# Electron-Nucleus Scattering for Neutrino Interactions and Oscillations

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For the e4ν collaboration

Hen Lab

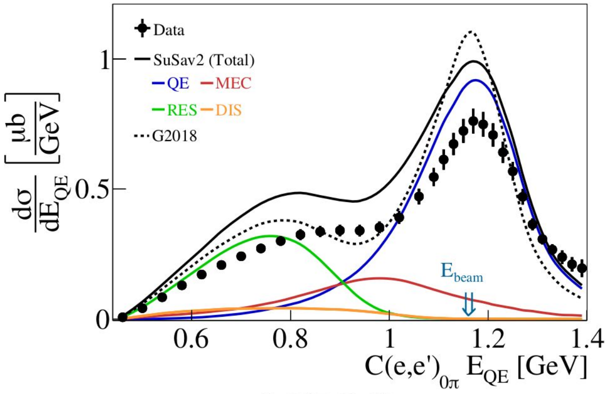
Laboratory for Nuclear Science @ MIT

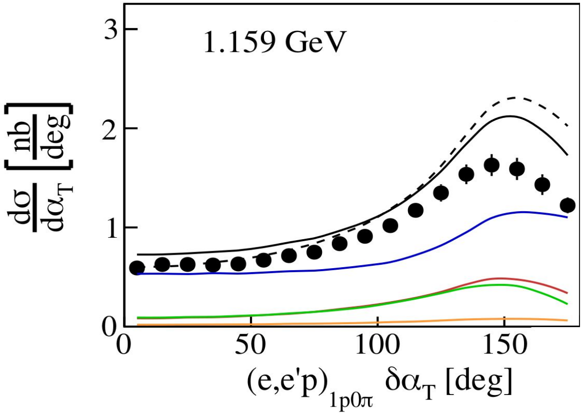
March 28 2022

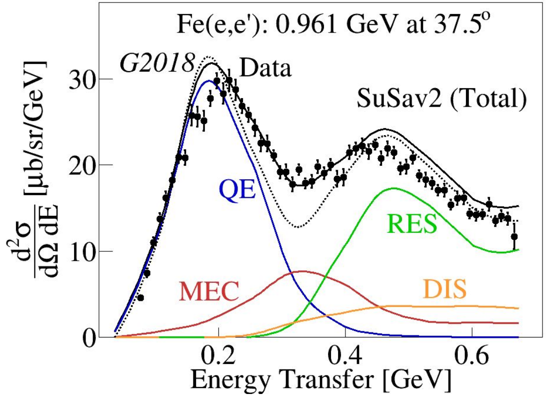
NuSTEC Workshop on Electron Scattering

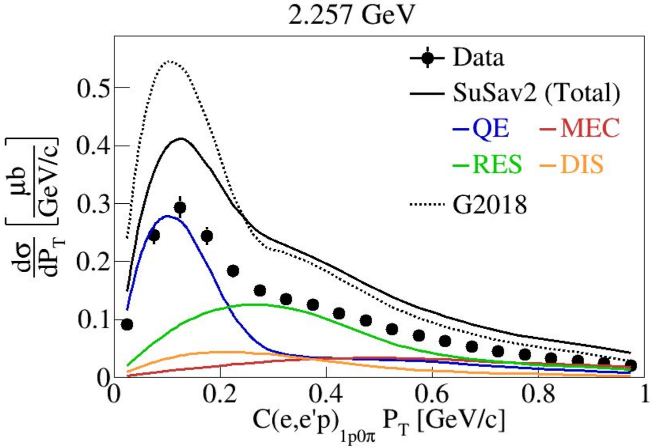
# The e4ν Result Factory

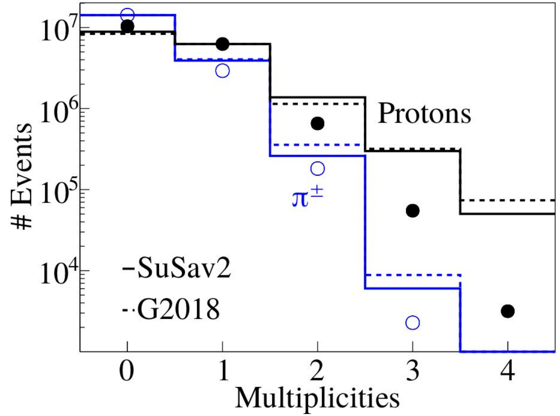
Many
- nuclei
- beam energies
- channels
- variables







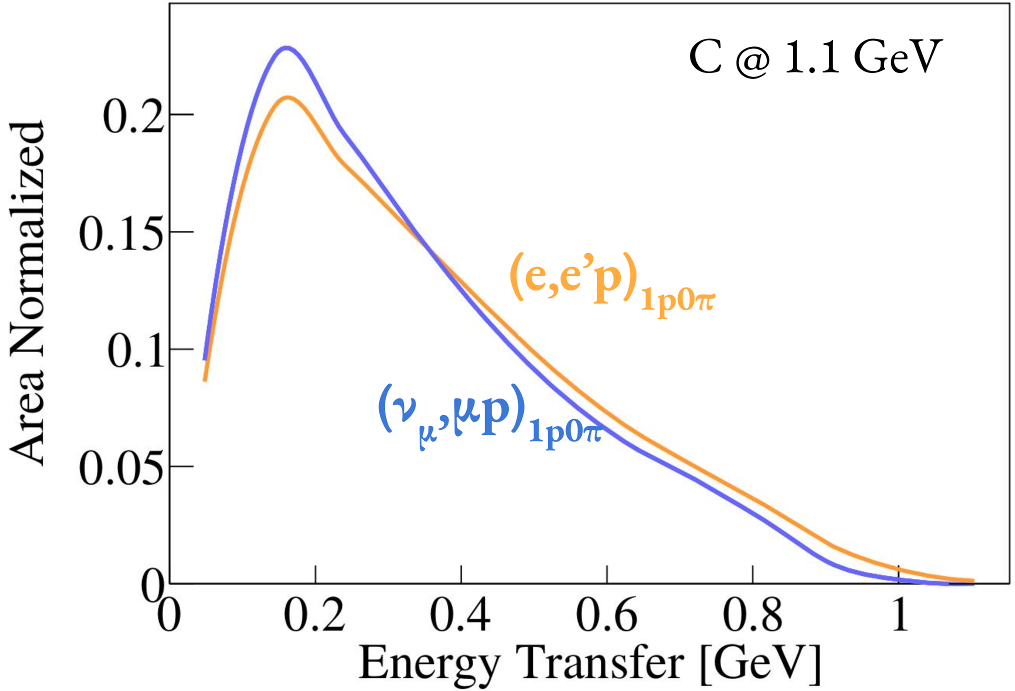




Nature 599, 565–570 (2021)

Phys. Rev. D 103, 113003 (2021)

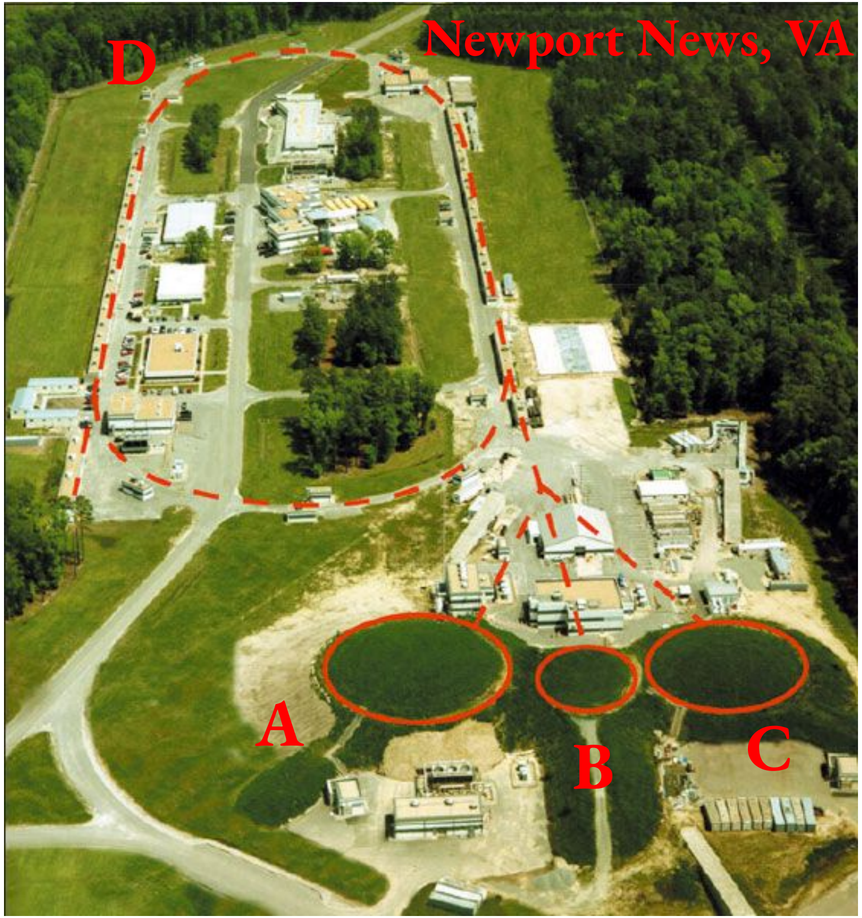
# Similar ν & e Distributions



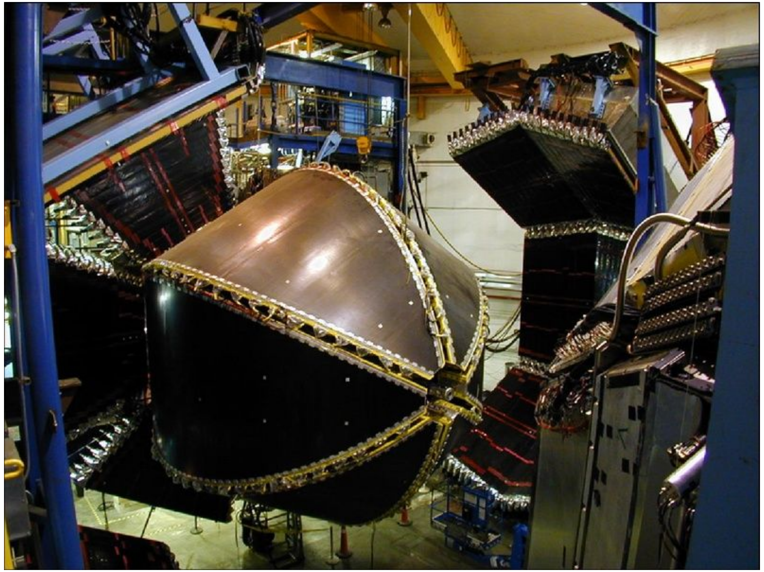
Accounting for propagator mass (γ vs W) via $Q^4$ scaling of the electron side

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

# Jefferson Laboratory

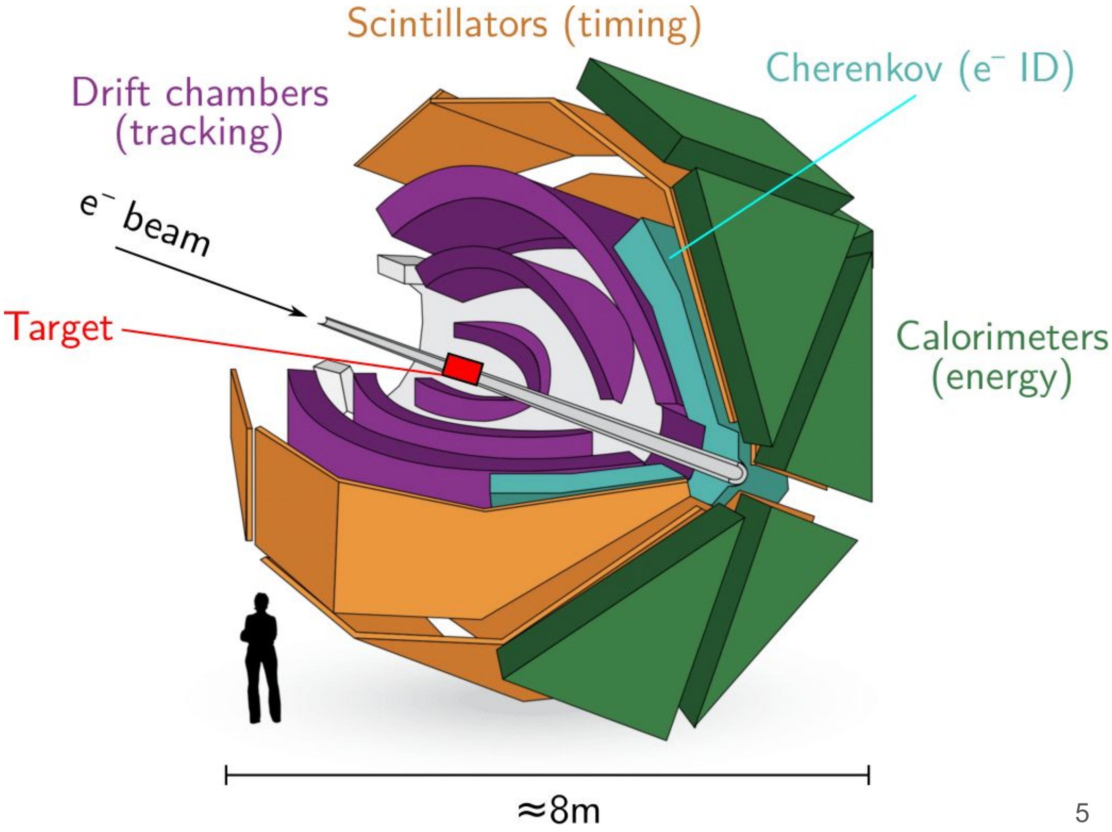


- Electron beam accelerator facility
- Energies up to 12 GeV
- Using Hall B & CLAS detector



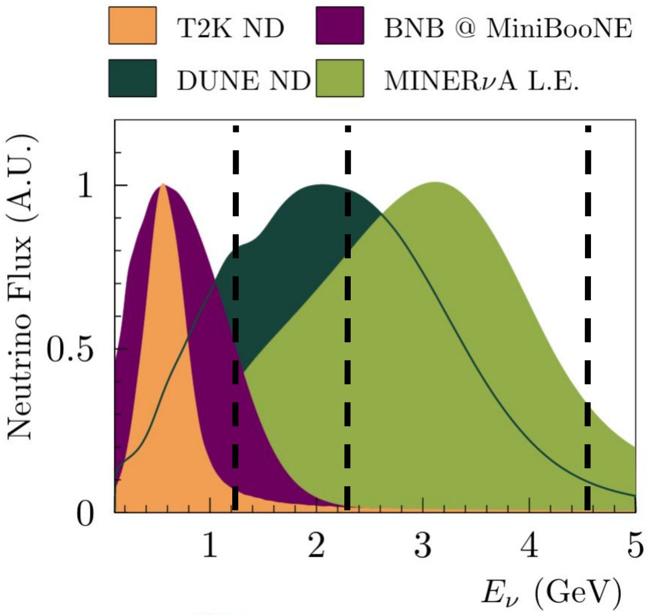
# e4ν Data-Mining W/ CLAS

- Large acceptance @ $\theta_e > 15^o$
- Charged particle threshold similar to ν tracking detectors
- ~50% of "4π" coverage



# e4$\nu$ Data-Mining W/ CLAS

- Large acceptance @ $\theta_e > 15^o$
- Charged particle threshold similar to $\nu$ tracking detectors
- ~50% of "4$\pi$" coverage
- Energies: 1, 2 & 4 GeV
- Targets: $^4$He, $^{12}$C, $^{56}$Fe

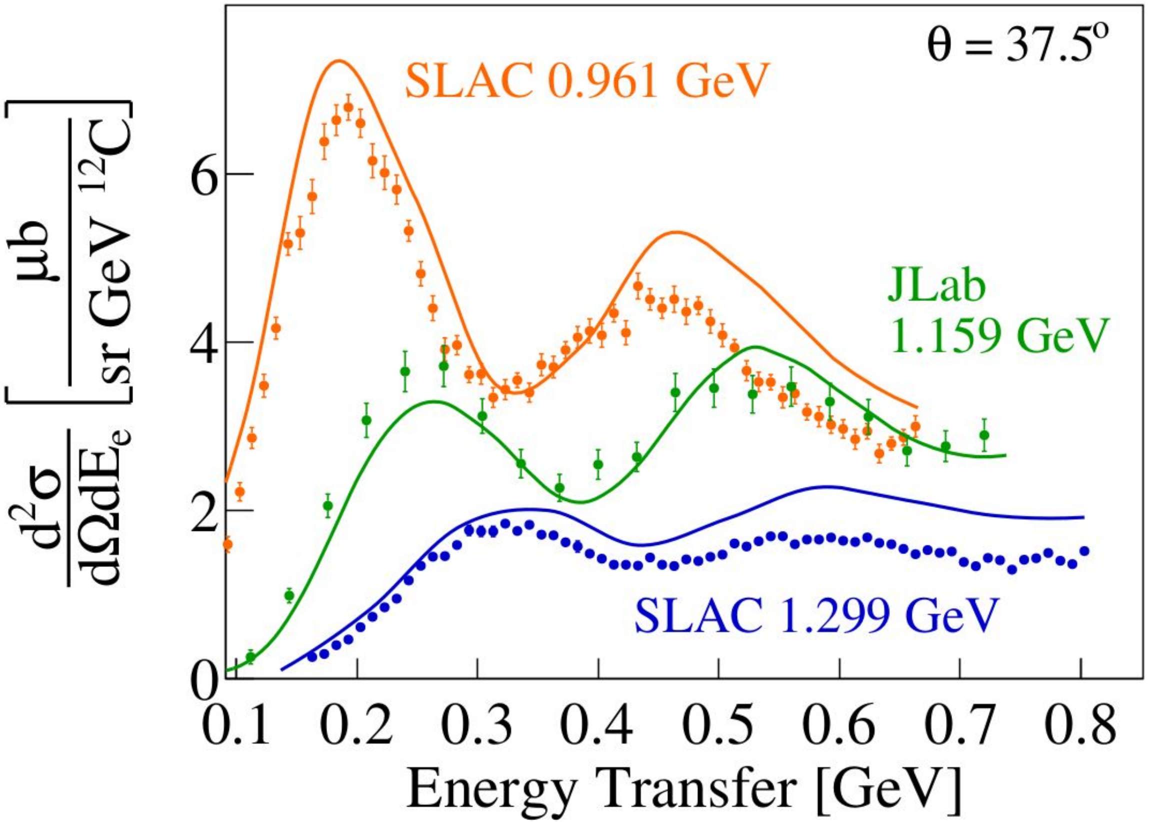


T2K $H_2O$

NOvA CH

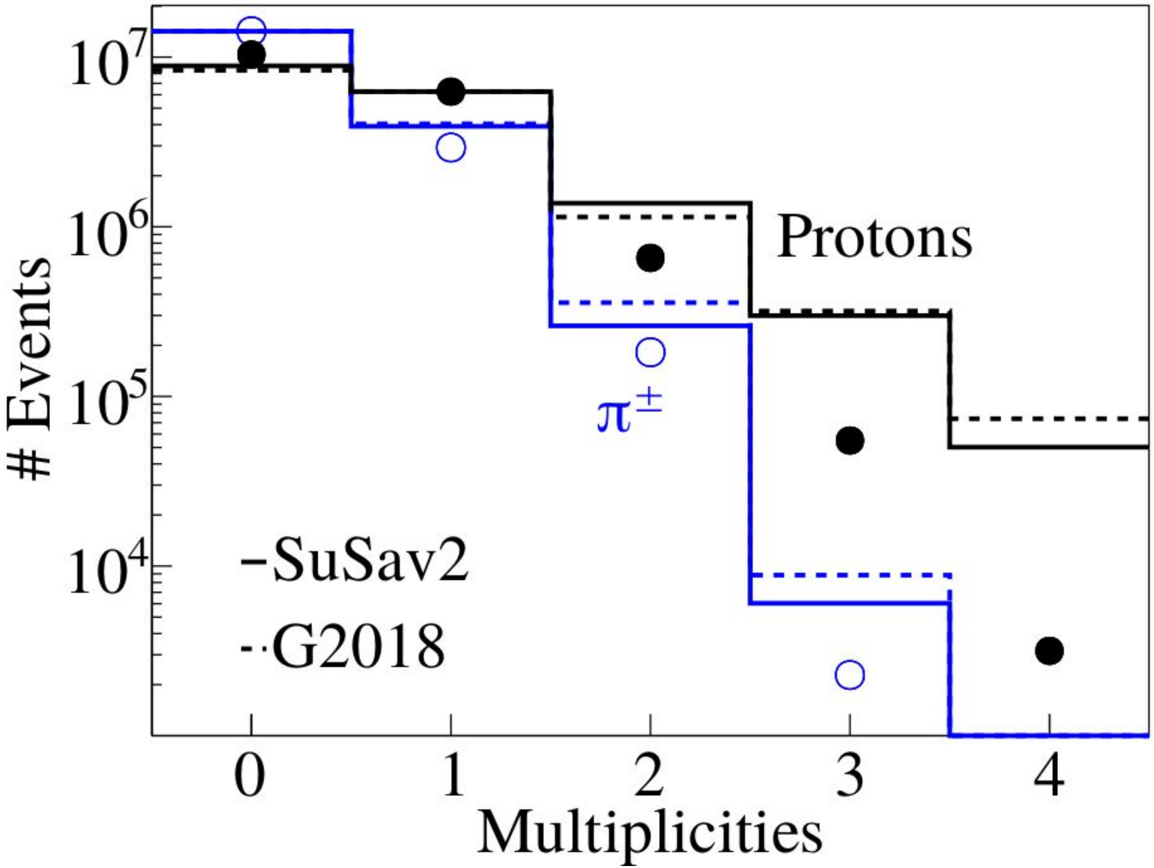
SBN Program DUNE Ar

# 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
$P_\pi > 150$ MeV/c

Simulation overpredicts hadron multiplicities

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

# Playing The QE-like Neutrino Game

µBooNE

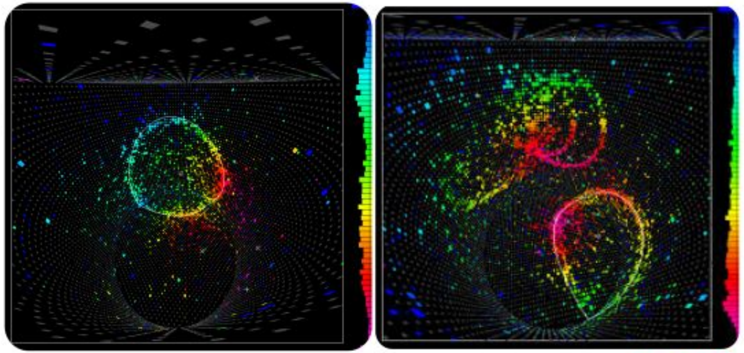
- 1 proton (> 300 MeV/c)
- No $\pi^{\pm}$ (> 70 MeV/c)

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

# QE Energy Reconstruction

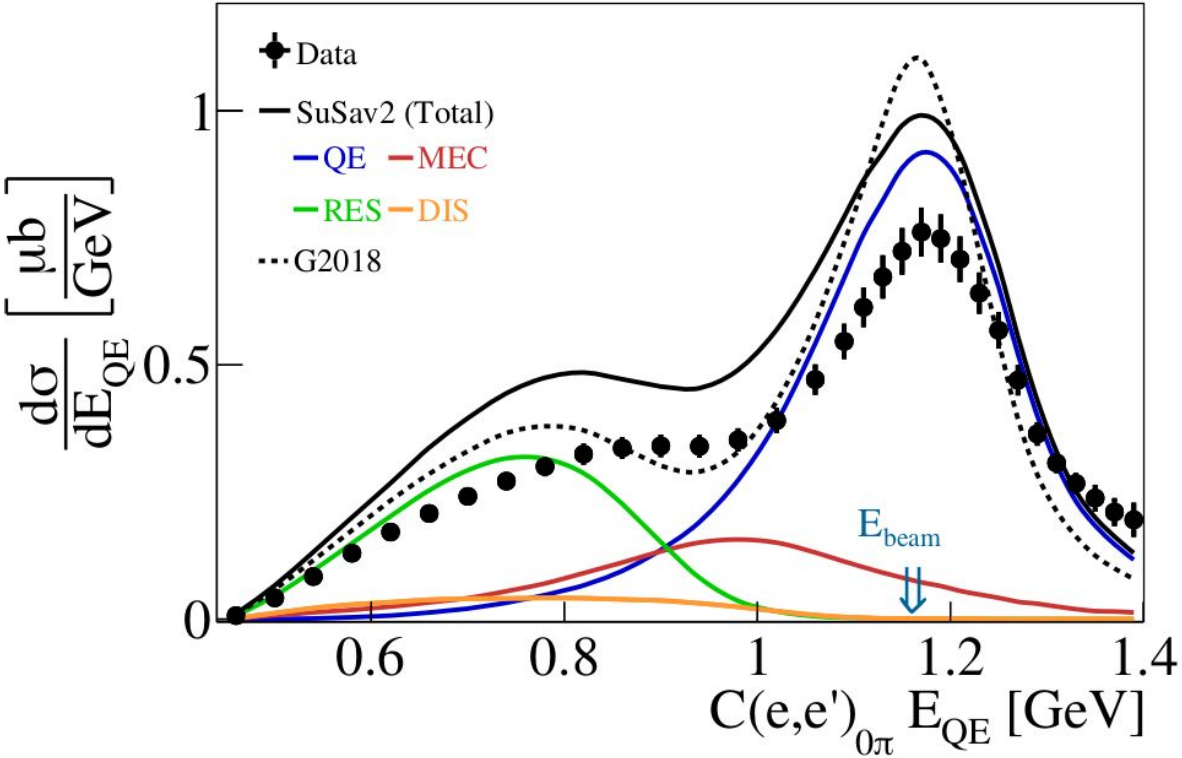


Cherenkov detectors
Assuming QE interaction
Using lepton kinematics

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

# QE Energy Reconstruction

C @ 1.1 GeV



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

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

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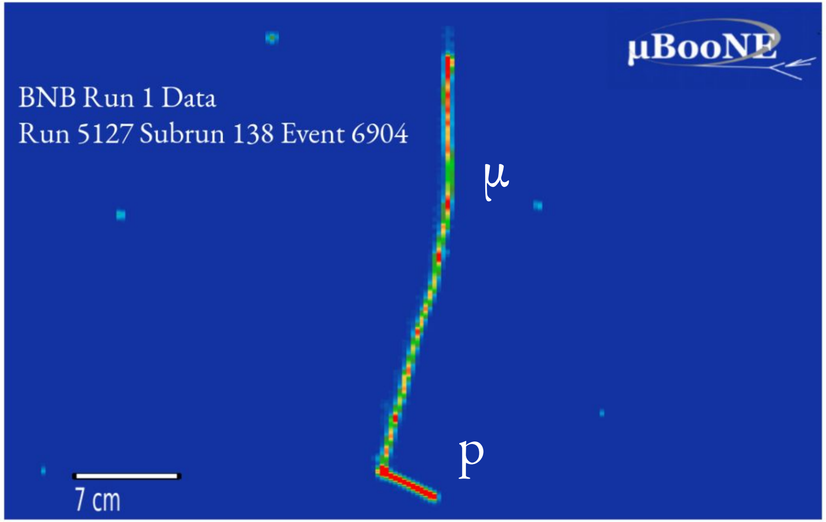
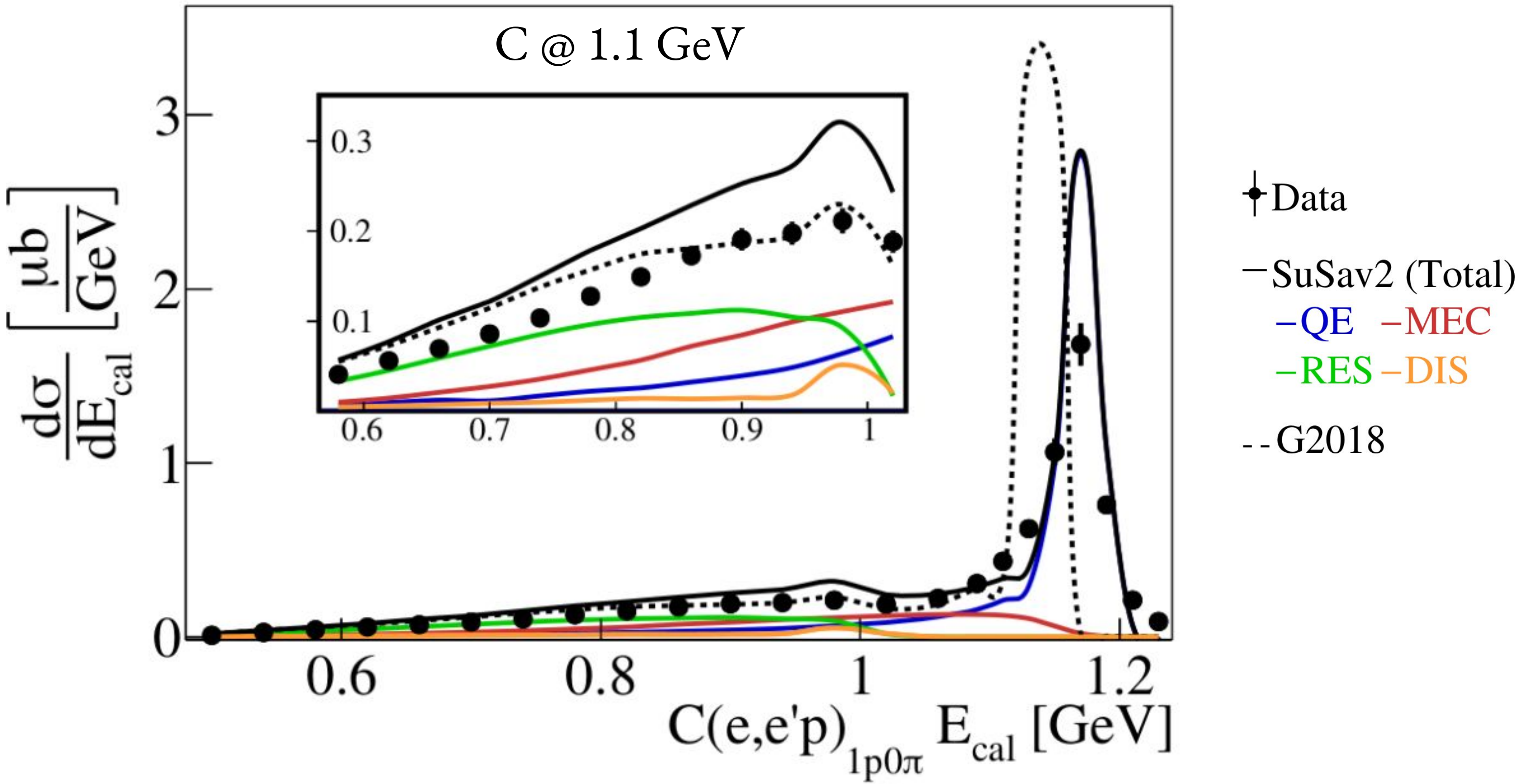
# Calorimetric Energy Reconstruction



Tracking detectors
Calorimetric sum
Using all detected particles

$$\mathrm{E}_{cal} = \mathrm{E}_l + \mathrm{T}_p + \epsilon_{\mathrm{B}}$$

# Calorimetric Energy Reconstruction



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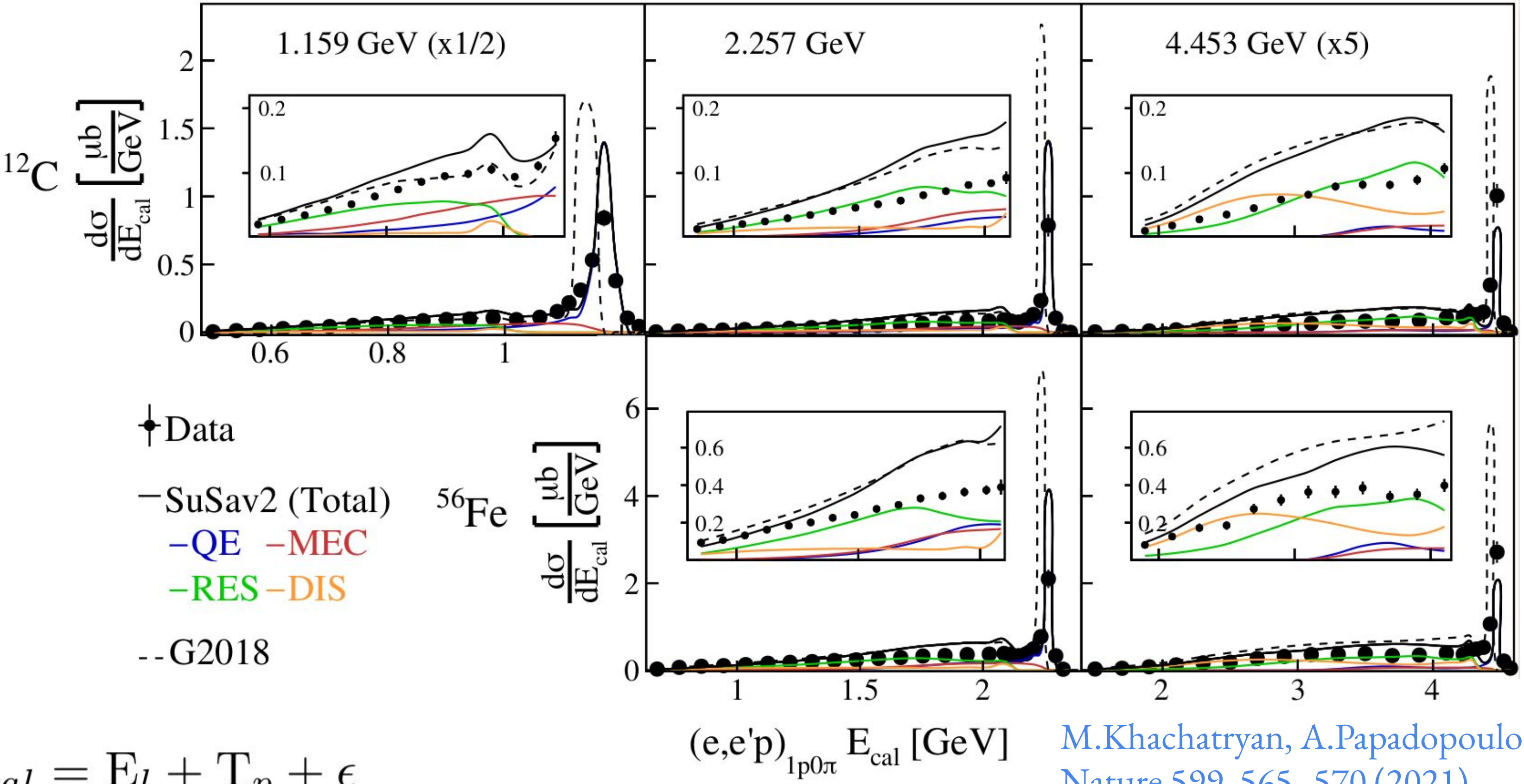
$$E_{cal} = E_l + T_p + \epsilon$$

# $E_{cal}$ Nucleus & Energy Dependence



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

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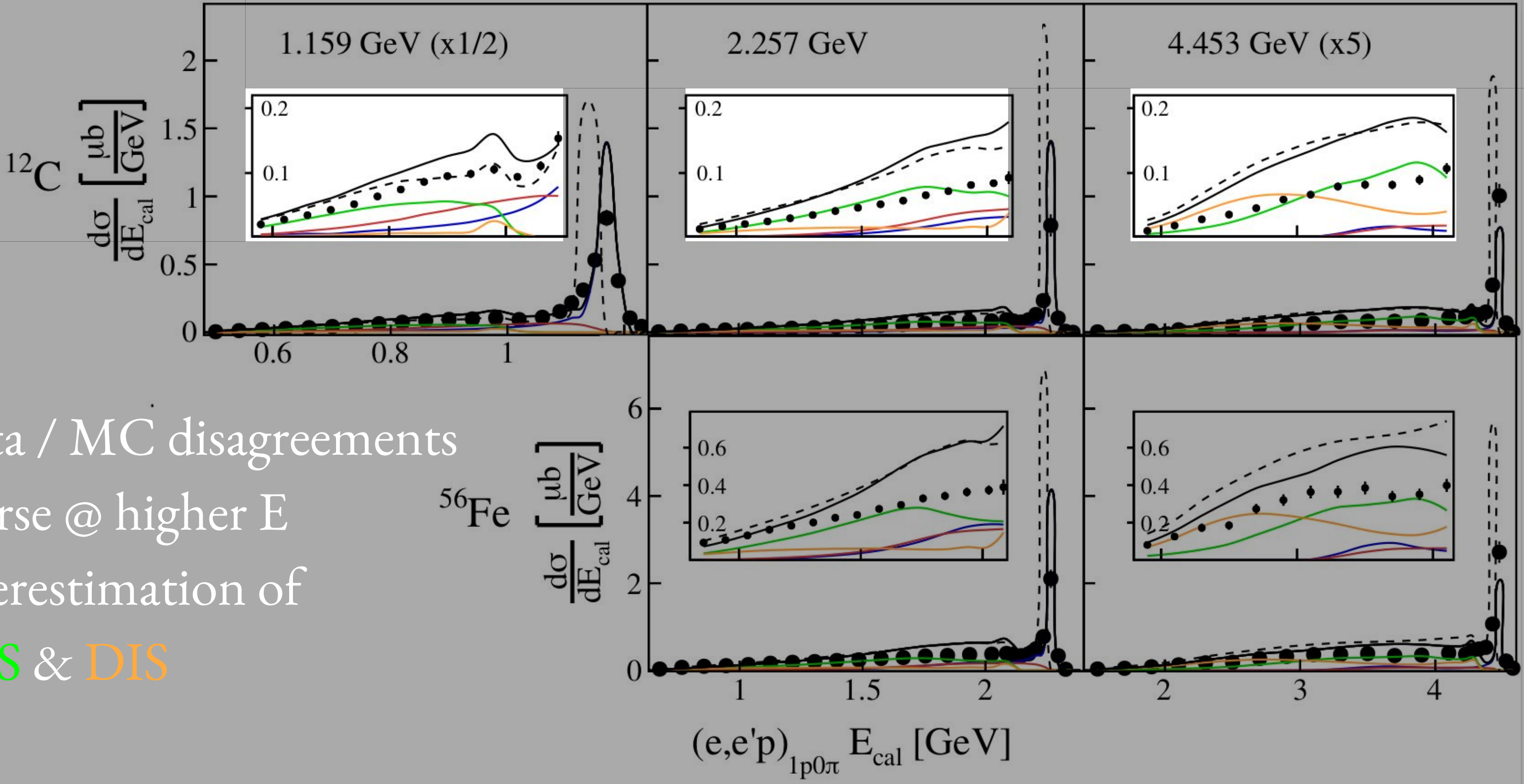
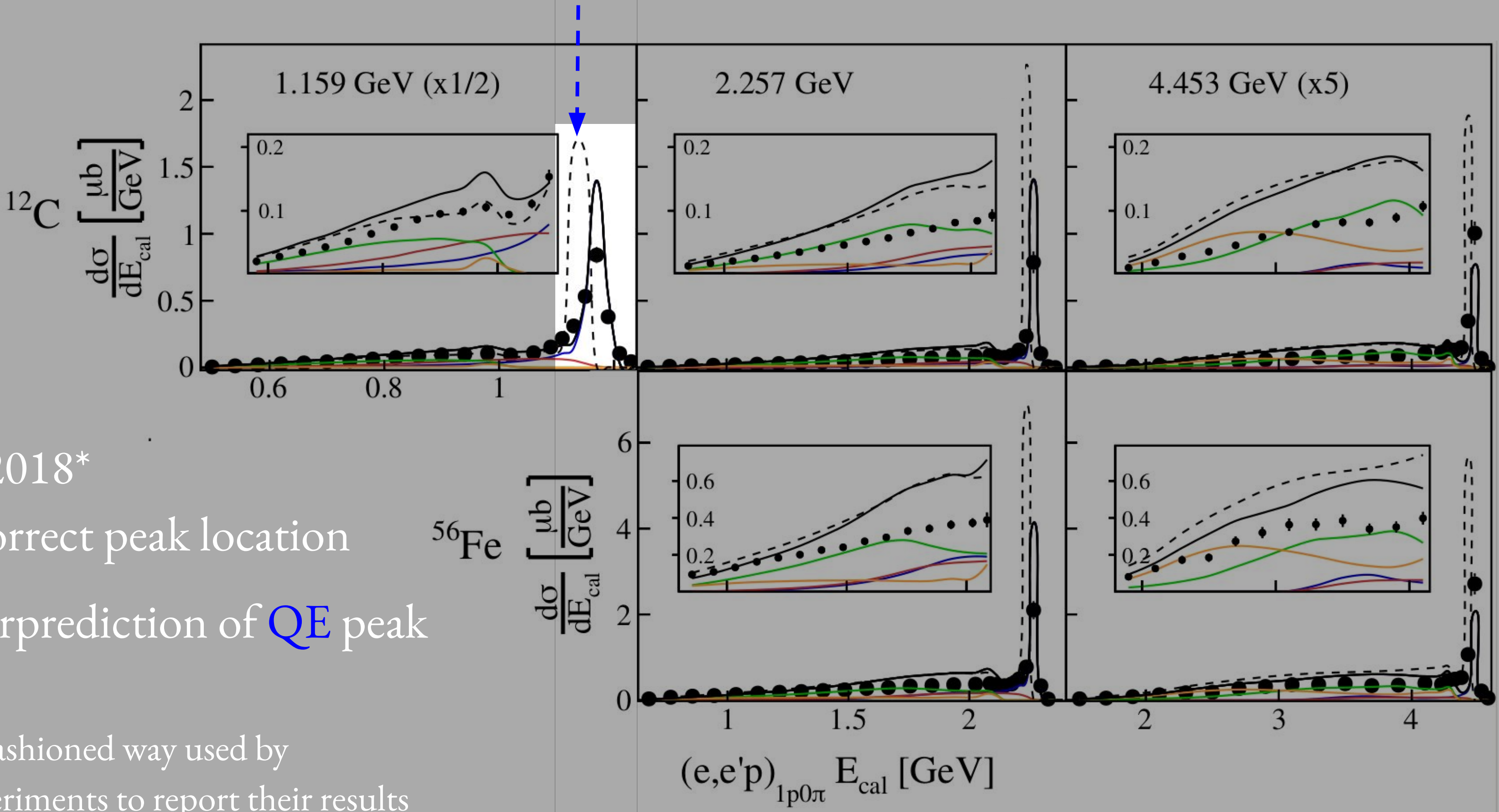
# Nucleus & Energy Dependence



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

# Nucleus & Energy Dependence

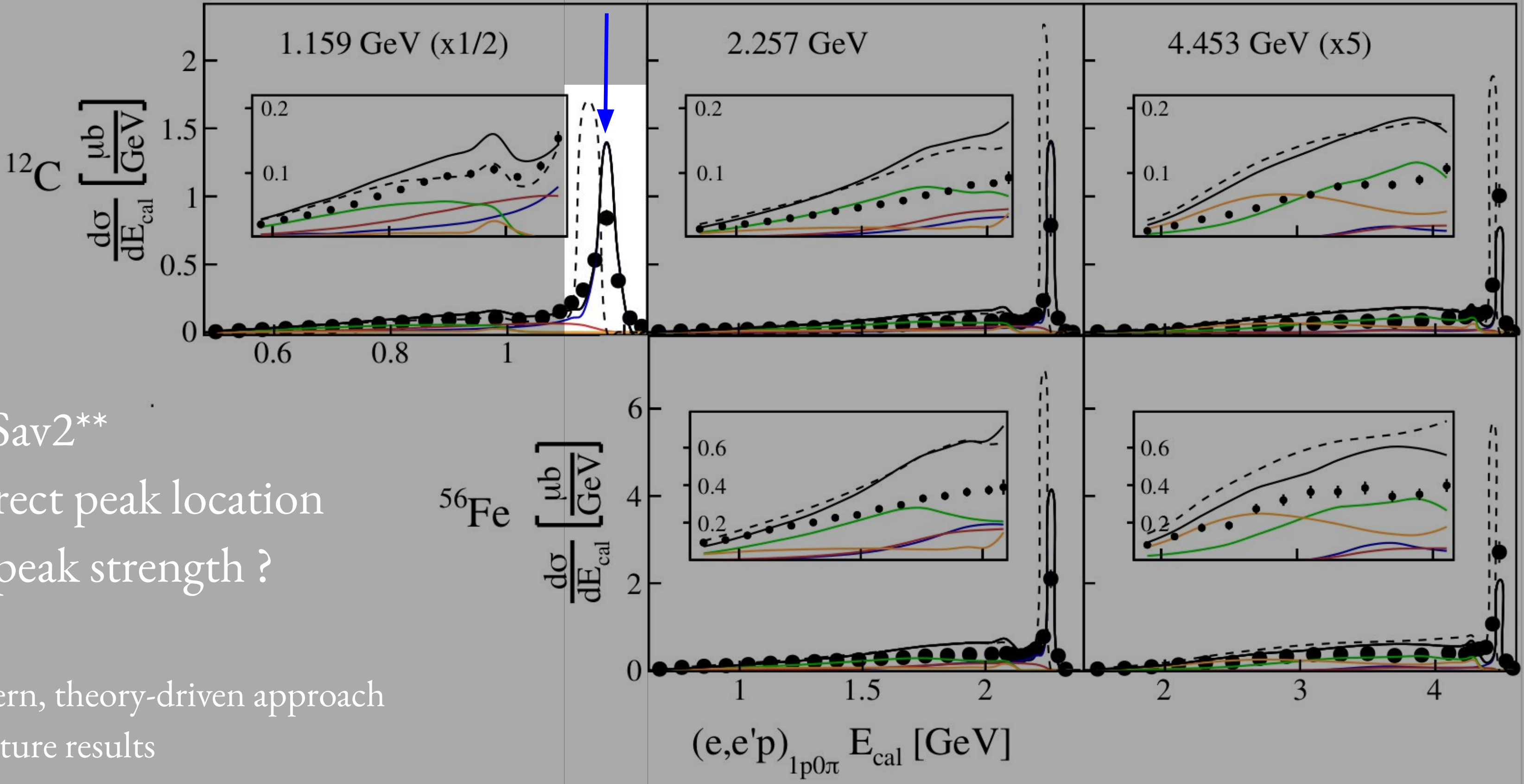


--- G2018*

- Incorrect peak location
- Overprediction of QE peak

* Old-fashioned way used by
$\nu$ experiments to report their results

# Nucleus & Energy Dependence

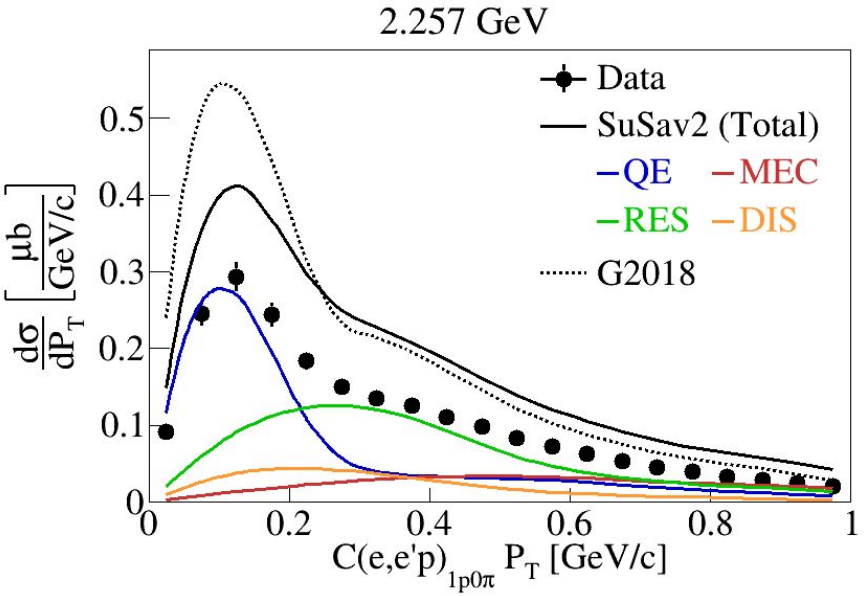


— SuSav2**

- Correct peak location
- QE peak strength ?

** Modern, theory-driven approach for future results

# Transverse Momentum



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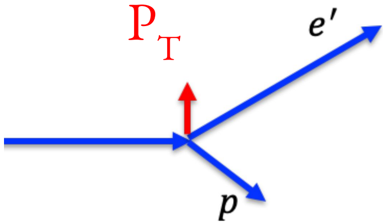
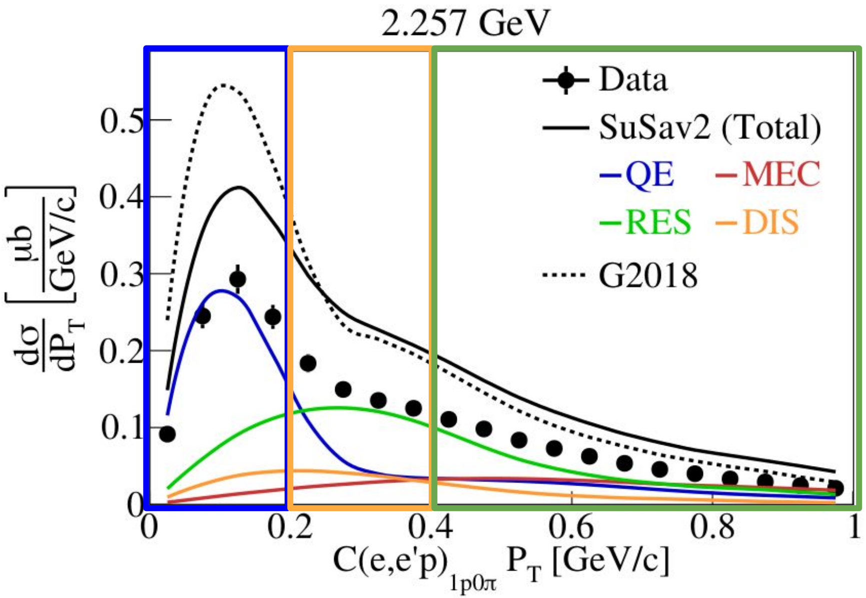
$$P_T = |\mathbf{P_T}^{e'} + \mathbf{P_T}^{p}|$$



- Overestimation of QE peak & RES tail

# Energy Reconstruction In $P_T$ Slices



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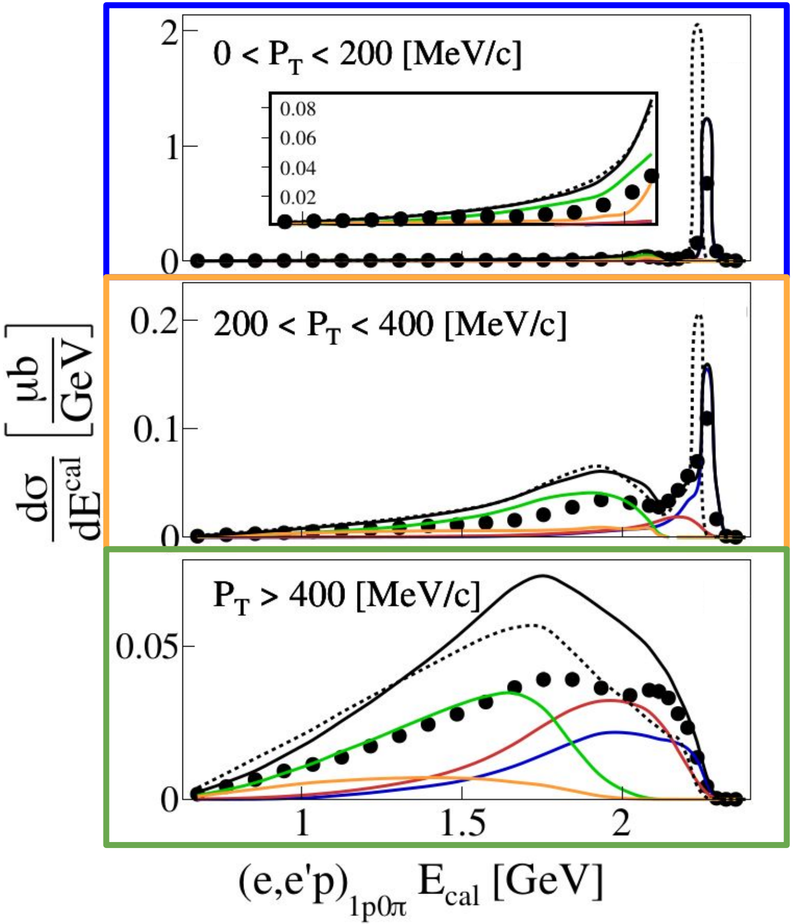
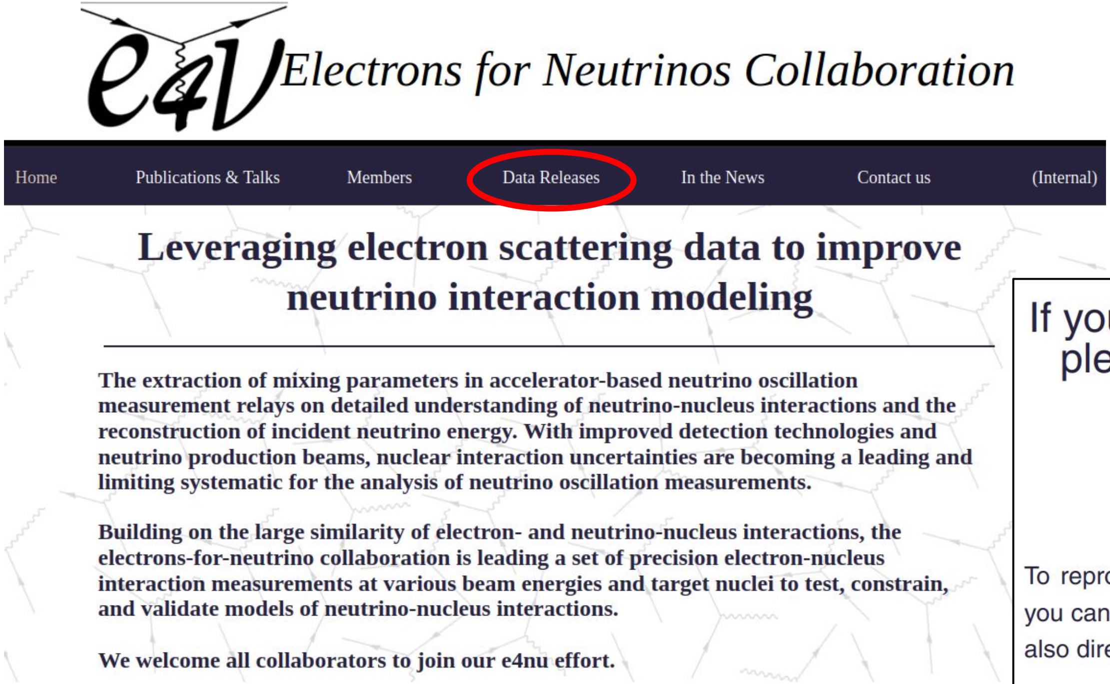


# e4ν Online



Electrons for Neutrinos Collaboration

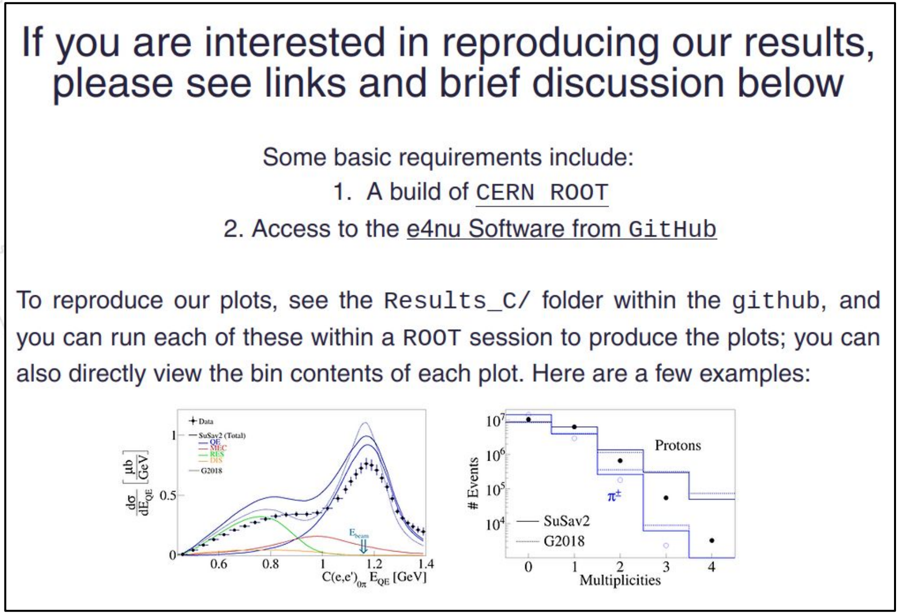
## Leveraging electron scattering data to improve neutrino interaction modeling

The extraction of mixing parameters in accelerator-based neutrino oscillation measurement relays on detailed understanding of neutrino-nucleus interactions and the reconstruction of incident neutrino energy. With improved detection technologies and neutrino production beams, nuclear interaction uncertainties are becoming a leading and limiting systematic for the analysis of neutrino oscillation measurements.

Building on the large similarity of electron- and neutrino-nucleus interactions, the electrons-for-neutrino collaboration is leading a set of precision electron-nucleus interaction measurements at various beam energies and target nuclei to test, constrain, and validate models of neutrino-nucleus interactions.

We welcome all collaborators to join our e4nu effort.

## Data releases



If you are interested in reproducing our results, please see links and brief discussion below

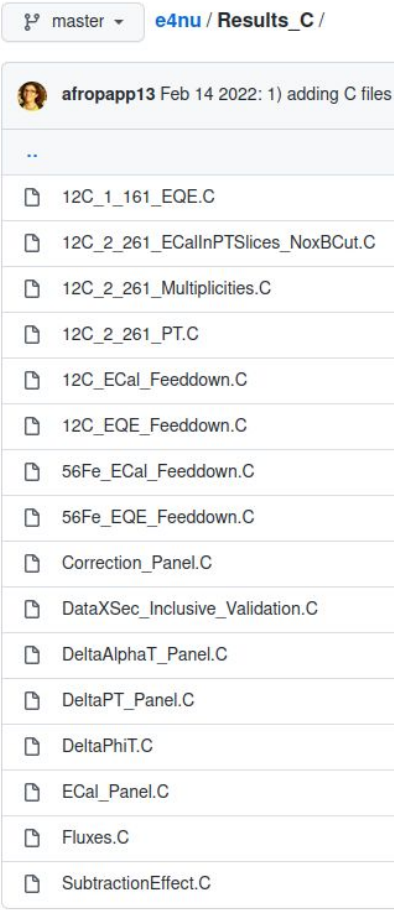
Some basic requirements include:

1. A build of `CERN ROOT`
2. Access to the e4nu Software from `GitHub`

To reproduce our plots, see the `Results_C/` folder within the `github`, and you can run each of these within a `ROOT` session to produce the plots; you can also directly view the bin contents of each plot. Here are a few examples:

NuSTEC hands-on tutorial

# e4ν Results



master ▾ e4nu / Results_C /

**afropapp13** Feb 14 2022: 1) adding C files

..

12C_1_161_EQE.C

12C_2_261_ECalInPTSlices_NoxBCut.C

12C_2_261_Multiplicities.C

12C_2_261_PT.C

12C_ECal_Feeddown.C

12C_EQE_Feeddown.C

56Fe_ECal_Feeddown.C

56Fe_EQE_Feeddown.C

Correction_Panel.C

DataXSec_Inclusive_Validation.C

DeltaAlphaT_Panel.C

DeltaPT_Panel.C

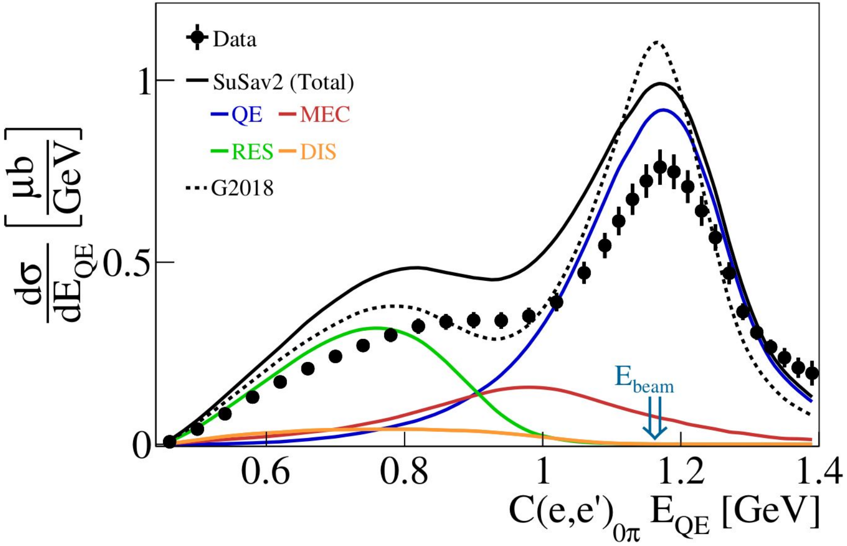
DeltaPhiT.C

ECal_Panel.C

Fluxes.C

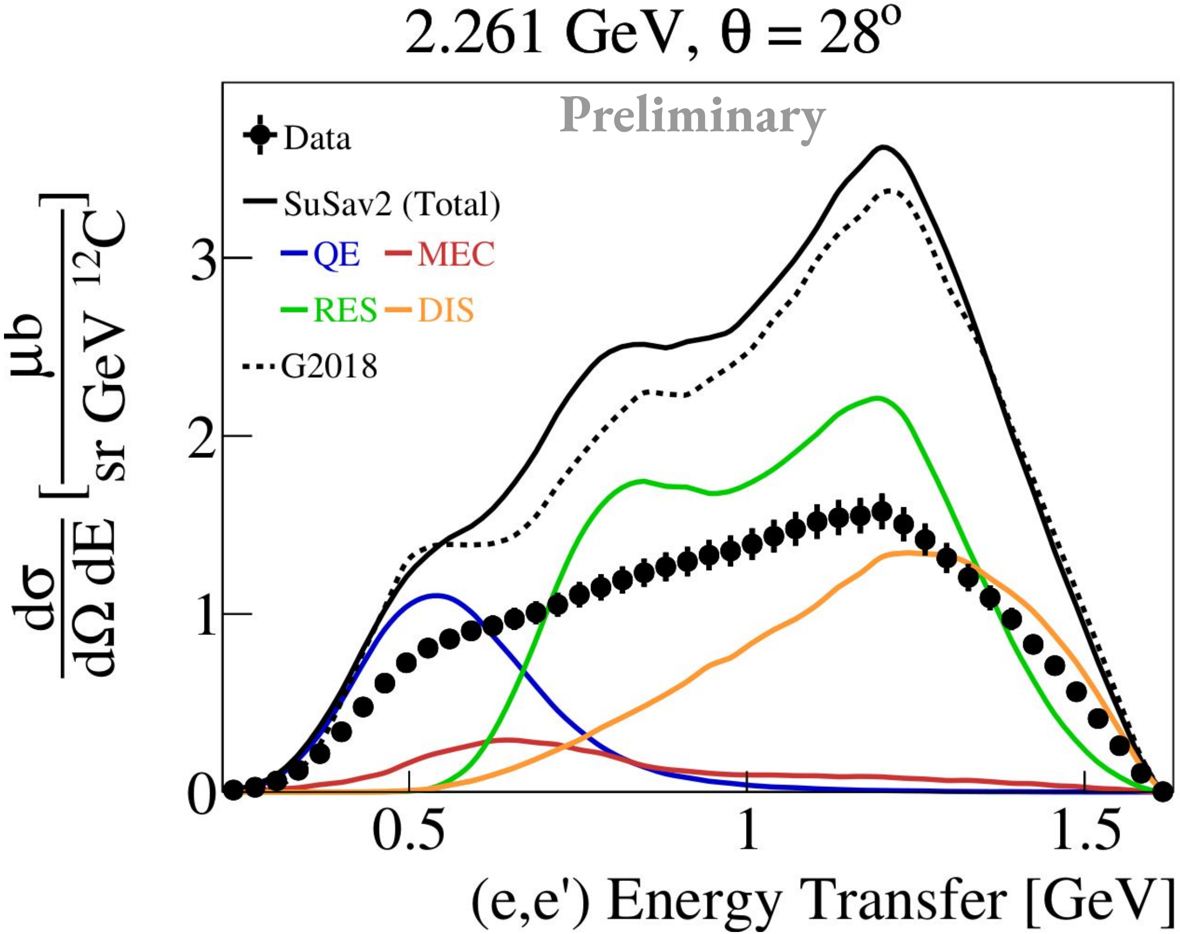
SubtractionEffect.C

```
git clone  https://github.com/adishka/e4nu.git
cd e4nu/Results_C
root -l 12C_1_161_EQE.C
```



Designated branches for truth-level studies (e4v_truth)
& fiducial cuts/acceptance maps (e4v_multiplicity)

# Inclusive Results

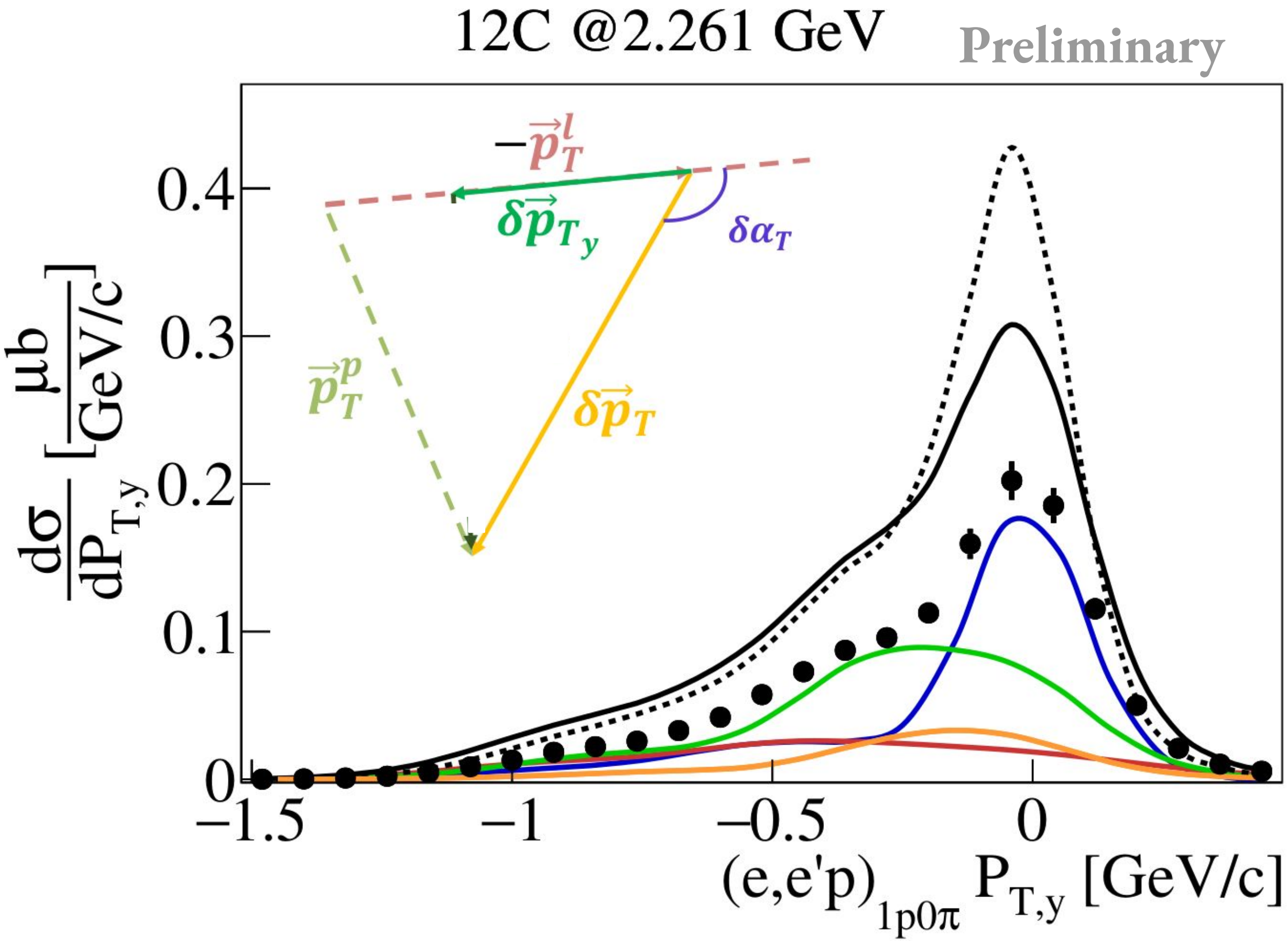


The e4ν Result Factory Continued!

- Scan over multiple angles
- Results on Argon soon

e4ν Collaboration
In preparation

# Nuclear Sensitivity Variables



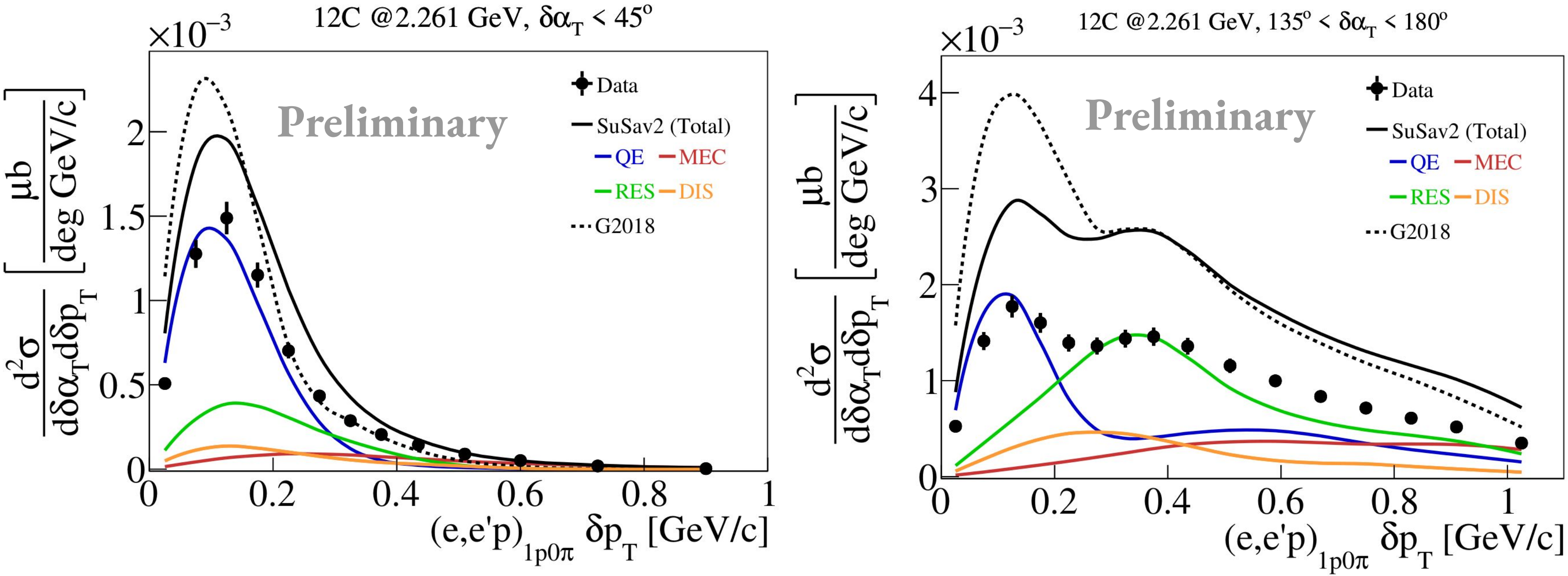
$$\delta p_{T_y} = -\hat{p}_T^{\,l} \cdot \delta\vec{p}_T = |\delta\vec{p}_T|\cos(\delta\alpha_T)$$

The e4ν Result Factory Continued!

- Fermi motion
- Final state interactions (FSI)

e4ν Collaboration
In preparation

# Double Differential Results



The e4ν Result Factory Continued!

- Handle over FSI / initial state effects
- Tuning potential

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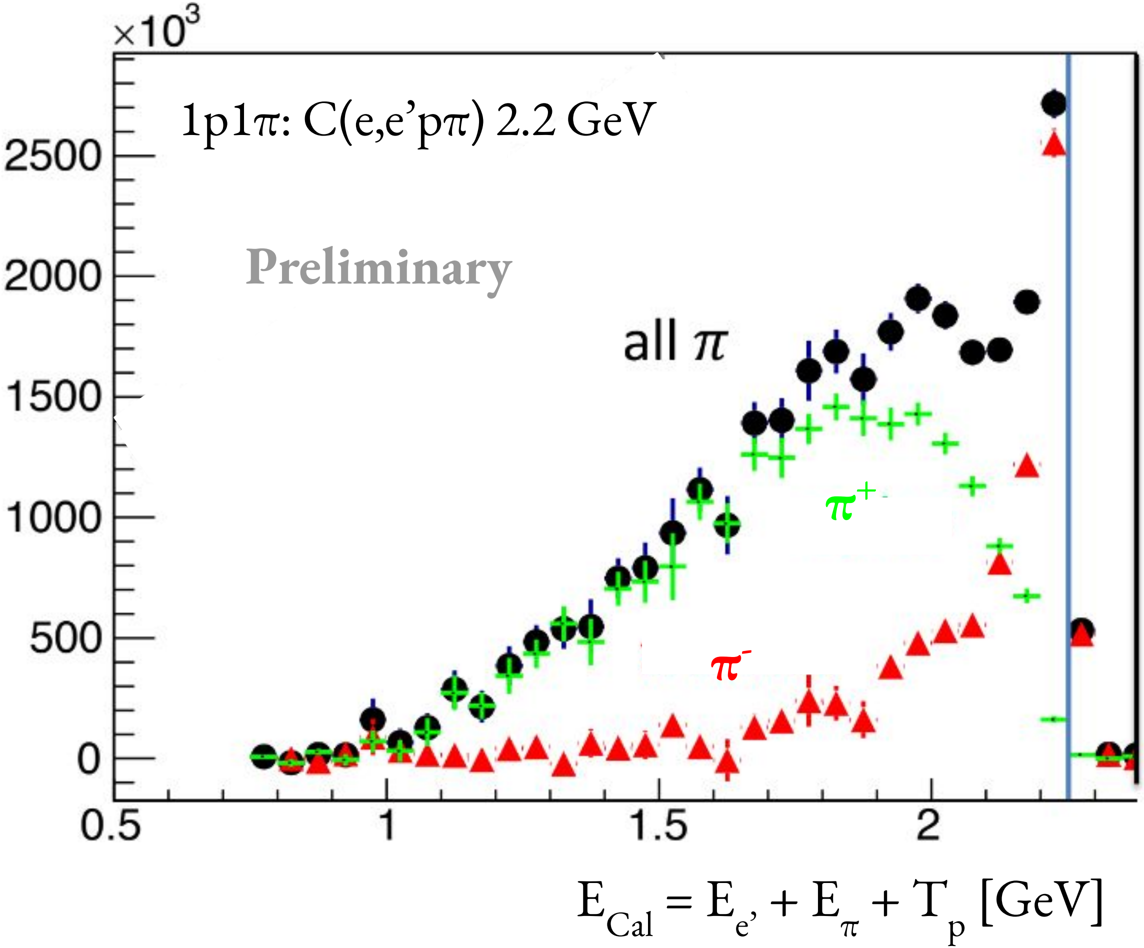
# More Complex Channels



The e4ν Result Factory Continued!

- Critical for DUNE
- LArTPCs cannot separate $\pi^+/\pi^-$

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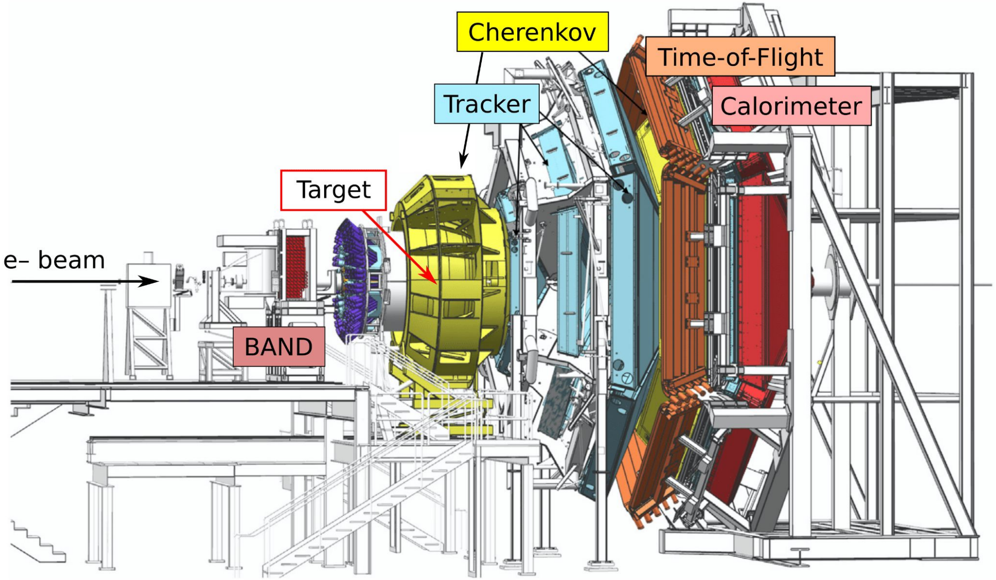
In preparation

# New Data W/ CLAS12

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

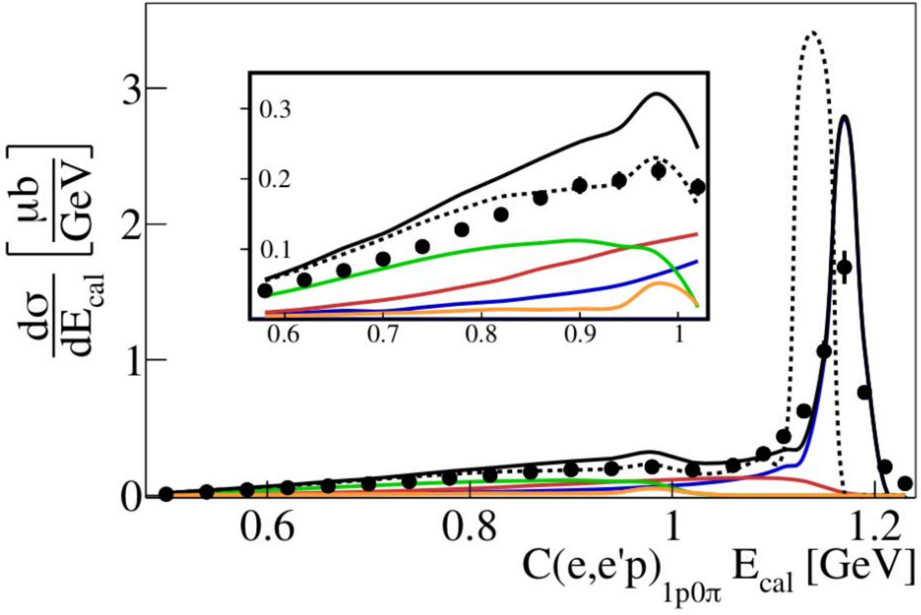


Support Letters

DUNE
ICECUBE SOUTH POLE NEUTRINO OBSERVATORY
Hyper-Kamiokande
T2K
NOvA
MINERvA
Fermilab
GiBUU The Giessen Boltzmann-Uehling-Uhlenbeck Project
Genie
μBooNE

# e4$\nu$ Wrap Up

- First use of wide phase-space electron data to test $\nu$ event generators
- Data/MC disagreement even for simple 1p0$\pi$ events
- Identified regions requiring modeling improvements
- Wealth of results to follow!



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

# Growing Collaboration !

e4V + ?

Join us!

Jefferson Lab

UCL

MAINE

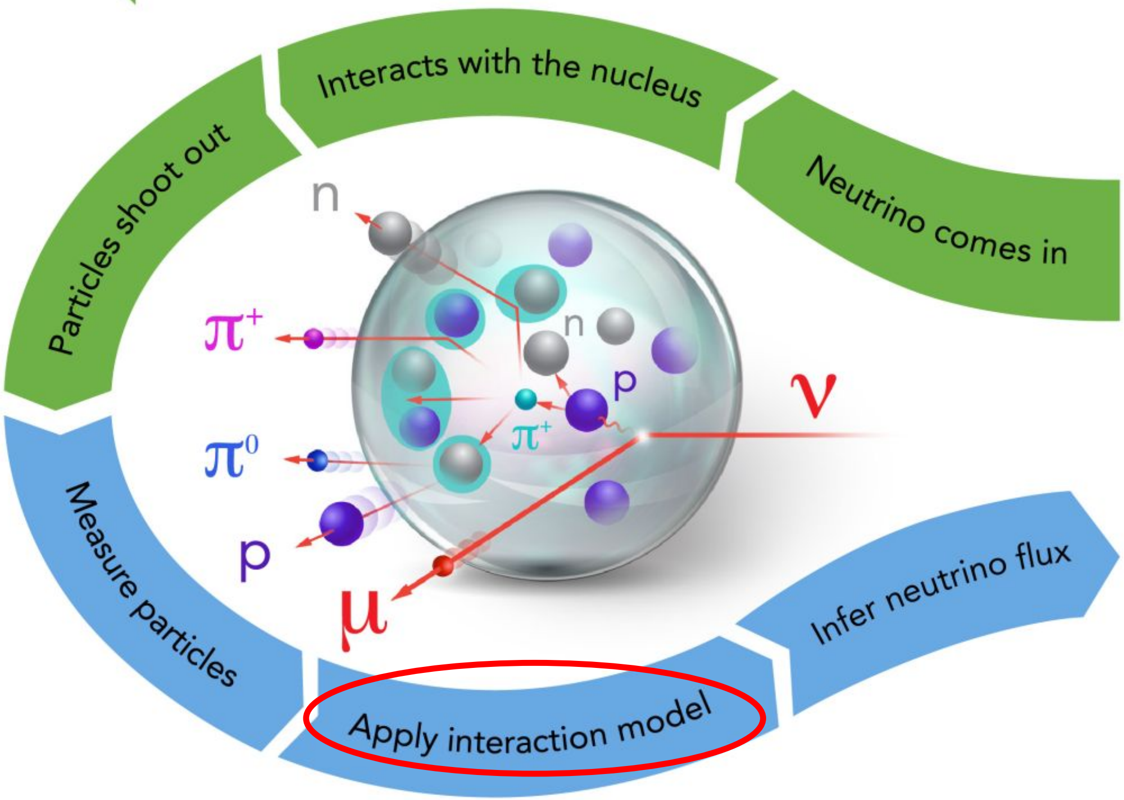
Berkeley Lab

CSIC
Consejo Superior de Investigaciones Científicas

# Thank you !

# Backup Slides

PHYSICS PROCESS



Neutrino comes in

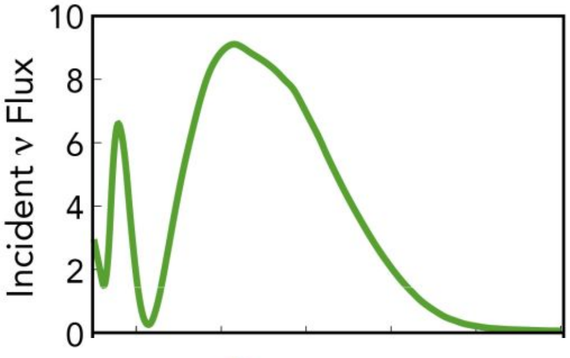
Interacts with the nucleus

Particles shoot out

Measure particles

Apply interaction model

Infer neutrino flux



?

EXPERIMENTAL ANALYSIS

# Attacking The Modeling Monster

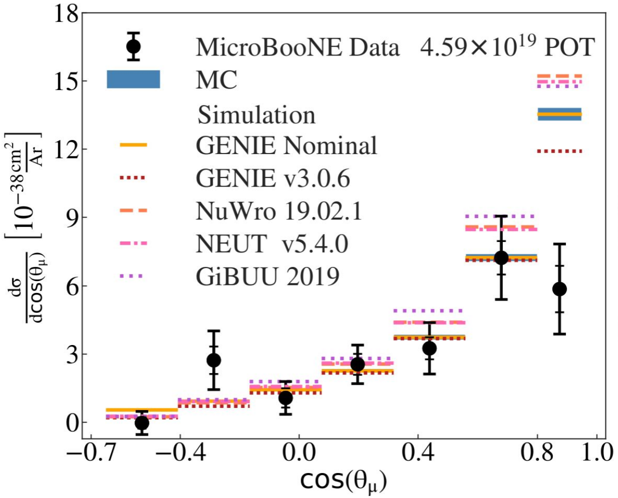
- $\nu$ cross sections

- Modeling in event generators

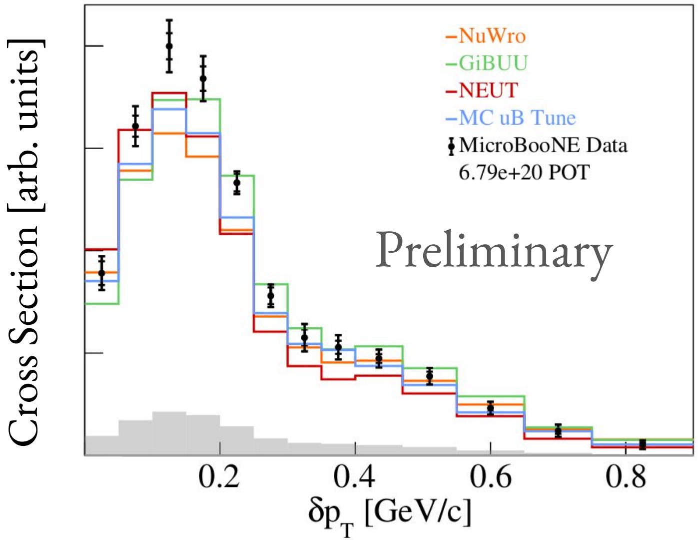
- Electron cross sections

# Attacking The Modeling Monster!

- $\nu$ cross sections



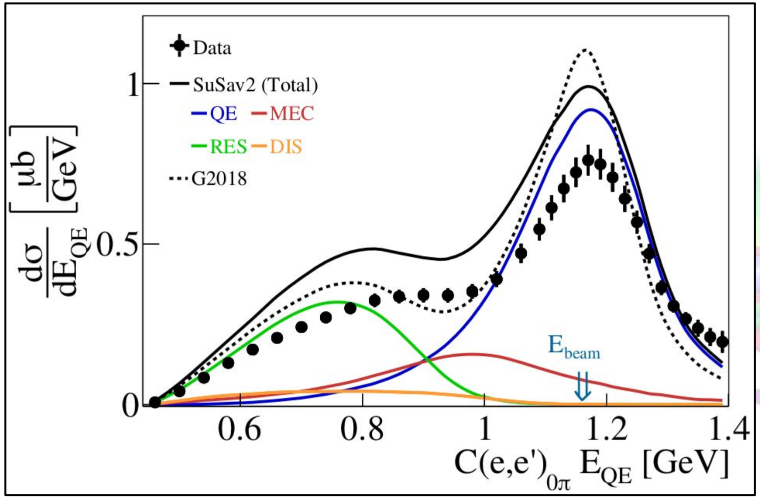
$\delta p_T = |\mathbf{p}_T^{\ell} + \mathbf{p}_T^{p}|$



- A.Papadopoulou, et al,
  Phys. Rev. Lett. 125, 201803 (2020)
- E.Cohen, A.Papadopoulou, et al,
  Eur. Phys. J. C 79, 673 (2019)

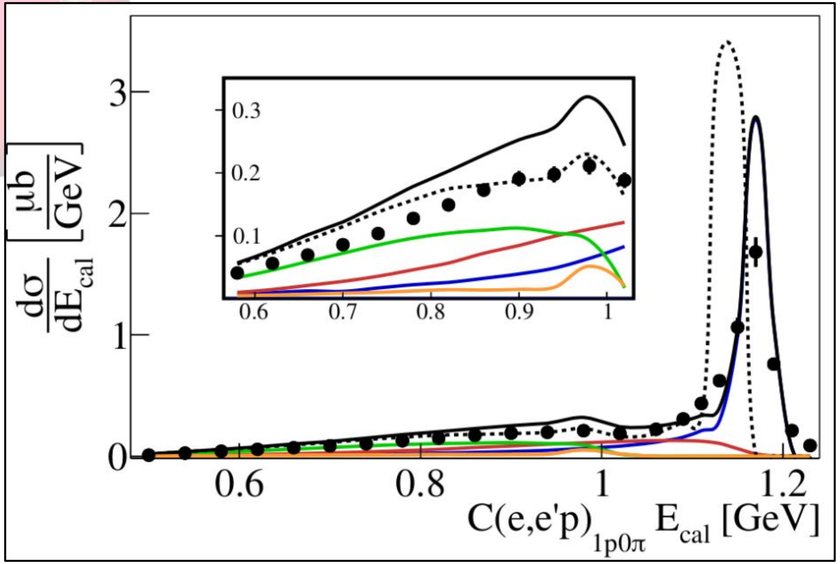
A.Papadopoulou, et al,
In preparation

# Today



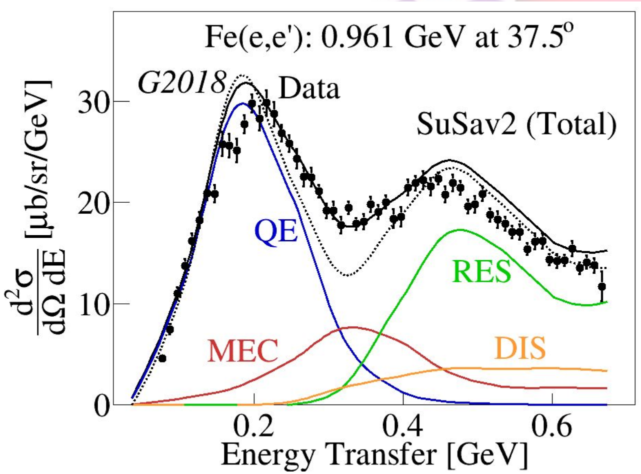
- Electron cross sections

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



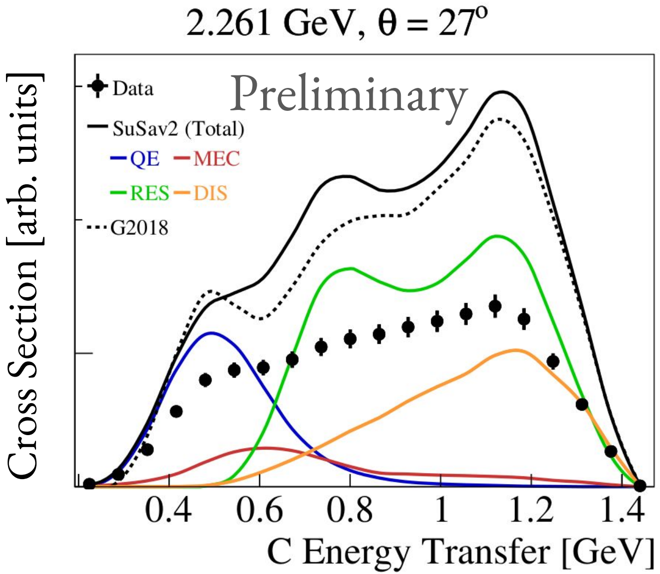
# Attacking The Modeling Monster!

- Modeling in event generators



A.Papadopoulou, et al,

Phys. Rev. D 103, 113003 (2021)



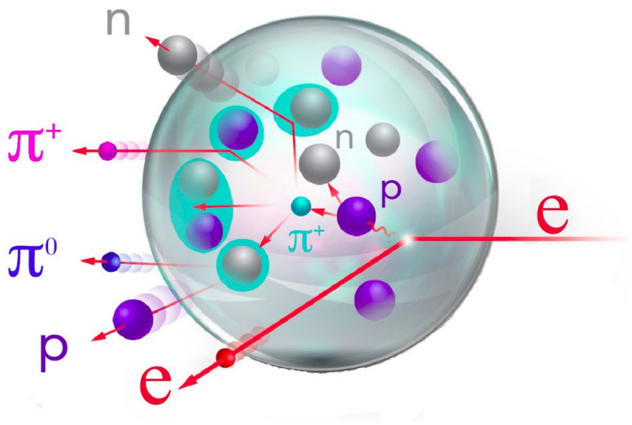
A.Papadopoulou, et al, In preparation

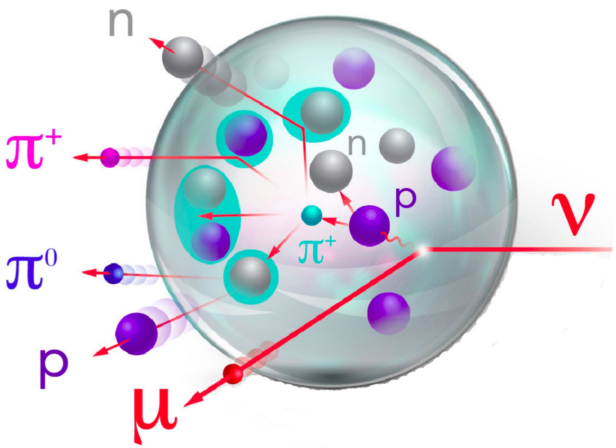
# Why electrons?

- 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 !

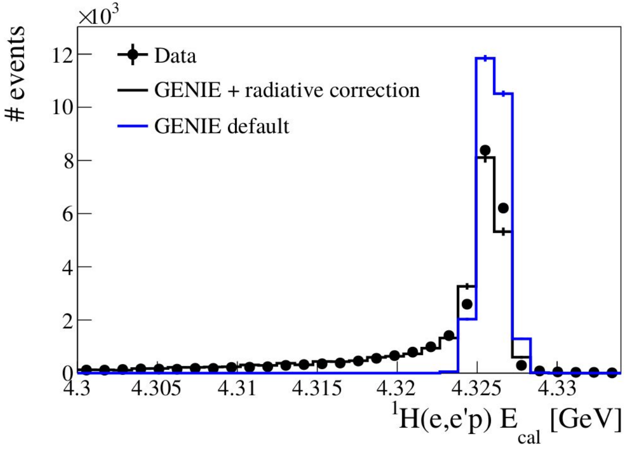




# Cross-Section Extraction

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

Systematic uncertainties on each correction plus variation among detector sectors



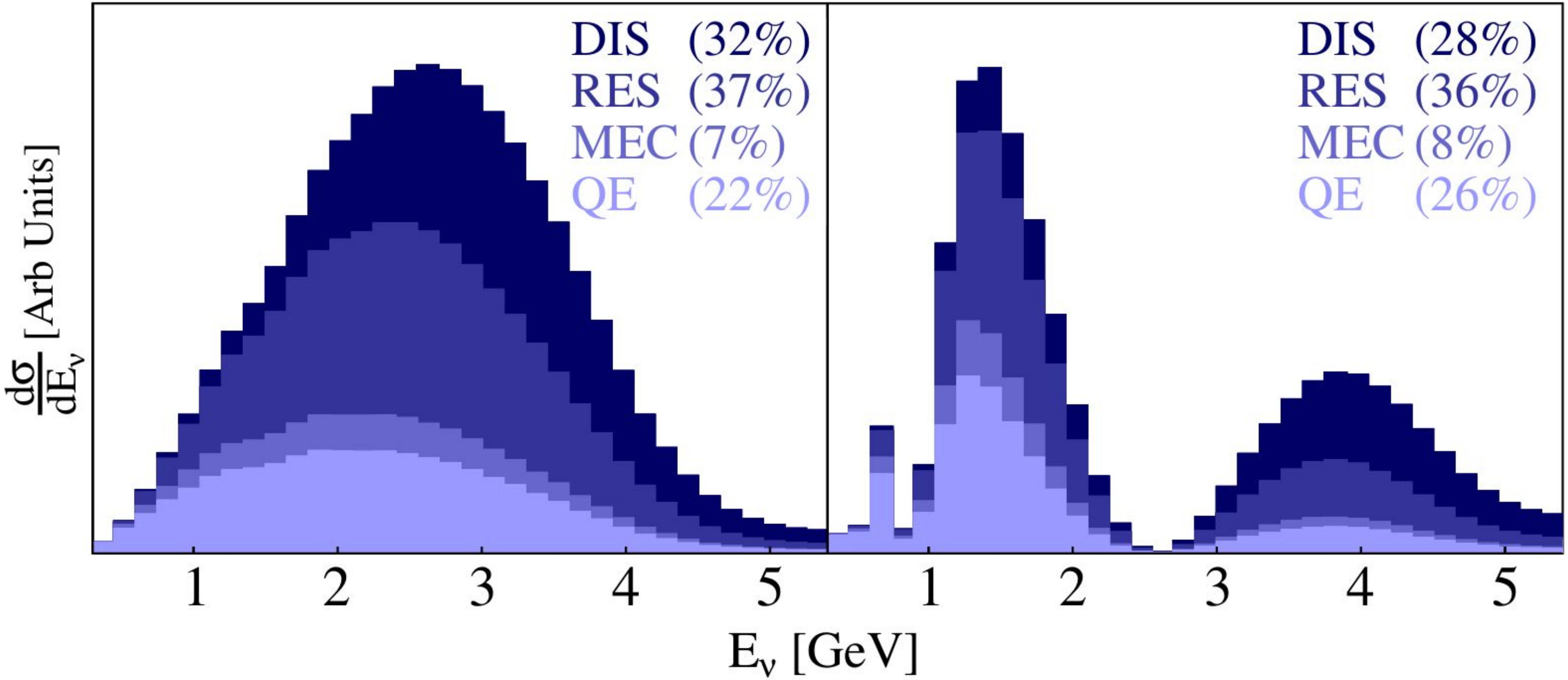
Hall A@ JLab

H(e,e'p) @ 4.32 GeV

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

# Mismodelling Impact On Mixing Parameters

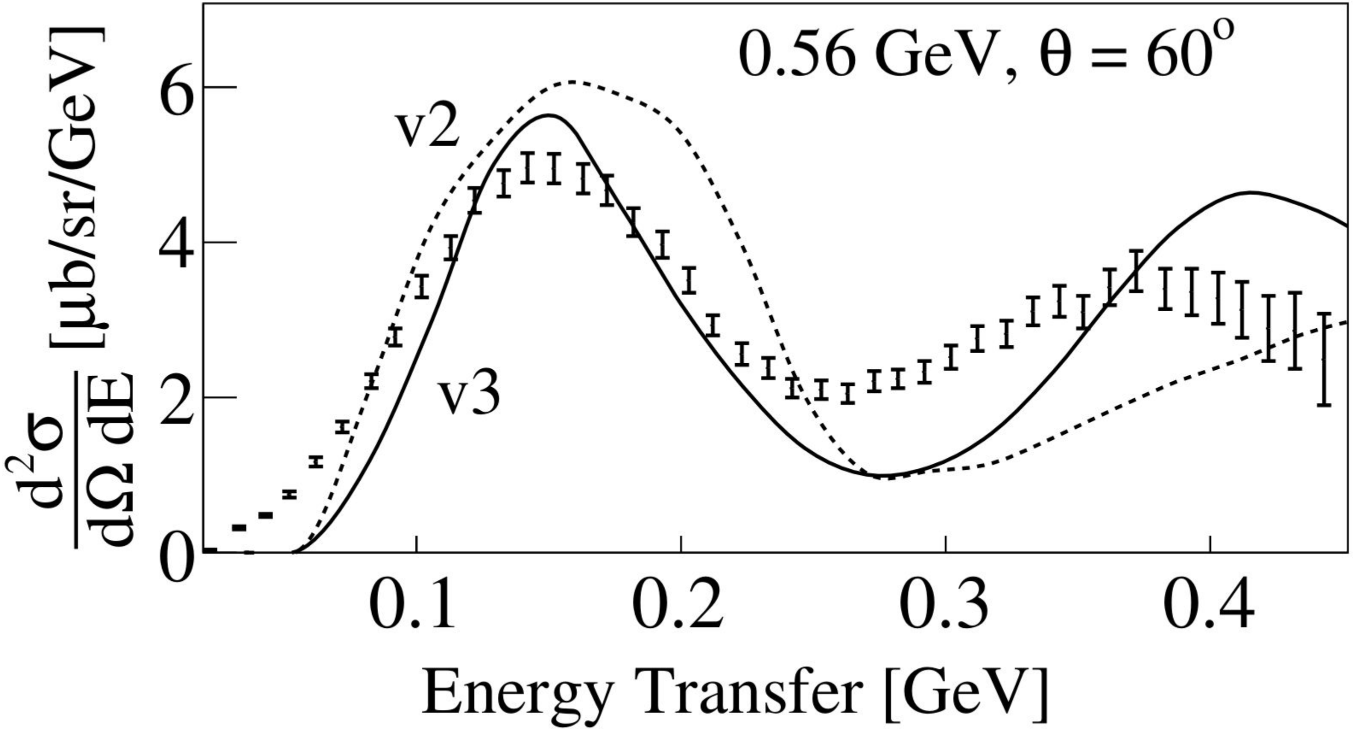
Charged current cross sections obtained using GENIE for the DUNE near detector (left) and far detector (right) oscillated fluxes



Phys. Rev. D 103, 113003 (2021)

# Issues Identified & Fixed In G2018

## (e,e’) $^{12}$C with G2018



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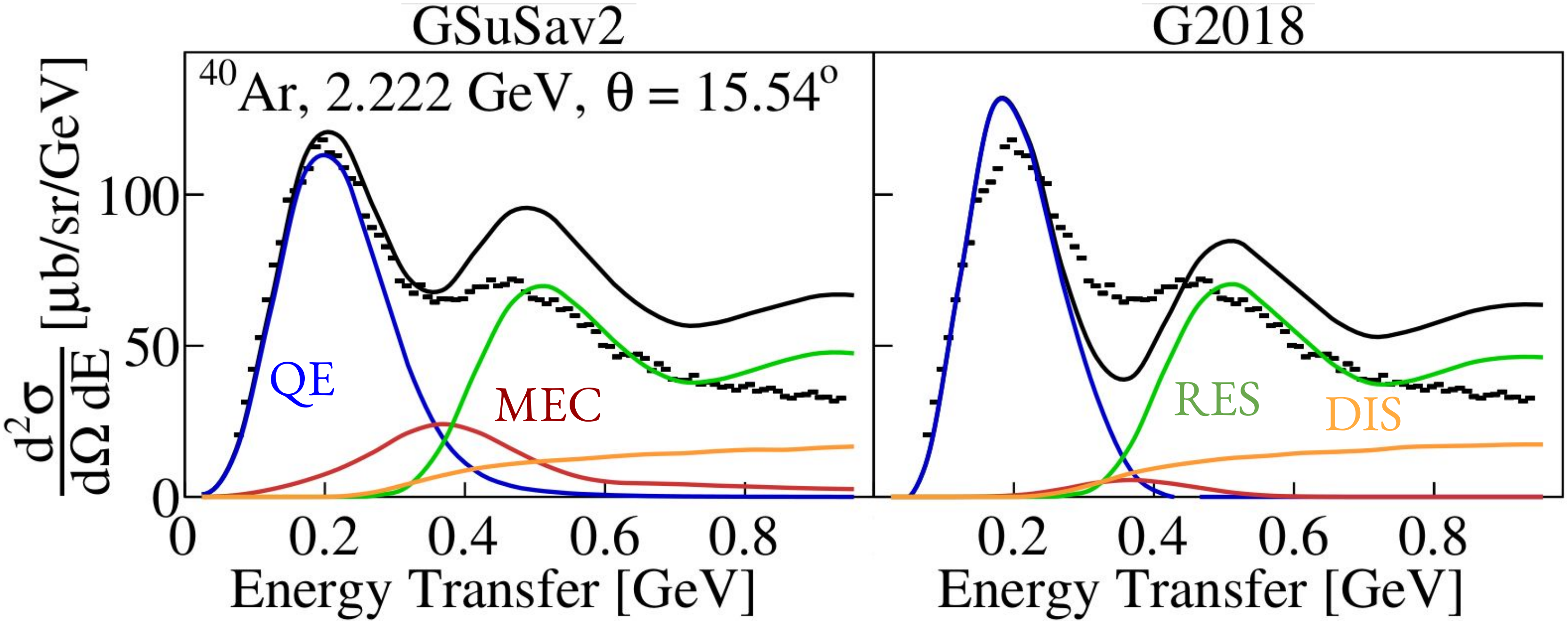
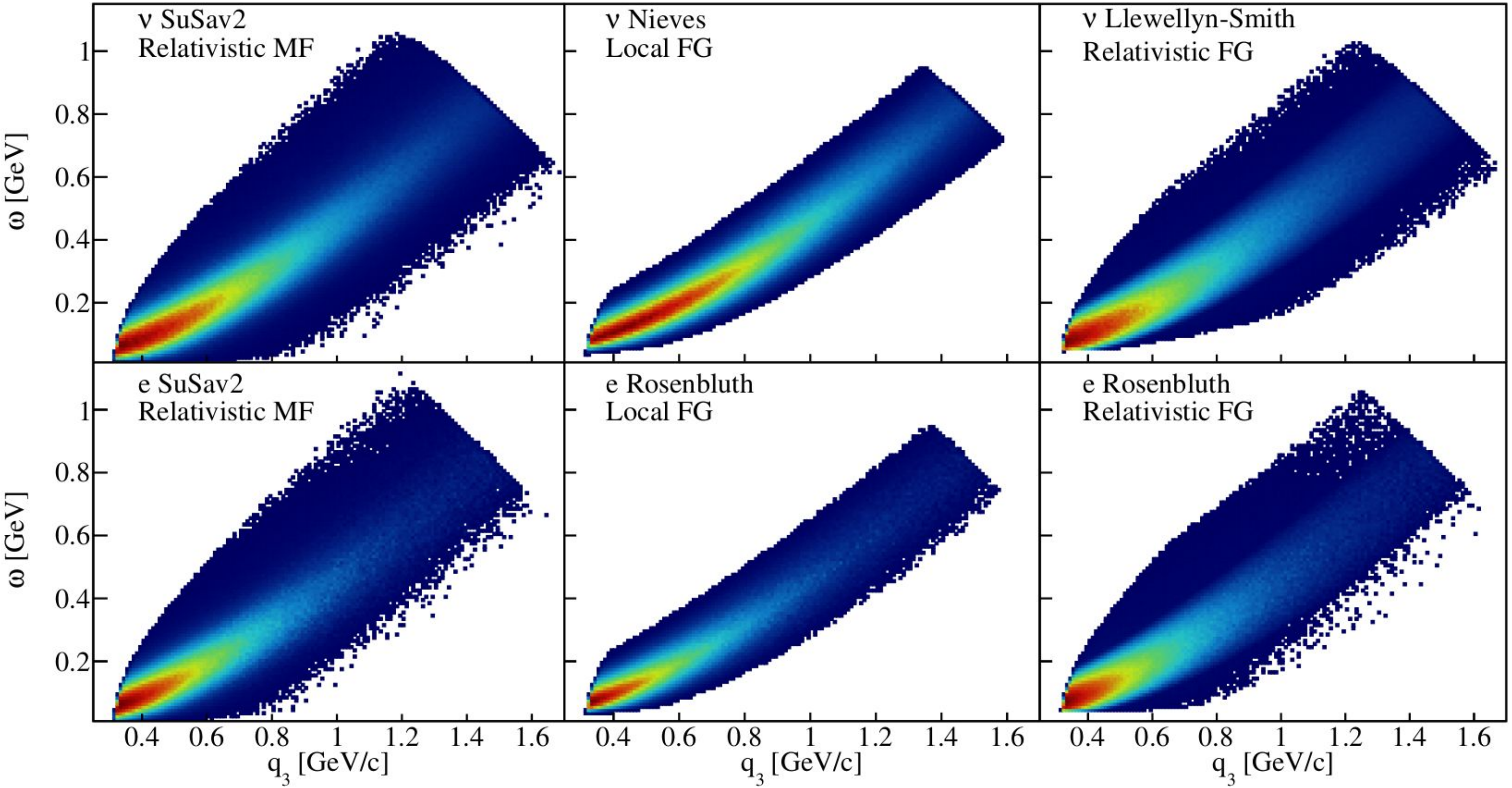
# SuSav2 Offers More Accurate Prediction



Phys. Rev. D 103, 113003 (2021)

# Probing The Neutrino Phase-Space With Electrons

QE Events

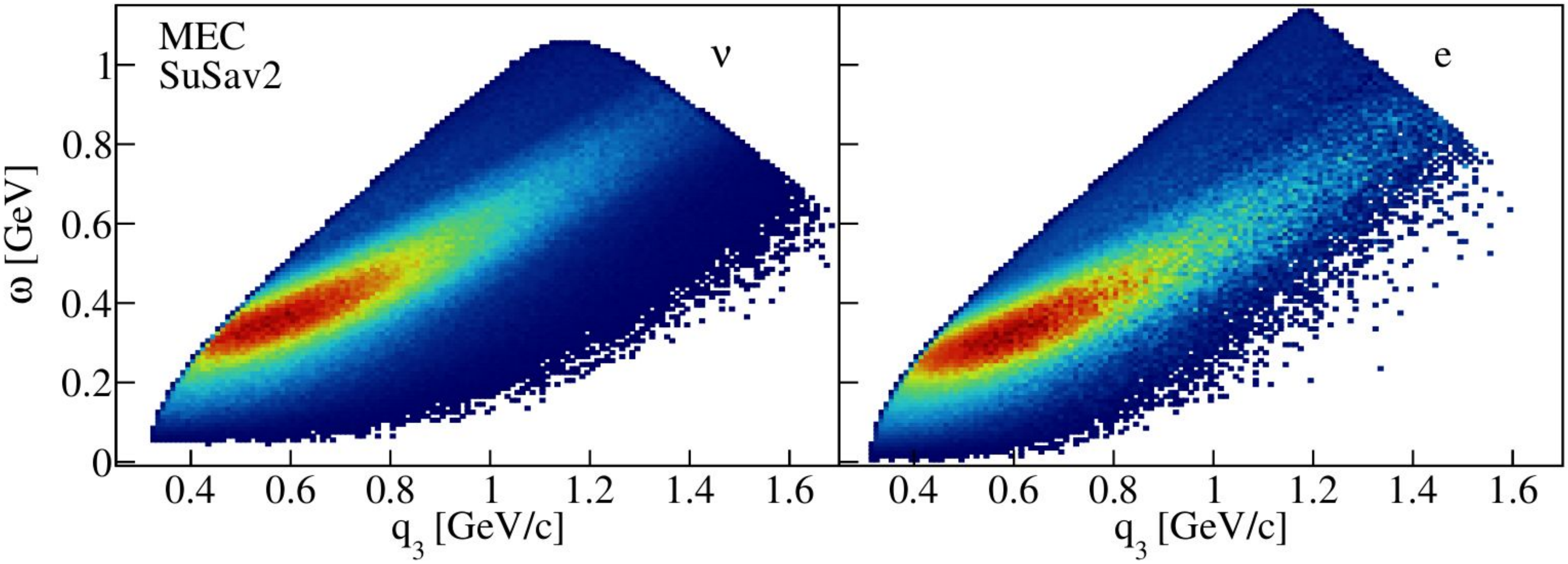


A.Papadopoulou, et al, Phys. Rev. D 103, 113003 (2021)

Electron results scaled by $Q^4$

# Consistent Treatment Of MEC Events With SuSav2

Unique chance to constraint one of least understood interaction channels

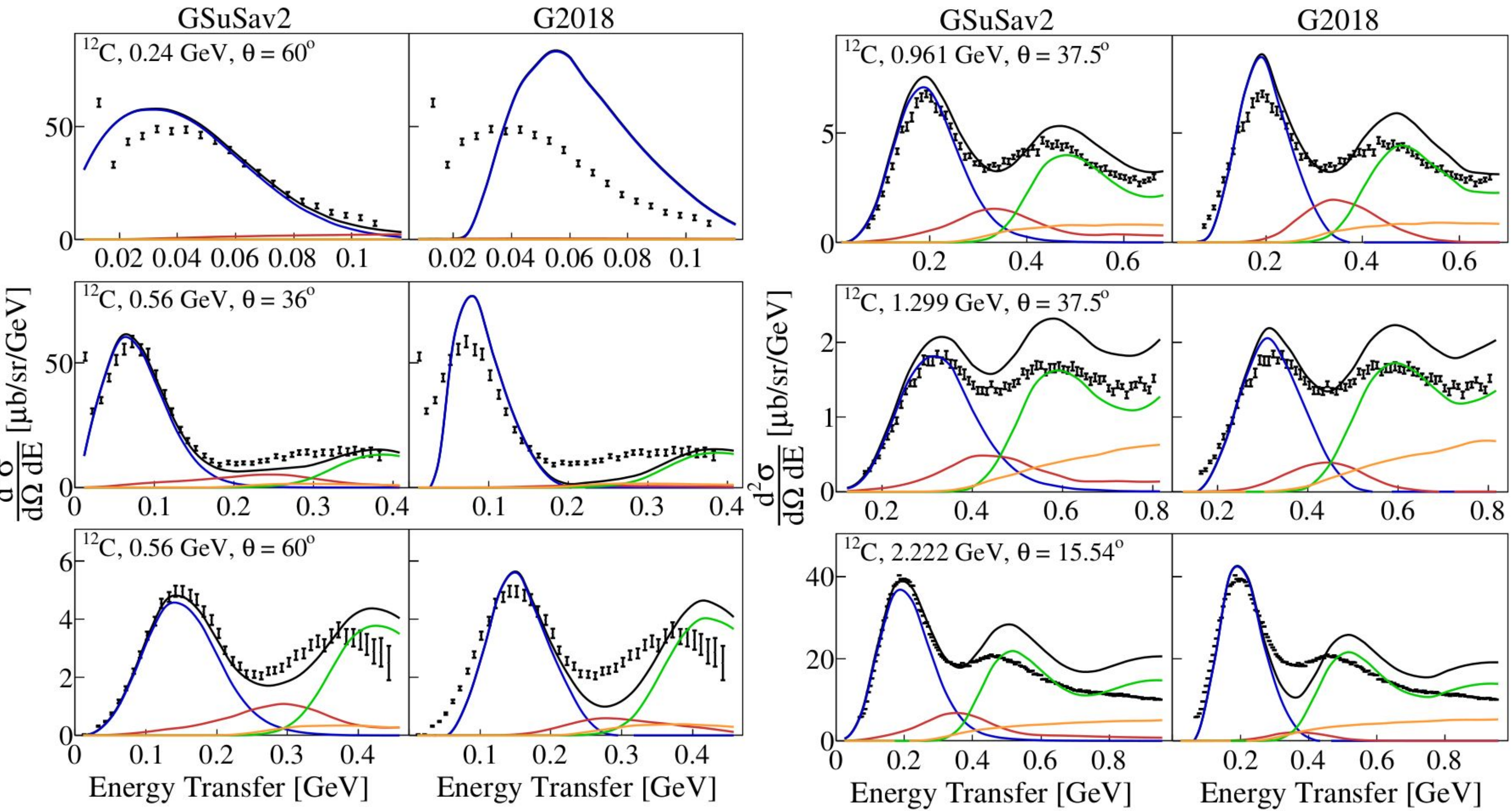


Phys. Rev. D 103, 113003 (2021)

Electron results scaled by $Q^4$

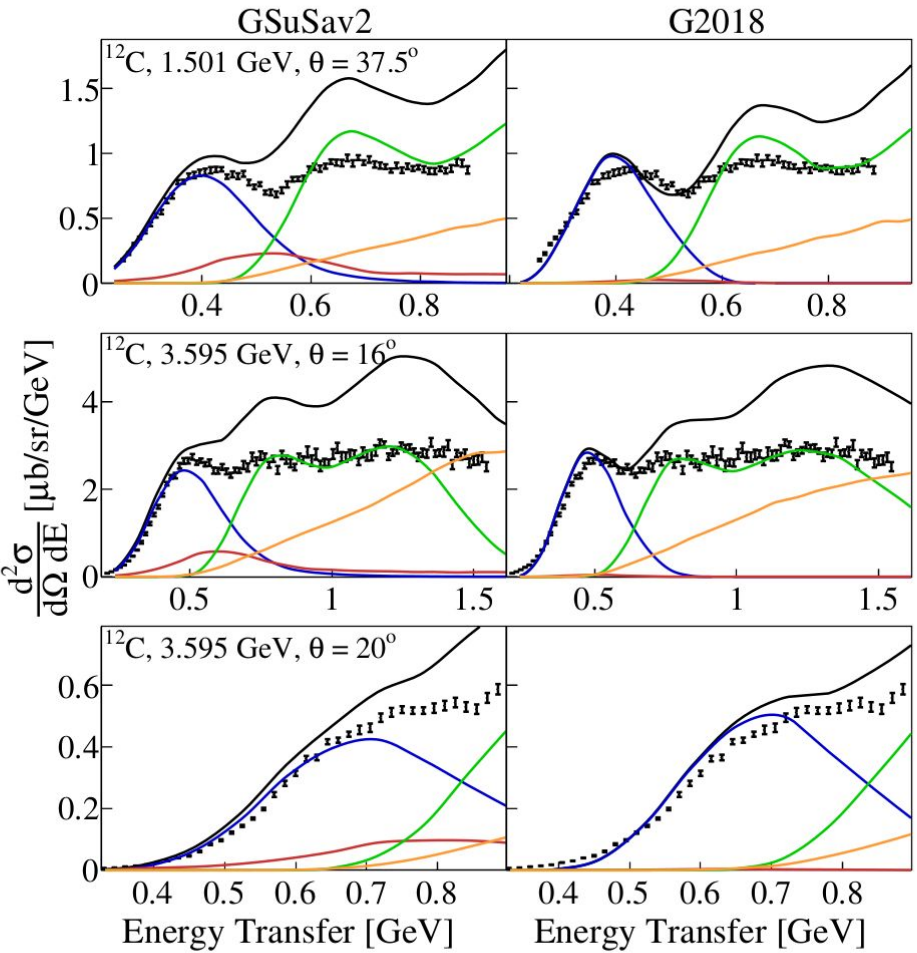
# Inclusive C cross sections

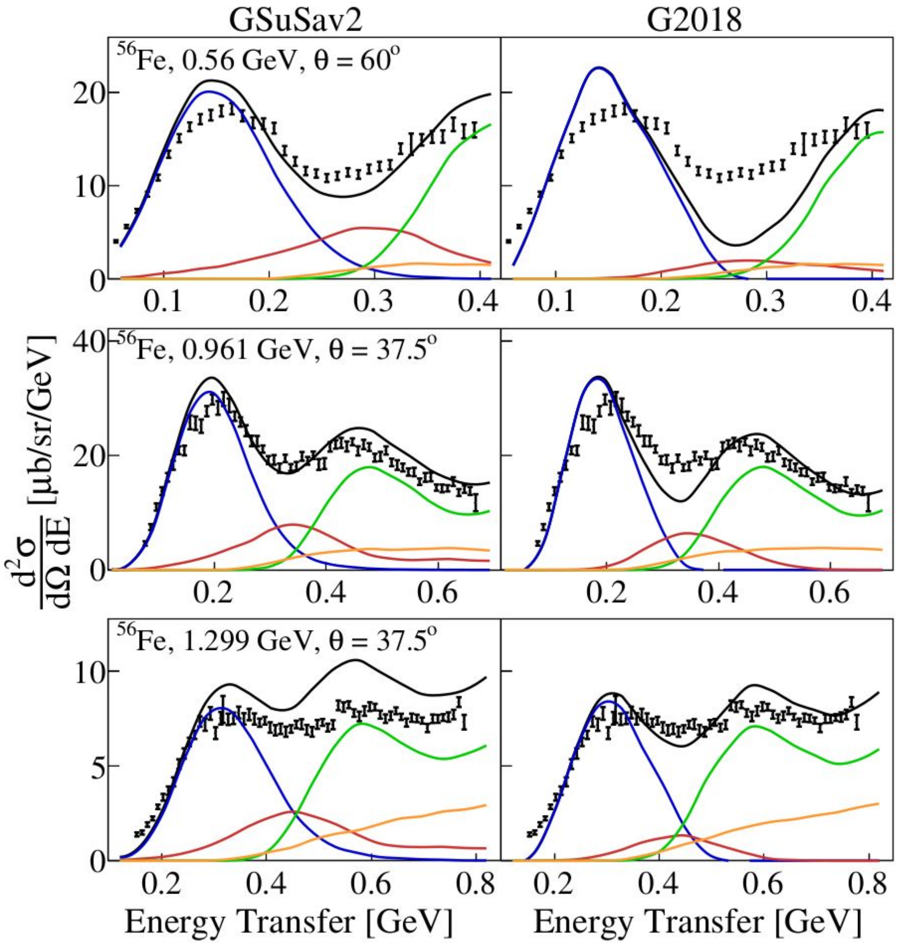
Phys. Rev. D 103, 113003 (2021)



# Inclusive C/Fe cross sections

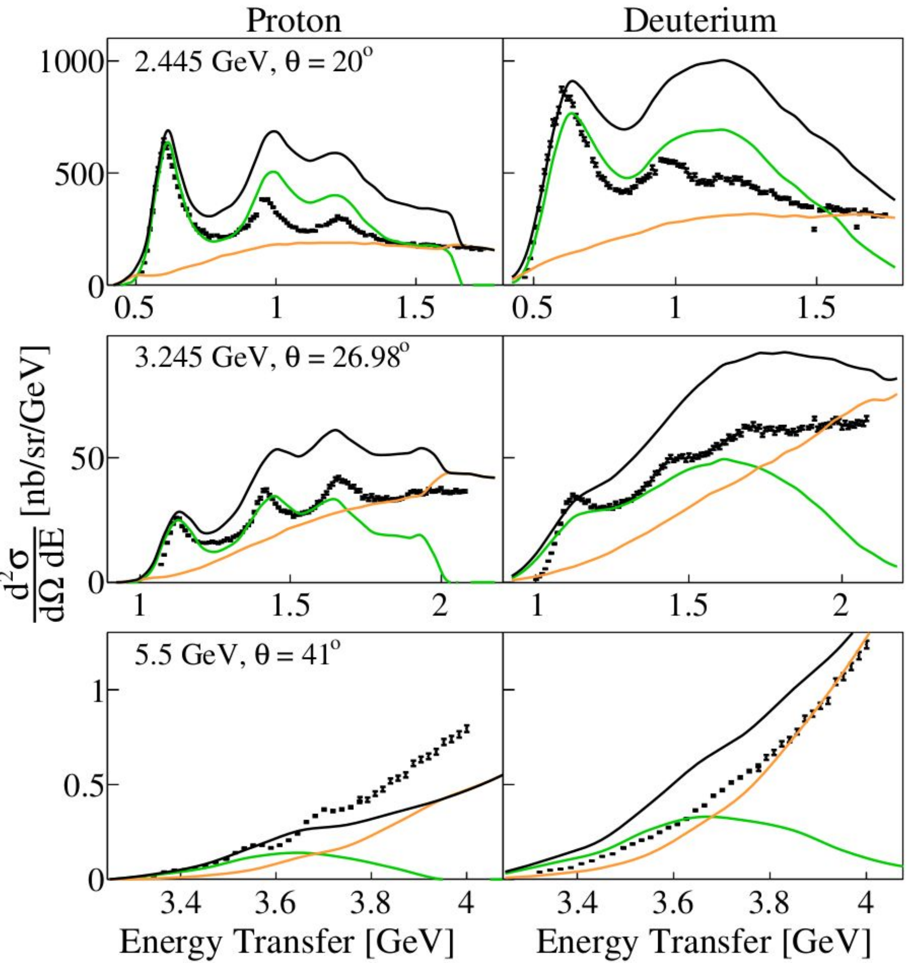
Phys. Rev. D 103, 113003 (2021)

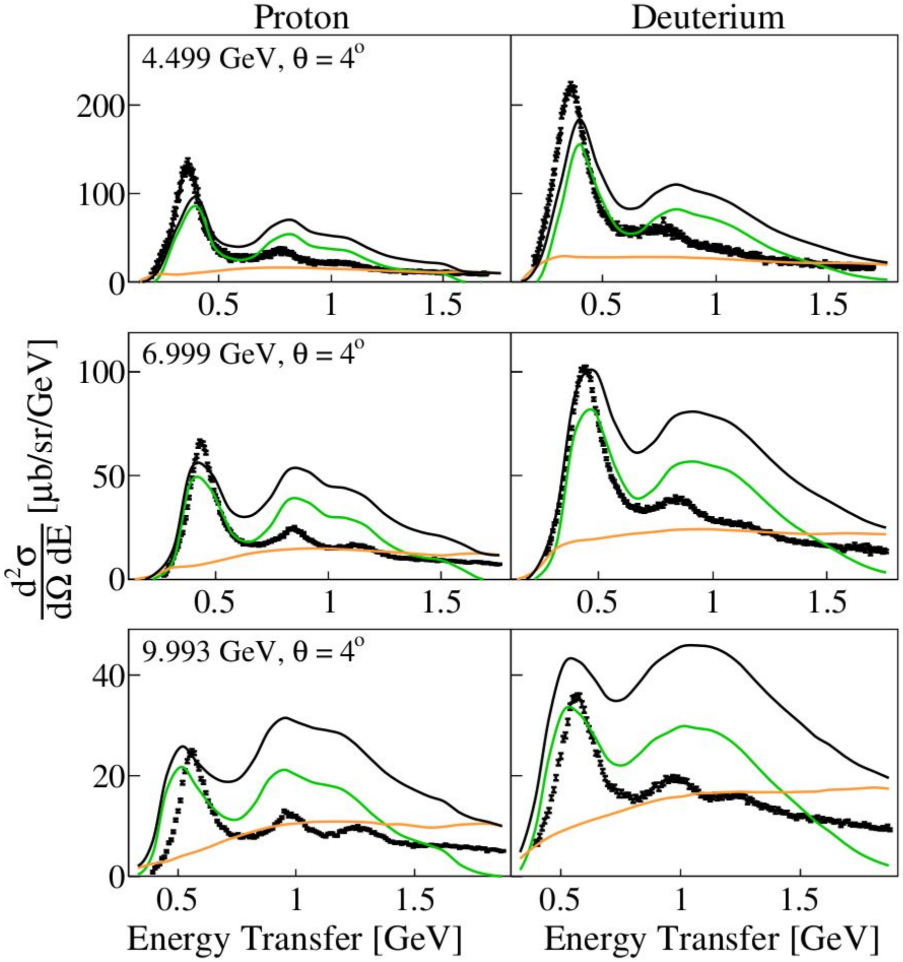




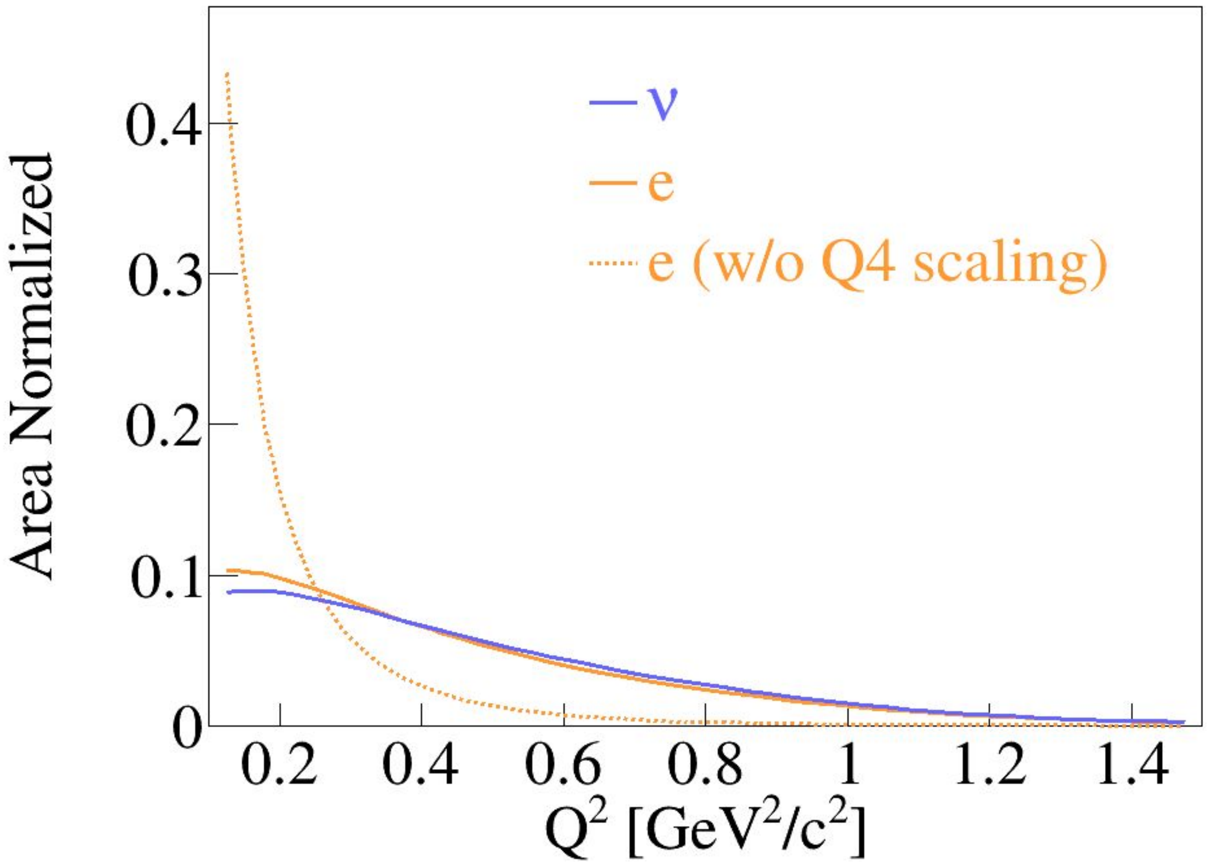
# Inclusive H cross sections

Phys. Rev. D 103, 113003 (2021)



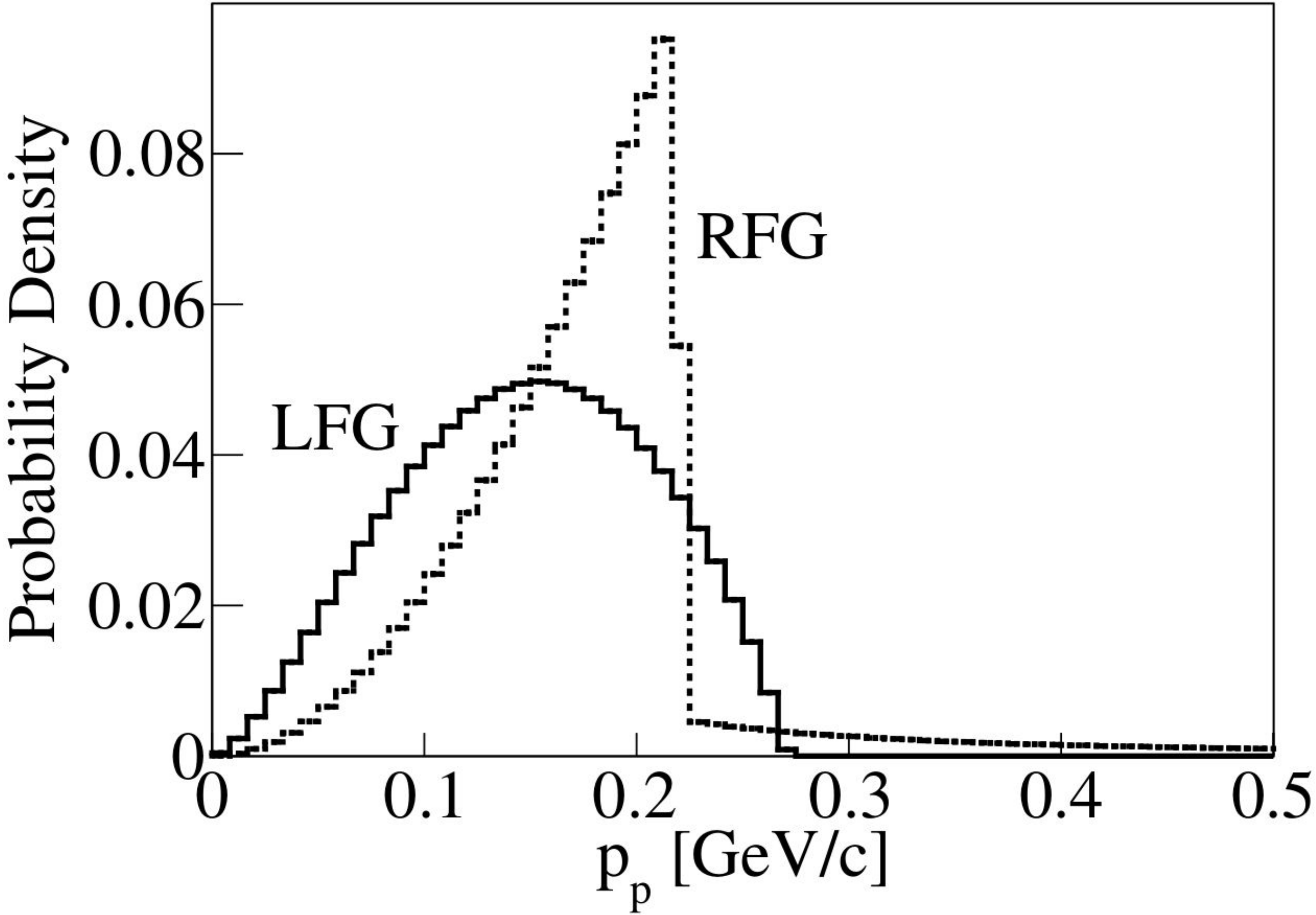


# $Q^4$ Scaling Effect



# Available Nuclear Models

Phys. Rev. D 103, 113003 (2021)



# SuSav2 Configuration / GEM21_11b_00_000

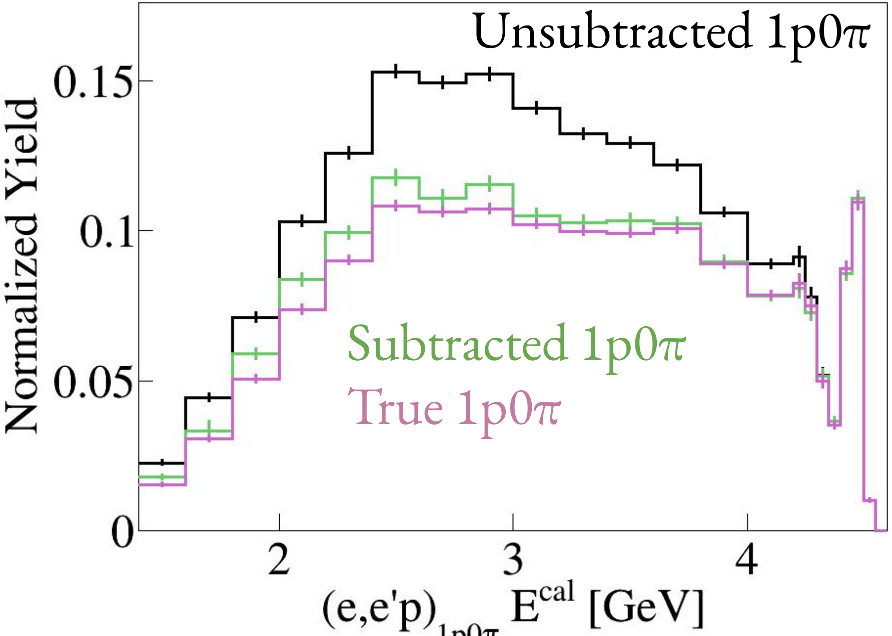
| | **Electrons** | **Neutrinos** |
|---|---|---|
| **QE** | SuSav2 | SuSav2 |
| **MEC** | SuSav2 | SuSav2 |
| **RES** | Berger-Sehgal | Berger-Sehgal |
| **DIS** | AGKY | AGKY |
| **FSI** | hN2018 | hN2018 |
| **Nuclear Model** | Relativistic Mean Field | Relativistic Mean Field |

# 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 |

# Closure Test

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



# Well defined signal definition: Min $\theta_e$ Cut

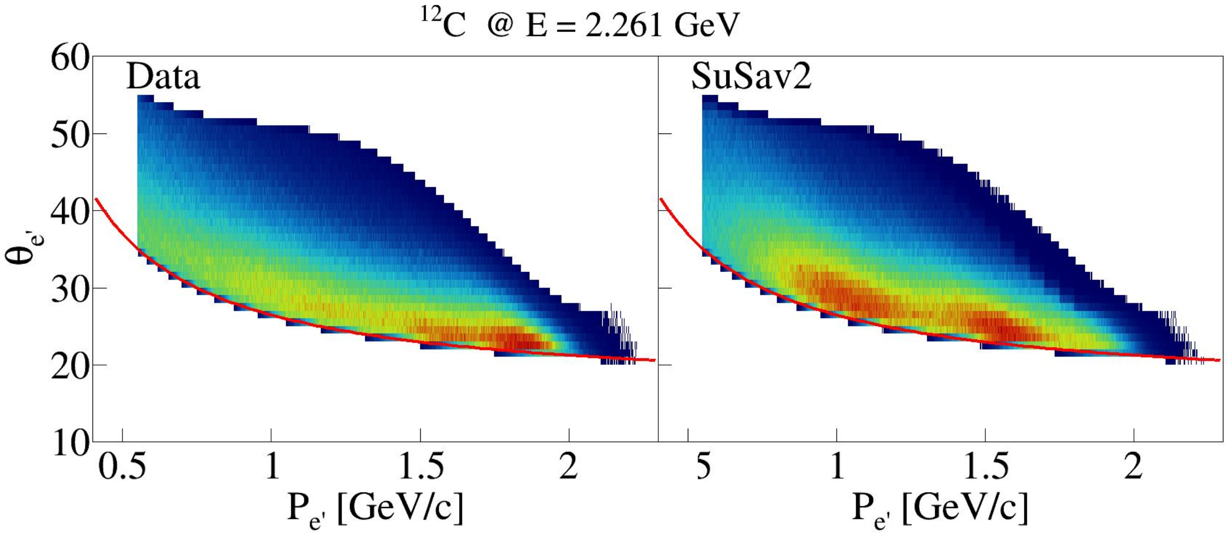
@ 1.1 GeV: $\theta = 17 + 7 / P$

@ 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 $\theta$



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

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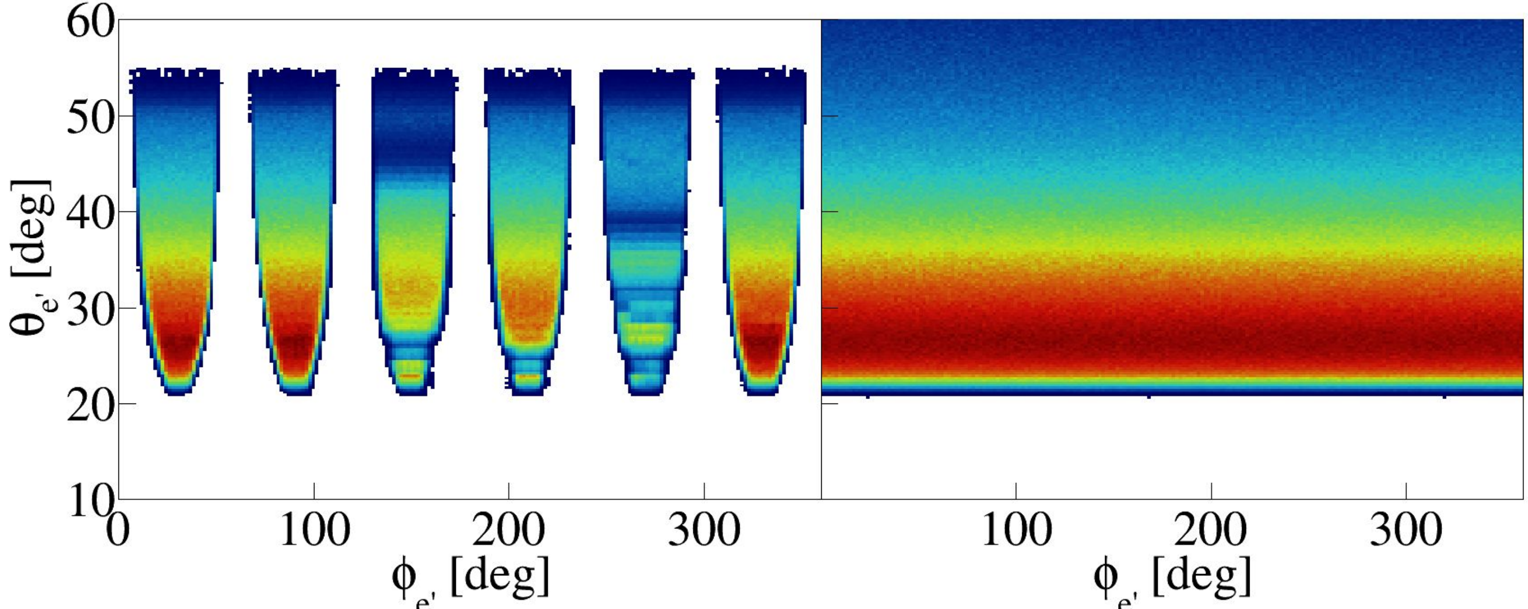
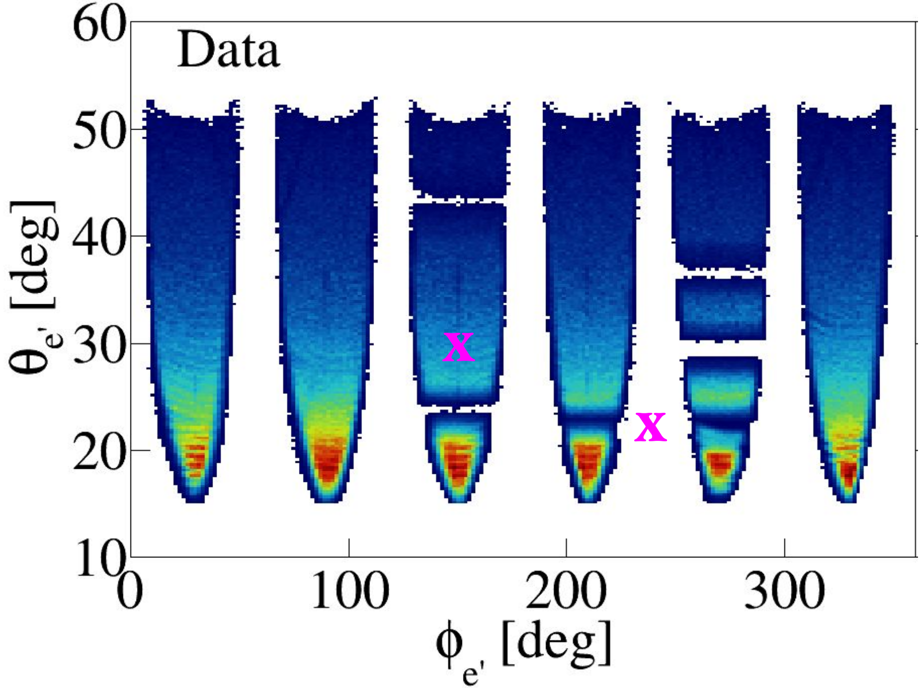
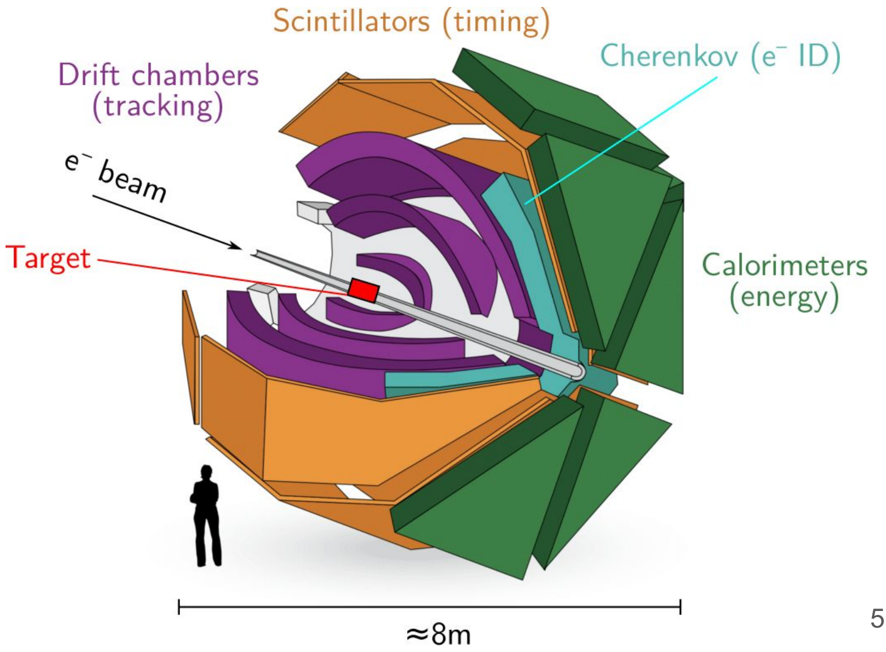
$^{12}$C @ E = 2.261 GeV



# Background Subtraction

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

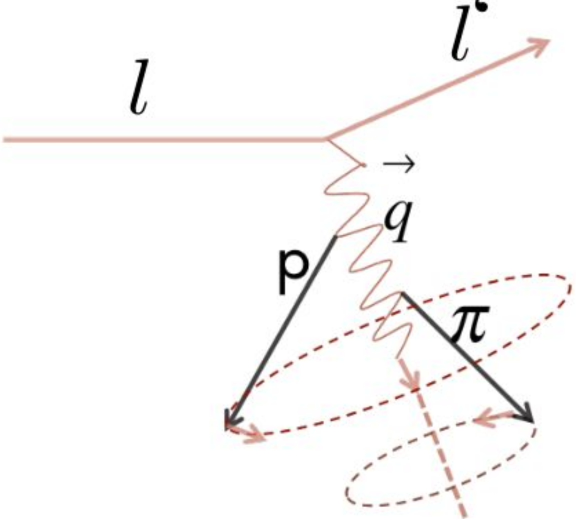




# Data Driven Correction

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

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



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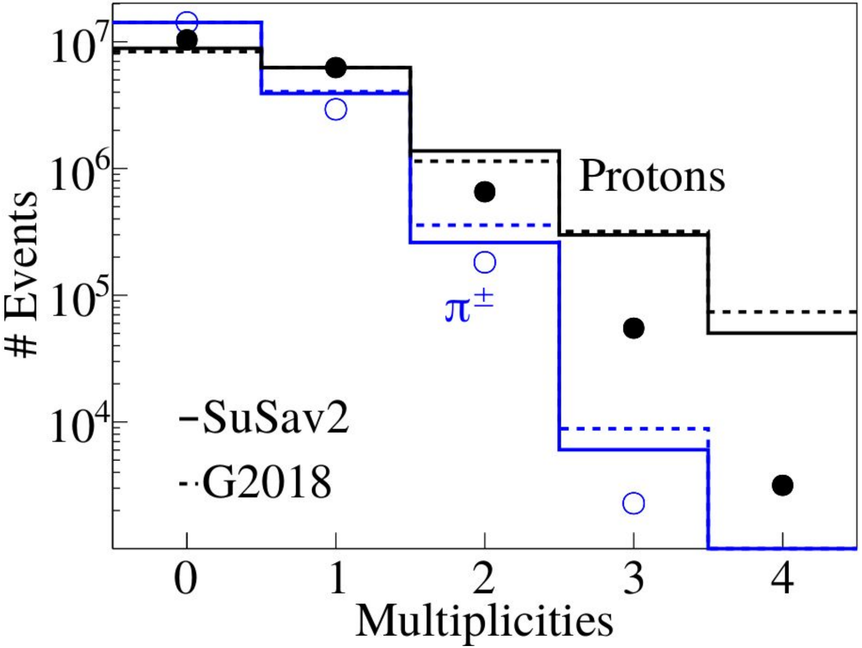
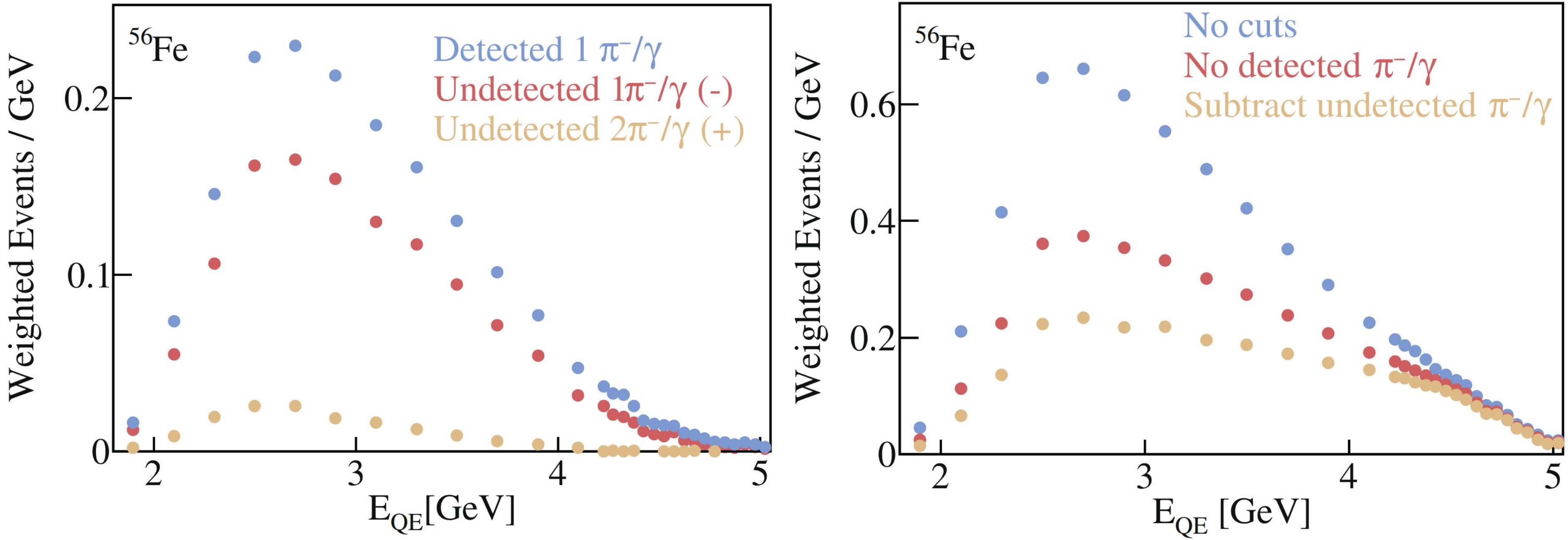
- Repeat for higher hadron multiplicities

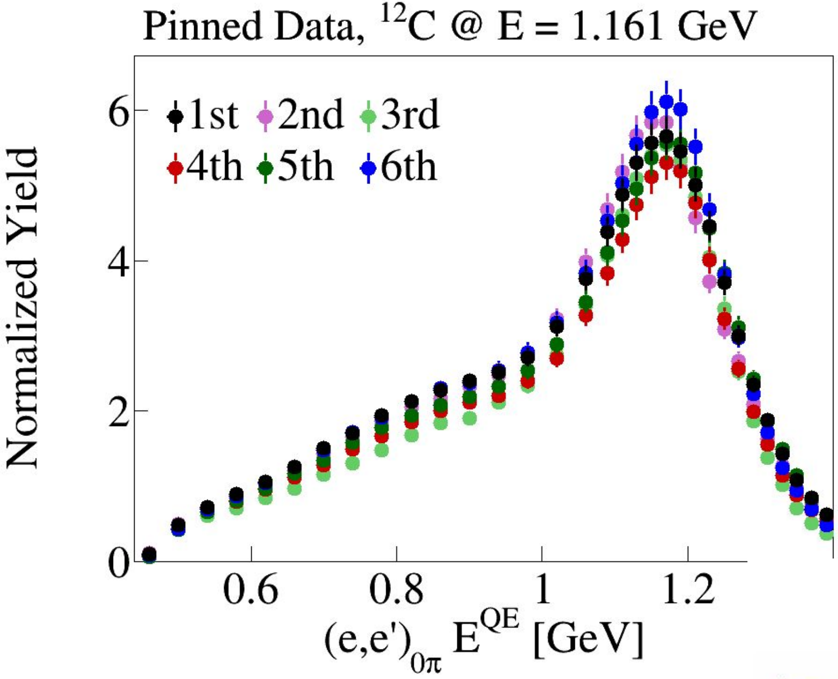
(2p, 3p, 2p+1π, …)

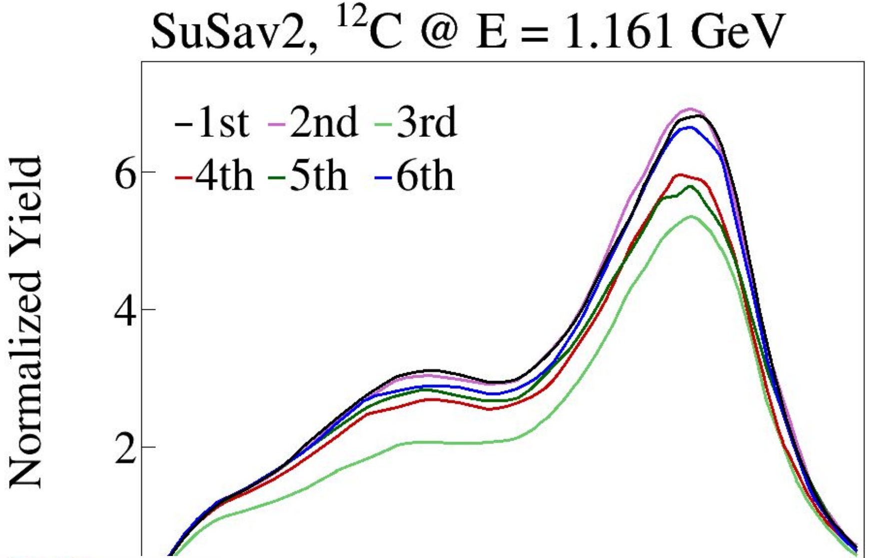


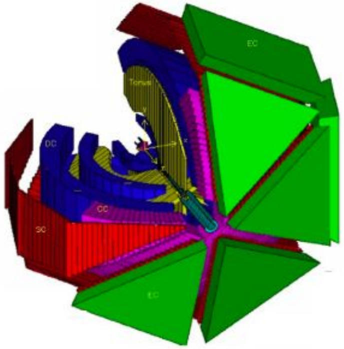
# Subtraction Effect



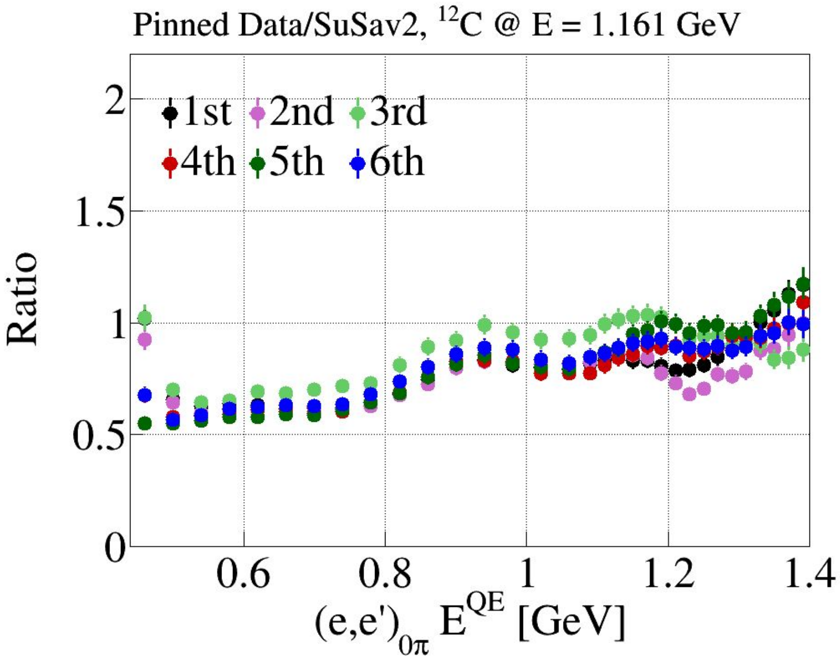
# Systematics: Sector Dependence

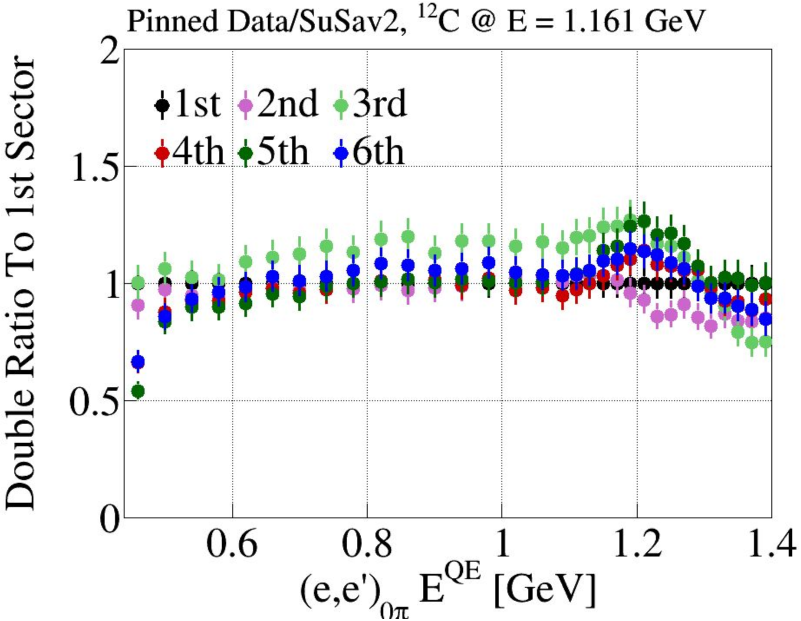






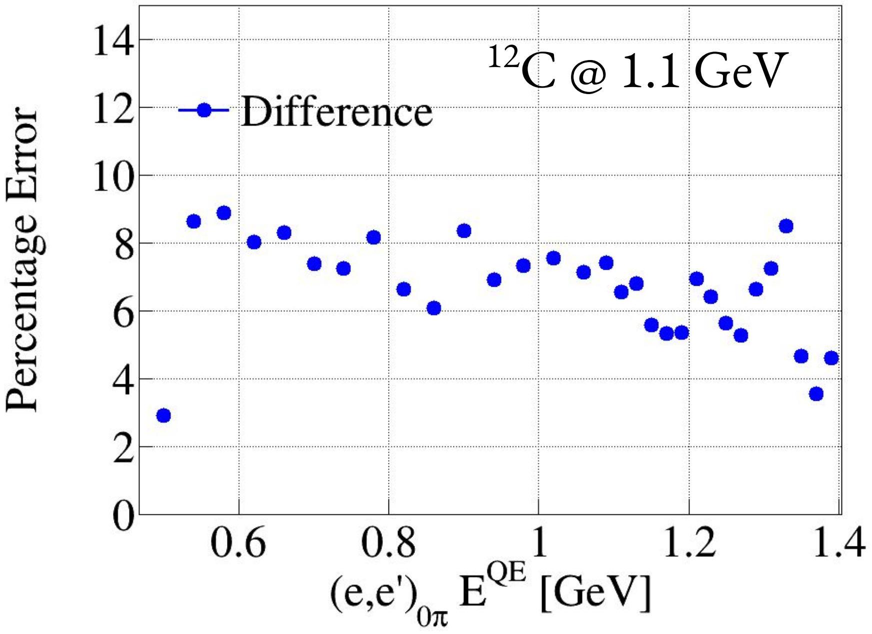
# Systematics: Sector Dependence





# Systematics: Sector Dependence

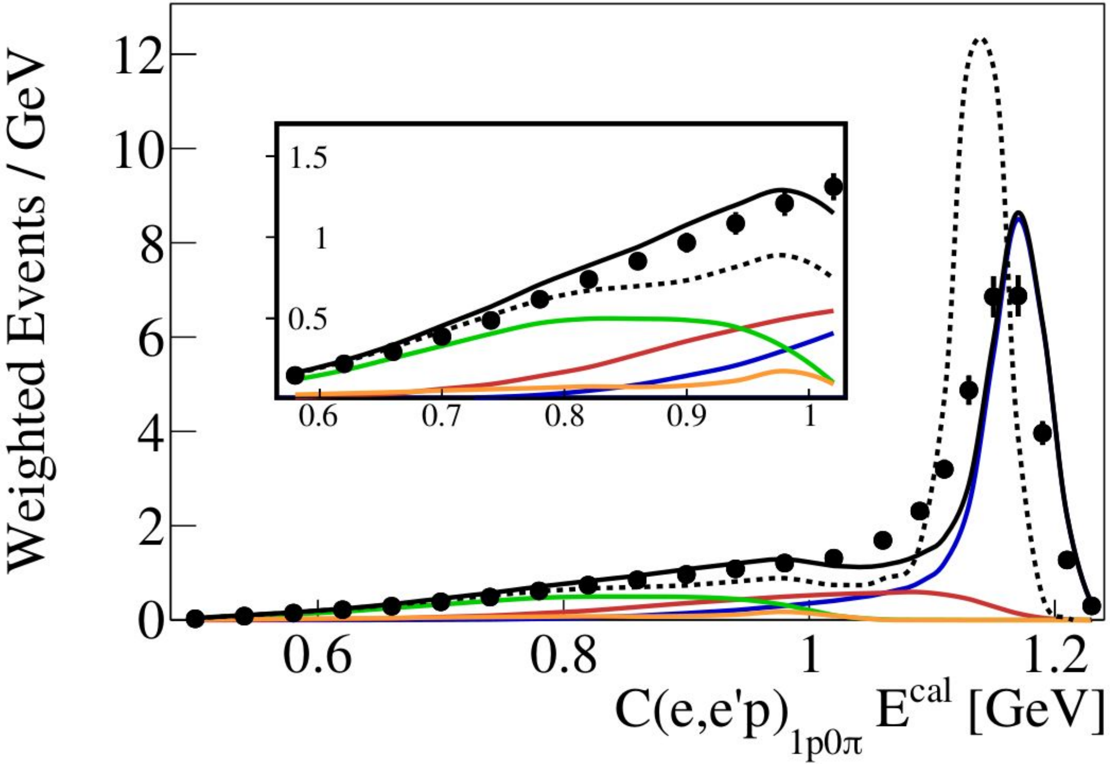
Quantifying uncertainty by using
unweighted variance & by subtracting variance from statistical uncertainty



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

# 1st e4$\nu$ Submission

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



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

# Step #2: Normalized Yield

Data

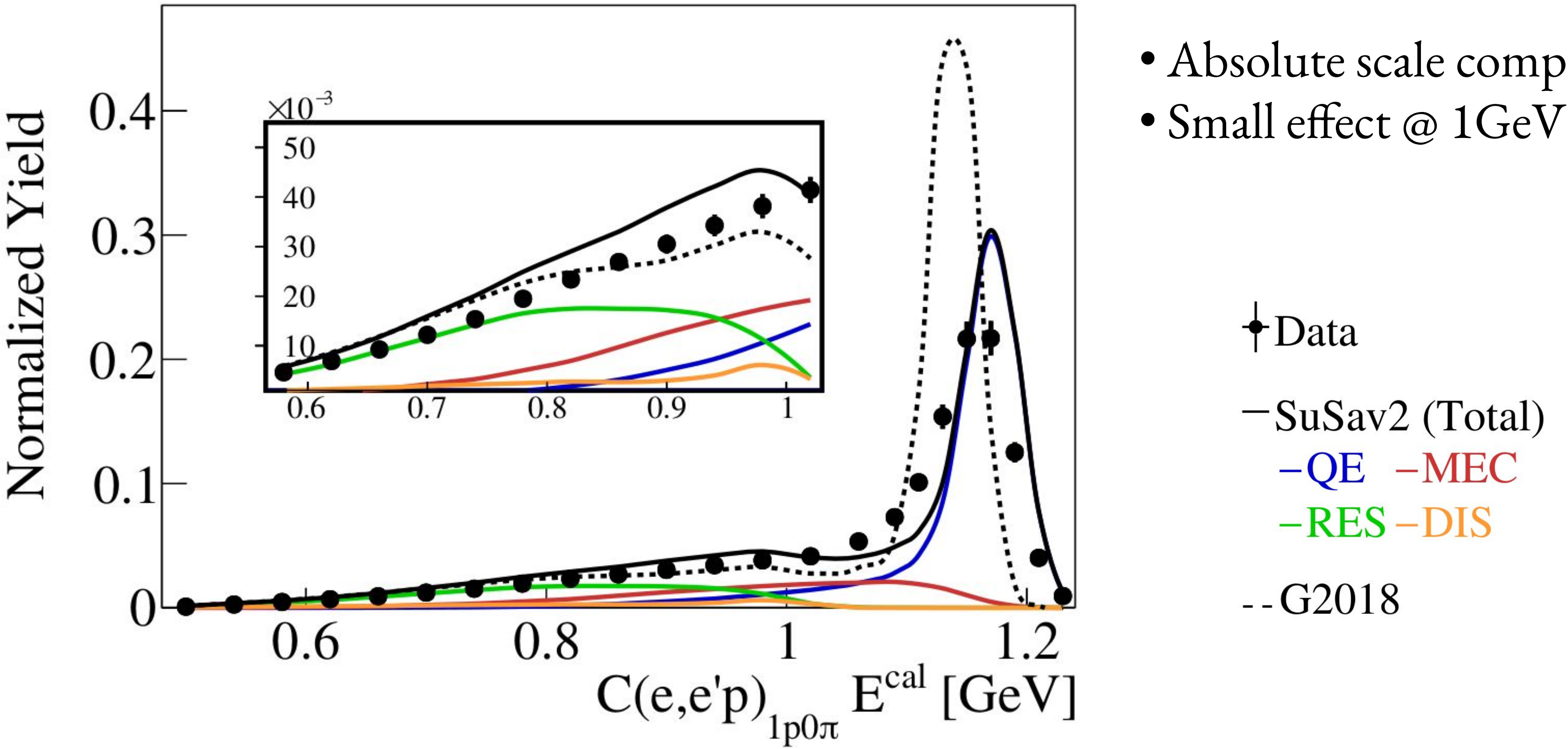
- Divide # events by integrated charge & target thickness to get xsec in μb
- Divide by bin width to get μb/GeV

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

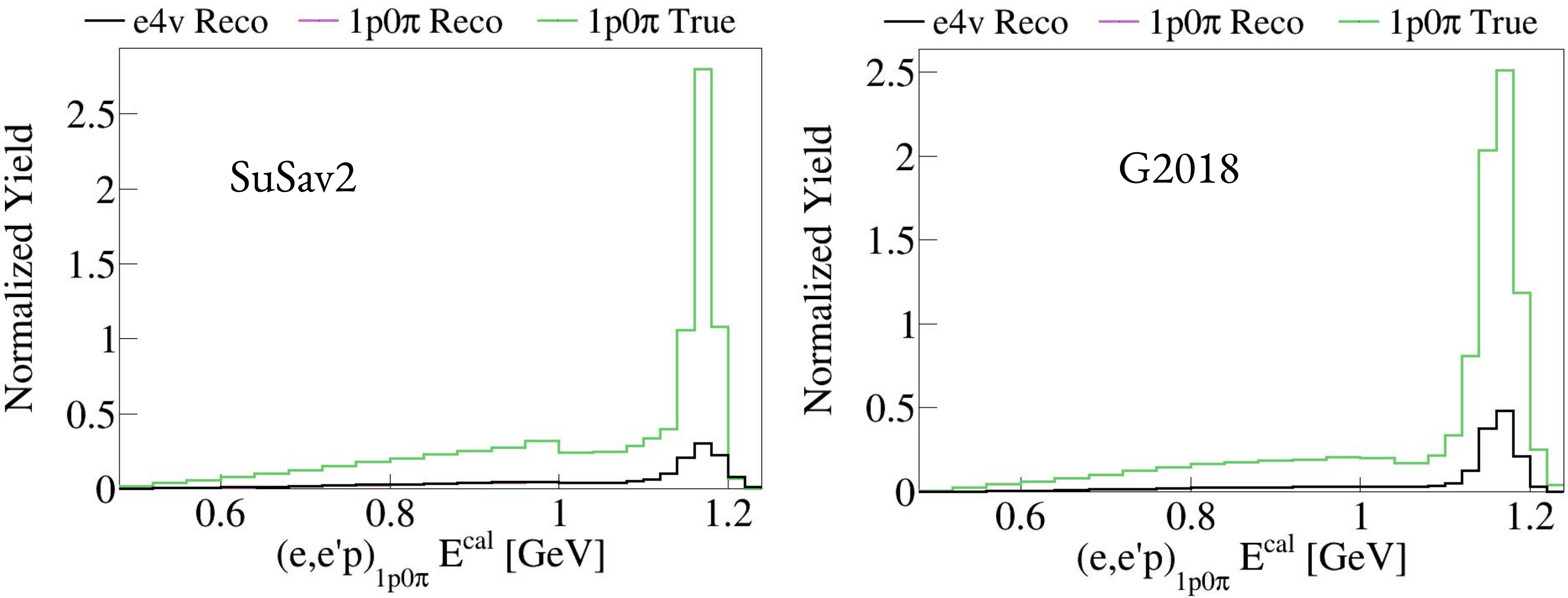


- Absolute scale comparison
- Small effect @ 1GeV

# Step #3a: Acceptance Correction

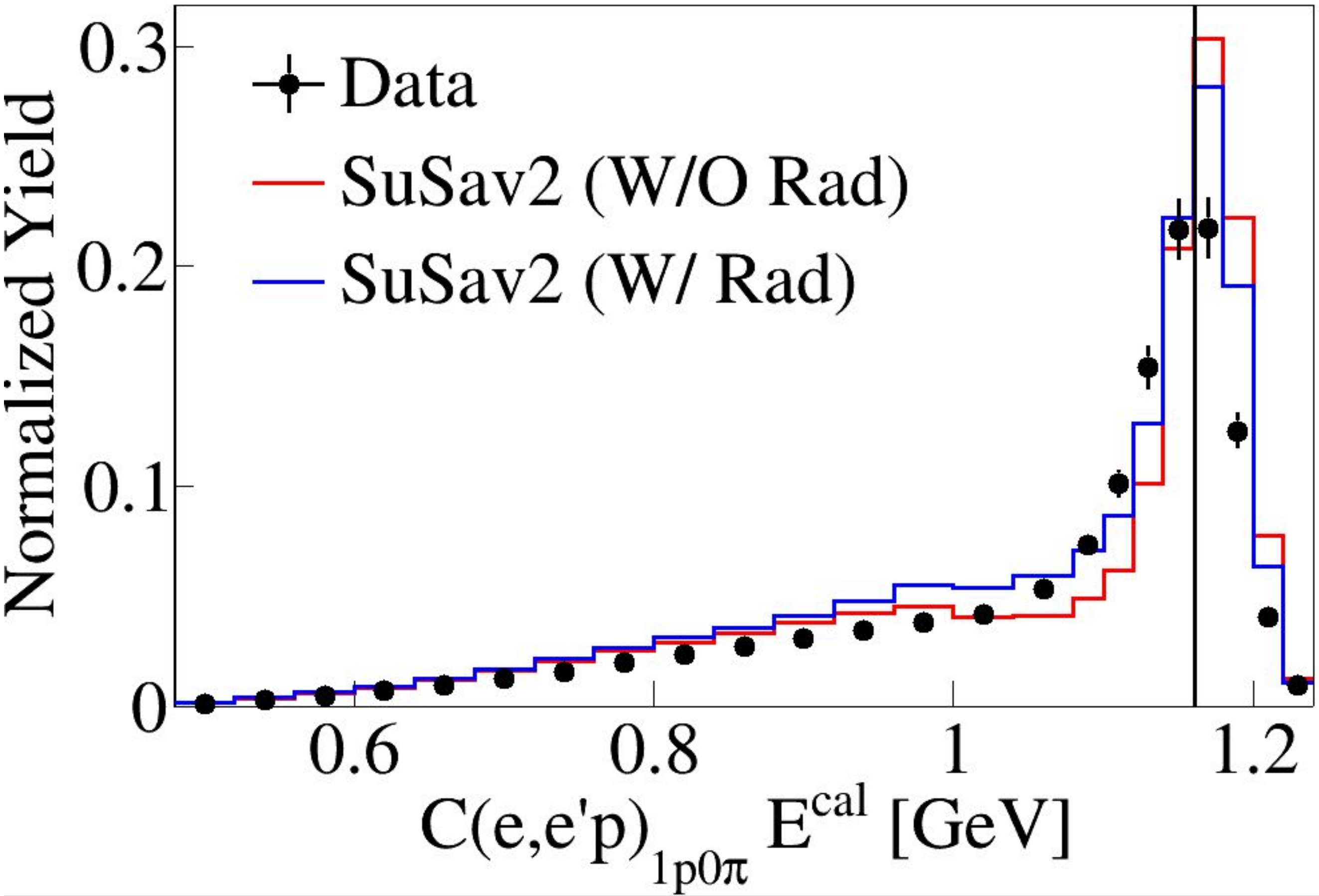
- Start from reco / true ratio w/o radiation to obtain acceptance correction
- Average on a bin-by-bin basis x = |SuSav2 + G2018| / 2
- Due to offset, G2018 Ecal predictions have been shifted by 10/25/36 MeV for 4He/12C/56Fe respectively

# 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

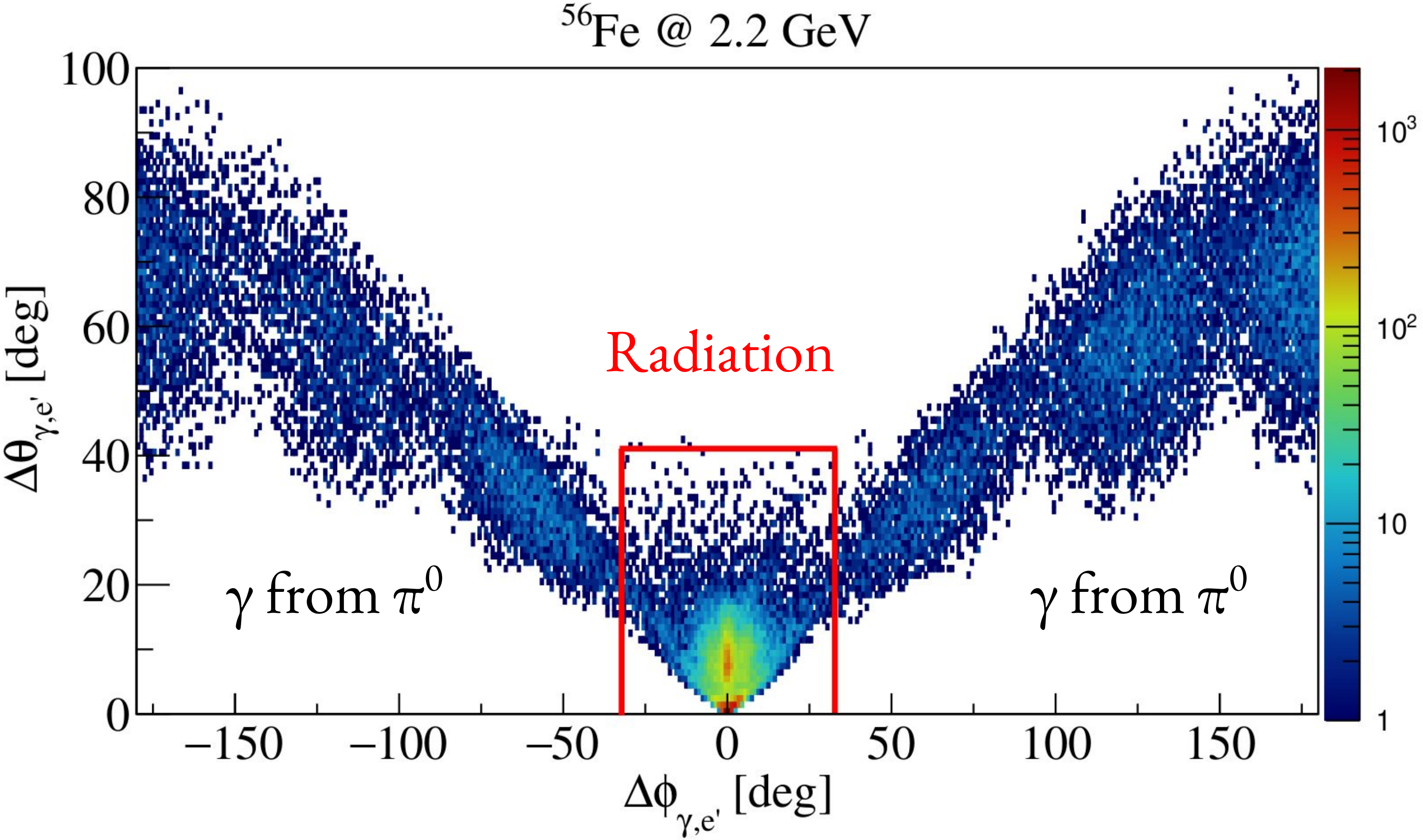
On a bin-by-bin basis

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

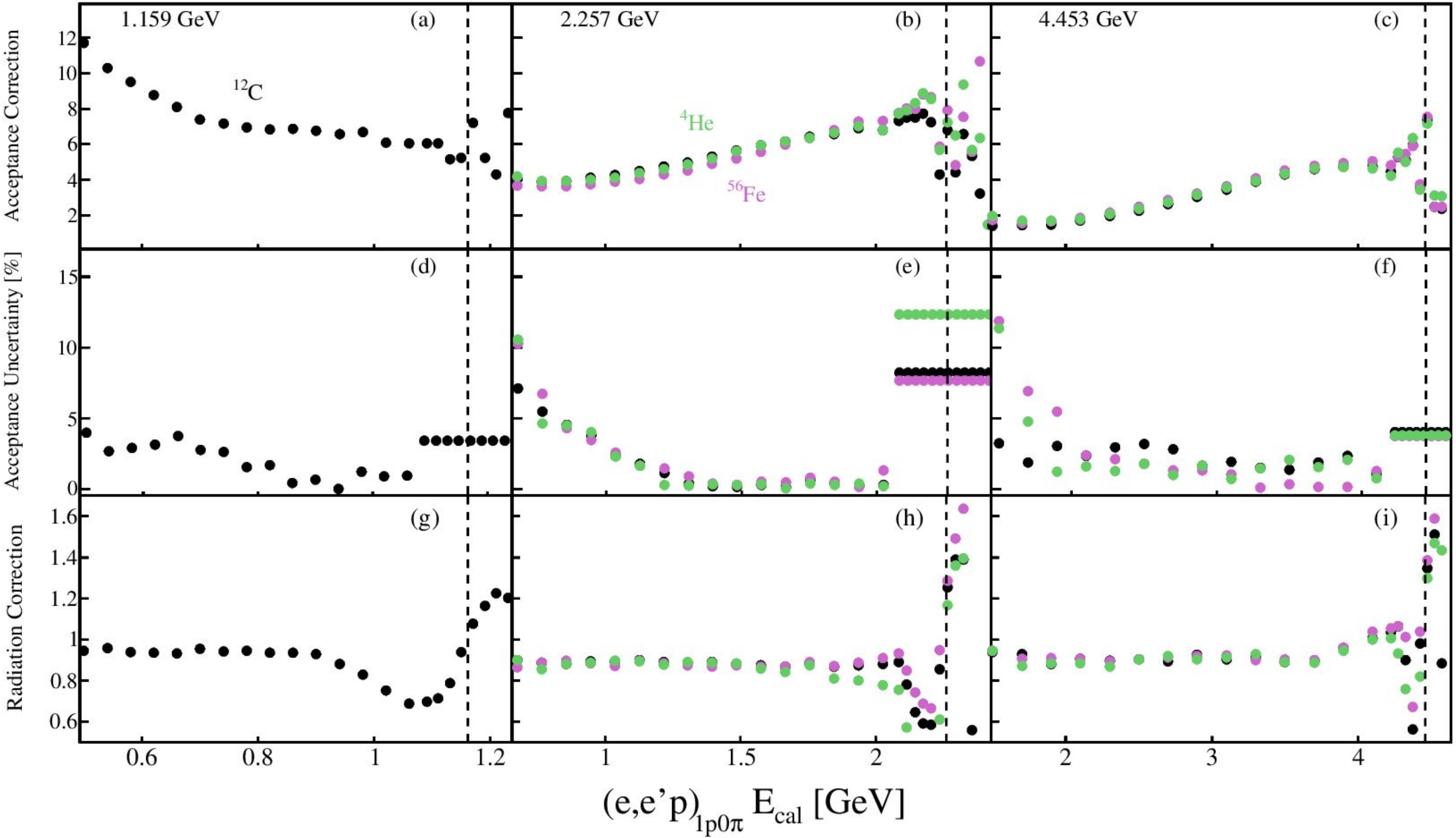
Bin Entry = x / Average * 100 %

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

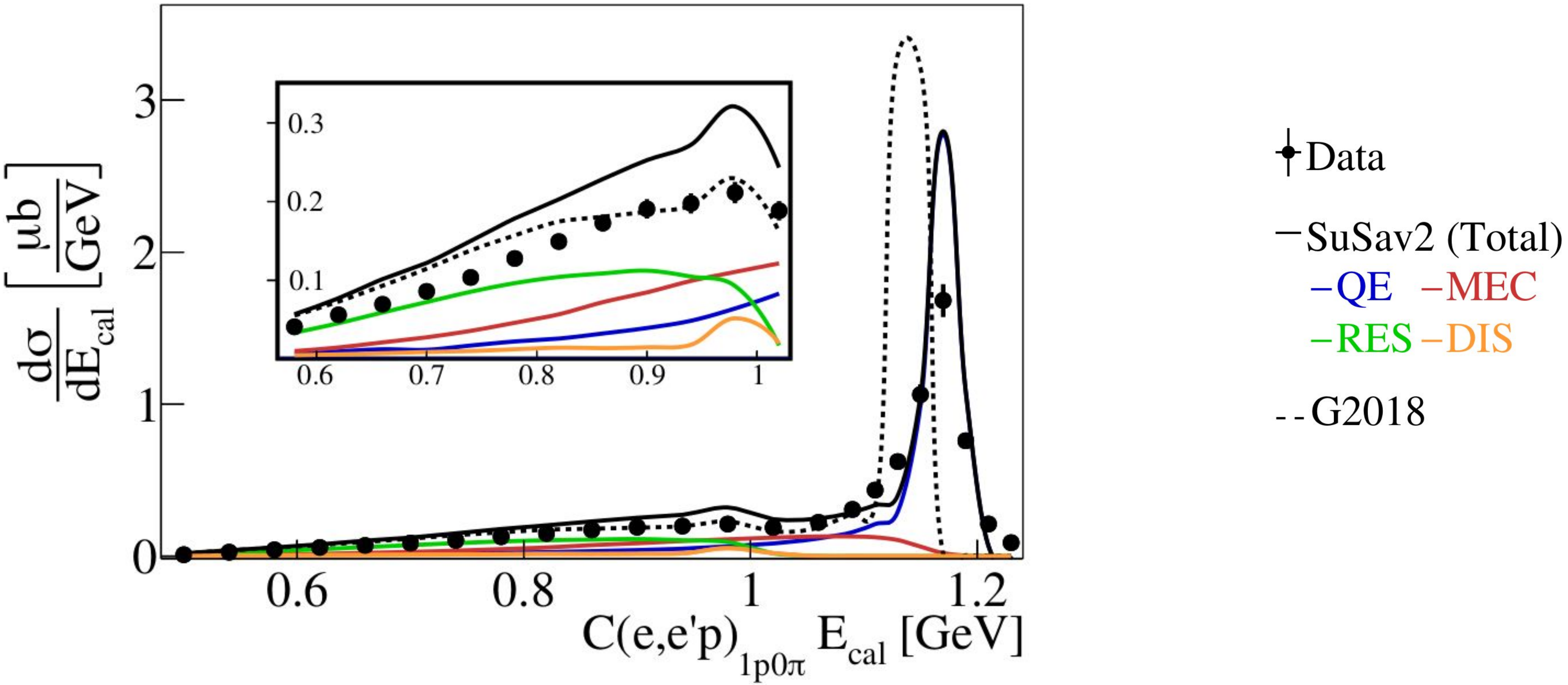


# Correction Factors



# Step #4: Absolute Cross Sections

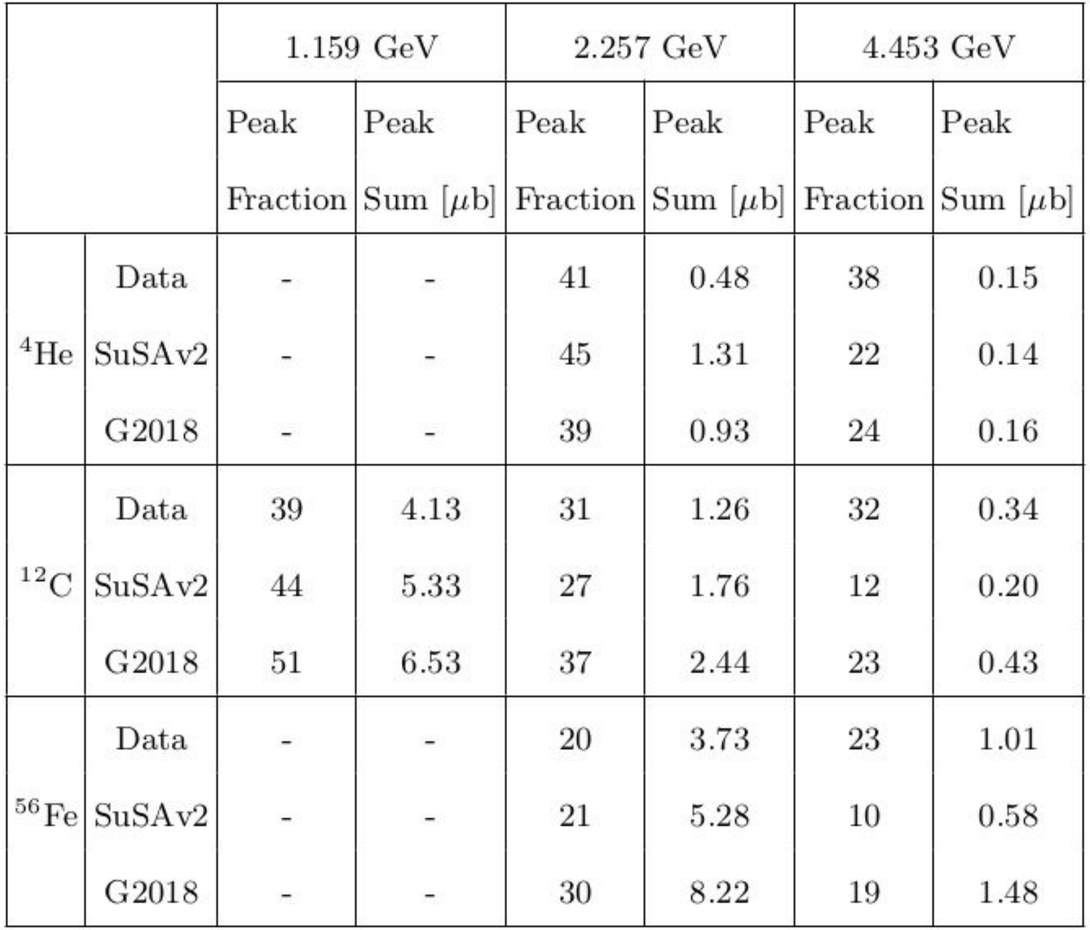
After both acceptance & radiation corrections, without systematics yet



# Systematics

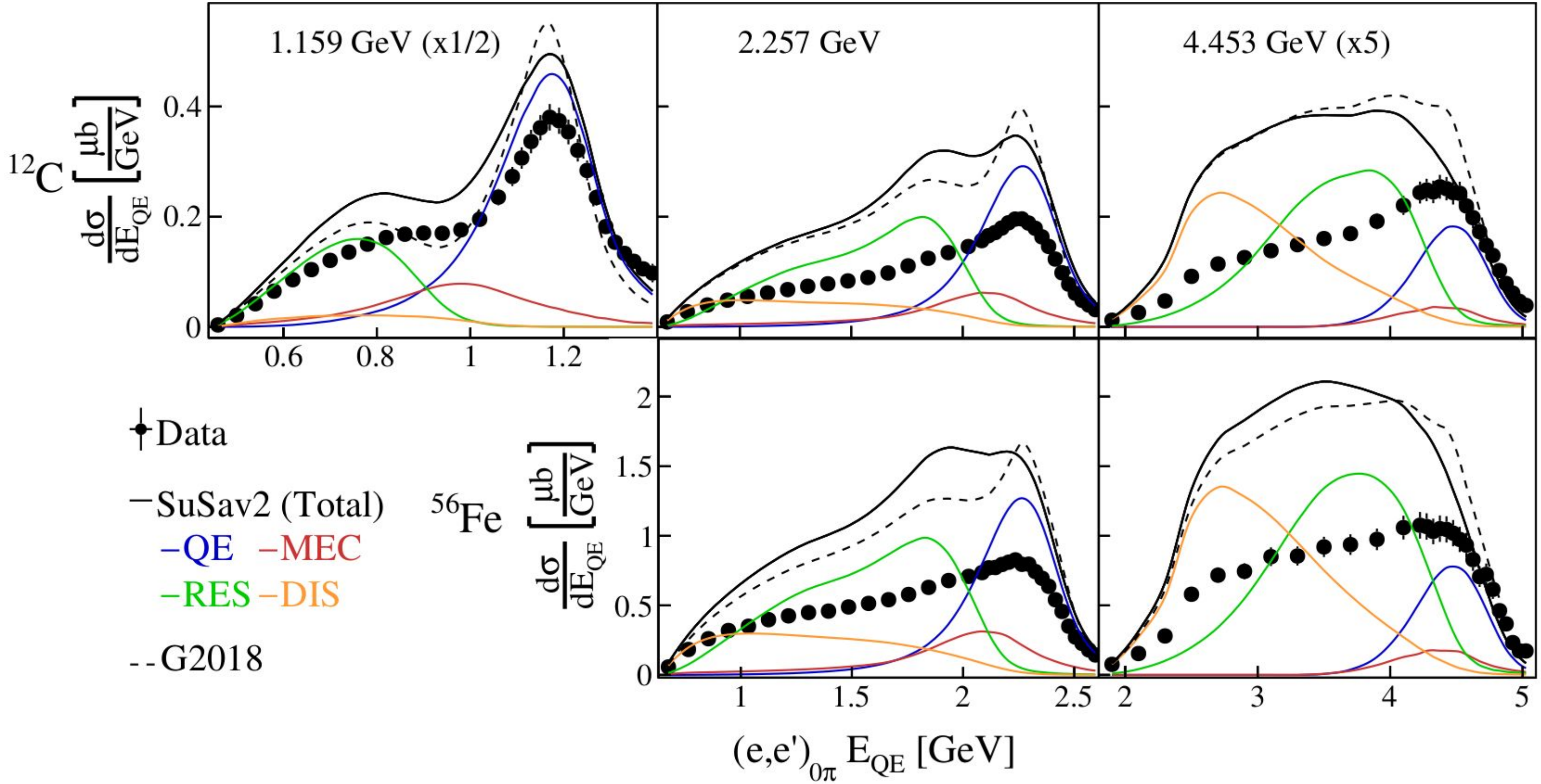
| Source | Uncertainty (%) |
|---|---|
| Detector acceptance<br>Identification cuts<br>$\varphi_{q\pi}$ cross section dependence<br>Number of rotations | 2,2.1,4.7<br>(@ 1.1,2.2,4.4 GeV) |
| Sector dependence | 6 |
| Acceptance correction | 2-15 |
| Overall normalization | 3 |
| Electron inefficiency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

# Energy Reconstruction Accuracy



| | | 1.159 GeV | | 2.257 GeV | | 4.453 GeV | |
|---|---|---|---|---|---|---|---|
| | | Peak Fraction | Peak Sum [$\mu$b] | Peak Fraction | Peak Sum [$\mu$b] | Peak Fraction | Peak Sum [$\mu$b] |
| $^4$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 |

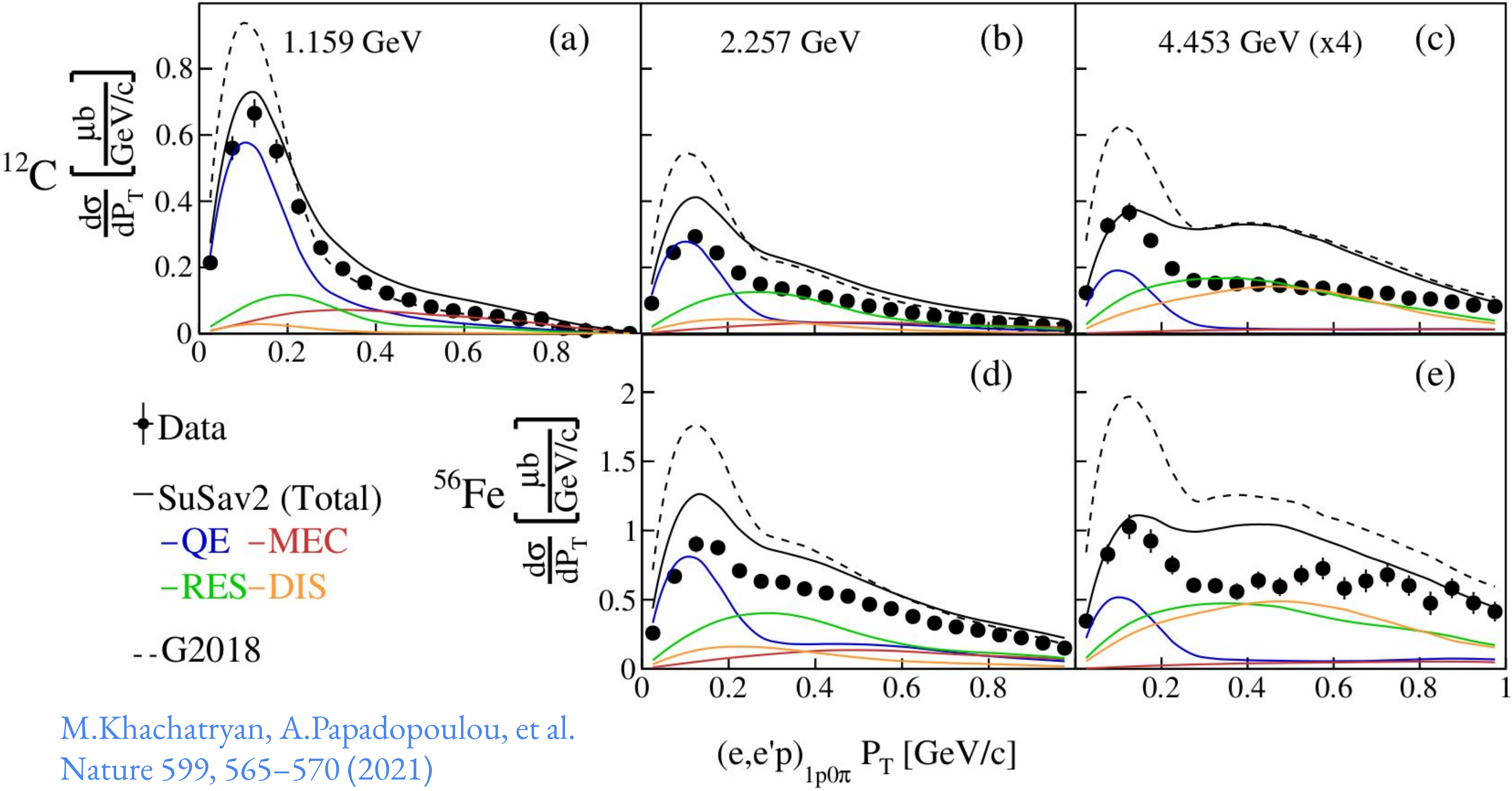
# $E_{QE}$ Nucleus & Energy Dependence



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

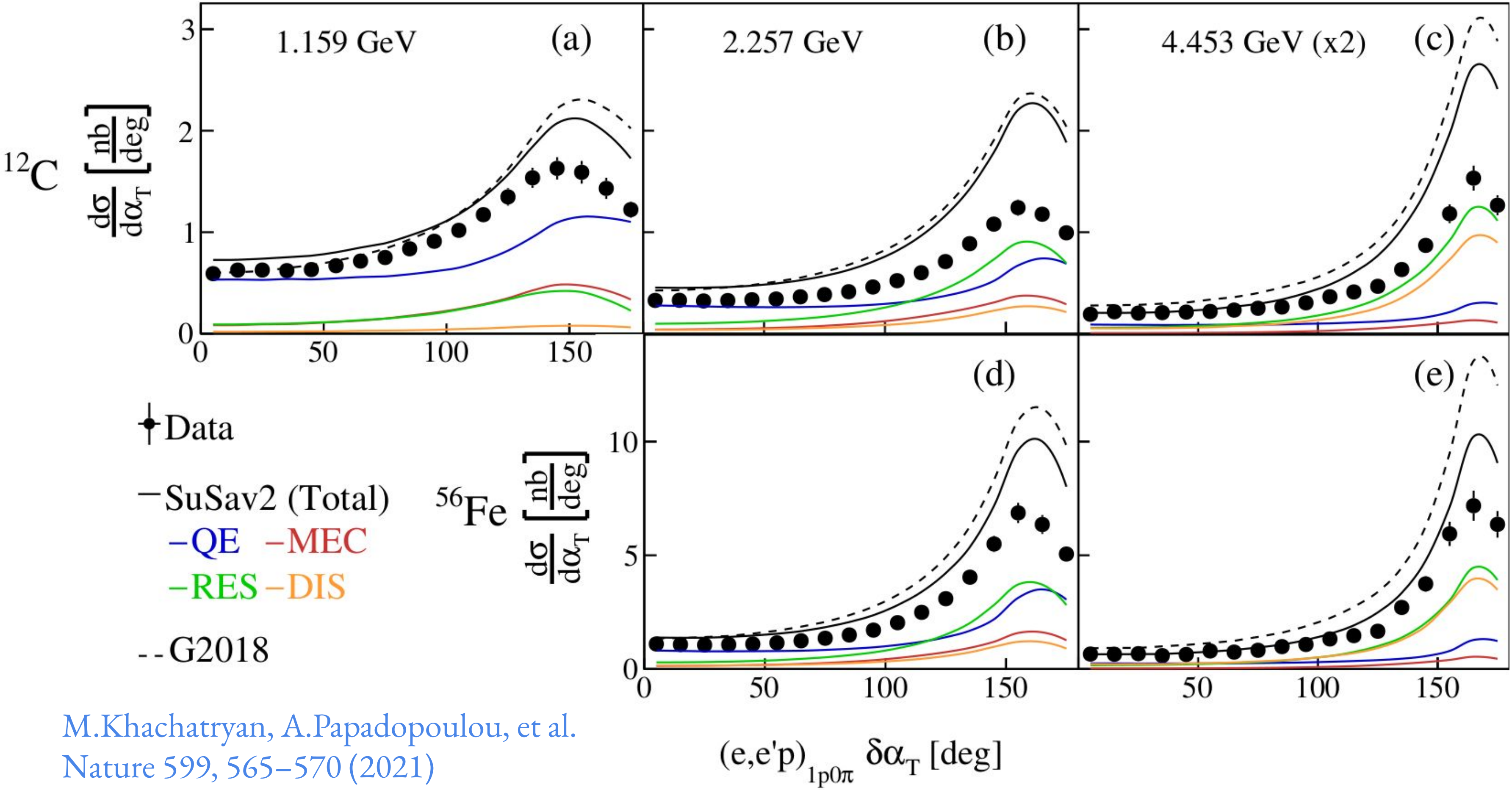
A.Papadopoulou, et al,
In preparation

# $P_T$ Nucleus & Energy Dependence



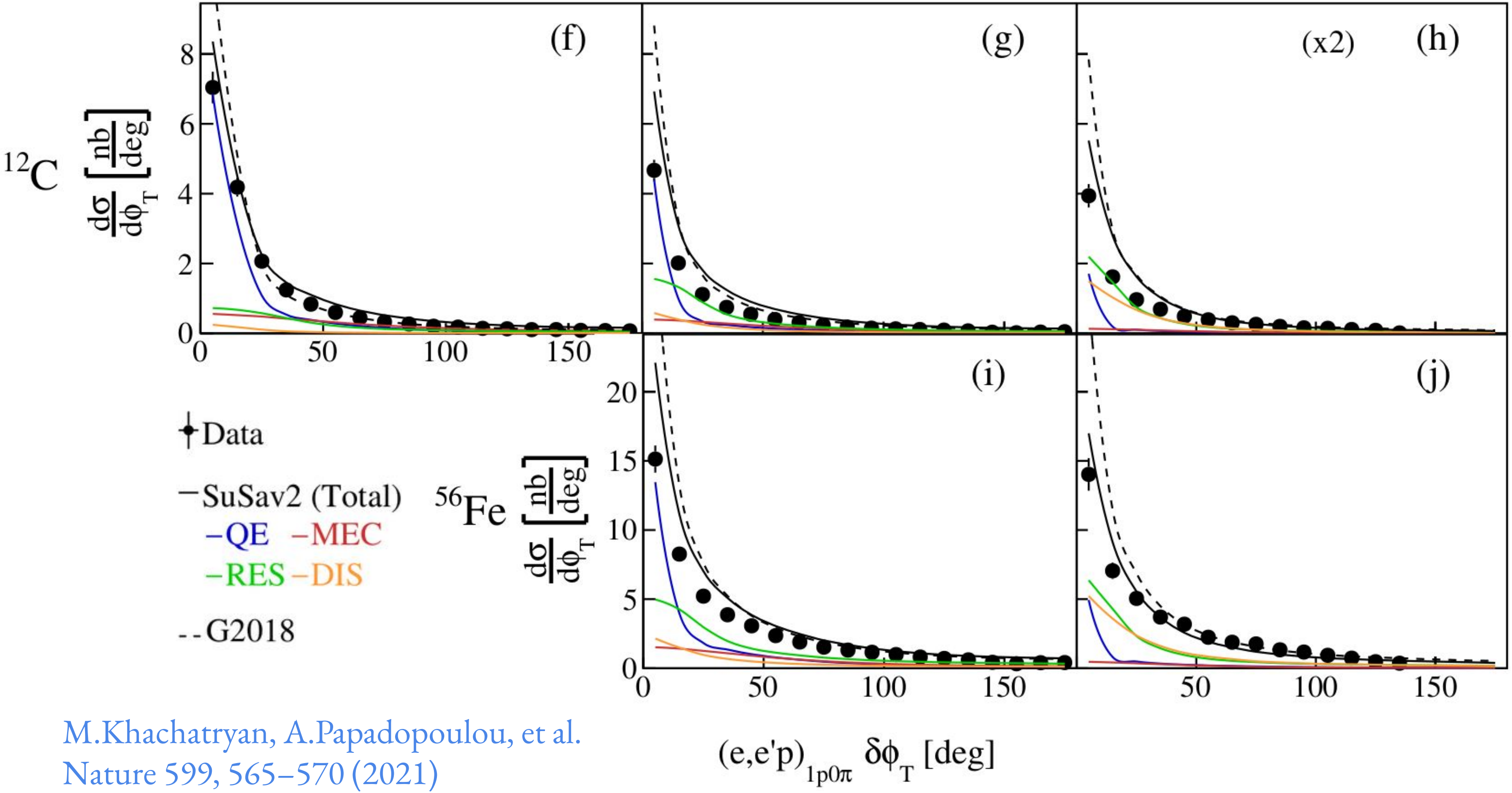
M.Khachatryan, A.Papadopoulou, et al.
Nature 599, 565–570 (2021)

# $\delta\alpha_T$ Nucleus & Energy Dependence



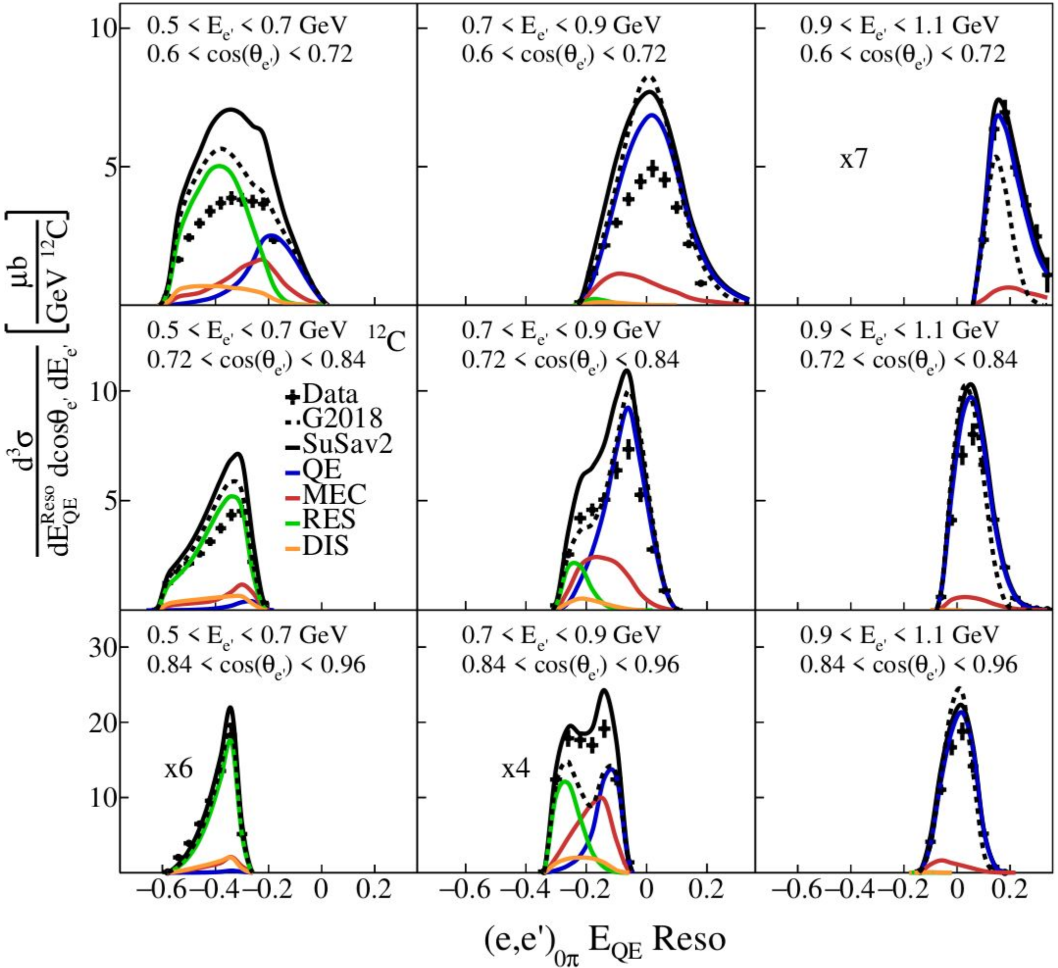
M.Khachatryan, A.Papadopoulou, et al.
Nature 599, 565–570 (2021)

# $\delta\varphi_T$ Nucleus & Energy Dependence



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

# Into The 3D e4ν Multiverse!



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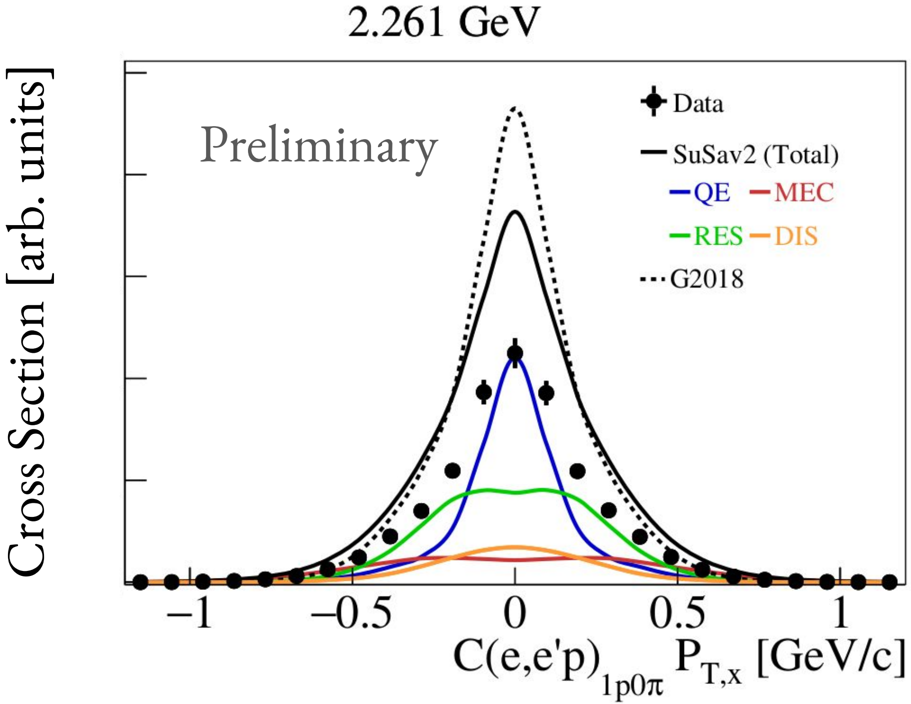
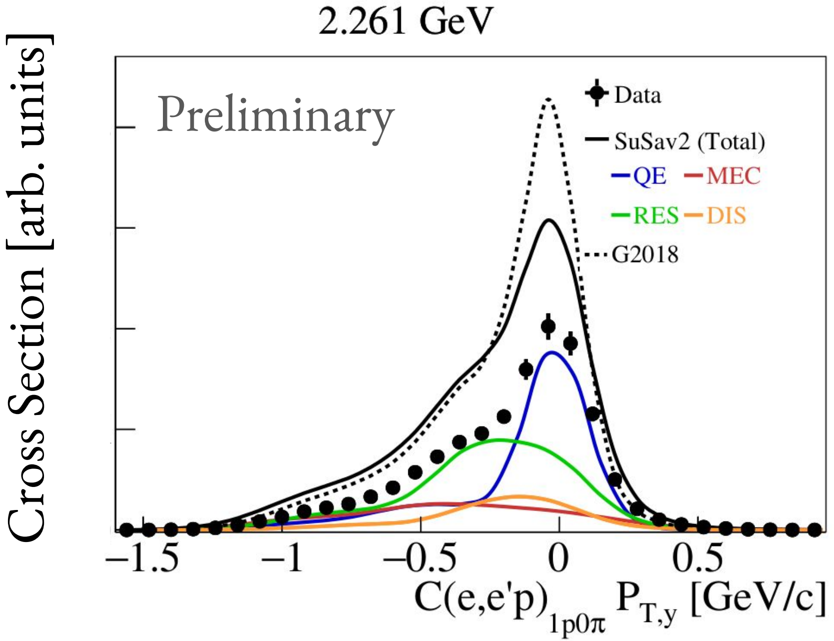
In preparation

# 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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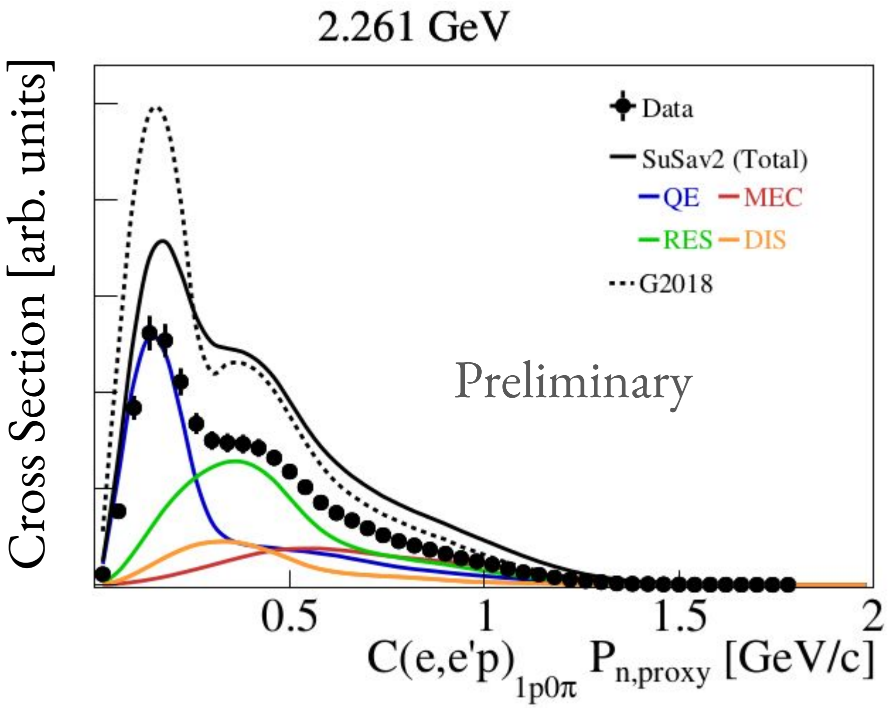
# Missing Momentum Approximation



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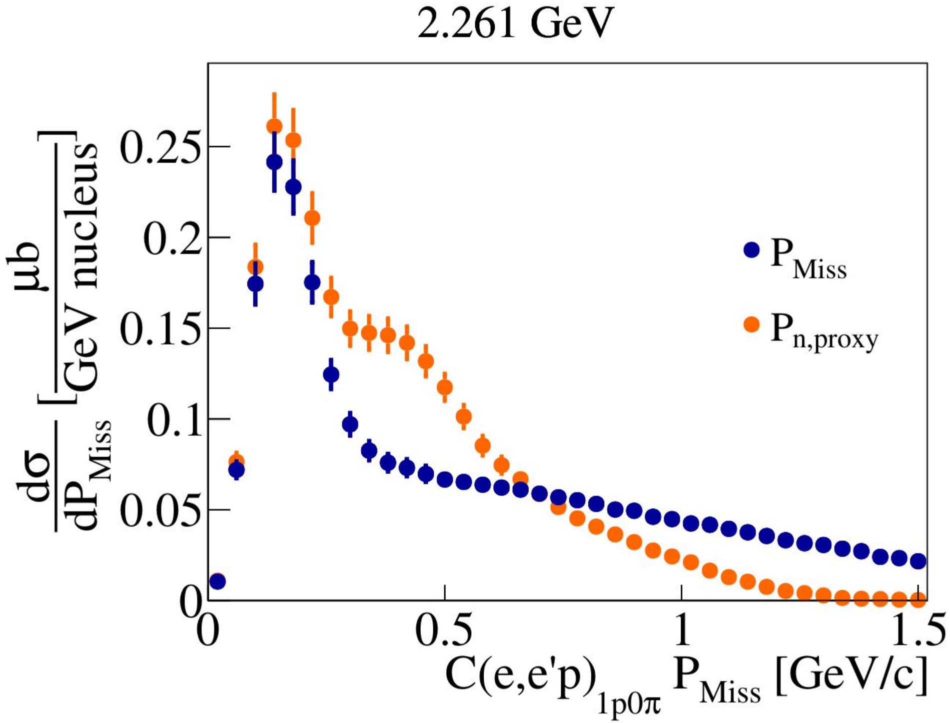
$$p_{n,proxy} = \sqrt{\delta p_L^2 + \delta p_T^2}$$

Under QE assumption

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

# Fails To Reproduce True Missing Momentum



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

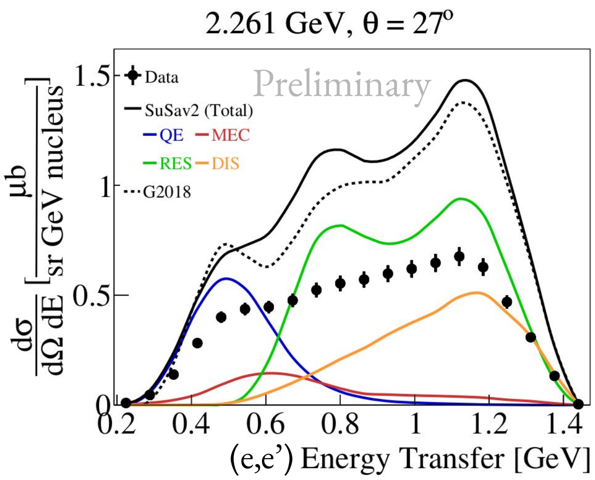
$$P_{miss} = |p - q|$$

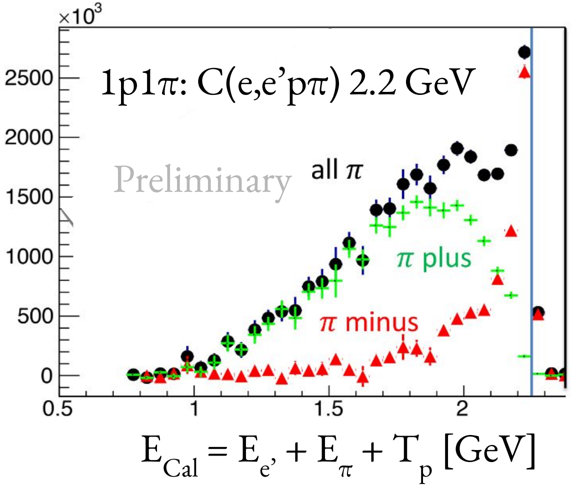
p = proton 3-vector
q = momentum transfer

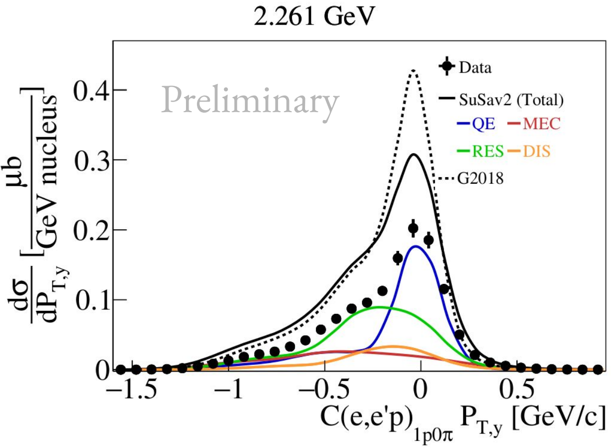
# The e4ν Result Factory Continued!

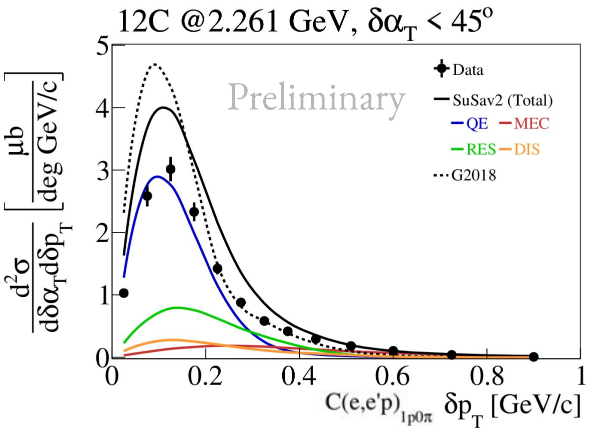
- More inclusive results
- More complex channels
- Nuclear sensitivity variables
- Multi-differential results

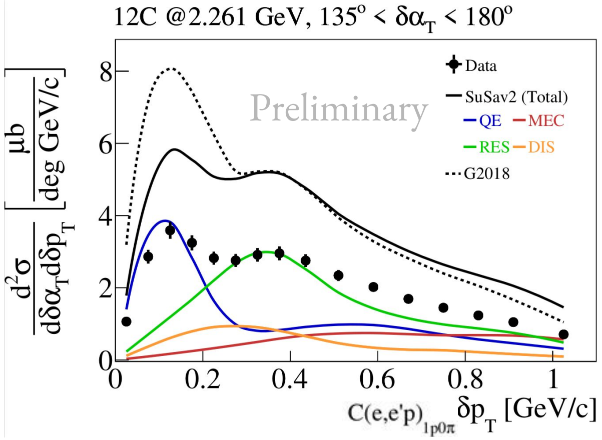
e4ν Collaboration, In preparation


2.261 GeV, θ = 27°


1p1π: C(e,e'pπ) 2.2 GeV


2.261 GeV


12C @2.261 GeV, $\delta\alpha_T < 45°$


12C @2.261 GeV, $135° < \delta\alpha_T < 180°$