Electron-Nucleus Scattering for Neutrino Interactions and Oscillations

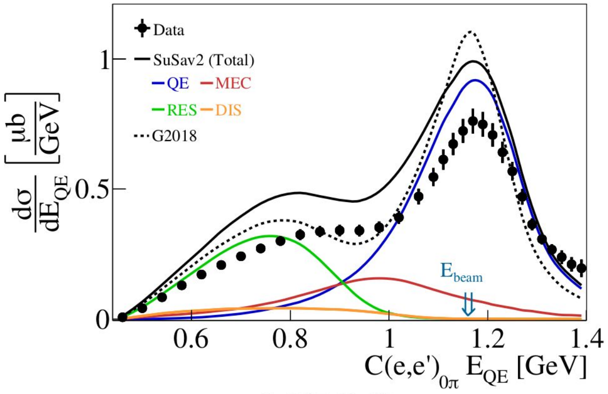
Afroditi Papadopoulou
On behalf of the $e4\nu$ collaboration

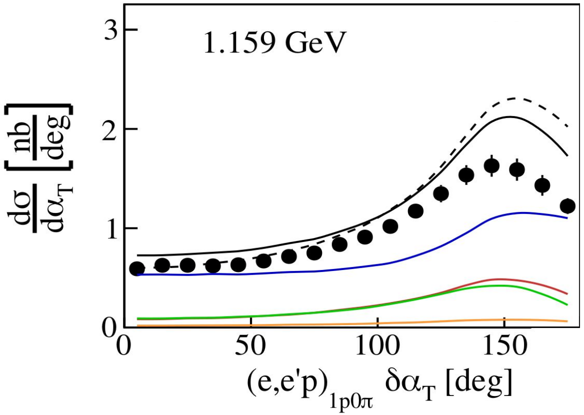
NuFACT 2022

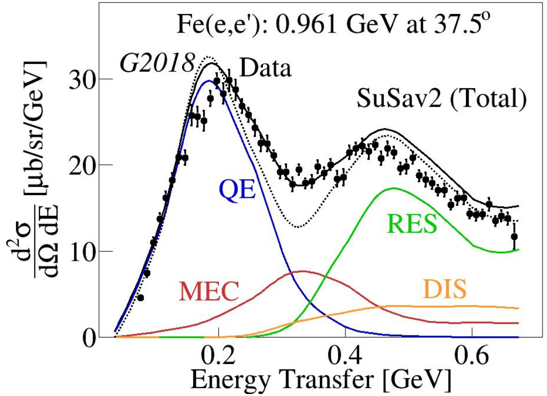
Argonne NATIONAL LABORATORY

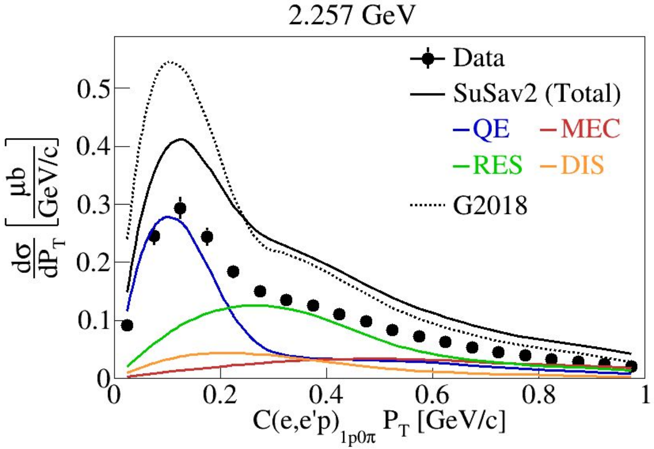
The e4ν Result Factory

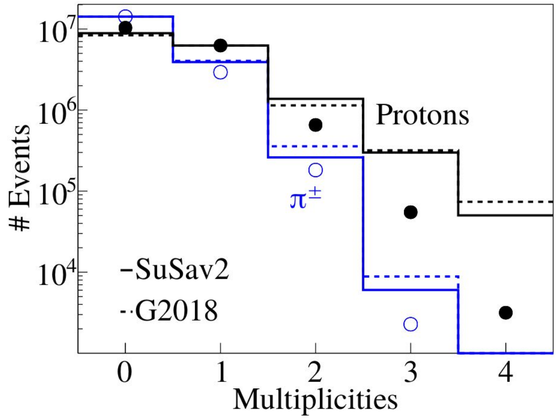
Many
- nuclei
- beam energies
- channels
- variables







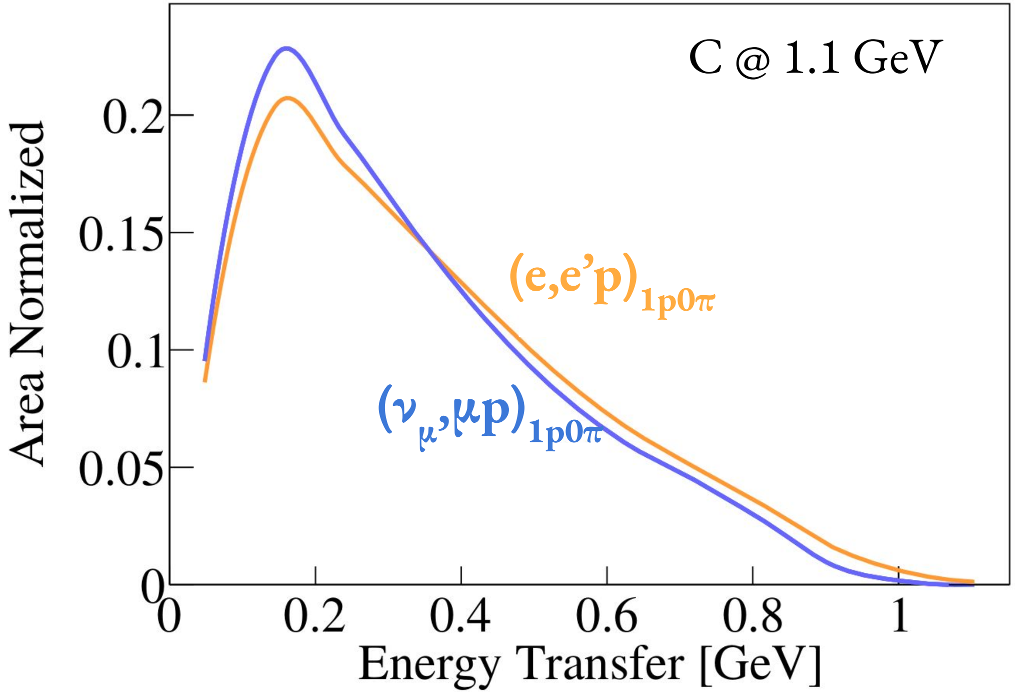




Nature 599, 565–570 (2021)

Phys. Rev. D 103, 113003 (2021)

Similar ν & e Distributions

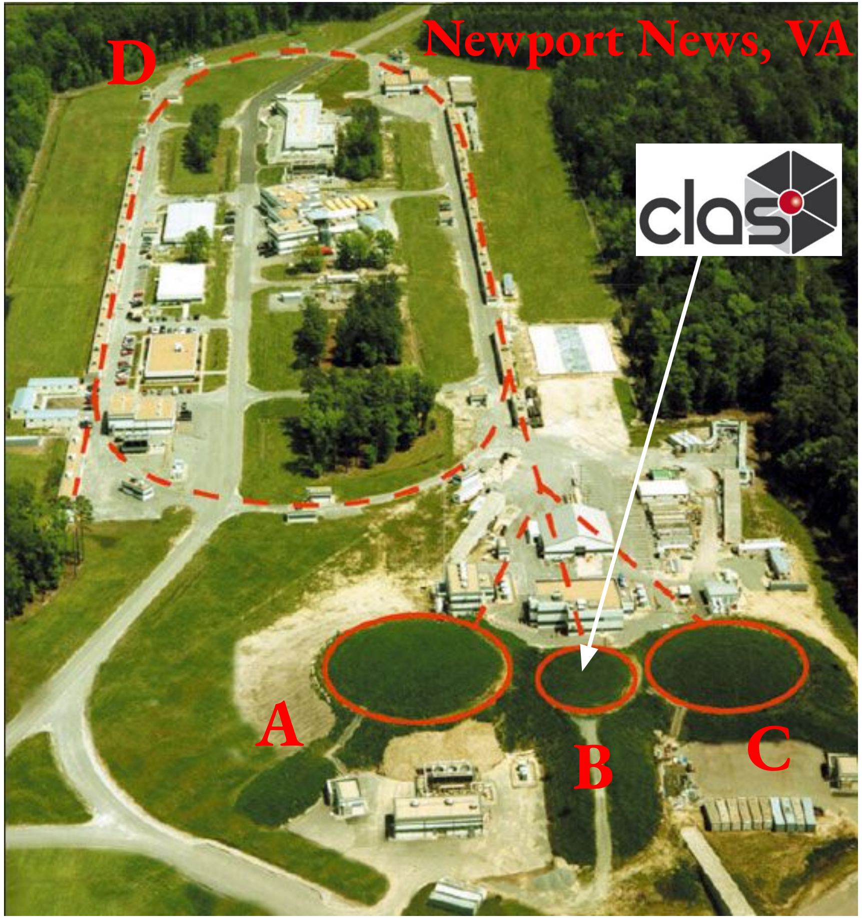


Also see talks by [N.Rocco]() & [V.Pandley]()

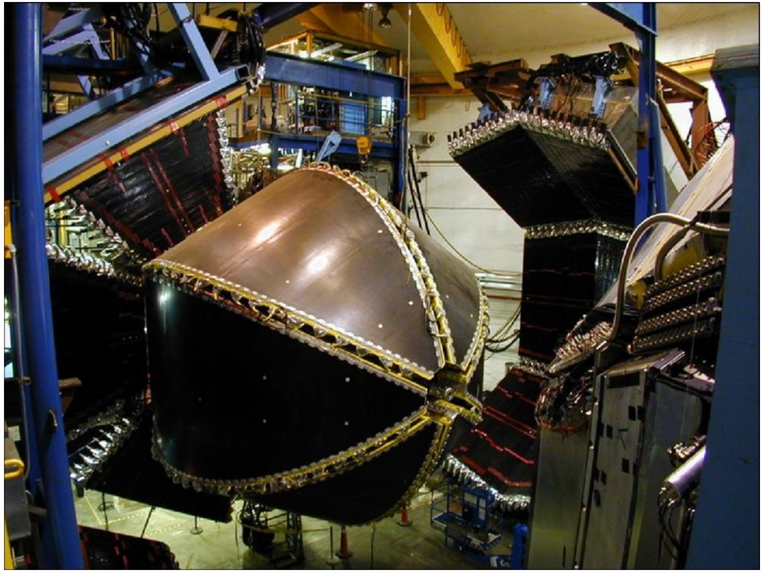
Accounting for propagator mass (γ vs W) via Q^4 scaling of the electron side

Phys. Rev. D 103, 113003 (2021)

Jefferson Laboratory

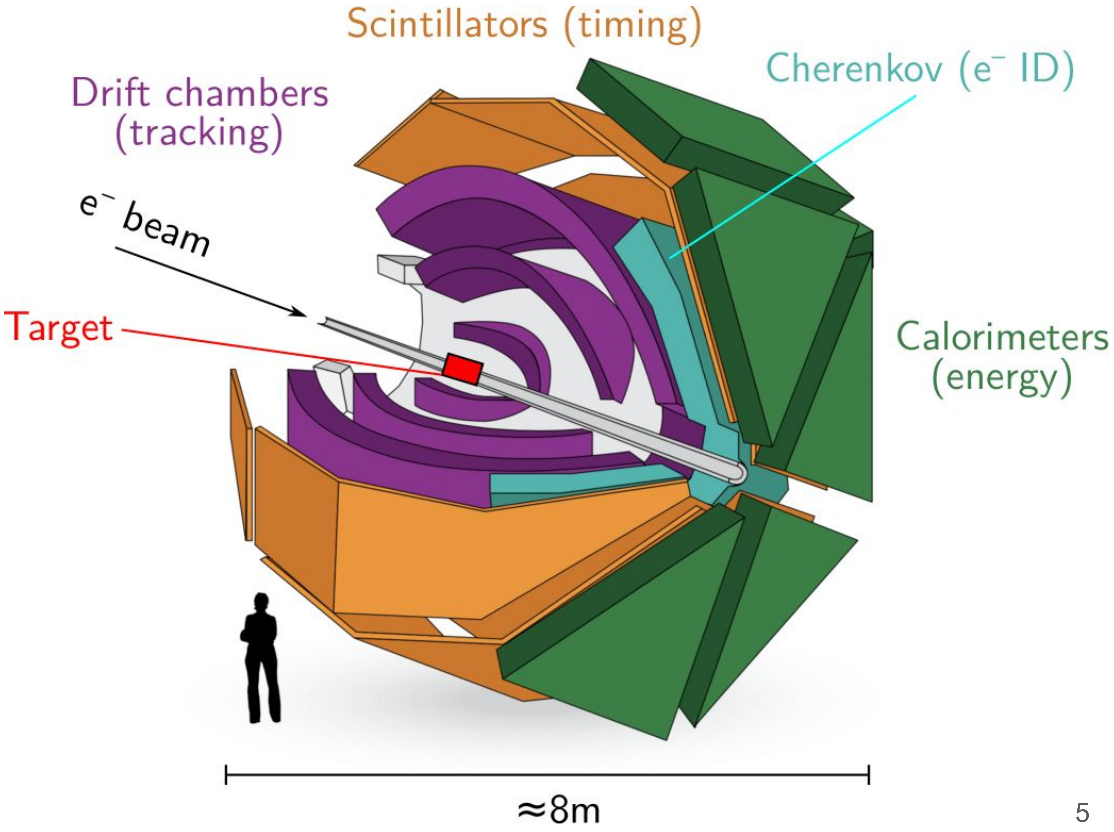


- Electron beam accelerator facility
- Energies up to 12 GeV
- Using Hall B & CLAS detector



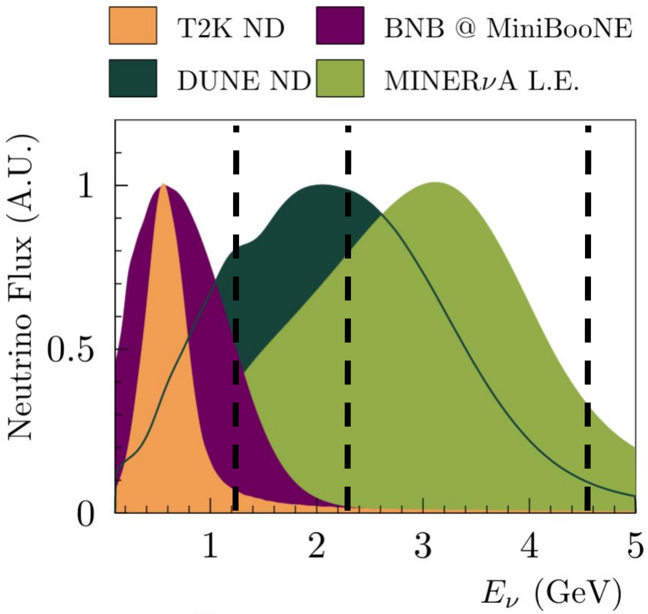
e4ν Data-Mining With CLAS

- 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



H_2O

CH

Ar

Playing The QE-like Neutrino Game

μBooNE

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

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

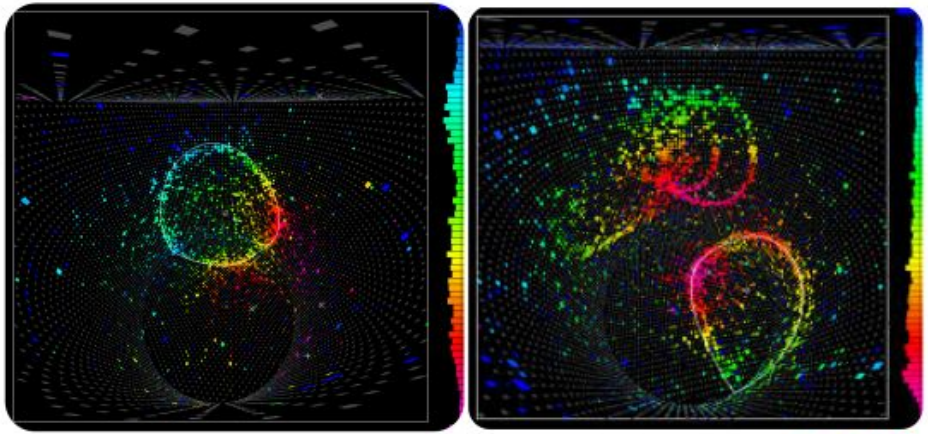
e4ν

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

- Study energy reconstruction
- Test against GENIE event generator

Also see talk by S.Gardiner

QE Energy Reconstruction

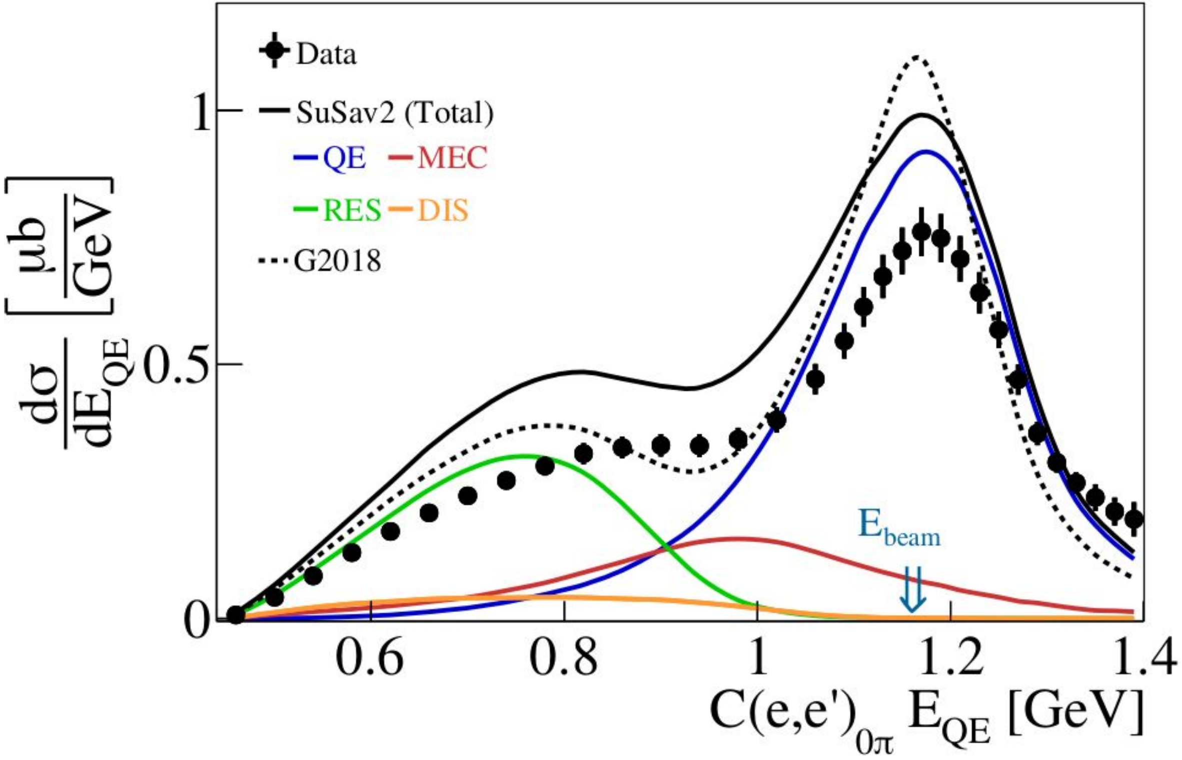


Cherenkov detectors
Assuming QE interaction
Using lepton kinematics

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

QE Energy Reconstruction

C @ 1.16 GeV

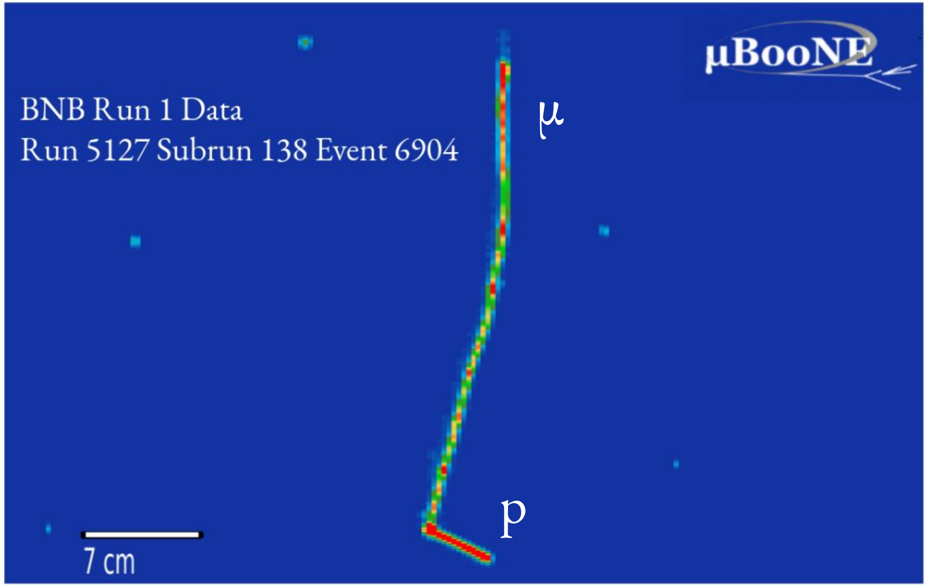


- Relevant for T2K
- Overestimation of QE peak & RES tail

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

Nature 599, 565–570 (2021)

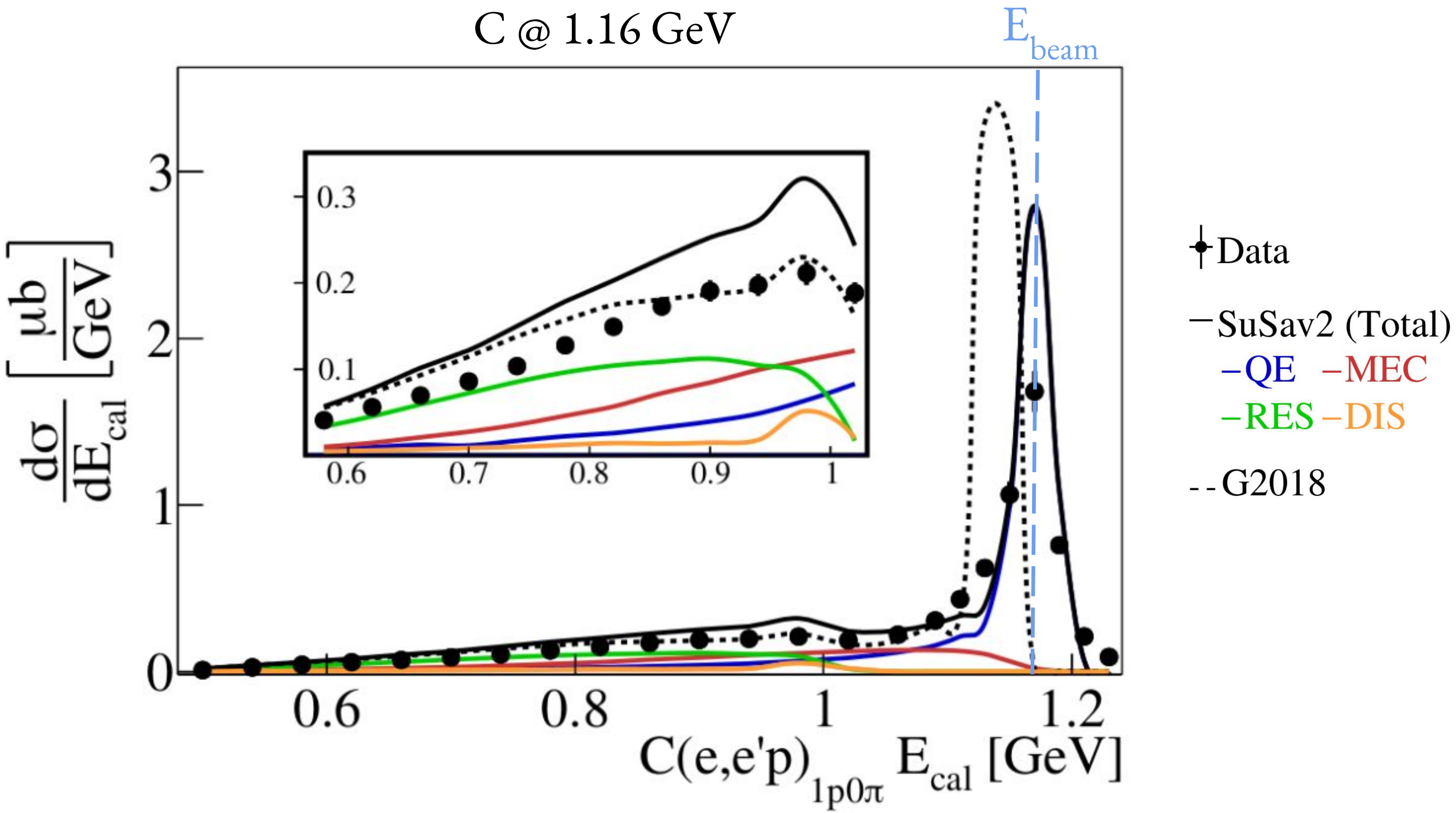
Calorimetric Energy Reconstruction



Tracking detectors
Calorimetric sum
Using all detected particles

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

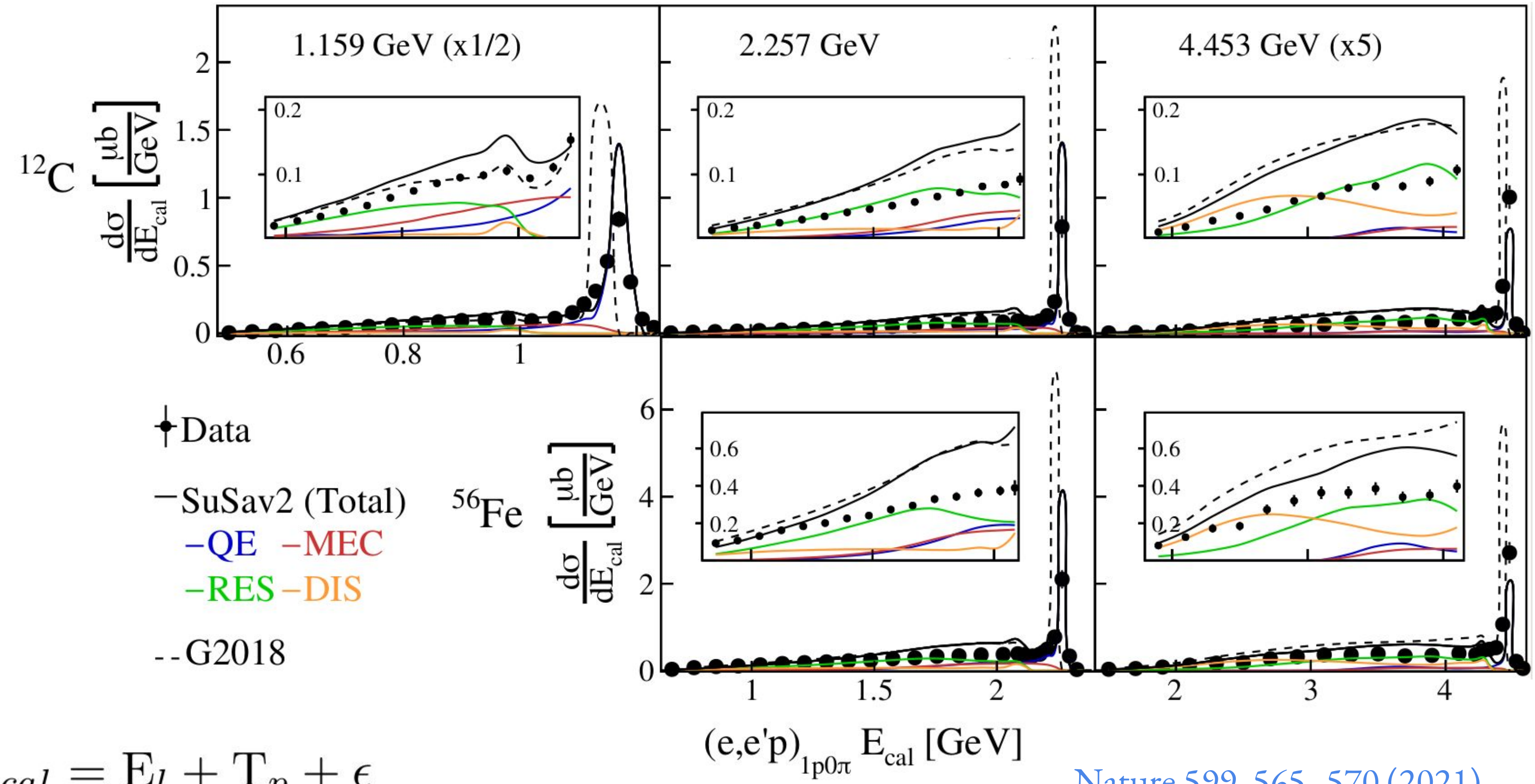
Calorimetric Energy Reconstruction



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

Nature 599, 565–570 (2021)

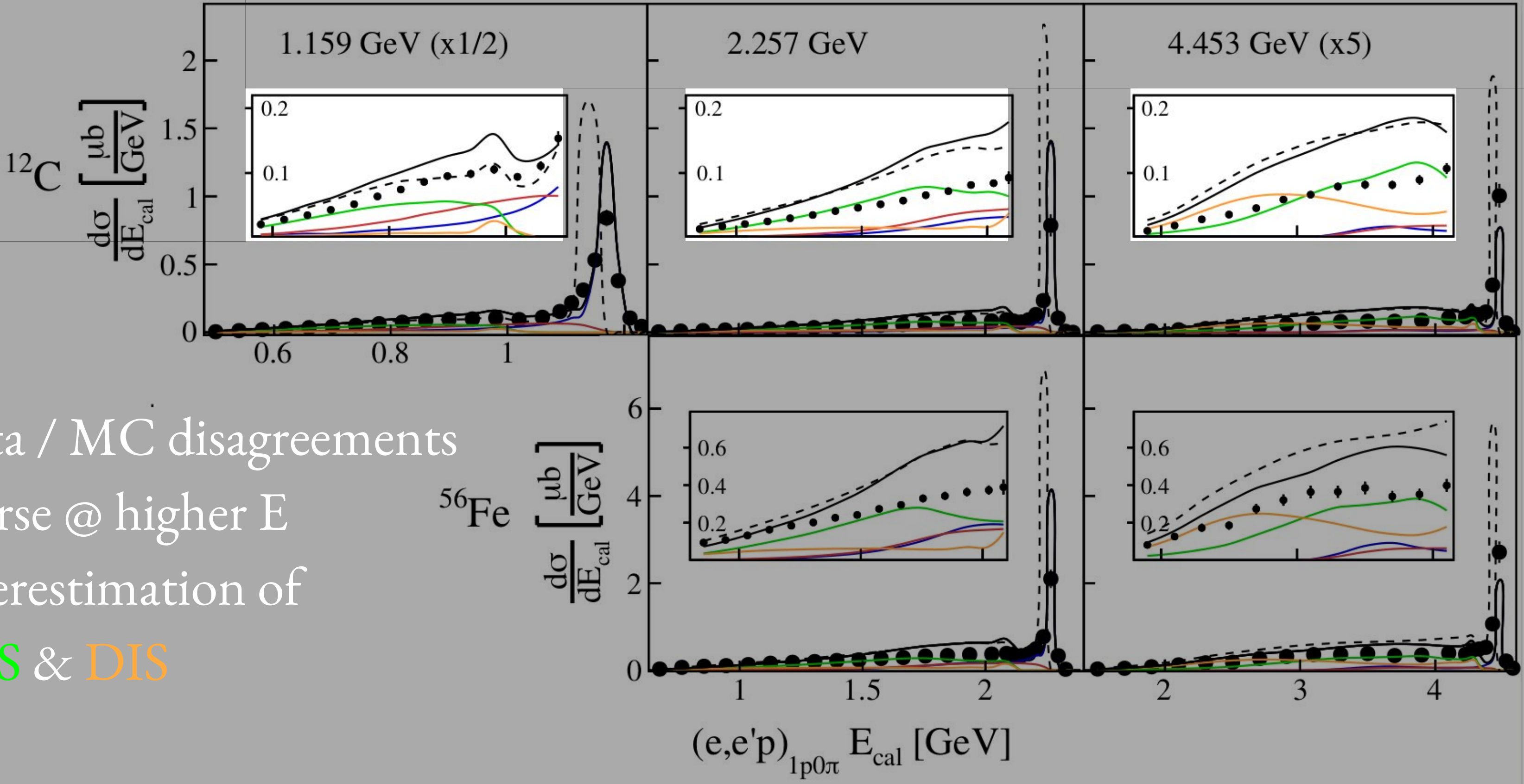
E_{cal} Nucleus & Energy Dependence



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

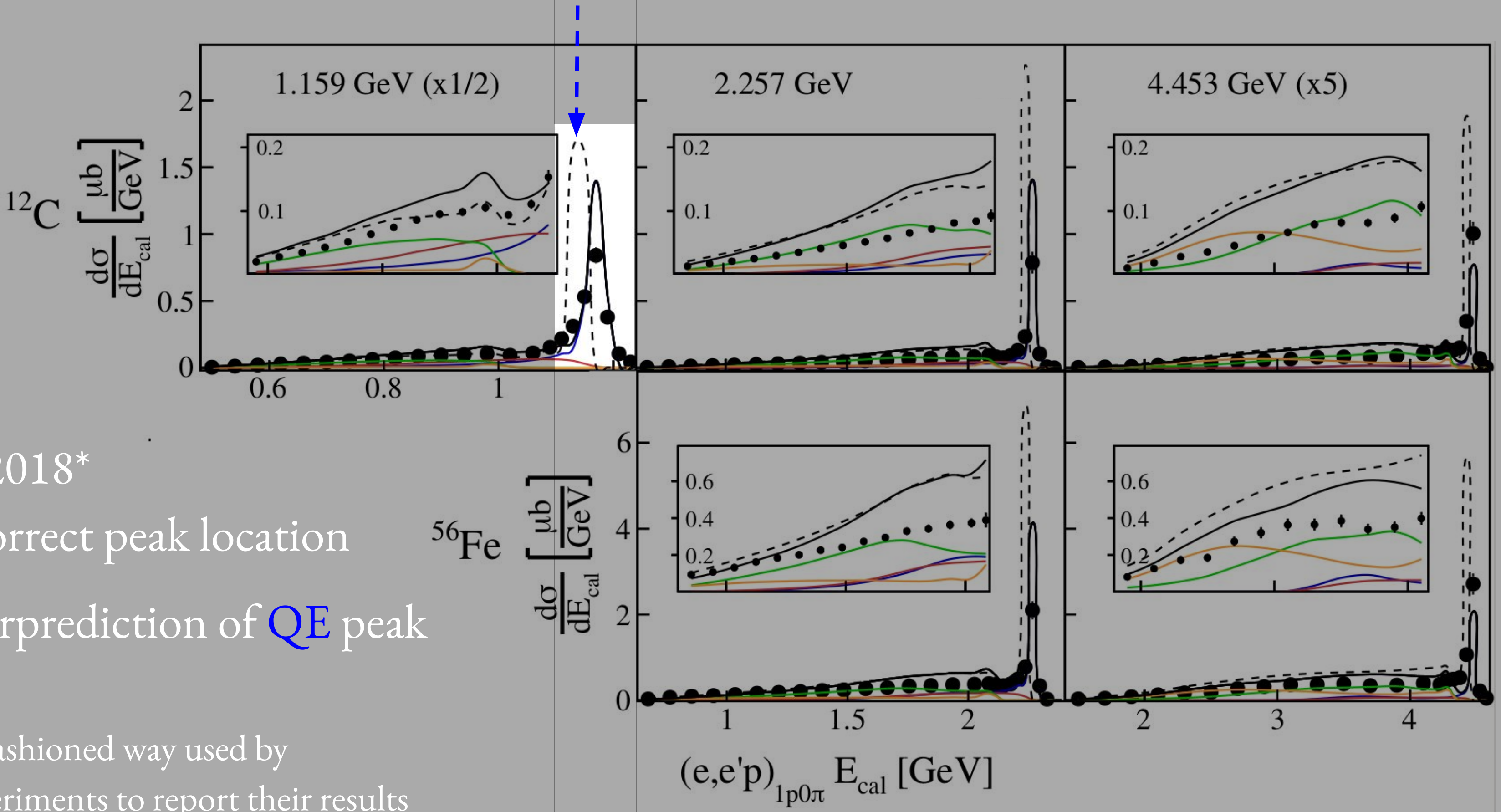
Nature 599, 565–570 (2021)

Nucleus & Energy Dependence



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

Nucleus & Energy Dependence

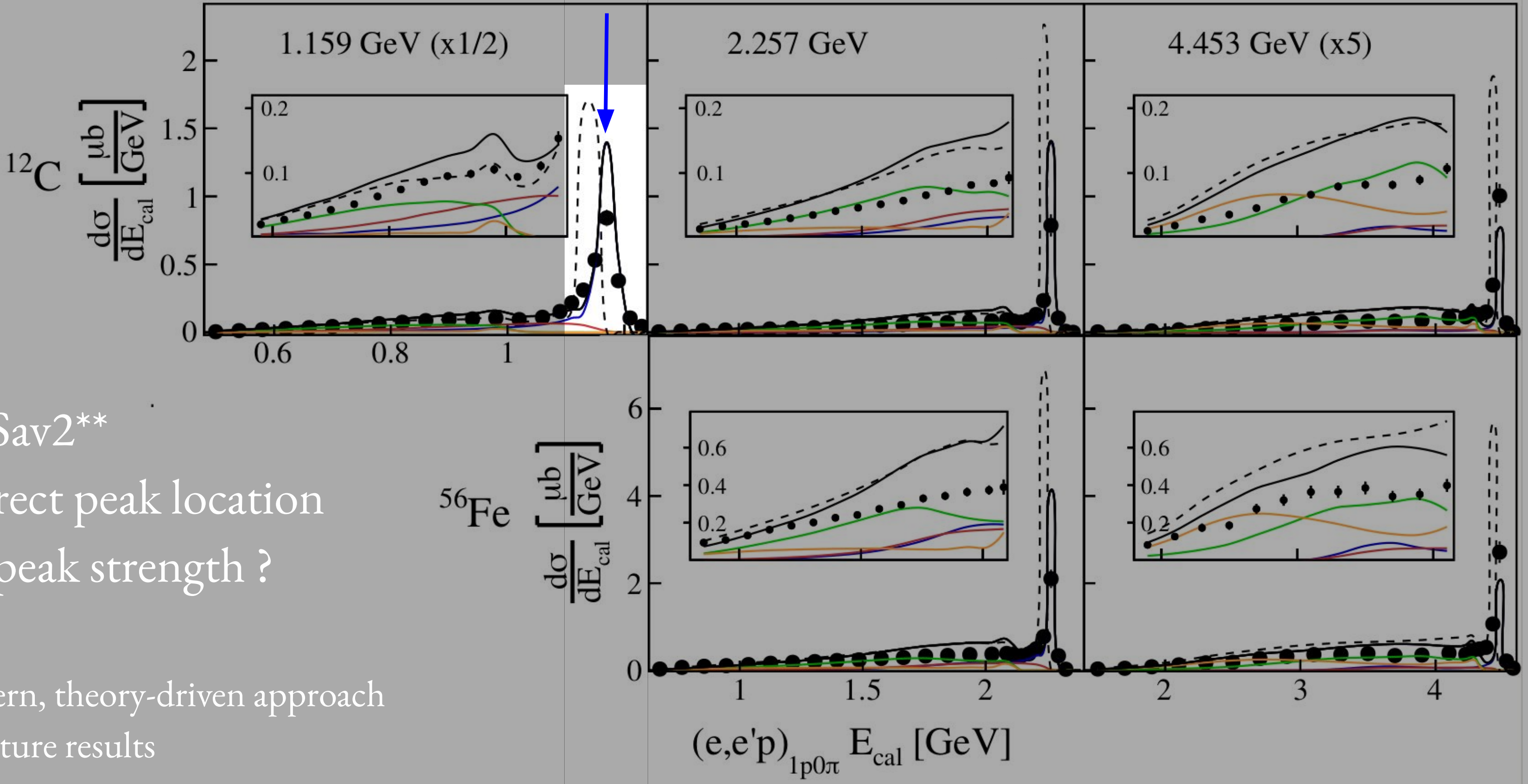


--- G2018*

- Incorrect peak location
- Overprediction of QE peak

* Old-fashioned way used by
ν experiments to report their results

Nucleus & Energy Dependence

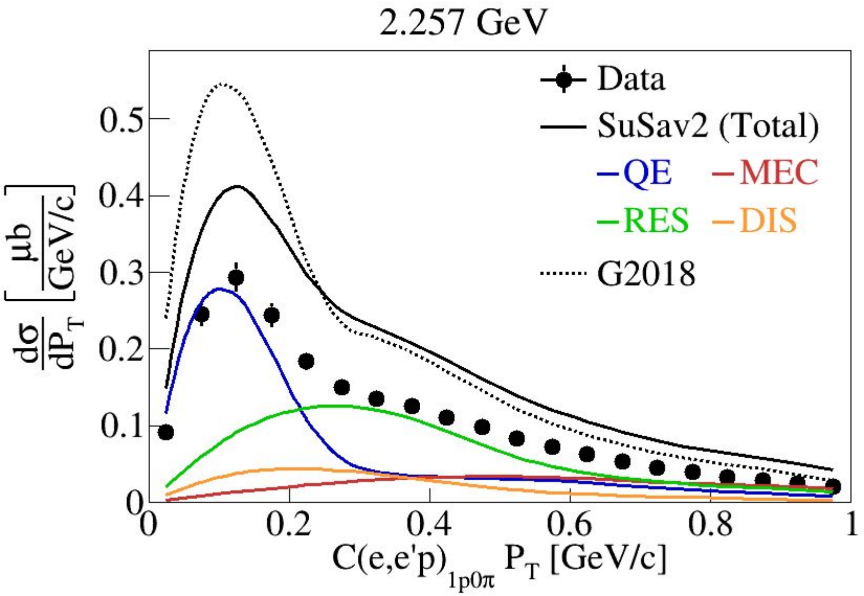


– SuSav2**

- Correct peak location
- QE peak strength ?

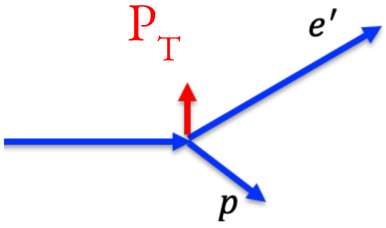
** Modern, theory-driven approach for future results

Transverse Momentum



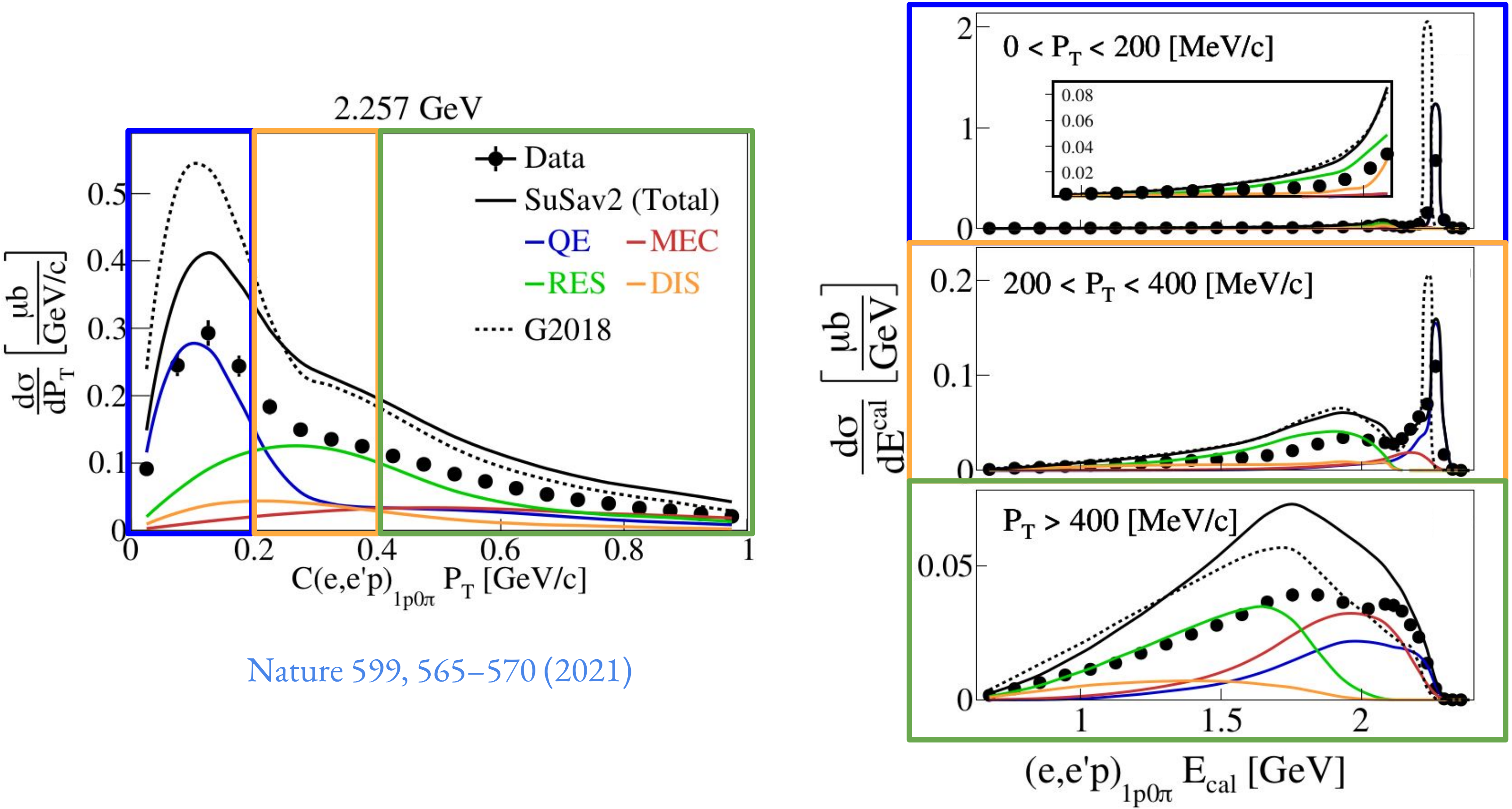
Nature 599, 565–570 (2021)

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



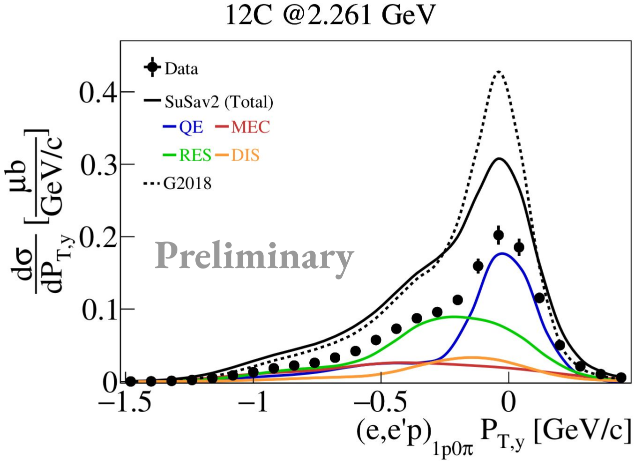
- P_T sensitivity to nuclear effects (fermi motion, final-state interactions, ...)
- Overestimation of QE peak & RES tail

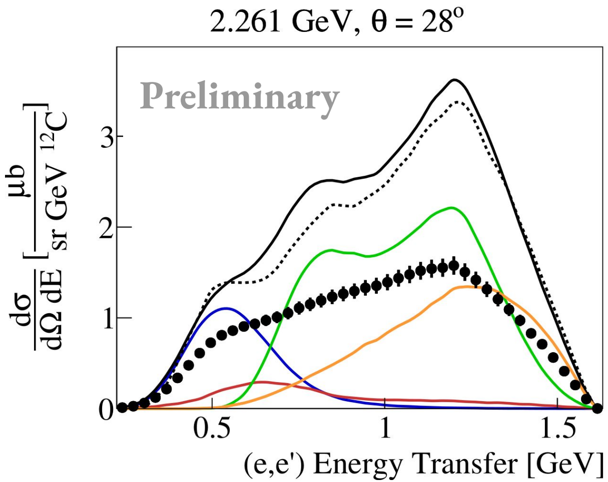
Energy Reconstruction In P_T Slices

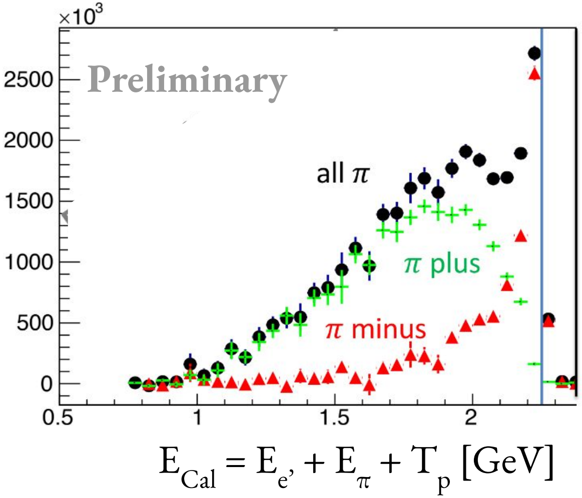


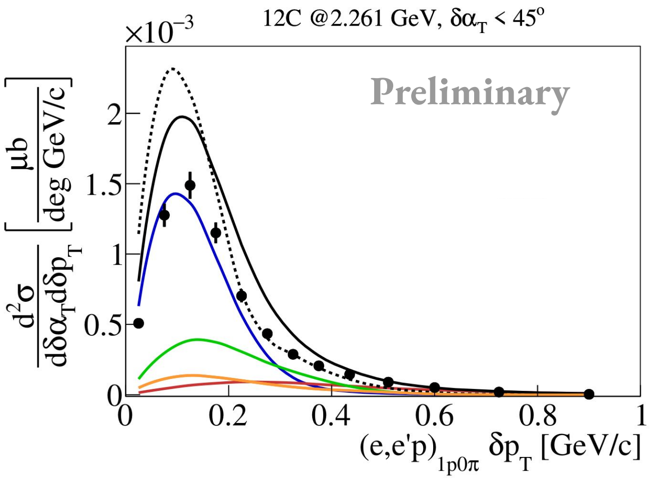
Nature 599, 565–570 (2021)

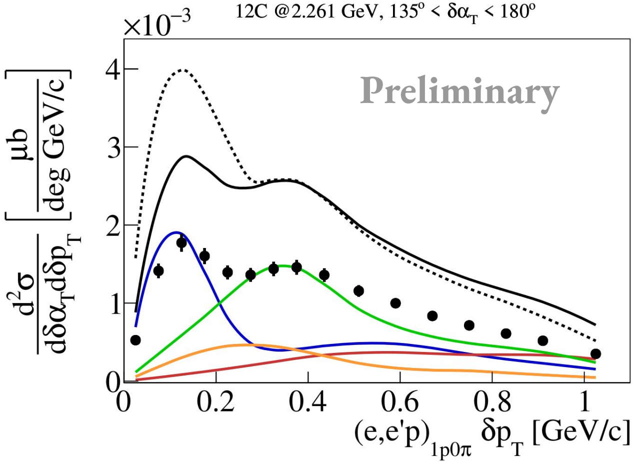
New Results





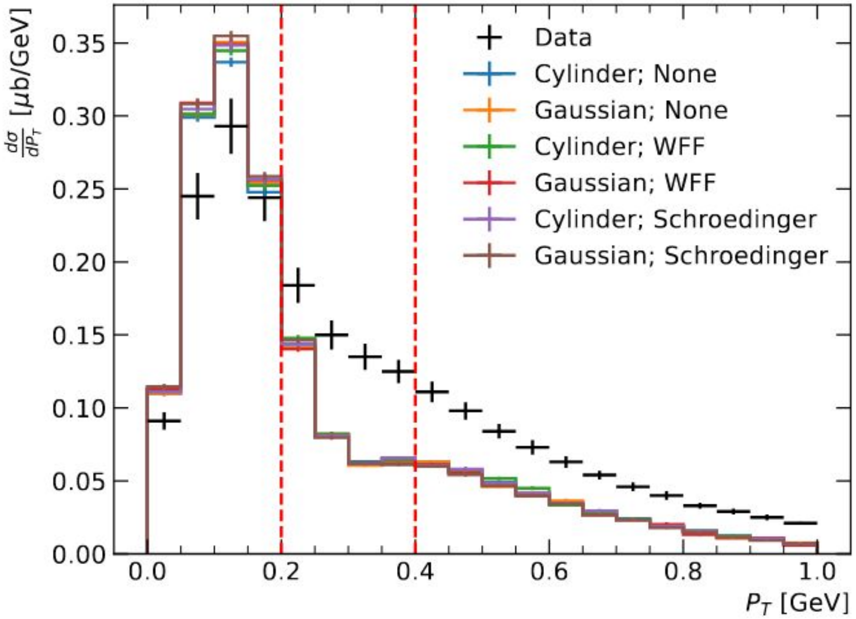


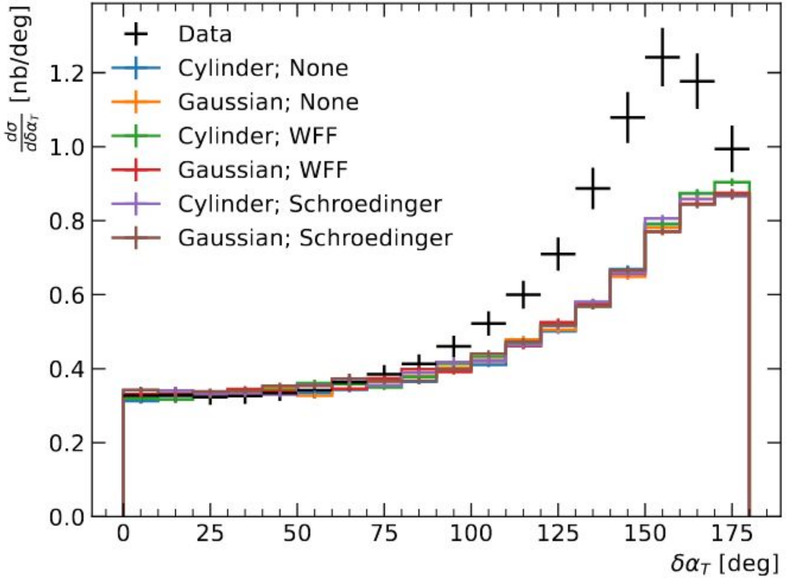


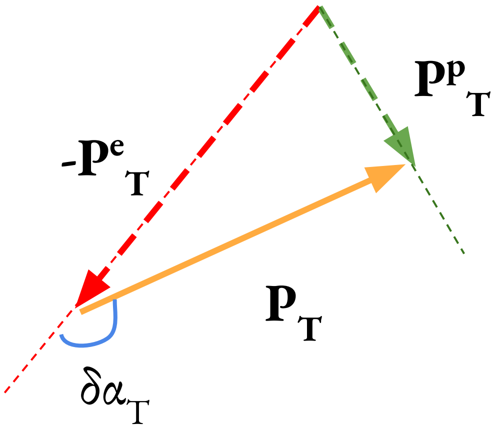


- Multi-differential
- Pion production
- Transparency studies
- Novel variables
- Tuning efforts
- New generators

Example: Benchmarking New Generators & Kinematic Variables!



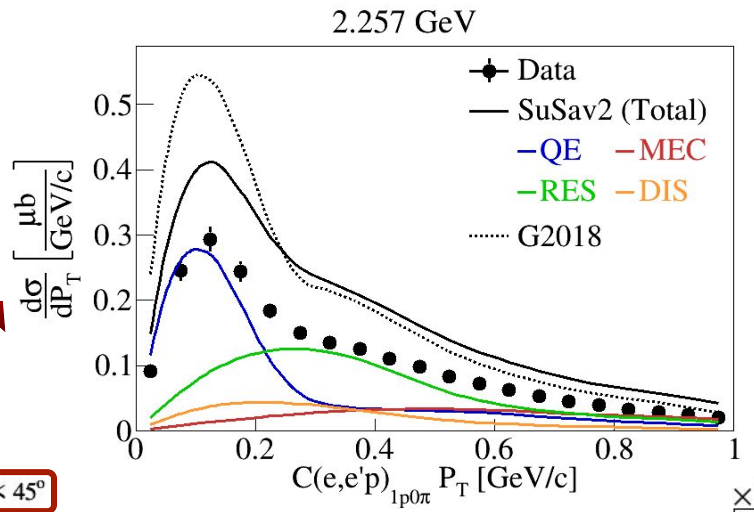


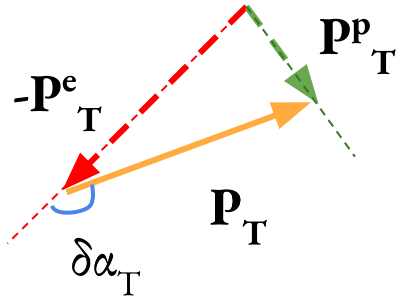


- $\delta\alpha_T$ sensitivity to final-state interactions

First step: only QE & FSI
ACHILLES arXiv: 2205.06378

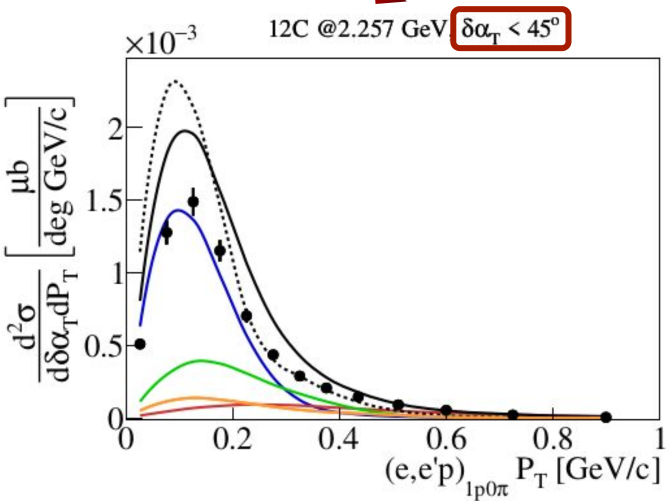
Example: 2D Kinematic Imbalance

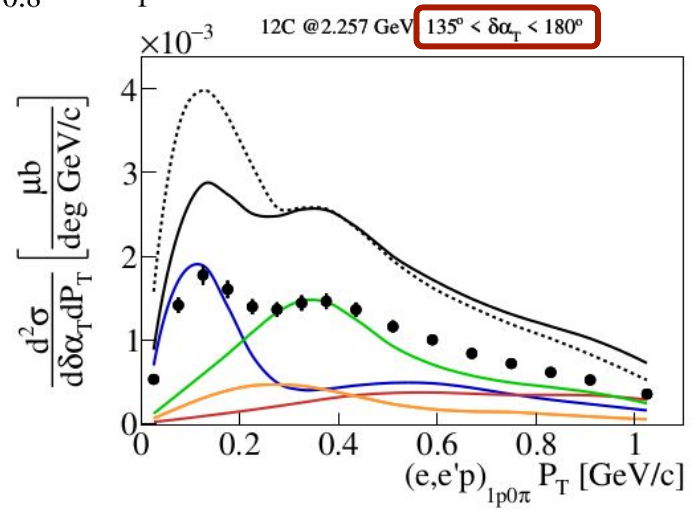




Low $\delta\alpha_T$

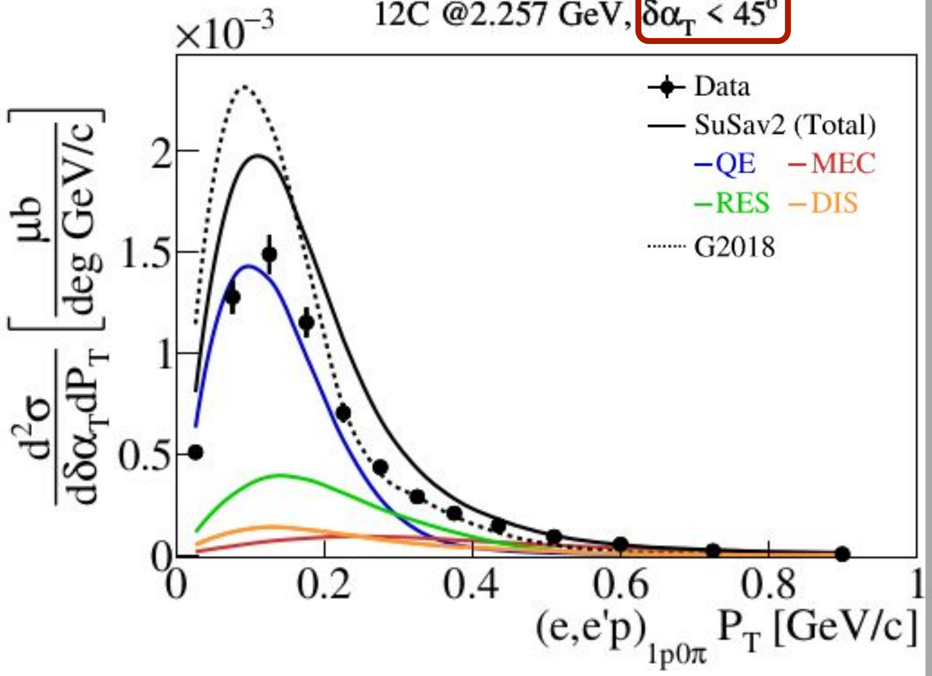
High $\delta\alpha_T$



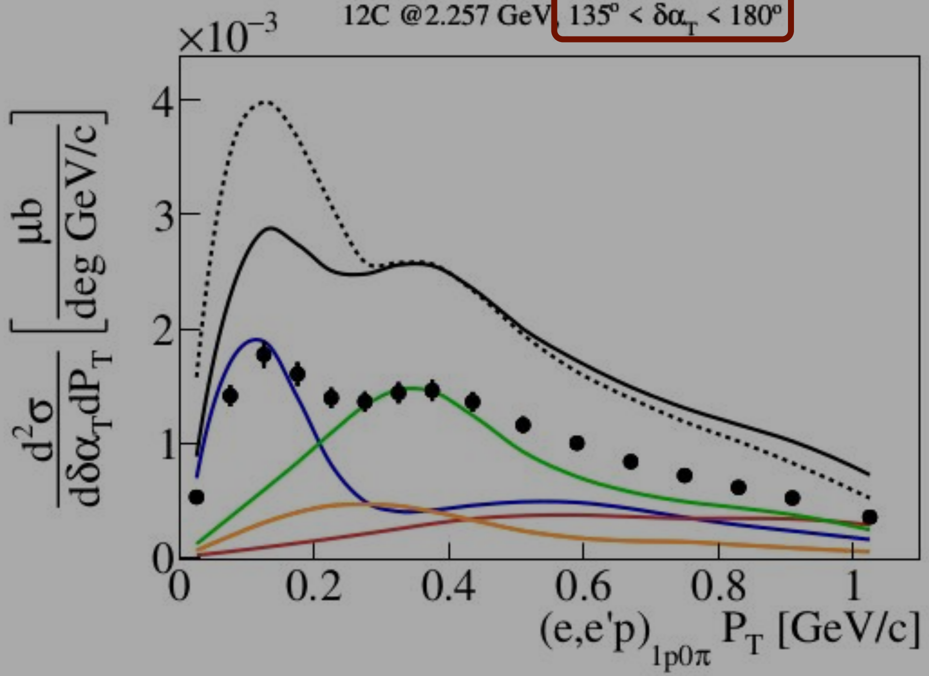


Example: 2D Kinematic Imbalance

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



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



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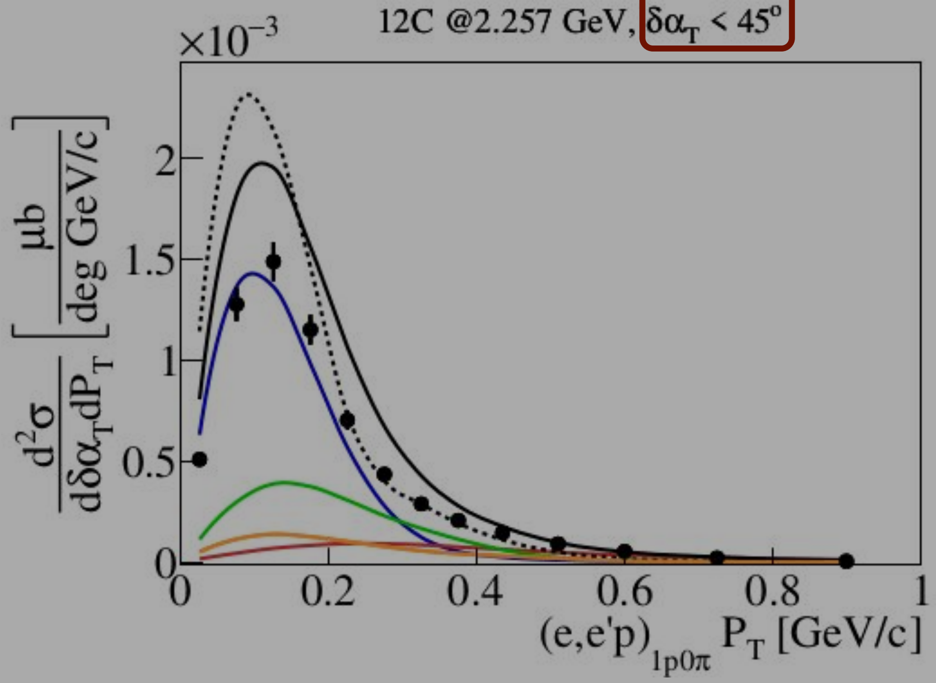

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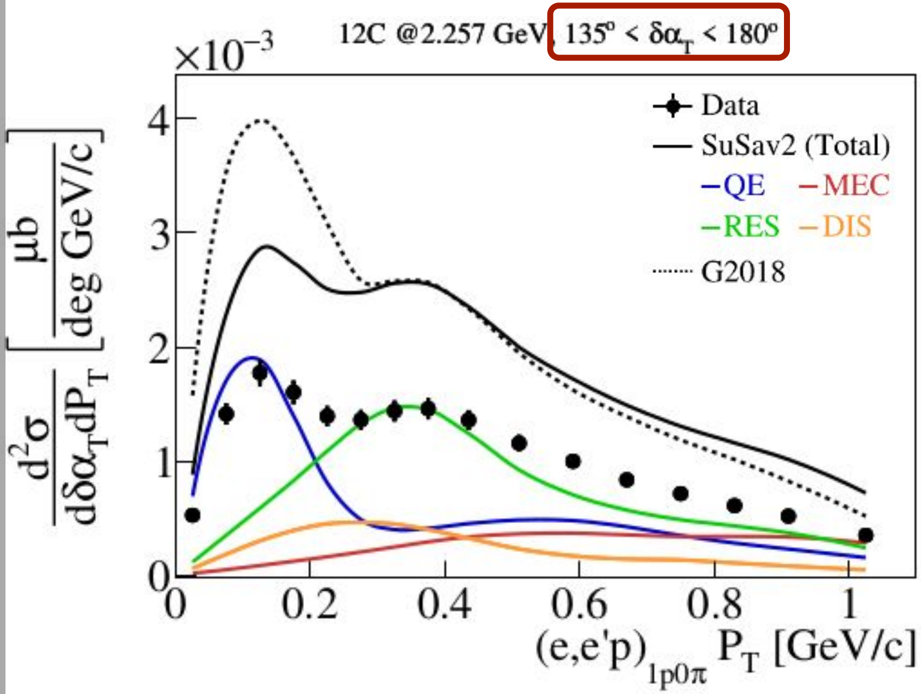
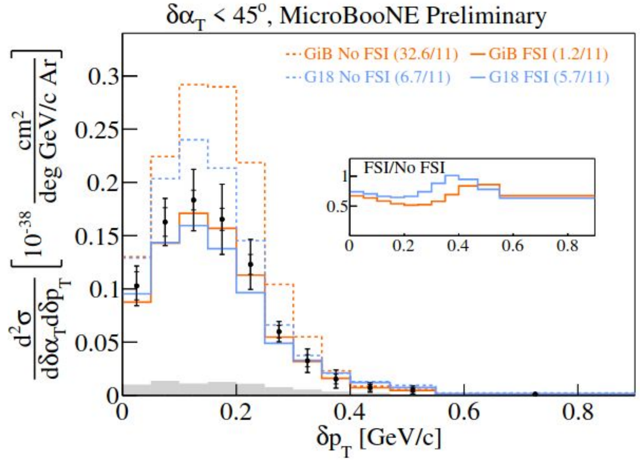
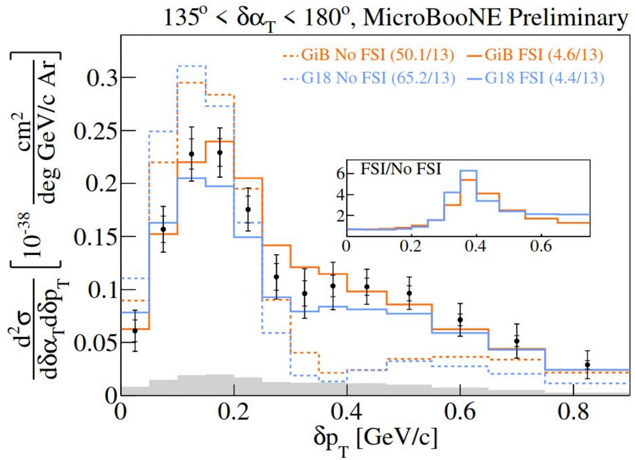
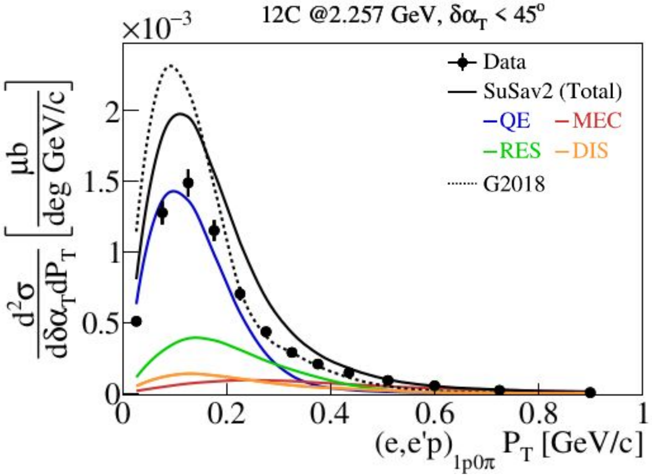


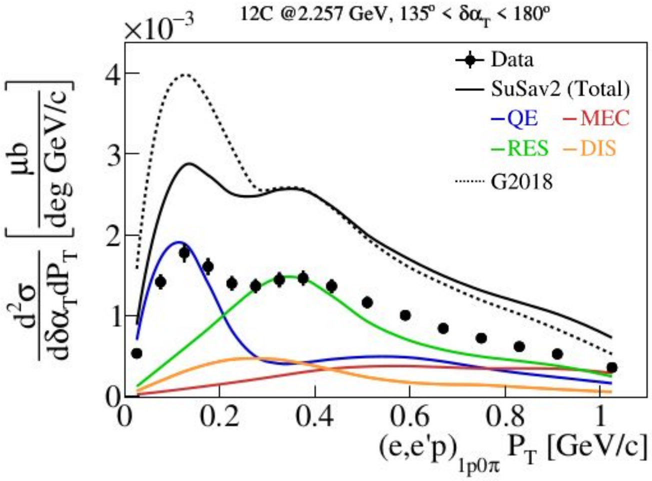
Complementarity To "Sister" Neutrino Analysis





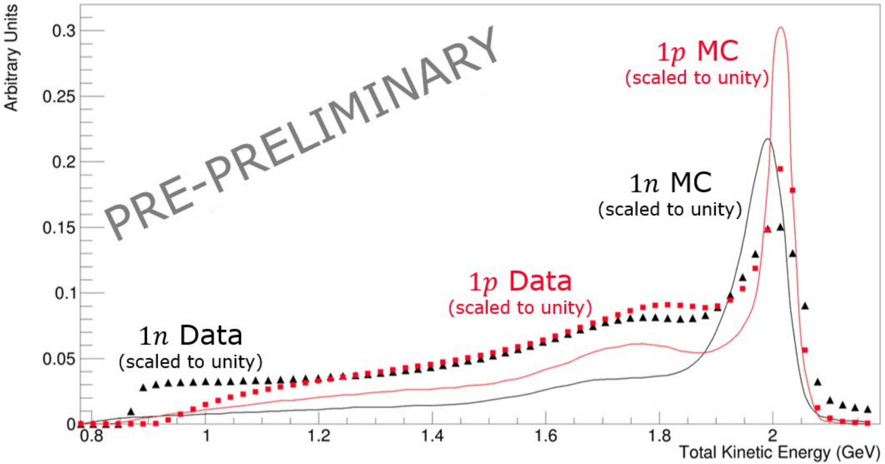
Also see talk by [A.Papadopoulou]()

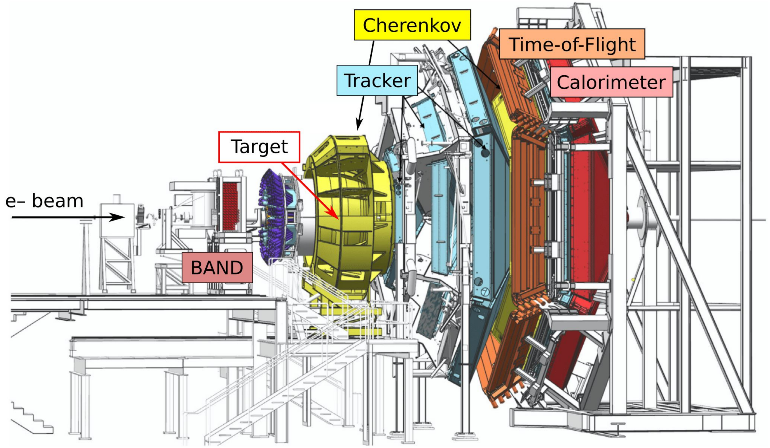




New Data With CLAS12

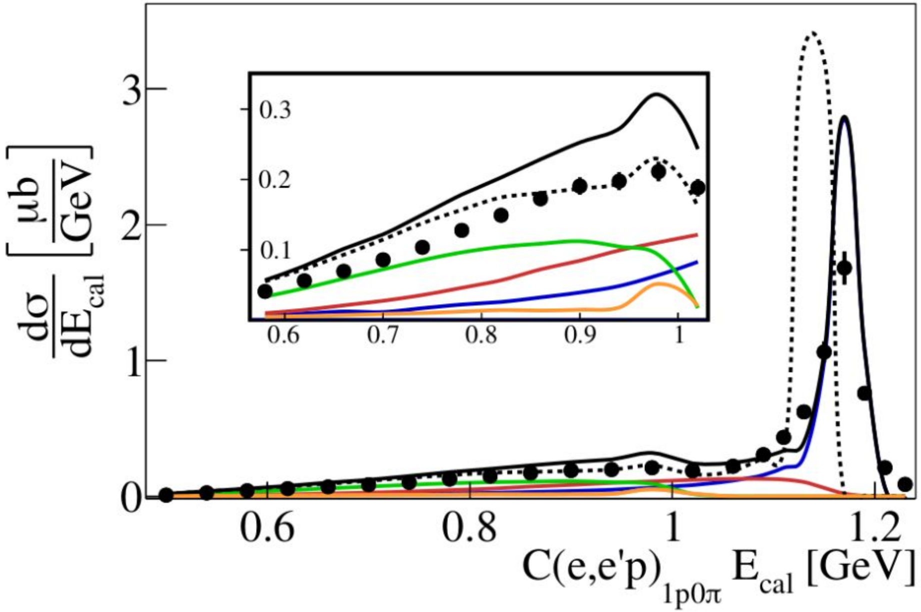
- Targets
  ^{4}He, ^{12}C, $^{\mathbf{40}}$**Ar**, ^{120}Sn
- 2 - 6 GeV beam energies





Wrap Up

- First use of wide phase-space electron data to test ν event generators
  www.e4nu.com
- Data/MC disagreement even for simple 1p0π events
- Identified regions requiring modeling improvements
- Wealth of results to follow!



Nature 599, 565–570 (2021)

Thank you !

$e4\nu$ + ?

Join us!

Jefferson Lab

CSIC
CONSEJO SUPERIOR DE INVESTIGACIONES CIENTÍFICAS

Backup Slides

Attacking The Modeling Monster

- Event Generator Modeling

Phys. Rev. D 103, 113003 (2021)

- Neutrino Cross Sections

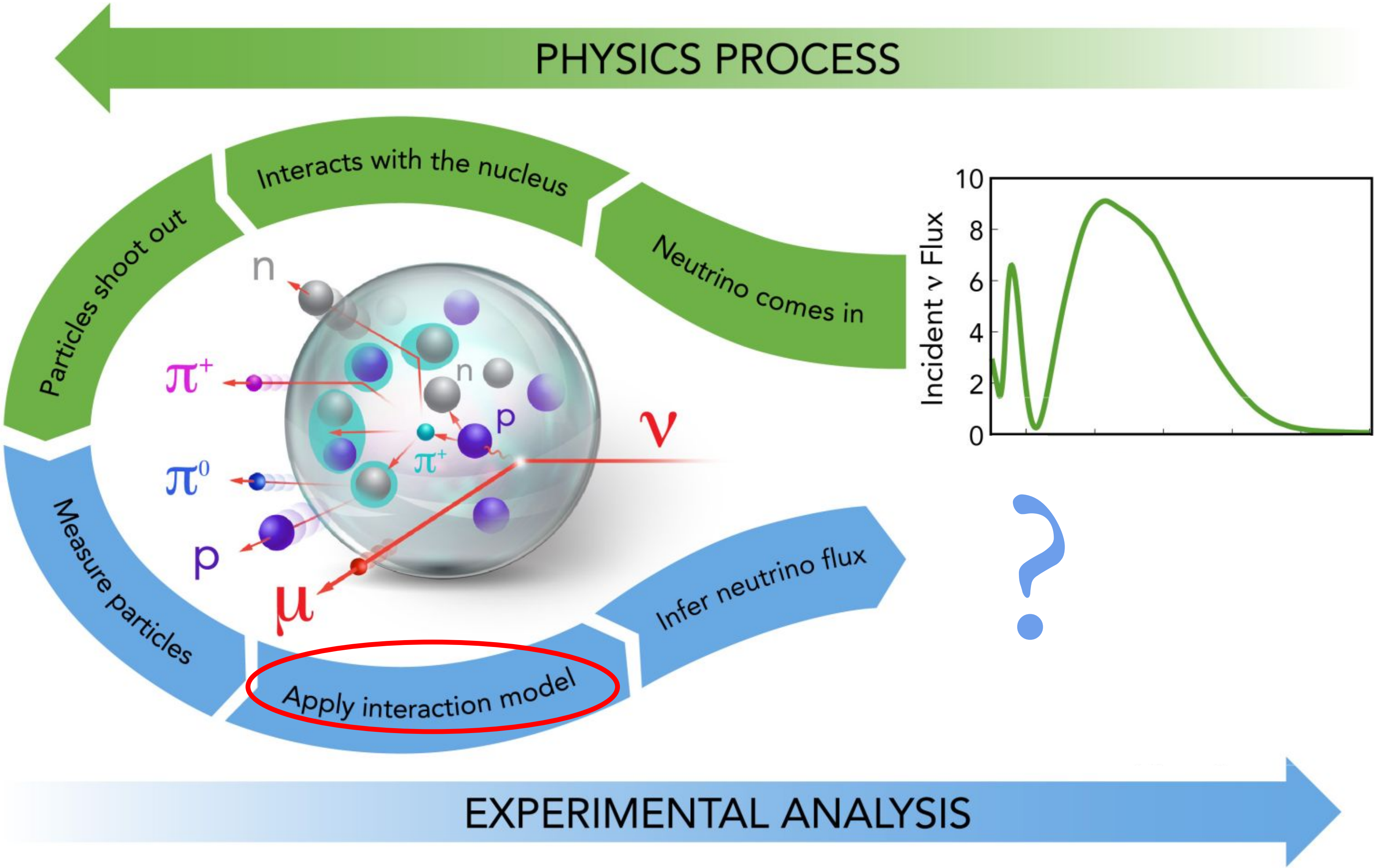
Phys. Rev. Lett. 125, 201803 (2020)

μBooNE

- Electron Cross Sections

Nature 599, 565–570 (2021)

e4ν

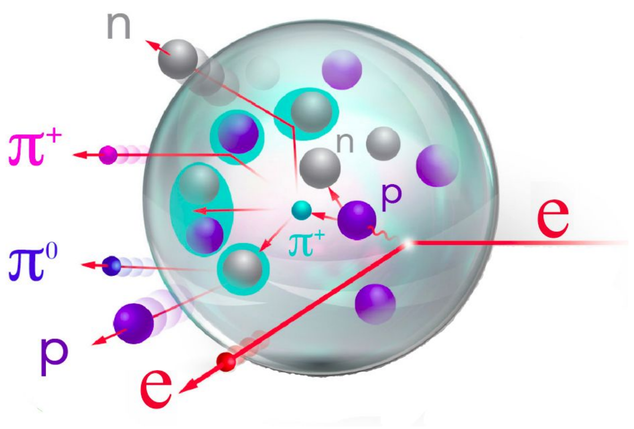

PHYSICS PROCESS
Interacts with the nucleus
Particles shoot out
Neutrino comes in
n
n
p
ν
π+
π0
π+
p
μ
Incident ν Flux
10
8
6
4
2
0
?
Measure particles
Apply interaction model
Infer neutrino flux
EXPERIMENTAL ANALYSIS

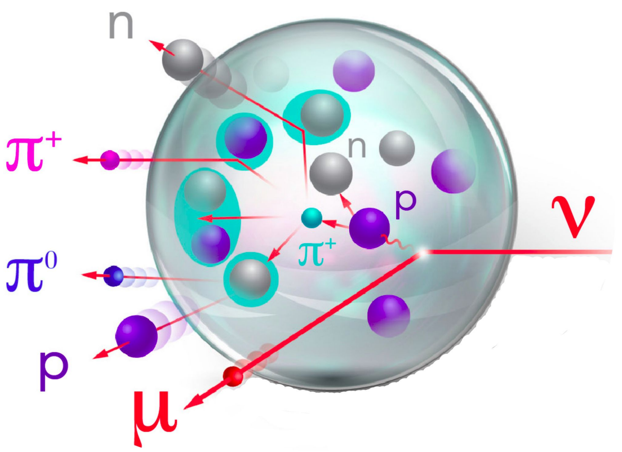
Why electrons?

- 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 !

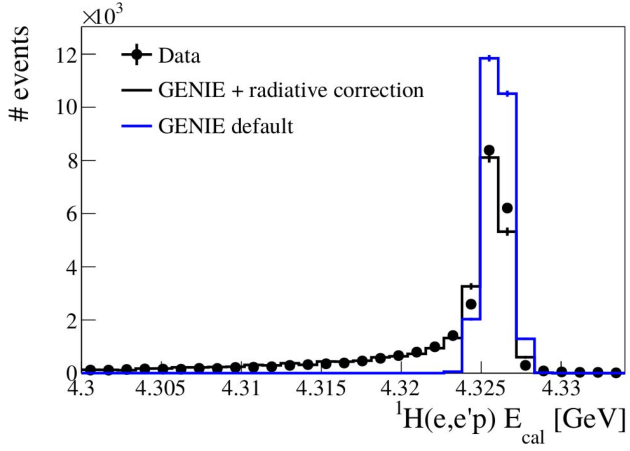




Cross-Section Extraction

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

Systematic uncertainties on each correction plus variation among detector sectors



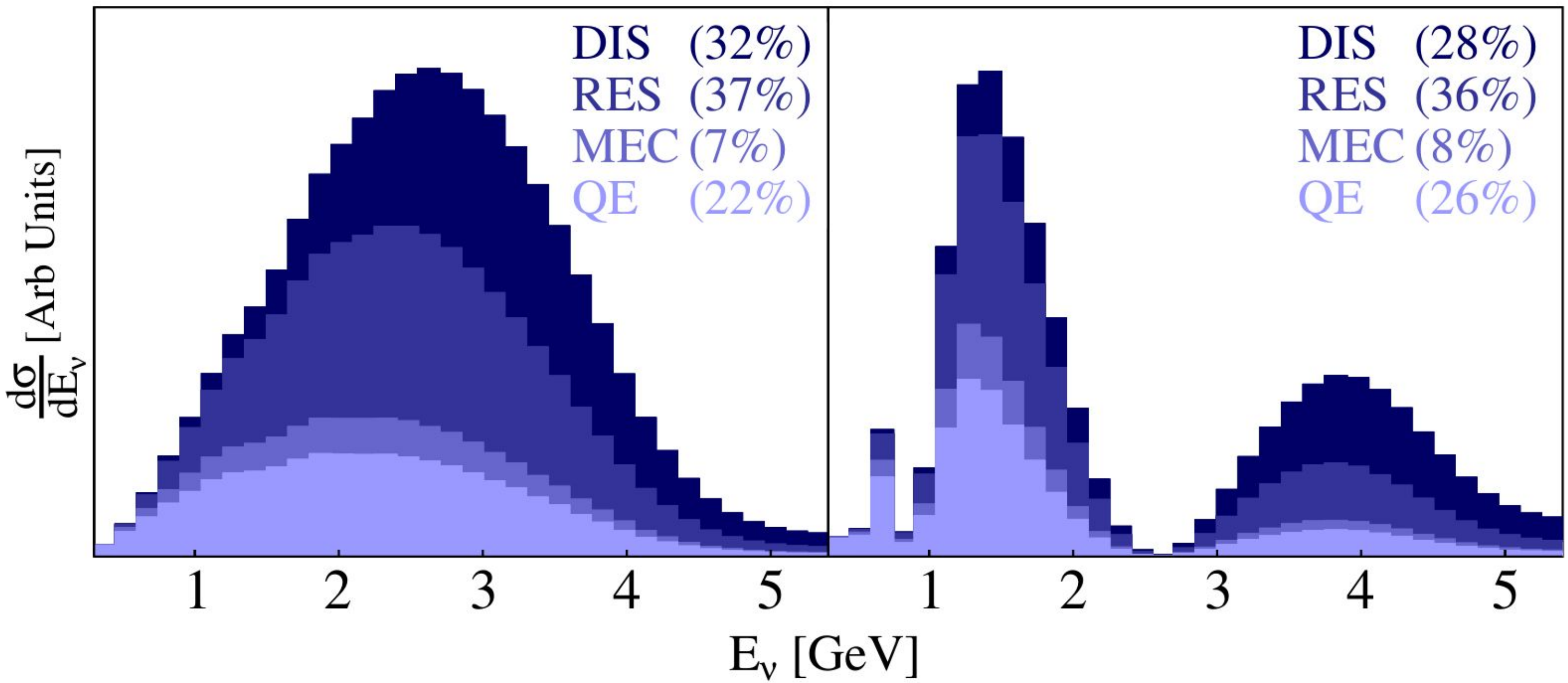
Hall A@ JLab

H(e,e'p) @ 4.32 GeV

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

Mismodelling Impact On Mixing Parameters

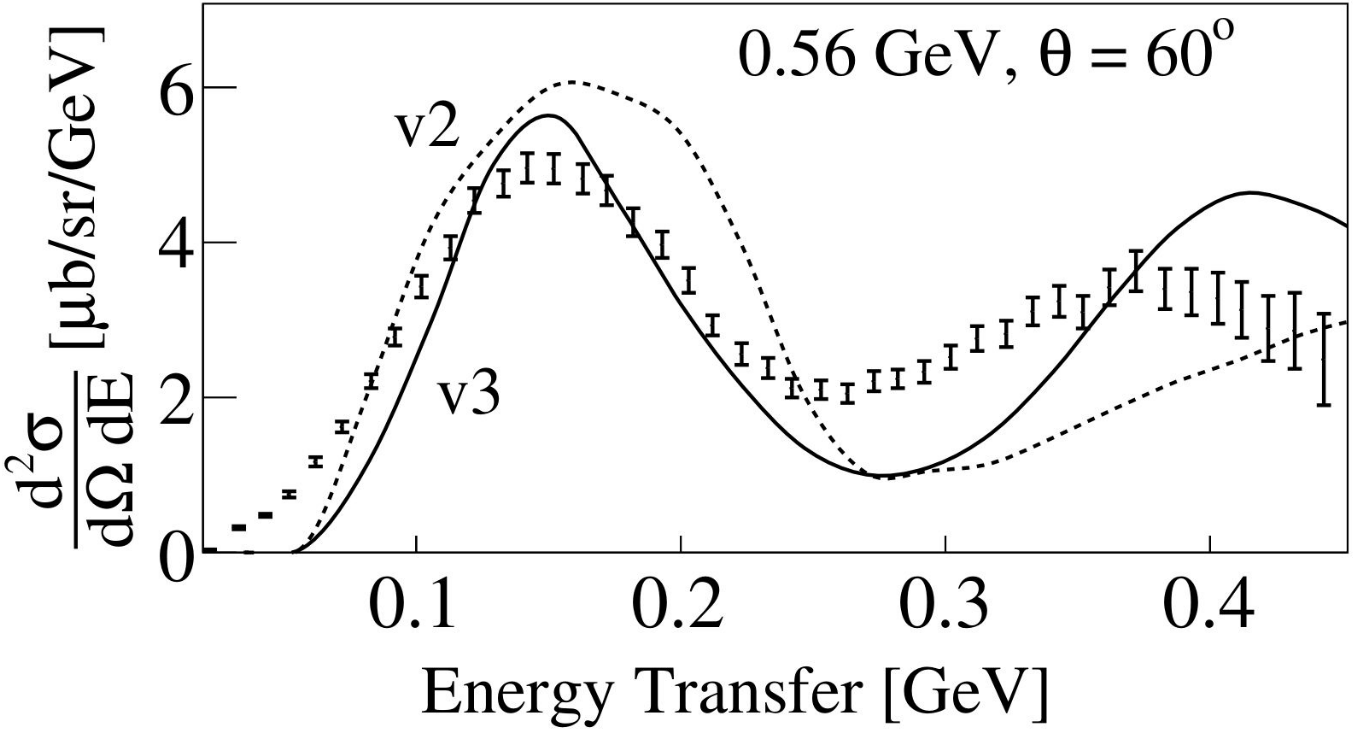
Charged current cross sections obtained using GENIE for the DUNE near detector (left) and far detector (right) oscillated fluxes



Phys. Rev. D 103, 113003 (2021)

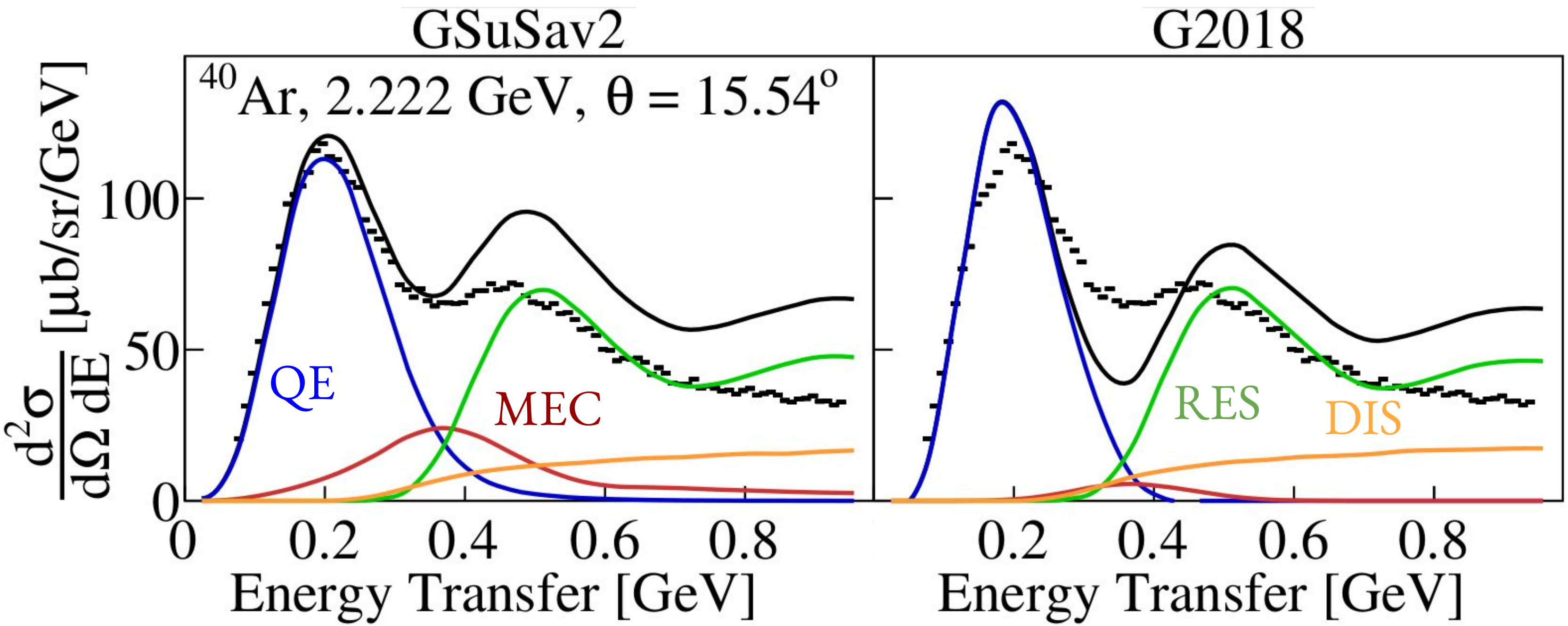
Issues Identified & Fixed In G2018

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



Phys. Rev. D 103, 113003 (2021)

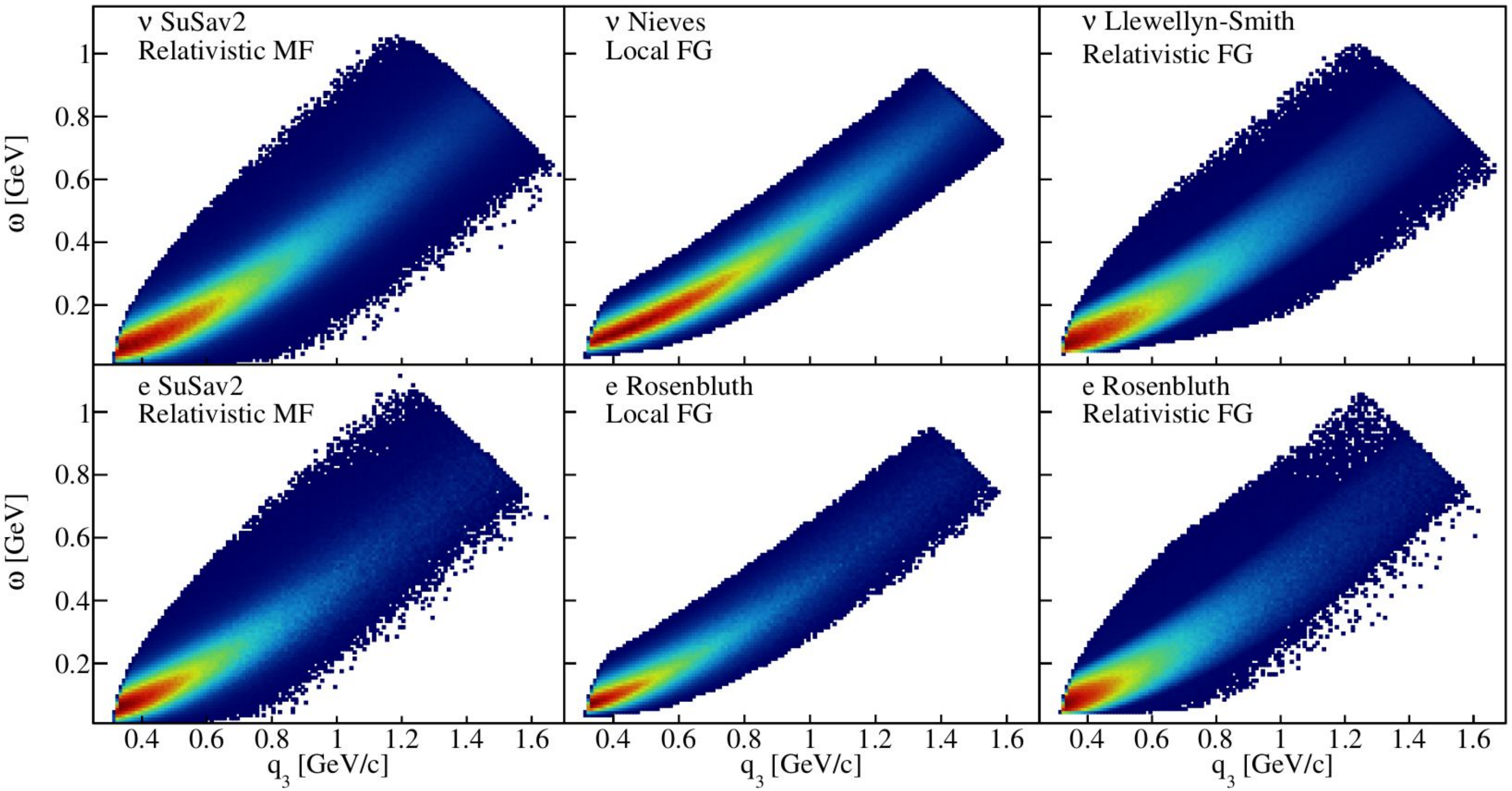
SuSav2 Offers More Accurate Prediction



Phys. Rev. D 103, 113003 (2021)

Probing The Neutrino Phase-Space With Electrons

QE Events

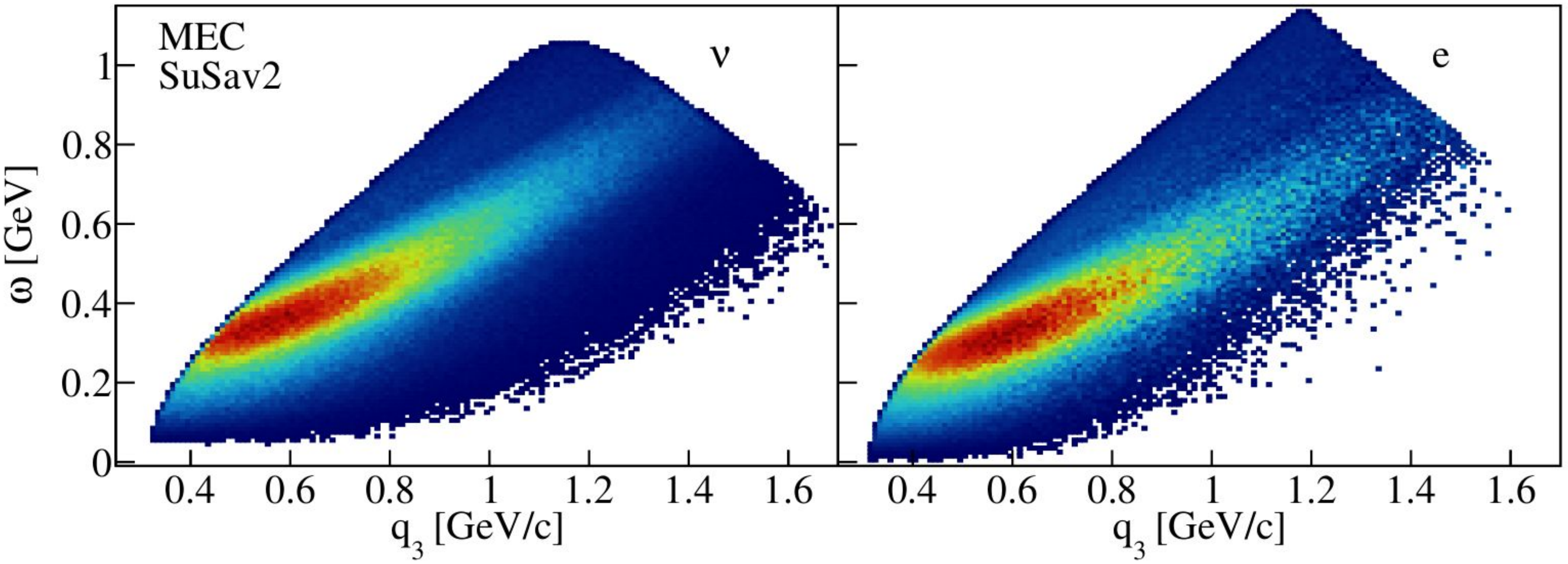


A.Papadopoulou, et al, Phys. Rev. D 103, 113003 (2021)

Electron results scaled by Q^4

Consistent Treatment Of MEC Events With SuSav2

Unique chance to constraint one of least understood interaction channels

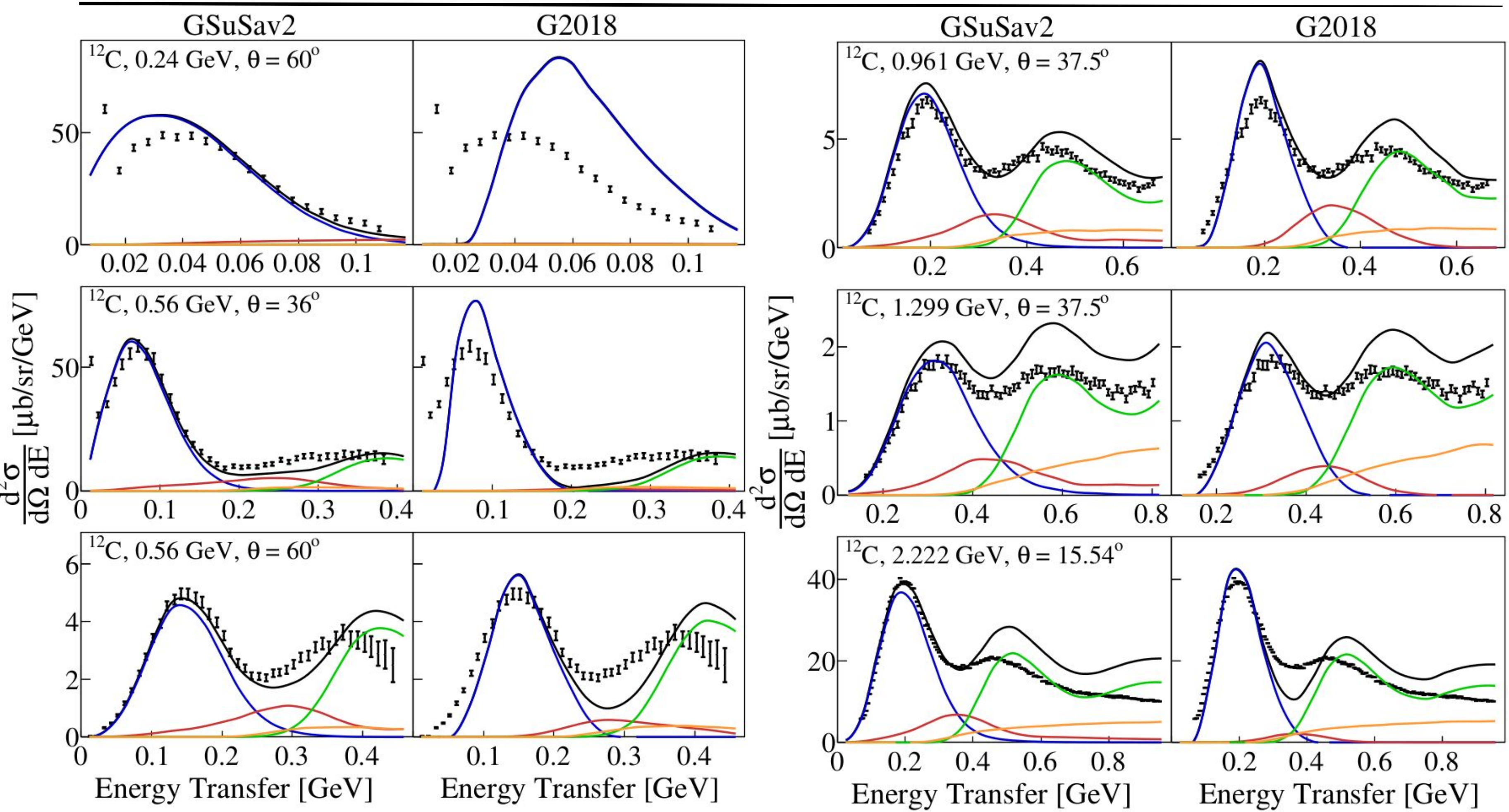


Phys. Rev. D 103, 113003 (2021)

Electron results scaled by Q^4

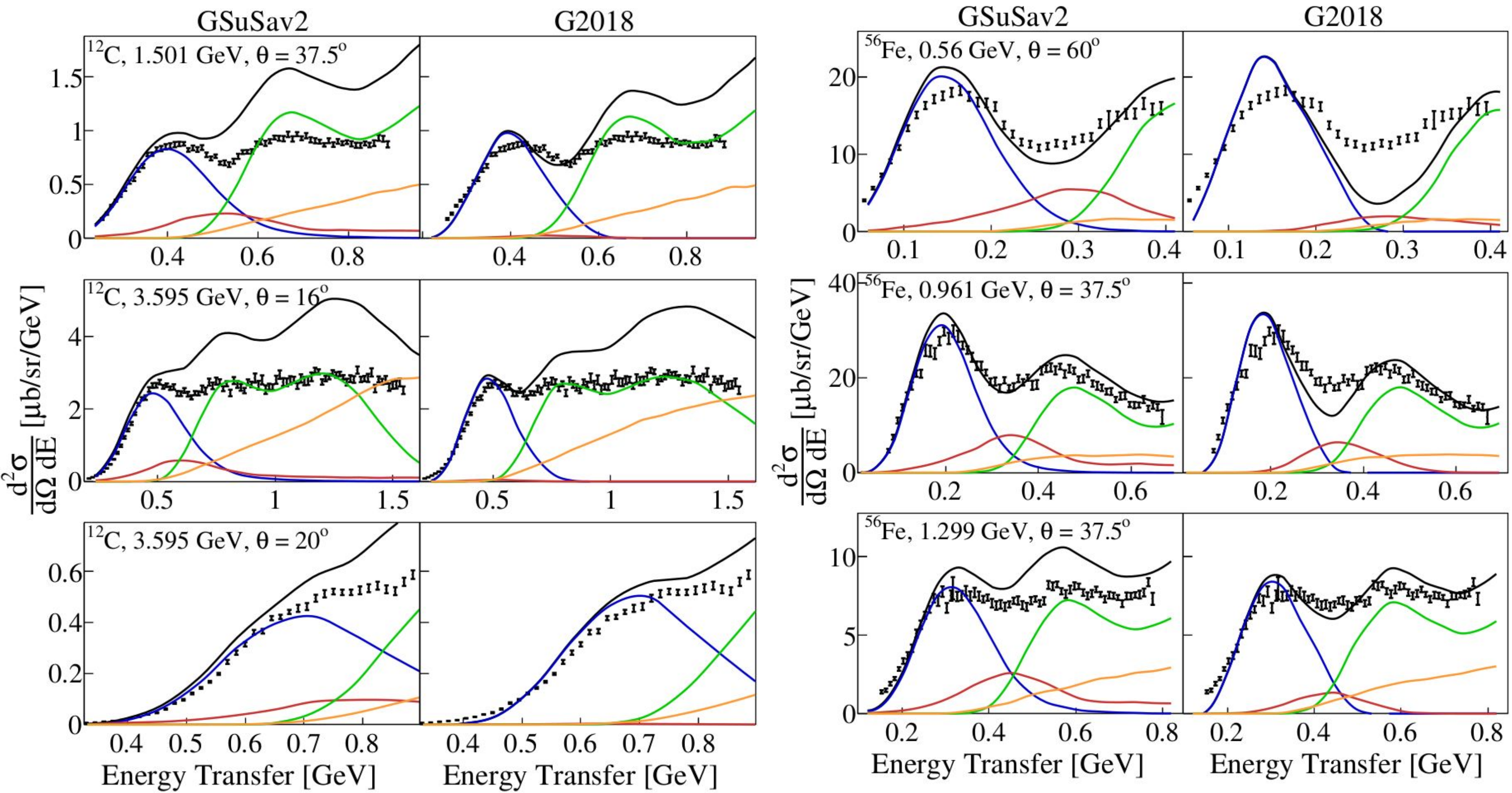
Inclusive C cross sections

Phys. Rev. D 103, 113003 (2021)



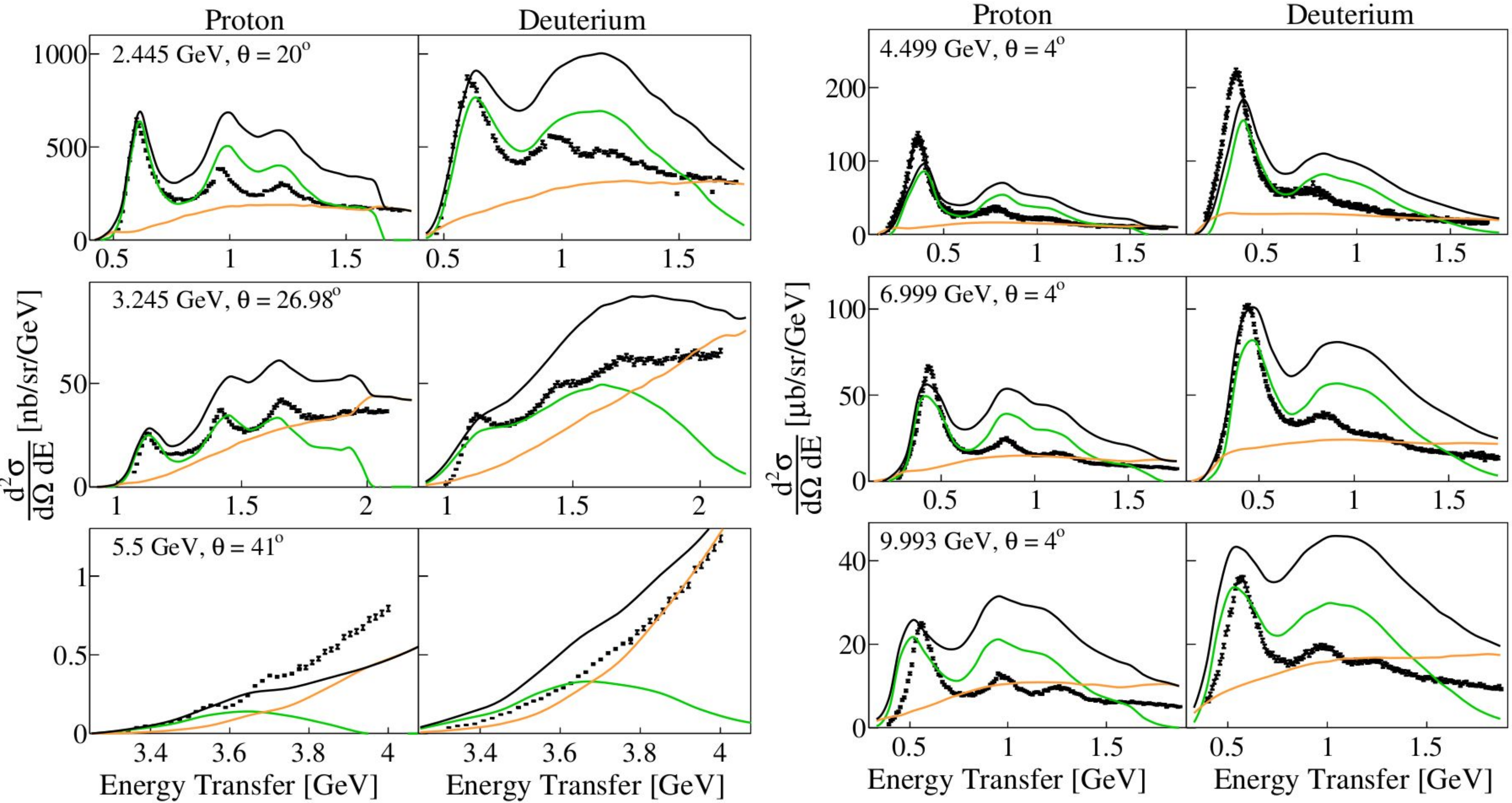
Inclusive C/Fe cross sections

Phys. Rev. D 103, 113003 (2021)

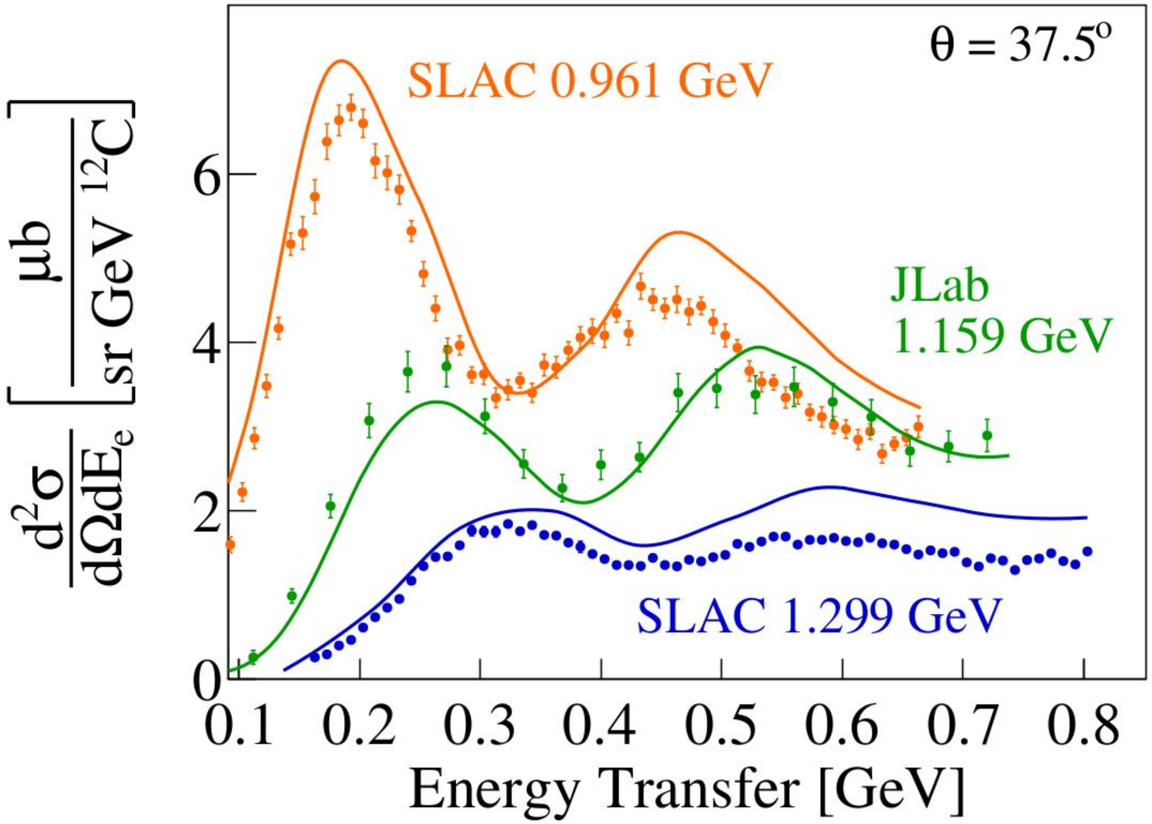


Inclusive H cross sections

Phys. Rev. D 103, 113003 (2021)

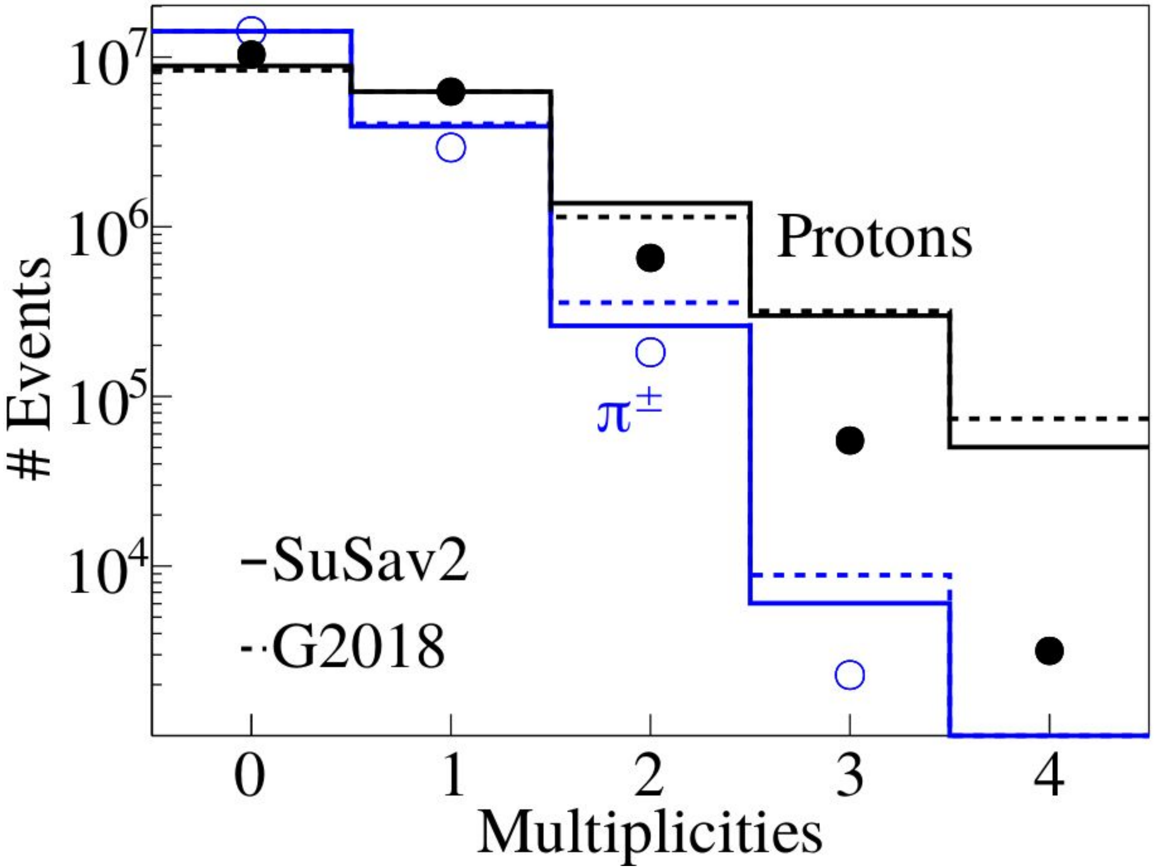


Sanity Check With Inclusive Cross Sections



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

Detected Hadron Multiplicities



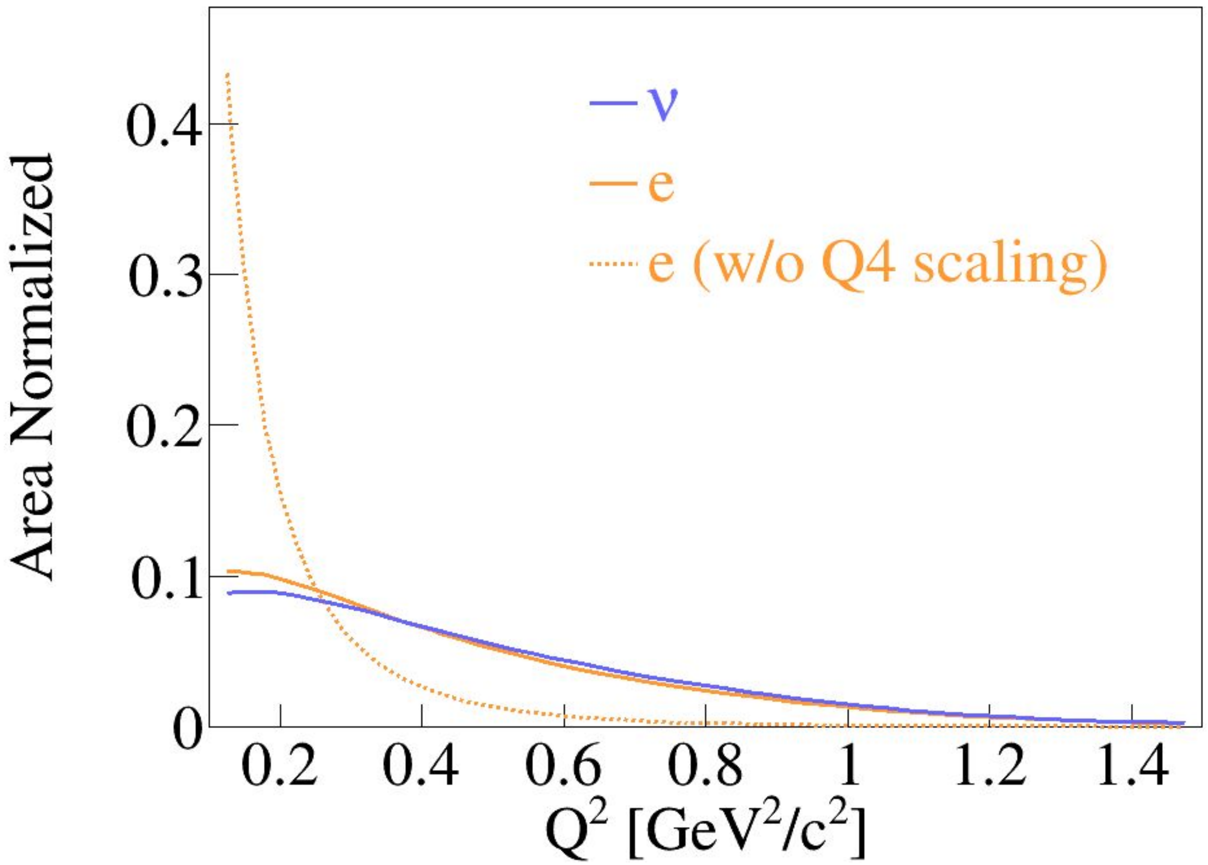
^{12}C @ 2.2 GeV

P_p > 300 MeV/c
P_π > 150 MeV/c

Simulation overpredicts hadron multiplicities

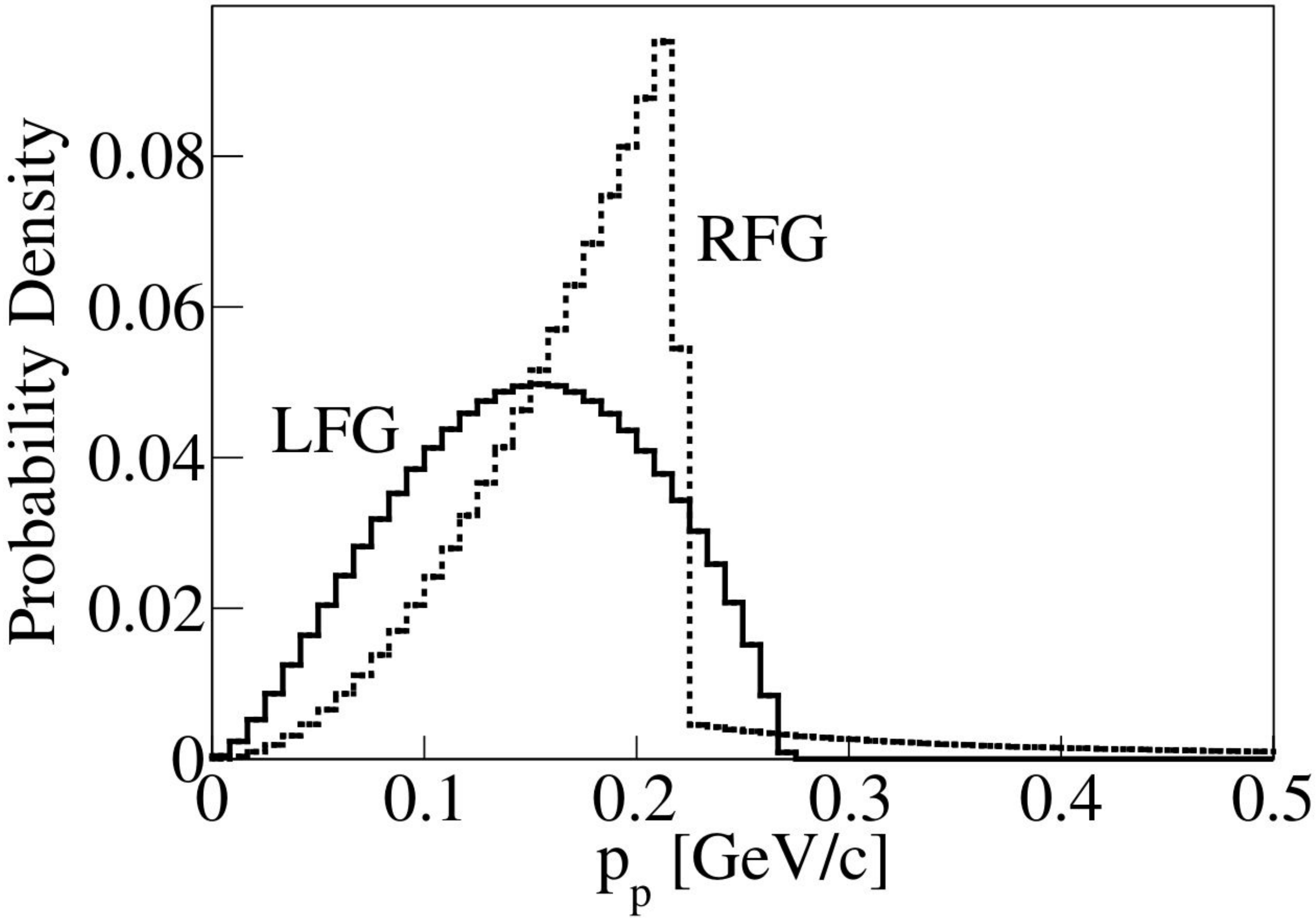
M.Khachatryan, A.Papadopoulou, et al.
Nature 599, 565–570 (2021)

Q^4 Scaling Effect



Available Nuclear Models

Phys. Rev. D 103, 113003 (2021)



SuSav2 Configuration / GEM21_11b_00_000

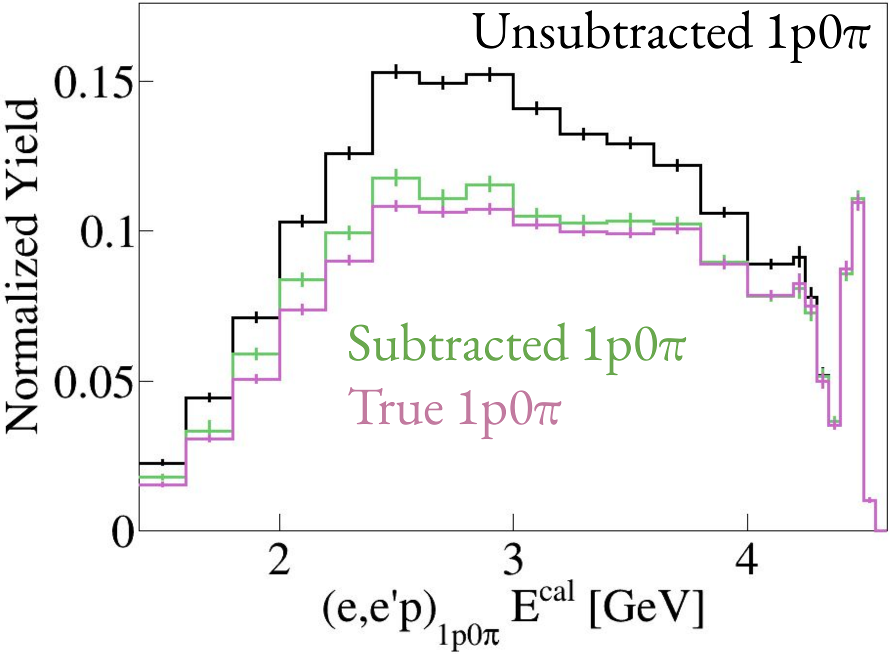
	Electrons	**Neutrinos**
QE	SuSav2	SuSav2
MEC	SuSav2	SuSav2
RES	Berger-Sehgal	Berger-Sehgal
DIS	AGKY	AGKY
FSI	hN2018	hN2018
Nuclear Model	Relativistic Mean Field	Relativistic Mean Field

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

Closure Test

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



Well defined signal definition: Min θ_e Cut

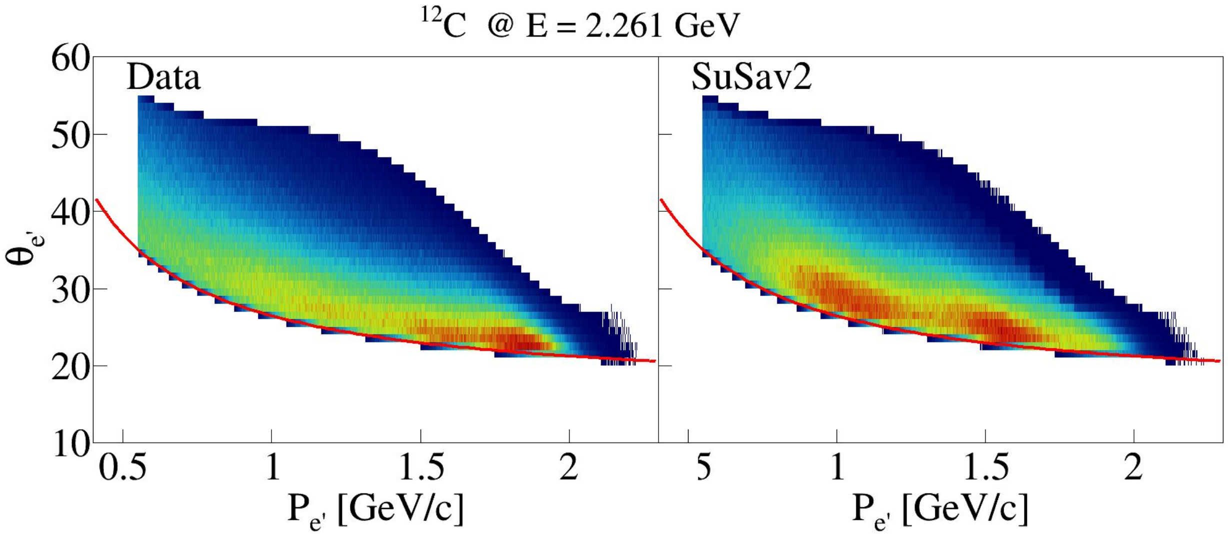
@ 1.1 GeV: $\theta = 17 + 7 / P$

@ 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



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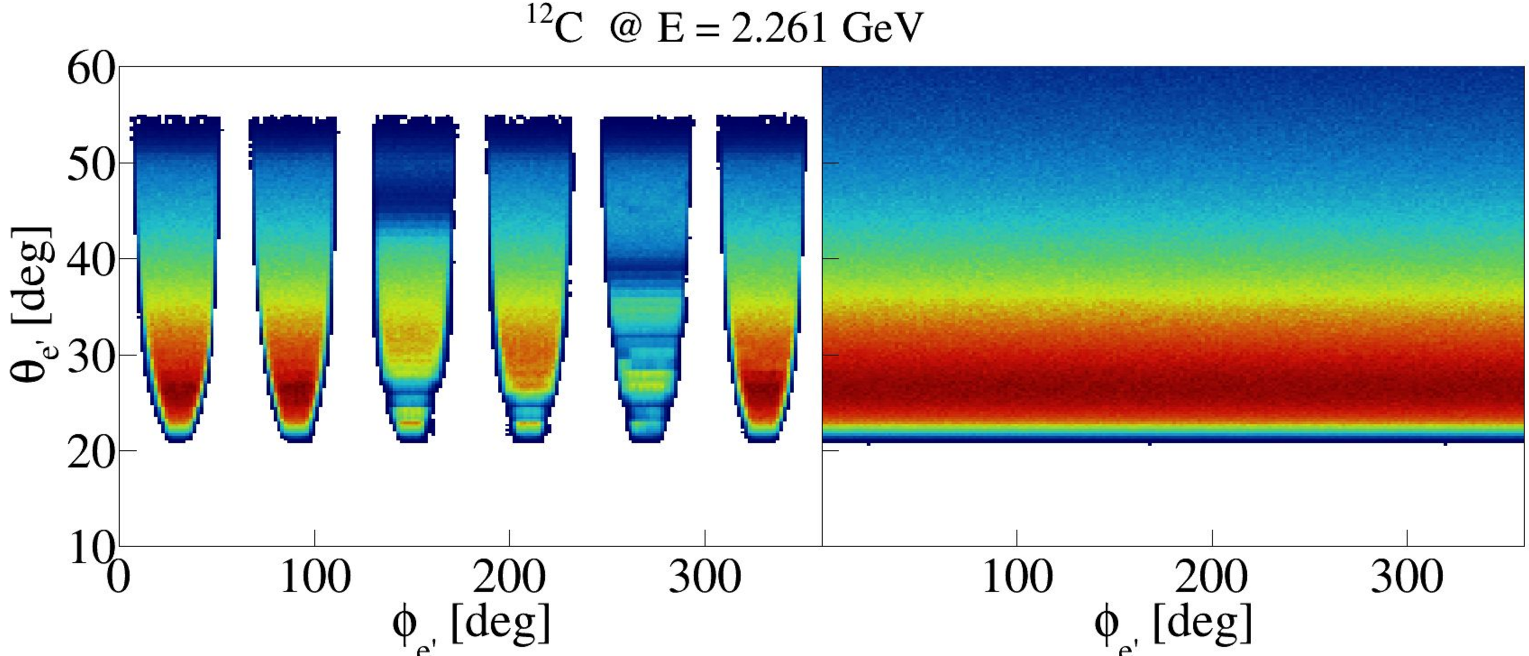
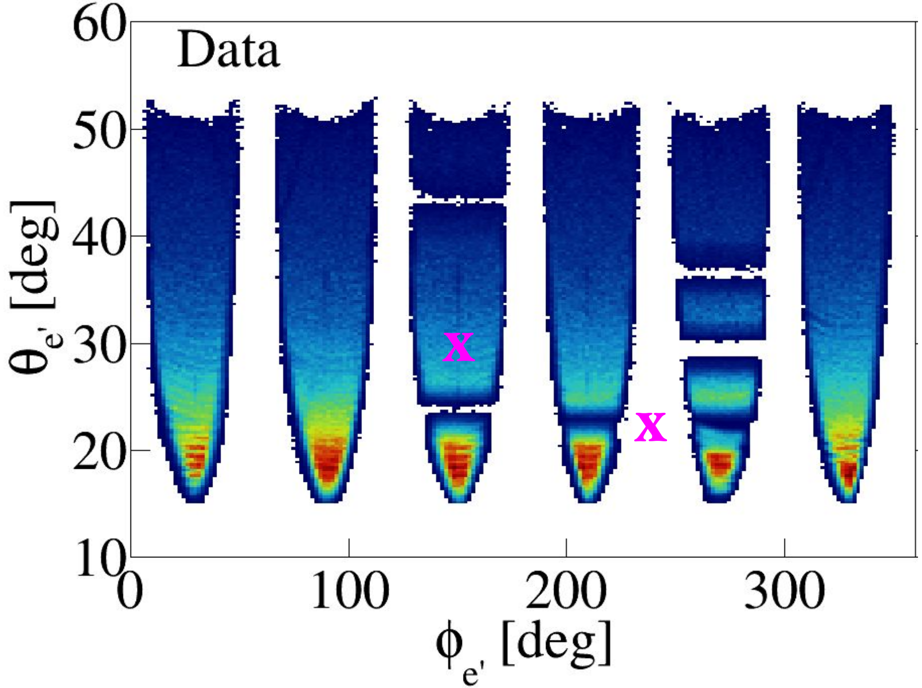
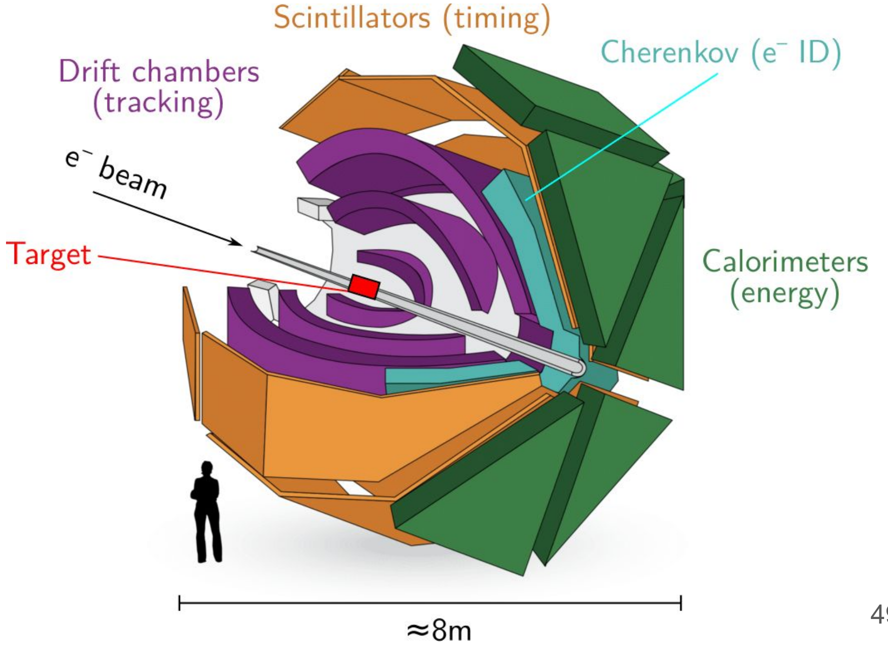


Background Subtraction

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

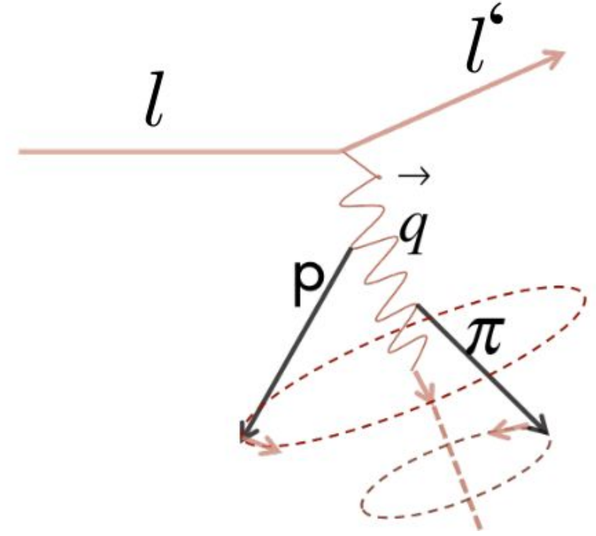




Data Driven Correction

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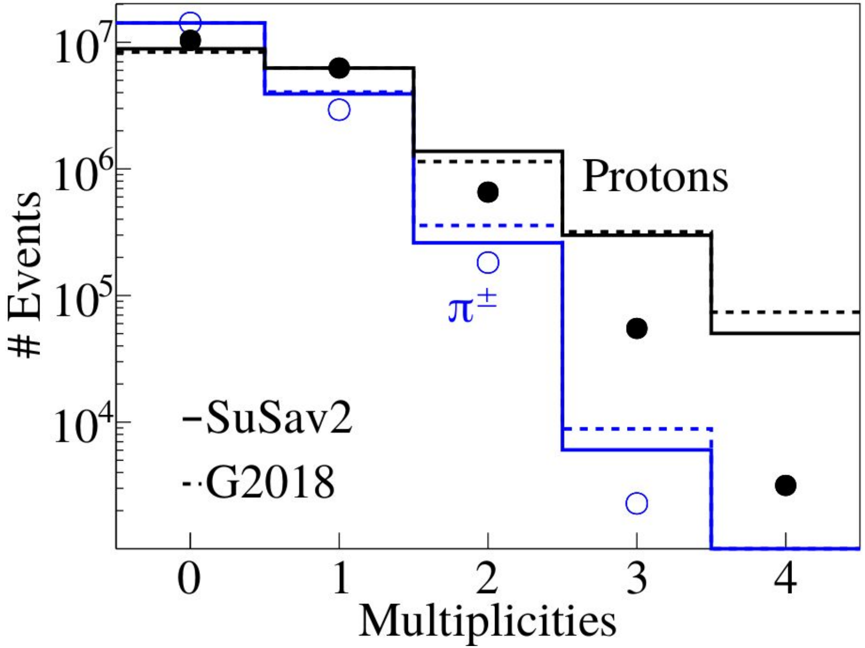
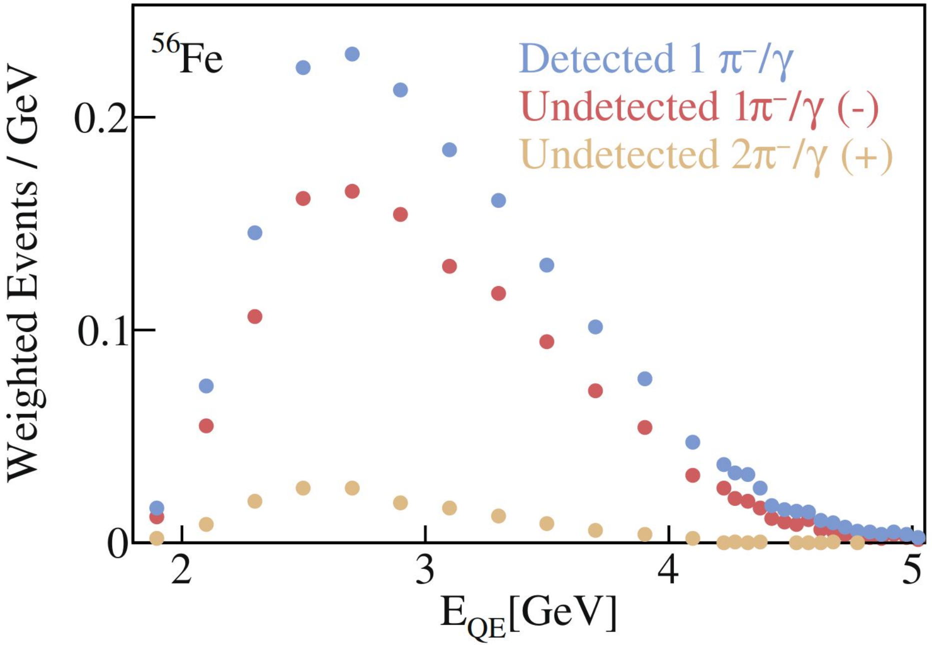
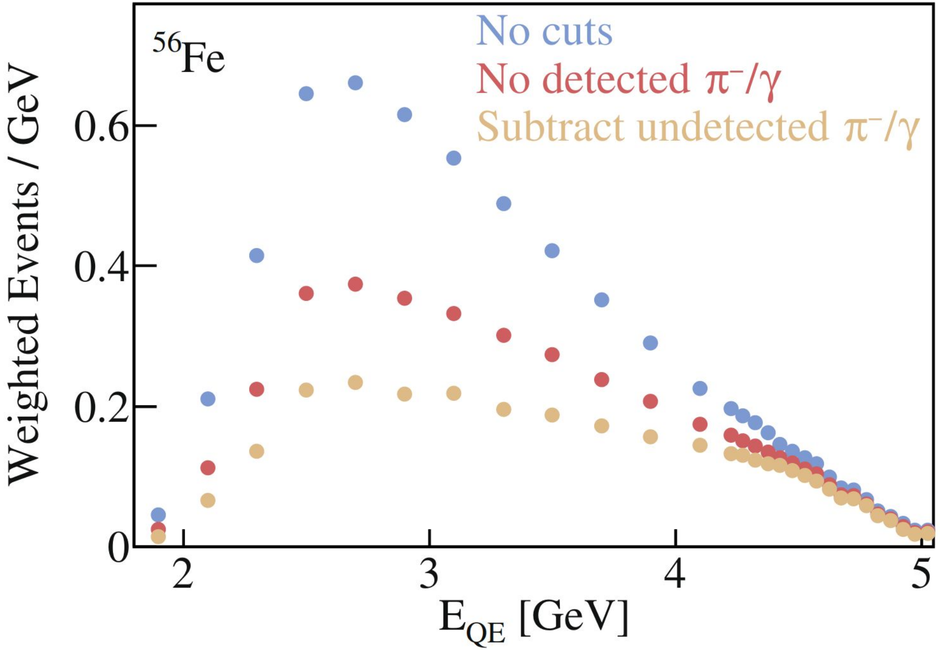
- Use measured (e,e’pπ) events
- Rotate p, π around q to determine π detection efficiency
- Subtract for undetected (e,e’pπ)
- Repeat for higher hadron multiplicities

(2p, 3p, 2p+1π, …)

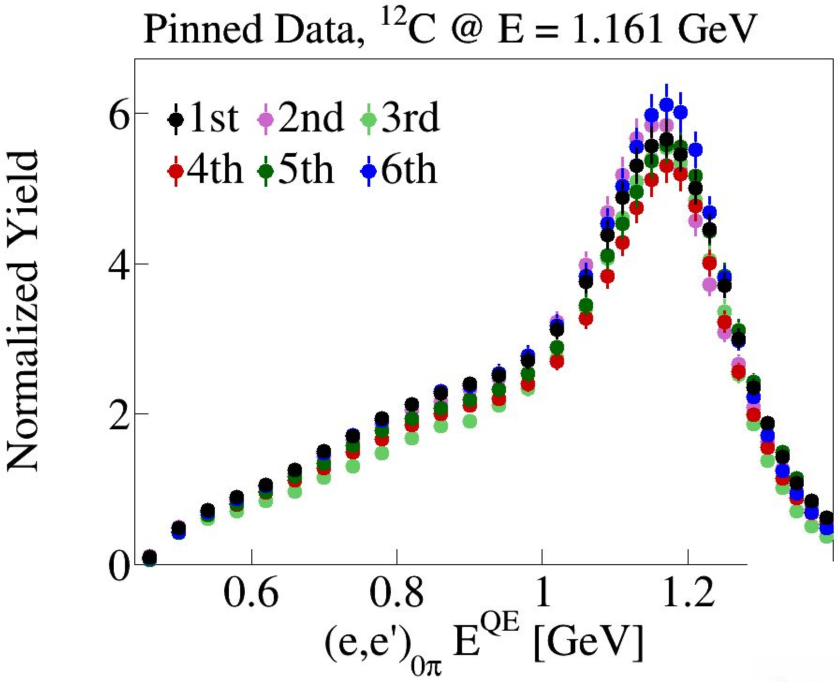


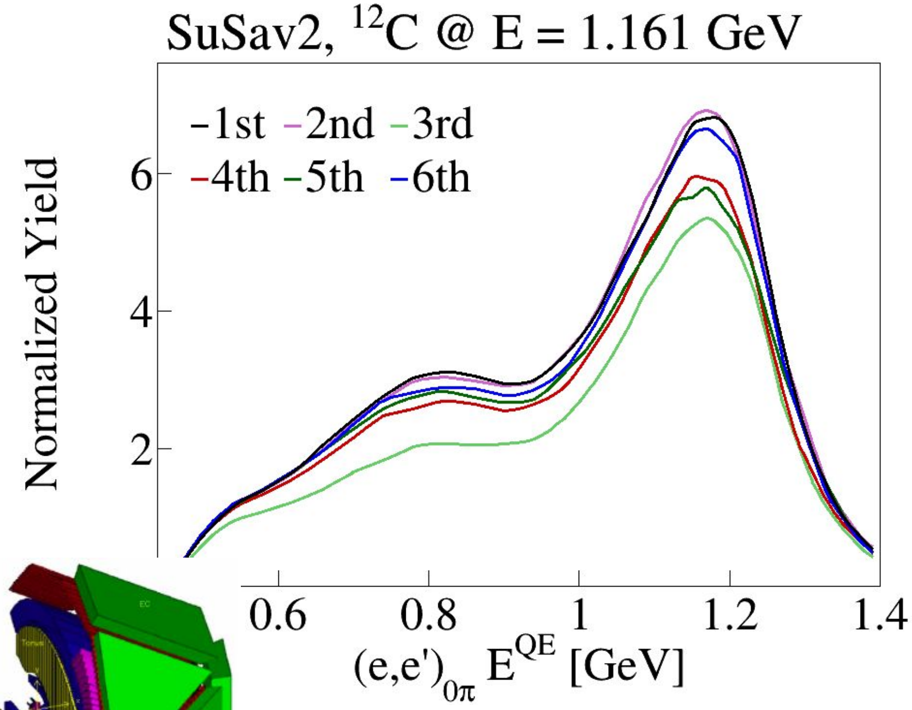
Subtraction Effect

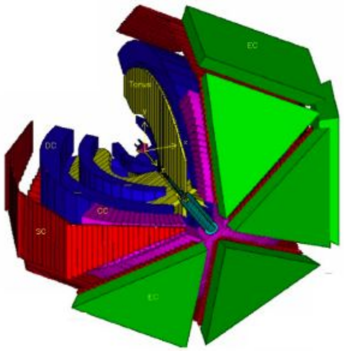




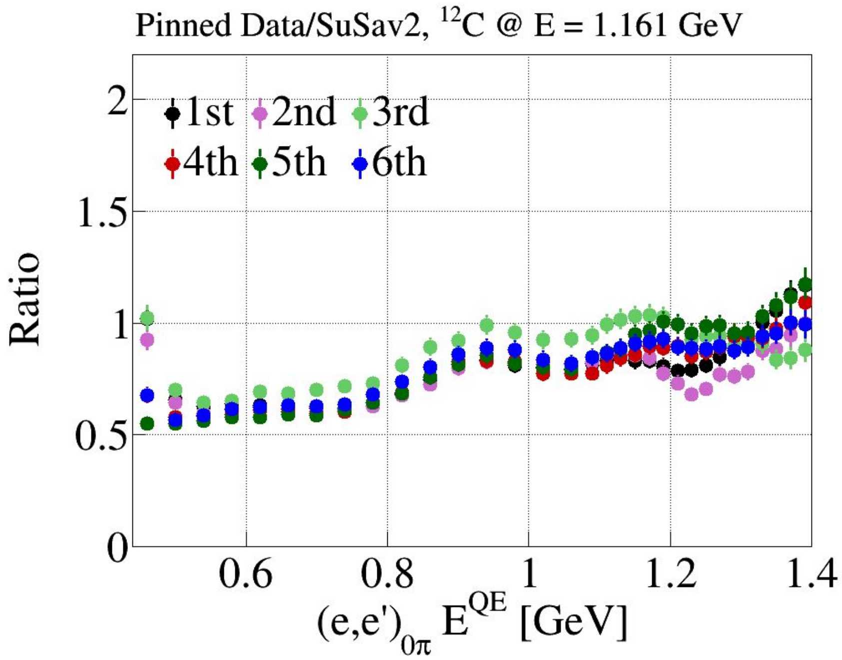
Systematics: Sector Dependence

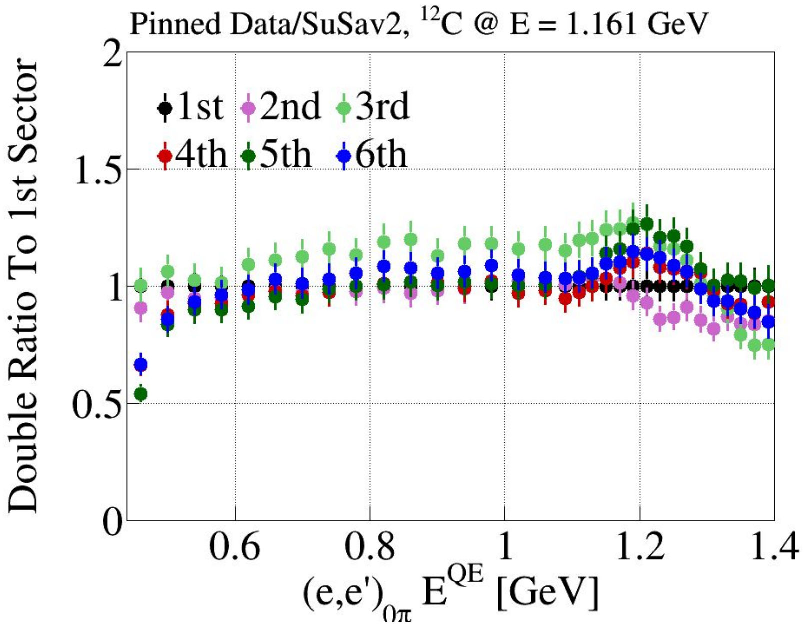






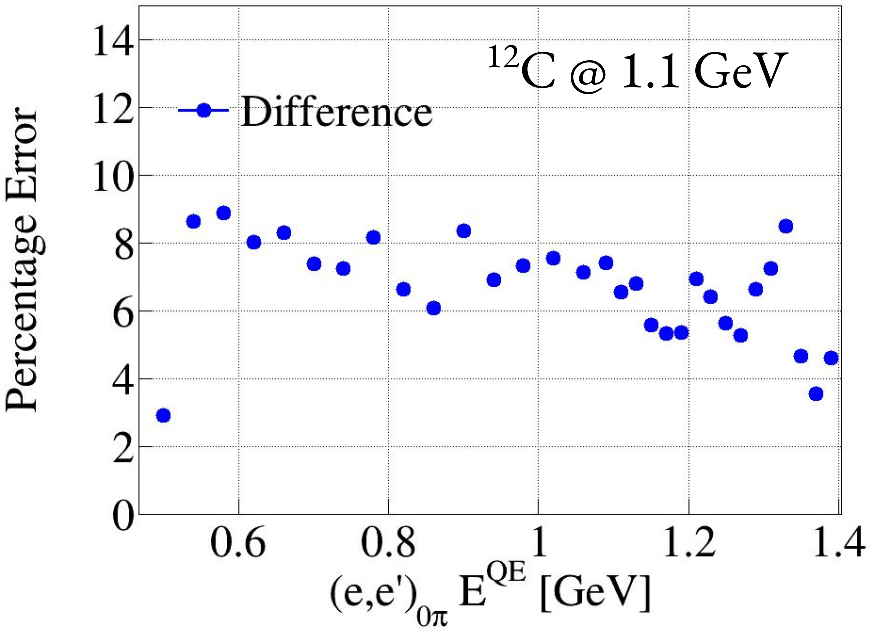
Systematics: Sector Dependence





Systematics: Sector Dependence

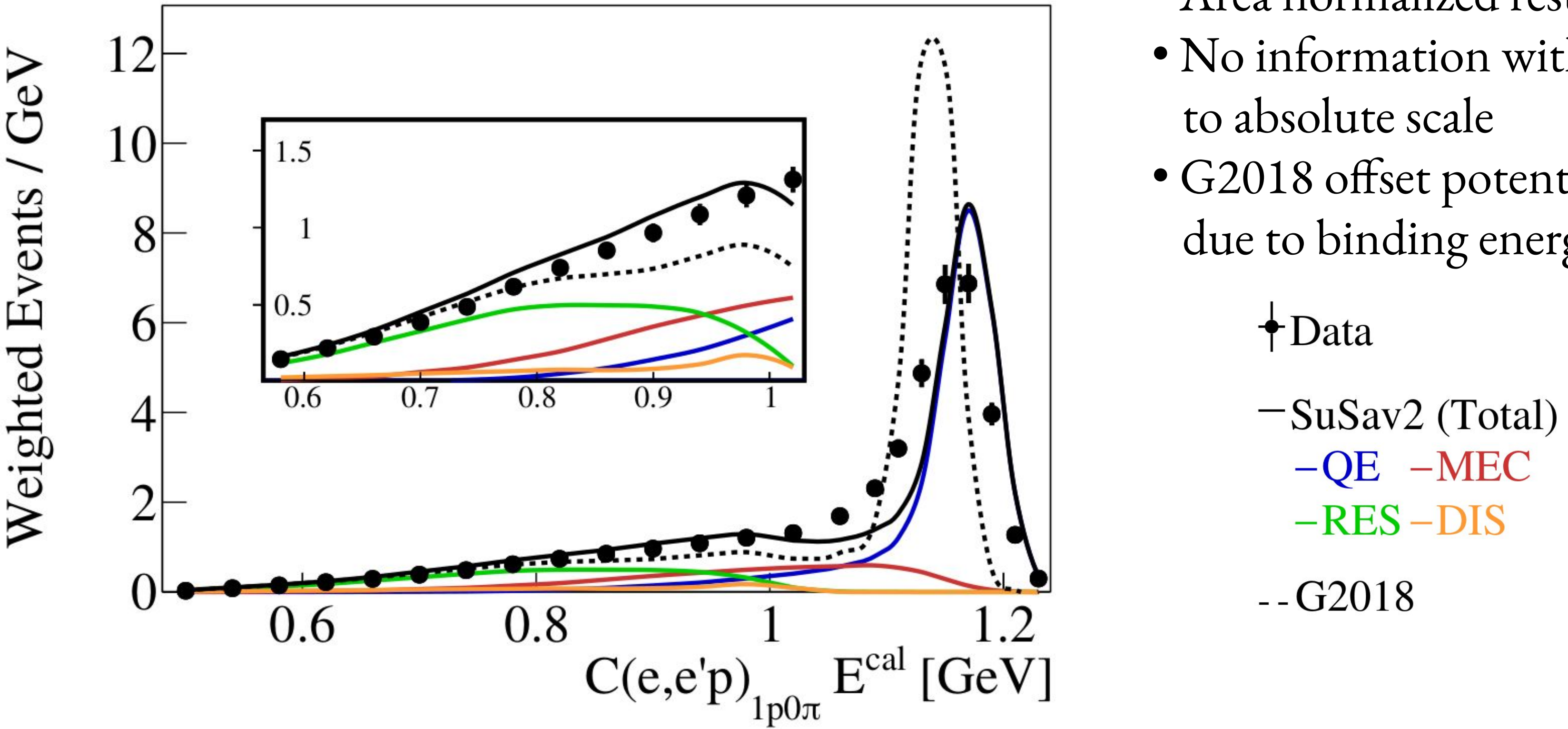
Quantifying uncertainty by using
unweighted variance & by subtracting variance from statistical uncertainty



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

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

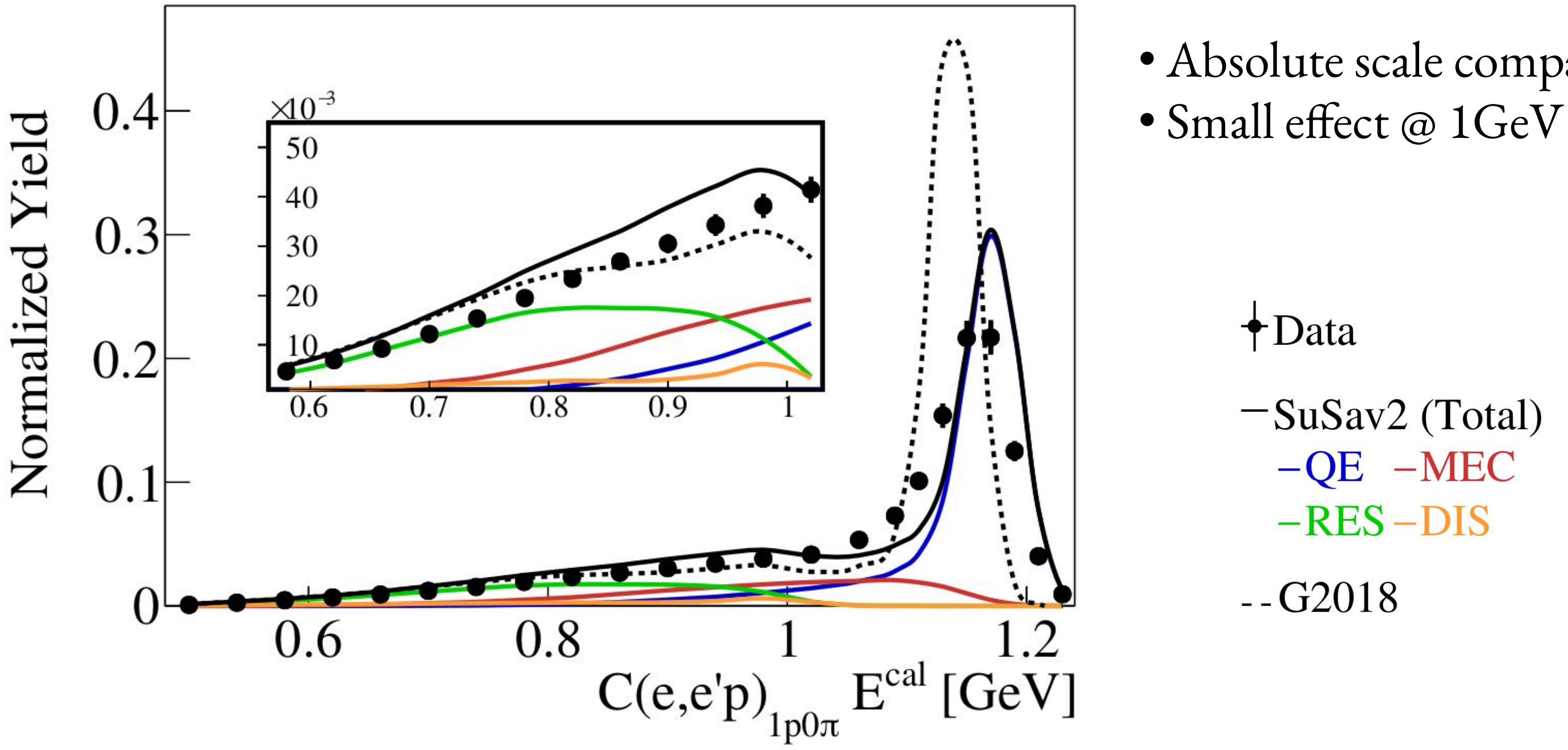
- Divide # events by integrated charge & target thickness to get xsec in μb
- Divide by bin width to get μb/GeV

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

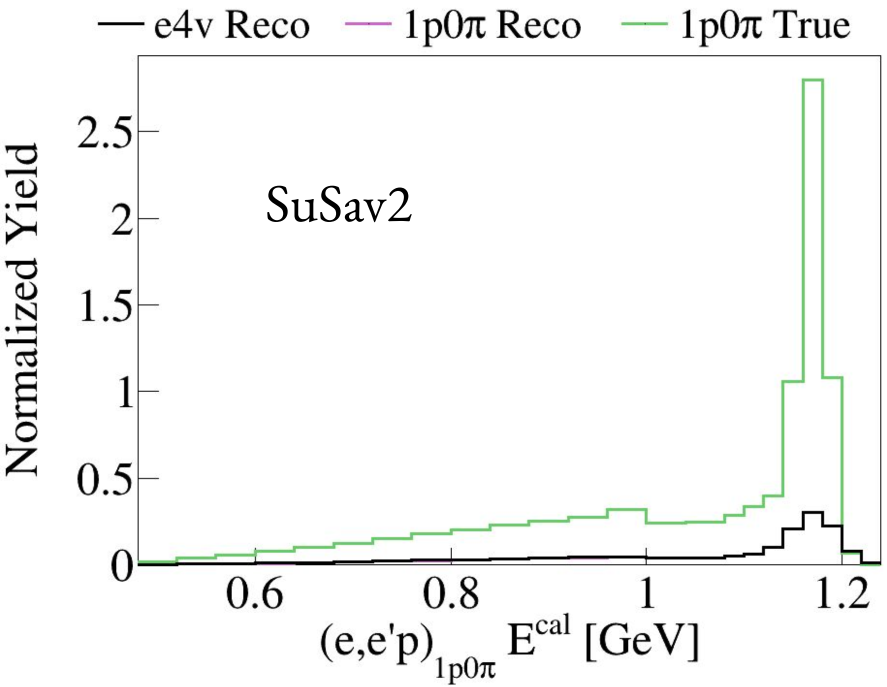


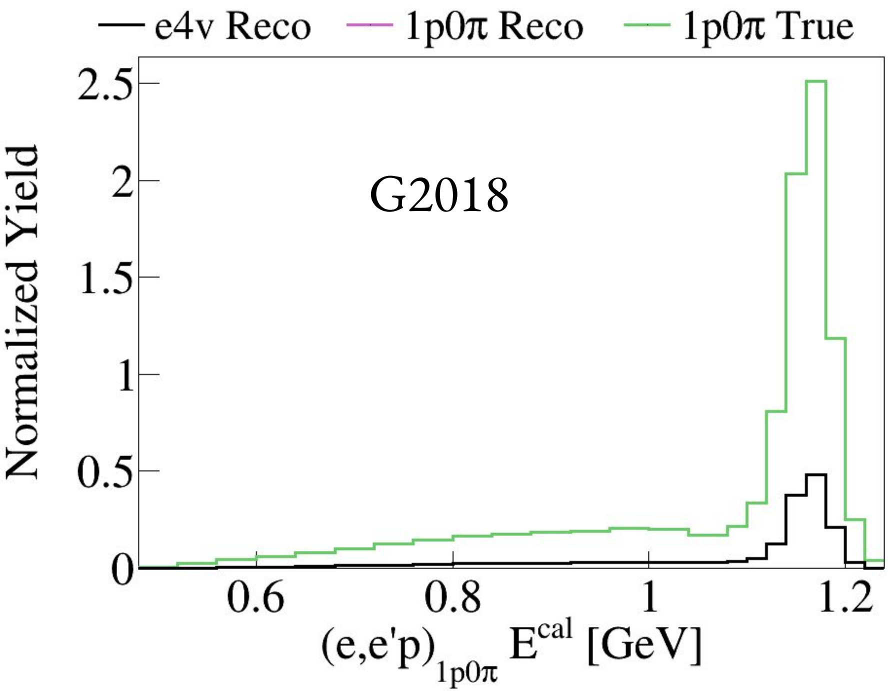
- Absolute scale comparison
- Small effect @ 1GeV

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

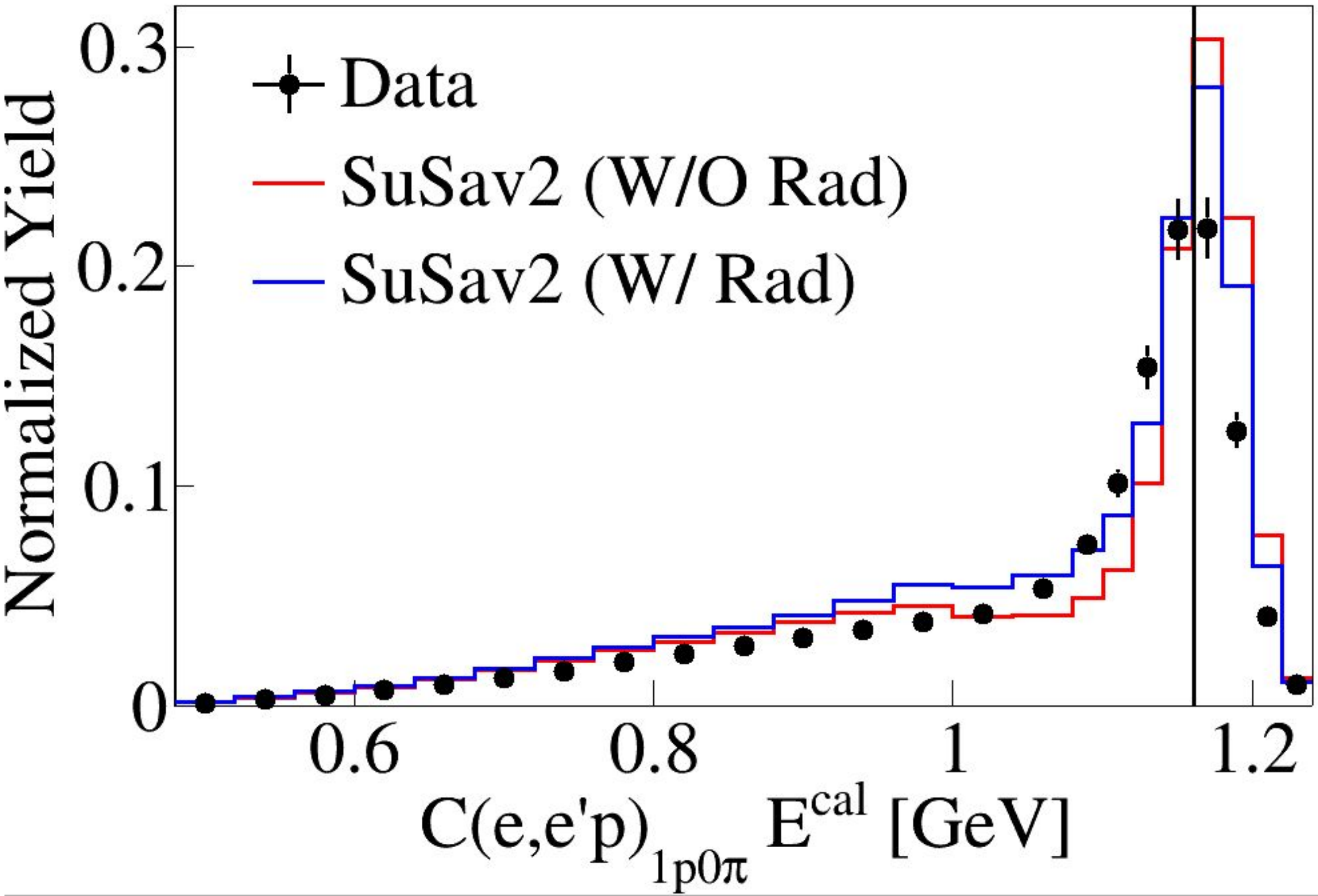
Step #3a: Example 12C @ 1.1 GeV





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

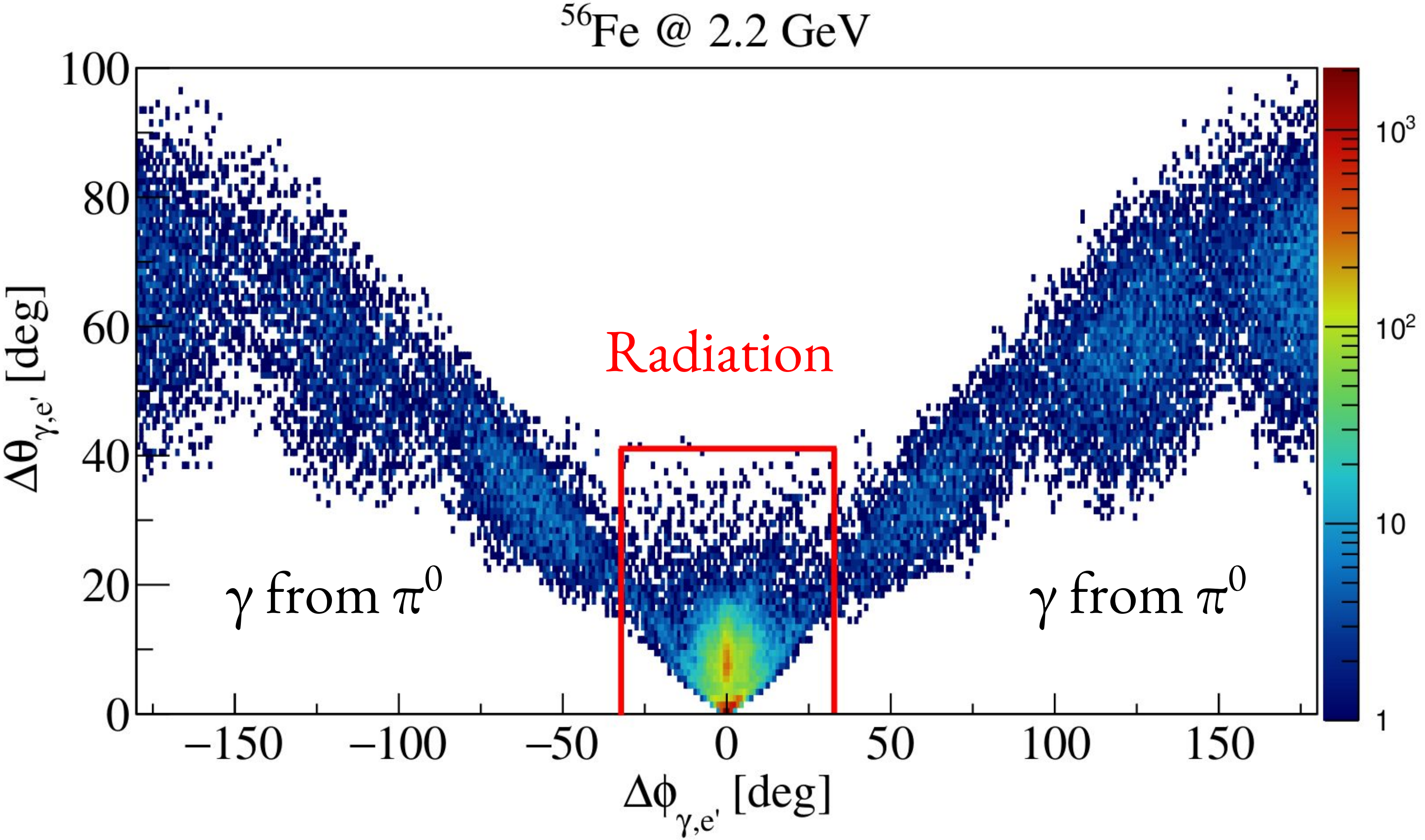
On a bin-by-bin basis

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

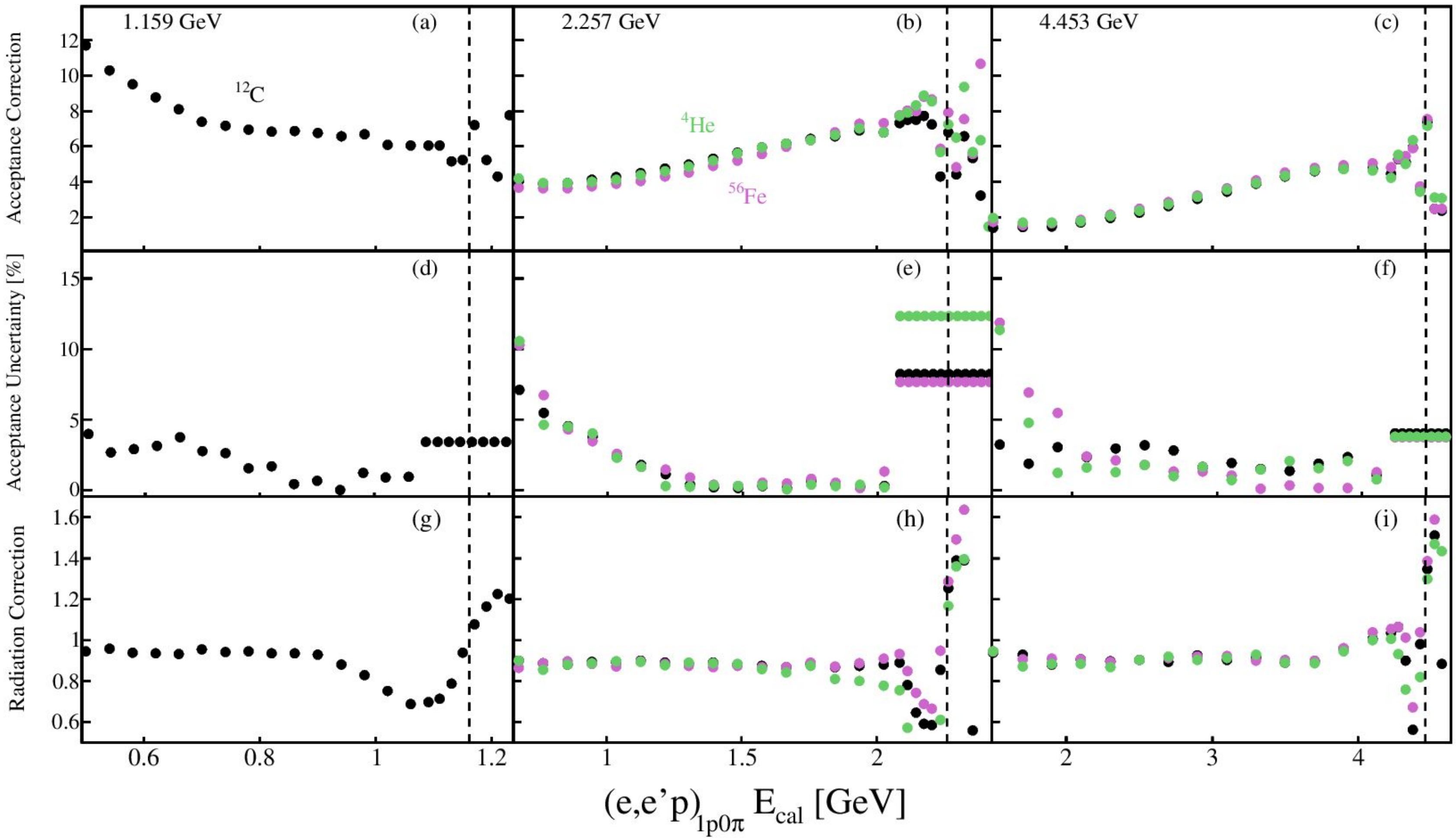
Bin Entry = x / Average * 100 %

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

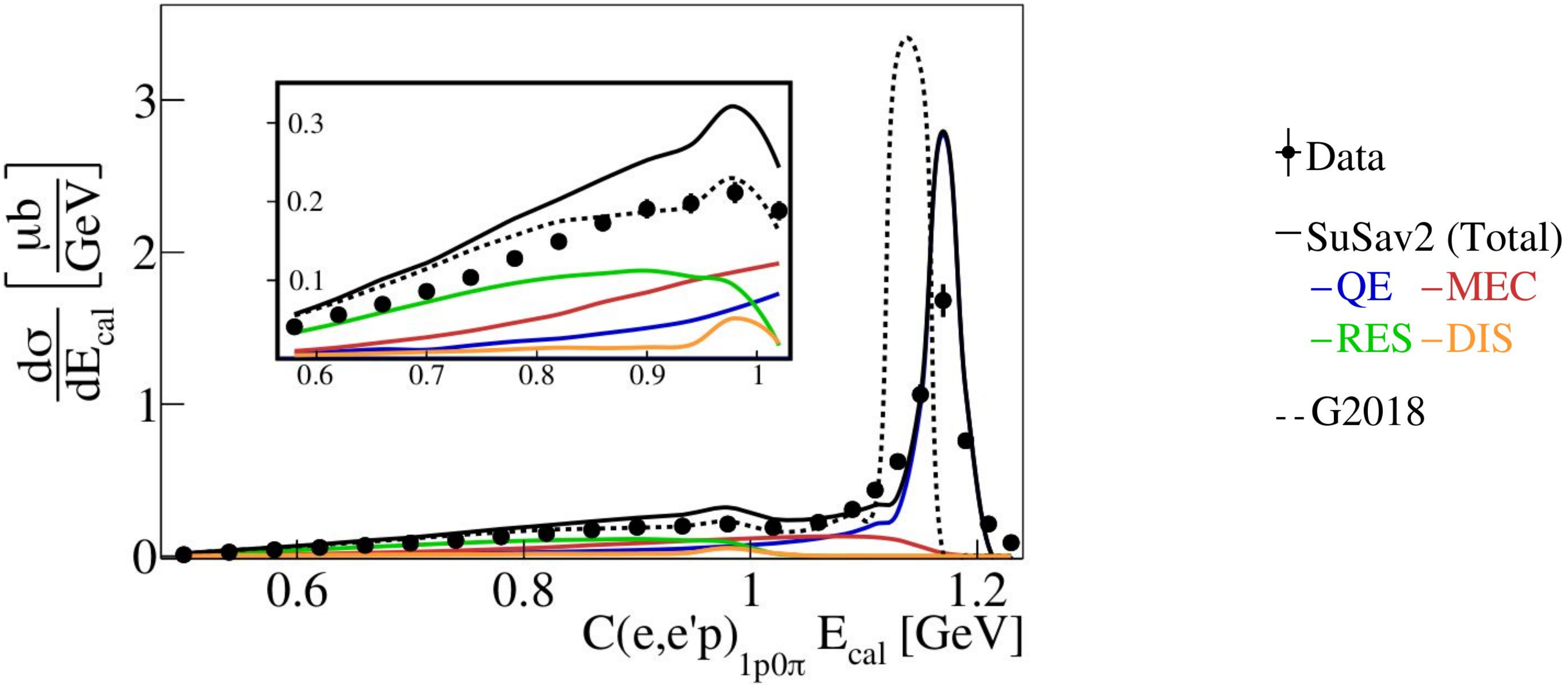


Correction Factors



Step #4: Absolute Cross Sections

After both acceptance & radiation corrections, without systematics yet



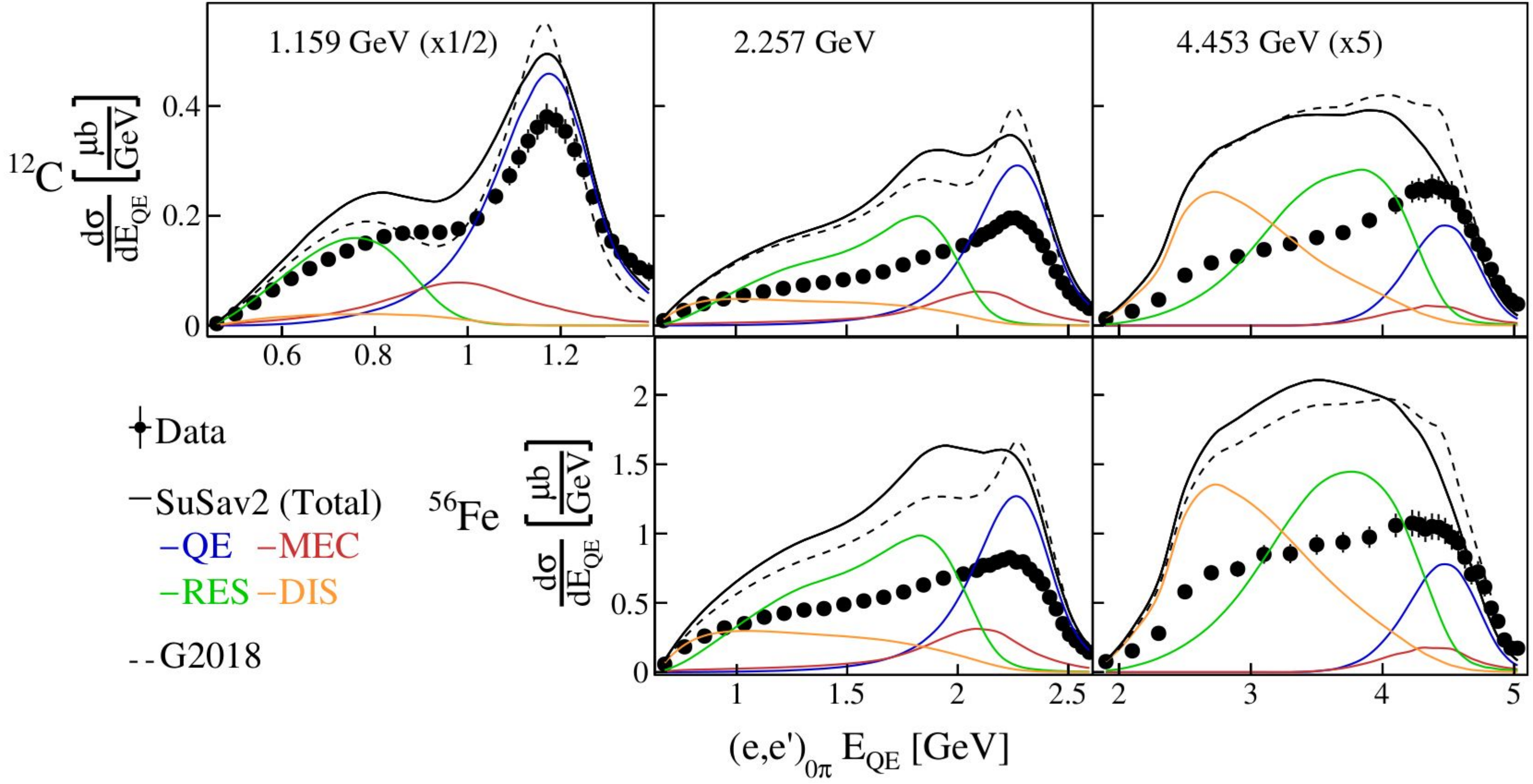
Systematics

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



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

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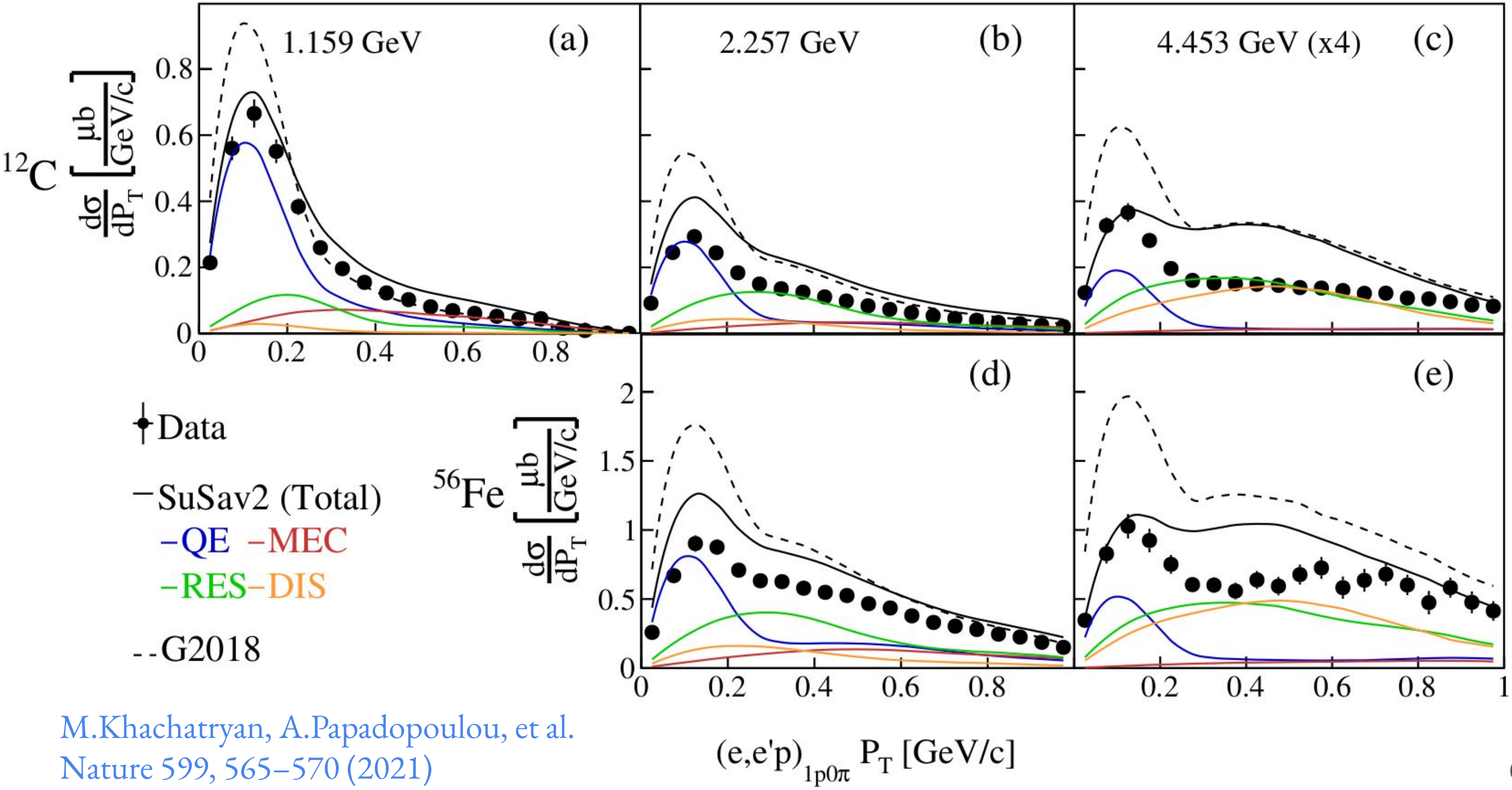
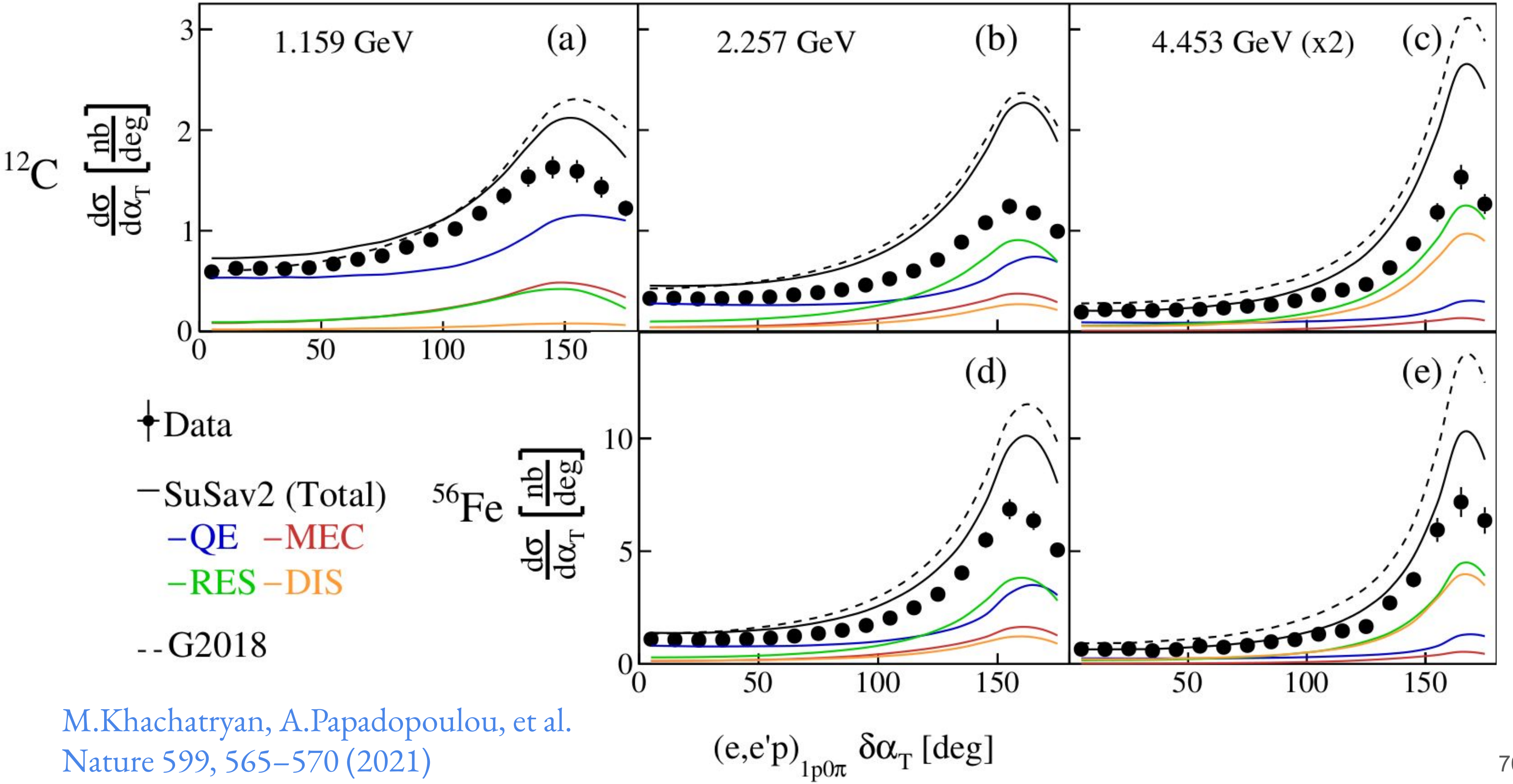
In preparation

P_T Nucleus & Energy Dependence



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

$\delta\alpha_T$ Nucleus & Energy Dependence



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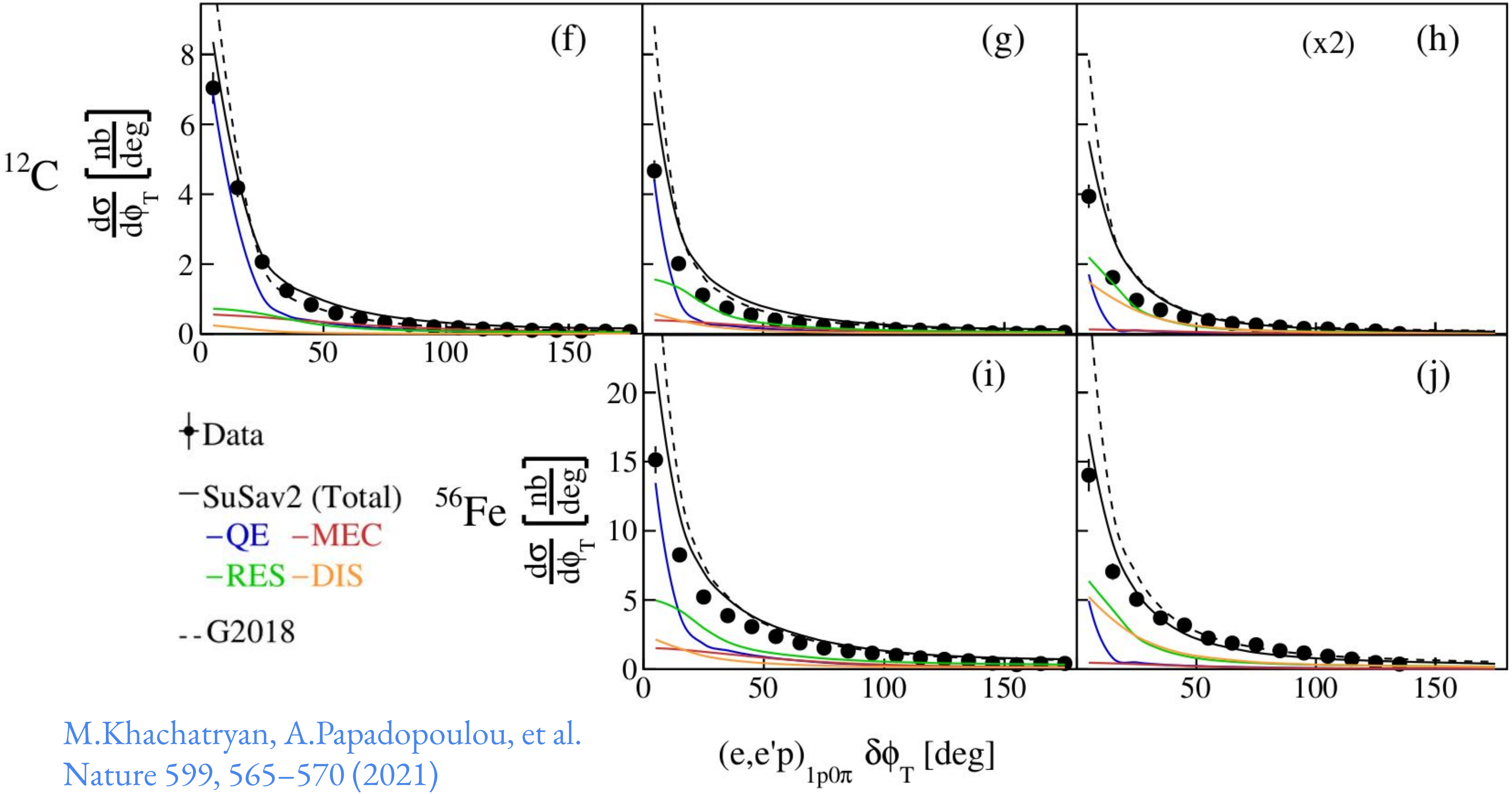
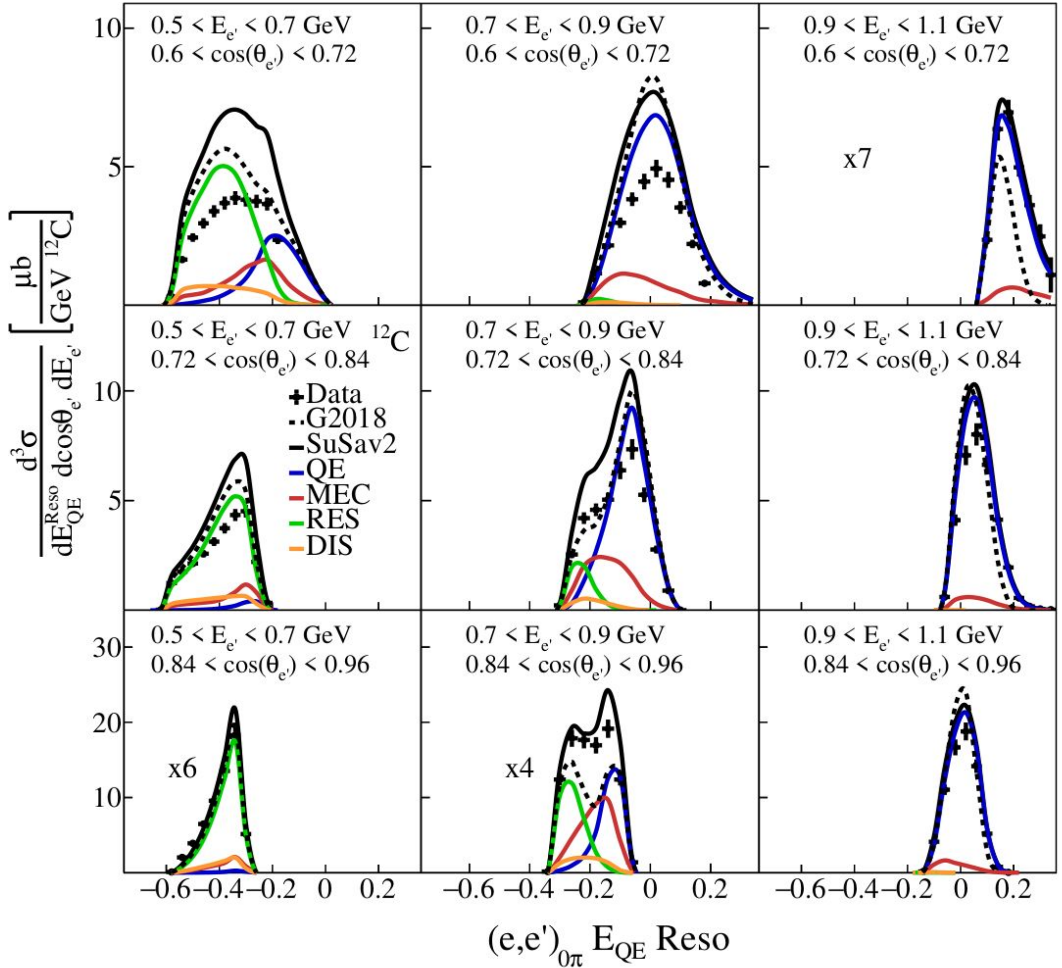
$\delta\phi_T$ Nucleus & Energy Dependence



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

Into The 3D e4ν Multiverse!



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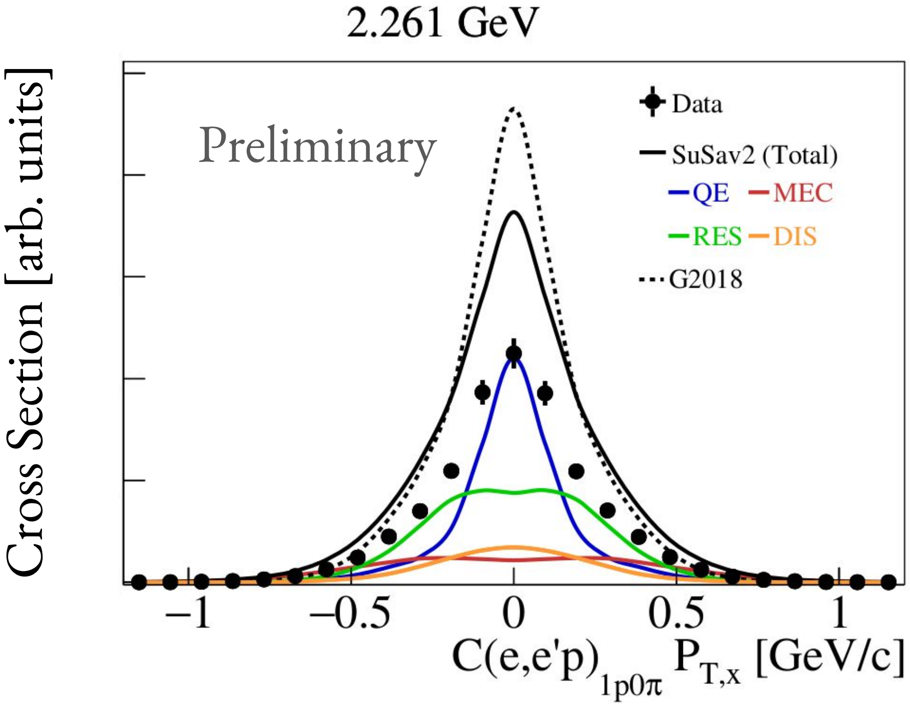
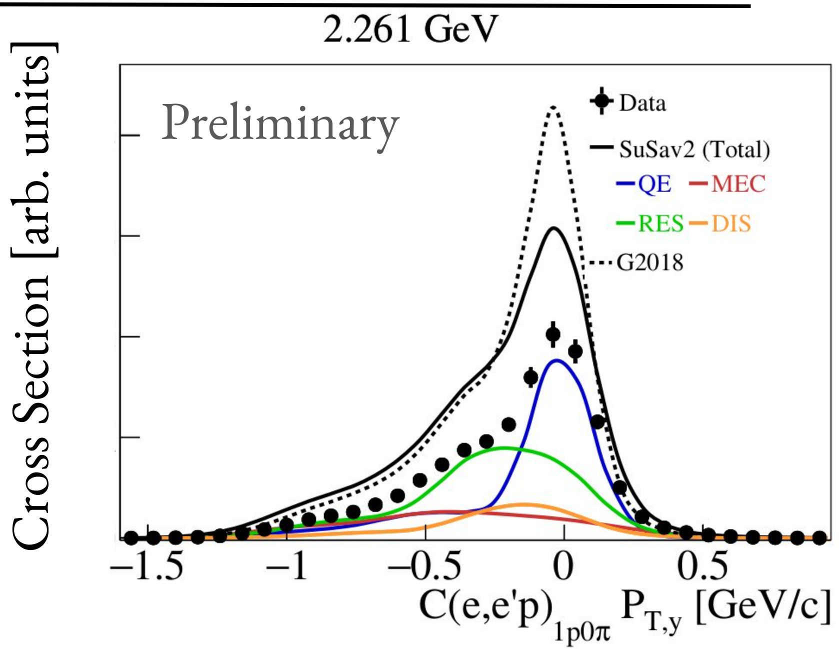
In preparation

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

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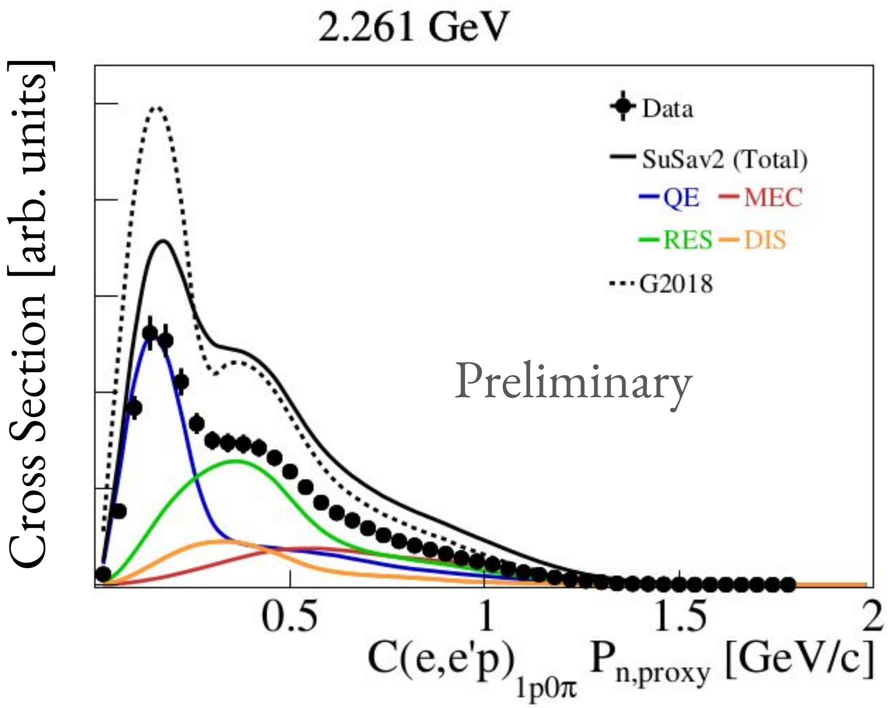
Missing Momentum Approximation



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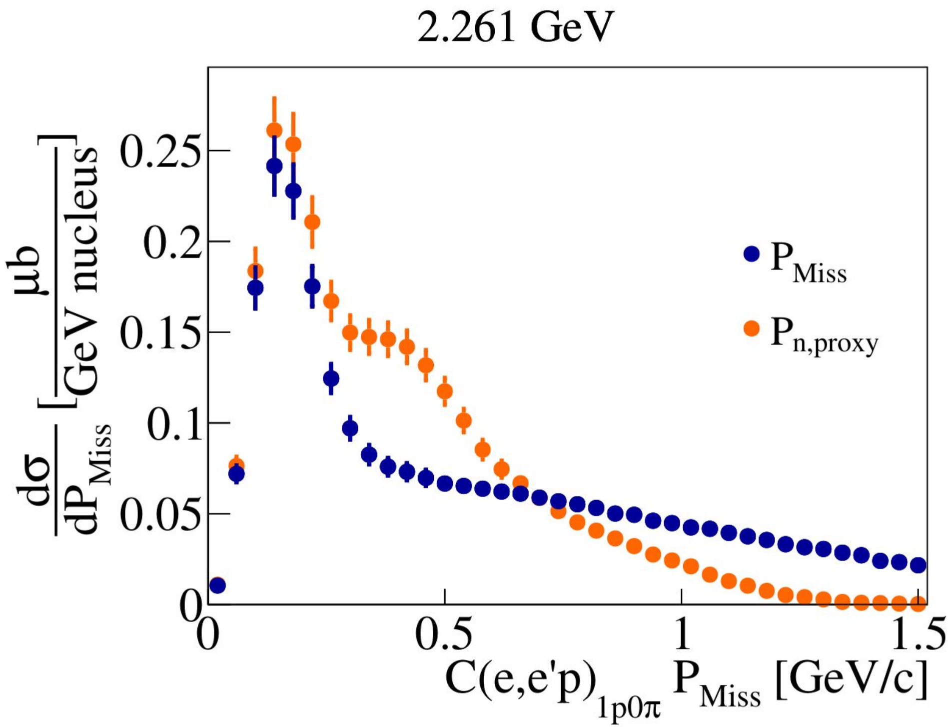
$$p_{n,proxy} = \sqrt{\delta p_L^2 + \delta p_T^2}$$

Under QE assumption

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

Fails To Reproduce True Missing Momentum



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

Under QE assumption

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

True missing momentum

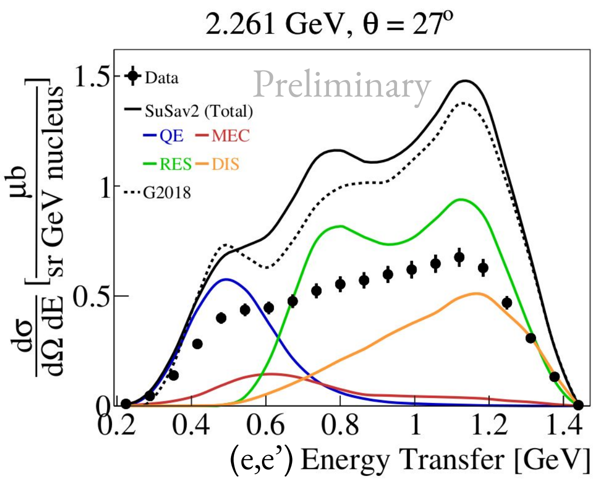
$$P_{miss} =| p - q|$$

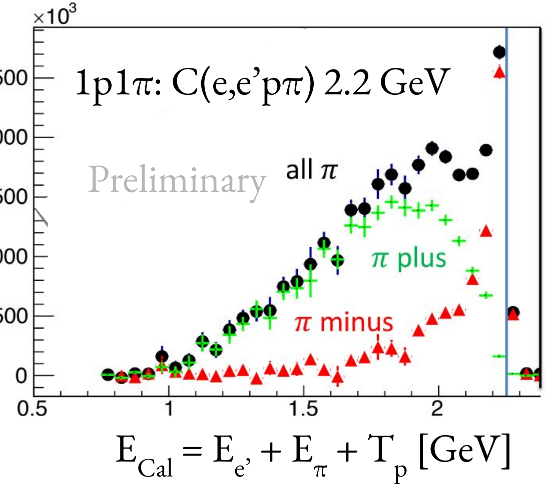
p = proton 3-vector
q = momentum transfer

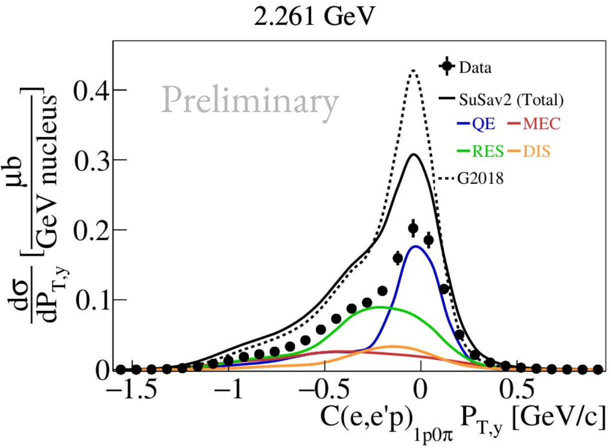
The e4ν Result Factory Continued!

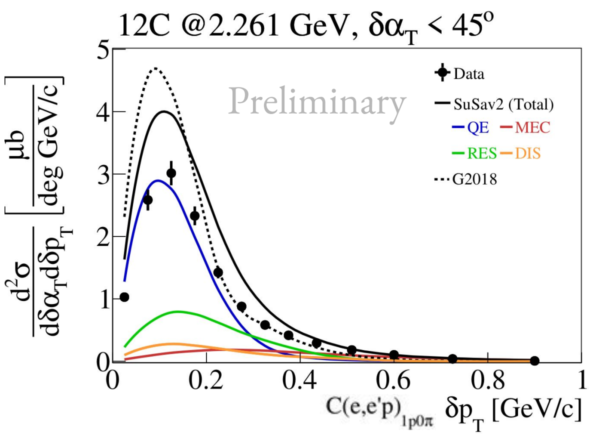
- More inclusive results
- More complex channels
- Nuclear sensitivity variables
- Multi-differential results

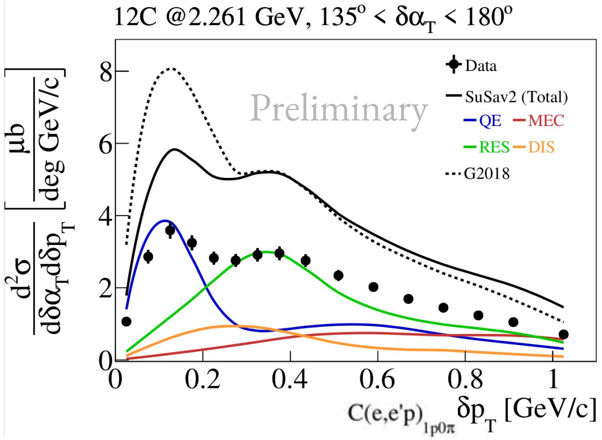
e4ν Collaboration, In preparation



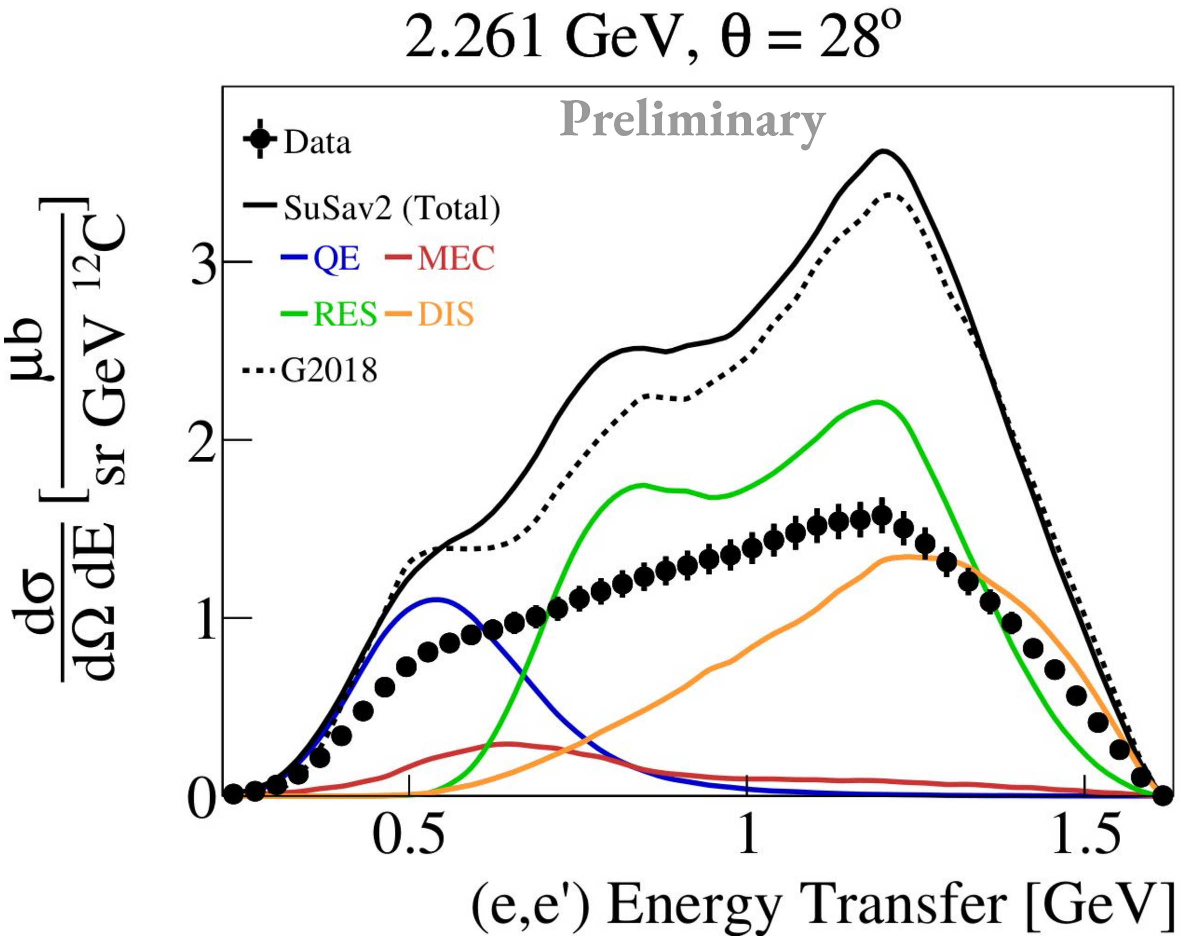








Inclusive Results

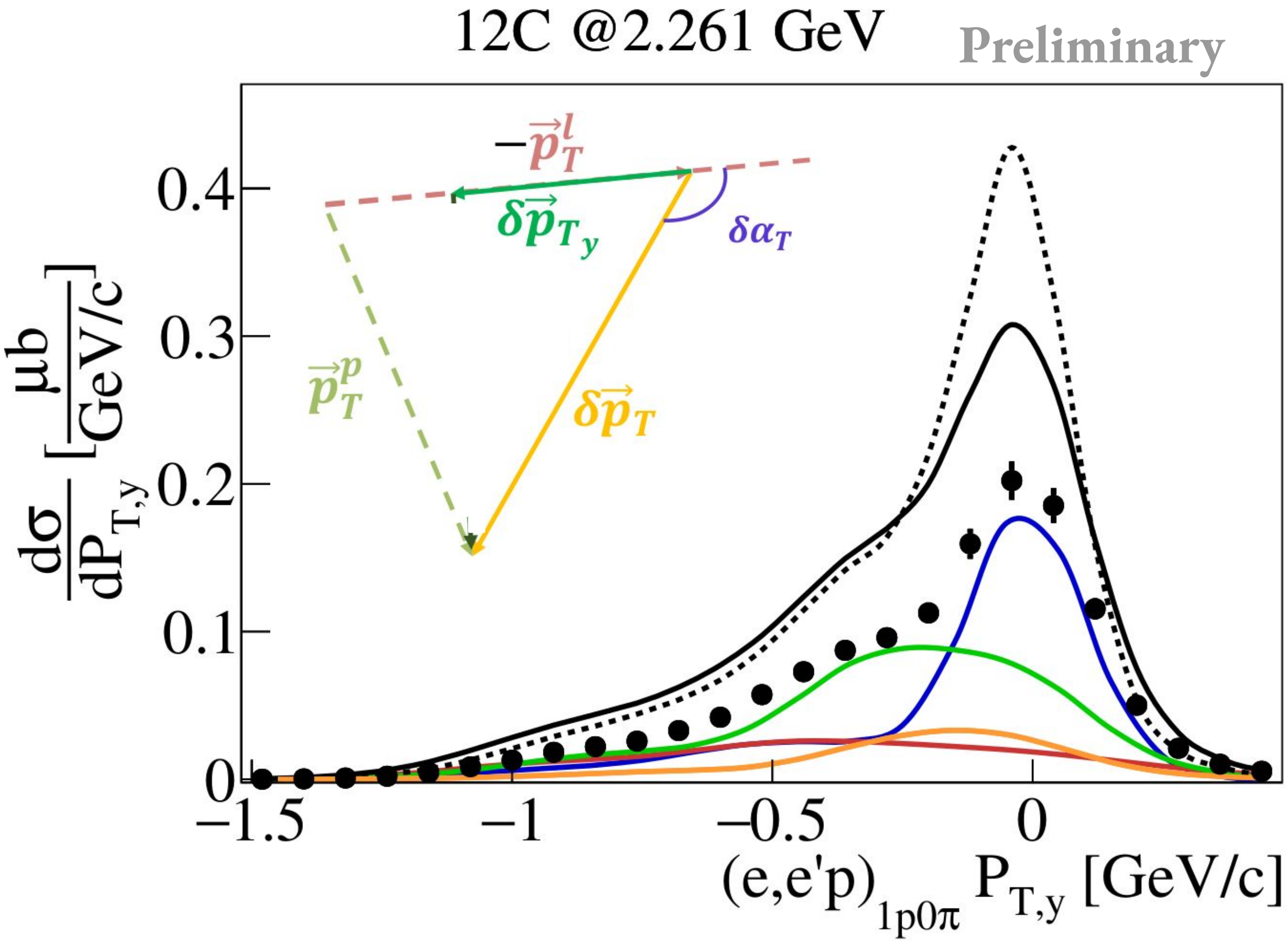


The e4ν Result Factory Continued!

- Scan over multiple angles
- Results on Argon soon

e4ν Collaboration
In preparation

Nuclear Sensitivity Variables



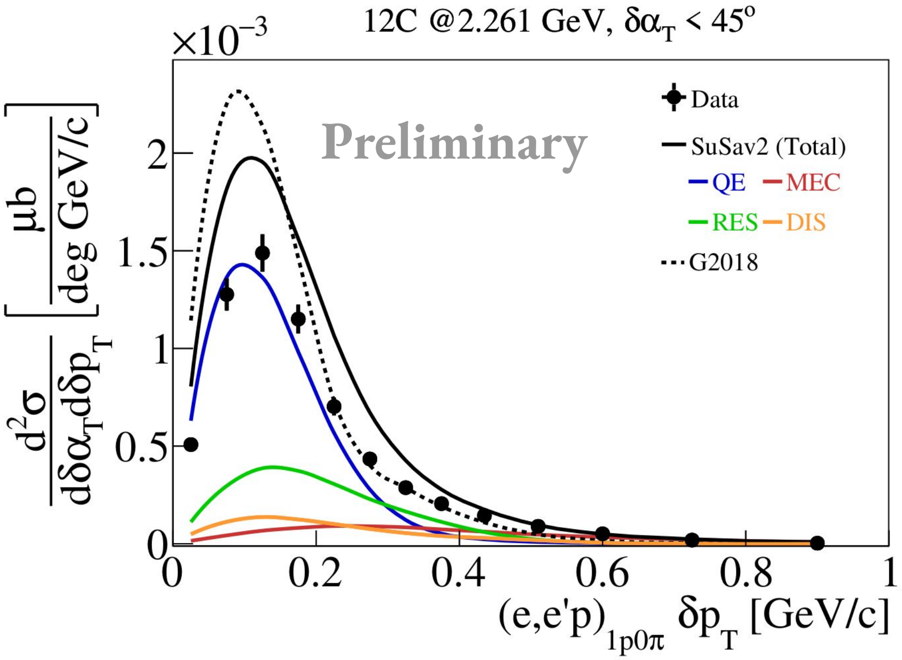
$\delta p_{T_y} = -\hat{p}_T^{\,l} \cdot \delta\vec{p}_T = |\delta\vec{p}_T| \cos(\delta\alpha_T)$

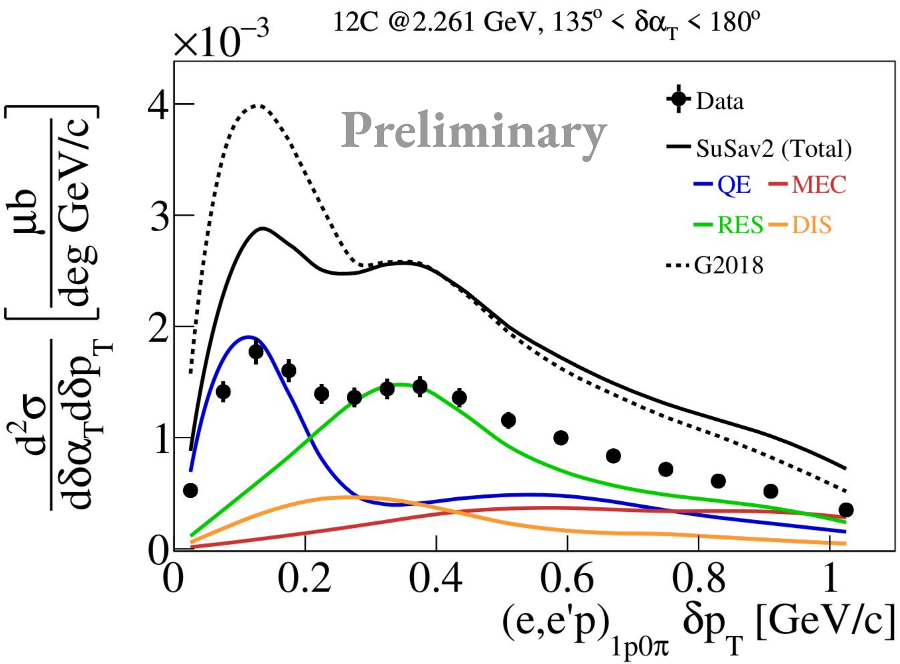
The e4ν Result Factory Continued!

- Fermi motion
- Final state interactions (FSI)

e4ν Collaboration
In preparation

Double Differential Results



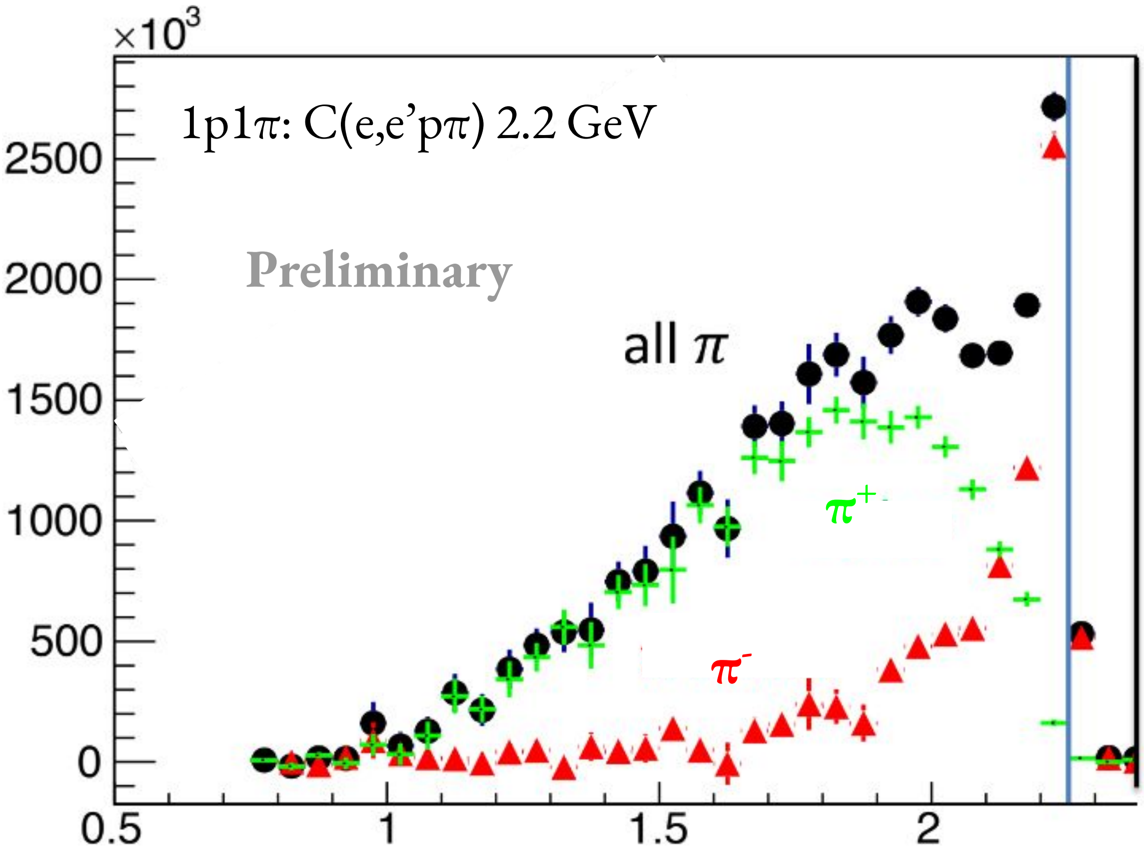


The e4ν Result Factory Continued!

e4ν Collaboration
In preparation

- Handle over FSI / initial state effects
- Tuning potential

More Complex Channels



$E_{Cal} = E_{e'} + E_{\pi} + T_p$ [GeV]

The e4ν Result Factory Continued!

- Critical for DUNE
- LArTPCs cannot separate π^+/π^-

e4ν Collaboration
In preparation