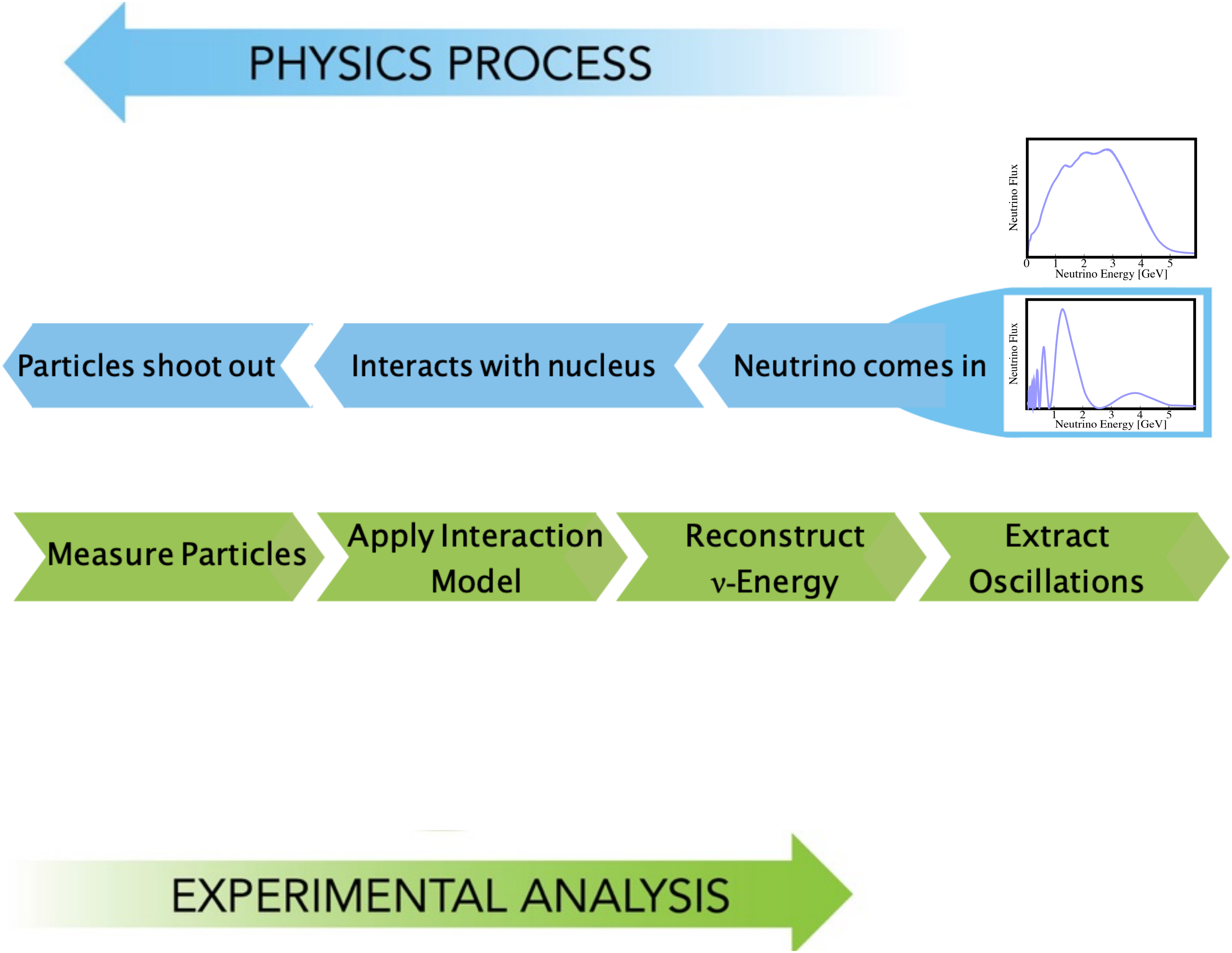
Electrons-4-Neutrinos: Trailblazing the Precision Oscillation Era

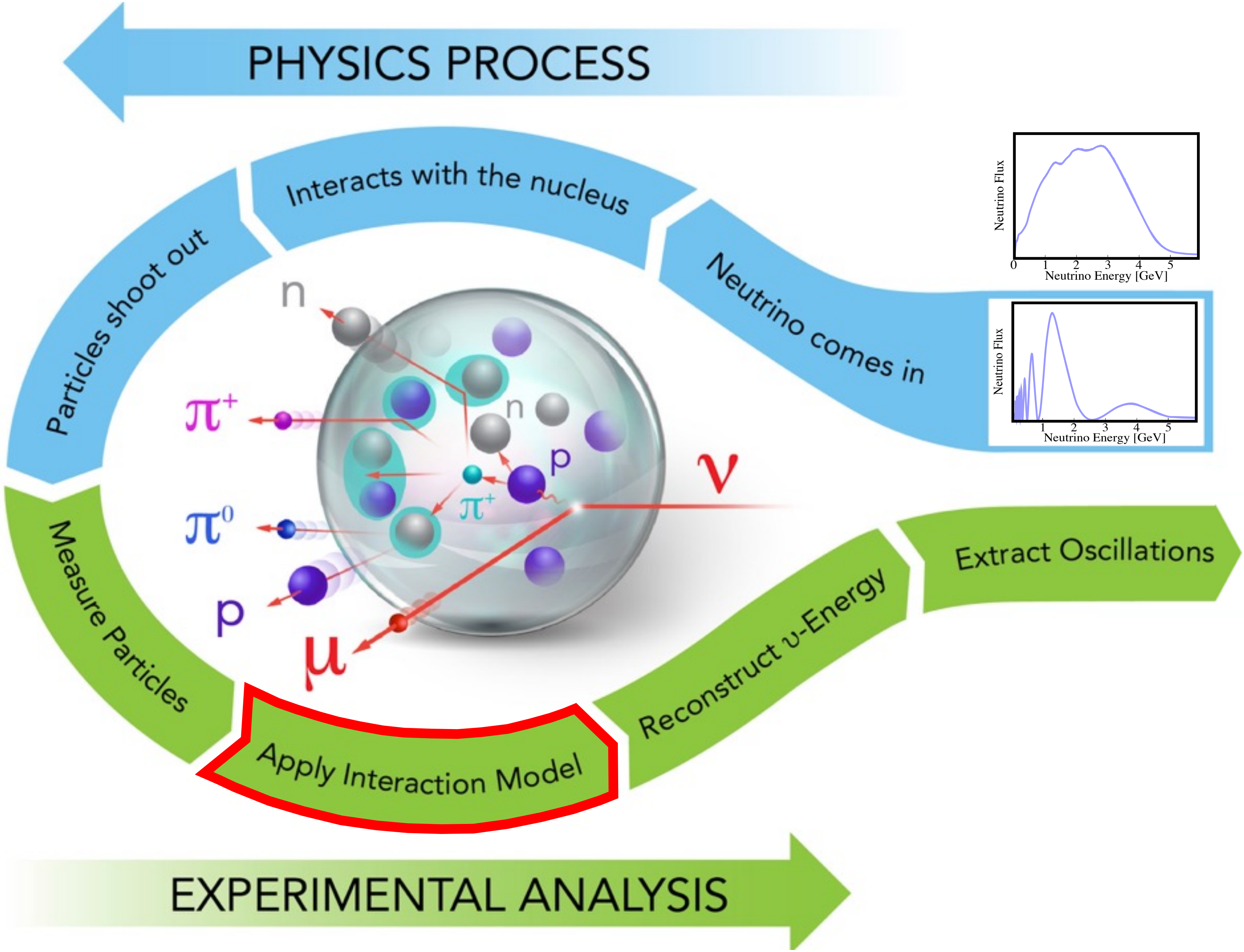
Or Hen (MIT)

For the Electrons-4-Neutrinos & CLAS collaborations

Measuring Neutrinos for Oscillations

Or… the Nuclear Reality of Oscillation Measurements


PHYSICS PROCESS
Neutrino Flux
0 1 2 3 4 5
Neutrino Energy [GeV]
Particles shoot out
Interacts with nucleus
Neutrino comes in
Neutrino Flux
1 2 3 4 5
Neutrino Energy [GeV]
Measure Particles
Apply Interaction Model
Reconstruct ν-Energy
Extract Oscillations
EXPERIMENTAL ANALYSIS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n
n
p
π+
π0
p
μ
ν
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EXPERIMENTAL ANALYSIS

In practice:

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

Measure

Want

Theory Input

In practice:

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

Measure — Want — Theory Input

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

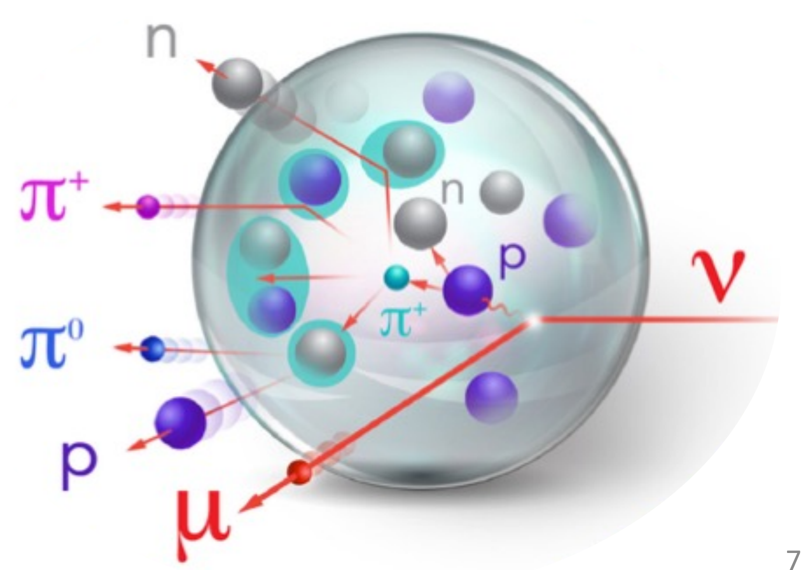
$f_\sigma(E, E_{rec})$: Energy reconstruction smearing matrix

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

Theory Input:

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

$\Rightarrow$ **MUST TUNE TO DATA!**



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

Near Detector data:

- No oscillations @ L ≈ 0
- ϕ(E, L ≈ 0) generally known

➔ Provide good $\sigma(E)$ & $f_\sigma(E, E_{rec})$ constraint

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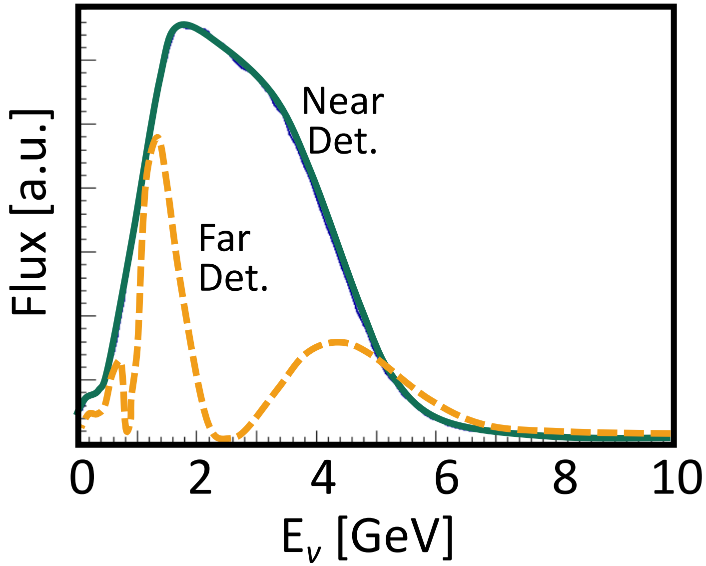

But... near flux ≠ far flux

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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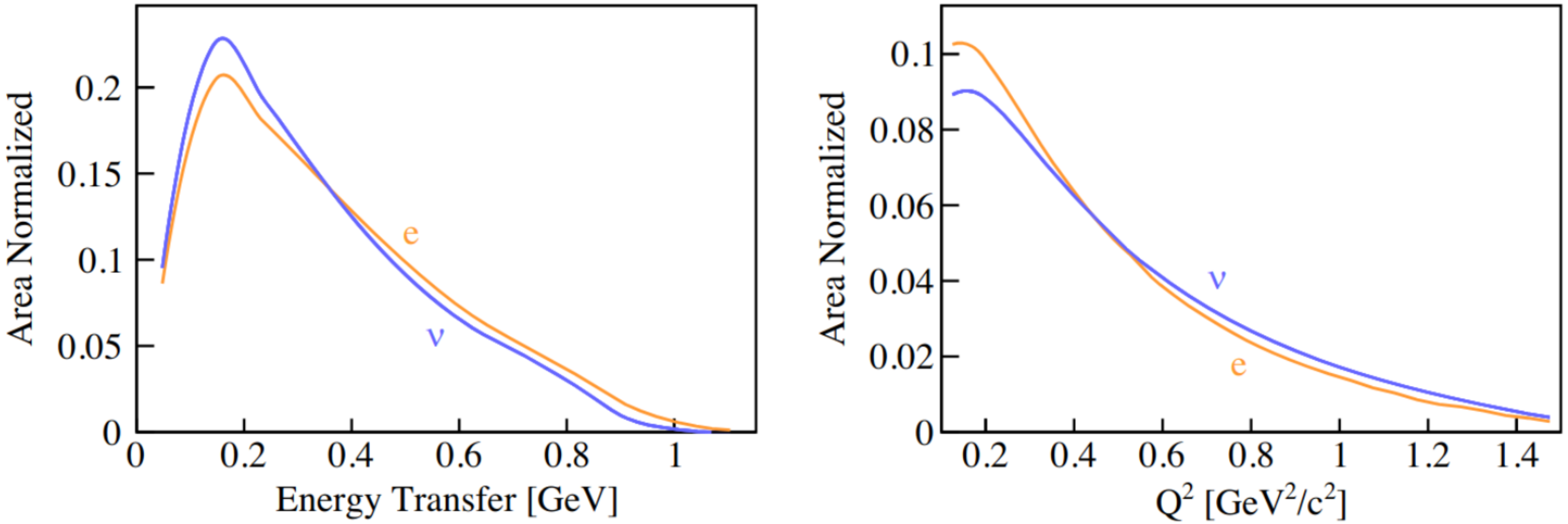

2.26 GeV on ^{12}C.

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

Papadopoulou and Ashkenazi et al
(e4ν collaboration) Phys. Rev. D **103**, 113003 (2021).

*e^- scaled by Q^4

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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
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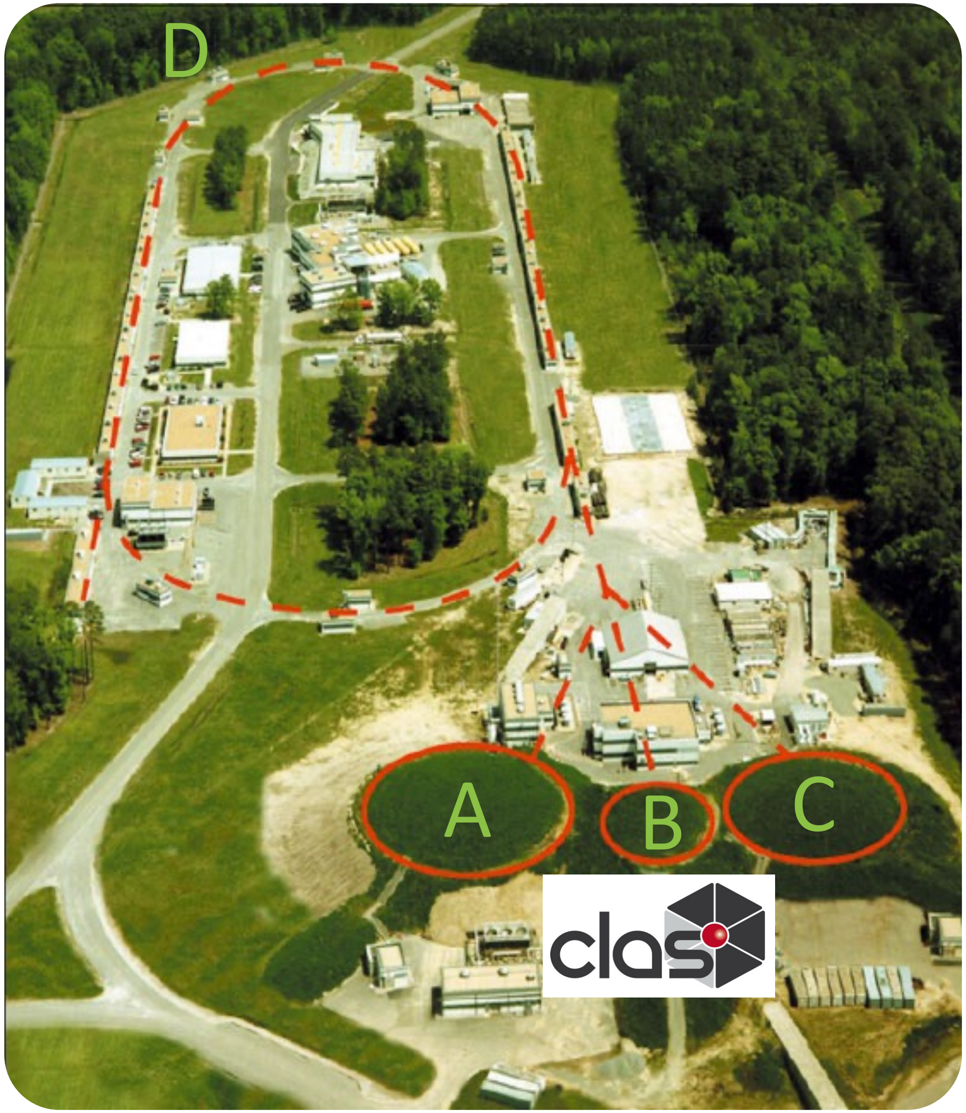
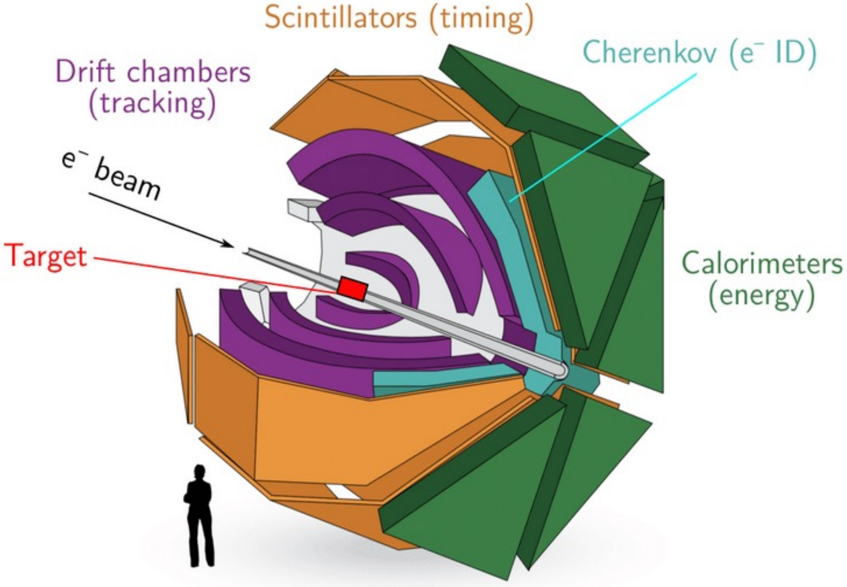
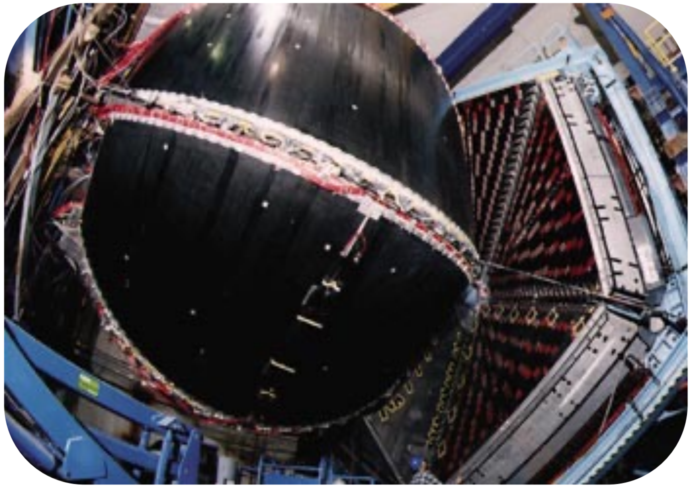
e4ν @ Jefferson-Lab







✧ ~4π acceptance (~ 8 - 143^o)

✧ low thresholds:

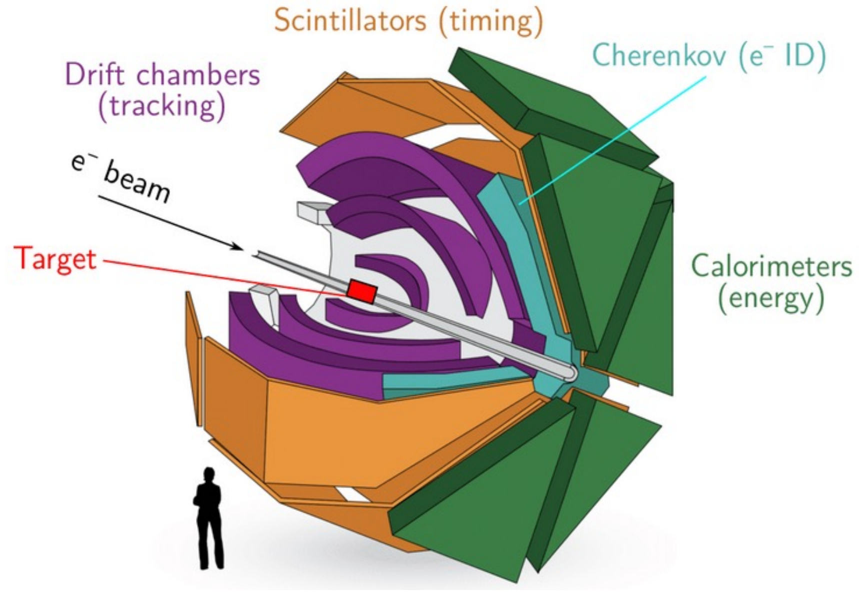
- P_p>300 MeV/c
- P_π >150 MeV/c

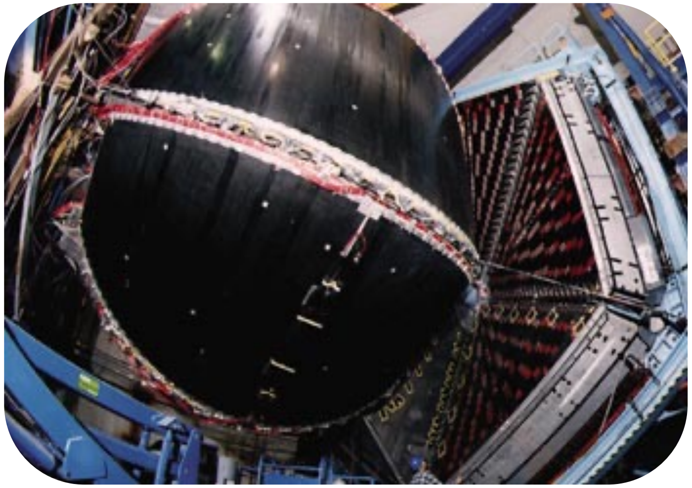
✧ Neutral particles:

- EM calorimeter (8-75^o)
- TOF (8-143^o)

✧ ^{4}He, C, Fe Targets

✧ E_{beam} = 1.1, 2.2, 4.4 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 $\sigma_{e\text{-}N} / \sigma_{\nu\text{-}N}$ (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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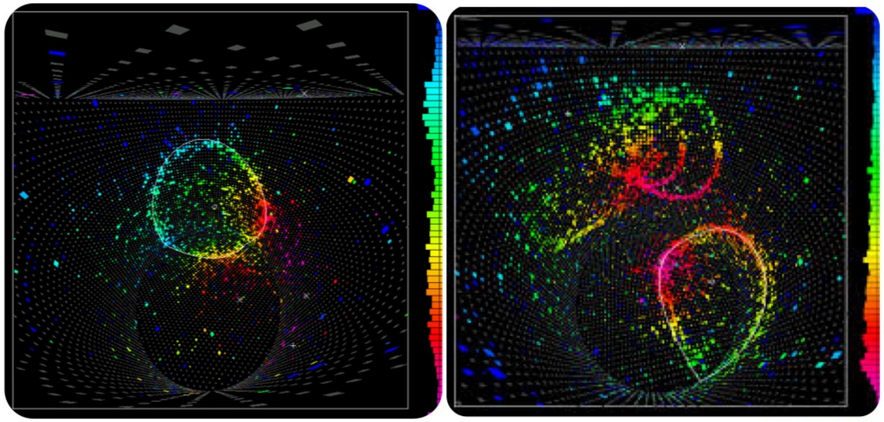
Kinematic Energy Reconstruction



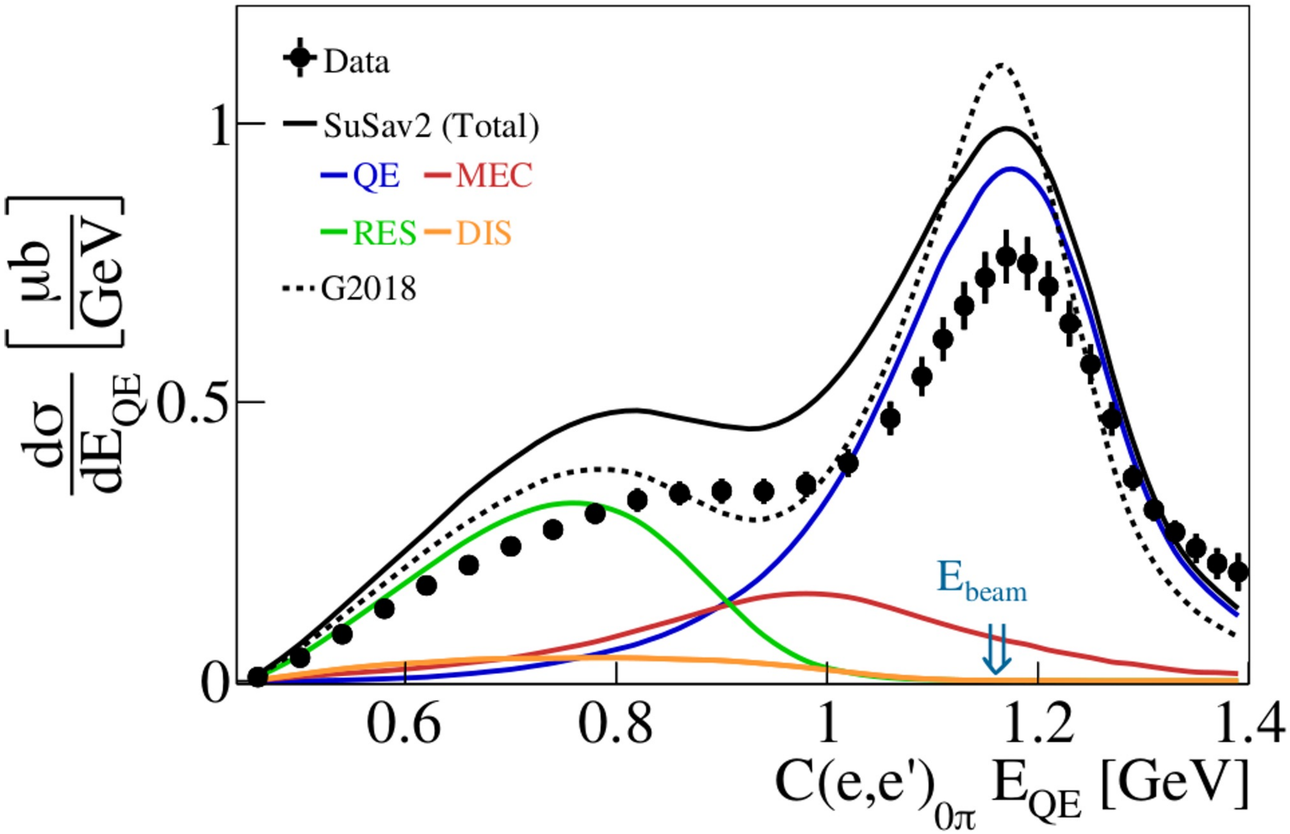
Cherenkov detectors:

Assuming QE interaction

Using lepton only

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

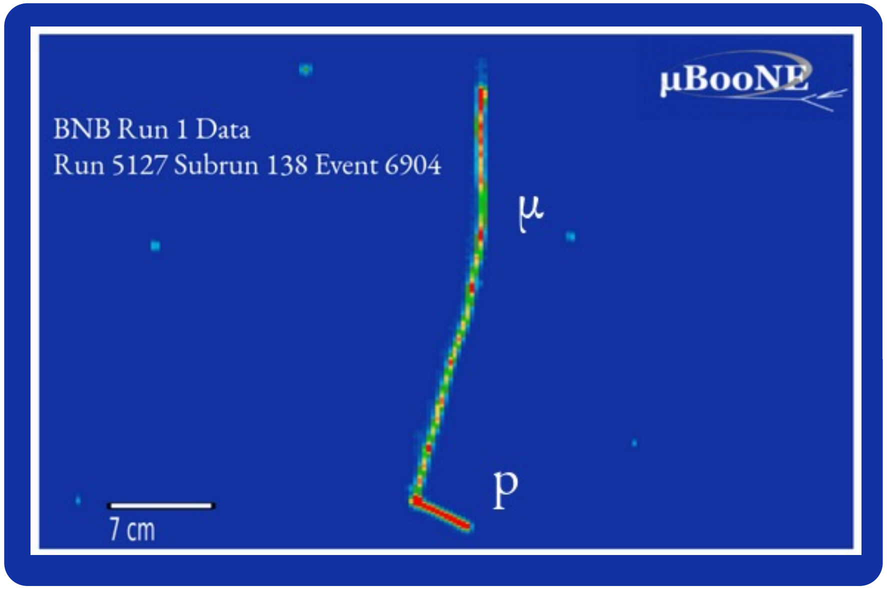
$(e,e')_{0\pi}$ Data-Theory Disagreements



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

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

Calorimetric Energy Reconstruction



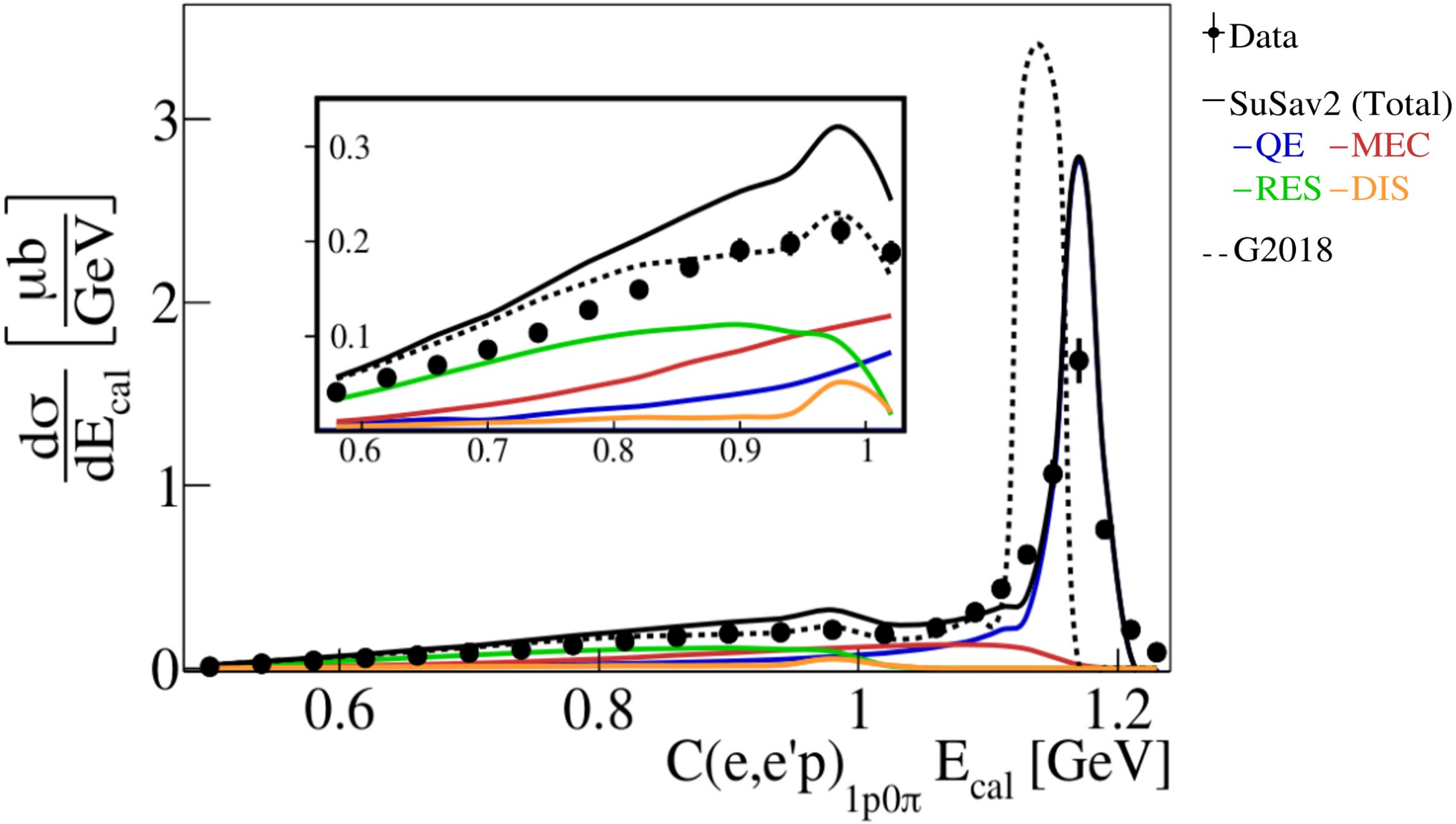
Tracking detectors:

Calorimetric sum

Using All detected particles

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

(e,e'p) Energy Reconstruction



Khachatryan, Papadopoulou, and Ashkenazi et al.
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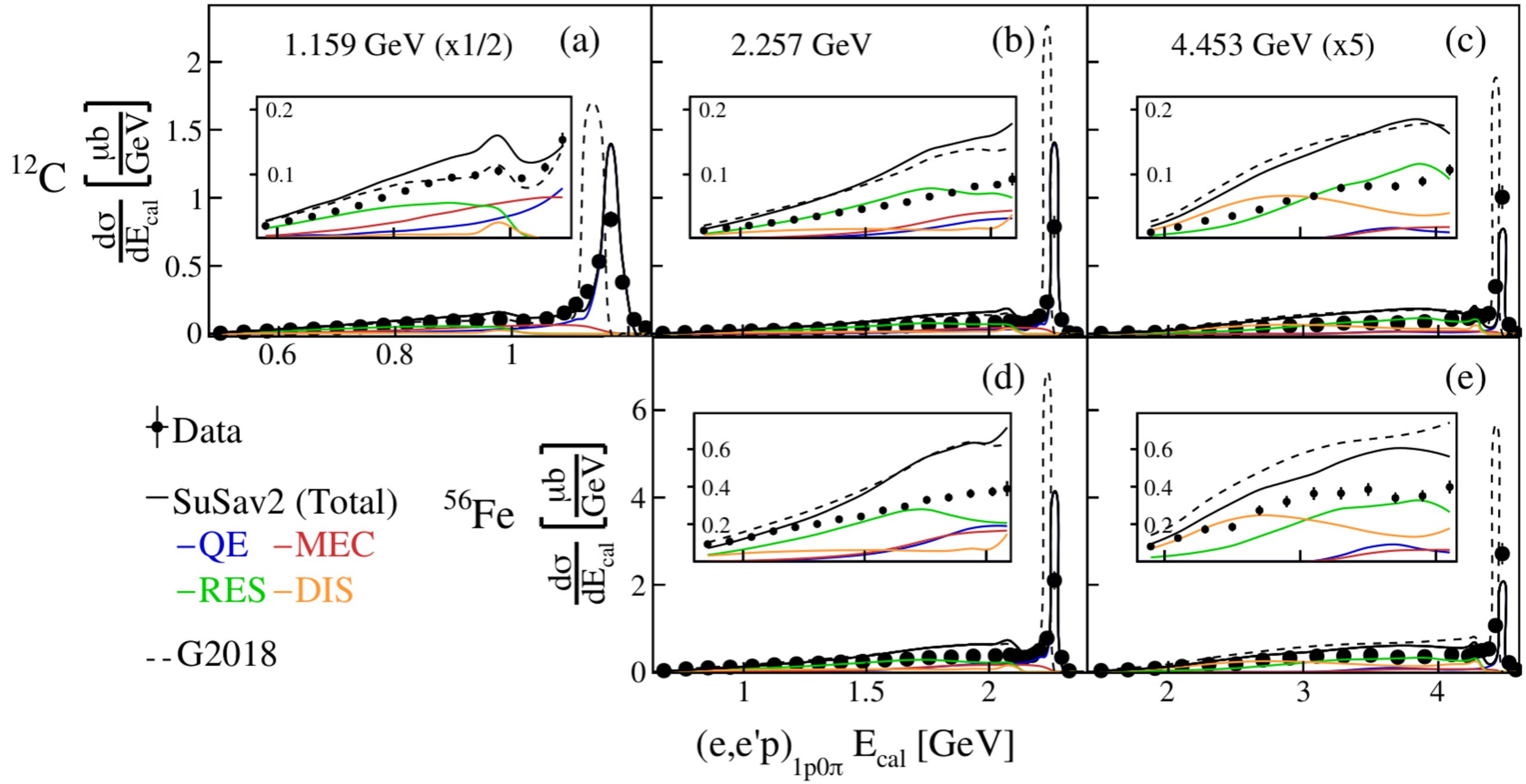
$$E_{cal} = E_l + T_p + \epsilon$$

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



Khachatryan, Papadopoulou, and Ashkenazi et al.
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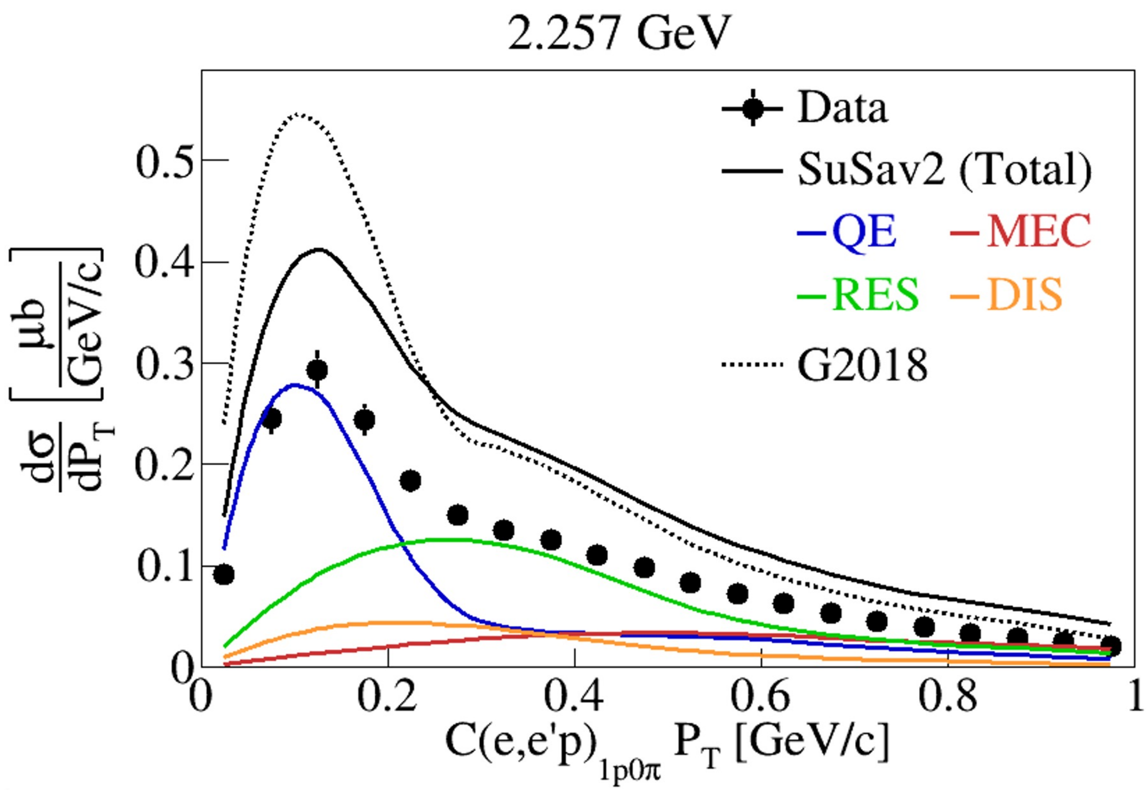
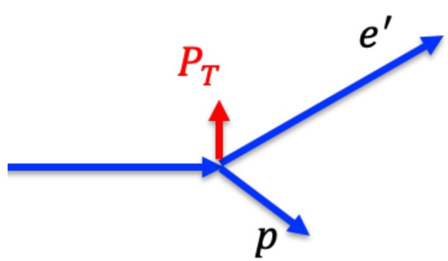
Transverse Constraints



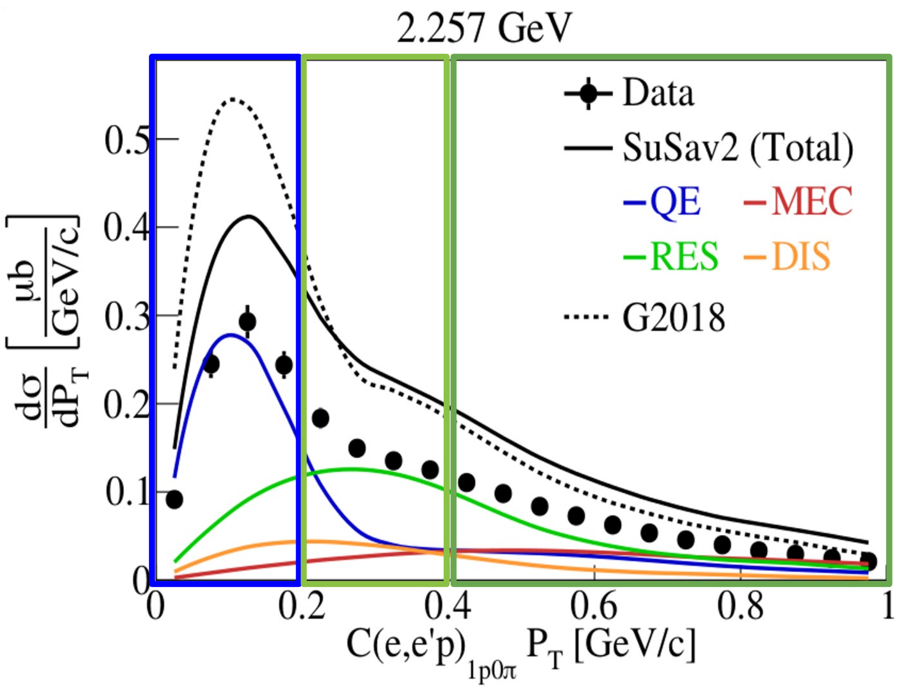
$P_T = |\,\mathbf{P}_T^{e'} + \mathbf{P}_T^{p}\,|$

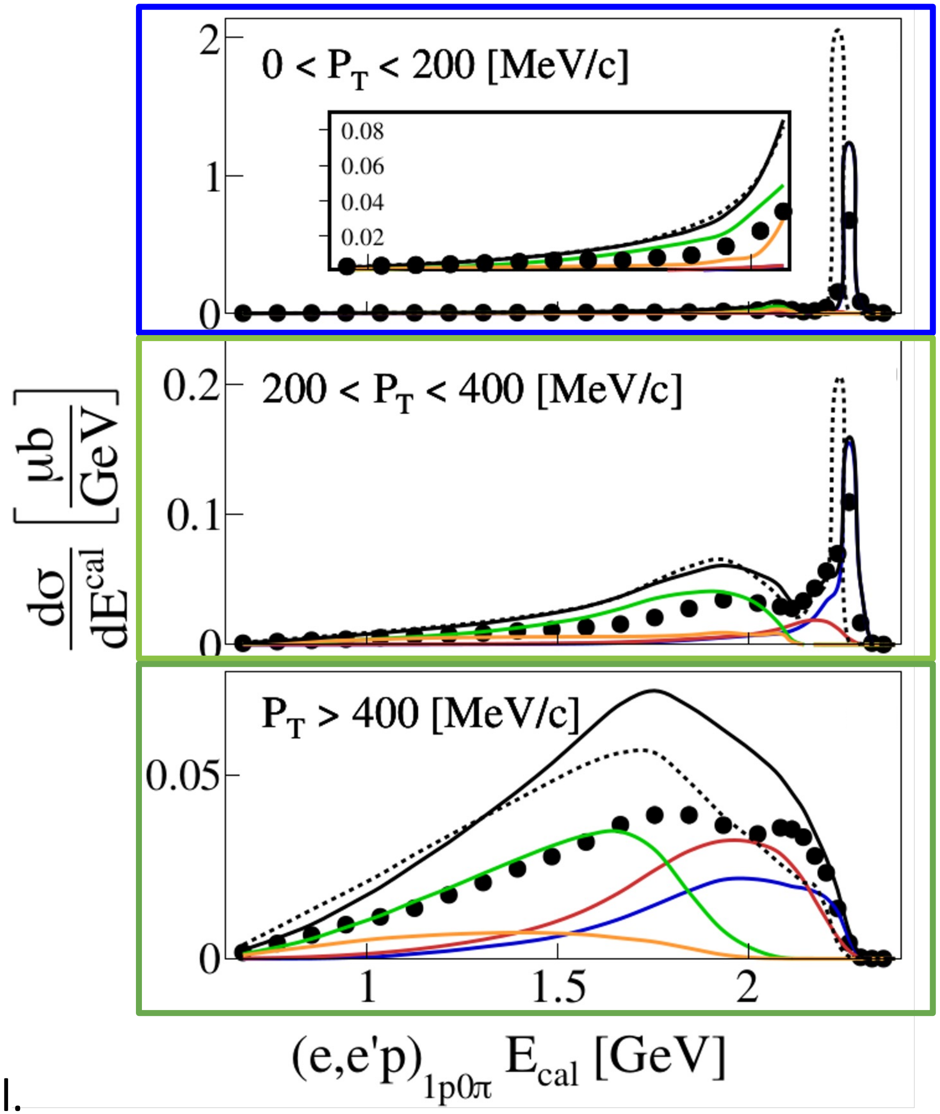


Overestimation of QE peak & RES tail

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

Impacts E_{beam} reconstruction





Khachatryan, Papadopoulou, and Ashkenazi et al.
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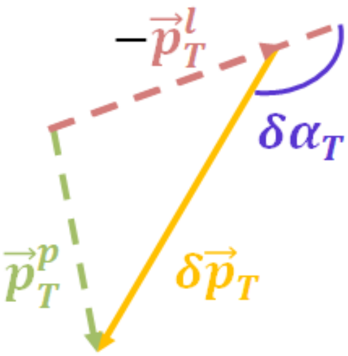
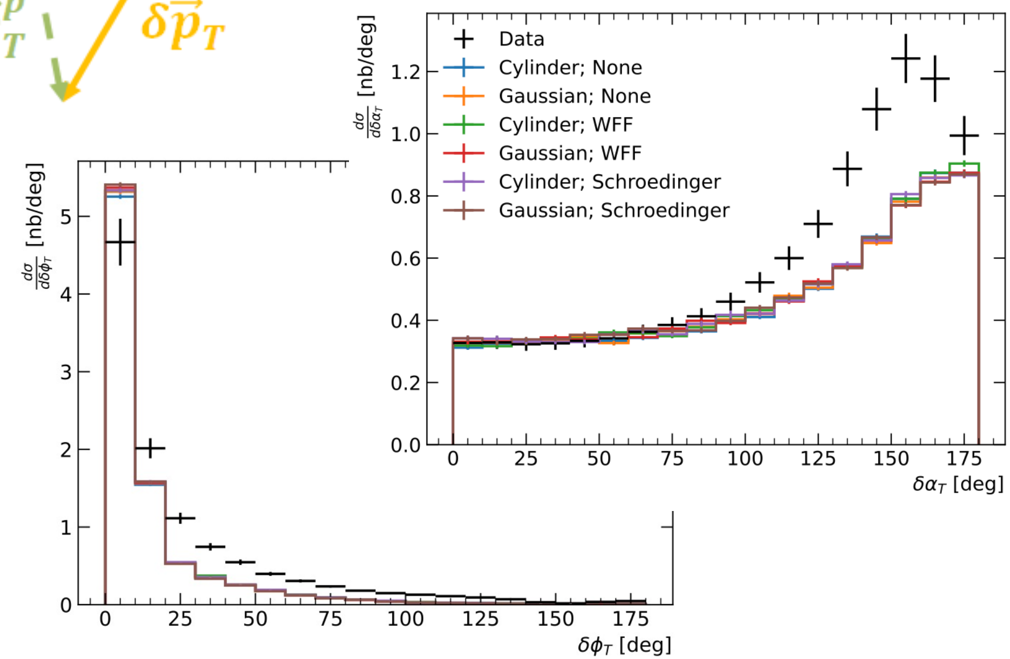
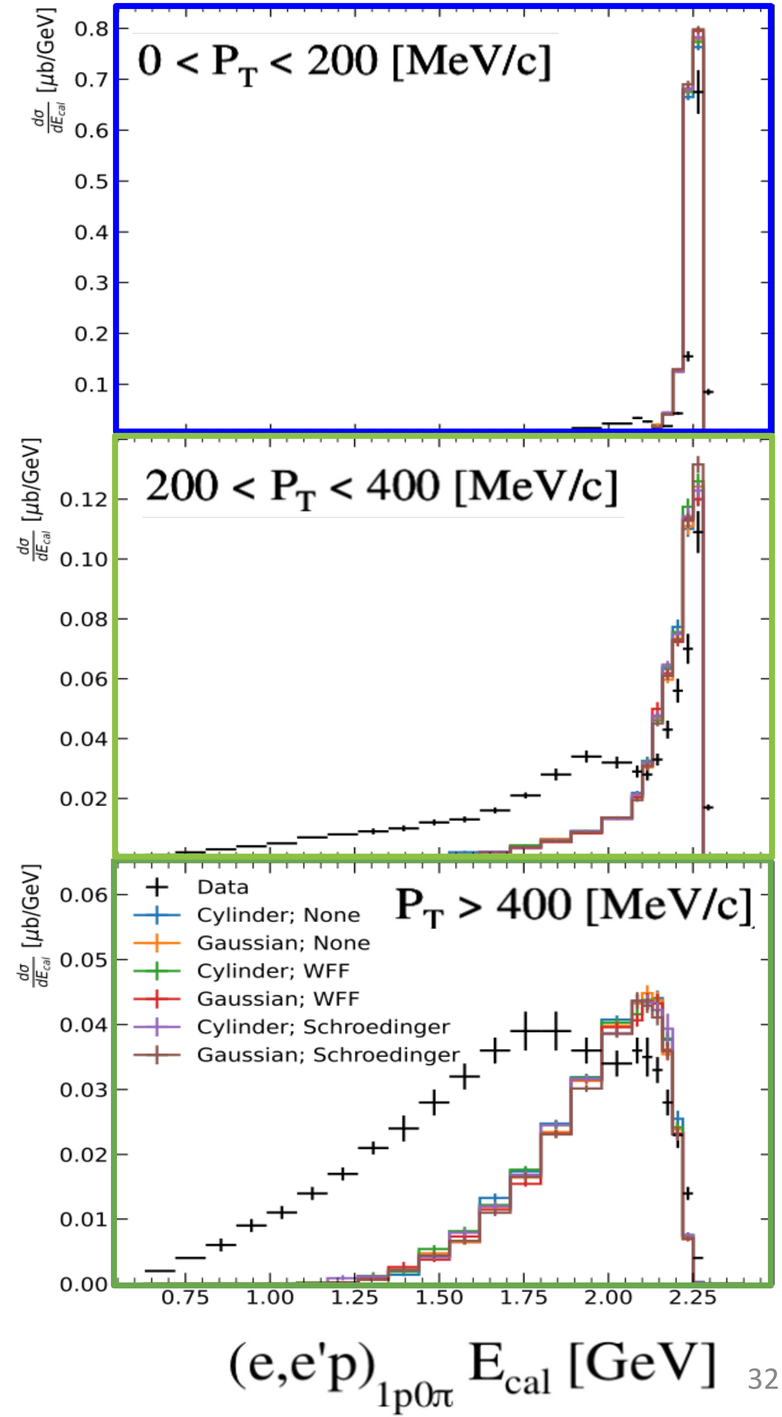
Benchmarking new generators! (ACHILLES)



First step: only QE & FSI





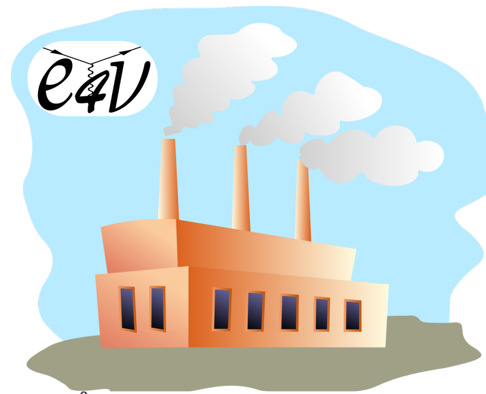
Isaacson, Jay, Lovato, Machado, and Rocco
arXiv: 2205.06378 (2022)

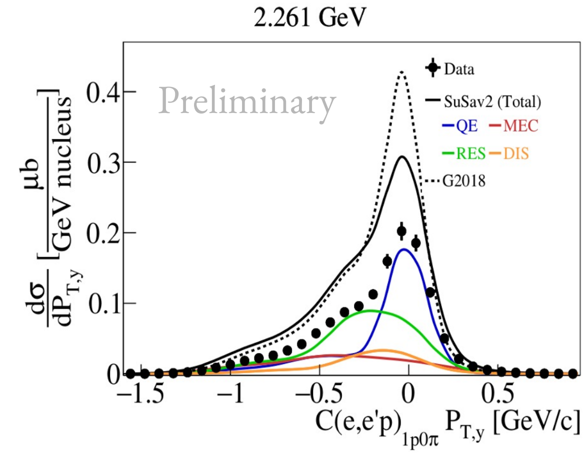
LOTS of new results!

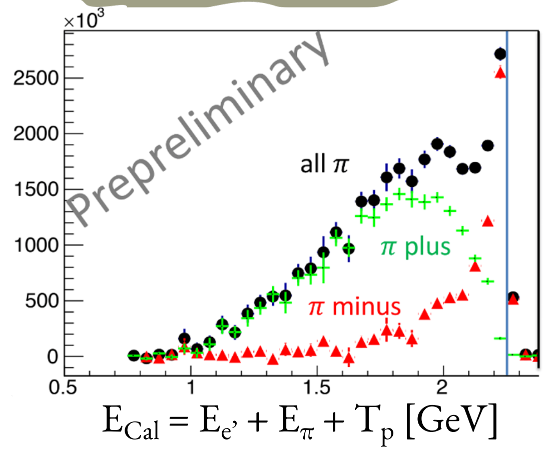
- Multi-differential
- Pion production
- p & π transparency
- Complex variables
- …
  [all nuclei & beams]

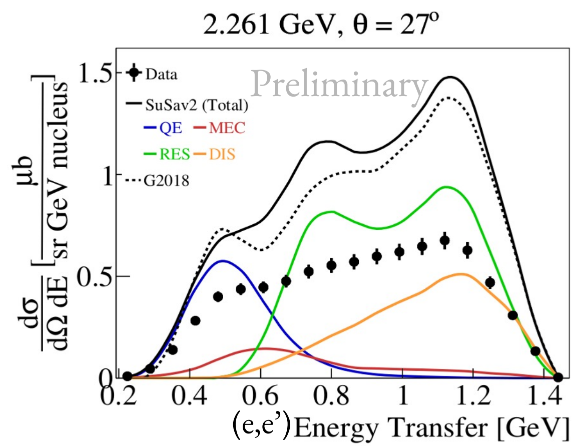
+ µ4ν @ µBooNE [J. Barrow poster]

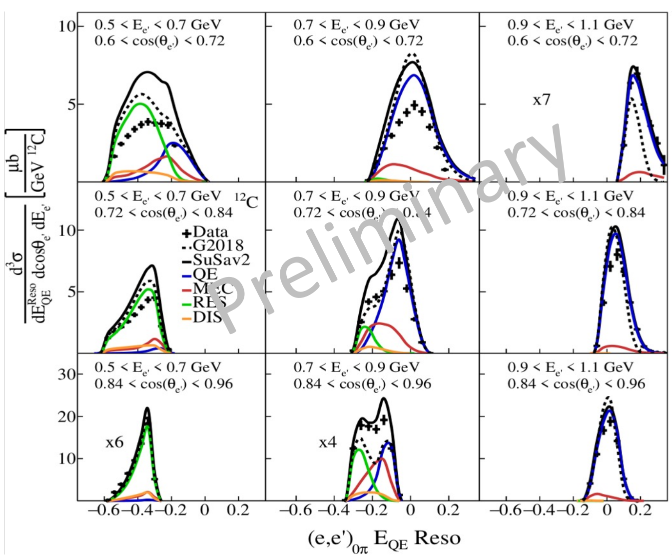
+ New CLAS12 e4ν data

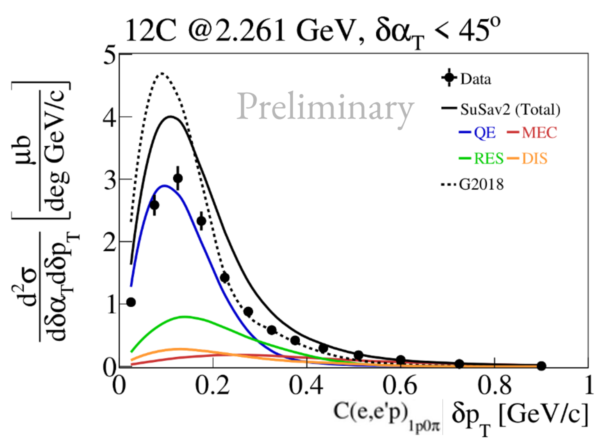


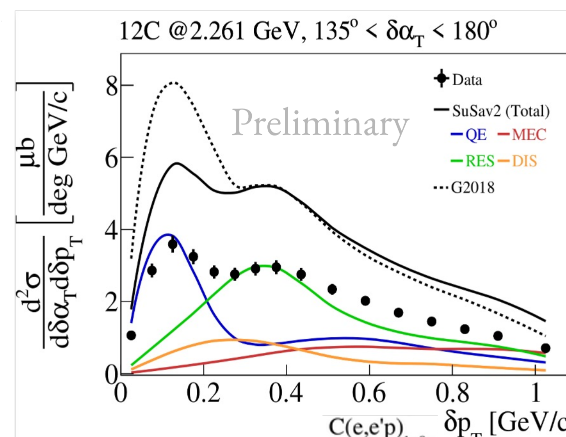




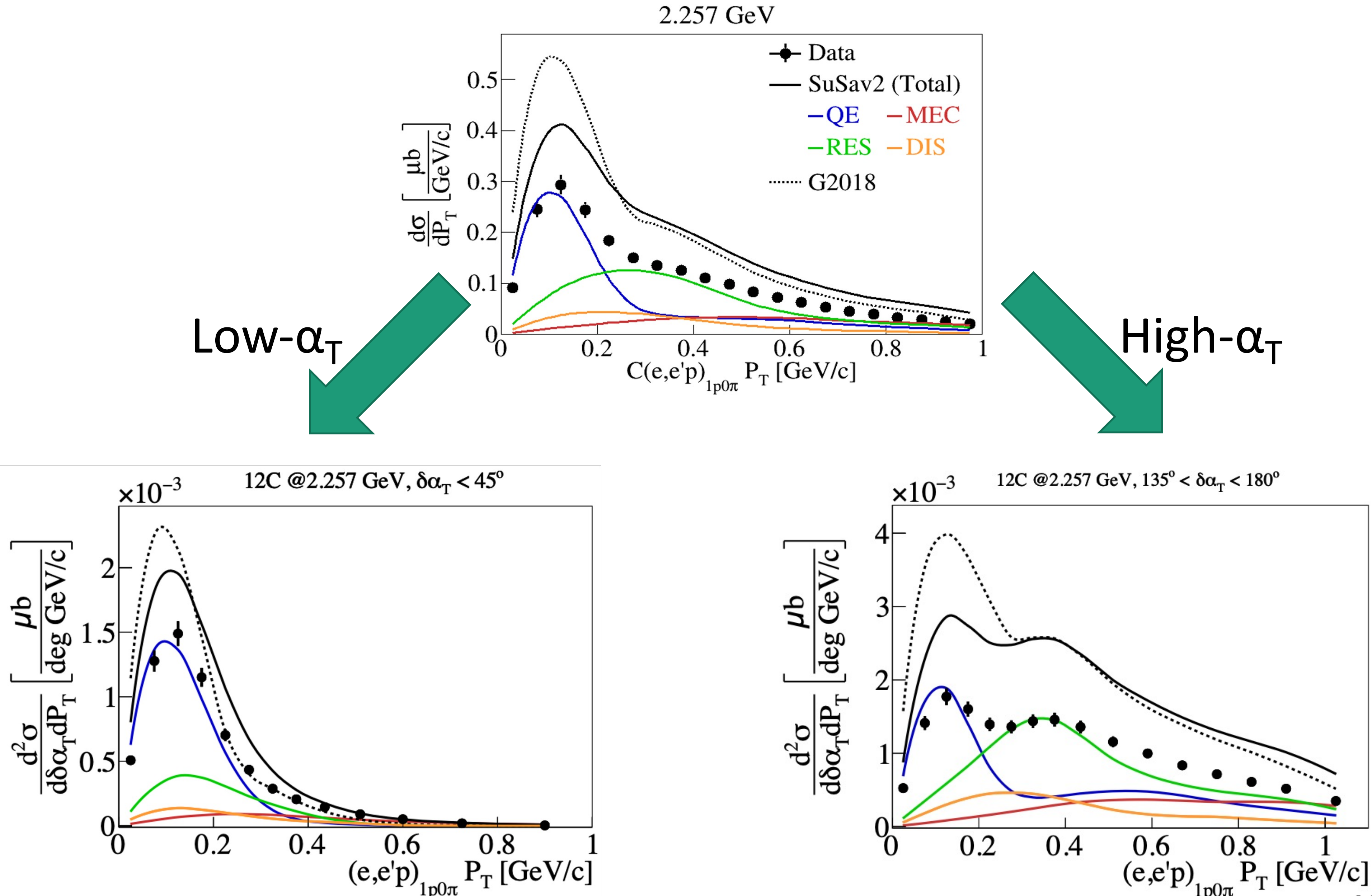








Example: 2D Transverse Variables



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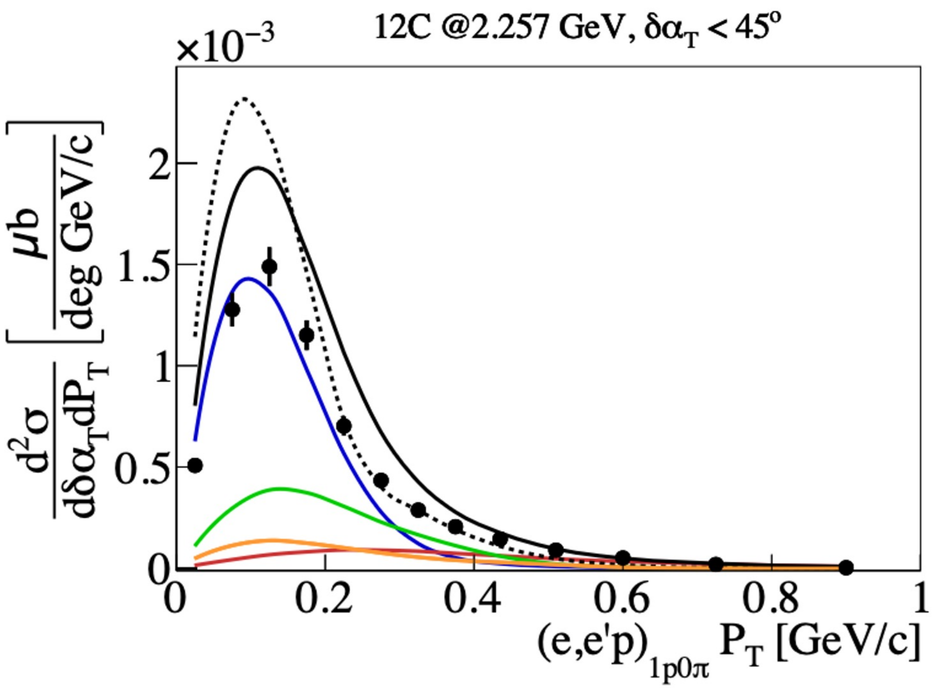
Low-α_T

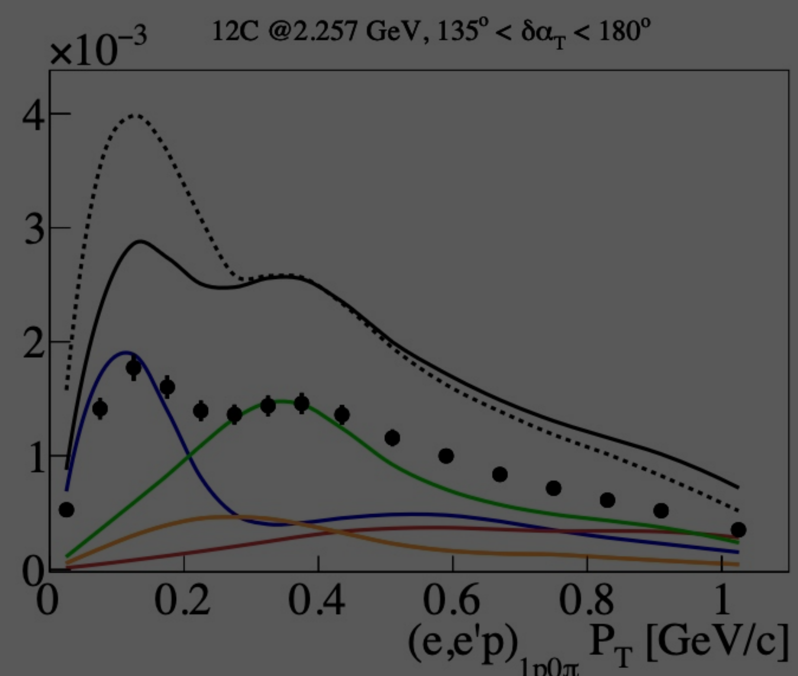
QE Enhanced region

➔ Sensitive to ground-state model



High-α_T

Large non-QE contributions



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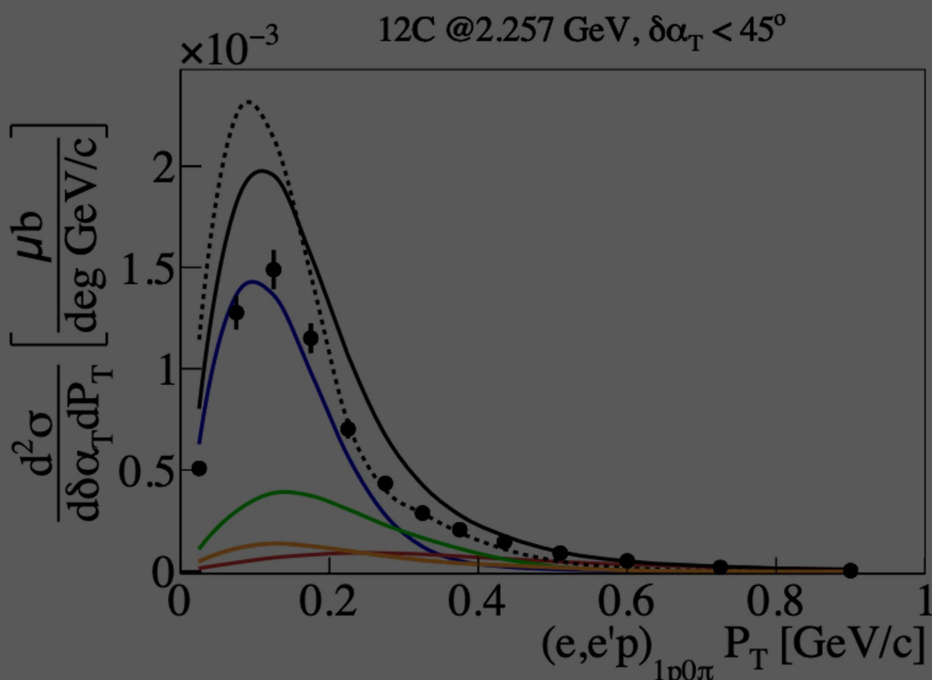

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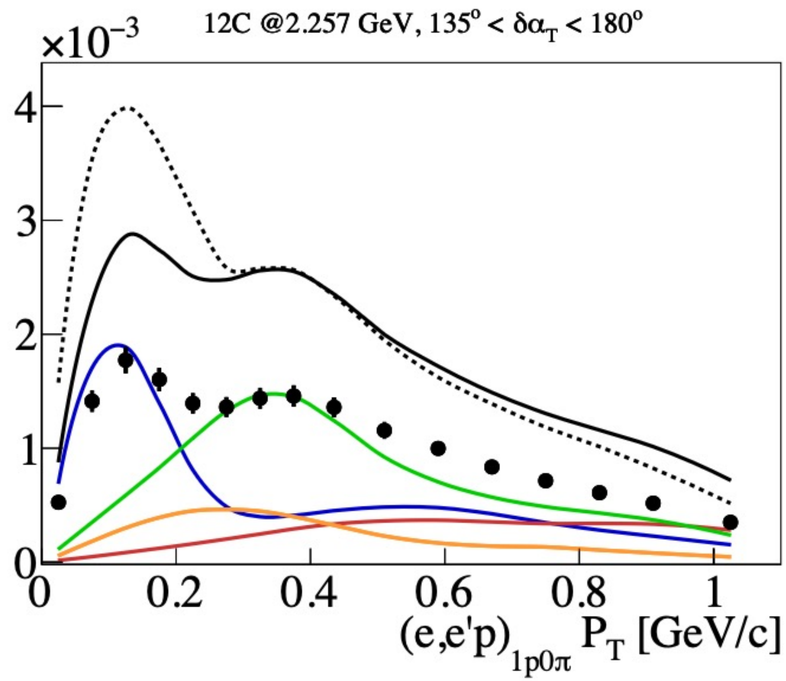
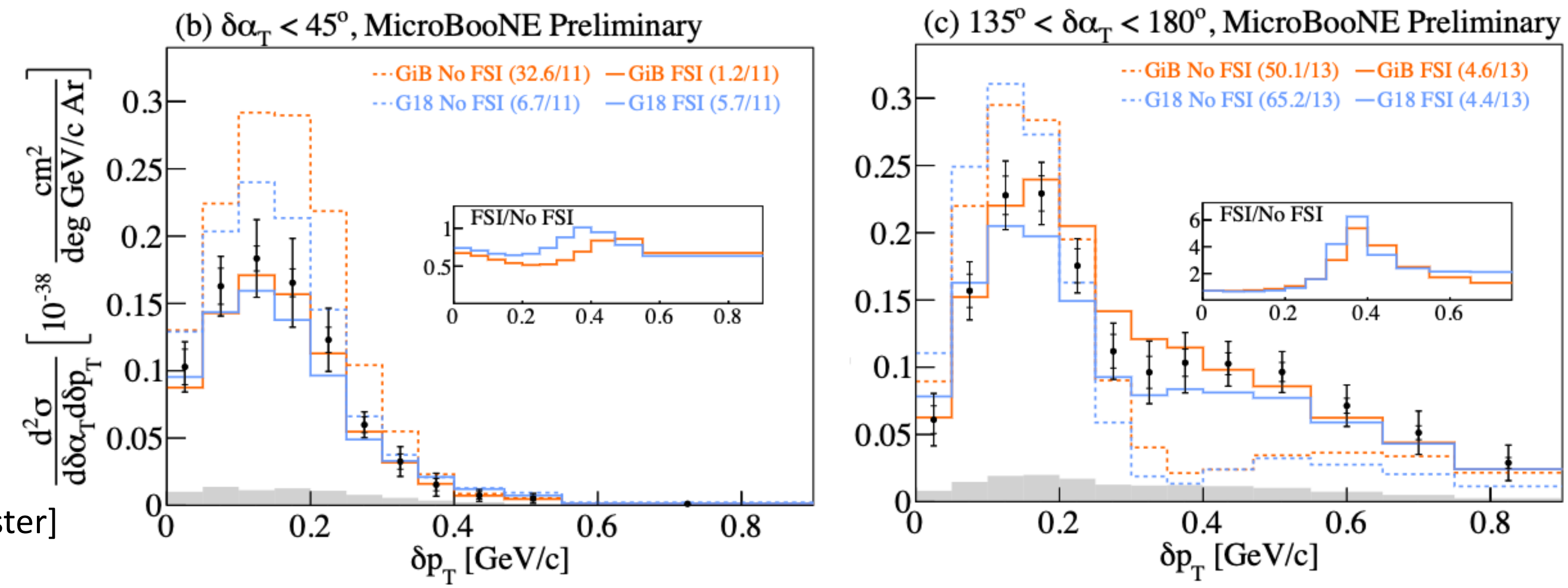


Complements ‘sister’ neutrino analysis

μBooNE

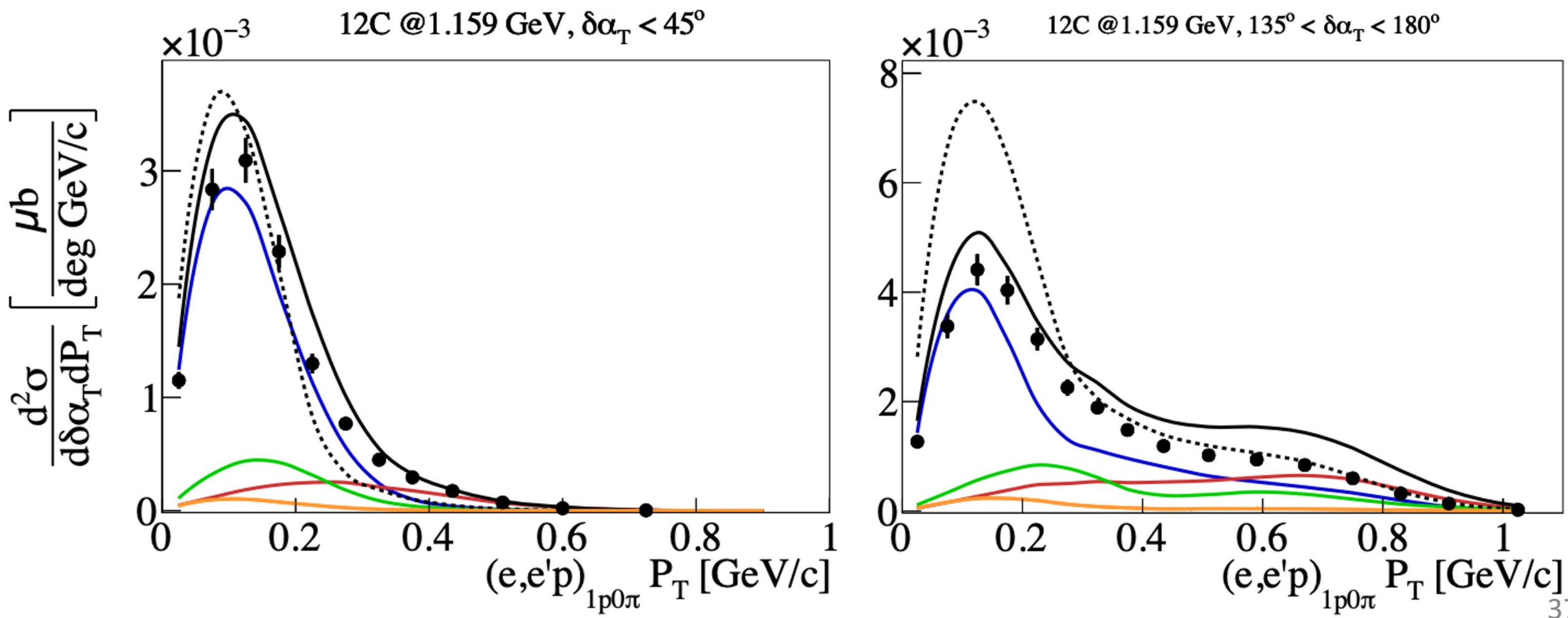
ν_μ

[S. Gardiner talk,
A. Papadopoulou poster]



e4ν

e^-



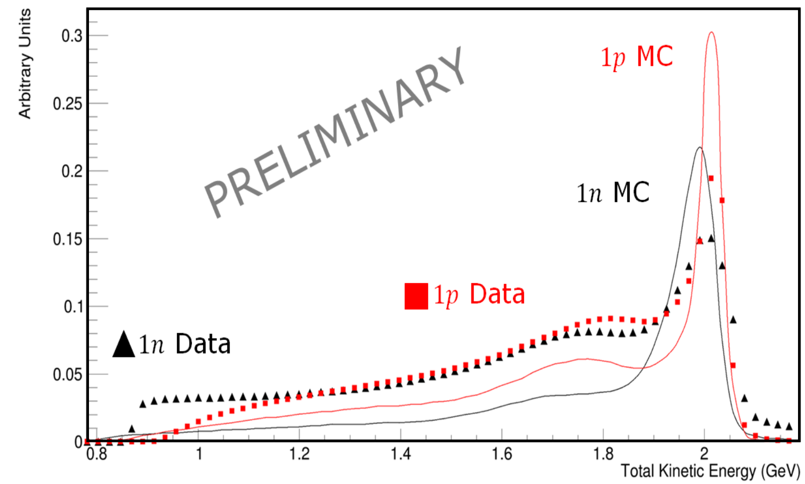
Newly Measured CLAS-12 data

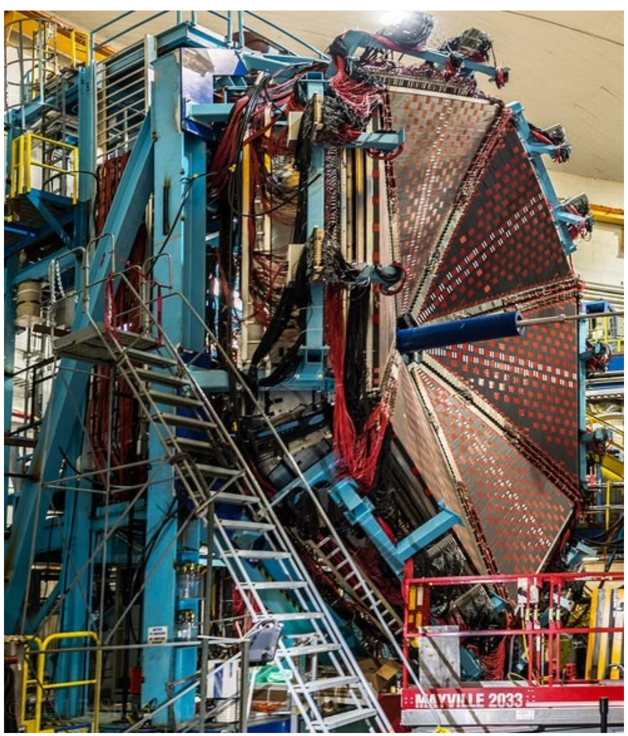
Targets:

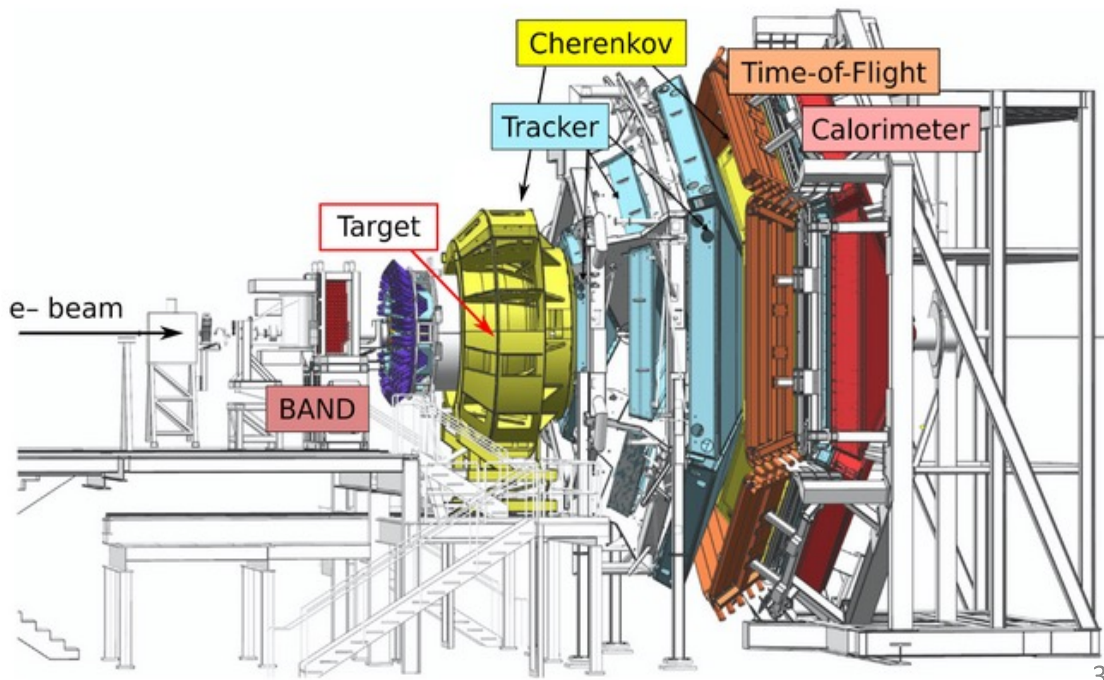
^{4}He, ^{12}C, ^{16}O, ^{40}Ar, ^{120}Sn

Beam Energies:

1, 2, 4, 6 GeV







New Paradigm for Precision Oscillation Studies

Event-Generators

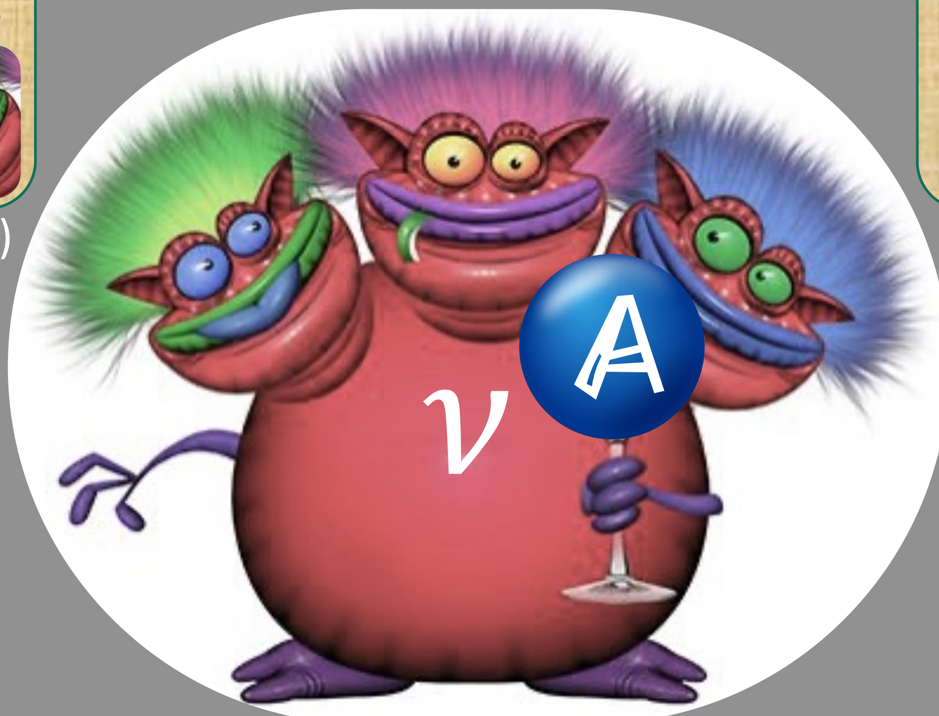
PRD **103**, 113003 (2021)

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 constrain
- Double differential & pion data coming (very) soon
- Theorists & model builder encouraged to also work with electrons to test their work!
- www.e4nu.com

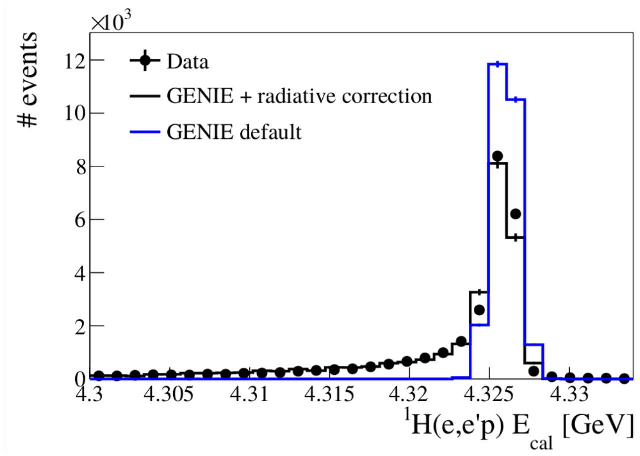
We welcome new collaborators!

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

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

Well defined signal definition: Min θ_e Cut

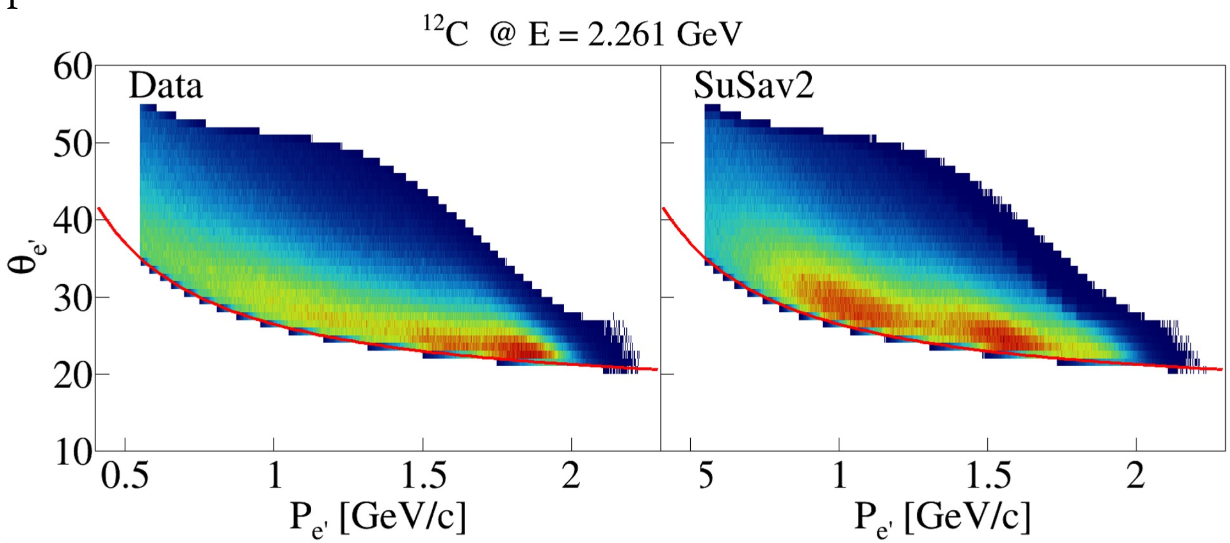
@ 1.1 GeV: $\theta = 17 + 7 / P$

@ 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



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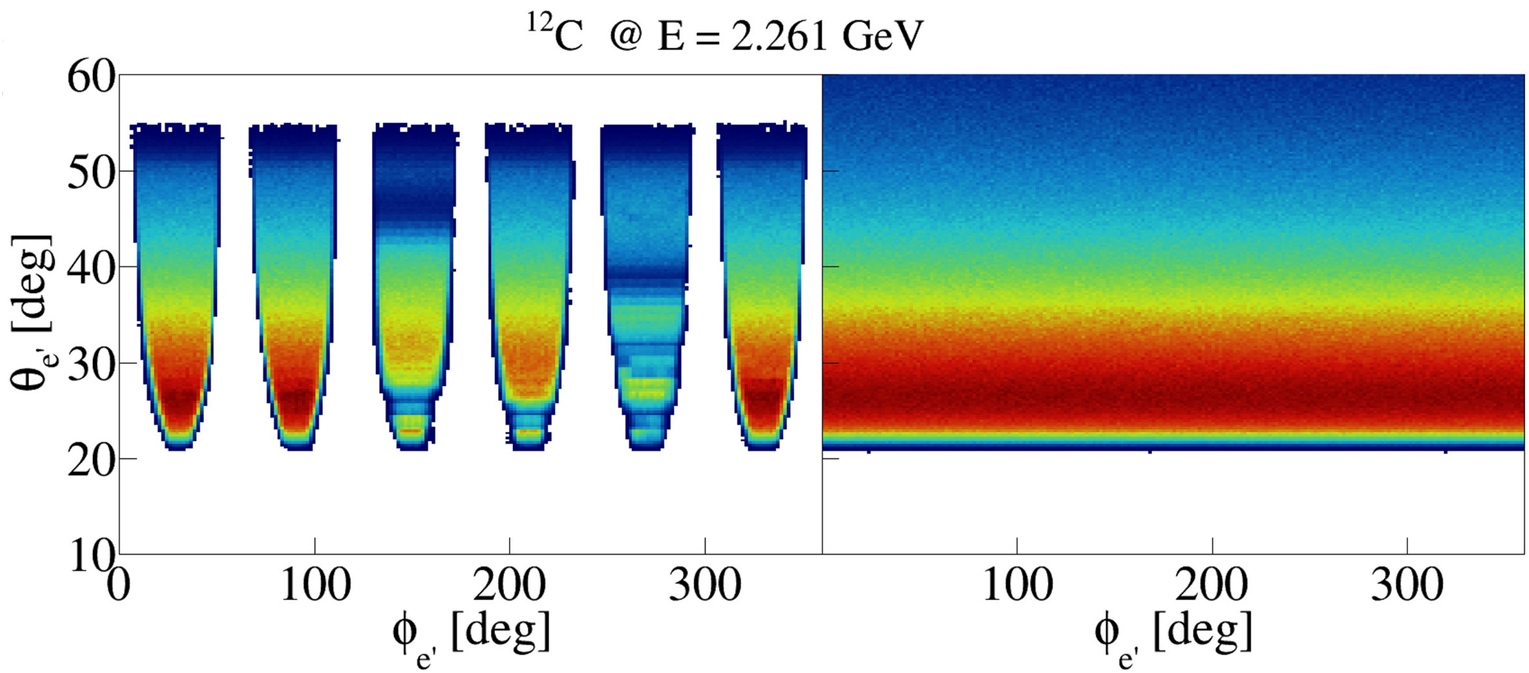
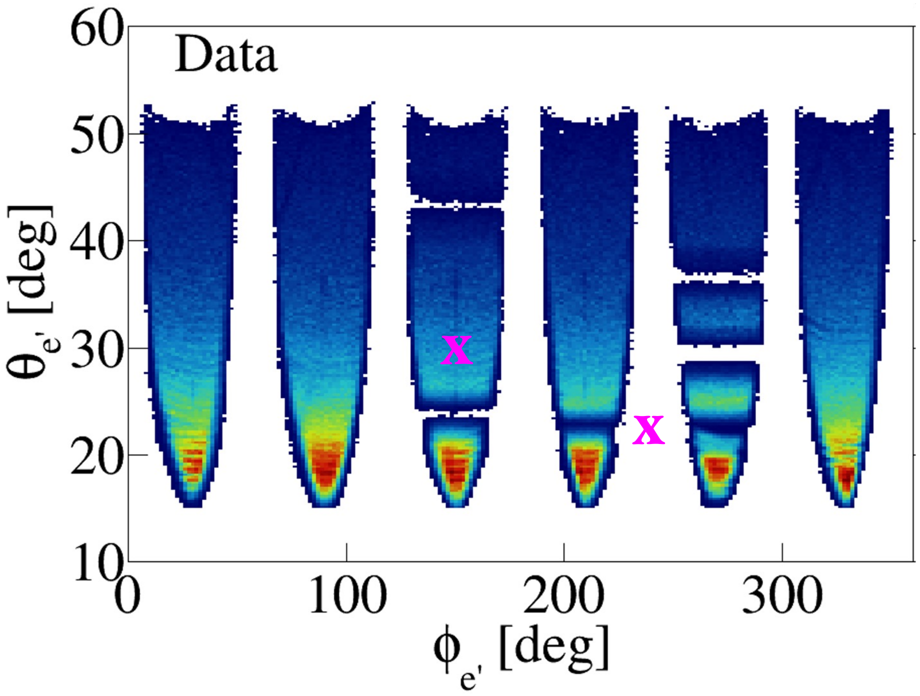
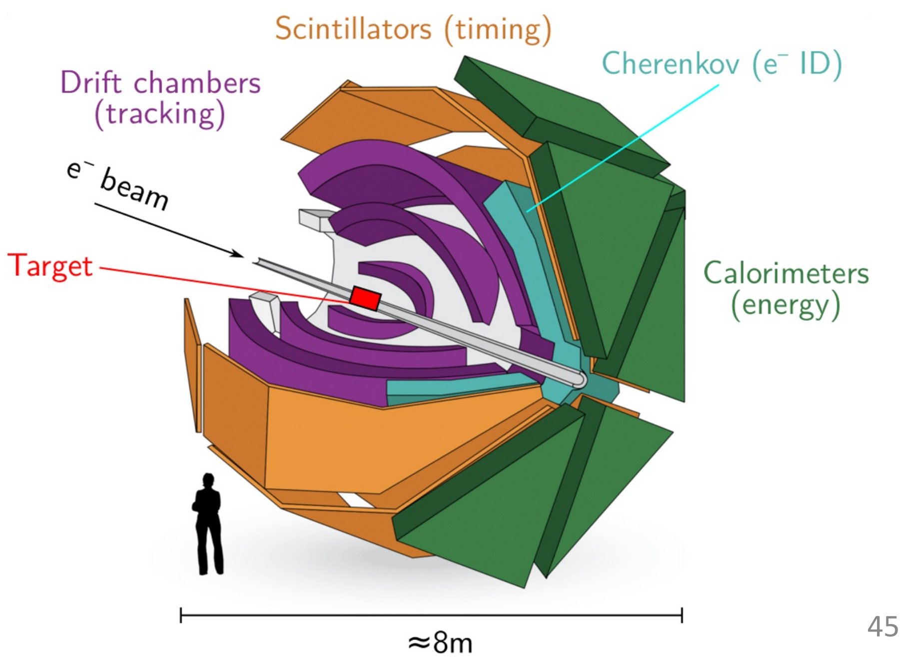


Background Subtraction

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

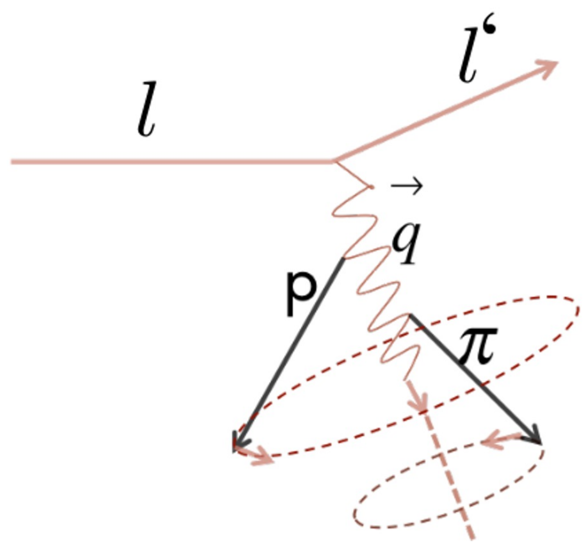




Data Driven Correction

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

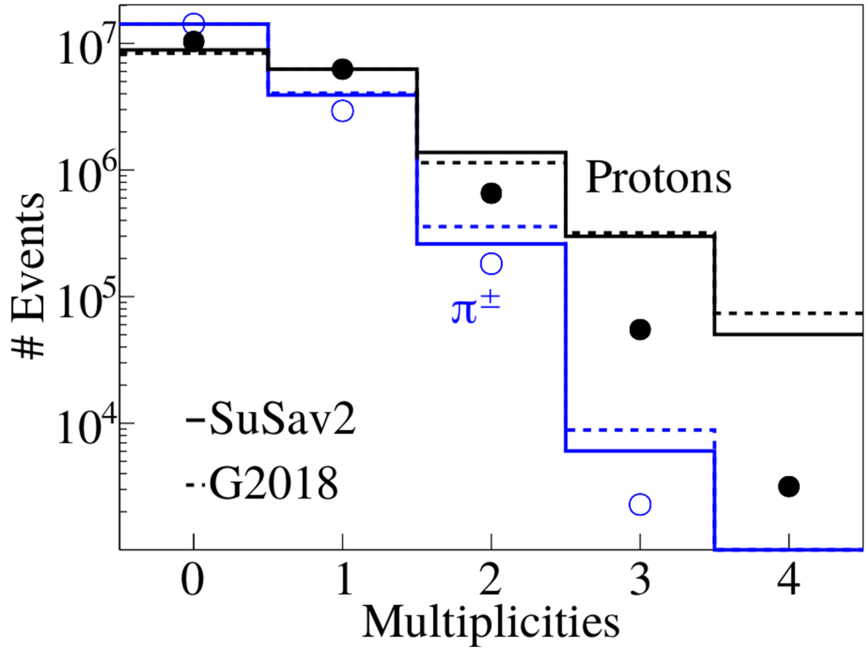
- Use measured (e,e'pπ) events
- Rotate p, π around q to determine π detection efficiency
- Subtract undetected (e,e'pπ)
- Repeat for higher hadron multiplicities



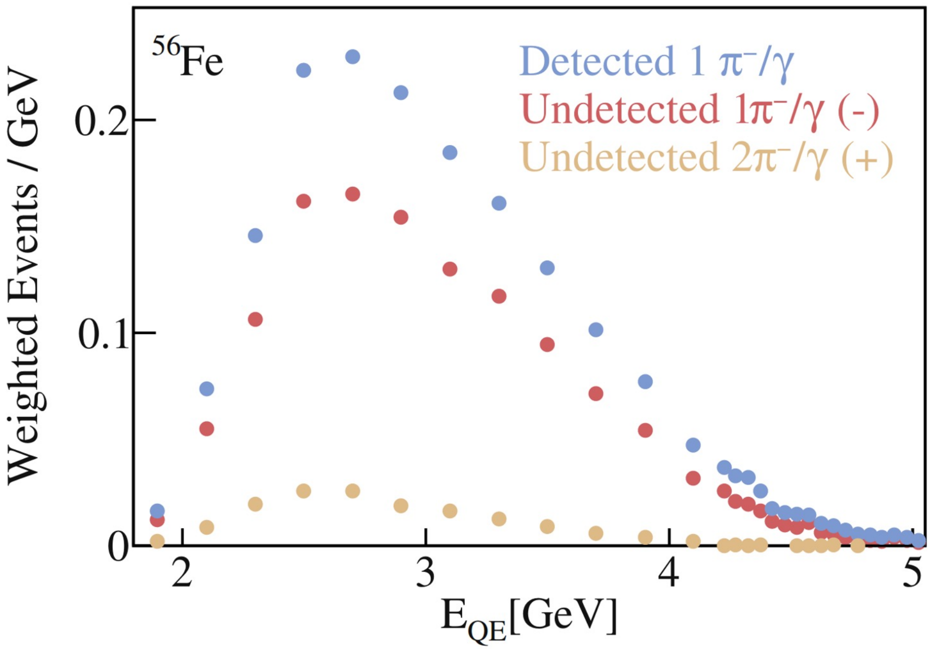
Data Driven Correction

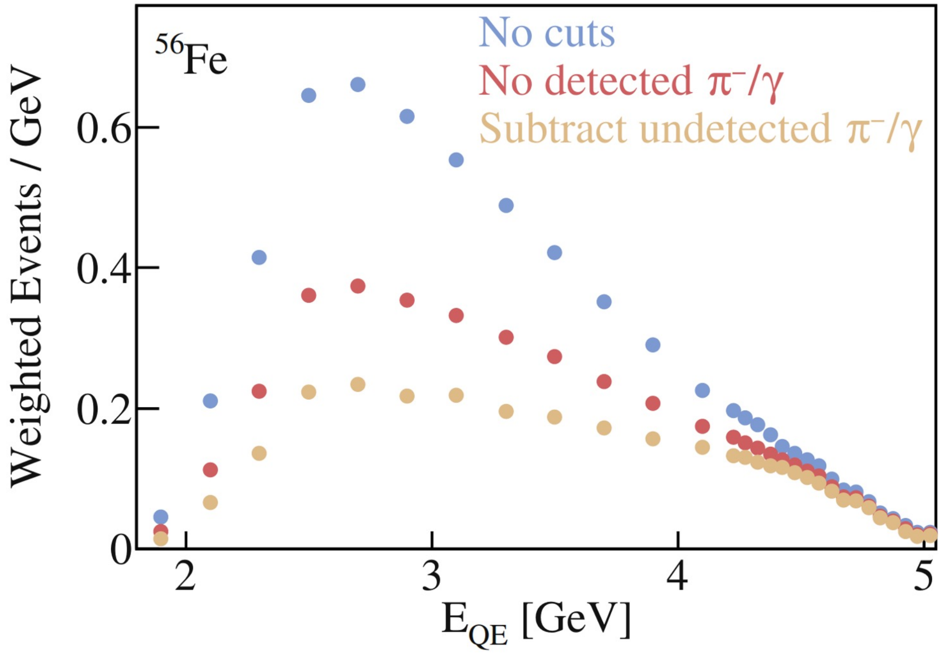
Non-(e,e'p) interactions lead to multi-hadron final states
Gaps can make them look like (e,e'p) events

- 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, ...)

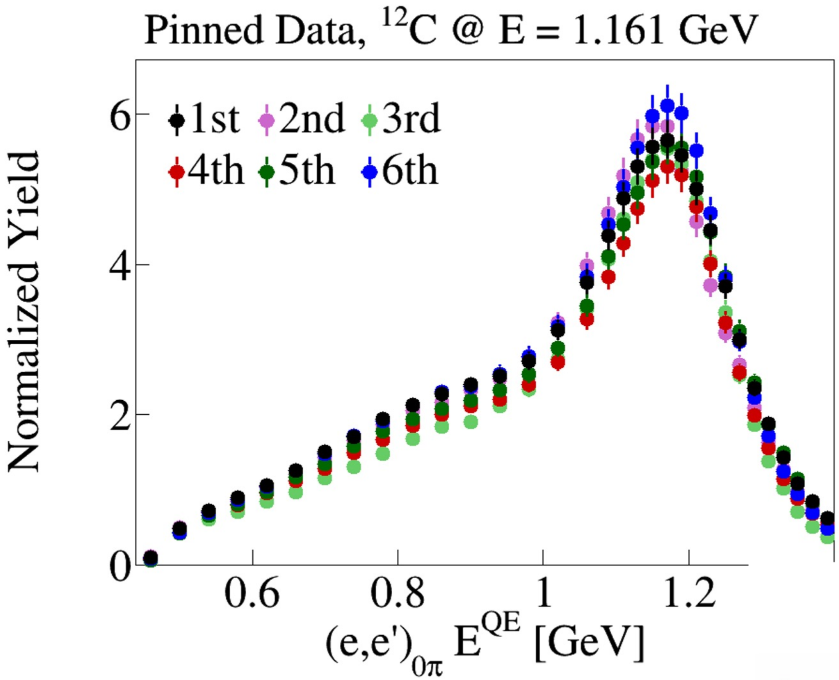


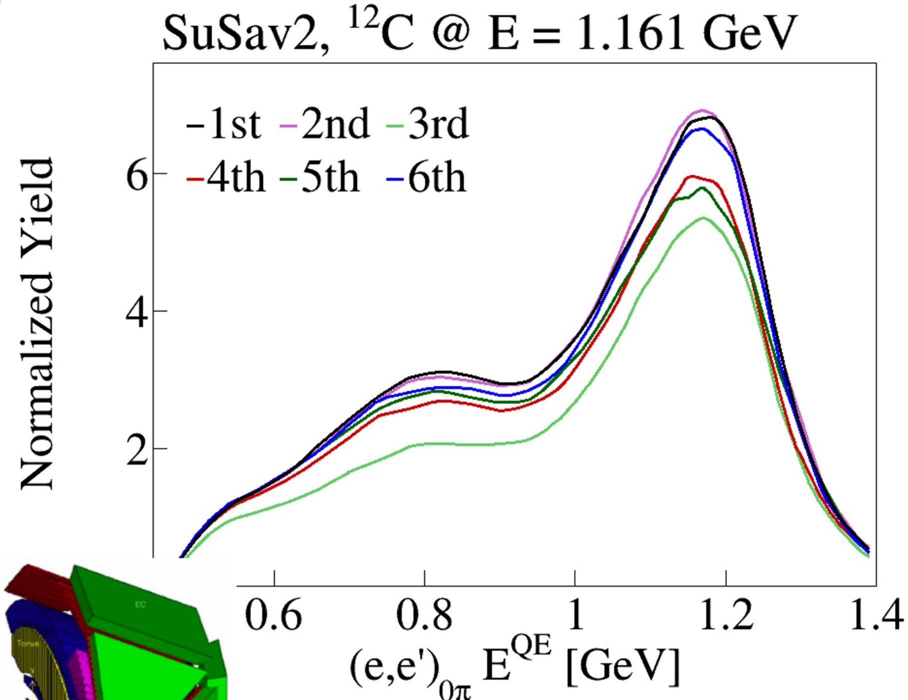
Subtraction Effect

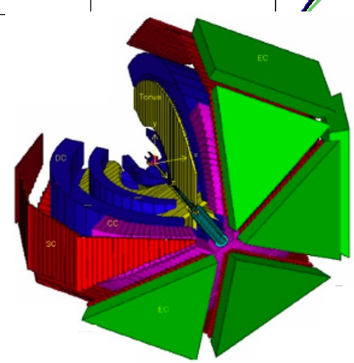




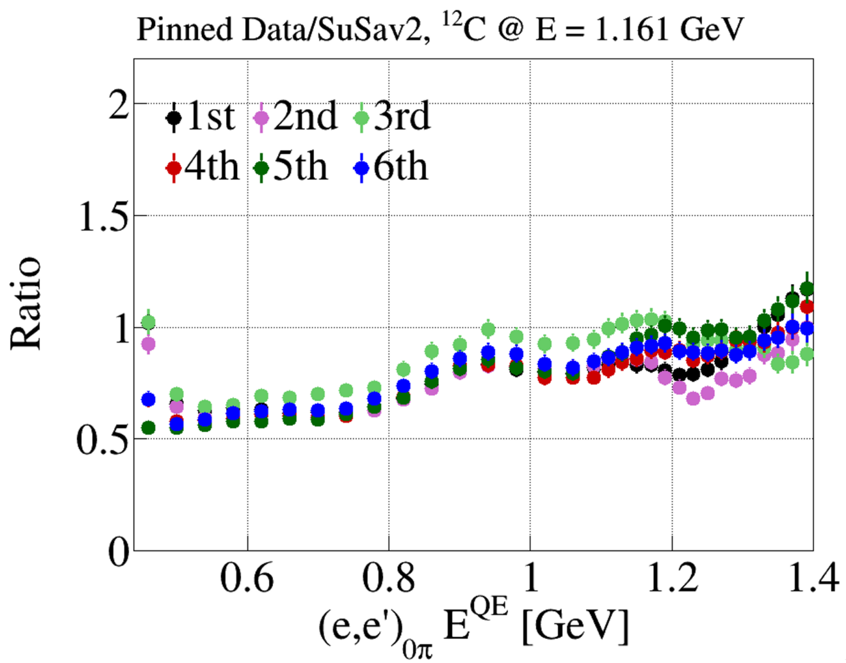
Systematics: Sector Dependence

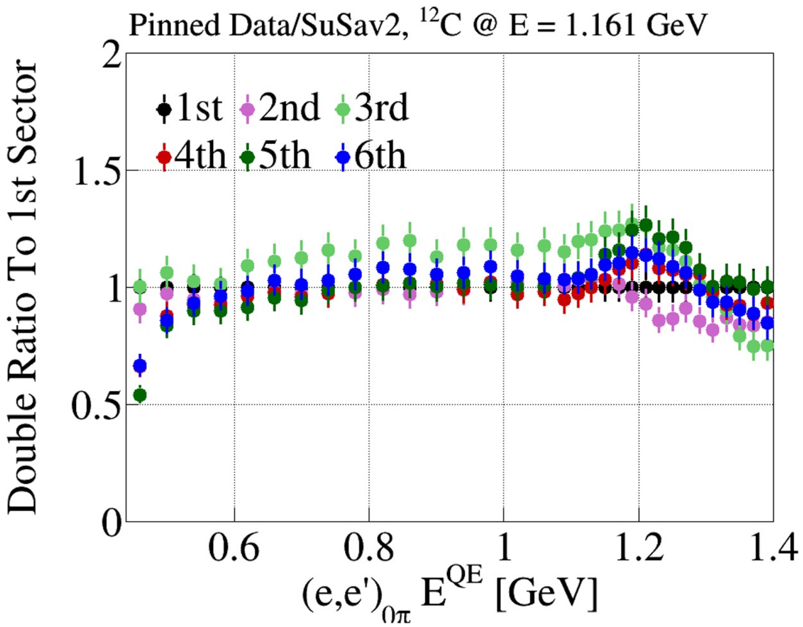






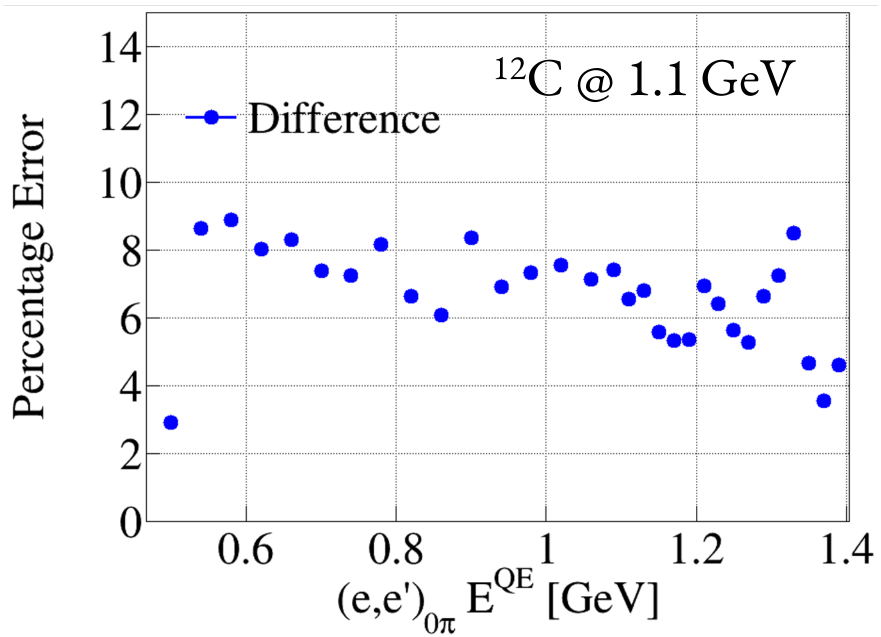
Systematics: Sector Dependence





Systematics: Sector Dependence

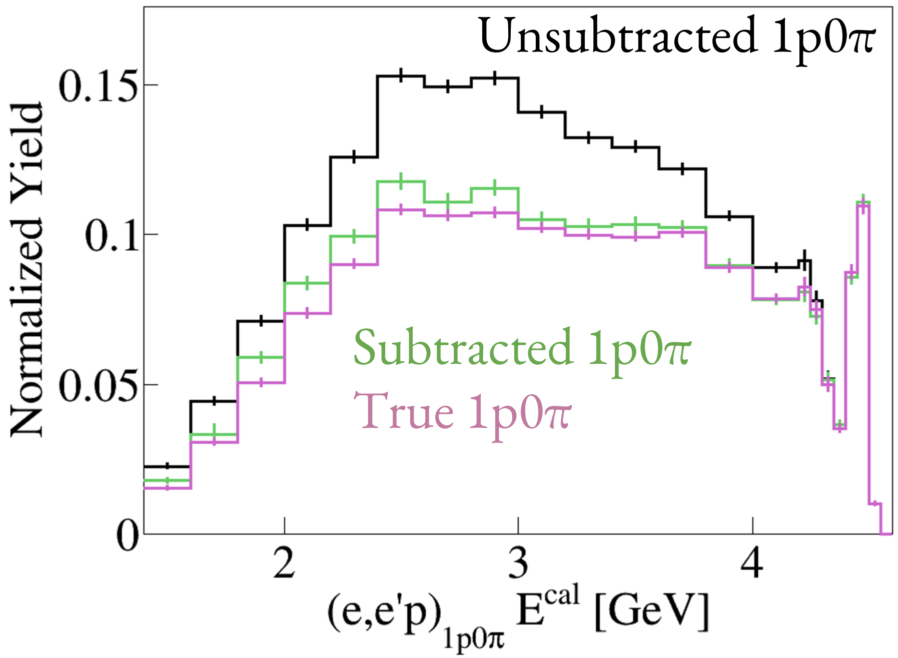
Quantifying uncertainty by using
unweighted variance & by subtracting variance from statistical uncertainty



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

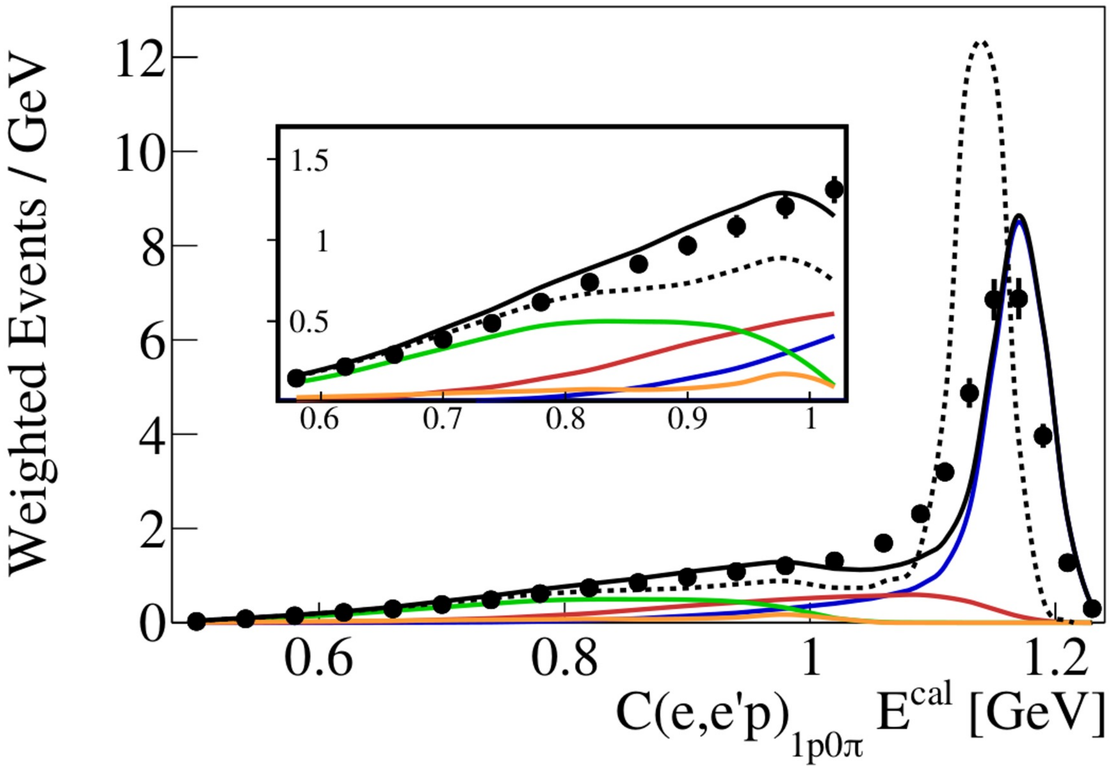
Closure Test

- Use GENIE files
- Filter specific topologies (e.g. 1p0πp + 1p1π)
- Subtracted & True 1p0π are in good agreement

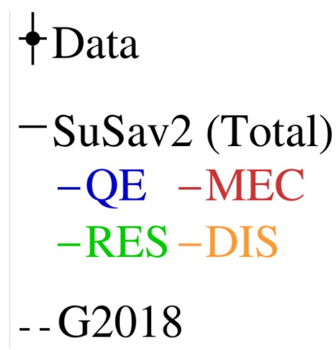


1st e4ν Submission

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

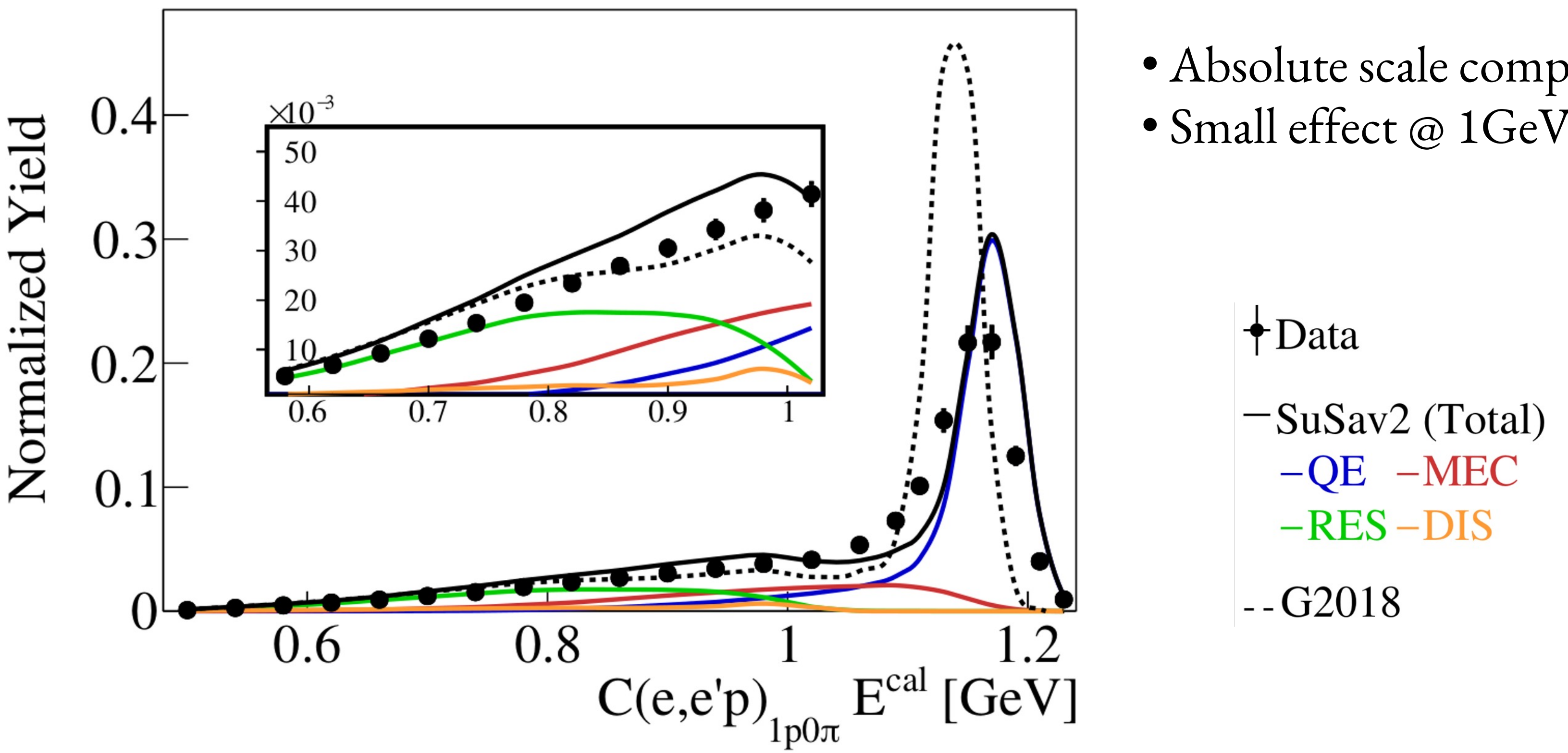
- Divide # events by integrated charge & target thickness to get xsec in μb
- Divide by bin width to get μb/GeV

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

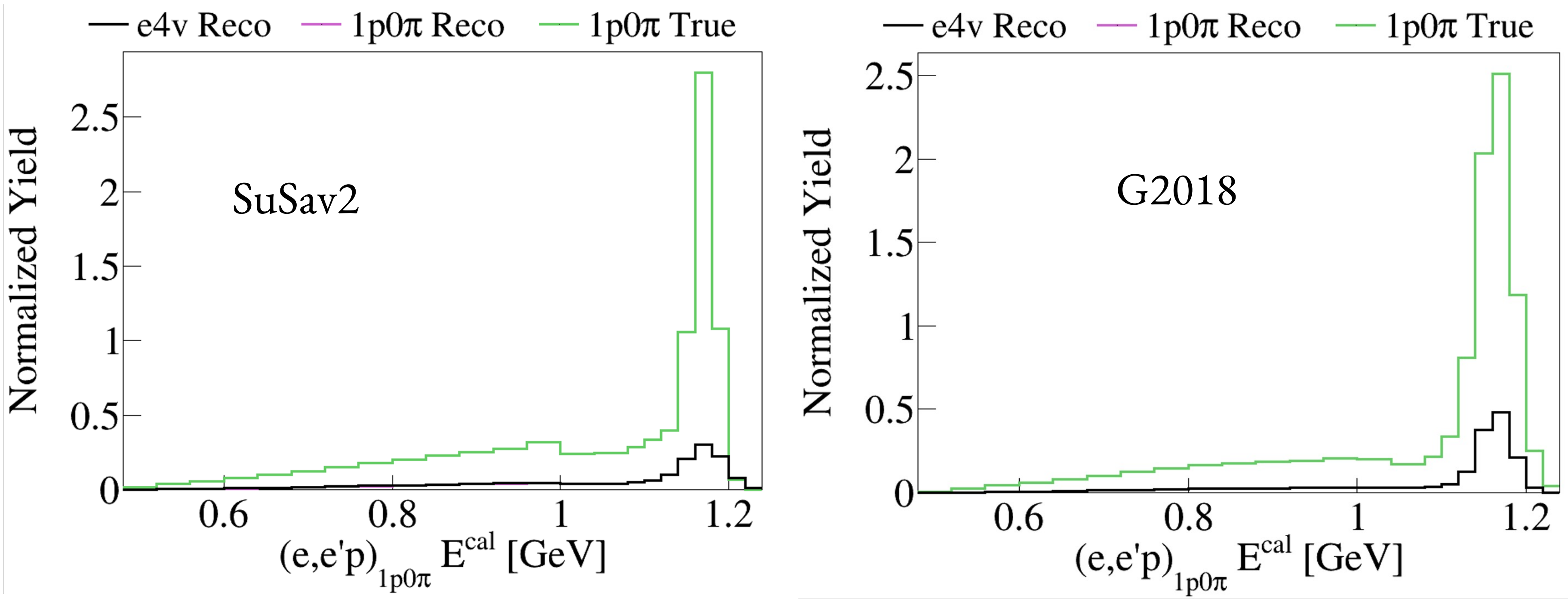


- Absolute scale comparison
- Small effect @ 1GeV

Step #3a: Acceptance Correction

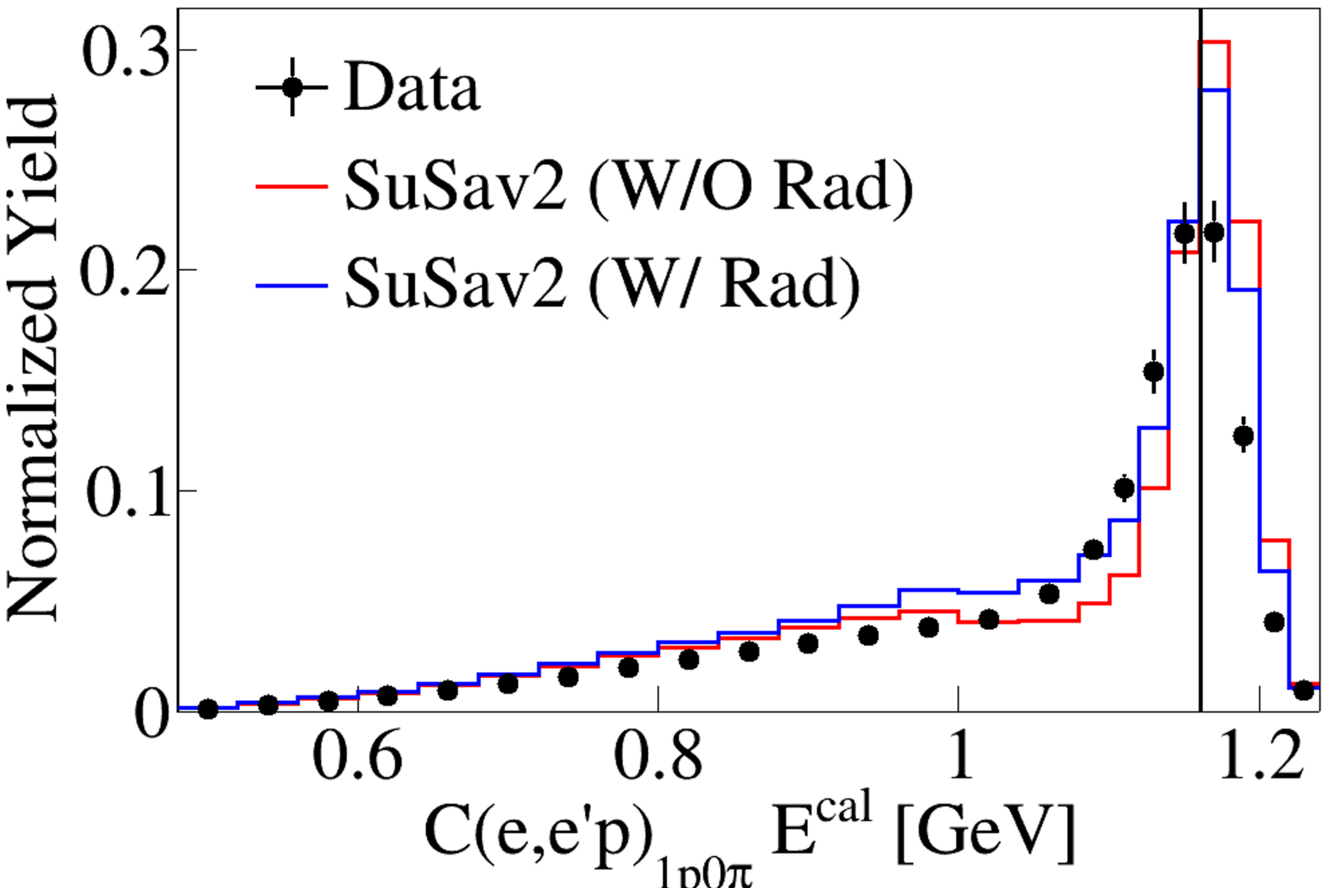
- Start from reco / true ratio w/o radiation to obtain acceptance correction
- Average on a bin-by-bin basis x = |SuSav2 + G2018| / 2
- Due to offset, G2018 Ecal predictions have been shifted by 10/25/36 MeV for 4He/12C/56Fe respectively

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

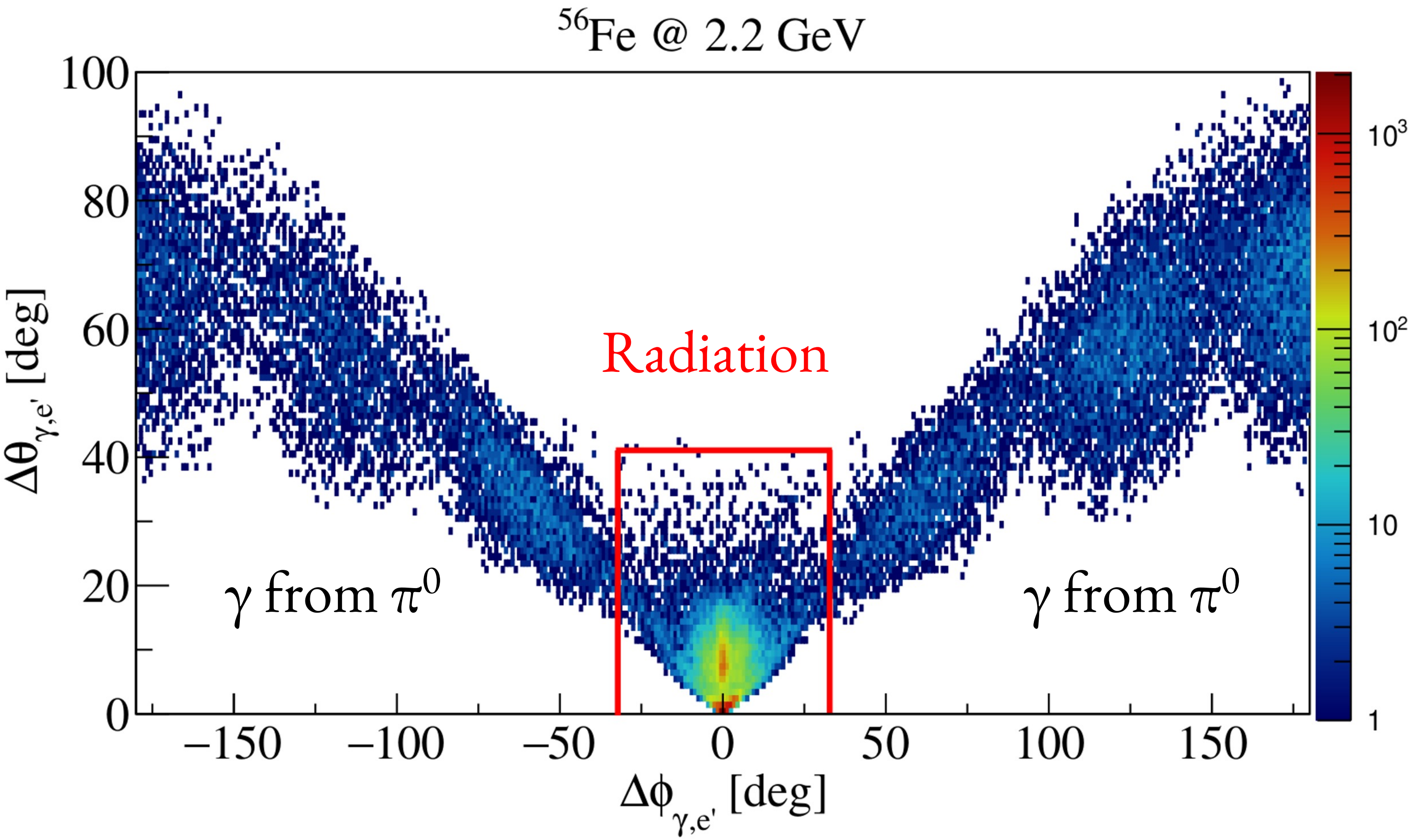
On a bin-by-bin basis

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

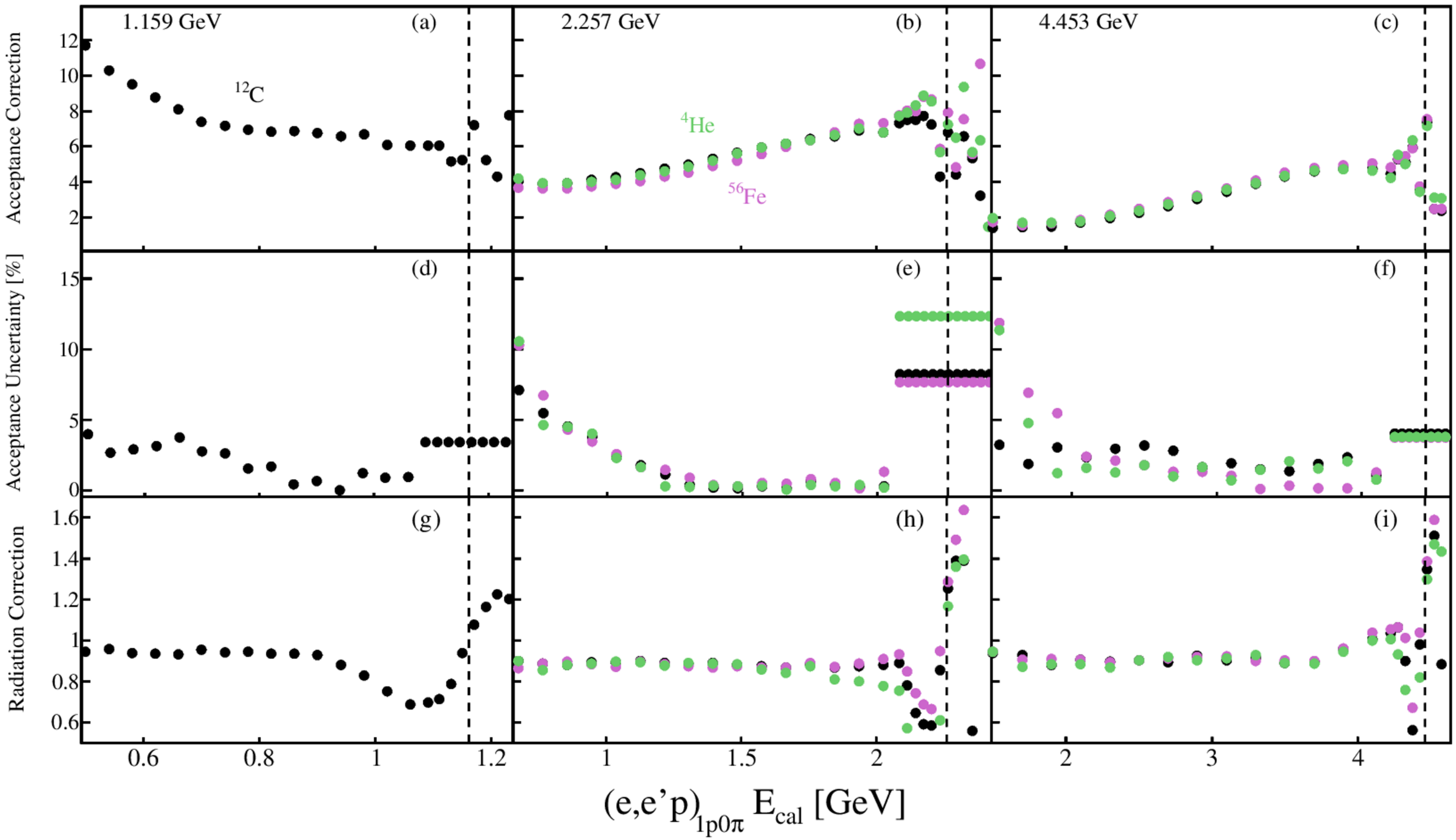
Bin Entry = x / Average * 100 %

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

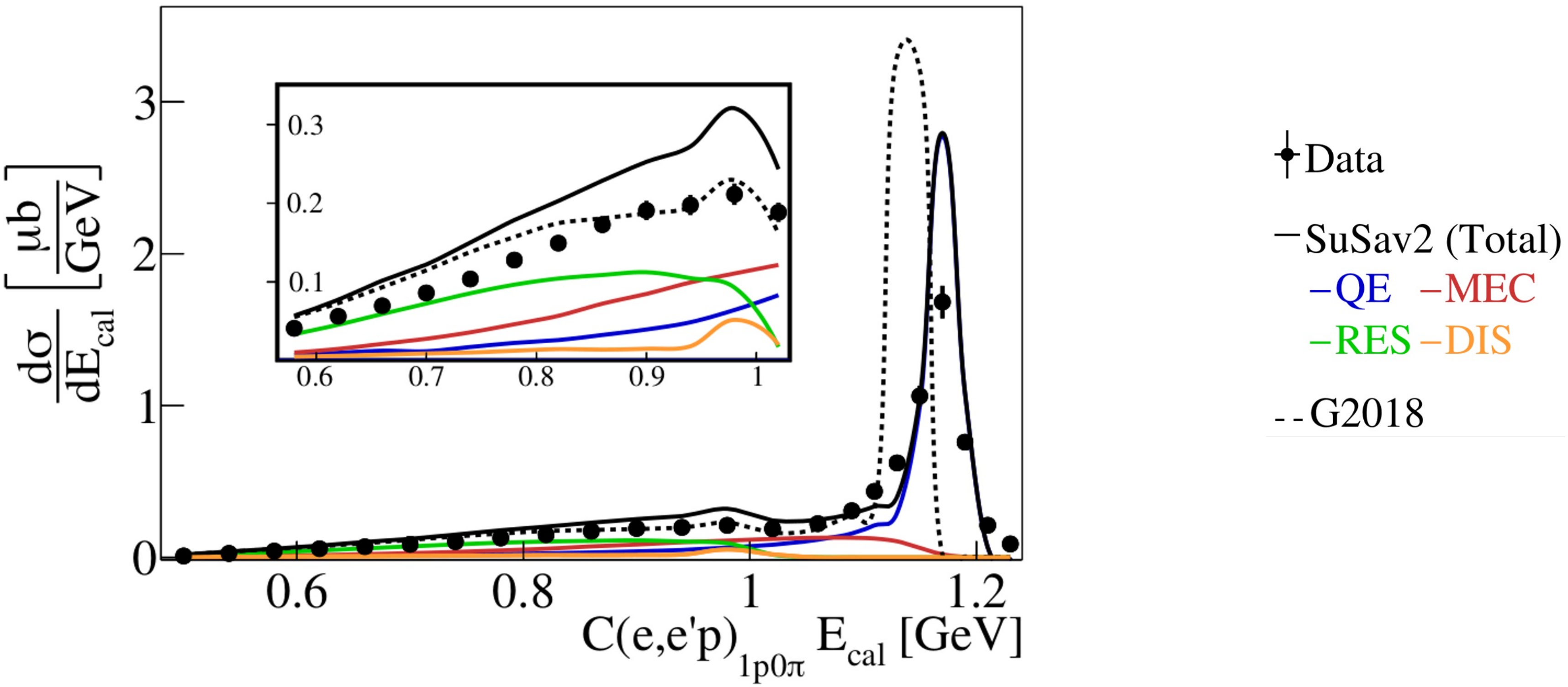


Correction Factors

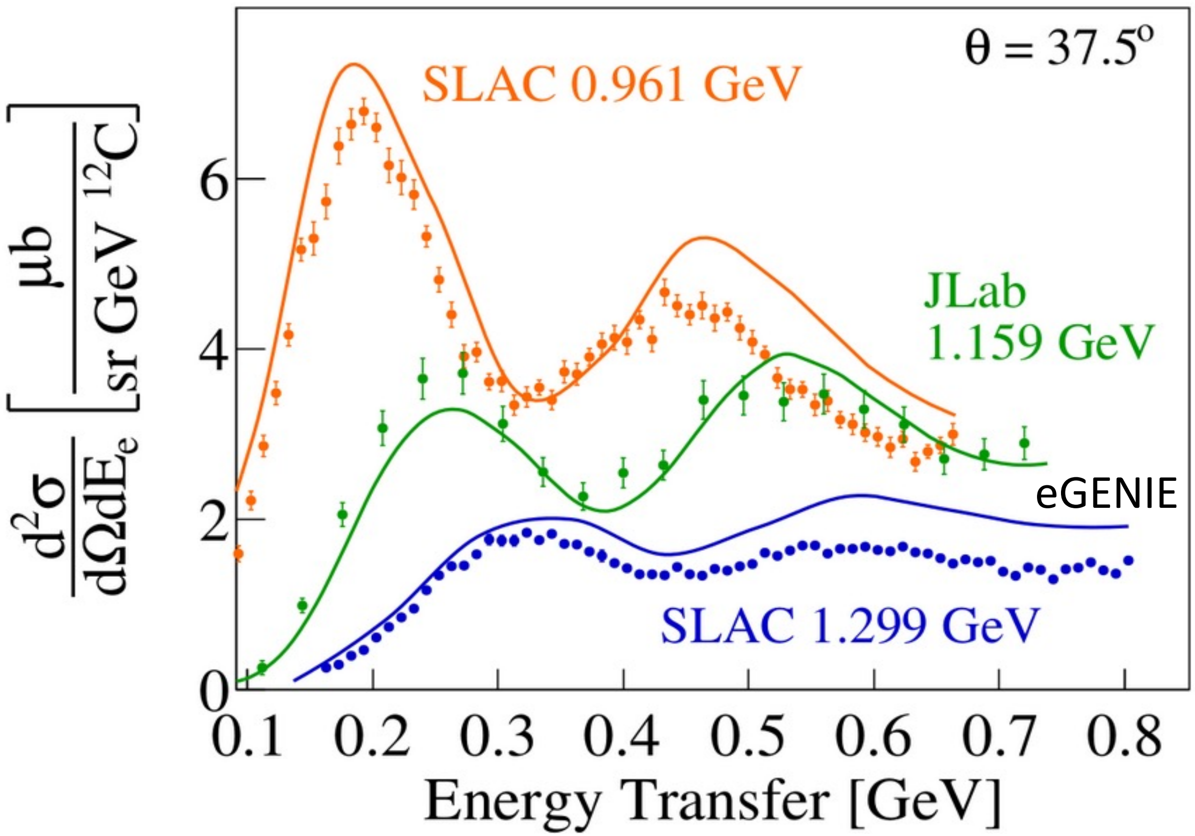


Step #4: Absolute Cross Sections

After both acceptance & radiation corrections, without systematics yet



Sanity Check: (e,e’) cross-sections



Khachatryan, Papadopoulou, and Ashkenazi et al.
(CLAS & e4ν collaborations), Nature **599**, 565 (2021).

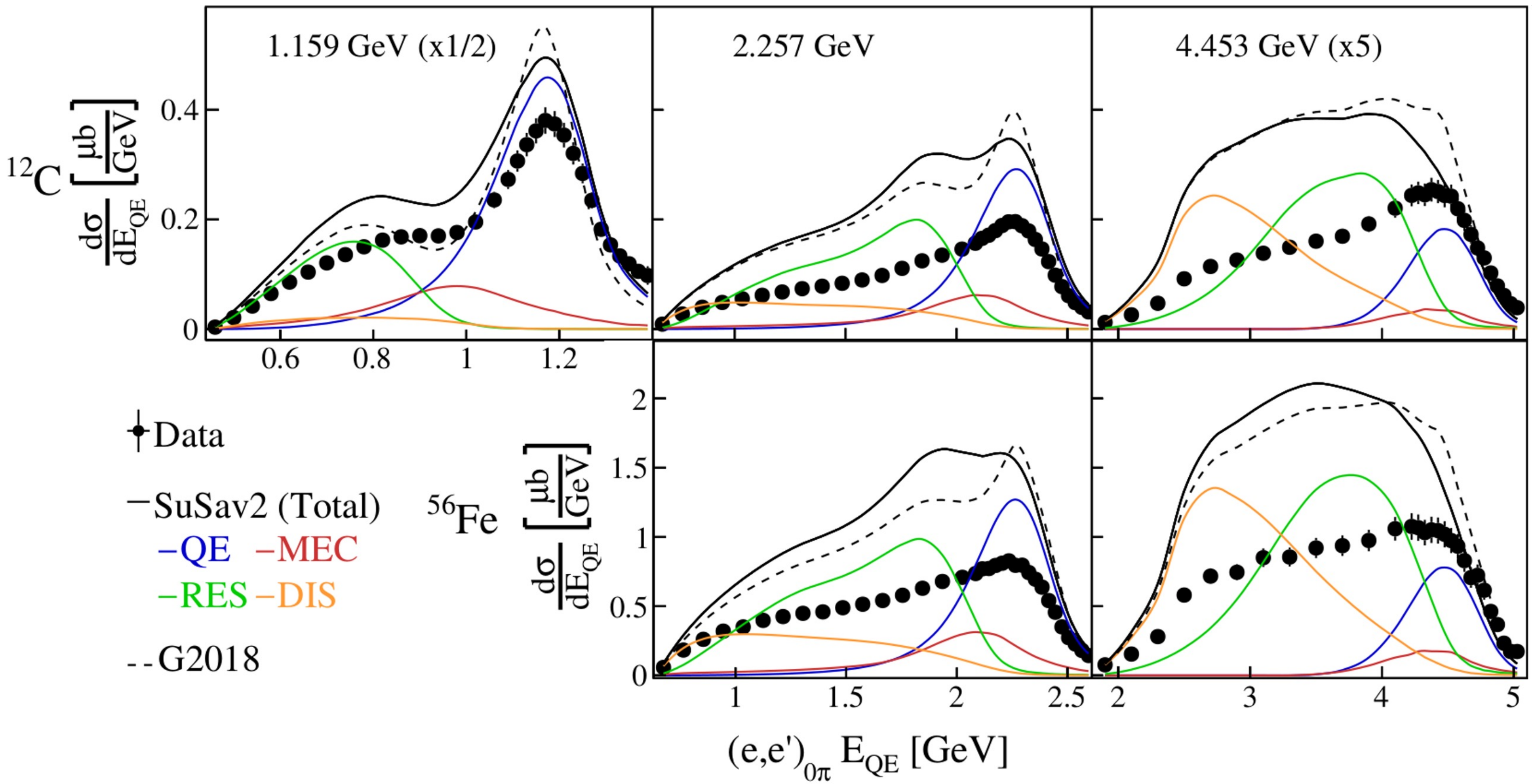
Systematics

Source	Uncertainty (%)
Detector acceptance Identification cuts $\varphi_{q\pi}$ 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 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

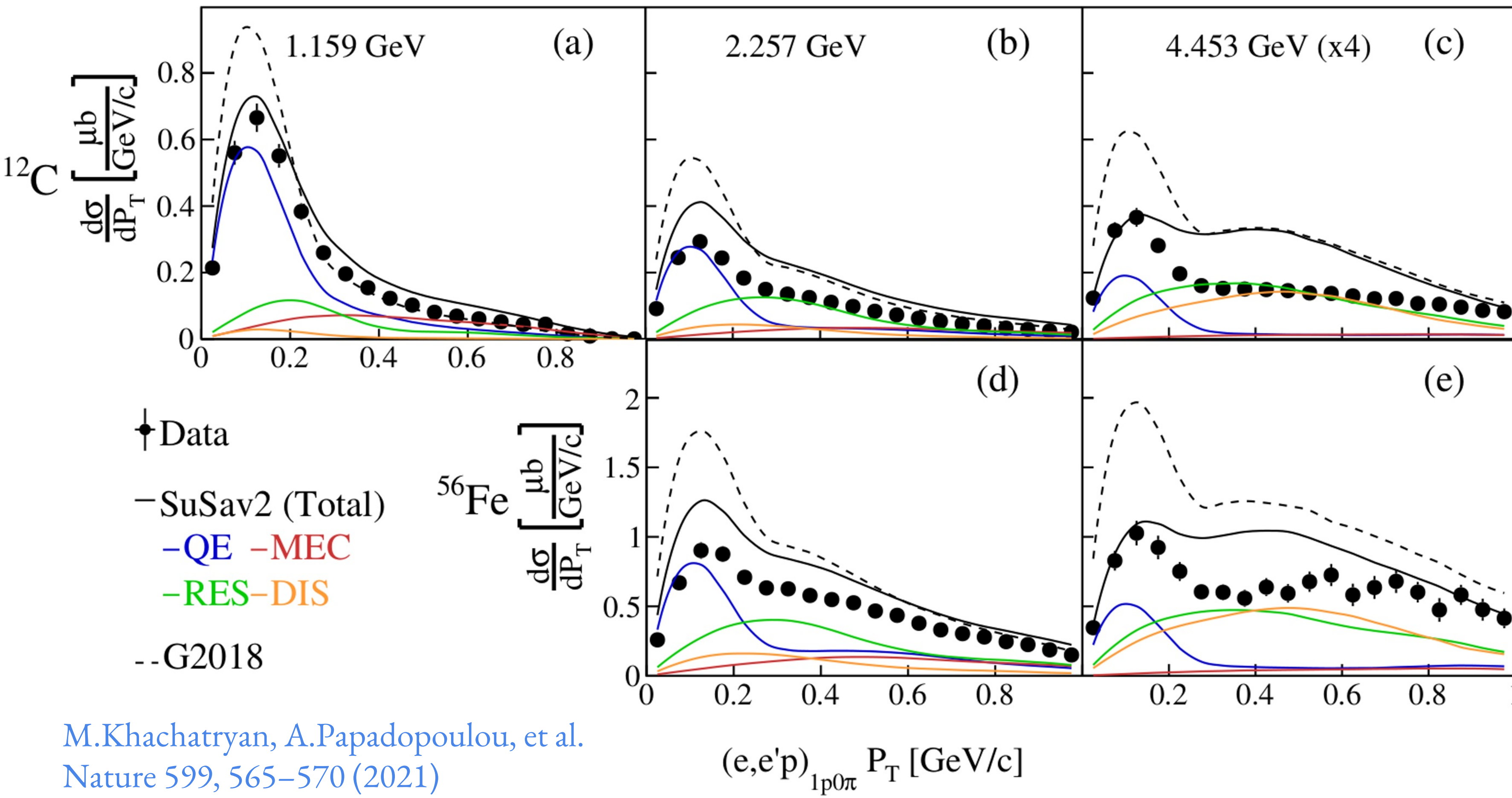
E_{QE} Nucleus & Energy Dependence



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

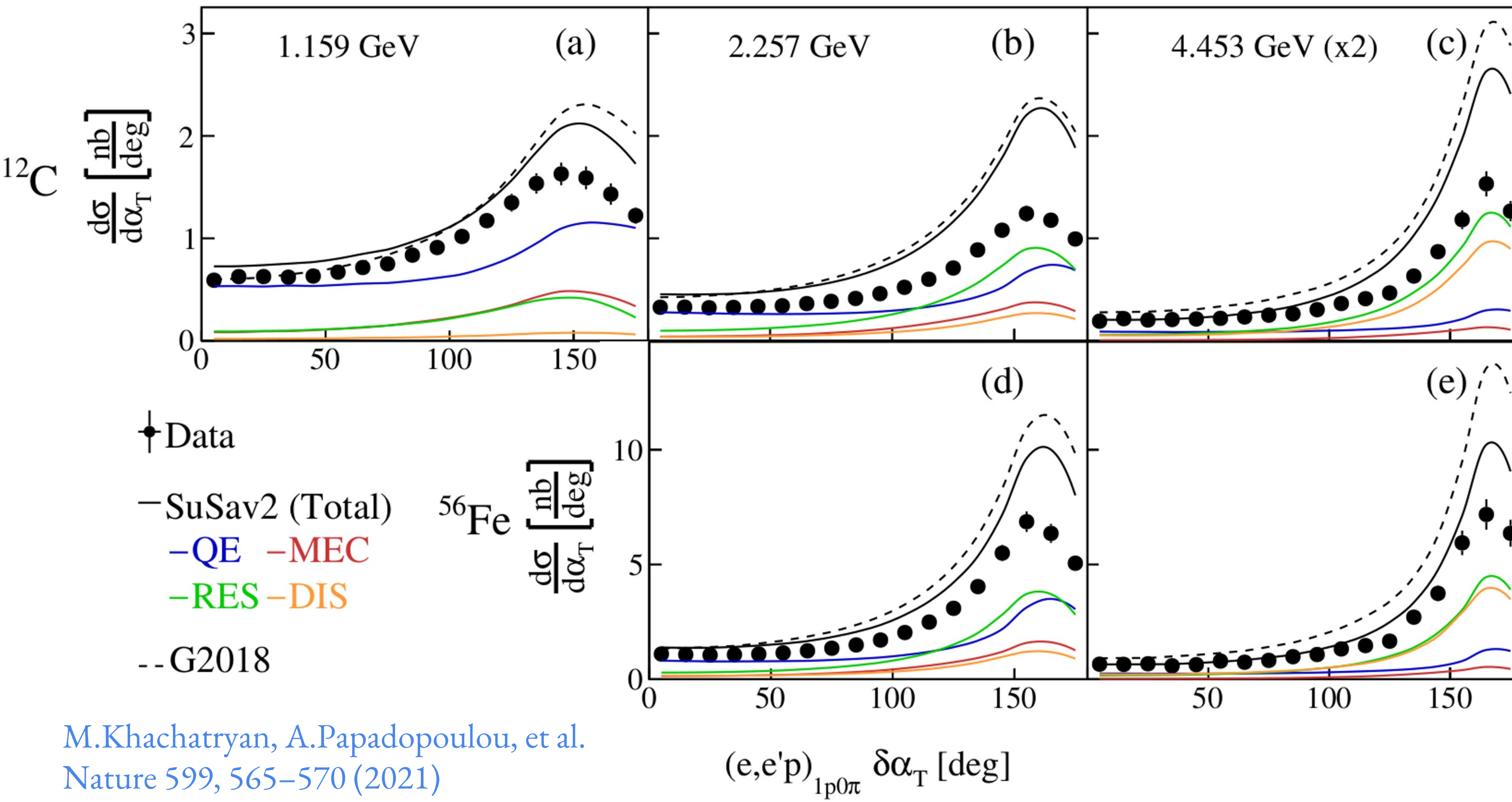
A.Papadopoulou, et al,
In preparation

P_T Nucleus & Energy Dependence



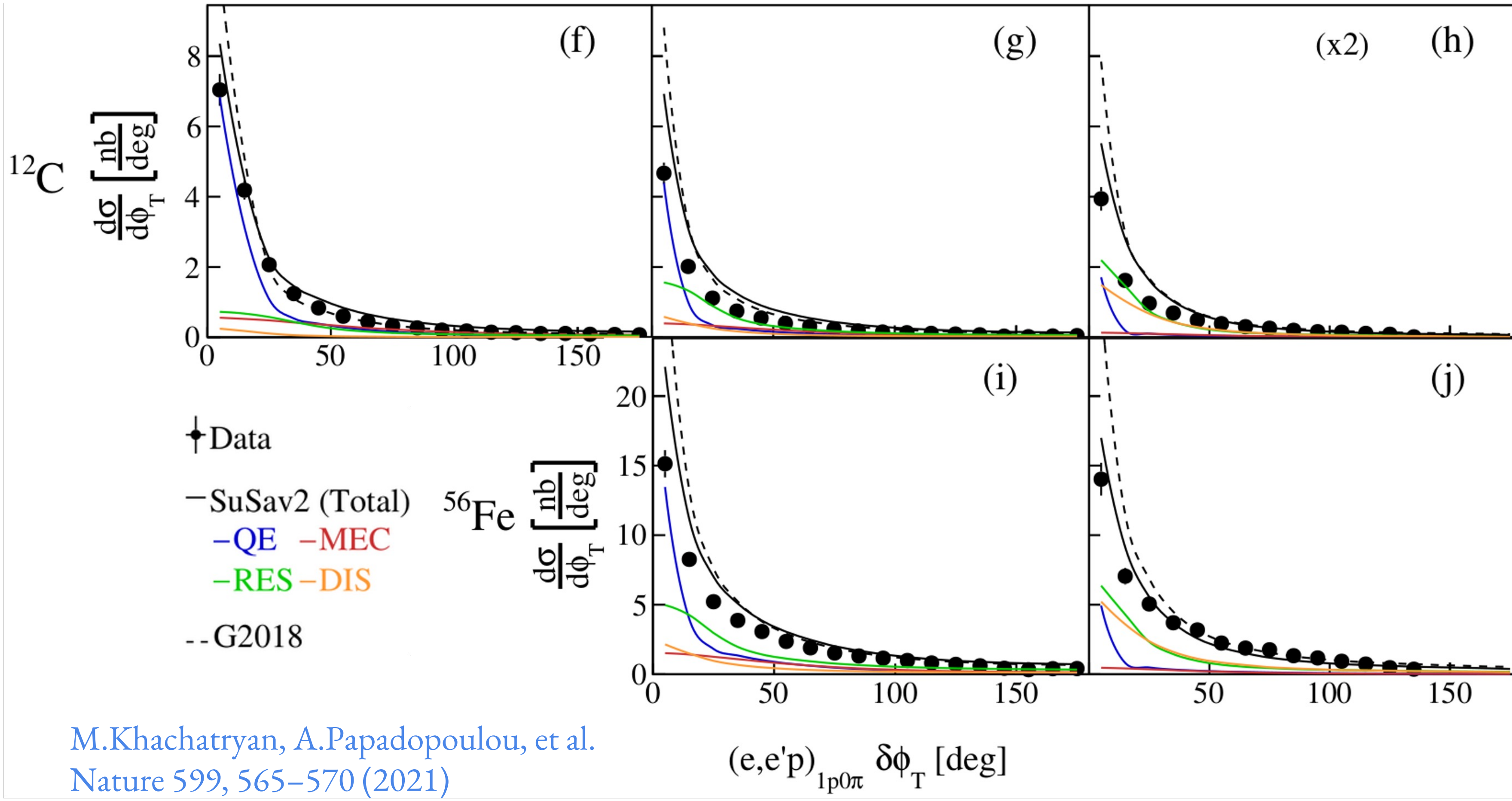
M.Khachatryan, A.Papadopoulou, et al.
Nature 599, 565–570 (2021)

$\delta\alpha_T$ Nucleus & Energy Dependence



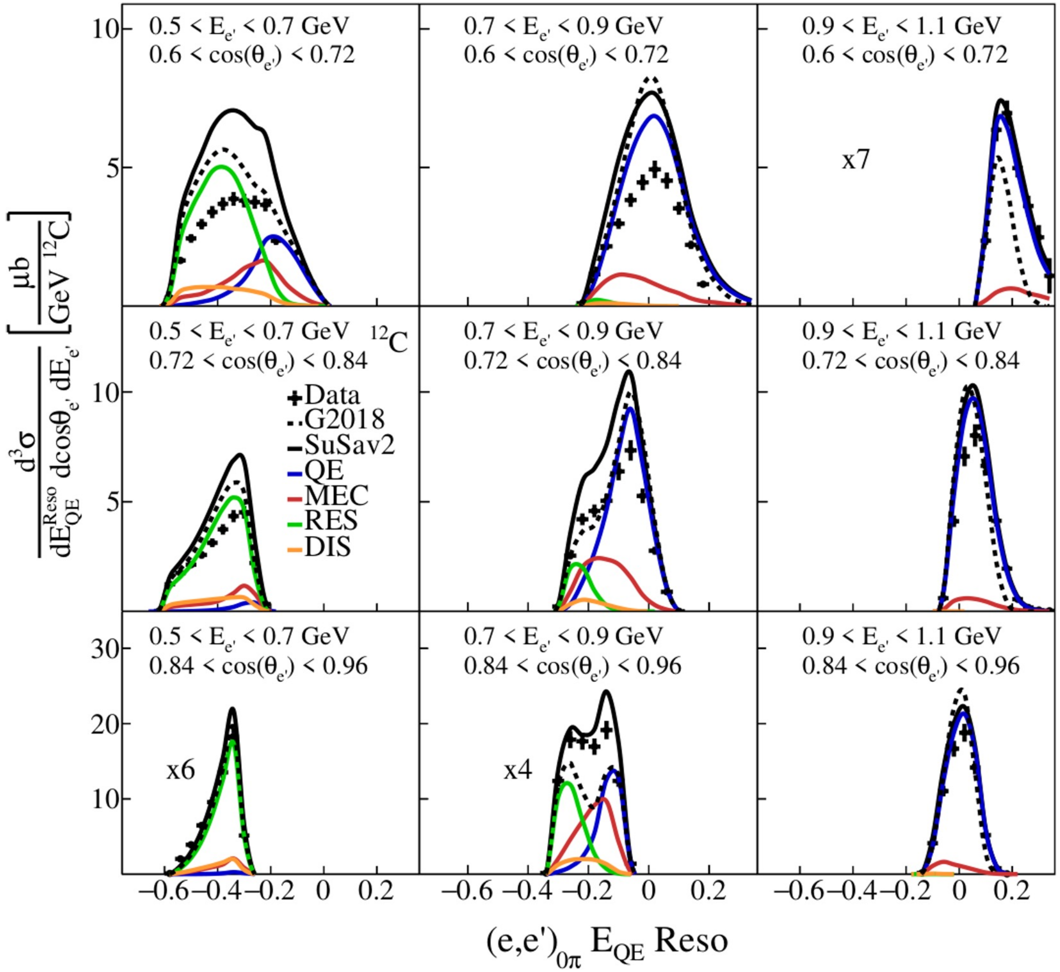
M.Khachatryan, A.Papadopoulou, et al.
Nature 599, 565–570 (2021)

$\delta\varphi_T$ Nucleus & Energy Dependence



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

Into The 3D e4ν Multiverse!

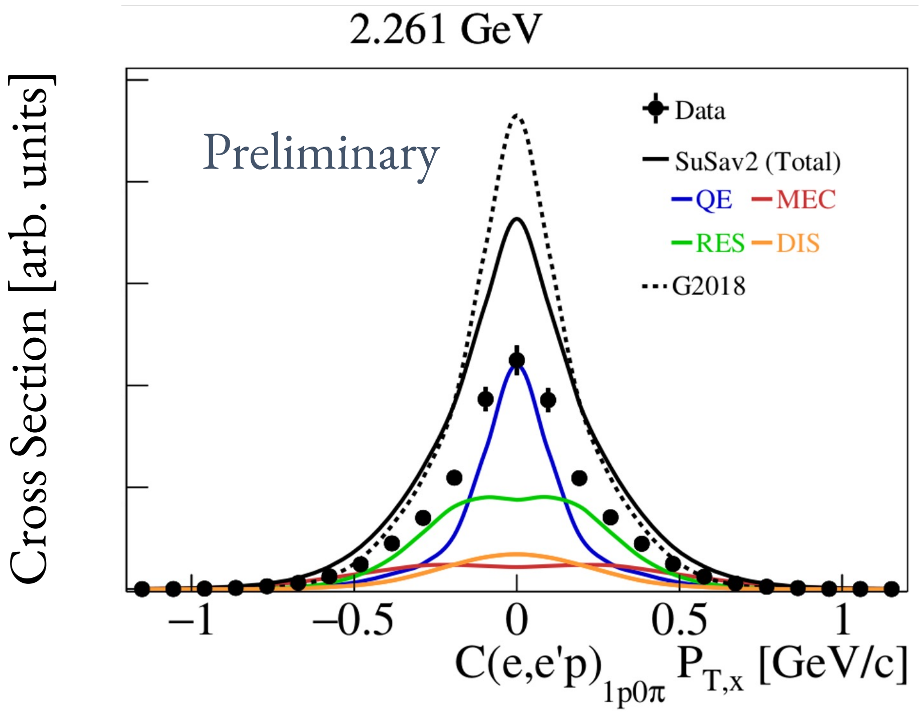


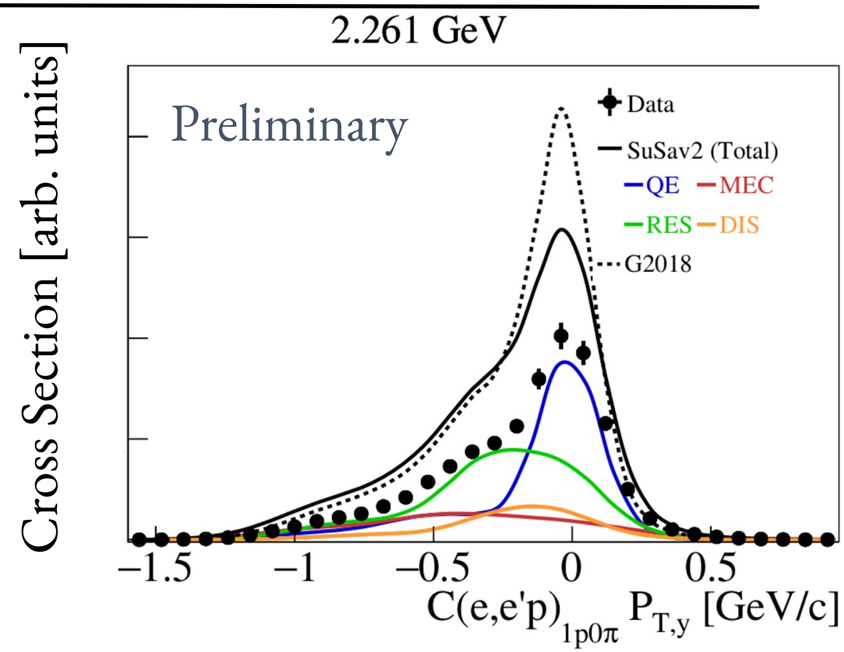
A.Papadopoulou, et al,
In preparation

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



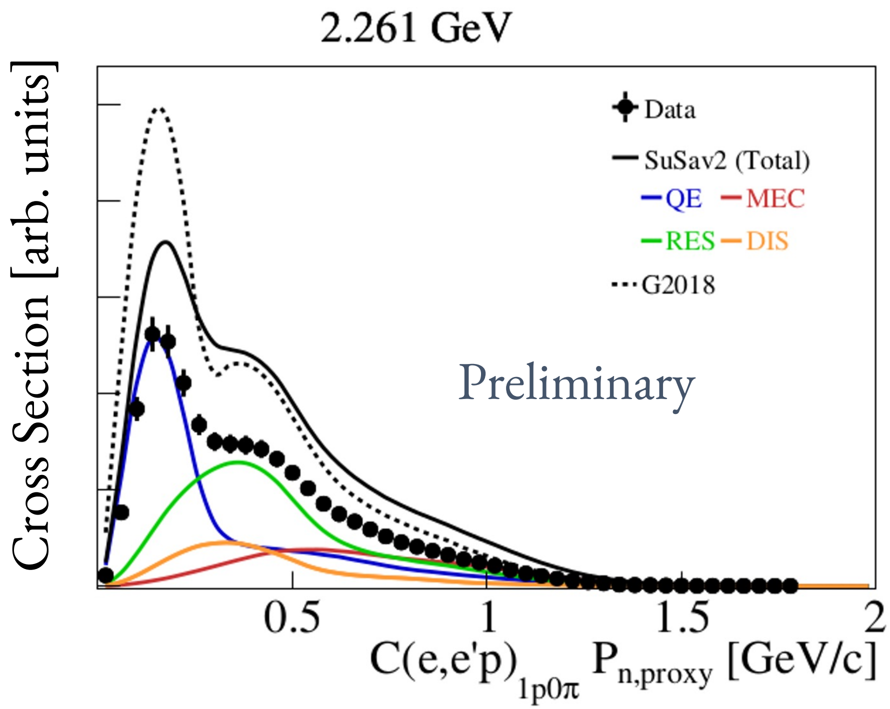


$$\delta p_{T_y} = -\hat{p}_T^l \cdot \delta\vec{p}_T = |\delta\vec{p}_T| \cos(\delta\alpha_T)$$

Sensitivity to final state interactions

A.Papadopoulou, et al, In preparation

Missing Momentum Approximation



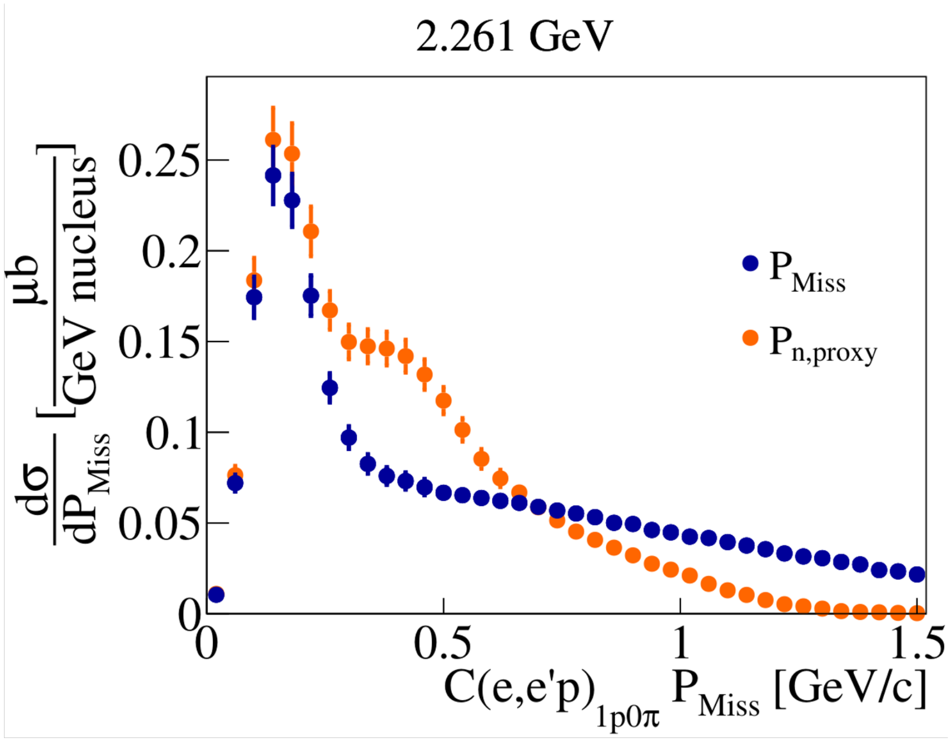
A.Papadopoulou, et al, In preparation

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

Under QE assumption

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

Fails To Reproduce True Missing Momentum



A.Papadopoulou, et al, In preparation

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

Under QE assumption

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

True missing momentum

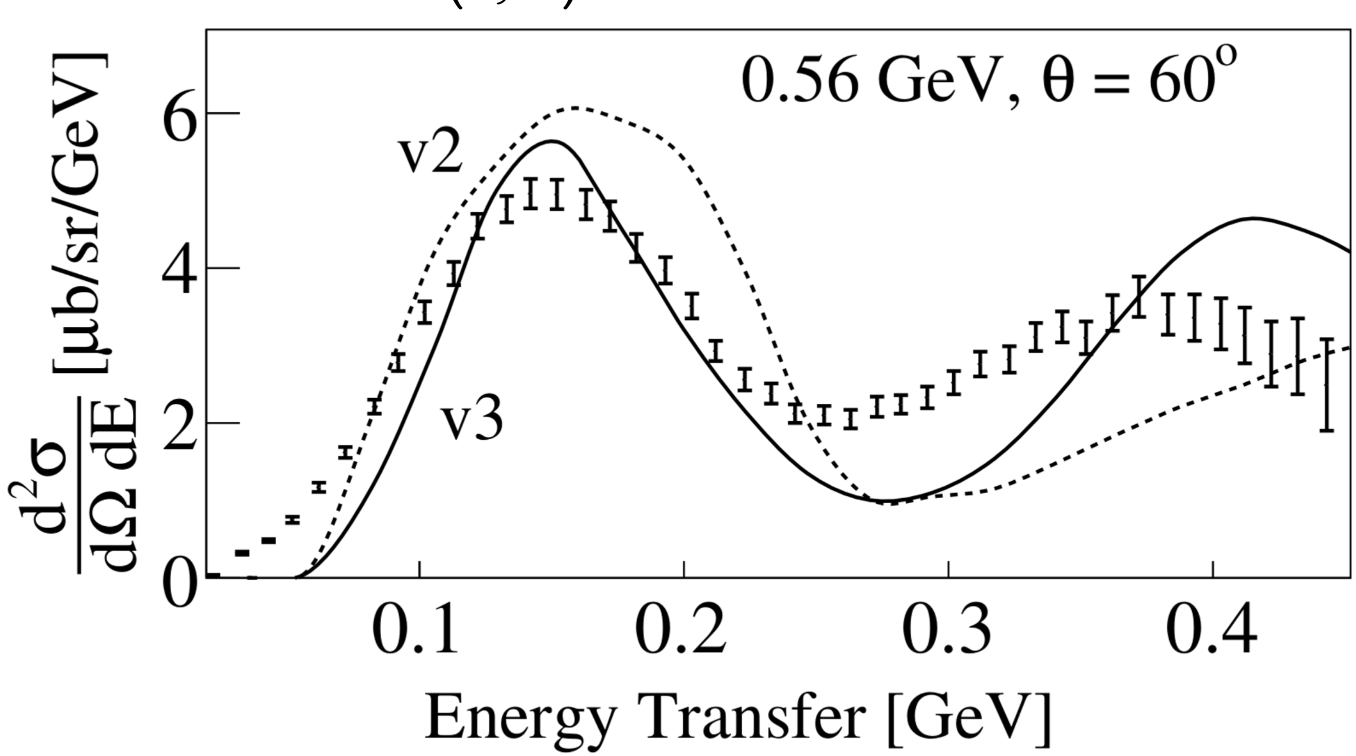
$$P_{miss} = |p - q|$$

p = proton 3-vector

q = momentum transfer

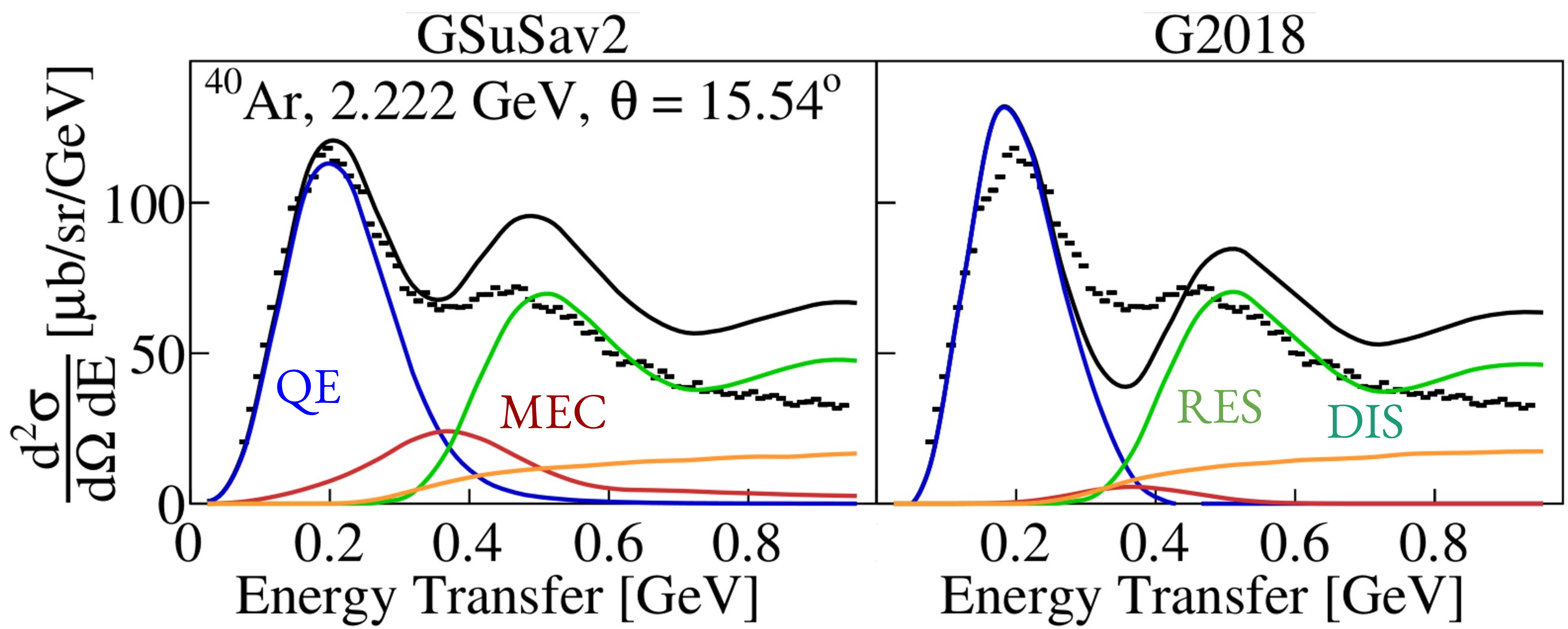
Issues Identified & Fixed In G2018

(e,e’) ^{12}C with G2018



Phys. Rev. D 103, 113003 (2021)

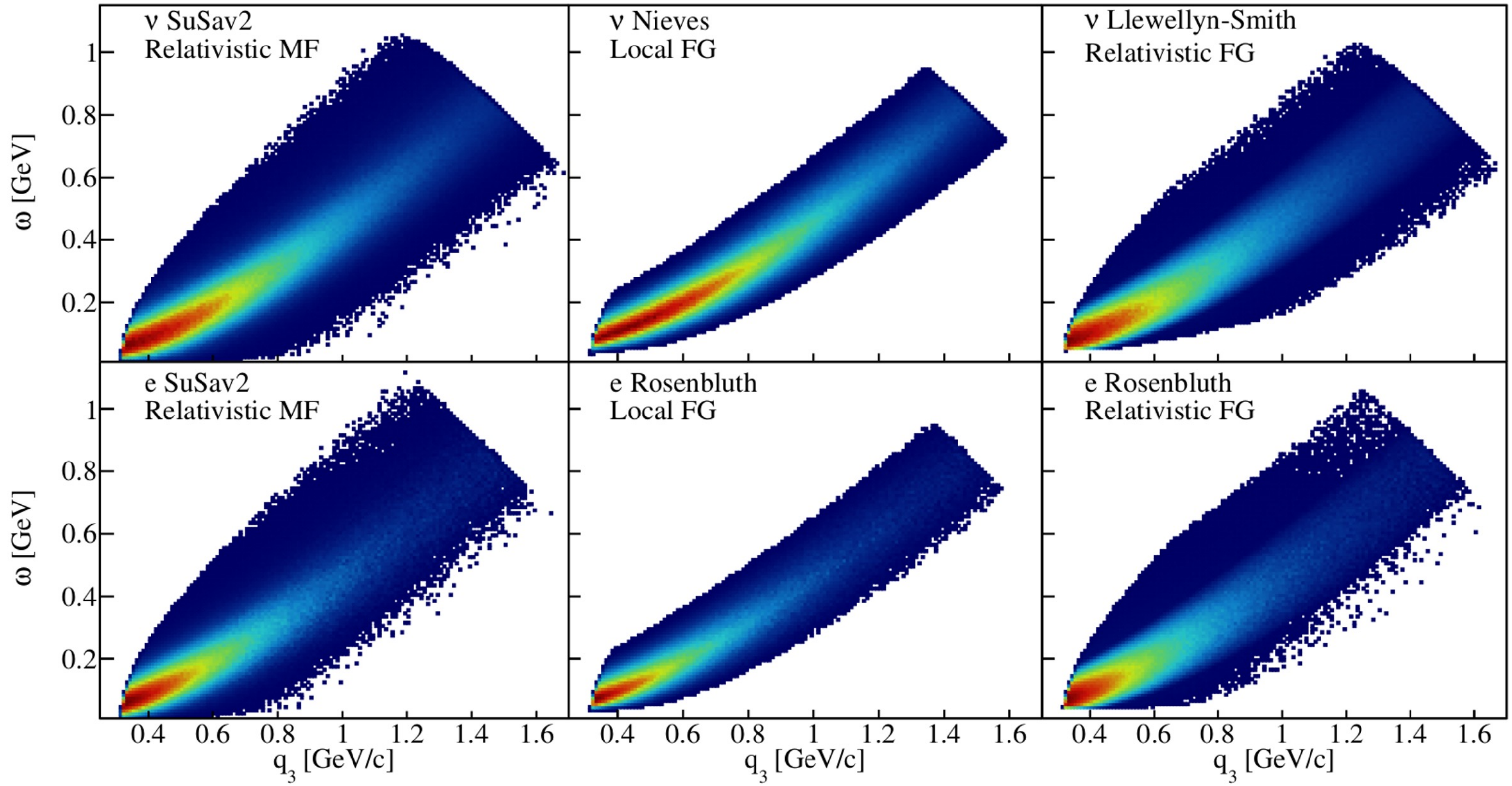
SuSav2 Offers More Accurate Prediction



Phys. Rev. D 103, 113003 (2021)

Probing The Neutrino Phase-Space With Electrons

QE Events

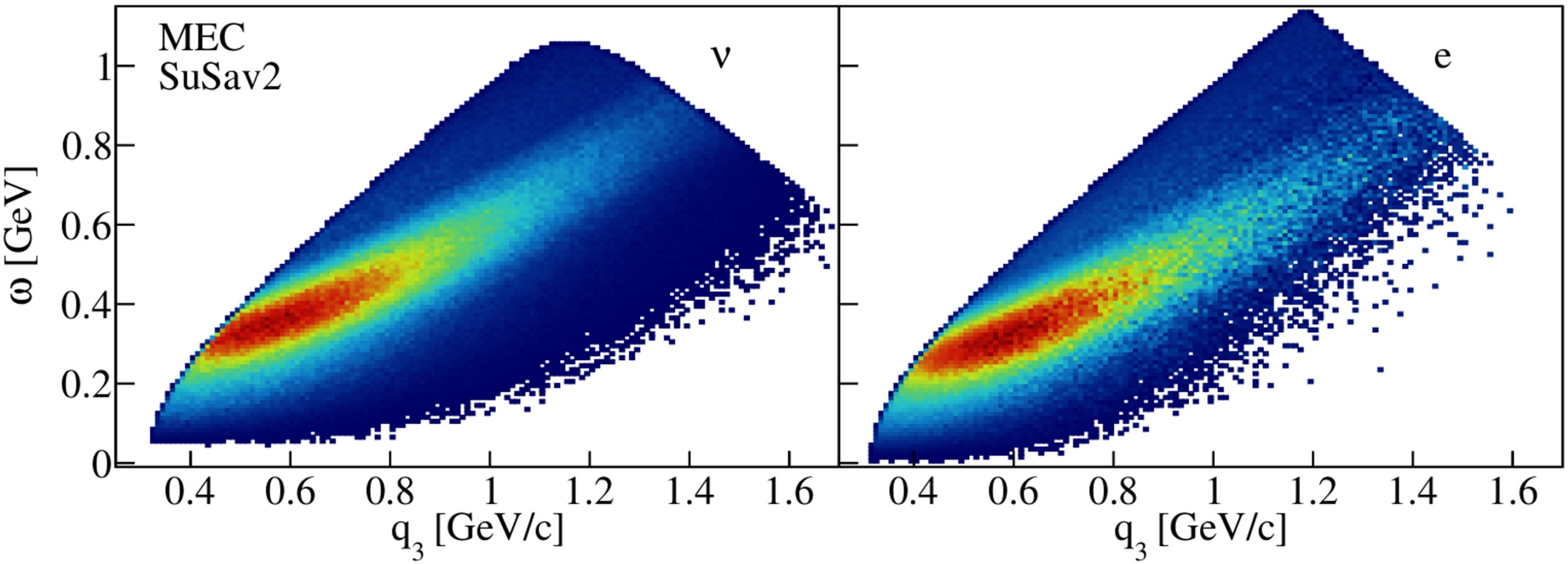


A.Papadopoulou, et al, Phys. Rev. D 103, 113003 (2021)

Electron results scaled by Q^4

Consistent Treatment Of MEC Events With SuSav2

Unique chance to constraint one of least understood interaction channels

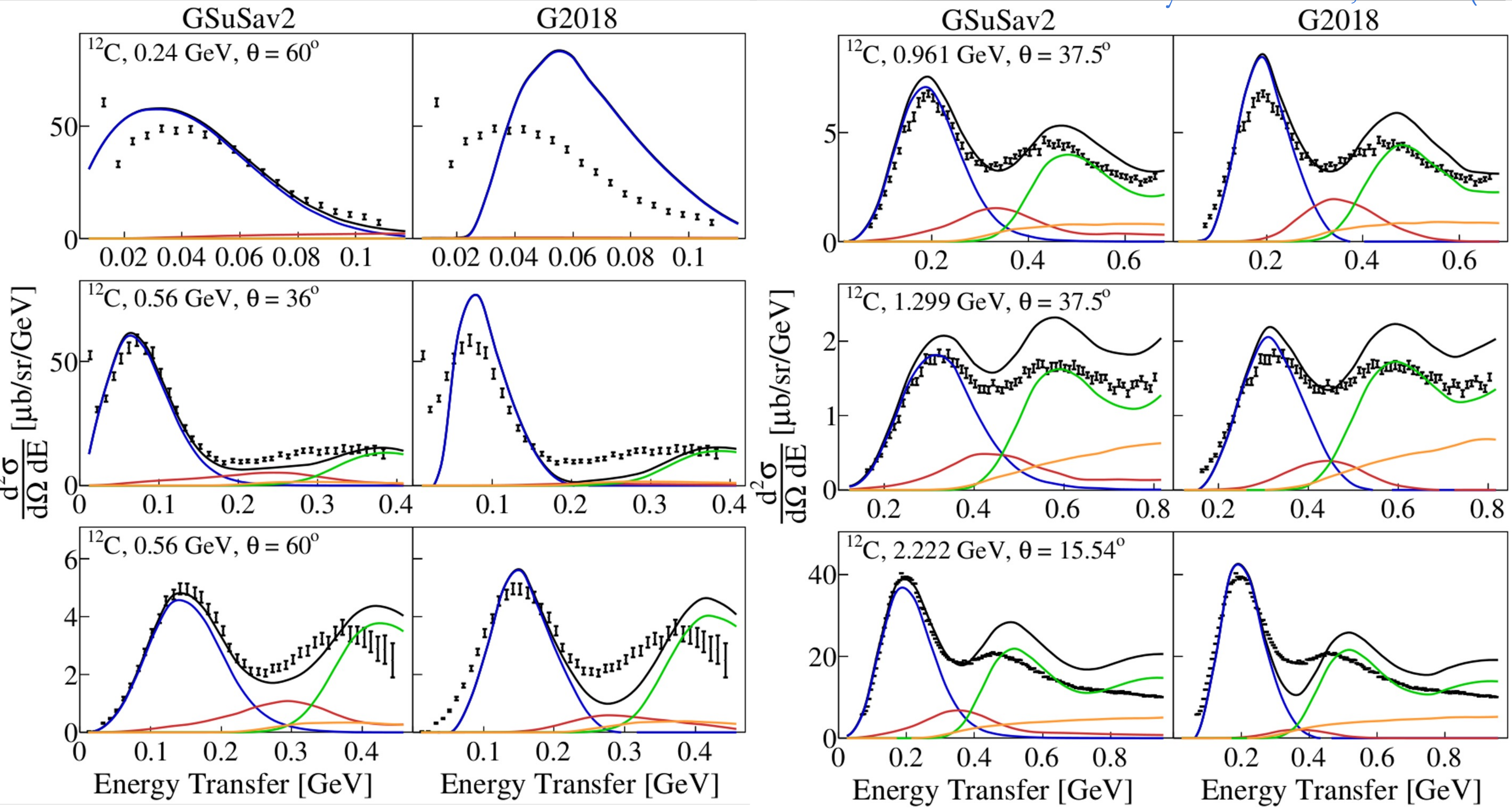


Phys. Rev. D 103, 113003 (2021)

Electron results scaled by Q^4

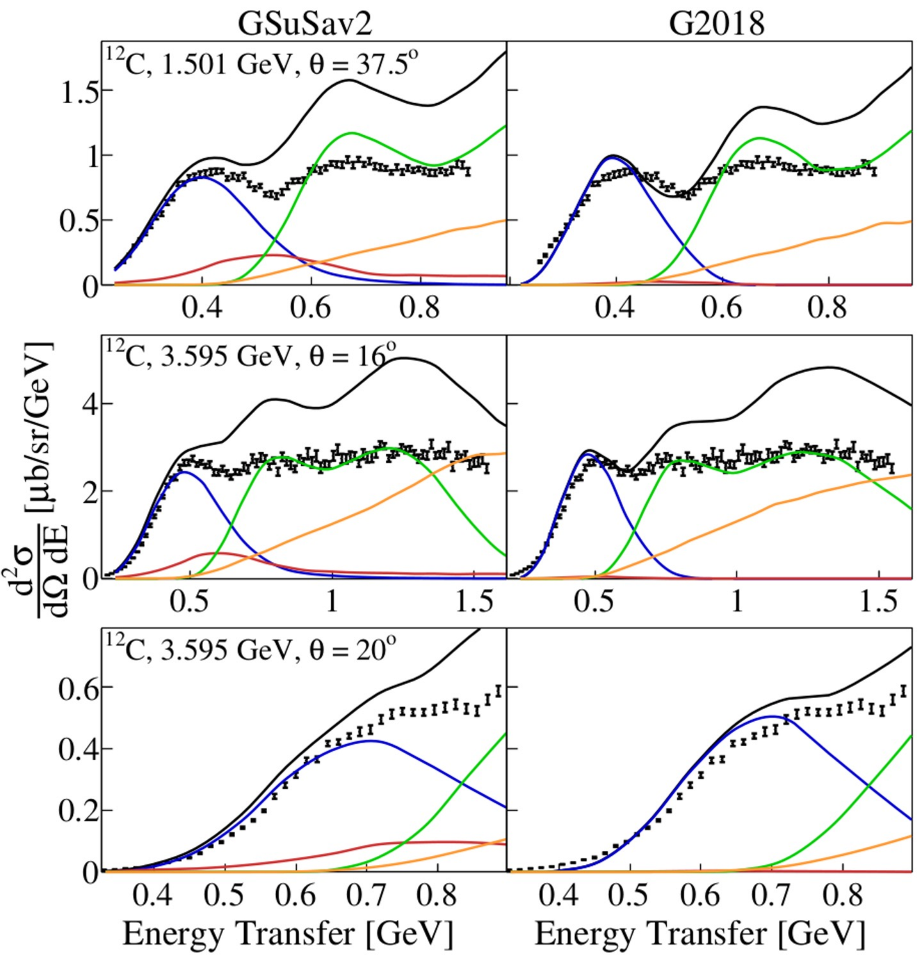
Inclusive C cross sections

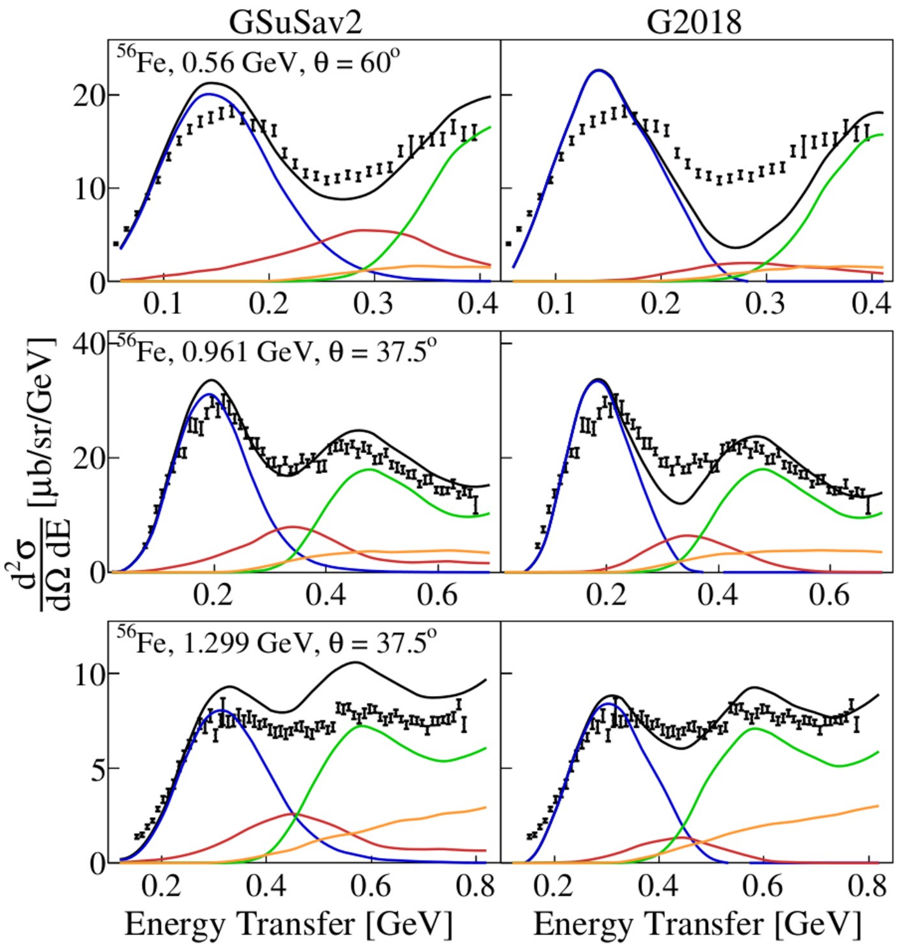
Phys. Rev. D 103, 113003 (2021)



Inclusive C/Fe cross sections

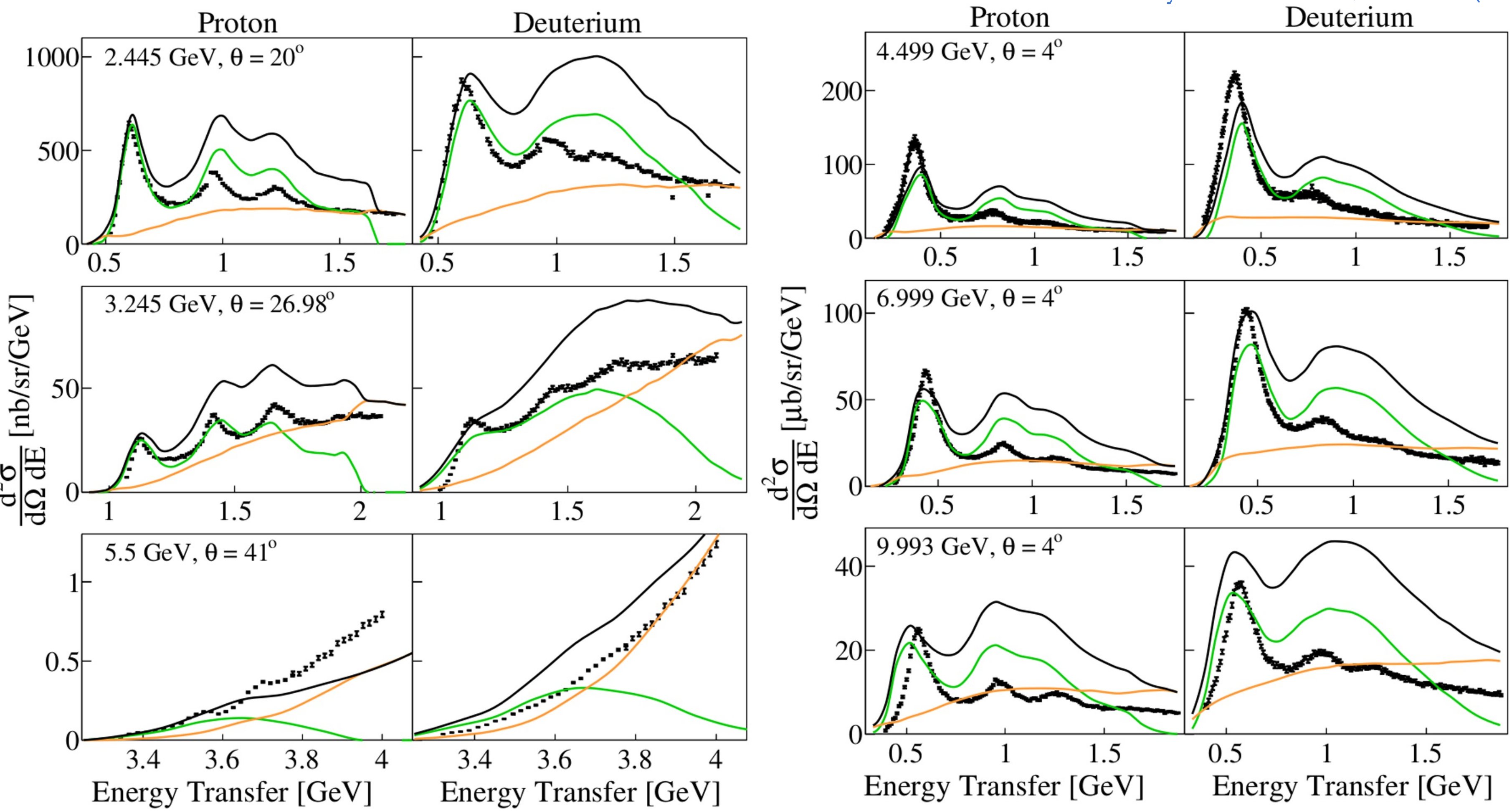
Phys. Rev. D 103, 113003 (2021)



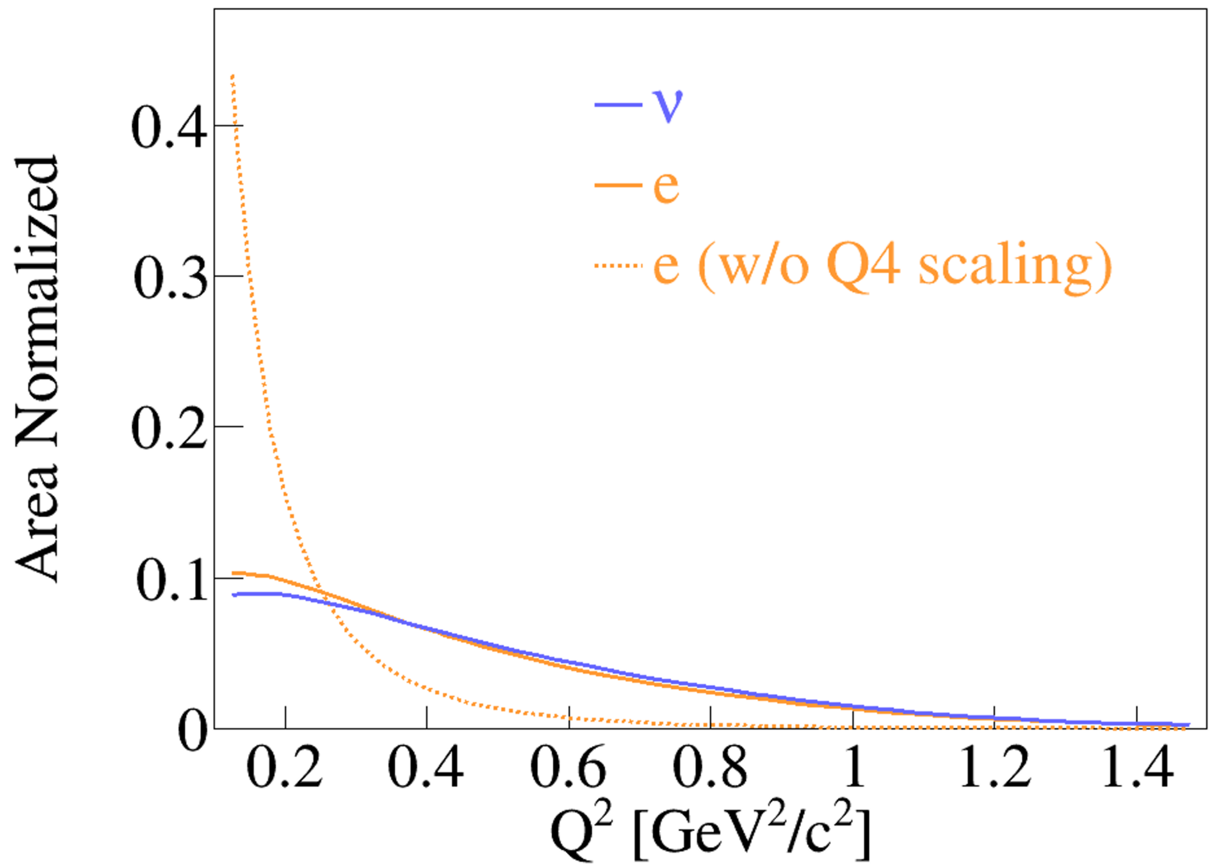


Inclusive H cross sections

Phys. Rev. D 103, 113003 (2021)

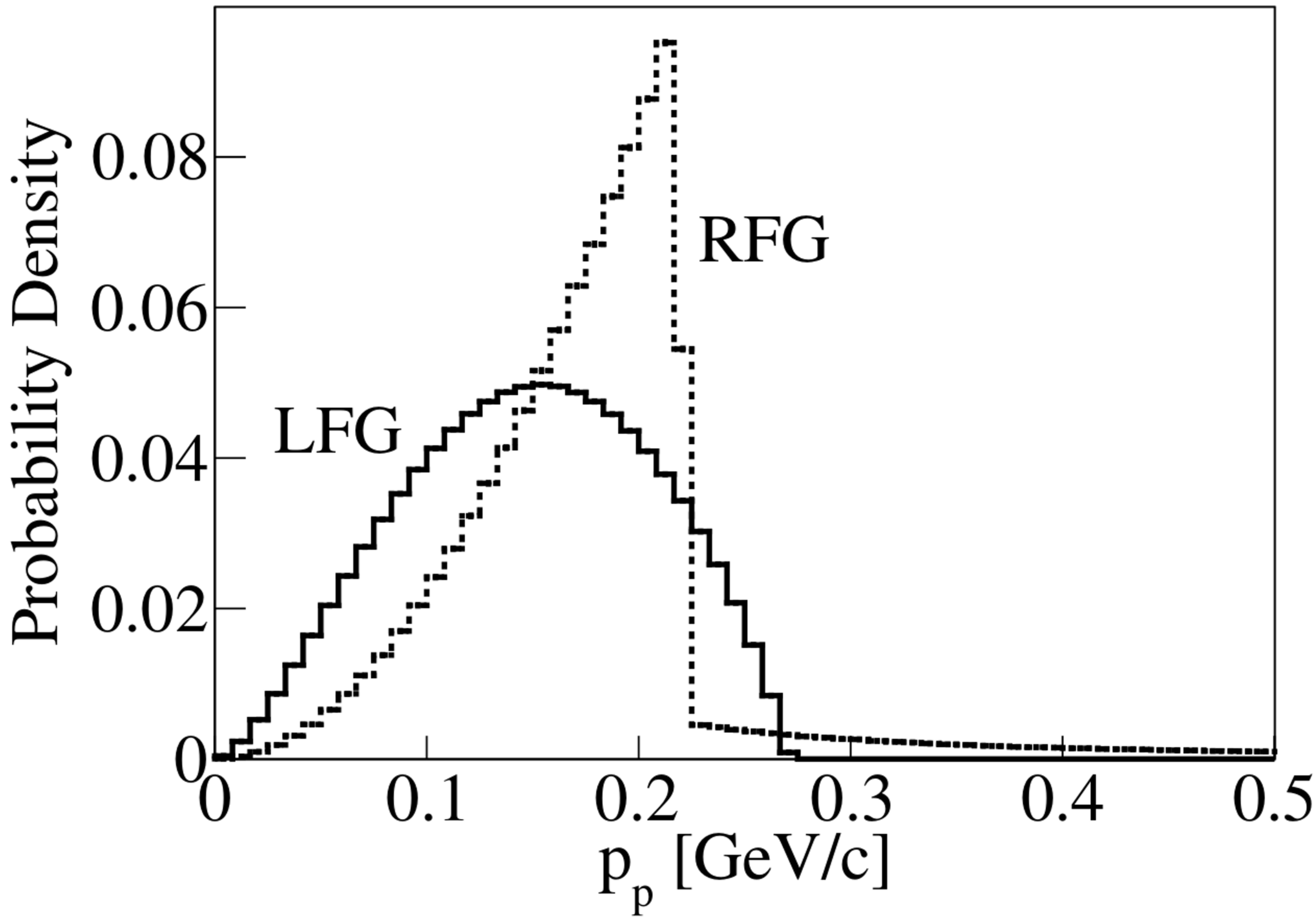


Q^4 Scaling Effect



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