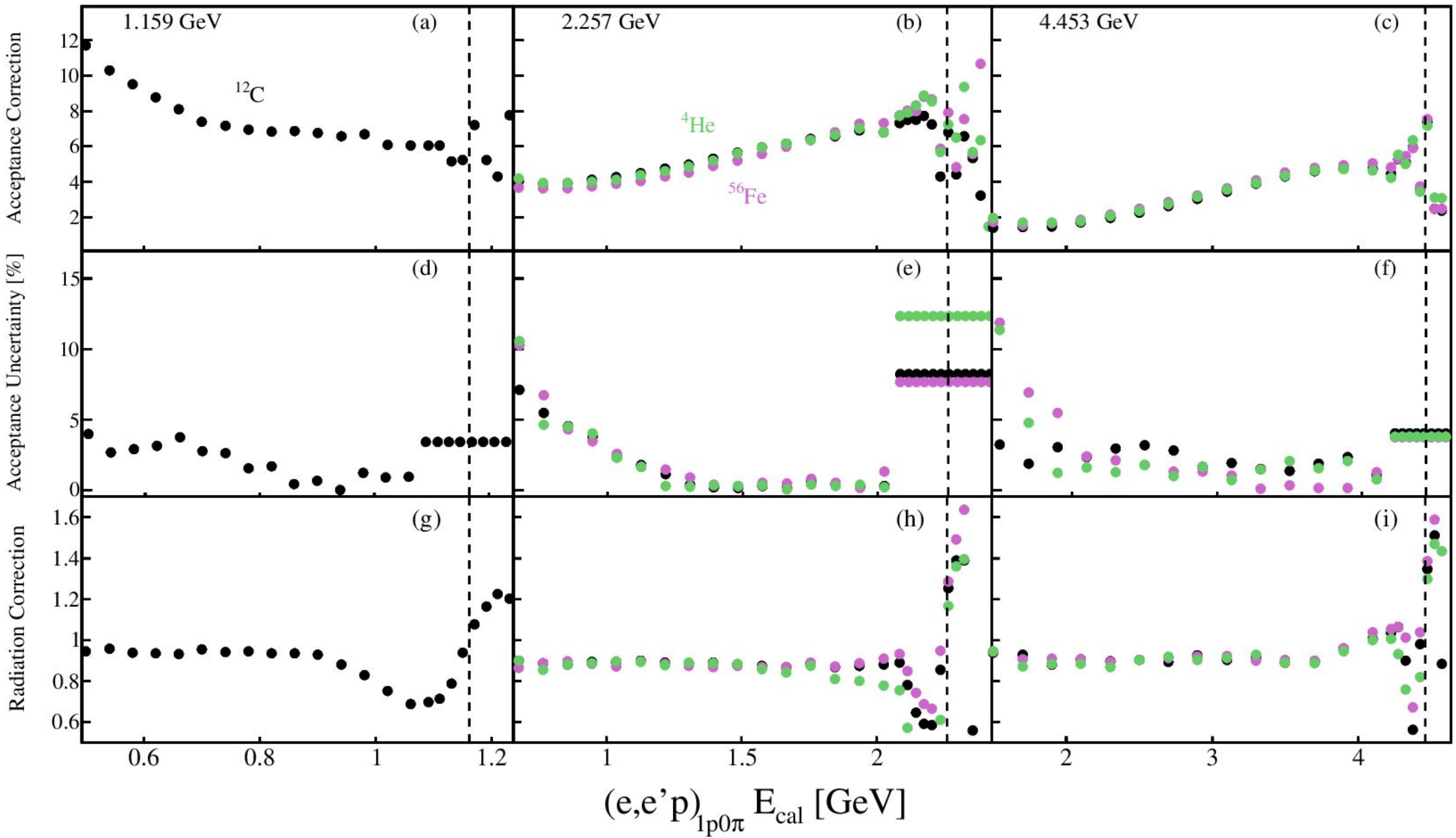
Bin Entry = x / Average * 100 %

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

Excluding Radiation

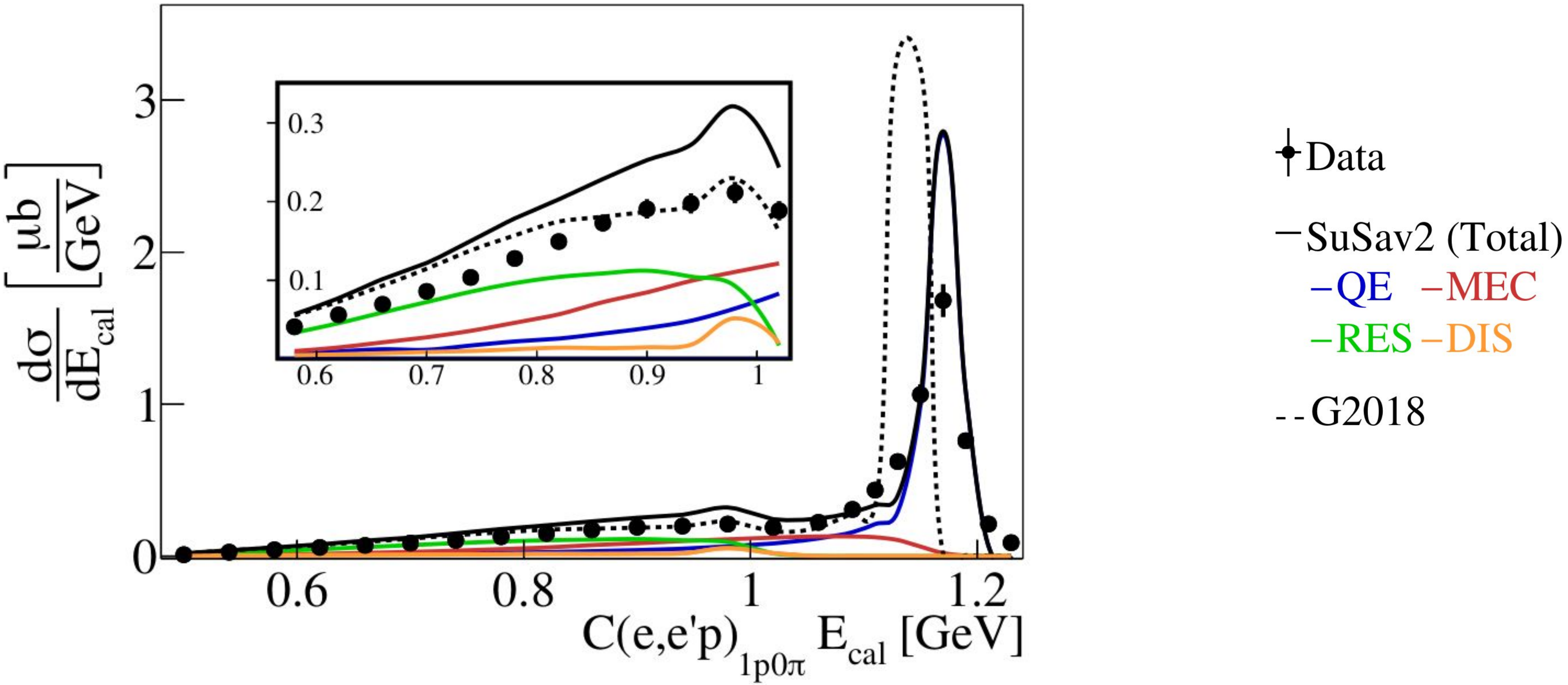


Correction Factors



Step #4: Absolute Cross Sections

After both acceptance & radiation corrections, without systematics yet



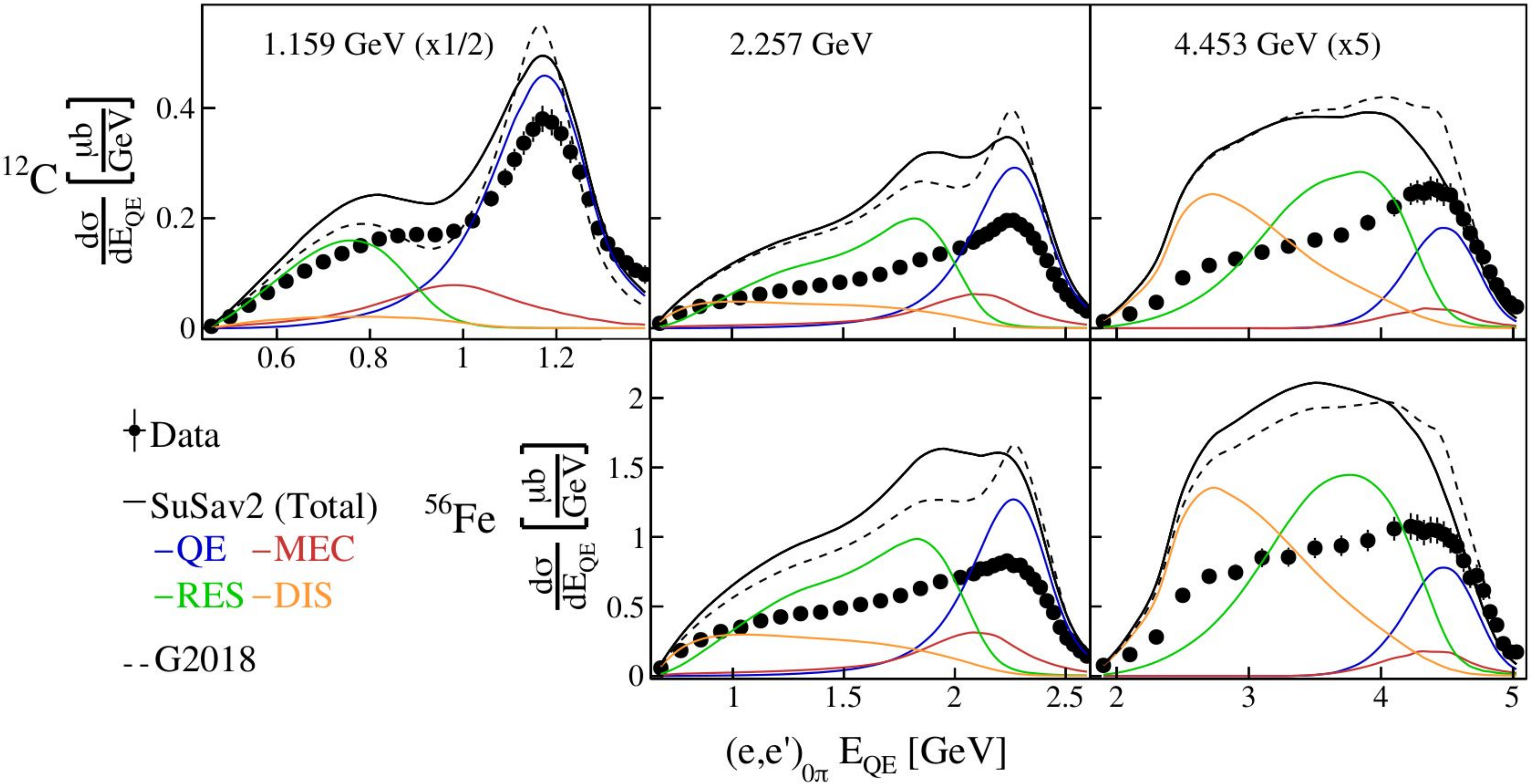
Systematics

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

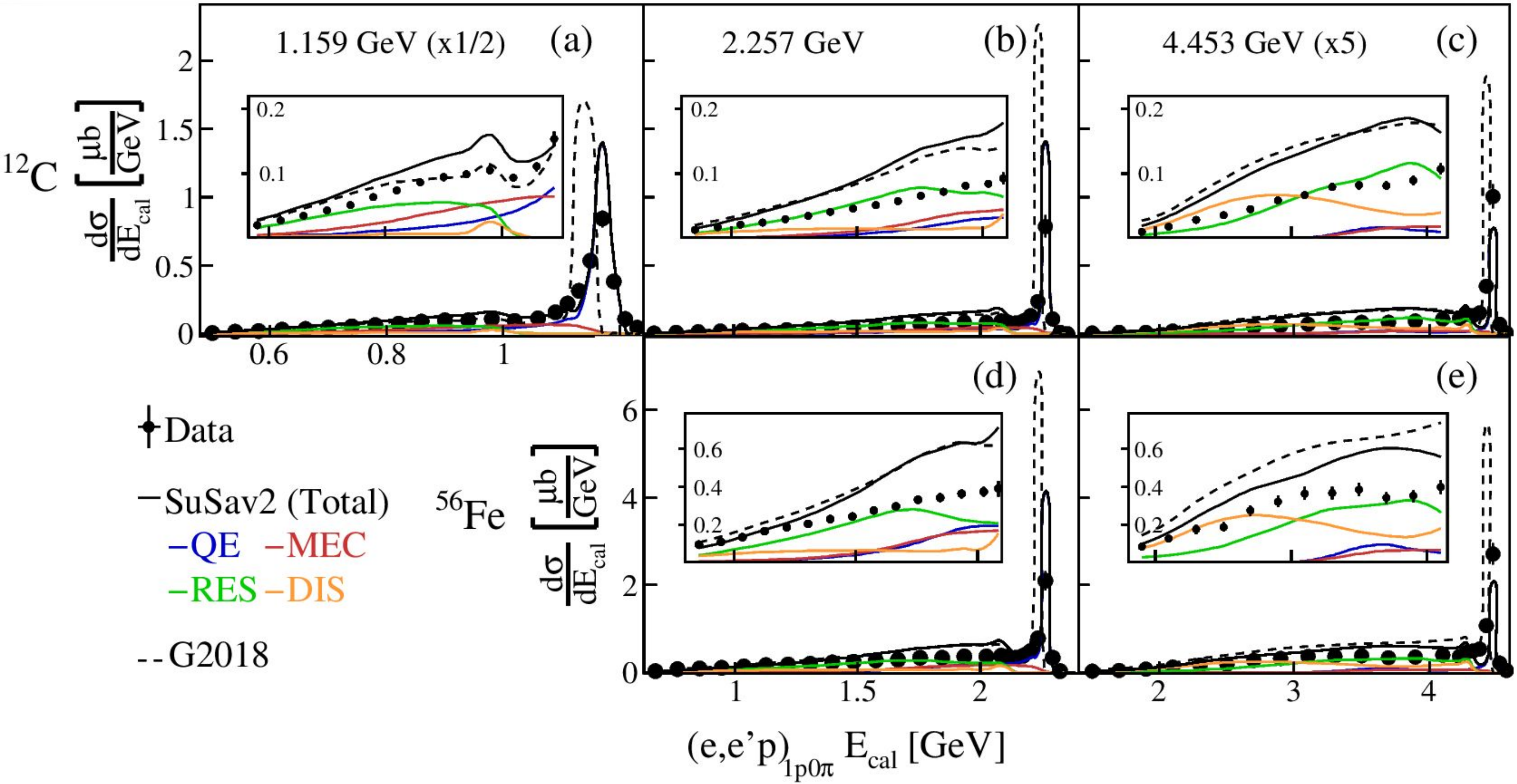
Energy Reconstruction Accuracy

		1.159 GeV		2.257 GeV		4.453 GeV	
		Peak Fraction	Peak Sum [μb]	Peak Fraction	Peak Sum [μb]	Peak Fraction	Peak Sum [μb]
^{4}He	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} All Nuclei & Energies



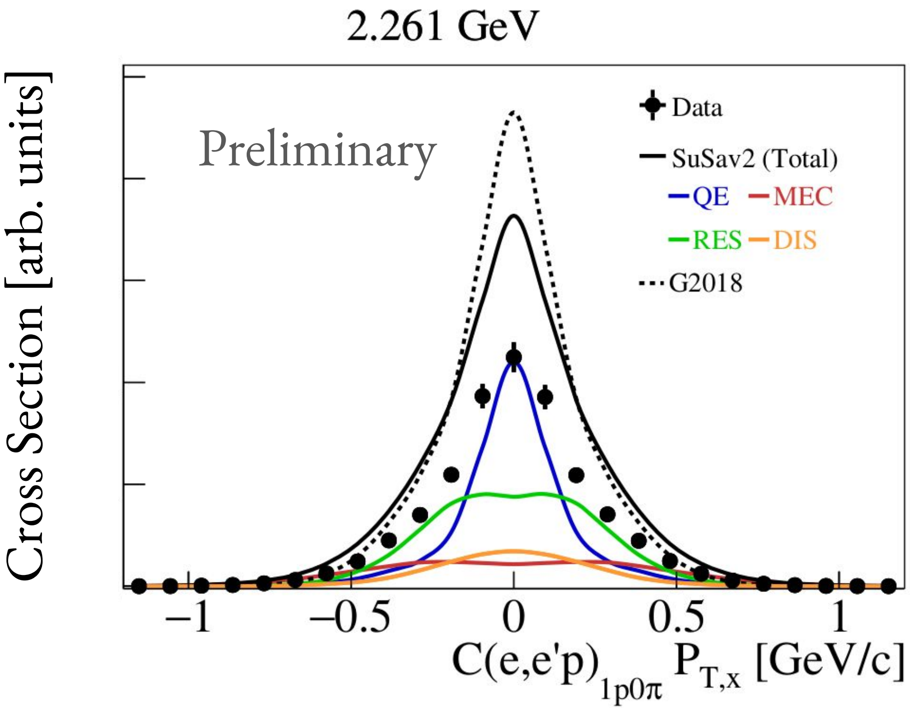
E_{Cal} All Nuclei & Energies

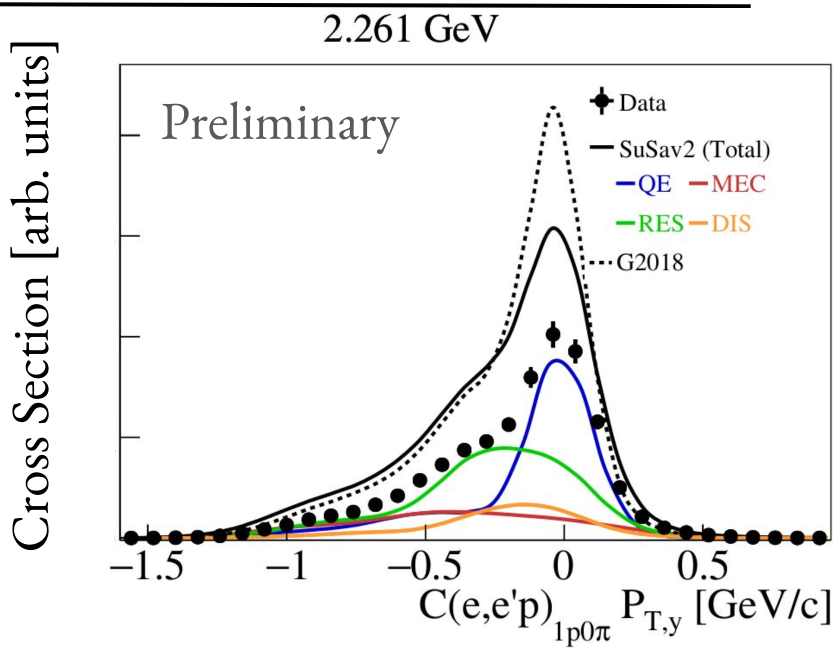


Getting The Most Out Of The Neutrino QE-like Game

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

Sensitivity to Fermi motion





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

Sensitivity to removal energy

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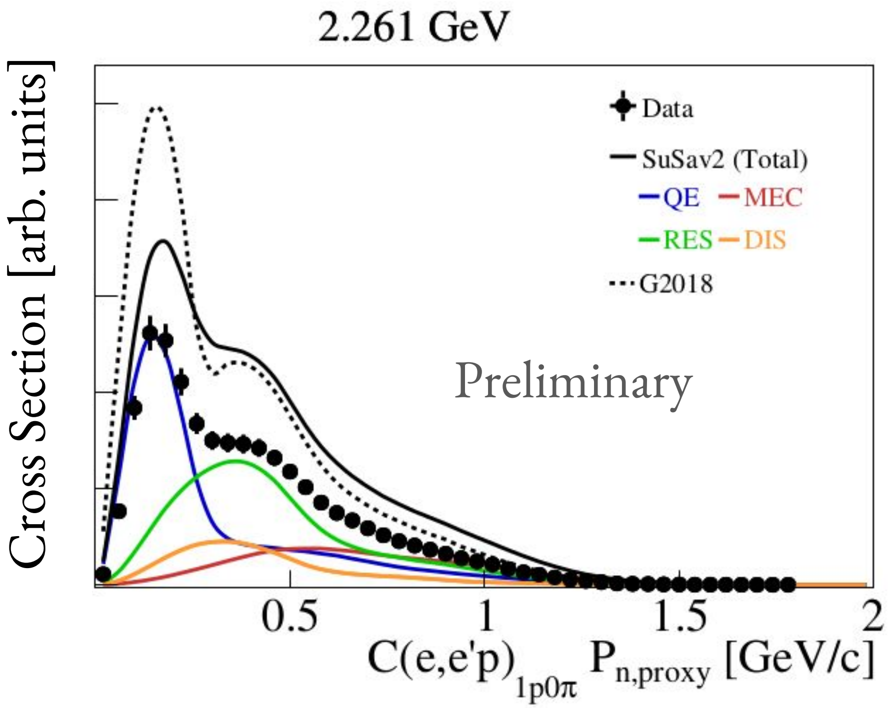
In preparation

Getting The Most Out Of The Neutrino QE-like Game



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

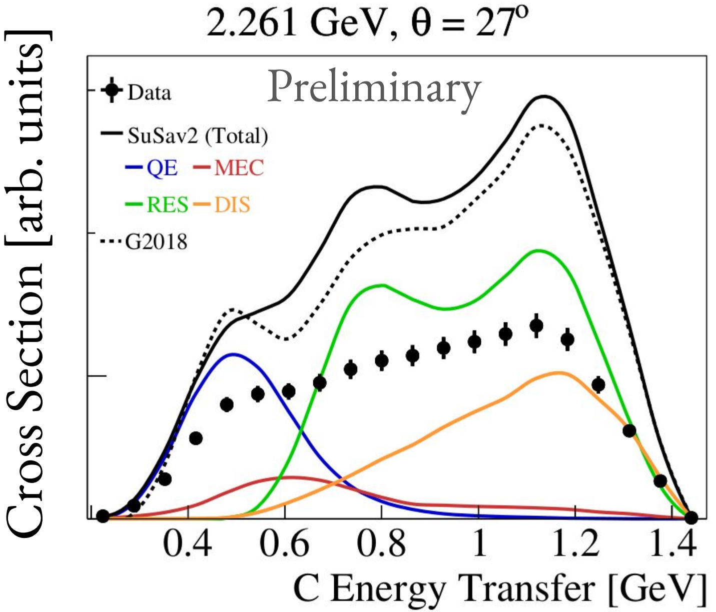
Under QE assumption

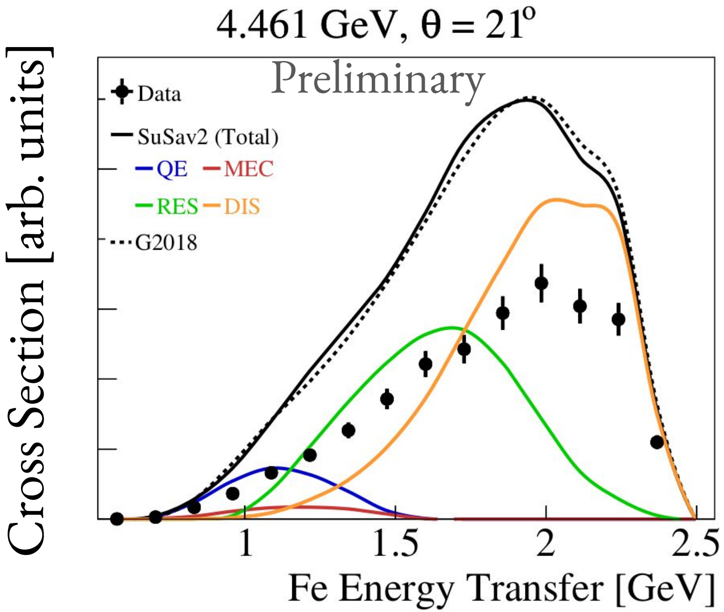
Phys. Rev. Lett. 121, 022504 (2018)

A.Papadopoulou, et al,
In preparation

High-Precision Lepton-Nucleus Measurements

- Analyze electron data
  → Lots of energies, targets, event topologies
- Modeling improvement
- Tune free event generator parameters starting from inclusive (e,e’) channel

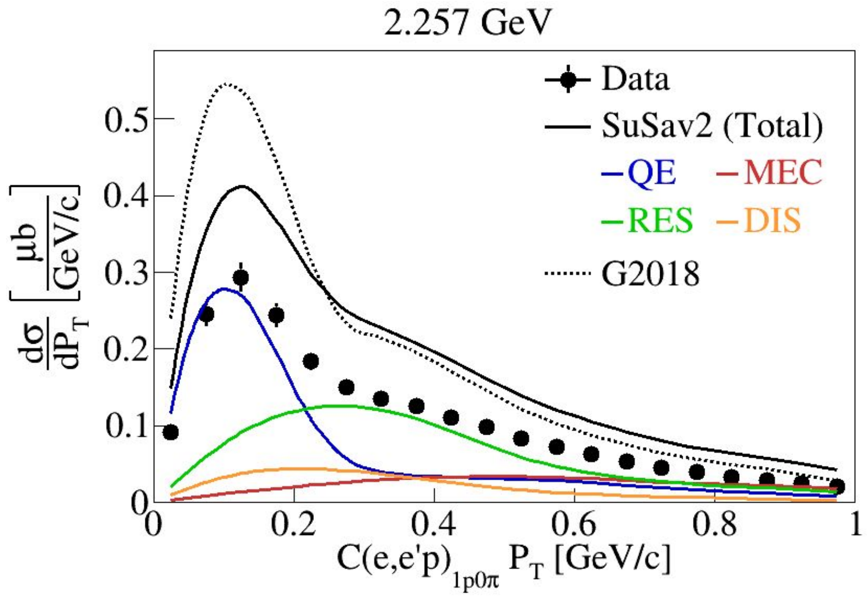


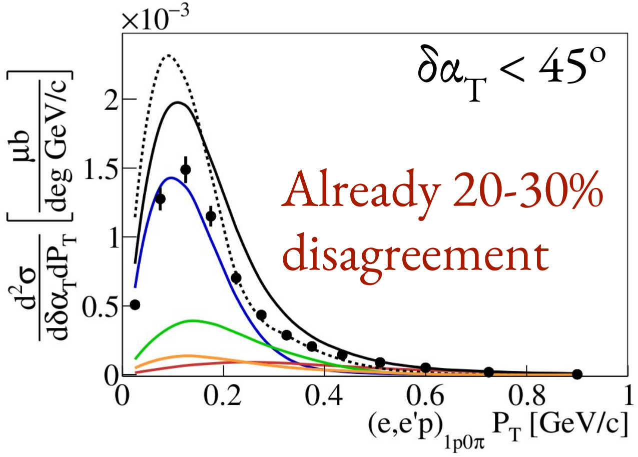


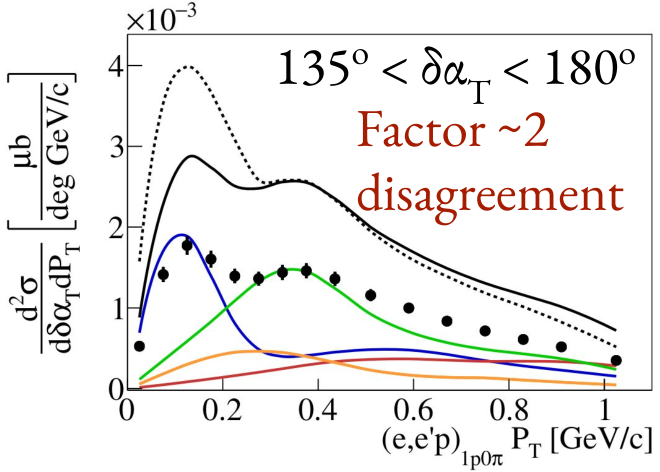
A.Papadopoulou, et al,
Publication in preparation

Complementarity To MicroBooNE

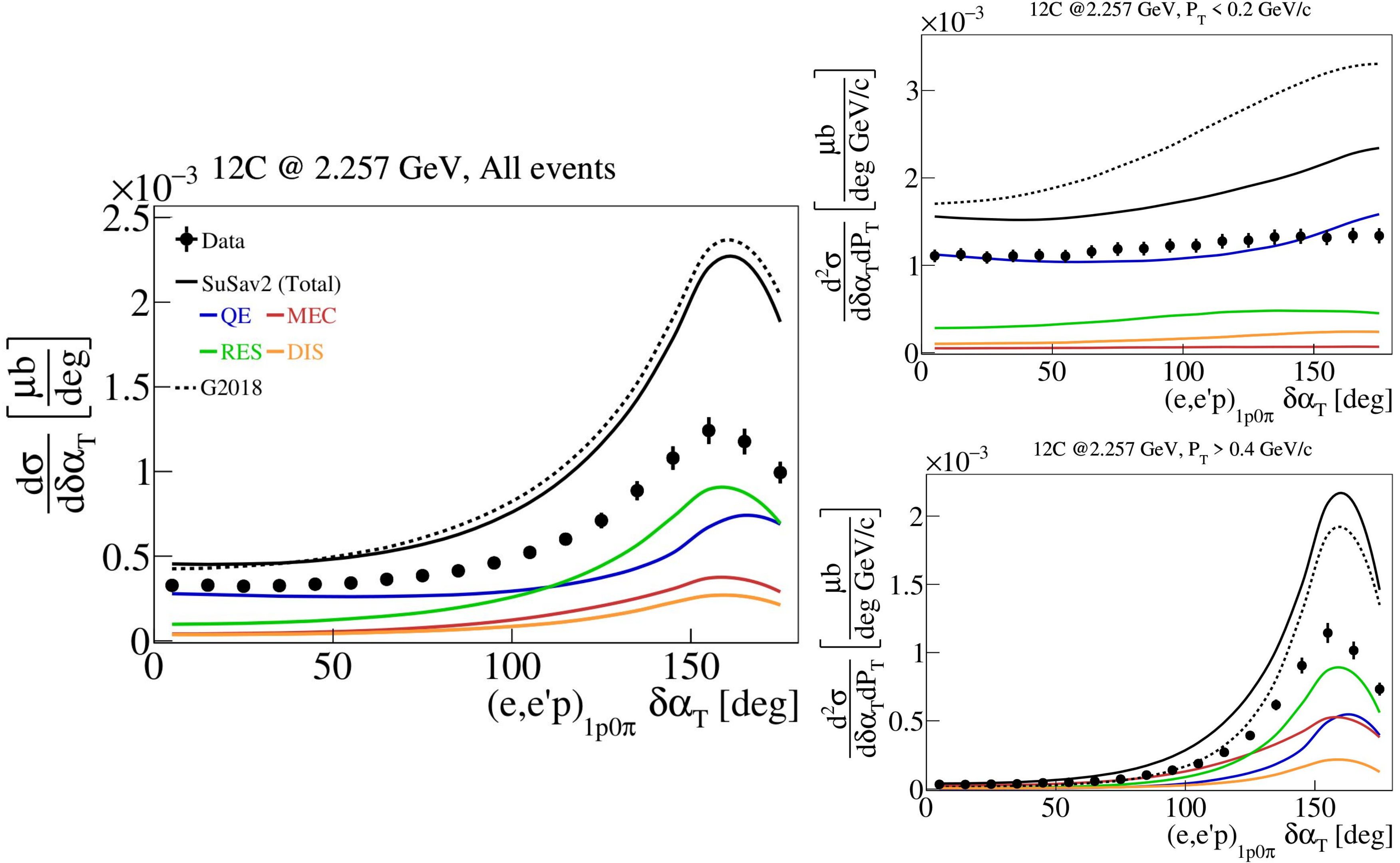
M.Khachatryan, **A.Papadopoulou**, et al.
Nature 599, 565–570 (2021)



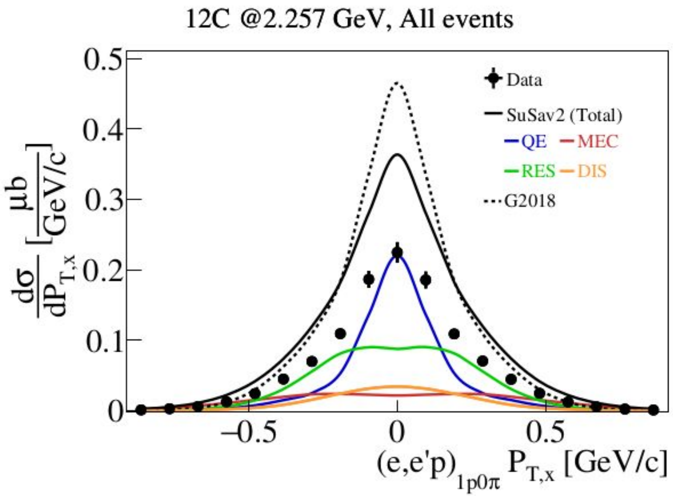




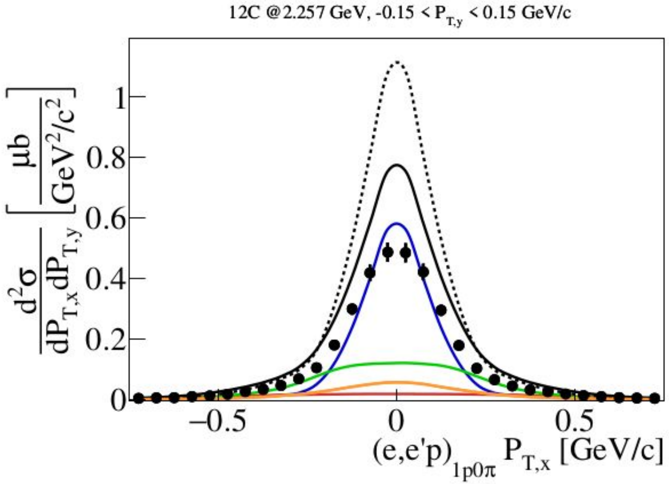
A.Papadopoulou, et al.
In preparation

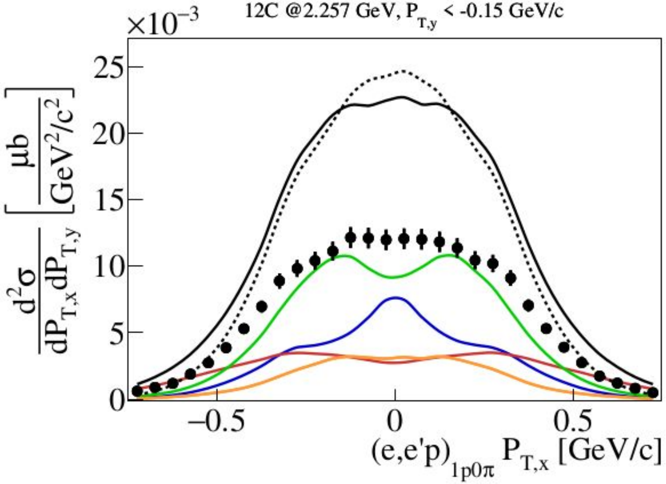


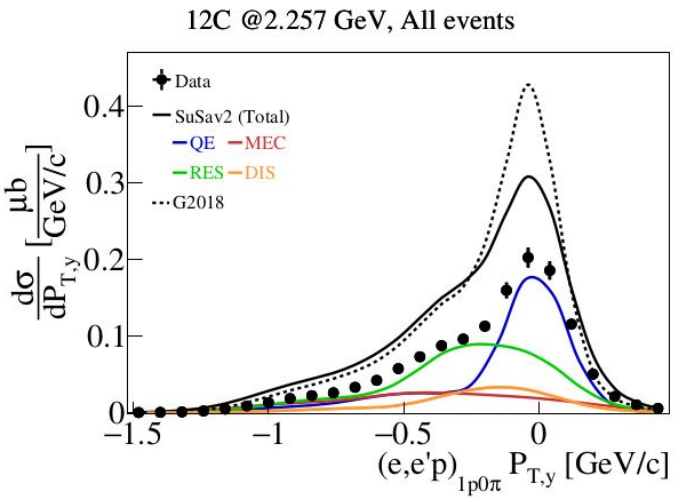
12C @ 2.257 GeV, All events
Data
SuSav2 (Total)
QE
MEC
RES
DIS
G2018
$(e,e'p)_{1p0\pi}$ $\delta\alpha_T$ [deg]
12C @2.257 GeV, P_T < 0.2 GeV/c
12C @2.257 GeV, P_T > 0.4 GeV/c



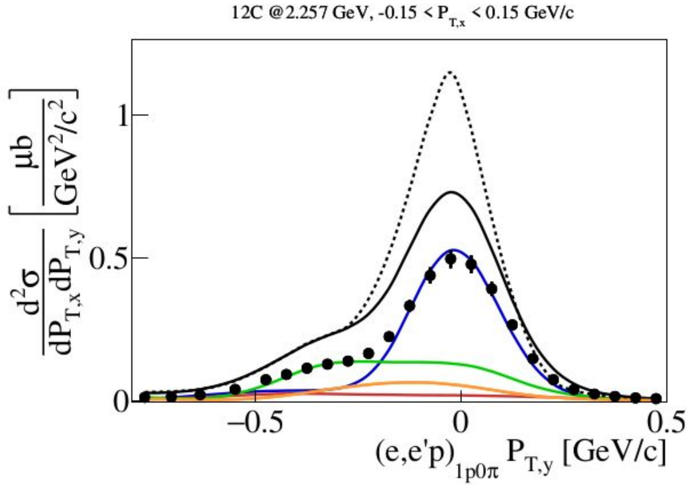
$$\delta p_{Tx} = \delta p_T \cdot sin\delta\alpha_T$$
$$\delta p_{Ty} = \delta p_T \cdot cos\delta\alpha_T.$$

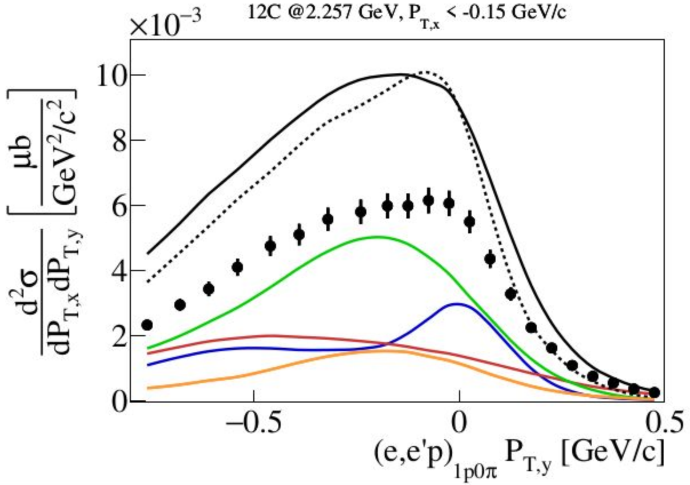


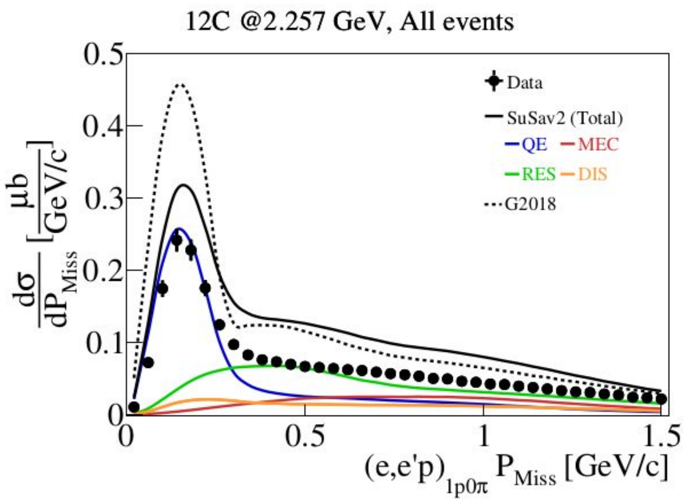


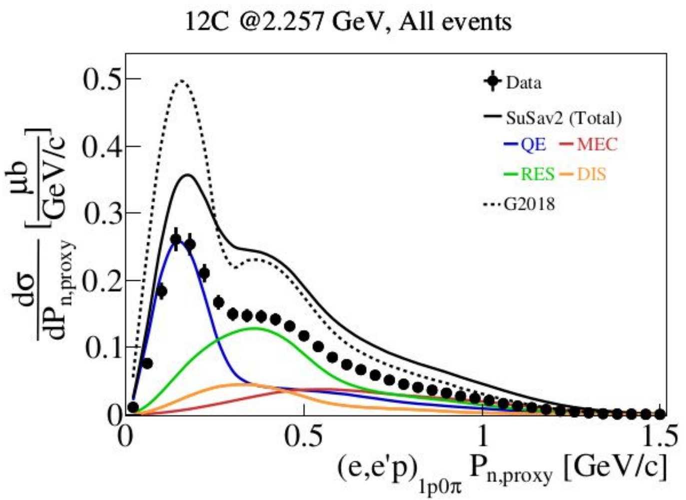


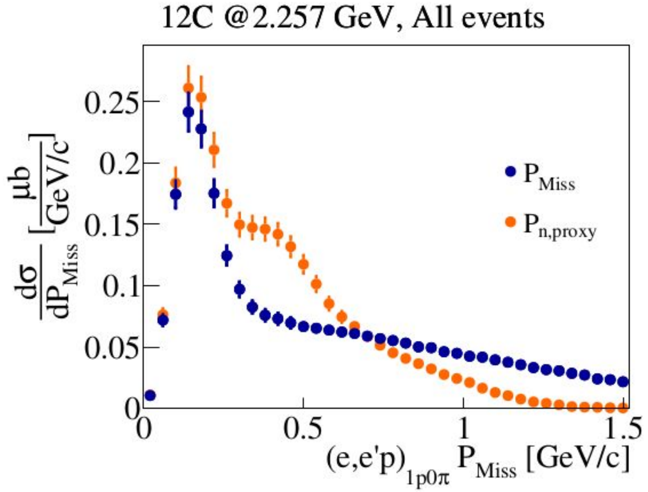
$$\delta p_{Tx} = \delta p_T \cdot sin\delta\alpha_T$$
$$\delta p_{Ty} = \delta p_T \cdot cos\delta\alpha_T.$$











$$P_{Miss} = |\vec{q} - \vec{p}|$$

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

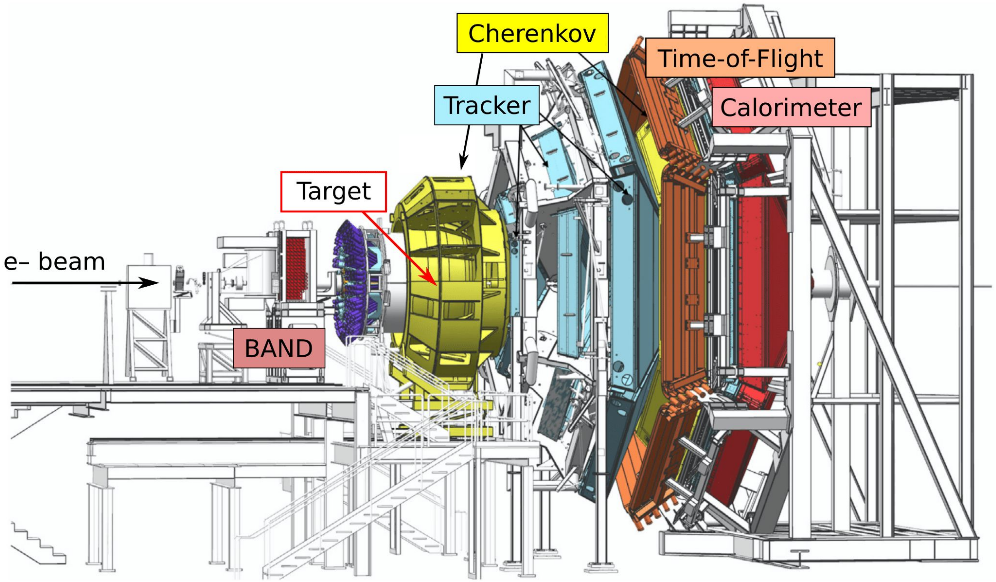
Experimental Efforts

Collaborations	Kinematics	Targets	Scattering
E12-14-012 (JLab) (Data collected: 2017)	$E_e = 2.222$ GeV $15.5° \leq \theta_e \leq 21.5°$ $-50.0° \leq \theta_p \leq -39.0°$	Ar, Ti Al, C	(e, e') e, p in the final state
e4nu/CLAS (JLab) (Data collected: 1999, 2022)	$E_e = 1, 2, 4, 6$ GeV $\theta_e > 5°$	H, D, He, C, Ar, ^{40}Ca, ^{48}Ca, Fe, Sn	(e, e') e, p, n, π, γ in the final state
LDMX (SLAC) (Planned)	$E_e = 4.0, 8.0$ GeV $\theta_e < 40°$	W, Ti, Al	(e, e') e, p, n, π, γ in the final state
A1 (MAMI) (Data collected: 2020) (More data planned)	50 MeV $\leq E_e \leq 1.5$ GeV $7° \leq \theta_e \leq 160°$	H, D, He C, O, Al Ca, Ar, Xe	(e, e') 2 additional charged particles
A1 (eALBA) (Planned)	$E_e = 500$ MeV - few GeV	C, CH Be, Ca	(e, e')

Electron Scattering and Neutrino Physics,
Snowmass white paper arXiv:2203.06853 [hep-ex]

New Data W/ CLAS12

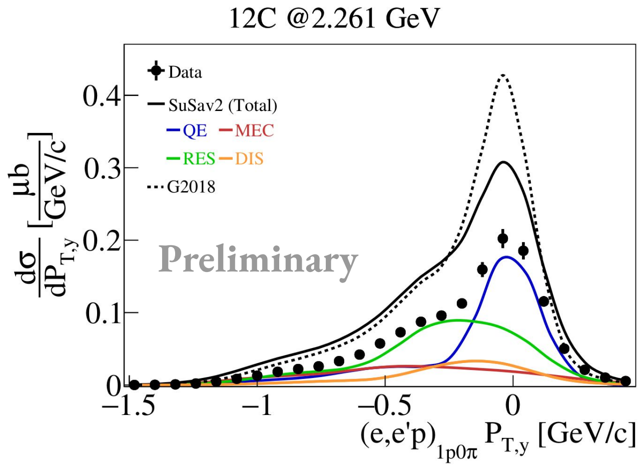
- $\theta_e > 5^o$
- x10 luminosity [10^{35} cm^{-2} s^{-1}]
- Targets
  ^{2}D, ^{4}He, ^{12}C, ^{16}O, $^{\mathbf{40}}$**Ar**, ^{120}Sn
- 1 - 6 GeV beam energies

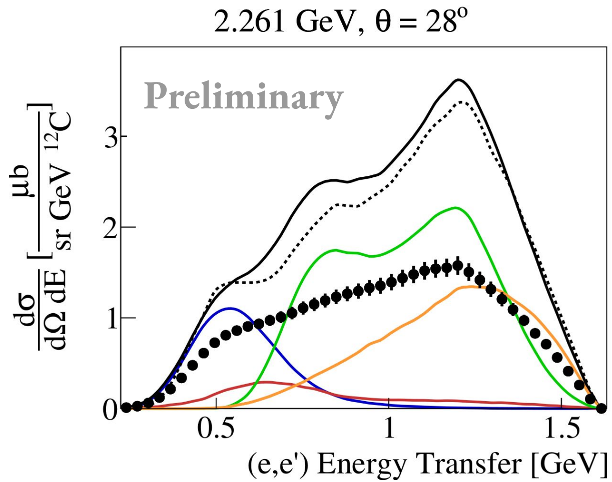


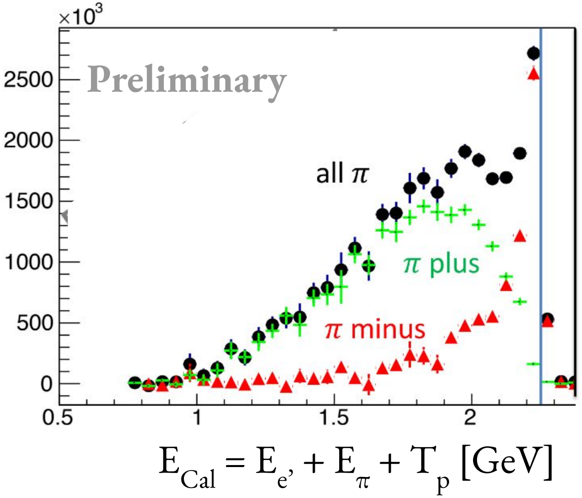
Support Letters

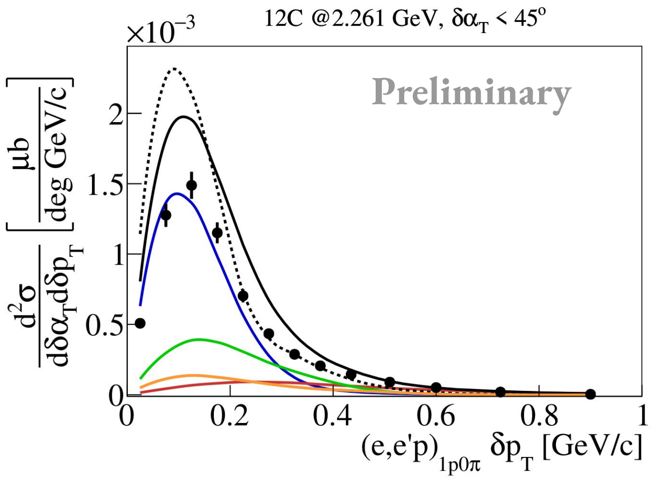
DUNE, IceCube South Pole Neutrino Observatory, Hyper-Kamiokande, T2K, NOvA, MINERvA, Fermilab, GiBUU The Giessen Boltzmann-Uehling-Uhlenbeck Project, Genie, μBooNE

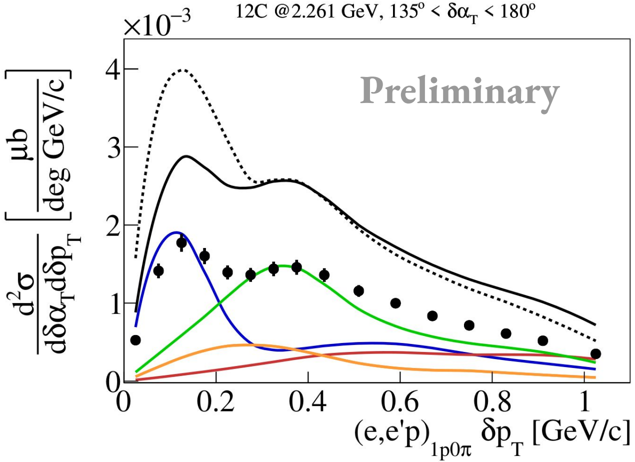
New Results









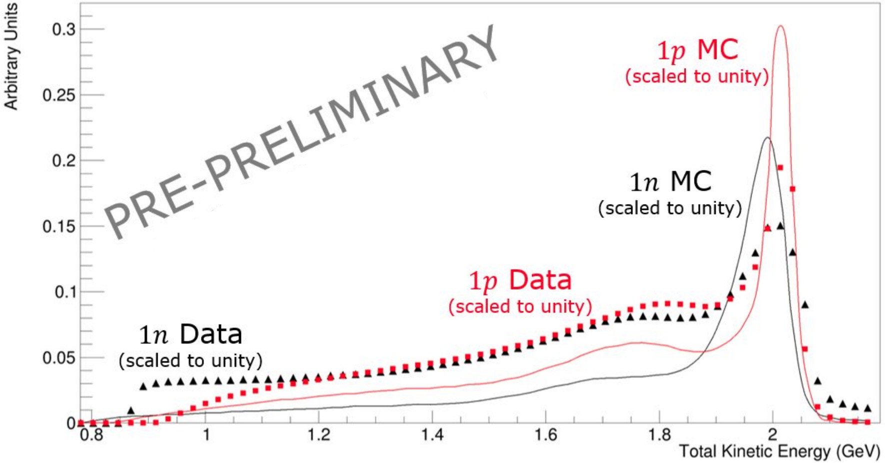


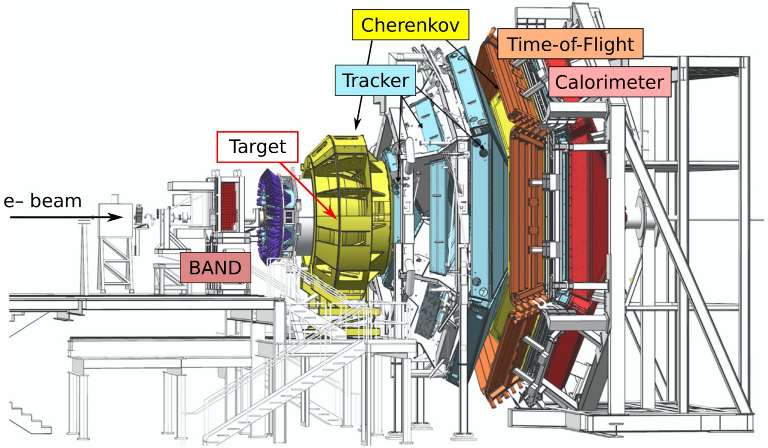
- Multi-differential
- Pion production
- Transparency studies
- Novel variables
- Tuning efforts
- New generators

New Data With CLAS12

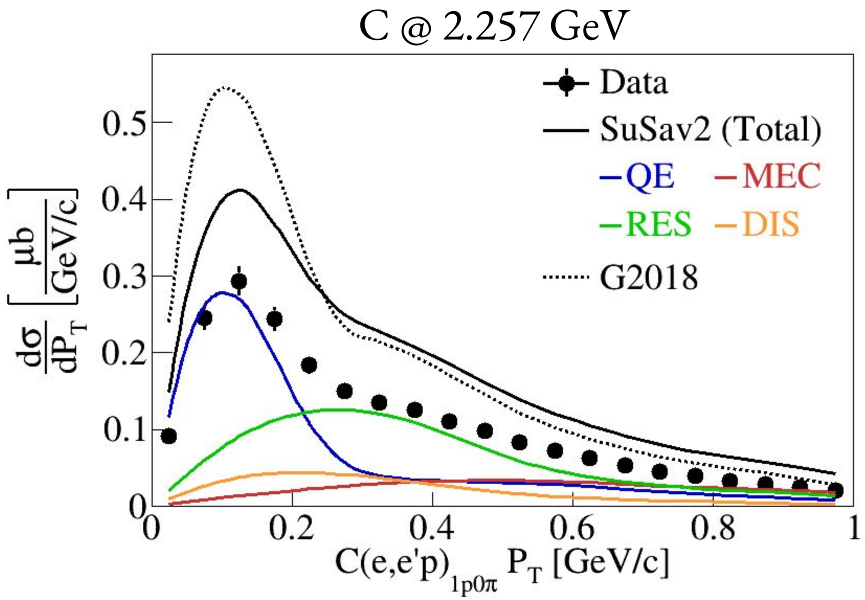
- Targets
  ^{4}He, ^{12}C, $^{\mathbf{40}}$**Ar**, ^{120}Sn

- 2 - 6 GeV beam energies





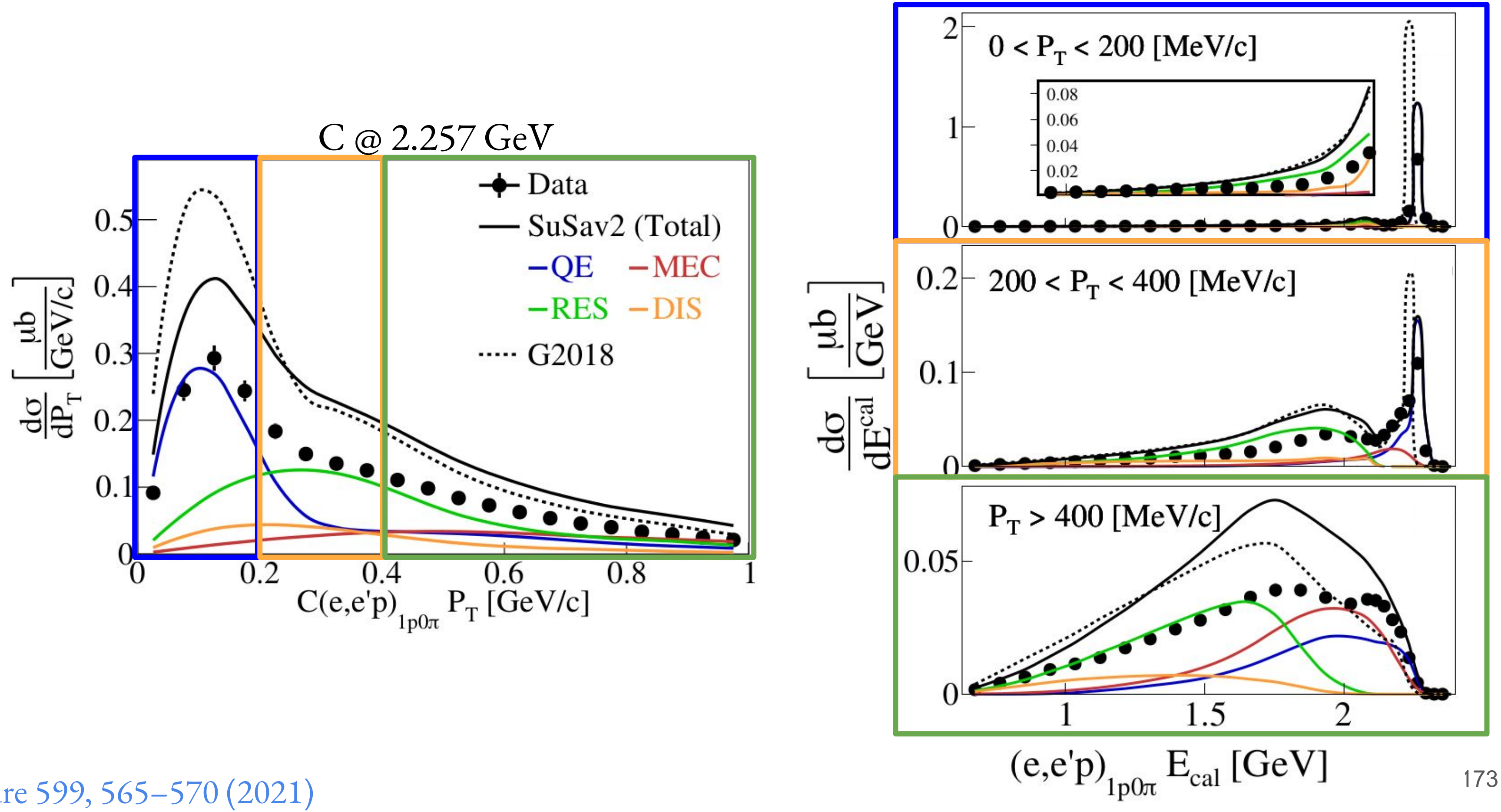
Transverse Momentum



High statistics →
Into the multiverse

Nature 599, 565–570 (2021)

Energy Reconstruction In P_T Slices



Nature 599, 565–570 (2021)