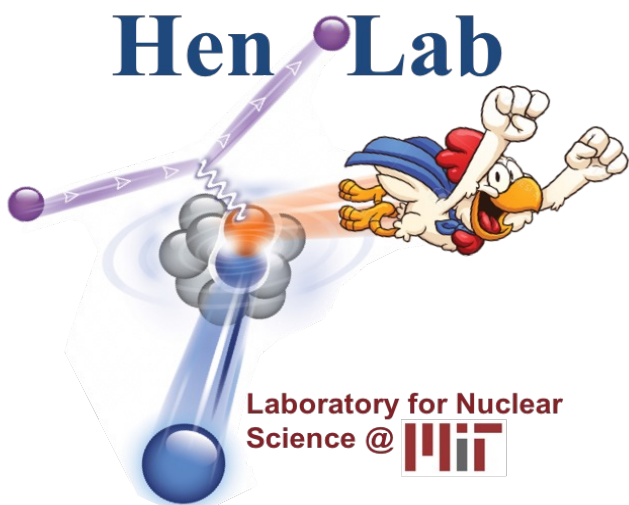


Electrons-4-Neutrinos: Trailblazing the Precision Oscillations Era

Or Hen (MIT)

For the Electrons-4-Neutrinos & CLAS collaborations



Measuring Neutrinos for Oscillations

Or... the Nuclear Reality of Oscillation Measurements

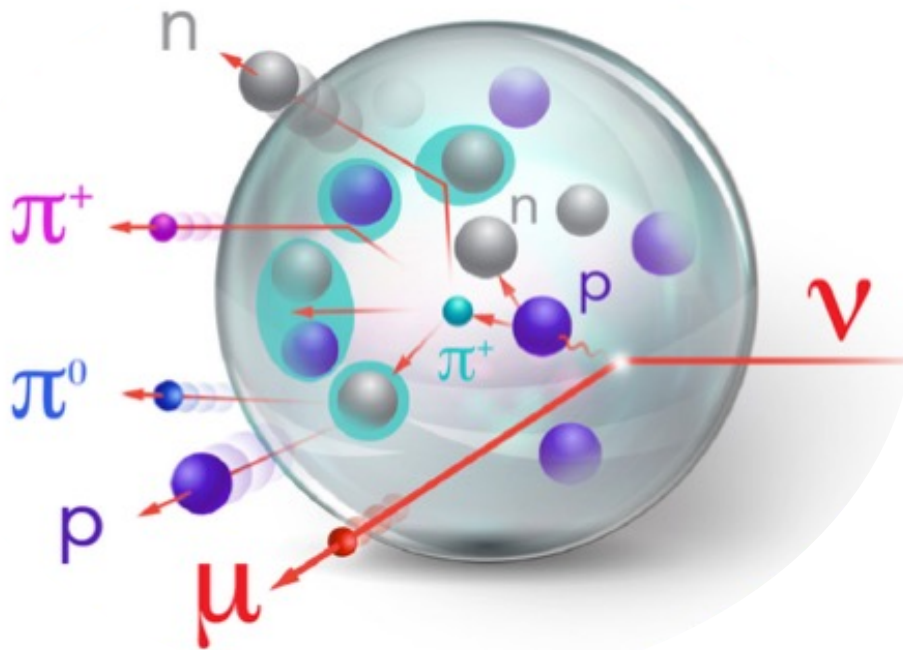
Oscillations study in practice:

$$N_{\alpha}(E_{rec}, L) = \sum_i \int \underbrace{\Phi_{\alpha}(E, L)}_{\text{Want [flux]}} \underbrace{\sigma_i(E) f_{\sigma_i}(E, E_{rec})}_{\text{Theory Input}} dE$$

Measure
[# interactions]

$\sigma(E)$: Scattering cross-section

$f_{\sigma}(E, E_{rec})$: Energy reconstruction
smearing matrix

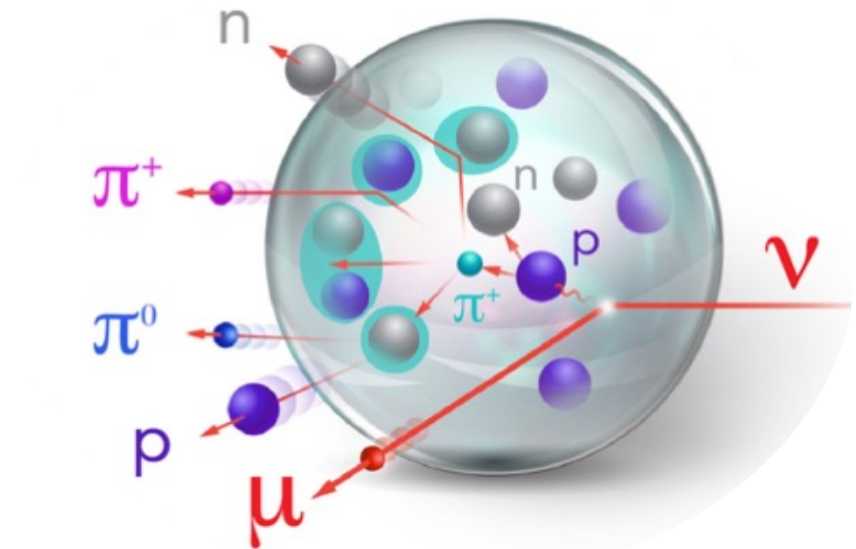


$$N_{\alpha}(E_{rec}, L) = \sum_i \int \Phi_{\alpha}(E, L) \sigma_i(E) \underline{f_{\sigma_i}(E, E_{rec})} dE.$$

Theory Input:

- Complex models; Implemented in event-generators
- Often effective, empirical, semi-classical, ...

⇒ **MUST TUNE
TO DATA!**



$$N_{\alpha}(E_{rec}, L) = \sum_i \int \Phi_{\alpha}(E, L) \sigma_i(E) \underline{f_{\sigma_i}(E, E_{rec})} dE$$

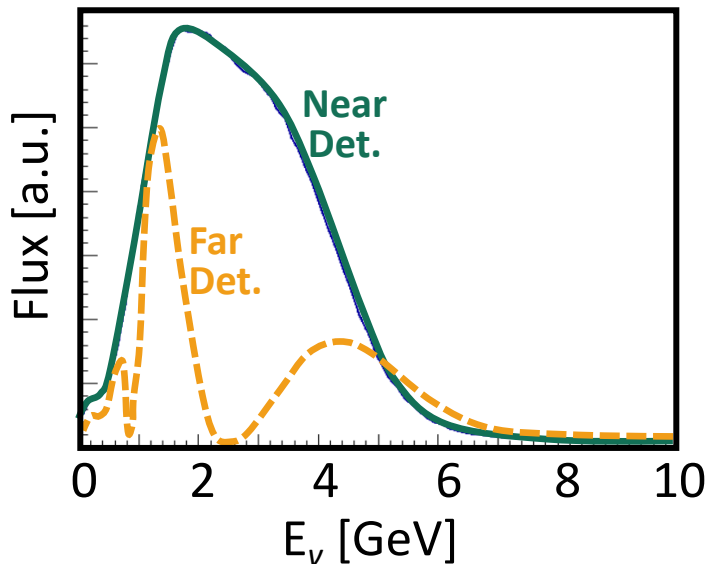
Near Detector data:

- No oscillations @ $L \approx 0$
 - $\phi(E, L \approx 0)$ generally known
- ➔ Provide good $\sigma(E)$ & $f_{\sigma}(E, E_{rec})$ integral constraint

$$N_{\alpha}(E_{rec}, L) = \sum_i \int \Phi_{\alpha}(E, L) \sigma_i(E) \underline{f_{\sigma_i}(E, E_{rec})} dE$$

Near Detector data:

- No oscillations @ $L \approx 0$
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But... near flux \neq far flux

Interaction modeling is
a leading systematic in
oscillation experiments

Need external constraints!

Our Approach:

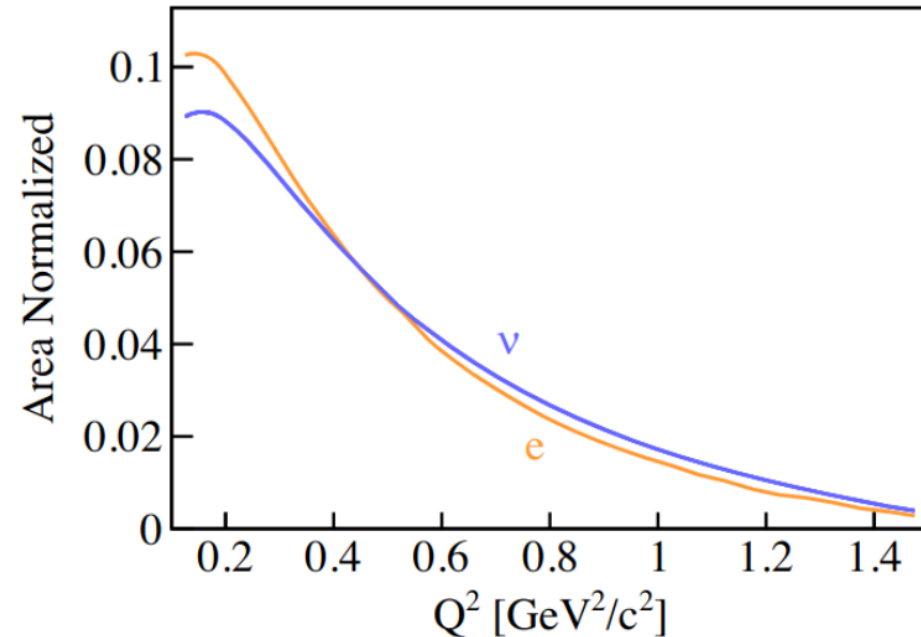
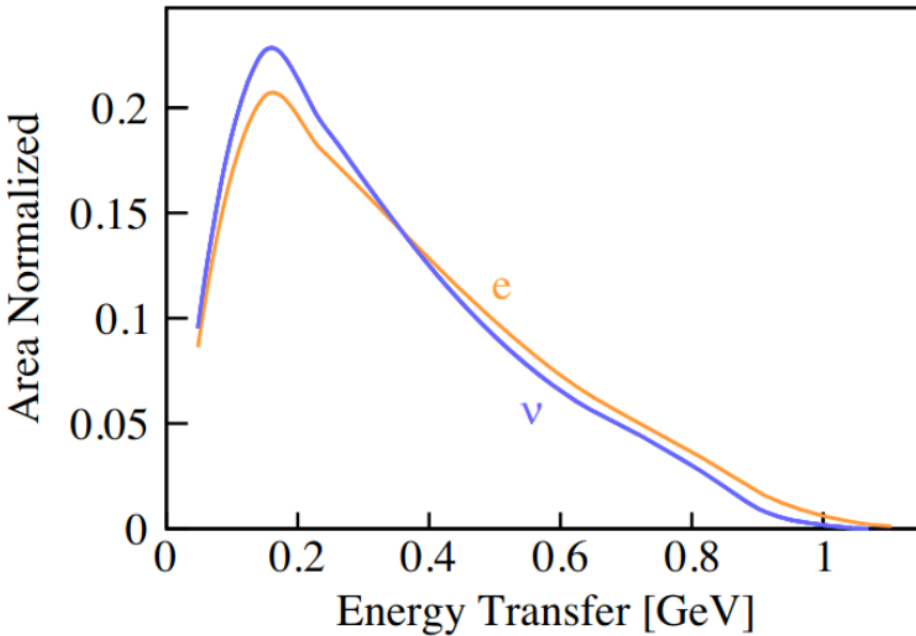
Use Electron Scattering Data!

- e & ν interact similarly
- Many nuclear effects identical (FSI, multi-N effects, ...).
- e beam energy is known
- Test ν event generators by running in e -mode (turn off axial response, scale for propagator mass)

Electron Scattering Data

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e & ν interact similarly



2.26 GeV on ^{12}C .

$1p0\pi$ events,
 $\theta_{lepton} > 15^\circ$.

Papadopoulou and Ashkenazi et al
(e4v collaboration) Phys. Rev. D **103**, 113003 (2021).

* e^- scaled by Q^4

Electron Scattering Data

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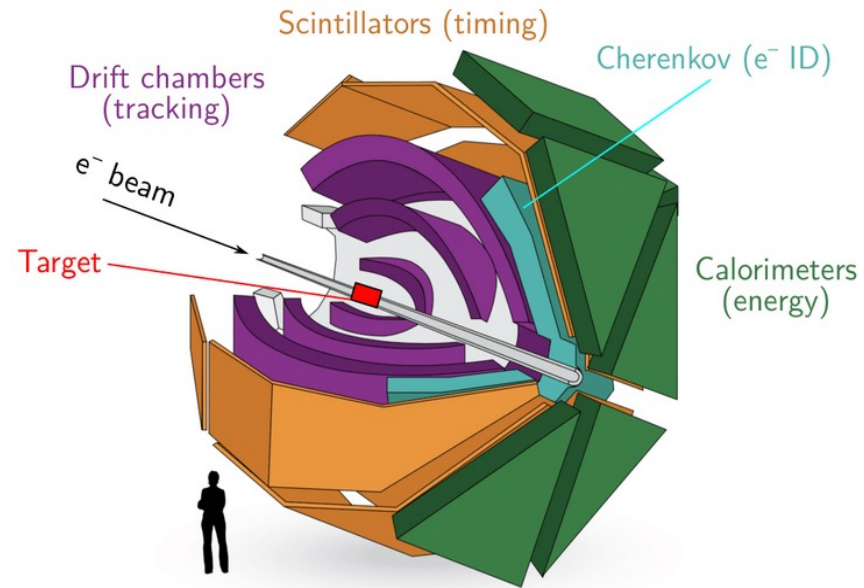
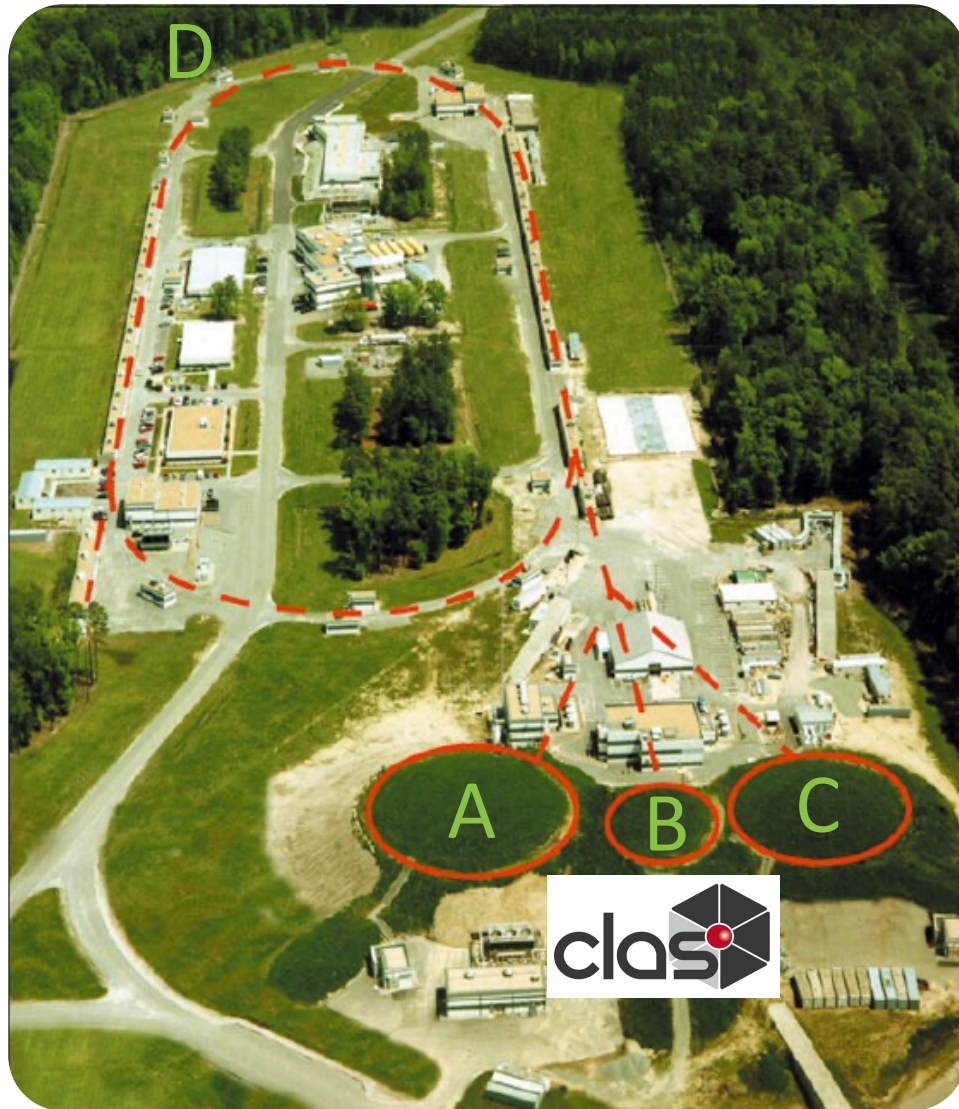
Electron Scattering Data

- ✓ e & ν interact similarly
- ✓ Many nuclear effects identical (FSI, multi-N effects, ...)
- ✓ e beam energy is known
- ➔ Test ν event generators by running in e -mode (turn off axial response, scale for propagator mass)

Electron Scattering Data

- ✓ Any model must work for electrons,
or it won't work for neutrinos!
- ✓ (FSI, multi-N effects, ...)
- ✓ e beam energy is known
- ➔ Test ν event generators by running in e-mode
(turn off axial response, scale for propagator mass)

$e4V$ @ Jefferson-Lab





✧ Large acceptance ($10 \sim 140^\circ$)

✧ low thresholds:

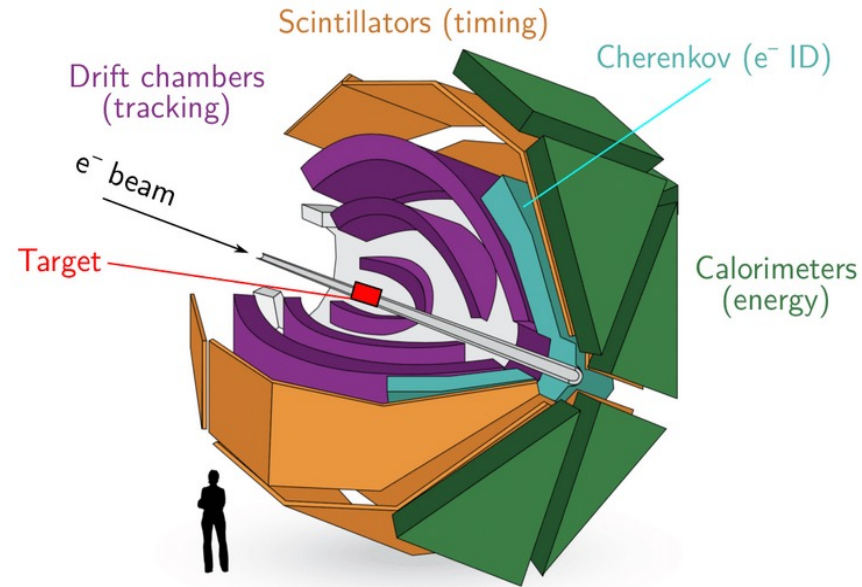
- $P_p > 300 \text{ MeV}/c$
- $P_\pi > 150 \text{ MeV}/c$

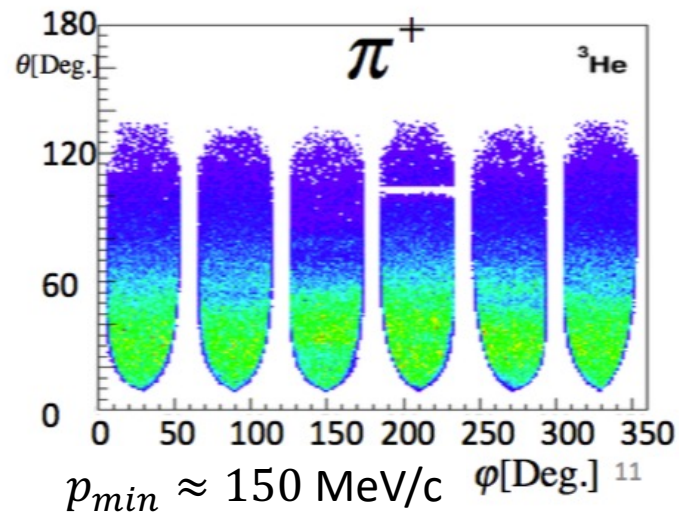
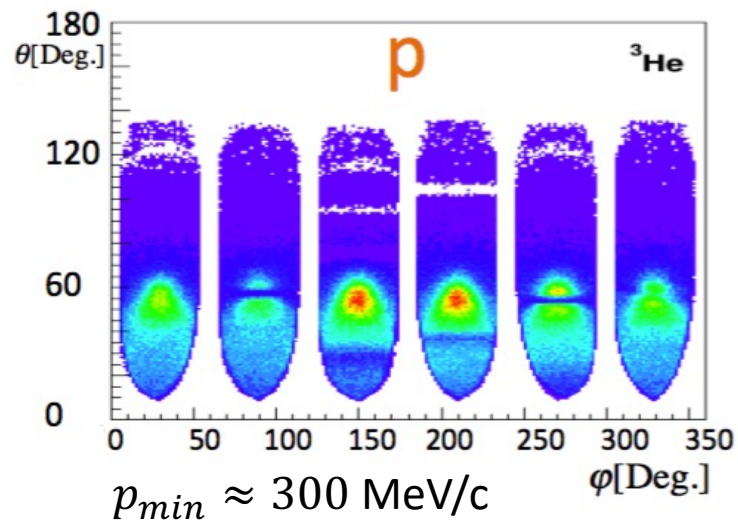
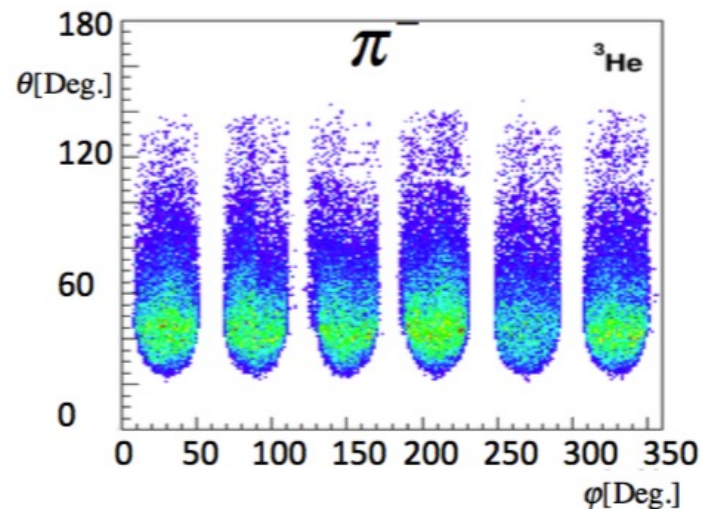
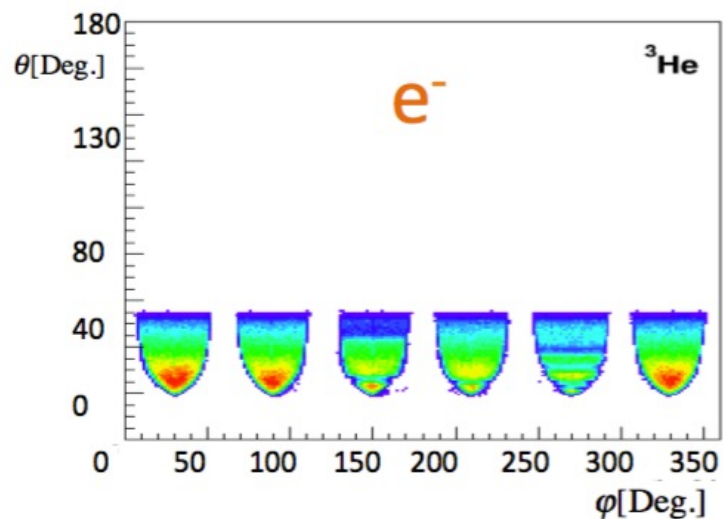
✧ Neutral particles:

- EM calorimeter ($10 \sim 60^\circ$)
- TOF ($10 \sim 140^\circ$)

✧ ^4He , C, Fe Targets

✧ $E_{\text{beam}} = 1.1, 2.2, 4.4 \text{ GeV}$





Playing the Neutrino Game

Goal: Study E_{beam} reconstruction & vector-current cross-sections for different energies / nuclei

Means (QE study):

- Select 'clean' (e,e'p) events (no π , 2nd p, ...),
- Reweight by $\sigma_{e-N} / \sigma_{\nu-N}(Q^4)$,
- Analyze as 'neutrino data' (not using E_{beam}),
- Reconstruct E_{beam} and measure cross-sections,
- Compare to theory predictions.

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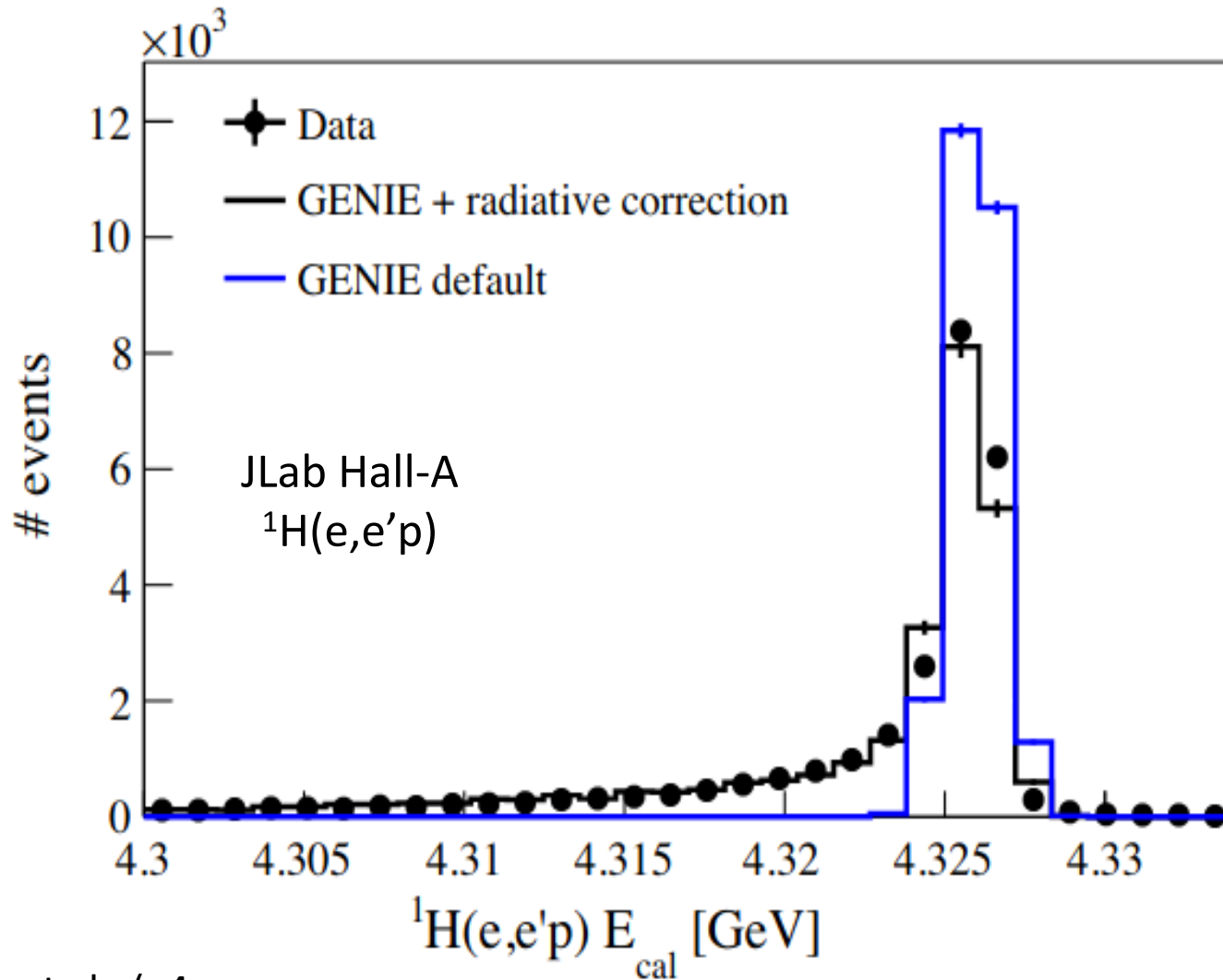
Playing the Neutrino Game

Goal: Study E_{beam} reconstruction & vector-current cross-sections for different energies / nuclei

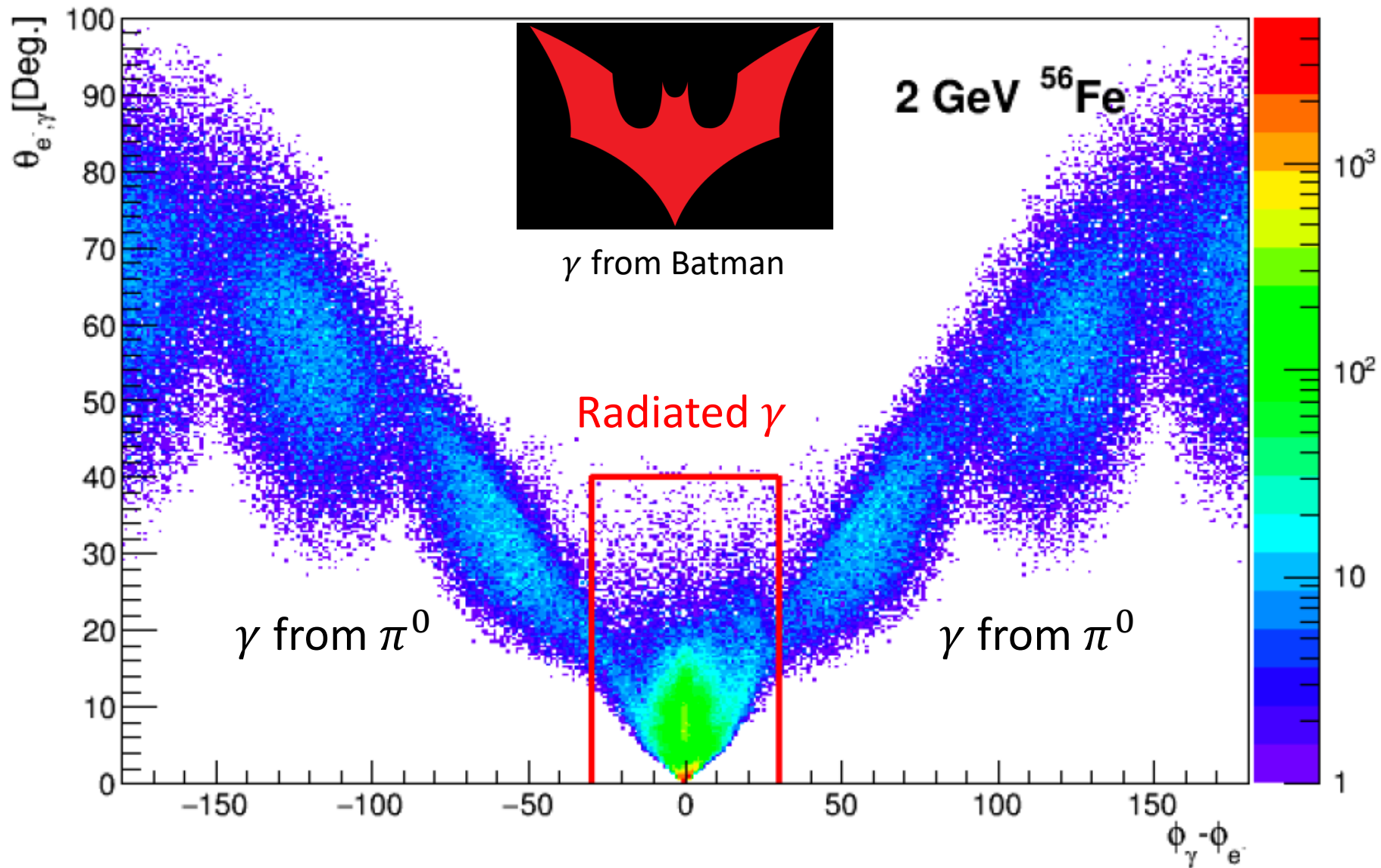
Means (QE study):

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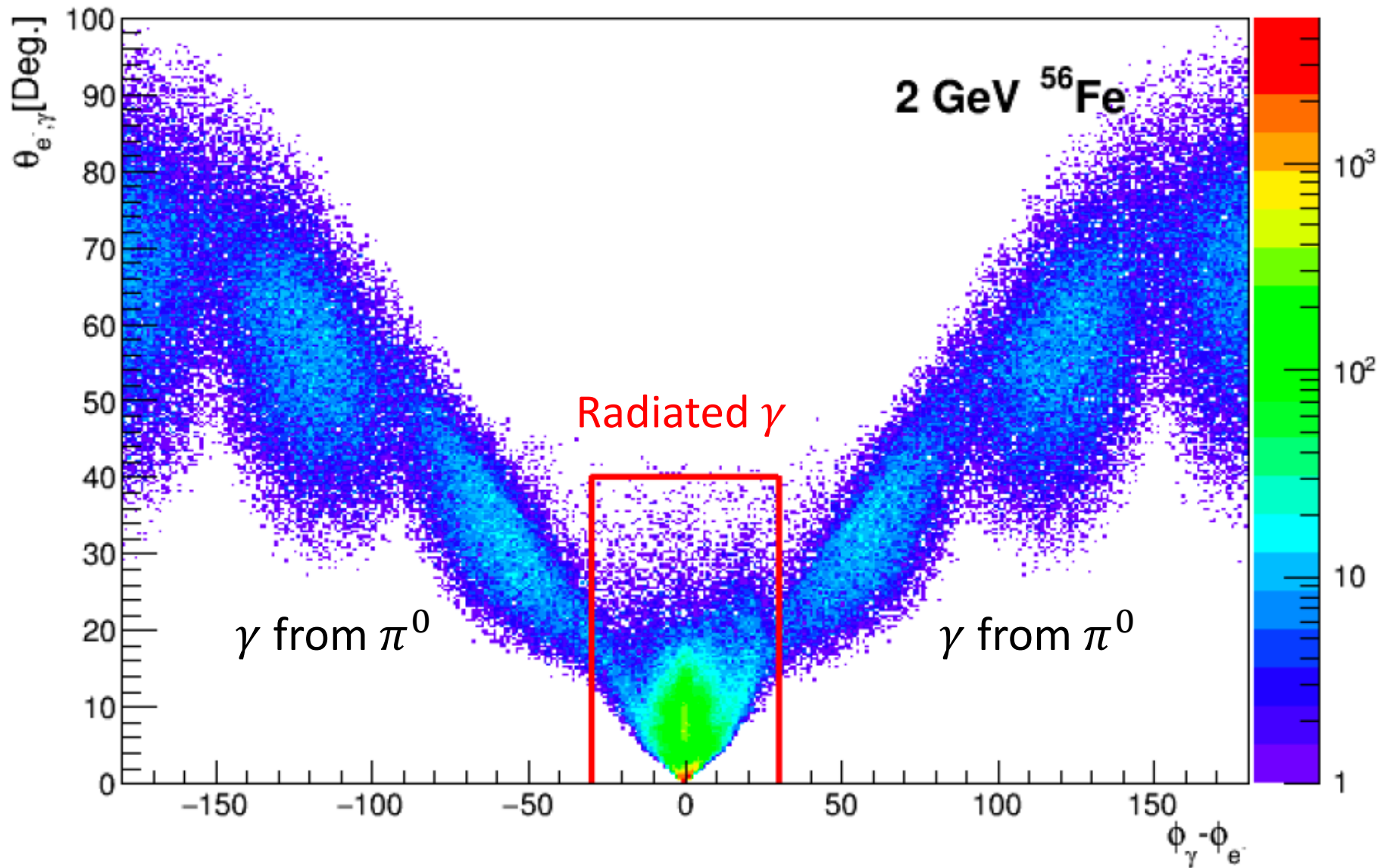
Adding Radiation to GENIE



Excluding Radiation in data



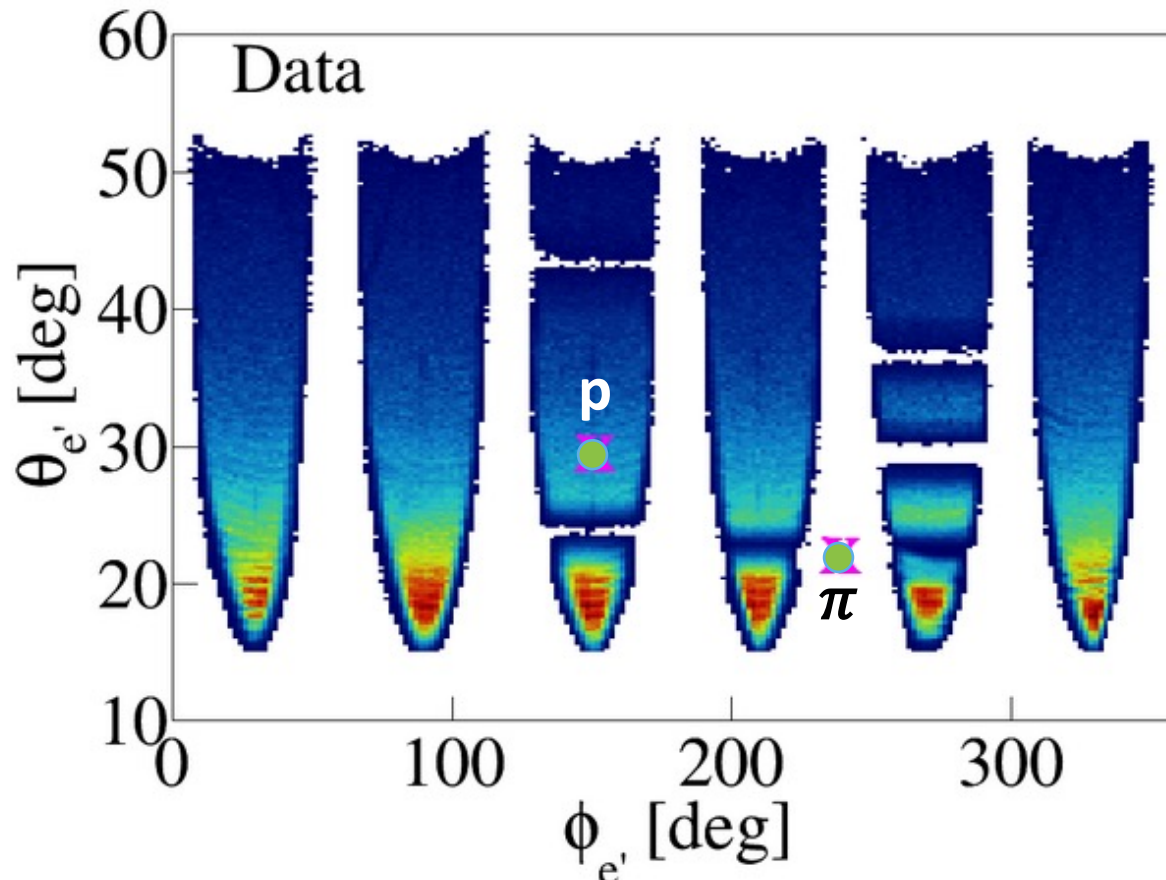
Excluding Radiation in data



Non-1p0 π Background Subtraction

Non-QE interactions lead to multi hadron final states.

Gaps in CLAS acceptance will make them look like (e,e'p) events.



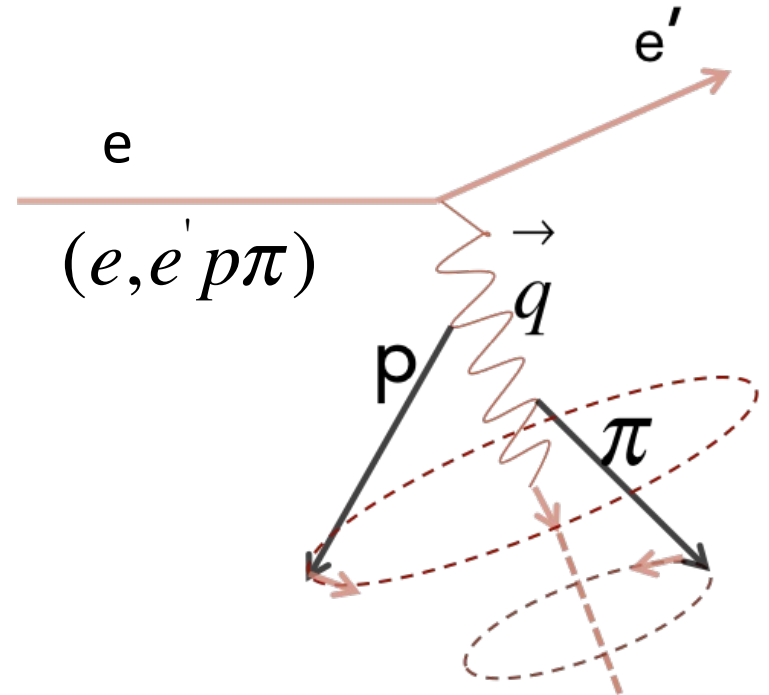
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Data Driven Correction:

1. Use measured $(e,e'p\pi)$ events,
2. Rotate π around q to determine its acceptance,
3. Subtract $(e,e'p\pi)$ contributions



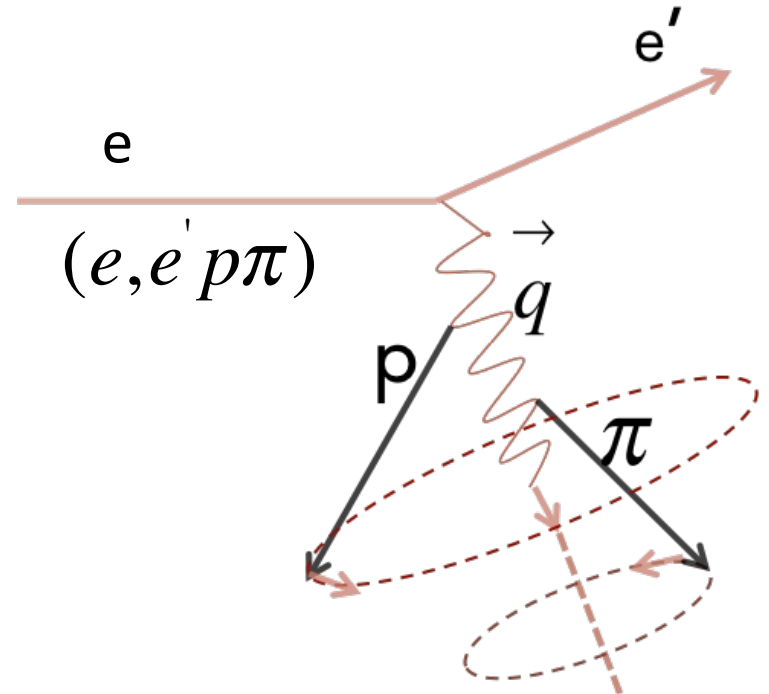
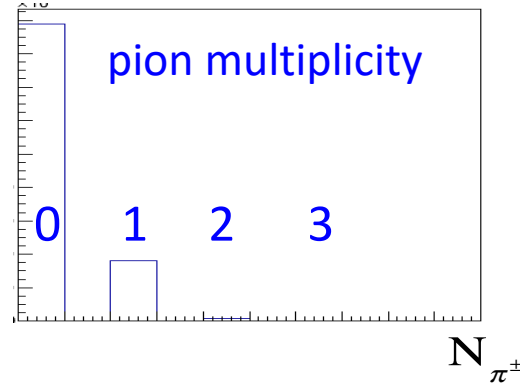
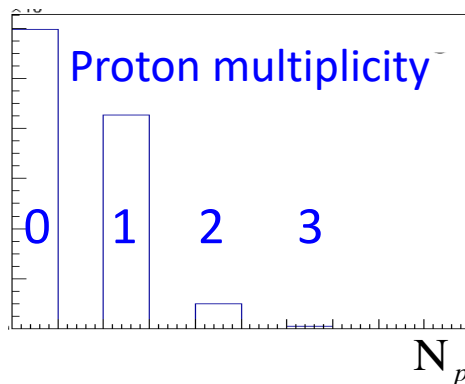
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4. Do the same for $2p$, $3p$ $2p+\pi$ etc.



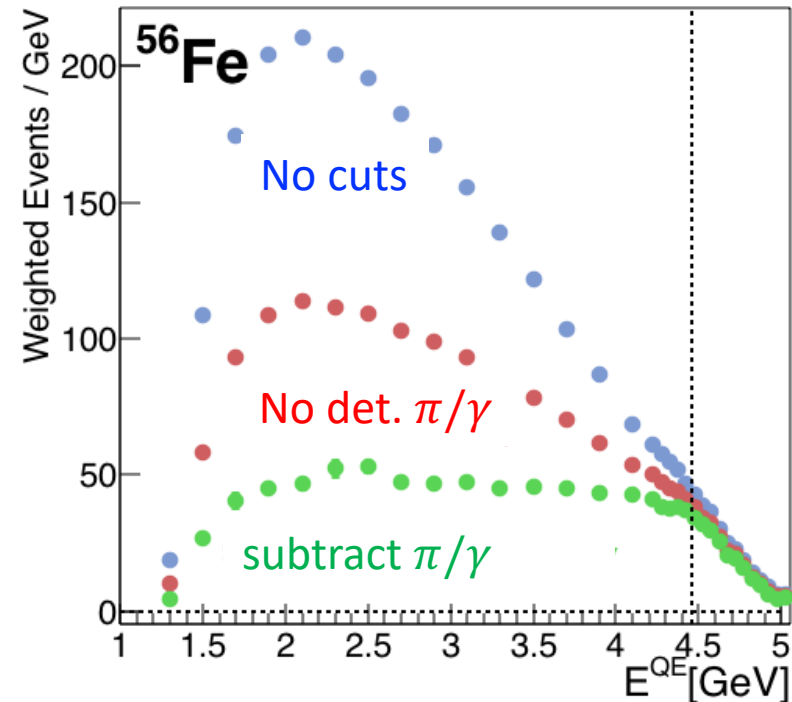
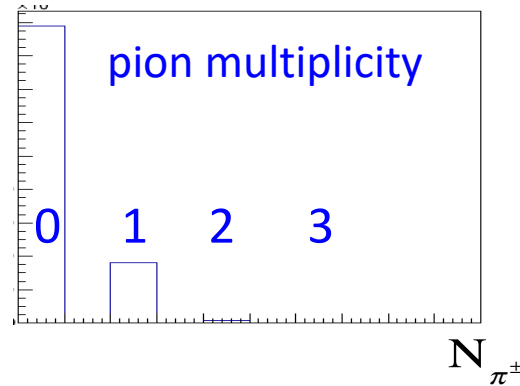
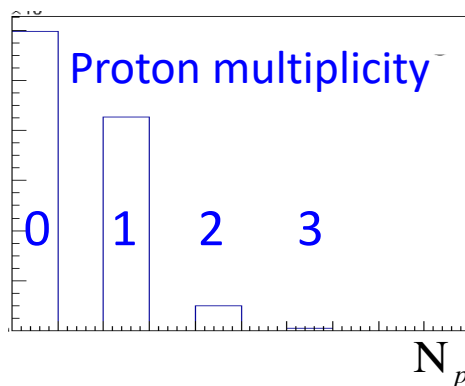
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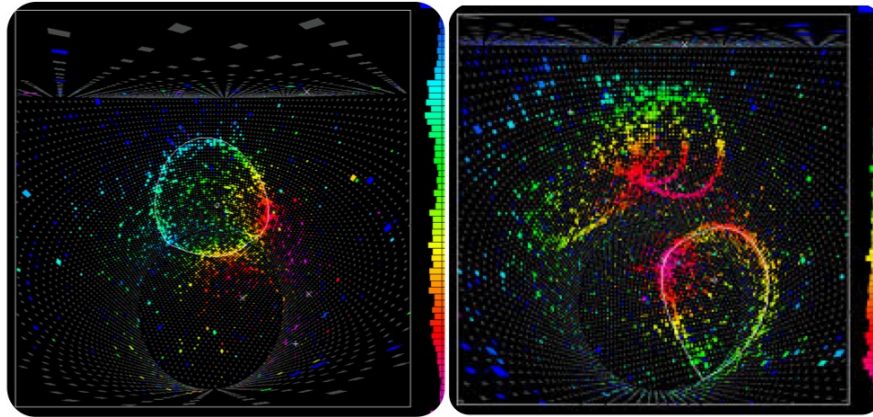


➔ True 0π event sample!

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

Kinematic Energy Reconstruction



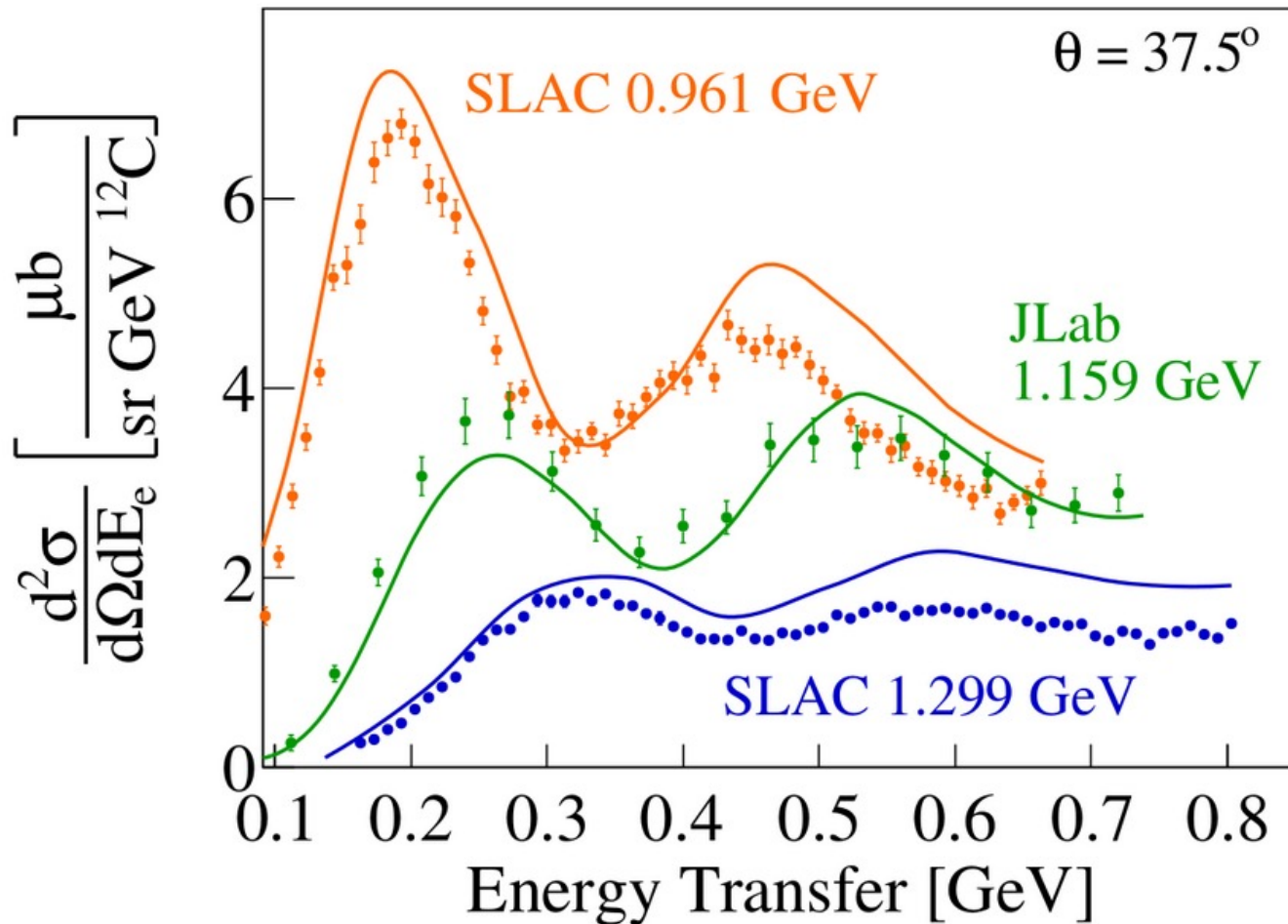
Cherenkov detectors:

Assuming QE interaction

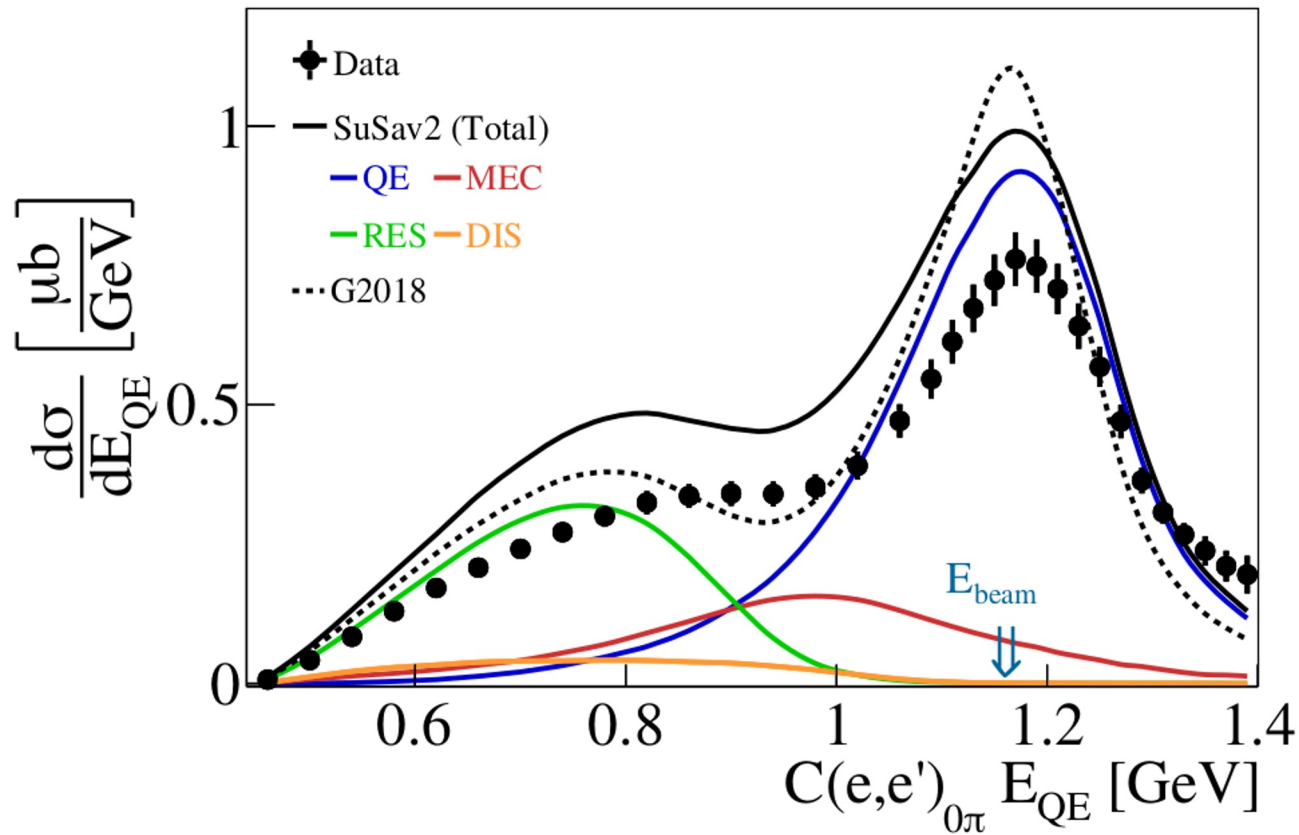
Using lepton only

$$E_{QE} = \frac{2M\epsilon + 2ME_l - m_l^2}{2(M - E_l + |k_l| \cos \theta_l)}_{[0\pi]}$$

Sanity Check: inclusive cross-sections



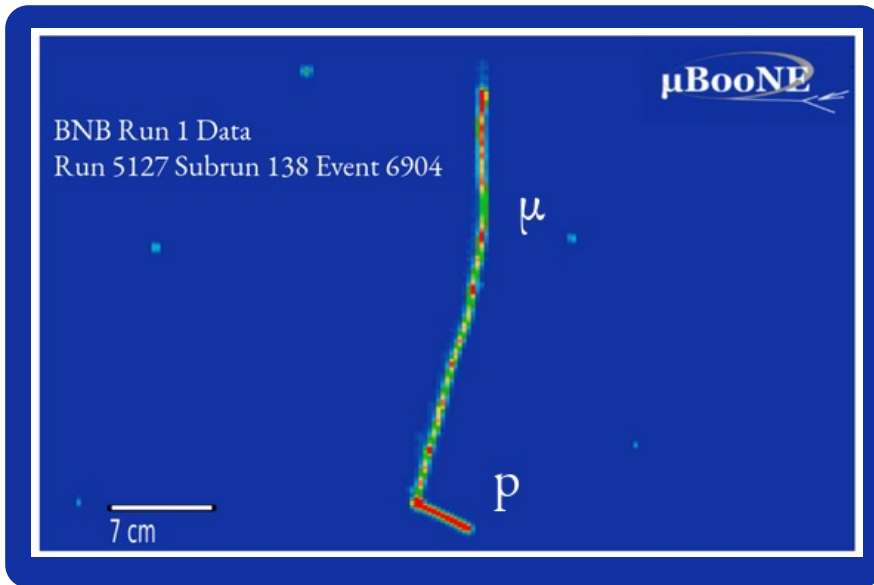
$^{12}\text{C}(e,e')_{0\pi}$ Data-Theory Disagreements



Khachatryan, Papadopoulou, and Ashkenazi et al.
(CLAS & e4v collaborations), Nature **599**, 565 (2021).

$$E_{QE} = \frac{2M\epsilon + 2ME_l - m_l^2}{2(M - E_l + |k_l|\cos\theta_l)} \quad 33$$

Calorimetric Energy Reconstruction



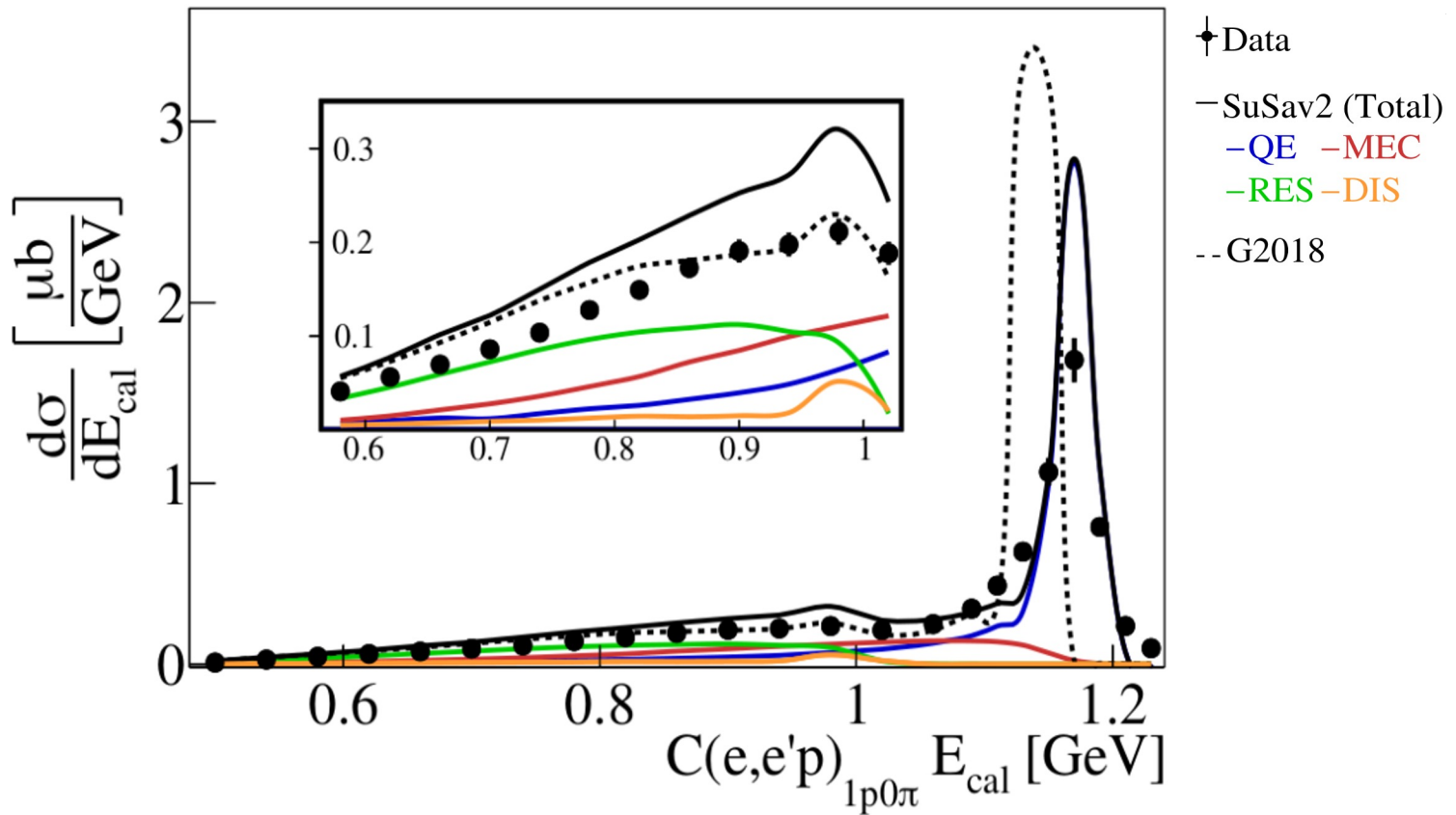
Tracking detectors:

Calorimetric sum

Using All detected particles

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

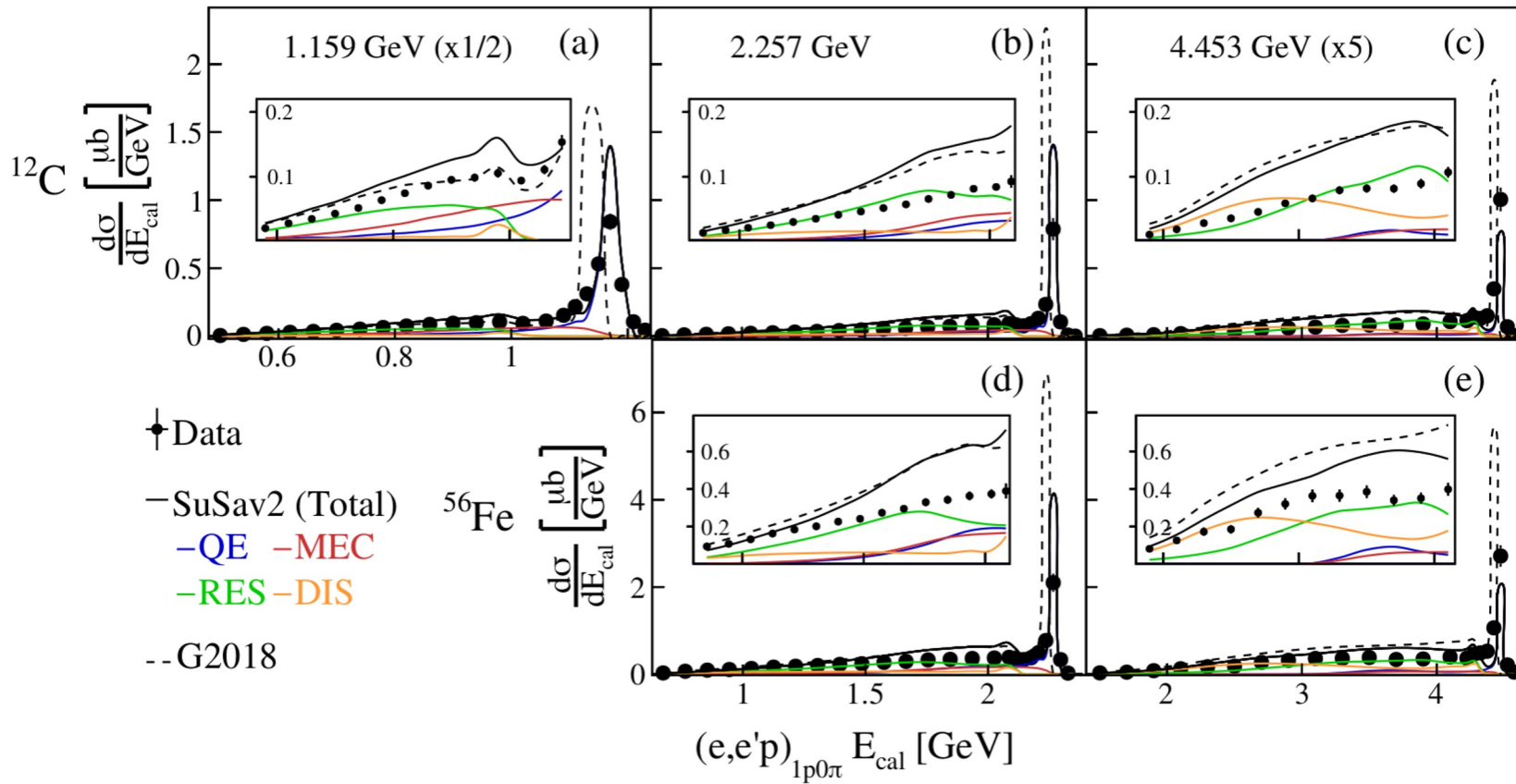
$^{12}\text{C}(e,e'p)$ Energy Reconstruction



Khachatryan, Papadopoulou, and Ashkenazi et al.
(CLAS & e4v collaborations), Nature **599**, 565 (2021).

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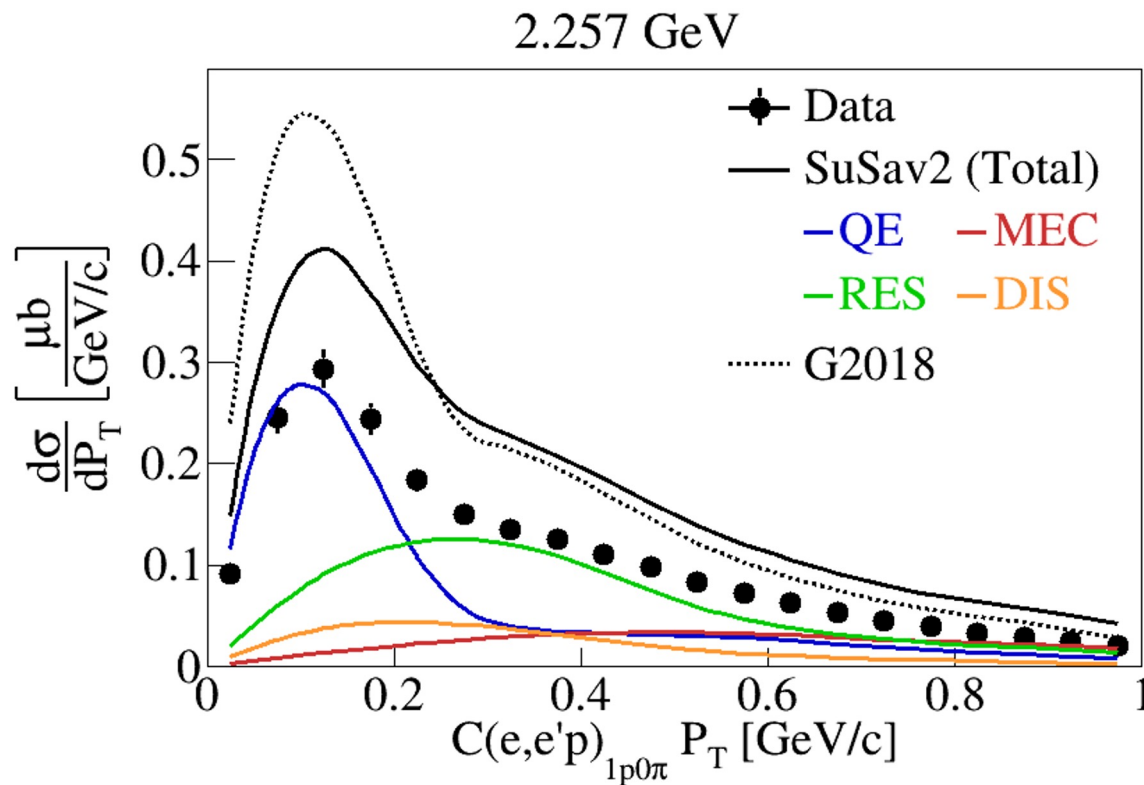
Worse for higher energy; Similar for A = 12 & 56



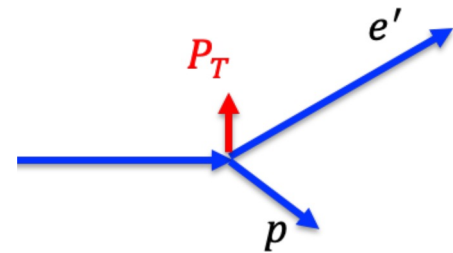
Khachatryan, Papadopoulou, and Ashkenazi et al.
(CLAS & e4v collaborations), Nature **599**, 565 (2021).

$$E_{cal} = E_l + T_p + \epsilon \quad 36$$

Transverse Constraints

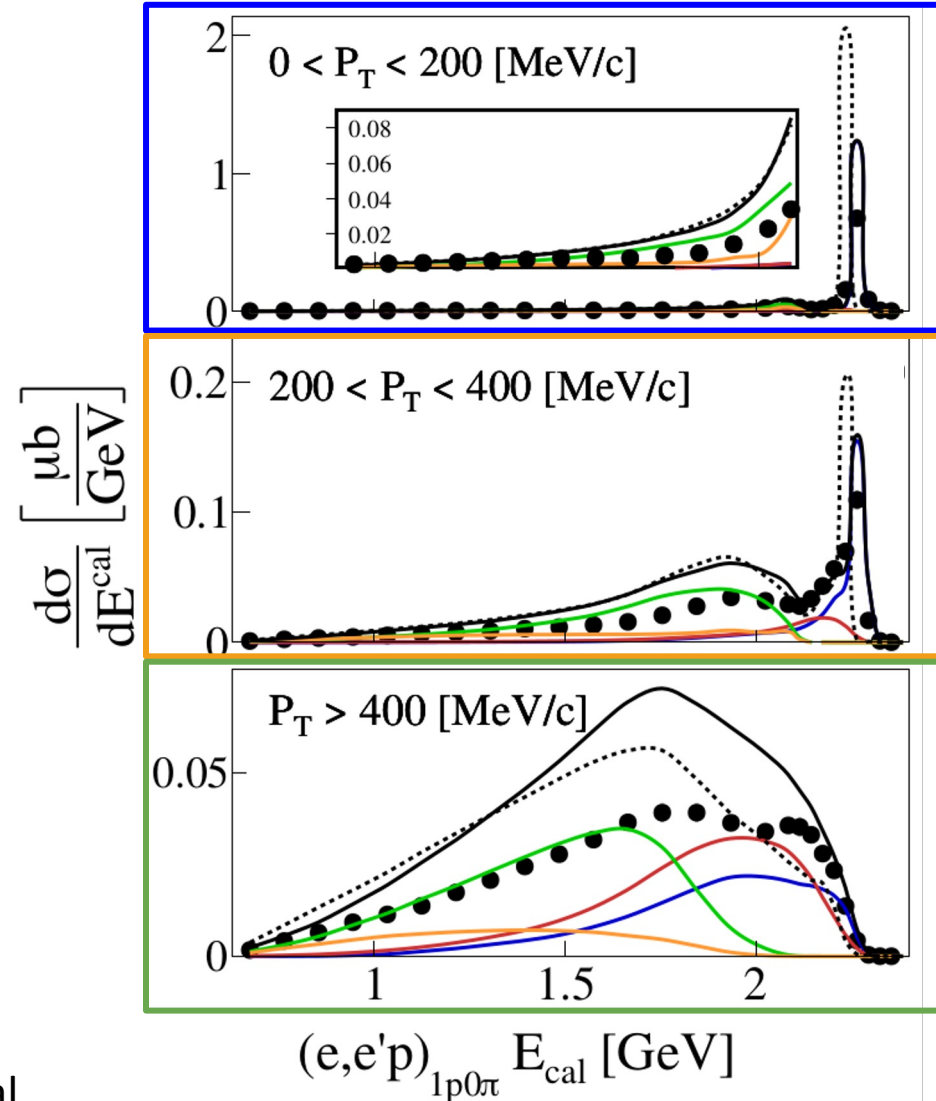
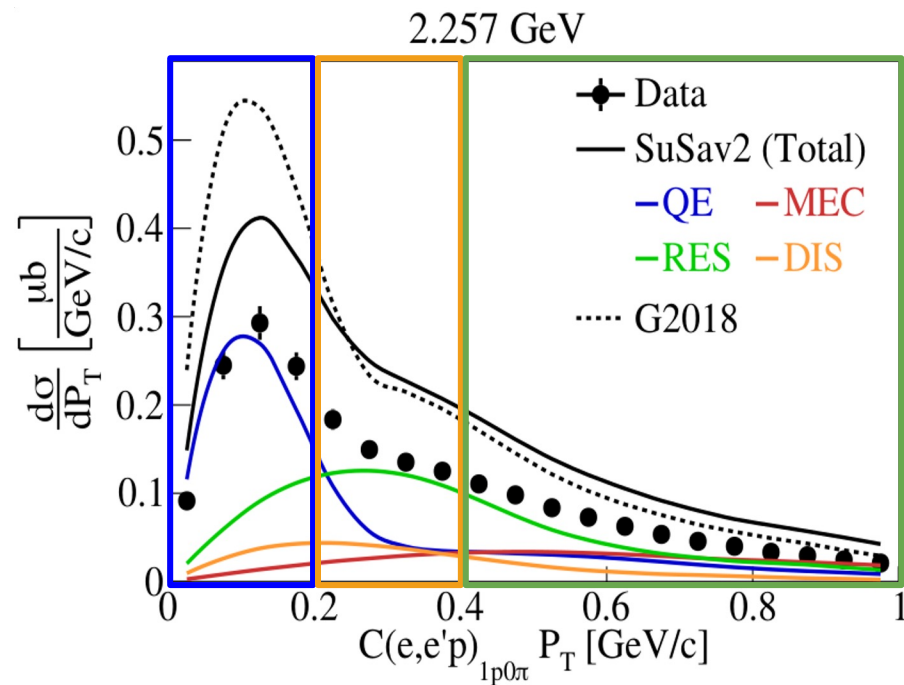


$$P_T = | \mathbf{P}_T^{e'} + \mathbf{P}_T^p |$$



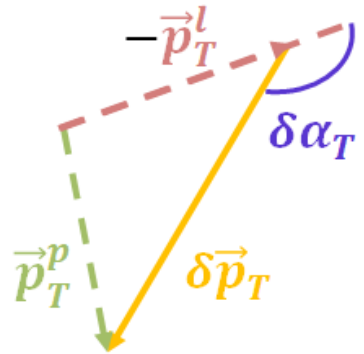
Overestimation of
QE peak & RES tail

Impacts E_{beam} reconstruction

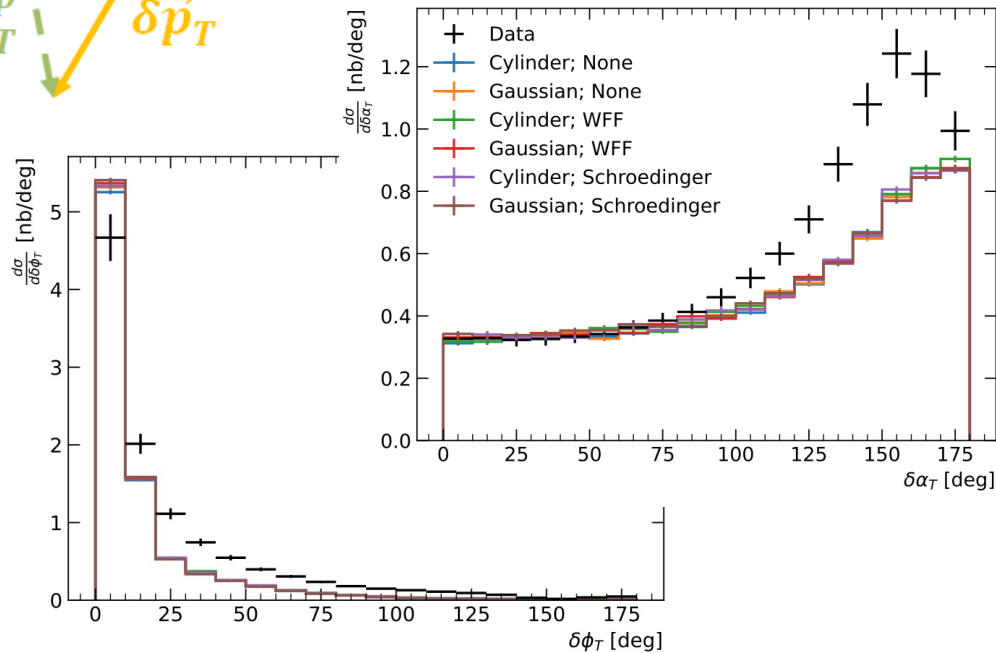


Khachatryan, Papadopoulou, and Ashkenazi et al.
(CLAS & e4v collaborations), Nature **599**, 565 (2021).

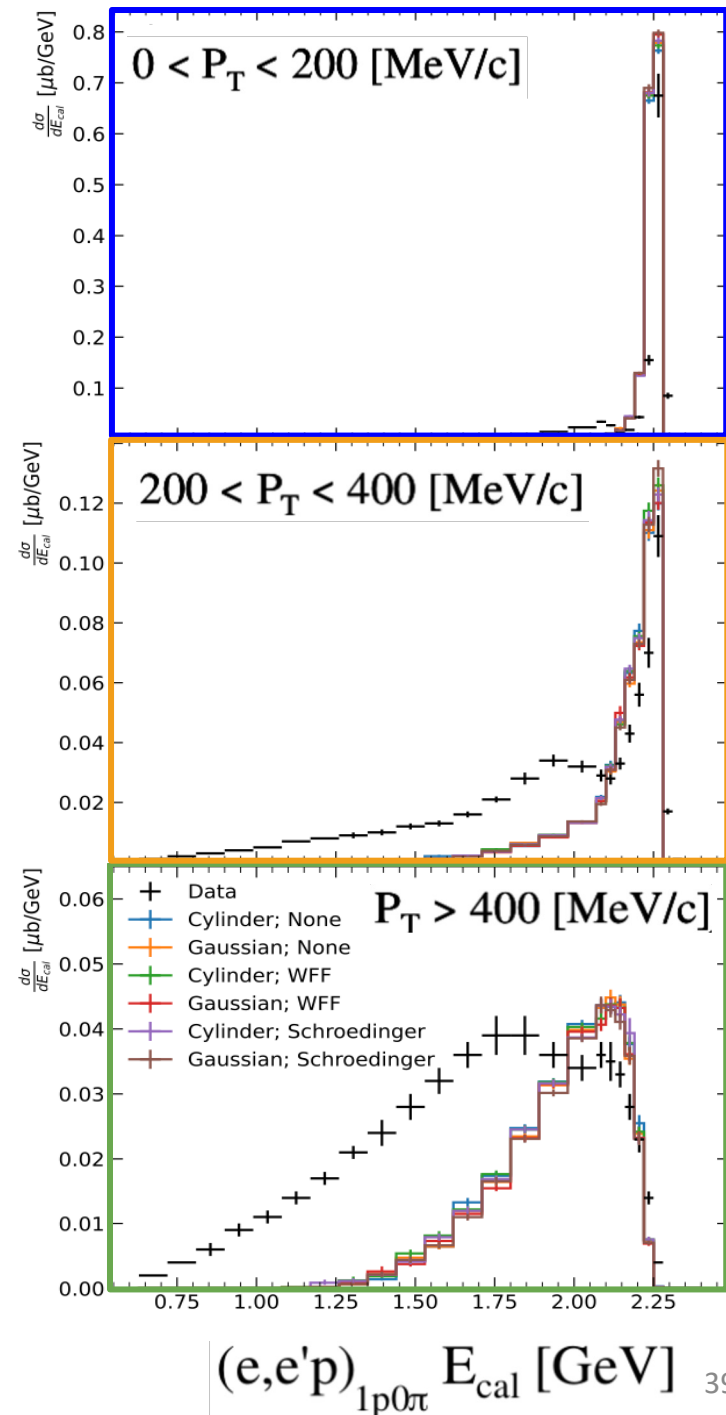
Benchmarking new generators! (ACHILLES)



First step: only QE & FSI



Isaacson, Jay, Lovato, Machado, and Rocco
arXiv: 2205.06378 (2022)



(e,e'p)_{1p0π} E_{cal} [GeV] 39

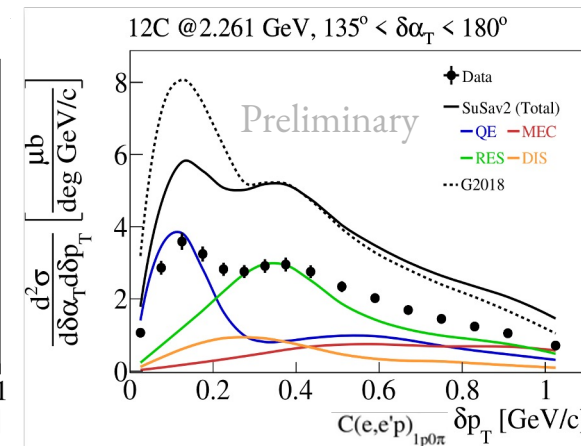
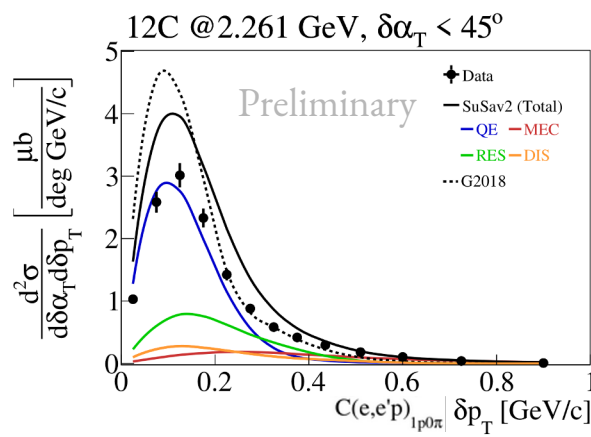
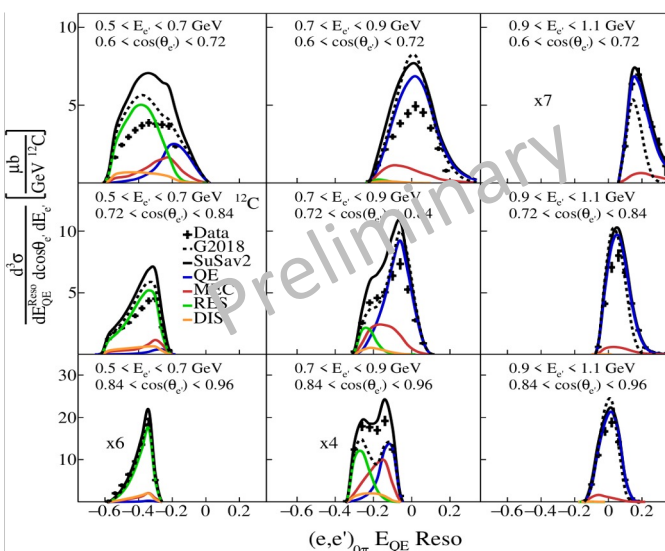
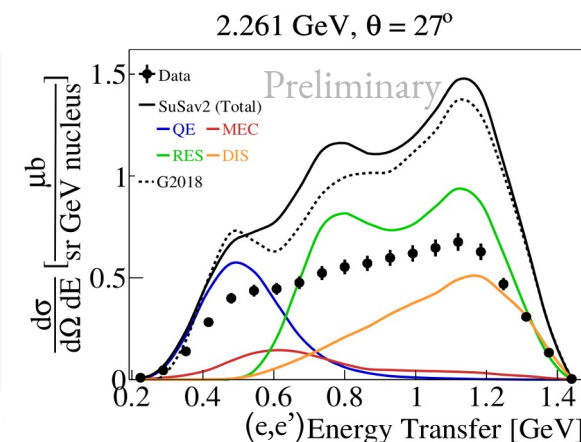
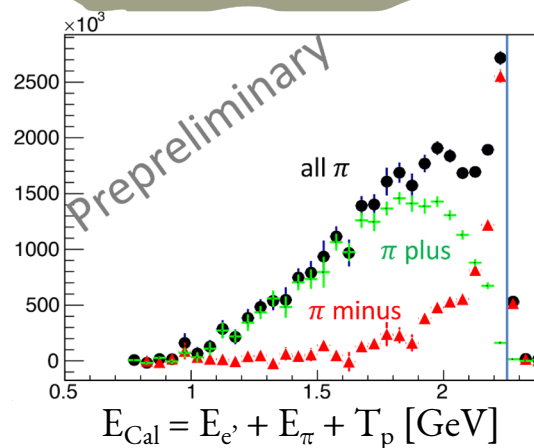
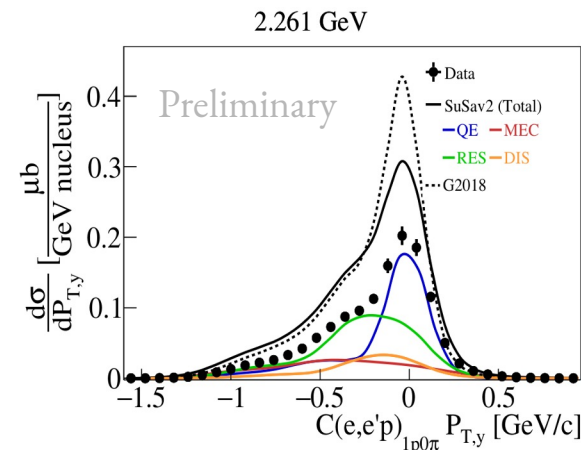
LOTS of new results!

- Multi-differential
- Pion production
- p & π transparency
- Complex variables
- ...

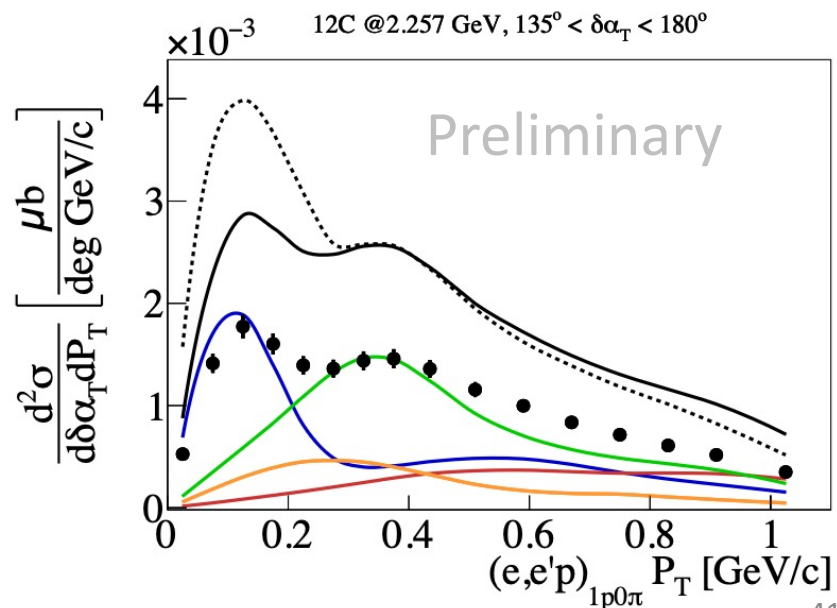
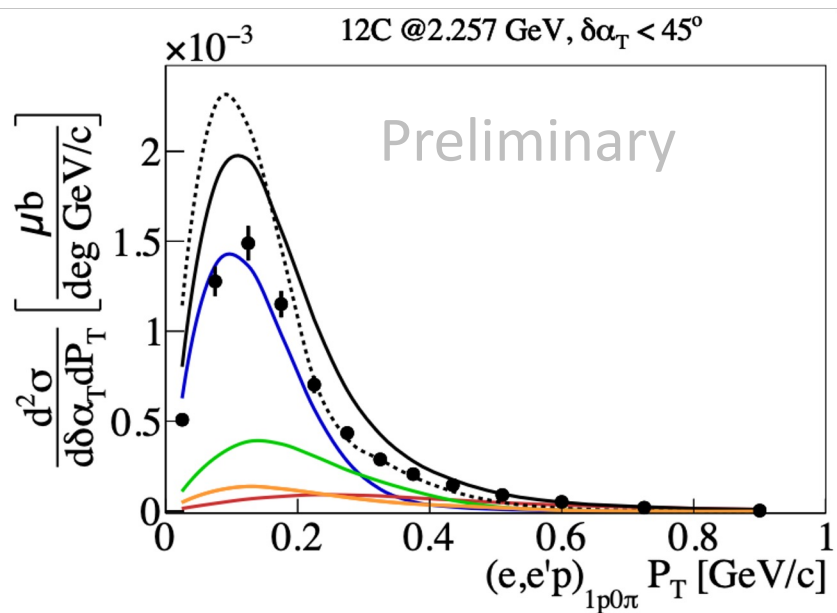
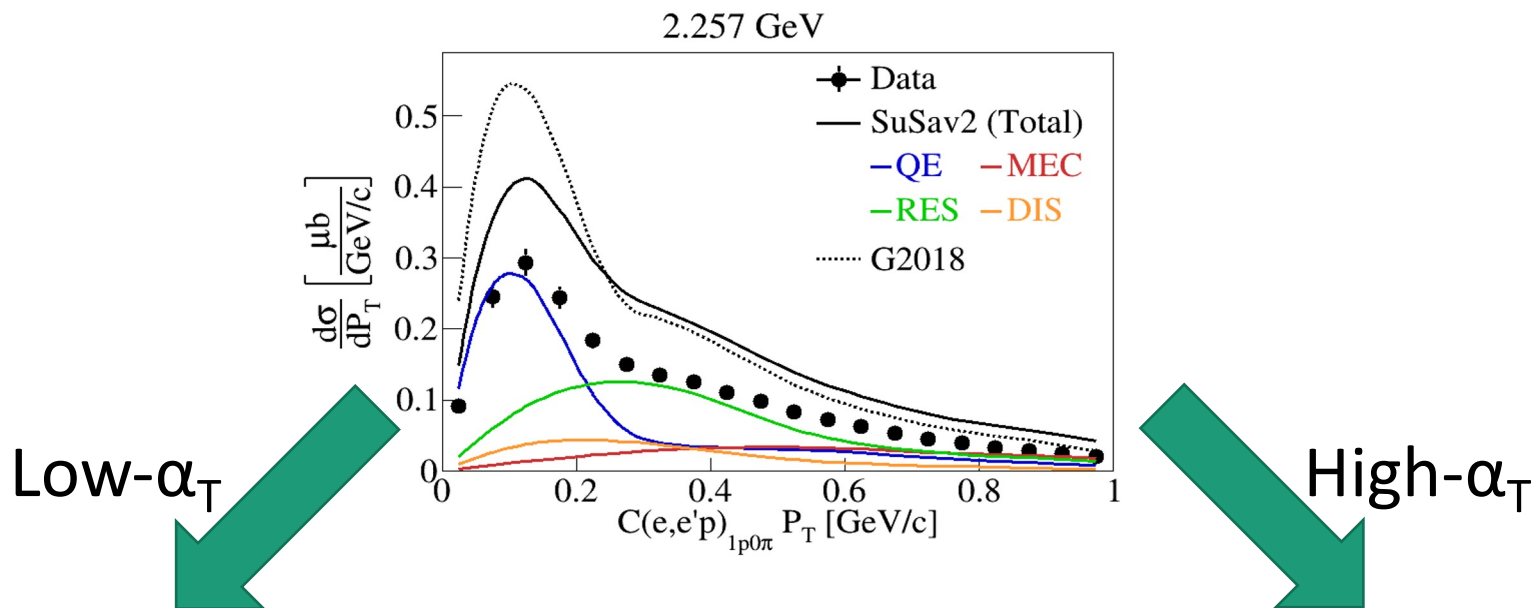
[all nuclei & beams]

+ $\mu 4V$ @ μBooNE

+ New CLAS12 $e4V$ data



Example: 2D Transverse Variables

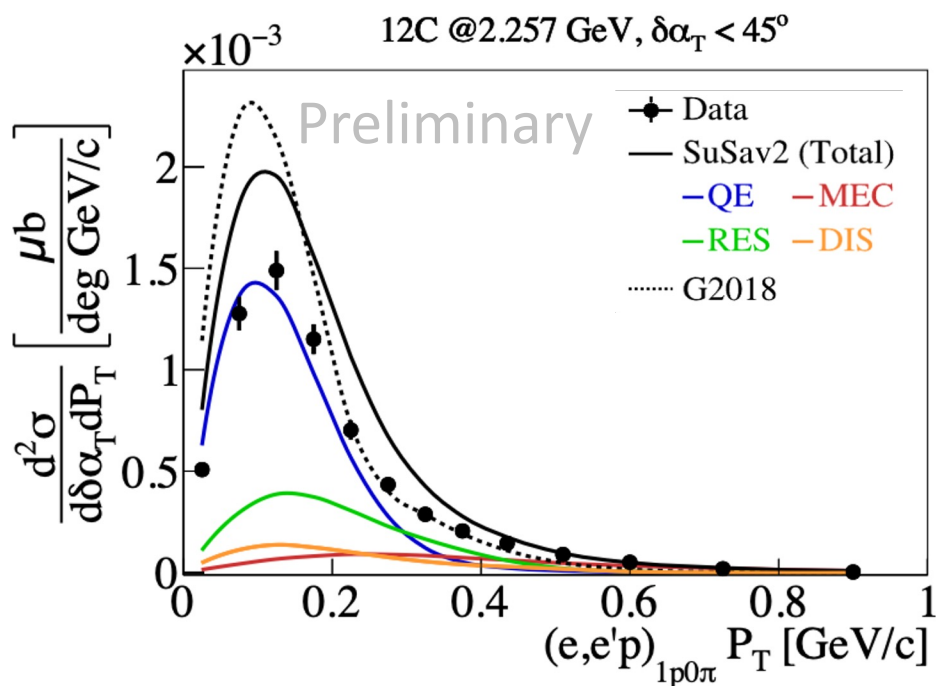


Example: 2D Transverse Variables

Low- α_T

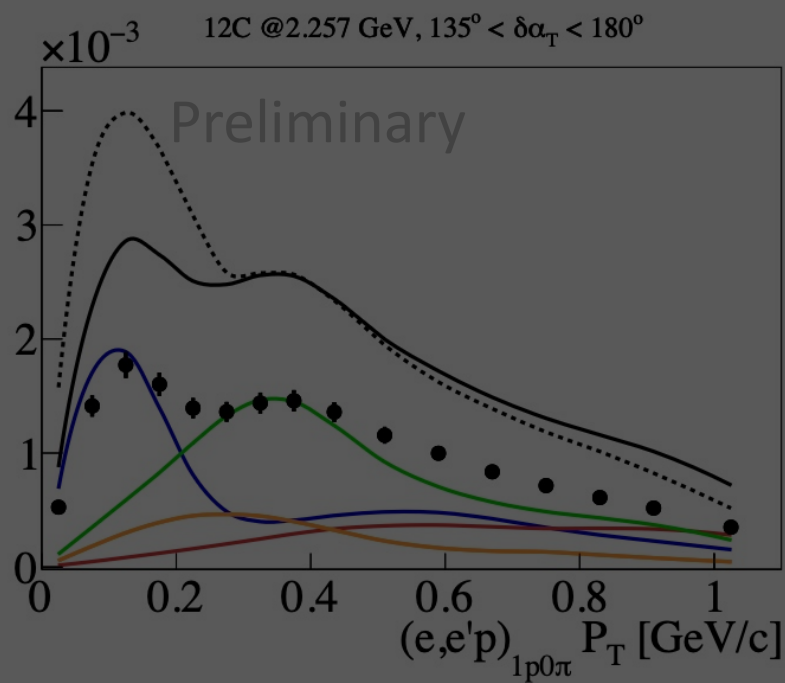
QE Enhanced region

→ Sensitive to ground-state model



High- α_T

Large non-QE contributions

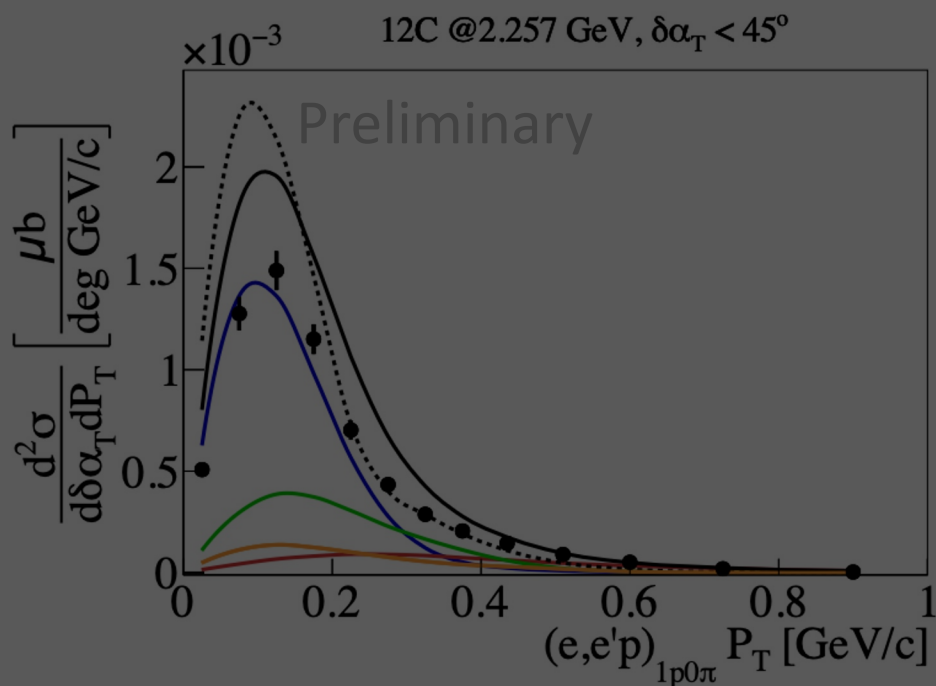


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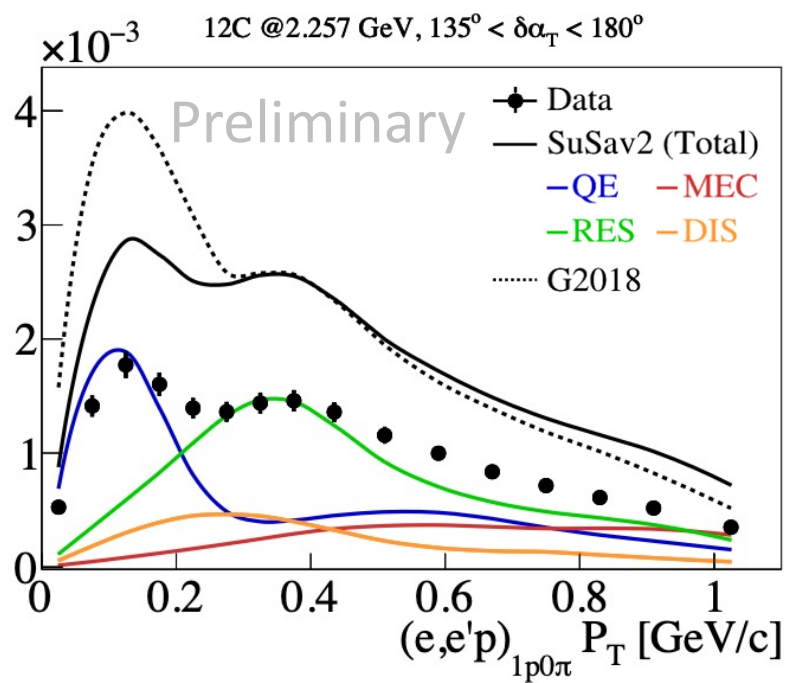
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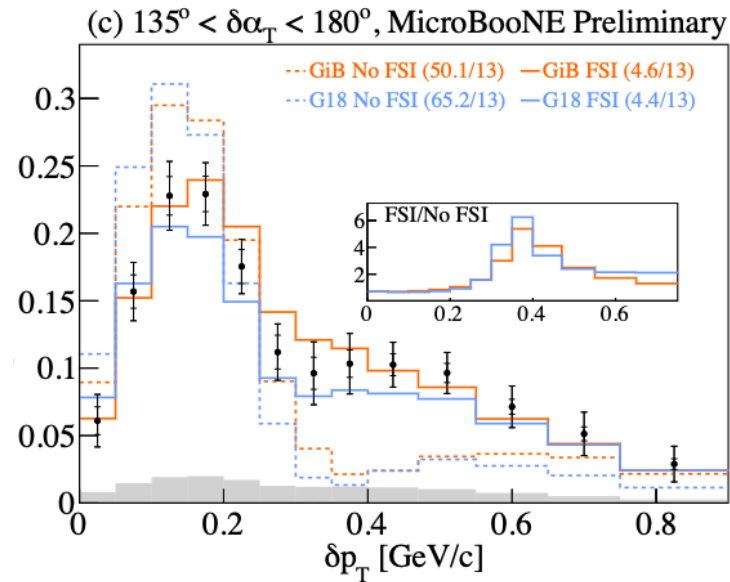
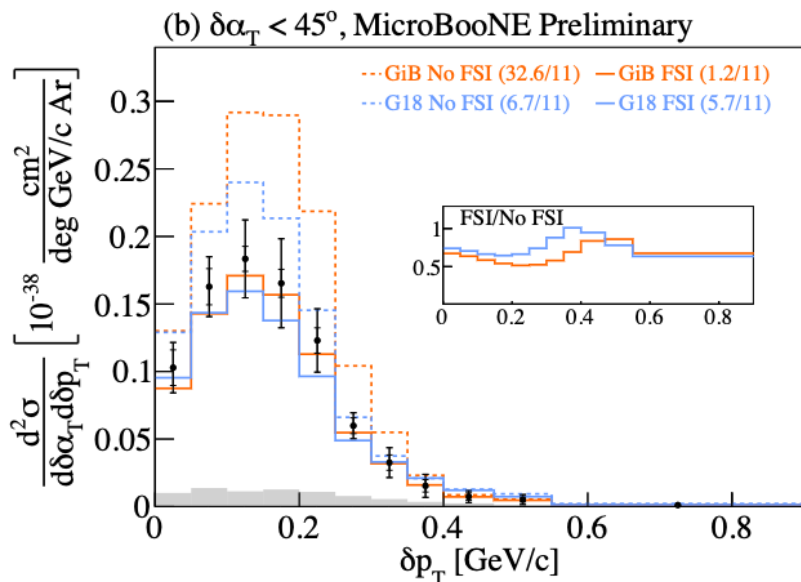
Large non-QE contributions



Complements 'sister' neutrino analysis

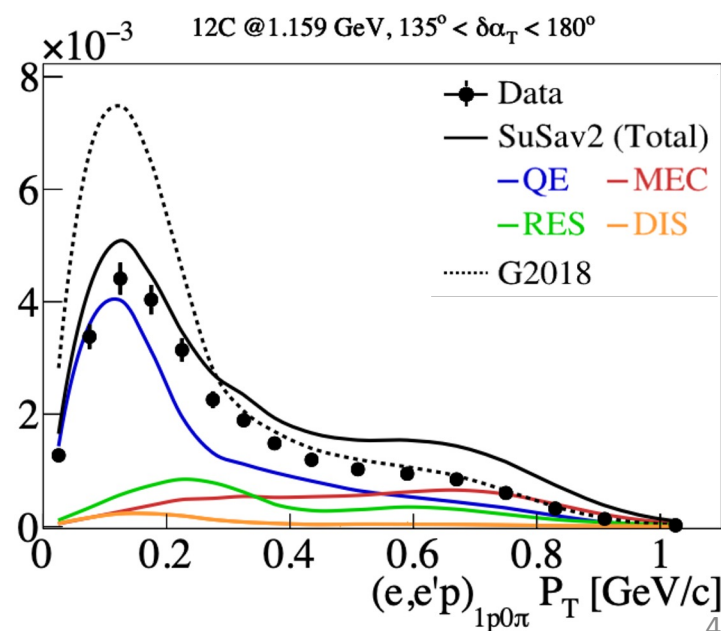
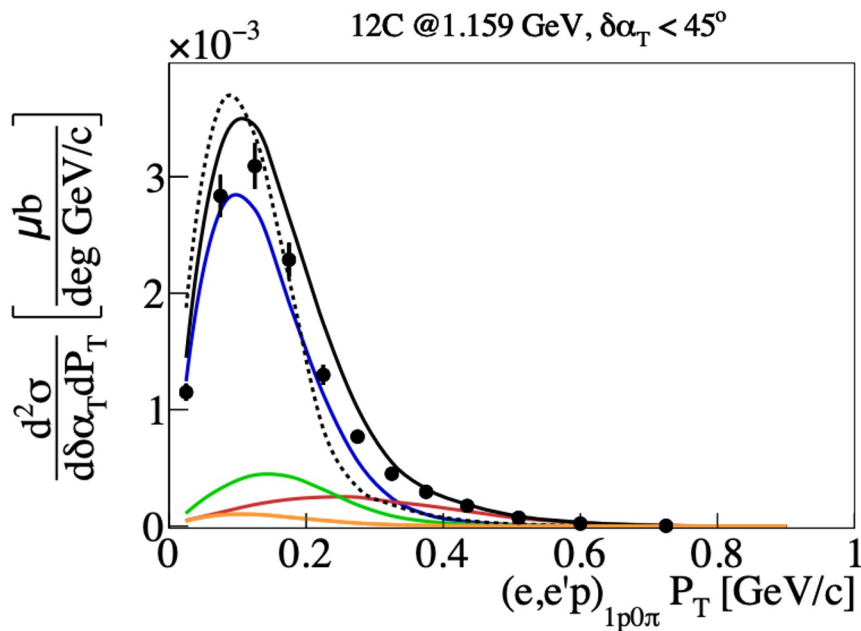
μBooNE

ν_μ



$e4\nu$

e^-



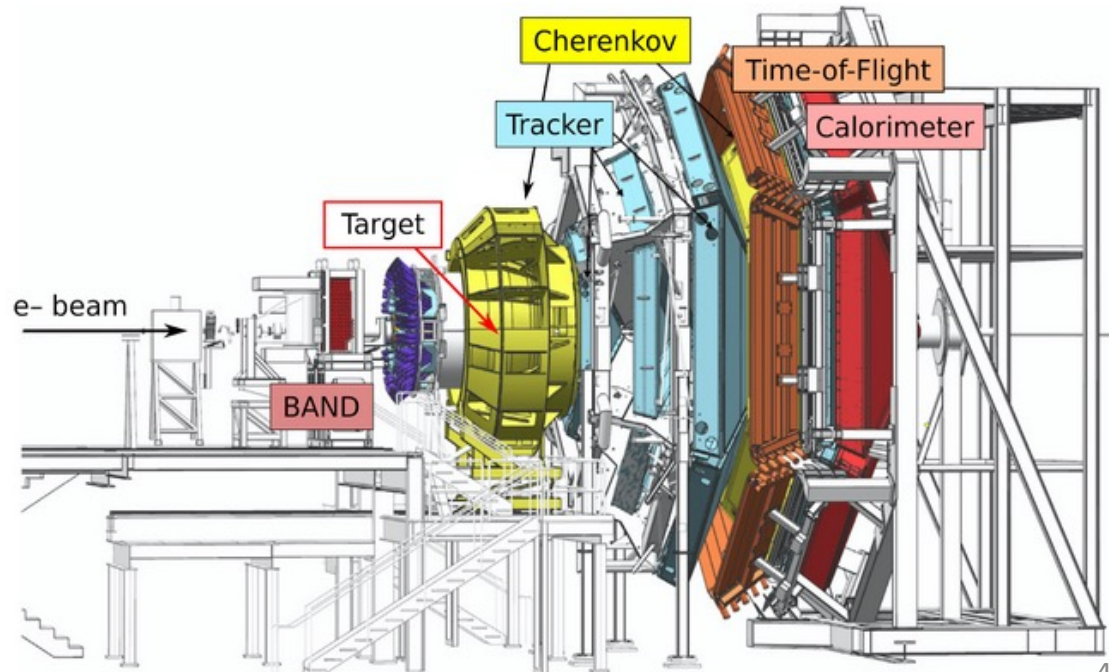
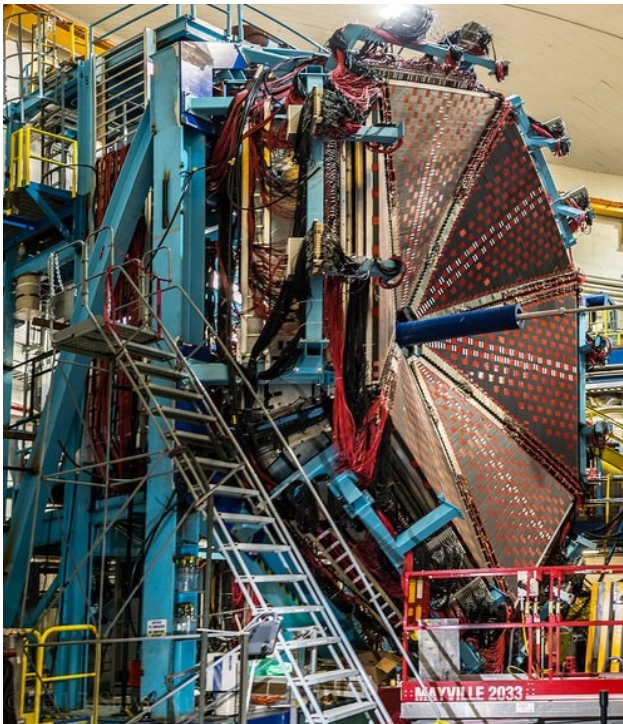
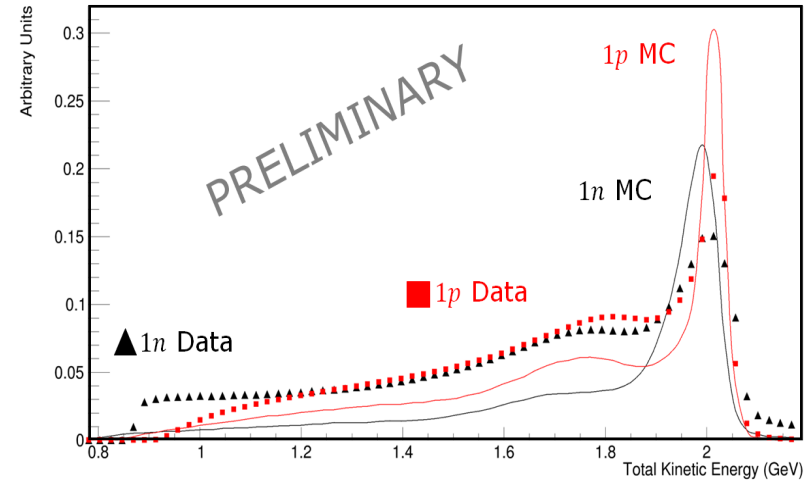
Newly Measured CLAS-12 data

Targets:

^4He , ^{12}C , ^{16}O , ^{40}Ar , ^{120}Sn

Beam Energies:

1, 2, 4, 6 GeV



New Paradigm for Precision Oscillation Studies

Event-Generators



PRD 103, 113003 (2021)

e-scattering



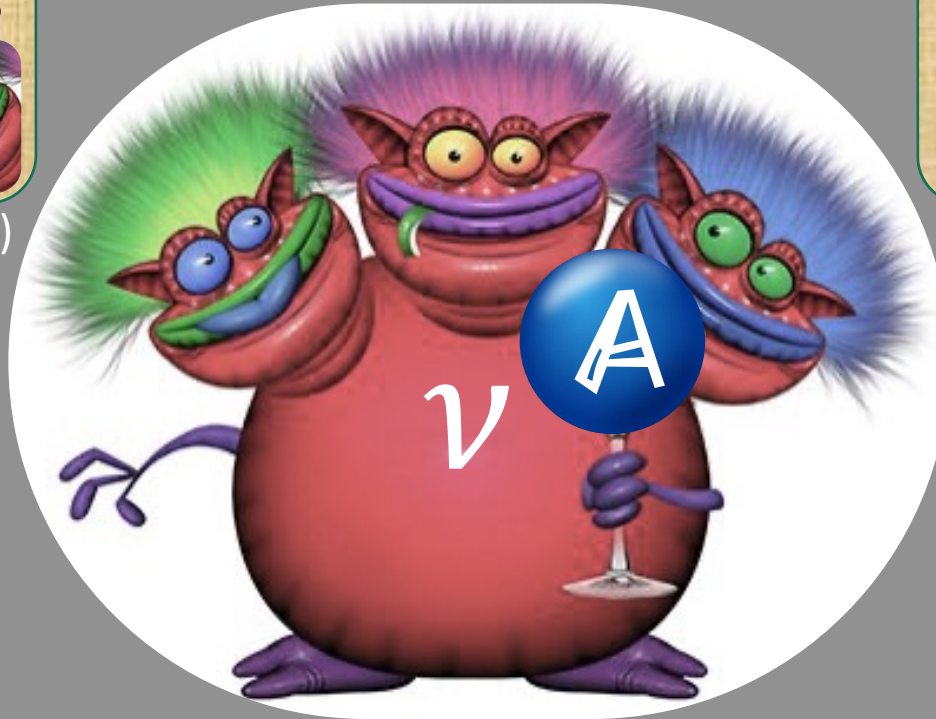
Nature 599, 565 (2021)



ν -scattering



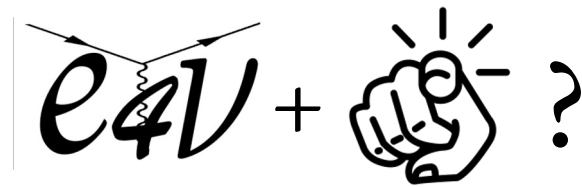
PRL 125, 201803 (2020)



+ Many works for other groups / collaborations!

Summary

- QE-like data available for comparison and constraints
- Double differential & pion data coming (very) soon
- Theorists & model builder encouraged to also use electron data!
- www.e4nu.com



We welcome new
collaborators!

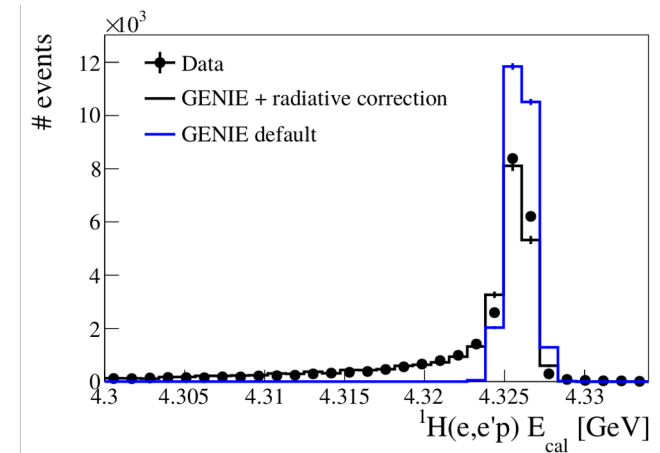


Backup Slides

Cross-Section Extraction

- Subtract backgrounds
- Scale counts by luminosity
- Correct for detector acceptance & radiation

Systematic uncertainties on each correction
plus variation among detector sectors



Hall A@ JLab

$H(e,e'p)$ @ 4.32 GeV

Well defined signal definition: Min θ_e Cut

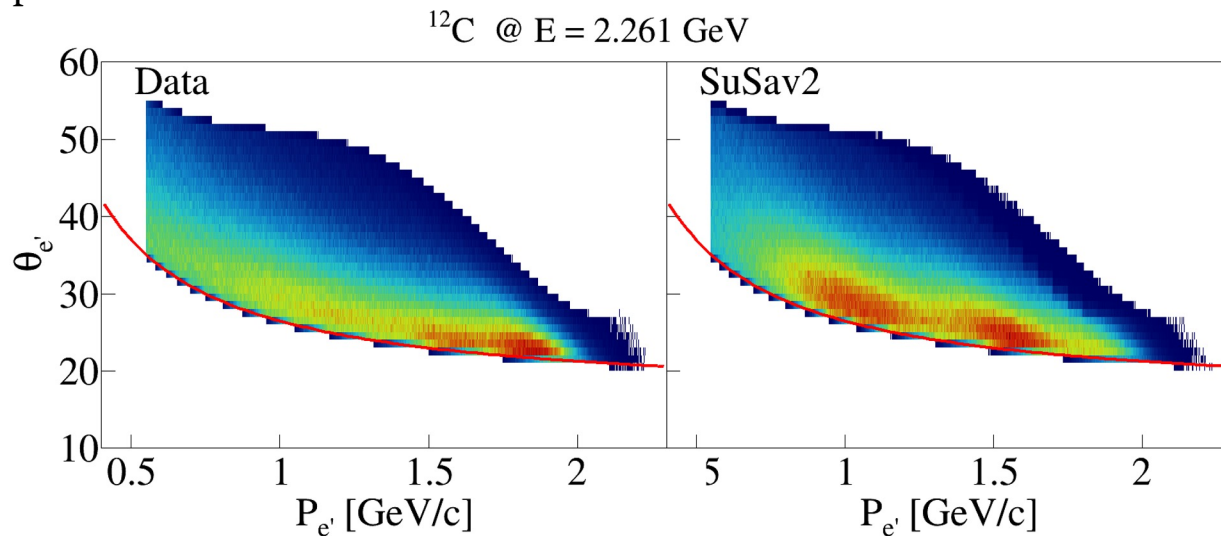
@ 1.1 GeV: $\theta = 17 + 7 / P$

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

- We do not acceptance correct below min θ

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

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



Well defined signal definition: Min θ_e Cut

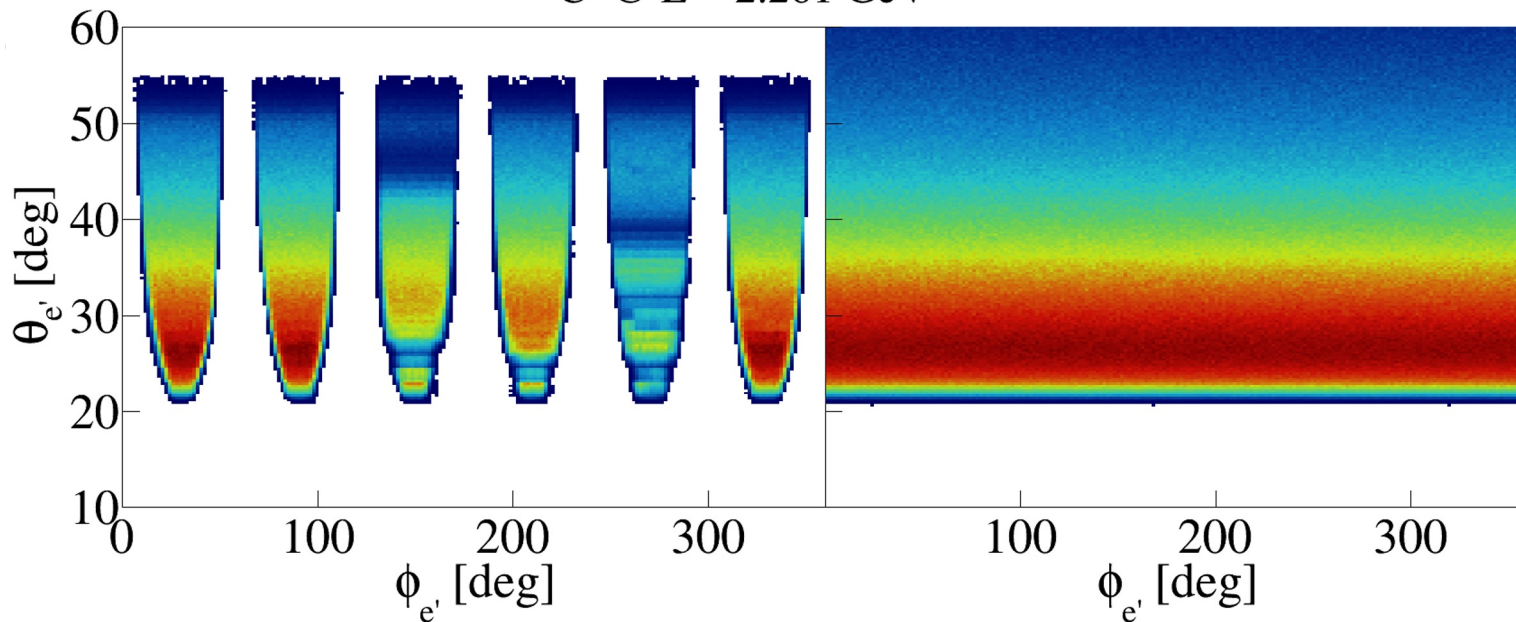
@ 1.1 GeV: $\theta = 17 + 7 / P$

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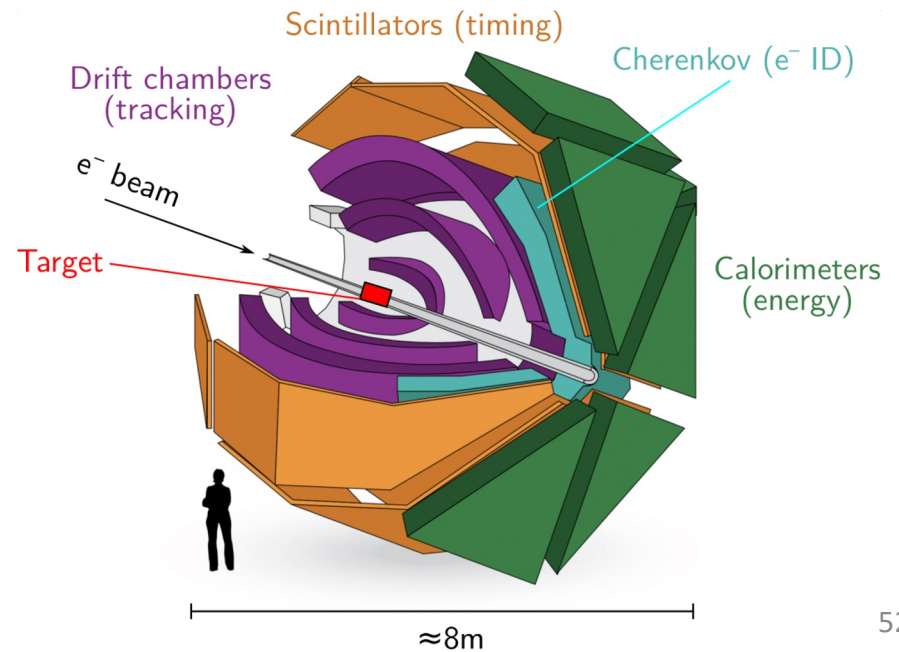
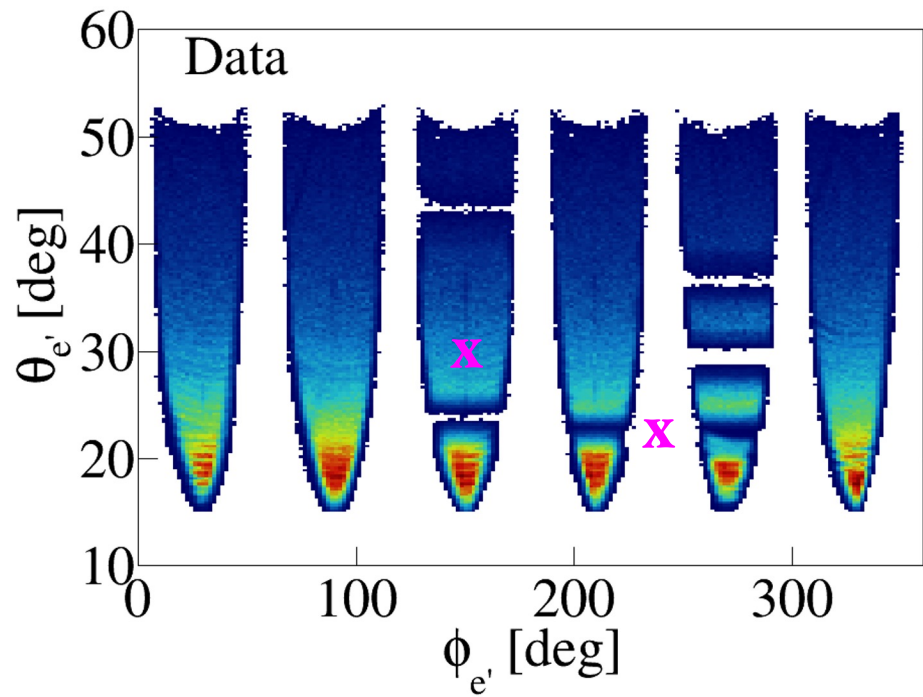
@ 4.4 GeV: $\theta = 13.5 + 15 / P$

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



Background Subtraction

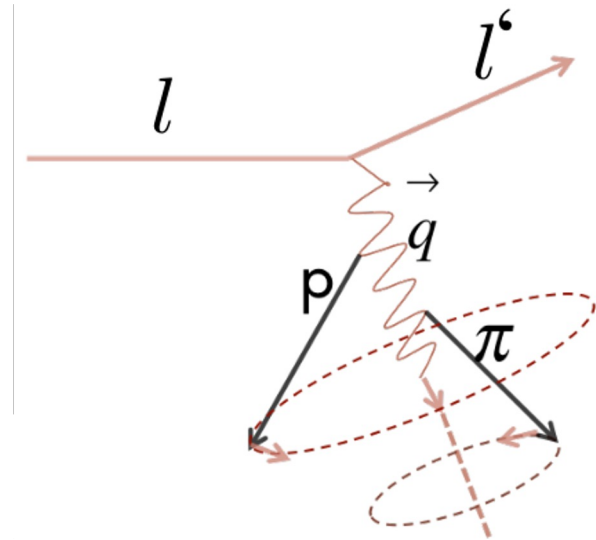
Non-(e,e'p) interactions lead to multi-hadron final states
Gaps can make them look like (e,e'p) events



Data Driven Correction

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

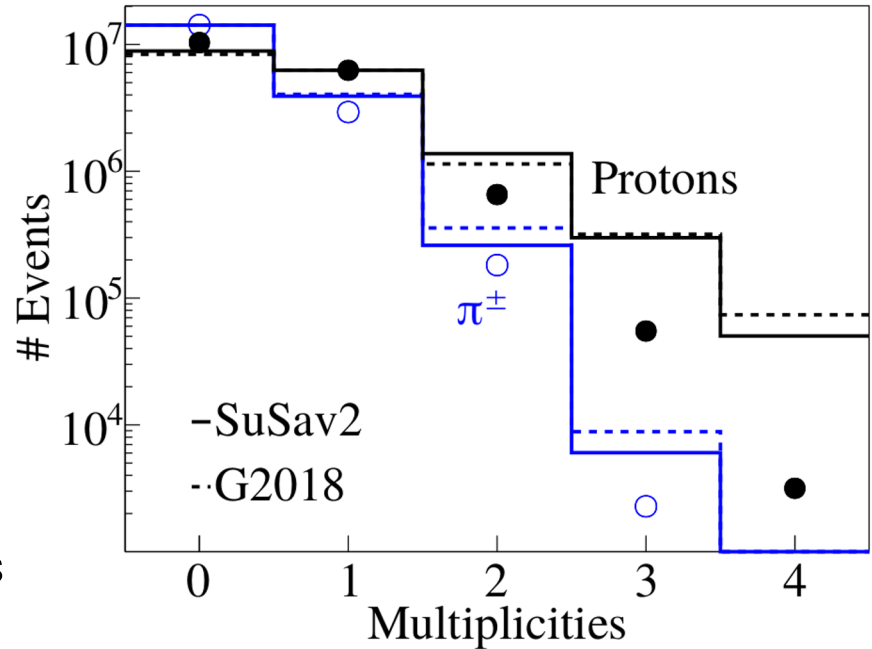
- Use measured (e,e'p π) events
- Rotate p, π around q to determine π detection efficiency
- Subtract undetected (e,e'p π)
- Repeat for higher hadron multiplicities



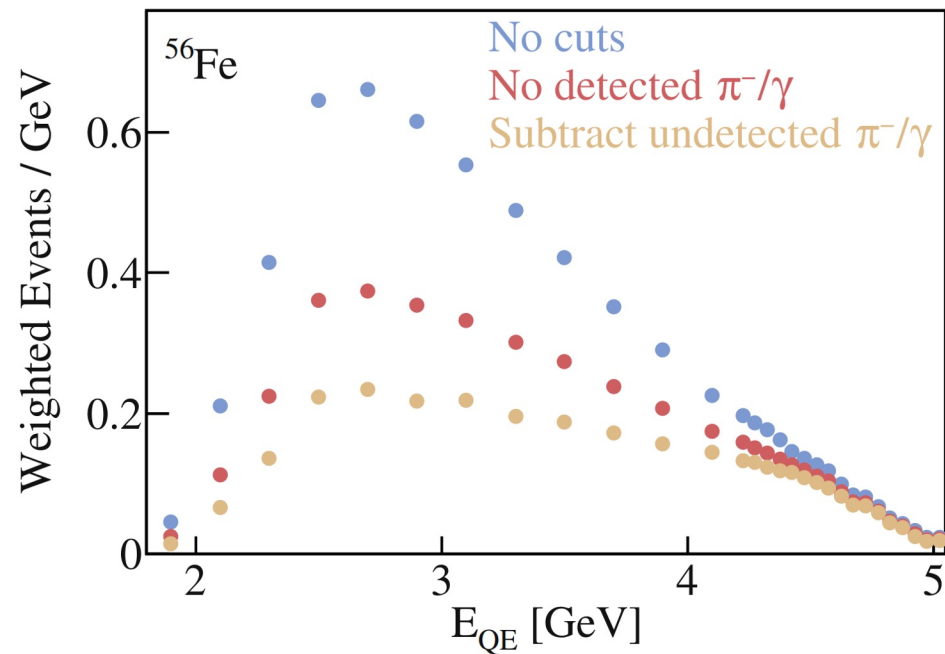
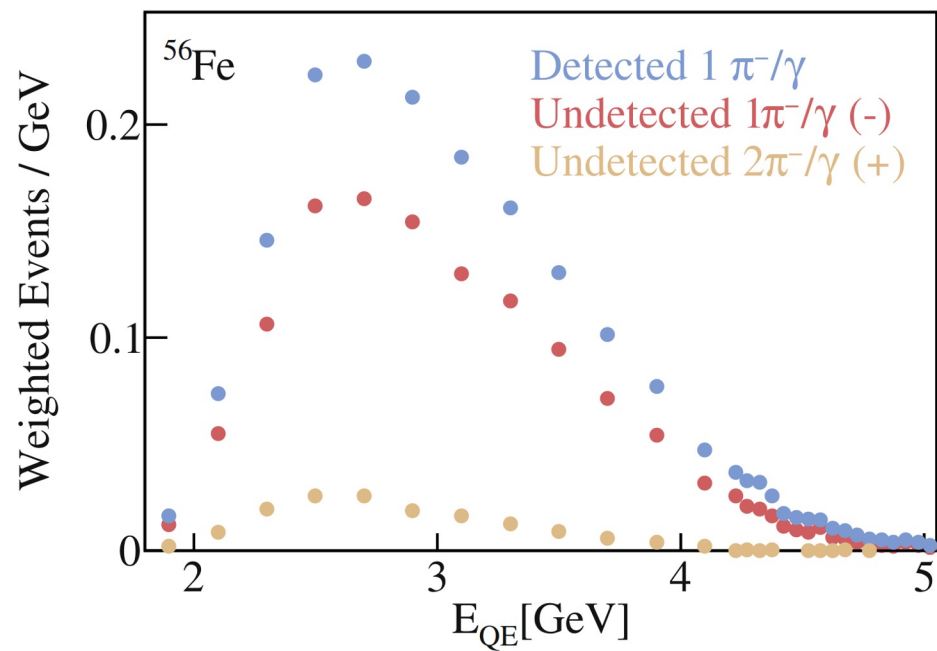
Data Driven Correction

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

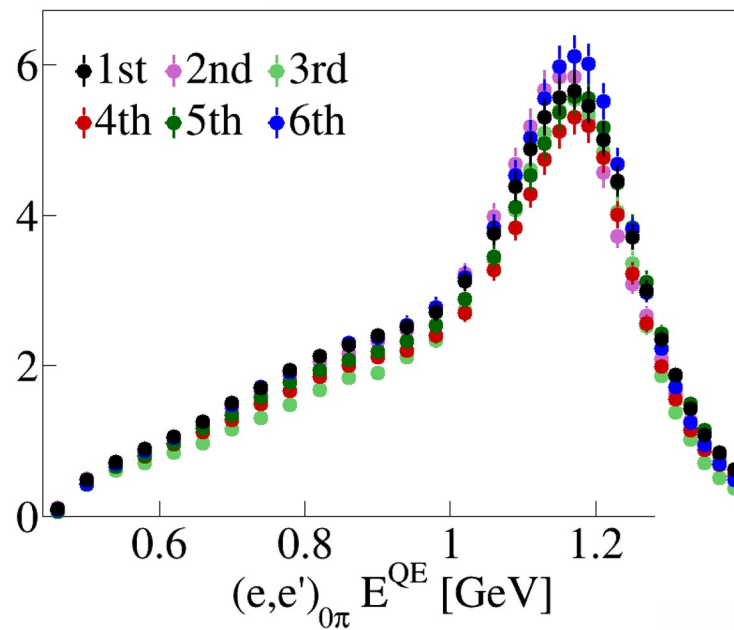


Subtraction Effect

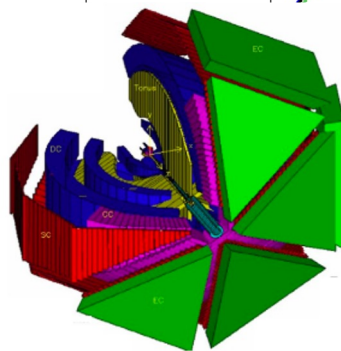
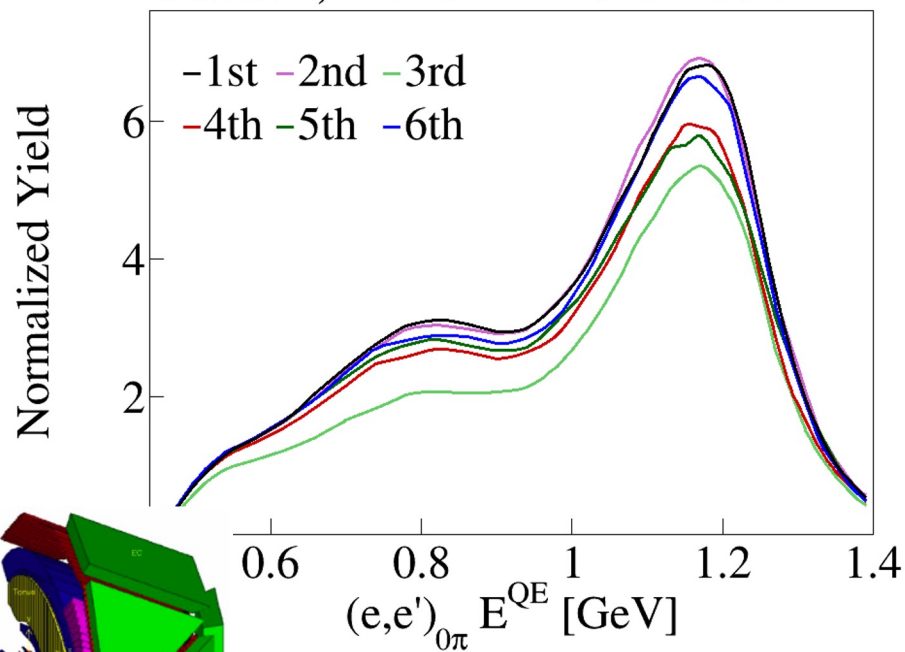


Systematics: Sector Dependence

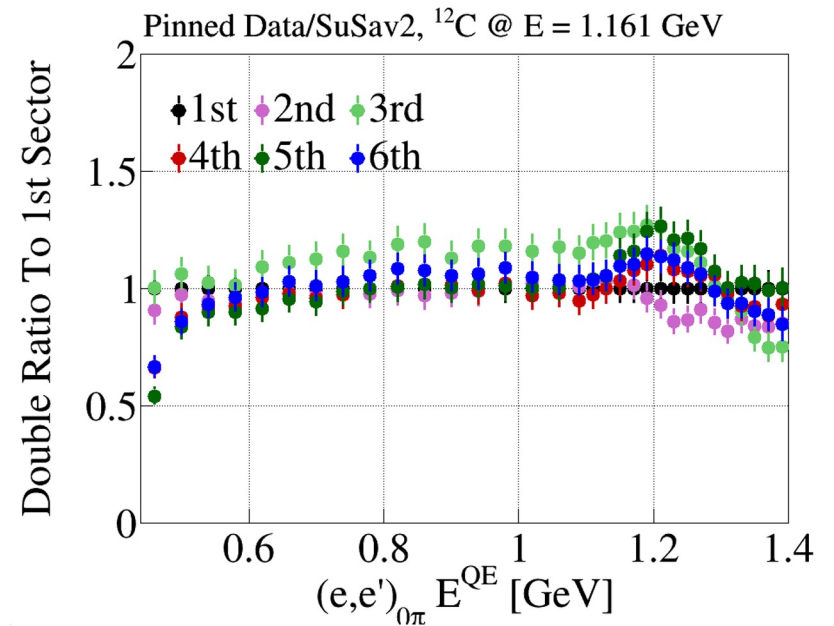
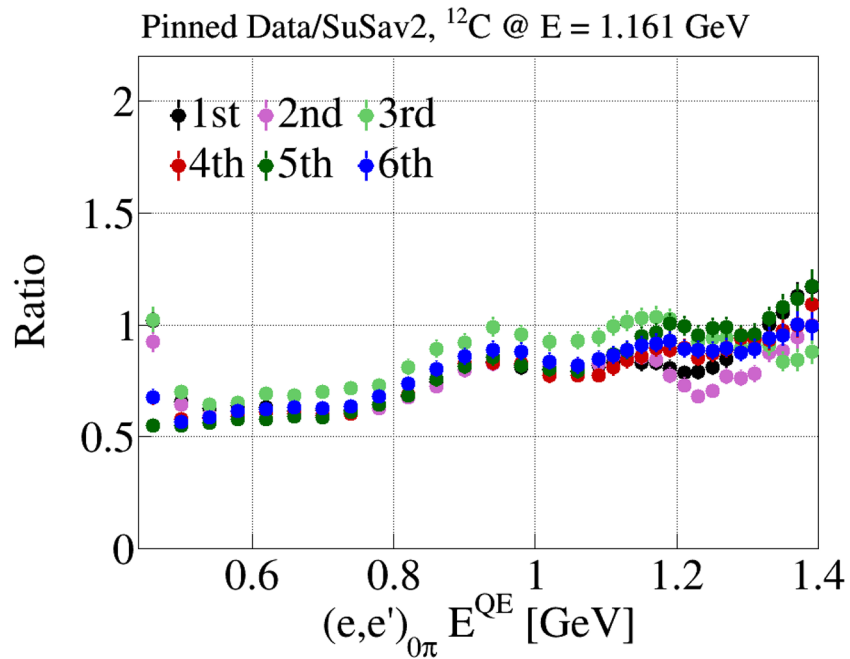
Pinned Data, ^{12}C @ $E = 1.161$ GeV



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

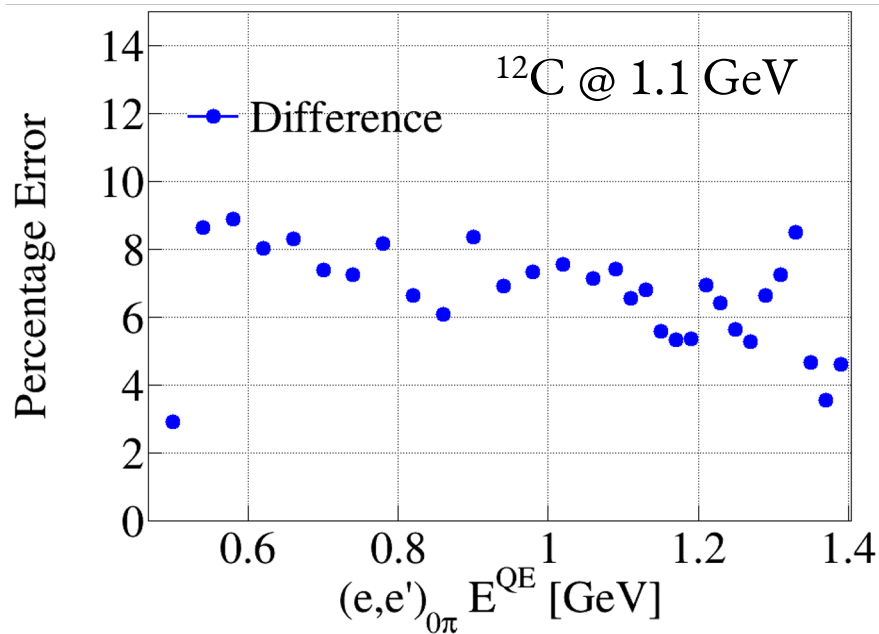


Systematics: Sector Dependence



Systematics: Sector Dependence

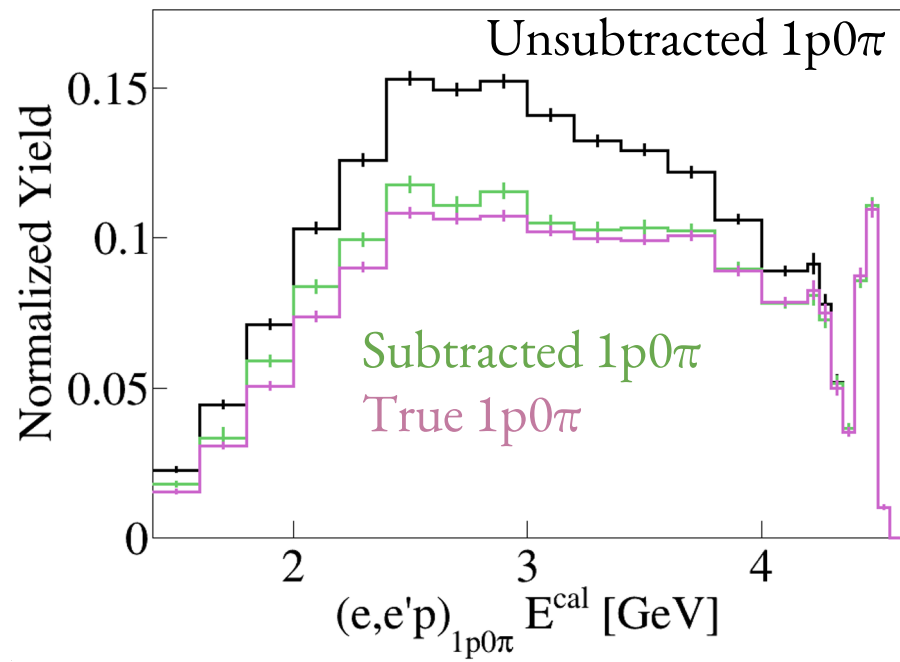
Quantifying uncertainty by using
unweighted variance & by subtracting variance from statistical uncertainty



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

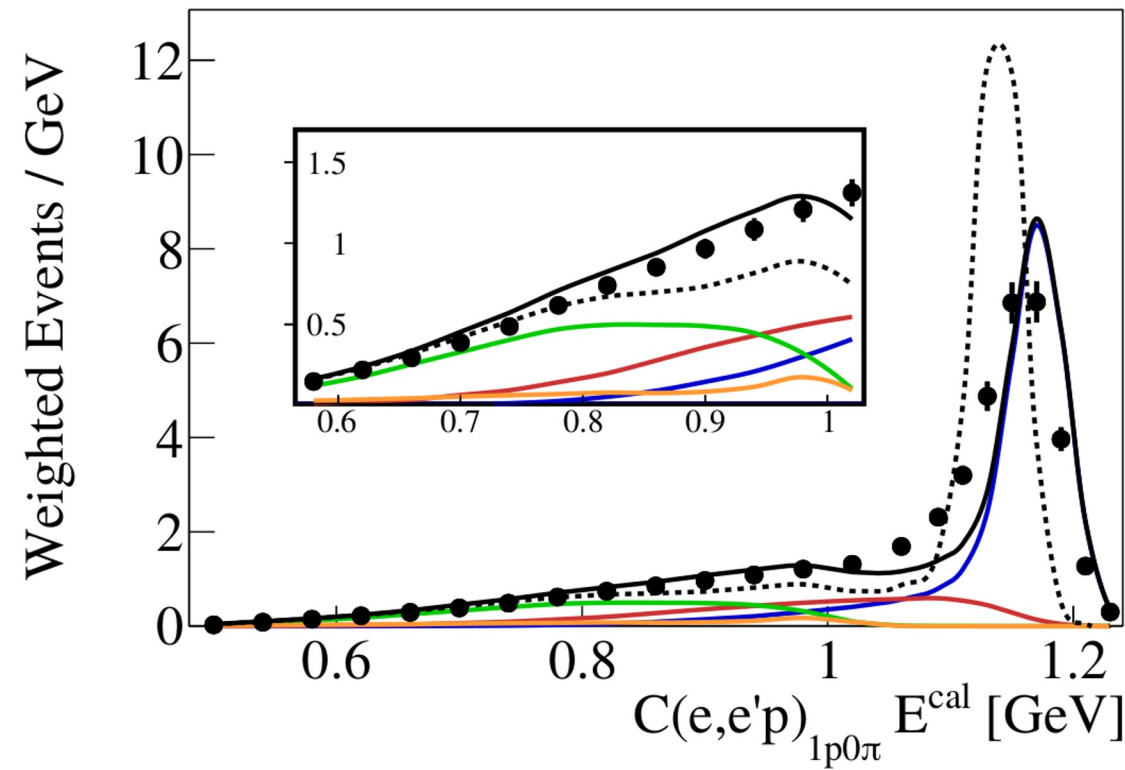
Closure Test

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



1st e4 ν Submission

Calorimetric energy reconstruction using the 1p0 π 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

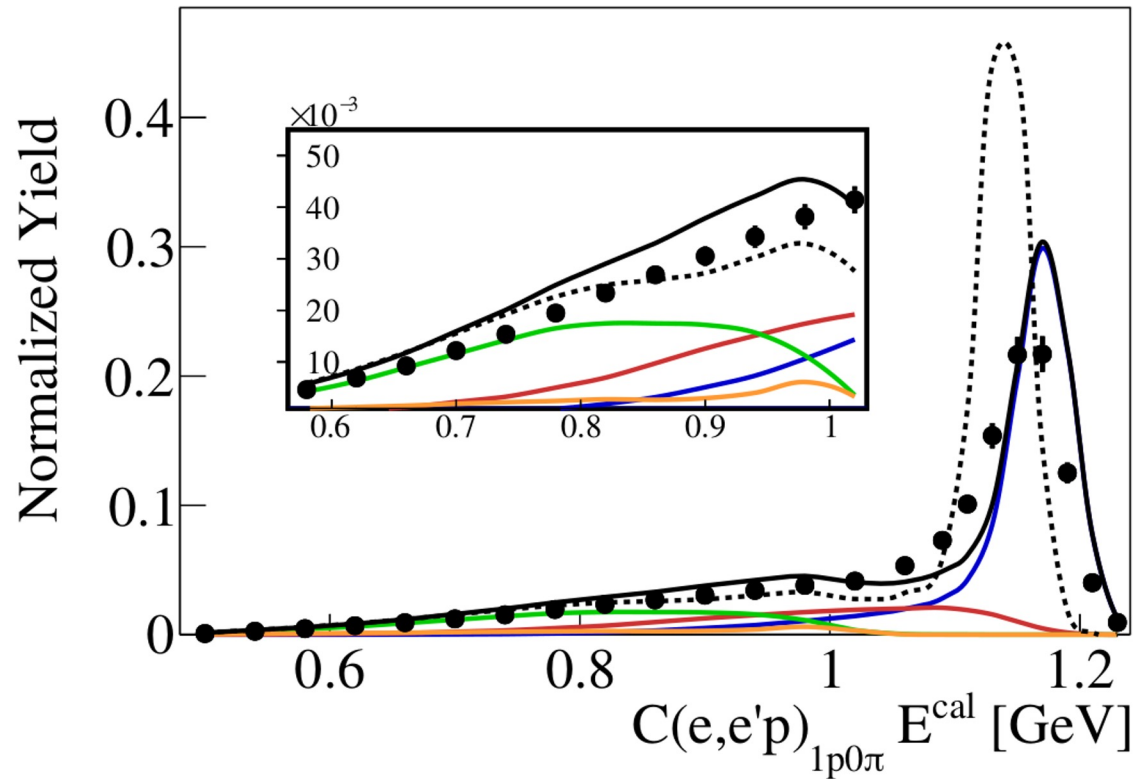
- Divide # events by integrated charge & target thickness to get xsec in μb
- Divide by bin width to get $\mu\text{b}/\text{GeV}$

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



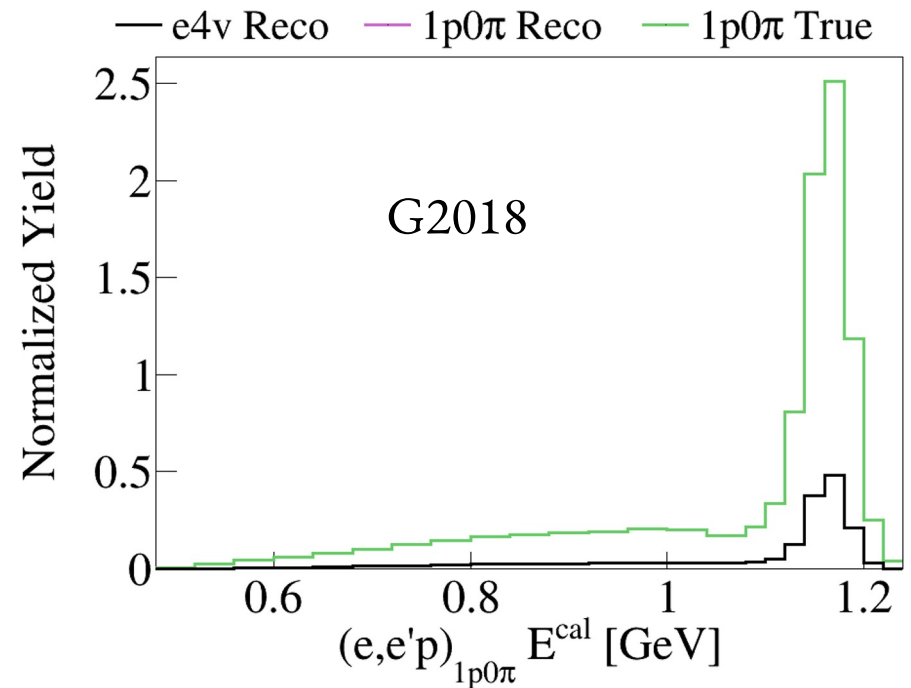
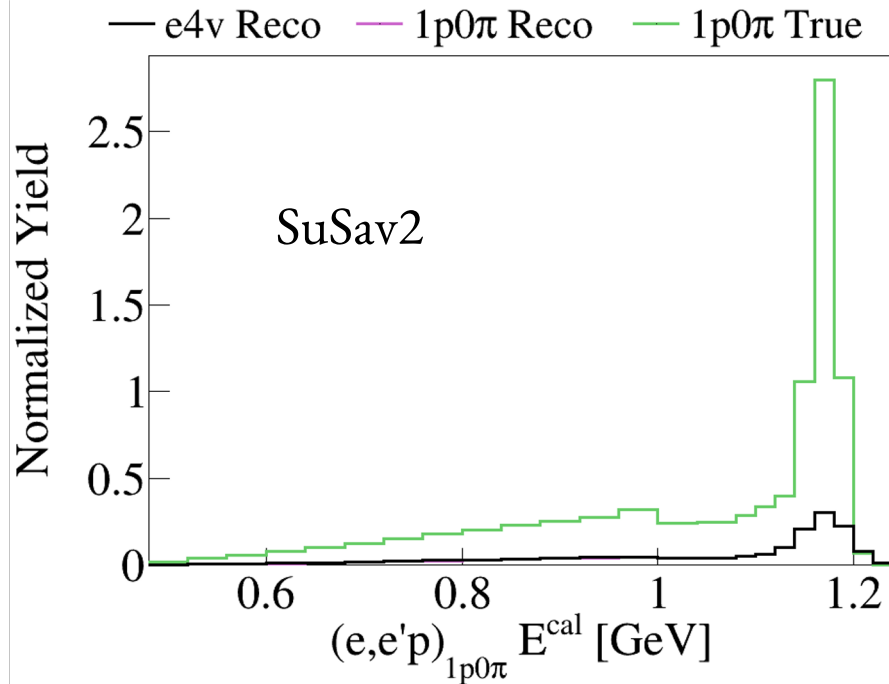
- Absolute scale comparison
- Small effect @ 1GeV

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

Step #3a: Acceptance Correction

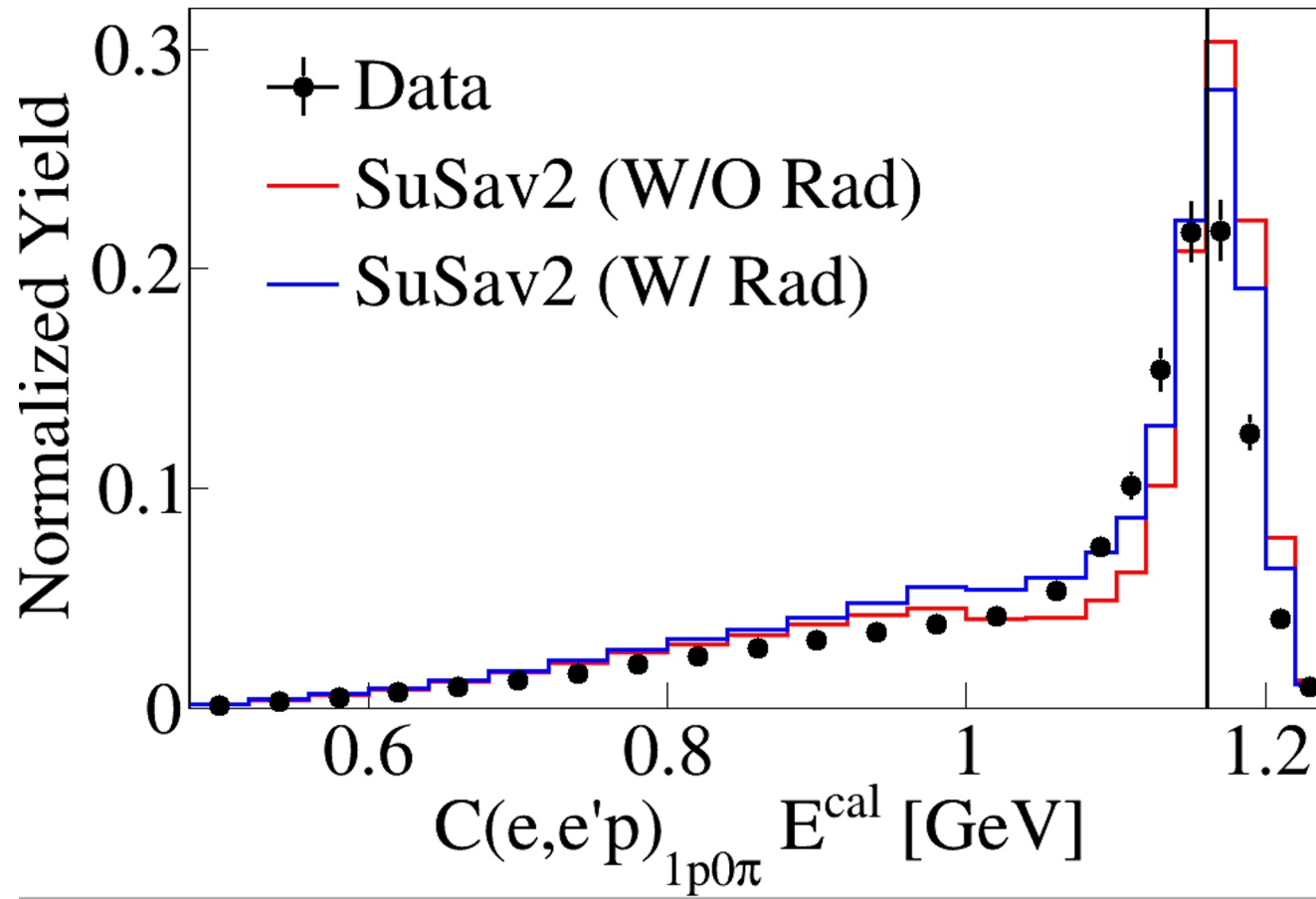
- Start from reco / true ratio w/o radiation to obtain acceptance correction
- Average on a bin-by-bin basis $x = |\text{SuSav2} + \text{G2018}| / 2$
- Due to offset, G2018 Ecal predictions have been shifted by
10/25/36 MeV for $^4\text{He}/^{12}\text{C}/^{56}\text{Fe}$ respectively

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

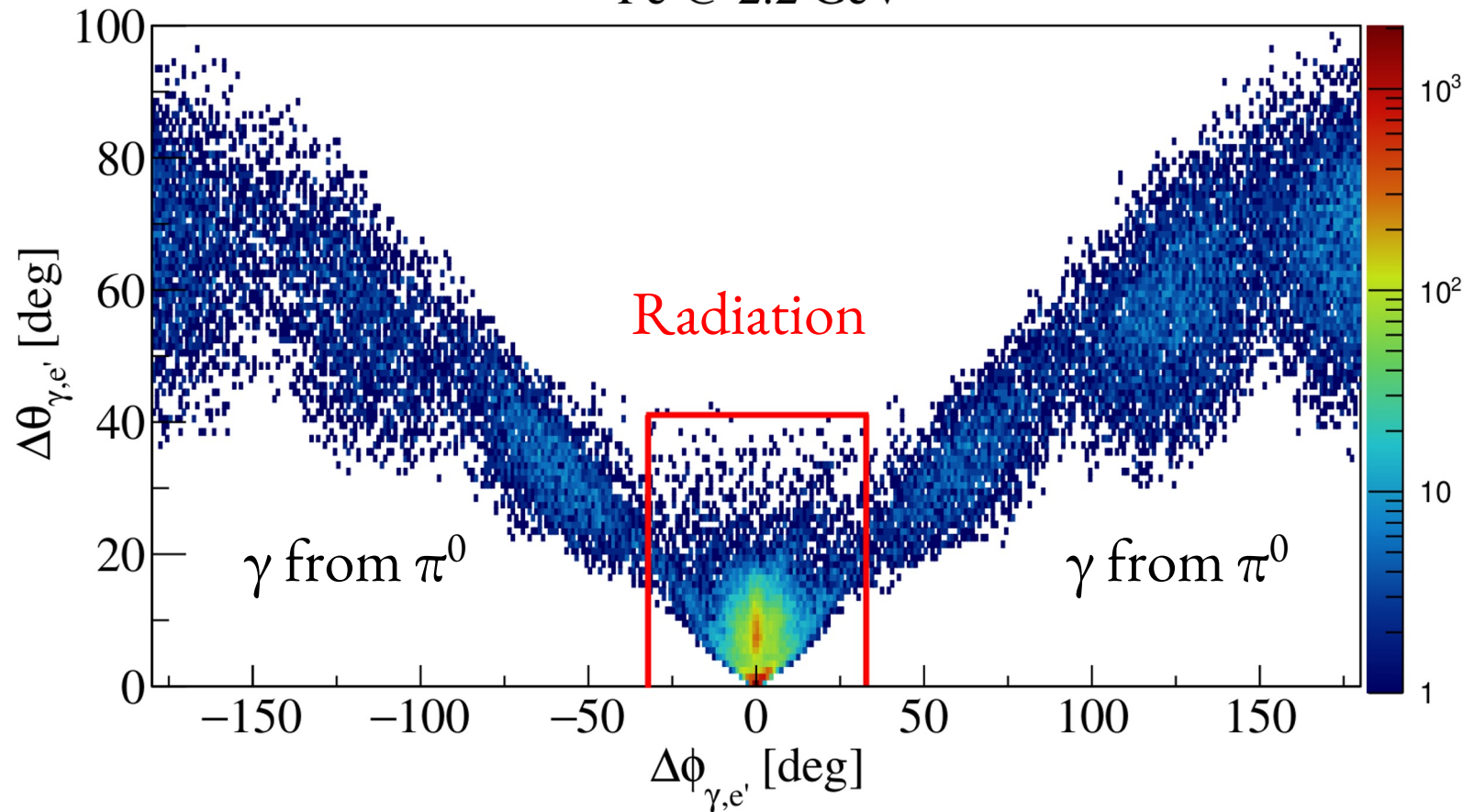
$$x = |\text{SuSav2} - \text{G2018}| / \text{Sqrt}(12)$$

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

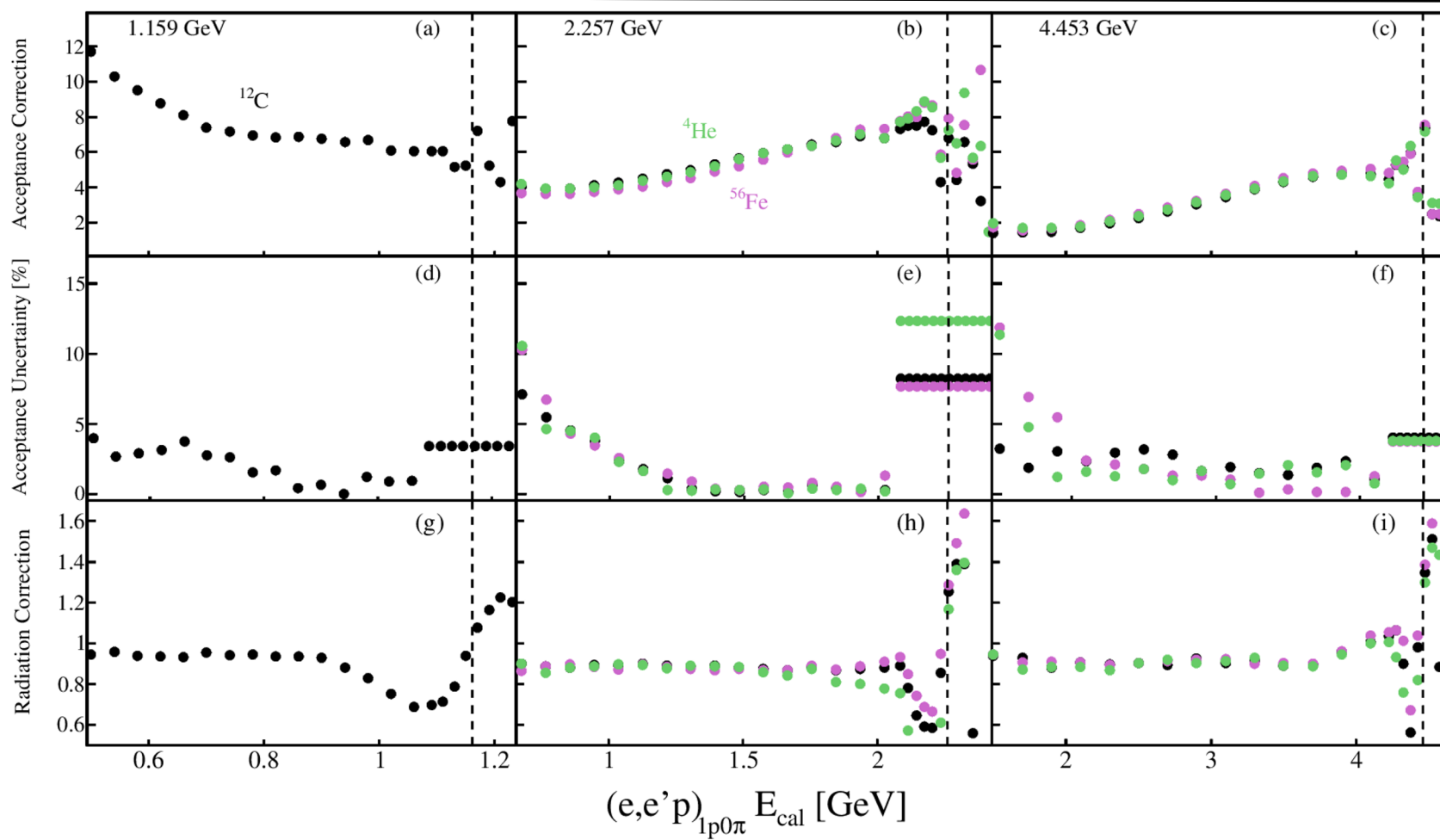
Same recipe as for acceptance correction but,
to avoid infinities, will use average (1 bin) around the peak and
 $\text{average}(\text{reco}) / \text{average}(\text{true})$ for correction factor

Excluding Radiation

^{56}Fe @ 2.2 GeV

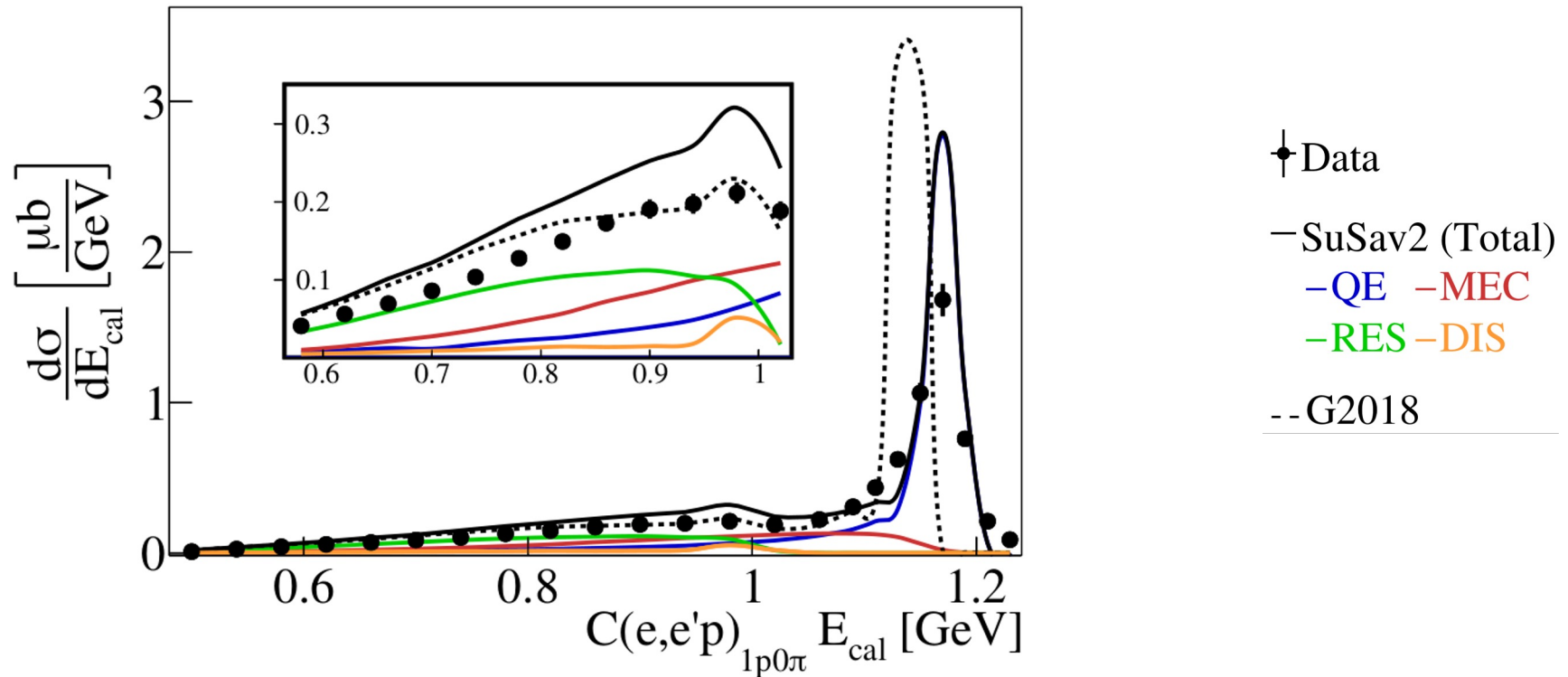


Correction Factors

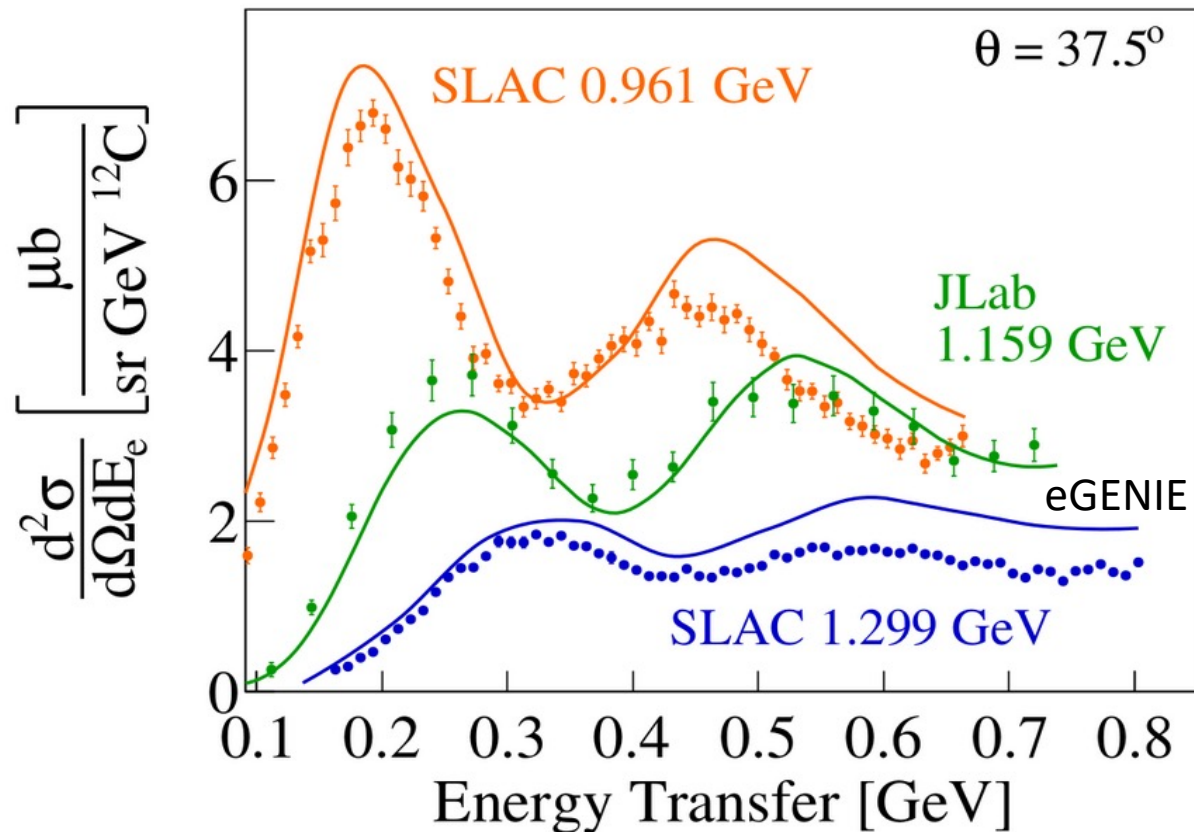


Step #4: Absolute Cross Sections

After both acceptance & radiation corrections, without systematics yet



Sanity Check: (e,e') cross-sections



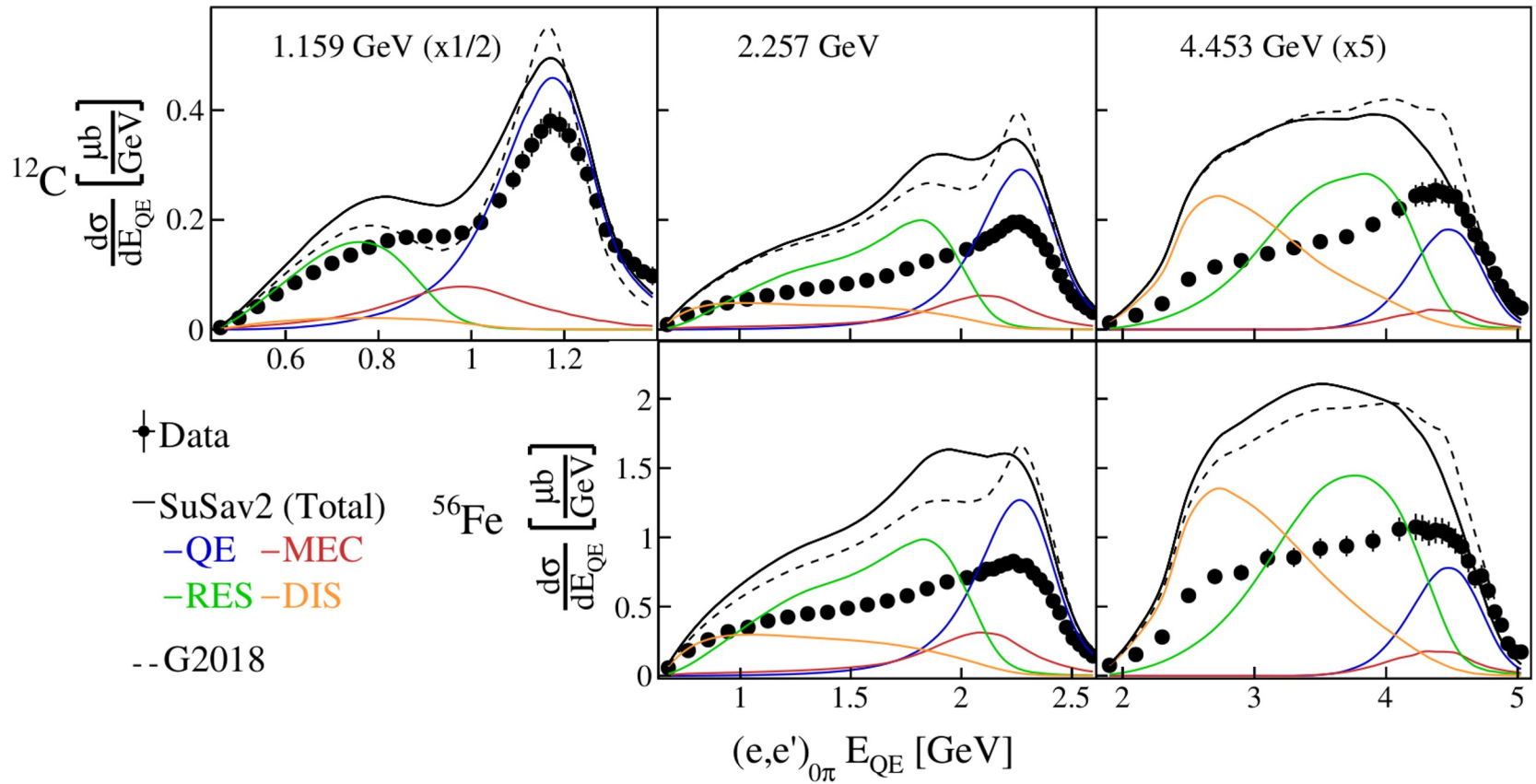
Systematics

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

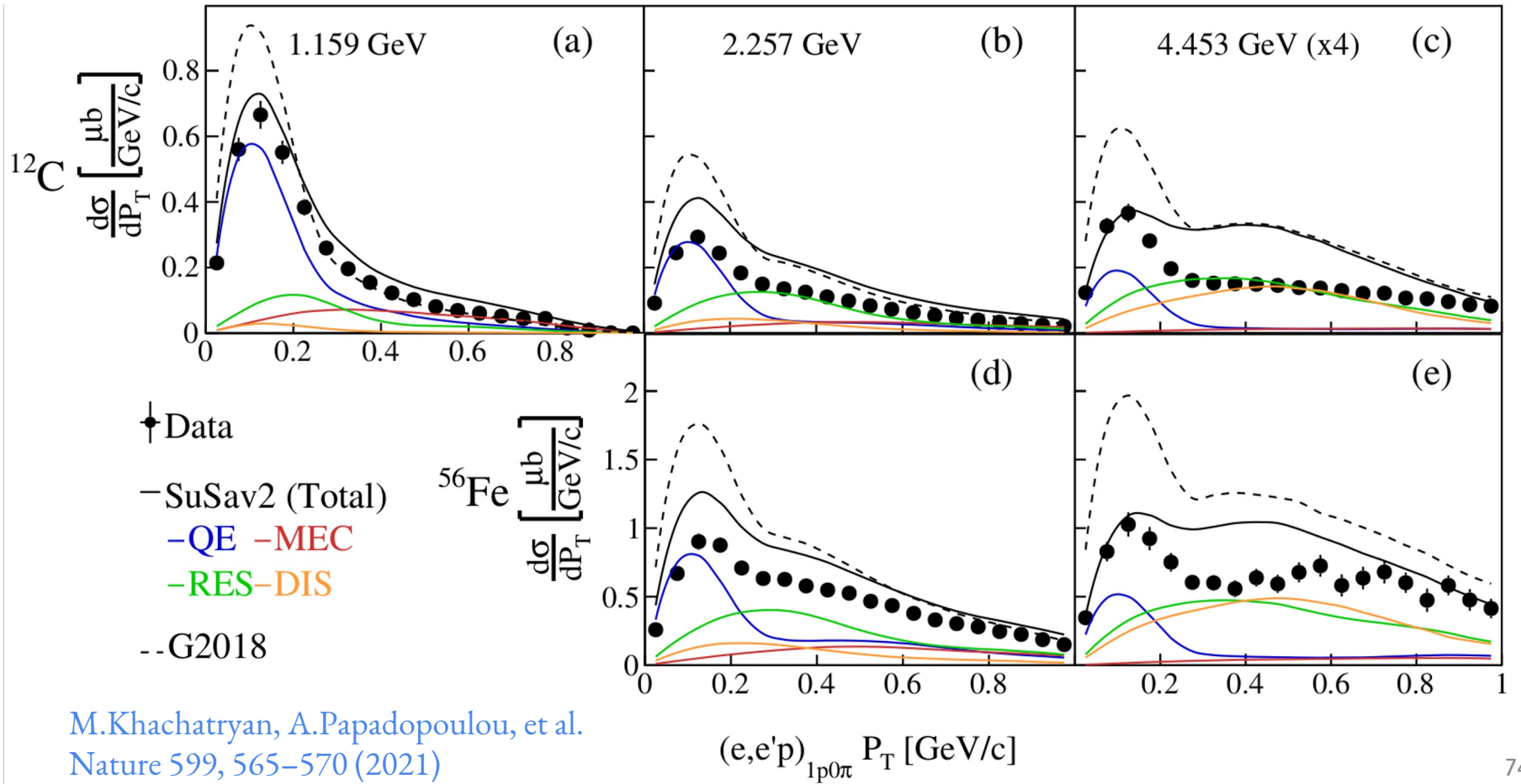
E_{QE} Nucleus & Energy Dependence



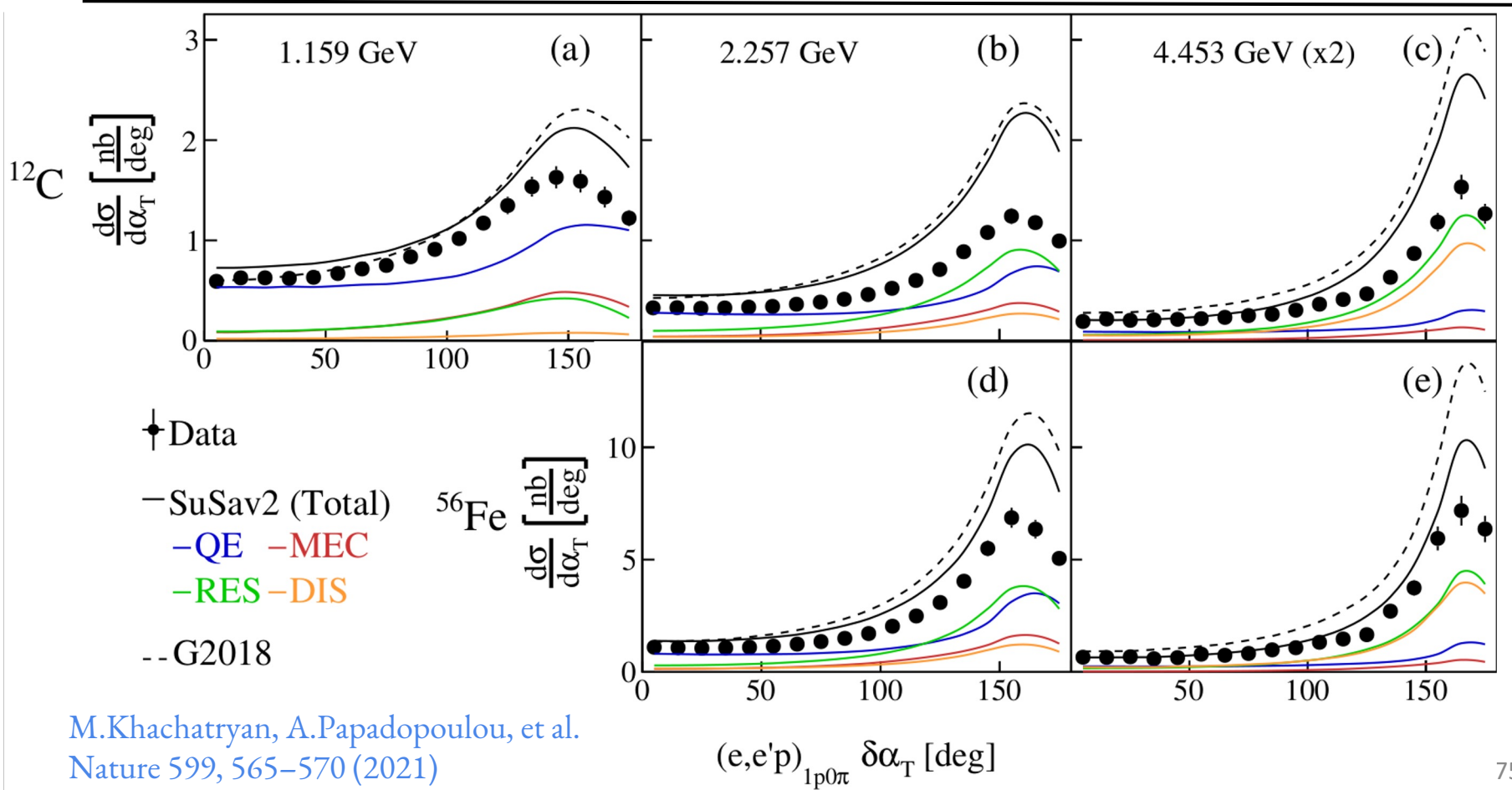
$$E_{QE} = \frac{2M\epsilon + 2ME_l - m_l^2}{2(M - E_l + |k_l|\cos\theta_l)}$$

A.Papadopoulou, et al,
In preparation

P_T Nucleus & Energy Dependence

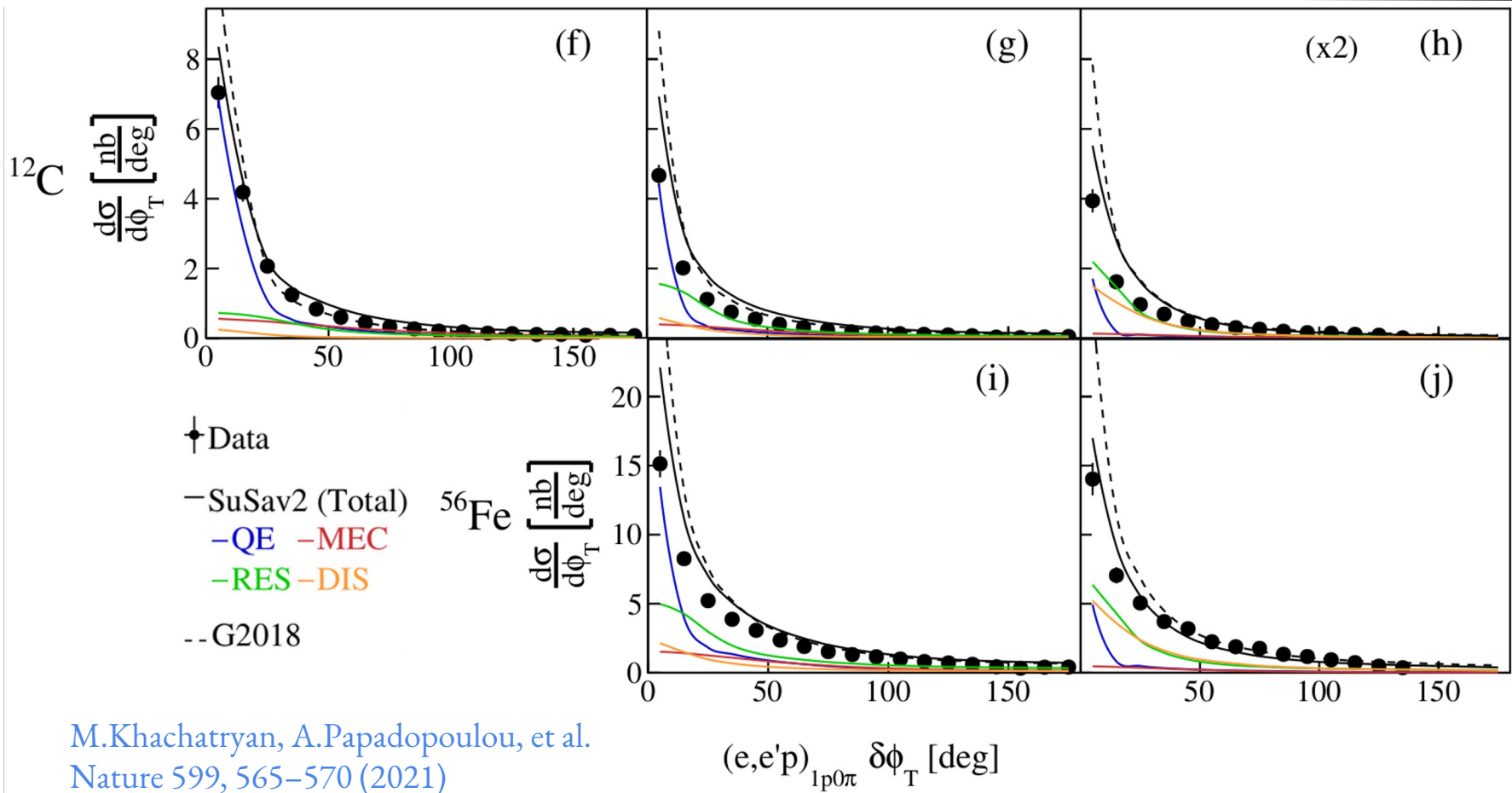


$\delta\alpha_T$ Nucleus & Energy Dependence

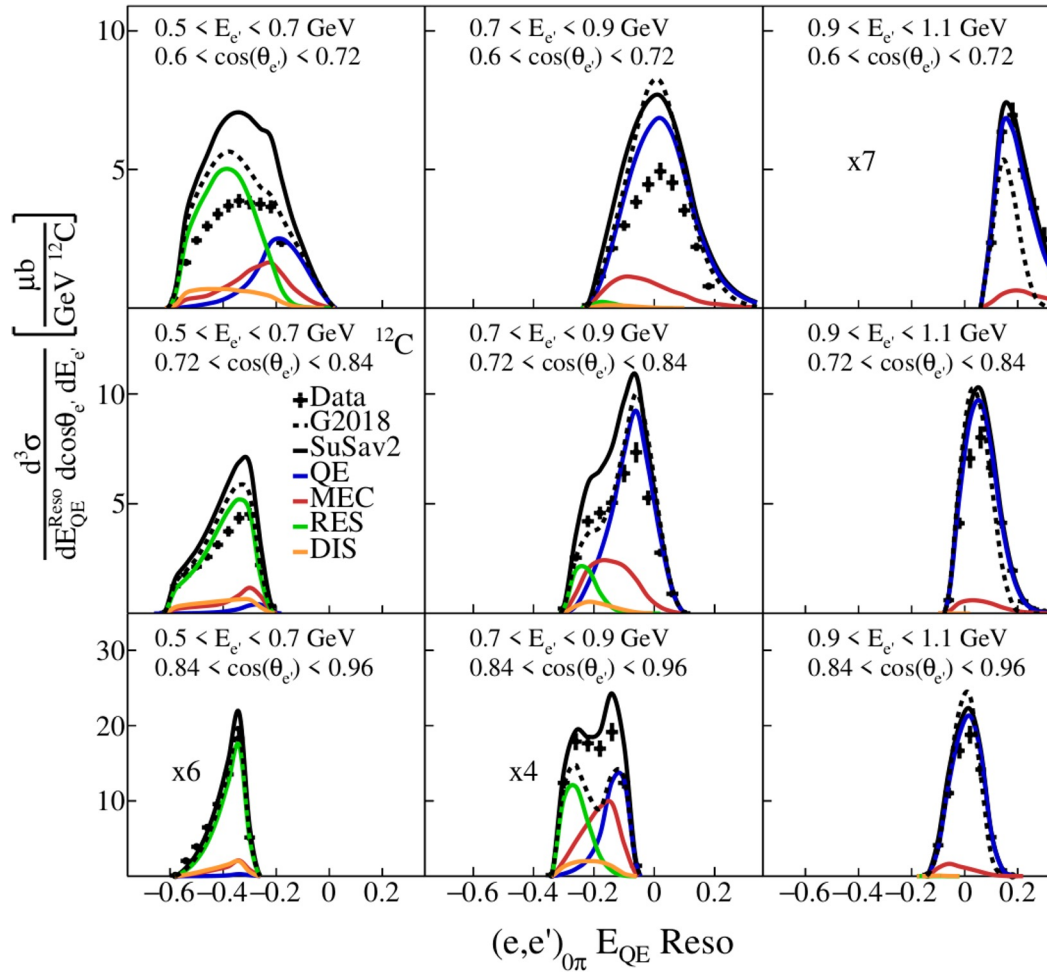


M.Khachatryan, A.Papadopoulou, et al.
Nature 599, 565–570 (2021)

$\delta\phi_T$ Nucleus & Energy Dependence



Into The 3D e4ν Multiverse!

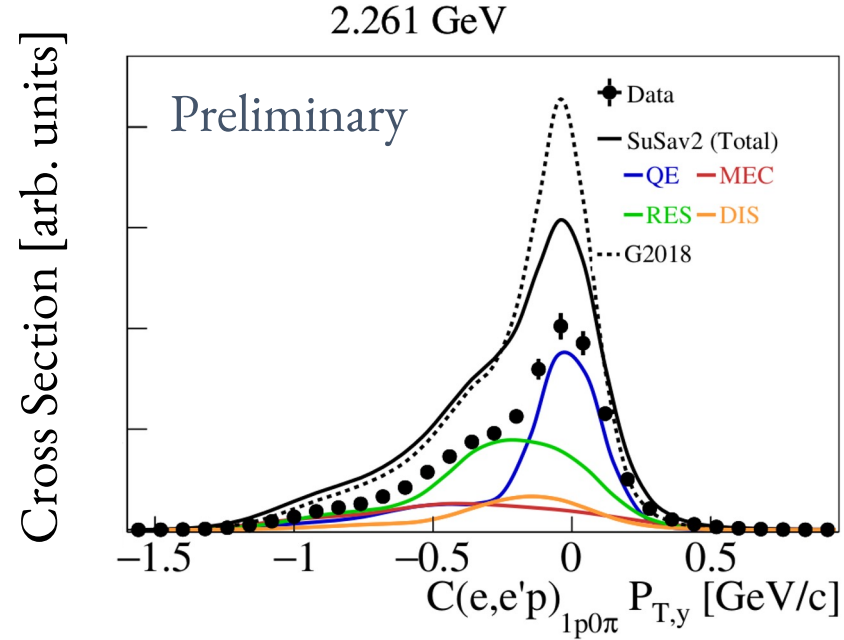
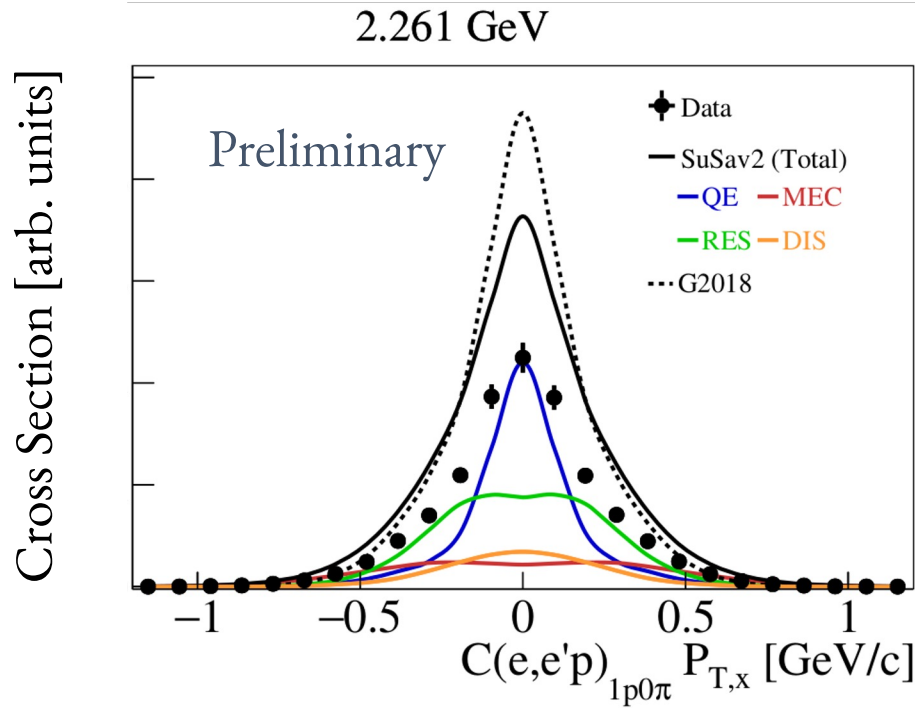


A.Papadopoulou, et al,
In preparation

Nuclear Sensitivity Variables

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

Sensitivity to Fermi motion

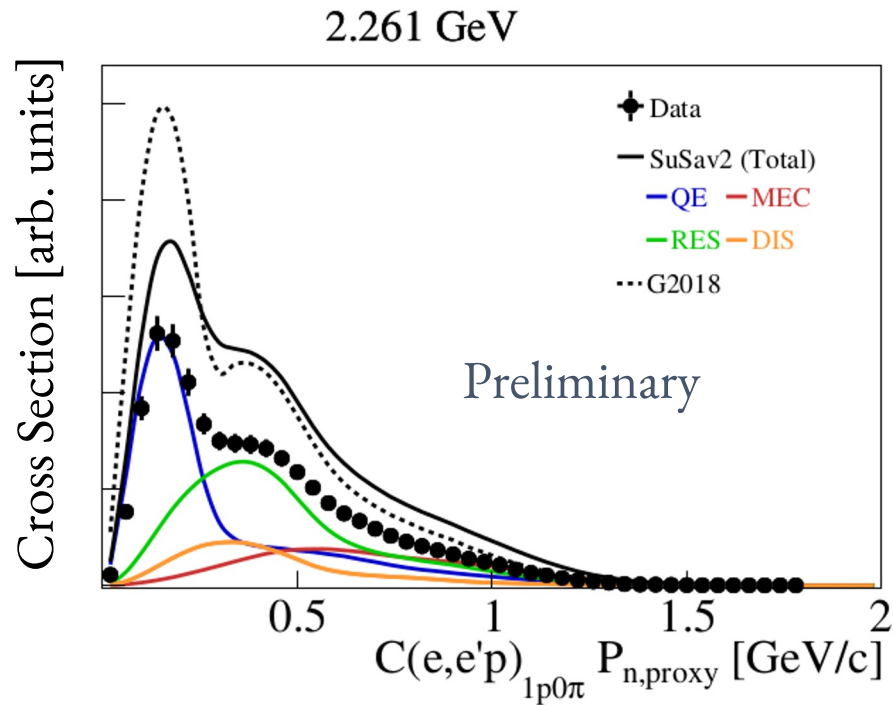


$$\delta \vec{p}_{T_y} = -\hat{\vec{p}}_T^l \cdot \delta \vec{p}_T = |\delta \vec{p}_T| \cos(\delta \alpha_T)$$

Sensitivity to final state interactions

A.Papadopoulou, et al, In preparation

Missing Momentum Approximation



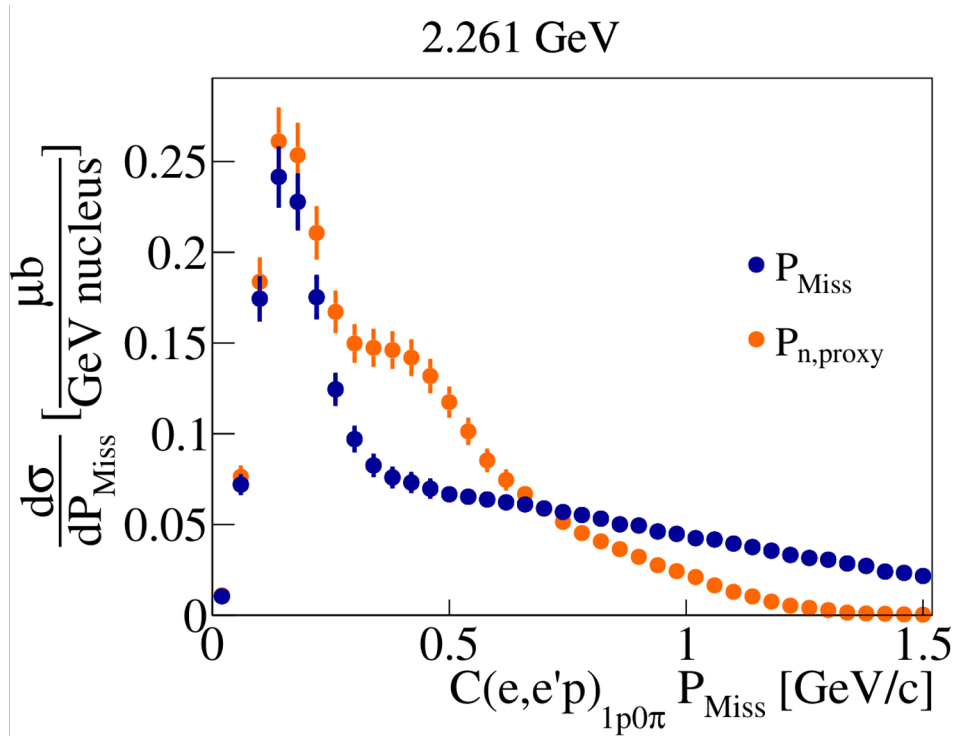
$$P_{n,proxy} = \sqrt{\delta p_L^2 + \delta p_T^2}$$

Under QE assumption

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

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

Fails To Reproduce True Missing Momentum



A.Papadoulou, et al, In preparation

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

Under QE assumption

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

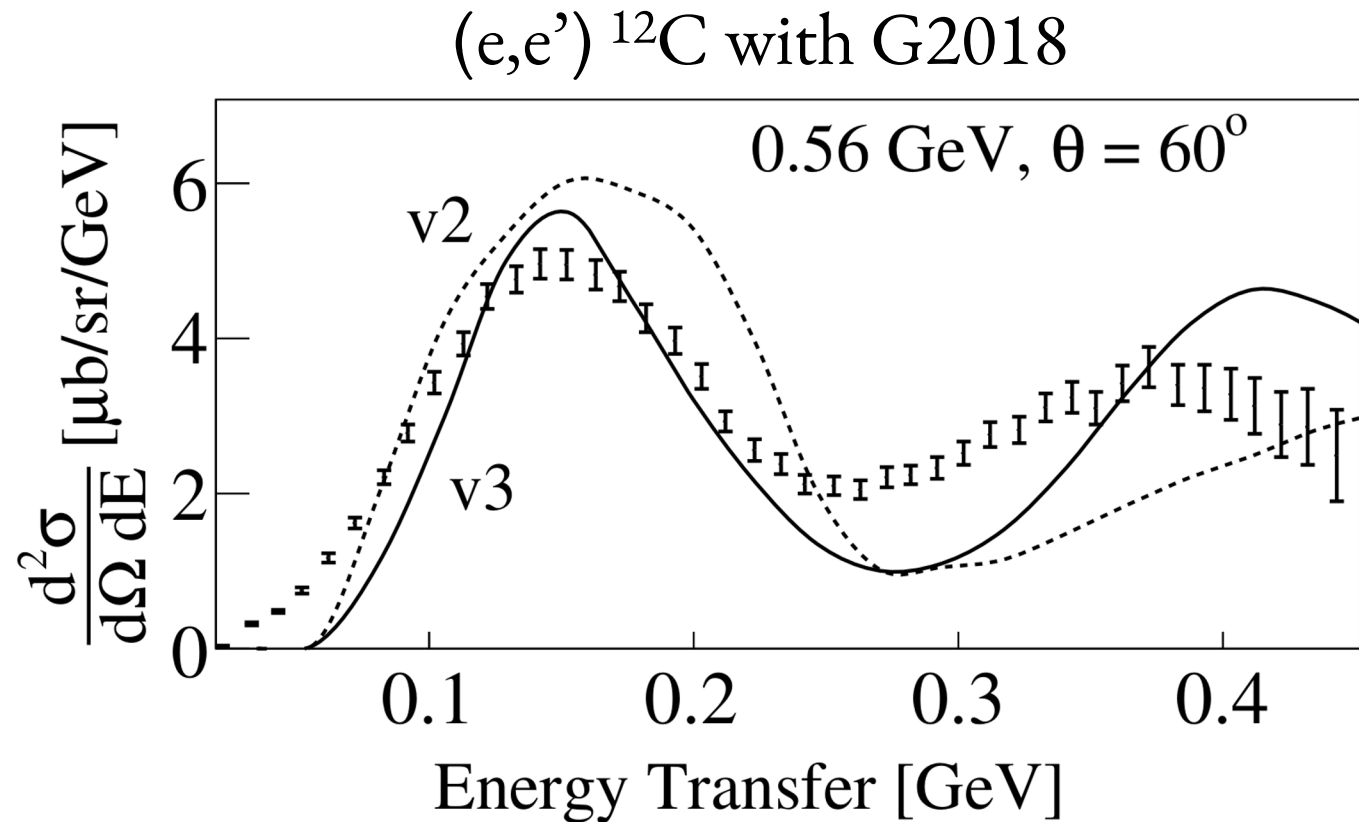
True missing momentum

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

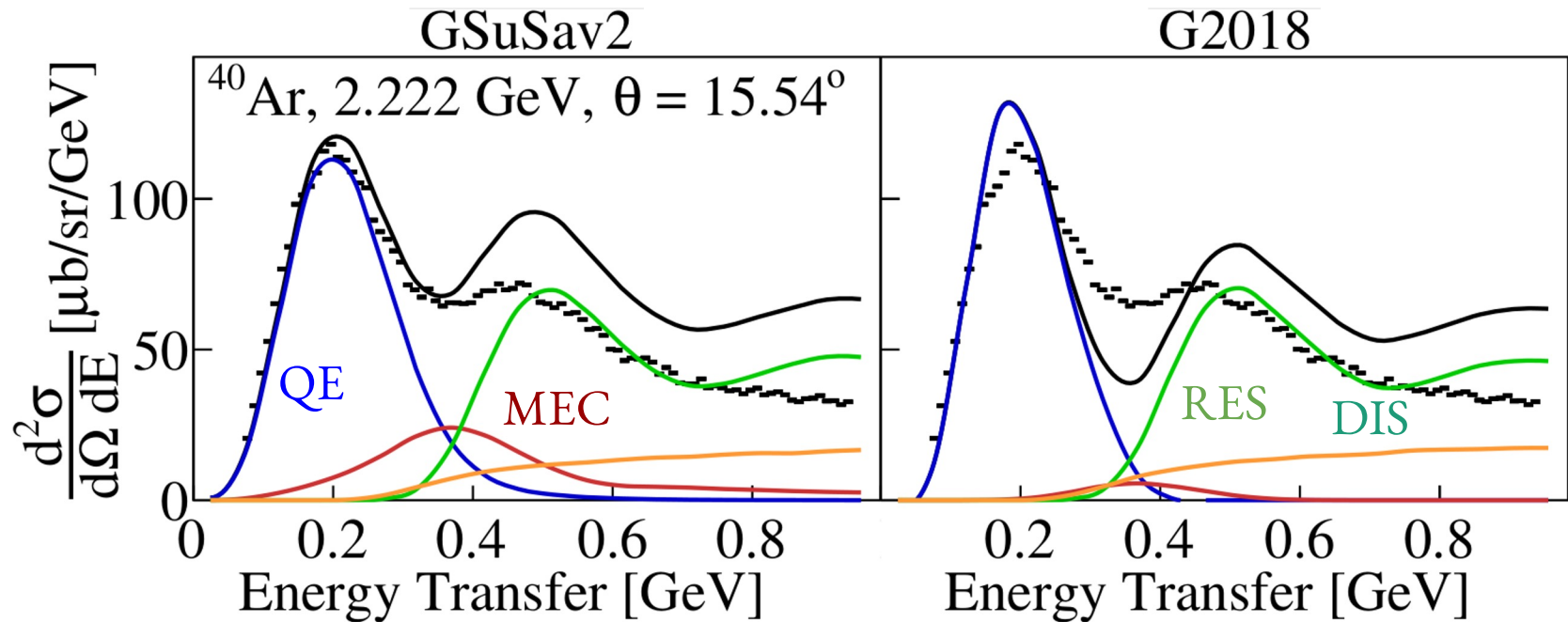
p = proton 3-vector

q = momentum transfer

Issues Identified & Fixed In G2018

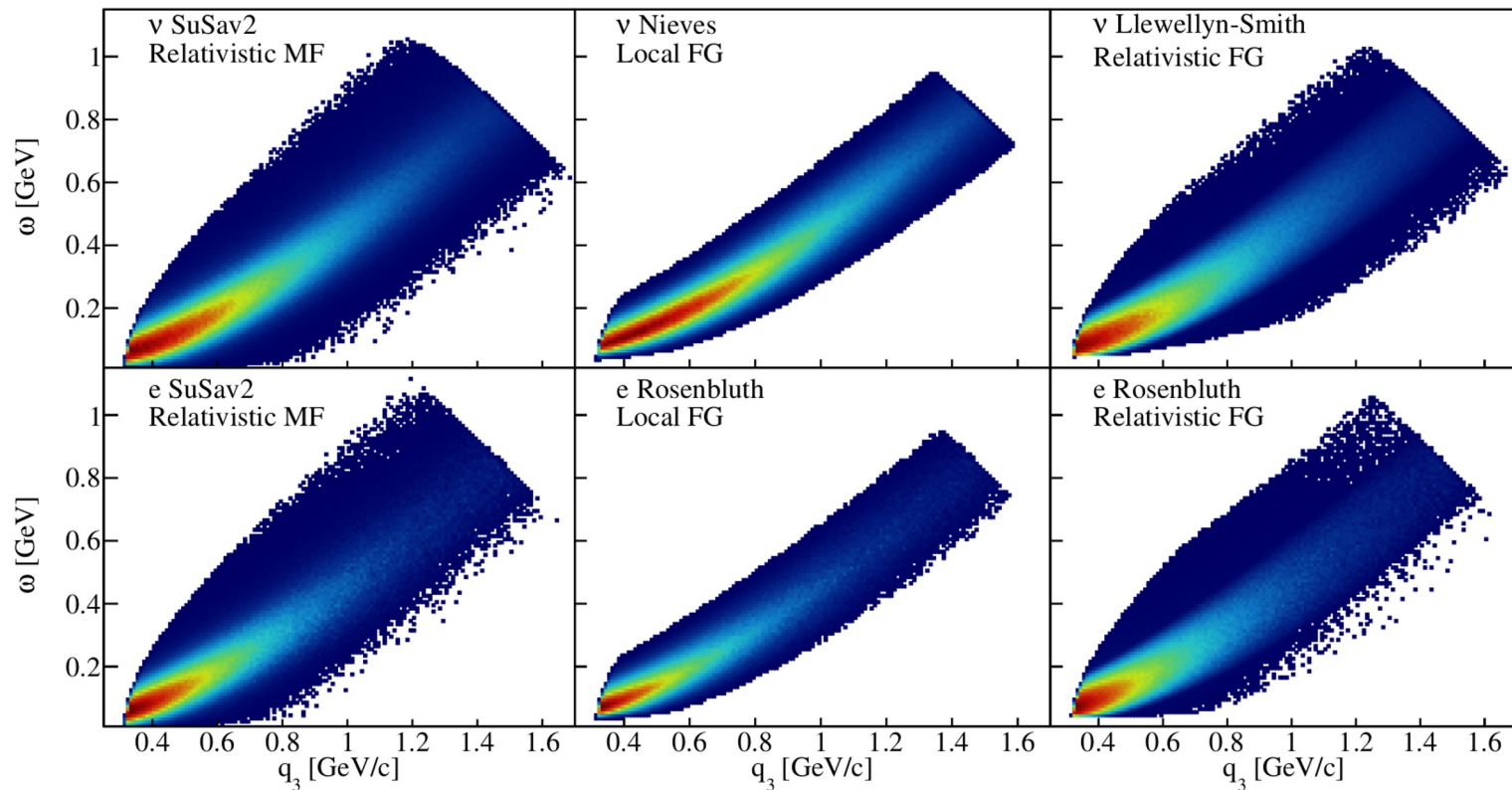


SuSav2 Offers More Accurate Prediction



Probing The Neutrino Phase-Space With Electrons

QE Events

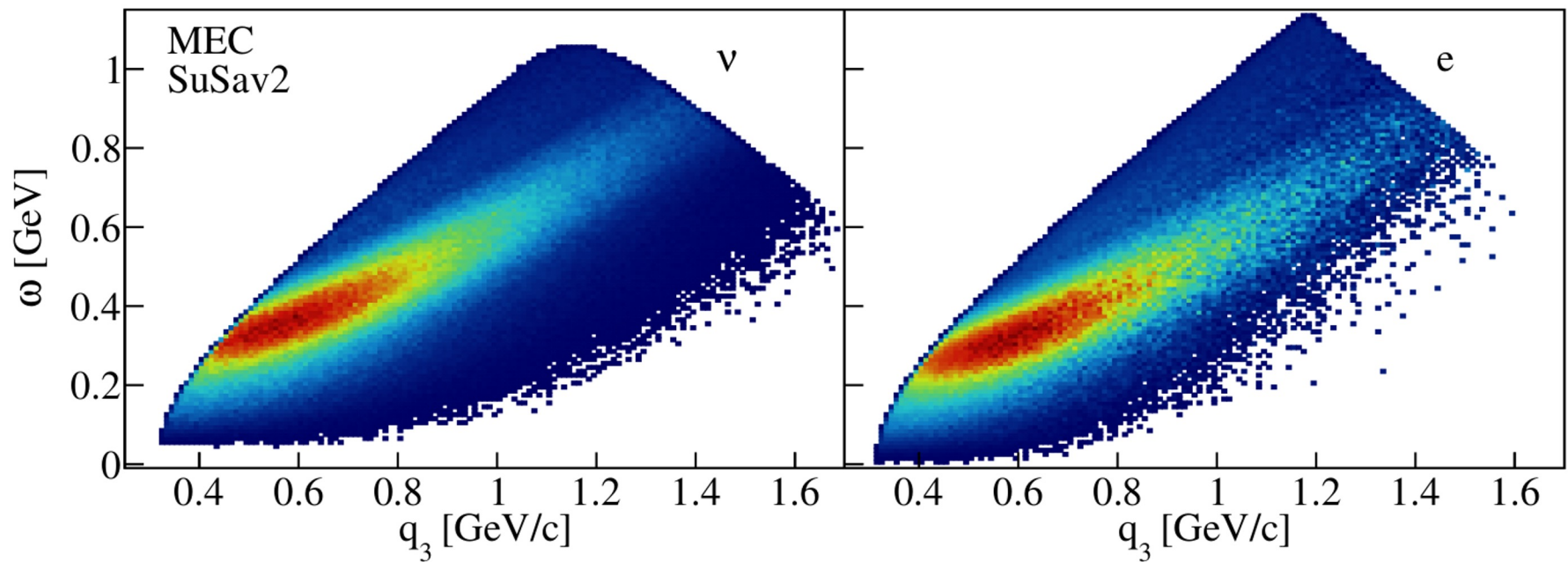


A.Papadopoulou, et al, Phys. Rev. D 103, 113003 (2021)

Electron results scaled by Q^4

Consistent Treatment Of MEC Events With SuSav2

Unique chance to constraint one of least understood interaction channels

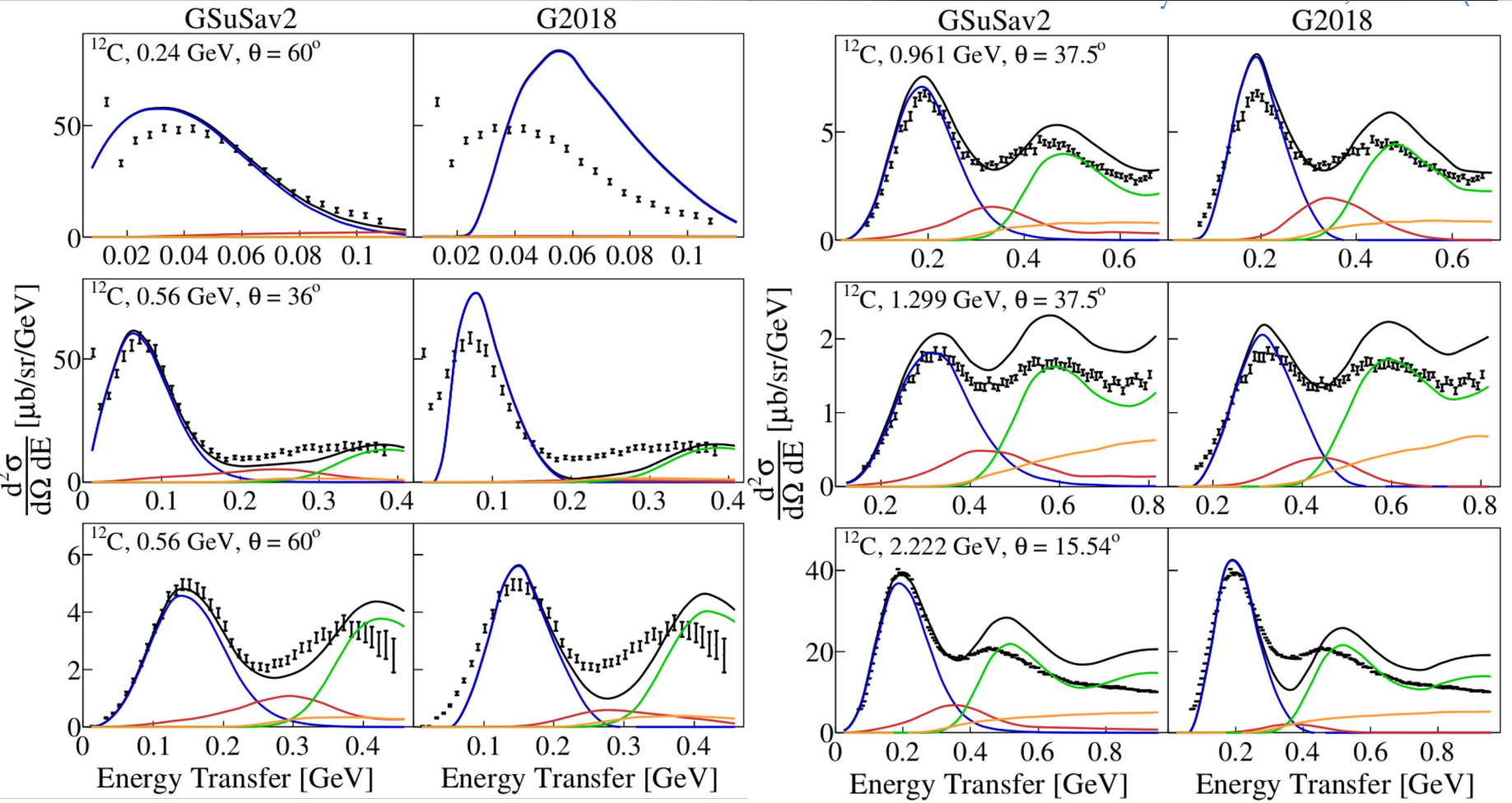


[Phys. Rev. D 103, 113003 \(2021\)](#)

Electron results scaled by Q^4

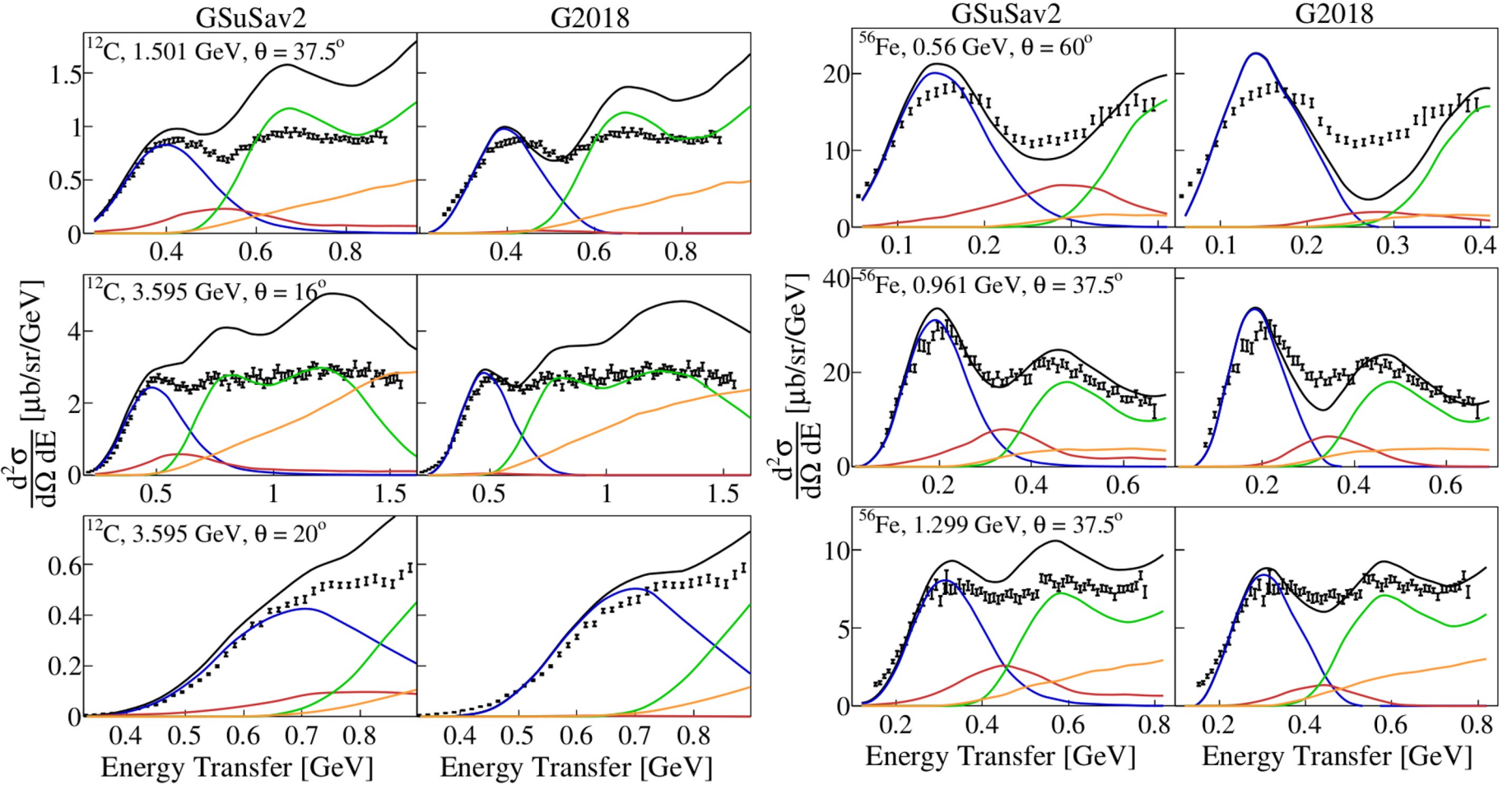
Inclusive C cross sections

Phys. Rev. D 103, 113003 (2021)



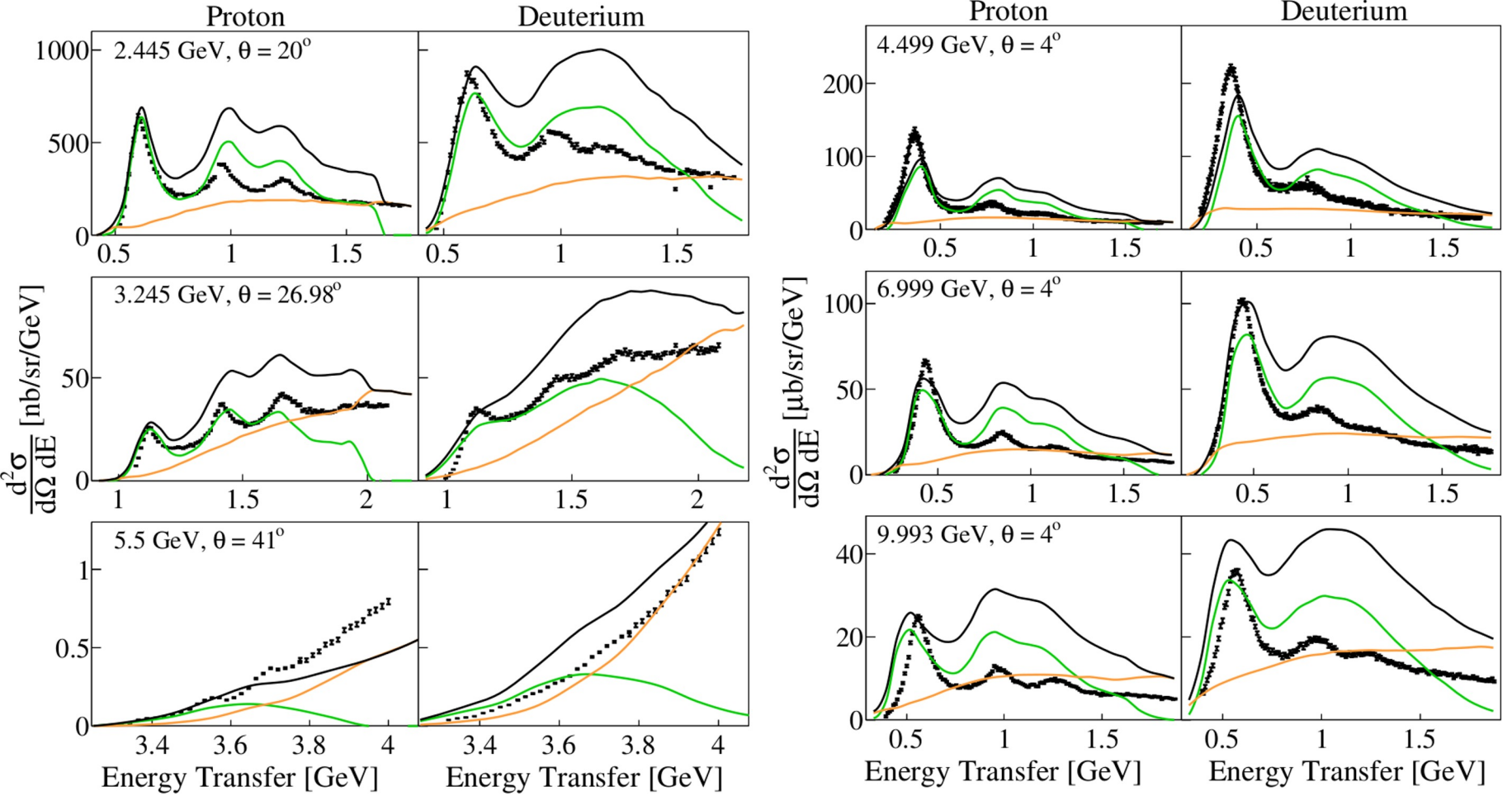
Inclusive C/Fe cross sections

Phys. Rev. D 103, 113003 (2021)

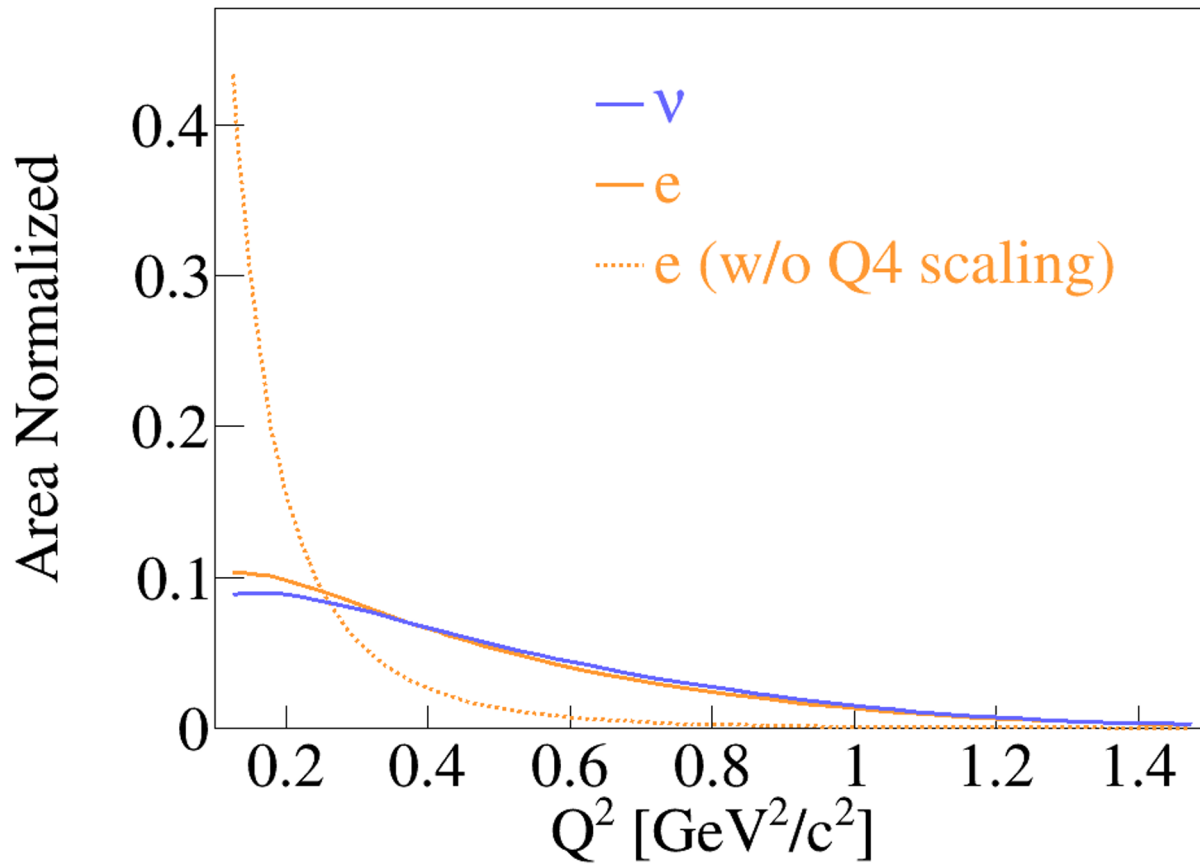


Inclusive H cross sections

Phys. Rev. D 103, 113003 (2021)

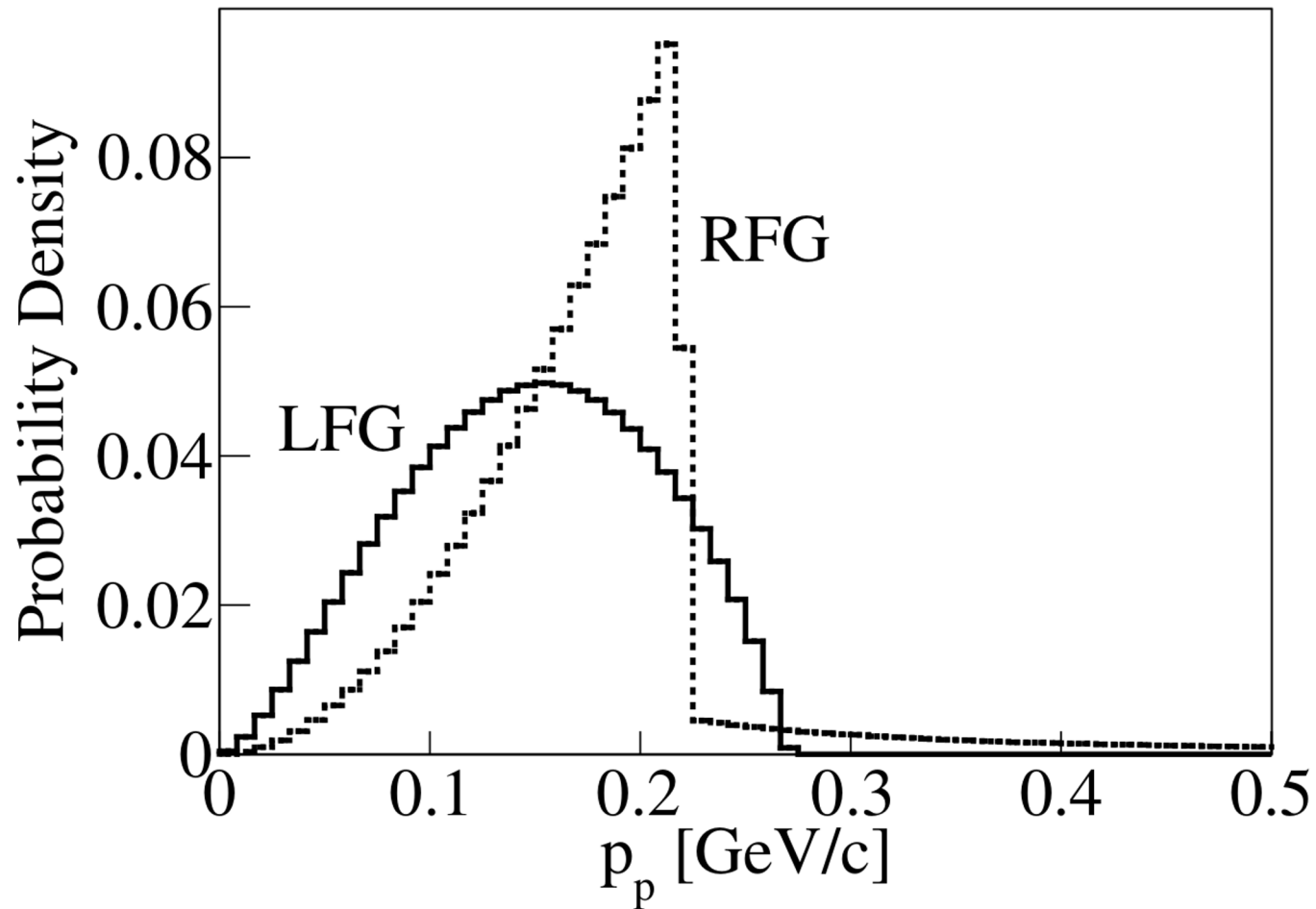


Q^4 Scaling Effect



Available Nuclear Models

[Phys. Rev. D 103, 113003 \(2021\)](#)



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