νA Interactions from the Experimental Side

Neutrino Platform Week

14/3/22

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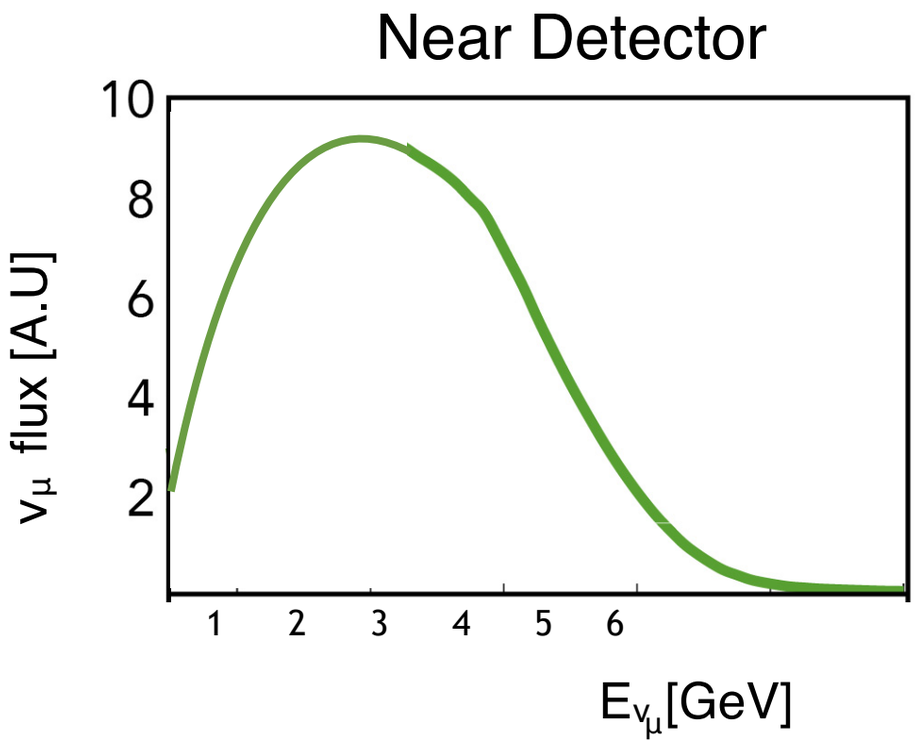
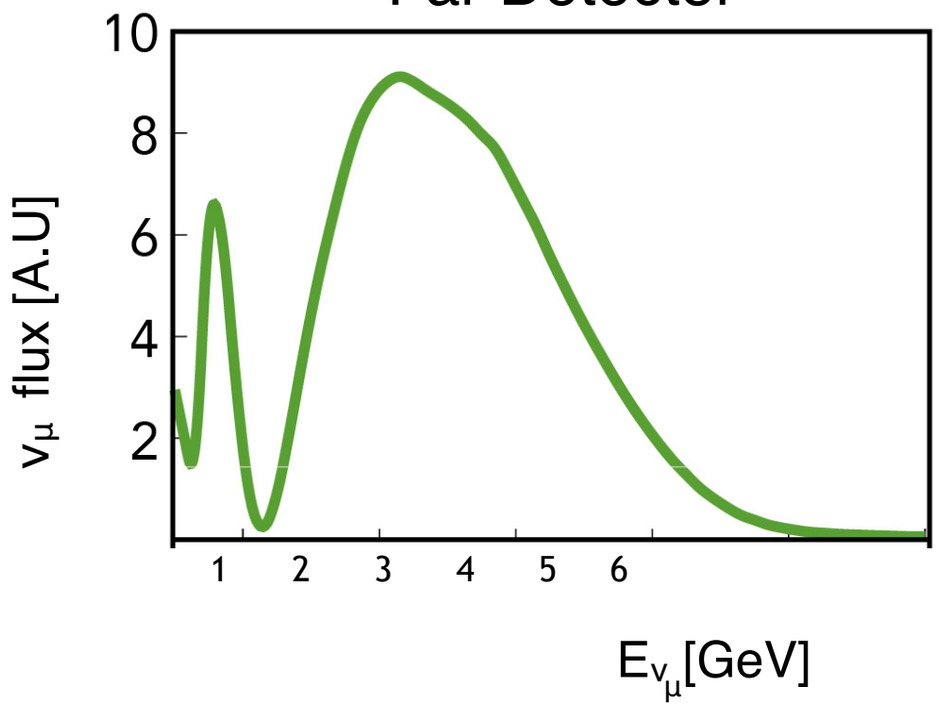
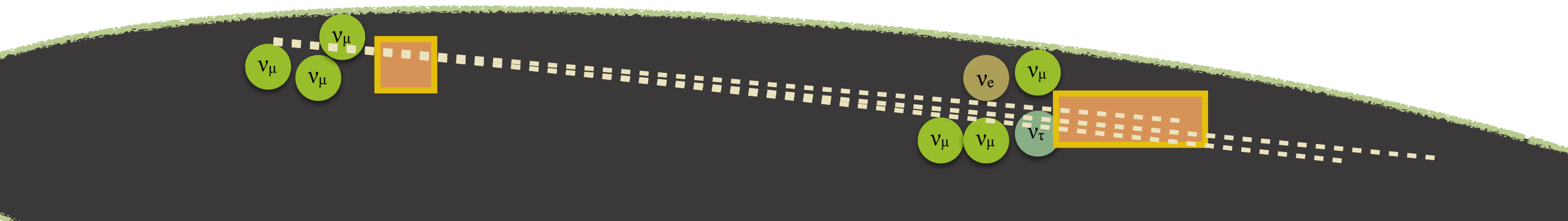
TEL AVIV UNIVERSITY

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



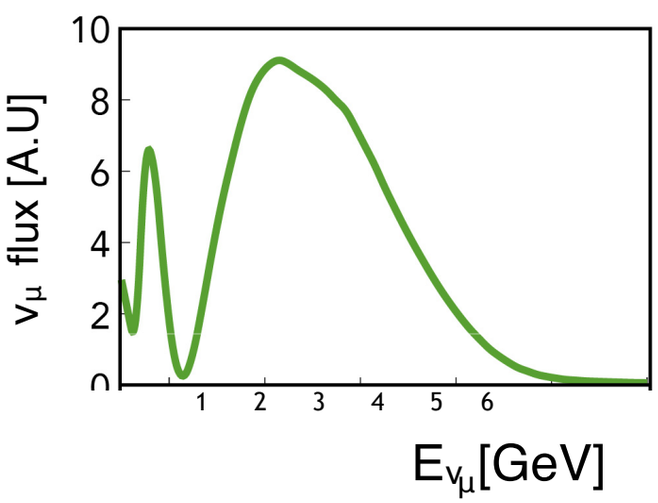


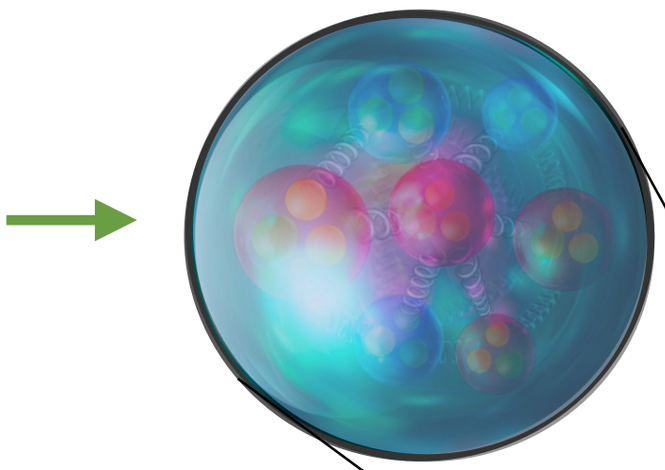


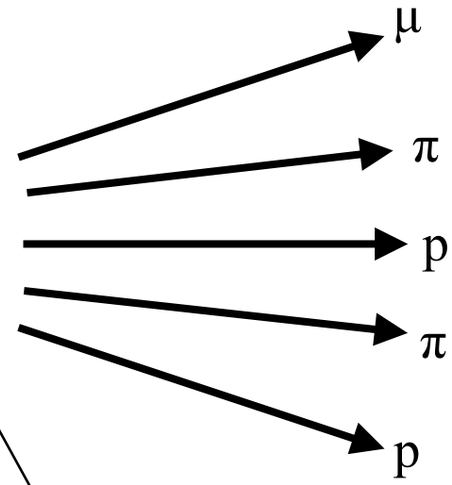
The challenge - next generation high precision

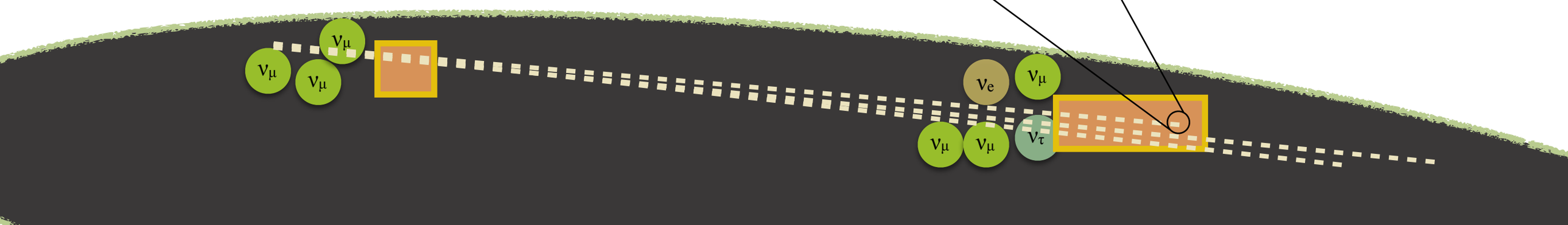
Incoming true flux | Modelling Input | Measurement

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

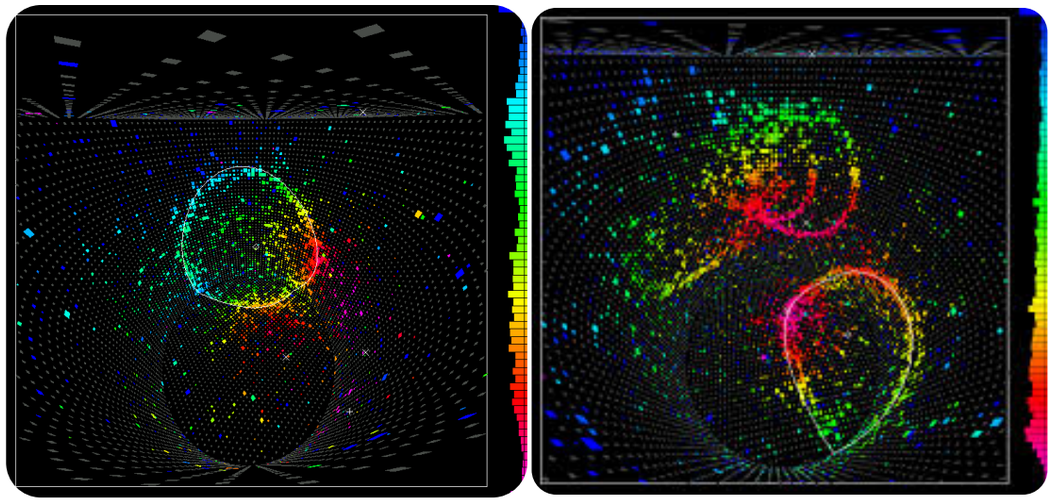


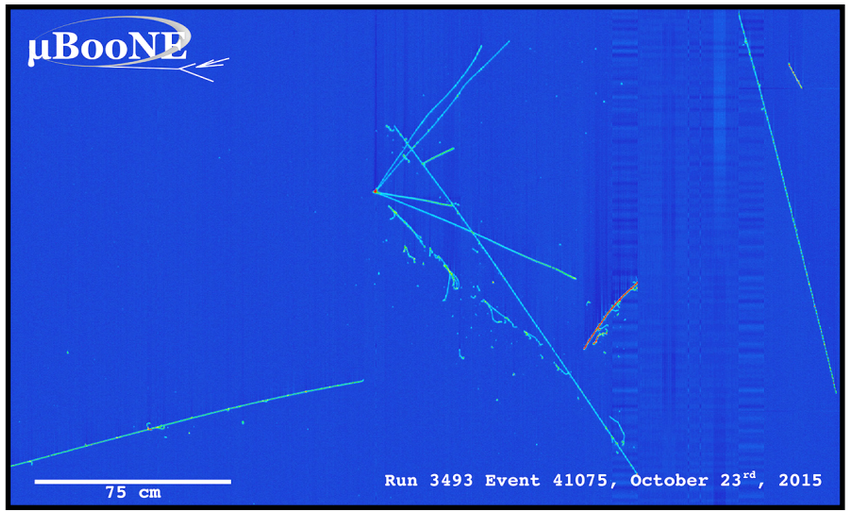






Incoming Energy Reconstruction





Cherenkov detectors:

Assuming QE interaction

Using lepton only

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

Tracking detectors:

Calorimetric sum

Using All detected particles

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

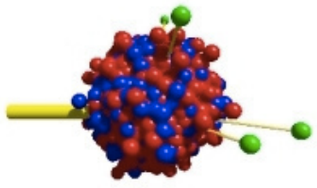
[1p0π]

ϵ is the nucleon separation energy ~ 20 MeV

Lepton-Nucleus Interaction Modelling - Need constraints

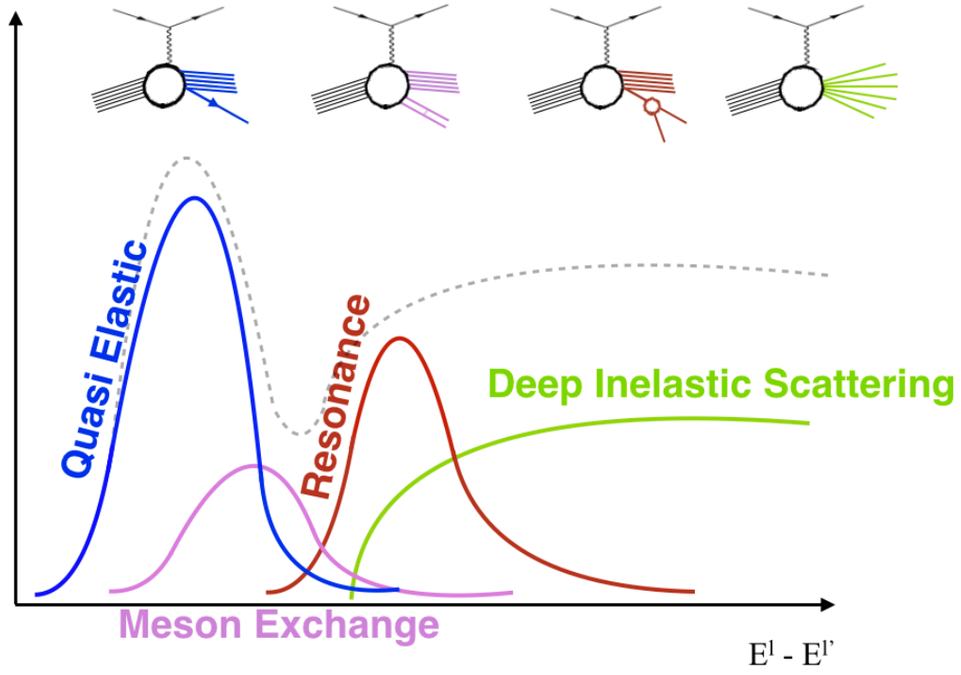
Neutrino event generators simulating νA interaction

Genie



GiBUU
The Giessen Boltzmann-Uehling-Uhlenbeck Project

and more



Factorisation of

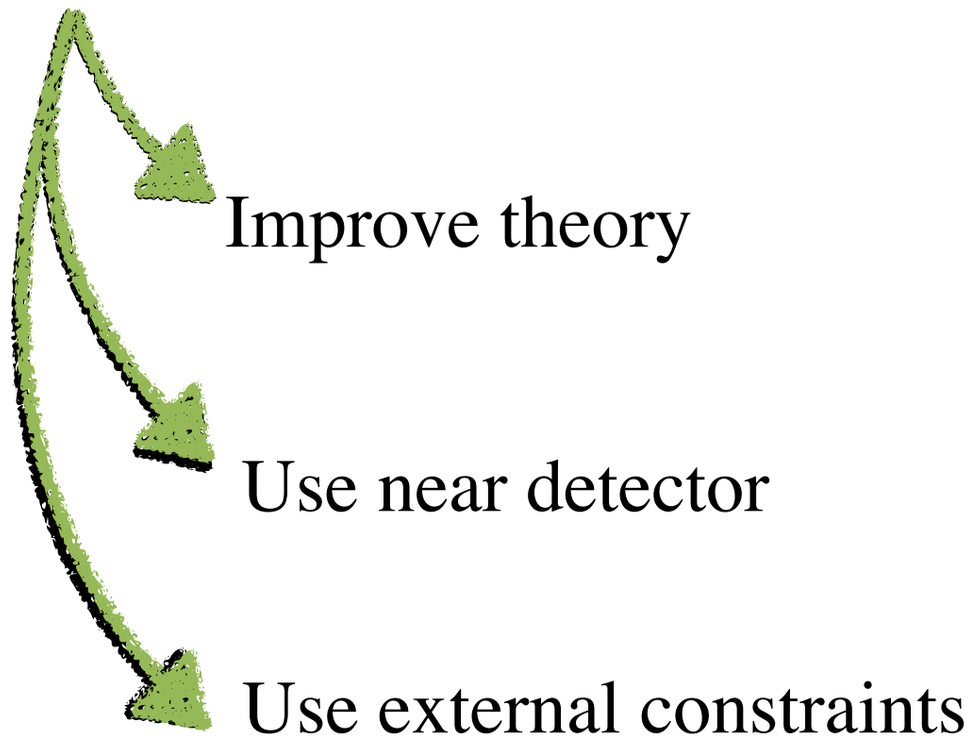
- Initial state
- Each interaction mechanism separately
- Final State Interactions

Empirical or semi classical models with many free parameters

The challenge - next generation high precision

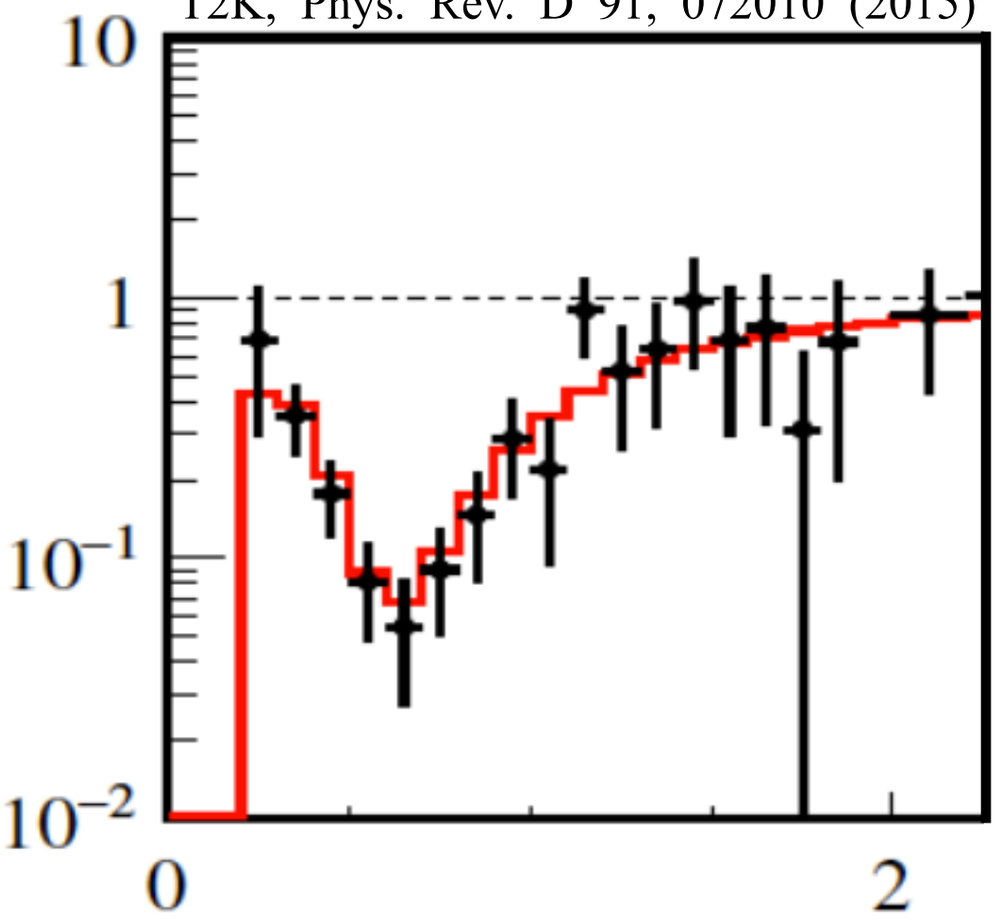
$$N(E_{rec}, L) \propto \int \Phi(E, L)\,\sigma(E)\,f_{\sigma}(E, E_{rec})\,dE$$

Measurement — Incoming true flux — Modelling input



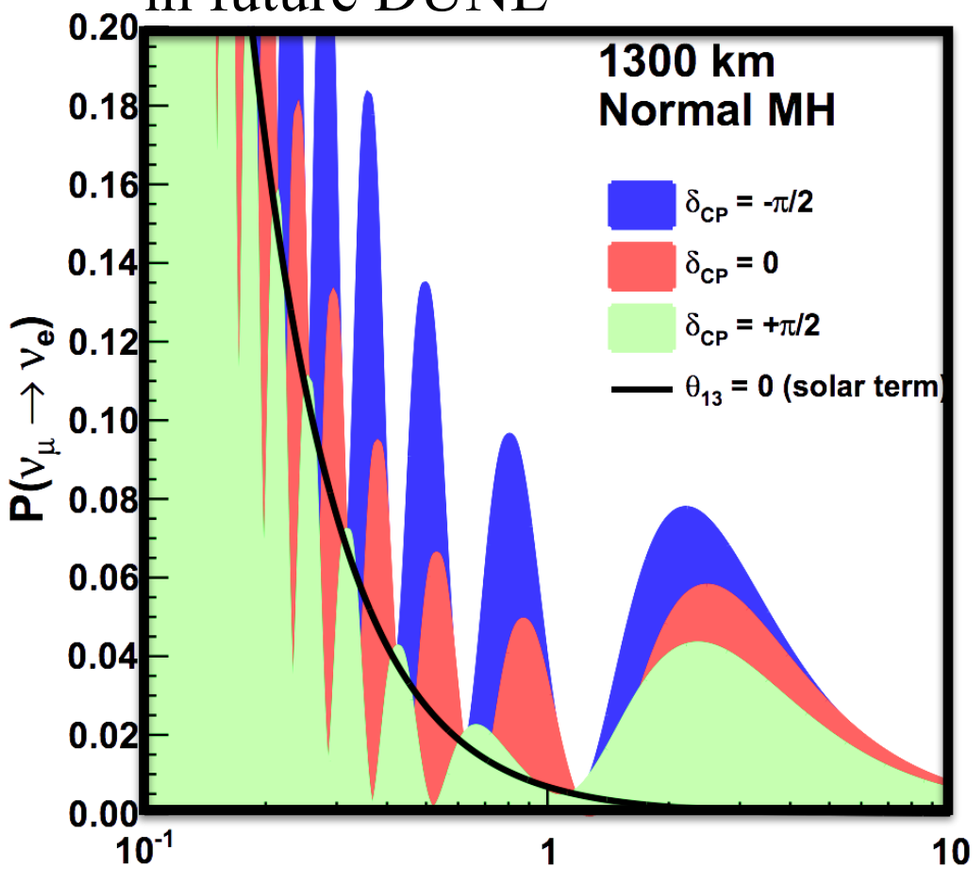
The challenge - next generation high precision

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



Neutrino Energy [GeV]

Simulation of oscillation effects in future DUNE



Neutrino Energy [GeV]


μBooNE

CCQE-like analysis in μBooNE

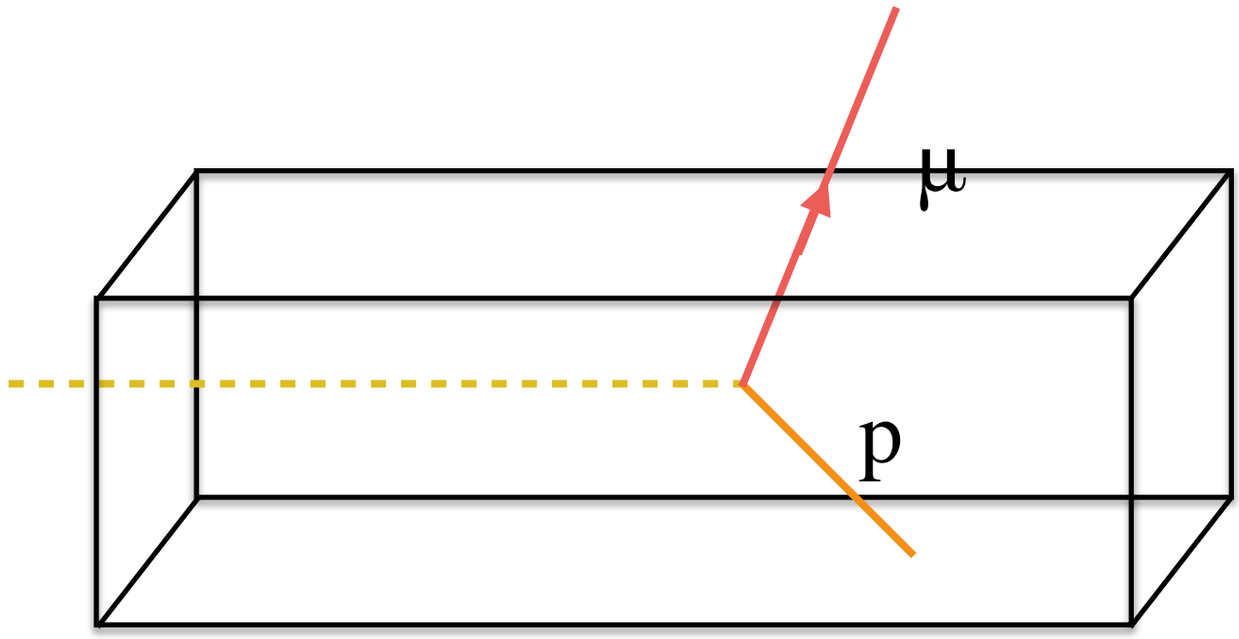
Vertex of 2 semi-contained tracks

(start within the fiducial volume)

one muon (**Pμ > 100 MeV/c**)

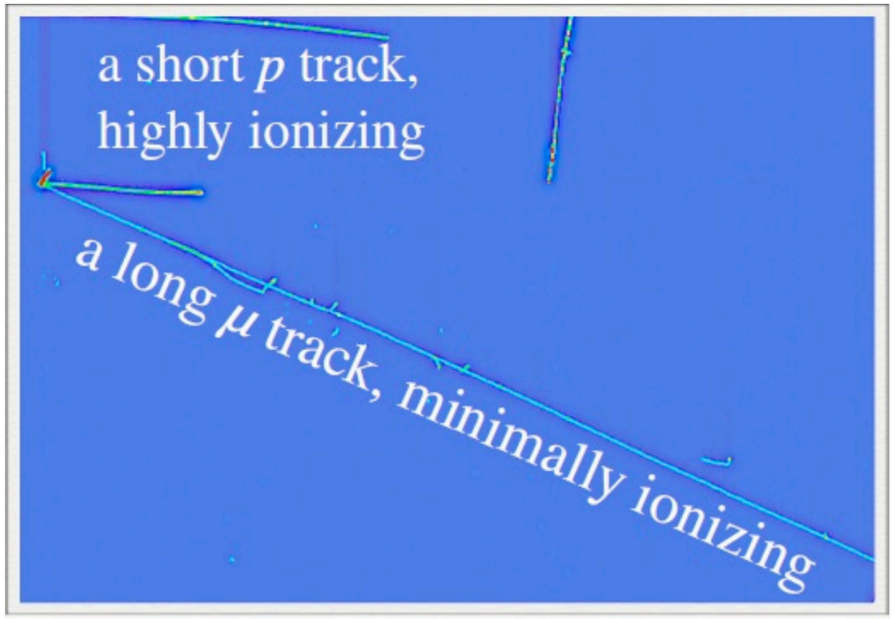
one proton (**Pp > 300 MeV/c**)

no π0 , no charged π (≥ 70 MeV/c)



Additional kinematical cuts on:

- To reduce cosmic contamination
  - $|\Delta\theta_{\mu p} - 90^{o}| < 55^{o}$
- To enhance QE contribution
  - $|\Delta\varphi_{\mu p} - 180^{o}| < 35^{o}$
  - $p_T = |p_{T,\mu} + p_{T,p}| < 350$ MeV/c

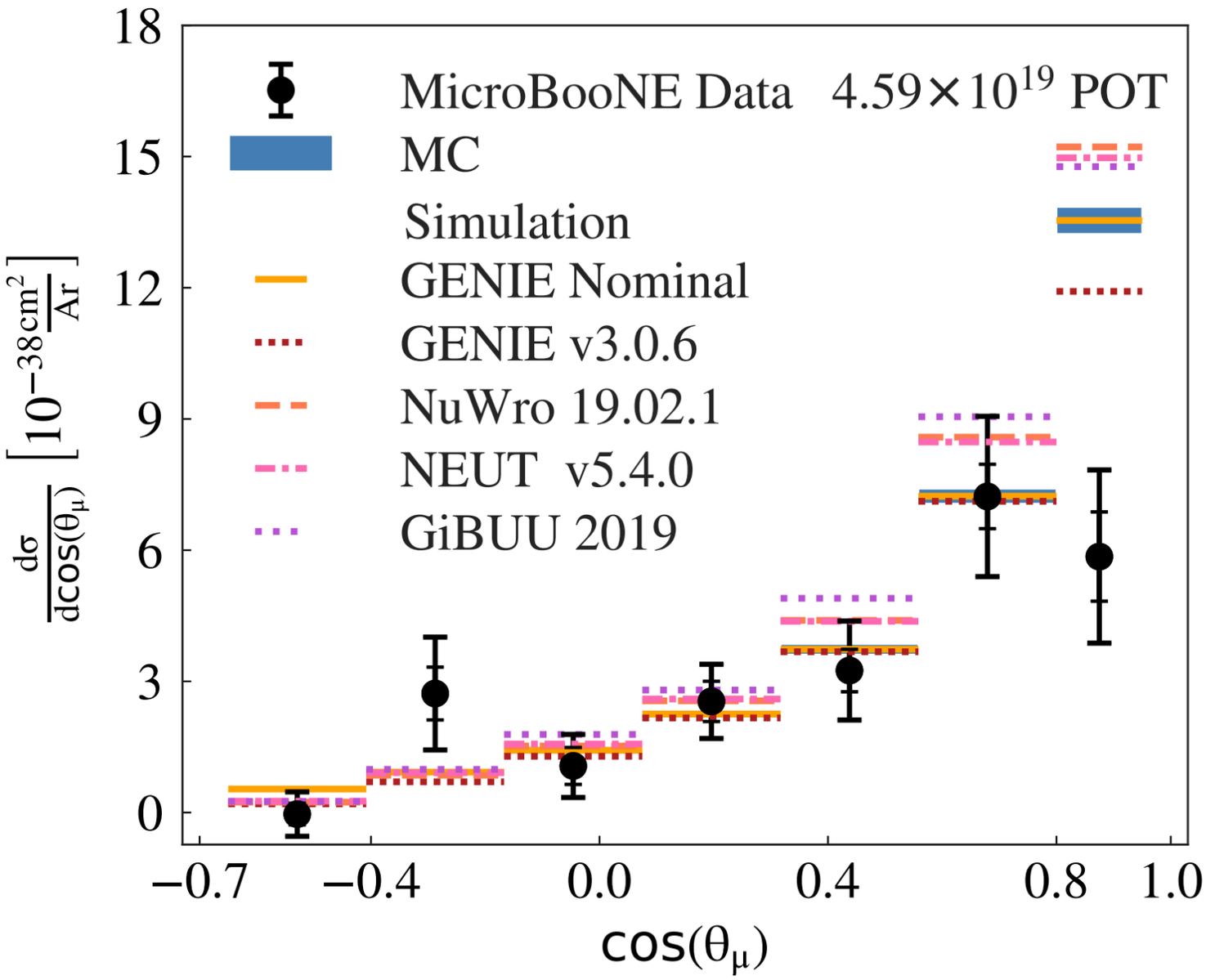


~84% CC1p0π (~81% CCQE) purity, 20% efficiency

CCQE-like: Results Old Model

Overall agreement except for forward muon scattering angle

$$\nu + {}^{40}\mathrm{Ar} \rightarrow \mu + p + {}^{39}\mathrm{Ar}$$

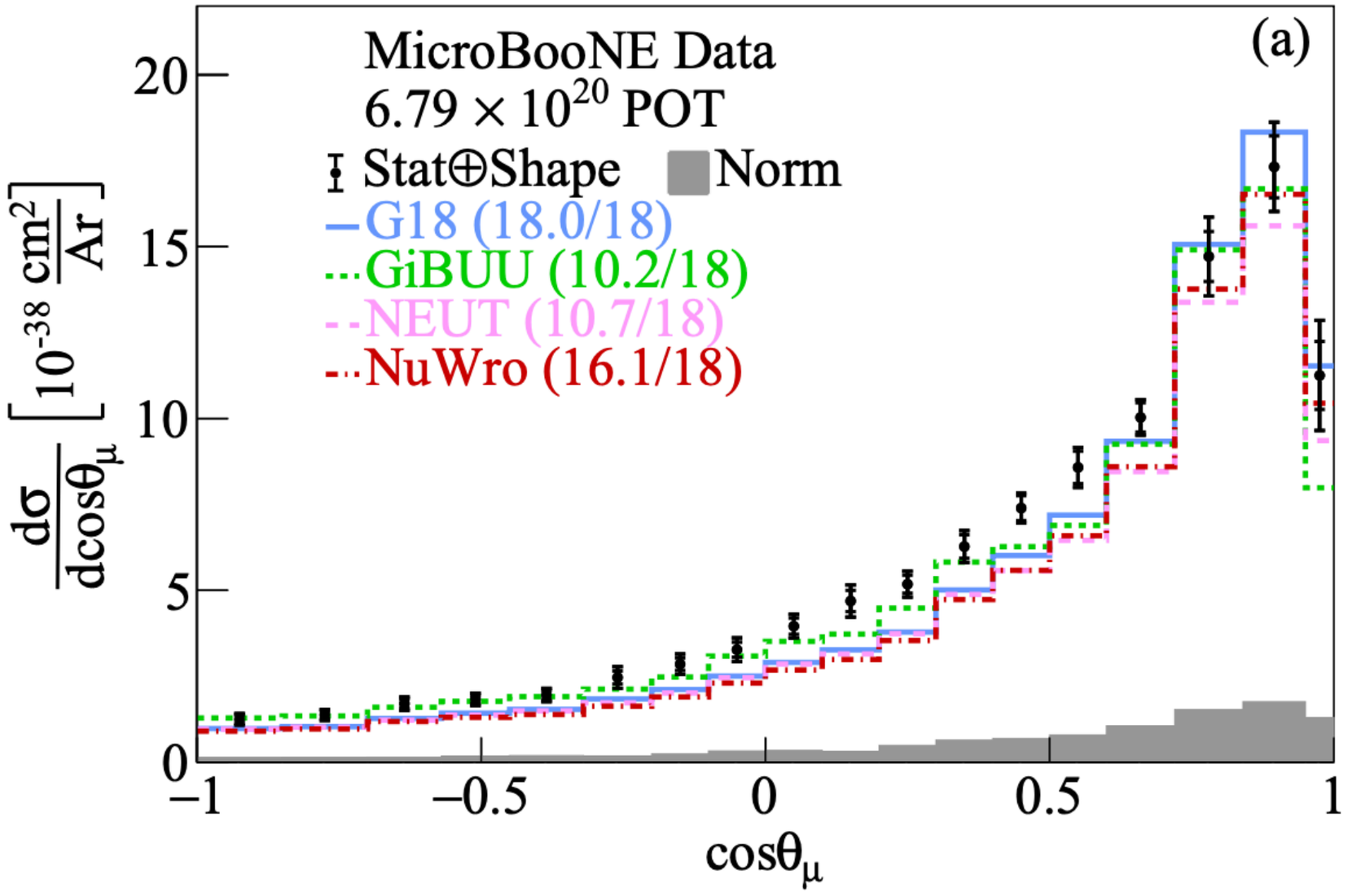


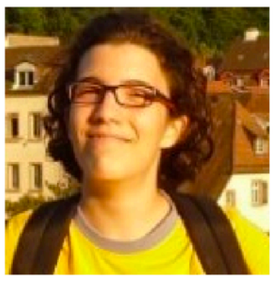
Phys Rev Lett. 125, 201803 (2020)

CCQE-like: New Results

$$\nu + {}^{40}\mathrm{Ar} \rightarrow \mu + p + {}^{39}\mathrm{Ar}$$

without additional kinematic cuts



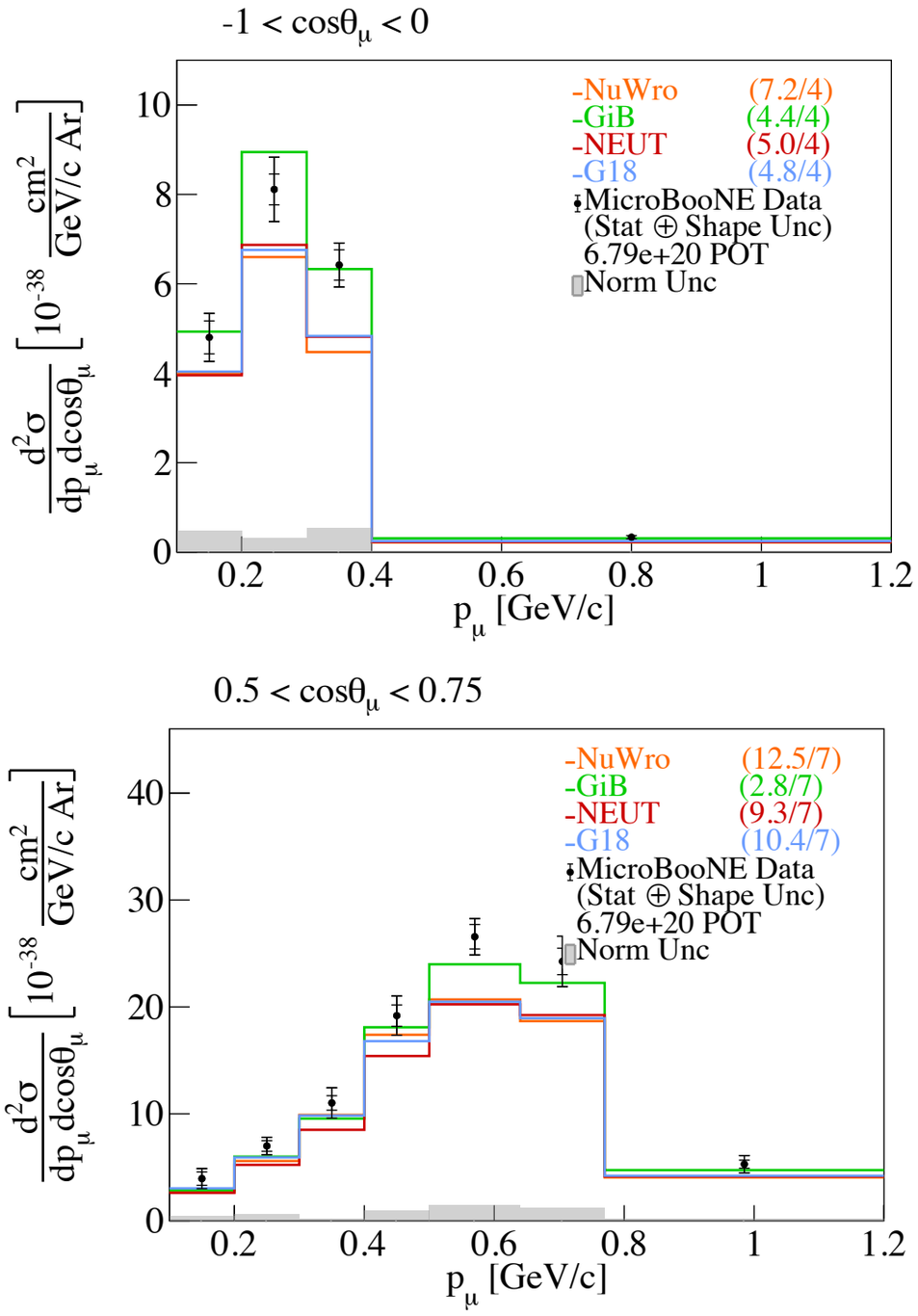


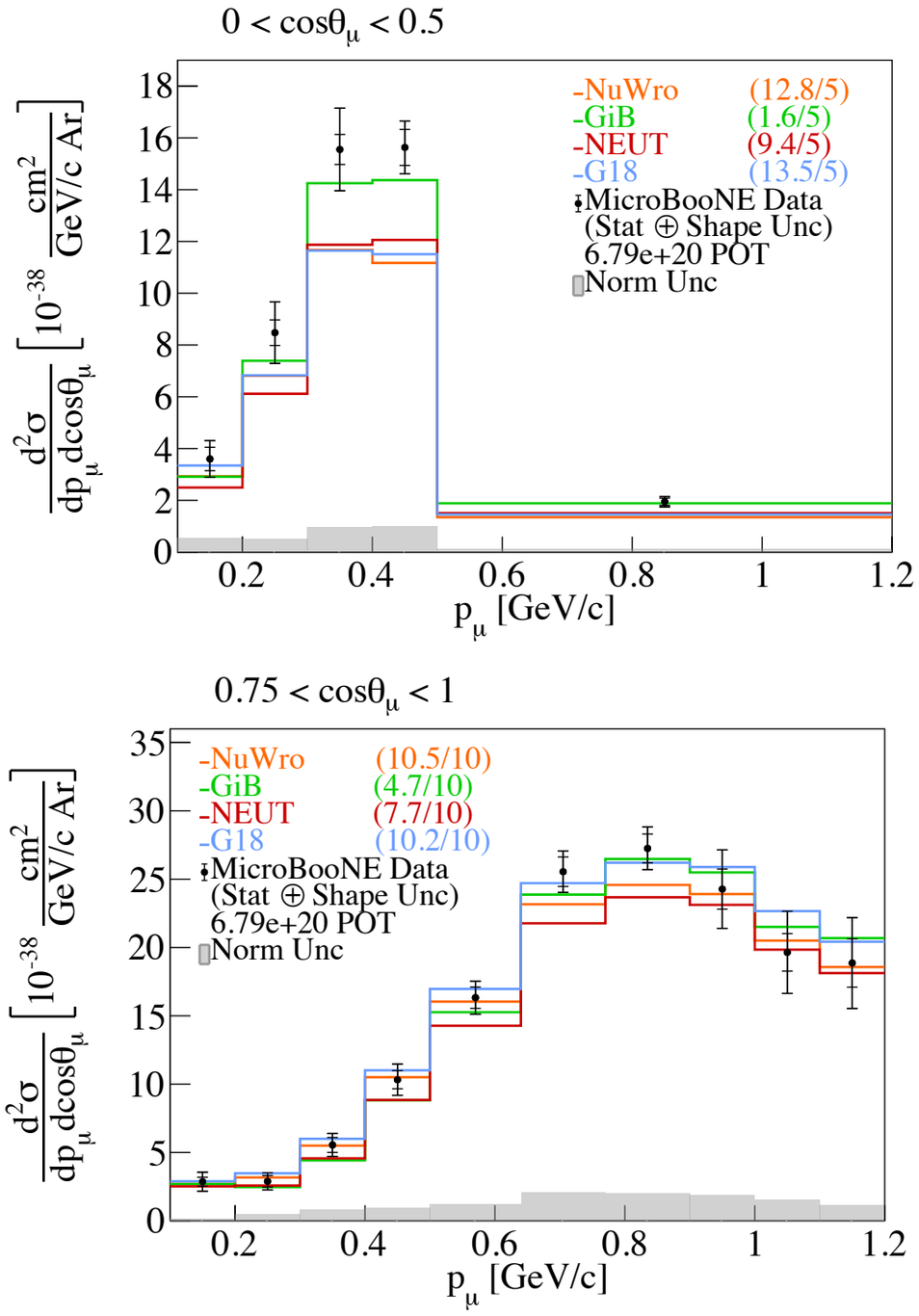
Afroditi Papadopoulou

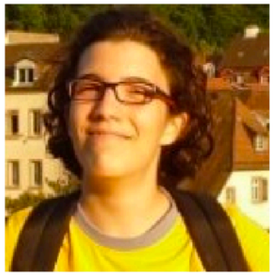
arXiv:2301.03700 [hep-ex]

See MicroBooNE Tune: arXiv:2110.14028

CCQE-like: New Results







Afroditi Papadopoulou

arXiv:2301.03700 [hep-ex]


e4V

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?

Electrons and Neutrinos have:

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

Useful to constrain model uncertainties

Electron beams have known energies

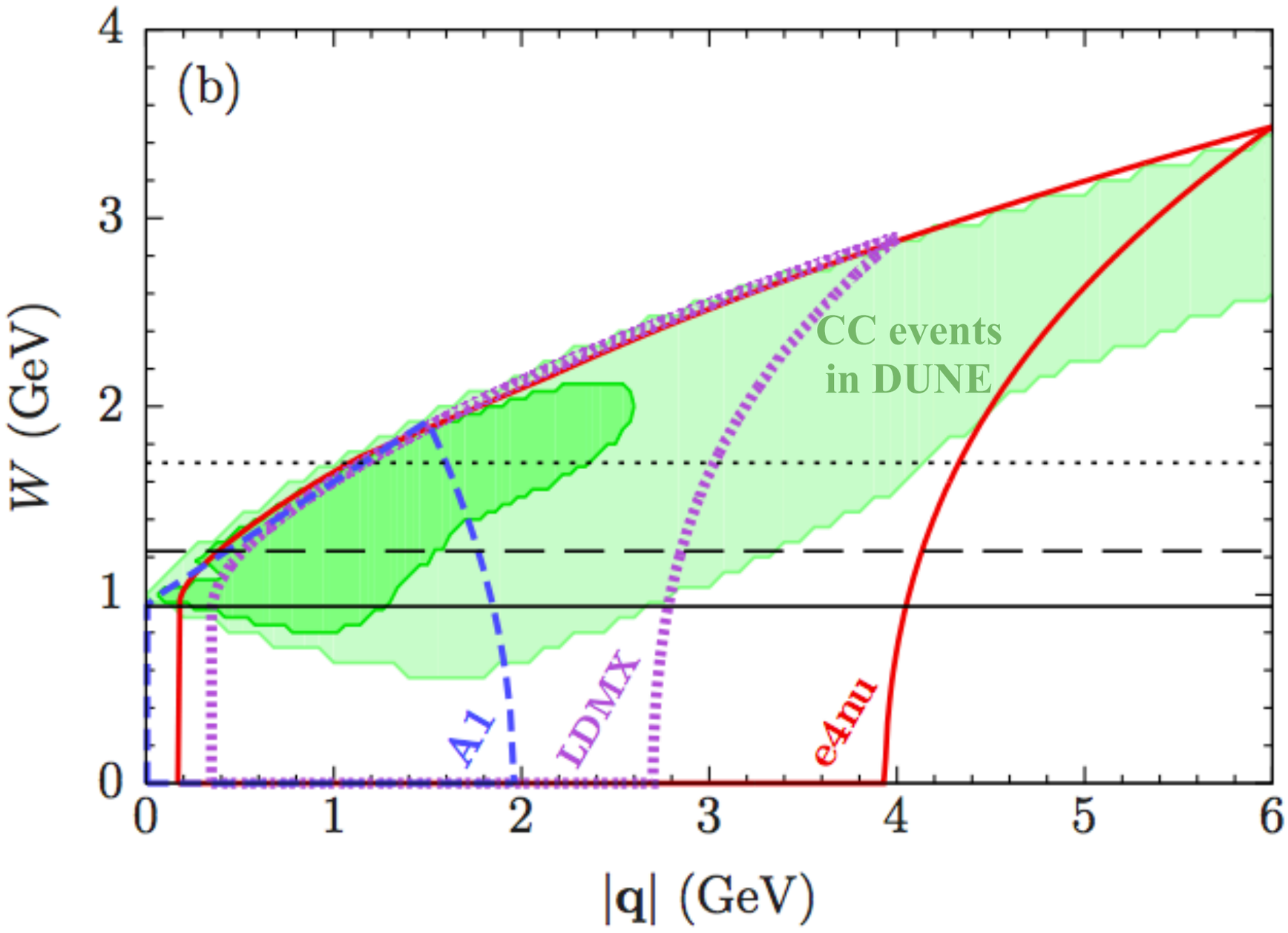
Useful to test incoming energy reconstruction methods

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) 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]

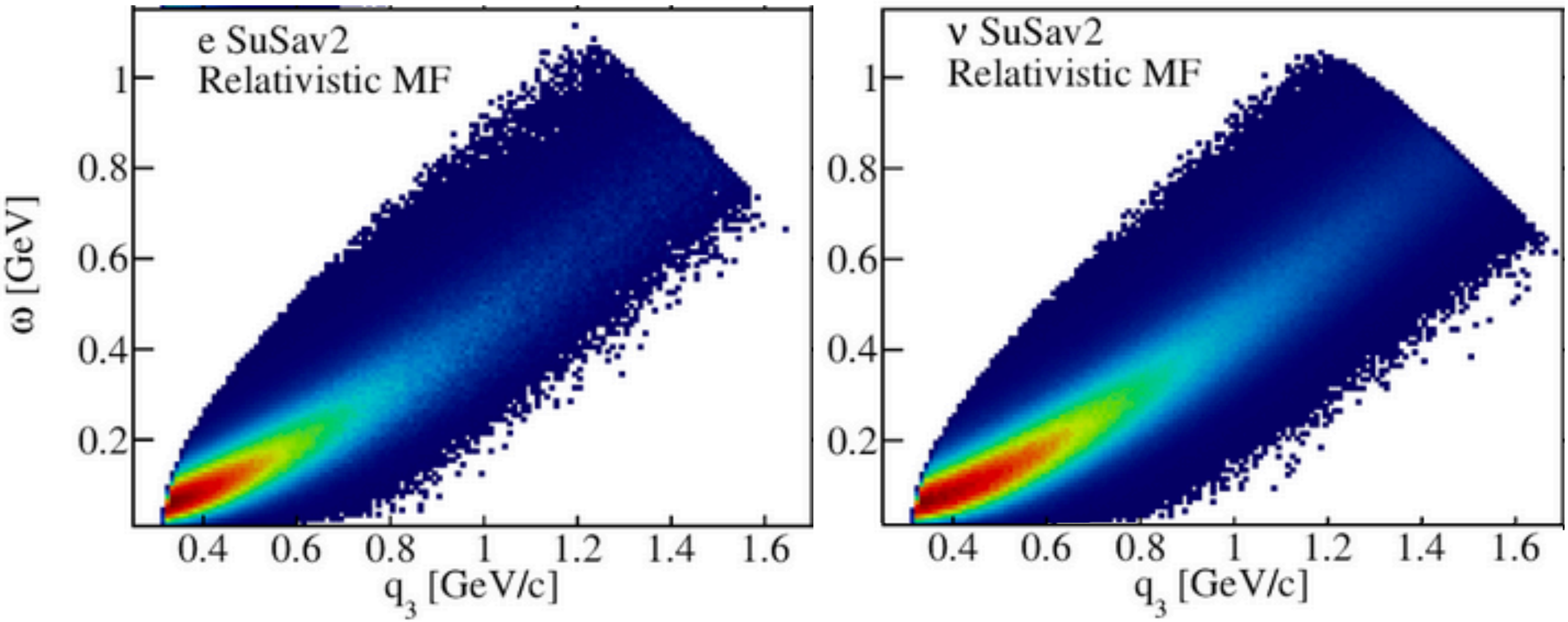
e4nu and DUNE



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

Similar eA and νA Cross sections

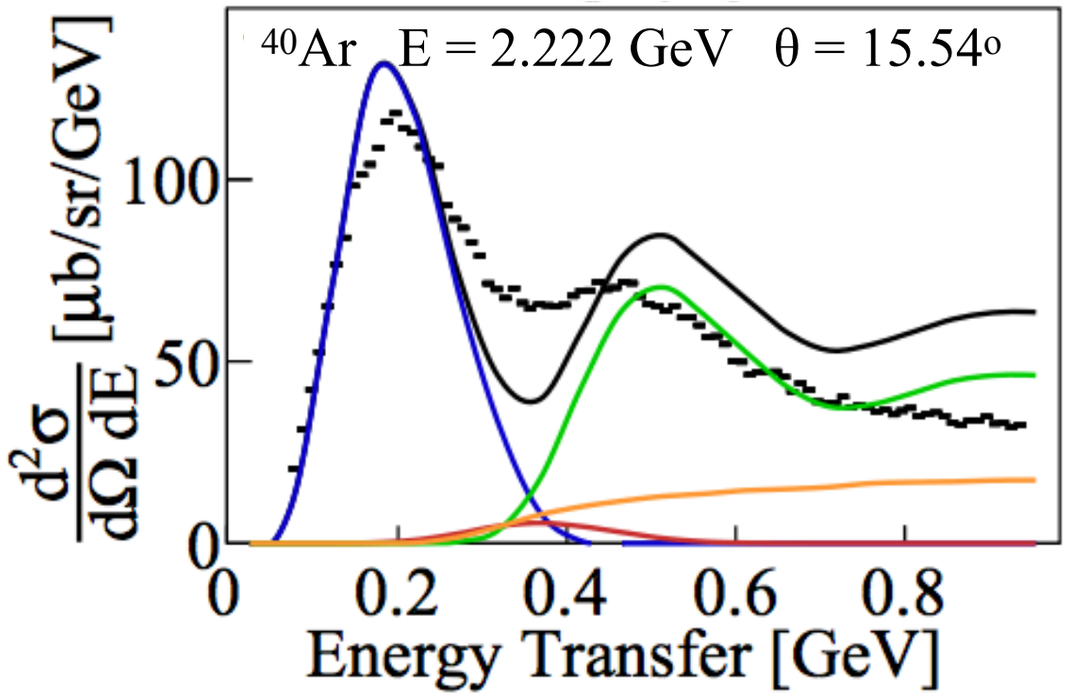
Test on 1p0π event selection

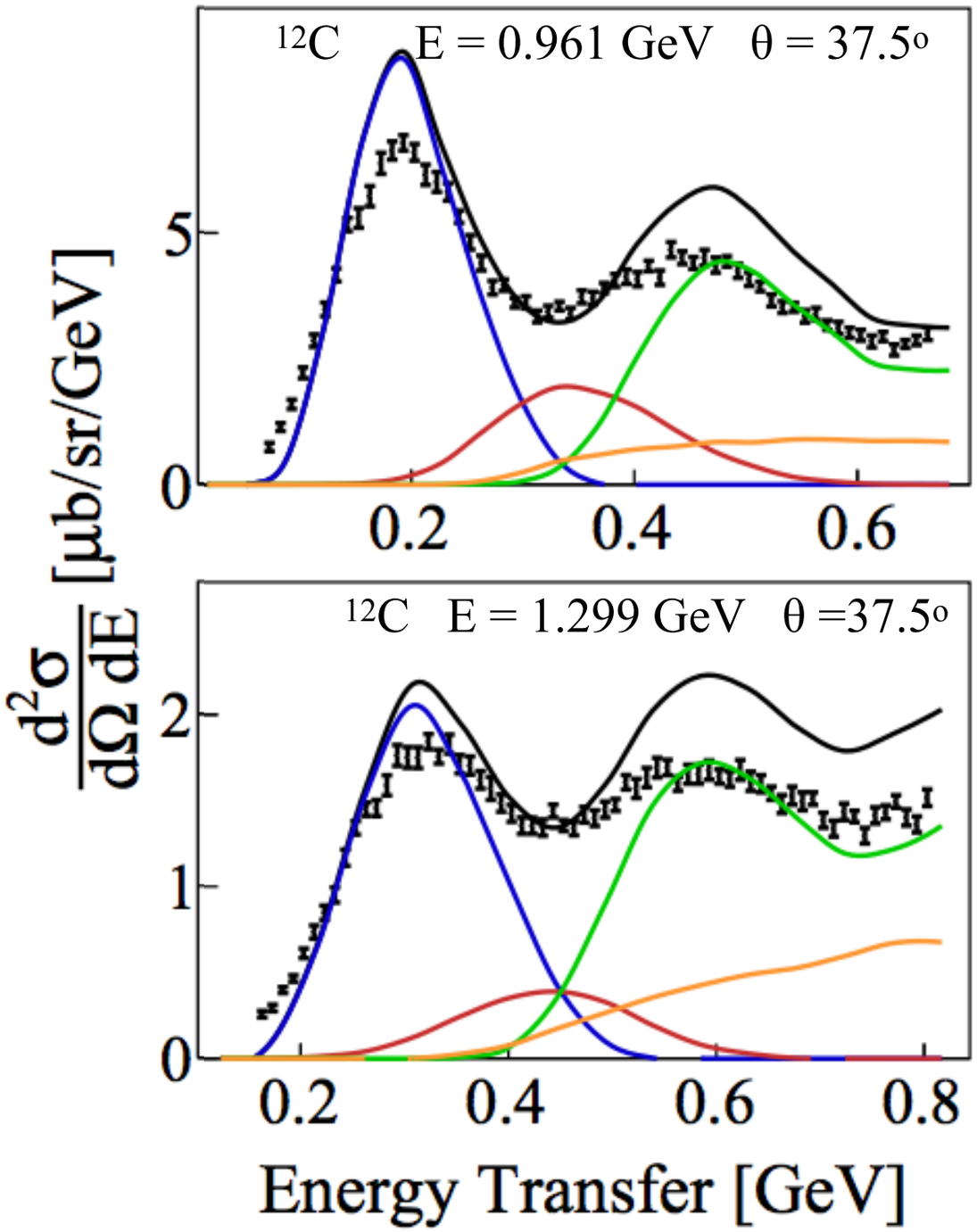


Genie v3.0.6 SuSA
Phys.Rev.D 103 (2021) 113003

Electron were weighted by $1/Q^4$

Inclusive e data and generators



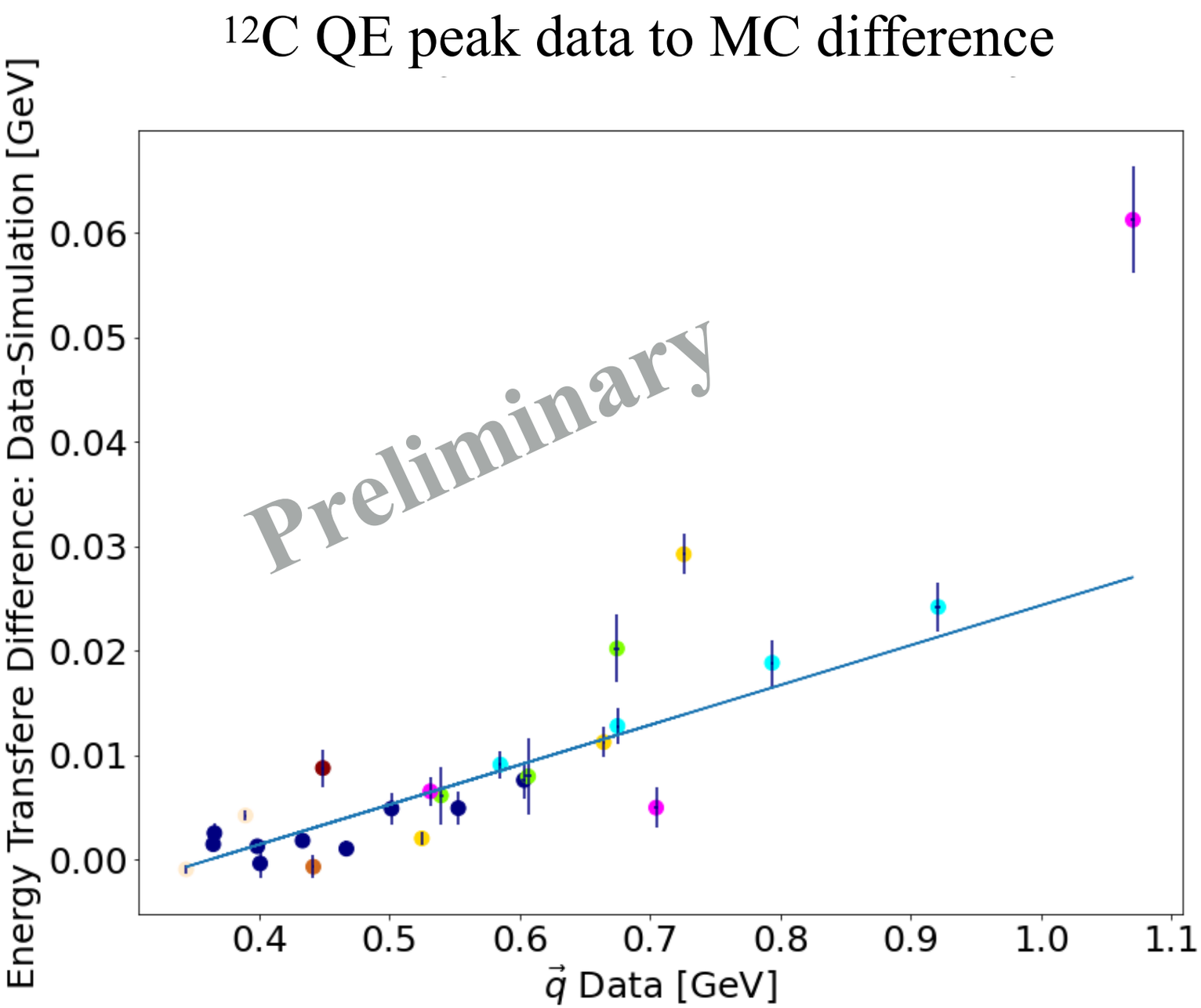


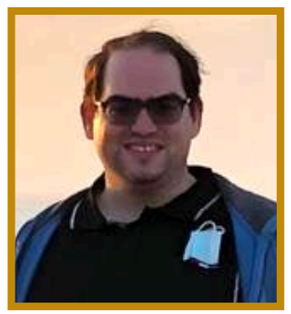
Genie

— v3.0.6 tune G18_10a_02_11a

Phys.Rev.D 103 (2021) 113003

Improving Models
Testing Binding Energy Using Inclusive Data





Matan Goldenberg

CLAS Detector

Electron beam with energies up to 6 GeV

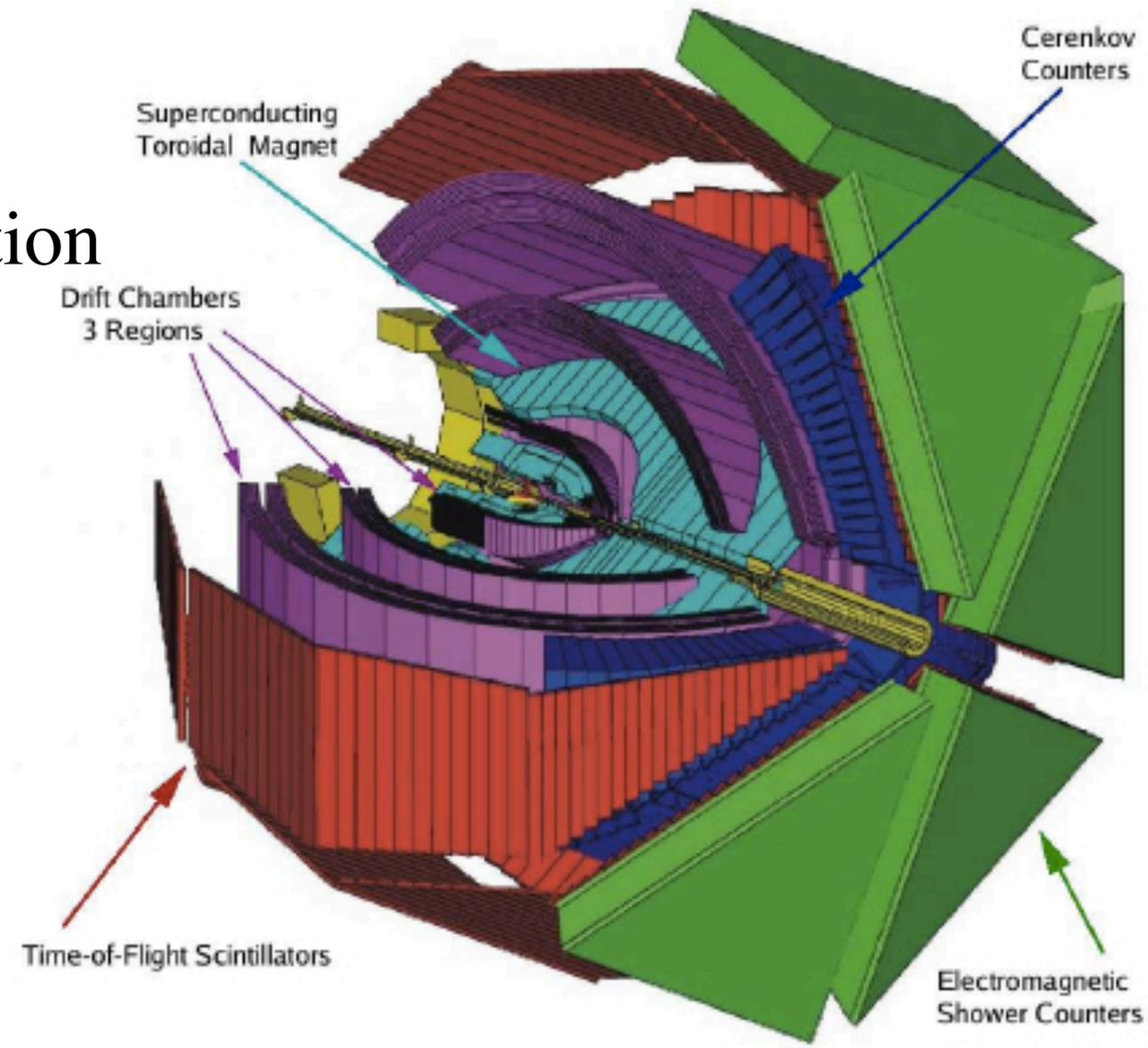
Large acceptance

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

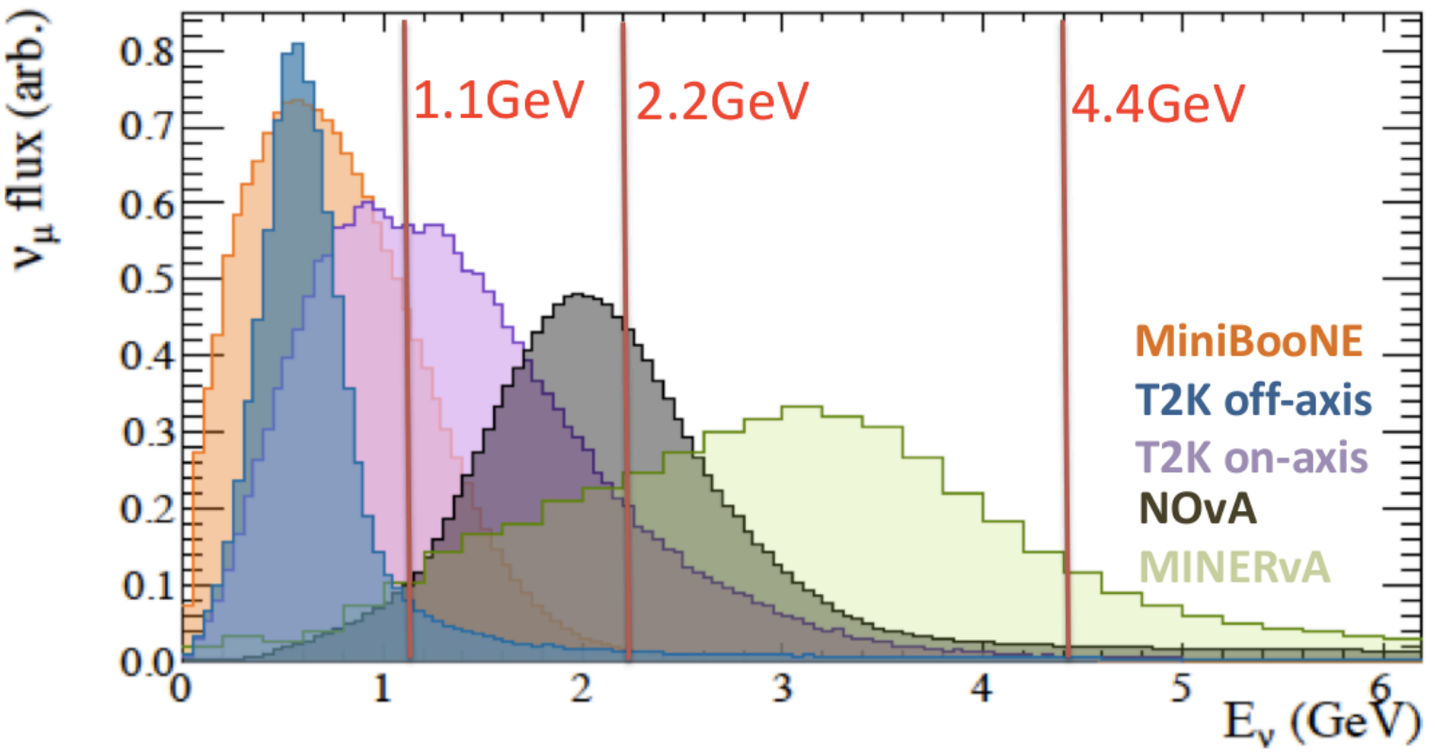
CLAS A(e,e'p) Data E2a

First test of neutrino energy reconstruction with exclusive data!

- Targets: ^{4}He, ^{12}C, ^{56}Fe  (H_2O),  (CH),  (Ar)

- Energies:

  1.1, 2.2, 4.4 GeV



e4ν 1p0π Event Selection

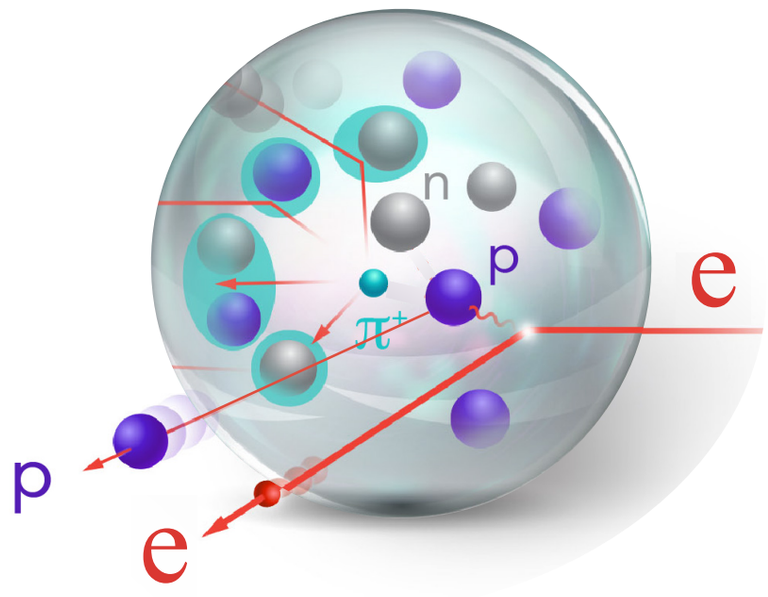
Focus on Quasi Elastic events:

1 proton above 300 MeV/c

no additional hadrons above detection threshold:

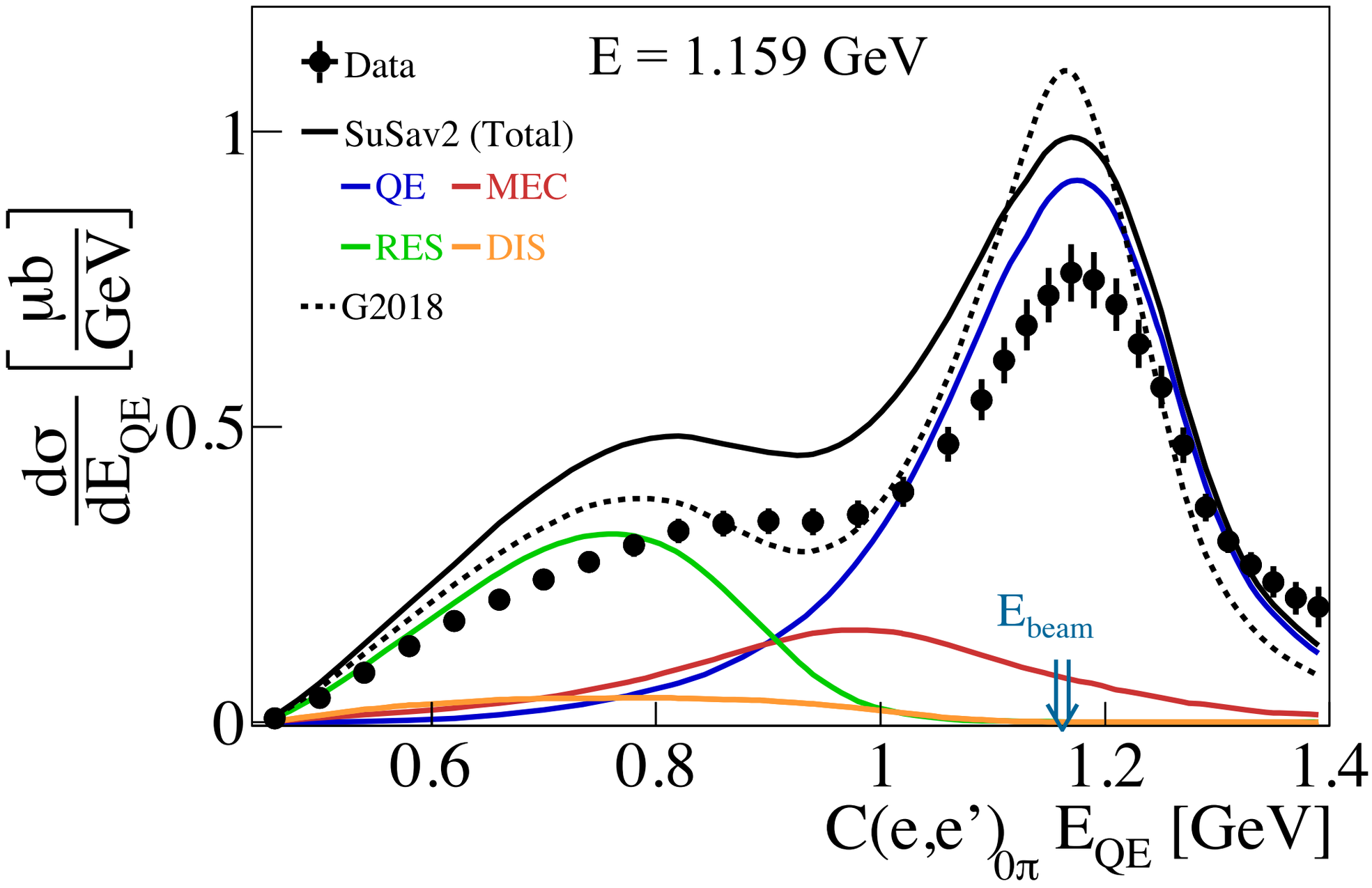
150 MeV/c for $P_{\pi^{+/-}}$

500 MeV/c for P_{π^0}



Data

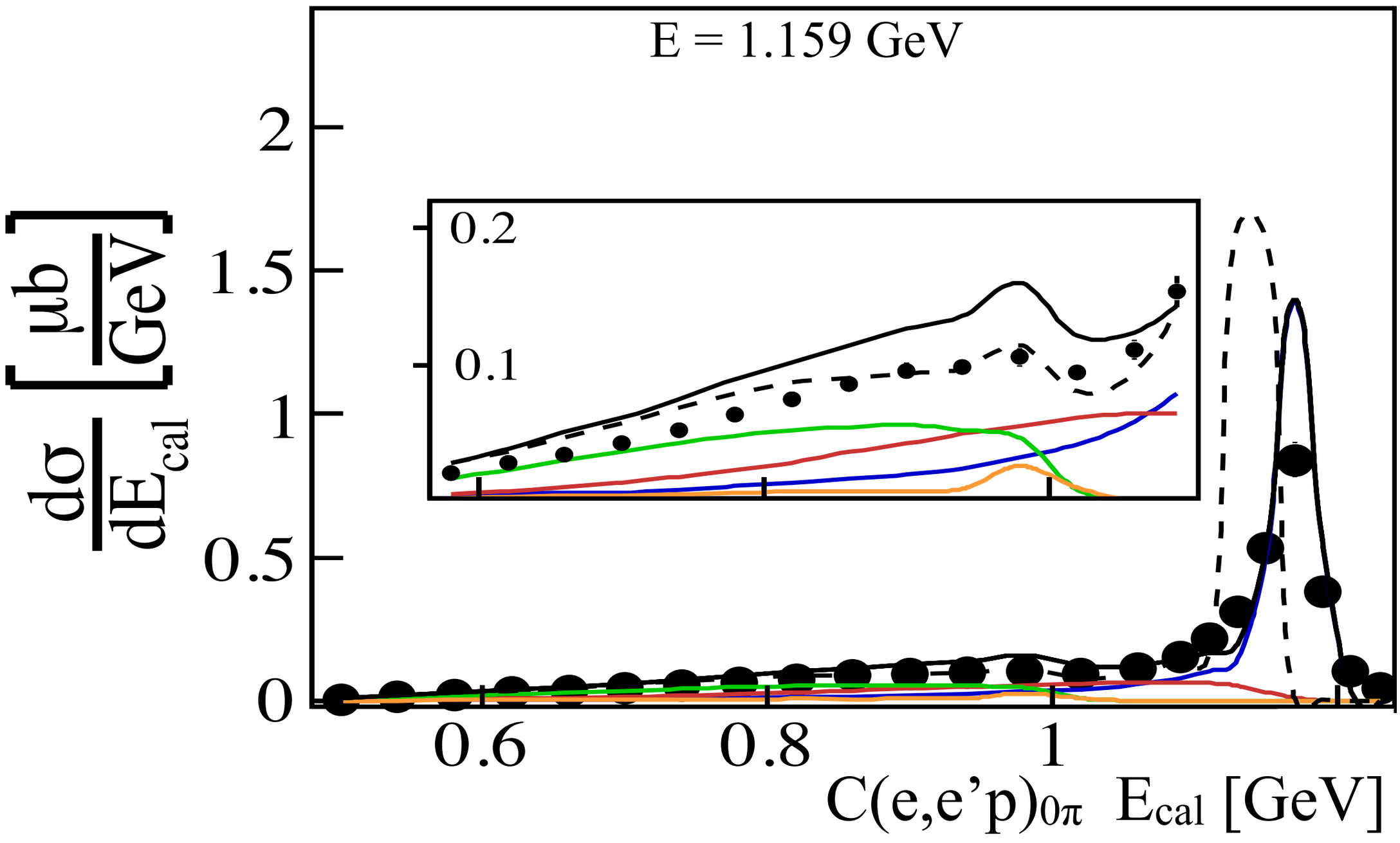
Inclusive Energy Reconstruction



Nature **599**, 565 (2021)

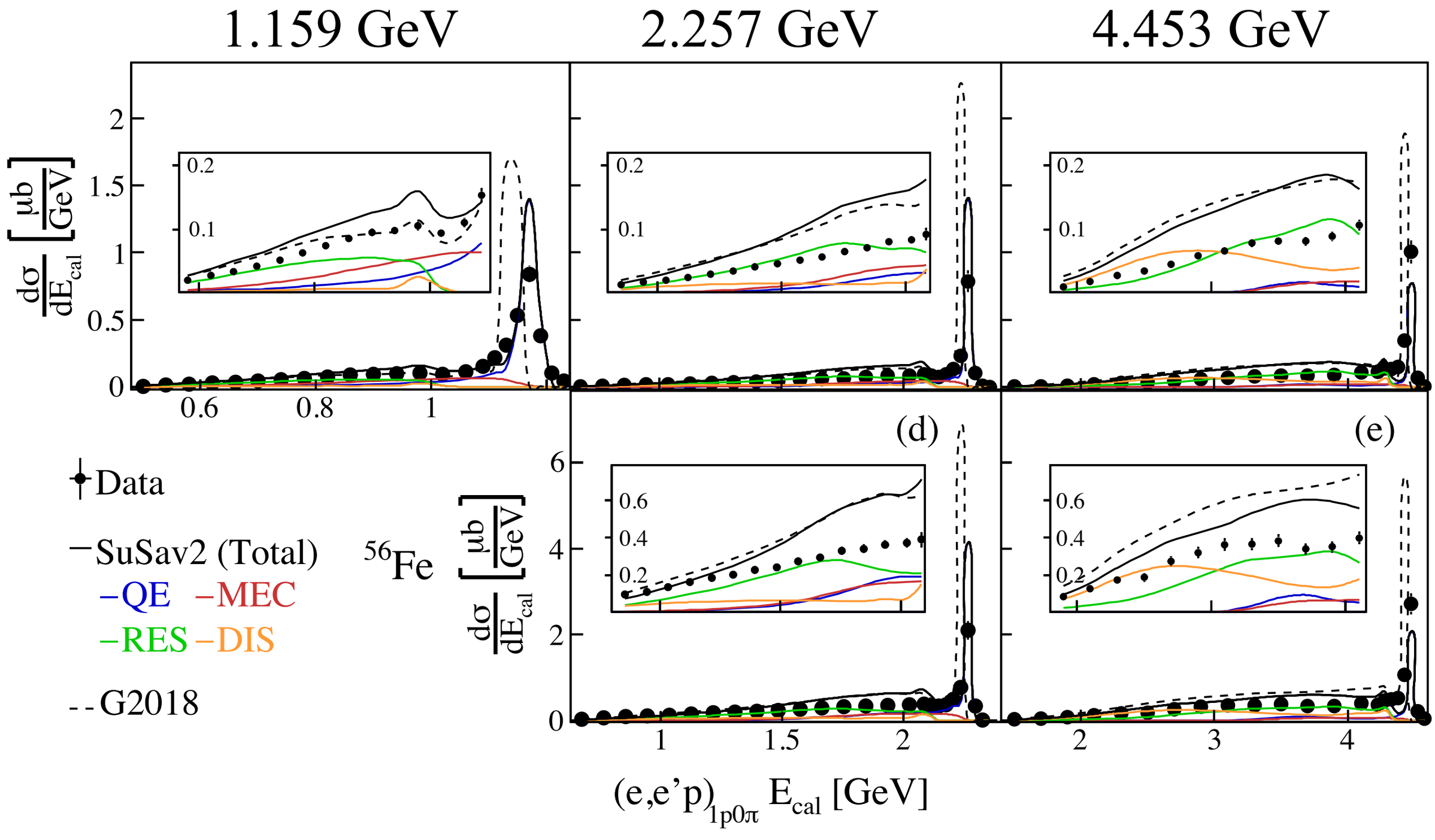
$$E_{QE} = \frac{2M\epsilon + 2ME_l - m_l^2}{2(M - E_l + |k_l|\cos\theta_l)}$$

Reconstructed Calorimetric Energy



Nature **599**, 565 (2021)

Reconstructed Calorimetric Energy



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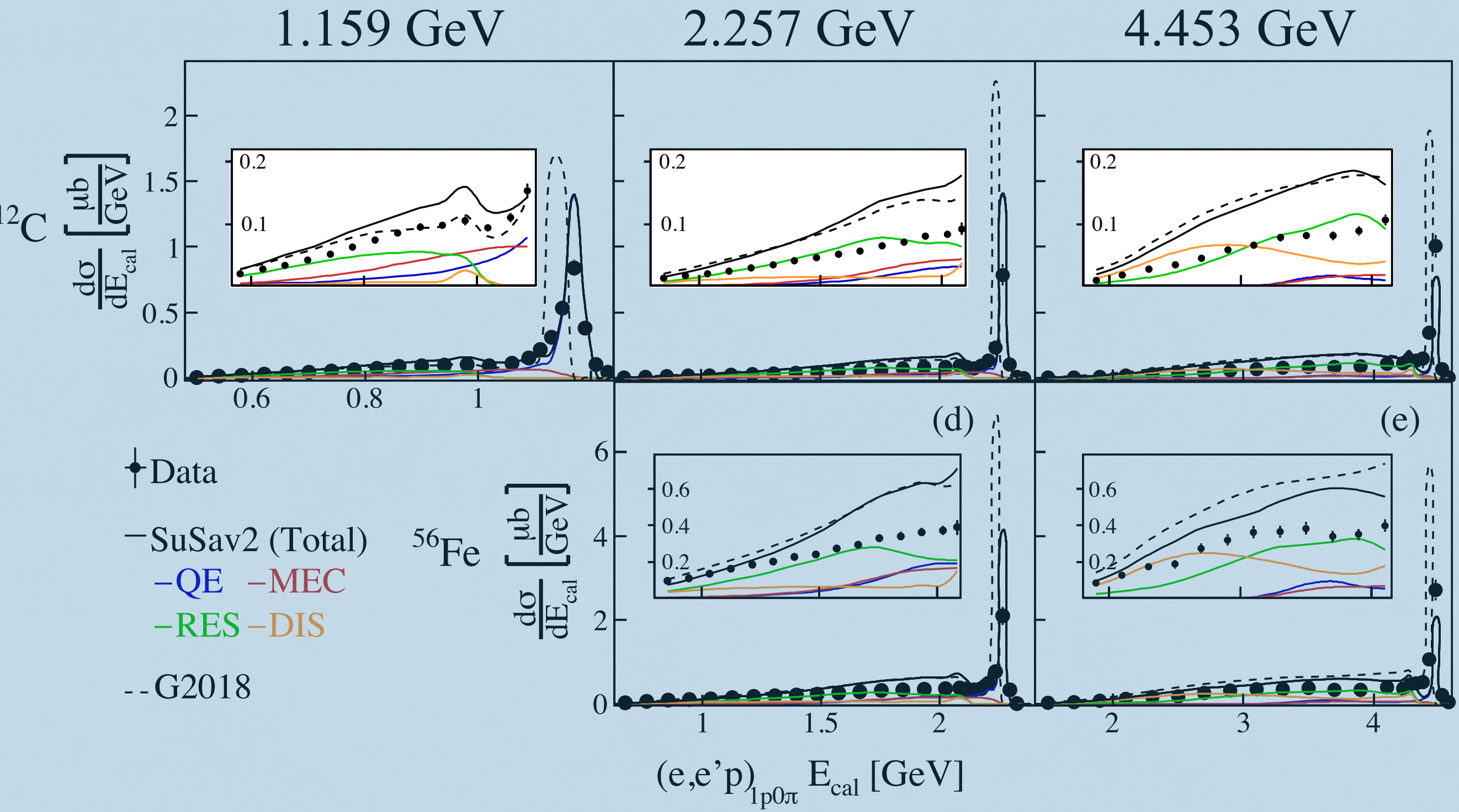
Reconstructed Calorimetric Energy



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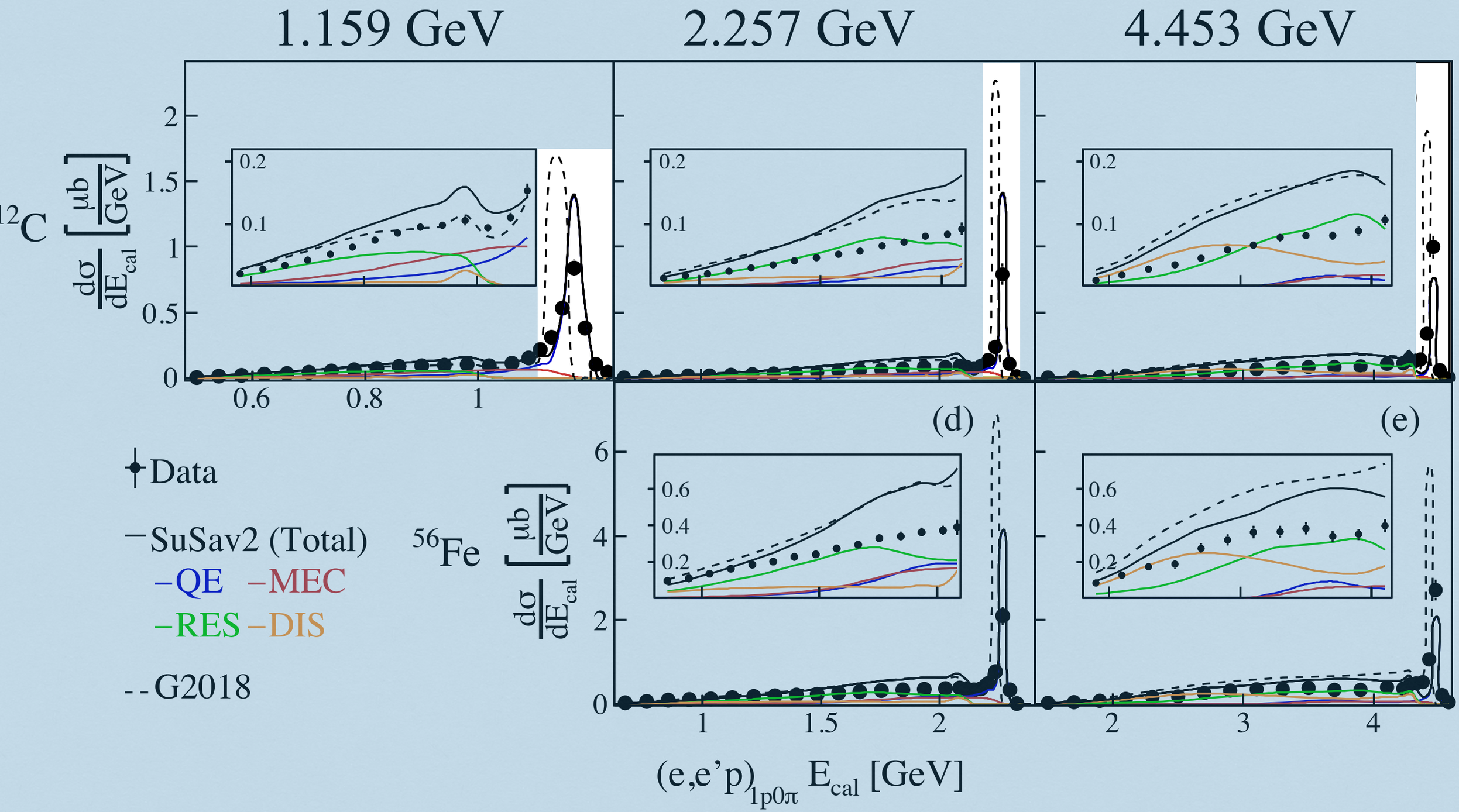
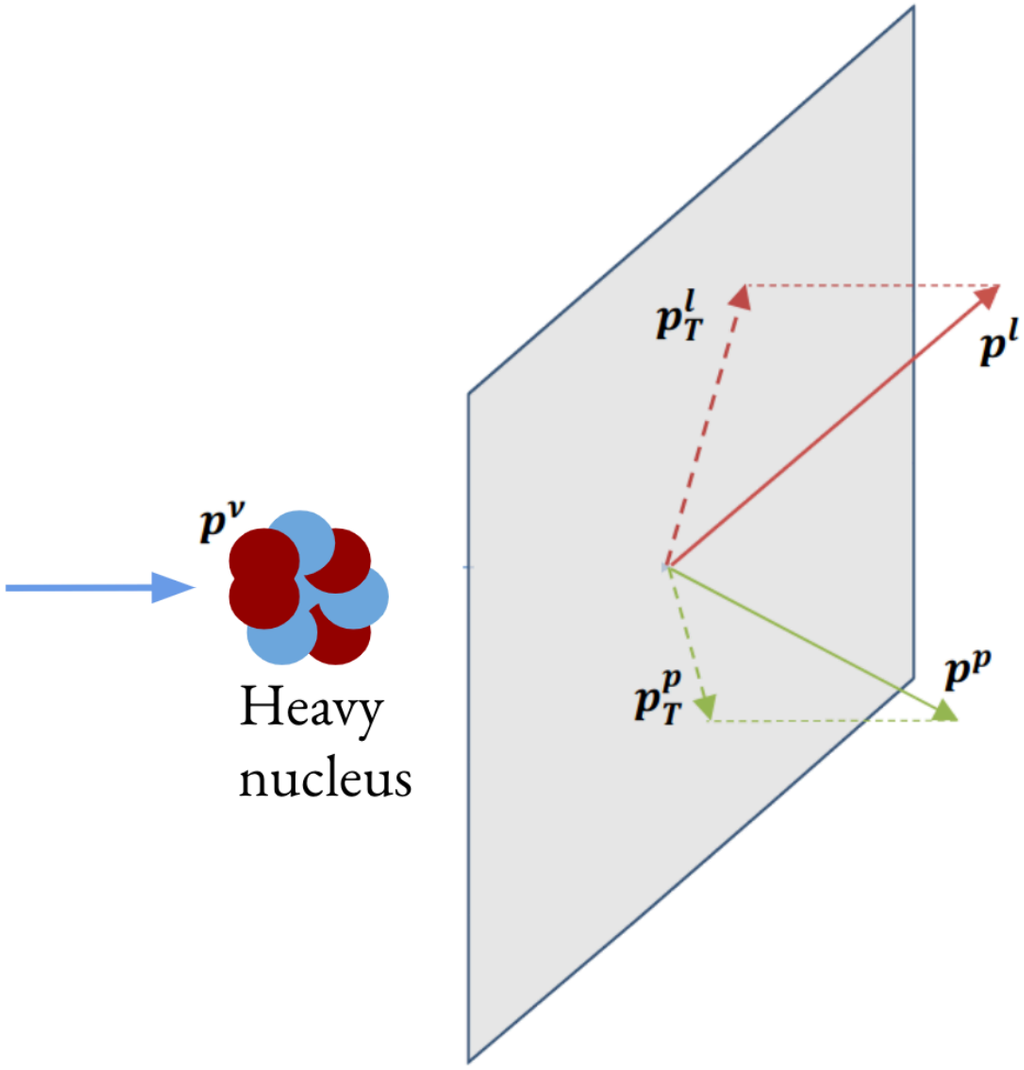


Nature **599**, 565 (2021)

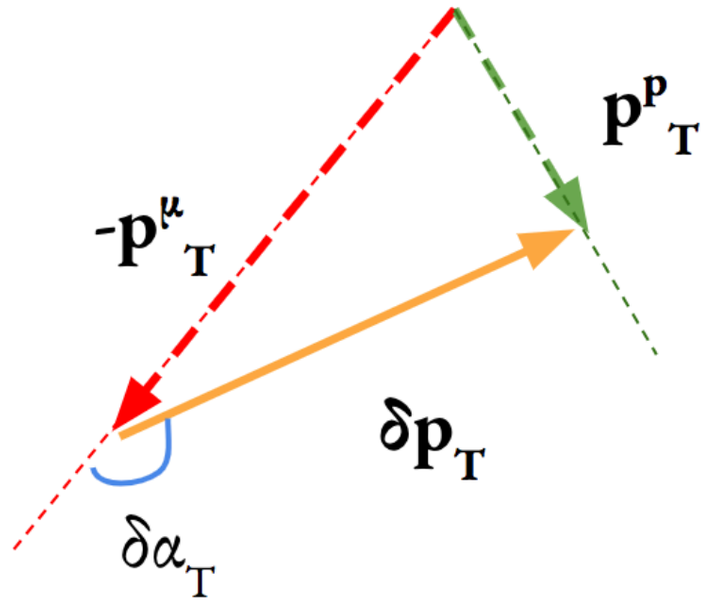
Focusing on different reaction mechanisms

Standard Transverse Variables



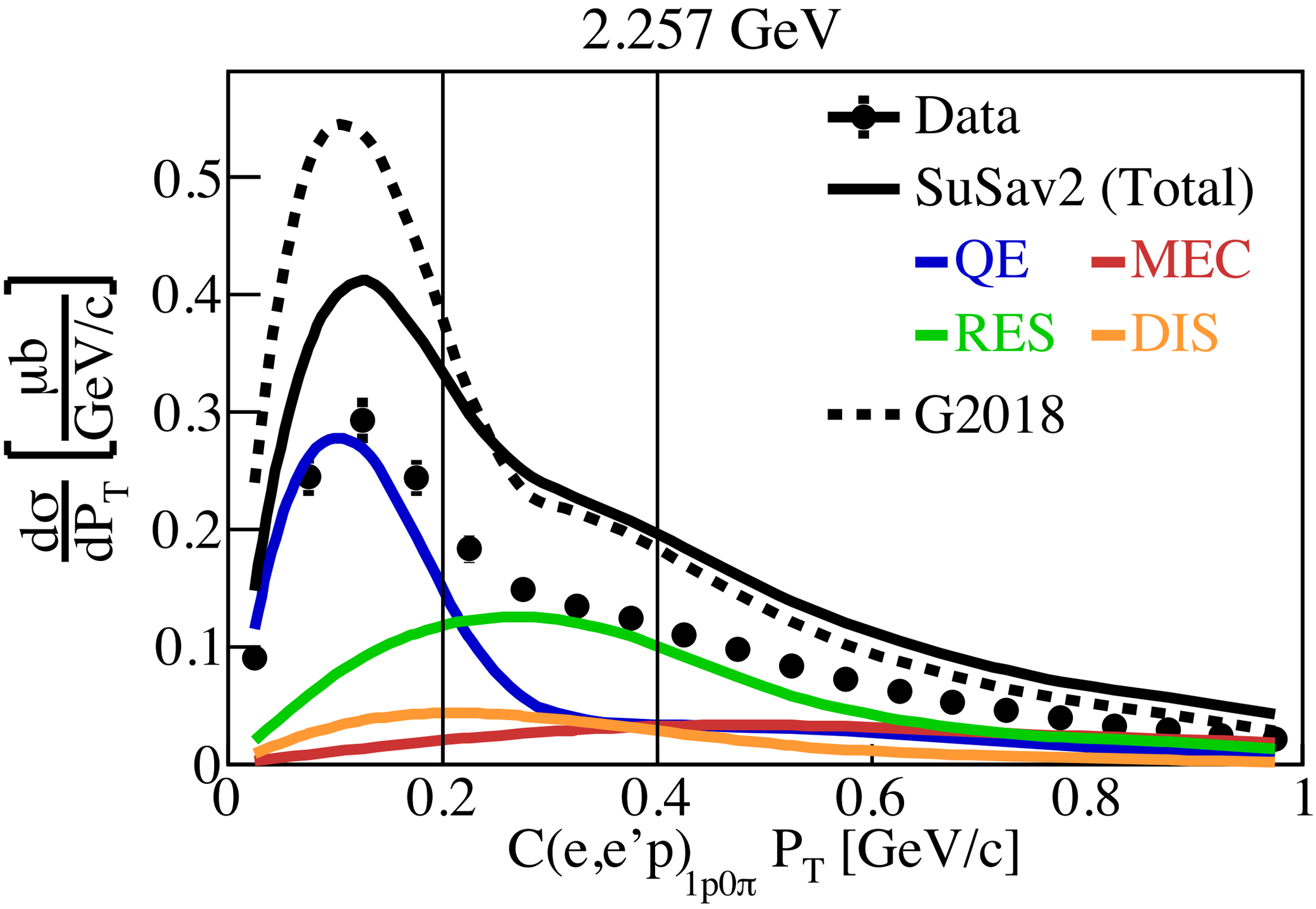
$$\vec{P}_T = \vec{P}_T^{e'} + \vec{P}_T^{p}$$

Sensitive to
hit nucleon momentum



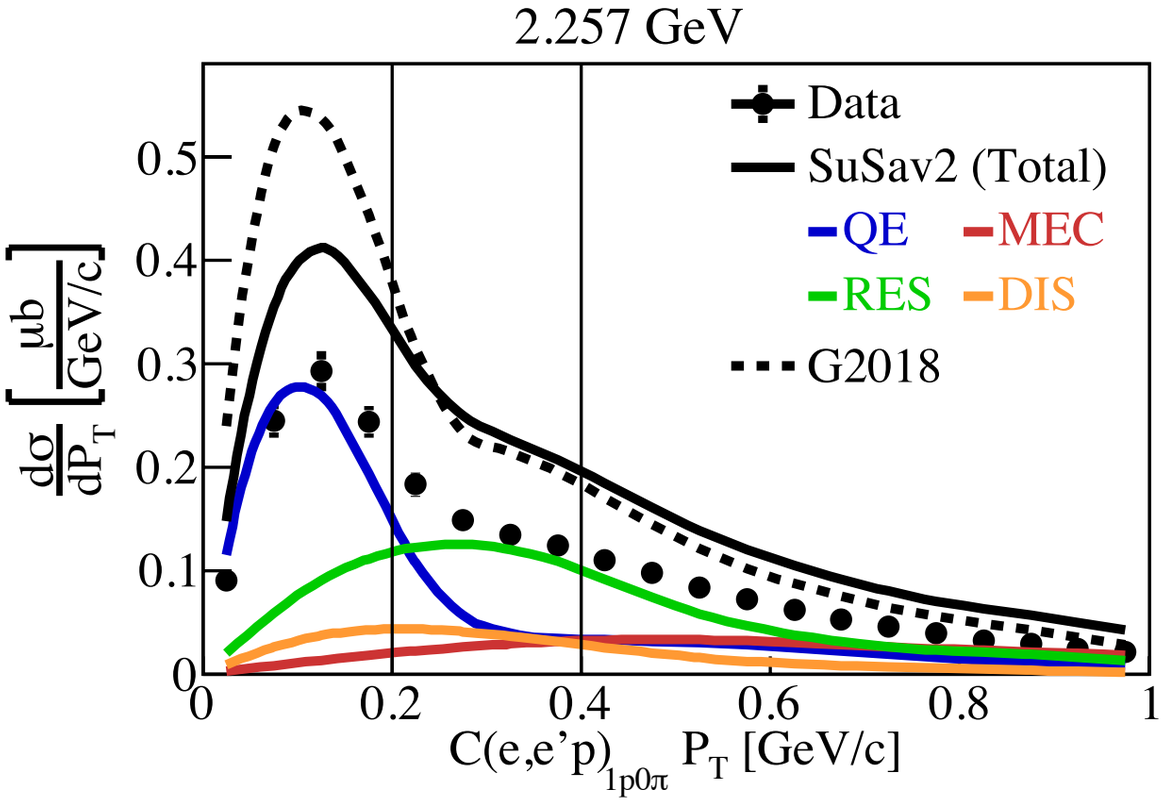
$\delta\alpha_T$
Sensitive to
Final State Interactions

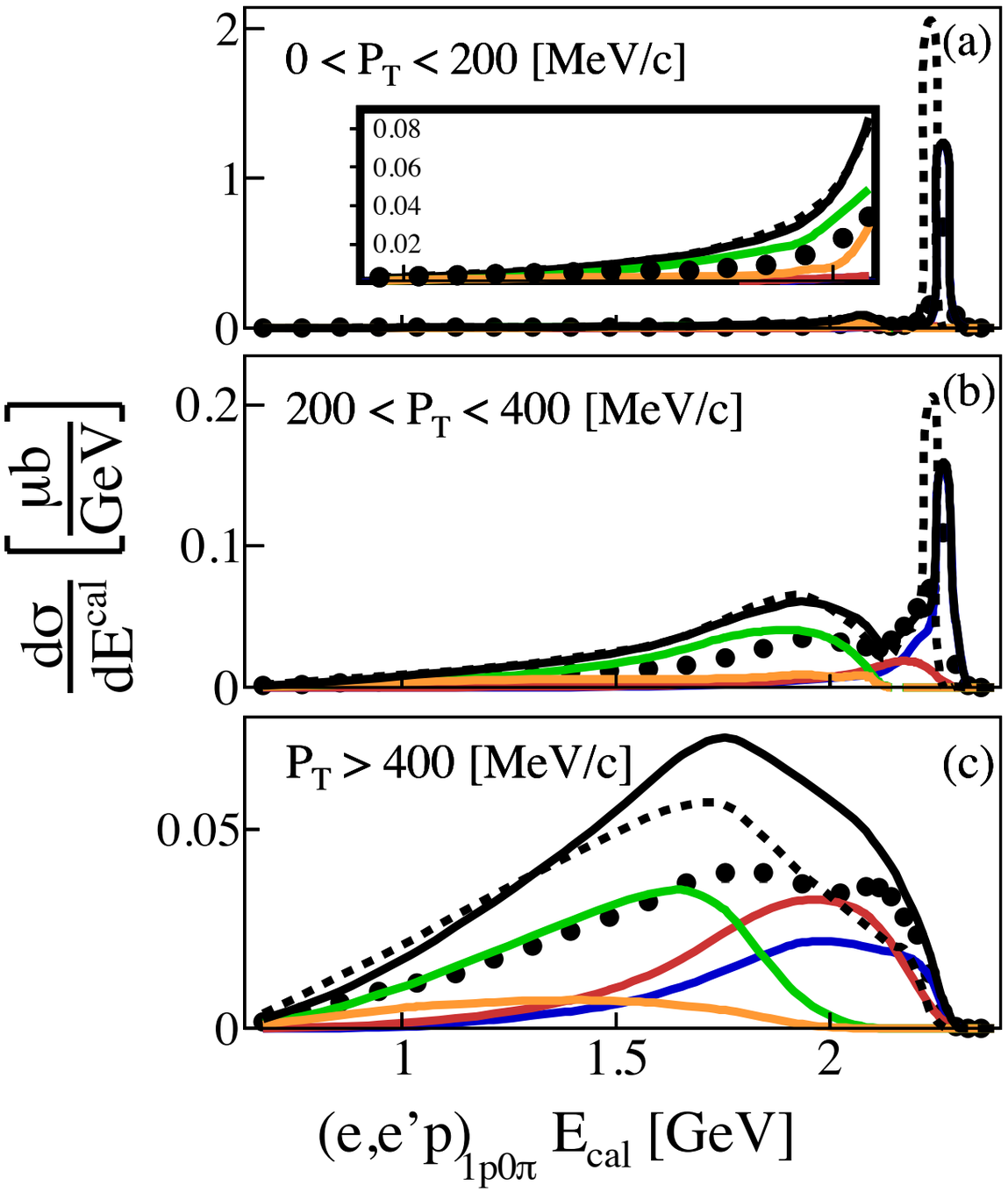
Transverse missing momentum



Nature **599**, 565 (2021)

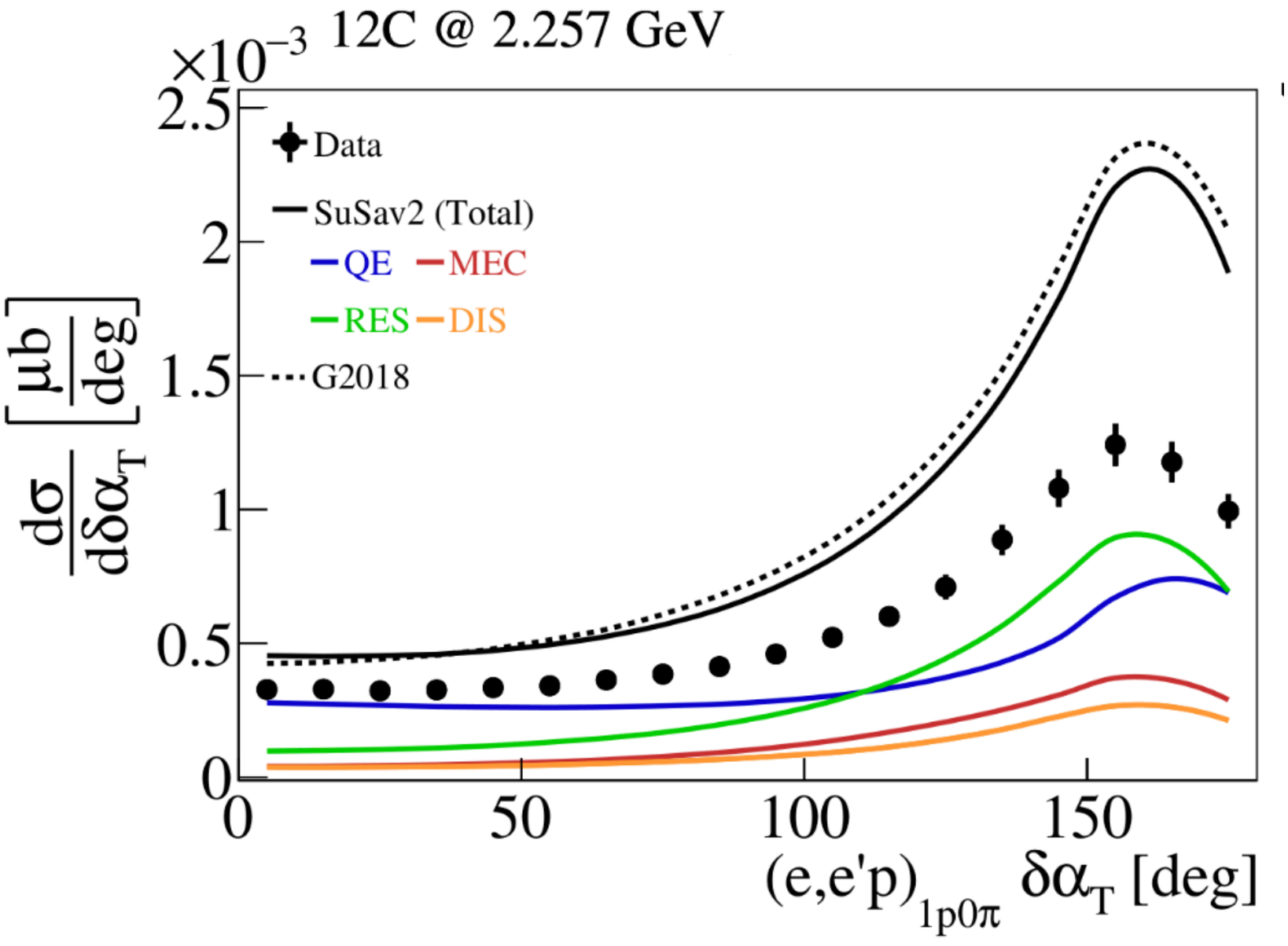
p_T sensitivity to interaction mechanisms





Nature **599**, 565 (2021)

Transverse Kinematic Variables - $\delta\alpha_T$



A. Papadopoulou et al. in preparation

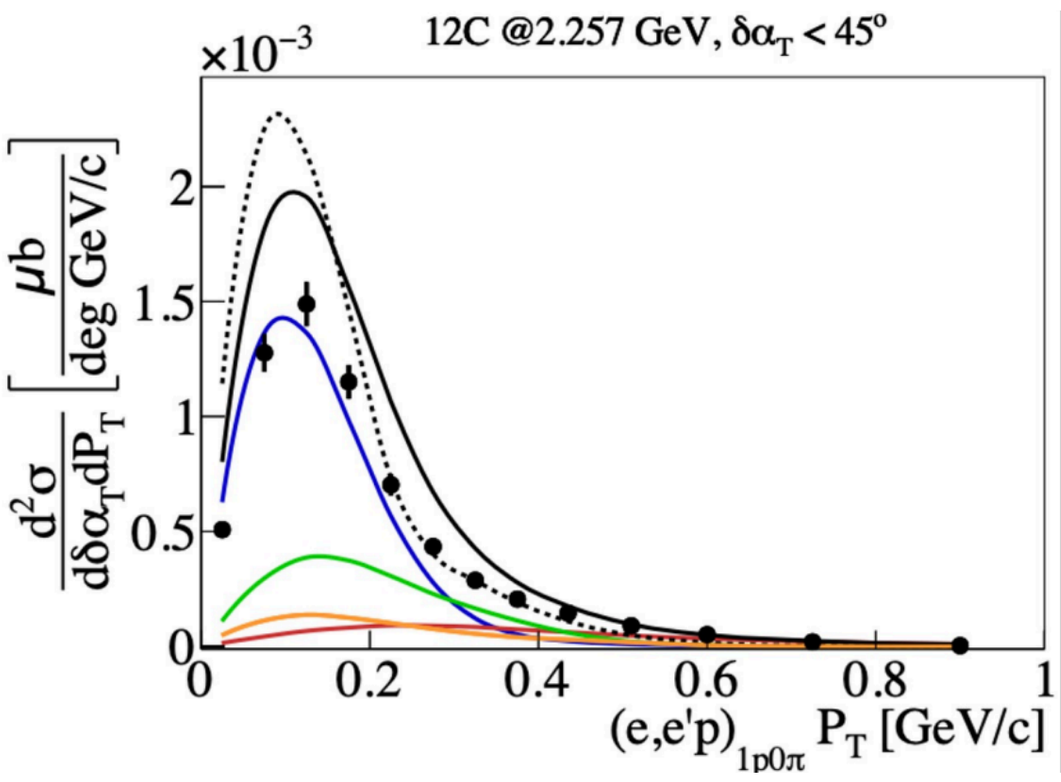
MC vs. (e,e'p) Transverse Variables

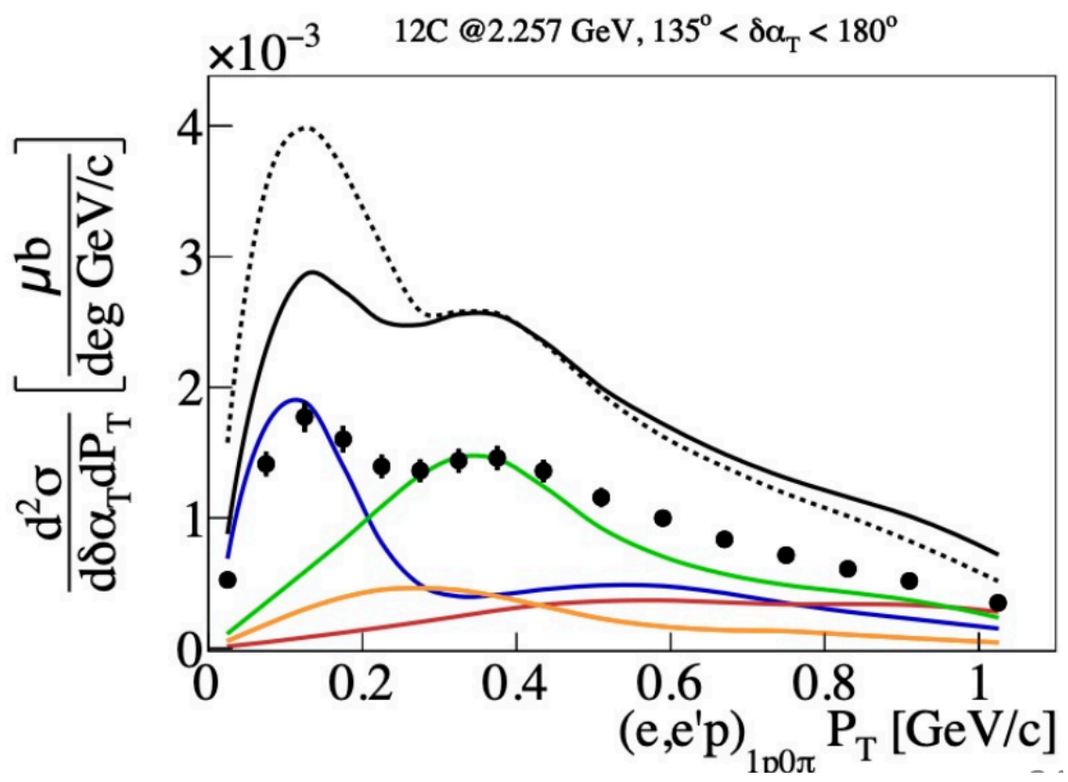
Low $\alpha T < 45$

QE enhanced region

High $135 < \alpha T < 180$

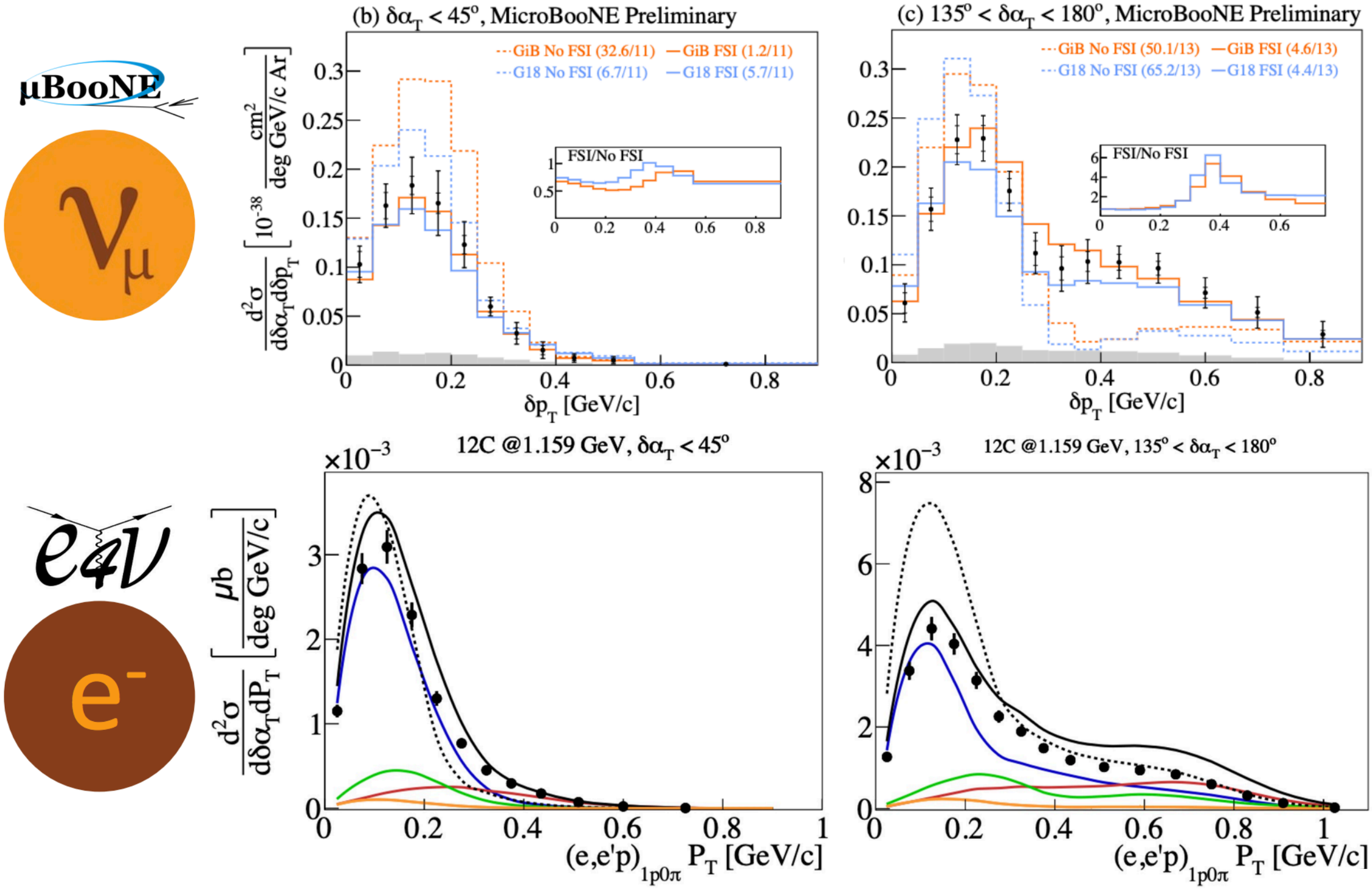
Non QE contributions





A. Papadopoulou et al. in preparation

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

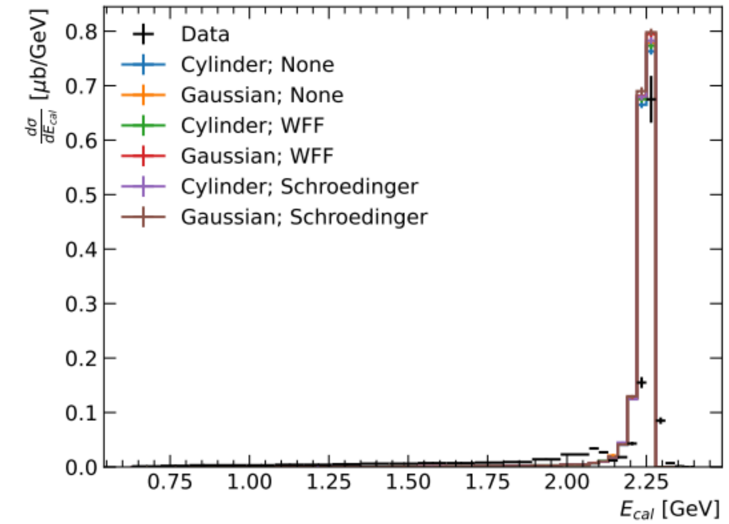


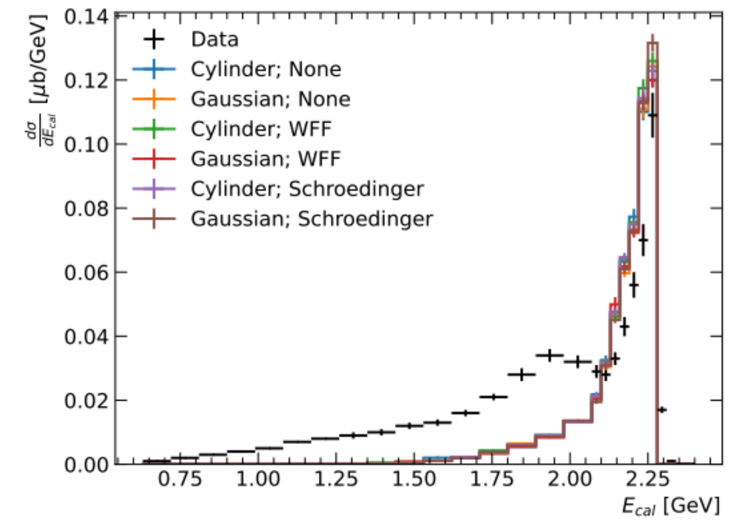
A. Papadopoulou et al. in preparation

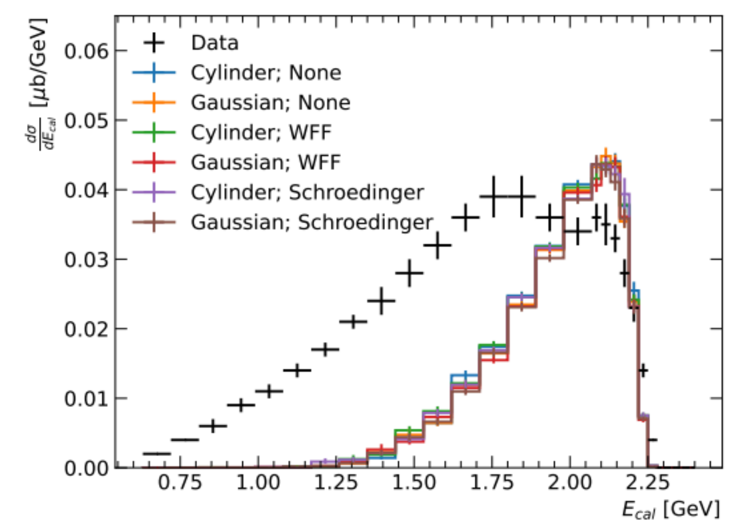
Impact on the neutrino community

Published data available
@ www.e4nu.com

Benchmarking new
models and generators







exp. ACCHILES

Isaacson, Jay, Lovato, Machado, and Rocco
arXiv: 2205.06378 (2022)

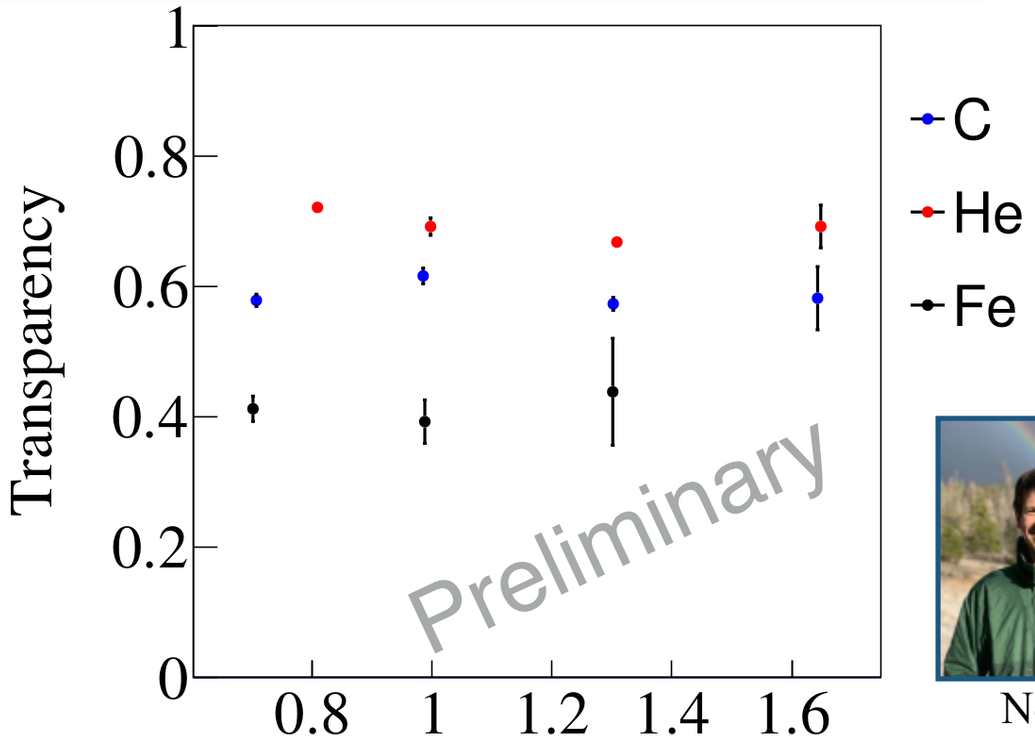
Future Plans

Working on:

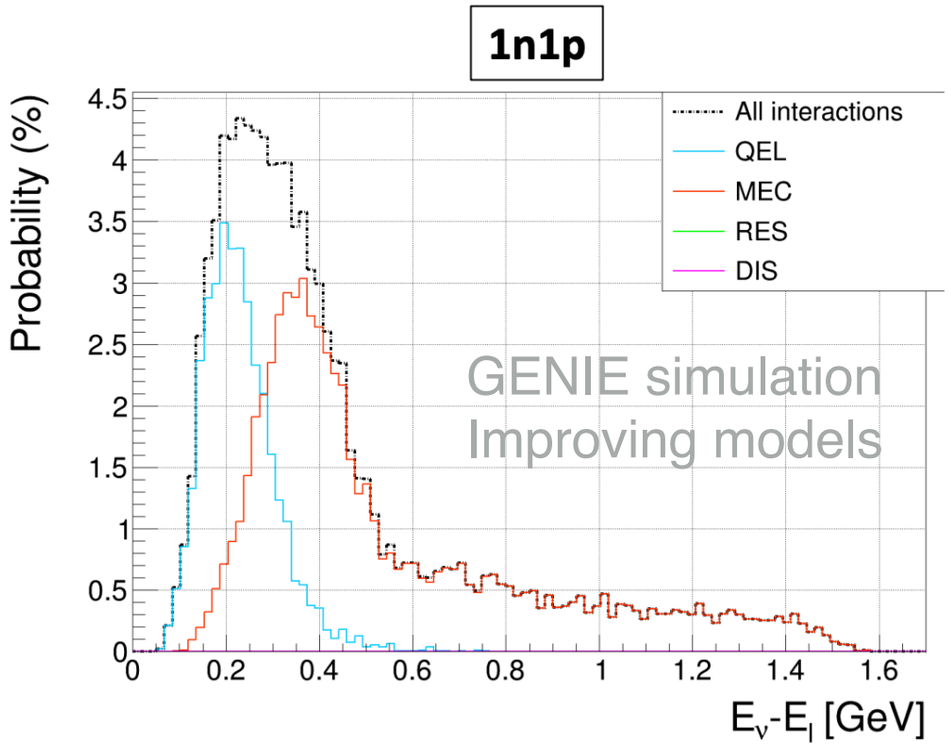
Multi differential analysis

Pion production

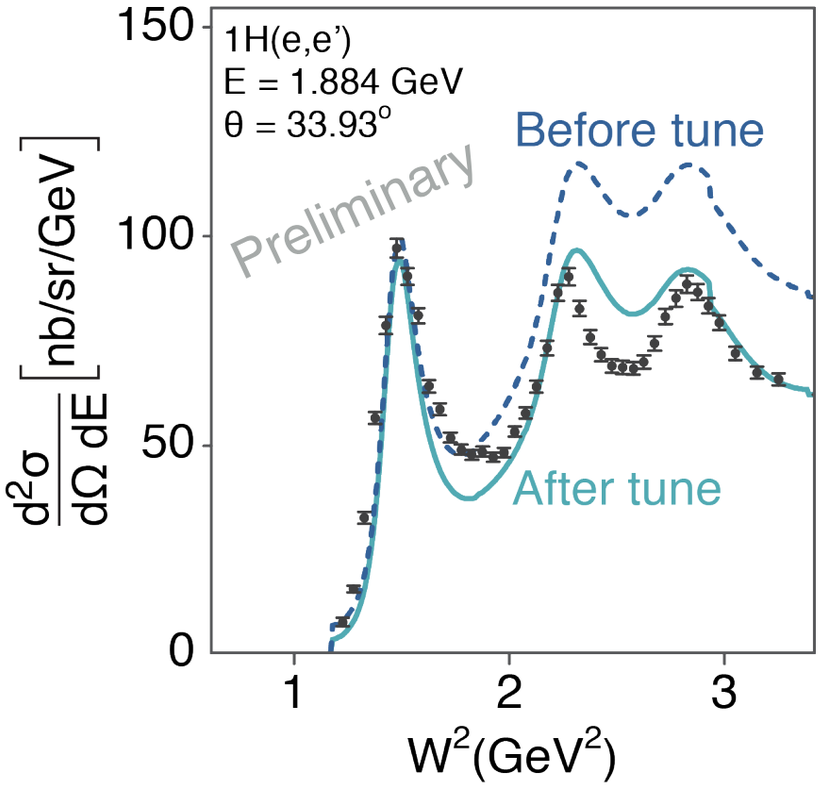
Two nucleon final state



Noah Steinberg



Alon Sportes



Julia Tena Vidal

Next step RG-M CLAS12

Better acceptance

Higher luminosity

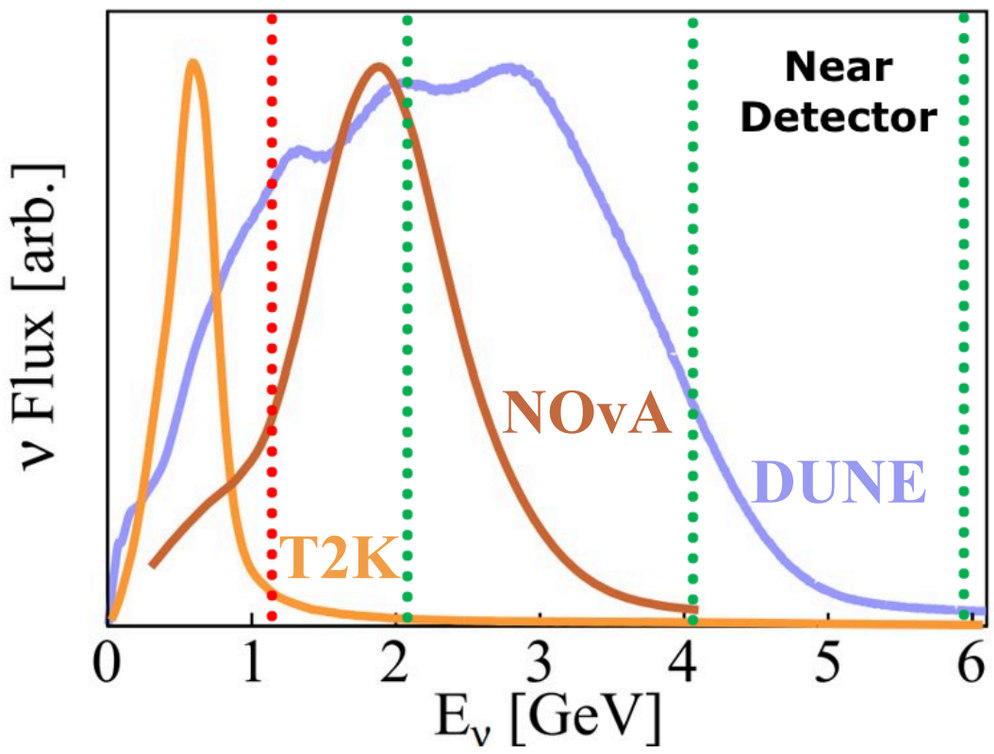
Low detection thresholds

Better neutron coverage

Targets: ^{2}D, ^{4}He, ^{12}C, ^{16}O, ^{40}Ar, ^{120}Sn

1, 2, 4, 6 GeV

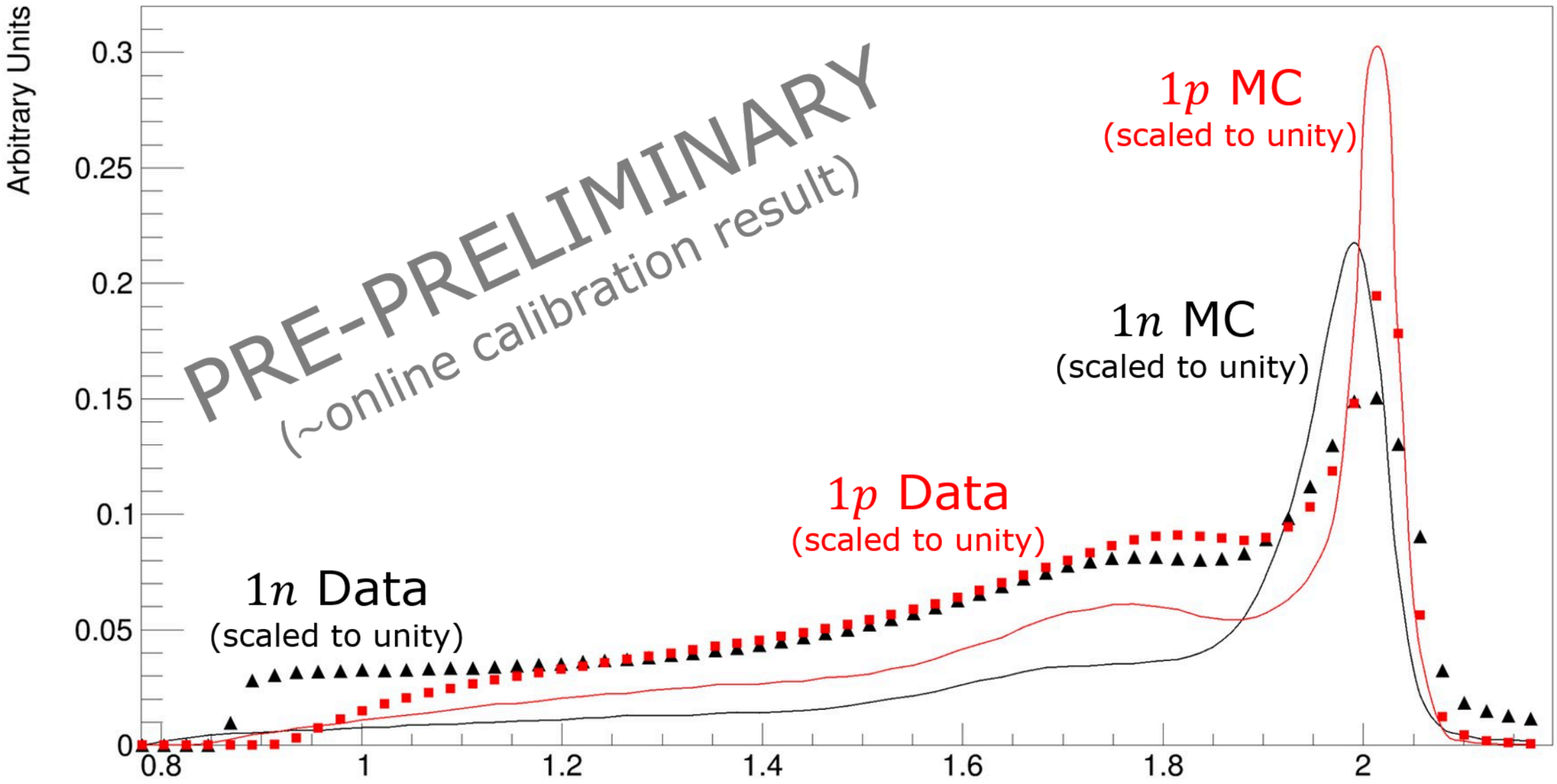
First run completed



Overwhelming support from:

DUNE, IceCube South Pole Neutrino Observatory, Hyper-Kamiokande, T2K, NOvA, MINERvA, Fermilab, GiBUU The Giessen Boltzmann-Uehling-Uhlenbeck Project, Genie, µBooNE

Next step RG-M CLAS12



$Ar(e,e'N)_{0\pi}$ E_{cal} [GeV]

Joshua Barrow

Summary

νA interaction uncertainties limit oscillation parameters extraction

First use of semi-exclusive eA data to explore νA uncertainties

- Energy reconstruction

- Comparison to event generators

Ongoing efforts using neutrinos and cosmic muon!

Data/model disagreement even for electron QE-like events

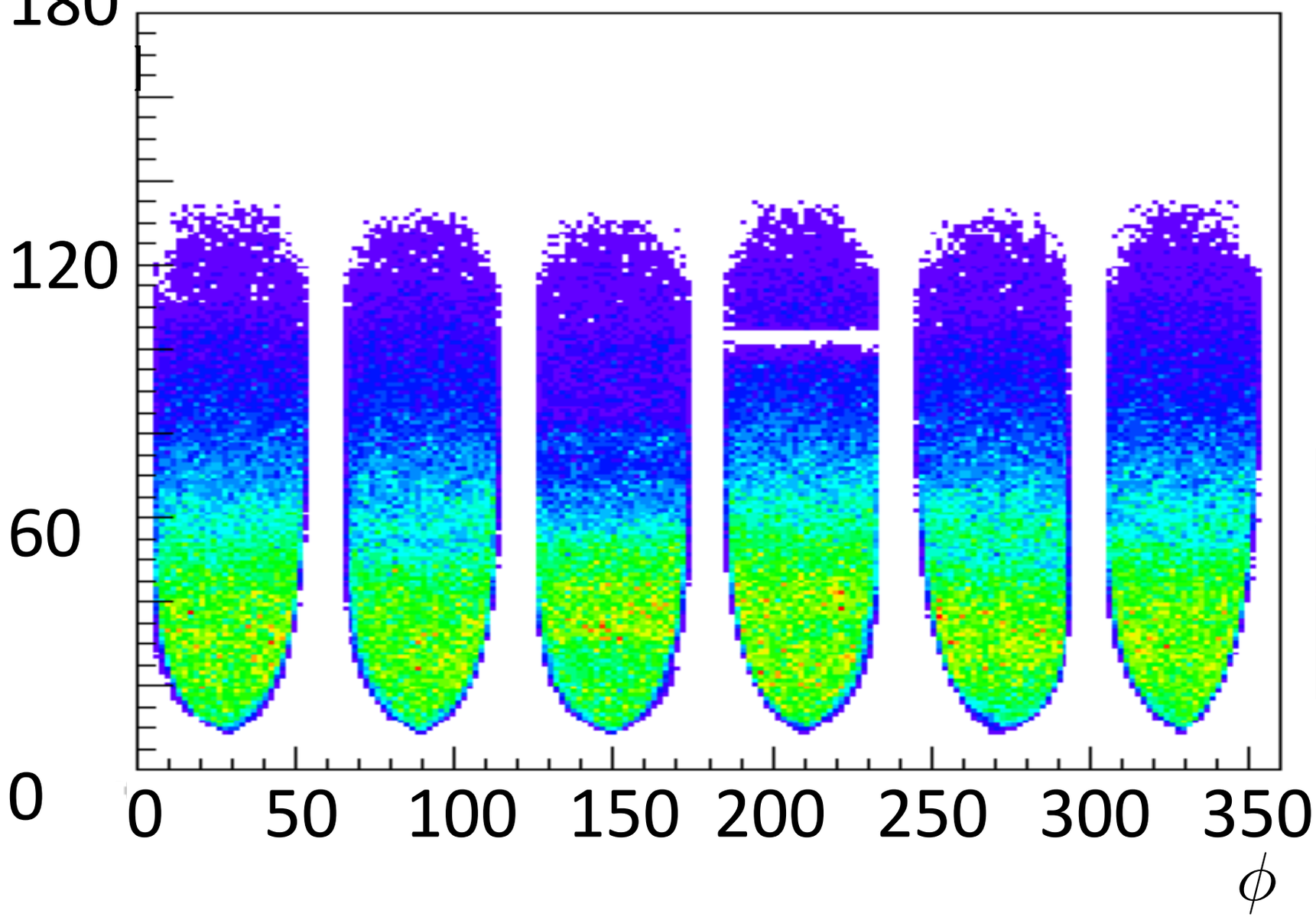
Charged and neutral leptons scattering data is on the way to constrain models

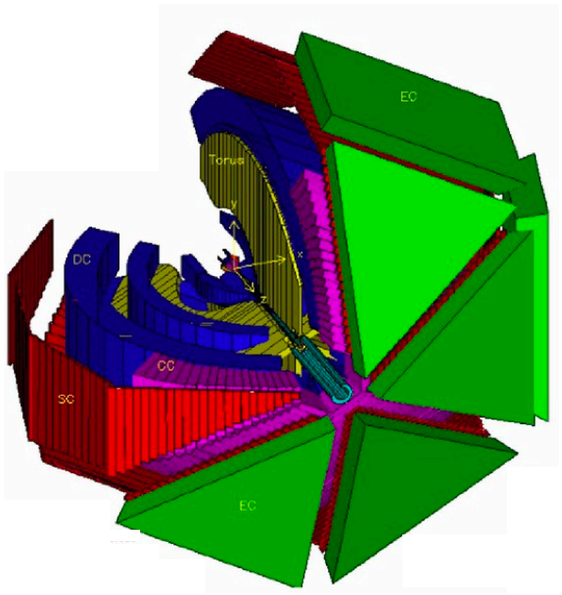
Thank you for your attention

Background Subtraction

Different interaction lead to multi-hadron final states

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





Background Subtraction

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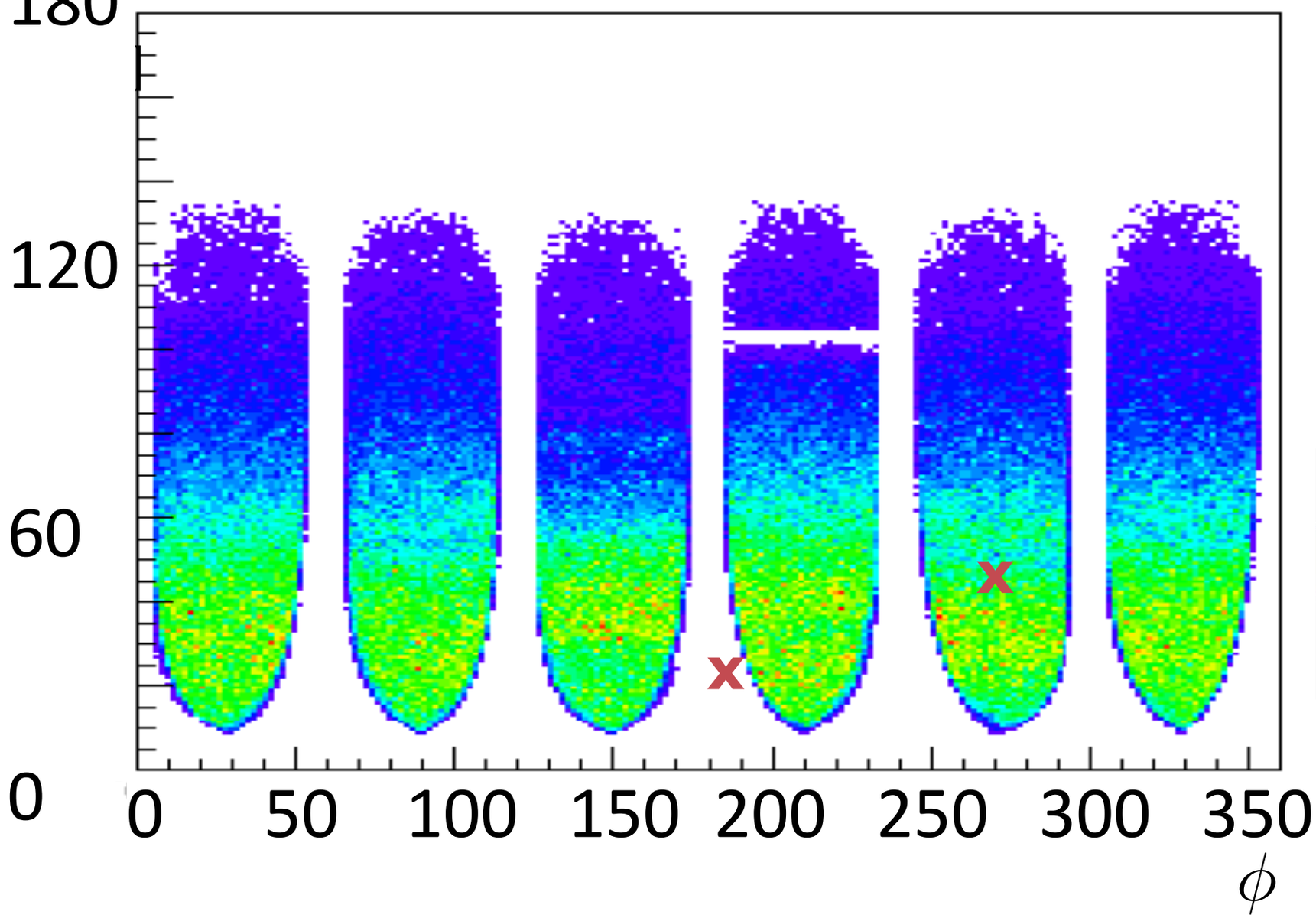
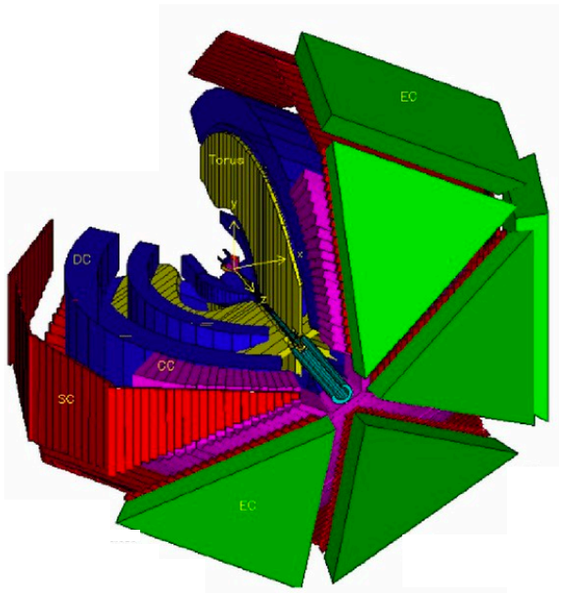
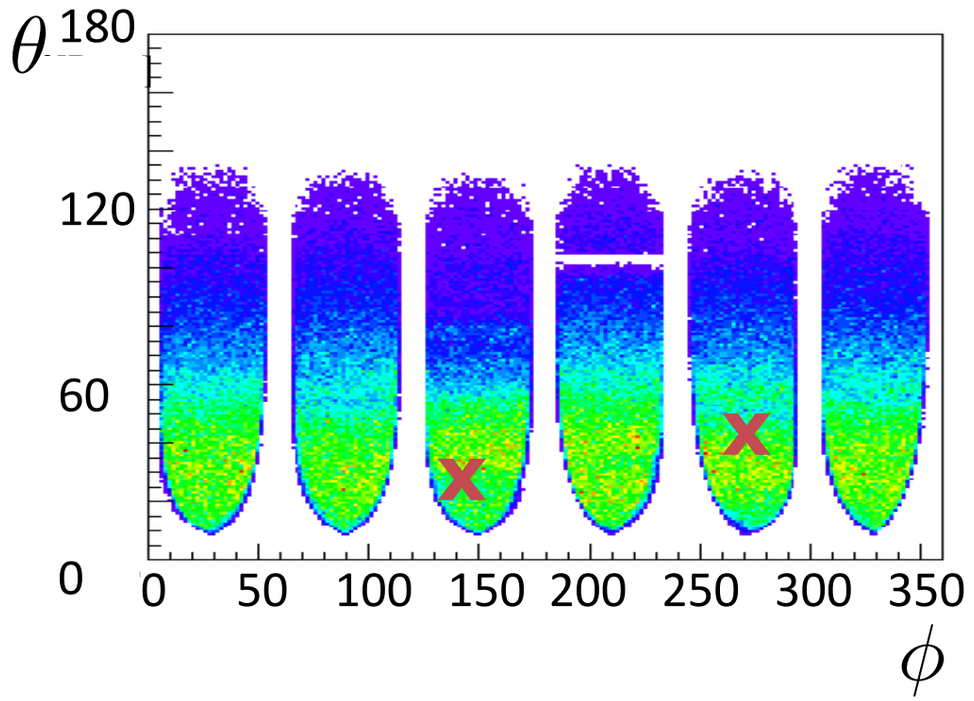


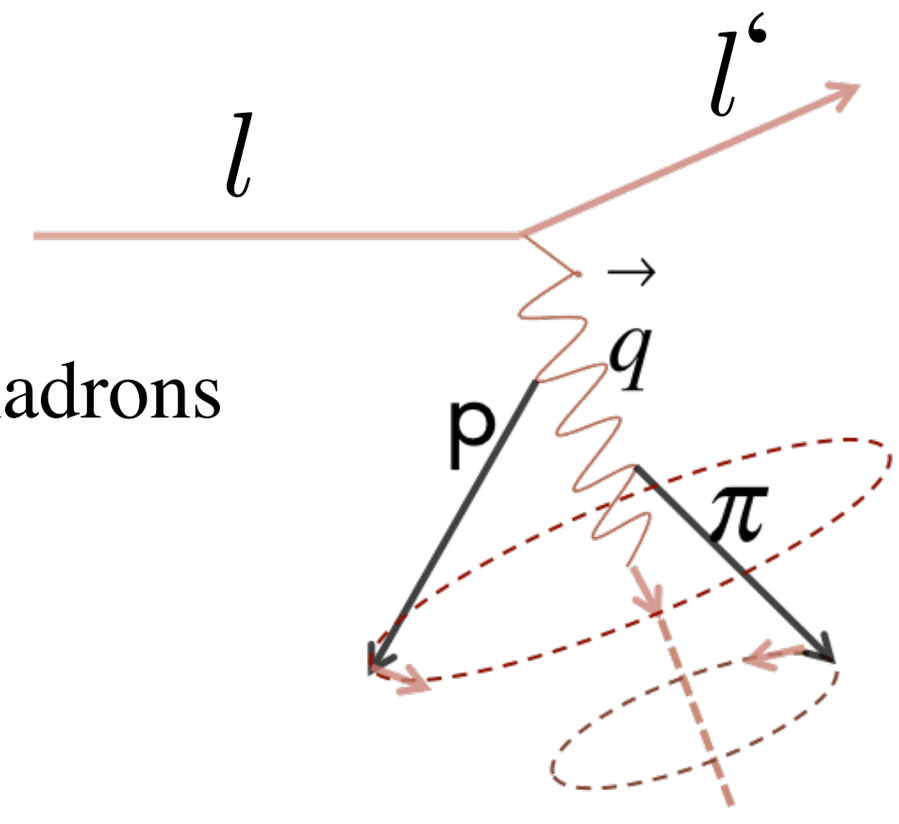


Data Driven Background Subtraction

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

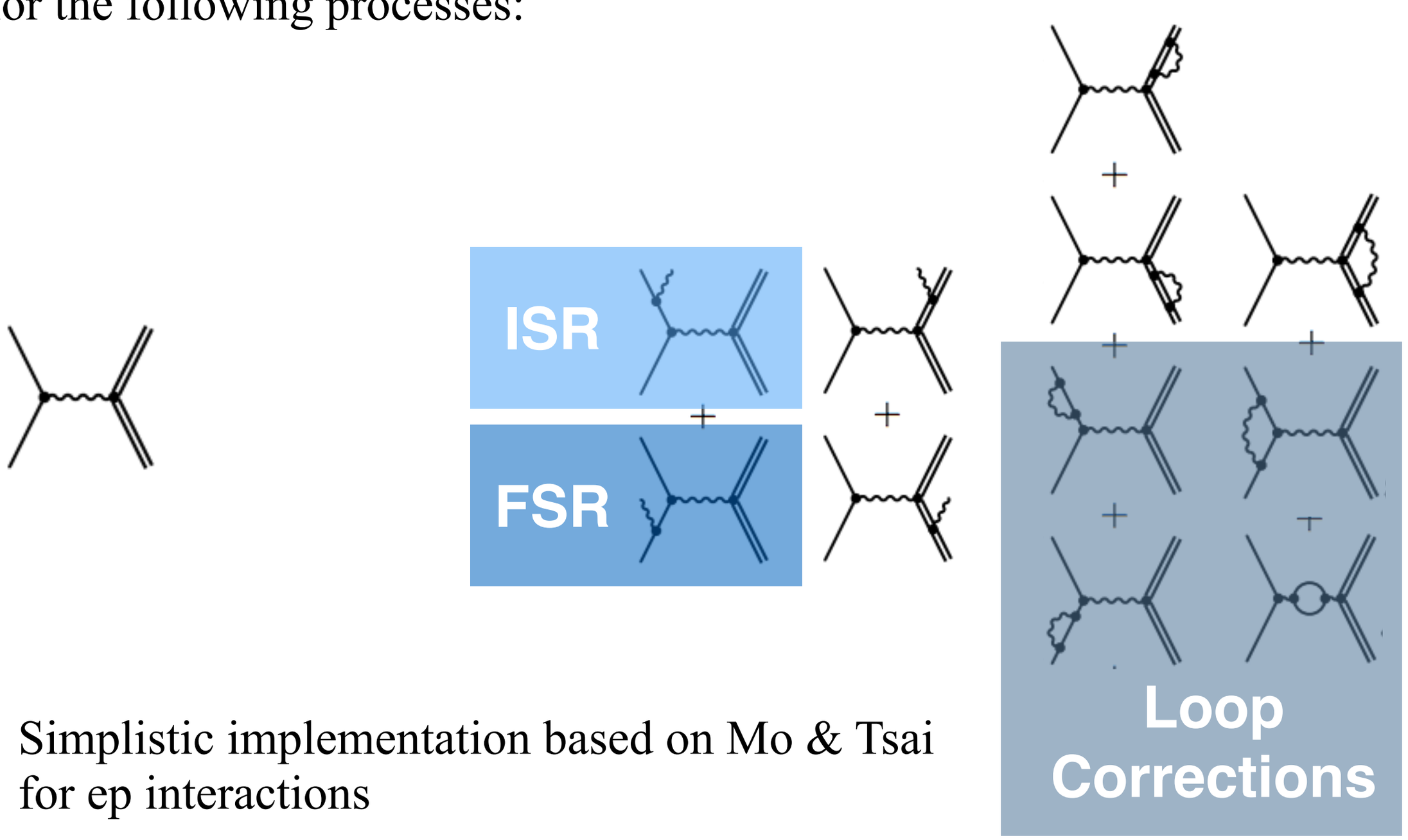


- Same for final states with more than 2 hadrons



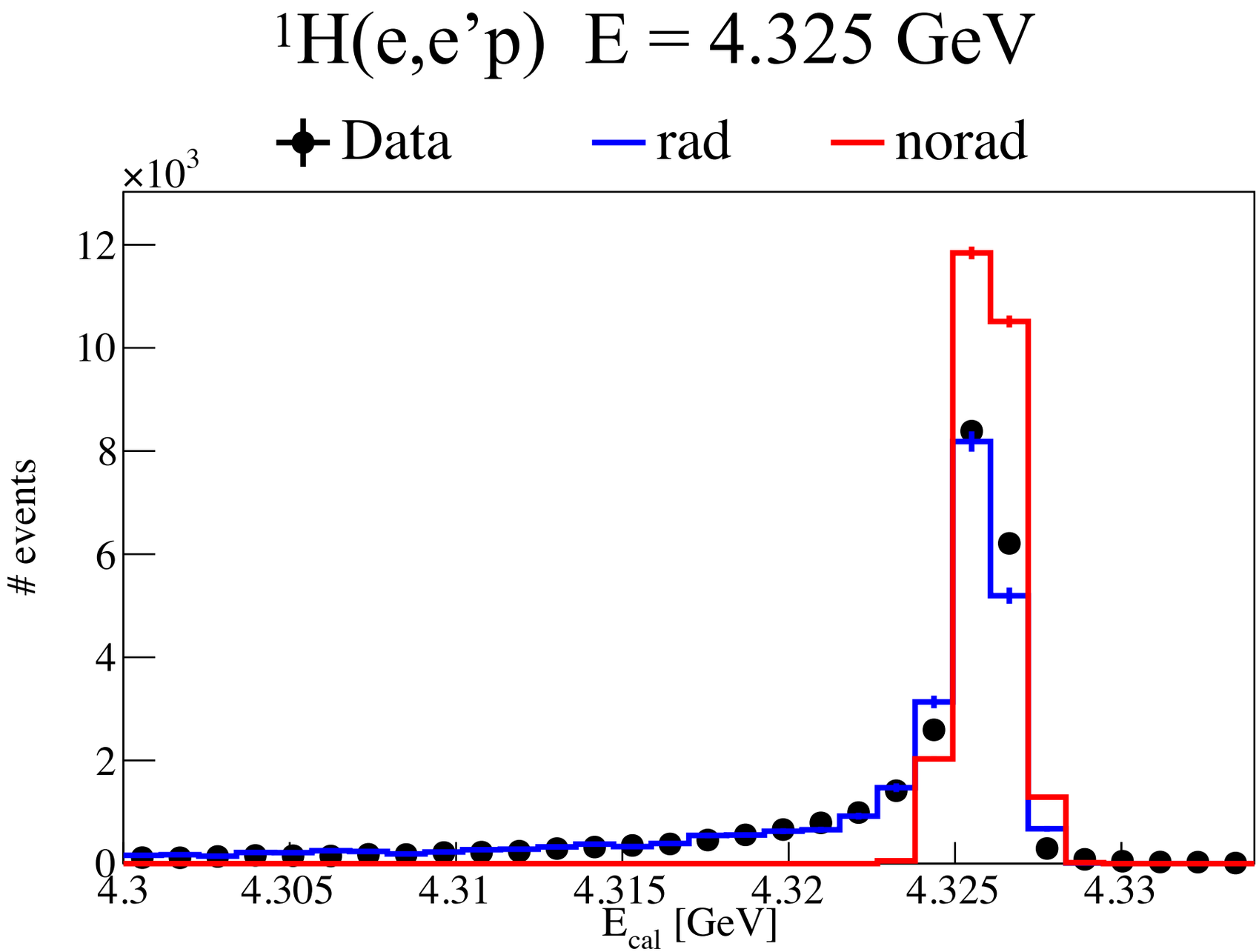
Radiative effects

A first implementation of the radiative corrections to GENIE to account for the following processes:



Simplistic implementation based on Mo & Tsai for ep interactions

Adding radiative effects to GENIE



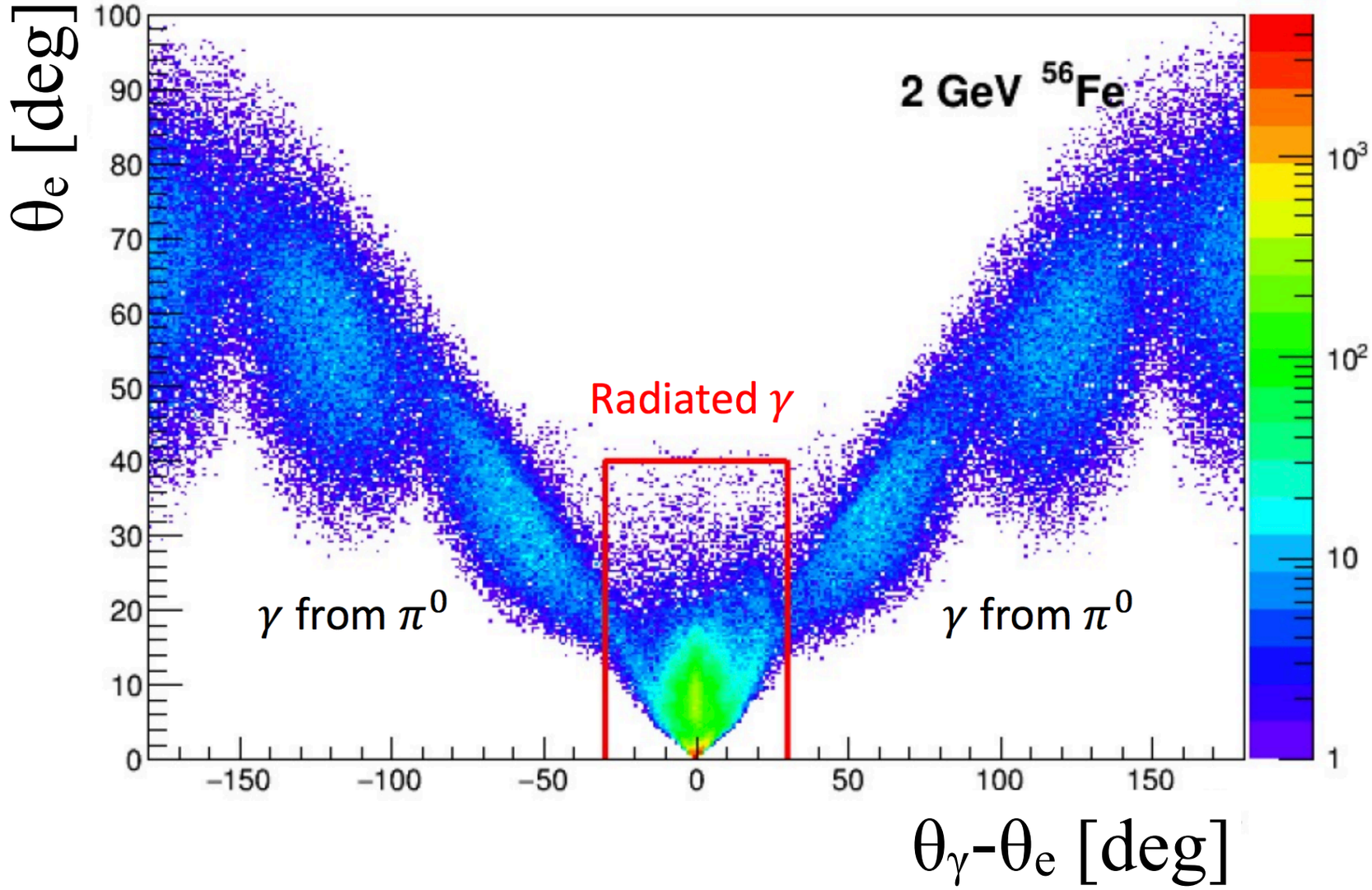
[Mo and Tsai]

Genie v3.0.6 tune GTEST19

Rejecting final state radiation events

Ignore events with:

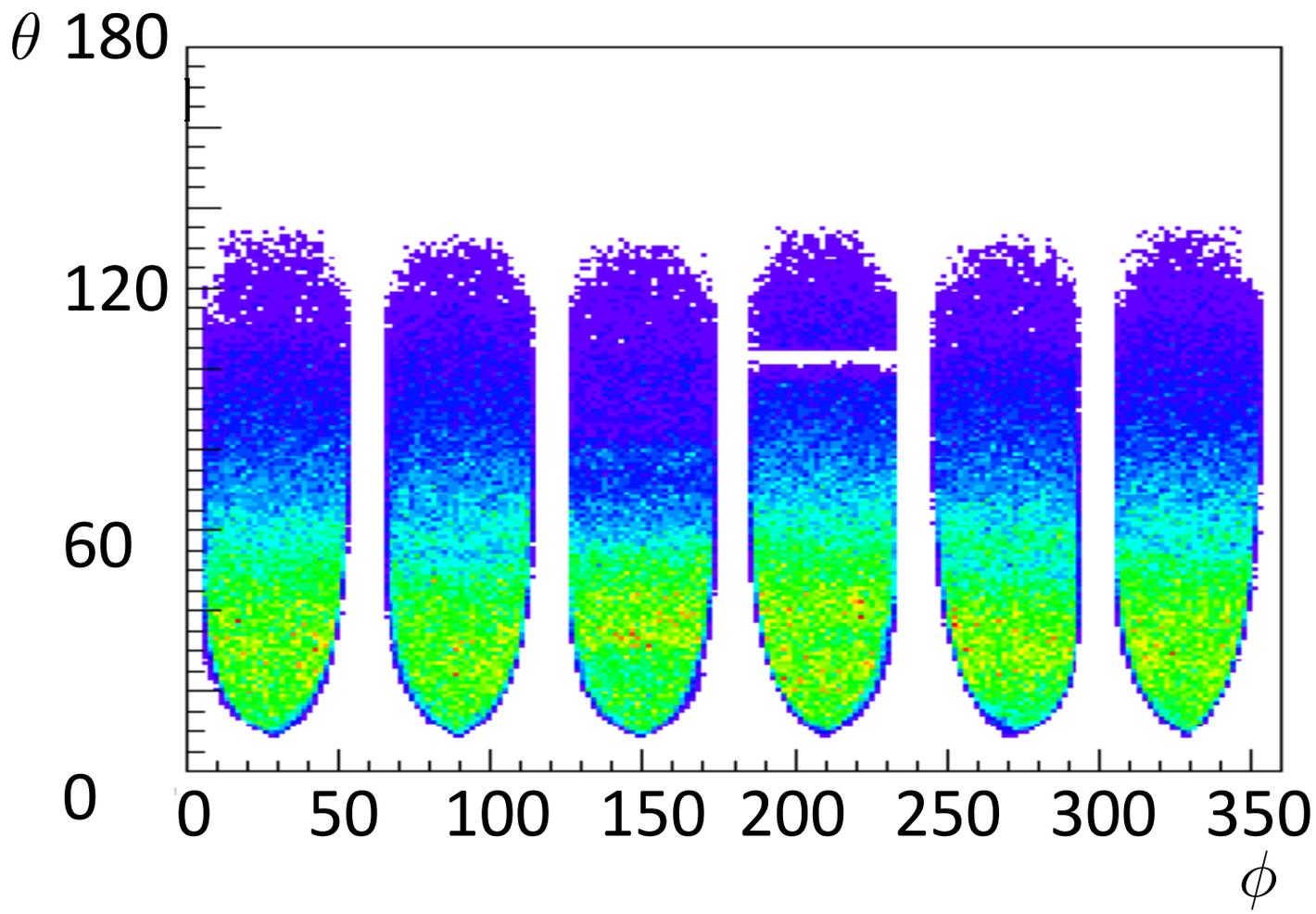
- A photon close to the final state electron
- $E_e' < 0.25\ E_e$



CLAS6: Acceptance maps available

CLAS6 has a different efficiency, which we will publish as acceptance maps for public use for each:

- Target
- Particle type
- Particle momentum



Axel Schmidt, Reynier Cruz Torres, Barak Schmookler, Adin Hrnjic

Data driven Background Subtraction

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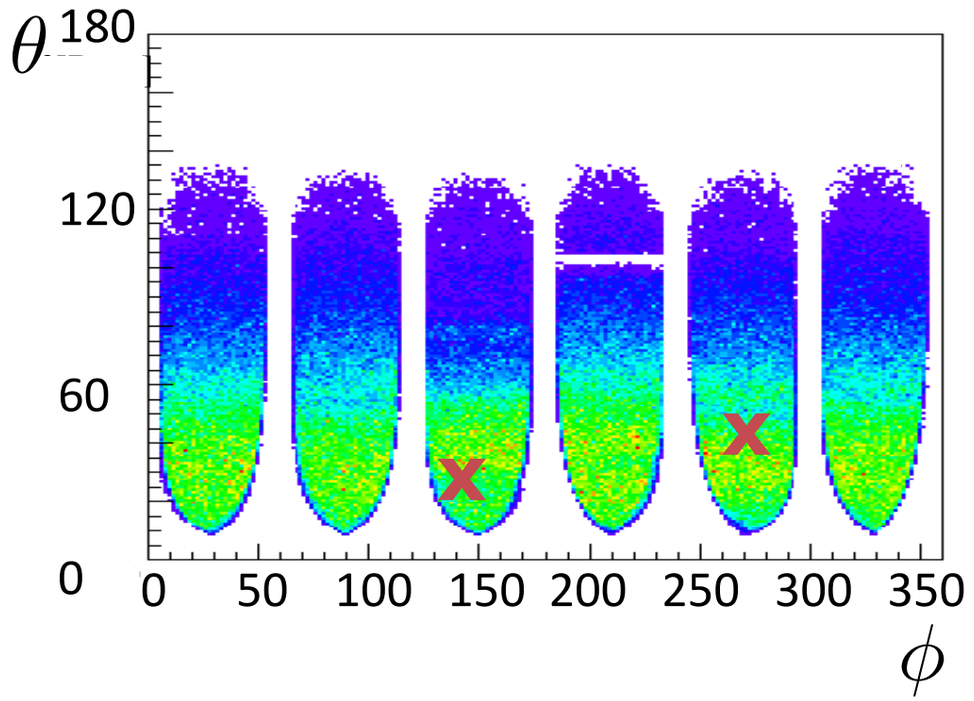
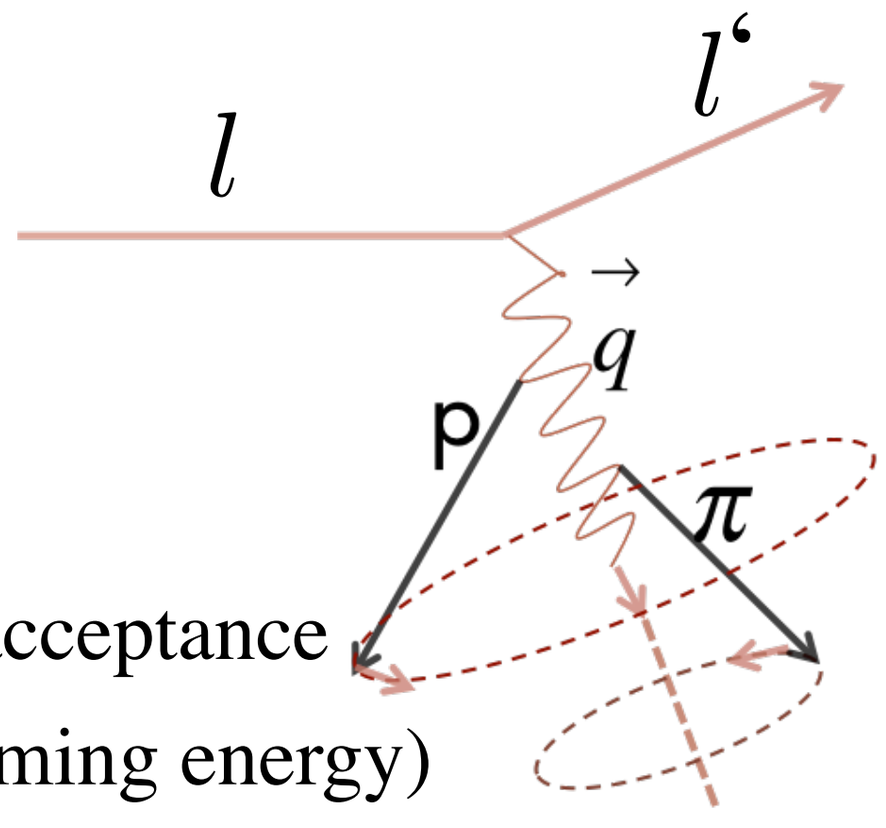
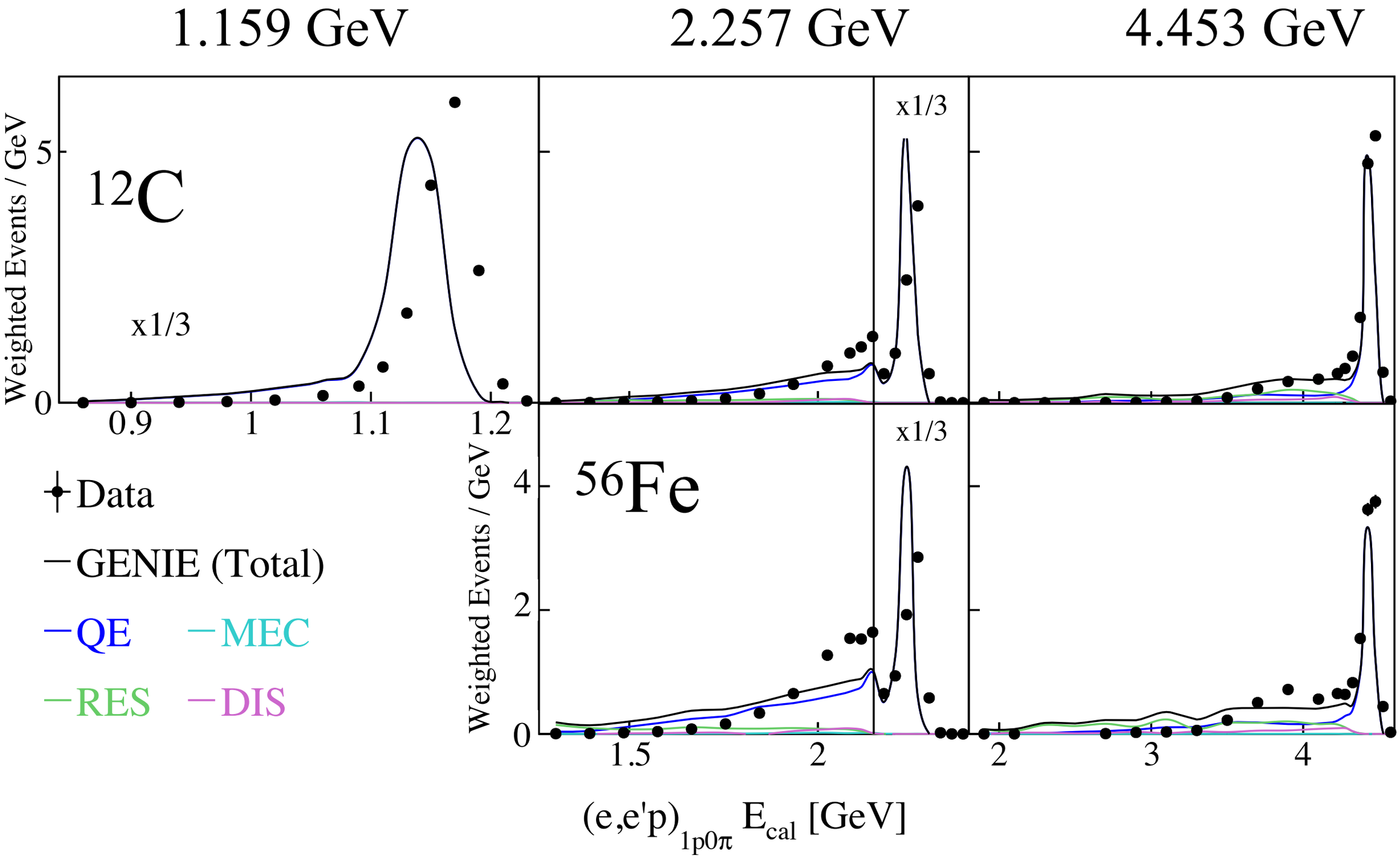


Same for final states with more than 2 hadrons

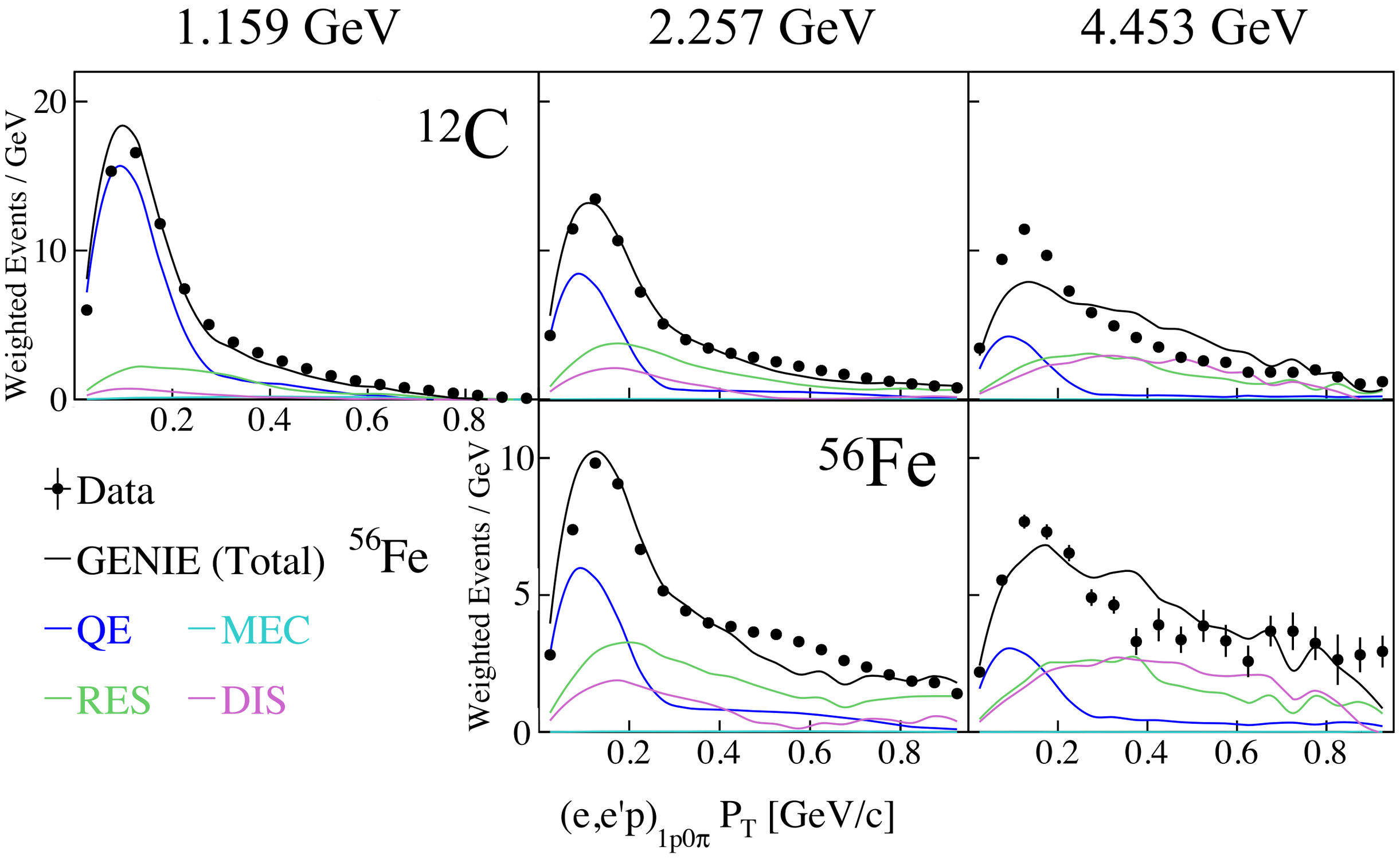


Systematics due to: $\phi_{q\pi}$ dependency, and acceptance resulting with 2%-5% (depending on incoming energy)

Ecal around the QE peak $0.8<X_B<1.2$



Ecal around the QE peak $0.8<X_B<1.2$



Systematic Uncertainties - Data side

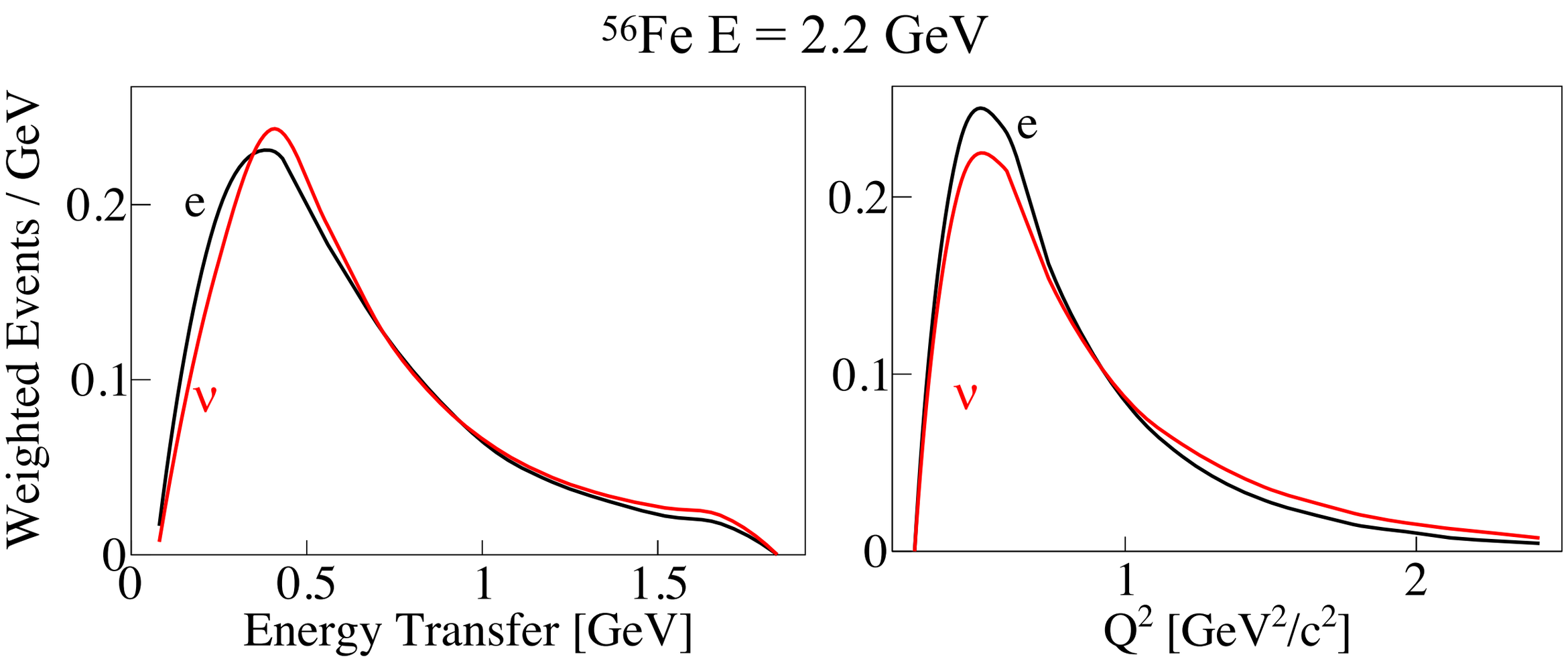
1. Background subtraction:
    1. Assuming no $\phi_{q\pi}$ dependency when rotation hadrons system around q vector. H(e, e'pπ) cross sections measured dependency affected the subtracted spectra by about 1%.
    2. Varying the CLAS ϕ acceptance in each sector reduced by10–20%. This changed the resulting subtracted spectra by about 1% at 1.159 and 2.257 GeV and by 4% at 4.453 GeV.
2. Varying the photon identification cuts using its velocity greater than two standard deviations (3σ at 1.159 GeV) below v = c, by $\pm$0.25σ. This gave an uncertainty in the resulting subtracted spectra of 0.1%, 0.5% and 2% at 1.159, 2.257 and 4.453 GeV.

Systematic Uncertainties - Data side

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

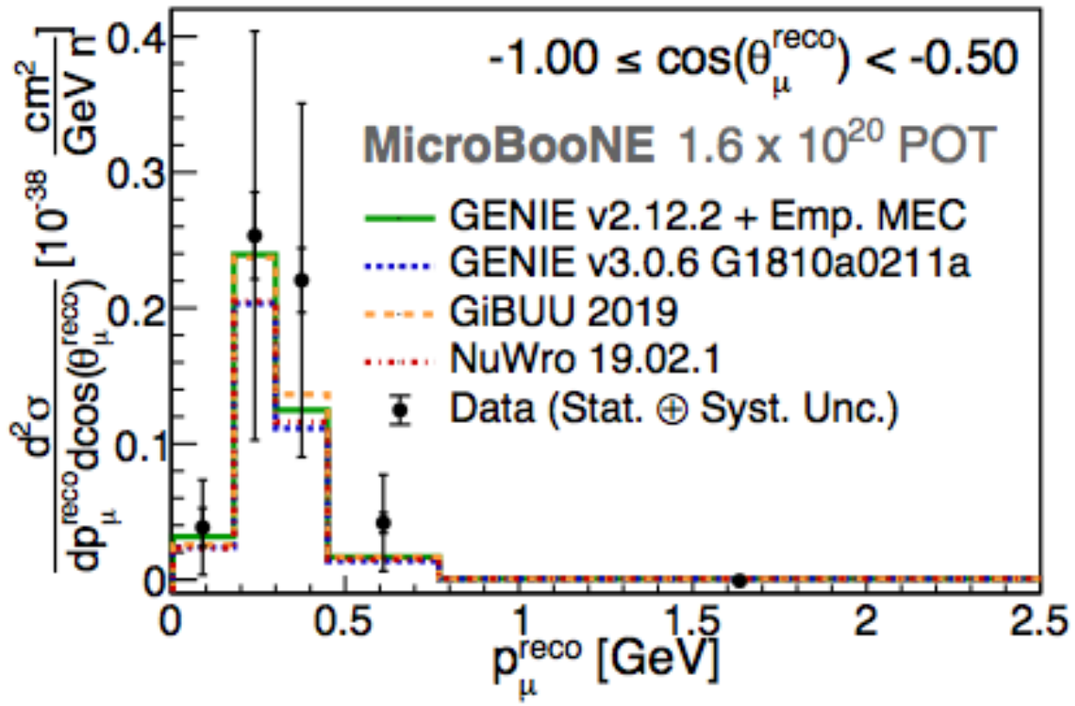
Similar eA and νA Cross sections

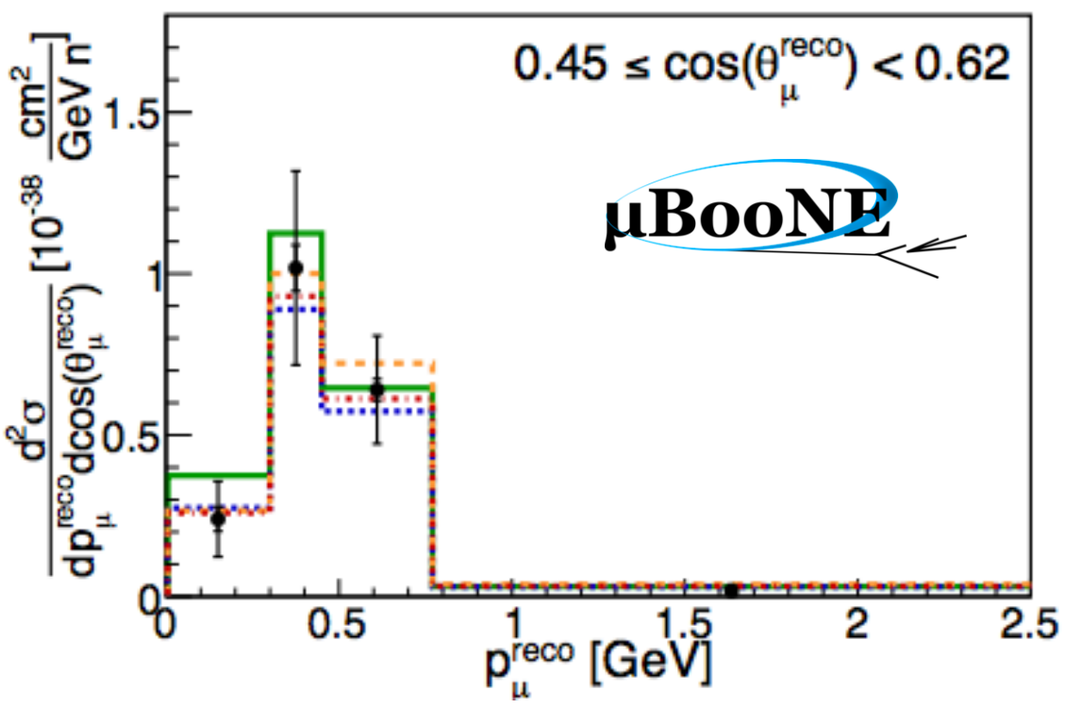
Test on 1p0π event selection



Genie v3.0.6 tune G18_10a_02_11a Electron were weighted by $1/Q^4$

Inclusive ν data and Generators

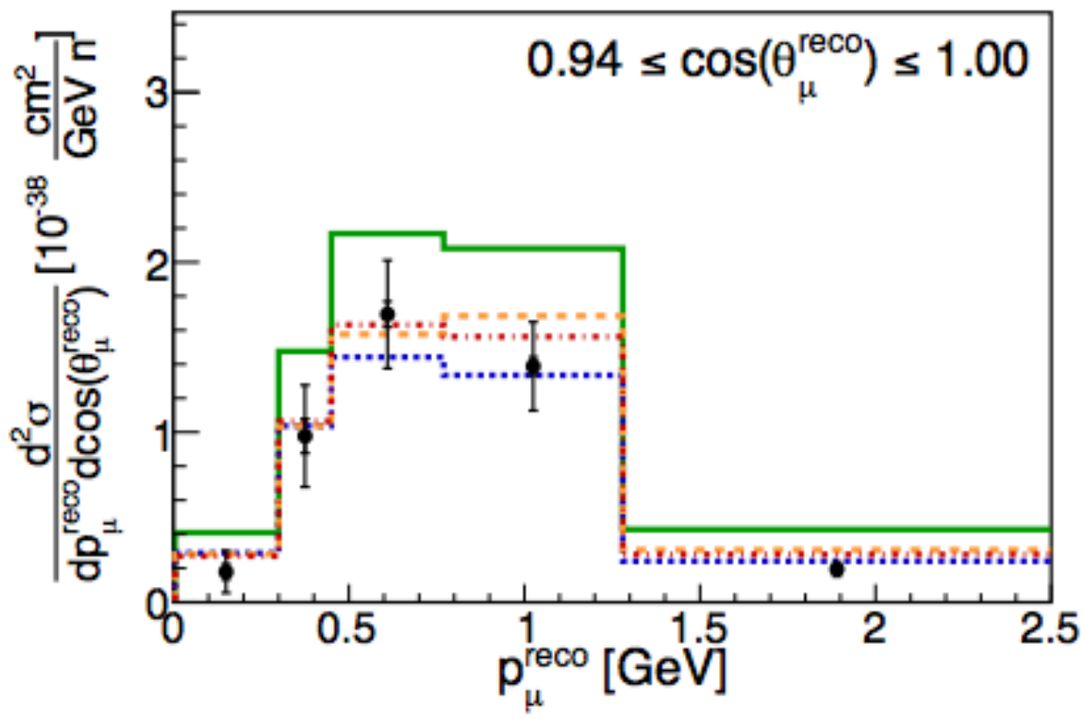




Genie

.... v3.0.6 tune G18_10a_02_11a

Phys. Rev. Lett. 123, 131801 (2019)

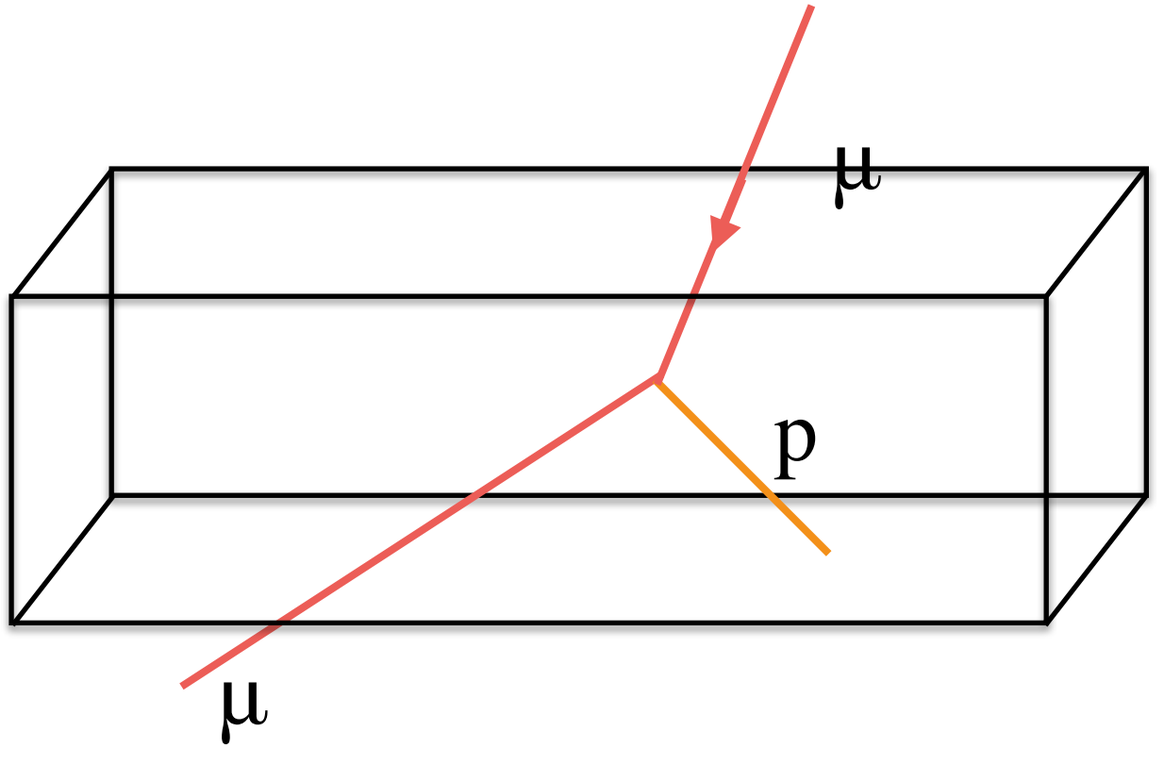



μ4ν

A(e,e'p) Event Selection

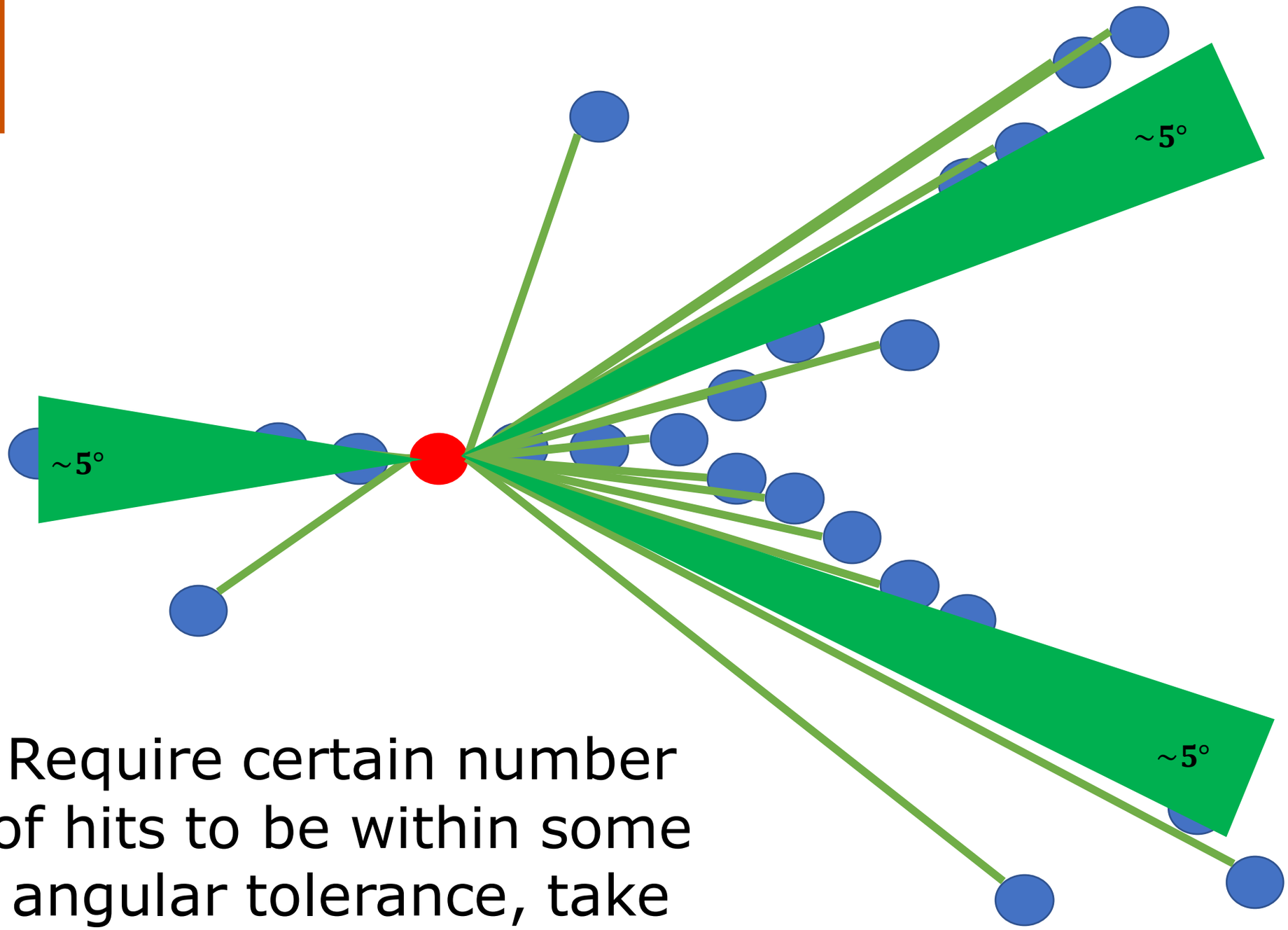
Repeat the e4nu analysis with cosmic muons inside MicroBooNE

Joshua
Barrow



Triggering scheme

Joshua
Barrow

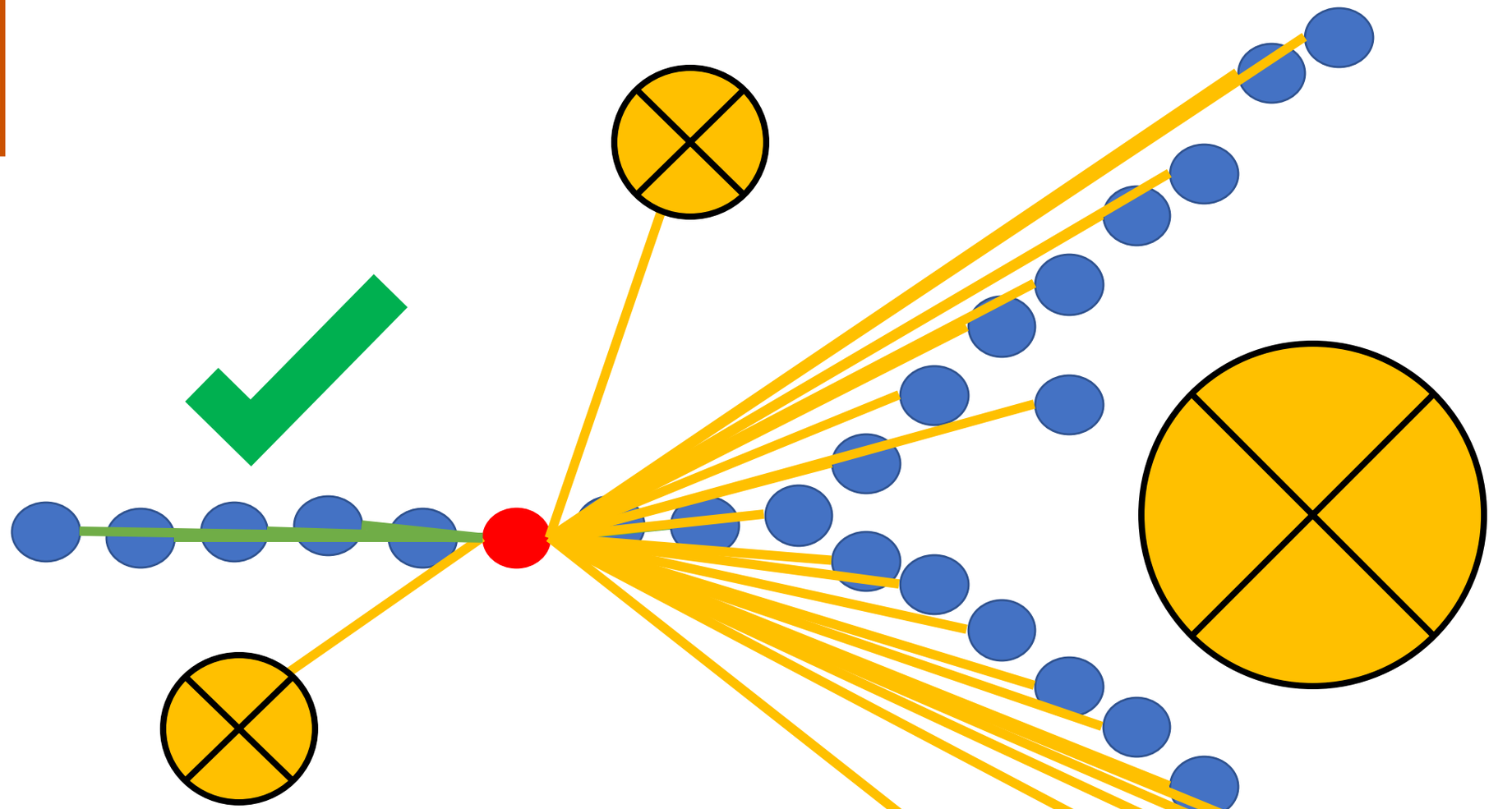


Require certain number of hits to be within some angular tolerance, take an average

Joshua Barrow

Triggering scheme

Joshua
Barrow

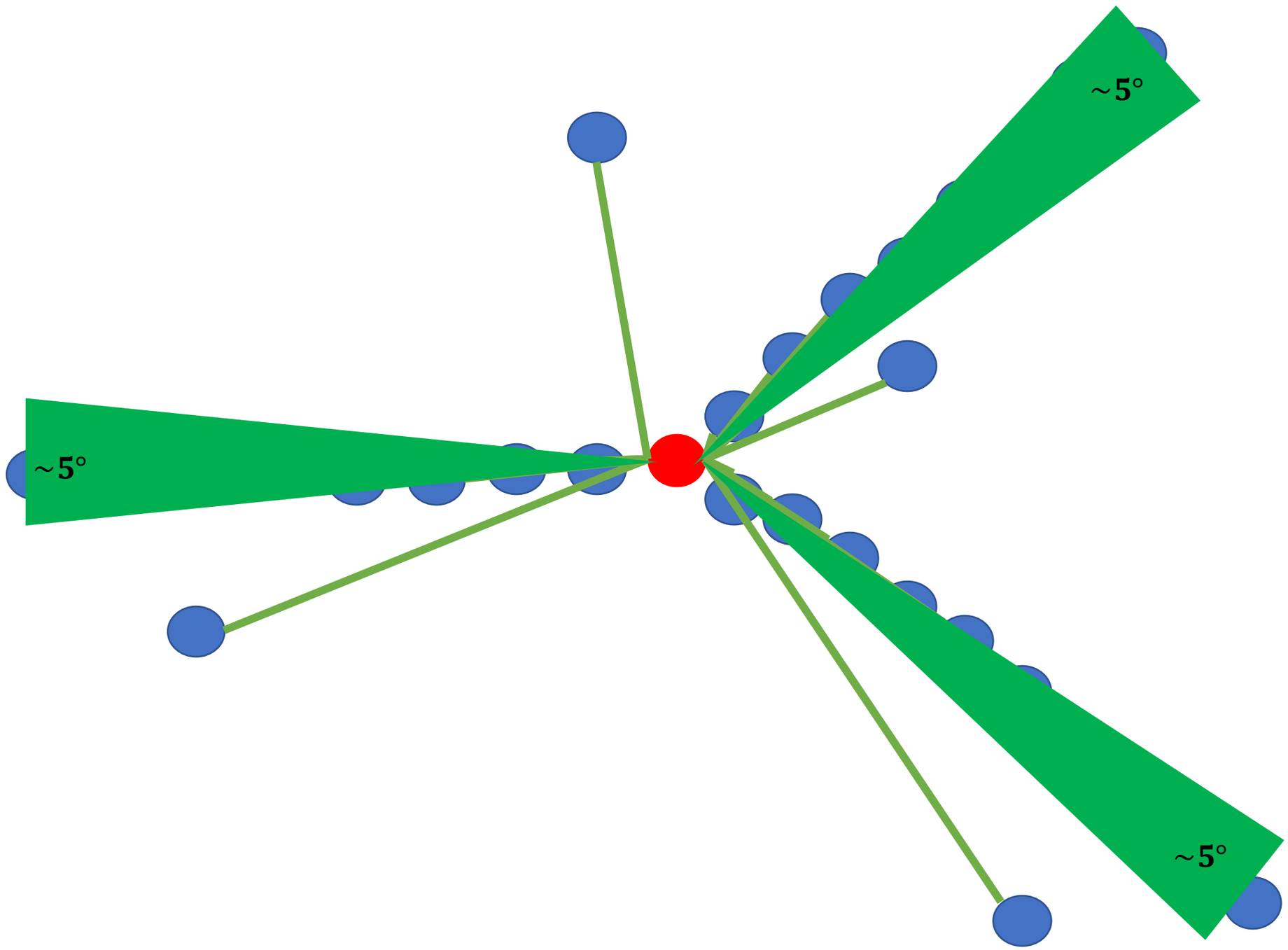


Most will have large enough angular differences to be outside angular tolerance

Joshua Barrow

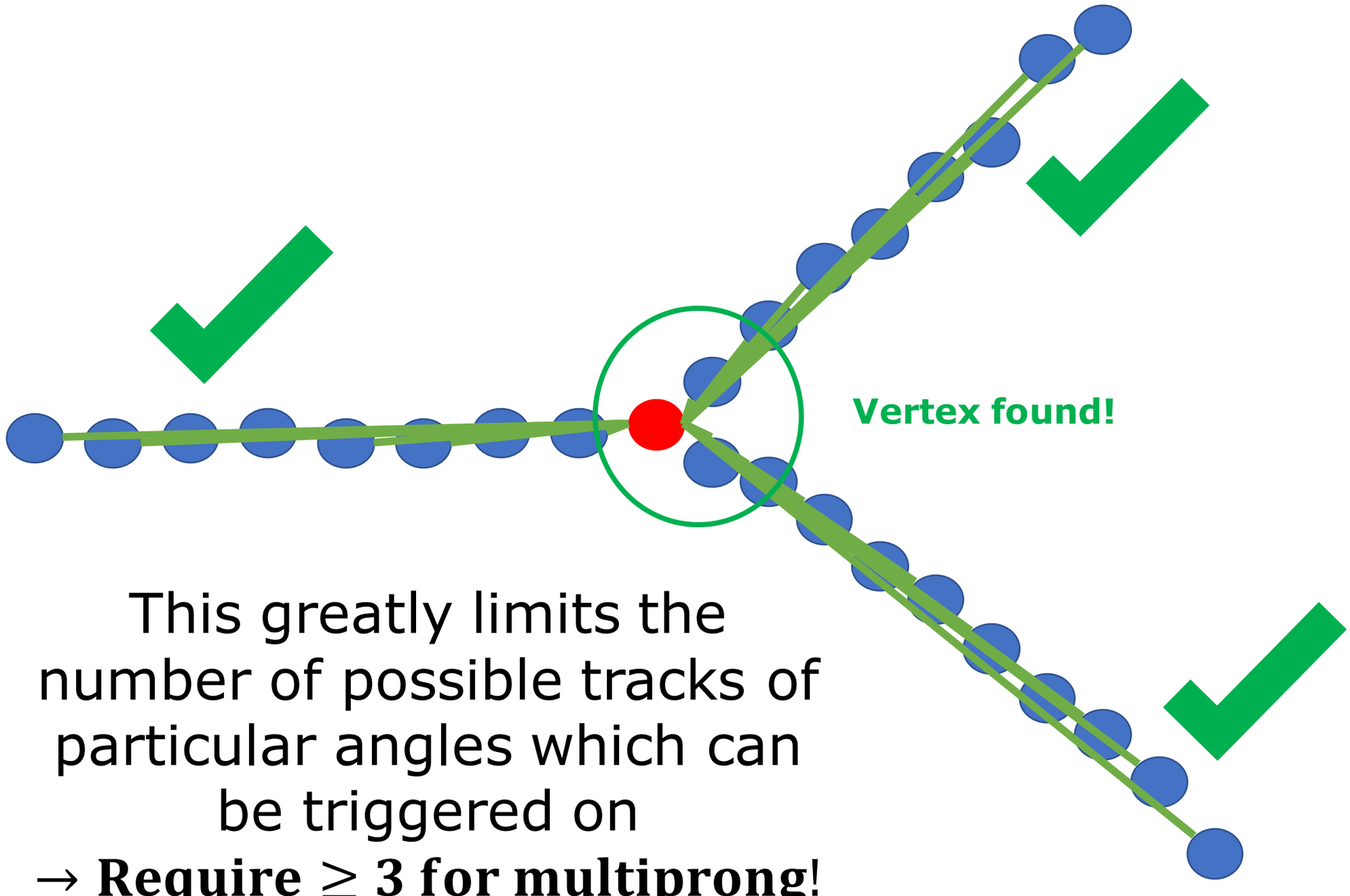
Triggering scheme

Joshua
Barrow



Triggering scheme

Joshua
Barrow



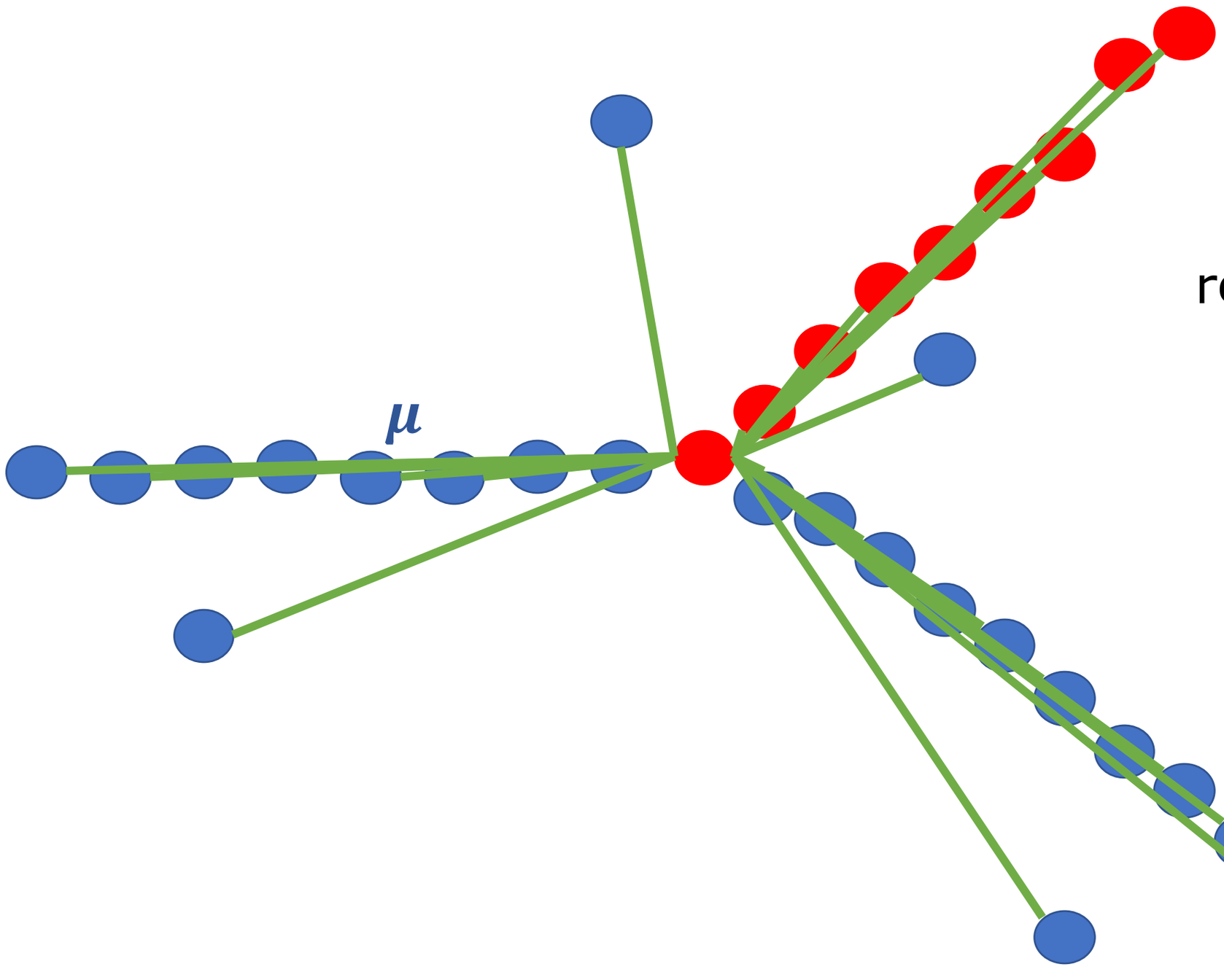
This greatly limits the number of possible tracks of particular angles which can be triggered on

→ **Require ≥ 3 for multiprong**!

Joshua Barrow

Triggering scheme

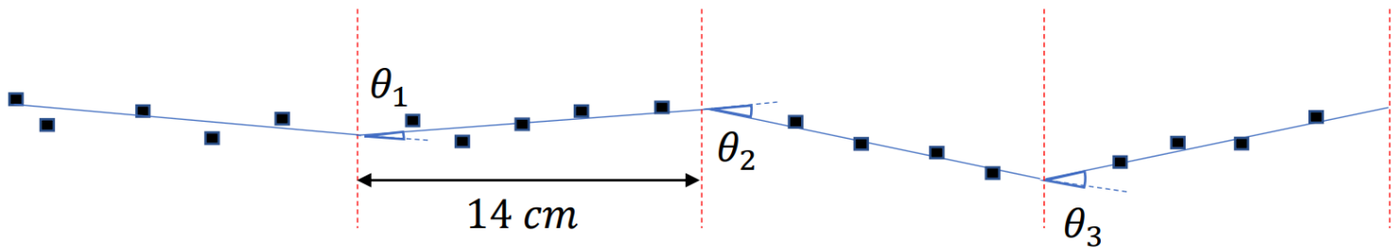
Joshua Barrow



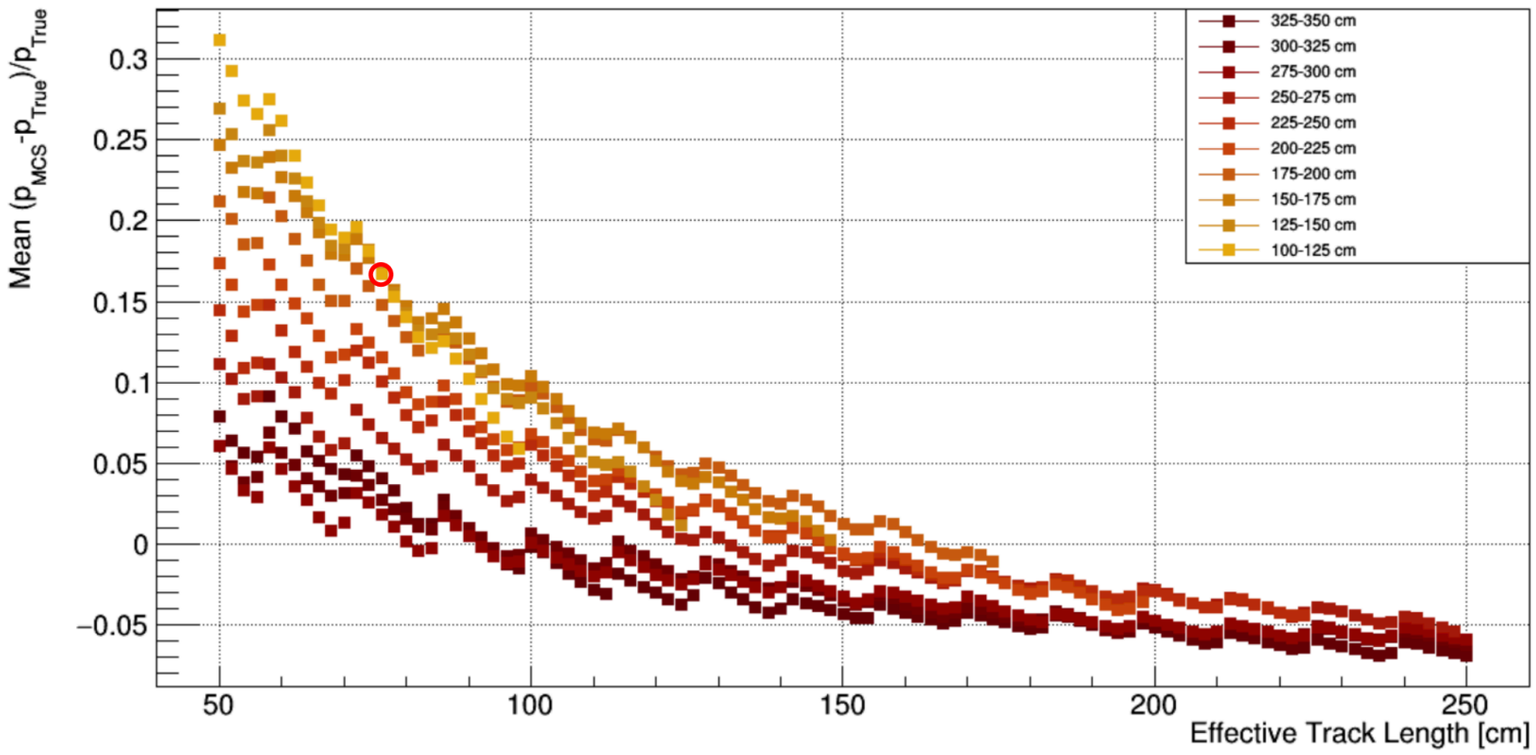
Including **high ADC** requirements makes this selection more pure

Improving momentum reconstruction

Exiting / entering tracks momentum can be reconstructed using multiple colours scattering



Amir Gruber



Amir Gruber