Electrons for Neutrinos

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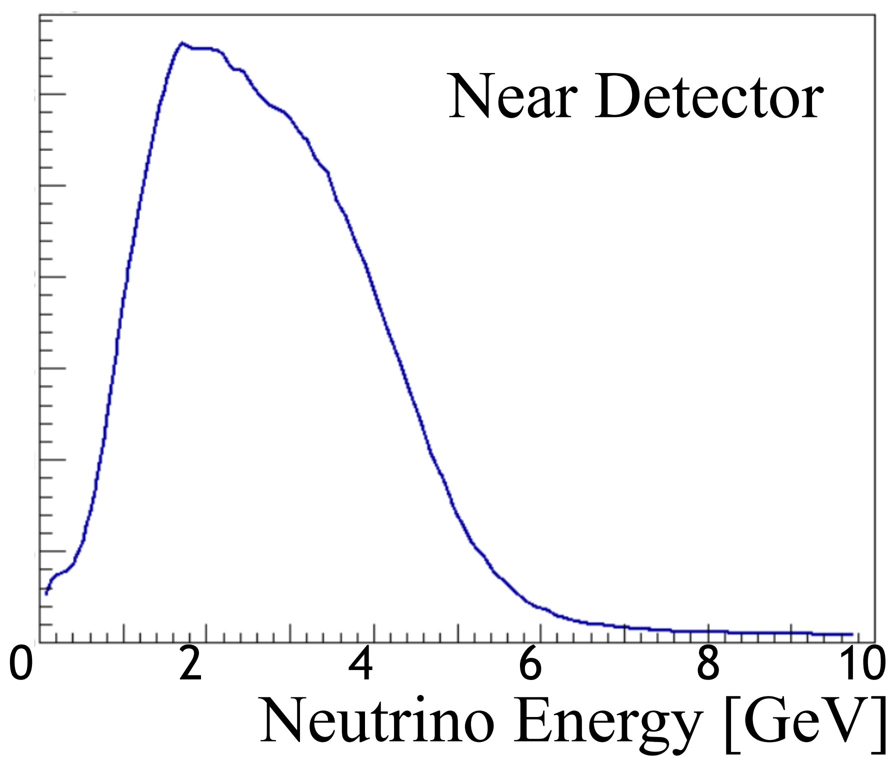
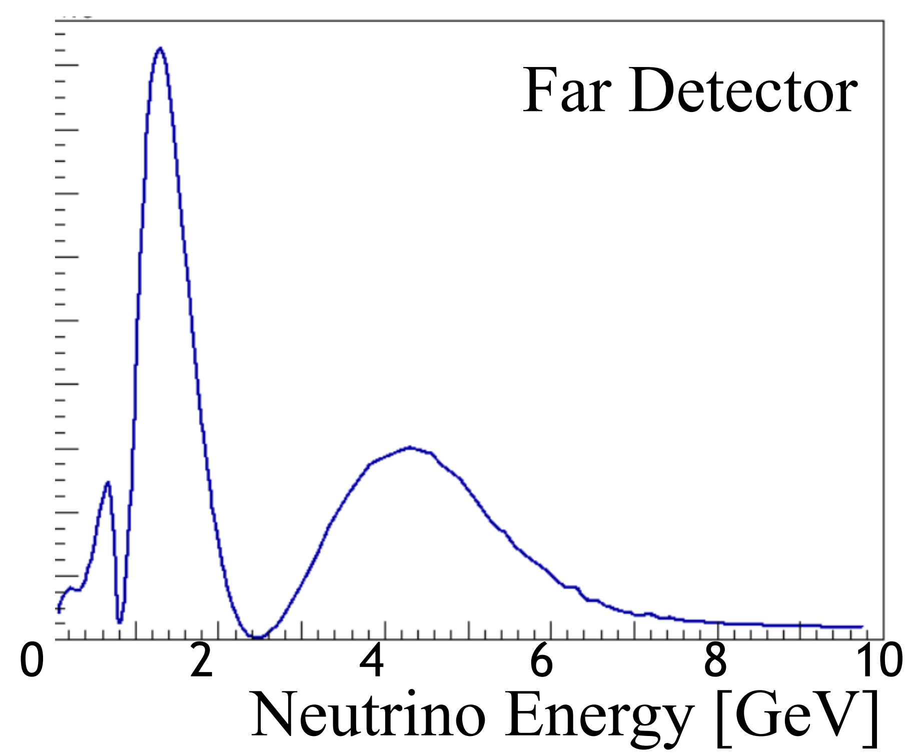
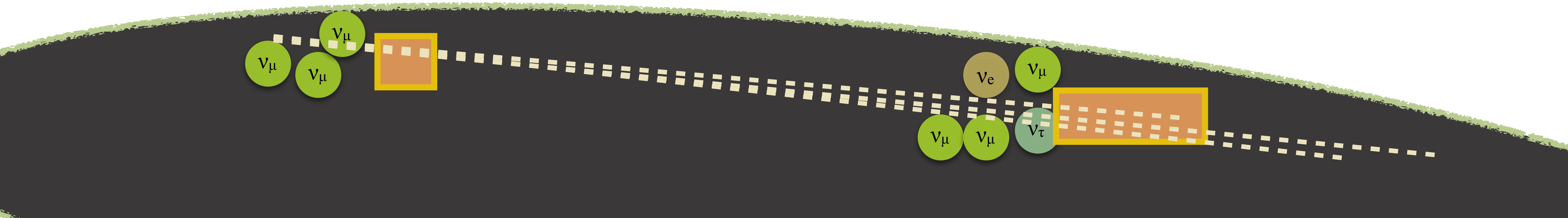
TEL AVIV UNIVERSITY

The challenge - next generation high precision

ν_μ flux



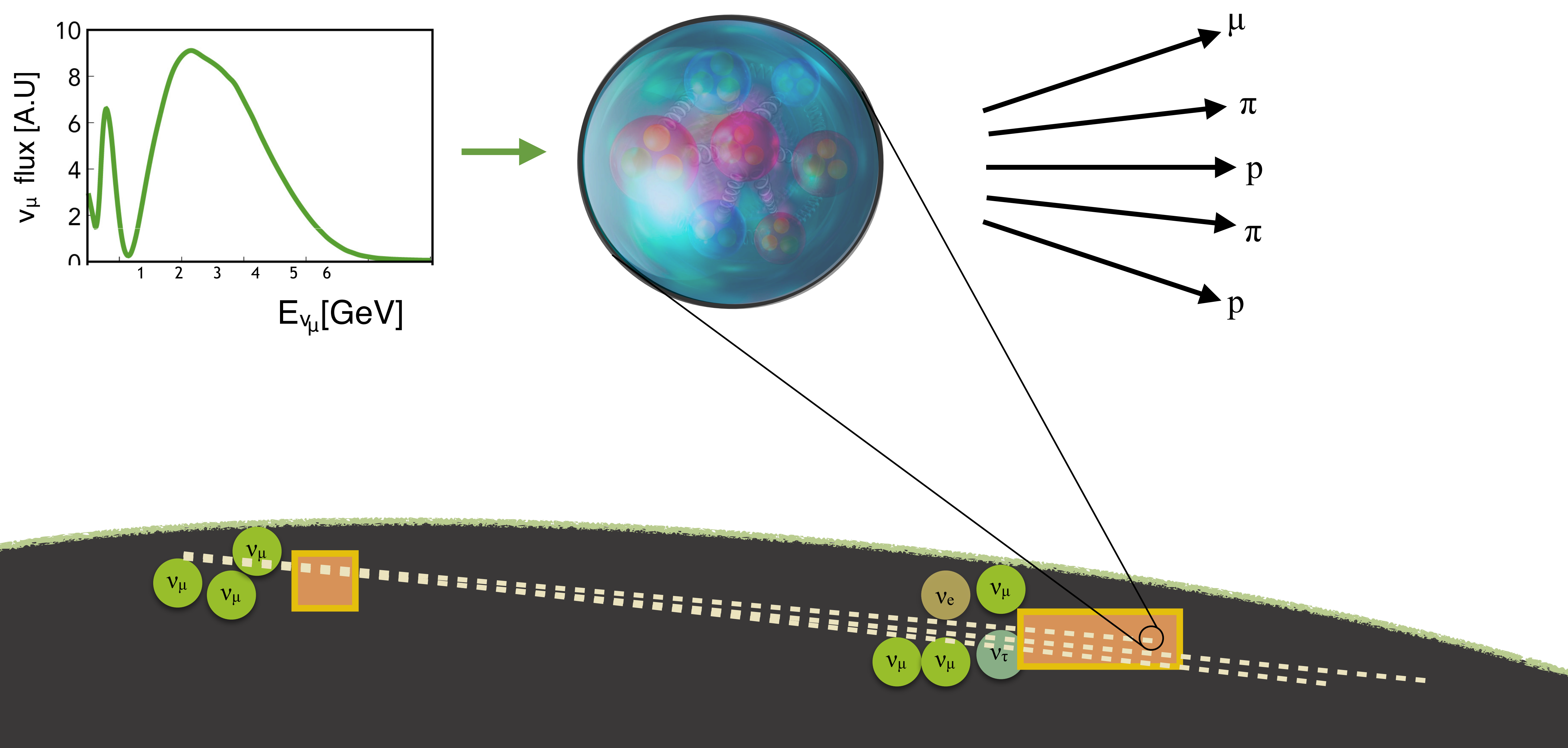




The challenge - next generation high precision

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

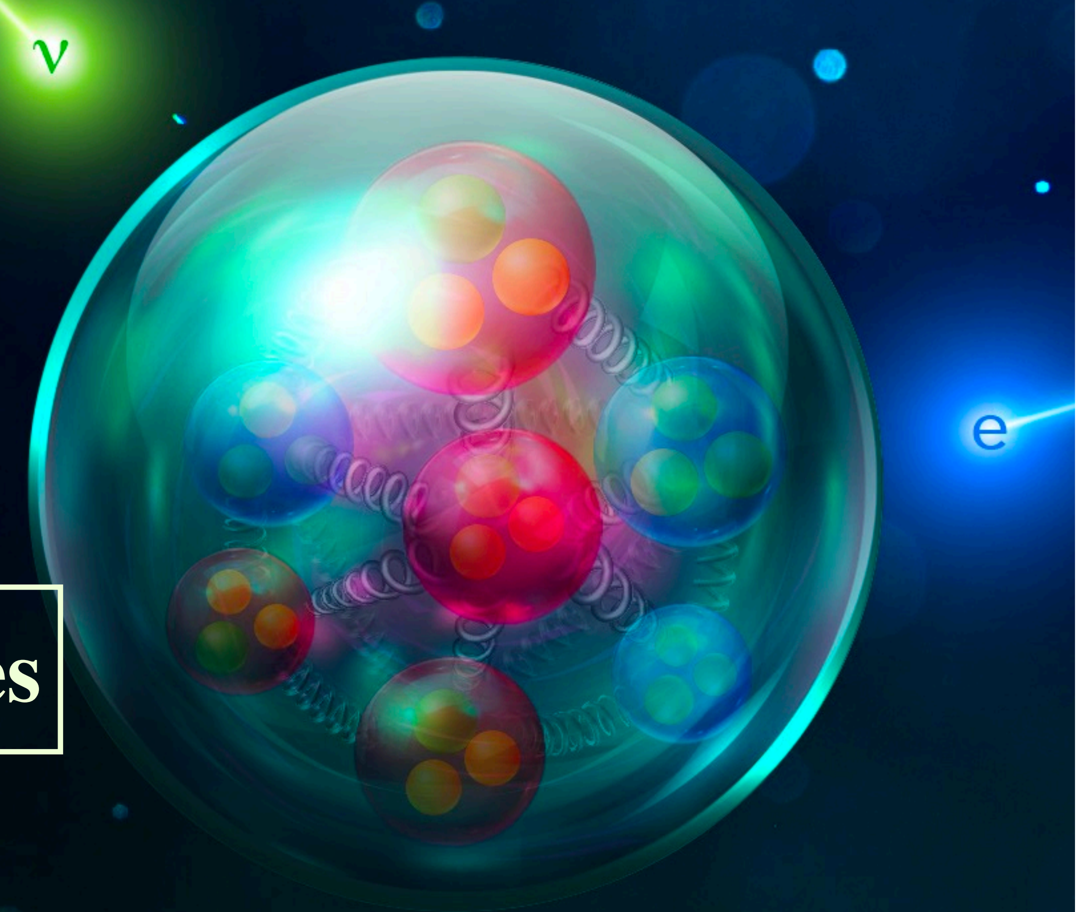
- Improve theory
- Use near detector
- Use external constraints
  e scattering

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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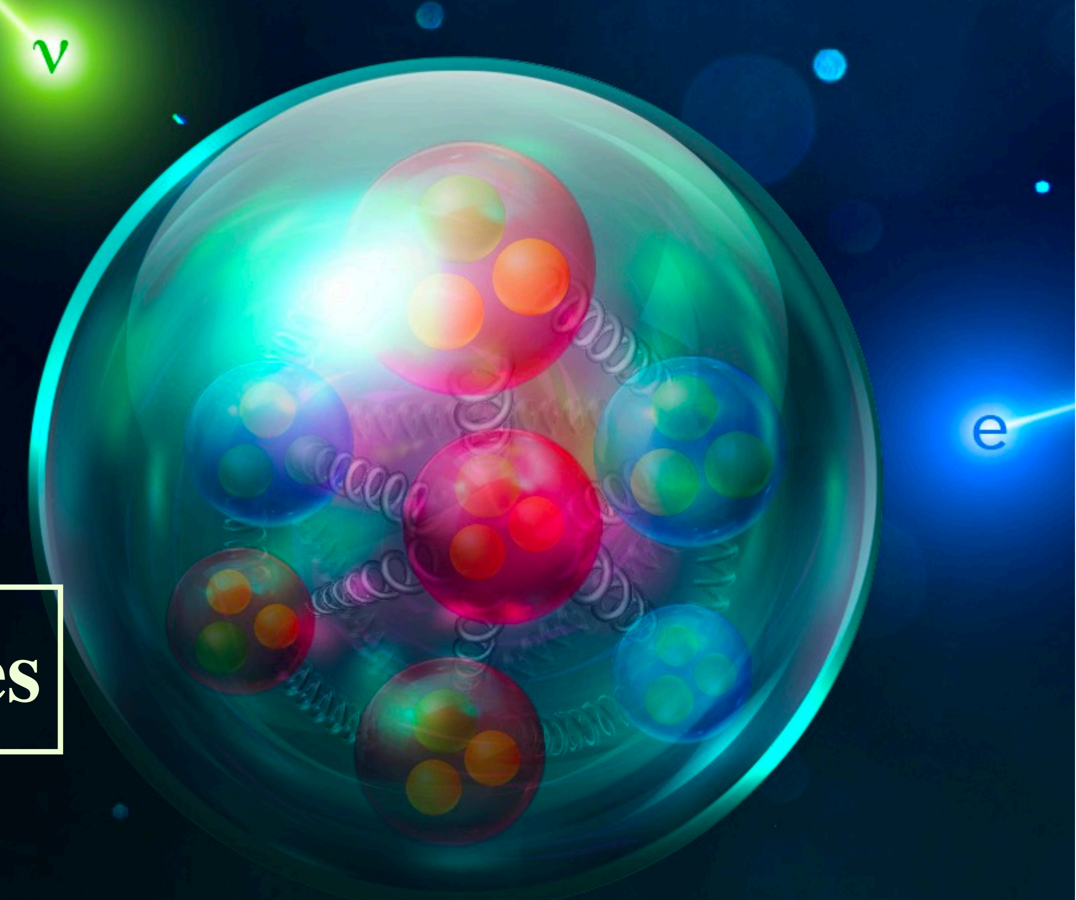
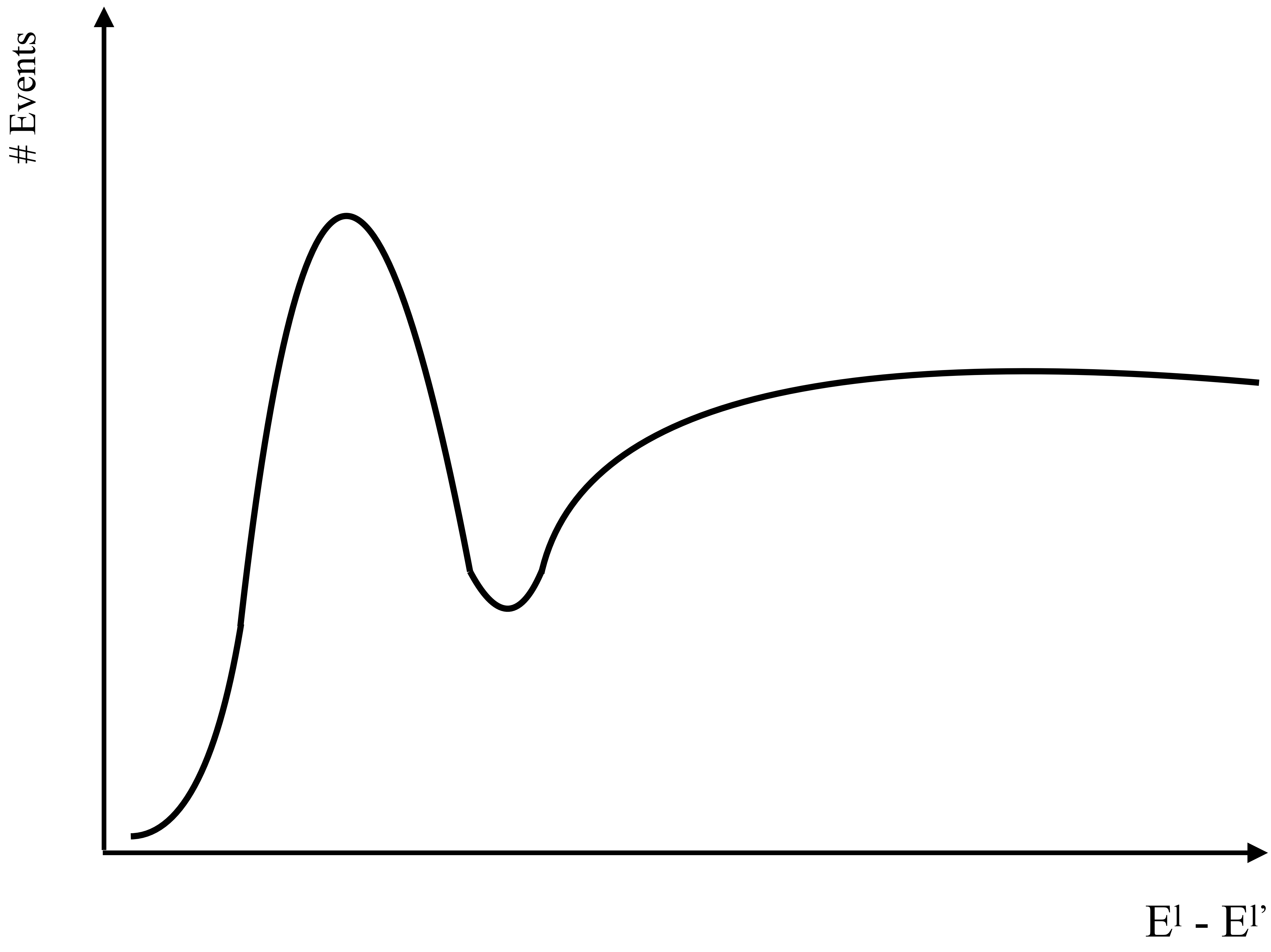


Useful to constrain model uncertainties

Electrons have known energies

Useful to test incoming energy reconstruction methods

E Reconstruction Requires Interaction Modelling



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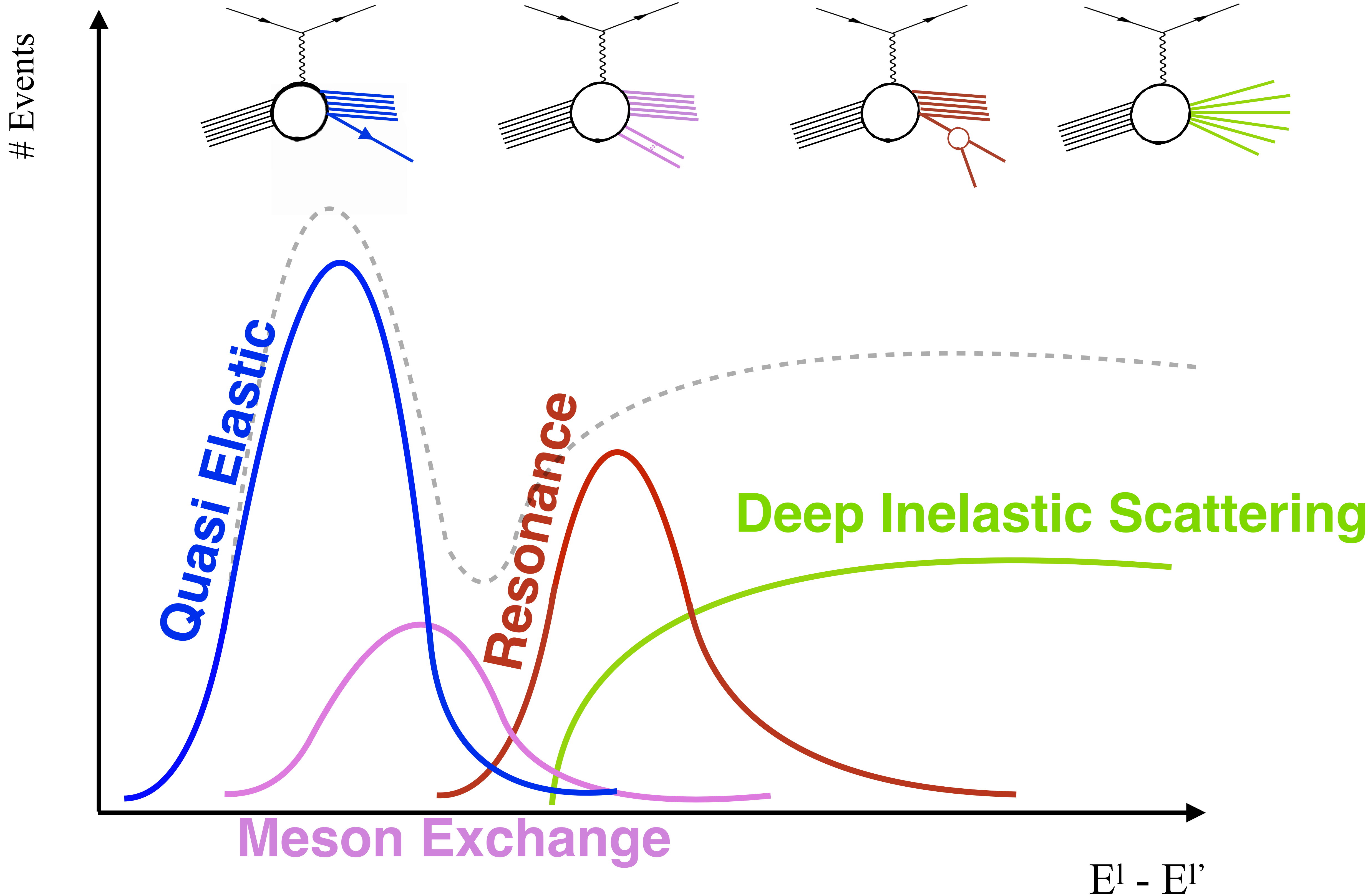
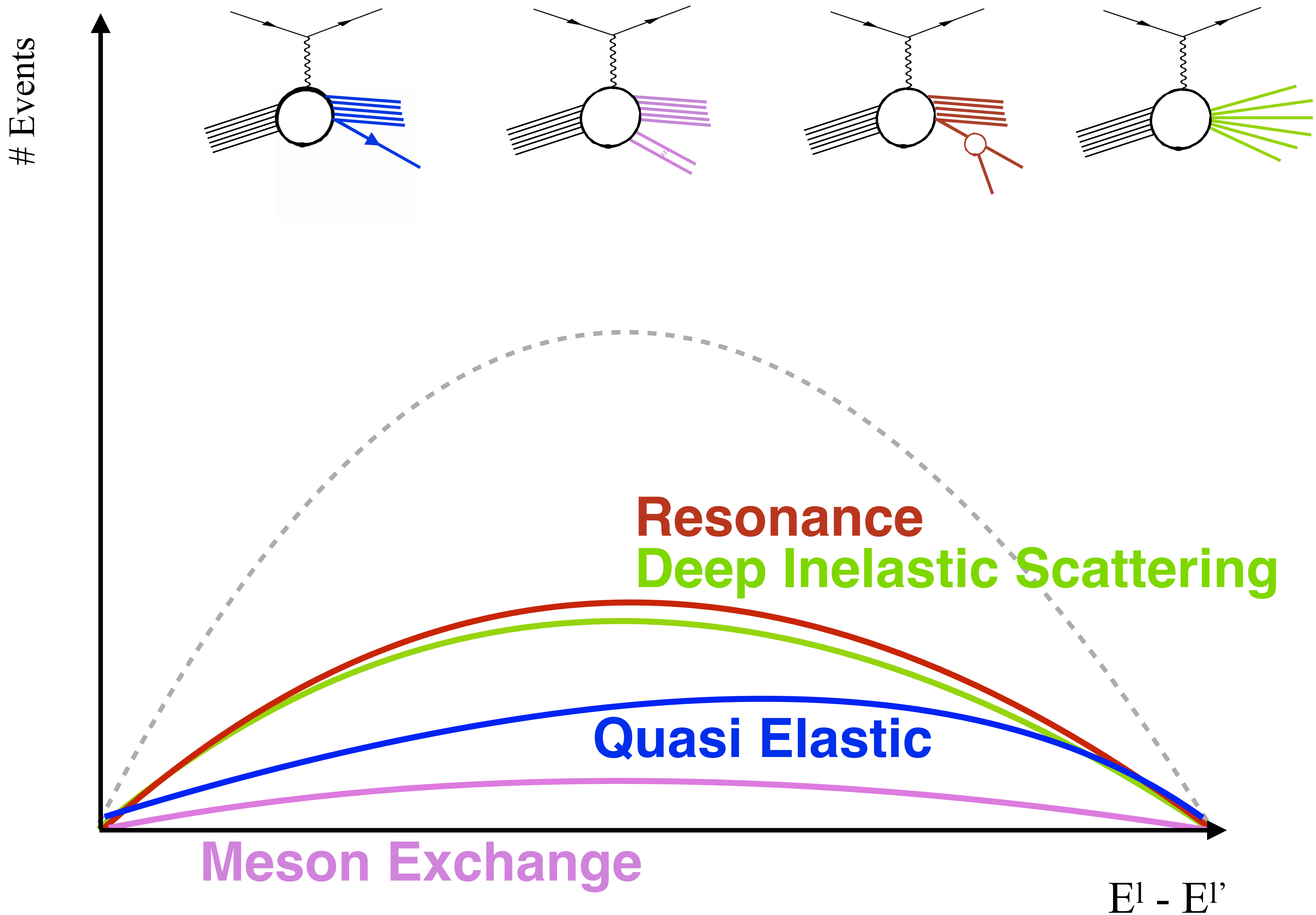
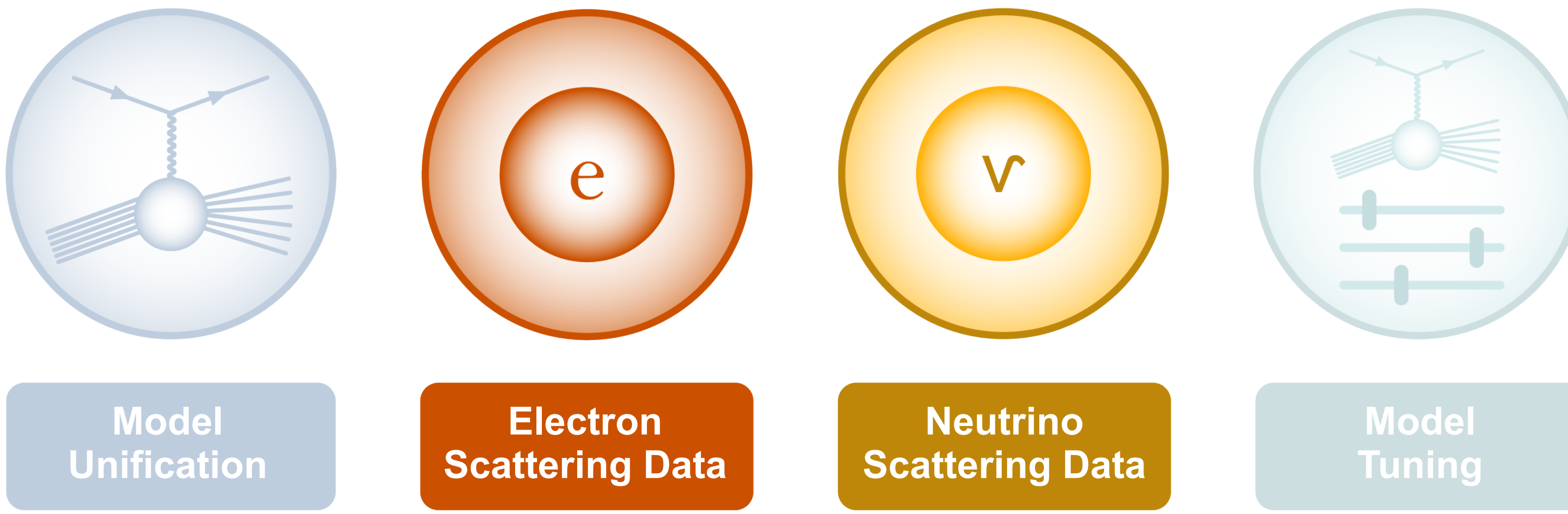


ν Experiments Fluxes Challenge our Understanding



Improving the Modelling Input

Our goal is to leverage neutrino and electron scattering data to constrain exiting models, and improve simulation environment



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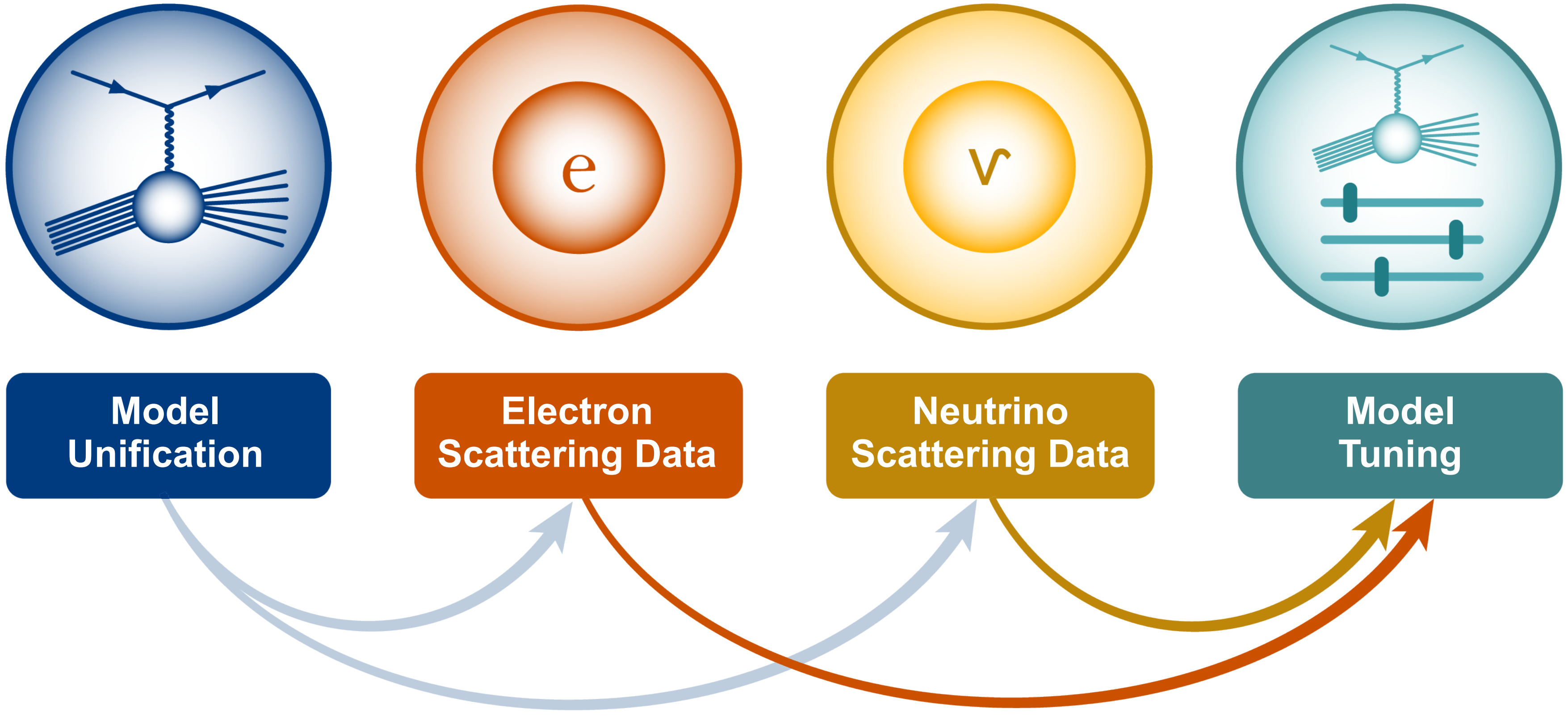

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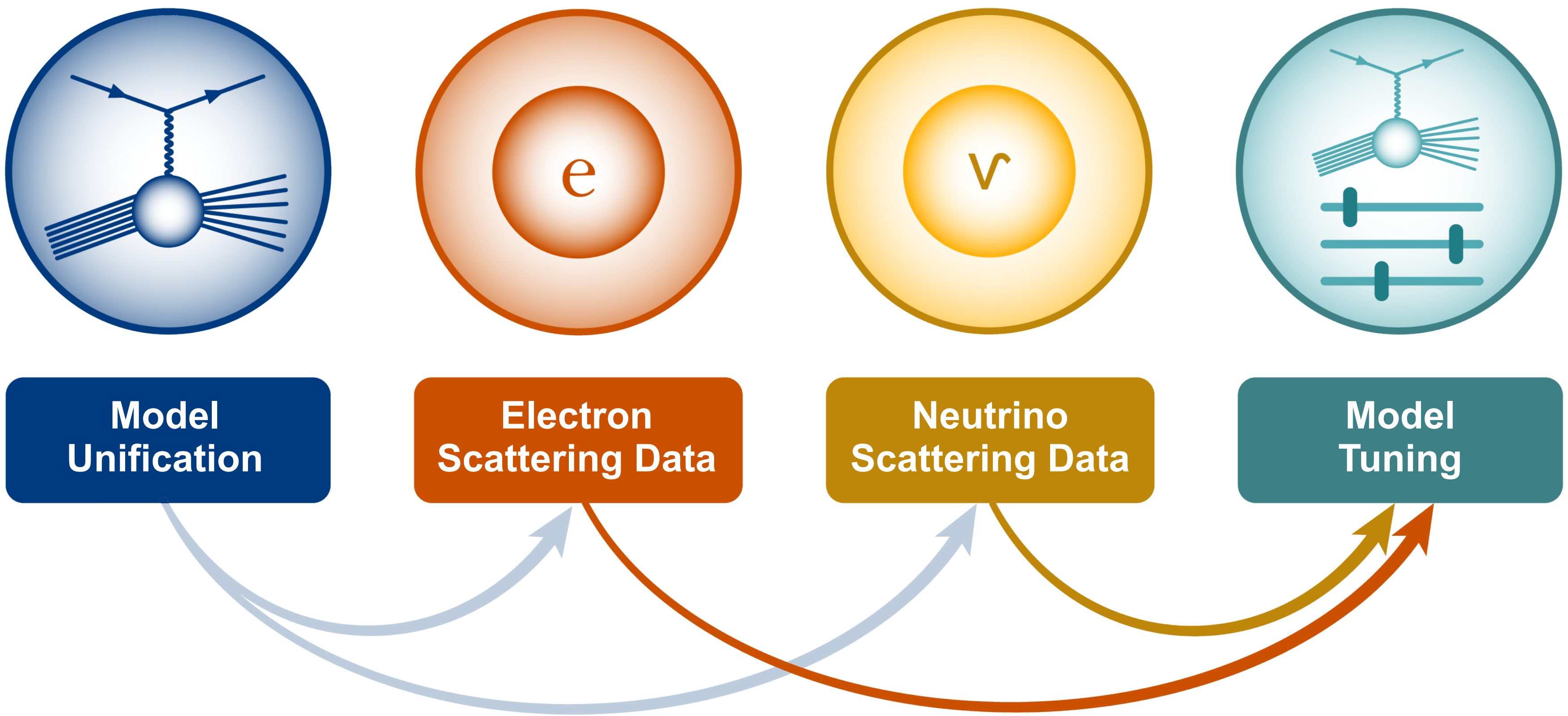


Today:

- **New** SuSA 1n1p, 2p implementation

- Coming **new** inclusive results
- **New** proton transparency results
- 1p0π Results

- **New** DUNE Prism analysis

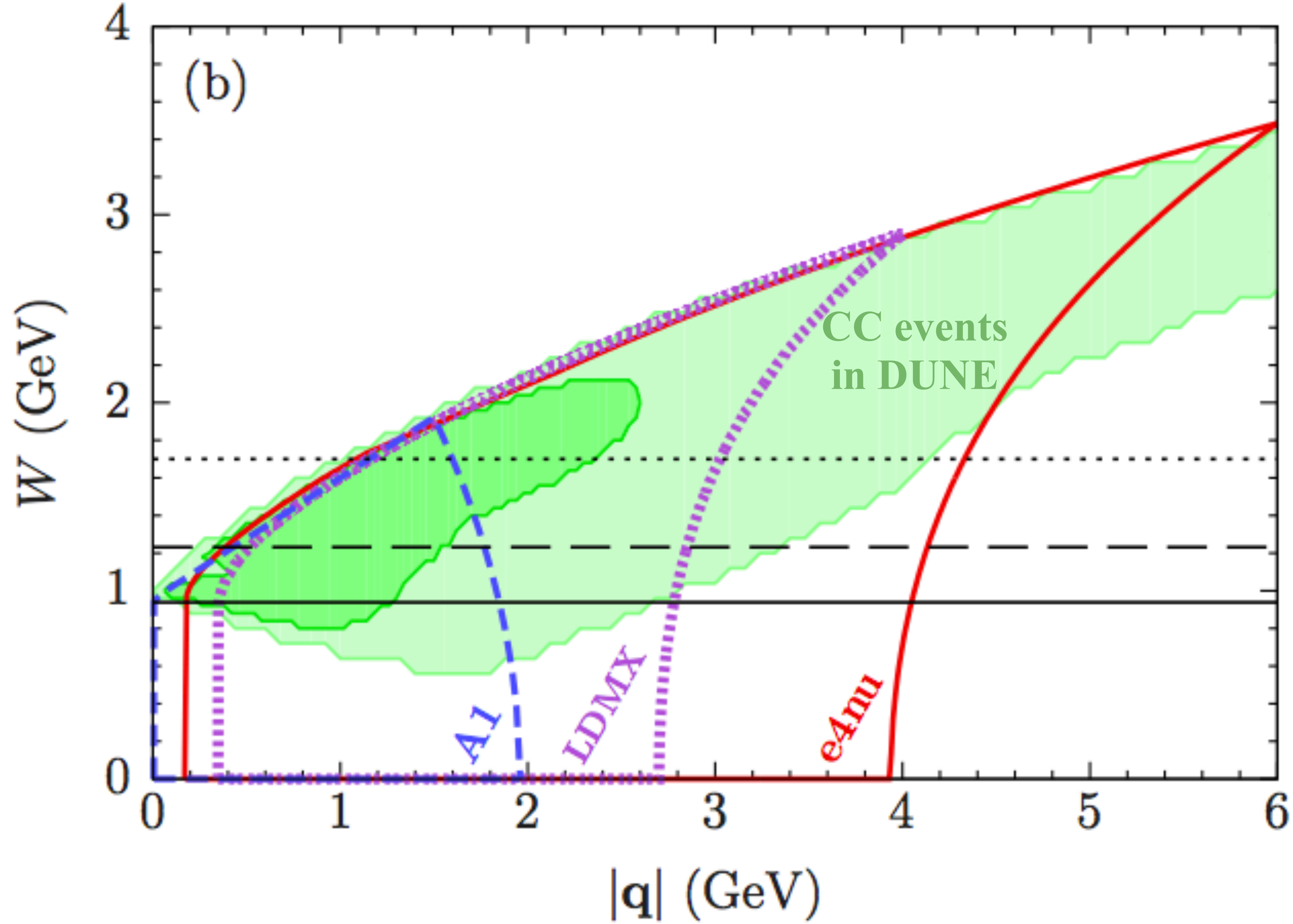
Tomorrow: See Julia Tena Vidal's talk

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]

e4nu and DUNE



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

CLAS Detector

Electron beam with energies up to 6 GeV

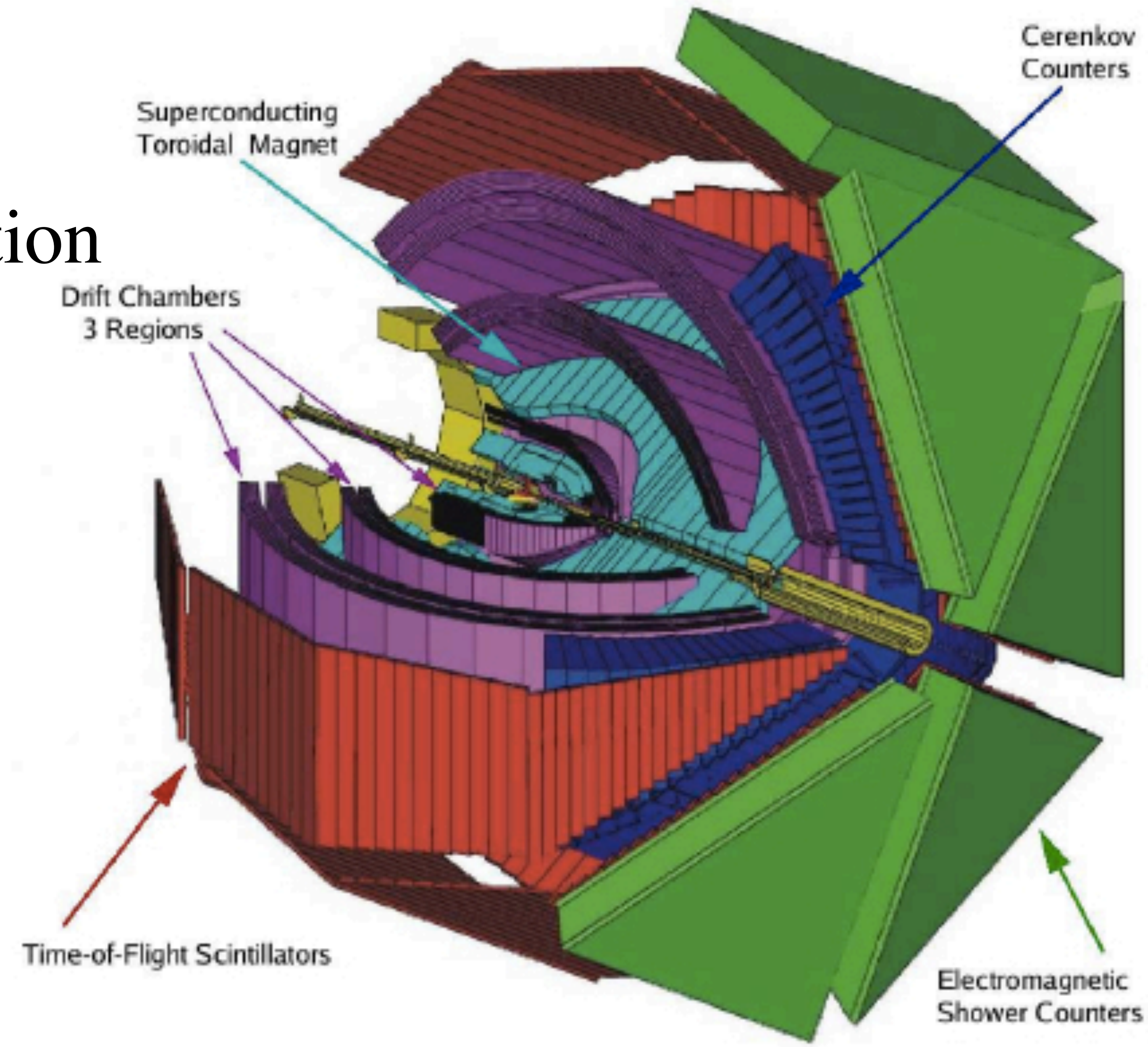
Large acceptance

Charged particles above detection threshold:

300 MeV/c for p

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

500 MeV/c for P_{π}^{0}



Open Trigger

New Data from CLAS12

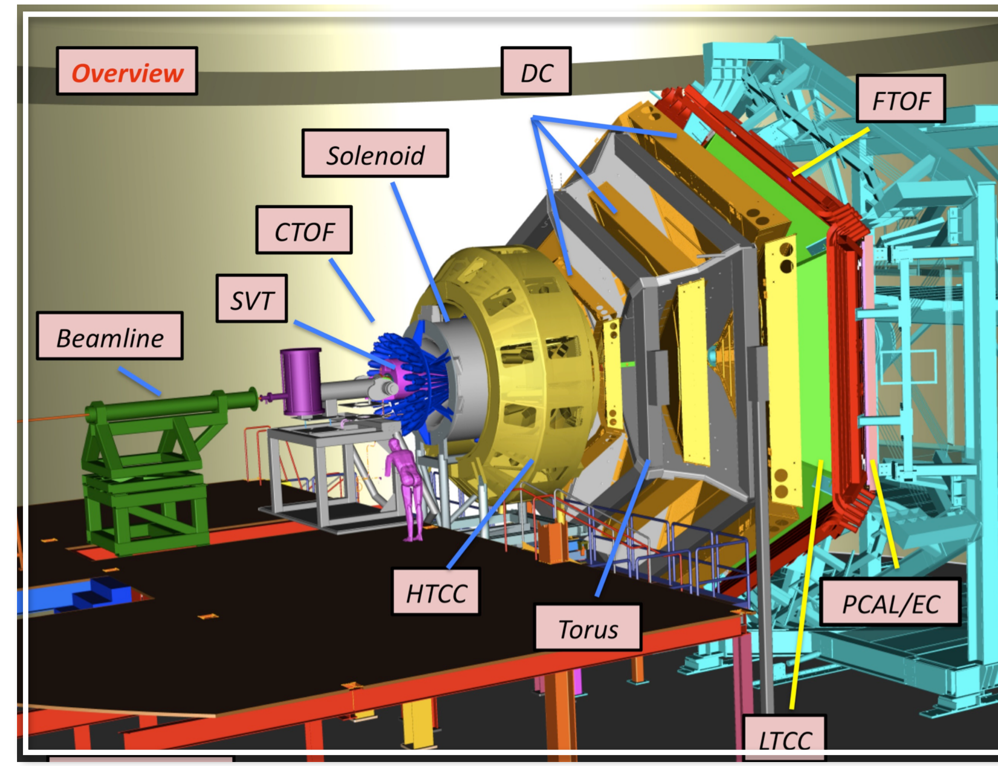
Acceptance down to 5^o $Q^2 > 0.04$ GeV^2

x10 luminosity [10^{35} cm^{-2}s^{-1}]

Keep low threshold, better neutron coverage

Targets: ^{2}D, ^{4}He, ^{12}C, ^{16}O, ^{40}Ar, ^{40}Ca

(1,) 2, 4, 6 GeV (relevant for DUNE)



Overwhelming support from:

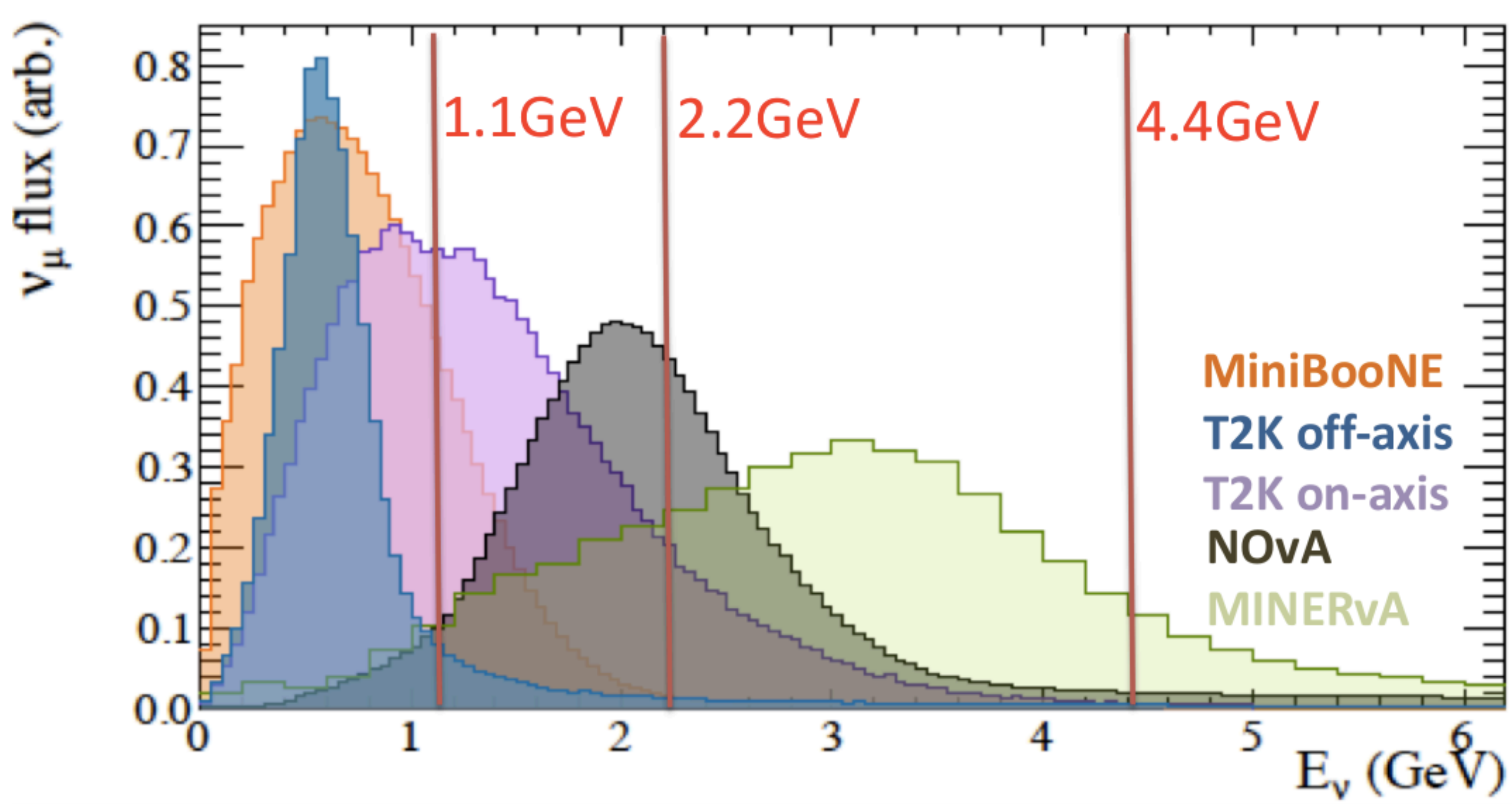
DUNE, ICECUBE SOUTH POLE NEUTRINO OBSERVATORY, Hyper-Kamiokande, T2K, NOvA, MINERvA, Fermilab, GiBUU The Giessen Boltzmann-Uehling-Uhlenbeck Project, Genie, μBooNE

CLAS A(e,e'p) Data

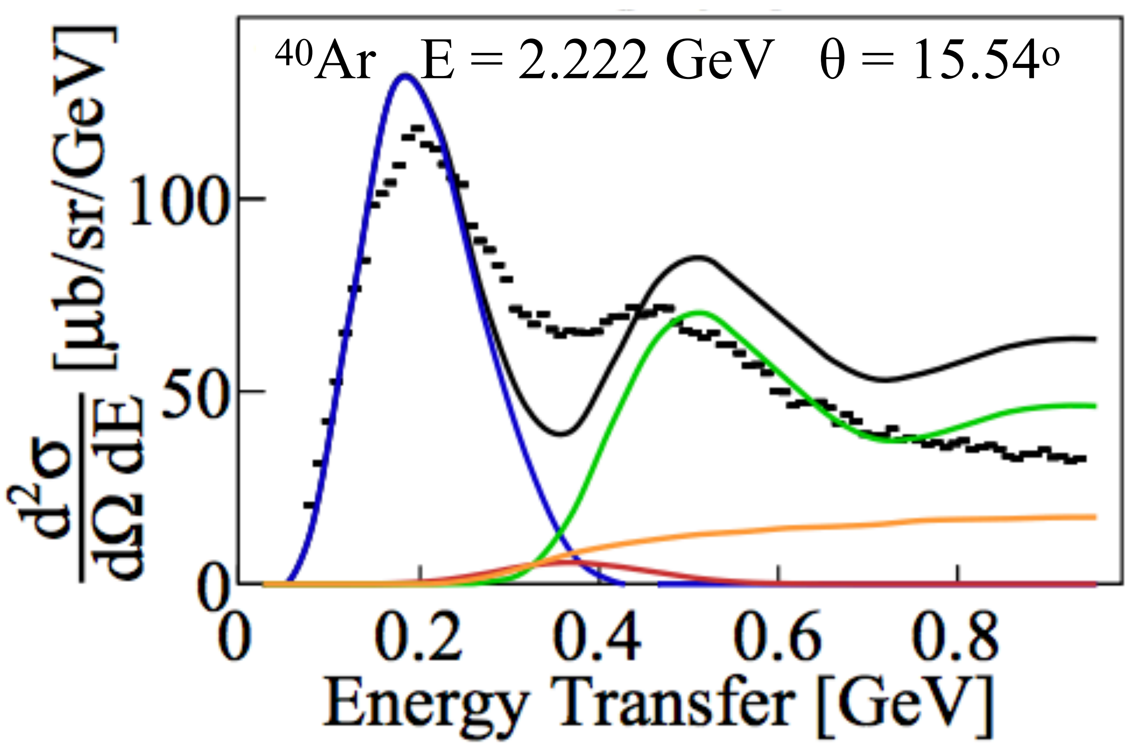
First test of neutrino energy reconstruction with exclusive data!

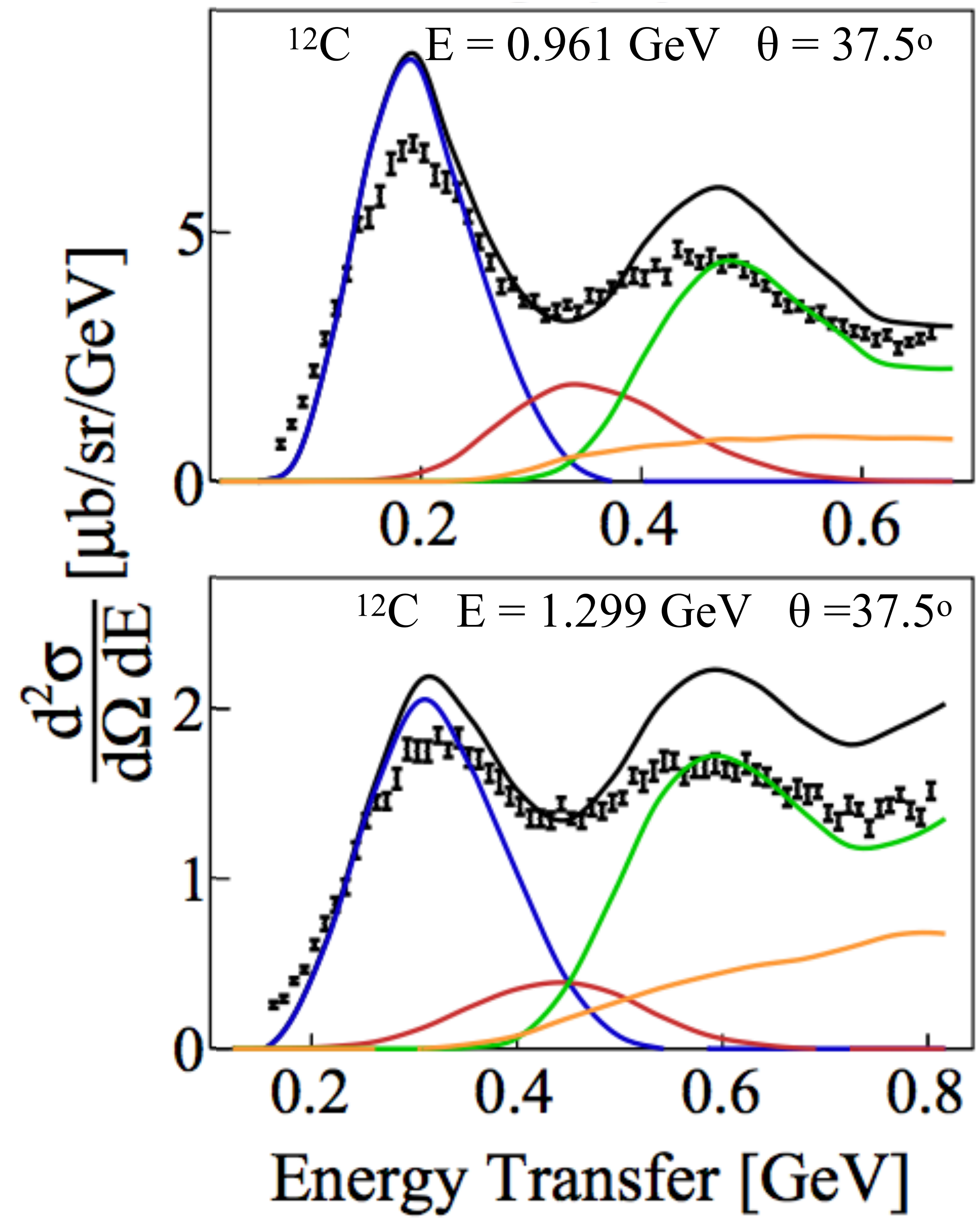
- Targets: H, D, ^{4}He, ^{12}C, ^{40}Ar, ^{40}Ca, ^{56}Fe — T2K (H_2O), NOvA (CH), DUNE (Ar)

- Energies:
  1.1, 2.2, 4.4 GeV
  2, 4, 6 GeV



Inclusive e data and generators



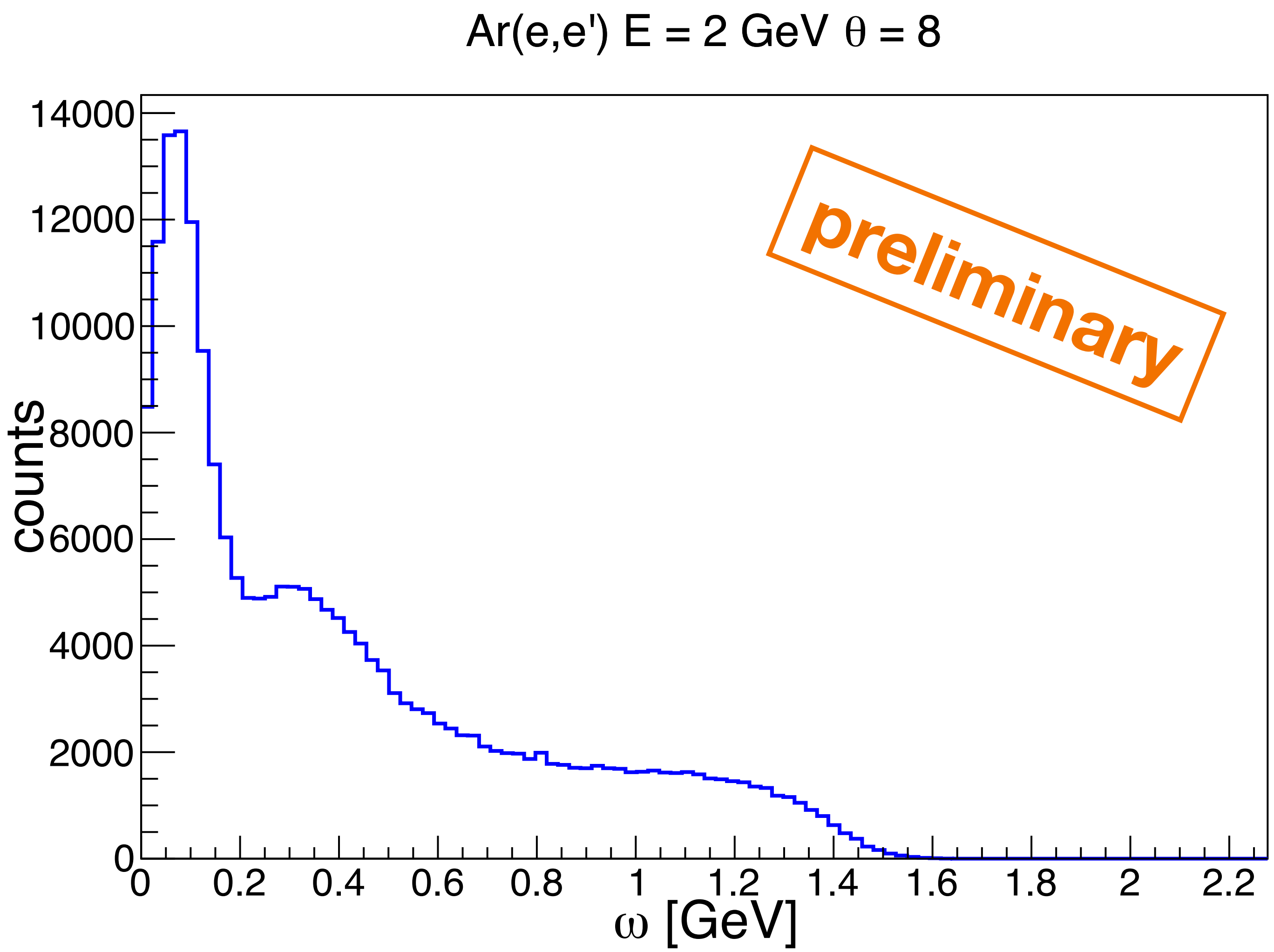


Genie

— v3.0.6 tune G18_10a_02_11a

Phys.Rev.D 103 (2021) 113003

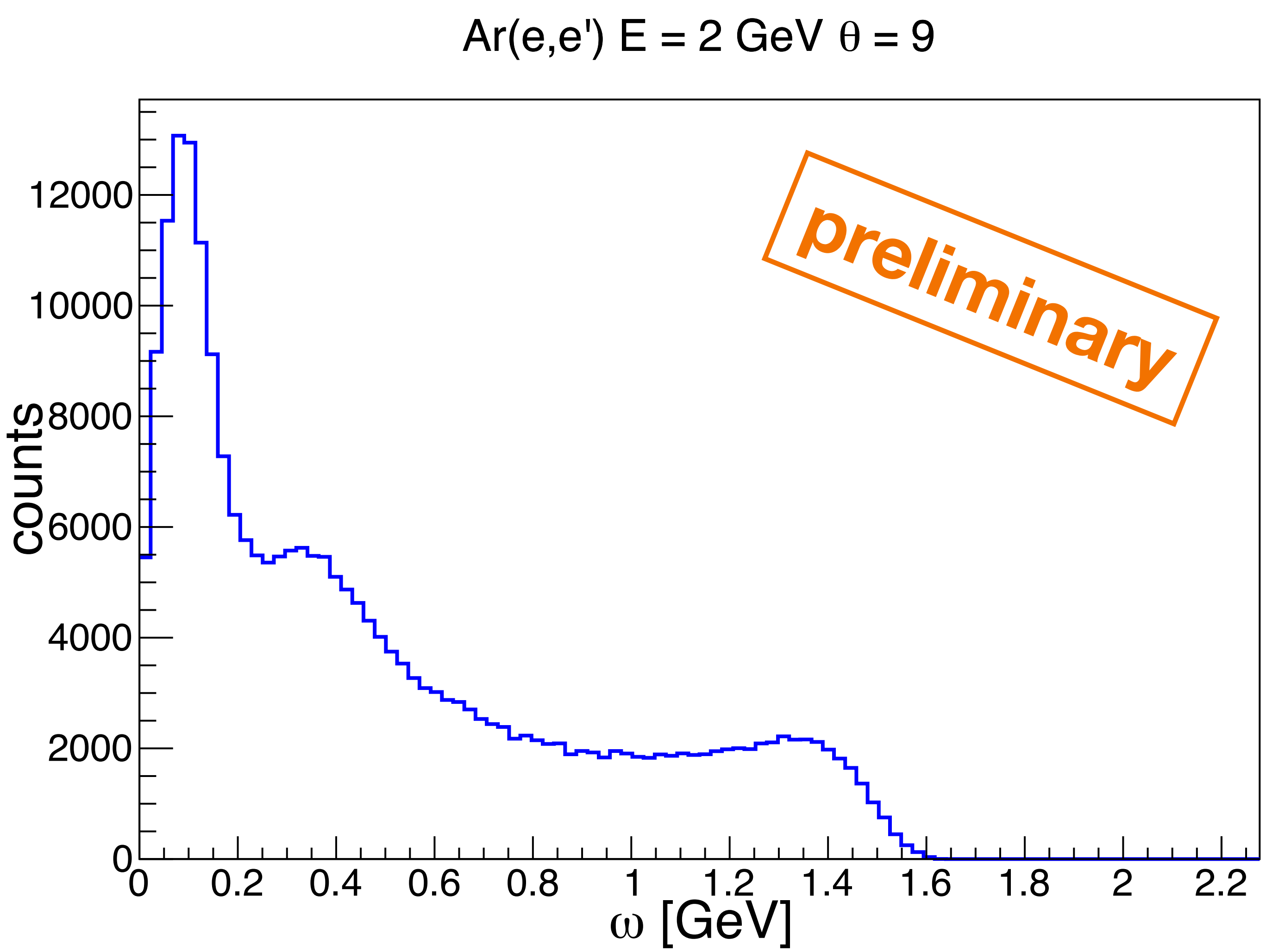
Towards new Inclusive results on Ar



Matan Goldenberg

Planing to extract Ar inclusive cross section at various Q^2

Towards new Inclusive results on Ar



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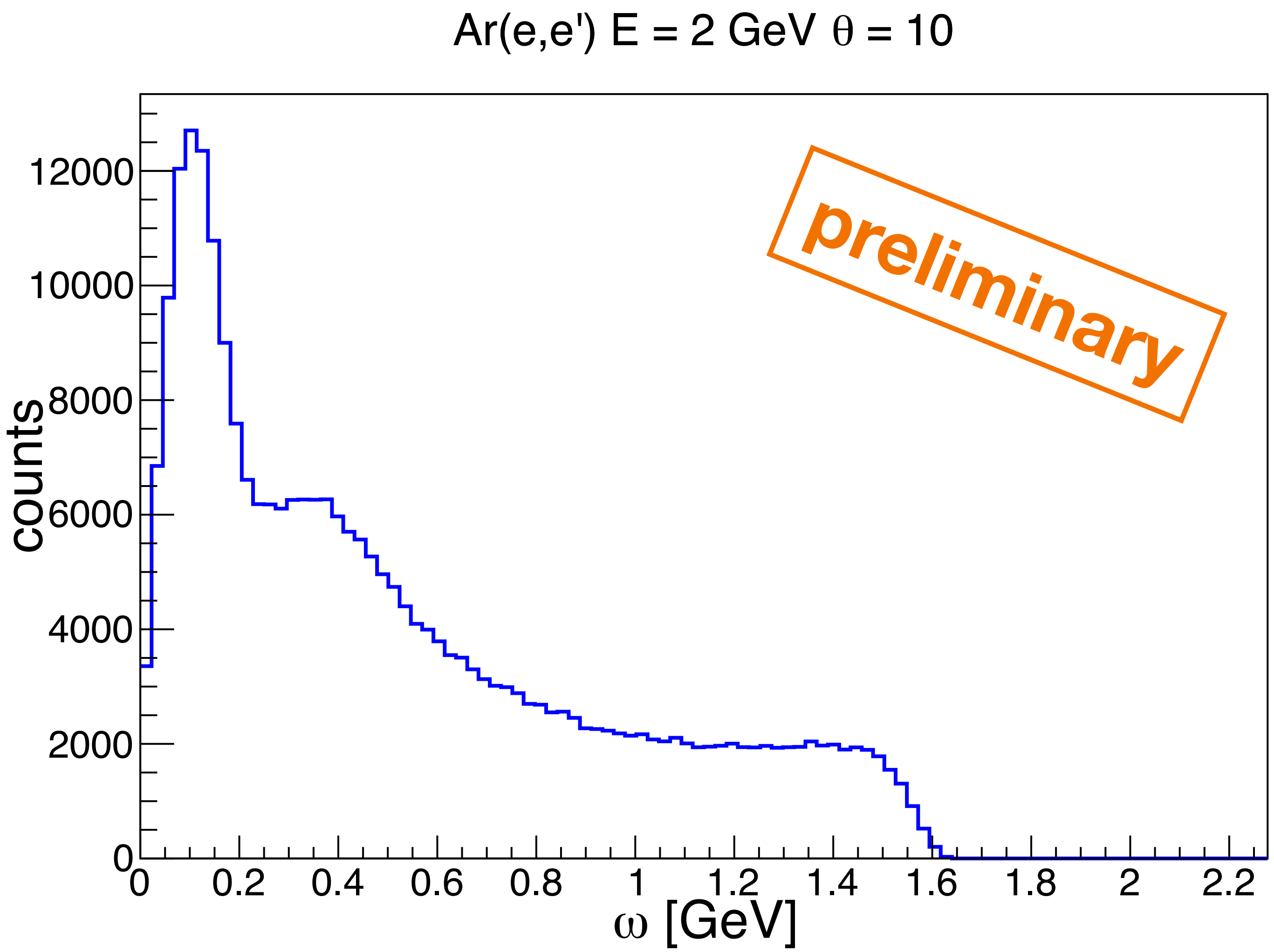

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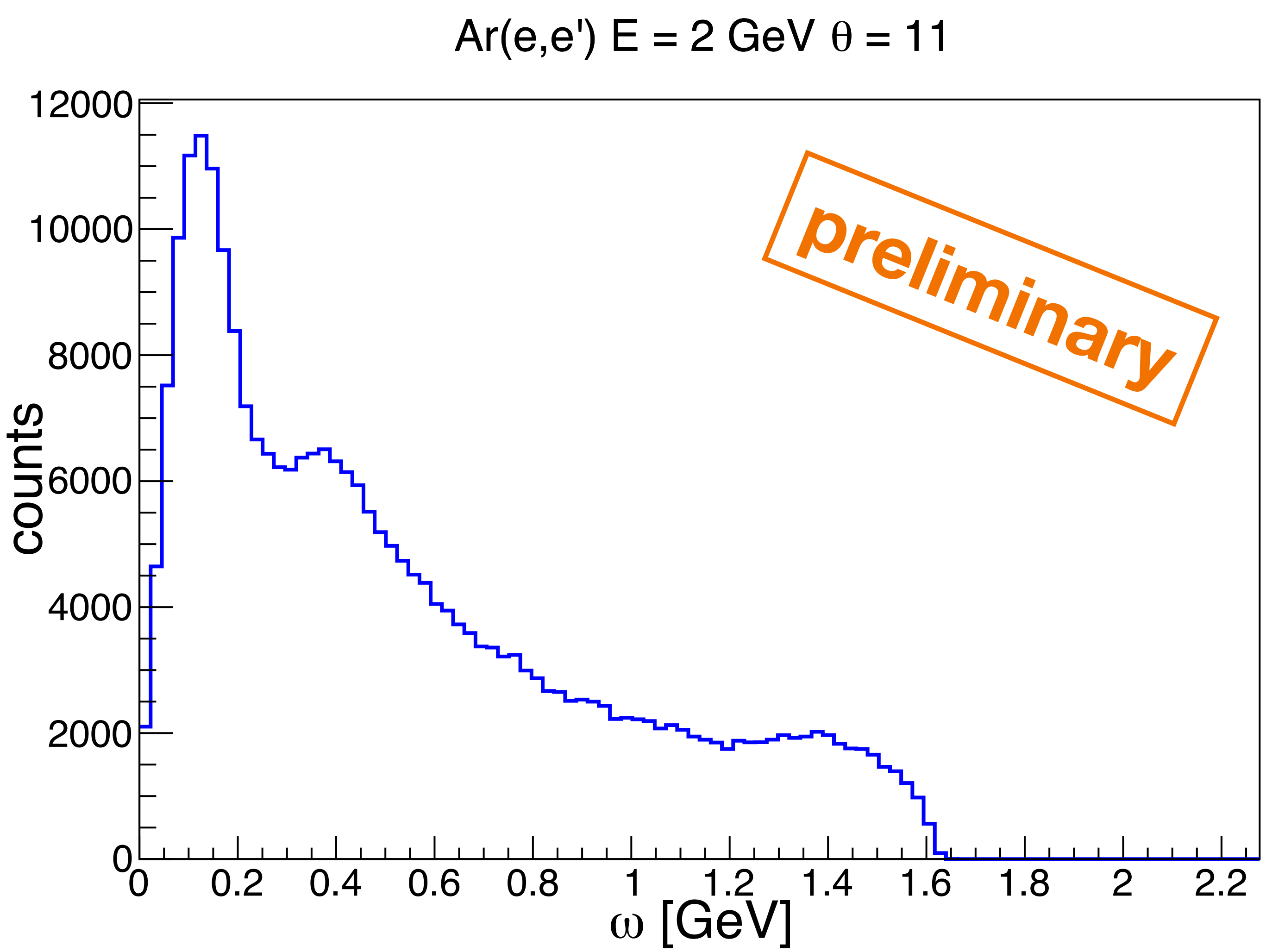

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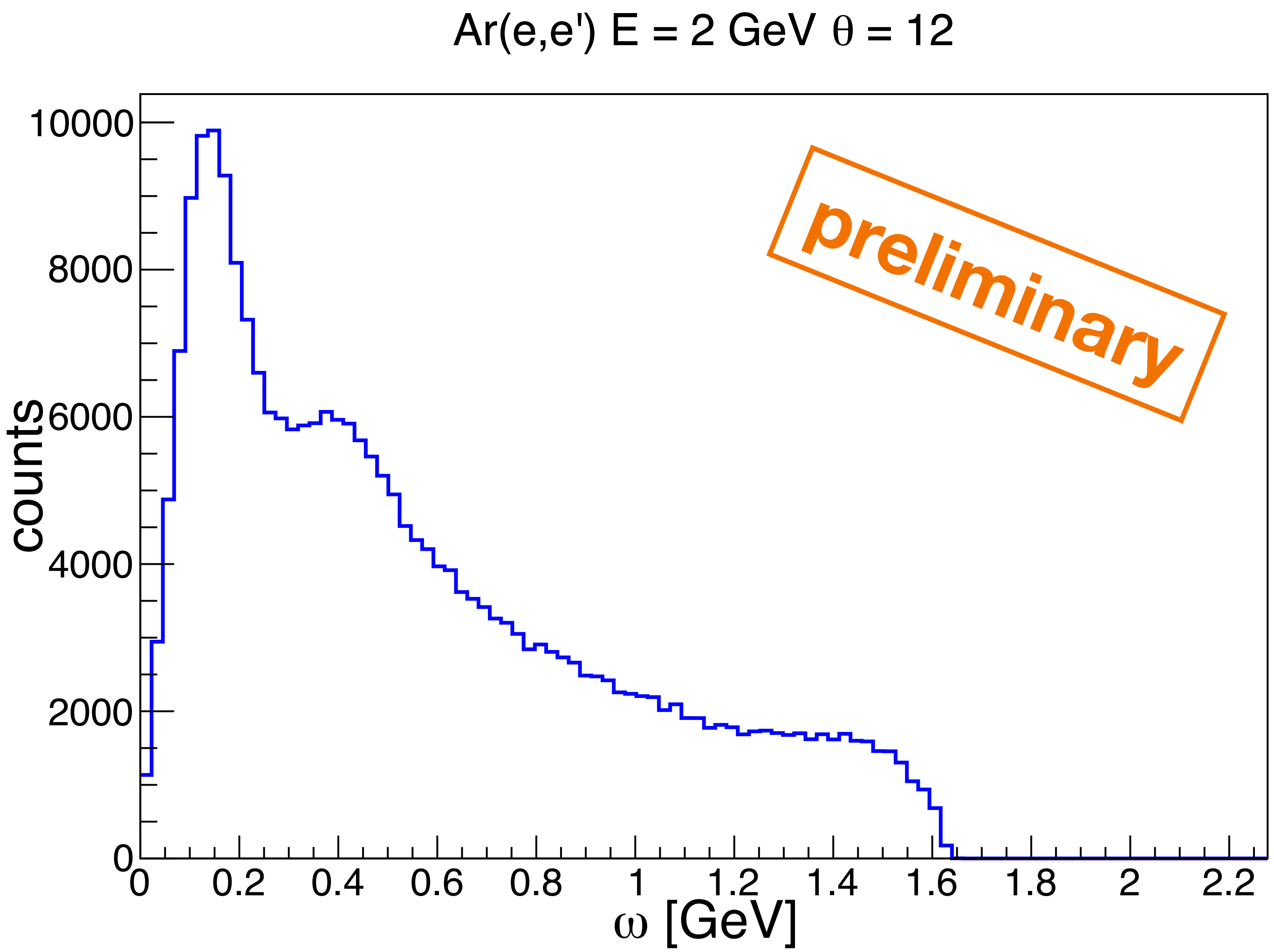

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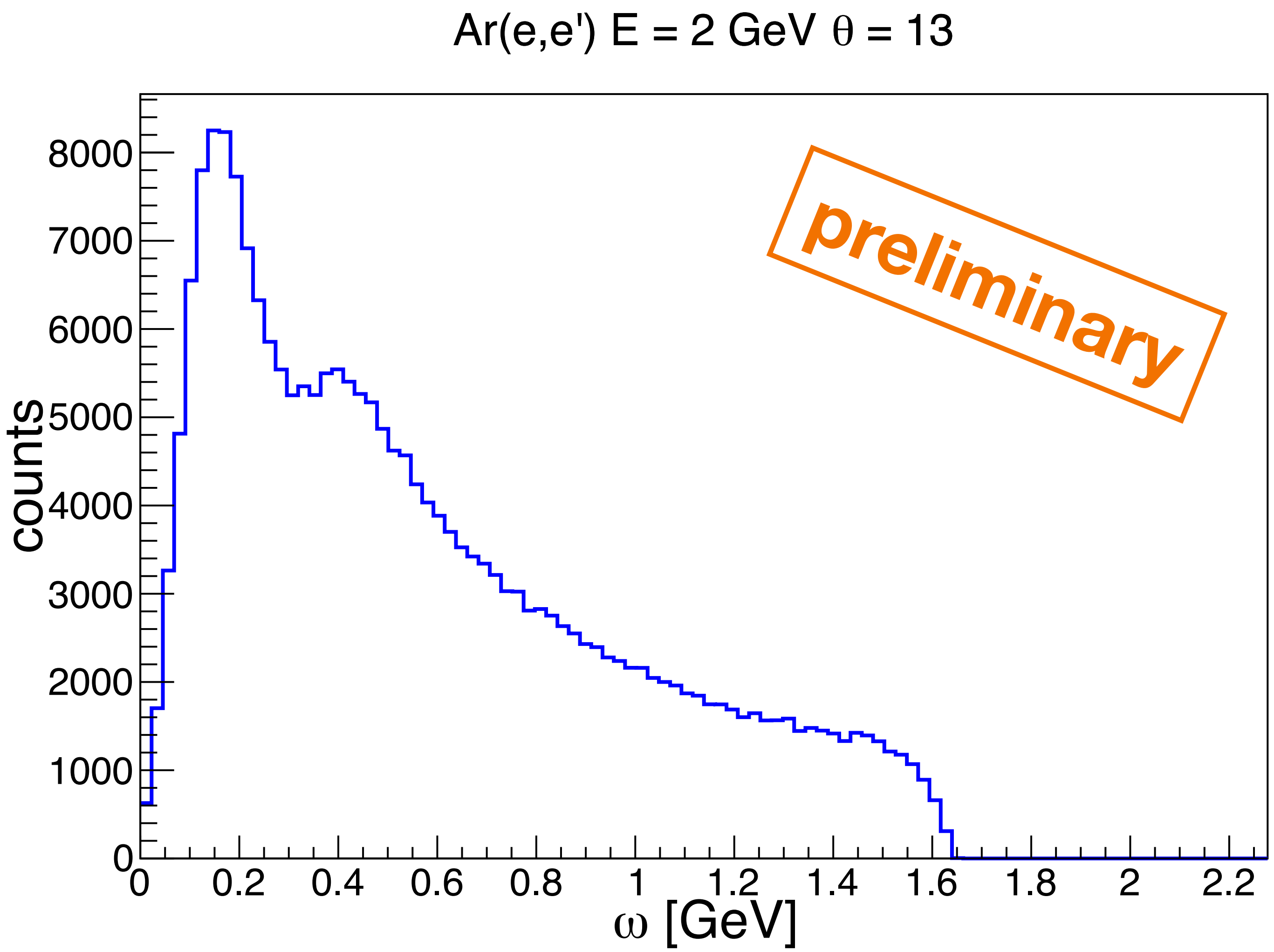

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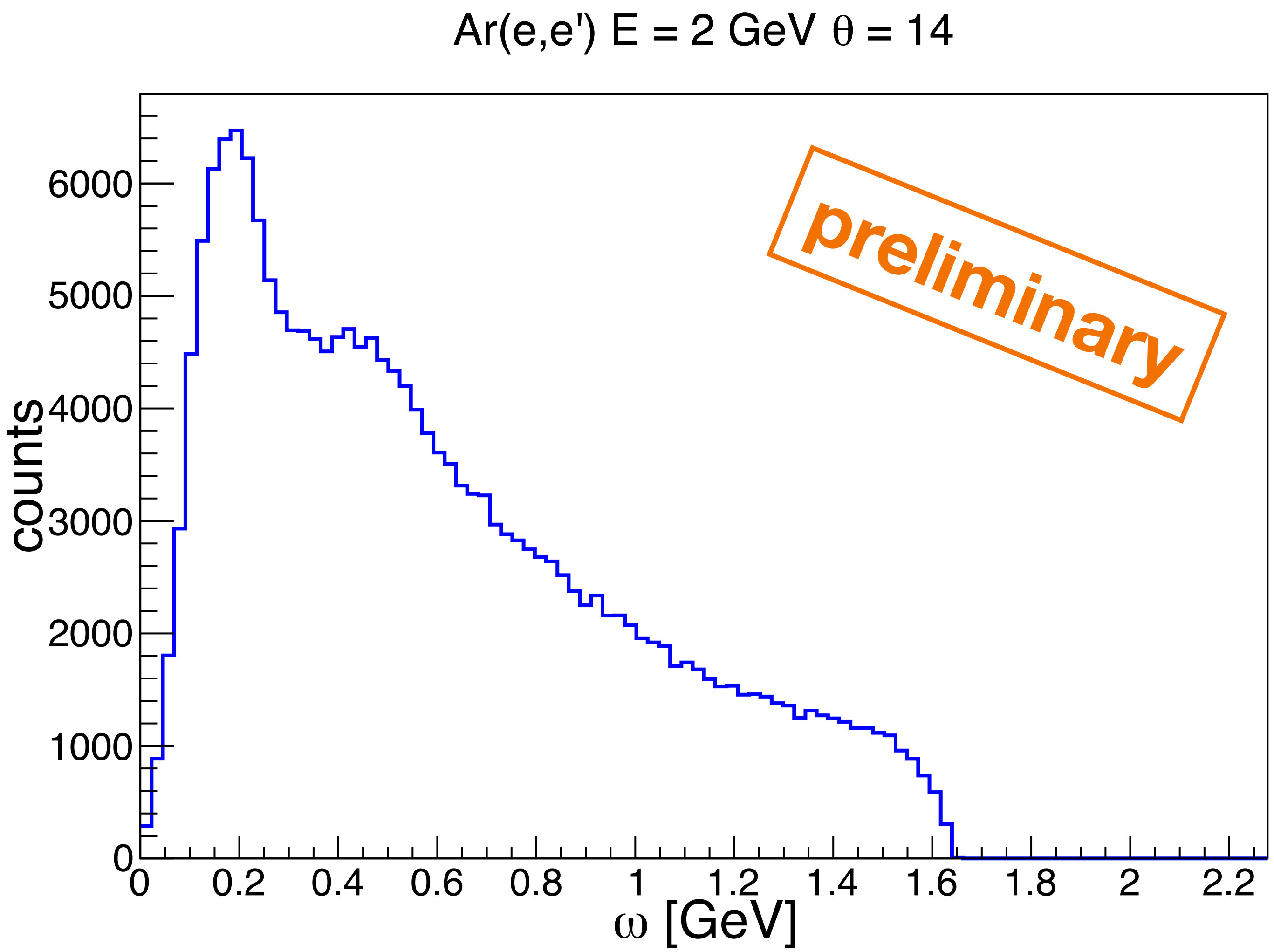

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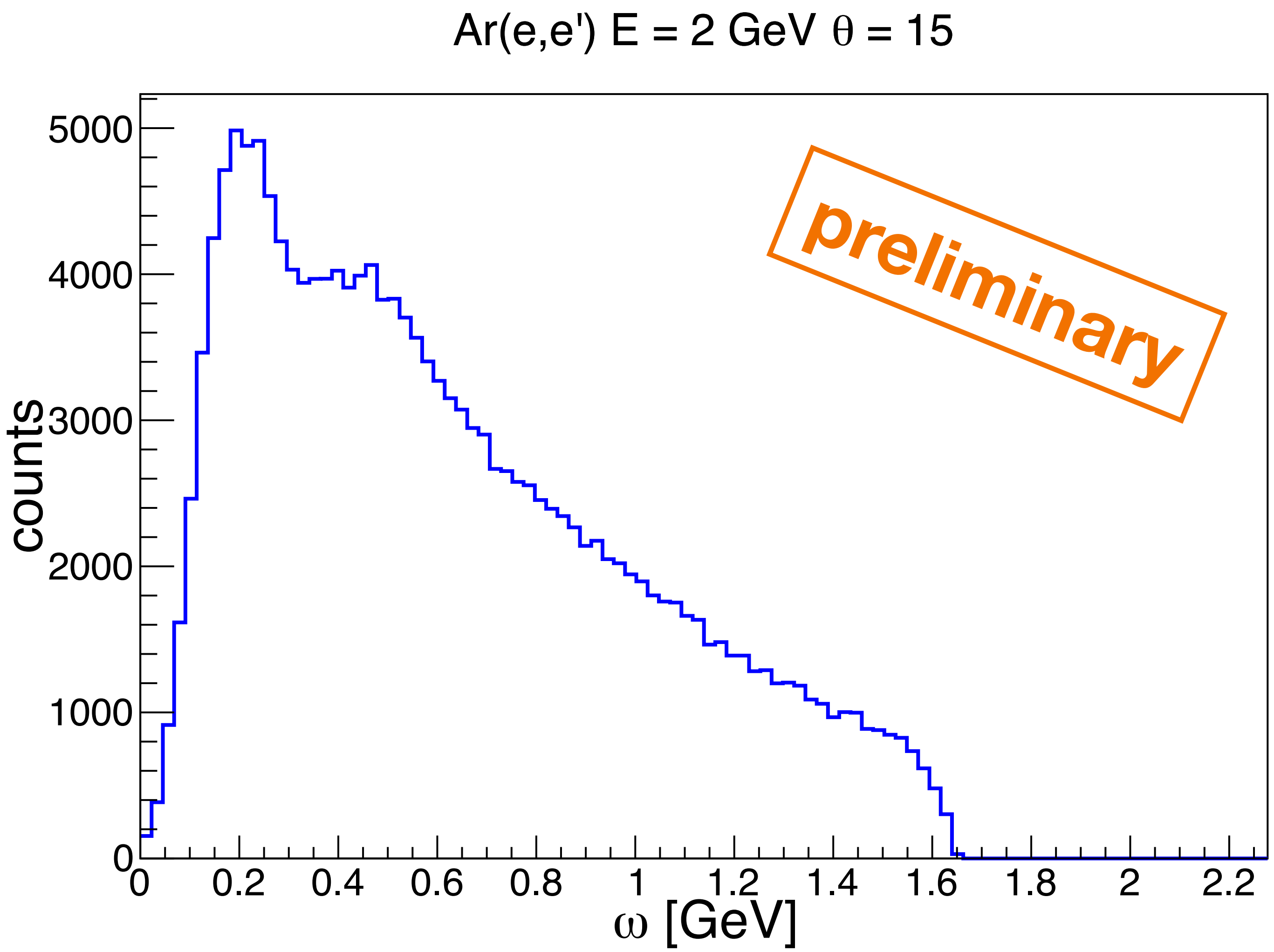

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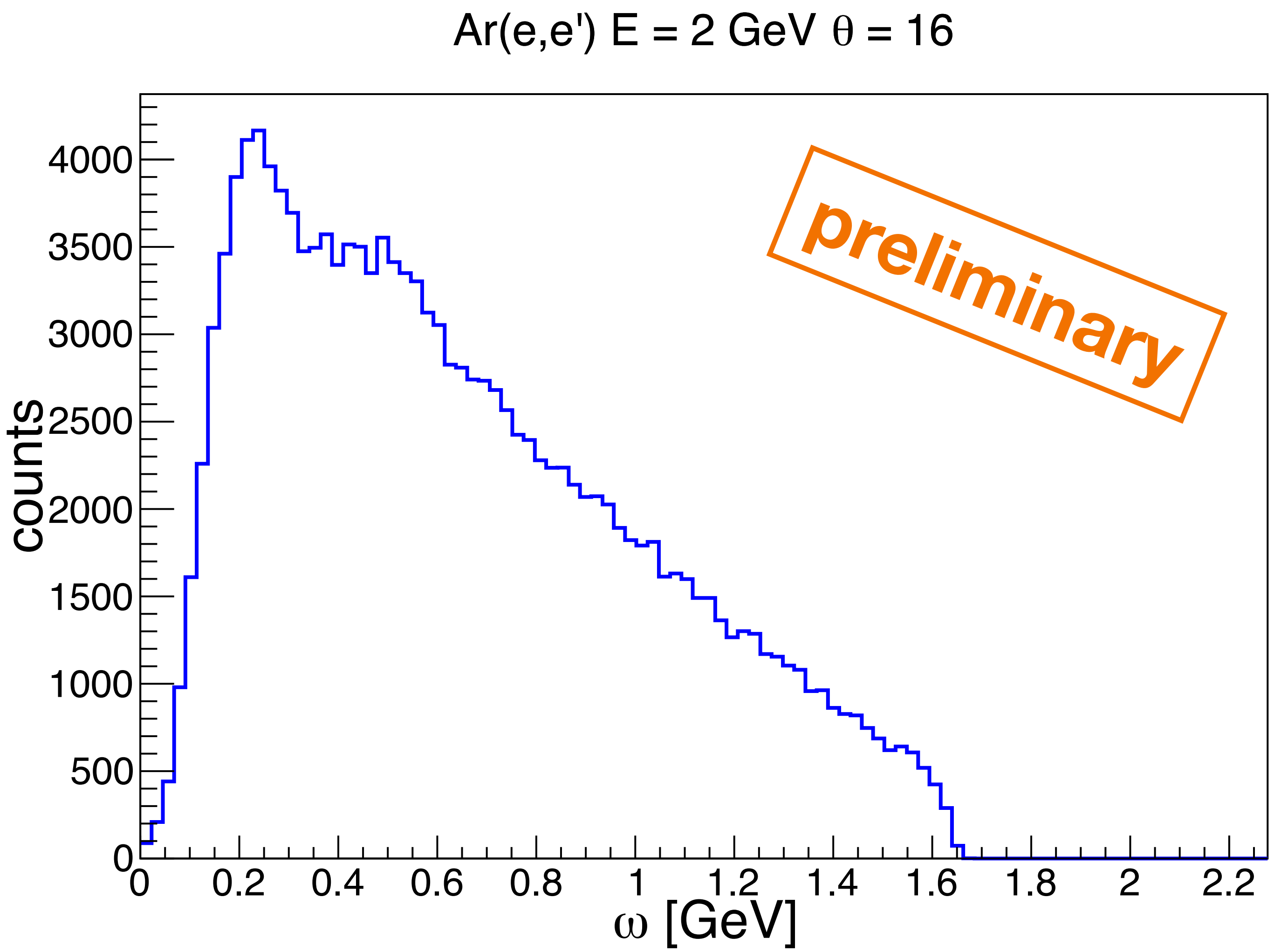

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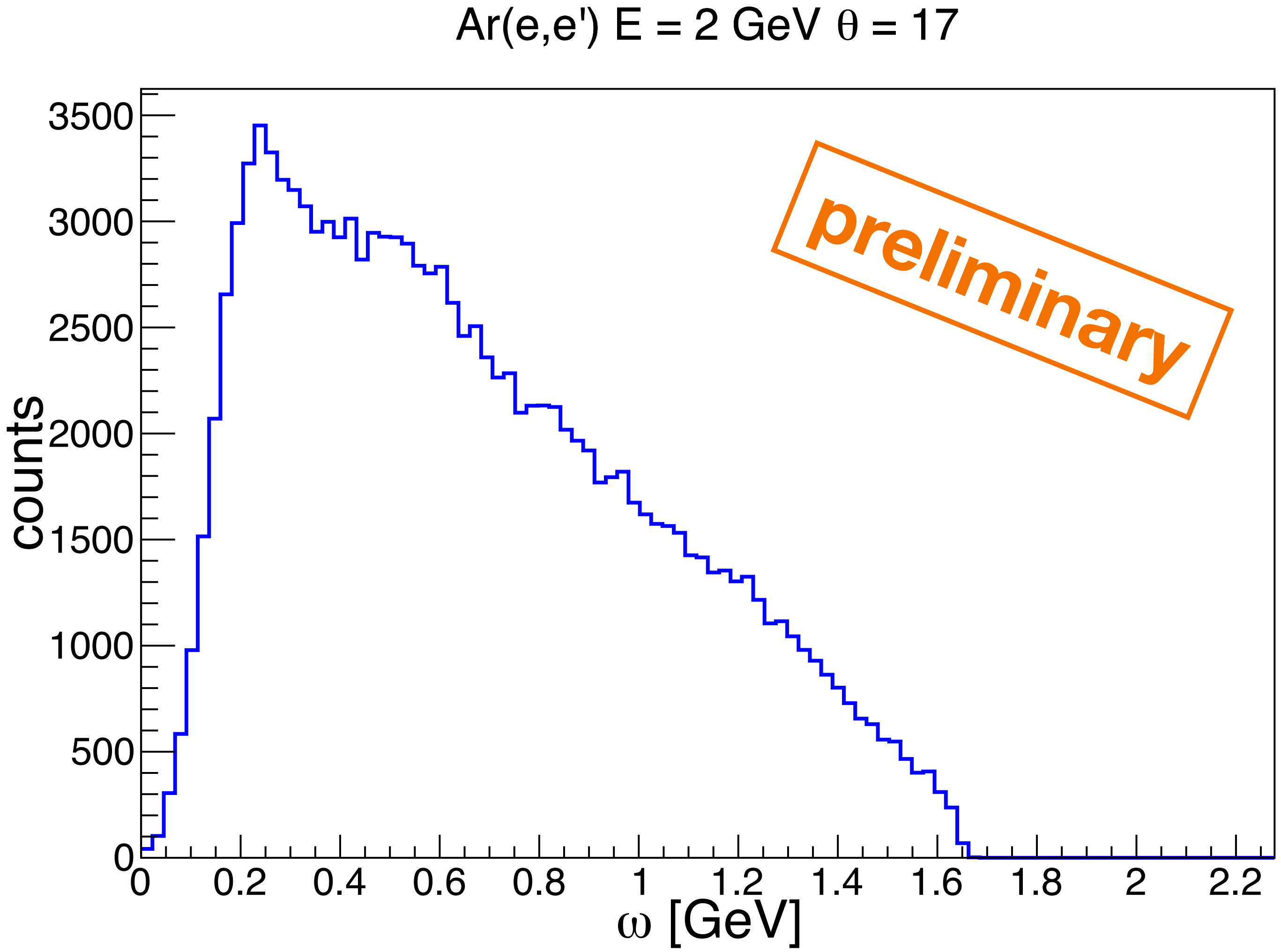

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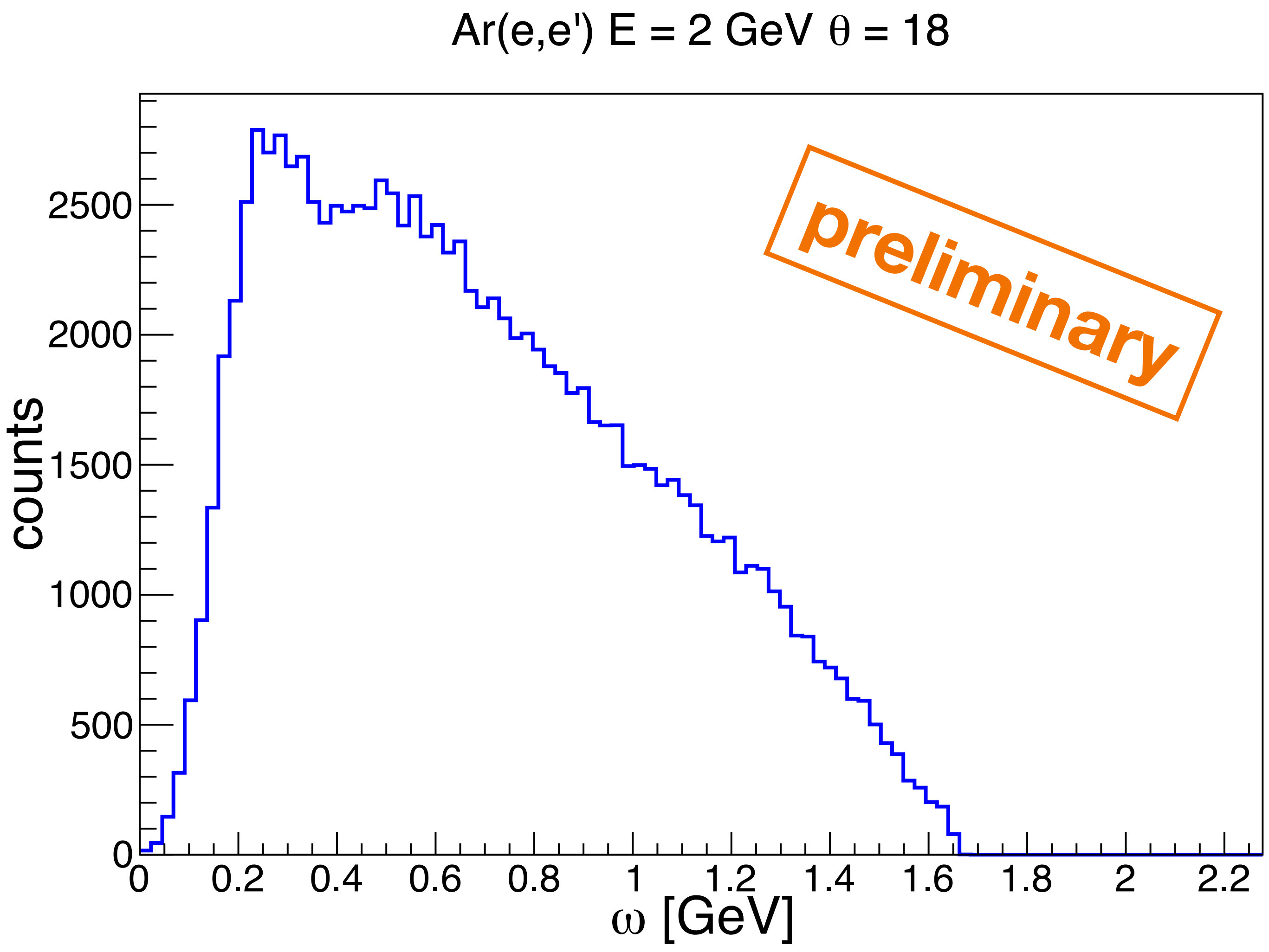

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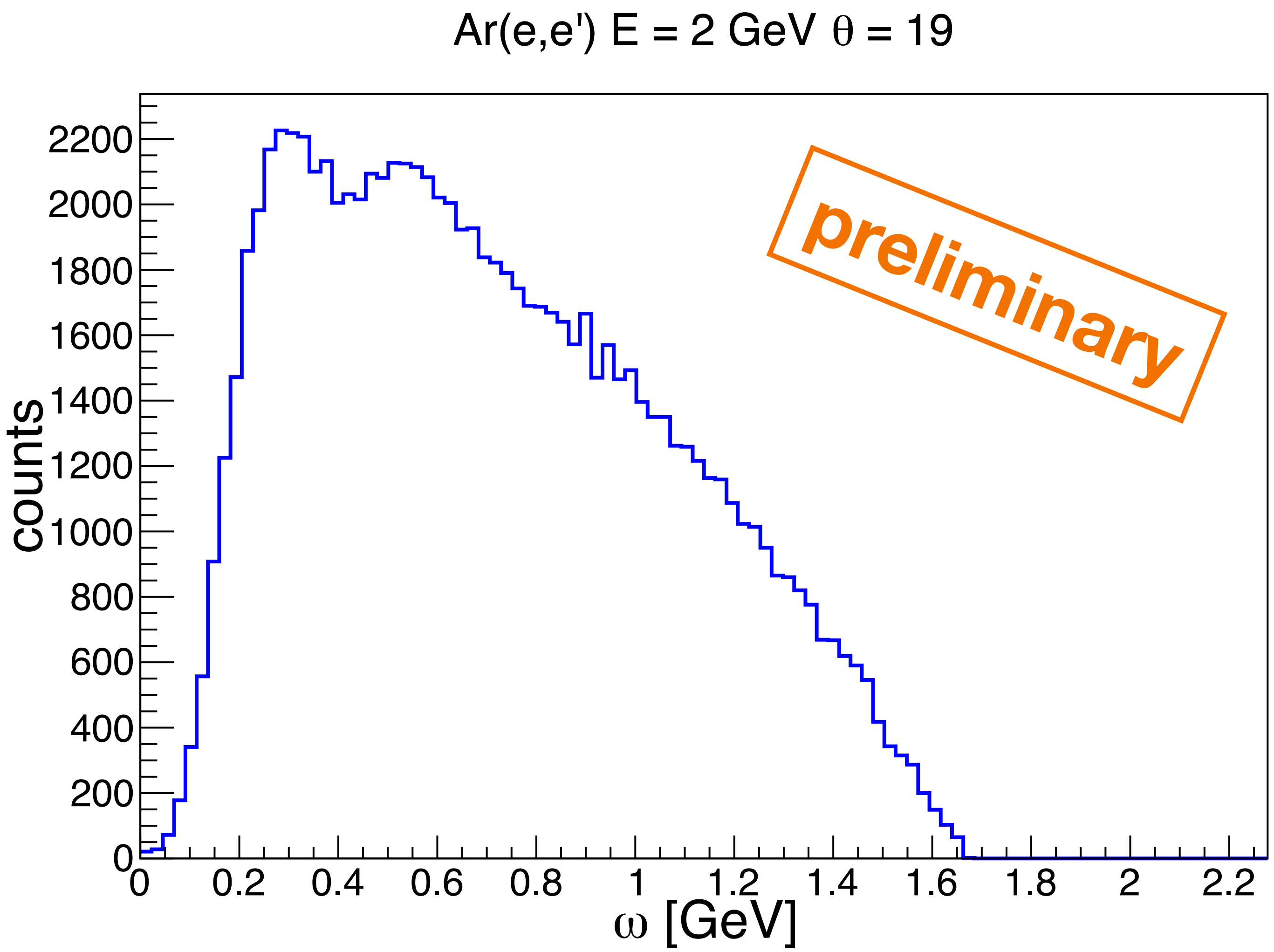

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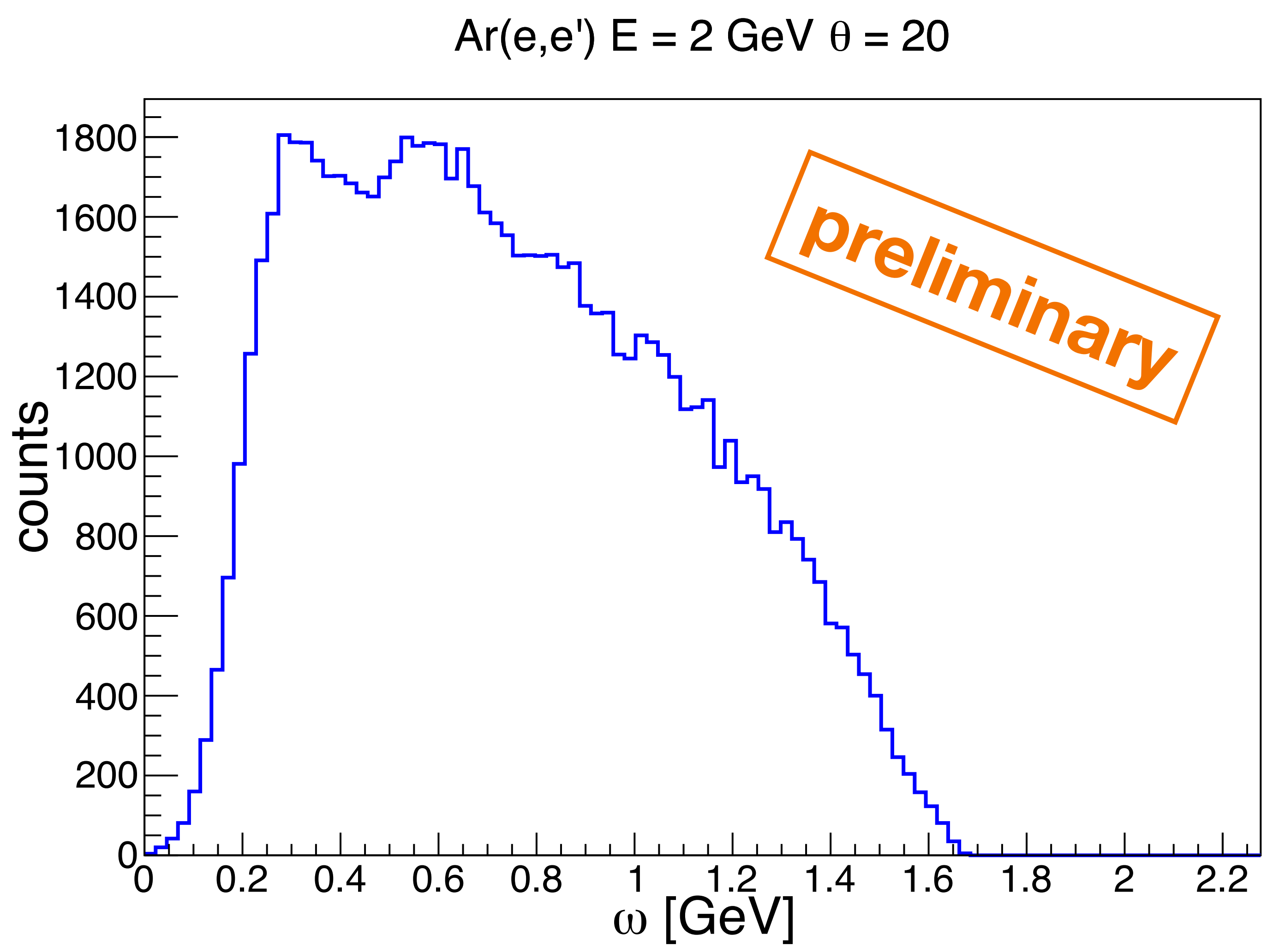

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Planing to extract Ar inclusive cross section at various Q^2

Nuclear Transparency - New Results

The probability that a struck proton leaves the nucleus without significant rescattering

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

at Quasielastic regions (X_B around 1)

Using MC to determine QE dominated regions

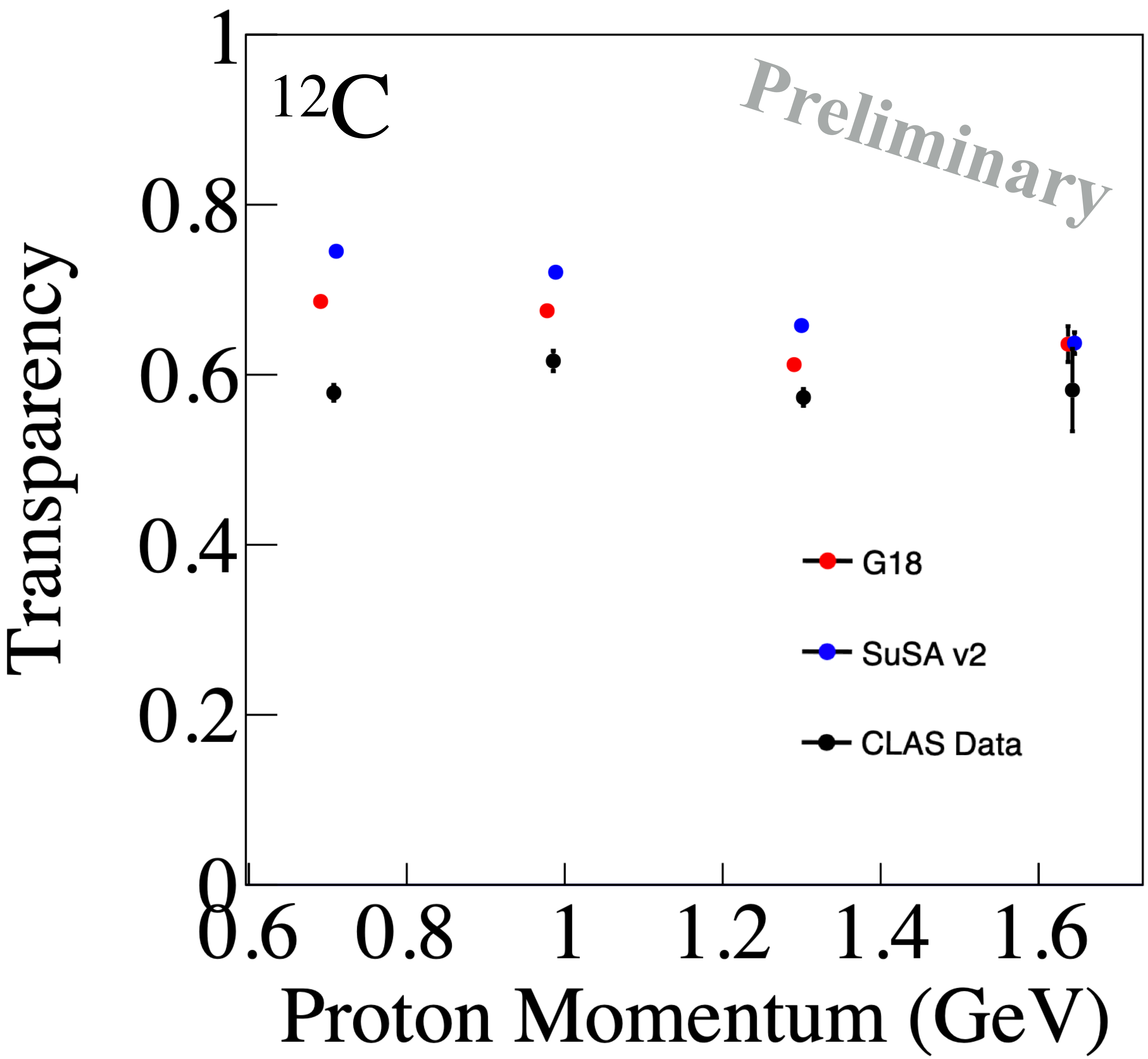
low P_l, high P_p, low θ_{pq}

Useful to constrain the FSI models

Better model independency

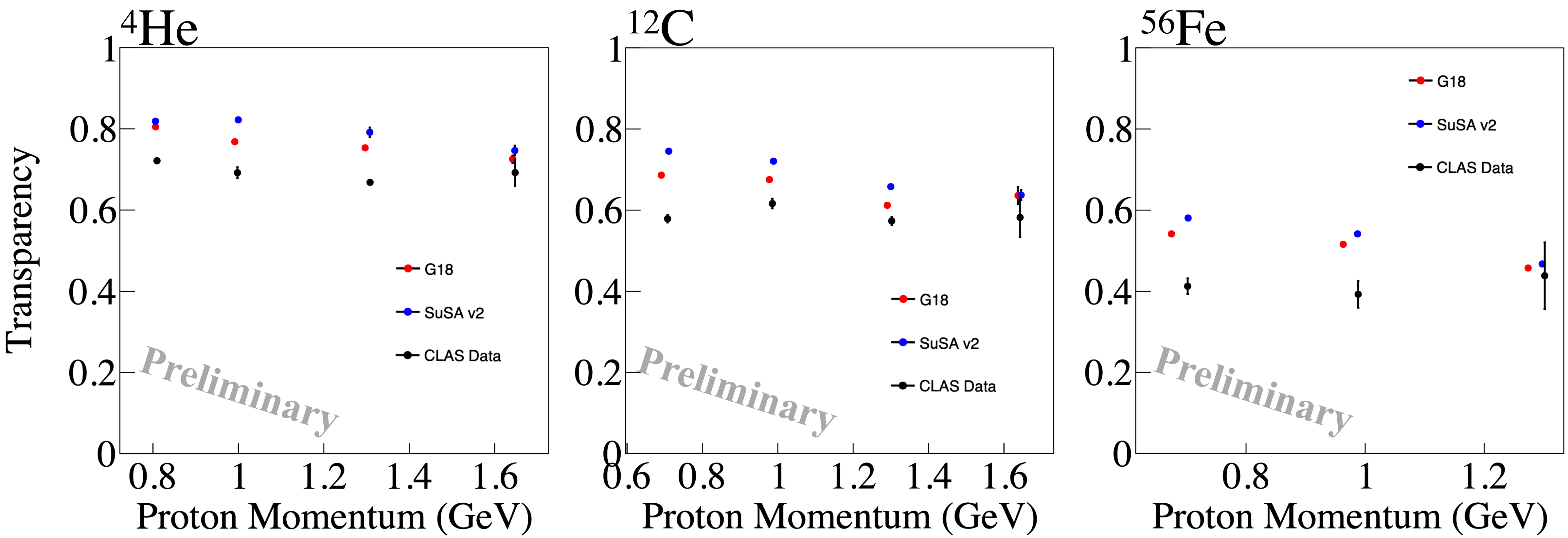
Noah Steinberg Fermilab

Nuclear Transparency - New Results



Noah
Steinberg
Fermilab

Nuclear Transparency - New Results

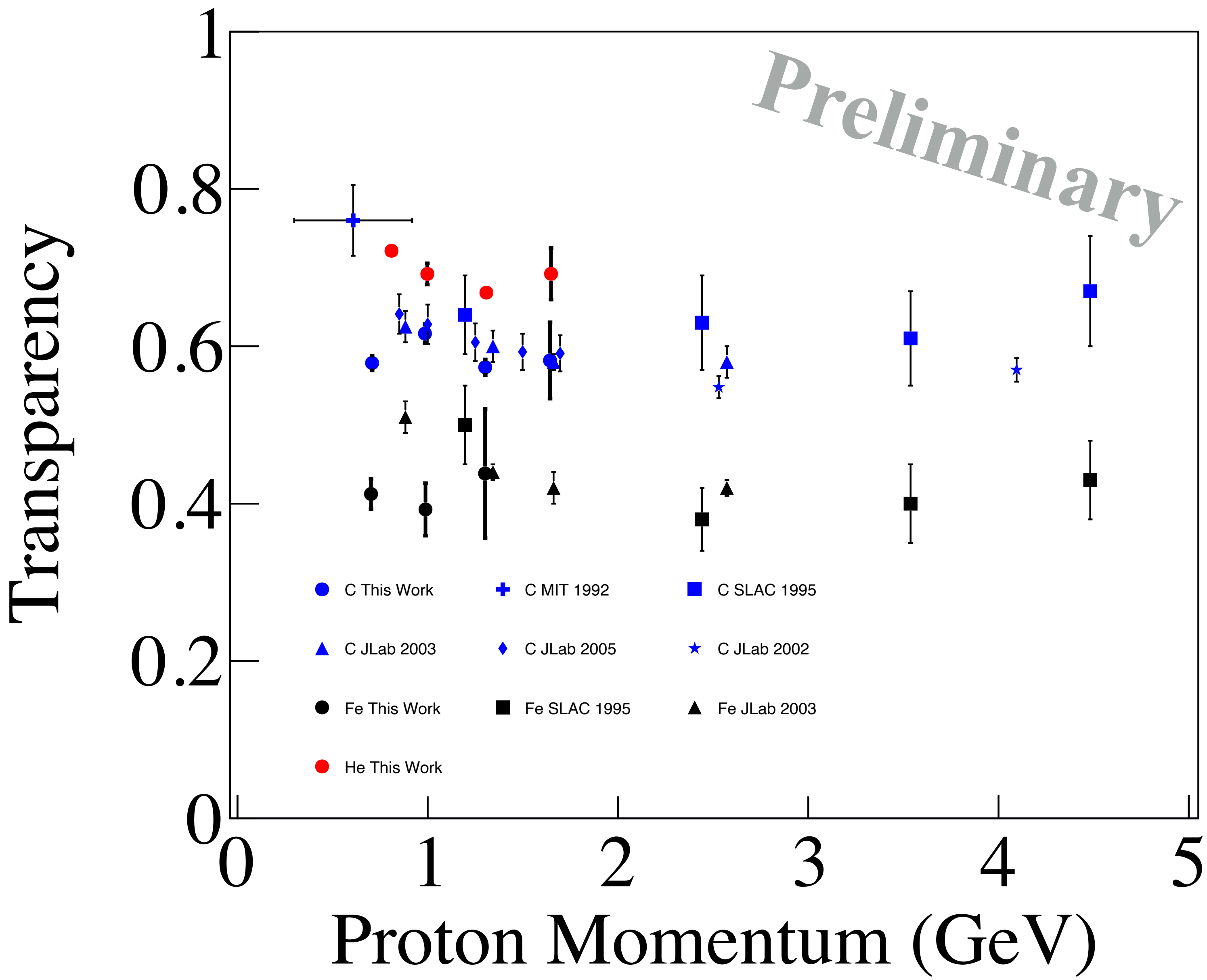


Data to MC differences

Larger at small momentum, Grow with A

Noah
Steinberg
Fermilab

Nuclear Transparency - New Results



Less model dependent measurement

Consistent with previous results on C, Fe

First measurement on He

Noah
Steinberg
Fermilab

e4ν 1p0π Event Selection

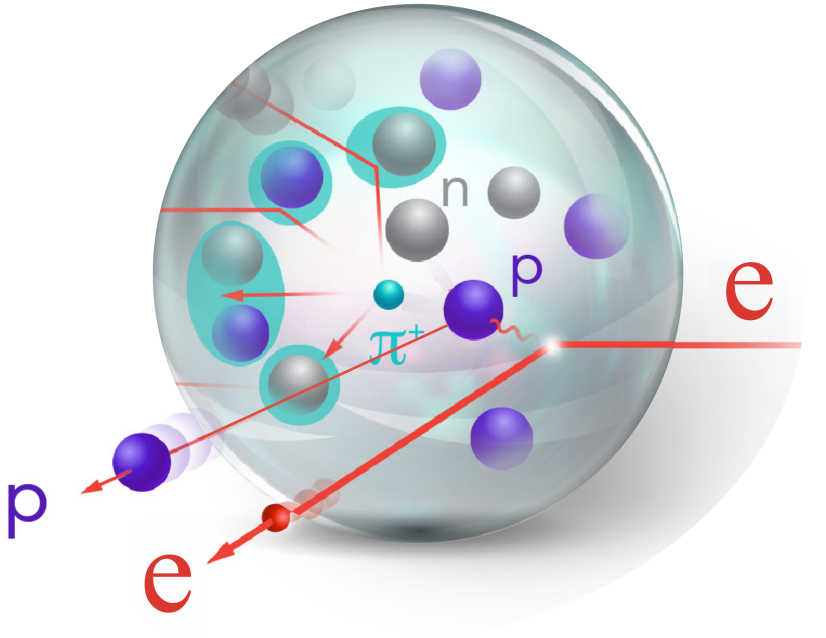
Focus on Quasi Elastic events:

1 proton above 300 MeV/c

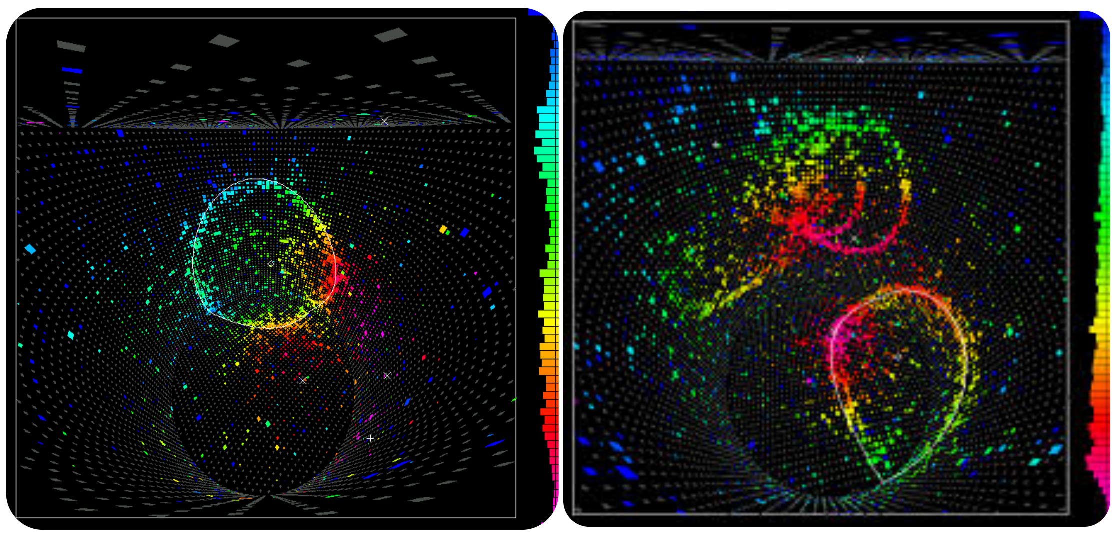
no additional hadrons above detection threshold:

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

500 MeV/c for P_{π^0}



Incoming Energy Reconstruction



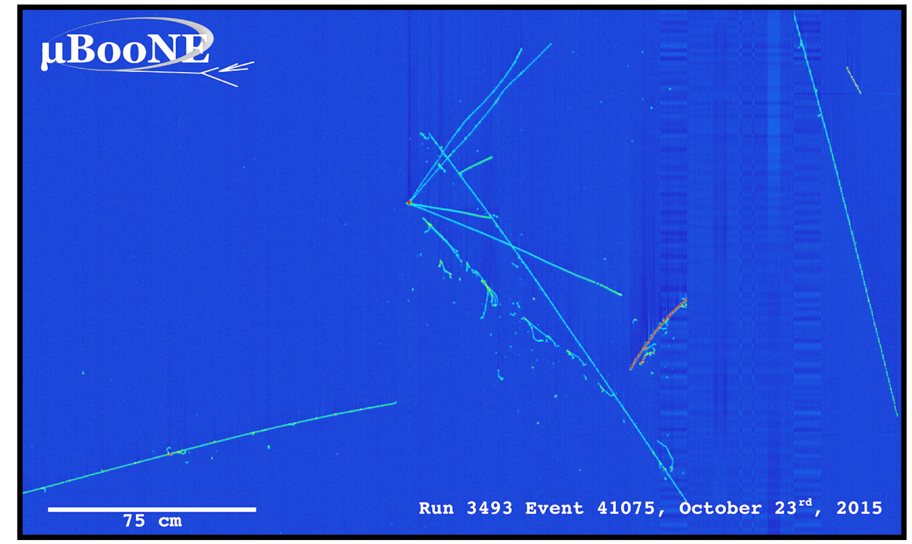
Cherenkov detectors:

Assuming QE interaction

Using lepton only

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

[0π]



Tracking detectors:

Calorimetric sum

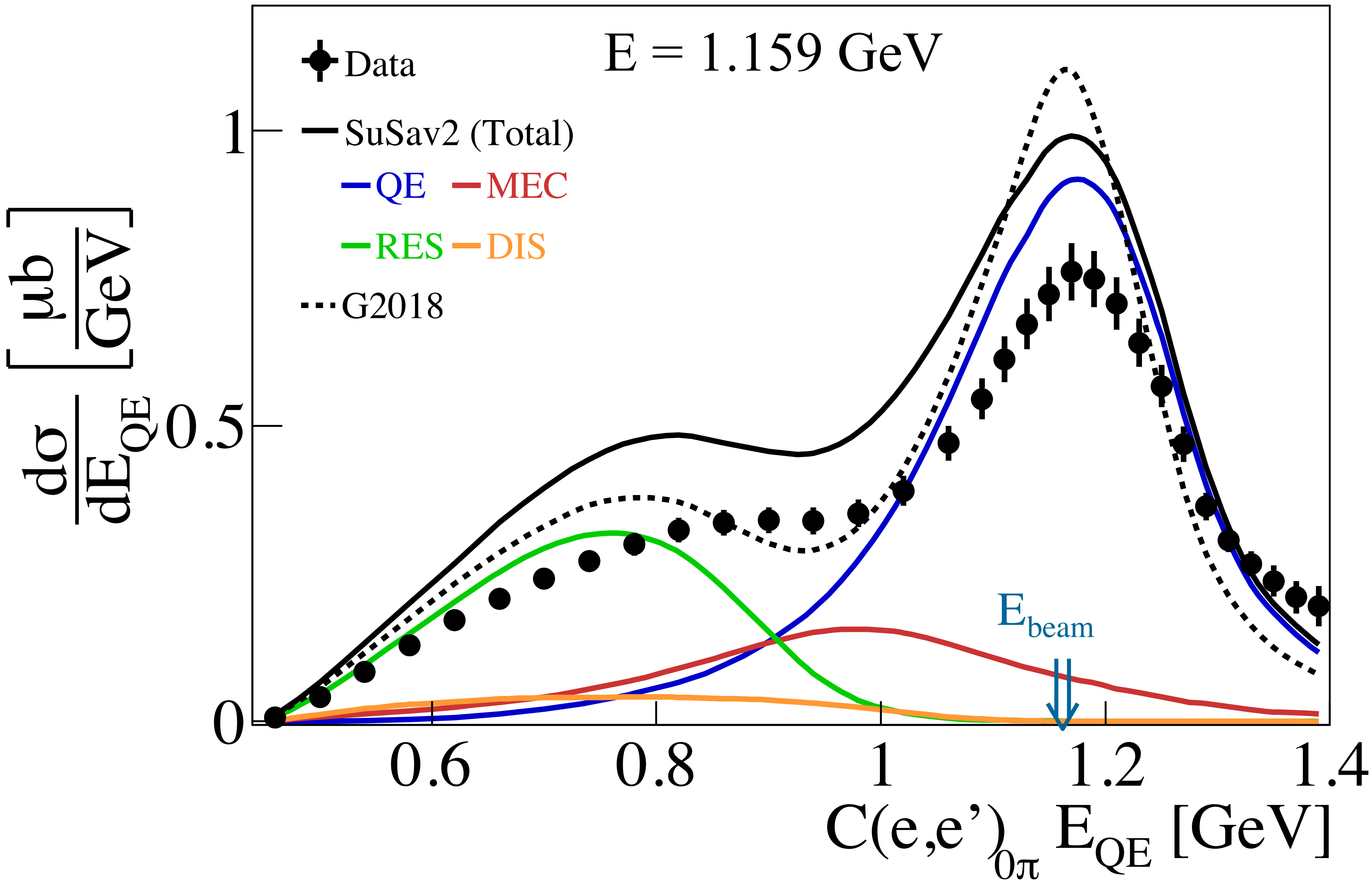
Using All detected particles

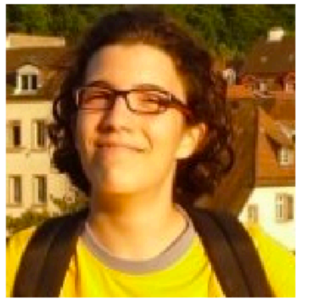
$$E_{\text{cal}} = E_l + E_p^{\text{kin}} + \epsilon$$

[1p0π]

ϵ is the nucleon separation energy ~ 20 MeV

Inclusive $(e,e')_{0\pi}$ Energy Reconstruction





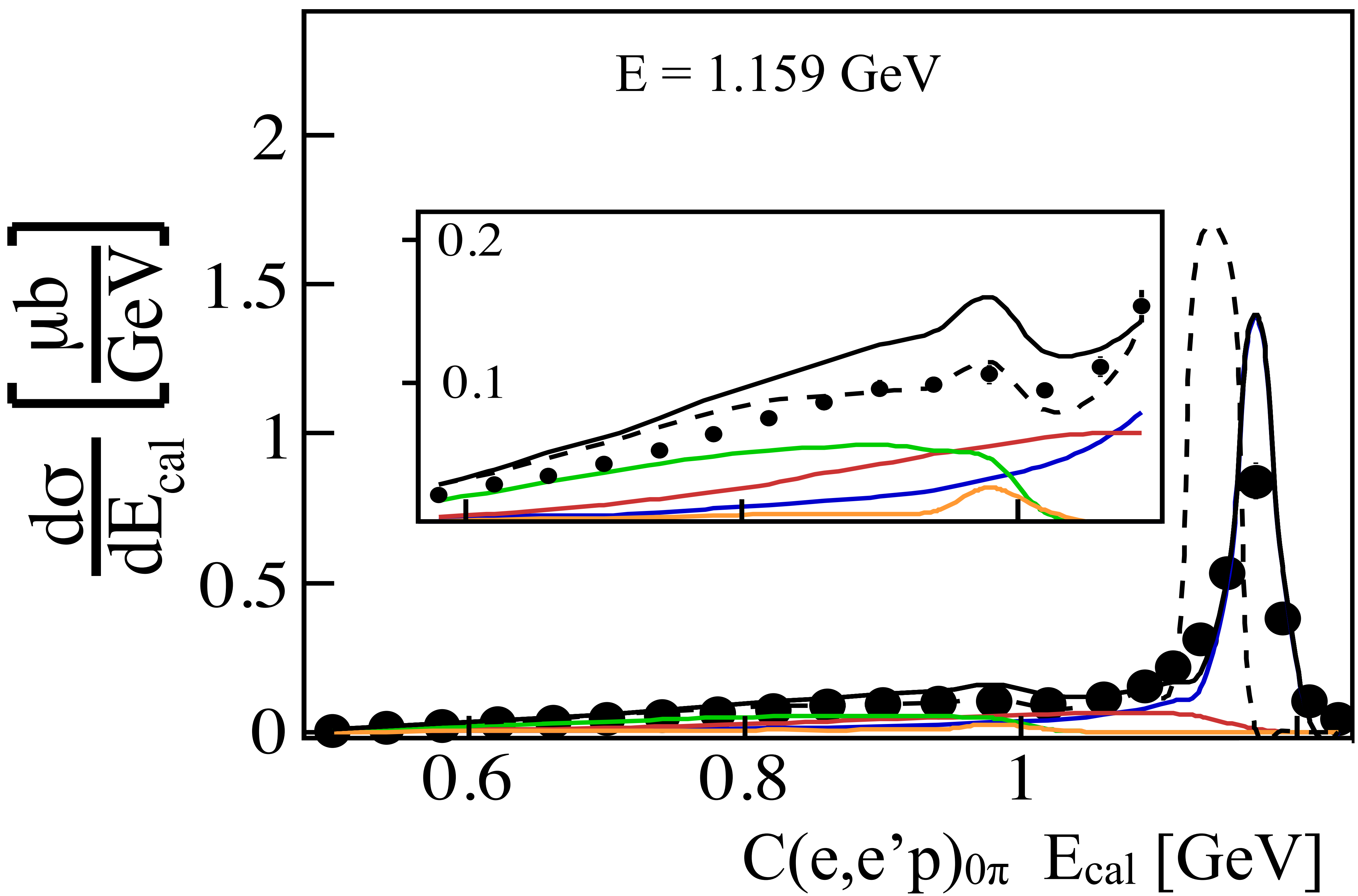
Afroditi Papadopoulou

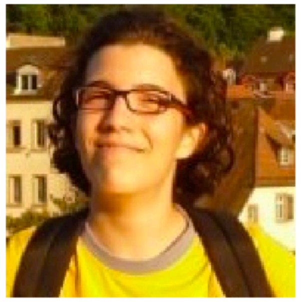
Mariana Khachatryan

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

Nature **599**, 565 (2021)

Inclusive $(e,e')_{0\pi}$ Energy Reconstruction



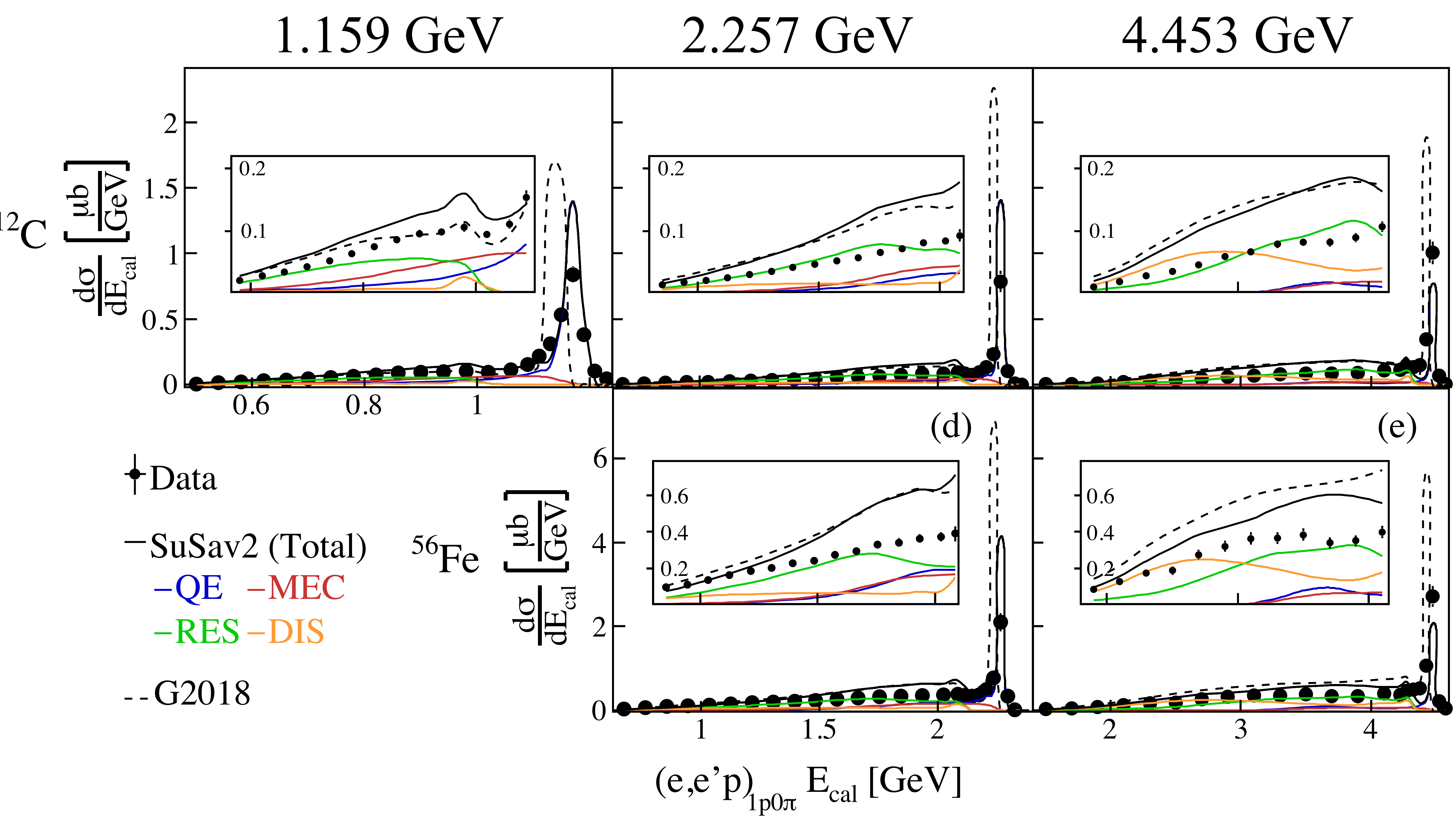


Afroditi Papadopoulou

Mariana Khachatryan

Nature **599**, 565 (2021)

Reconstructed $(e,e'p)_{1p0\pi}$ Calorimetric Energy



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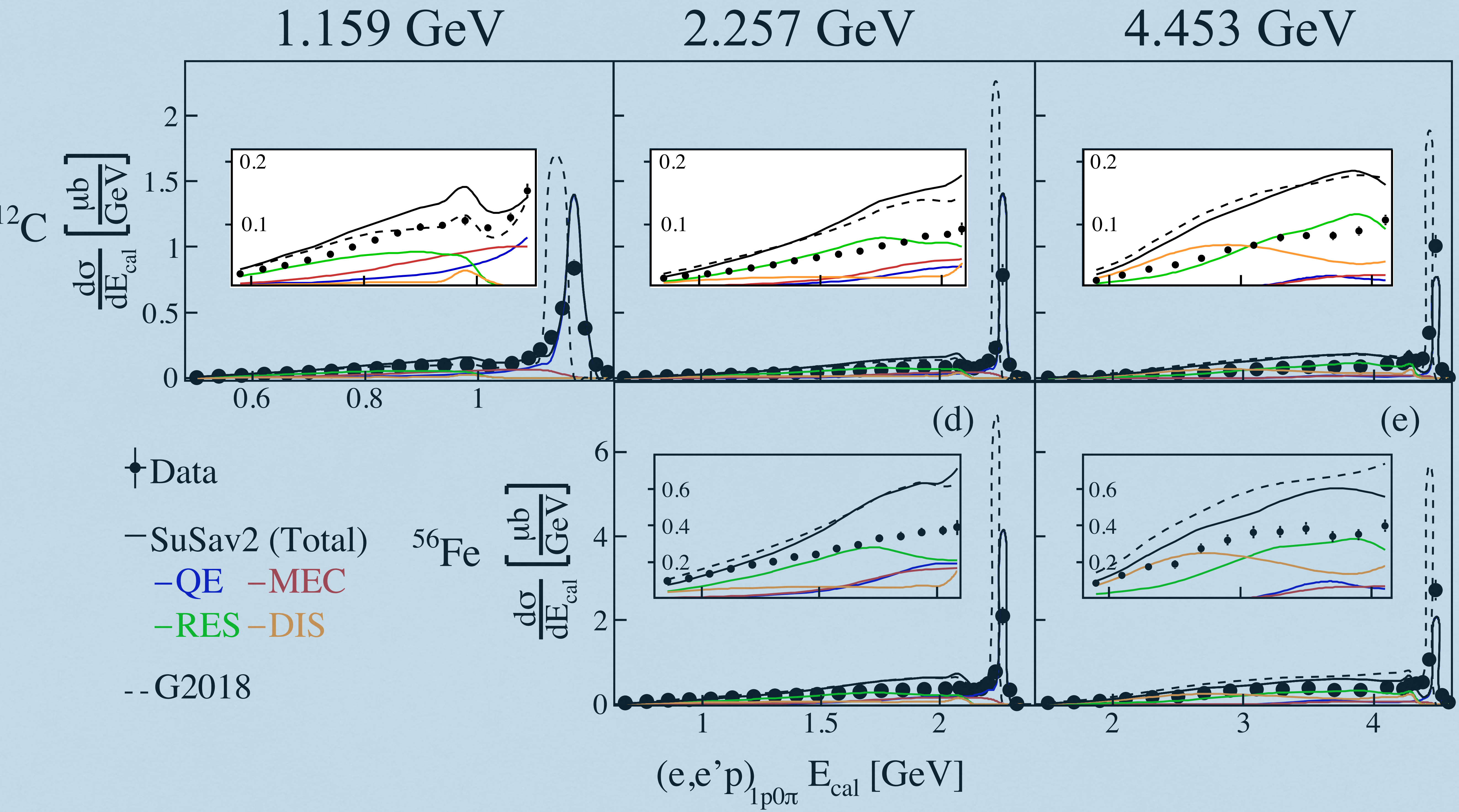

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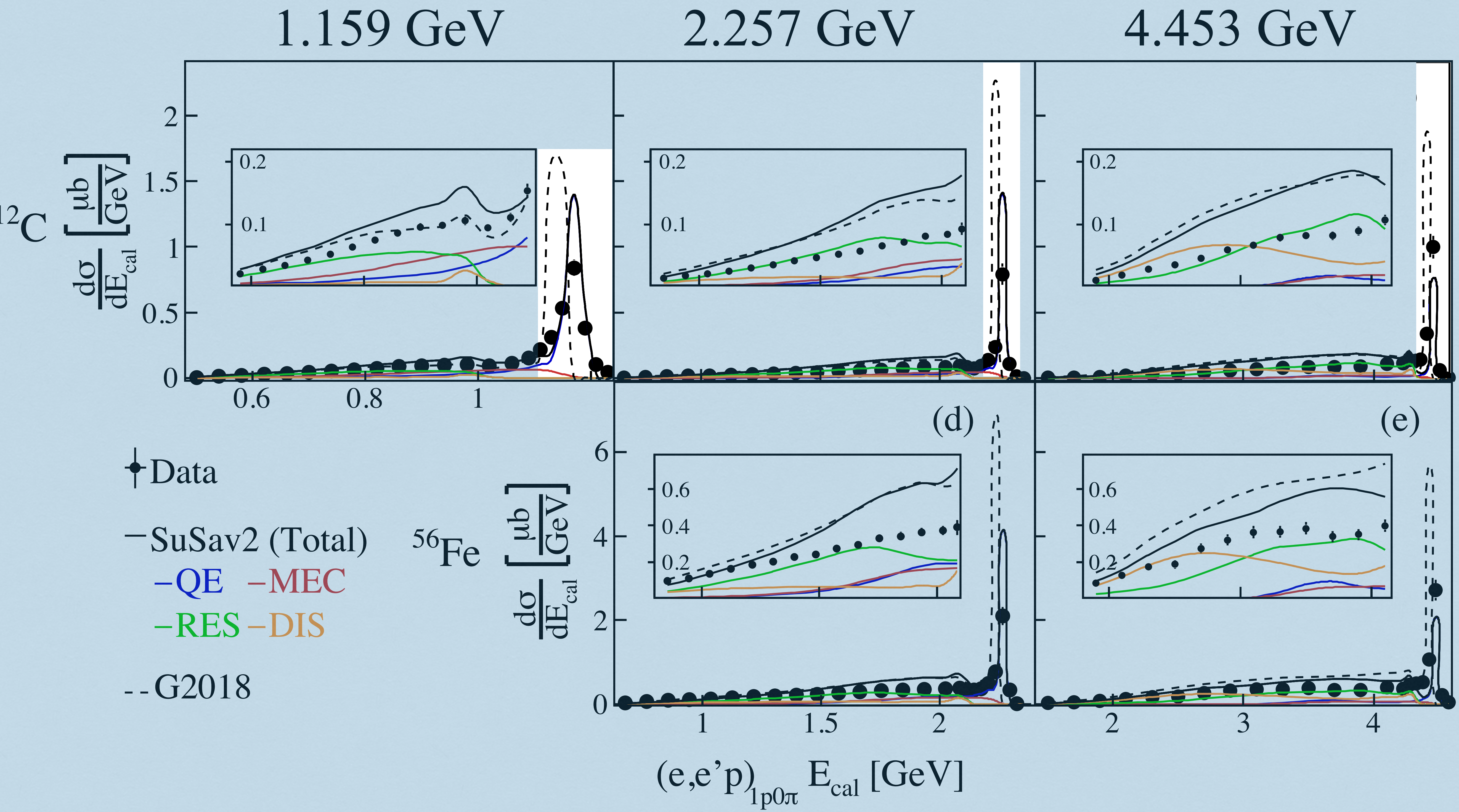
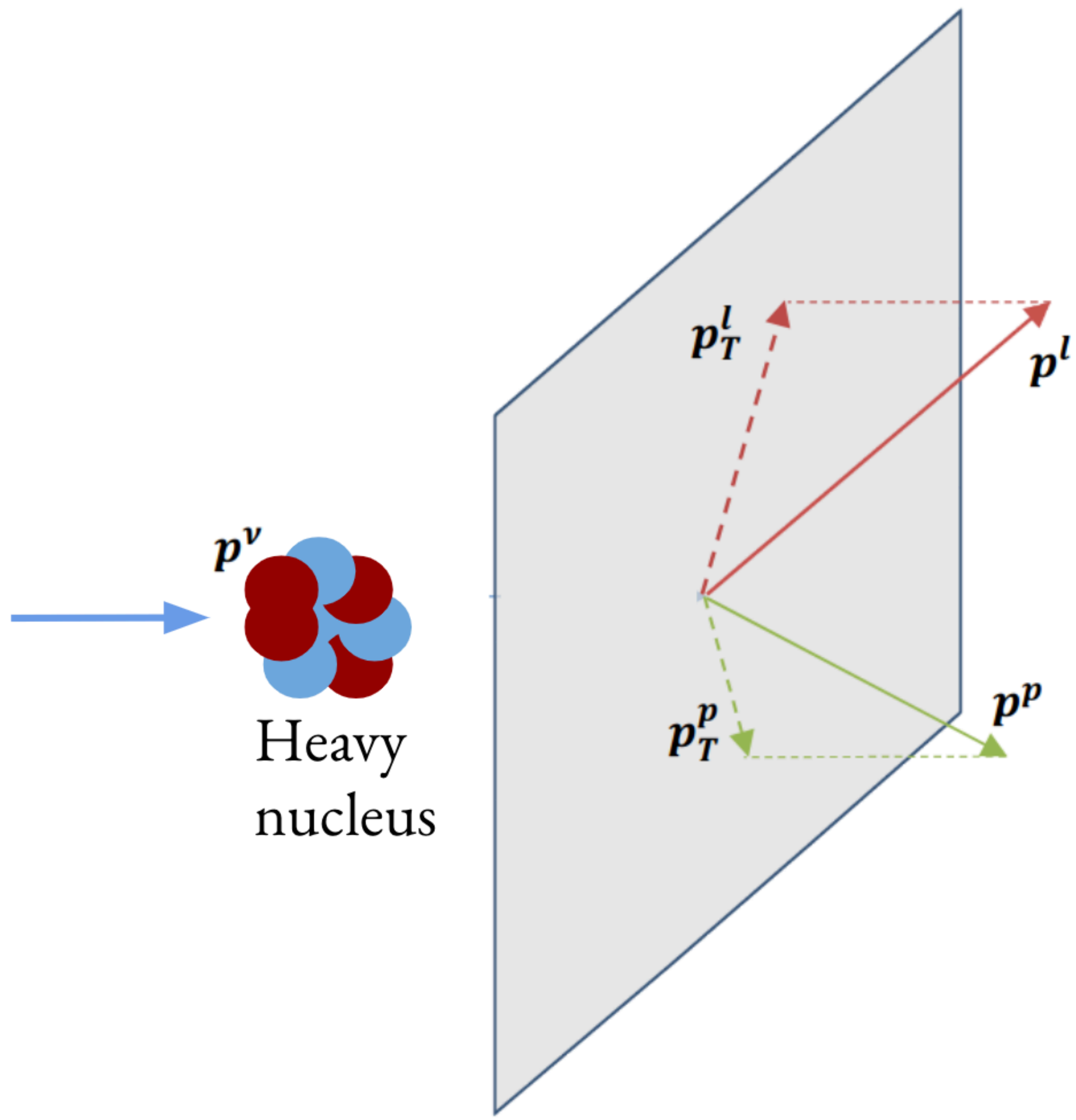
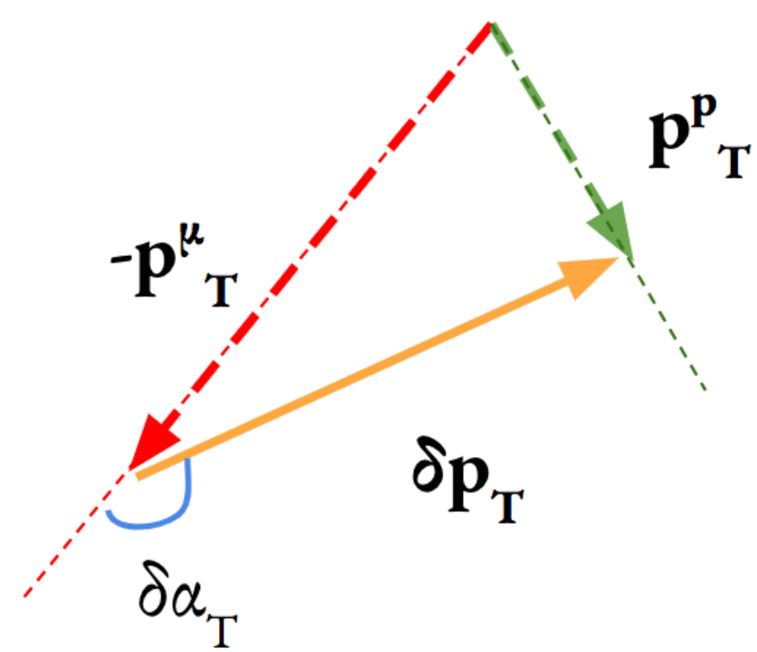


Nature **599**, 565 (2021)

Focusing on different reaction mechanisms

Standard Transverse Variables





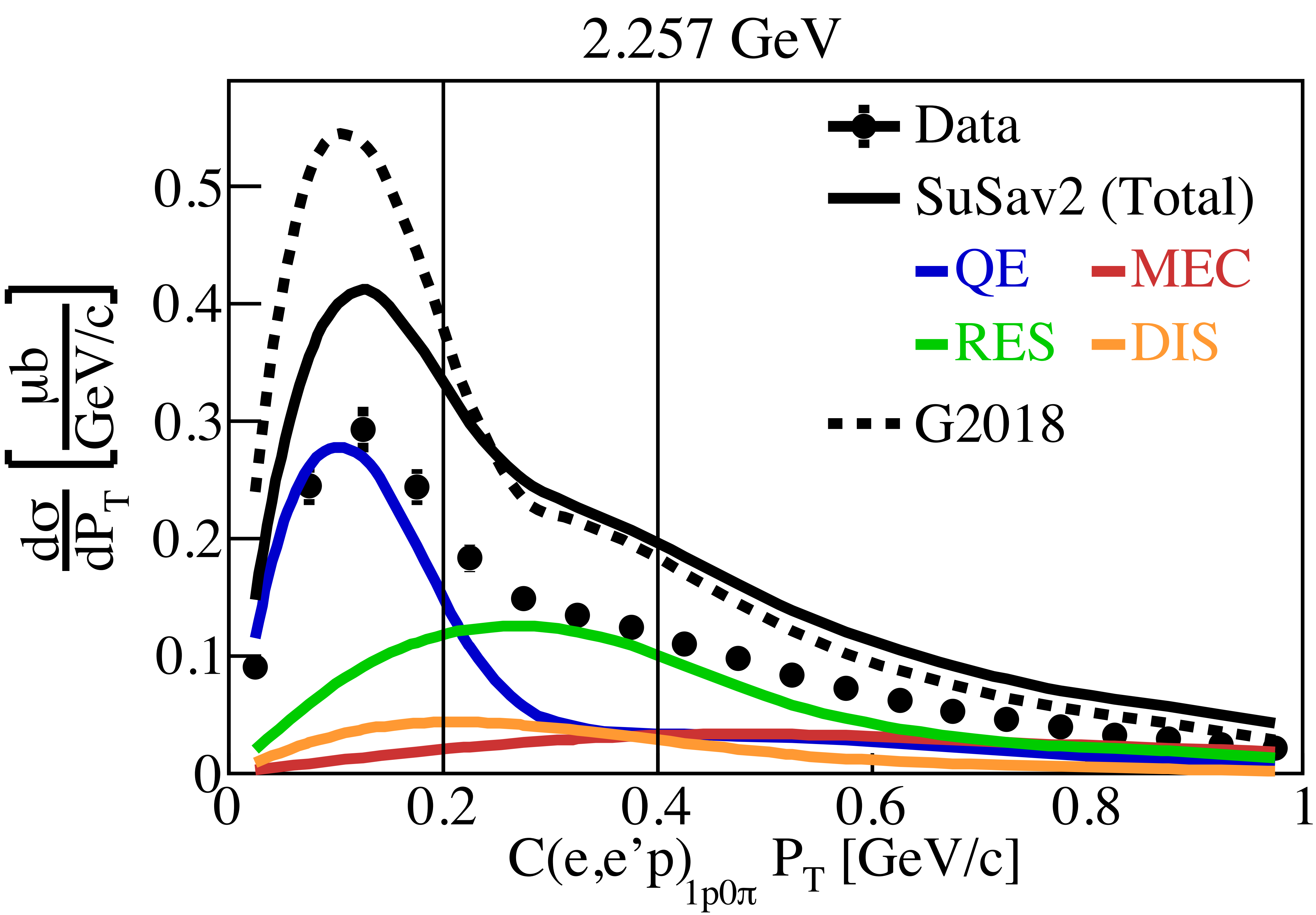
$$\vec{P}_T = \vec{P}_T^{e'} + \vec{P}_T^{p}$$

Sensitive to
hit nucleon momentum

$\delta\alpha_\mathrm{T}$

Sensitive to
Final State Interactions

Transverse missing momentum



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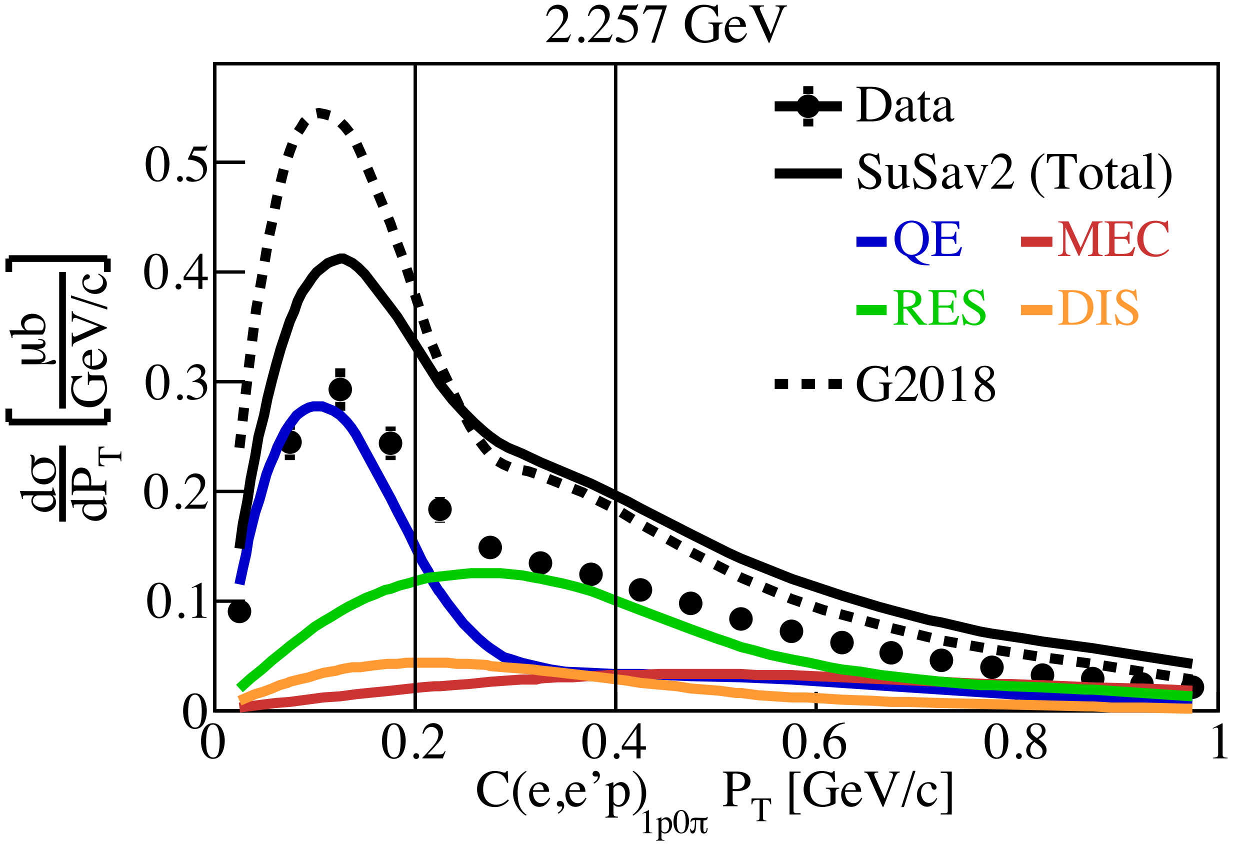
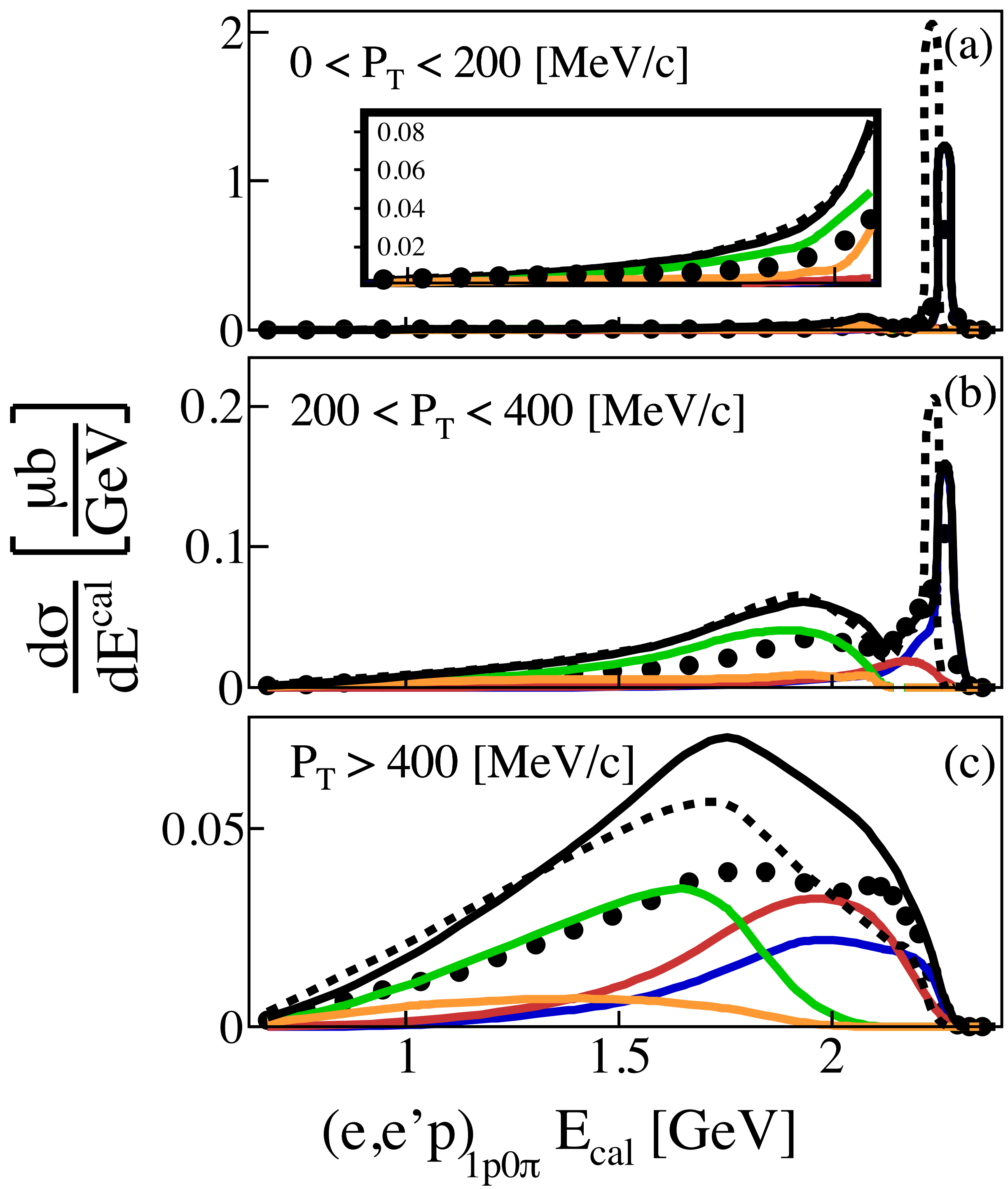
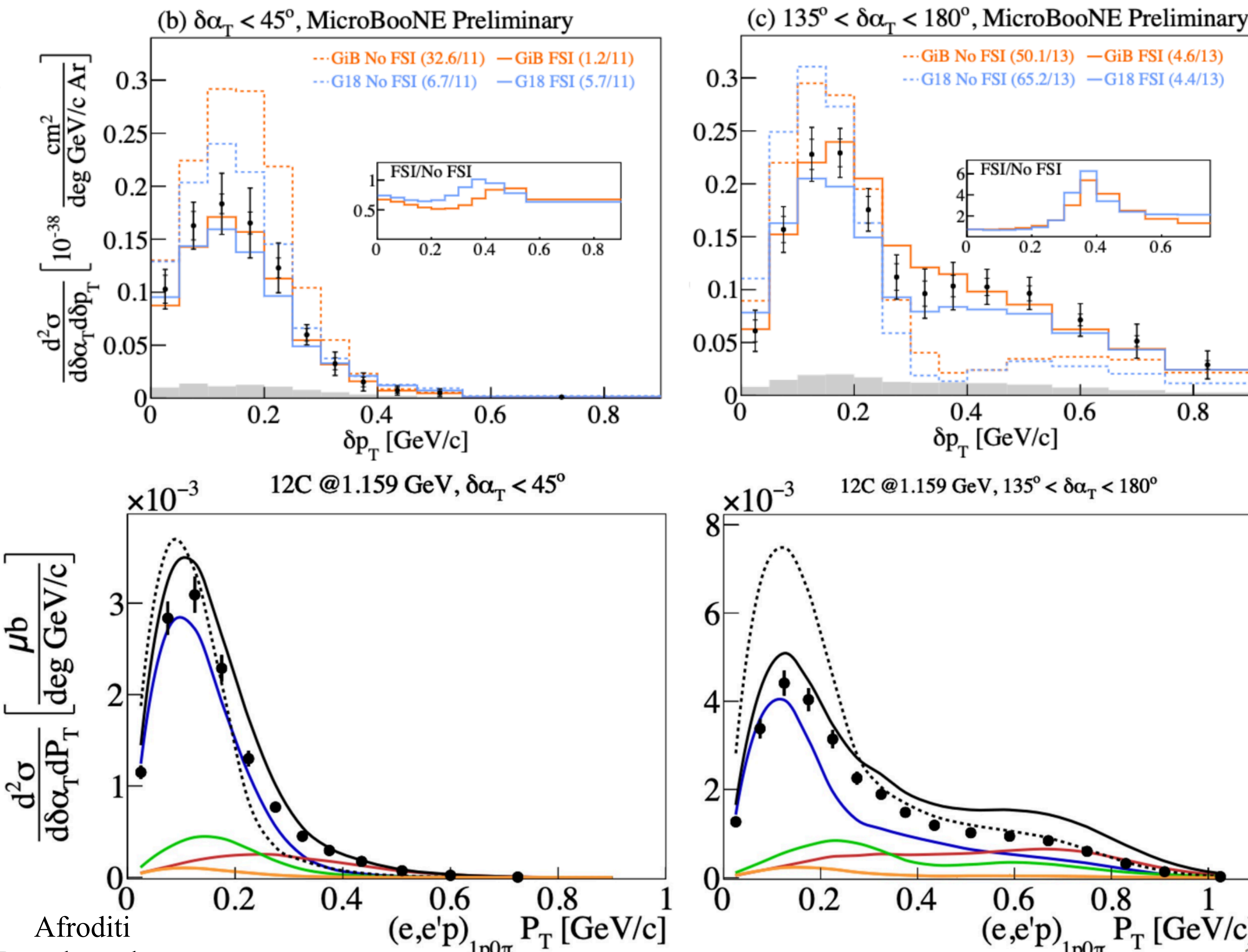
p_T sensitivity to interaction mechanisms

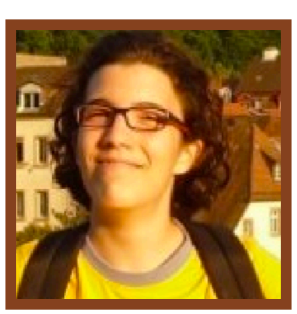




Nature **599**, 565 (2021)

MC vs. (e,e’p) Transverse Variables





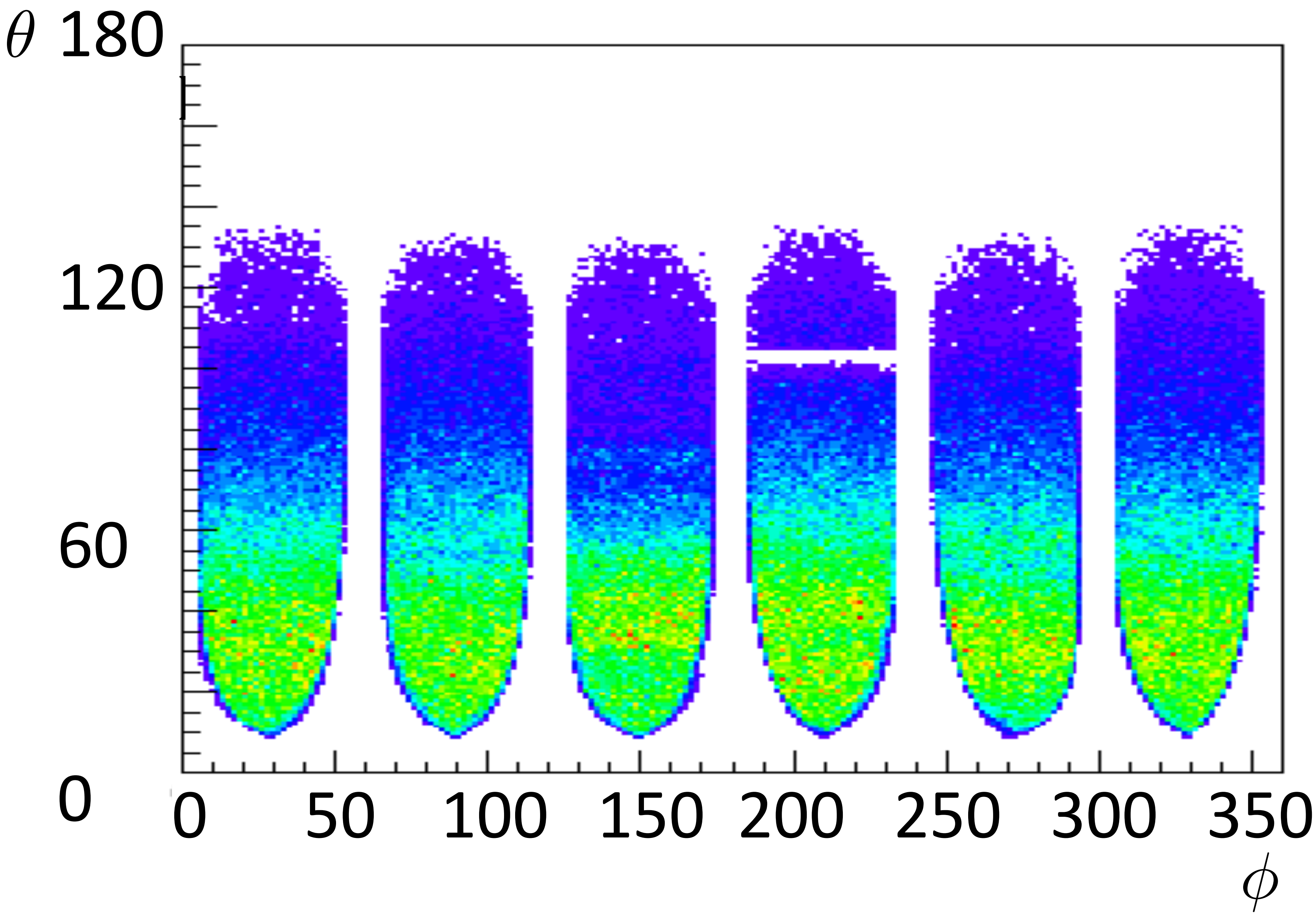
Afroditi Papadopoulou @ ANL

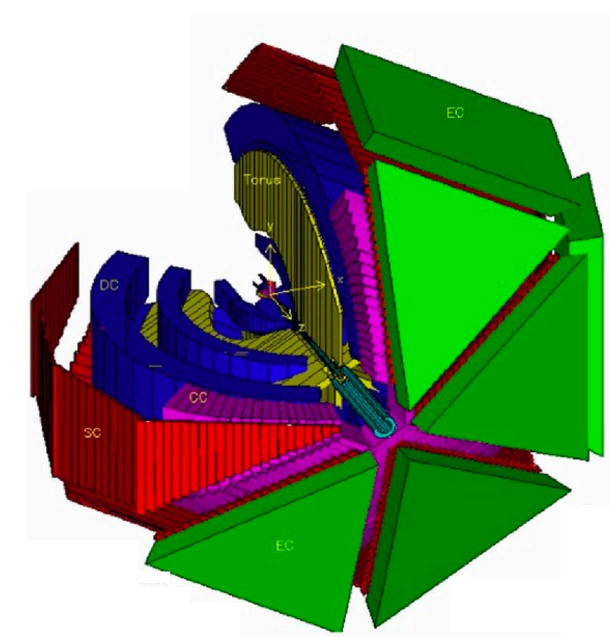
arXiv:2301.03700 [hep-ex]

Generalizing Background Subtraction

Different interaction lead to multi-hadron final states

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

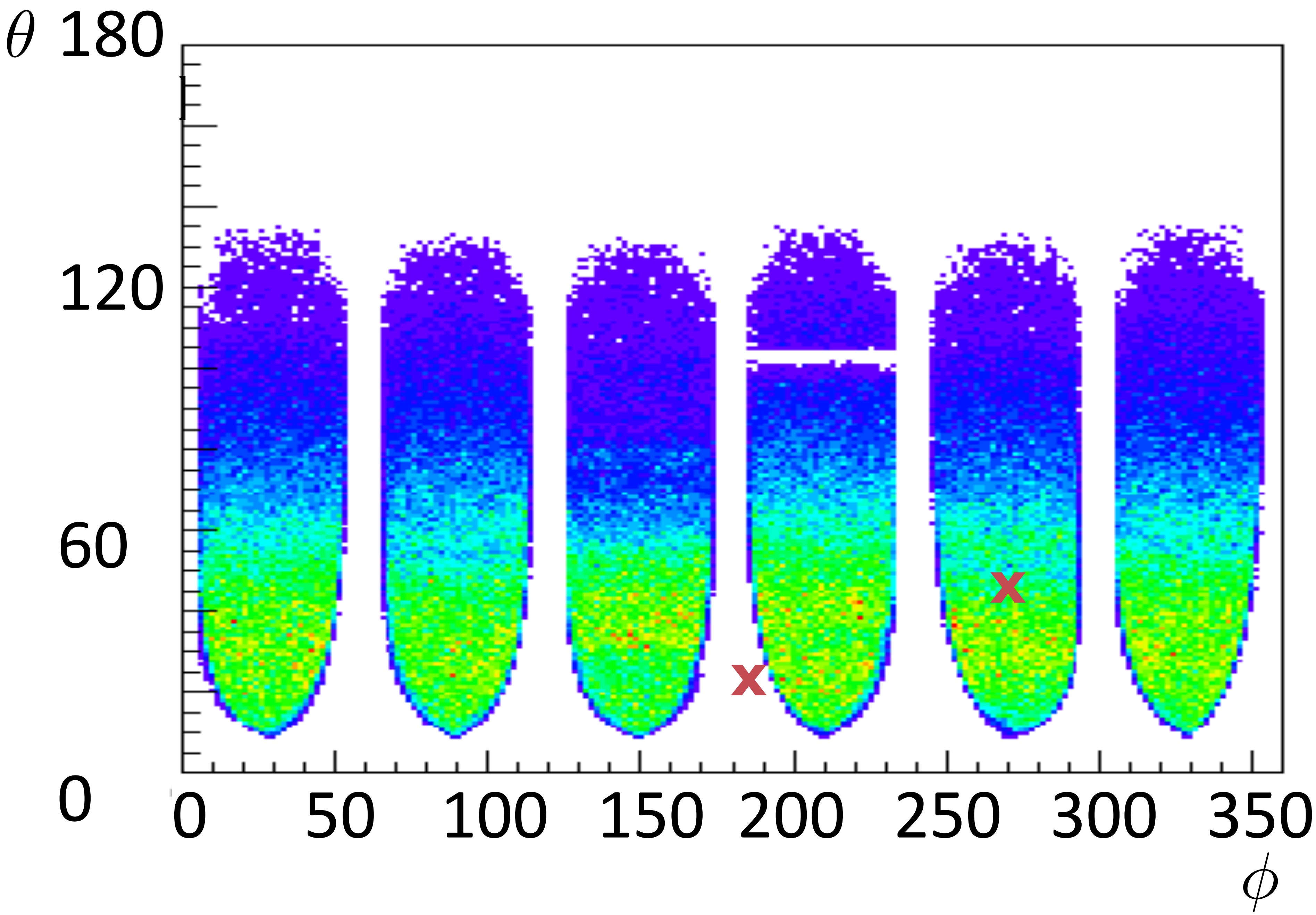


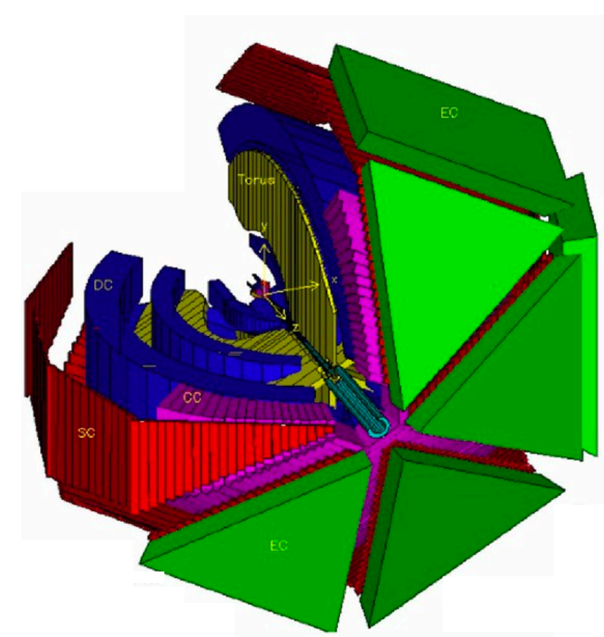


Background Subtraction

Different interaction lead to multi-hadron final states

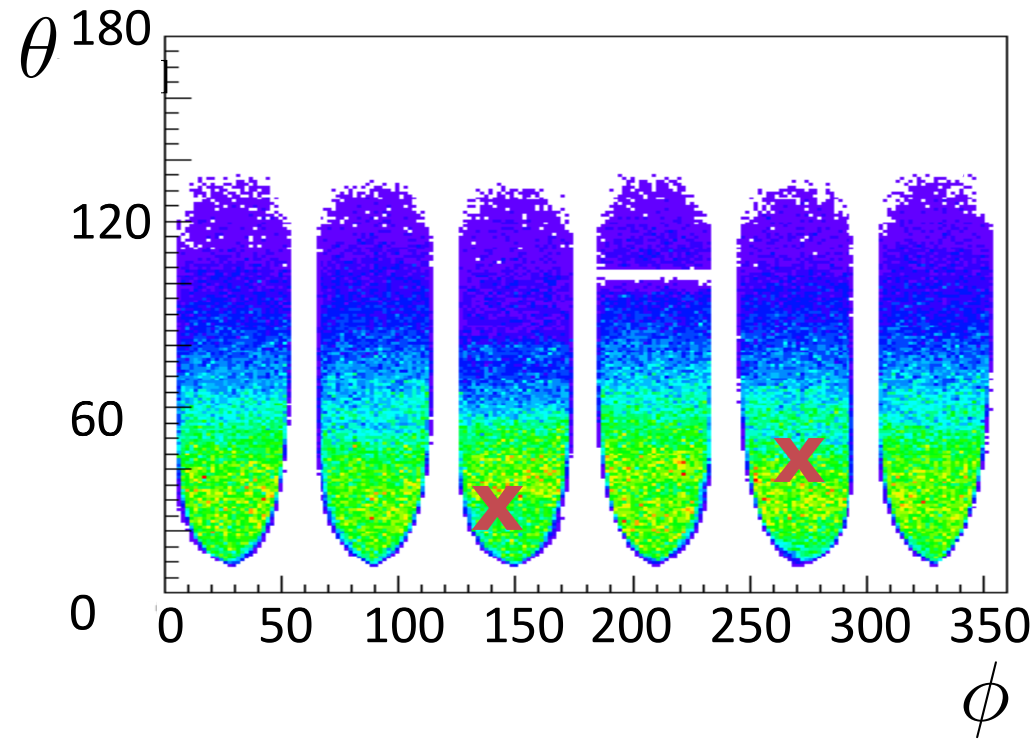
Gaps can make them loop like QE-like events with outgoing 1μ1p

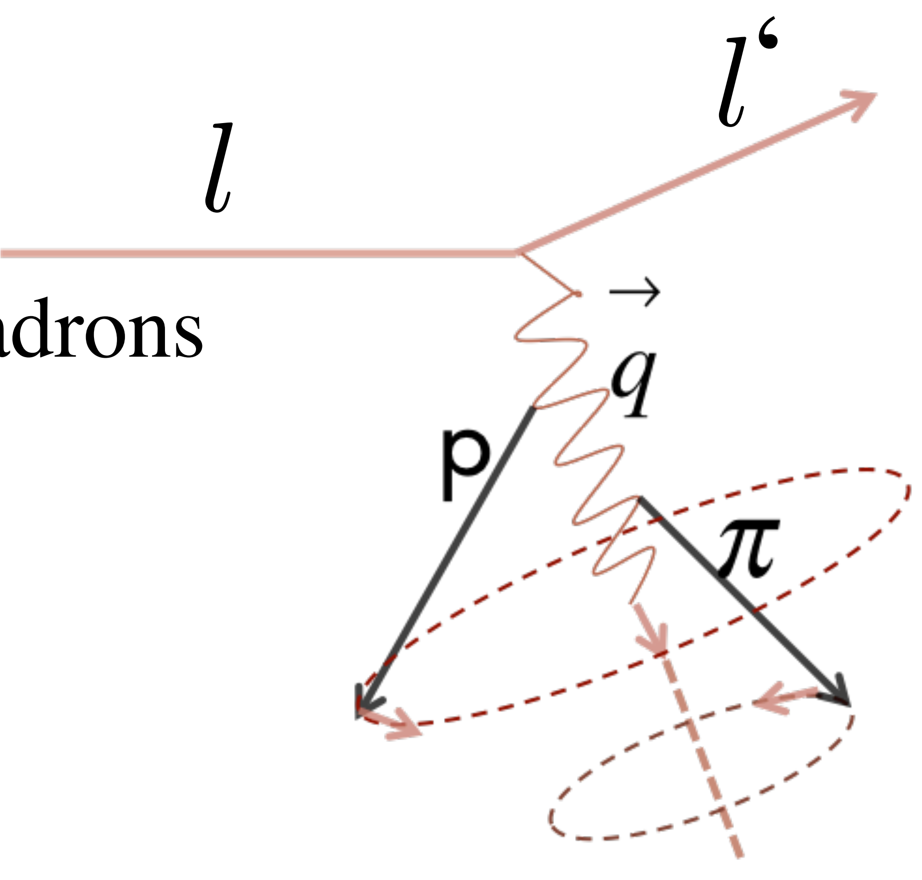




Data Driven Background Subtraction

- 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

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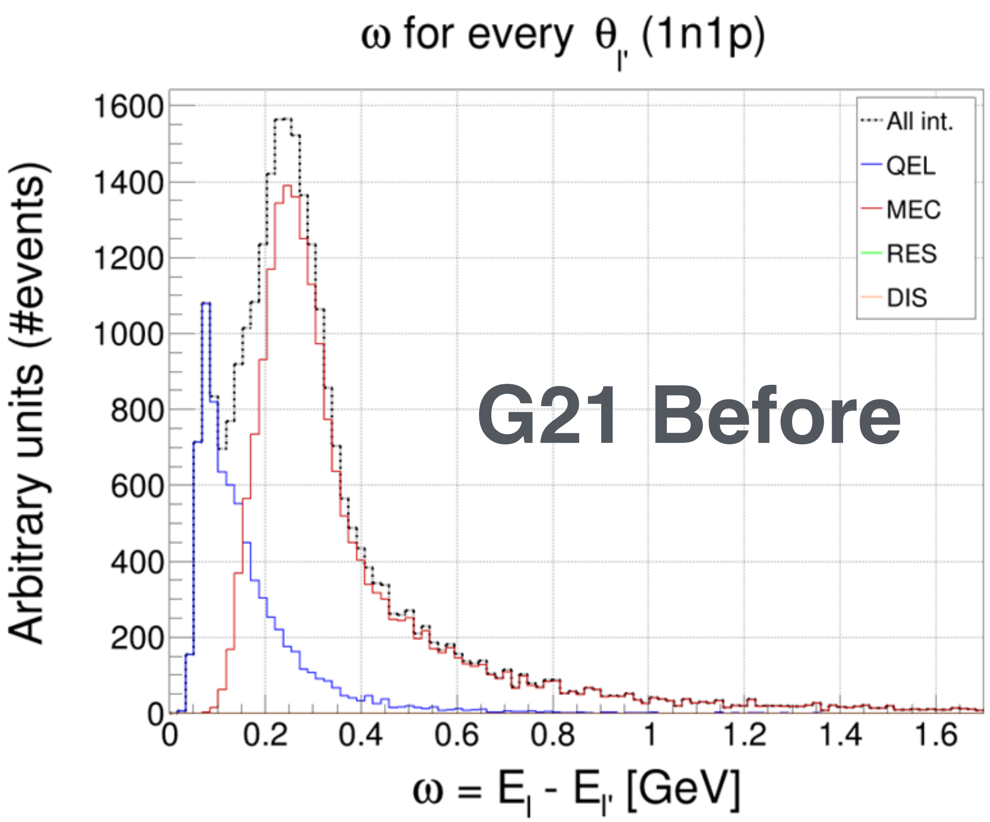
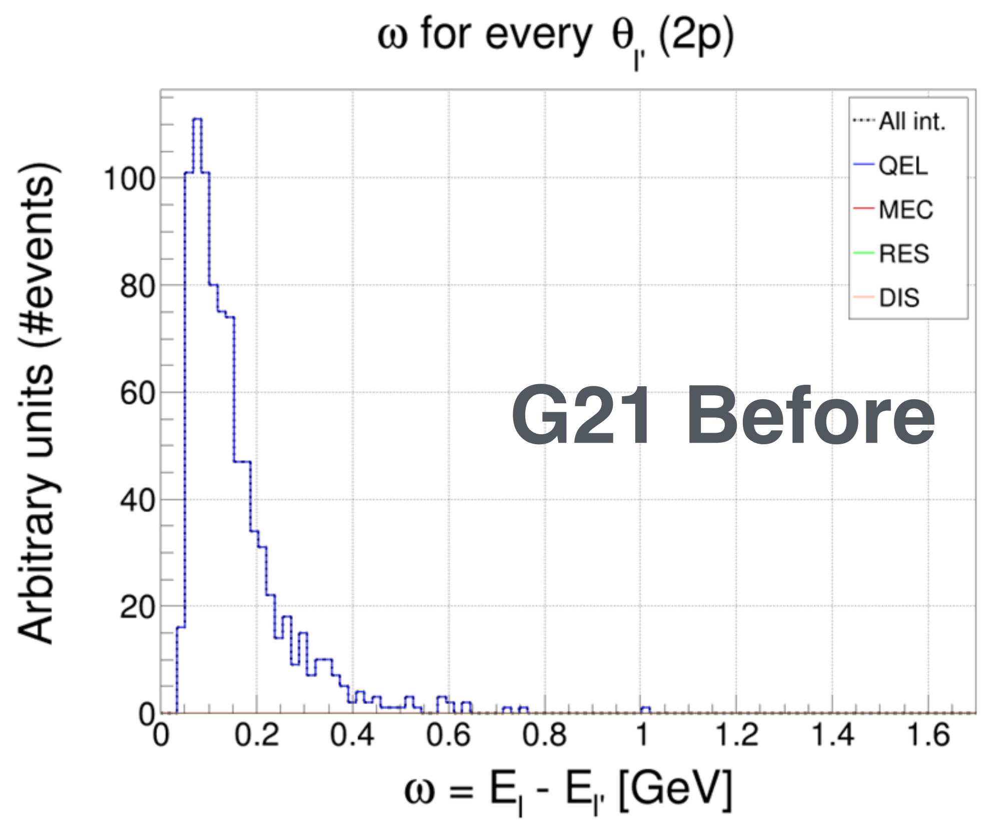
Tena Vidal

First Look at Multi hadrons final state

(e,e’1n1p0π), (e,e’2p0π)





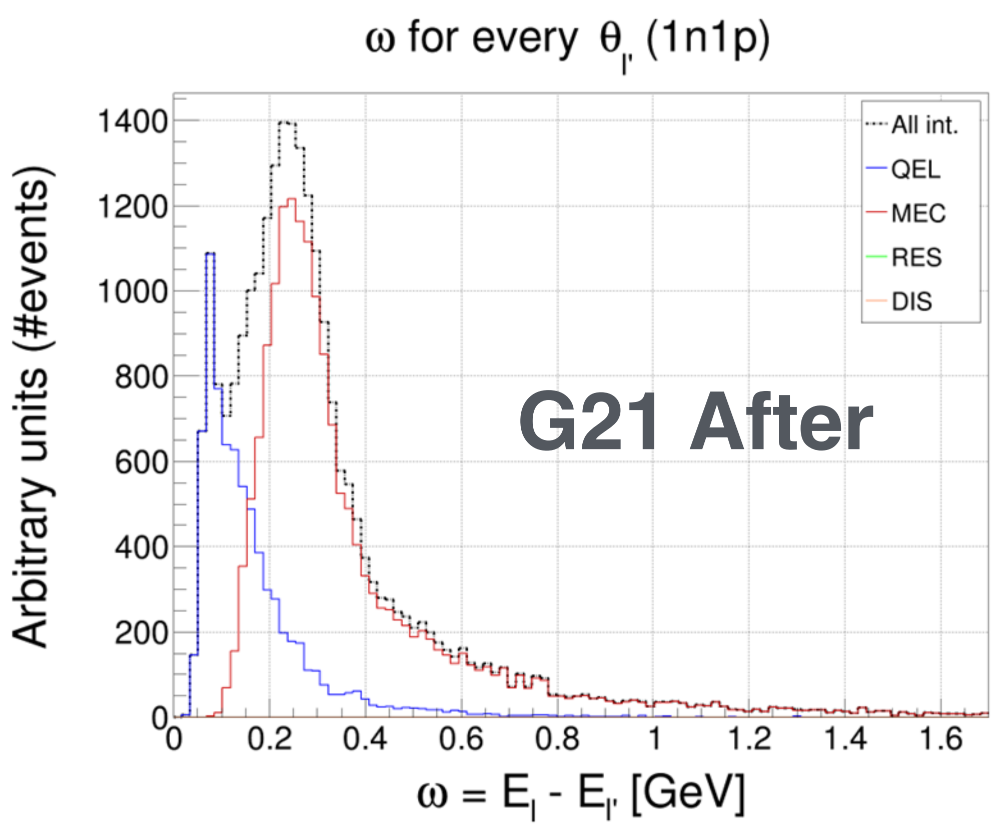
Alon Sportes

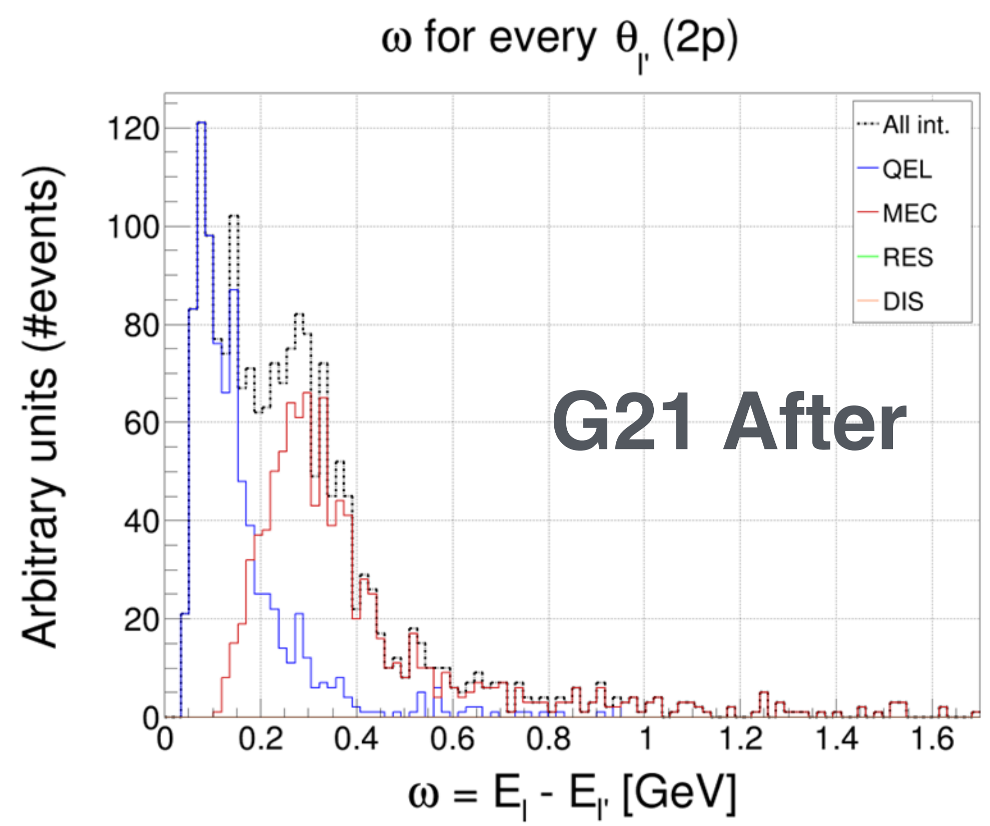
Implementing different 2N final state in MEC SuSA

Julia Tena Vidal

First Look at Multi hadrons final state

(e,e’1n1p0π), (e,e’2p0π)





Alon Sportes

Implementing different 2N final state in MEC SuSA

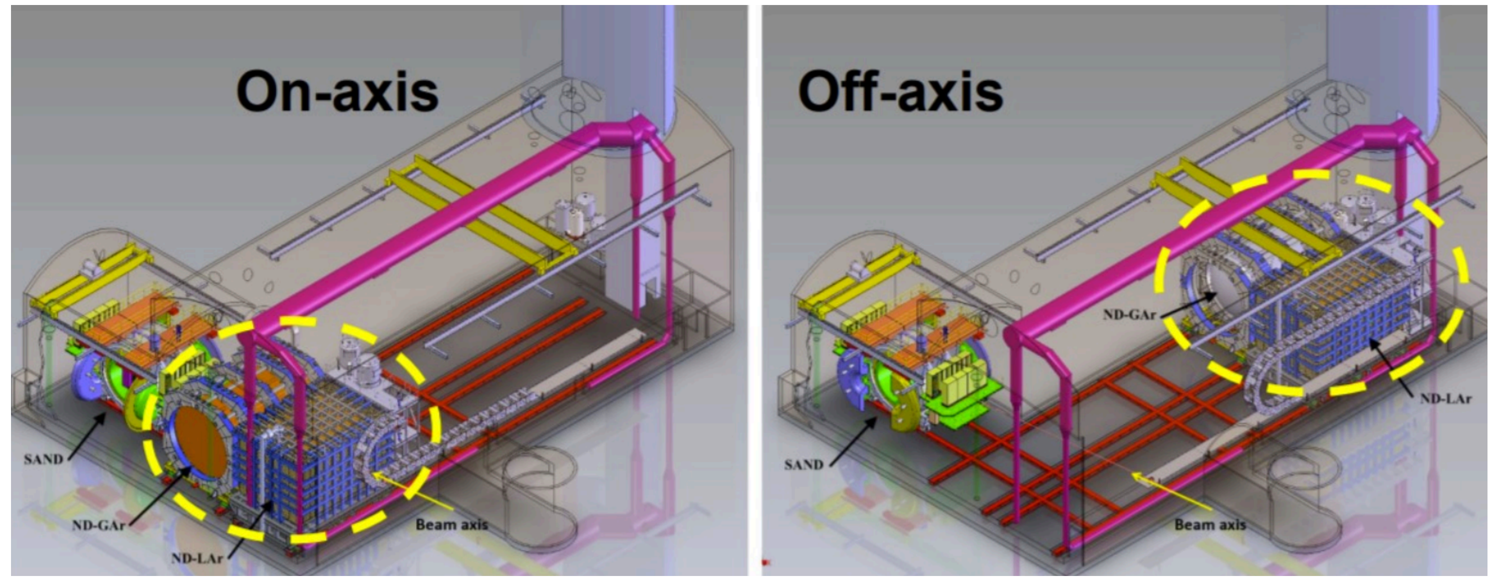
(e,e’1p1π) - coming soon

Julia Tena Vidal

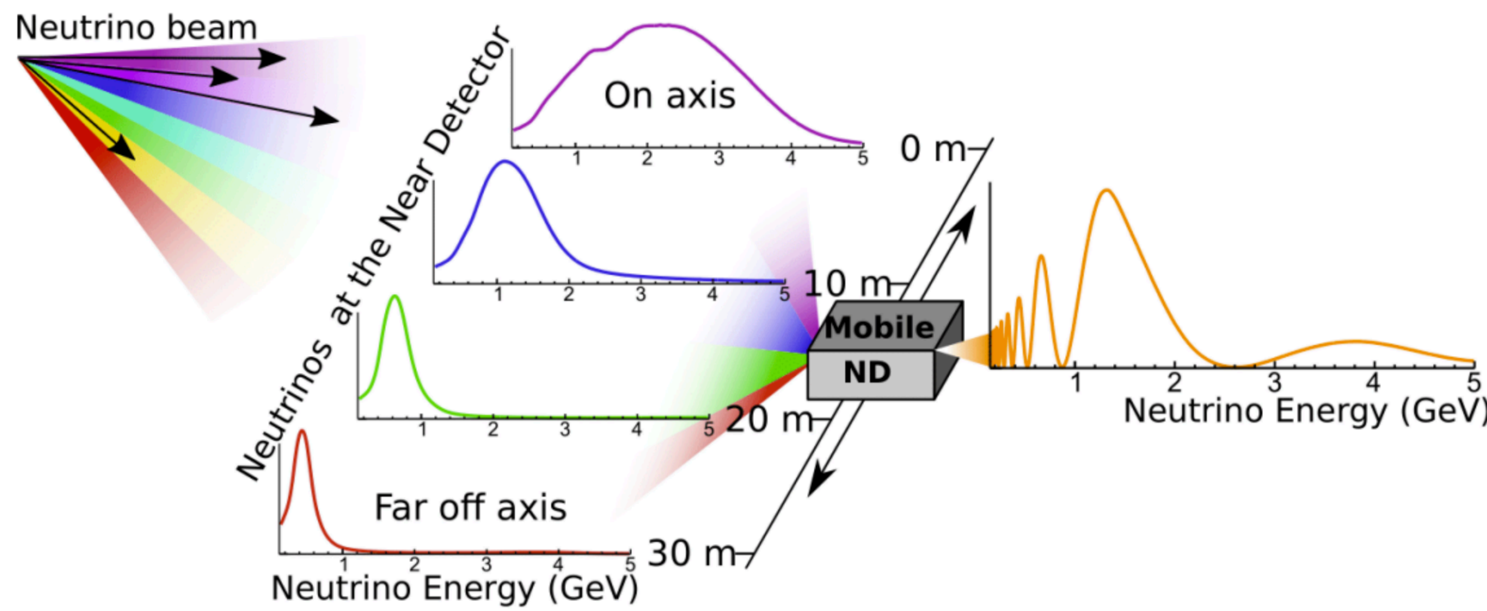
DUNE PRISM

DUNE PRISM Basic Idea

Some parts of the DUNE near detector can move

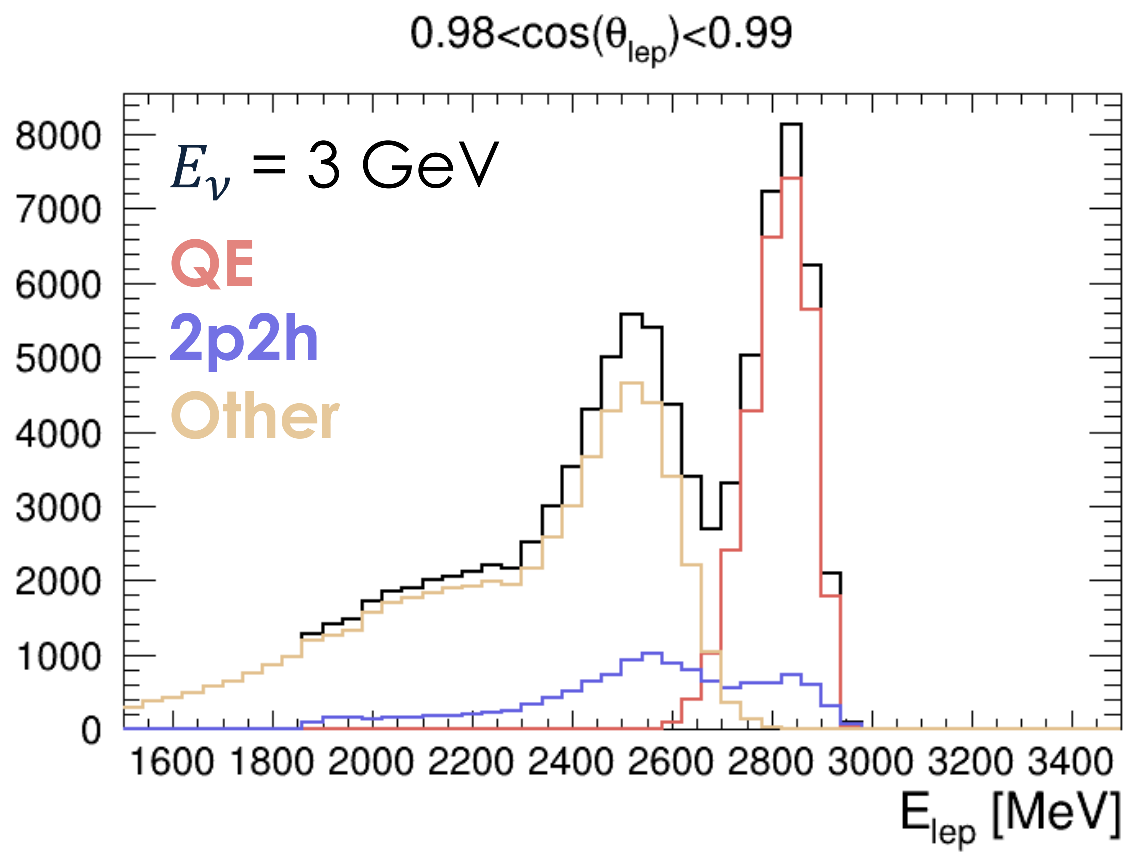


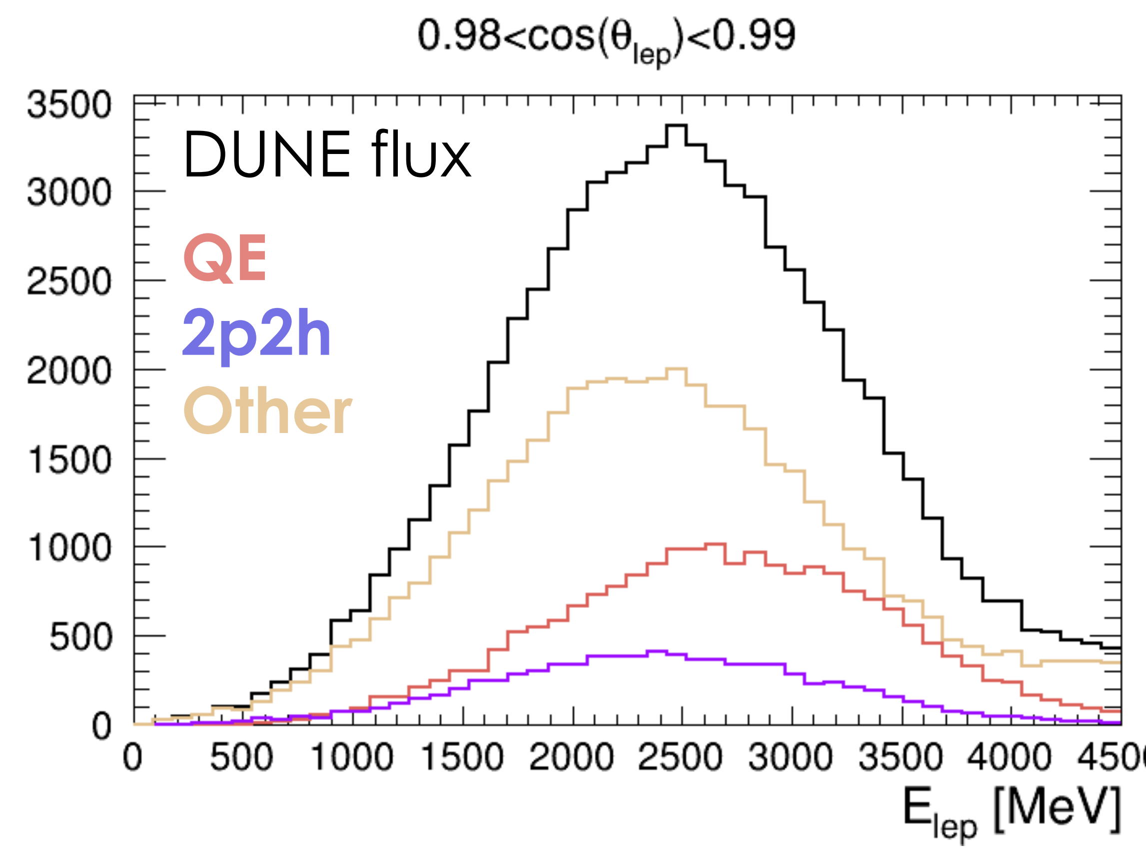
Each position will be exposed to a different flux



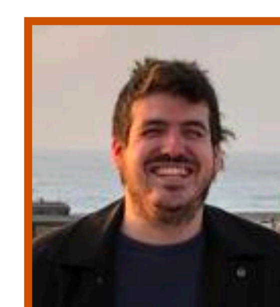
DUNE PRISM Leveraged to e4ν

Broad band fluxes are responsible for almost all of the degeneracies we have between different nuclear effects.





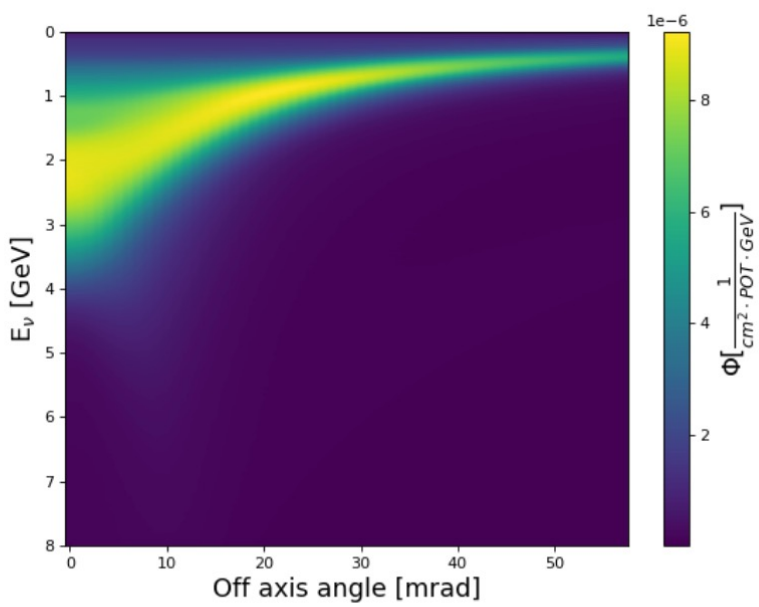
Amir Gruber
Co-advisory w. Stephen Dolan

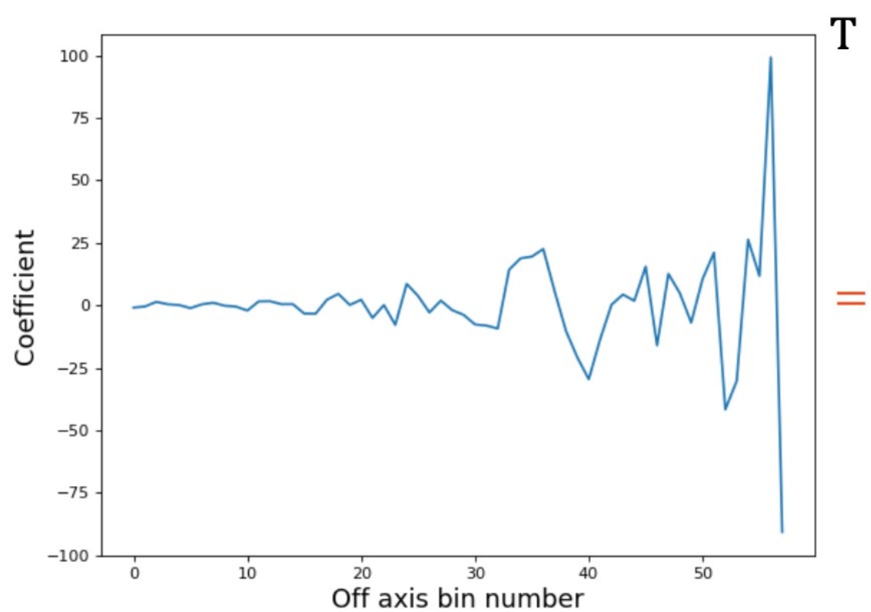


DUNE PRISM Leveraged to e4ν

Using PRISM to build a quasi mono energetic flux

Flux matrix ? Target Flux





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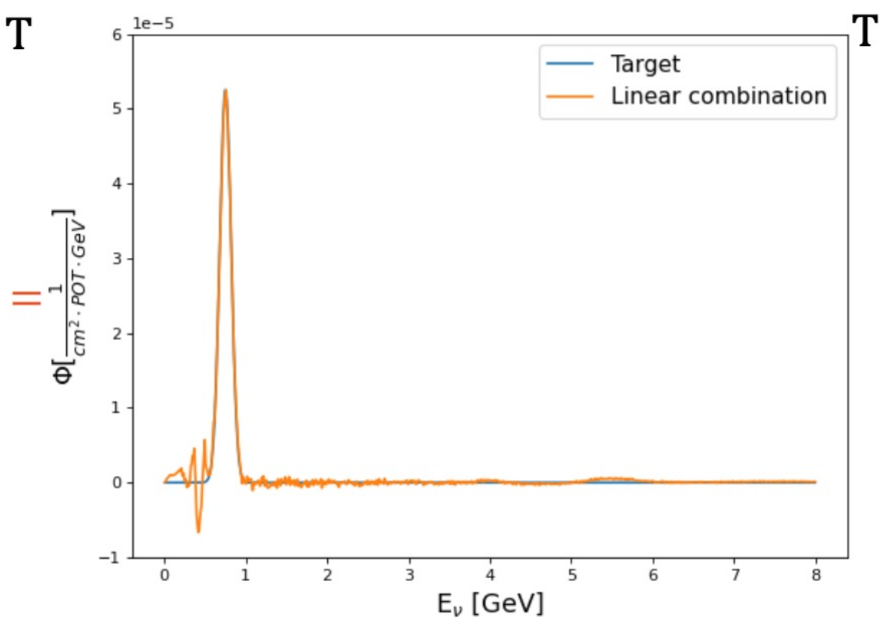

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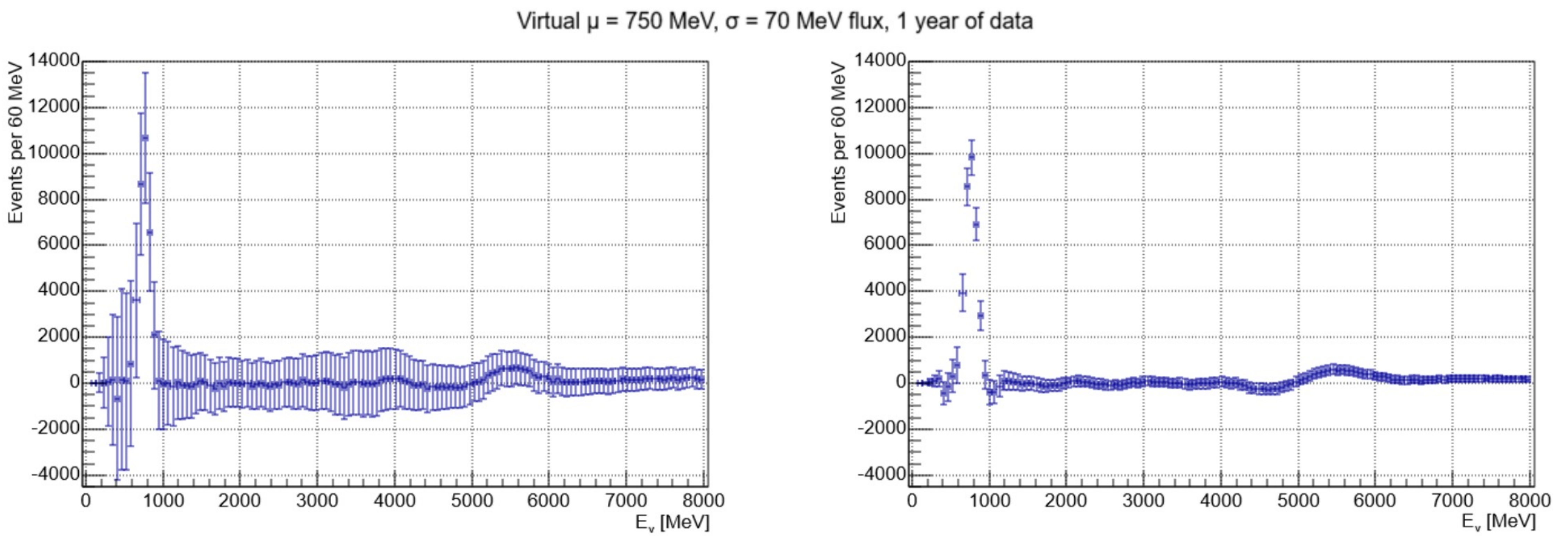
DUNE PRISM Leveraged to e4ν

The best solution can have large uncertainties

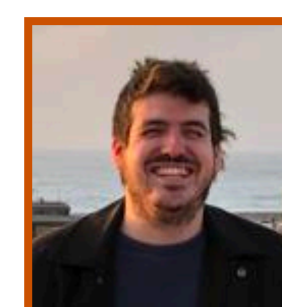
Thin enough flux is satisfactory

- employ regularization to penalize solution with large coefficients



Ordinary least squares
$\mu = 750\ MeV$
$\sigma = 71\ MeV$

Tikhonov regularization (Ridge regression) with $\alpha = 10^{-12}$
$\mu = 750\ MeV$
$\sigma = 78\ MeV$



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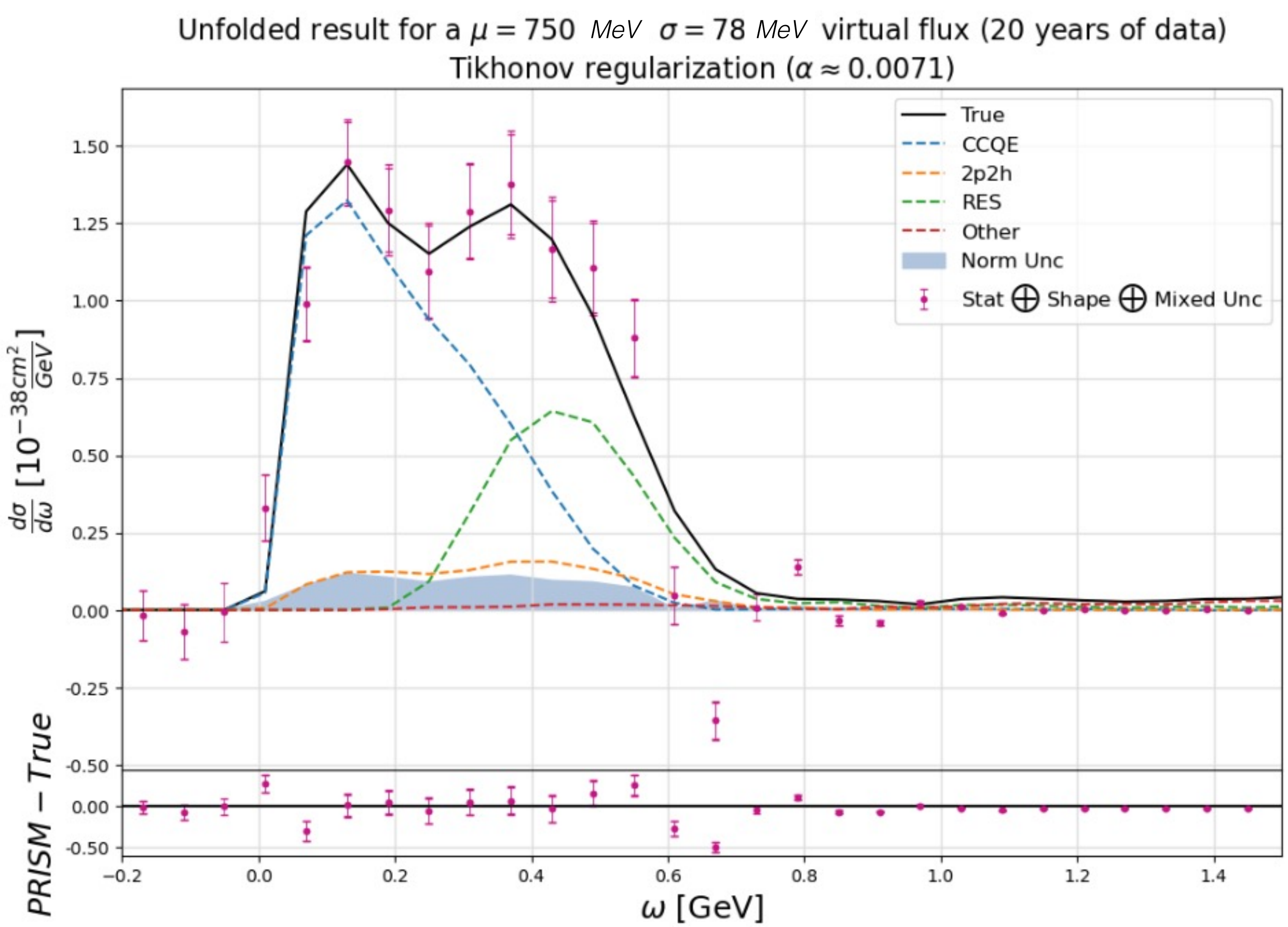
DUNE PRISM Leveraged to e4ν

Measurable: $\omega_{reco} = \langle E_\nu \rangle - E_l$ a proxy to ω smeared by flux width

If we assume CS change negligibly across flux we can assume all smearing comes from flux and unfold



First proof-of-concept, works for many energies

Will be part of DUNE TDR

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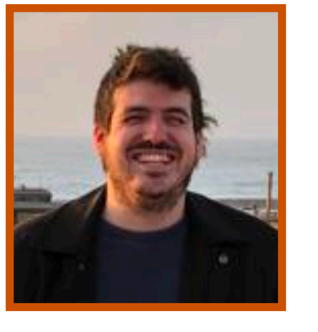

Summary

νA interaction uncertainties limit oscillation parameters extraction

Use of semi-exclusive eA data to explore νA uncertainties

- Energy reconstruction

- Comparison to event generators

Data/model disagreement even for electron QE-like events

Muon, Electron and neutrino scattering data is on the way to constrain models

Thank you for your attention