The Nuclear Aspects of Neutrino Oscillation Experiments

The 61st International Winter Meeting on Nuclear Physics
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Neutrino Physics

The Neutrino sector might hint to physics beyond the Standard Model

ν_e ν_μ ν_τ

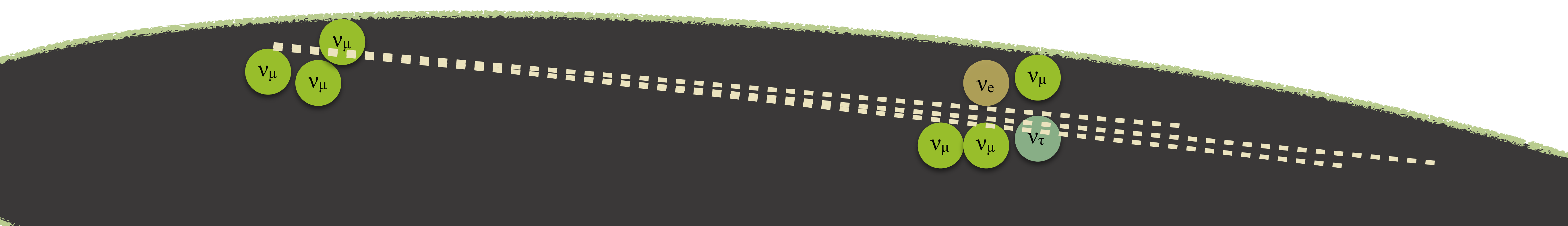
Neutrino oscillate from one flavour to another

Implying their mass and imposing many questions:

What is their mass ordering?

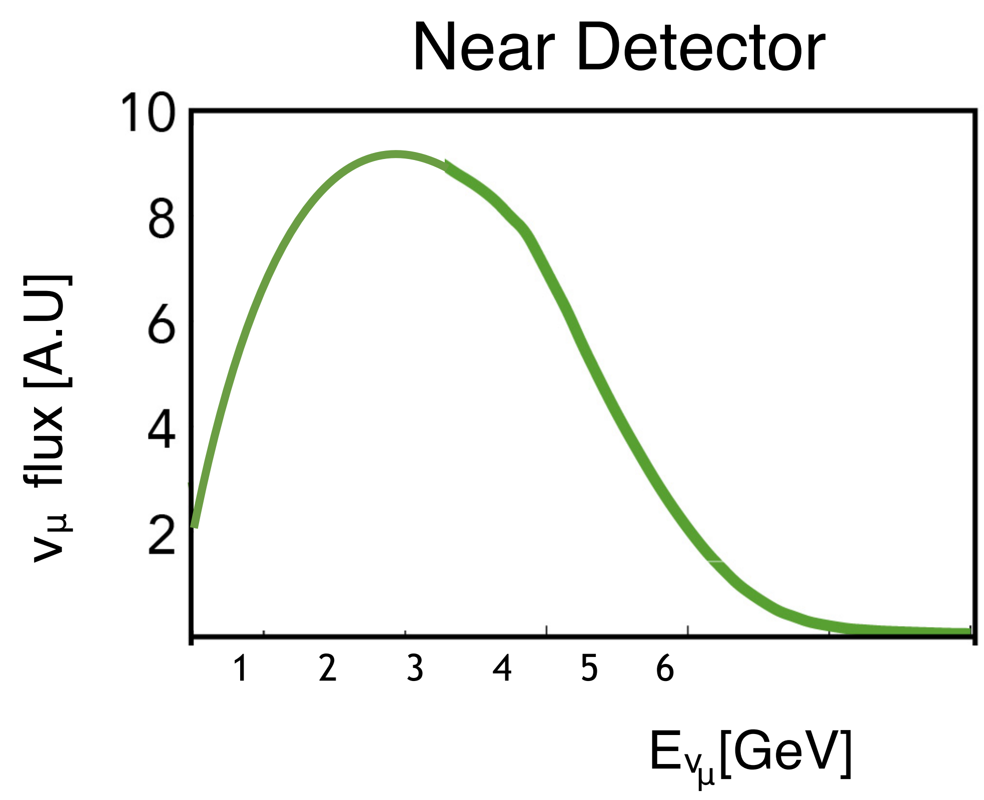
Is CP symmetry violated?

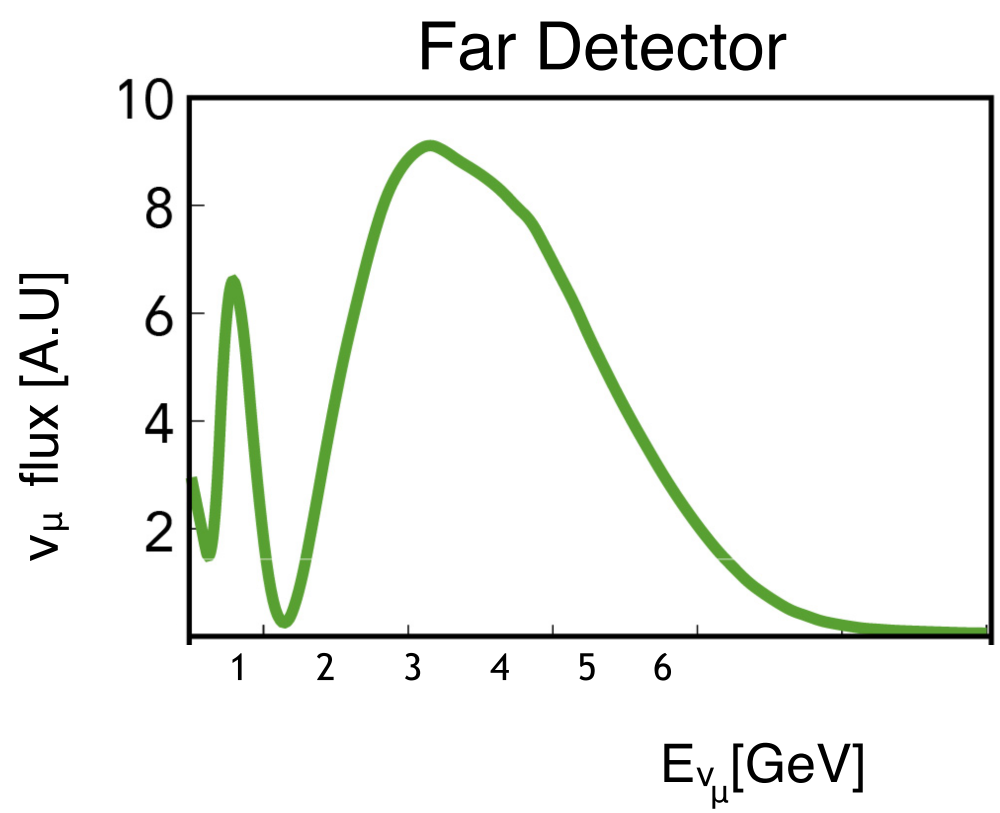
Are there more than the 3 light neutrinos?

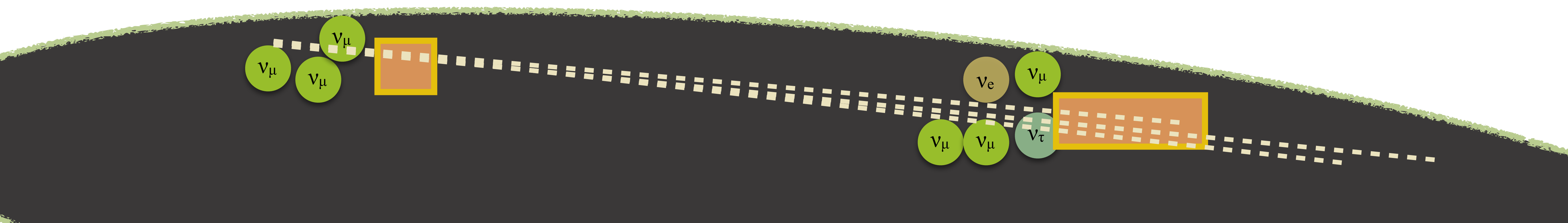


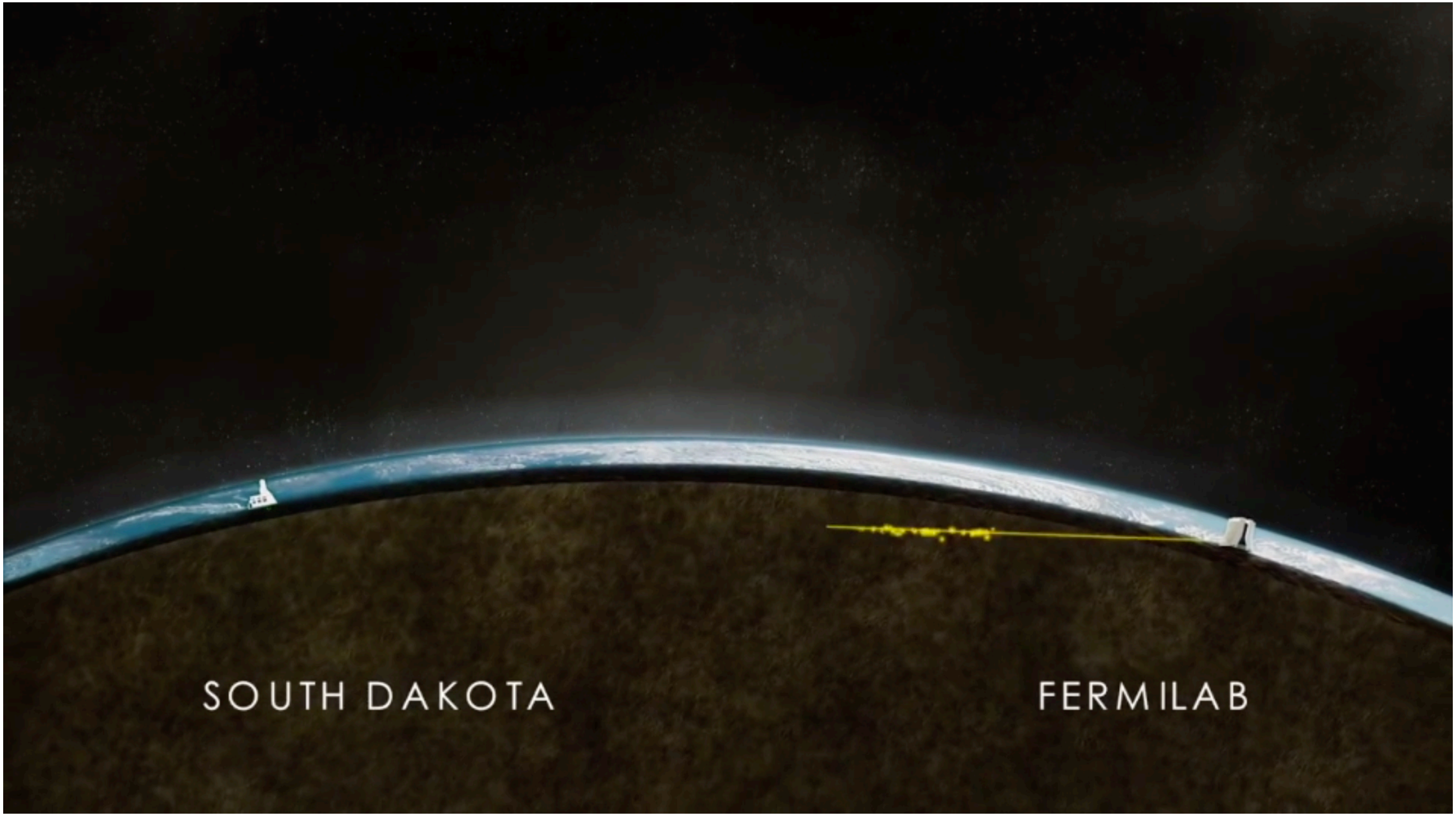
The challenge - next generation high precision

Oscillation experiments aim to answer the CP nature and the mass ordering of neutrinos as well as search for new physics



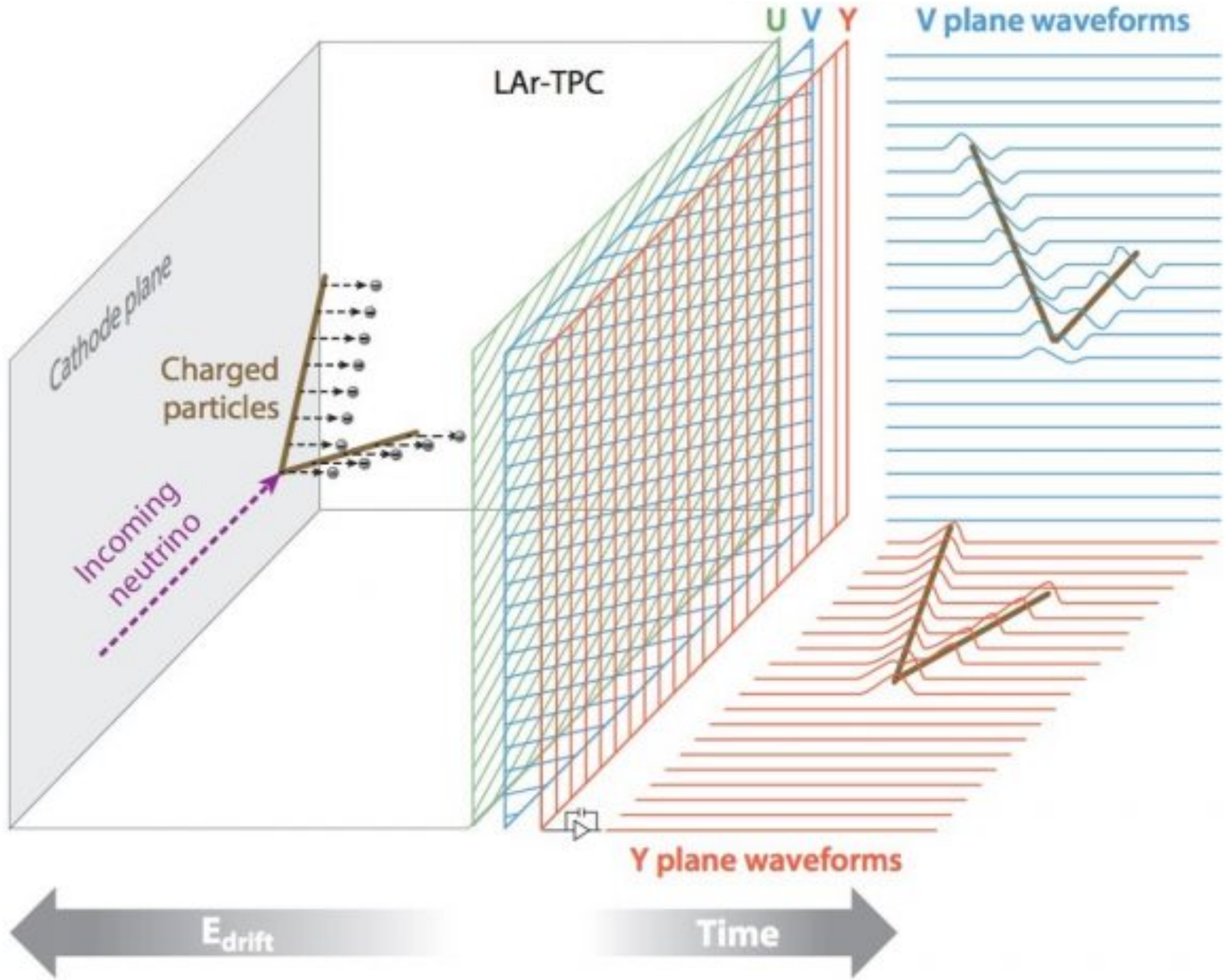






Long Baseline 1300 km, active mass ~70 kton
Sensitivity to: $\theta 23$, $\theta 13$, δCP, Mass ordering

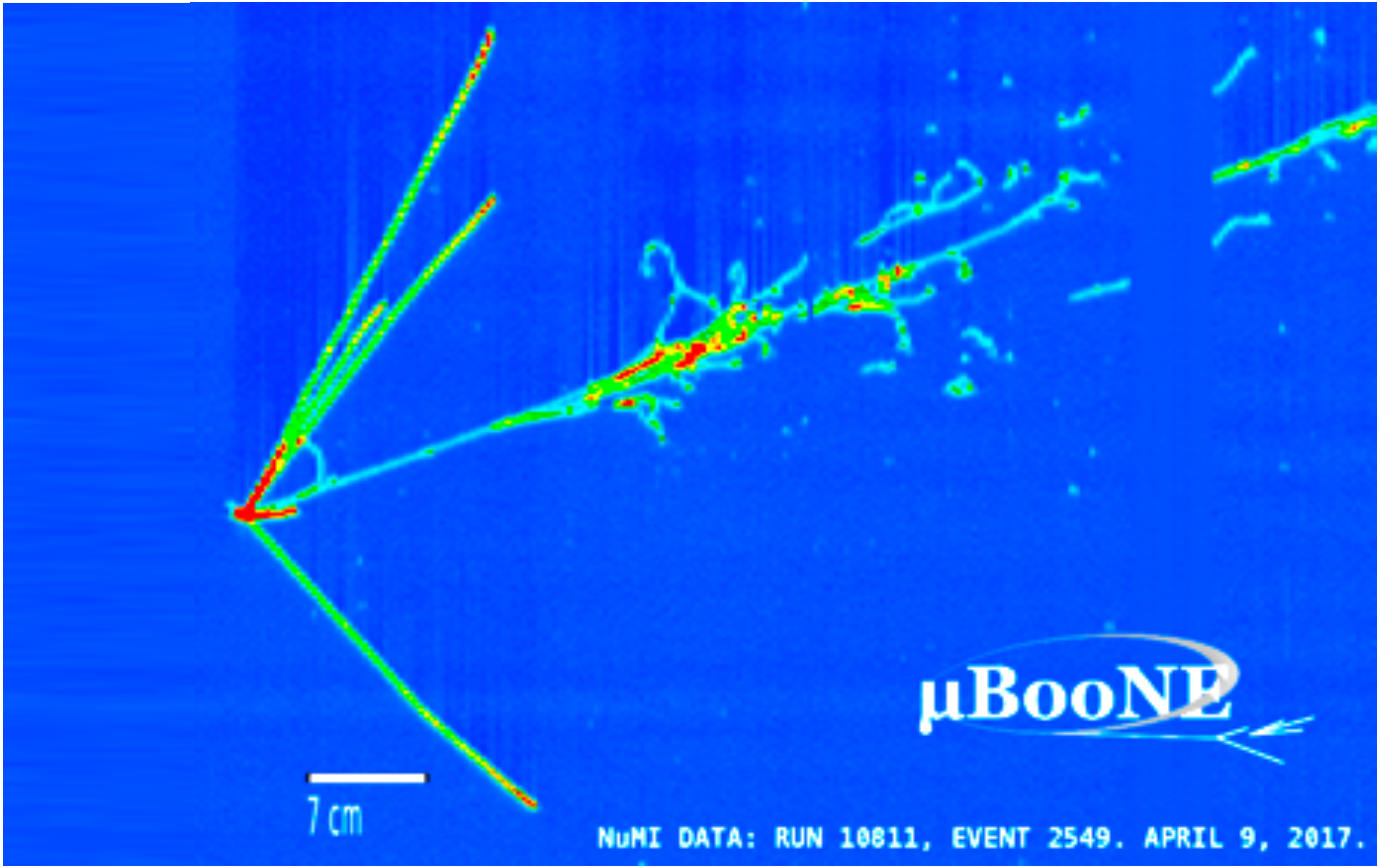
LAr Time Projection Chamber Technology



LAr Time Projection Chamber   Active mass : 85 tons

Triggered by PMTs, 3 wire planes with 3 mm spacing

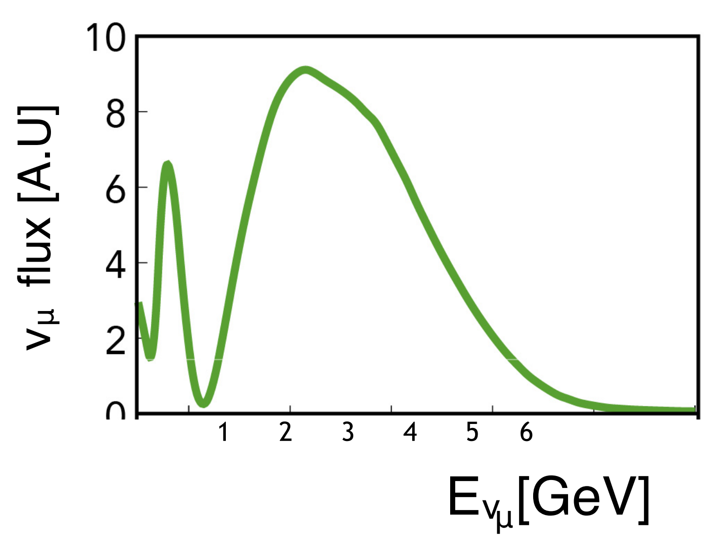
impeccable spatial resolution, calorimetric measurement

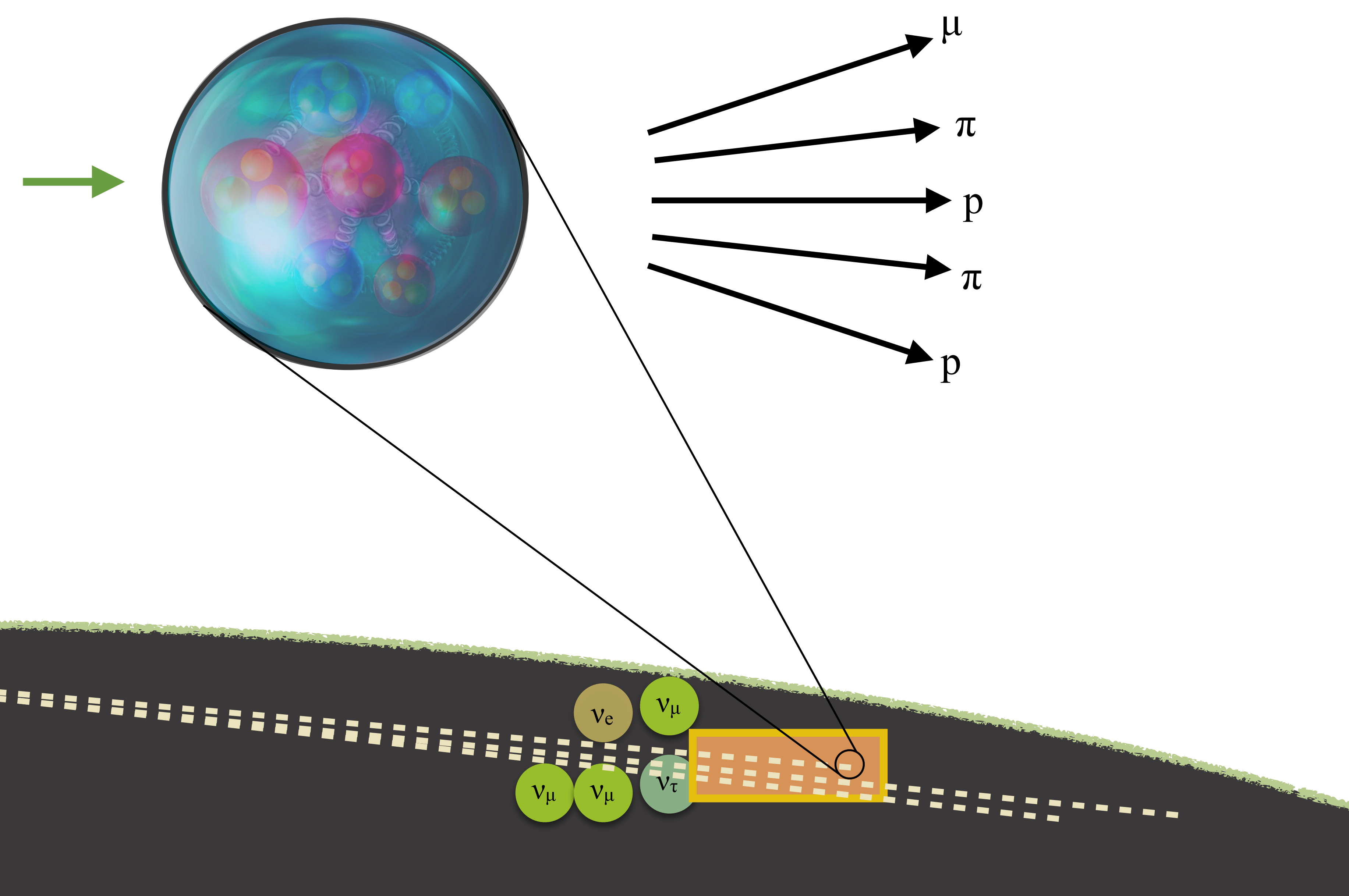

μBooNE
7 cm
NuMI DATA: RUN 10811, EVENT 2549. APRIL 9, 2017.

The challenge - next generation high precision

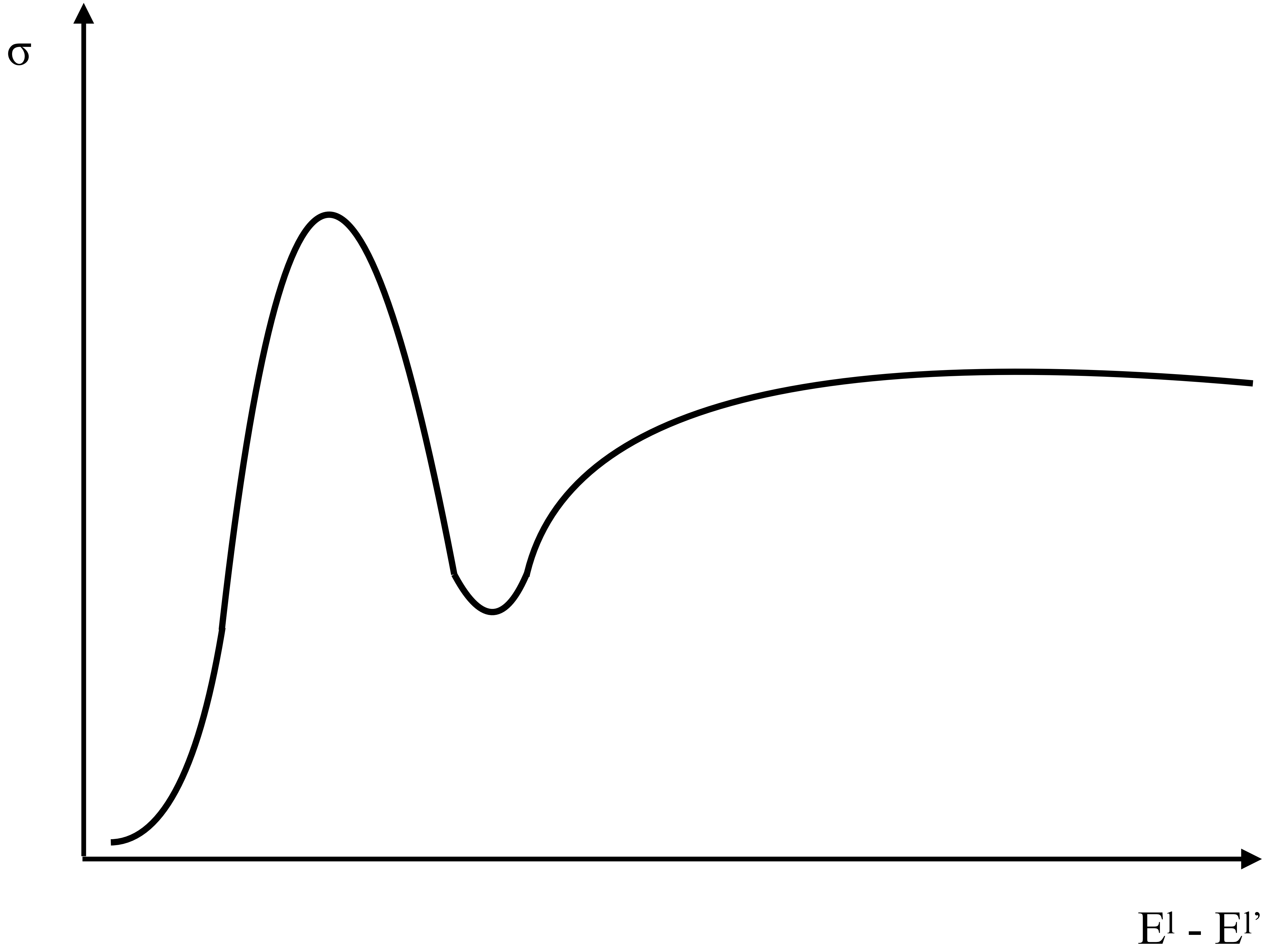
Incoming true flux | Modelling Input | Measurement

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





E Reconstruction Requires Interaction Modelling



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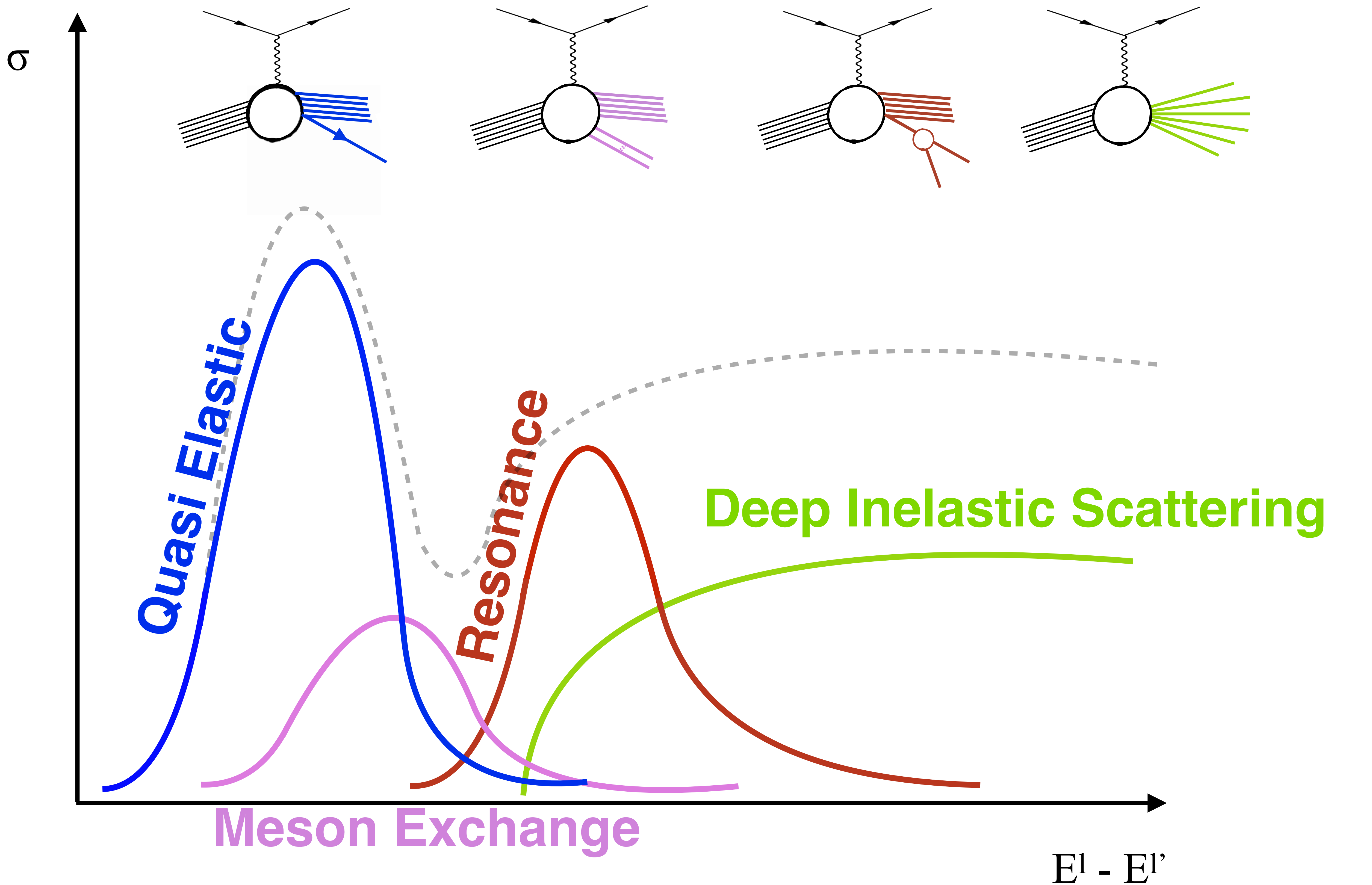
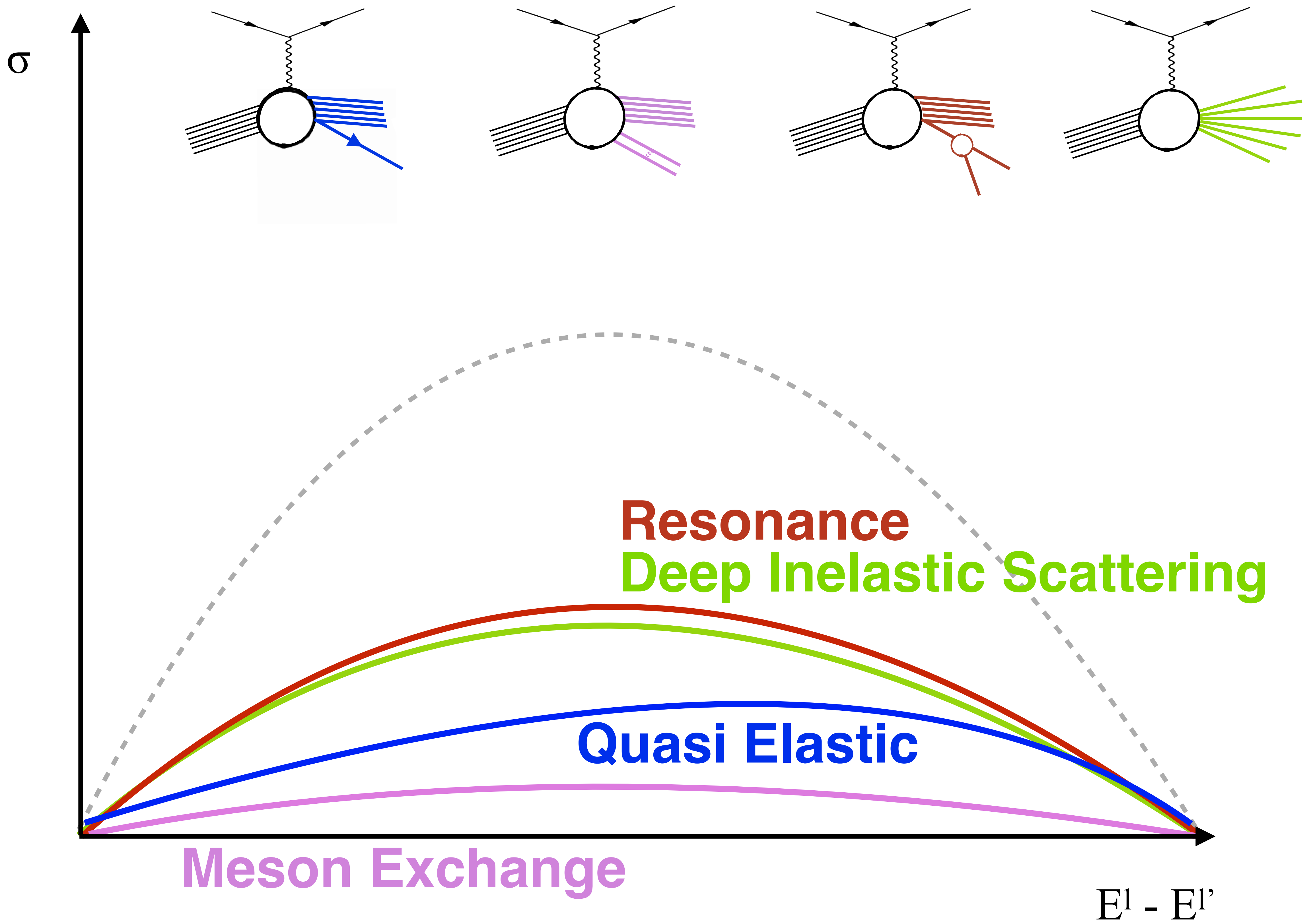
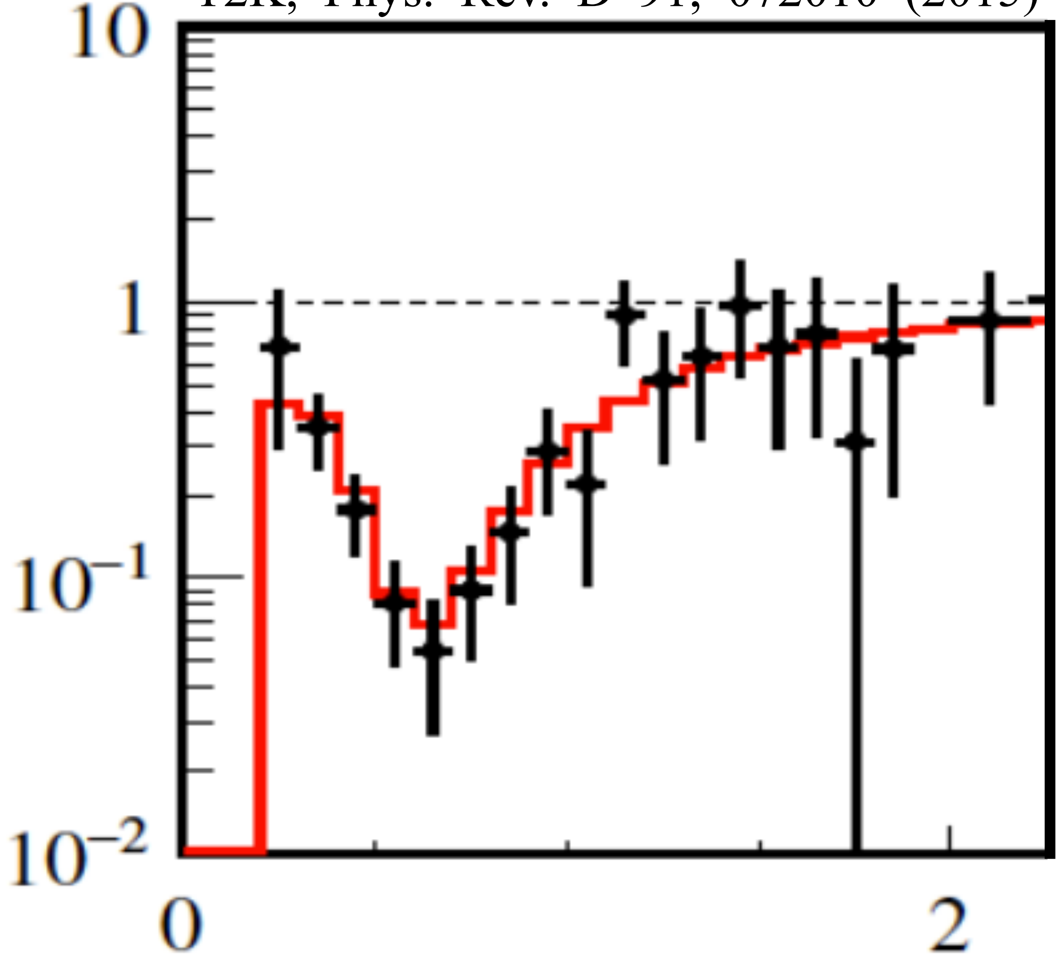


ν Reconstruction Requires Interaction Modelling



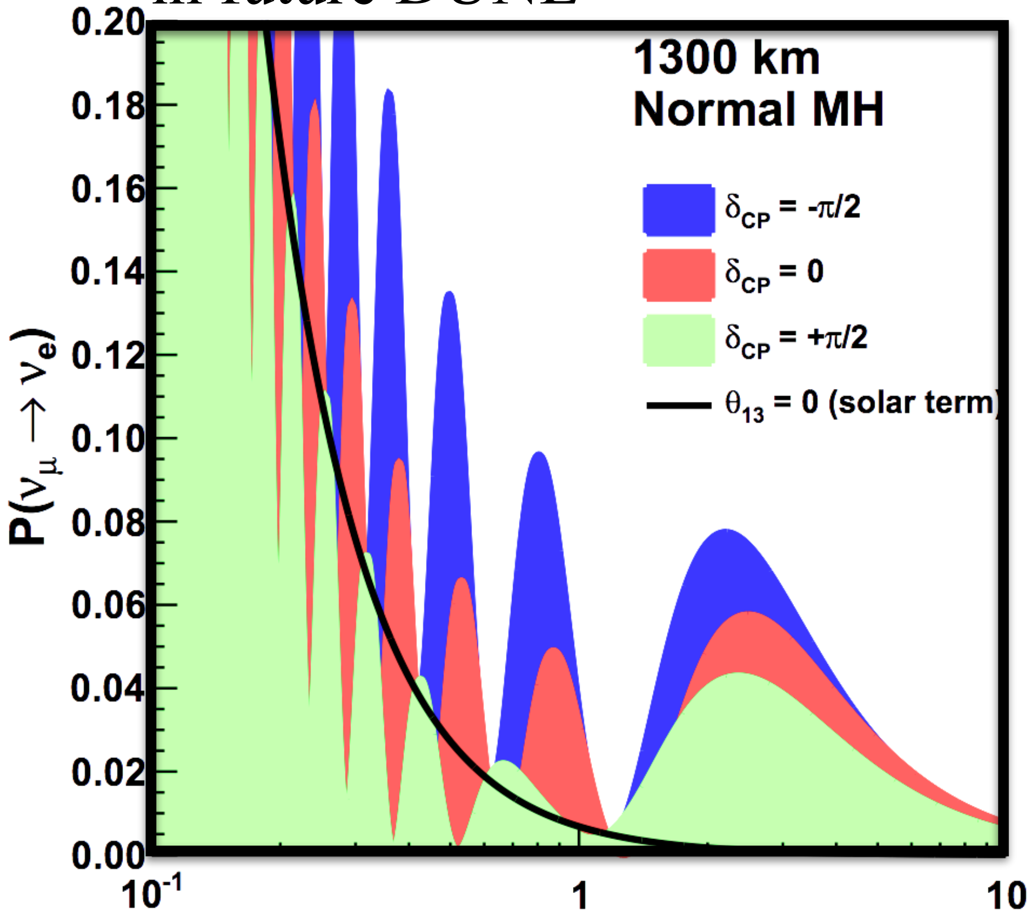
The challenge - next generation high precision

T2K, Phys. Rev. D 91, 072010 (2015)



Neutrino Energy [GeV]

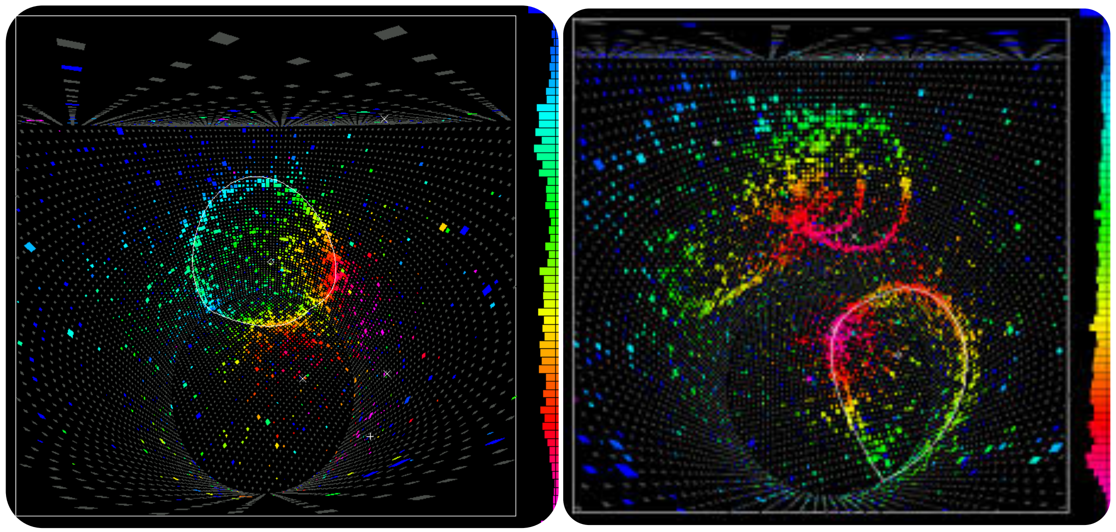
Simulation of oscillation effects in future DUNE



Neutrino Energy [GeV]

Incoming Energy Reconstruction

QE-like events

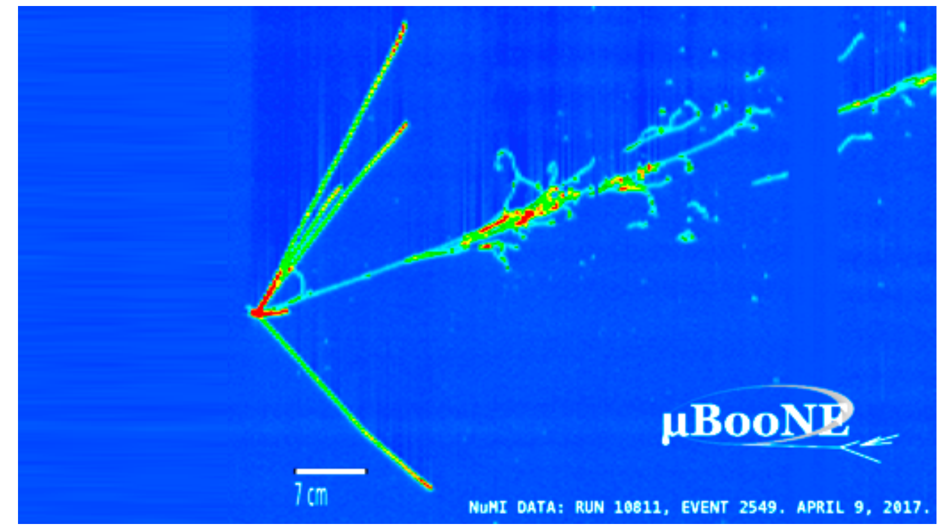


Cherenkov detectors:

Assuming QE interaction

Using lepton only

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



Tracking detectors:

Calorimetric sum

Using All detected particles

$$E_{\text{cal}} = E_l + E_p^{\text{kin}} + \epsilon$$

[1p0π]

ϵ is the nucleon separation energy ~ 20 MeV

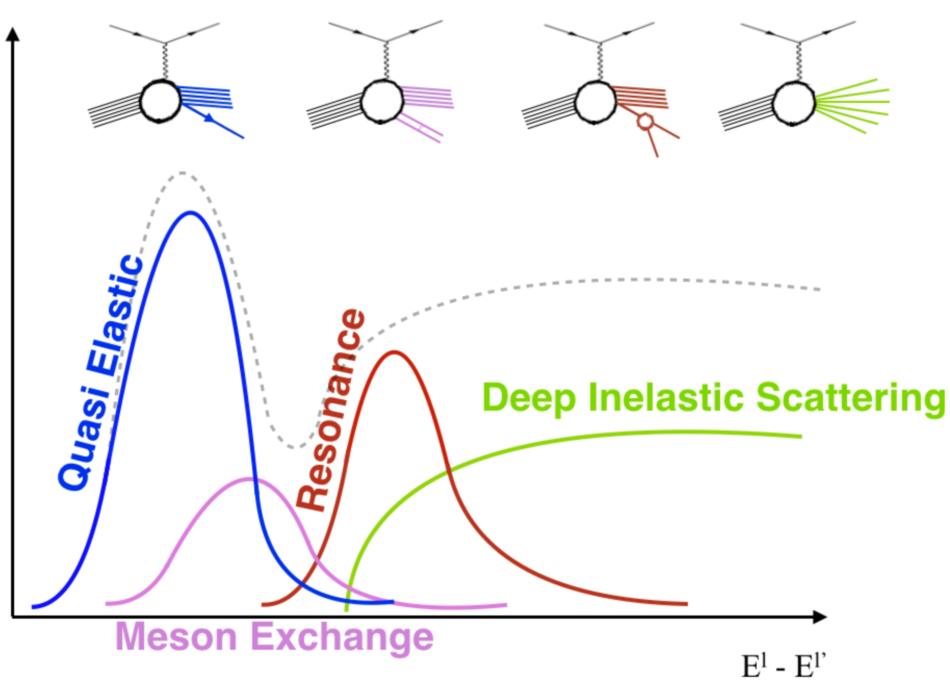
Lepton-Nucleus Interaction Modelling - Need constraints

Neutrino event generators simulating νA interaction

Genie

GiBUU
The Giessen Boltzmann-Uehling-Uhlenbeck Project

and more



Factorisation of

- Initial state
- Each interaction mechanism separately
- Final State Interactions

Empirical or semi classical models with many free parameters

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

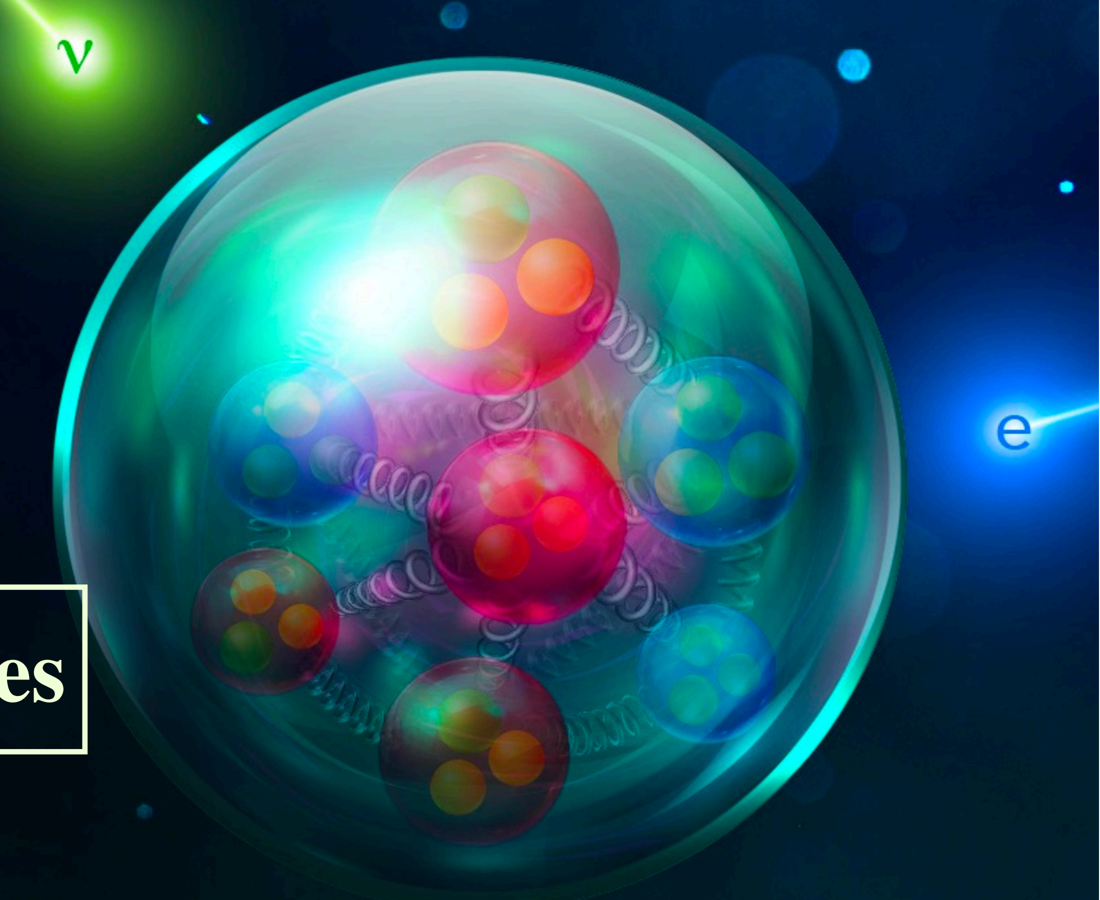
νA scattering

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

Why electrons?

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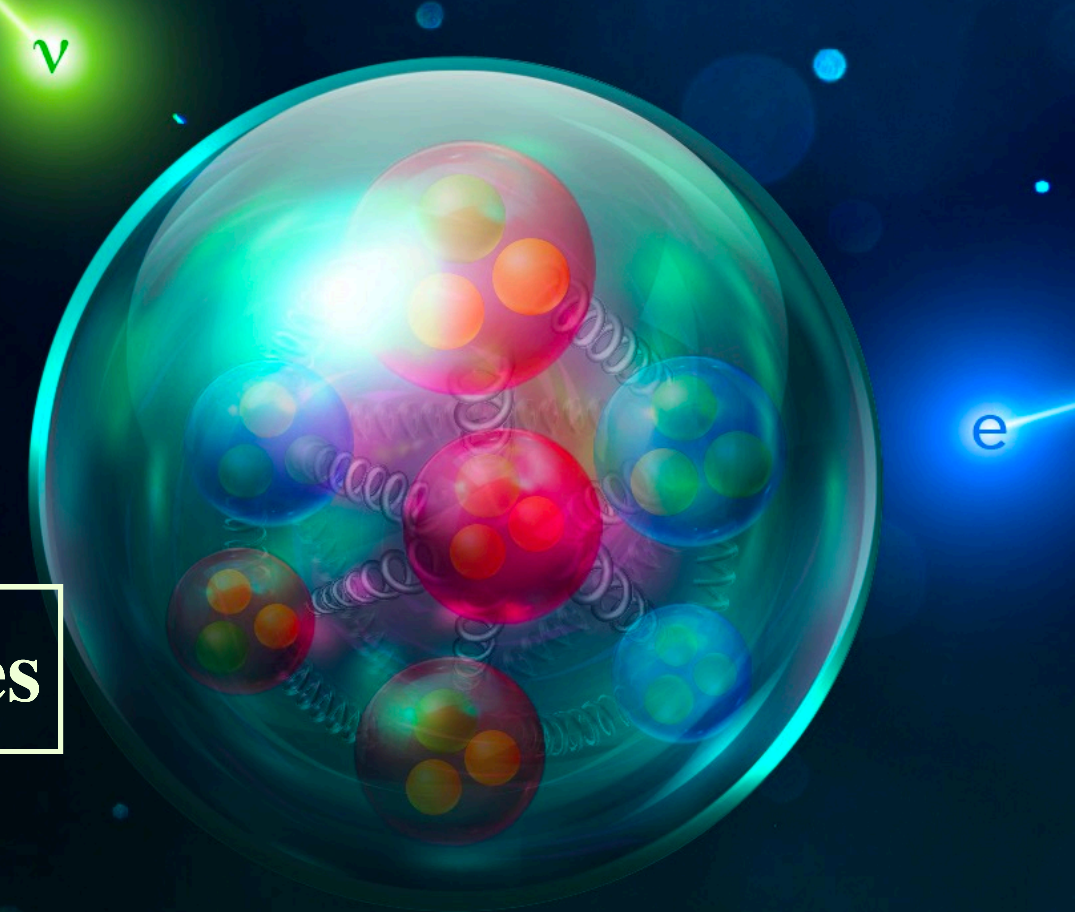


Useful to constrain model uncertainties

Electrons have known energies

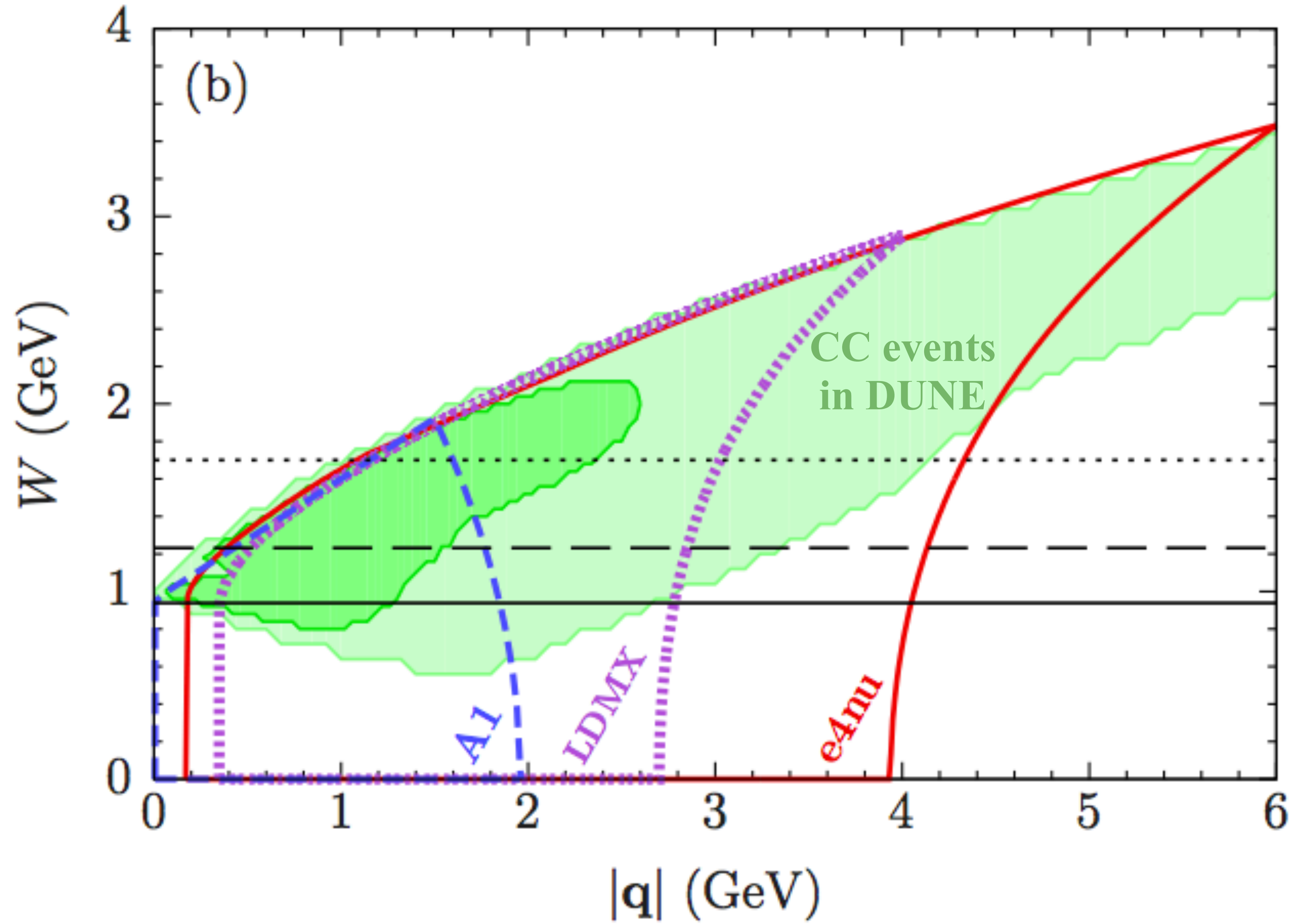
Useful to test incoming energy reconstruction methods

Complementary efforts

Collaborations	Kinematics	Targets	Scattering	Publications
E12-14-012 (JLab) (Data collected: 2017)	$E_e = 2.222$ GeV $\theta_e = 15.5, 17.5, 20.0, 21.5$ $\theta_p = -39.0, -44.0, -44.5, -47.0, -50.0$	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)	$E_e = 1, 2, 4, 6$ 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)	$E_e = 1.6$ GeV	H, D, He C, O, Al Ca, Ar, Xe	(e, e') 2 additional charged particles	
LDMX (SLAC) (Planned)	$E_e = 4.0$ GeV $\theta_e < 40$		(e, e') e, p, n, π in the final state	
eALBA (Planned)	$E_e = 500$ 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

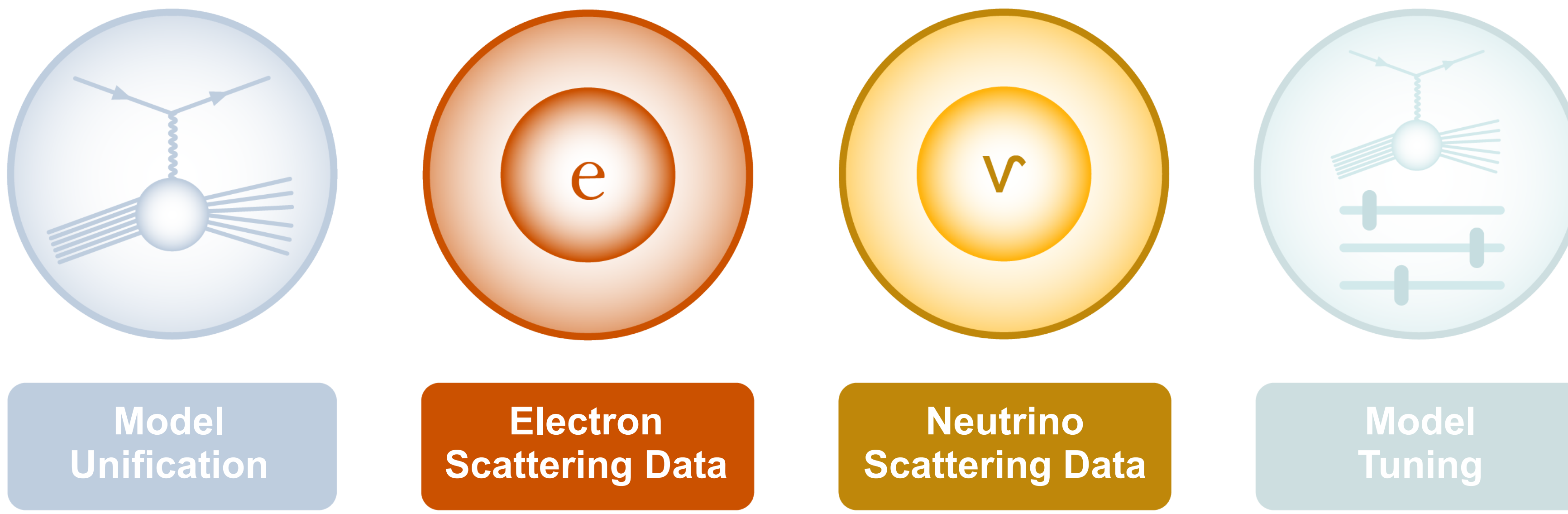


arXiv:2203.06853v1 [hep-ex]
A NF06 Contributed White Paper

e4ν demonstrate best coverage.

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

e4ν Getting Ready for DUNE



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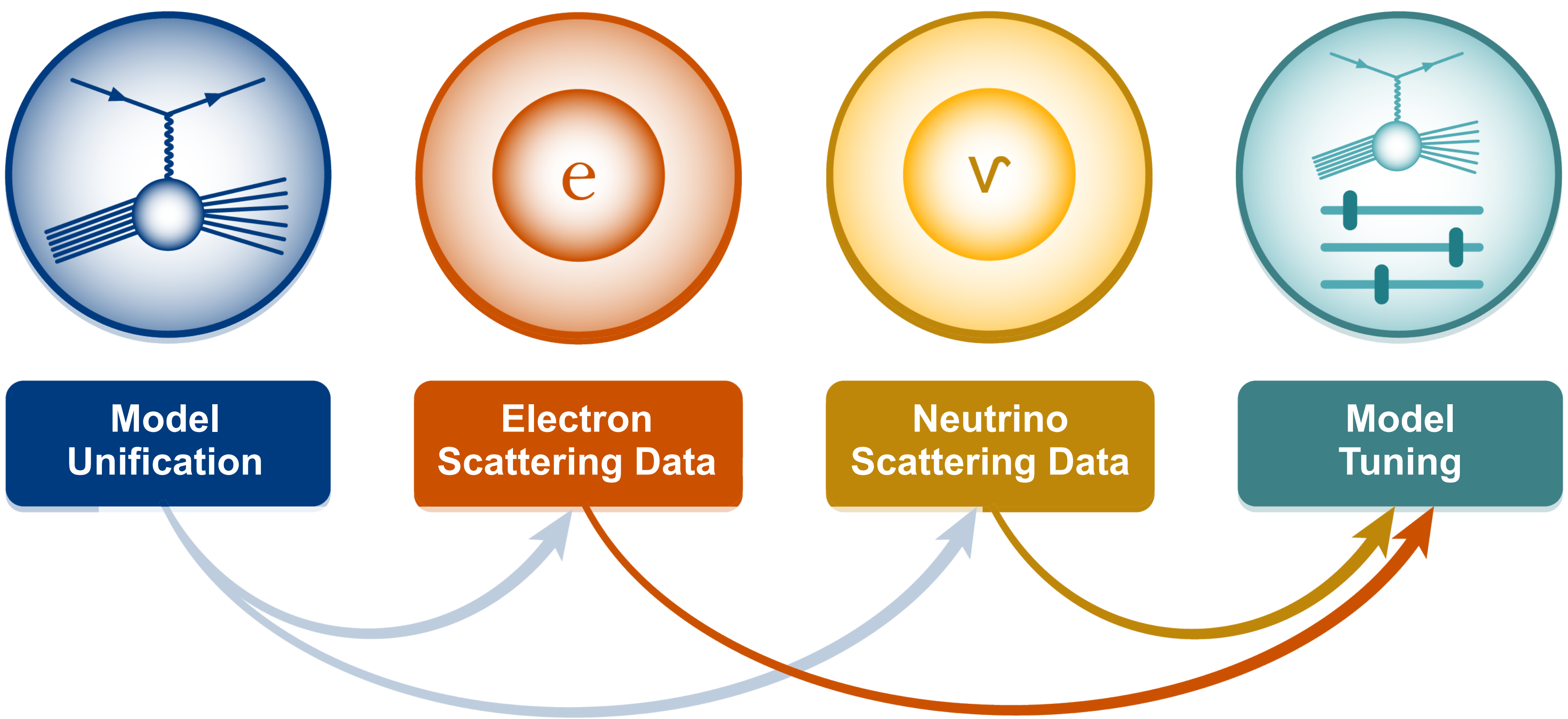
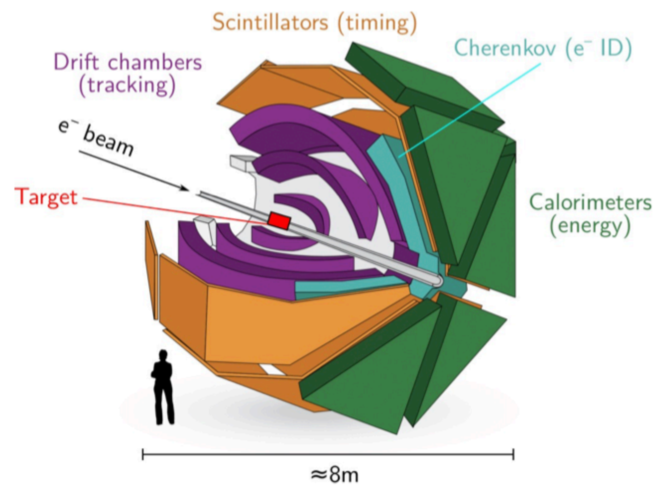
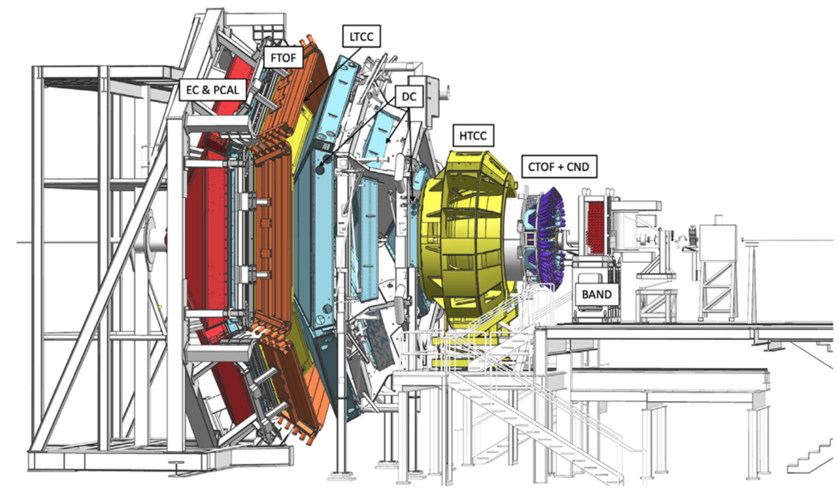


Hadron production with CLAS

Jefferson Lab





	CLAS	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	~10M C(e,e') events	~100M ^{40}Ar (e,e') events

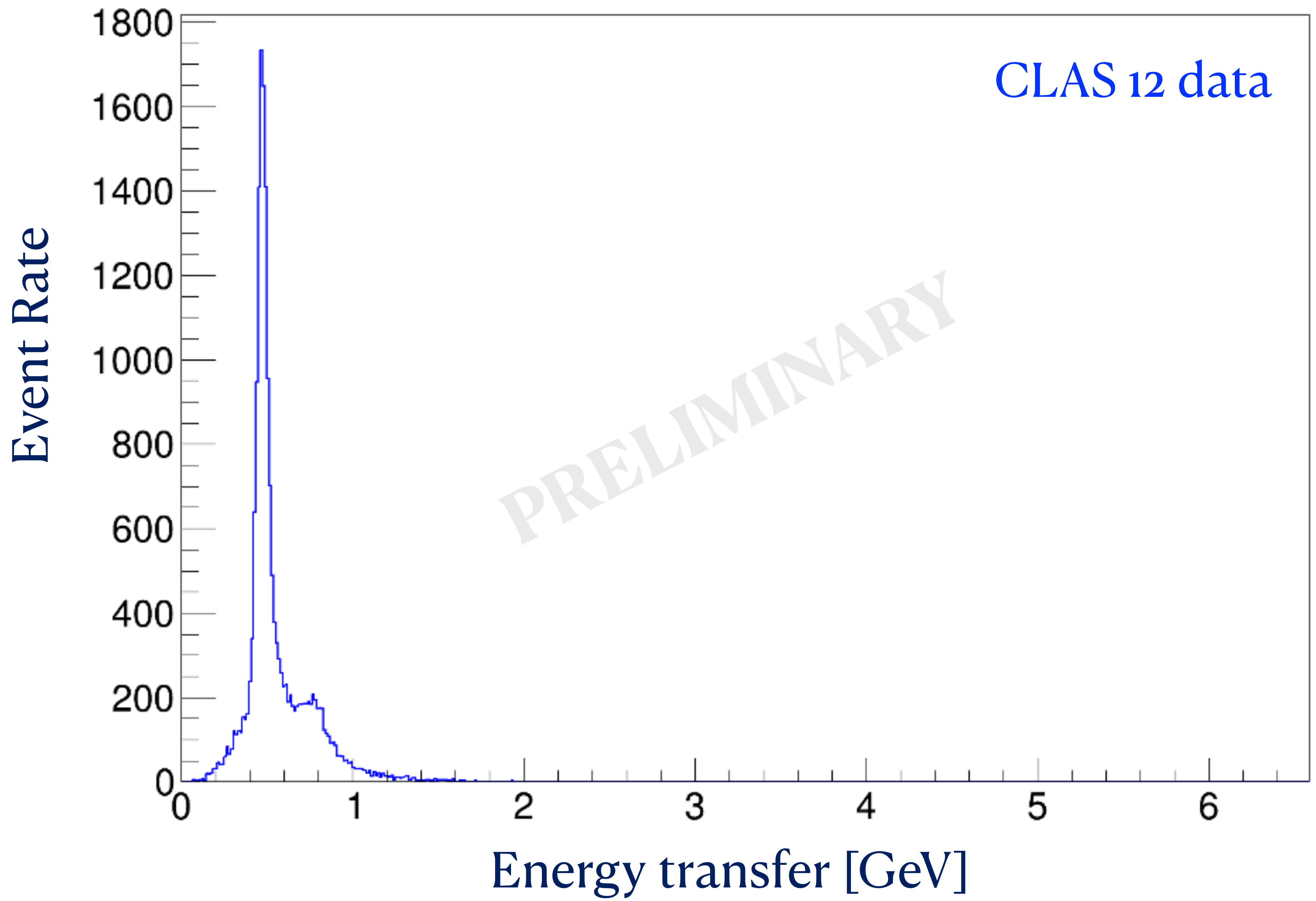
Data

Towards new Inclusive results on Ar

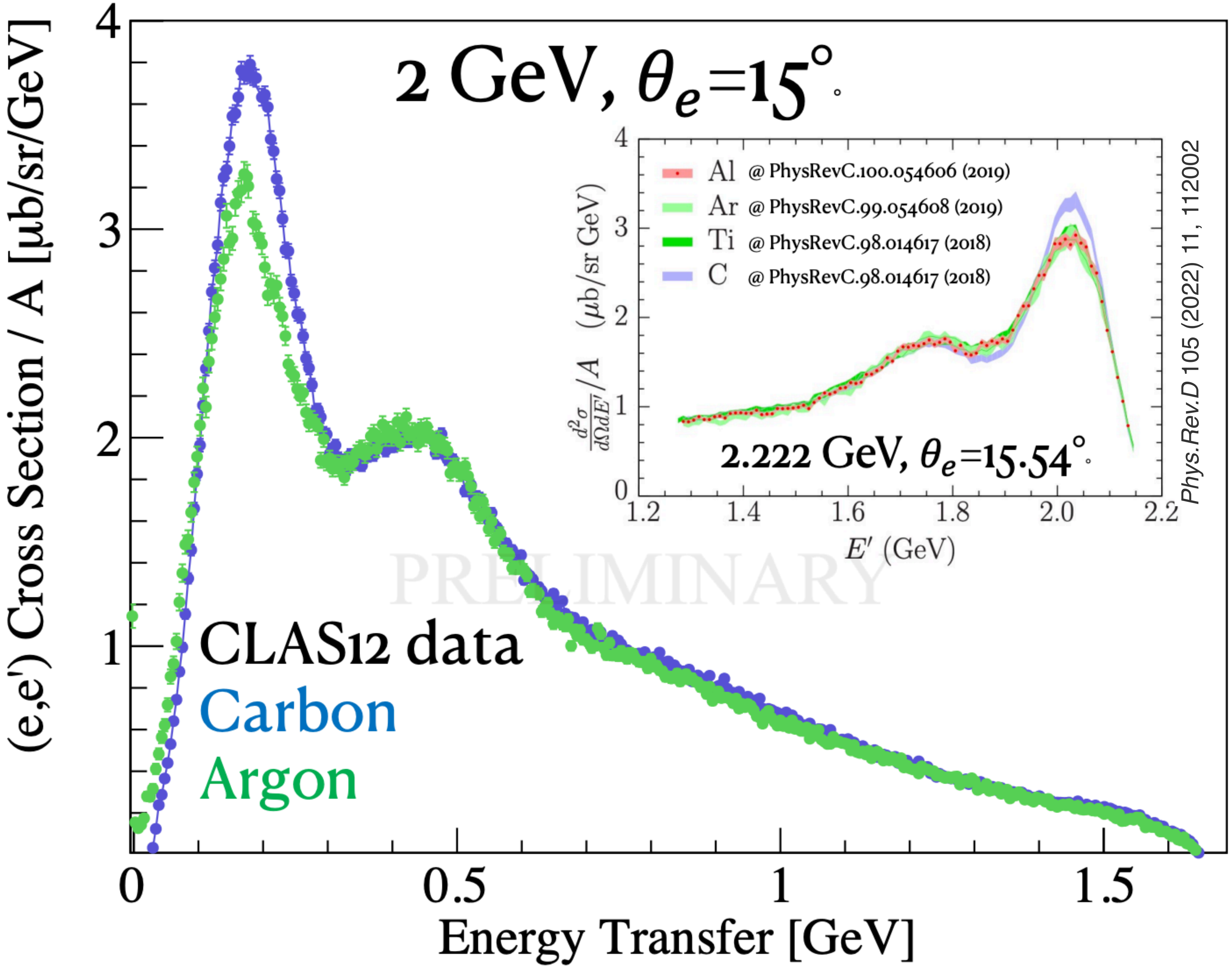
Matan Goldenberg

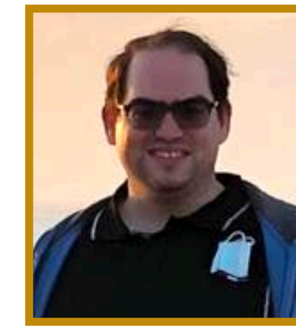
^{2}H at 6GeV

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



Towards new Inclusive results on C, Ar

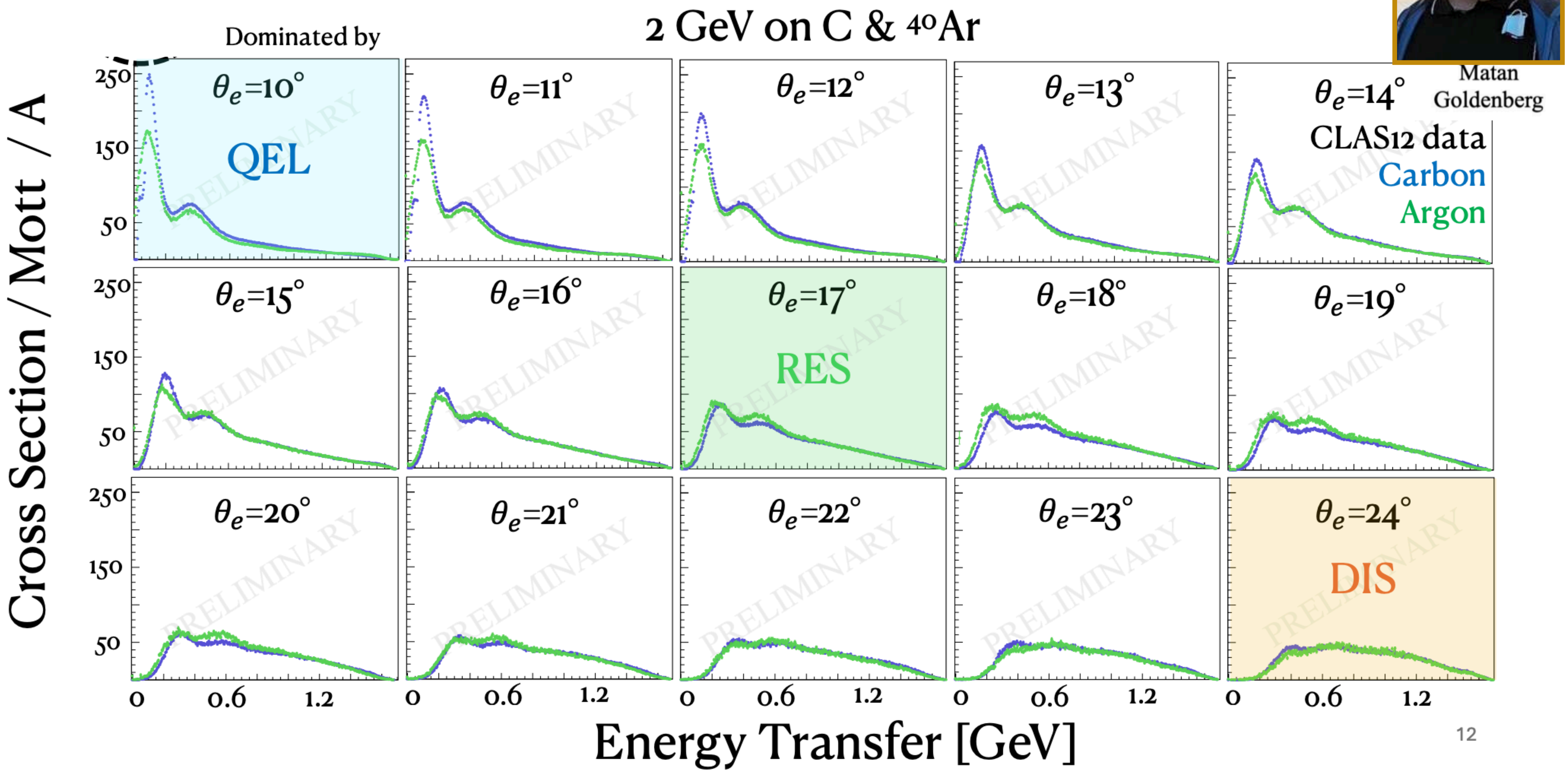




5,14.5]°

$\theta_e \in$ [17.5,18.5]°

Unprecedented Inclusive Angular Coverage



1p0π Event Selection

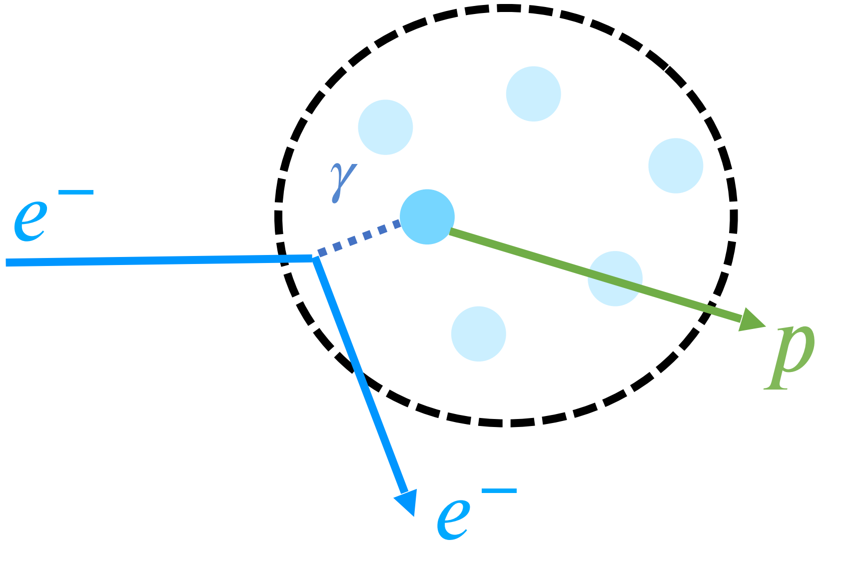
Focus on Quasi Elastic events:

1 proton above 300 MeV/c

no additional hadrons above detection threshold:

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

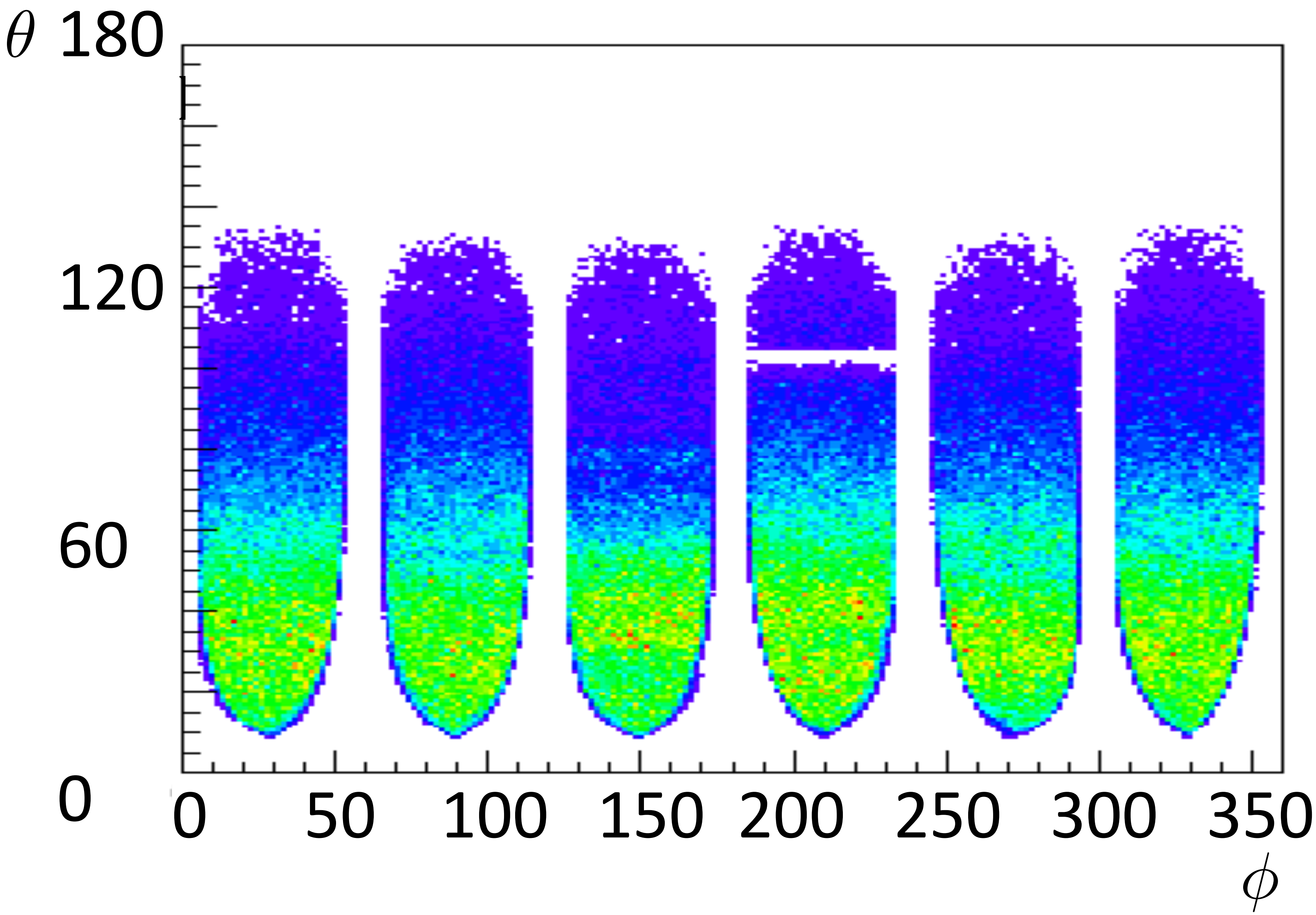
500 MeV/c for P_{π^0}

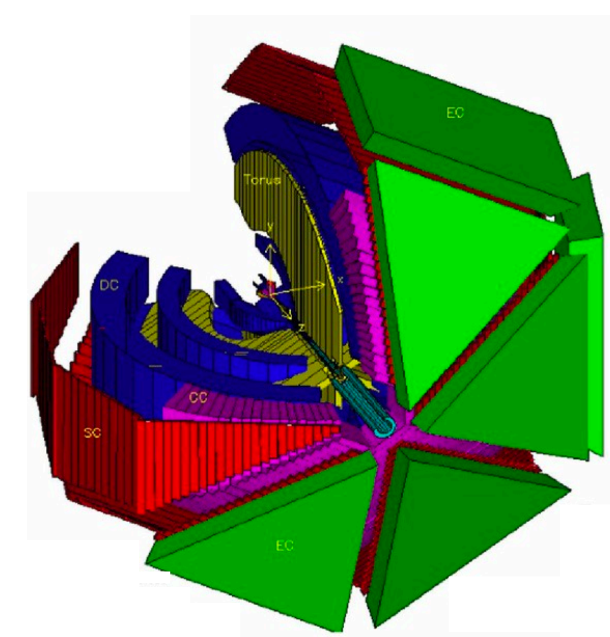


Background Subtraction

Different interaction lead to multi-hadron final states

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





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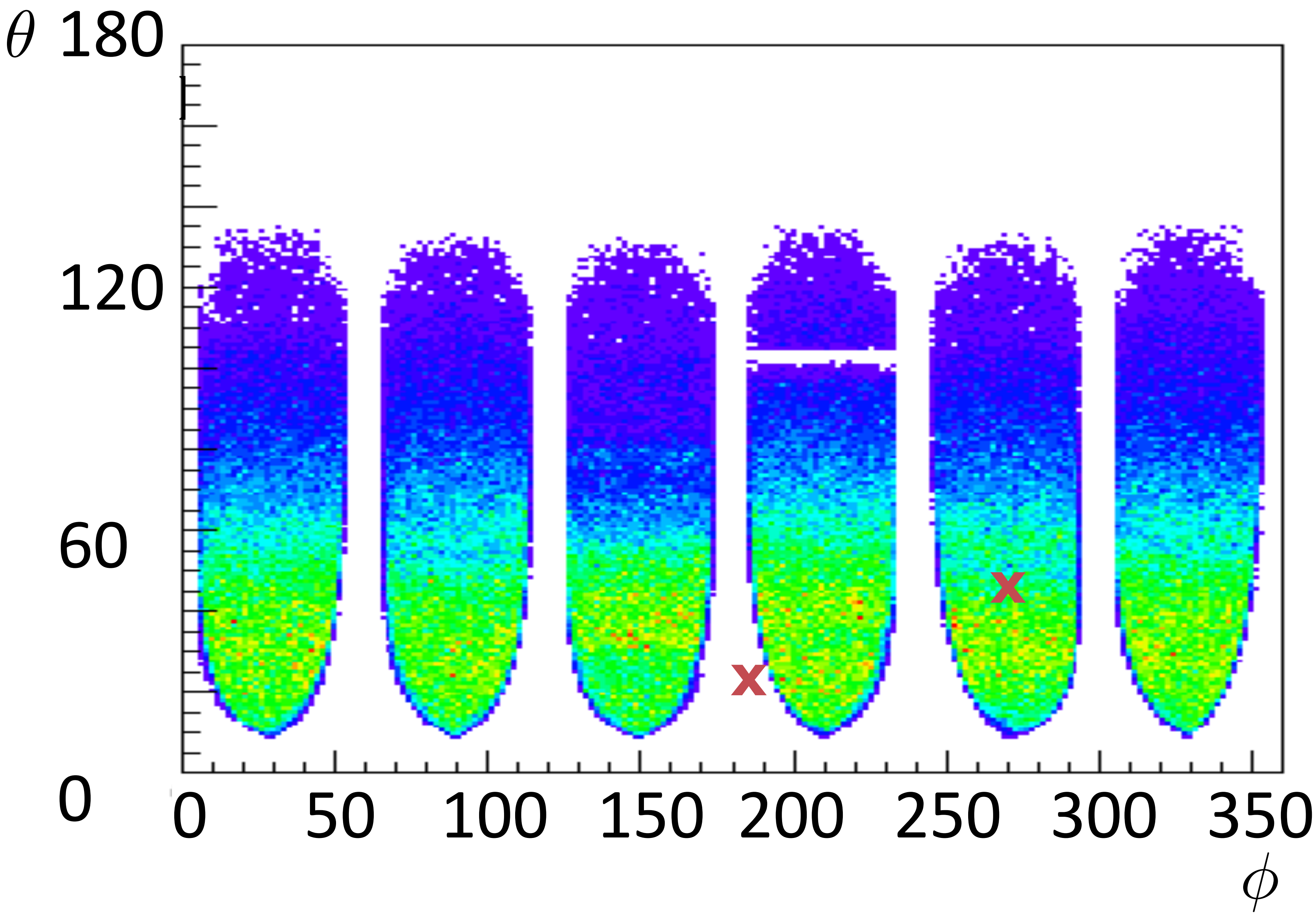
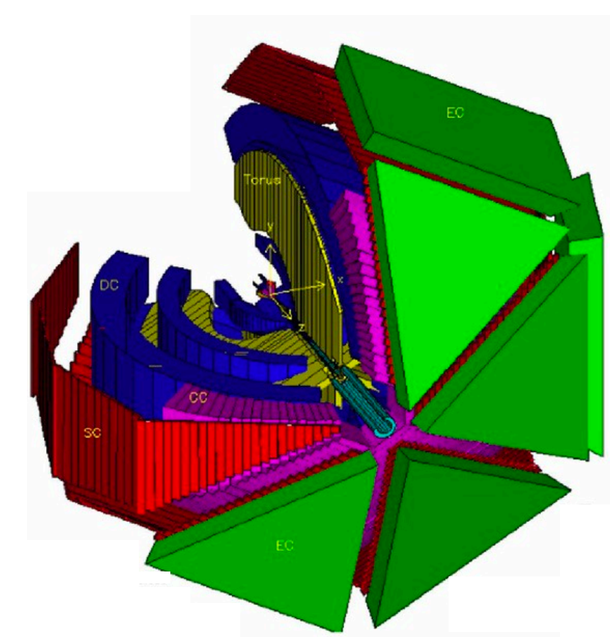
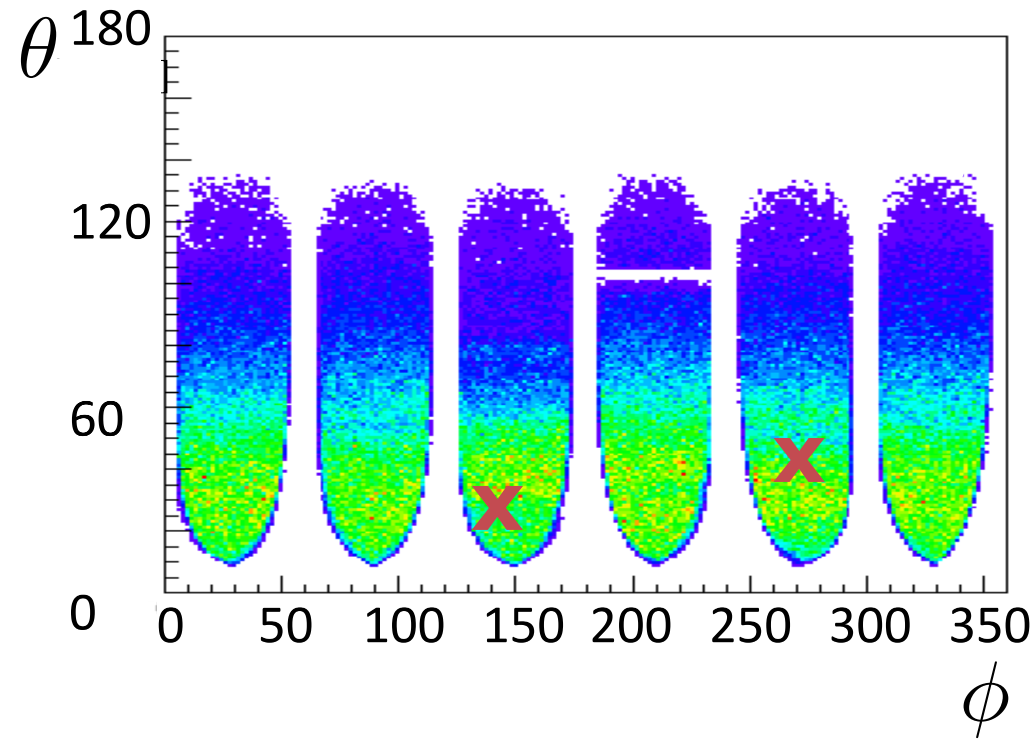


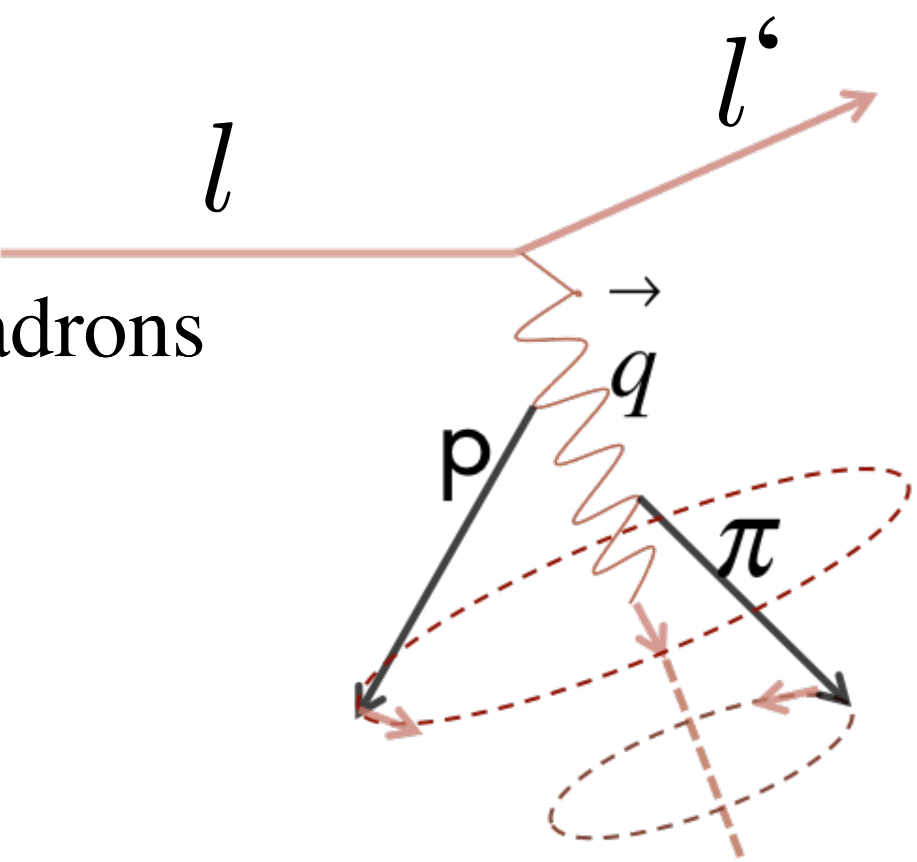


Data Driven Background Subtraction

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

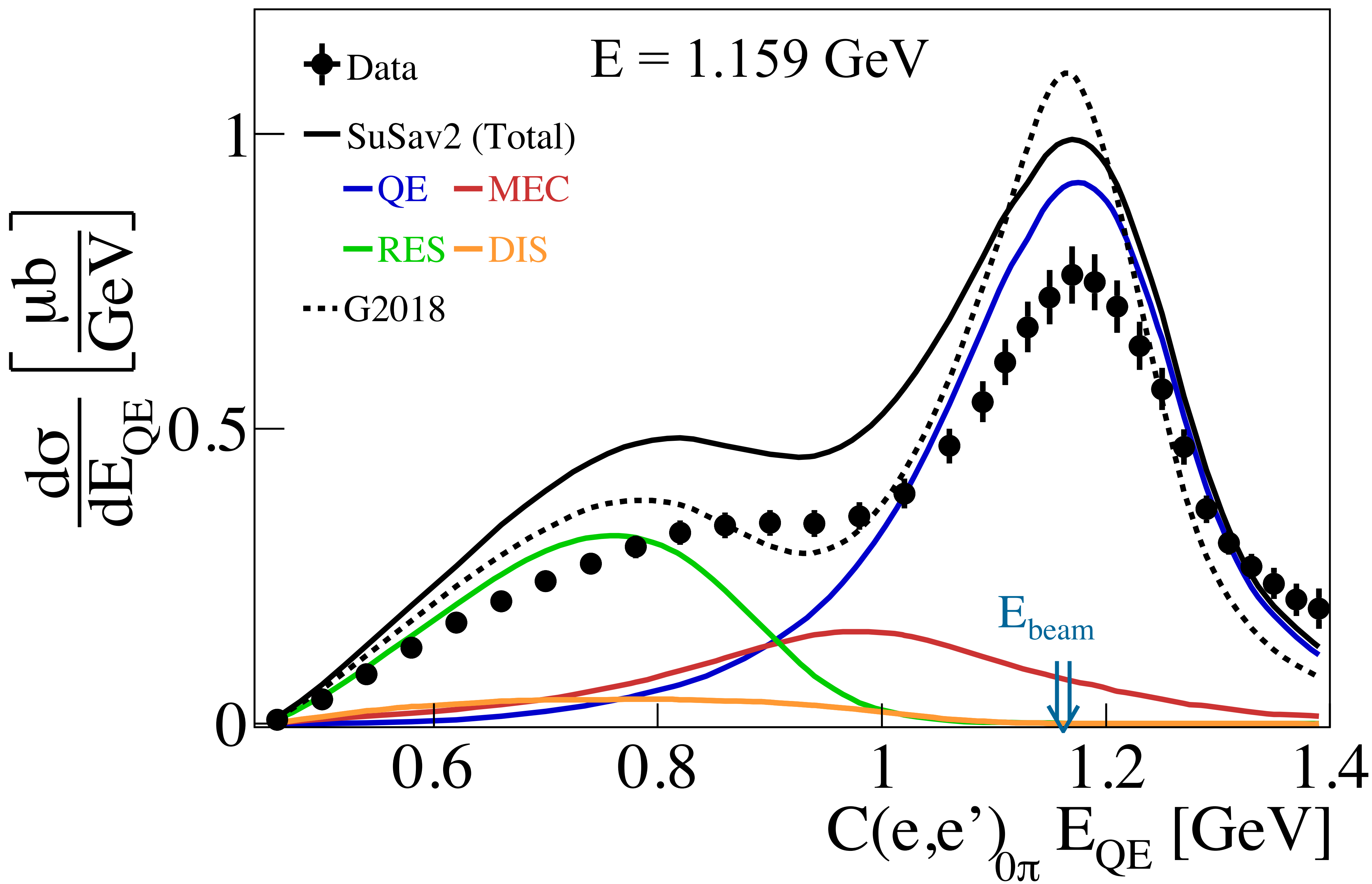


- Same for final states with more than 2 hadrons



Julia
Tena Vidal

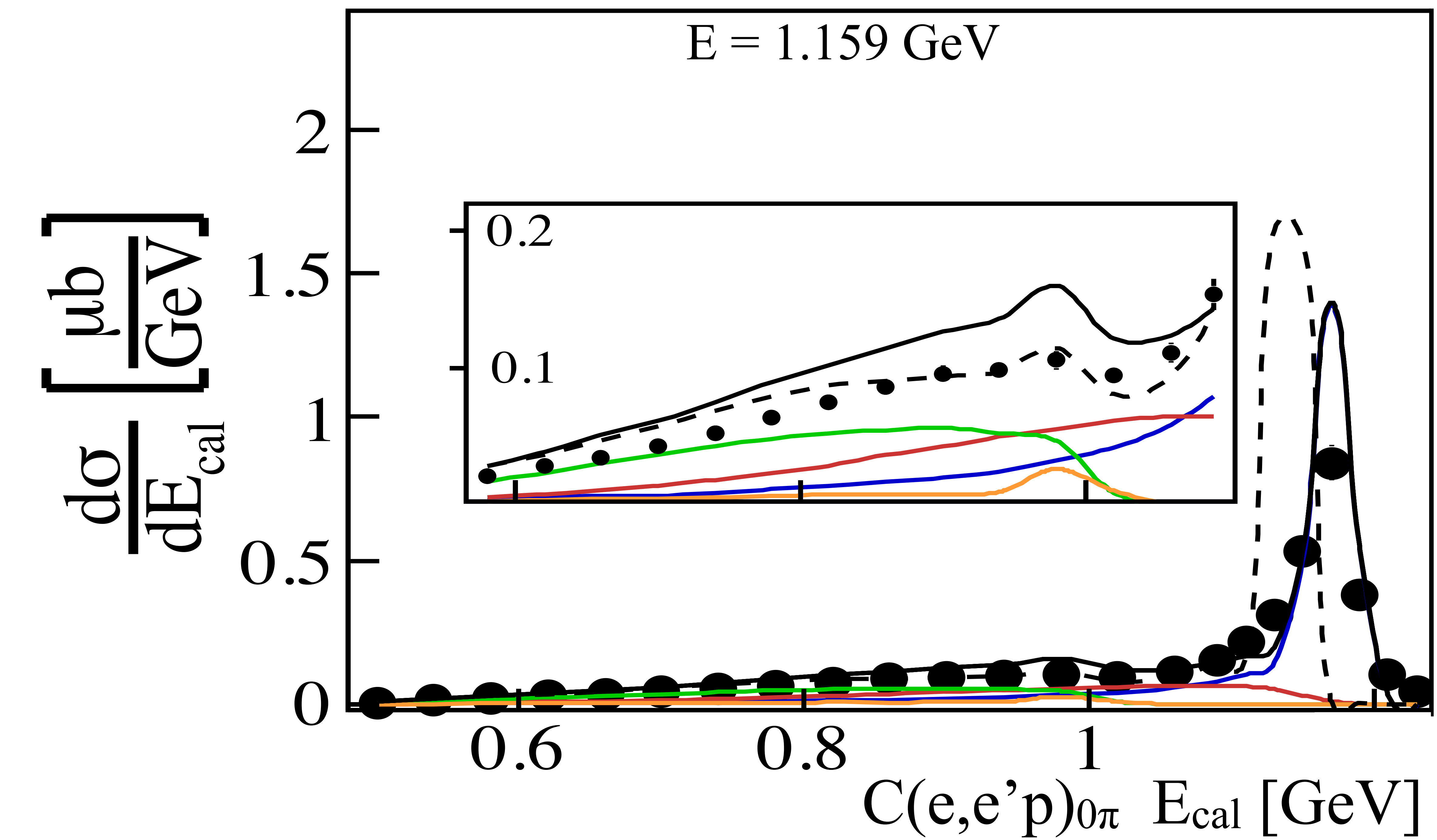
Inclusive Energy Reconstruction



Nature **599**, 565 (2021)

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

Reconstructed Calorimetric Energy



Nature **599**, 565 (2021)

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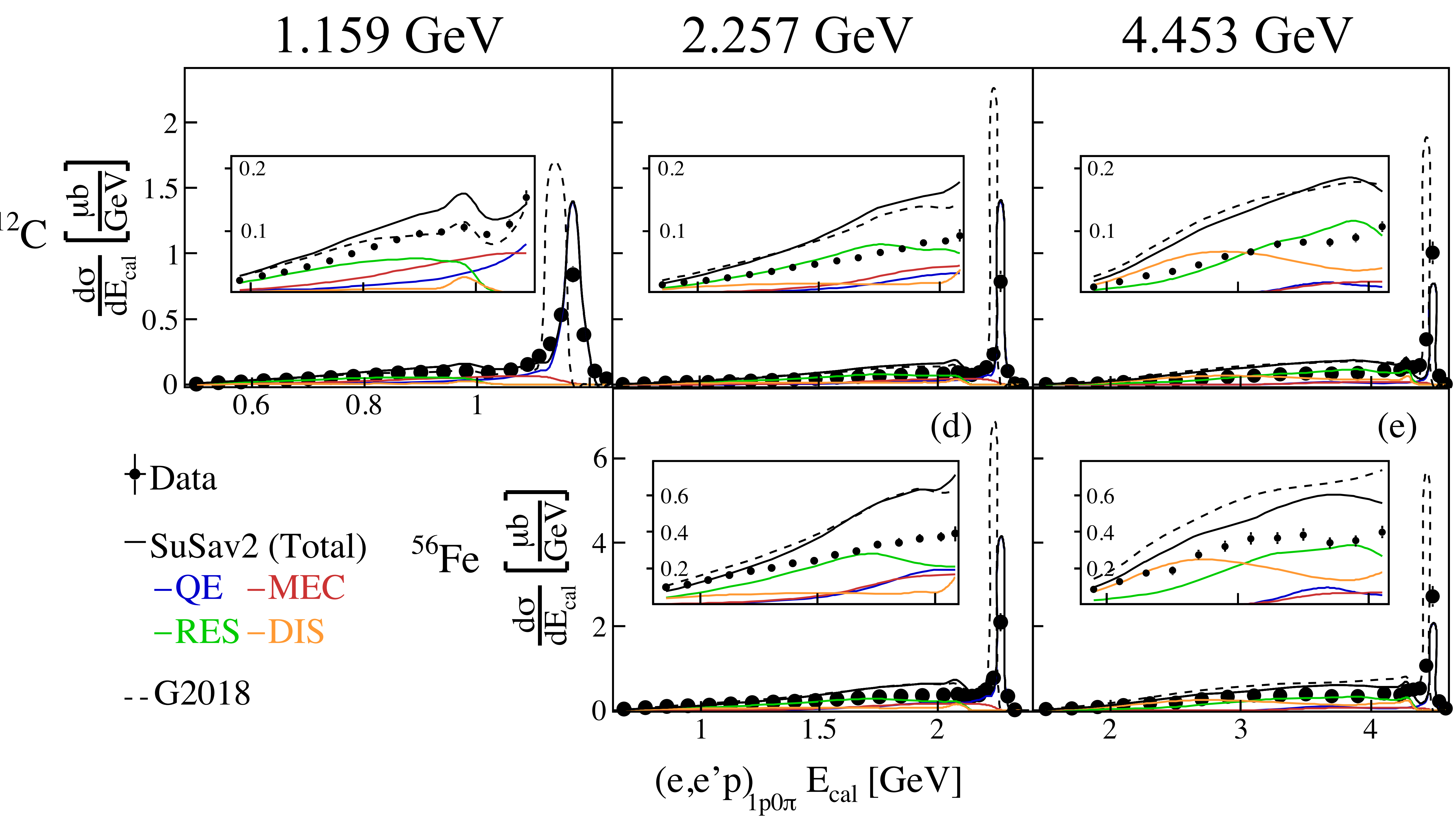

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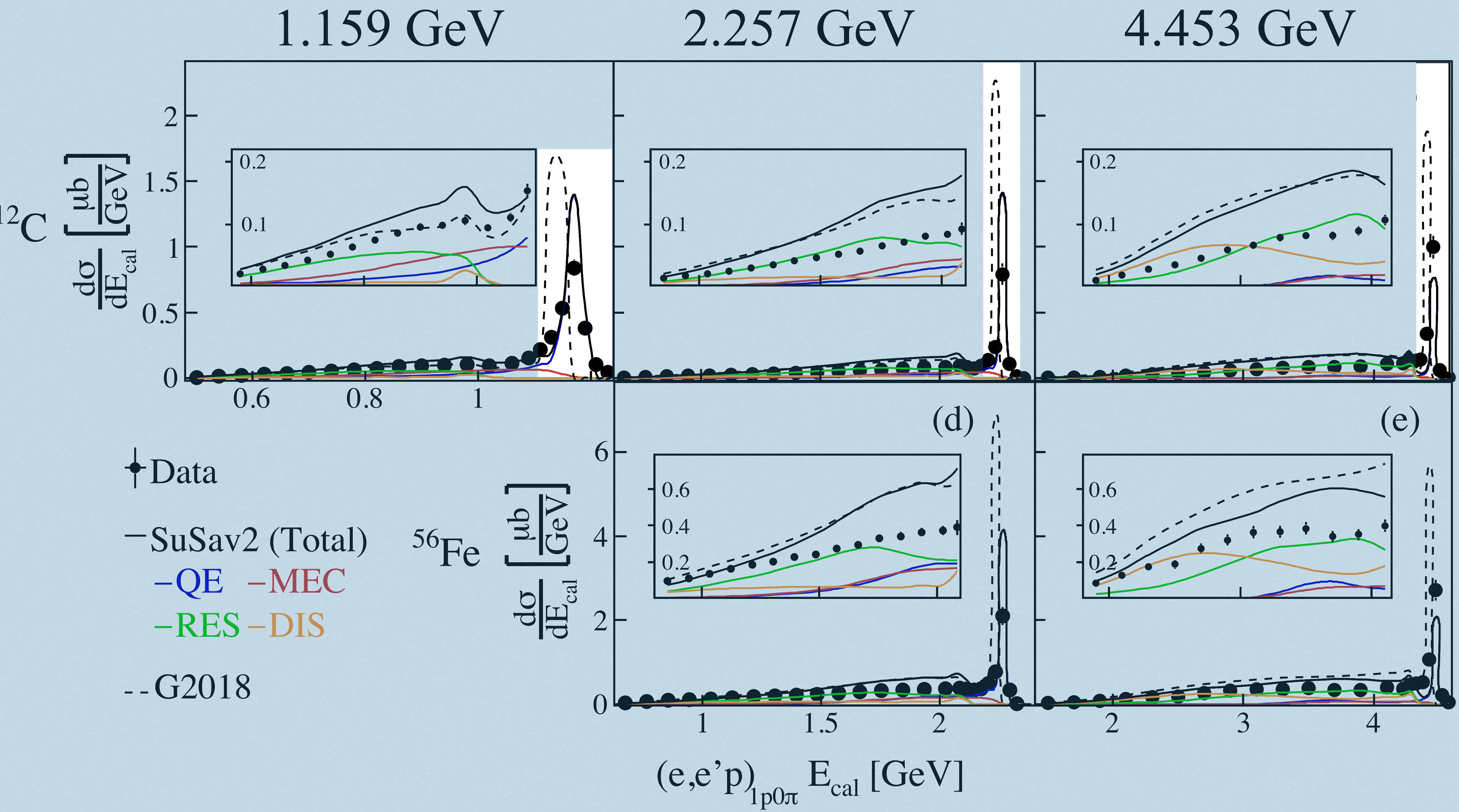

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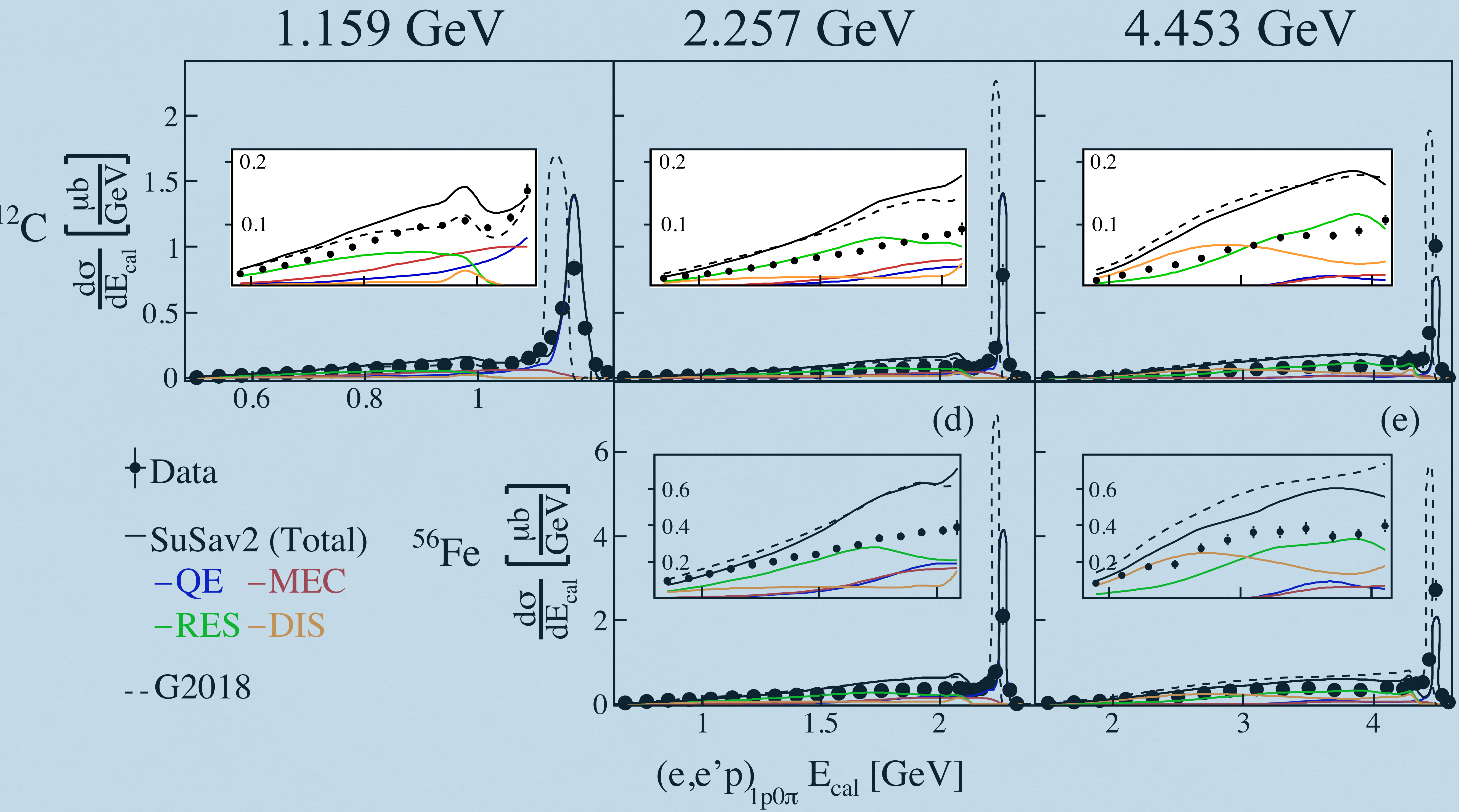
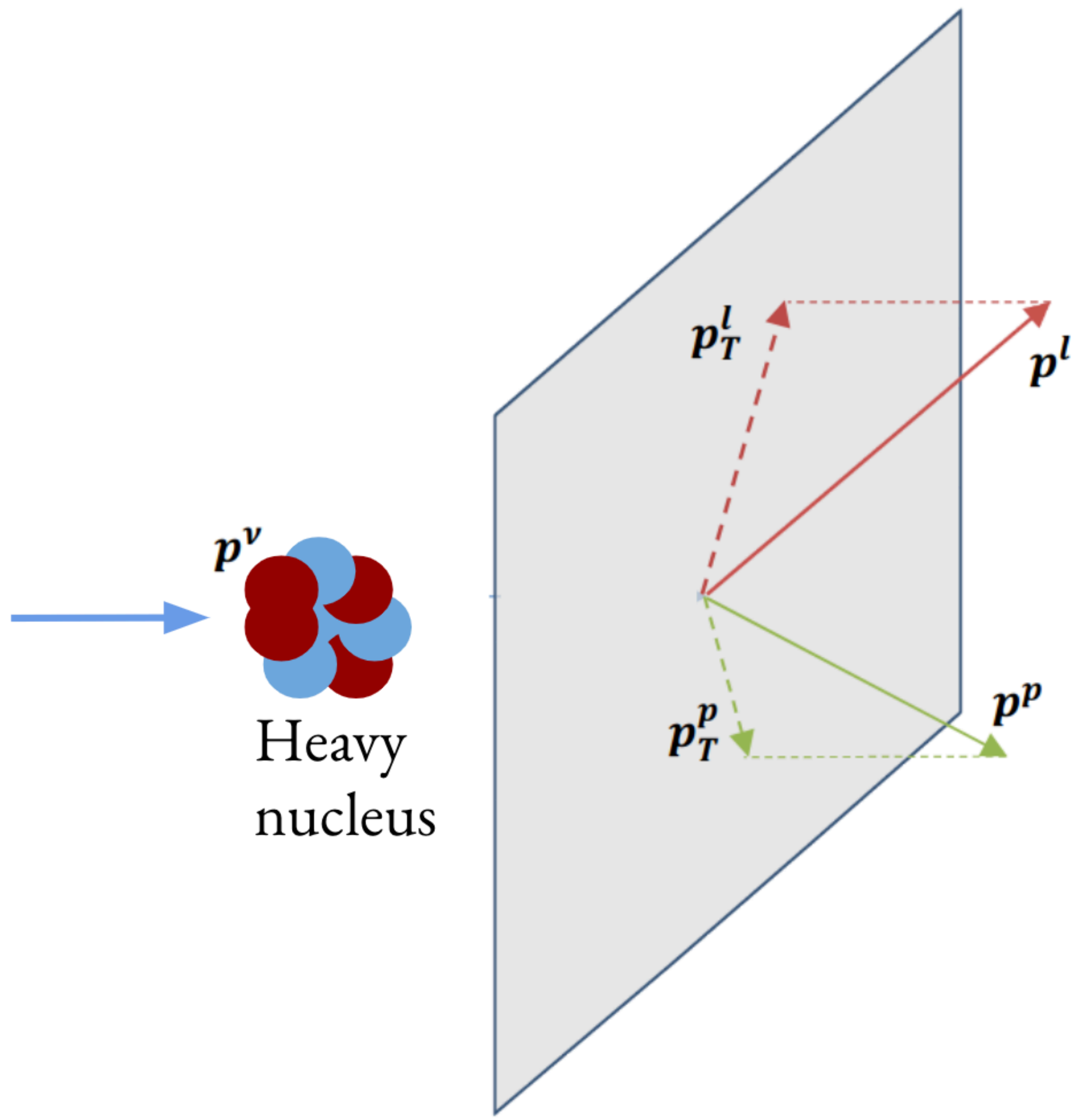
Reconstructed Calorimetric Energy

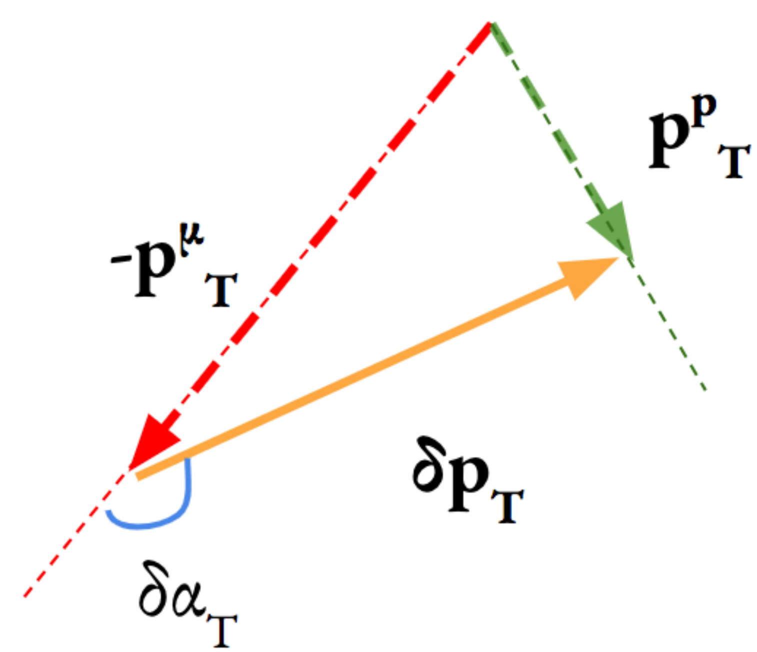


Nature **599**, 565 (2021)

Focusing on different reaction mechanisms

Standard Transverse Variables





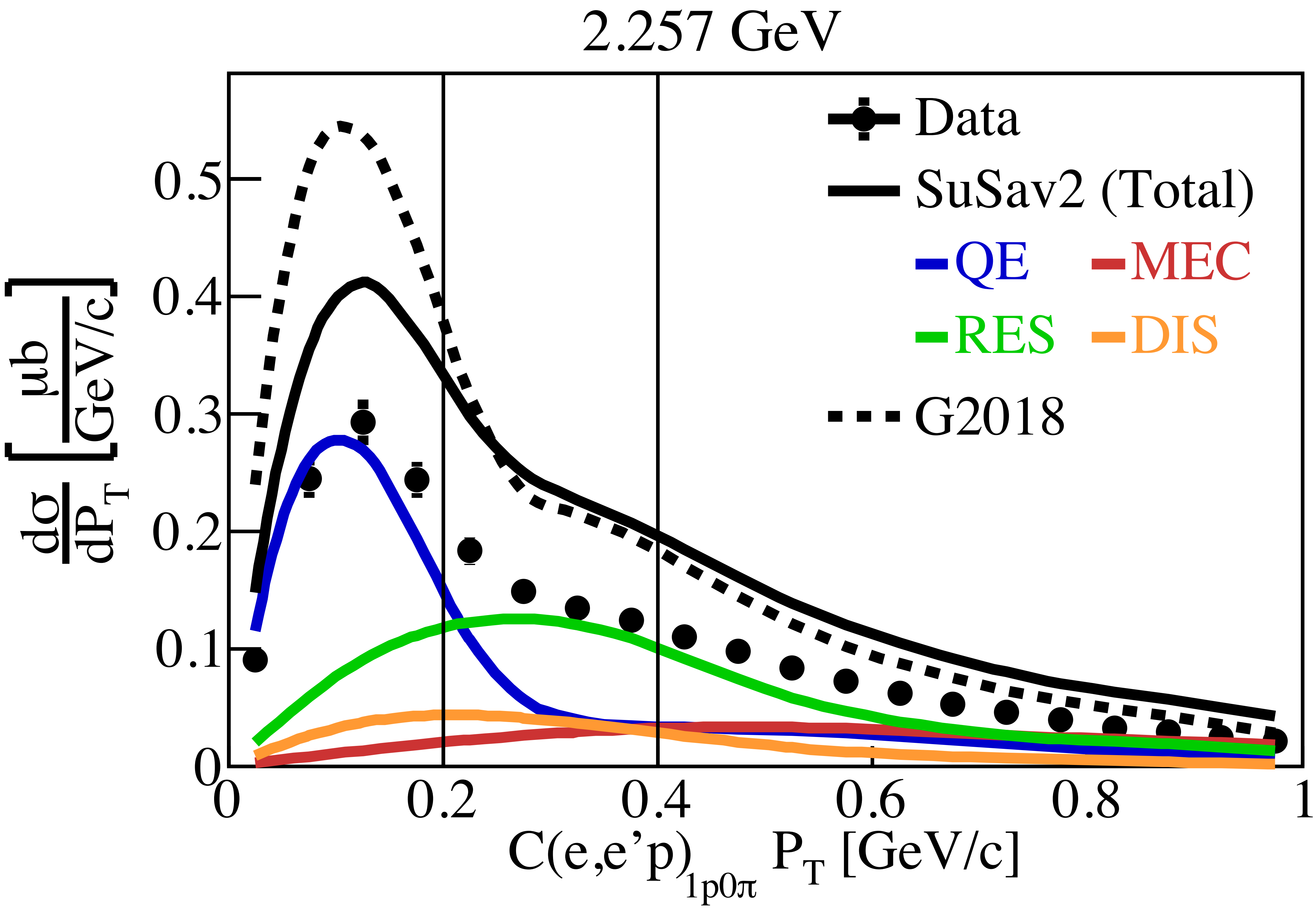
$$\vec{P}_T = \vec{P}_T^{e'} + \vec{P}_T^{p}$$

Sensitive to
hit nucleon momentum

$\delta\alpha_T$

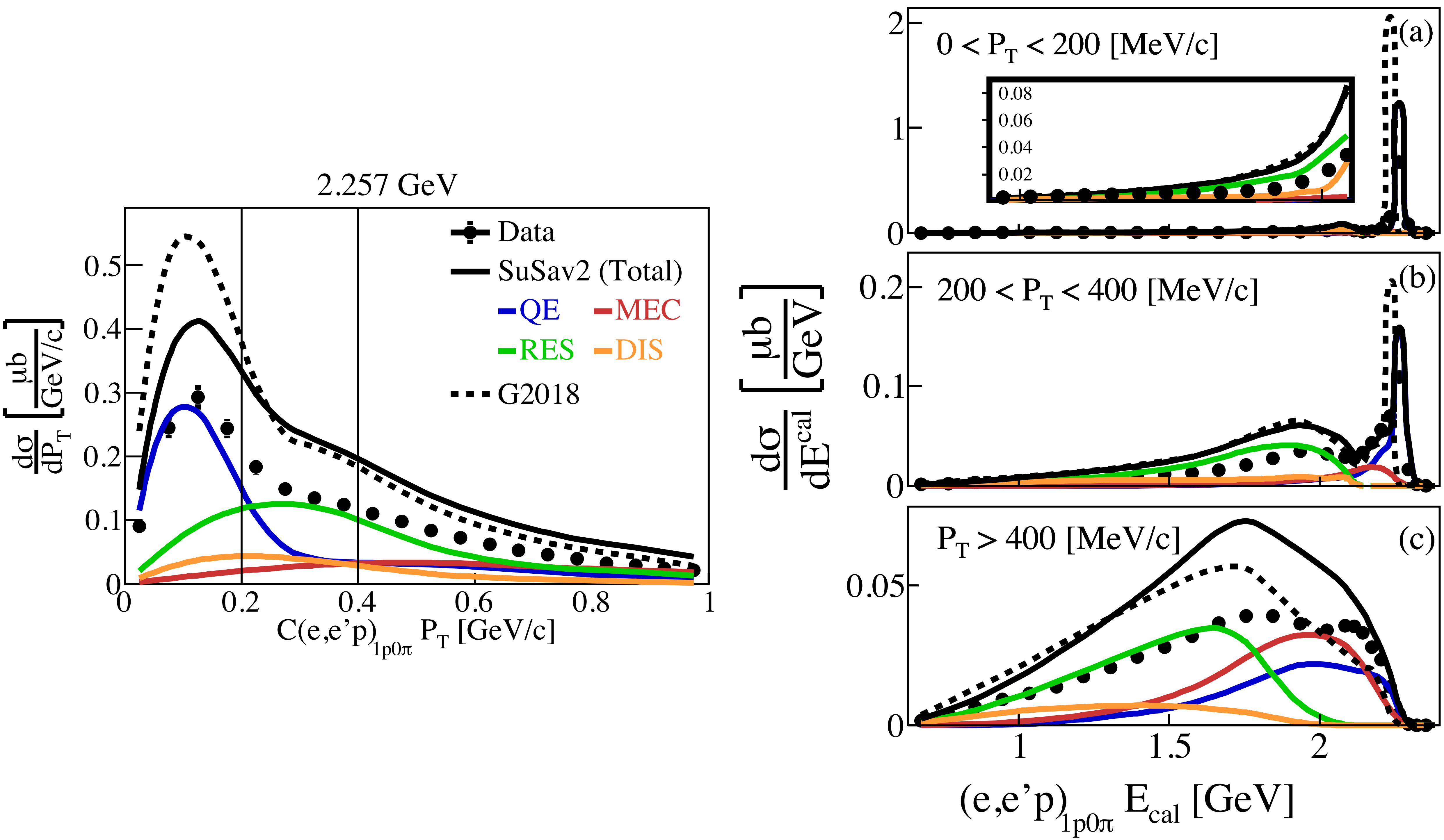
Sensitive to
Final State Interactions (FSI)

Transverse missing momentum



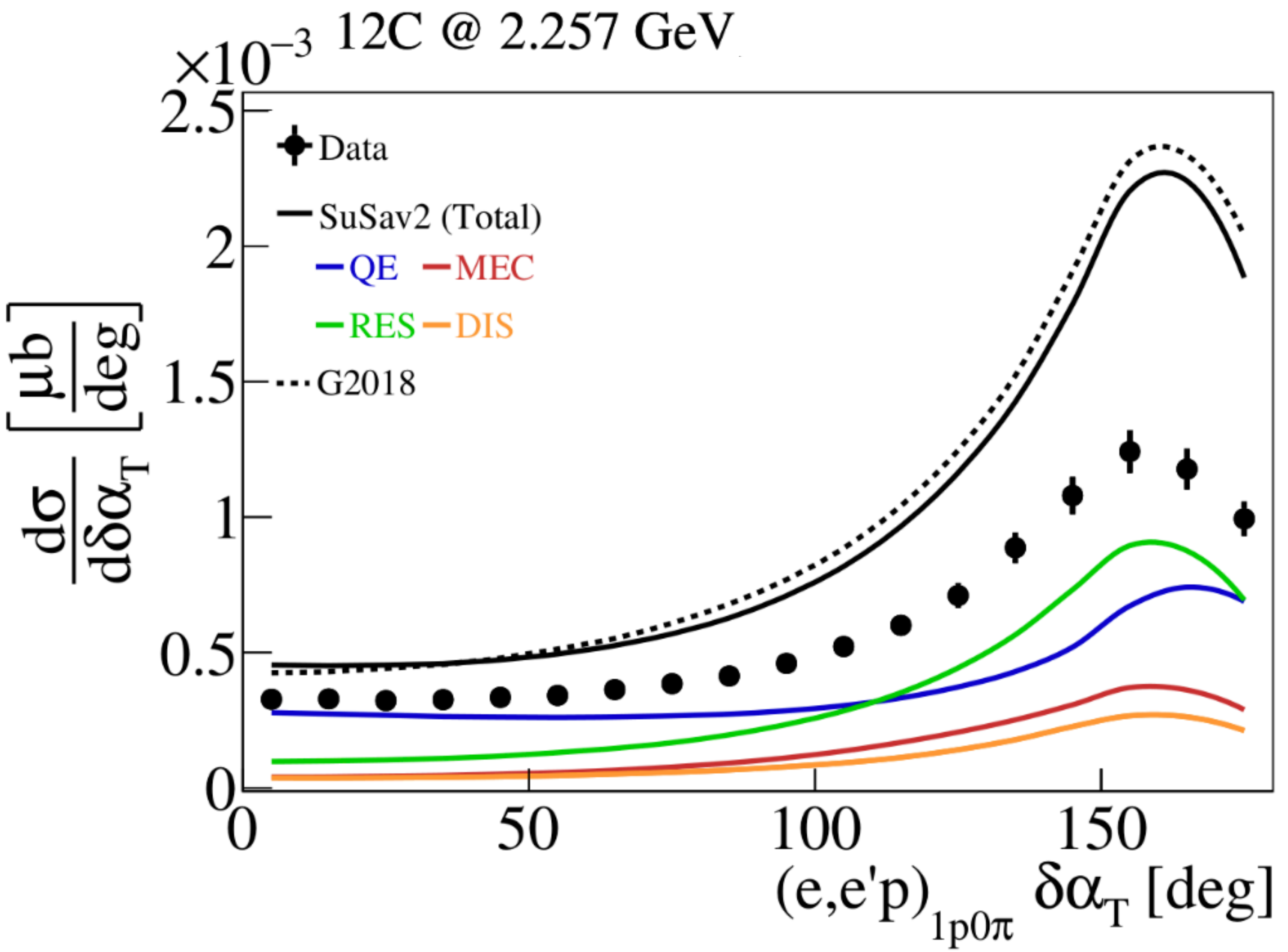
Nature **599**, 565 (2021)

p_T sensitivity to interaction mechanisms



Nature **599**, 565 (2021)

Transverse Kinematic Variables - $\delta\alpha_T$



A. Papadopoulou et al. in preparation

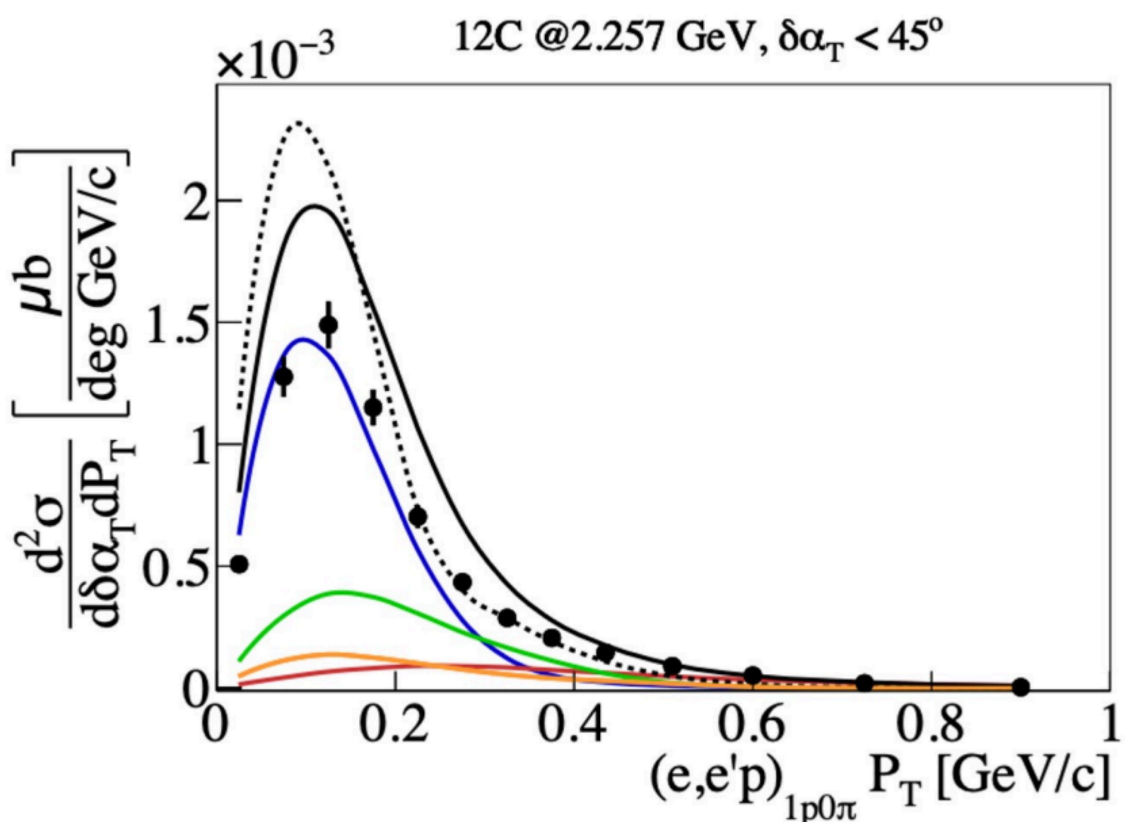
MC vs. (e,e'p) Transverse Variables

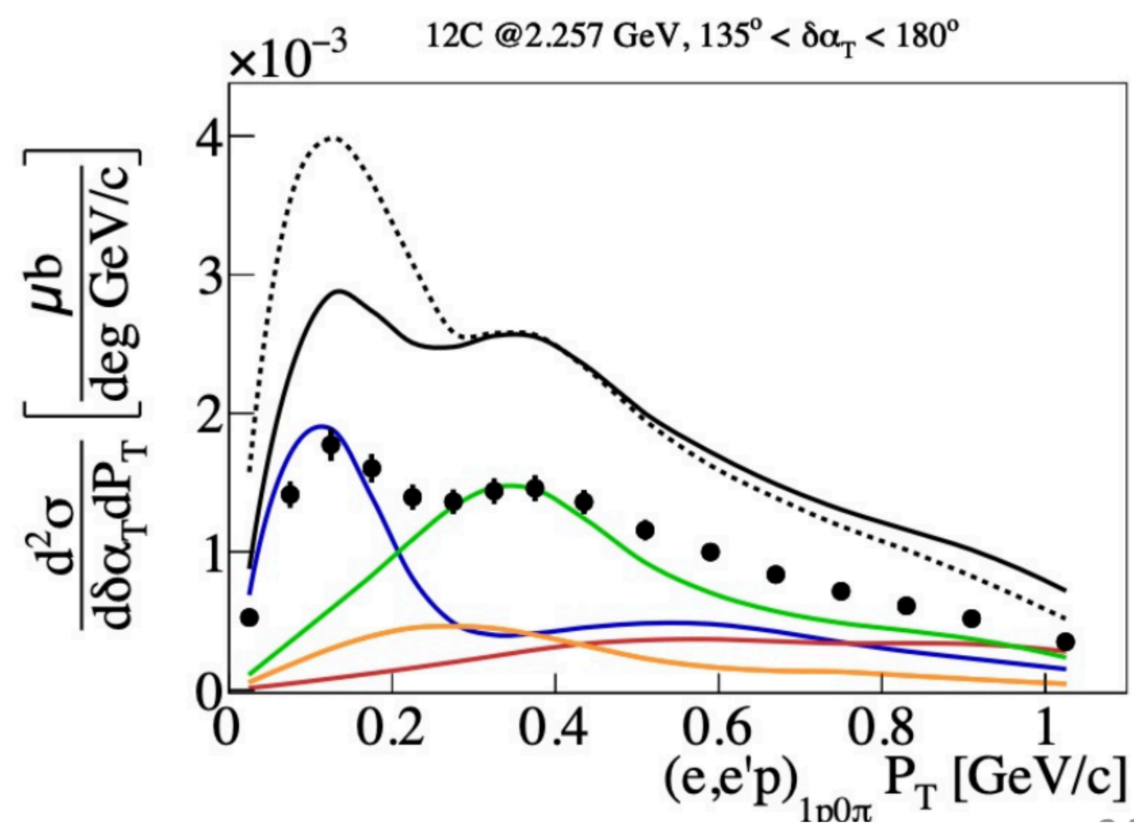
Low αT < 45

QE enhanced region

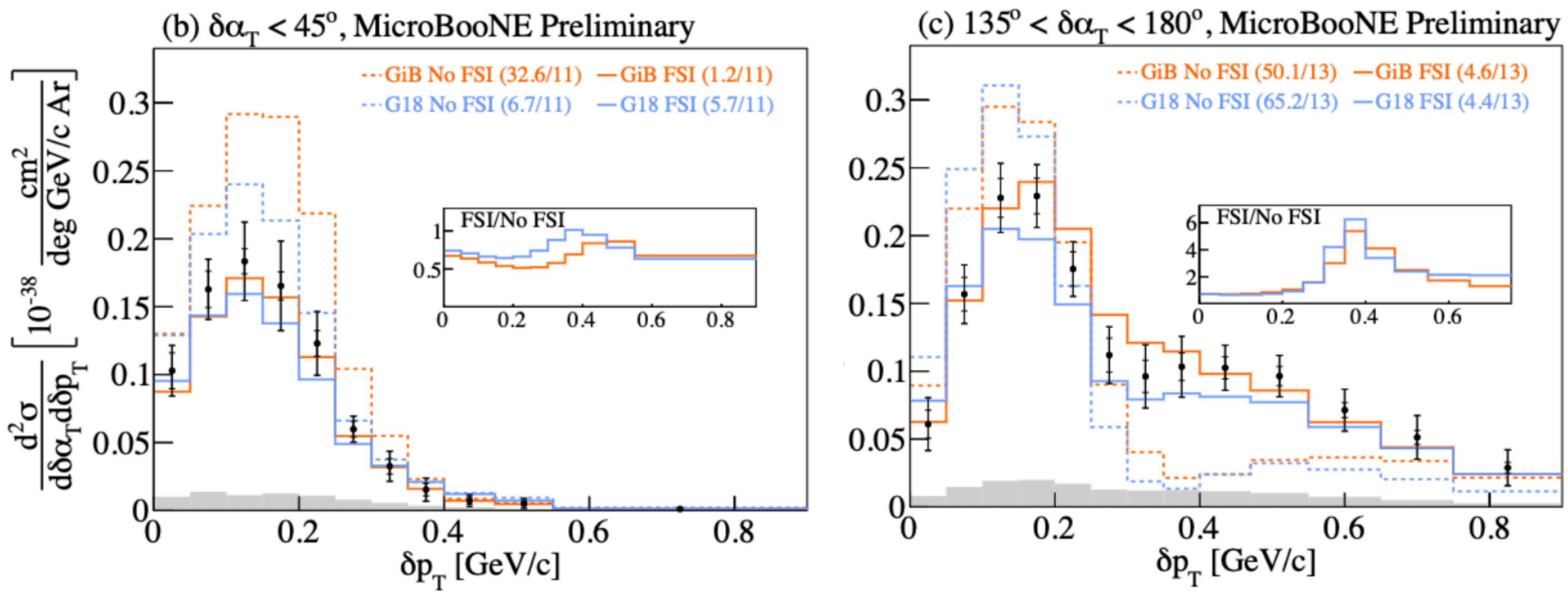
High 135 < αT < 180

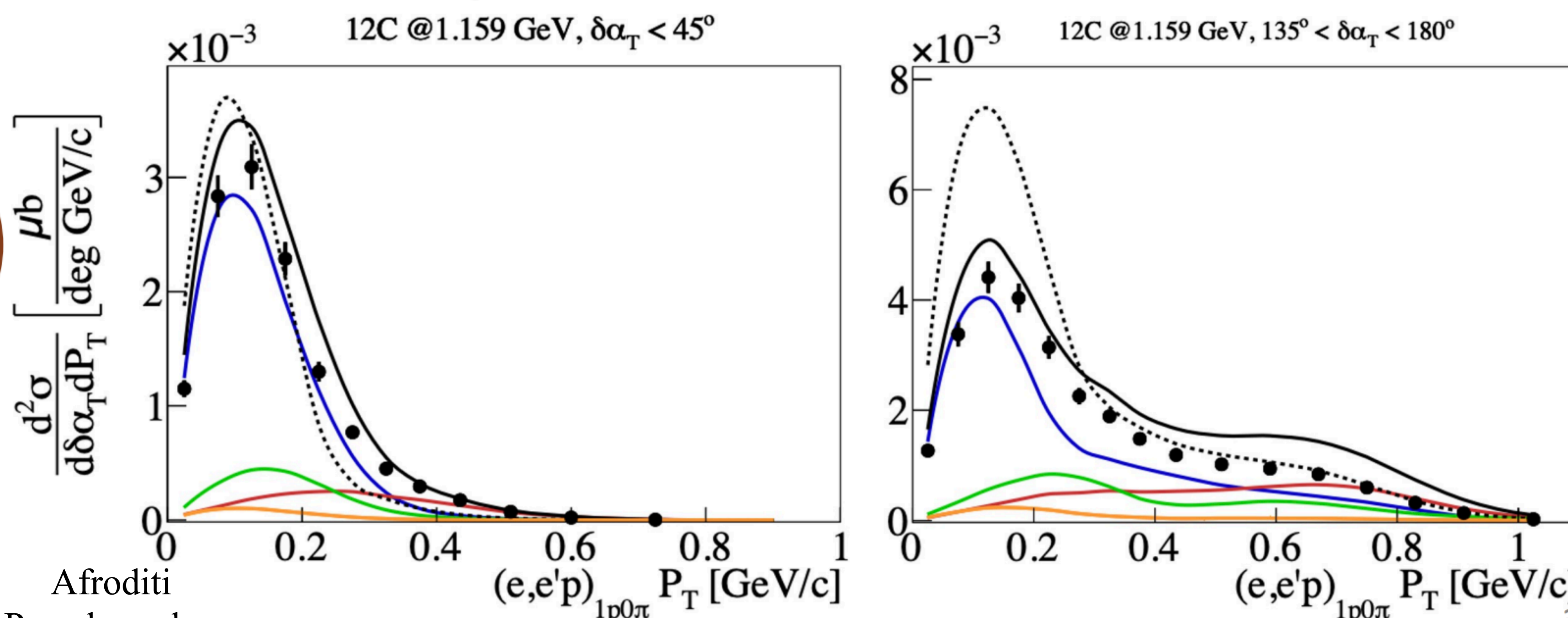
Non QE contributions

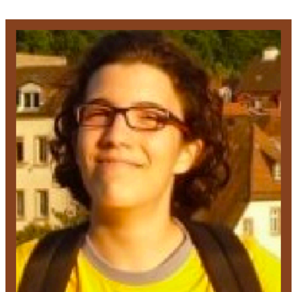




MC vs. (e,e’p) Transverse Variables







Afroditi Papadopoulou @ ANL

arXiv:2301.03700 [hep-ex]

Transparency Measurement

Noah Steinberg

Transparency

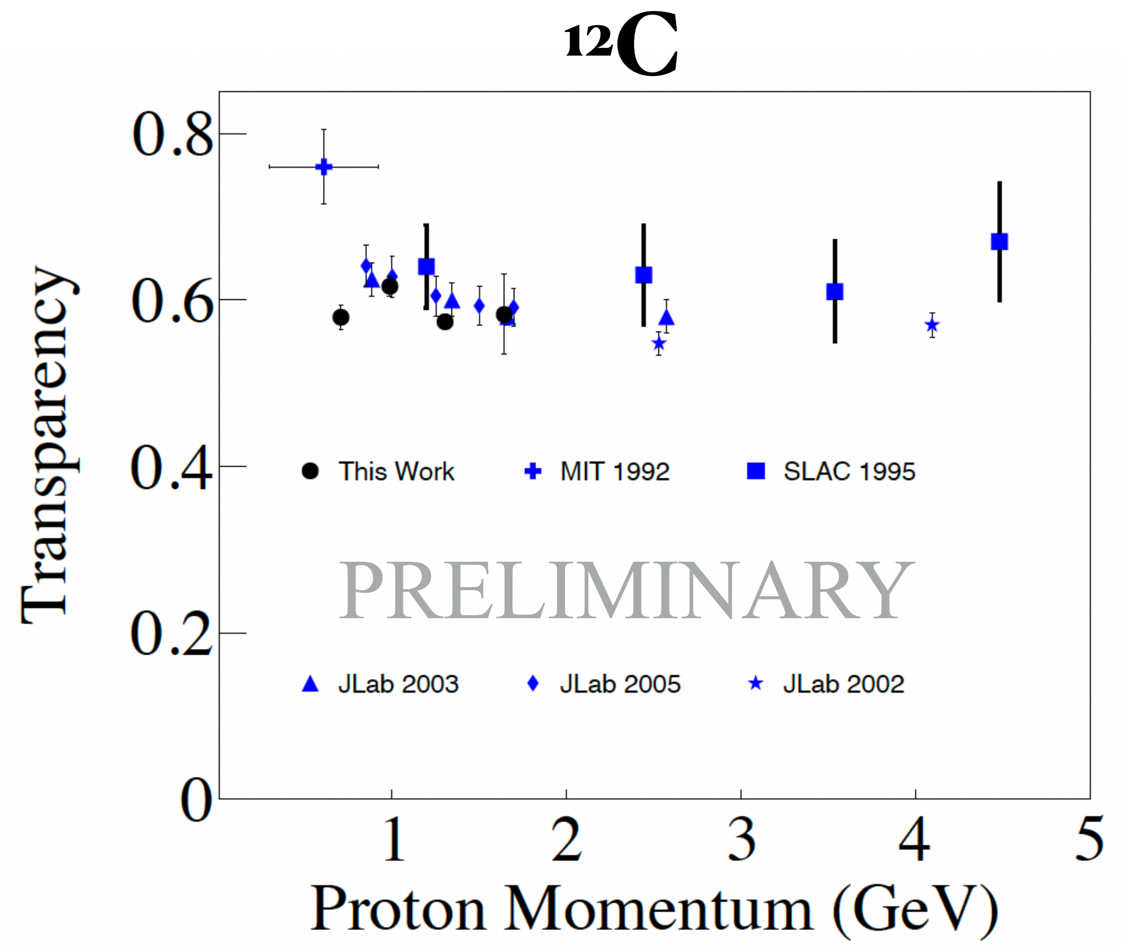
h-A data

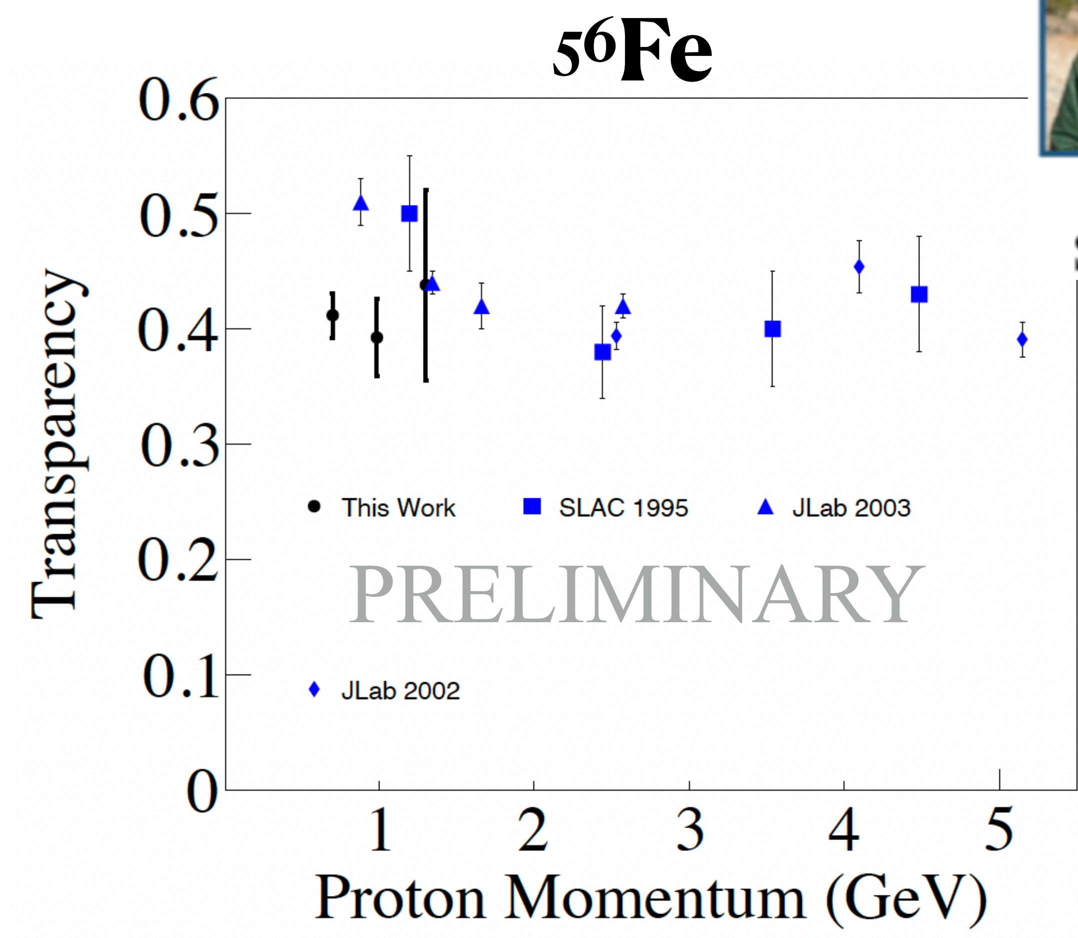
- Probability that a struck proton leaves the nucleus without significant re-scattering
- Complement to hadron nucleus interaction
- Study proton FSI similarly to neutrino scattering

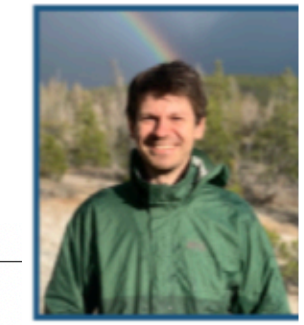
Sensitive to both FSI and nuclear structure (PRD **104** 053006 (2021))

Strong need for new data, especially at low proton momentum

Transparency Measurement



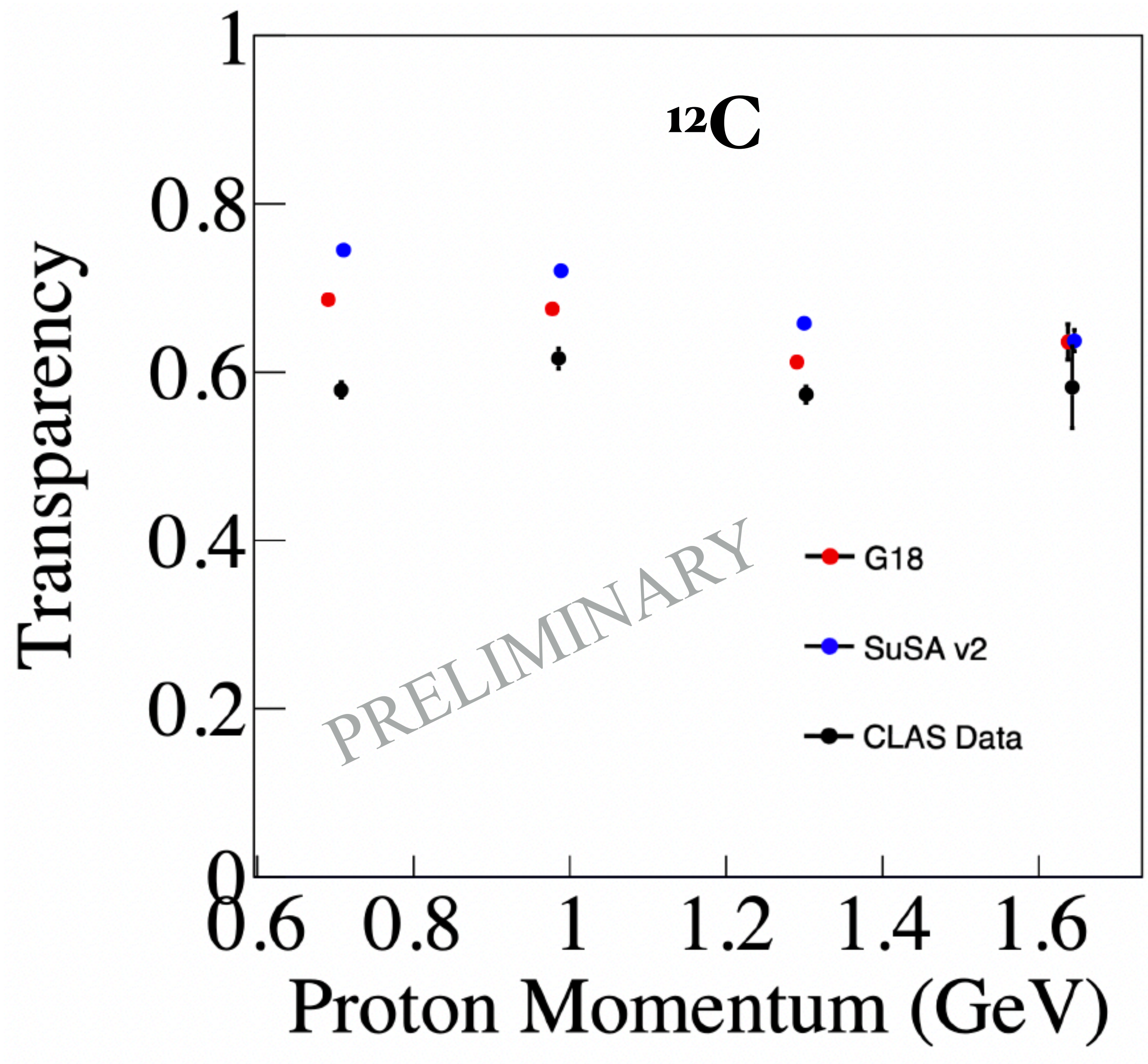




Noah Steinberg

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

Transparency Measurement



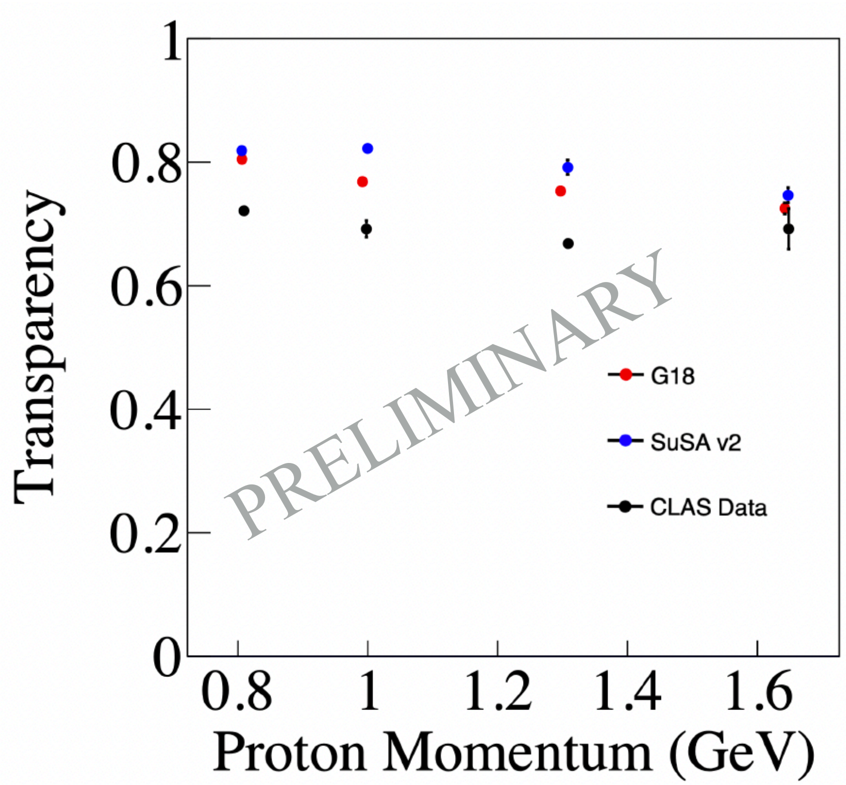
Noah Steinberg

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

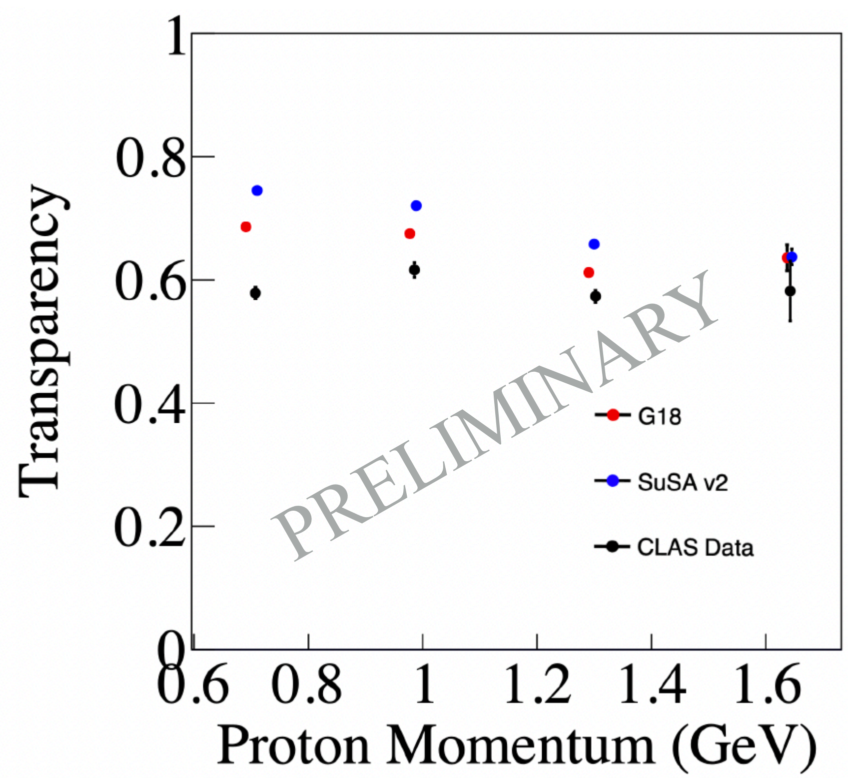
Transparency Measurement

Noah Steinberg

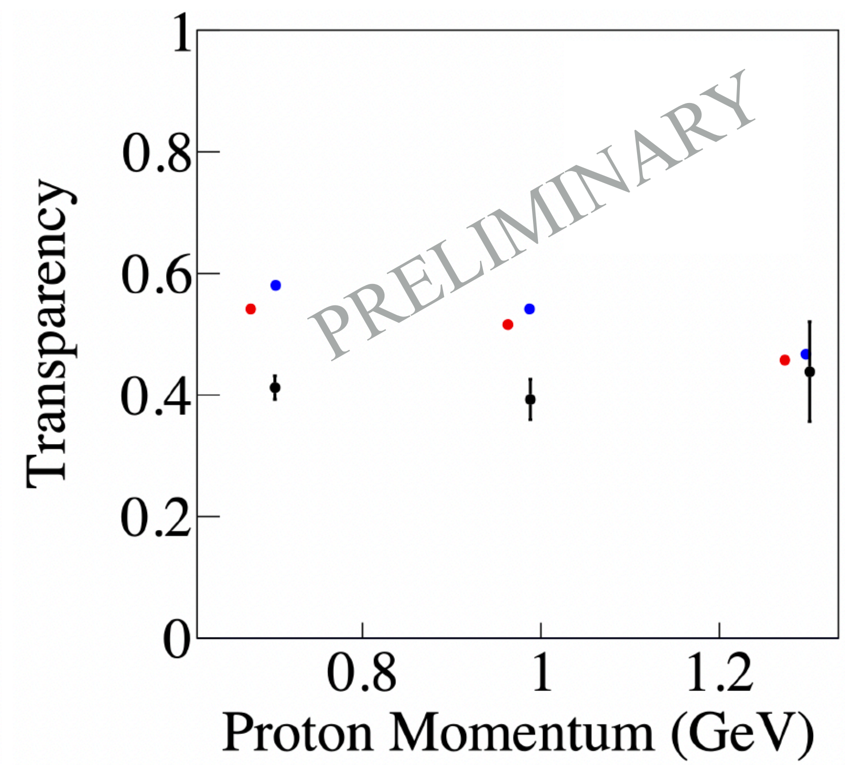
^{4}He



^{12}C



^{56}Fe



Presenting first measurement on He

Transparency decreases with A

Future Plans

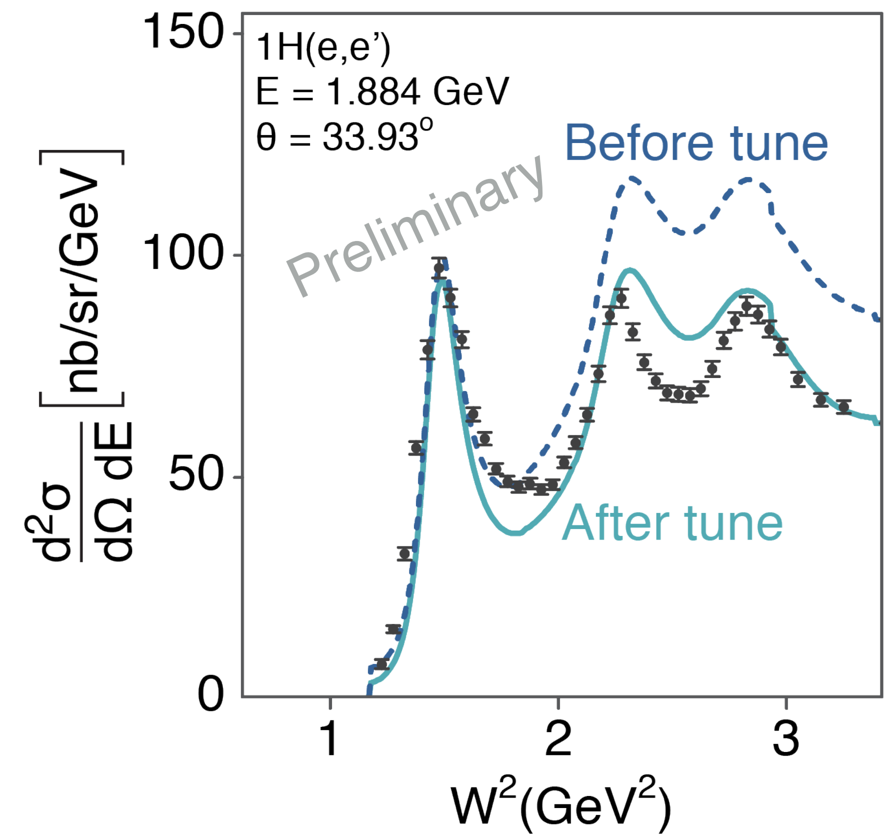
Working on:

New dataset including Argon

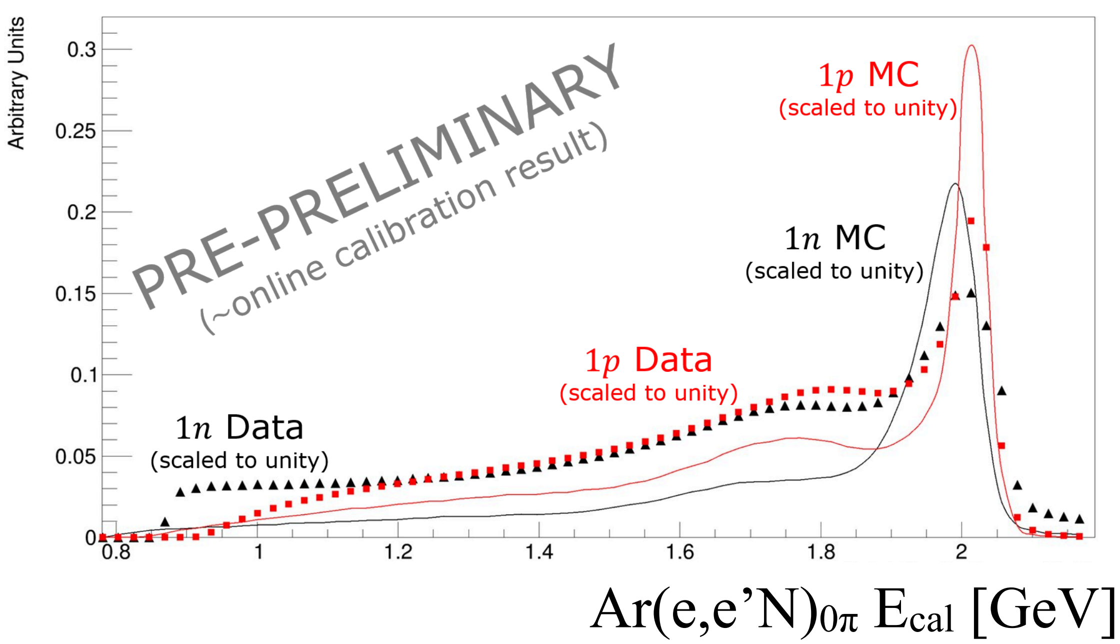
Multi differential analysis

Pion production

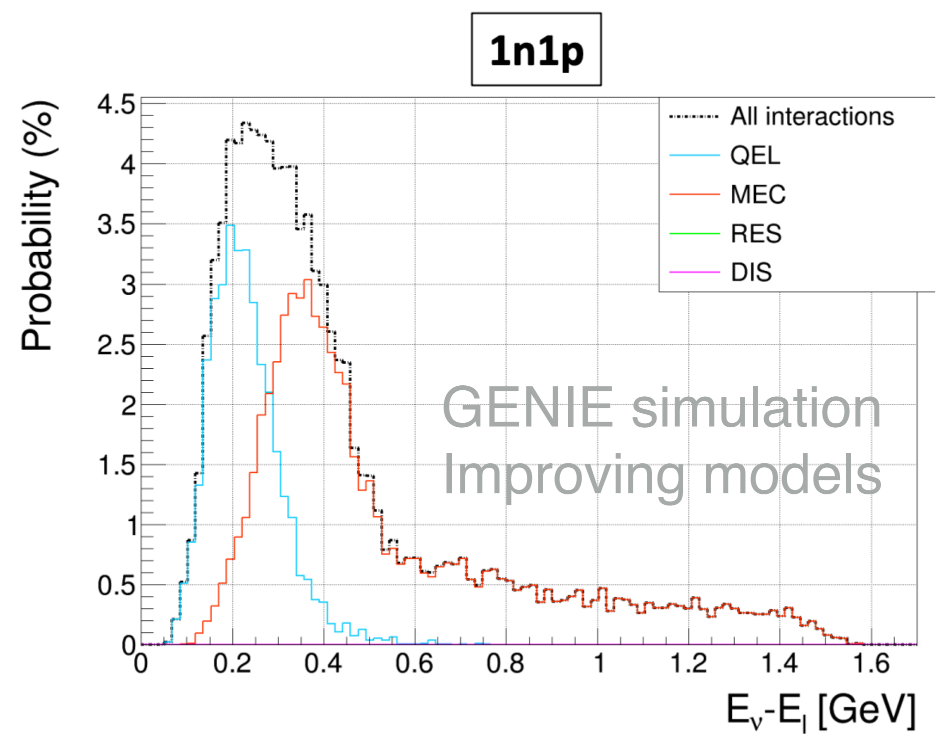
Two nucleon final state



Julia Tena Vidal



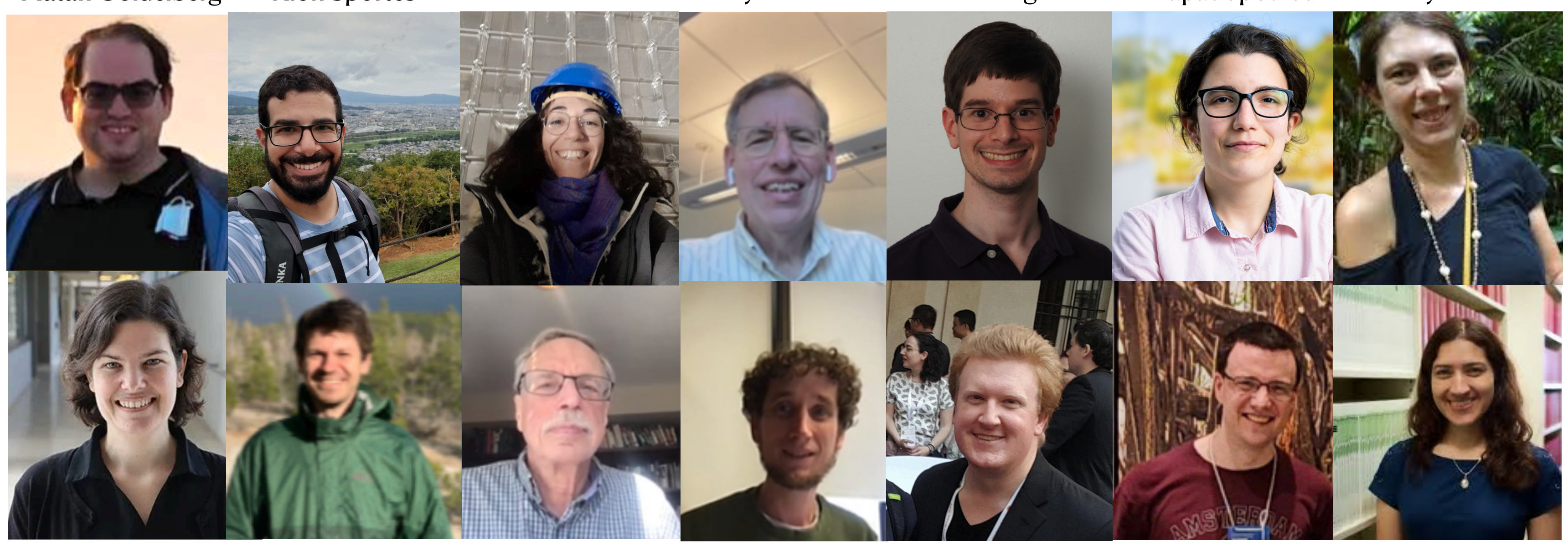
Joshua Barrow



Alon Sportes

The e4ν Collaboration

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



Adi Ashkenazi | Noah Steinberg | Steven Dytman | Brandon Eberly | Josh Barrow | Steven Gardiner | Minerva Betancourt

We’re hiring

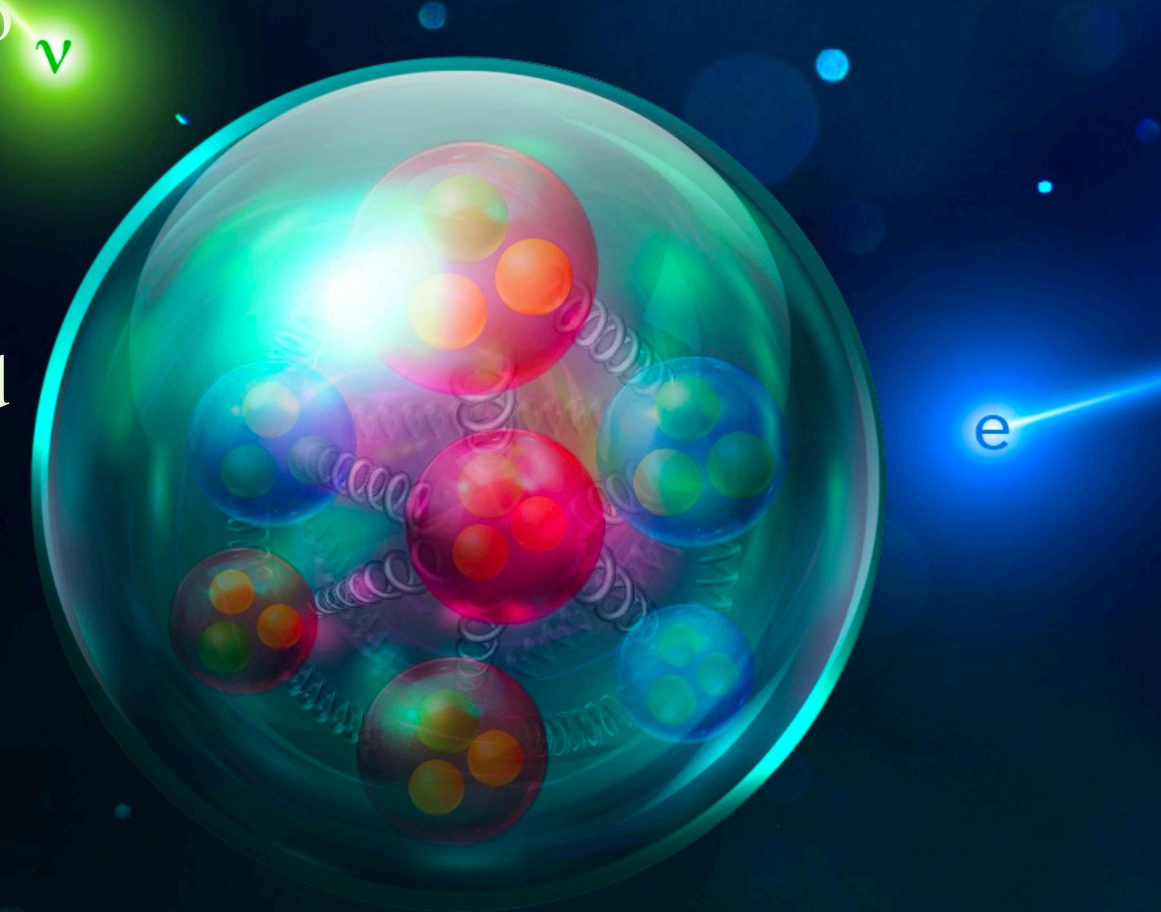
If interested contact: adishka@tauex.tau.ac.il

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