What can electron constraints do for neutrino interaction uncertainties? (And what they cannot)

e4ν

Measuring neutrino interactions for next-generation oscillation experiments workshop @ ECT*

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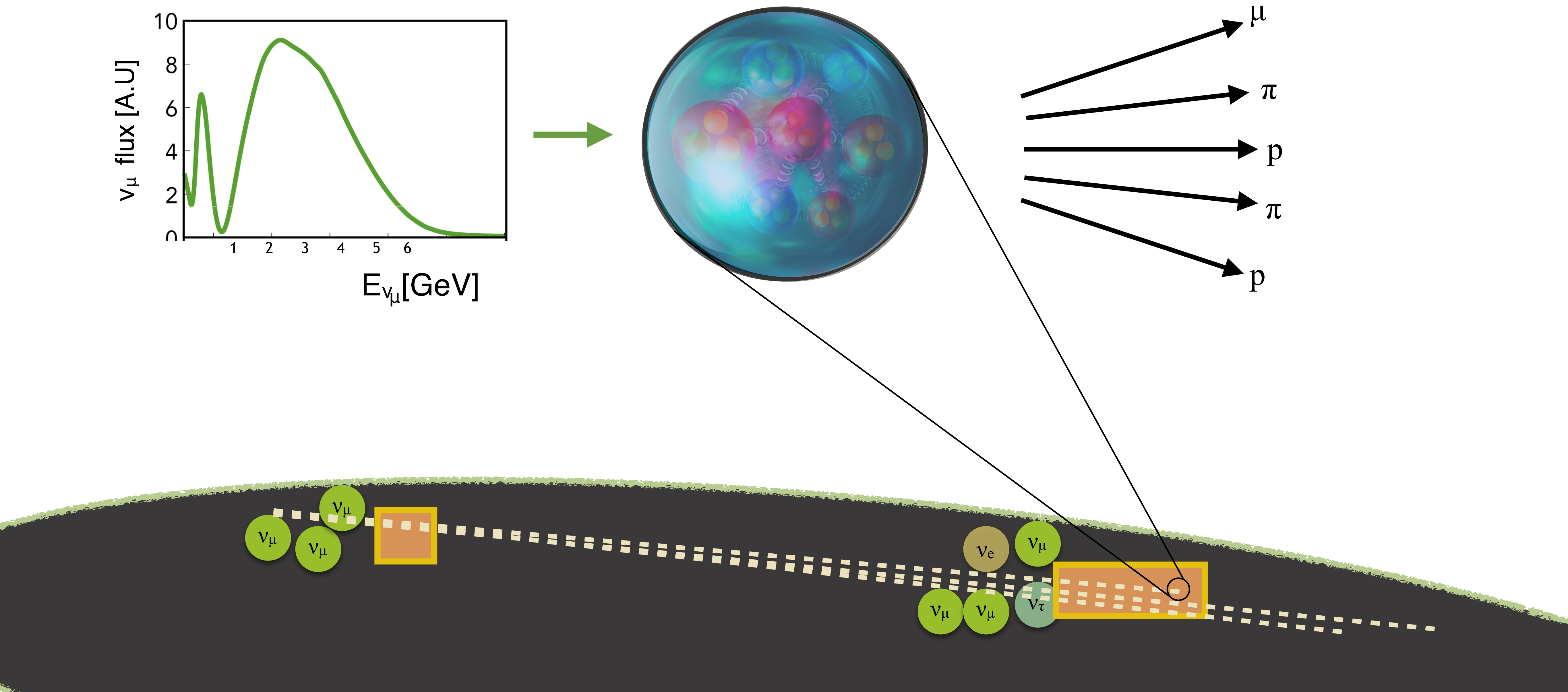
TEL AVIV UNIVERSITY

The challenge - next generation high precision

Incoming true flux | Modelling Input | Measurement

$$\int \Phi(E,L) \quad \sigma(E) f_\sigma(E, E_{rec})\, dE \quad \propto \quad N(E_{rec}, L)$$



The challenge - next generation high precision

$$N(E_{rec}, L) \propto \int \Phi(E, L)\sigma(E) f_{\sigma}(E, E_{rec}) dE$$

Measurement Incoming true flux Modelling input

The challenge - next generation high precision

$$N(E_{rec}, L) \propto \int \Phi(E, L)\sigma(E) f_\sigma(E, E_{rec}) dE$$

Measurement

Incoming true flux

Modelling input

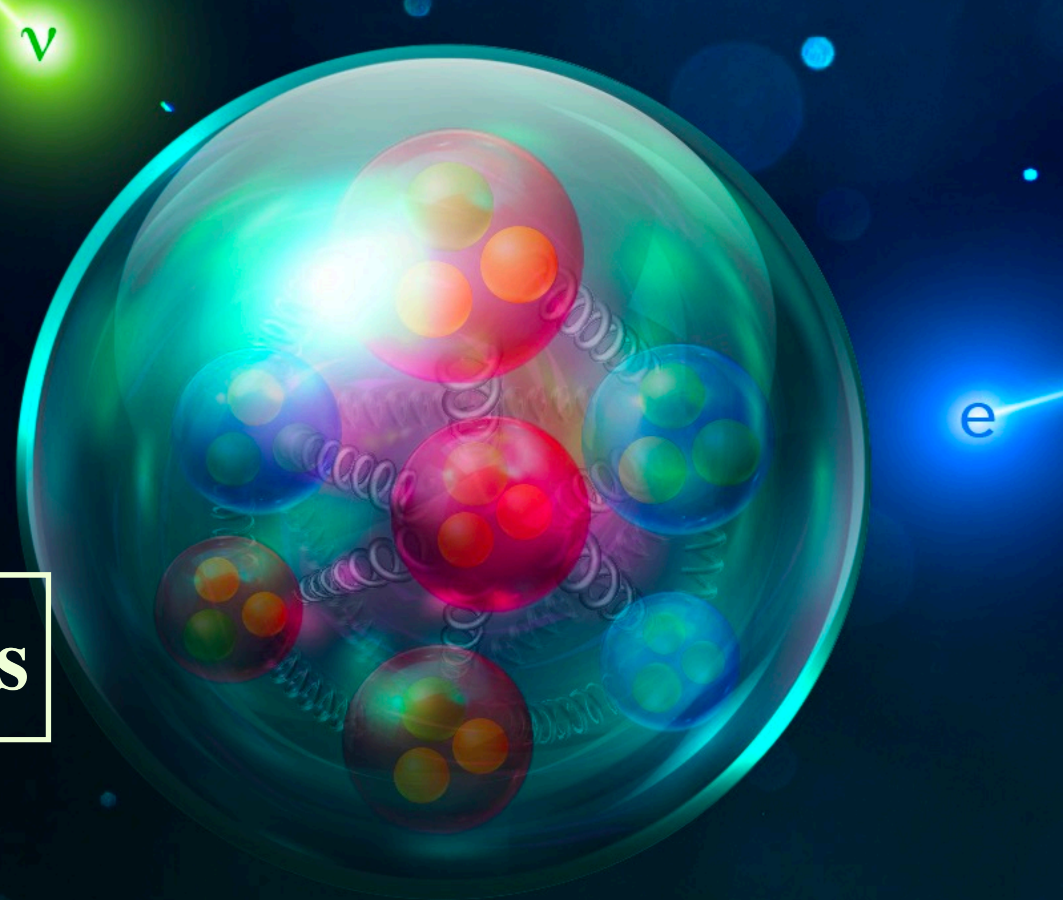
- Improve theory
- Use near detector
- Use external constraints
  - νA scattering
  - **eA scattering**

Why electrons?

Electrons and Neutrinos have:

- **Identical initial nuclear state**
- **Same Final State Interactions**
- **Similar interactions (vector vs. vector + axial)**

Useful to constrain model uncertainties



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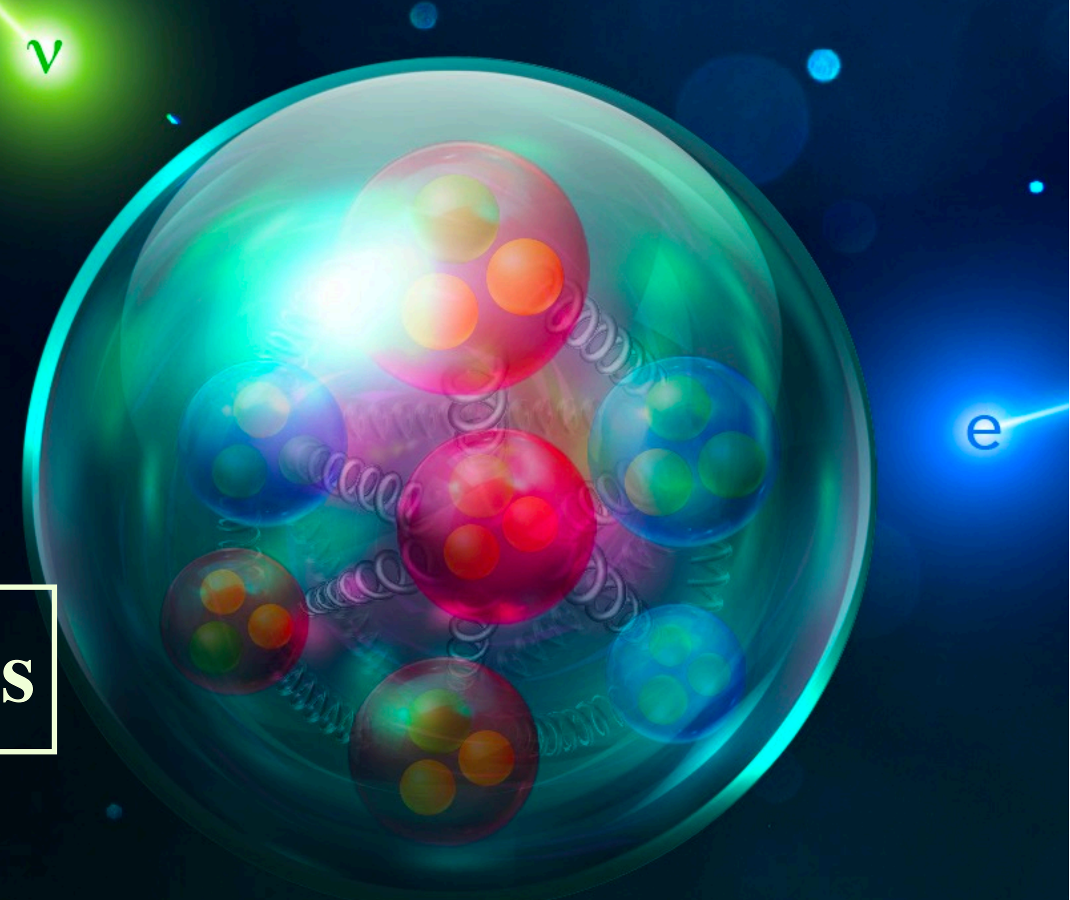


Useful to constrain model uncertainties

Electrons have known energies

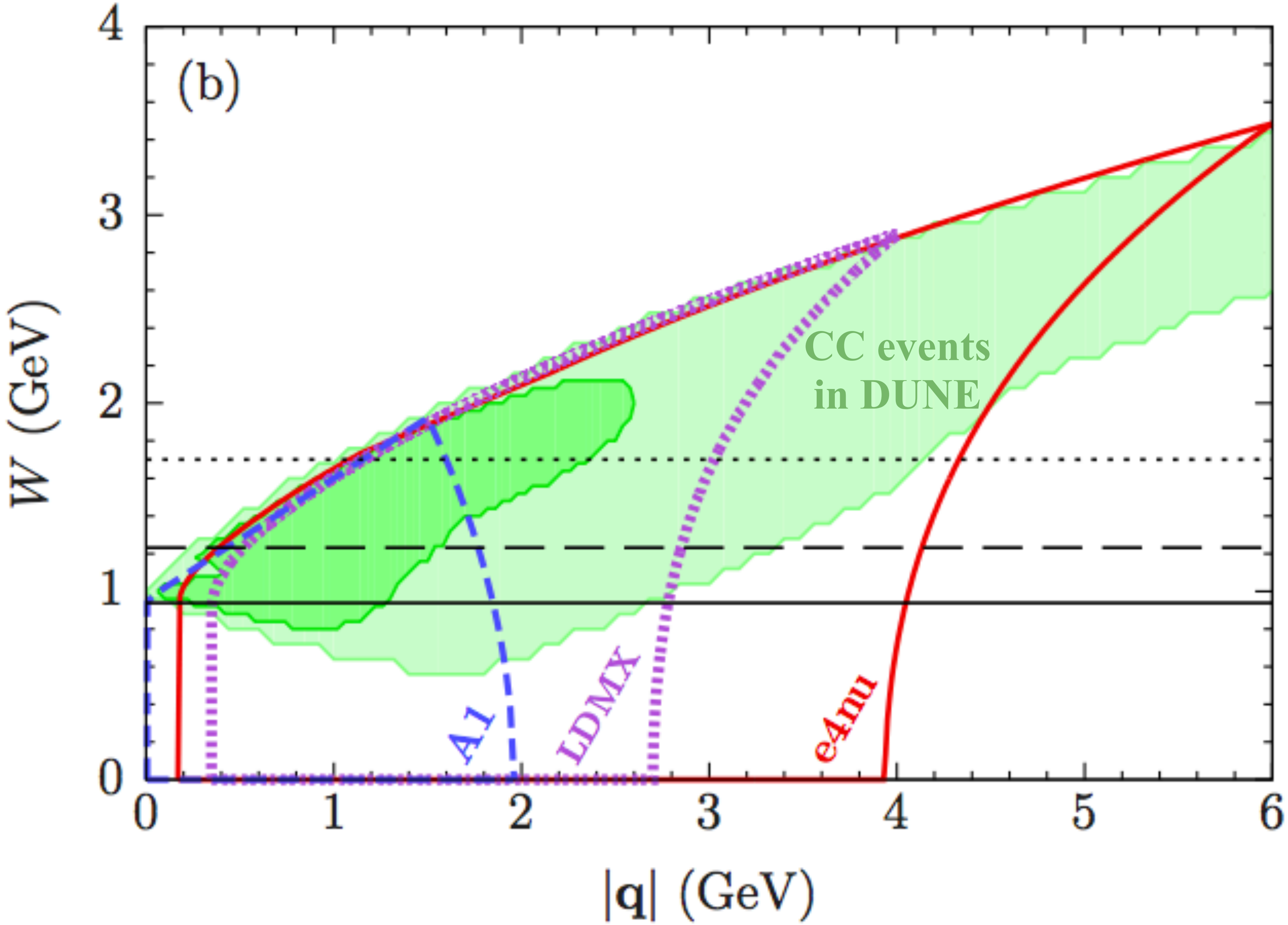
Useful to test incoming energy reconstruction methods

Complementary efforts

Collaborations	Kinematics	Targets	Scattering	Publications
E12-14-012 (JLab) (Data collected: 2017) Jefferson Lab	E_e = 2.222 GeV θ_e = 15.5, 17.5, 20.0, 21.5 θ_p = -39.0, -44.0, -44.5, -47.0 -50.0	Ar, Ti Al, C	(e, e') $(e, e'p)$	Phys. Rev. C **99**, 054608 Phys.Rev.D **105** 112002
e4nu/CLAS (JLab) (Data collected: 1999, 2022) Jefferson Lab	E_e = 1, 2, 4, 6 GeV $\theta_e > 5$	H, D, He, C, Ar, ^{40}Ca, ^{48}Ca, Fe, Sn	(e, e') e, p, n, π, γ in the final state	Nature **599**, 565 Phys.Rev.D **103** 113003
A1 (MAMI) (Data collected:2020) (More data planned) mami MAINZER MIKROTRON	E_e = 1.6 GeV	H, D, He C, O, Al Ca, Ar, Xe	(e, e') 2 additional charged particles	
LDMX (SLAC) (Planned) SLAC	E_e = 4.0 GeV $\theta_e < 40$		(e, e') e, p, n, π in the final state	
eALBA (Planned) ALBA	E_e = 500 MeV - few GeV	C, CH Be, Ca	(e, e')	

Adaptation from Proceedings of the US Community Snowmass2021
arXiv:2203.06853v1 [hep-ex]

e4ν and DUNE



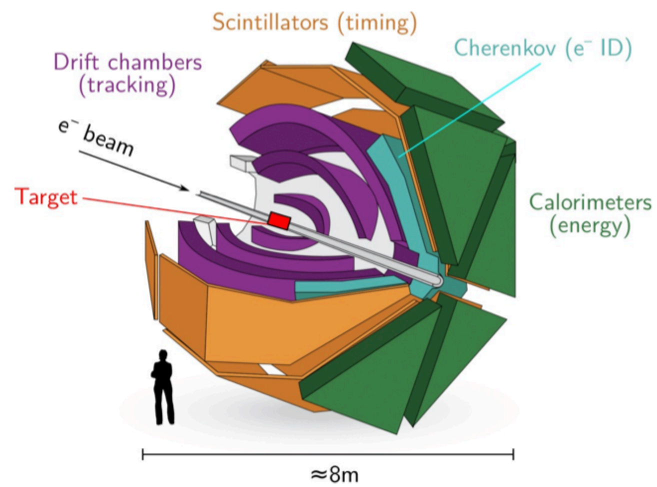
arXiv:2203.06853v1 [hep-ex]
A NF06 Contributed White Paper

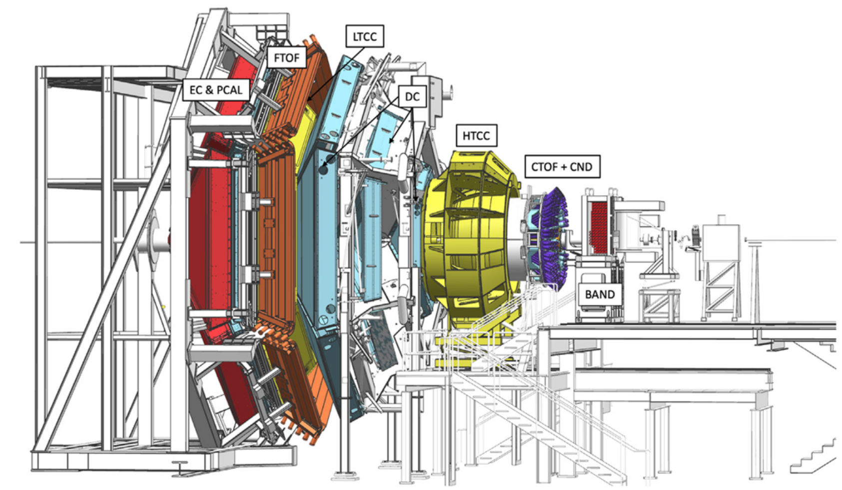
e4ν demonstrate best coverage.

The only effort with data already taken and expected exclusive measurements.

Jefferson Lab

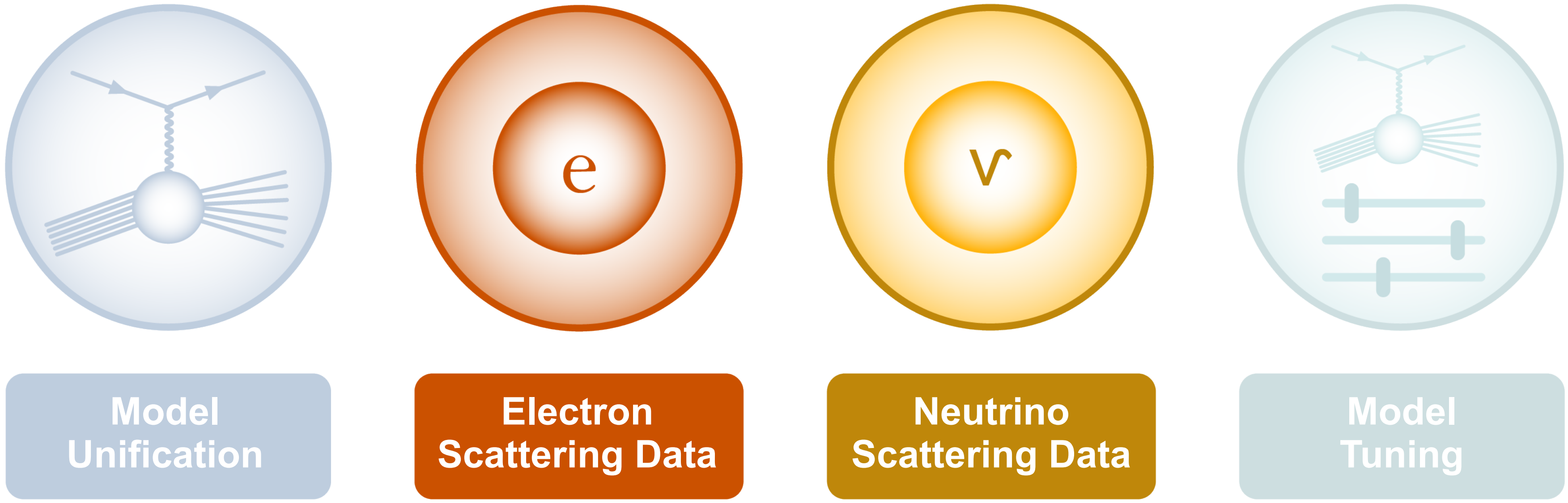
e4ν Data from CLAS



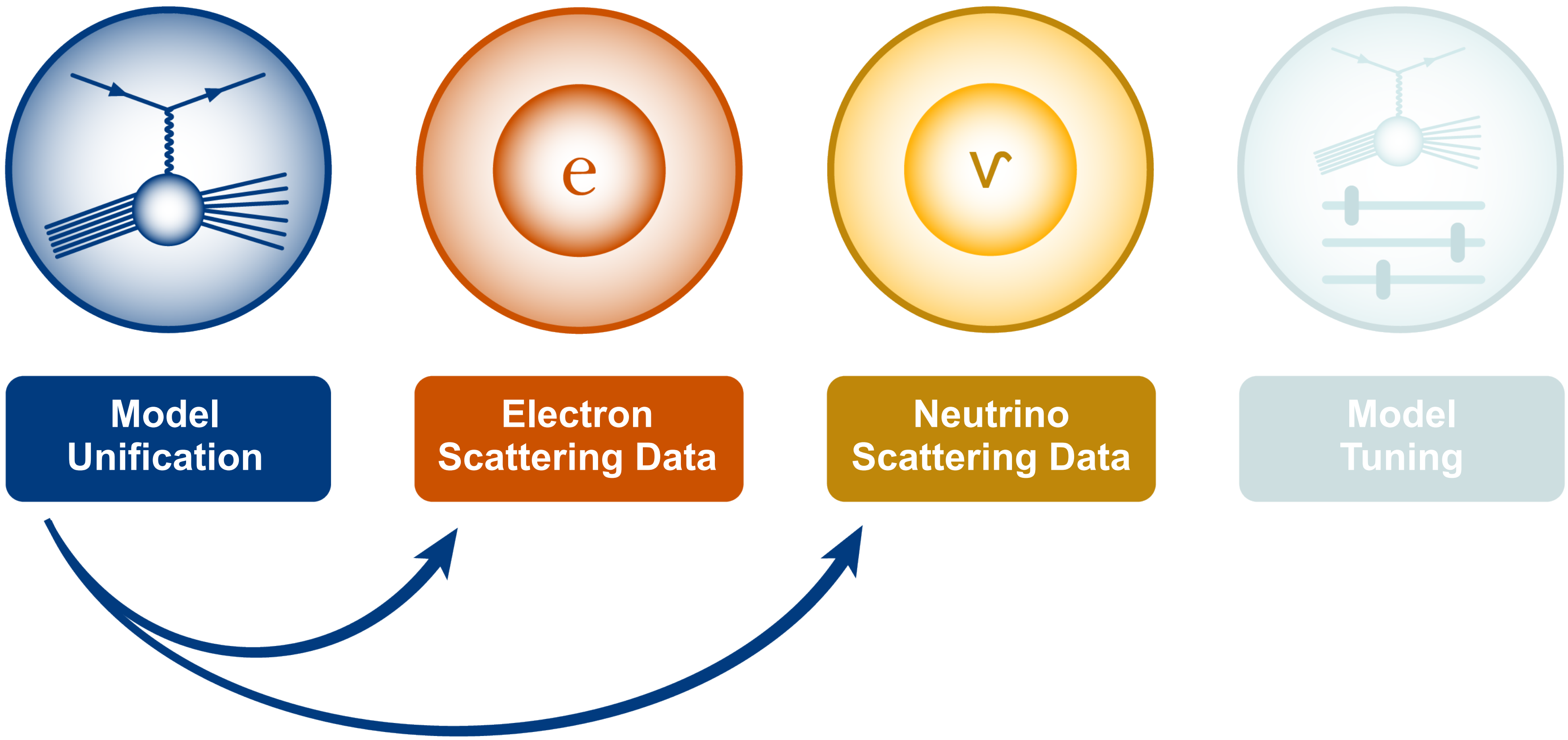


	CLAS6	CLAS12
Run years	1996-2013	2017 - ?
Luminosity		
Targets	C & Fe	H, D, , **C**, (O), **^{40}Ar** and more
Beam Energy	**1.1, 2.2, 4.4 GeV**	**(1), 2, 4, 6 GeV**
Electron acceptance	$\theta_e > 15^o$	$\theta_e > 5^o$
Solid angle coverage	~2π	~3π
Magnetic field	V	V
Particle thresholds	150 (300) MeV/c for (p/)	200 (400) MeV/c for (p/n)
Events	**M C(e,e’) events**	**^{40}Ar (e,e’) events**

e4ν Strategy

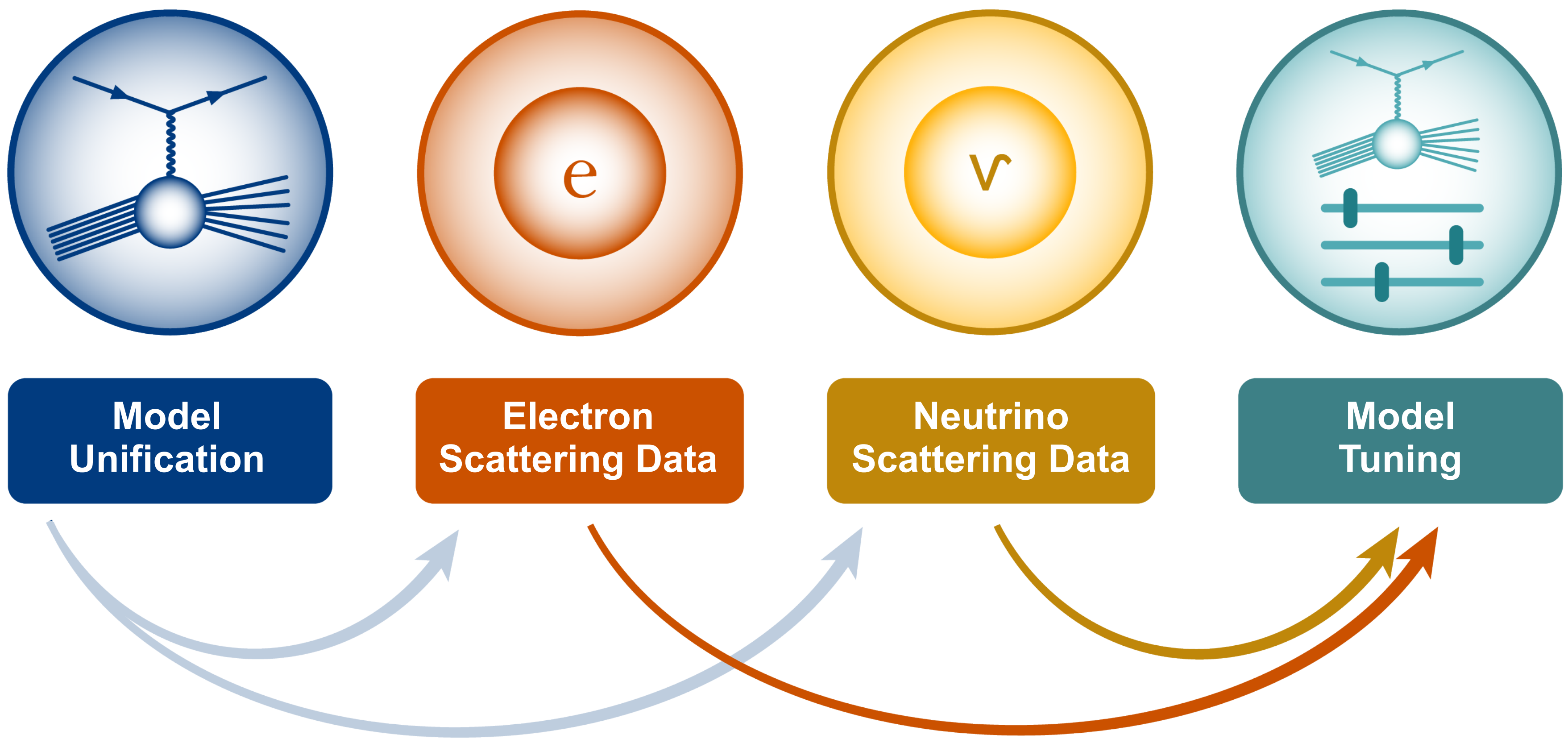


Strategy

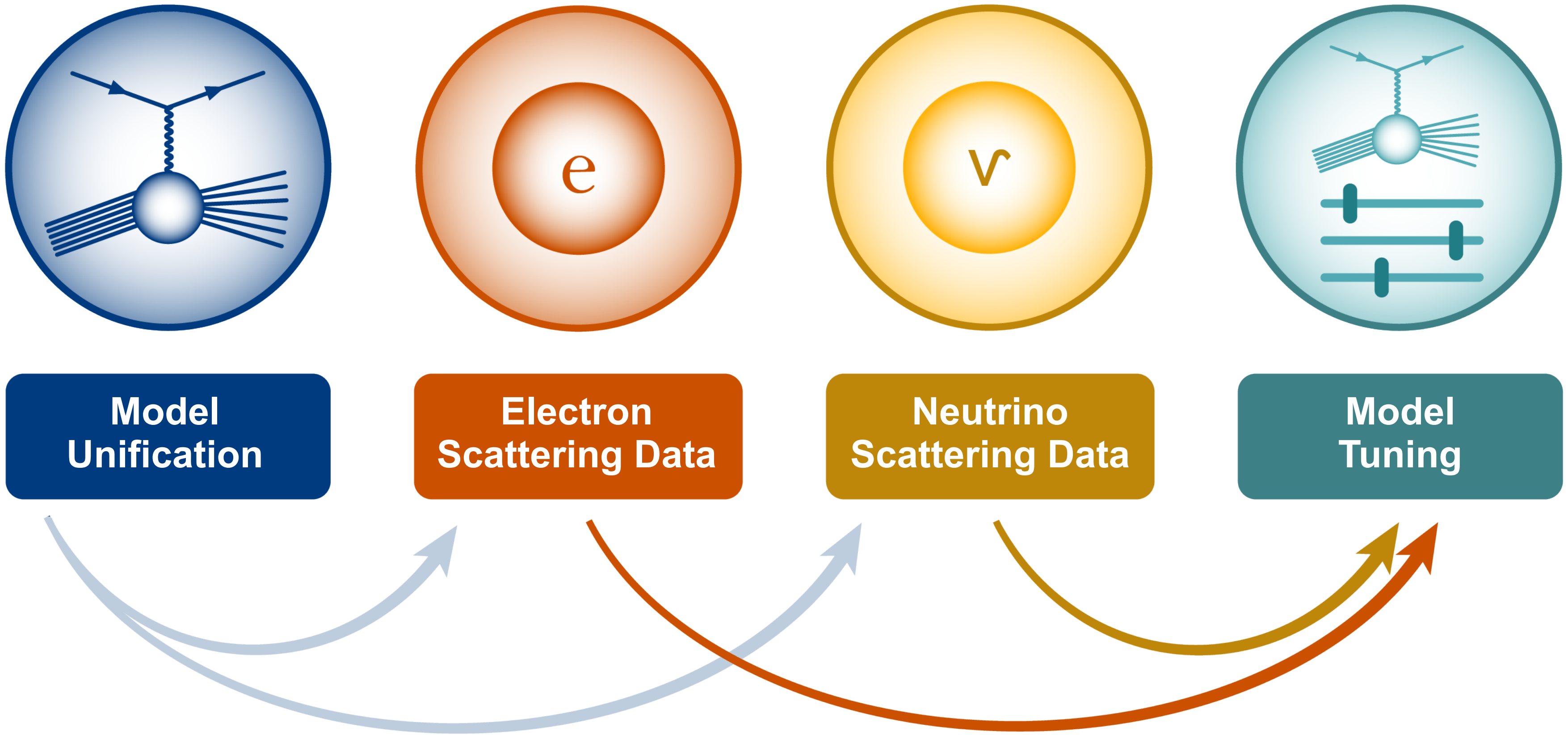


e
ν
Model
Unification
Electron
Scattering Data
Neutrino
Scattering Data
Model
Tuning

e4ν Strategy



e4ν Strategy



Know electron scattering data limitation, we'll always need neutrino data

Find variables which are sensitive to specific parameters

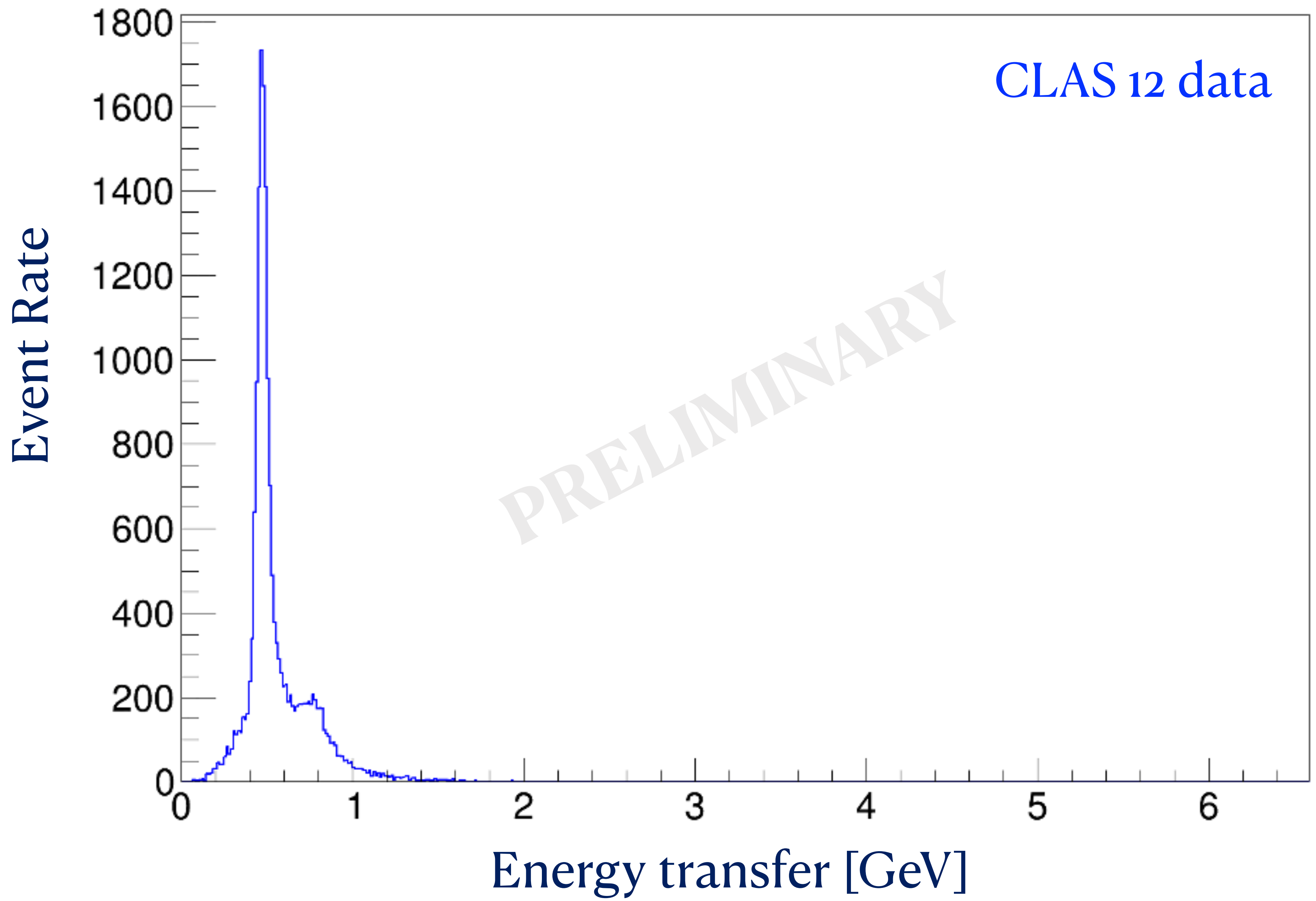
Focus on nuclear model and FSI where we know the electron model is sufficient

Inclusive Data

Towards new Inclusive results on Ar

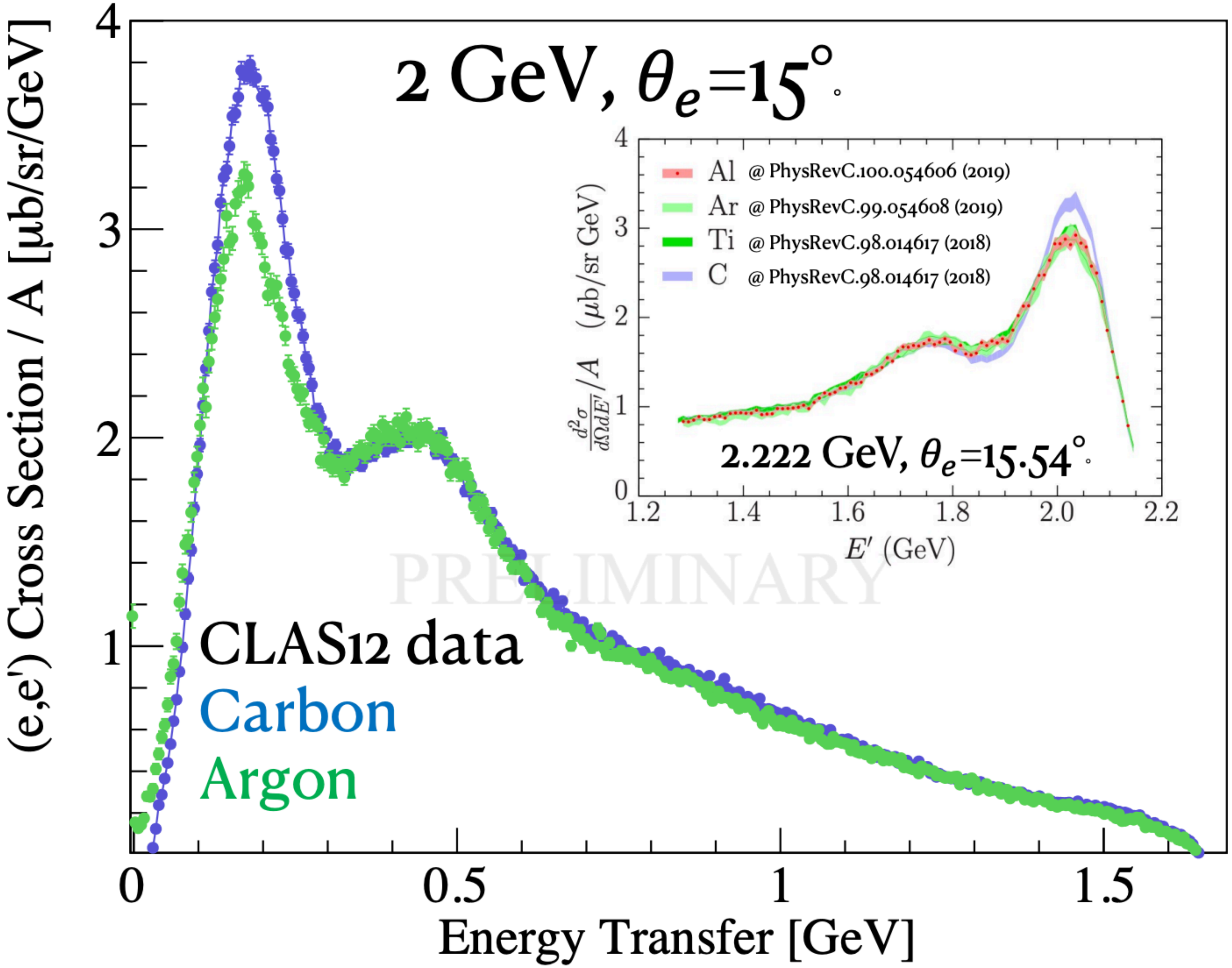
^{2}H at 6GeV

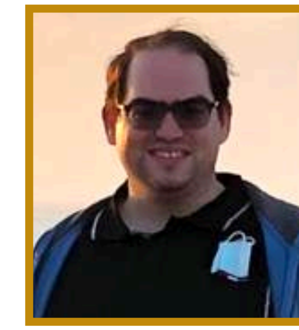
$\theta_e \in [10.5, 39.5]^\circ$ with 1° steps



Matan Goldenberg

Towards new Inclusive results on C, Ar

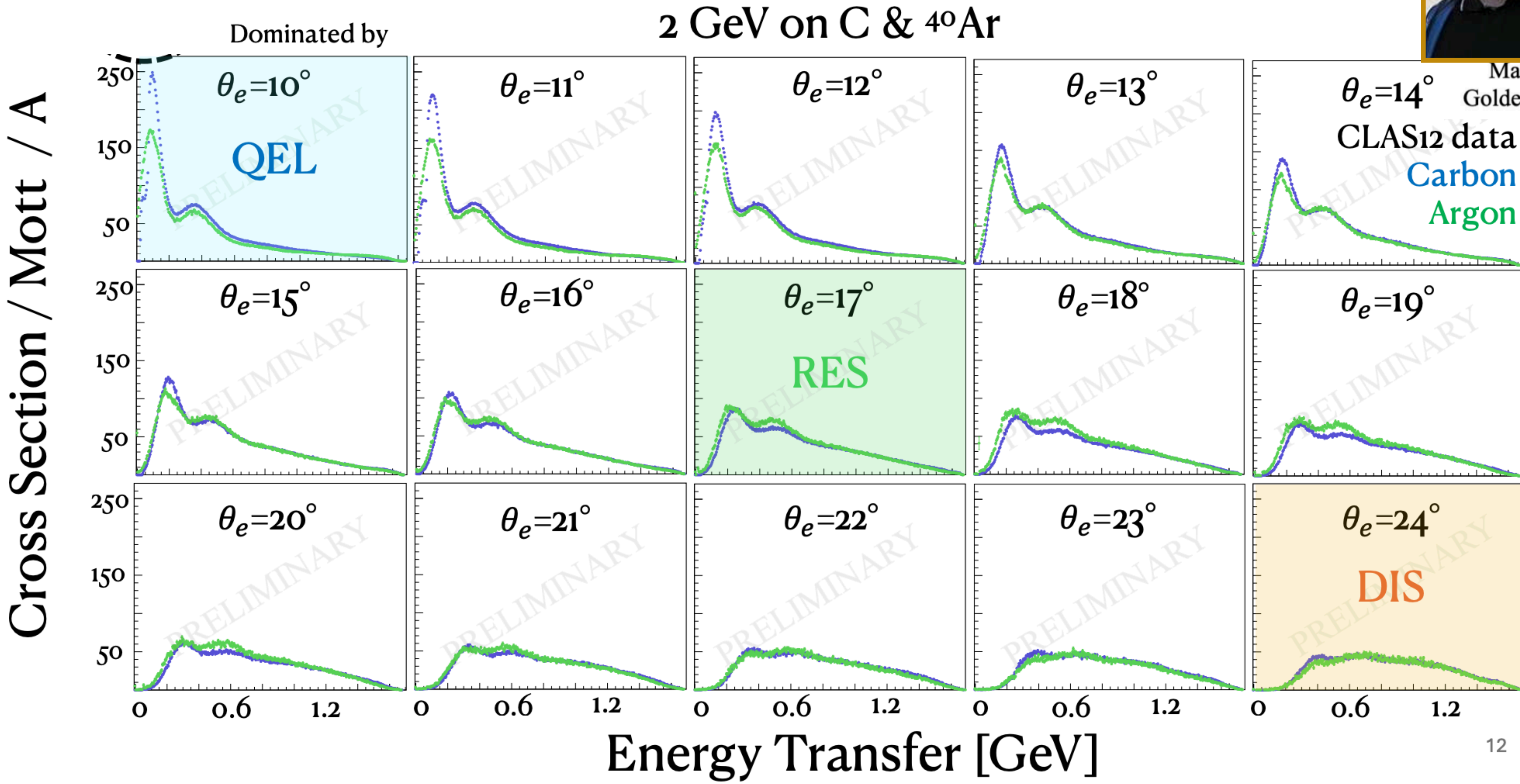




5,14.5]°

$\theta_e \in$ [17.5,18.5]°

Towards new Inclusive results on Ar



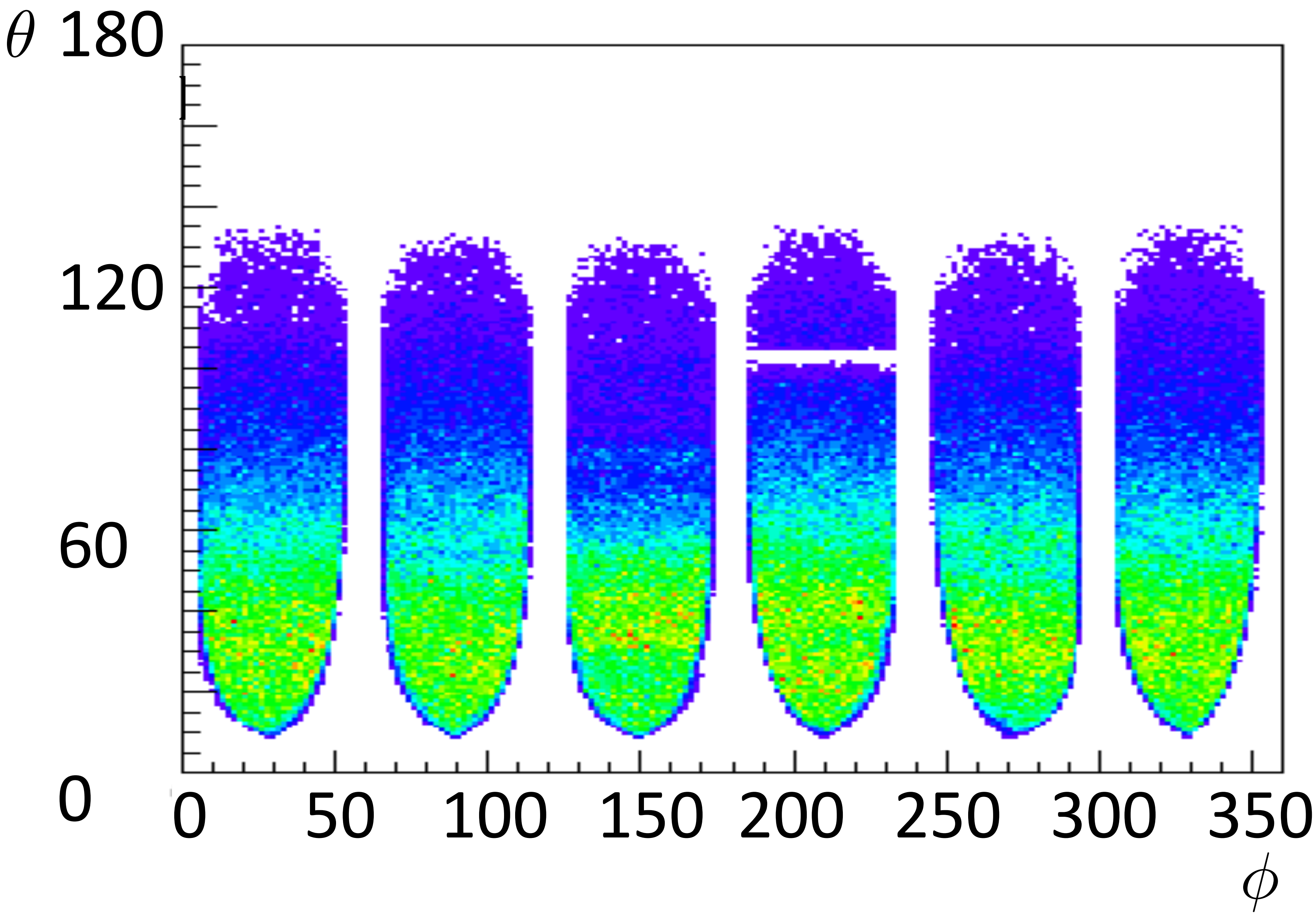
Matan Goldenberg

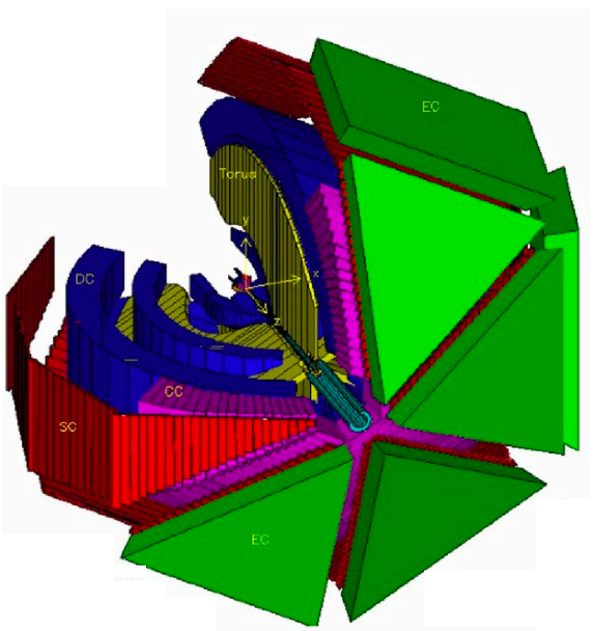
Exclusive Challenges

Background Subtraction

Different interaction lead to multi-hadron final states

Gaps can make them loop like QE-like events with outgoing 1μ1p





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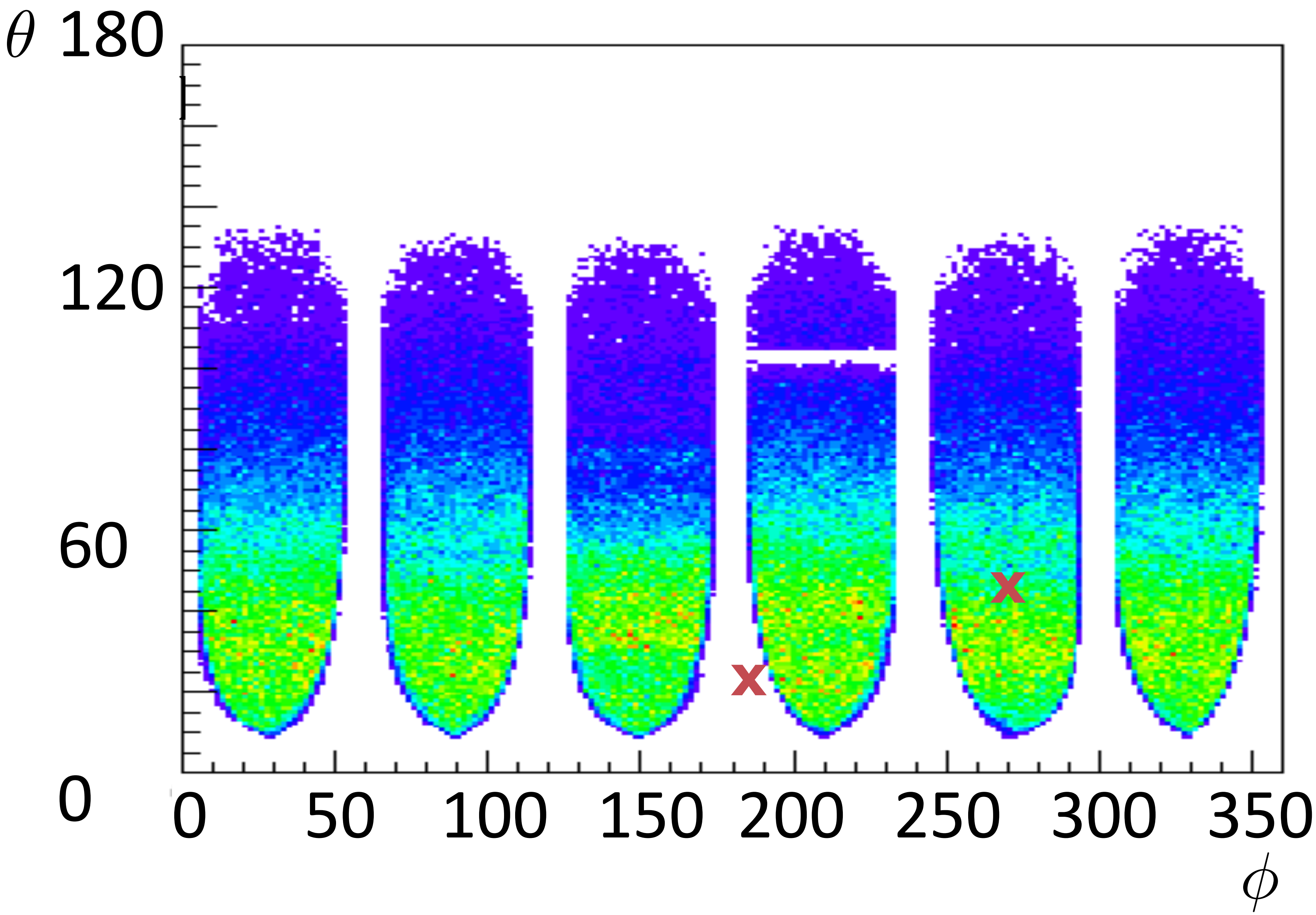
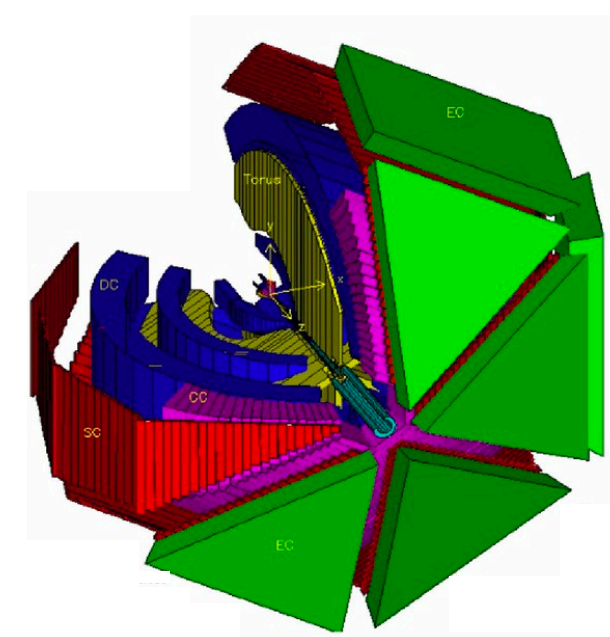
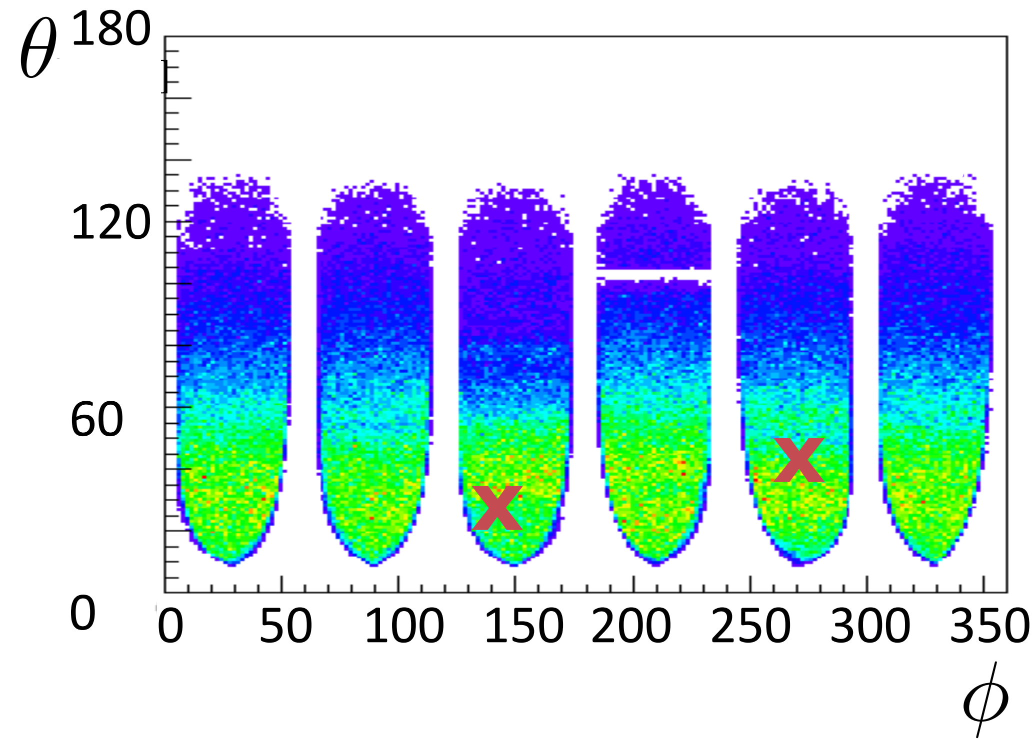


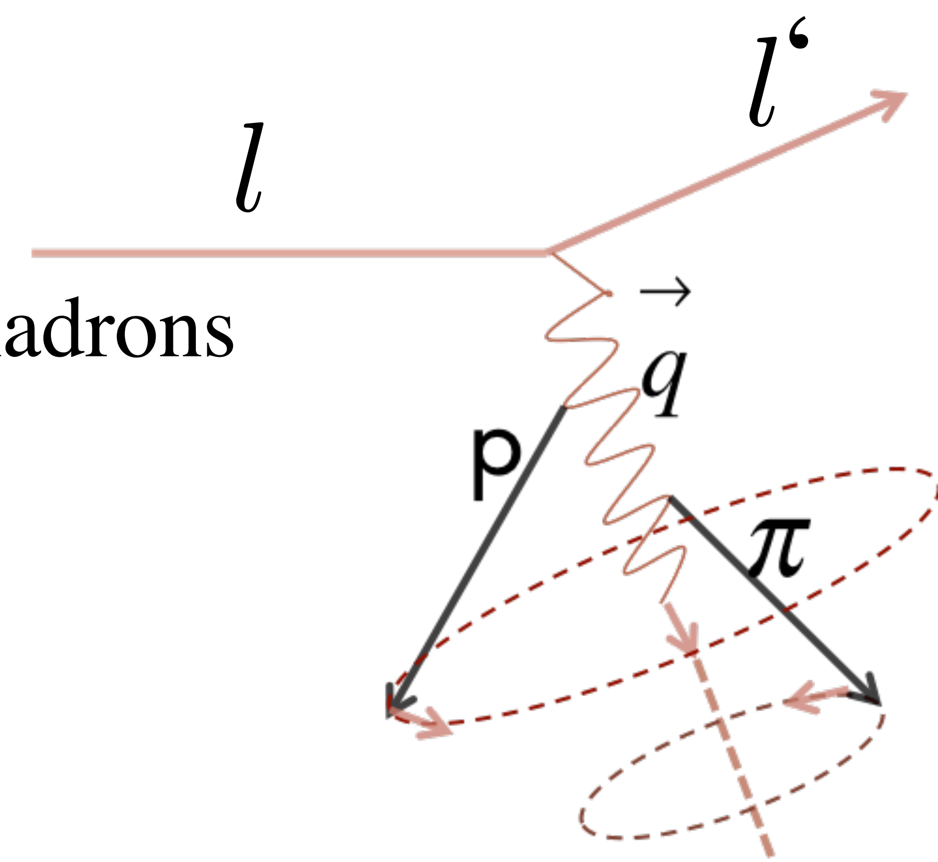


Data Driven Background Subtraction

- Using measured (e,e'pπ) events
- Rotate p,π around **q**
- Determine event acceptance
- Subtract (e,e'pπ) contribution



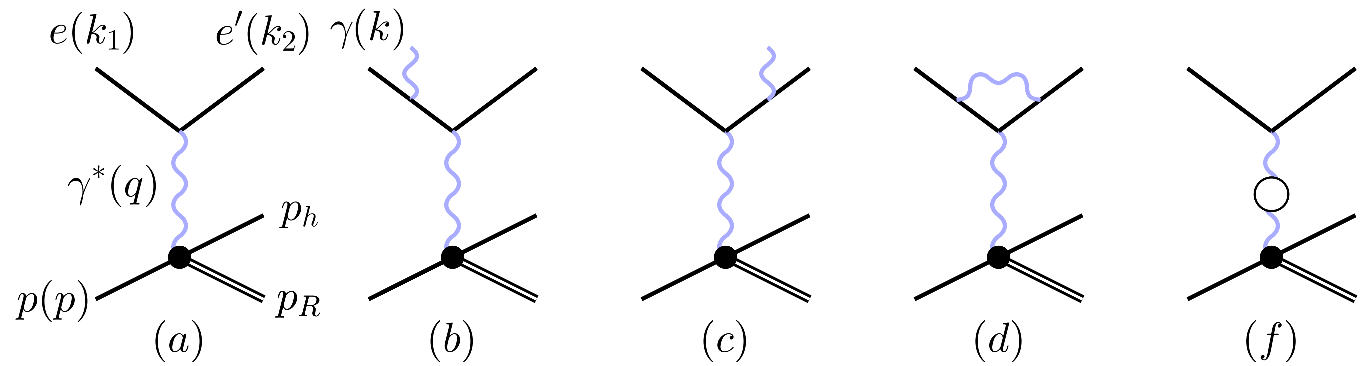
- Same for final states with more than 2 hadrons



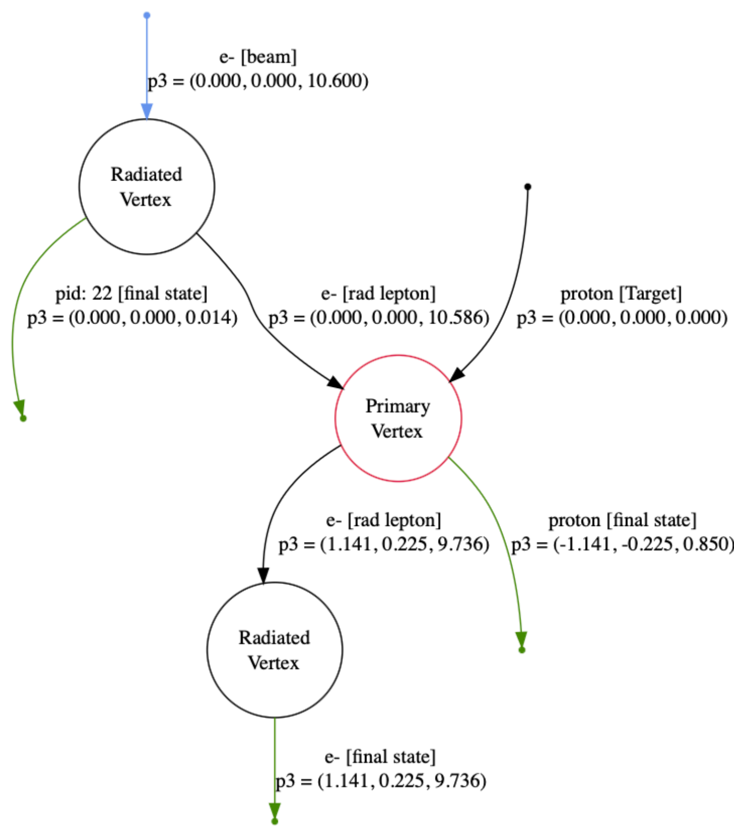
Julia
Tena Vidal

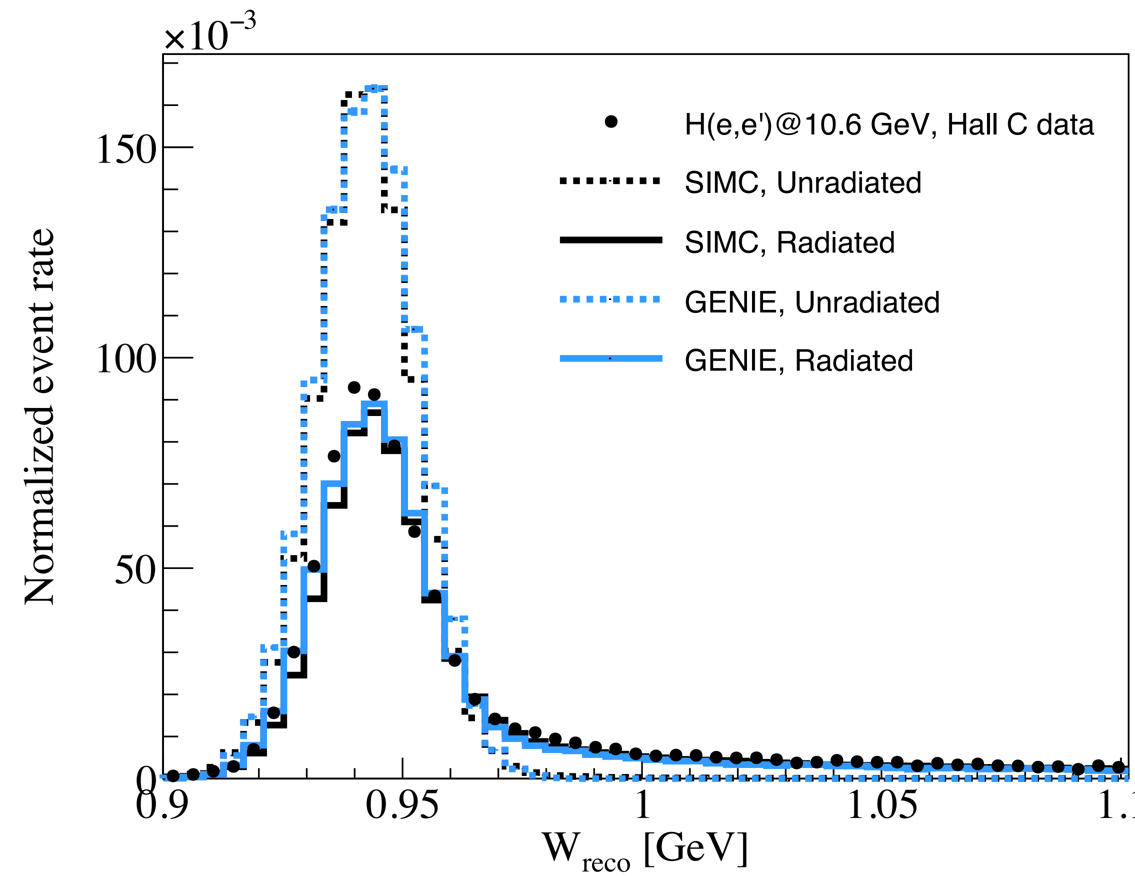
Radiative effects

When comparing electron scattering to prediction, radiative effects needs to be taken into account



Implemented and validated in GENIE





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Tena Vidal

Exclusive Data

e4V 1p0π Event Selection

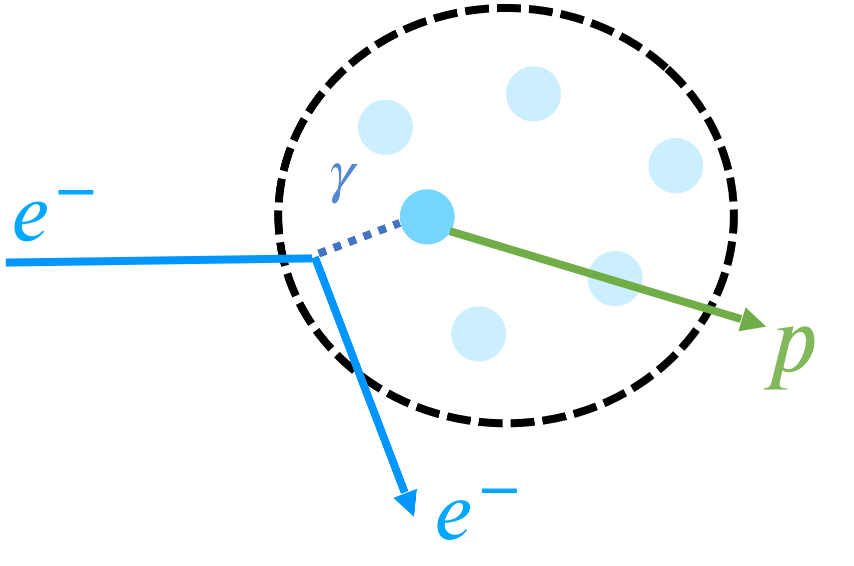
Focus on Quasi Elastic events:

1 proton above 300 MeV/c

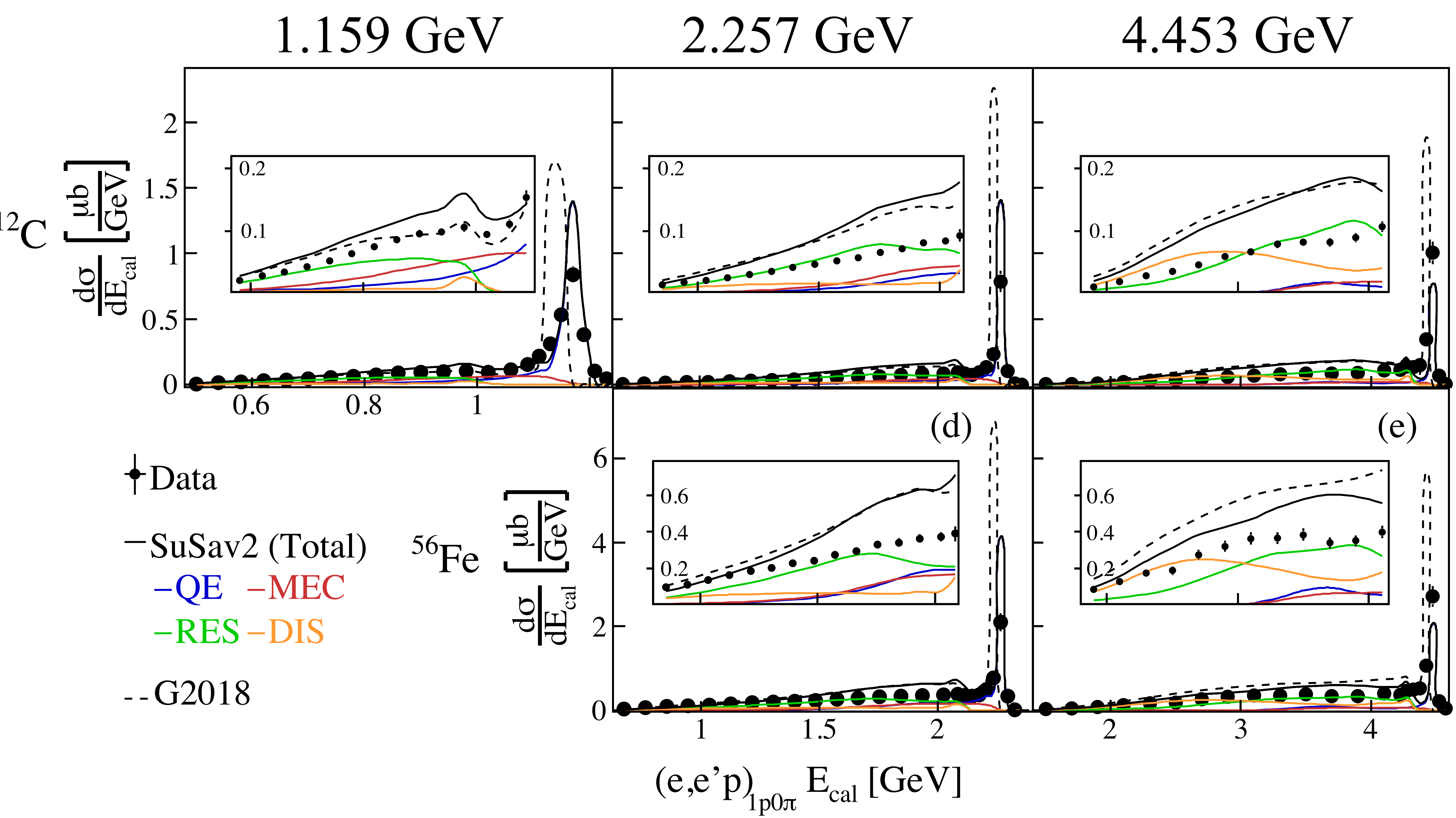
no additional hadrons above detection threshold:

150 MeV/c for $P_{\pi^{+/-}}$

500 MeV/c for P_{π^0}

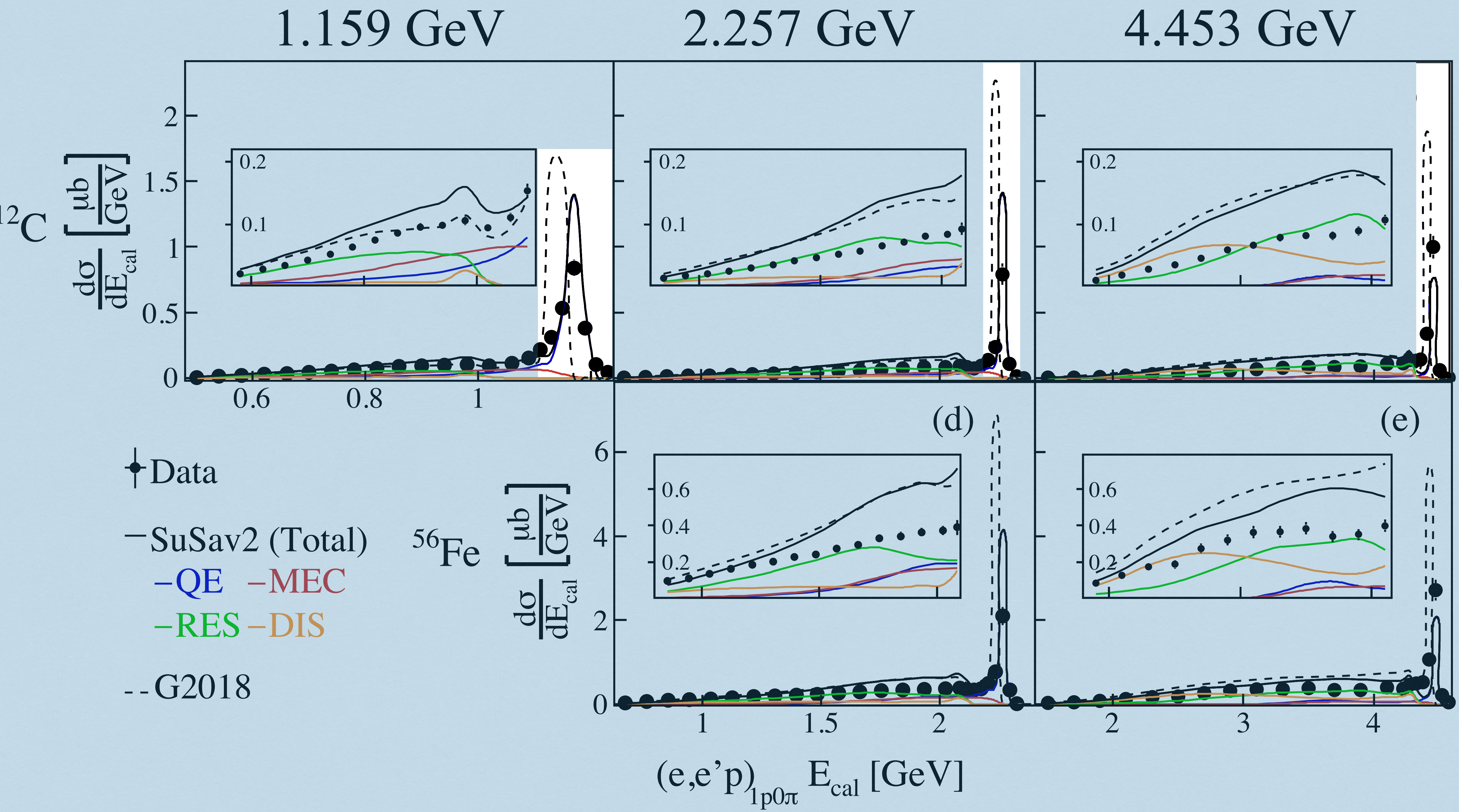


Reconstructed Calorimetric Energy



Nature **599**, 565 (2021)

Reconstructed Calorimetric Energy



Nature **599**, 565 (2021)

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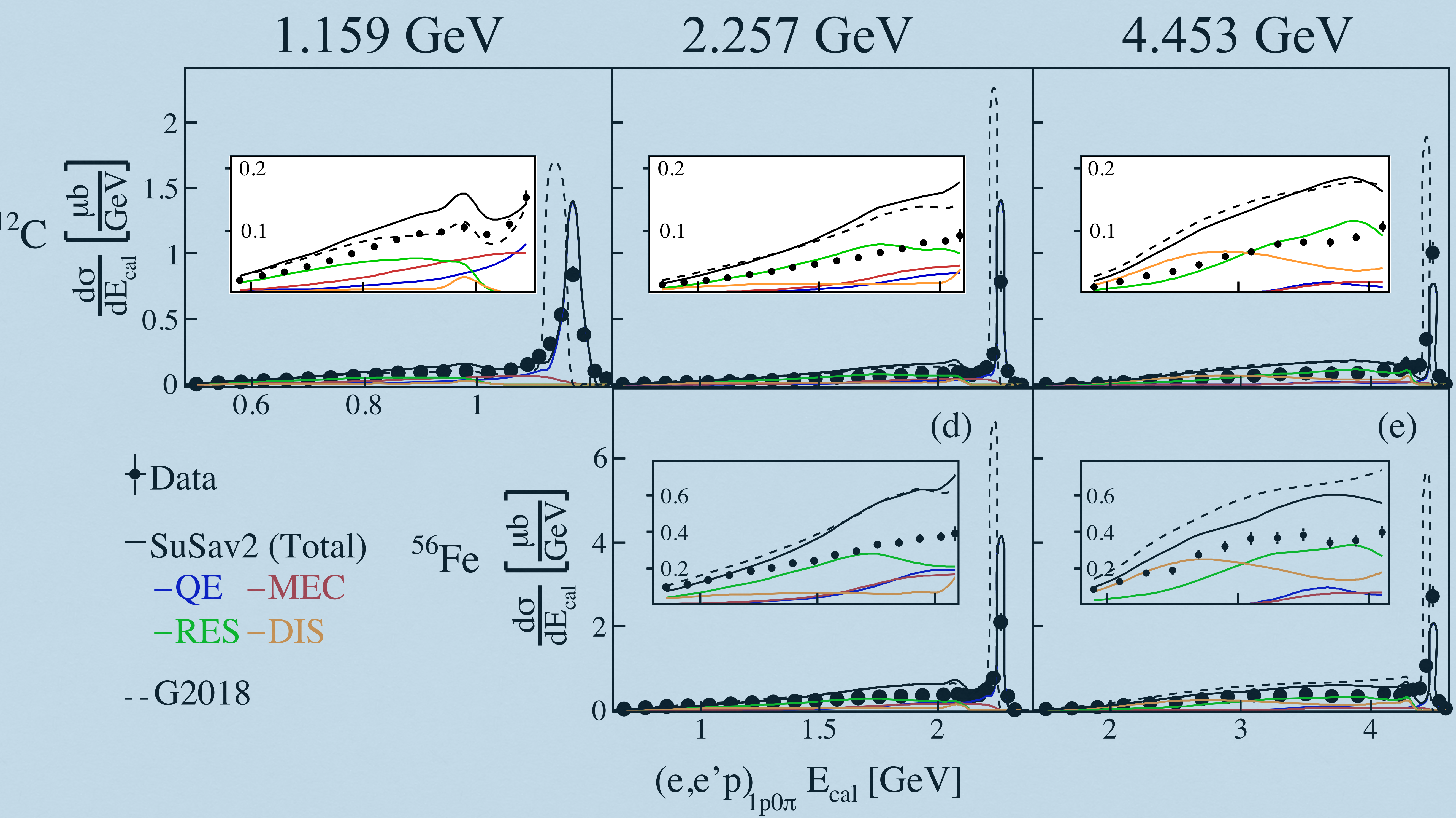

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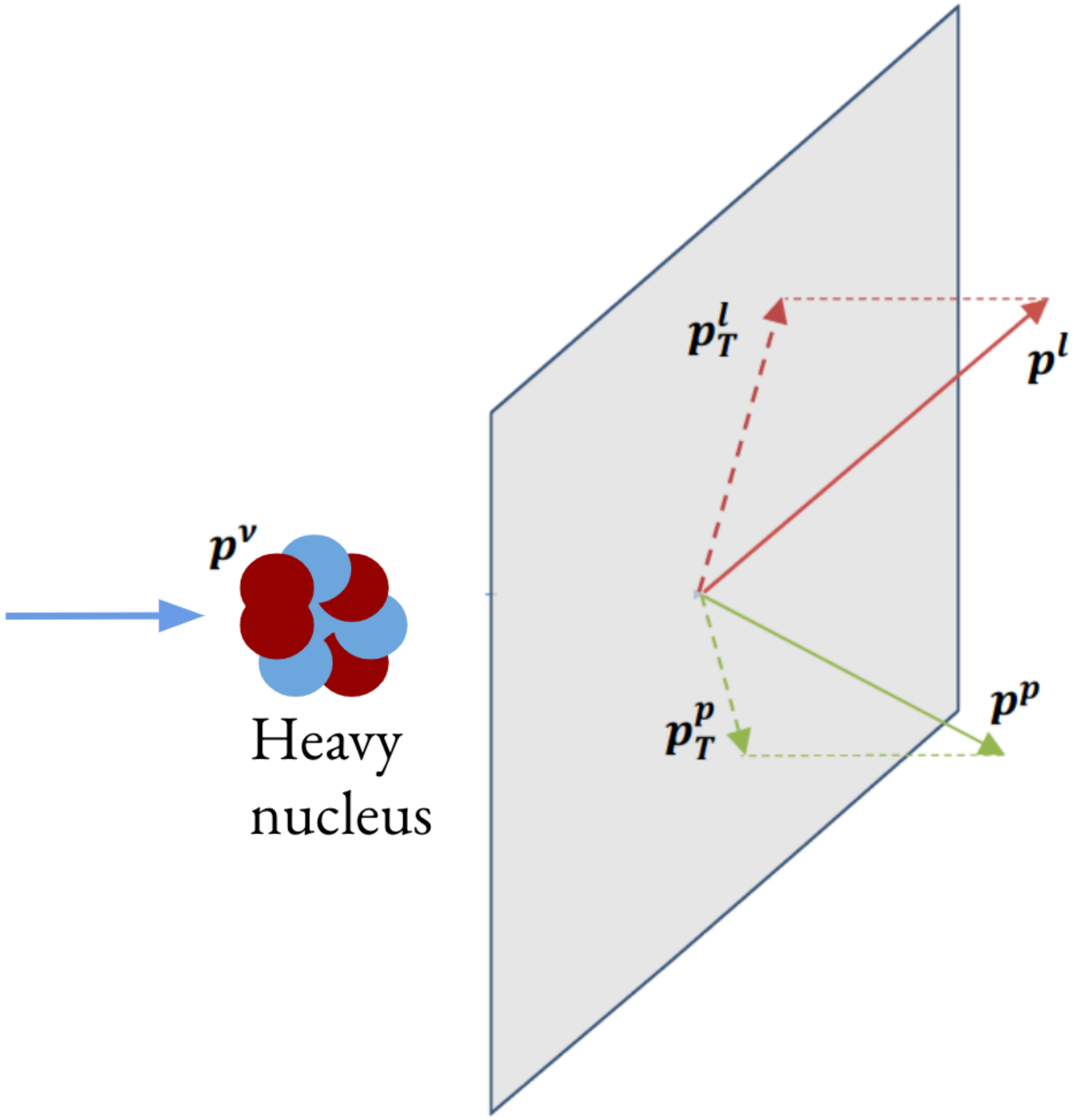
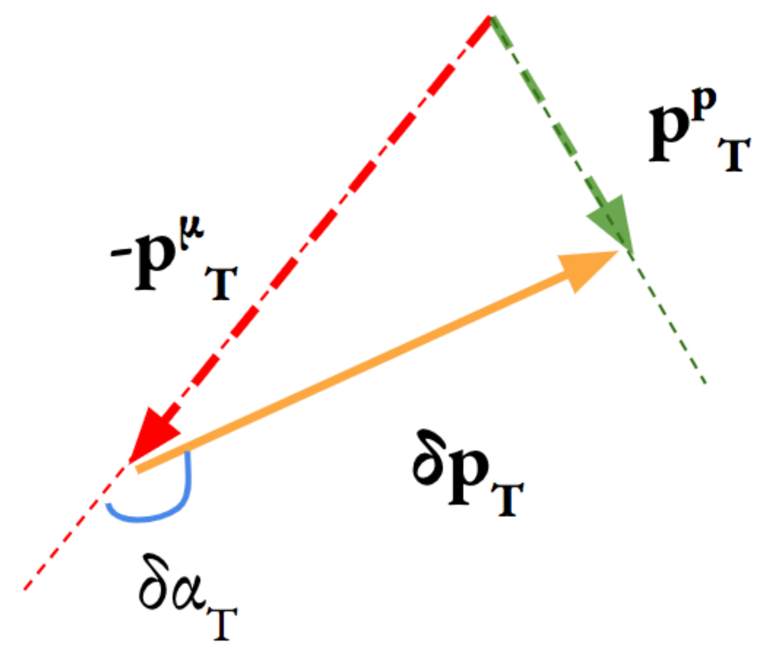
Focusing on different reaction mechanisms

Standard Transverse Variables





$\vec{P}_T = \vec{P}_T^{e'} + \vec{P}_T^p$

Sensitive to

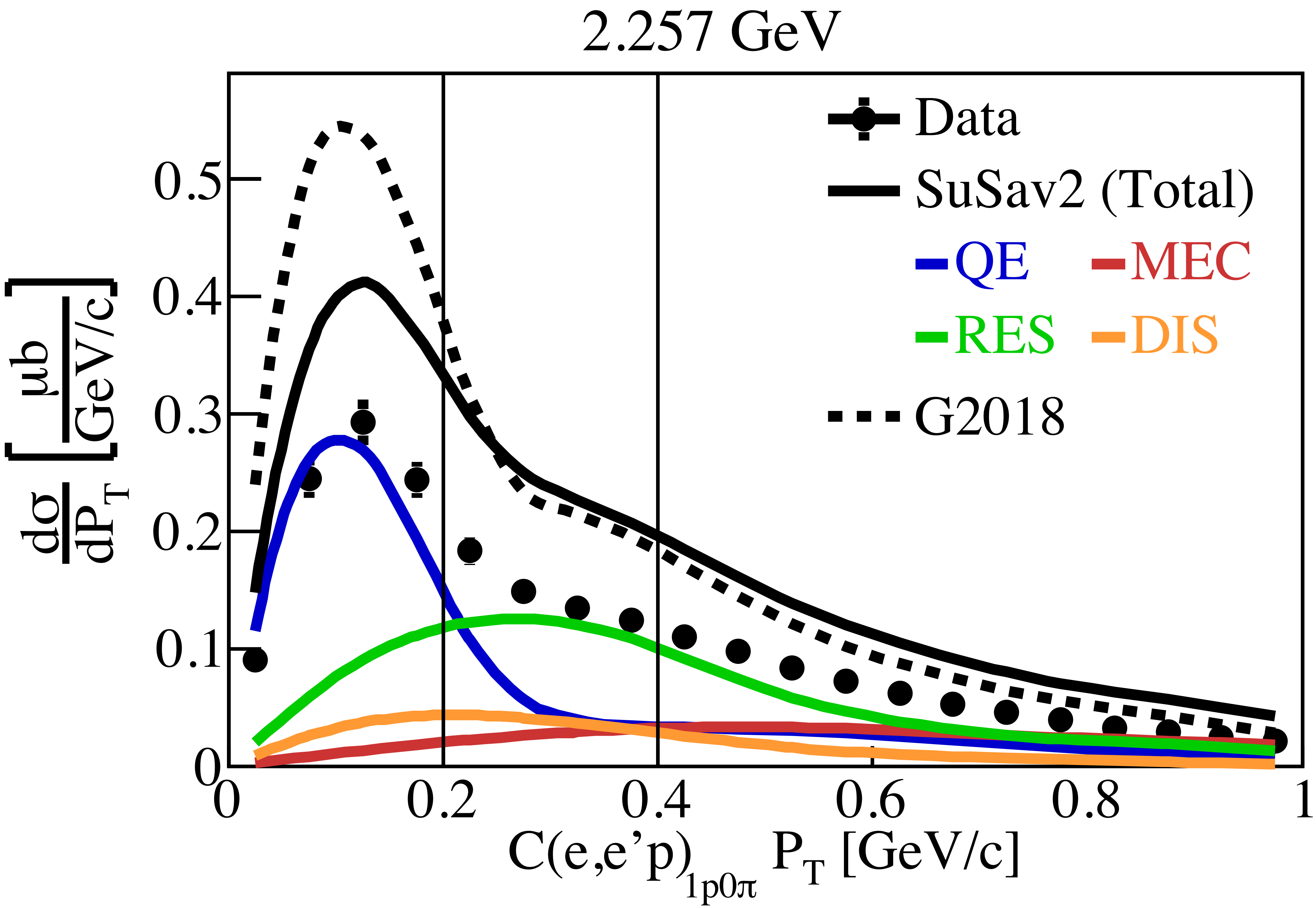
hit nucleon momentum

$\delta\alpha_T$

Sensitive to

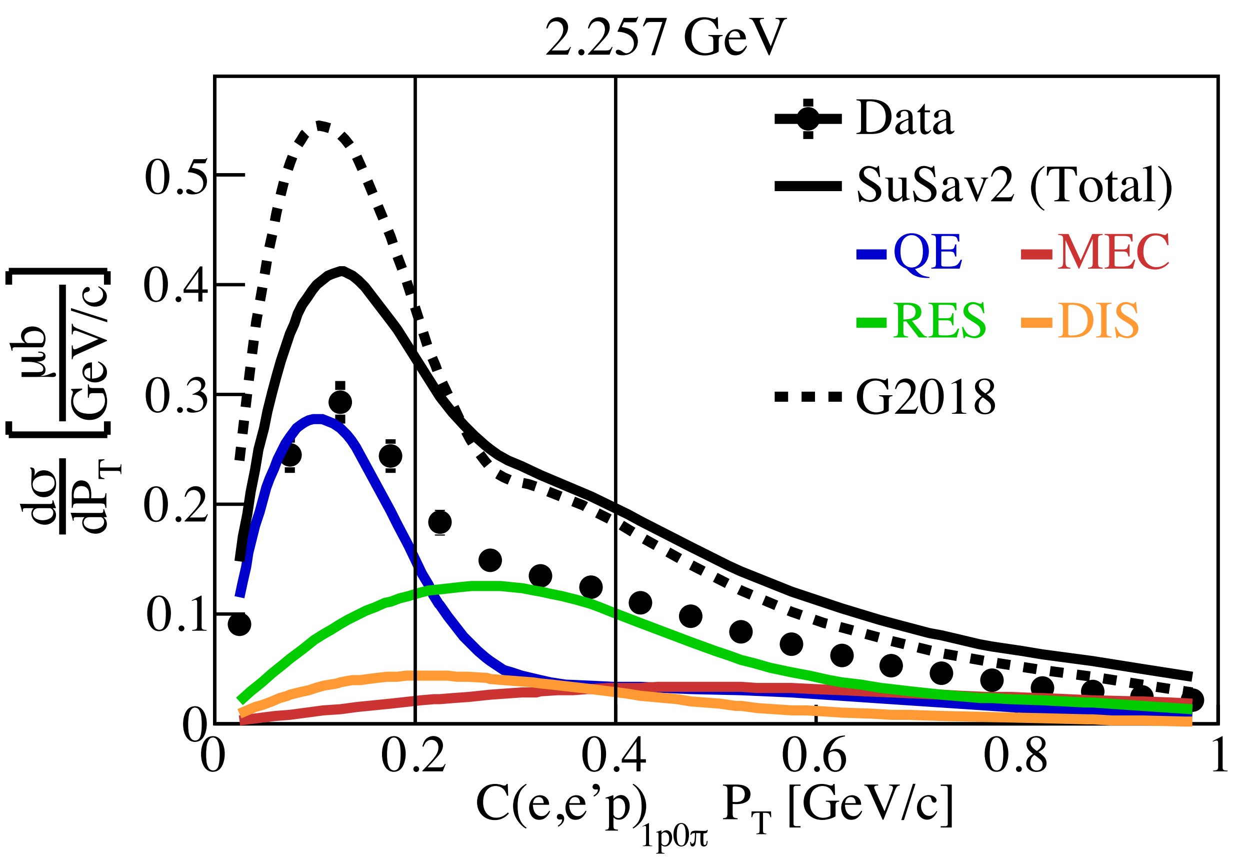
Final State Interactions

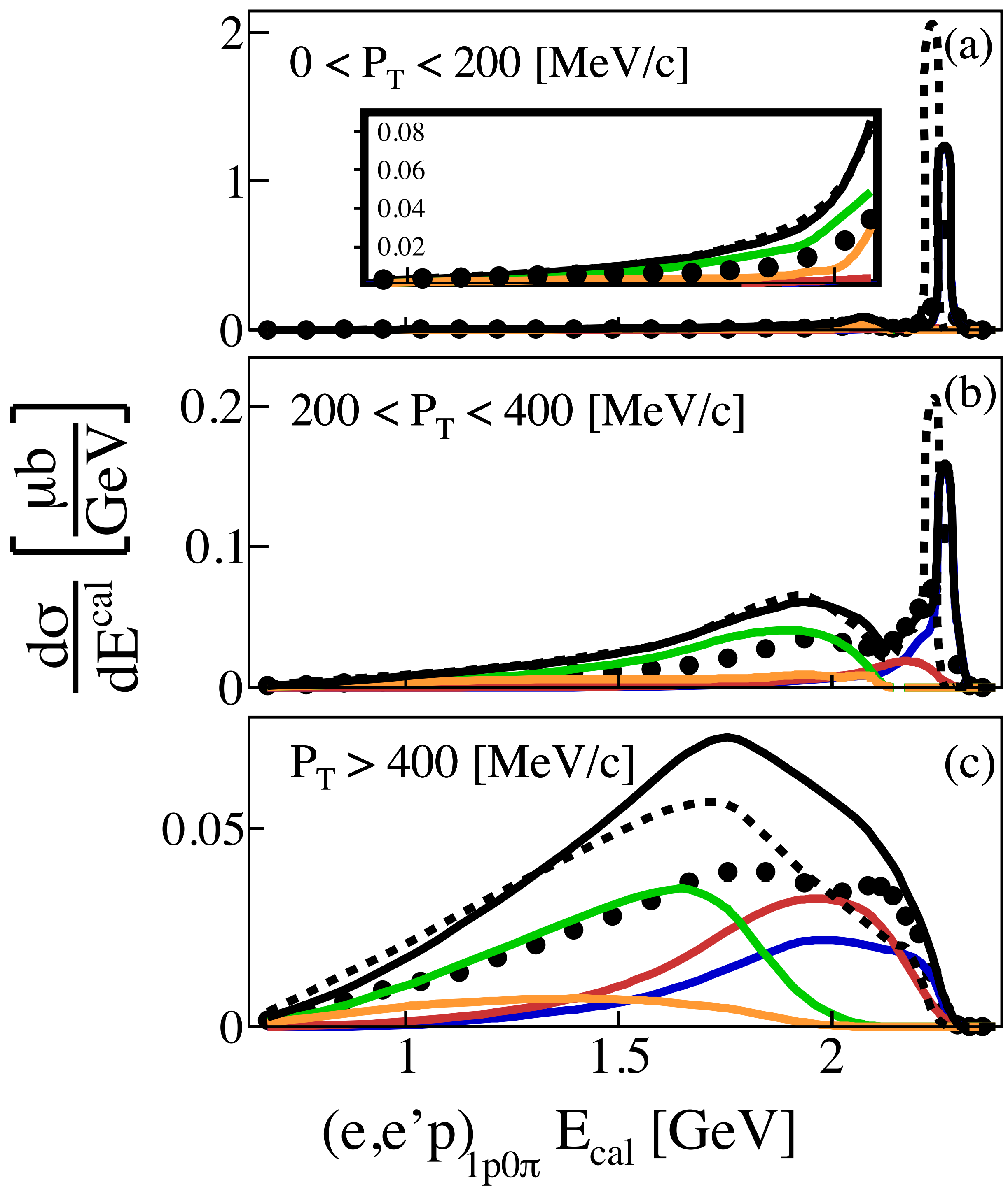
Transverse missing momentum



Nature **599**, 565 (2021)

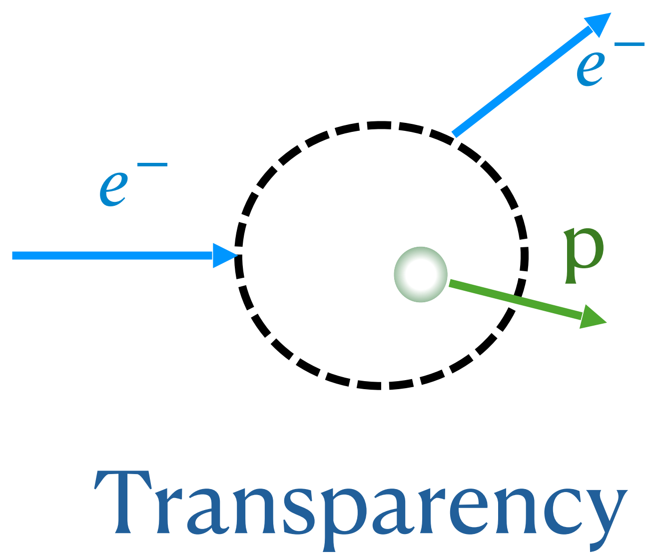
p_T sensitivity to interaction mechanisms

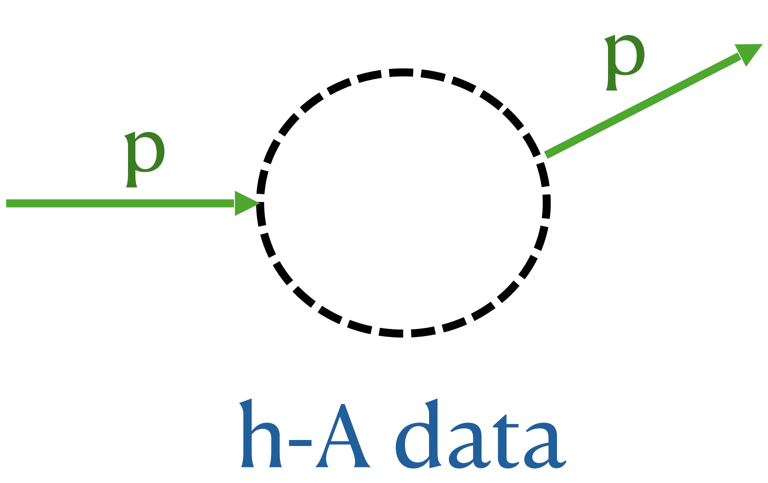




Nature **599**, 565 (2021)

Transparency Measurement





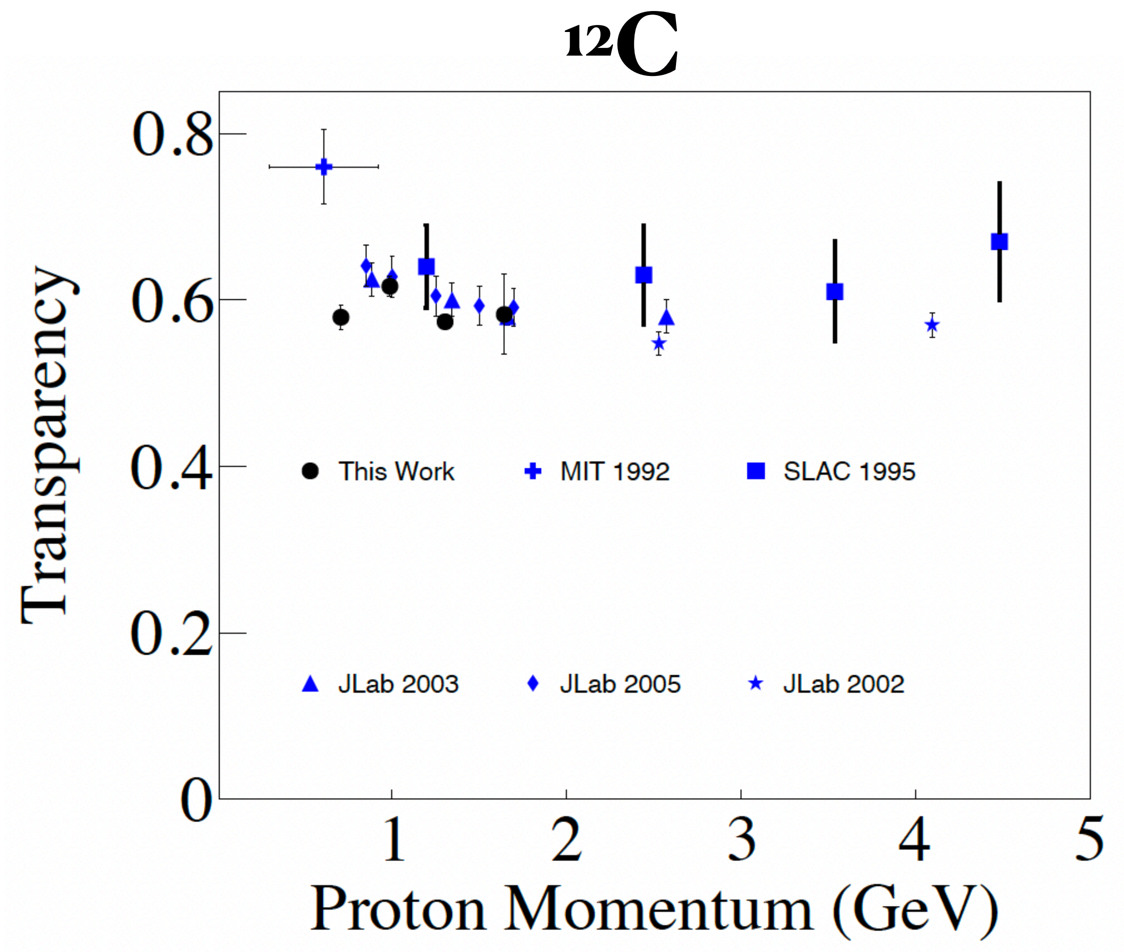
Noah Steinberg

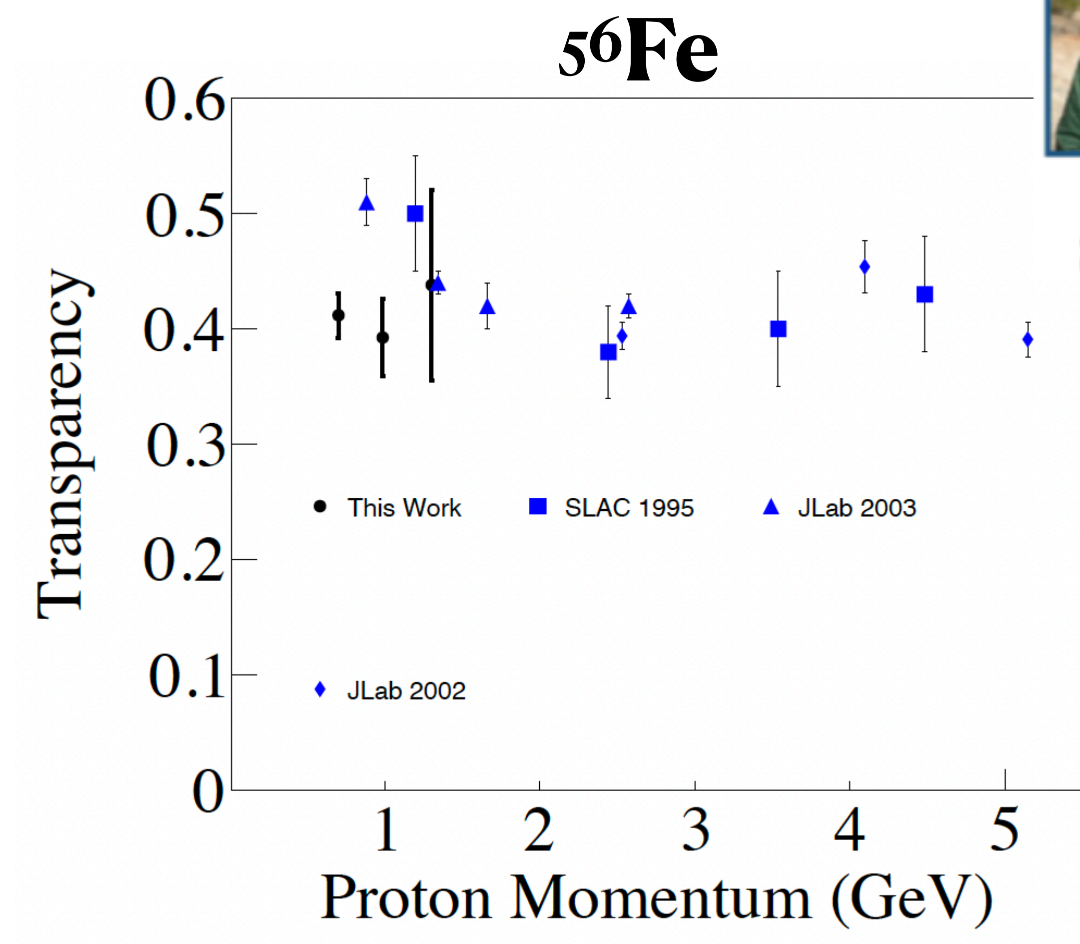
- Probability that a struck proton leaves the nucleus without significant re-scattering
- Complement to hadron nucleus interaction
- Study proton FSI similarly to neutrino scattering

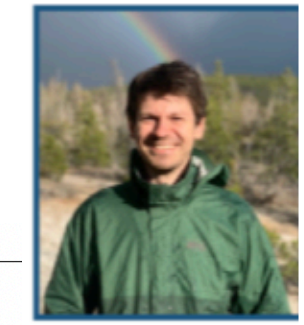
Sensitive to both FSI and nuclear structure (PRD **104** 053006 (2021))

Strong need for new data, especially at low proton momentum

Transparency Measurement



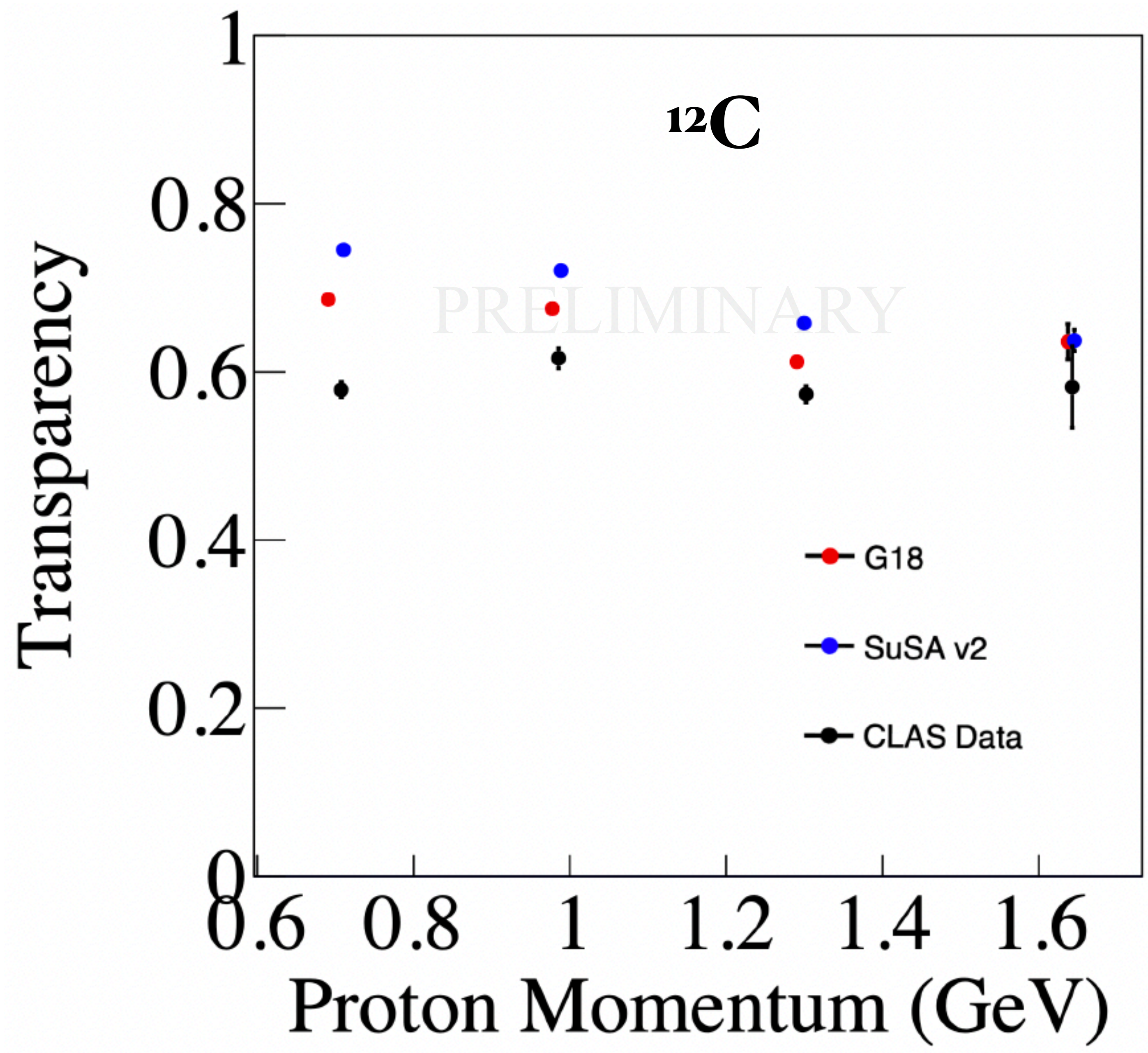




Noah Steinberg

$$T_A = N(e,e'p)_{o\pi} / N(e,e')_{QEL}$$

Transparency Measurement



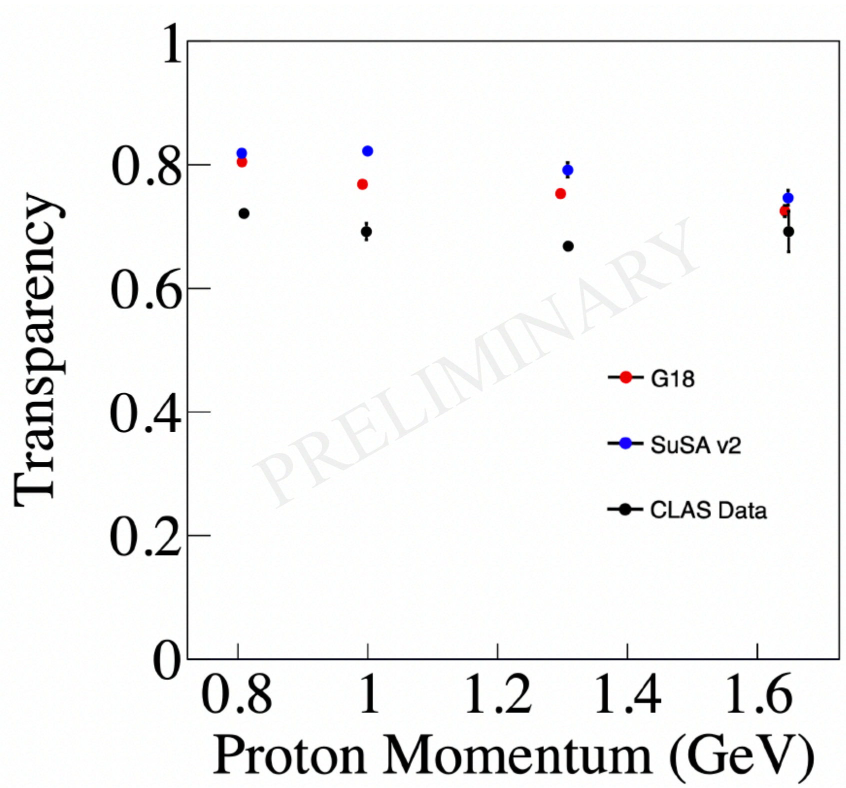
Noah Steinberg

$$T_A = \mathbf{N(e,e'p)}_{0\pi} / N(e,e')_{QEL}$$

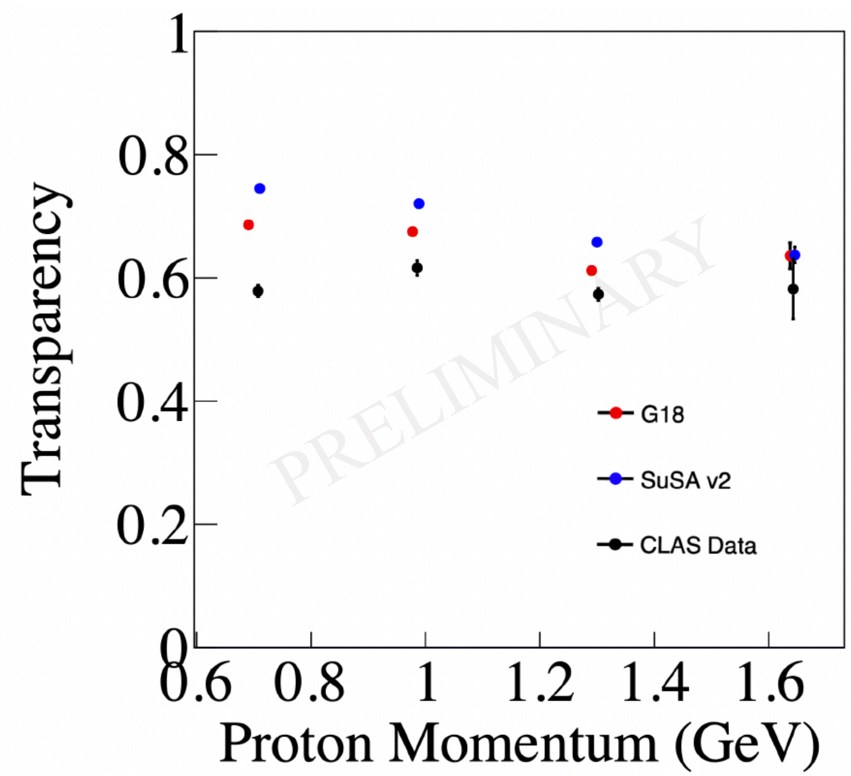
Transparency Measurement

Noah Steinberg

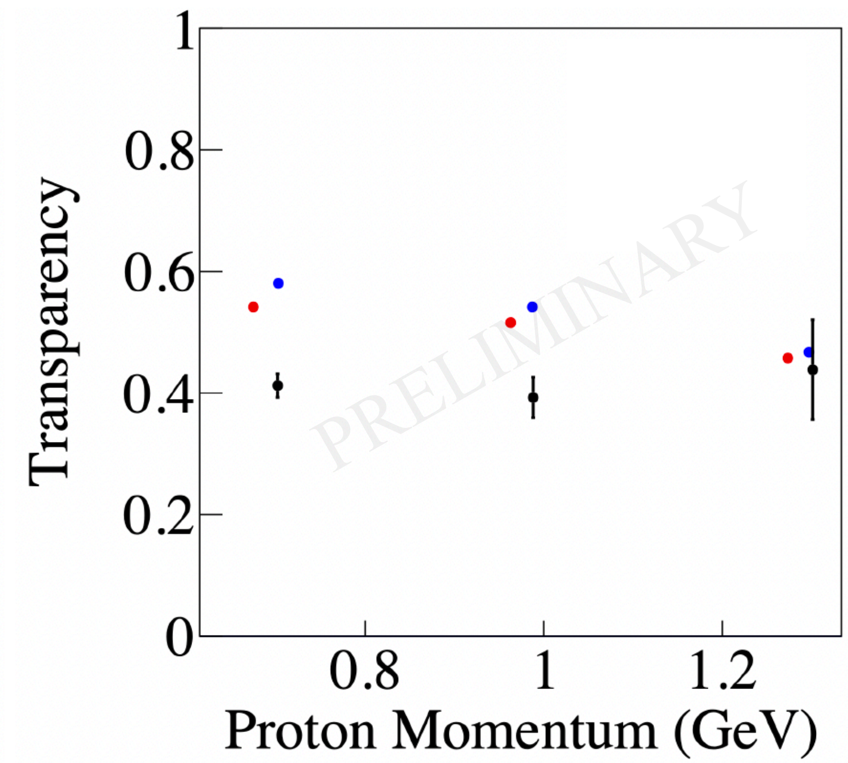
^{4}He



^{12}C



^{56}Fe



Presenting first measurement on He

Transparency decreases with A

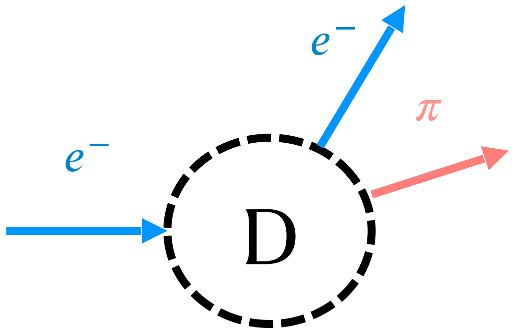
First Look at Pions

Deuterium @ 4.2 GeV

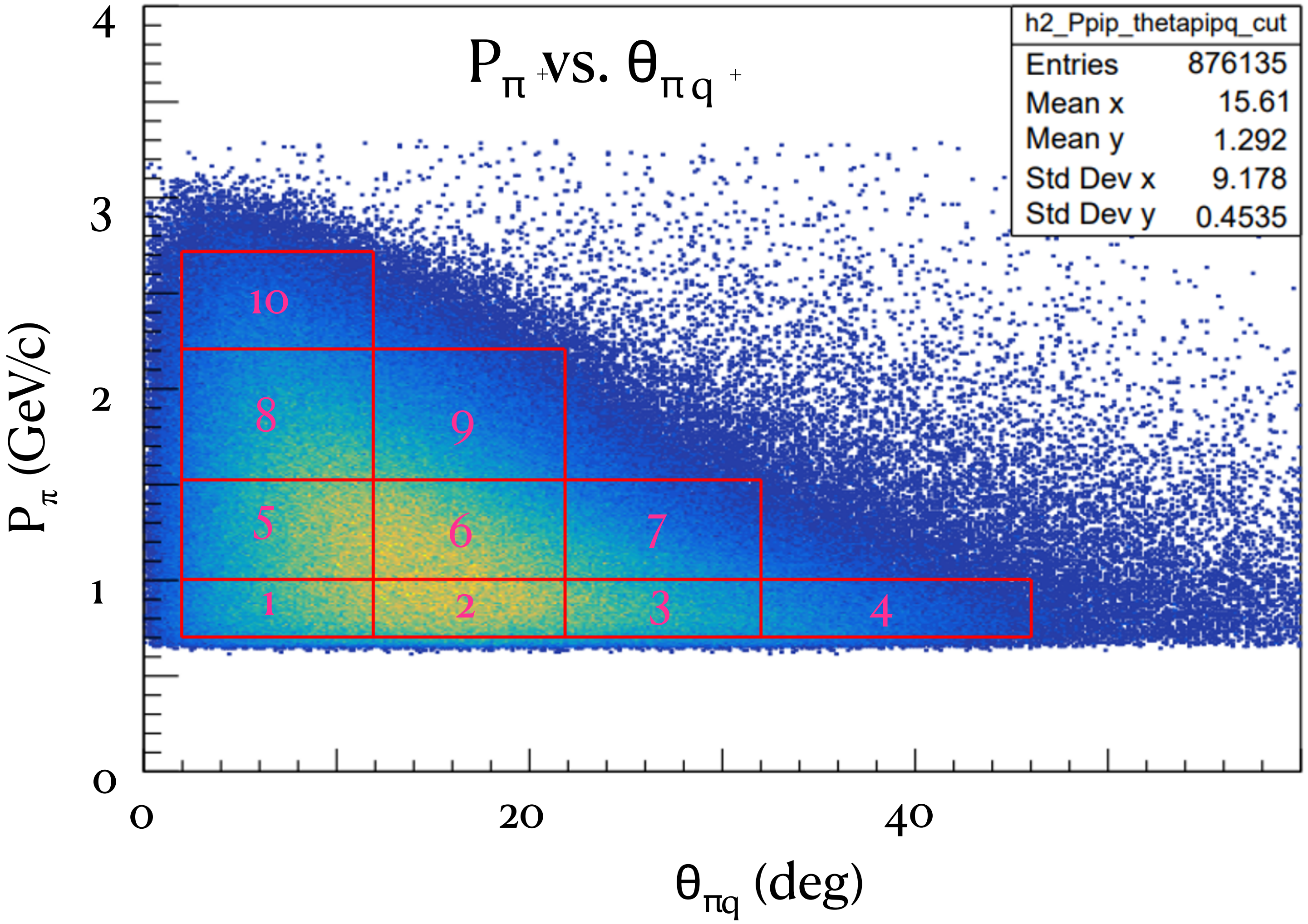

Caleb Fogler

Compared pion kinematics against

- GENIE (G18_10a)
- OnePiGen
  - Single pion event generator
  - MAID2007 model



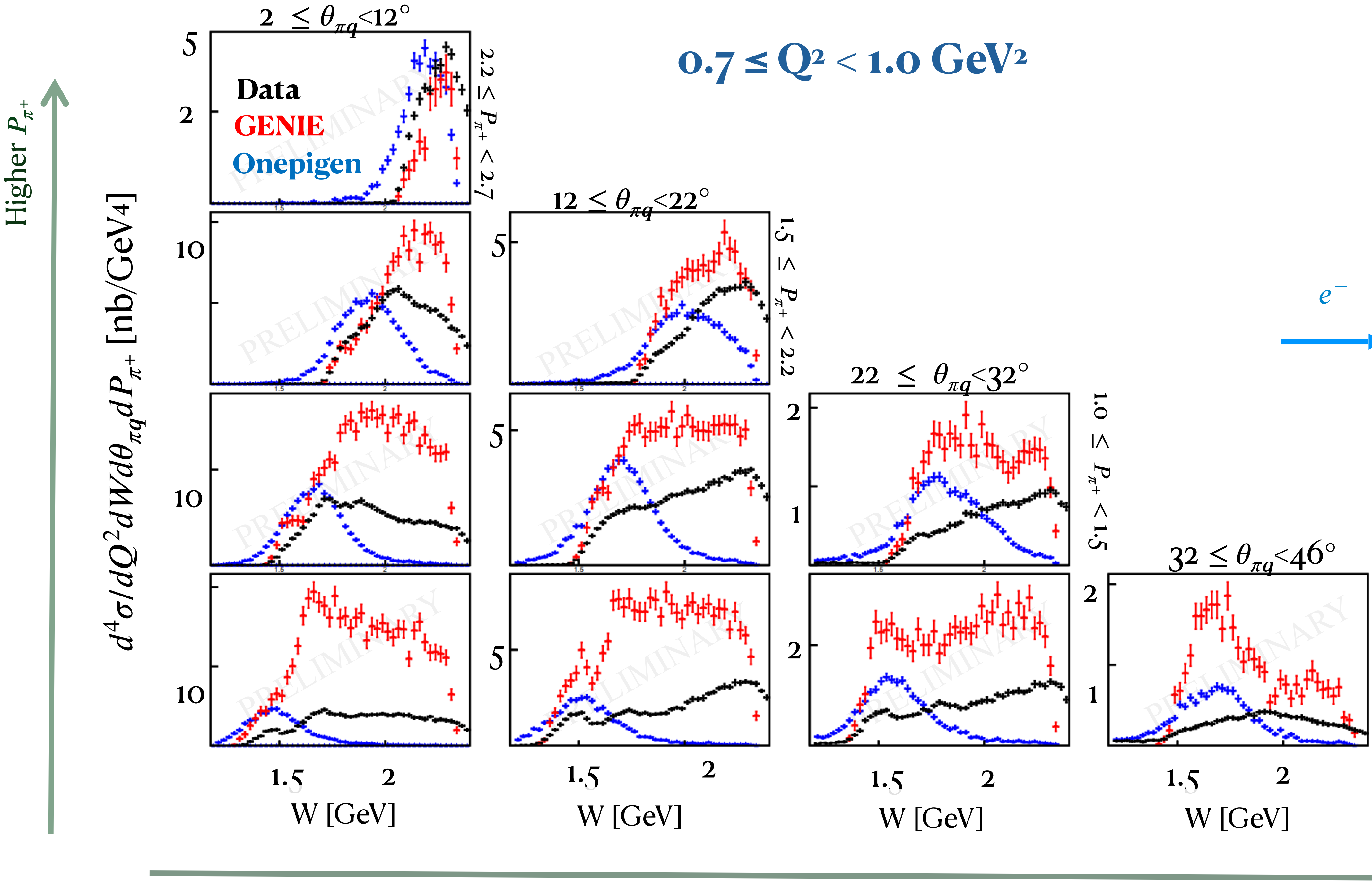
$0.7 \leq Q^2 < 1.0$ GeV^2



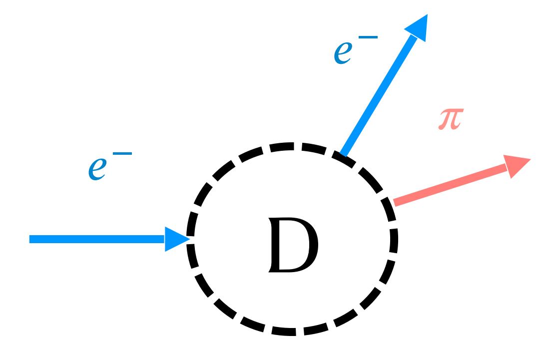
First Look at Pions

D(e,e'π+)

$0.7 \leq Q^2 < 1.0$ GeV²



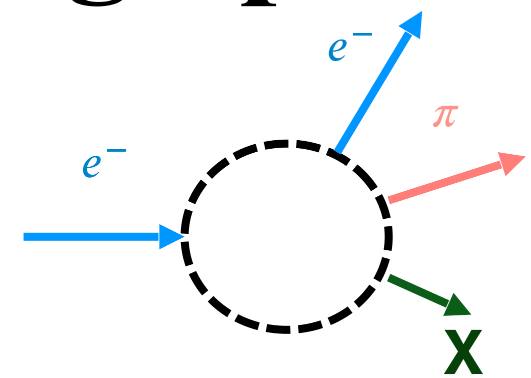
Caleb Fogler



First Look at Pions - coming up

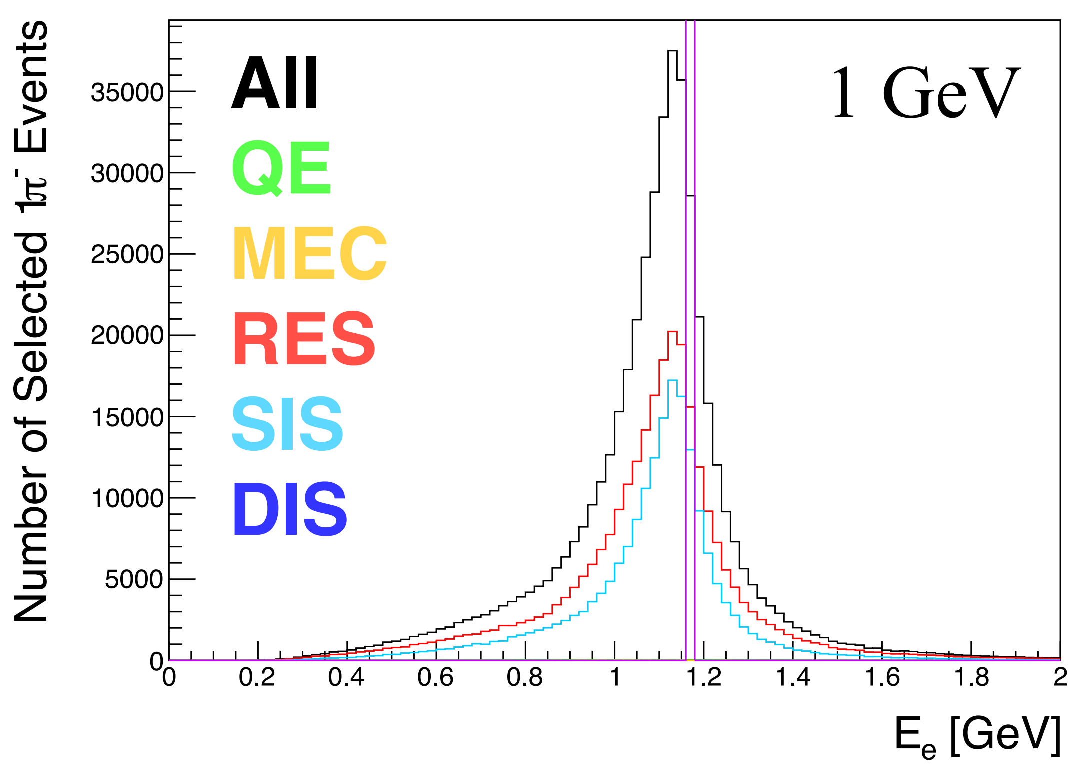
Inspired by MiniBooNE measurement

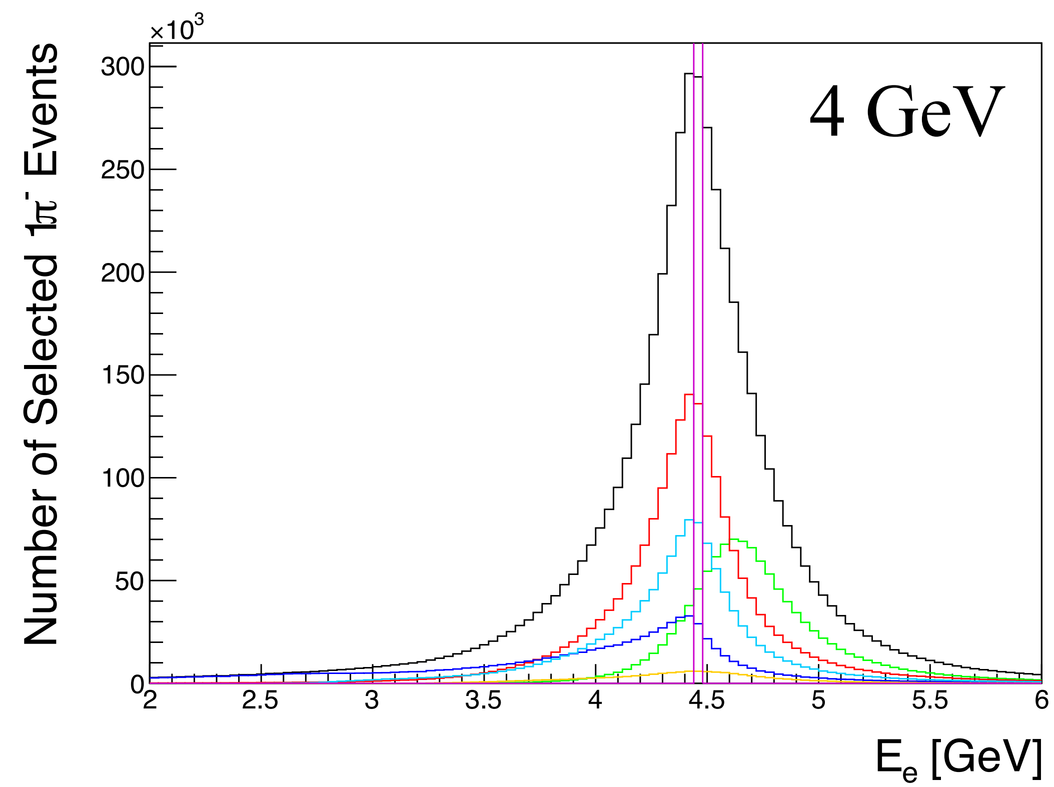
Based on simple kinematics in events with 1p1pi



Brittany Cohen

$$E_{rec} = \frac{2m_{e'}^2 + 2m_\pi^2 - 2M_N(E_{e'} + E_\pi + 2p_{e'} \cdot p_\pi)}{2(E_{e'} + E_\pi - |p_{e'}| \cos\Theta_{e'} - |p_\pi| \cos\Theta_\pi - M_N)},$$





True study of events with 1 pion

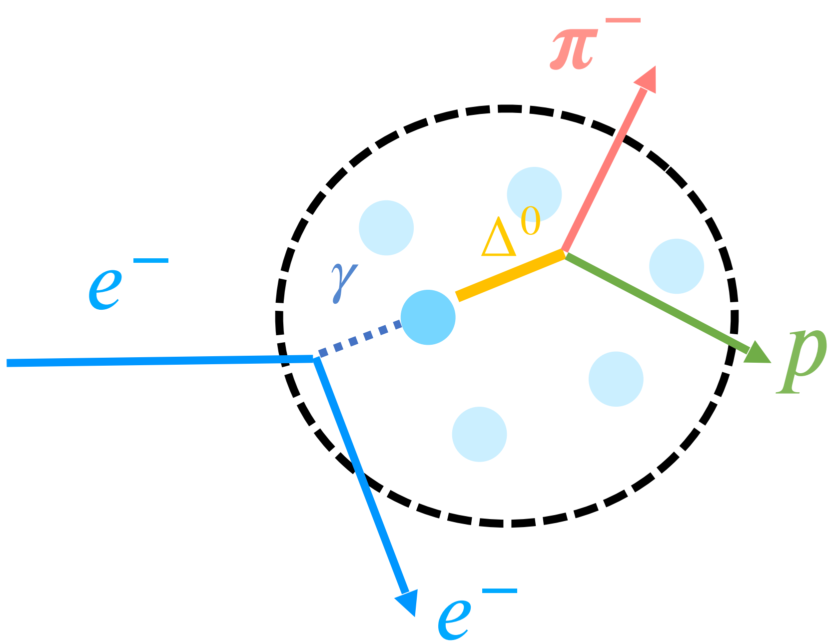
Will follow by comparison to data

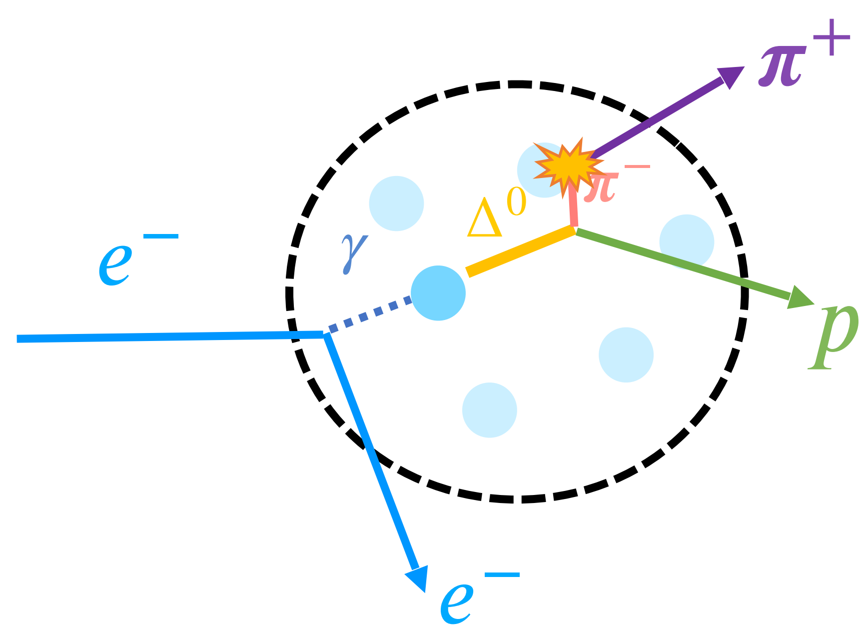
First Look at 1p1π

1p1π^- and **1p1π^+** and no other hadrons or photons

1p1π^- Possible at free nucleon level

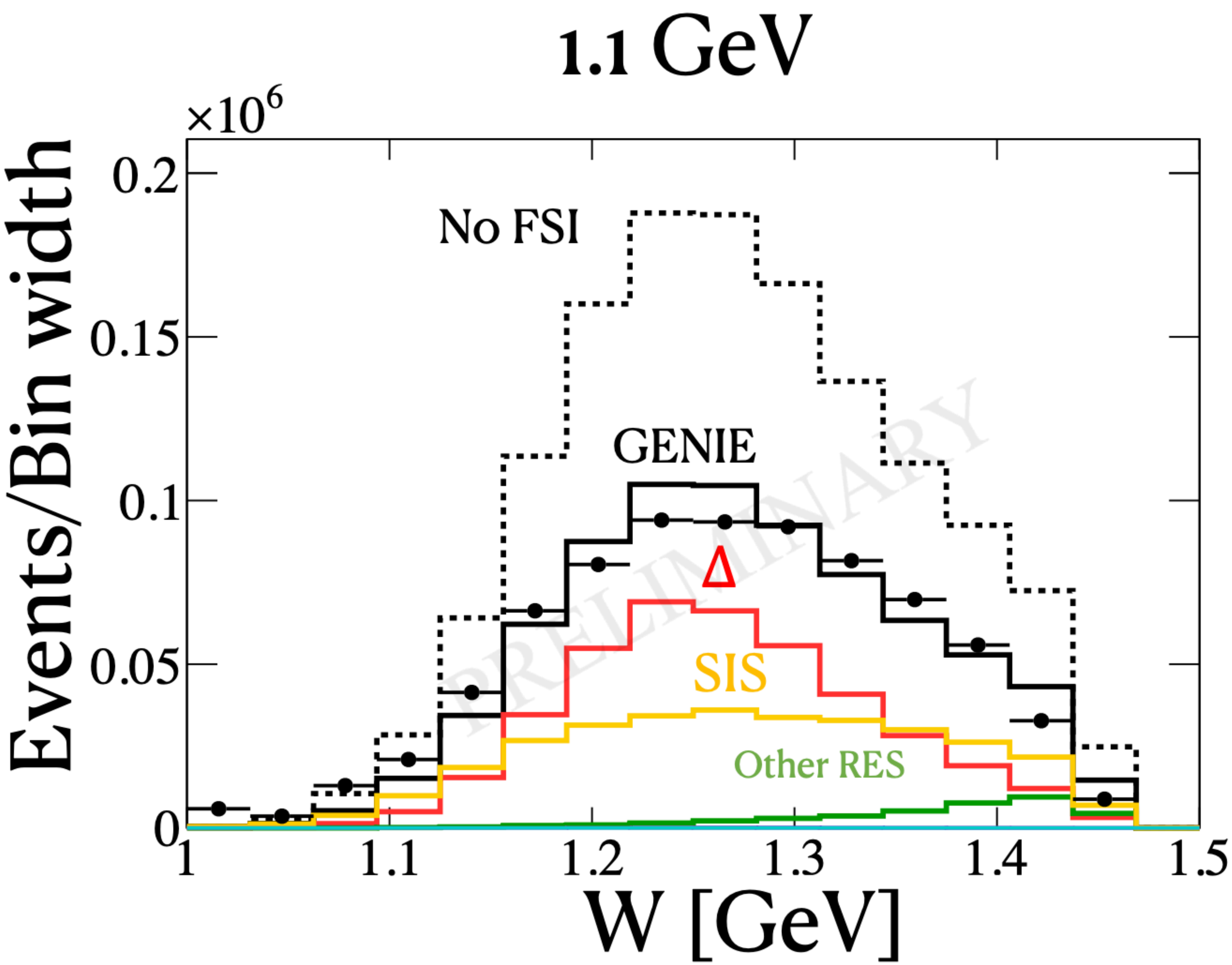
1p1π^+ needs two or more nucleons and or undetected particles (FSI)





Julia
Tena Vidal

First Look at 1p1π⁻



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Shape-only comparison
Data corrected for bkg.
Not radiative corrected yet
Only statistical errors

First Look at 1p1π^-

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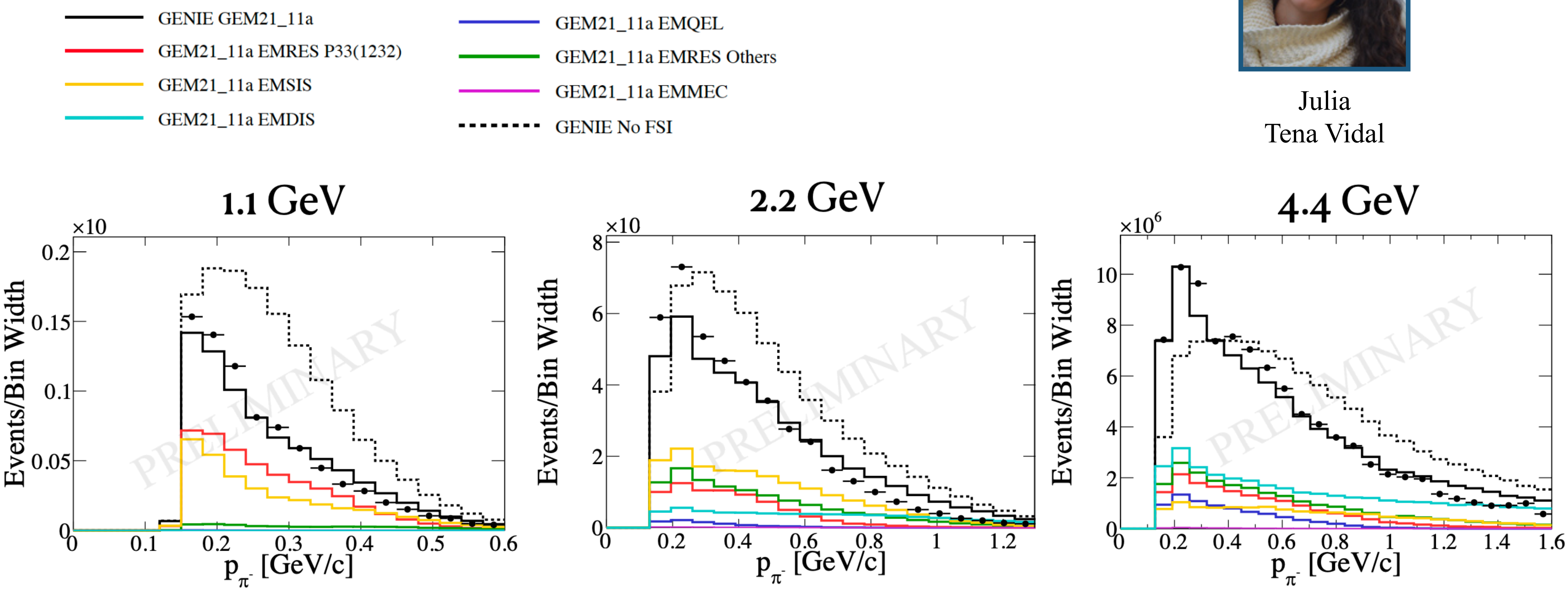

Shape is well described by GENIE with FSI

First Look at 1p1π^-

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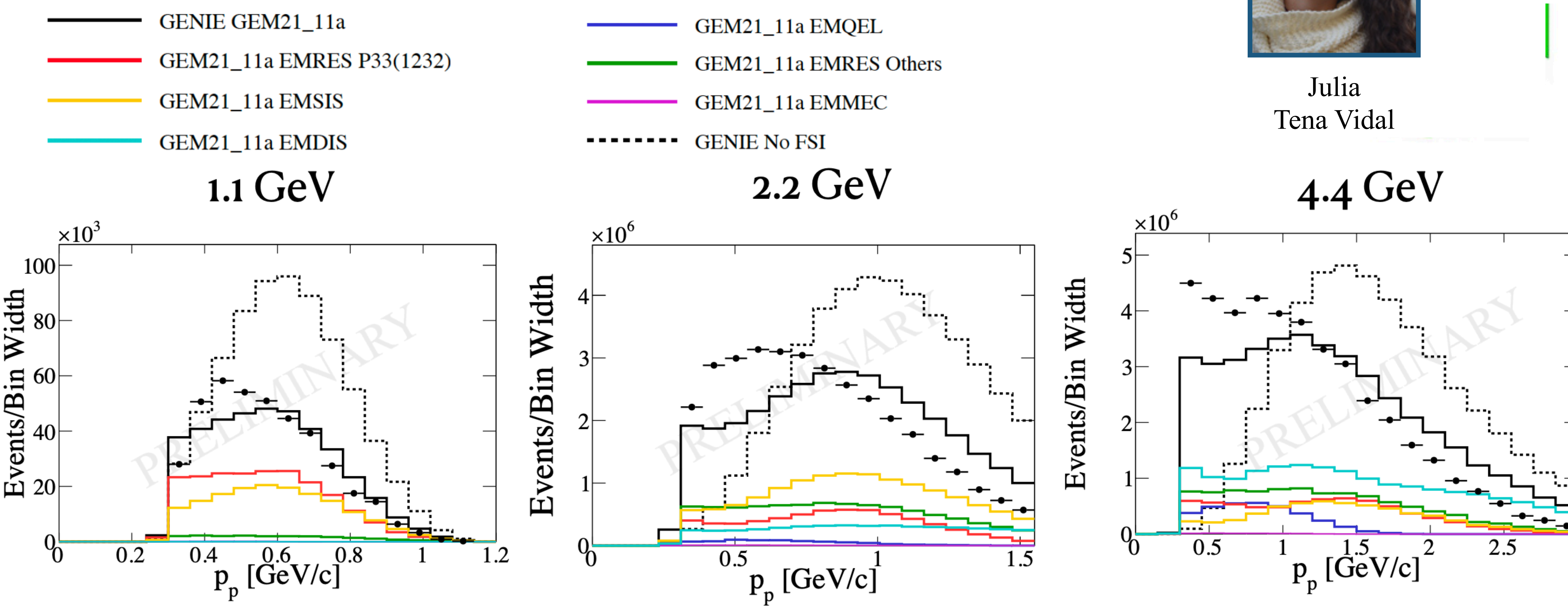

Low momentum protons are not well described

They are very sensitive to FSI

First Look at 1p1π^-

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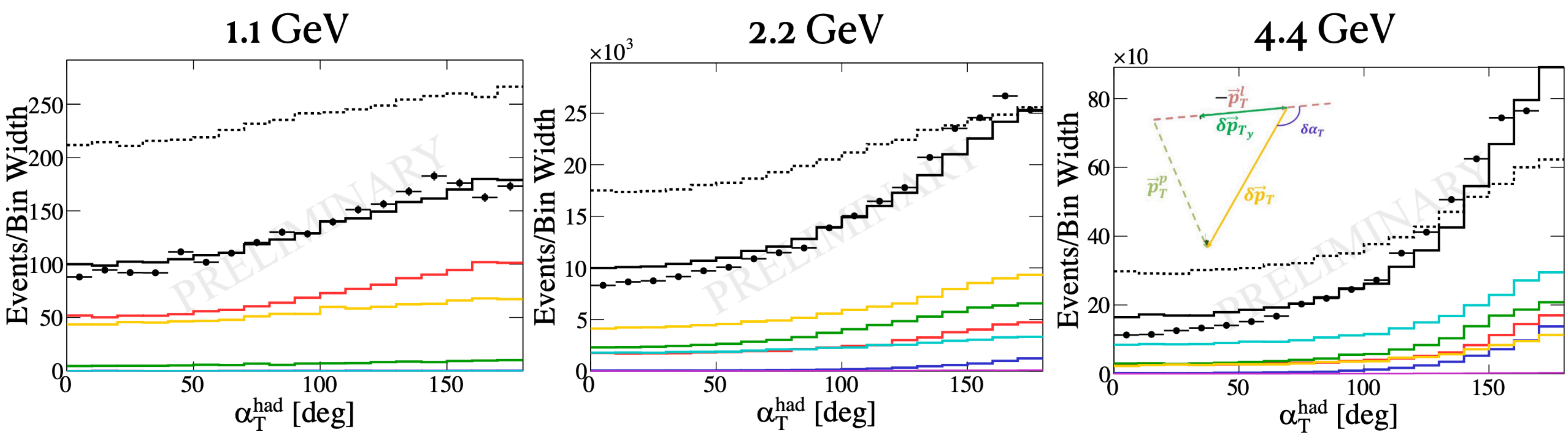
Tena Vidal

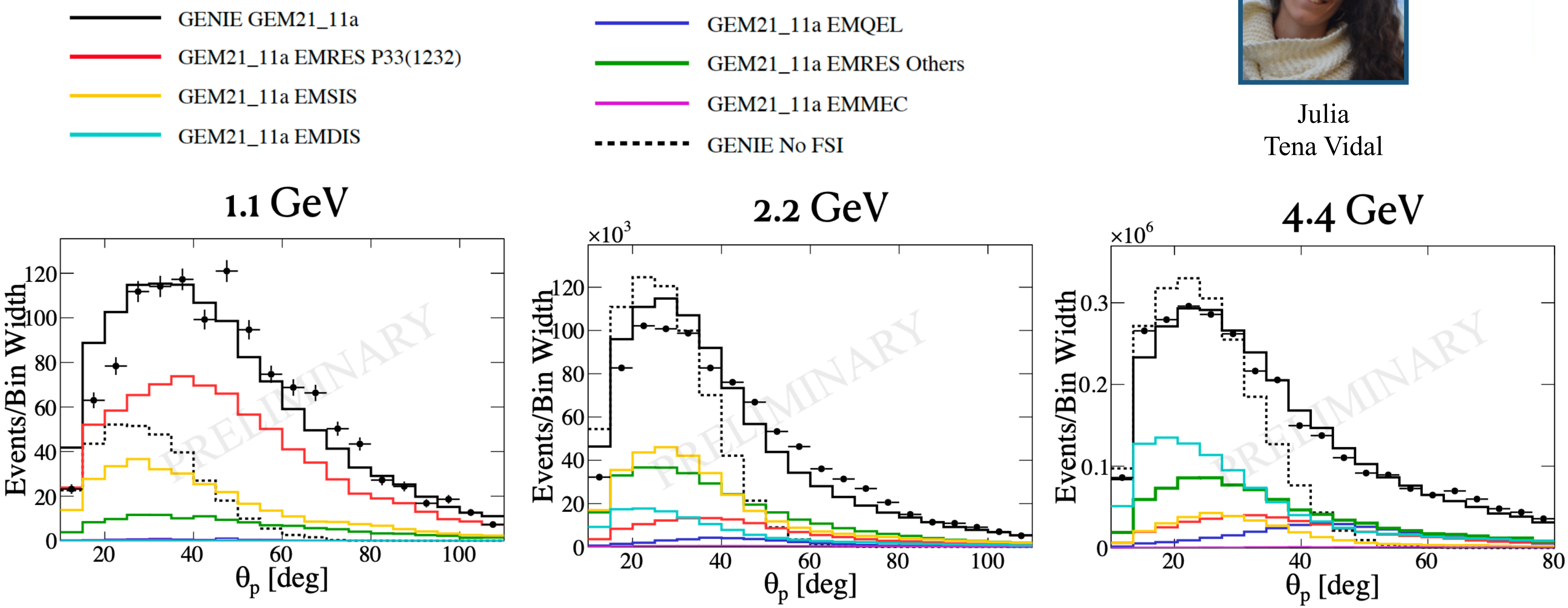
GENIE GEM21_11a
GEM21_11a EMRES P33(1232)
GEM21_11a EMSIS
GEM21_11a EMDIS
GEM21_11a EMQEL
GEM21_11a EMRES Others
GEM21_11a EMMEC
GENIE No FSI



α_T most sensitive to FSI is very well described

First Look at 1p1π^+

Julia
Tena Vidal



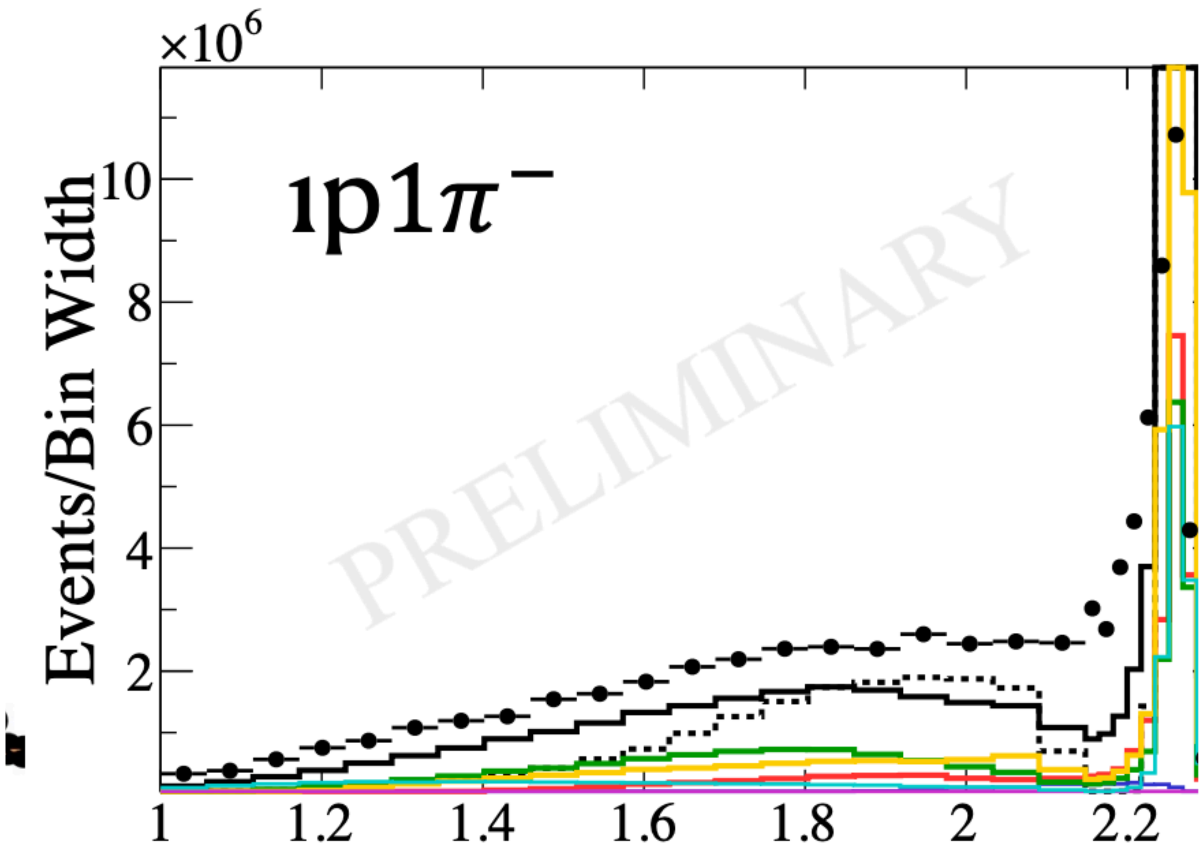
For 1p1π^+ most events are due to FSI

Well described

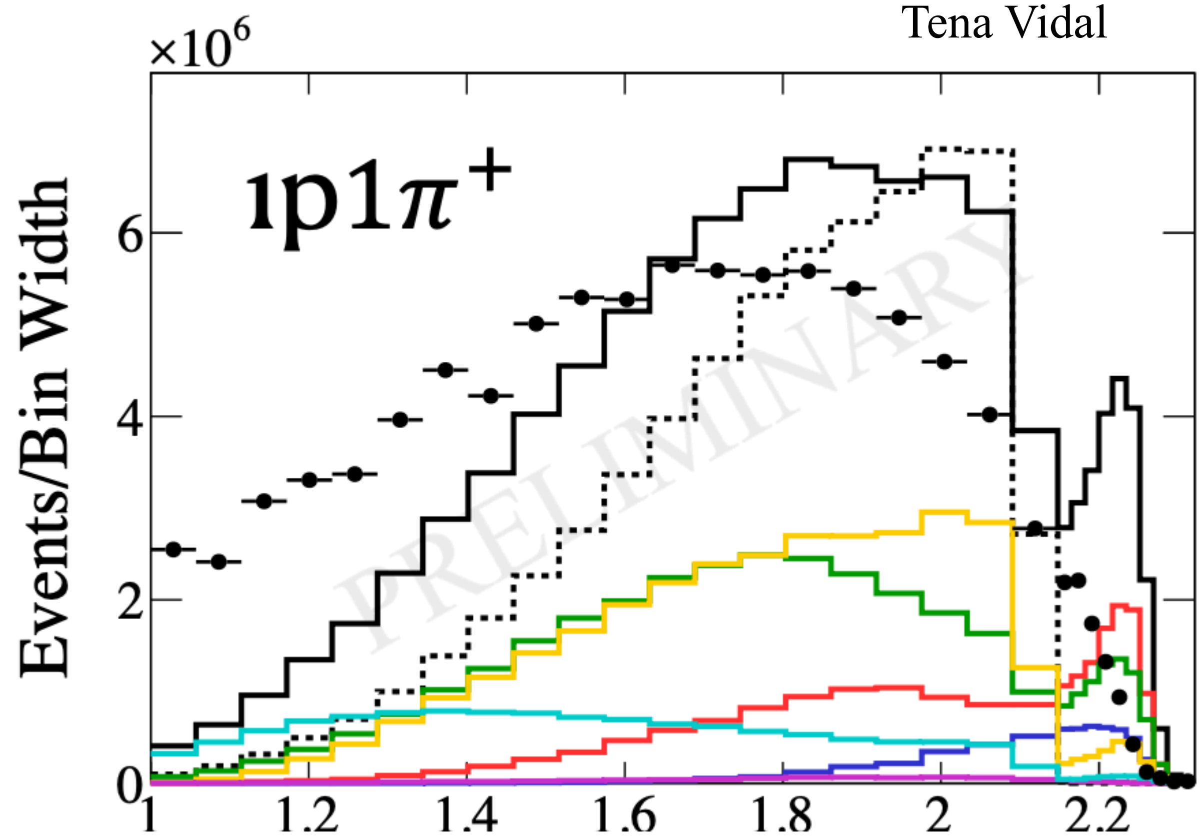
Reconstructed incoming energy for 1p1π

Julia
Tena Vidal

2.2 GeV on Carbon



$E_{Cal} = E_{e'} + E_{\pi} + T_p + \varepsilon_p$



$E_{Cal} = E_{e'} + E_{\pi} + T_p + \varepsilon_p$

Tail, due to missing particles, not well described

Future Plans

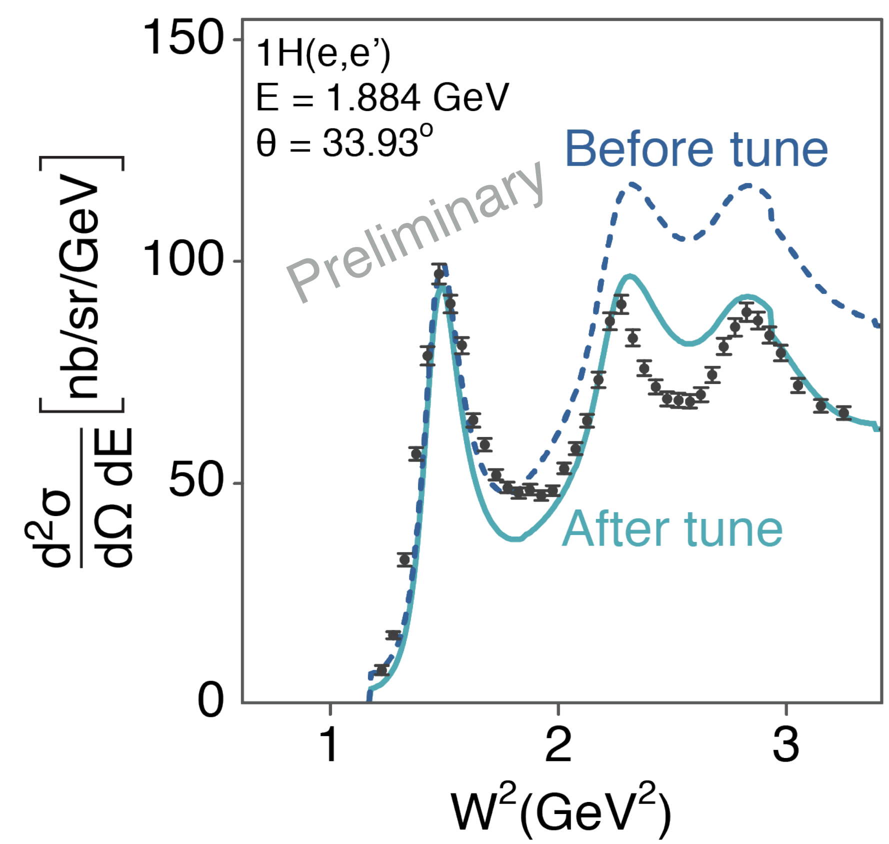
Working on:

New dataset including Argon

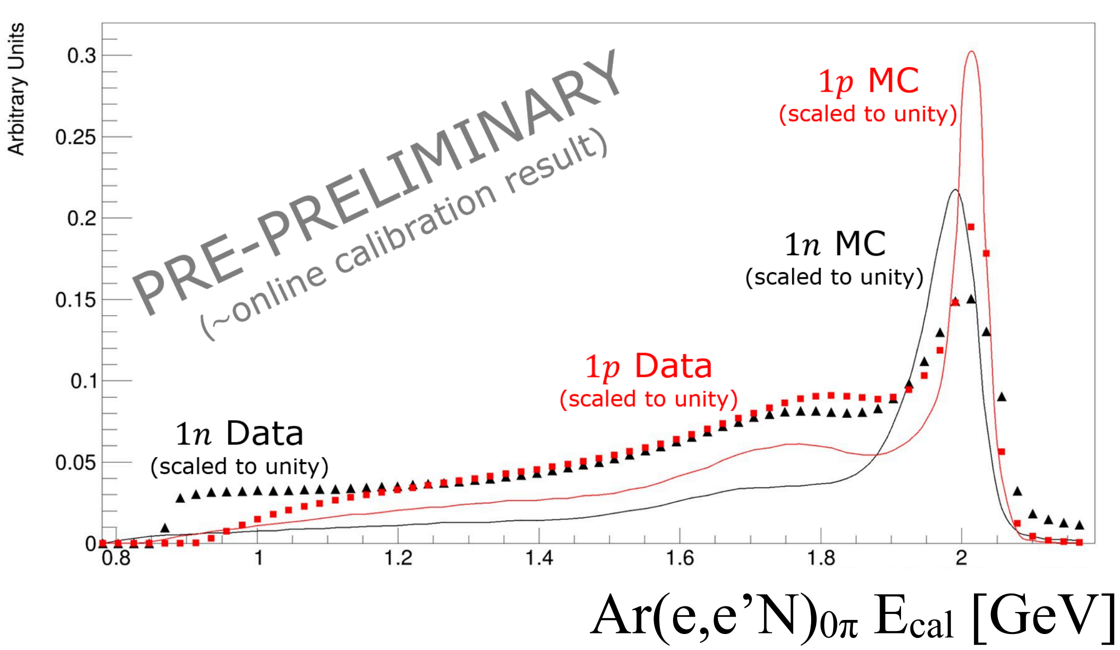
Multi differential analysis

Pion production

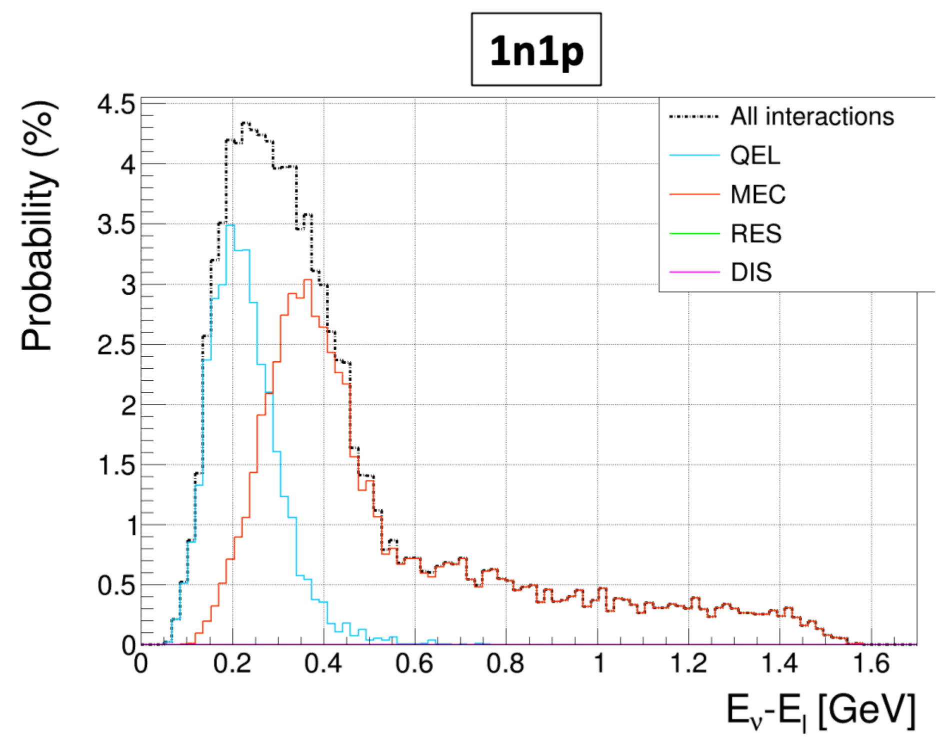
Two nucleon final state

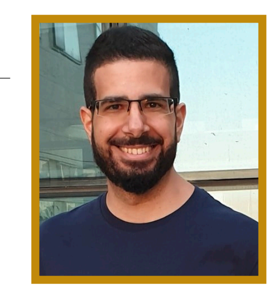


Julia Tena Vidal



Joshua Barrow

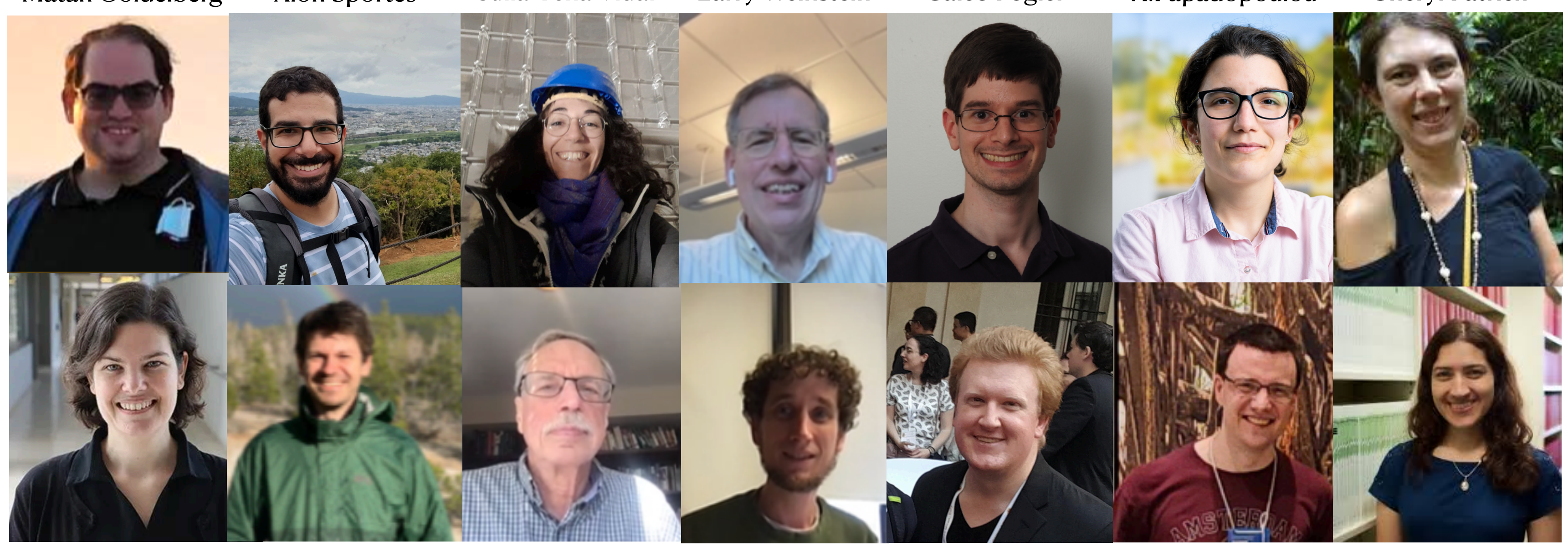




Alon Sportes

The e4ν Collaboration

Matan Goldelberg | Alon Sportes | Julia Tena Vidal | Larry Weinstein | Caleb Fogler | A.Papadopoulou | Cheryl Patrick



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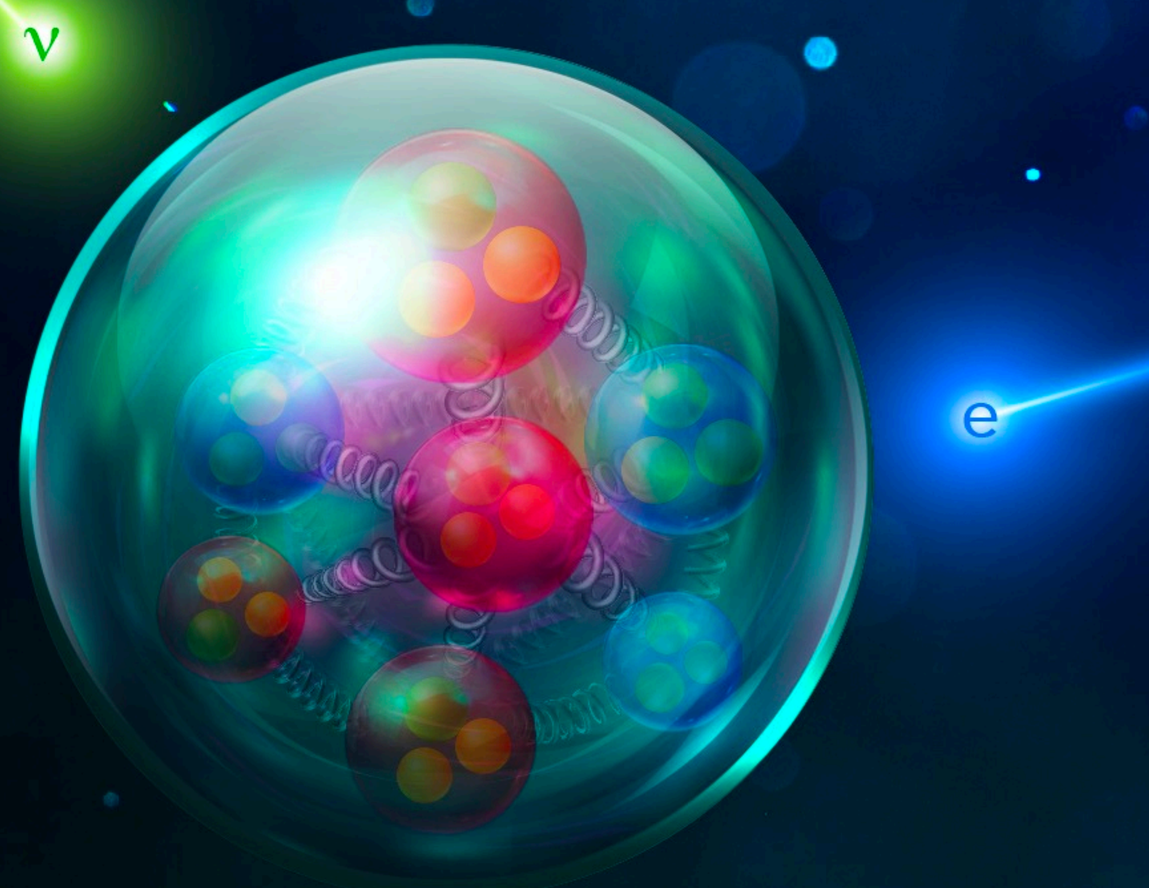
Summary

νA interaction uncertainties limit oscillation parameters extraction

Showing first use of semi-exclusive eA data to explore νA uncertainties

Data/model disagreement even for electron QE-like events, and in the various background signatures.



Time to utilize these datasets to constrain or models and get ready for the coming exciting years

Thank you for your attention