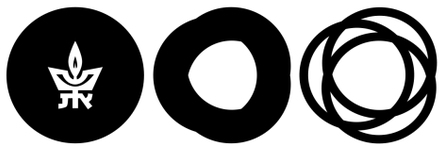
Electrons for Neutrinos

NuSTEC CEWG

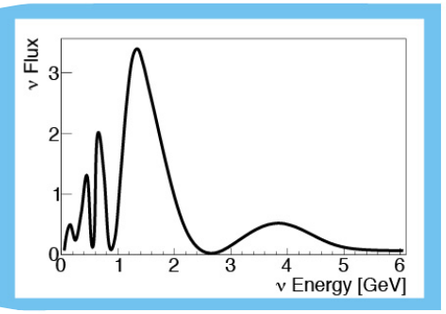
3/3/22

Adi Ashkenazi
adishka@tauex.tau.ac.il



PHYSICS PROCESS

Neutrino comes in

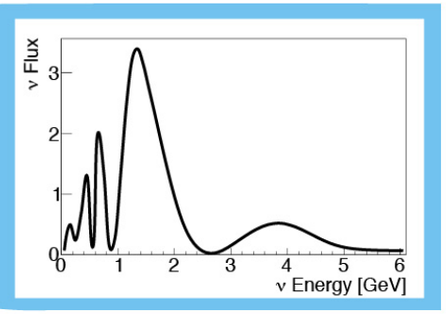


Interacts with nucleus

Particles shoot out

PHYSICS PROCESS

Neutrino comes in



Interacts with nucleus

Particles shoot out

Measure Particles

Apply Interaction Model

Reconstruct ν-Energy

Extract Oscillations

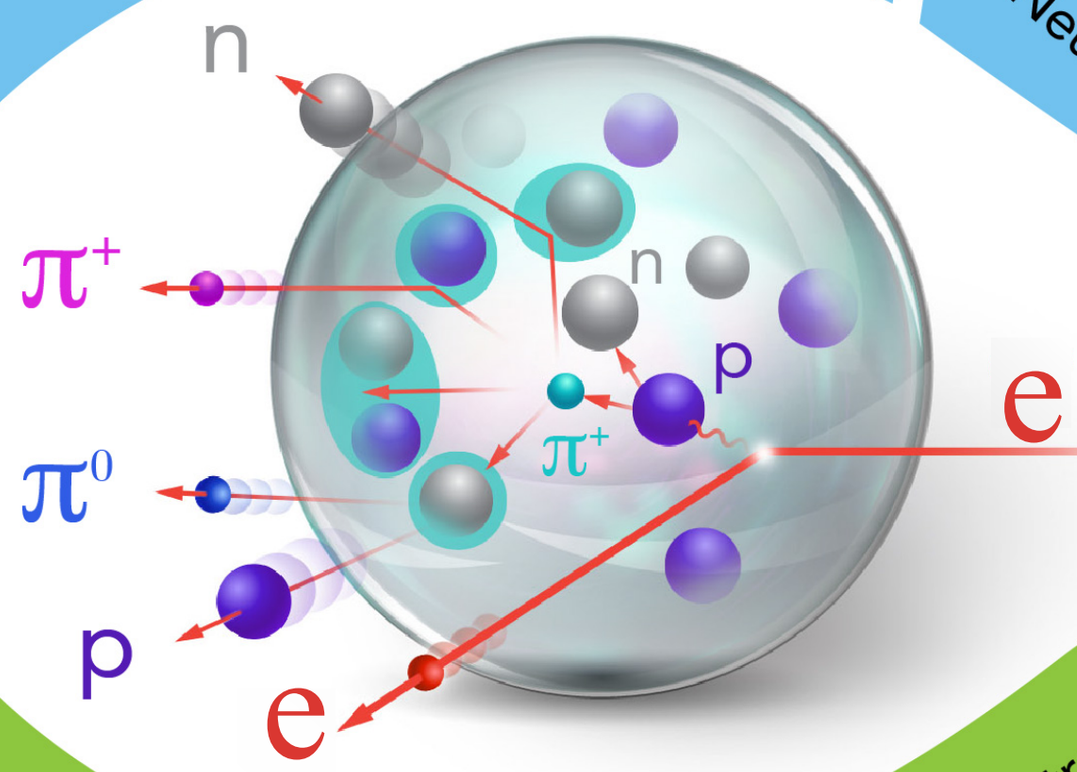
EXPERIMENTAL ANALYSIS

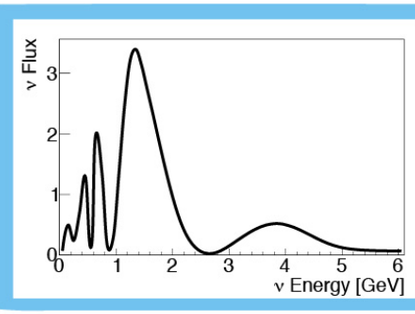
PHYSICS PROCESS

Particles shoot out

Interacts with the nucleus

Neutrino comes in





Measure Particles

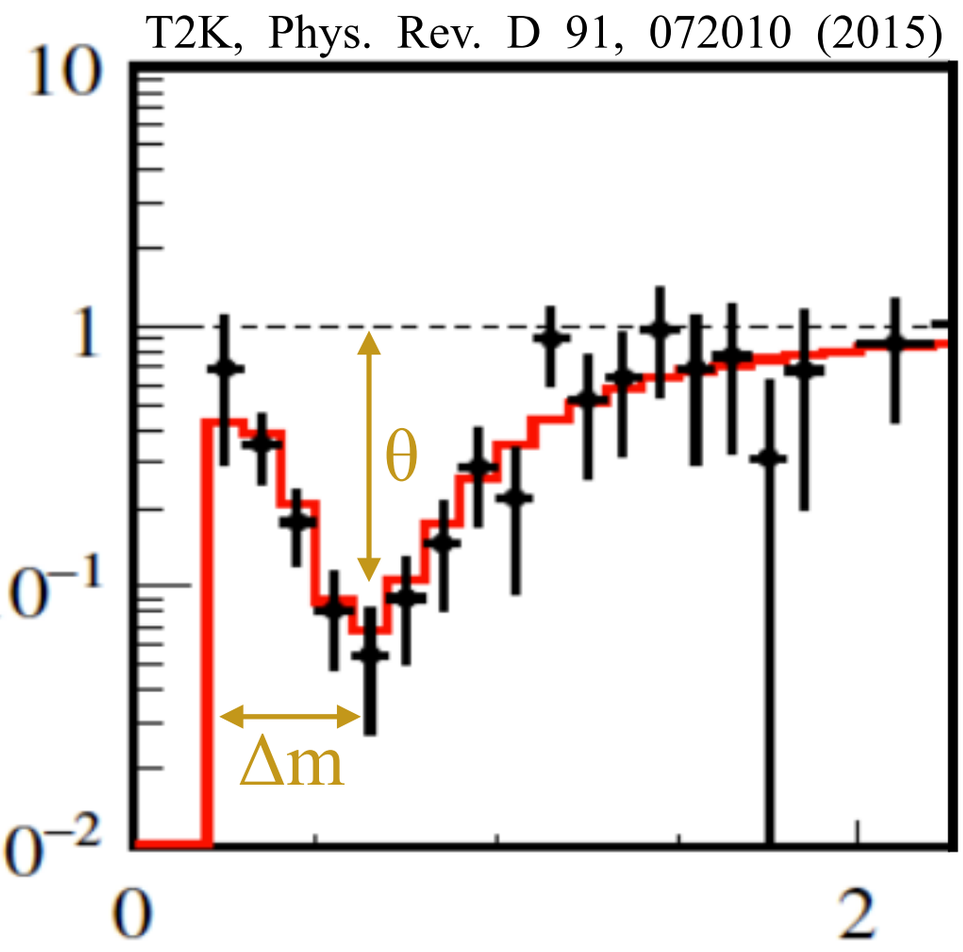
Apply Interaction Model

Reconstruct υ-Energy

Extract Oscillations

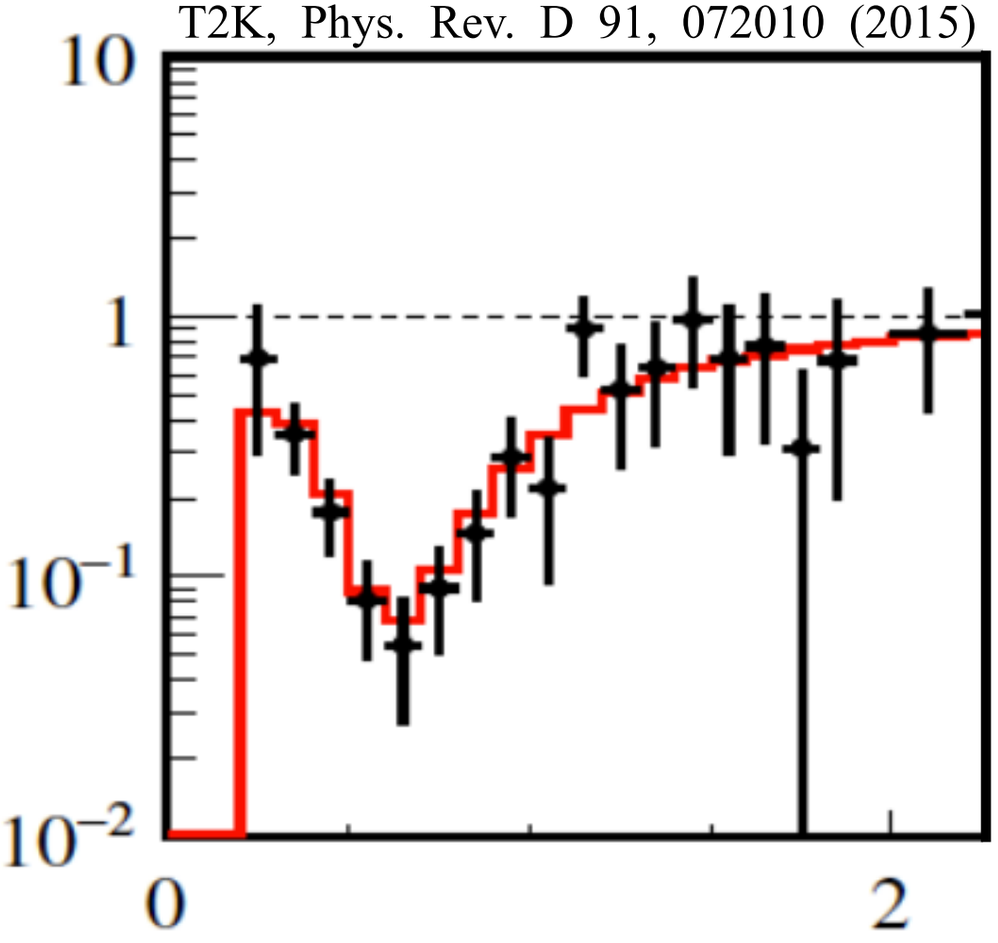
EXPERIMENTAL ANALYSIS

The challenge



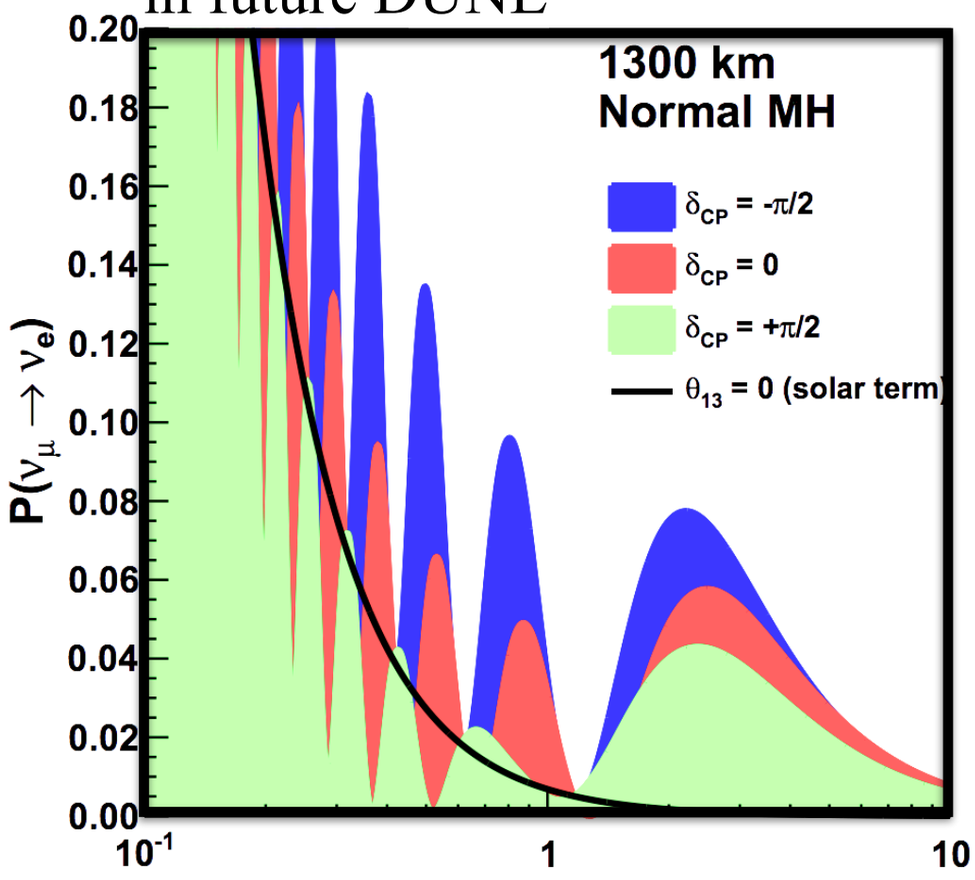
The challenge - next generation high precision

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



Neutrino Energy [GeV]

Simulation of oscillation effects in future DUNE



Neutrino Energy [GeV]

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

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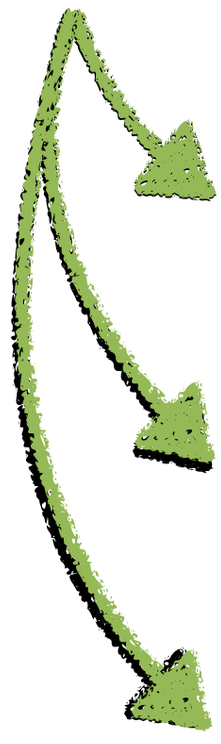
Measurement Incoming true flux Modelling input



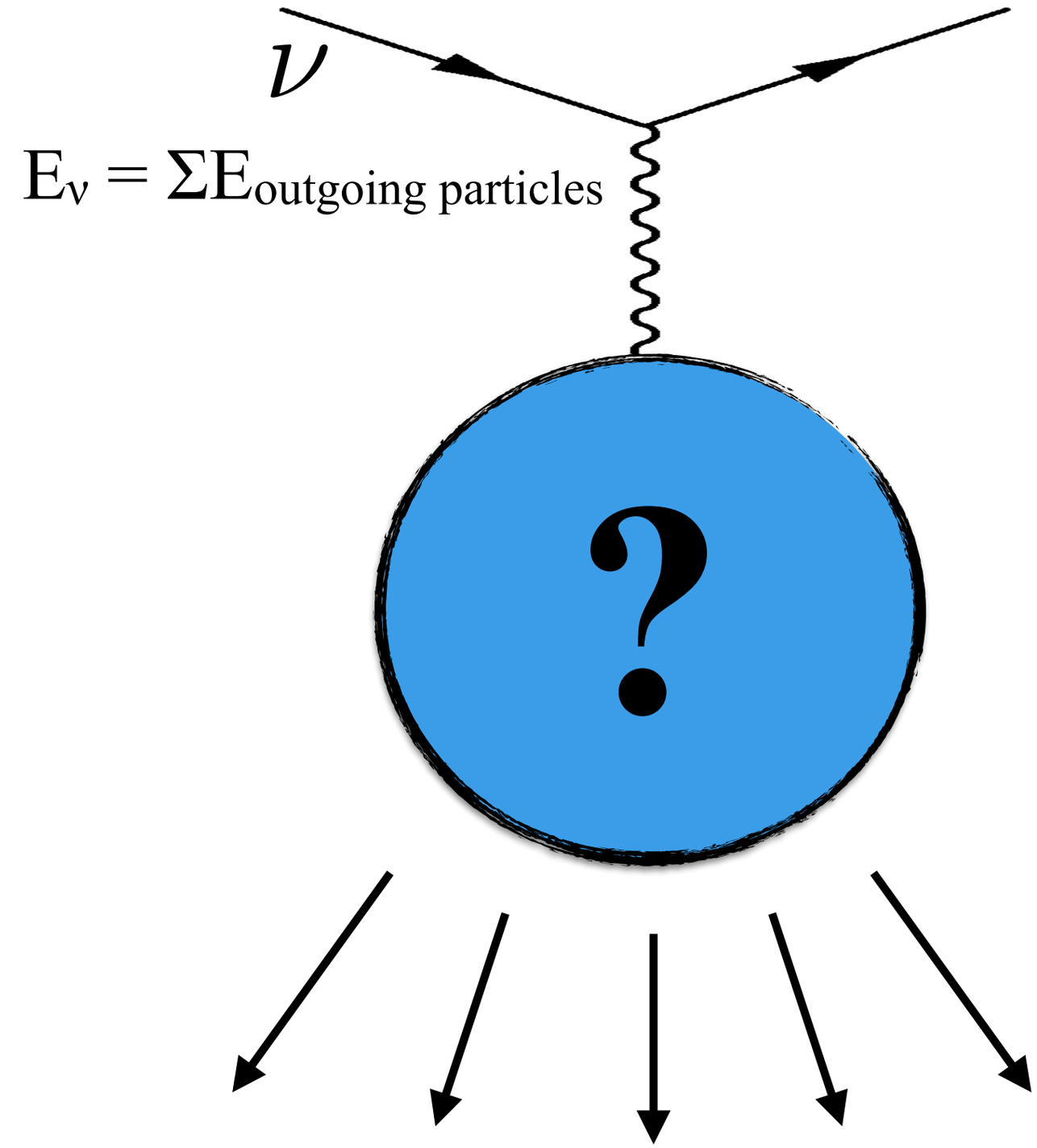
Improve theory

Use near detector

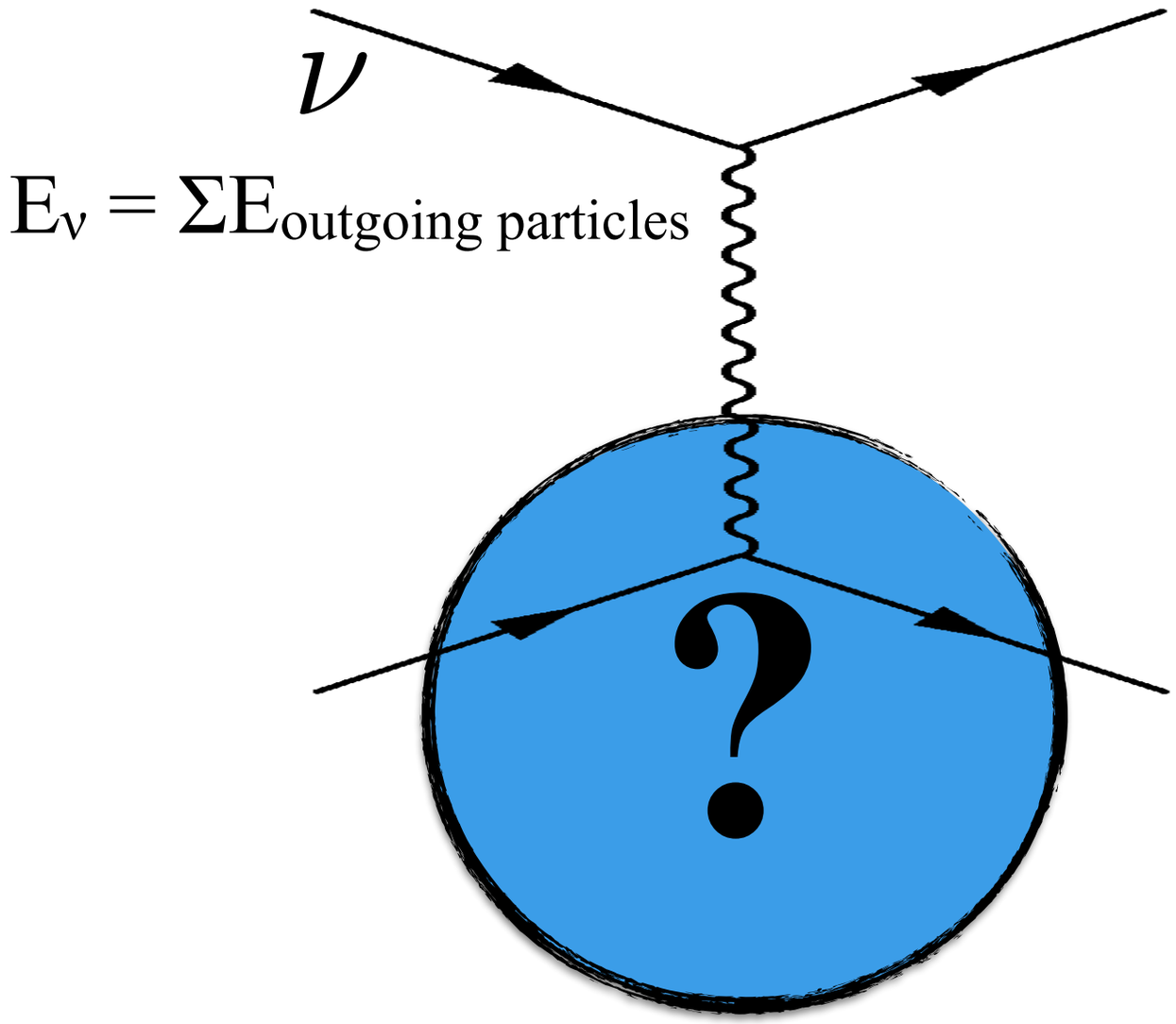
Use external constraints

e scattering

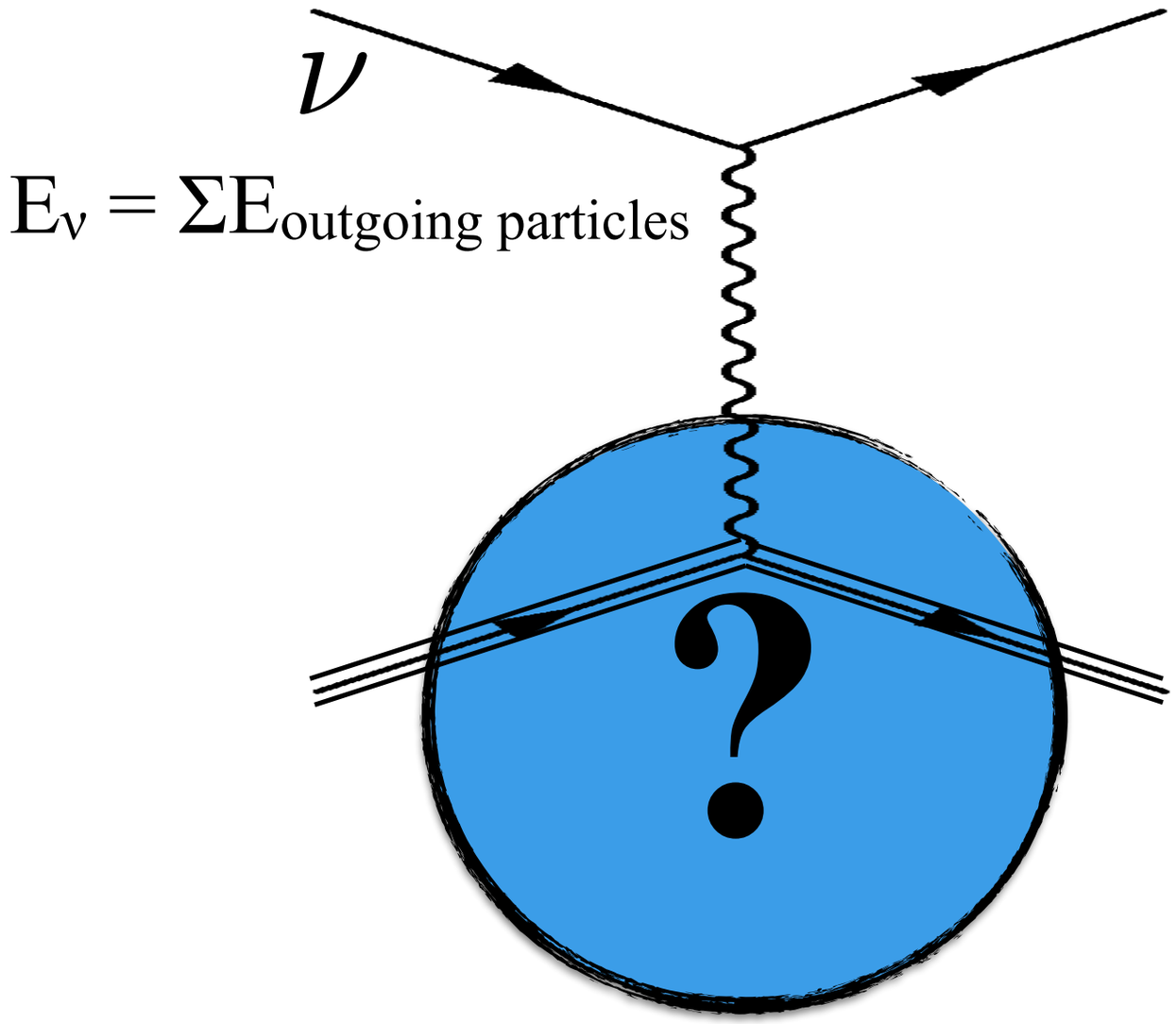
E_ν Reconstruction: Interaction Modeling



E_ν Reconstruction: Interaction Modeling

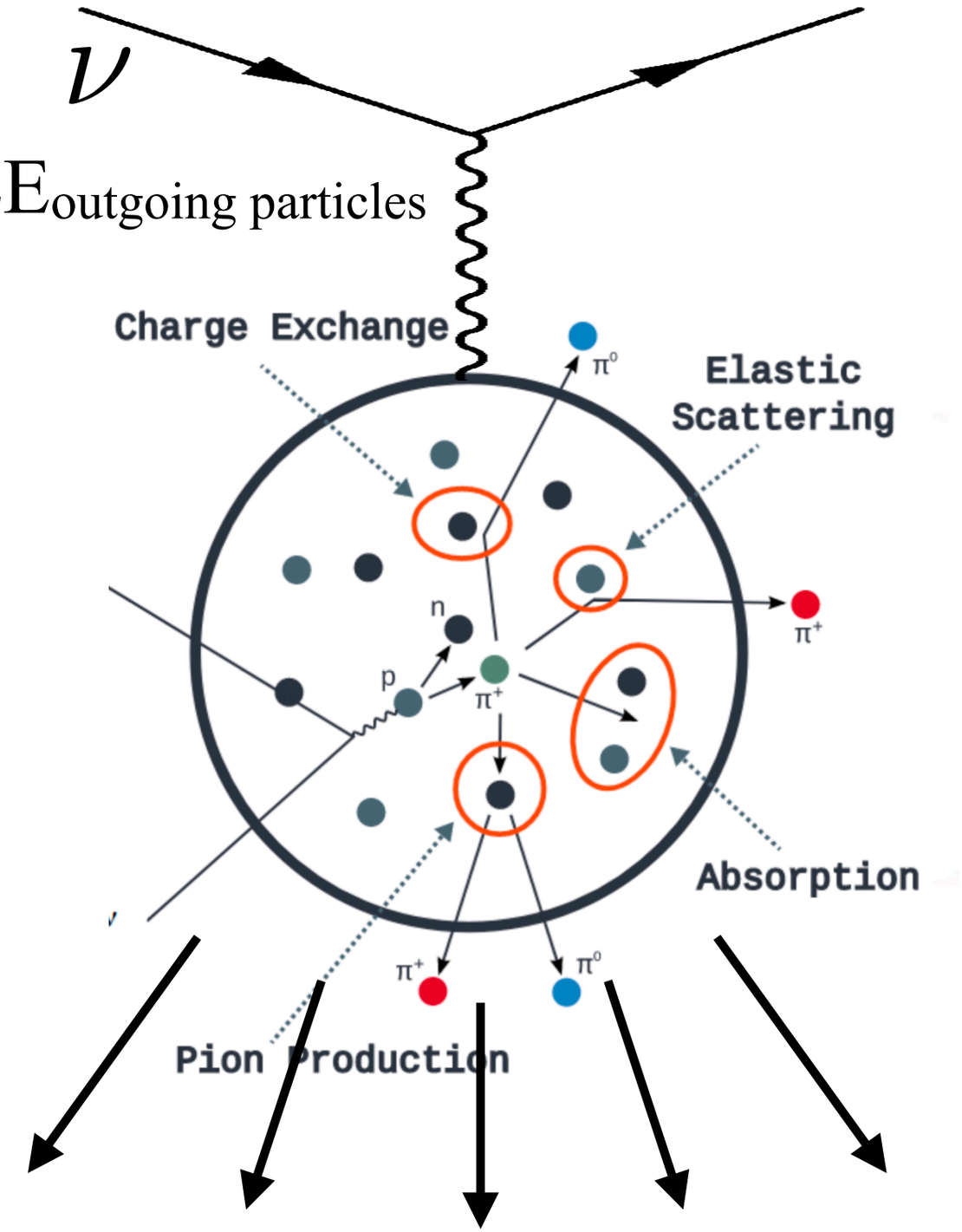


E_ν Reconstruction: Interaction Modeling

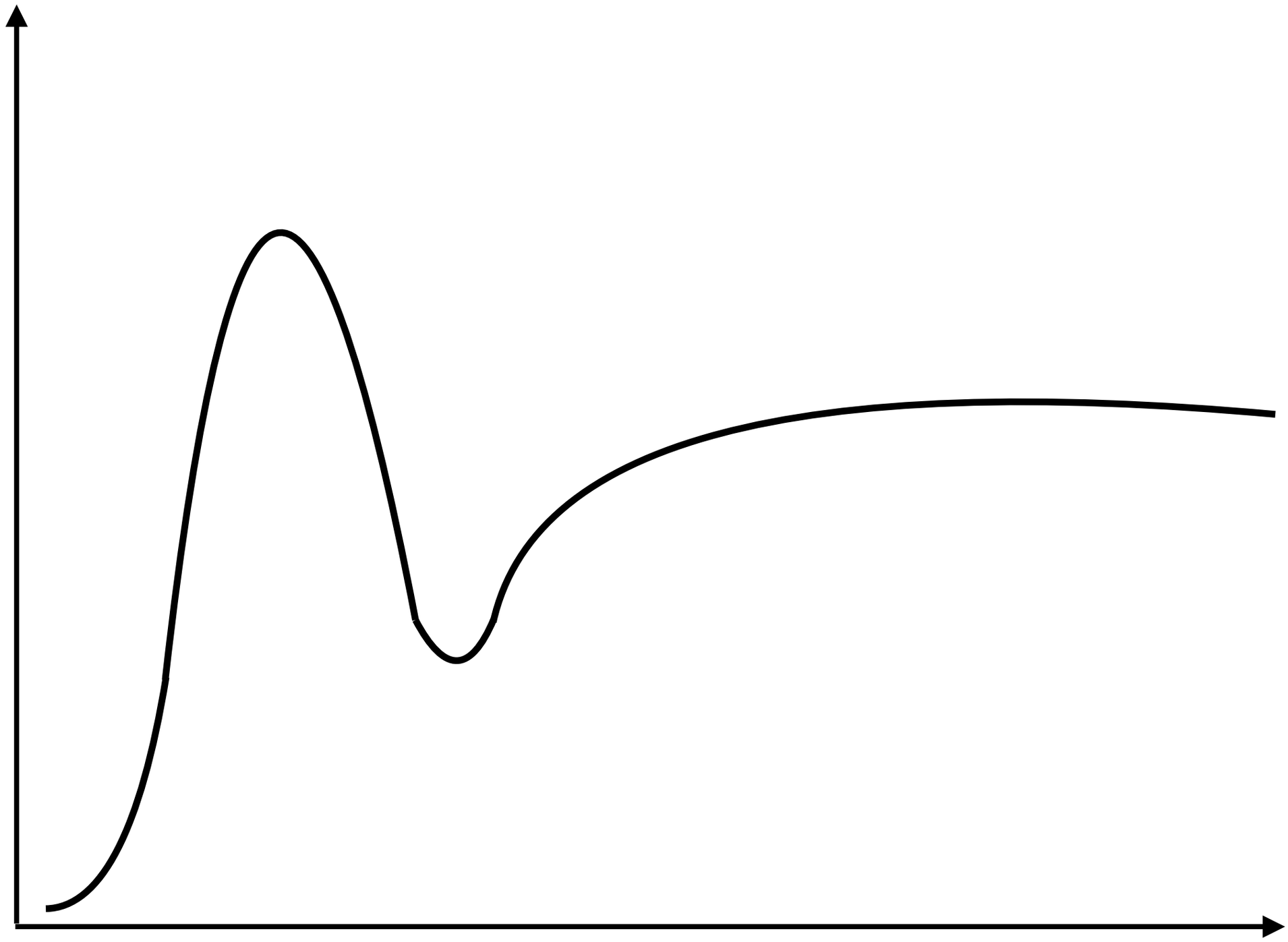


E_ν Reconstruction: Interaction Modeling

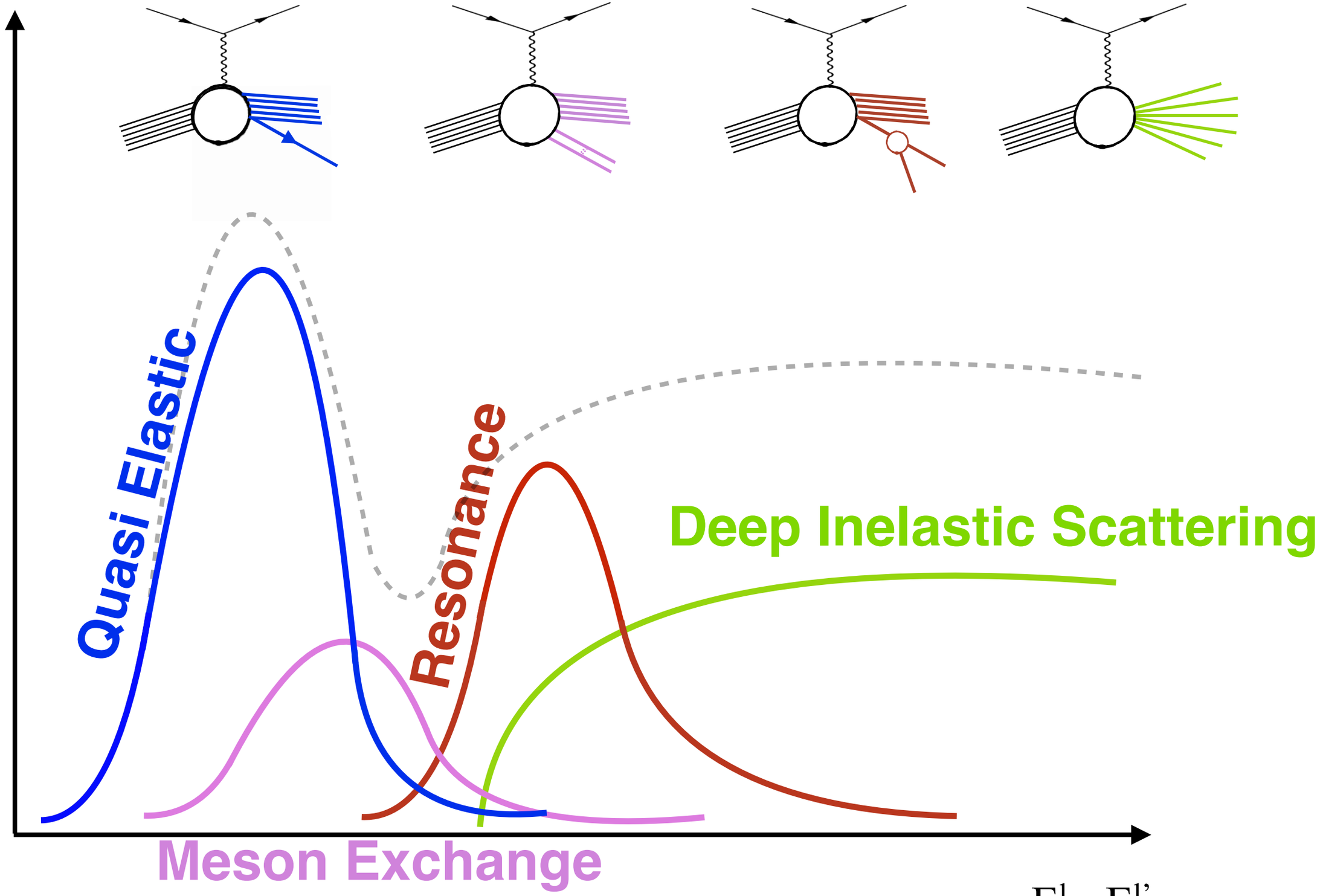
$$E_\nu = \Sigma E_{\text{outgoing particles}}$$



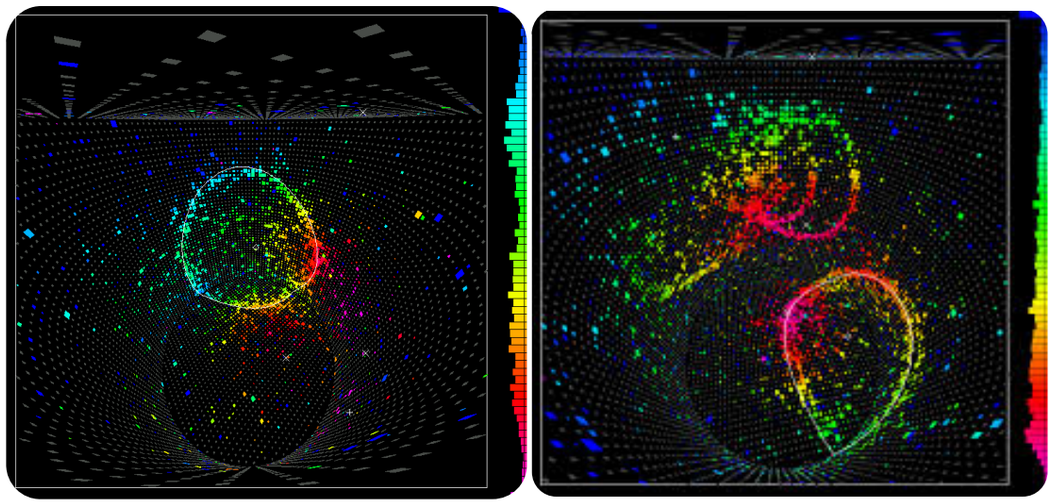
E_ν Reco Requires Interaction Modeling

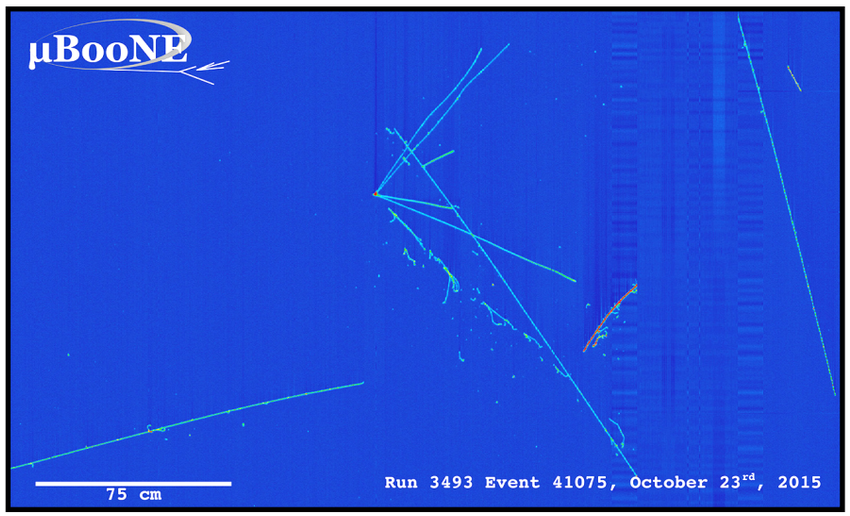


E_ν Reco Requires Interaction Modeling



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

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

[1p0π]

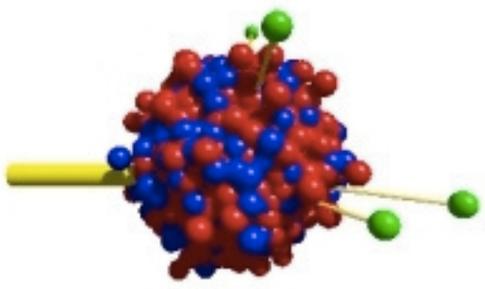
ϵ is the nucleon separation energy ~ 20 MeV

vA Interaction Modelling

Neutrino event generators are used to simulate a νA interaction

Among those:

Genie



GiBUU

The Giessen Boltzmann-Uehling-Uhlenbeck Project

and more

Electron for neutrinos

- Electrons and Neutrinos have:
  - Similar interactions
  - Same nuclear effects

Electron beam have known energy

e4ν: Playing the Neutrino game

Let's analyse electron data as if it was 'Neutrino data'

- Select a specific interaction
- Scale the electron data
- Compare to event generators

CLAS Detector

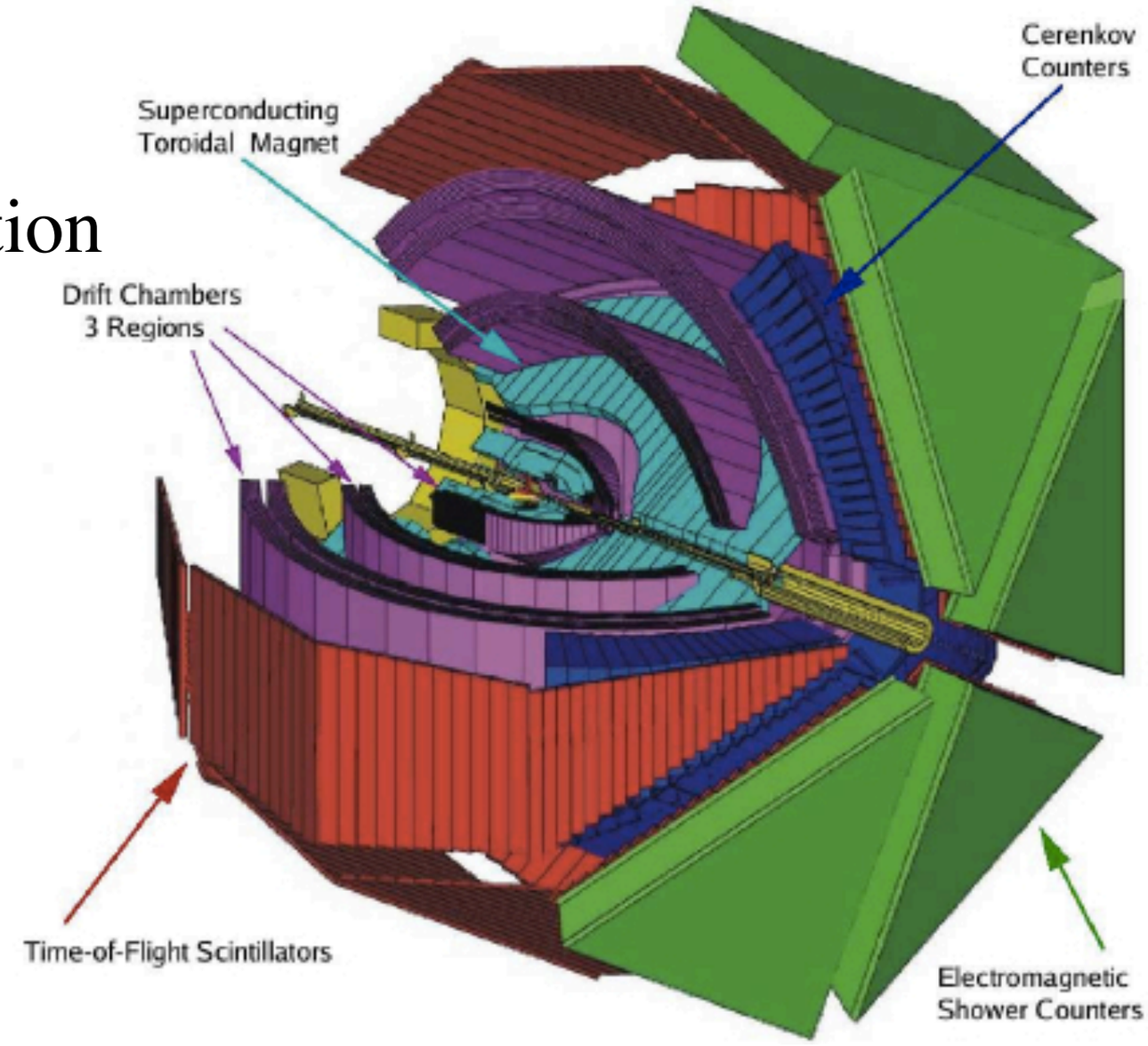
Electron beam with energies up to 6 GeV

Large (~4π) acceptance

Charged particles above detection threshold:

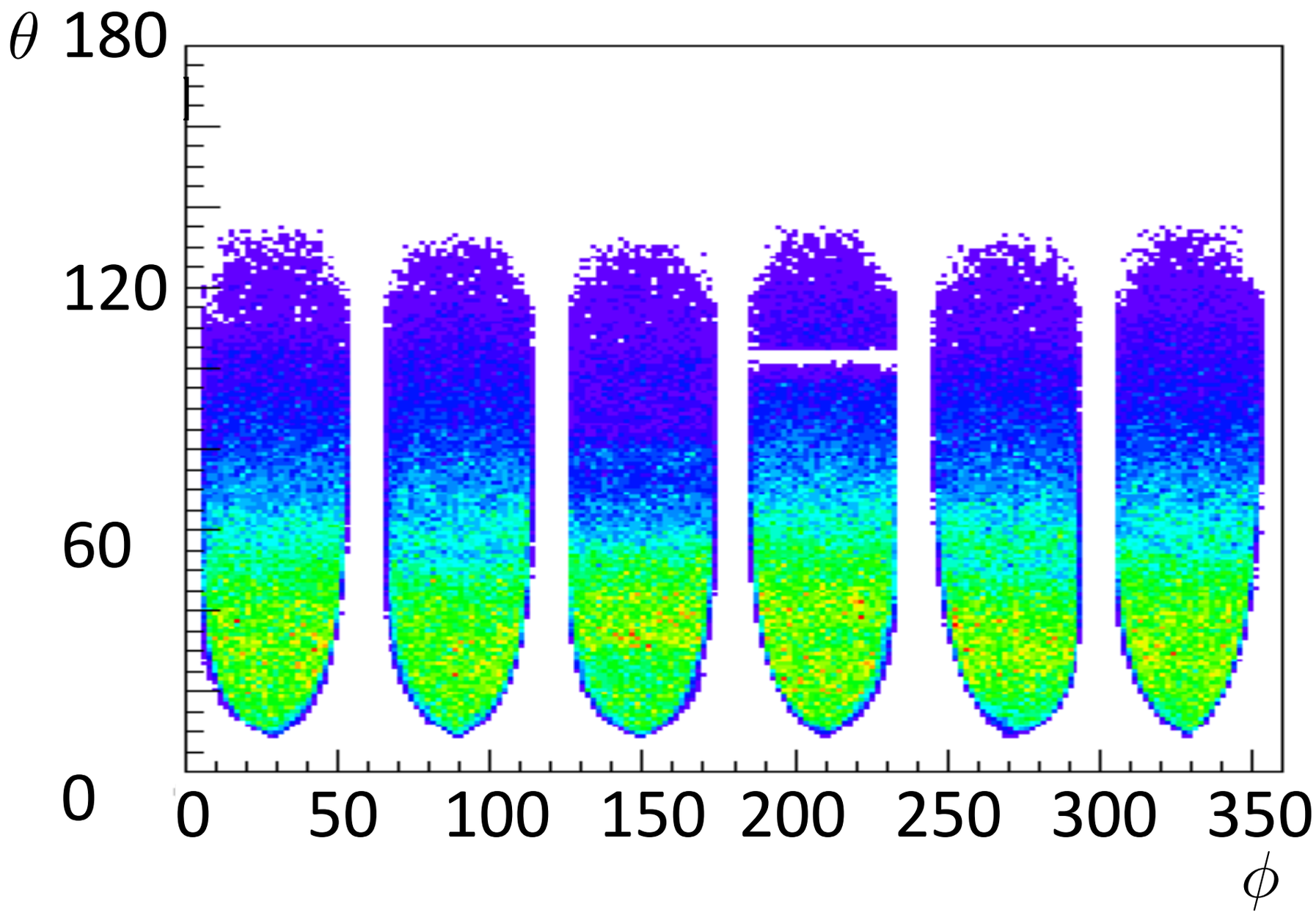
$P_p > 300$ MeV/c

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



Open Trigger

Wide Phase Space



CLAS A(e,e'p) Data

Targets:

^{4}He, ^{12}C, ^{56}Fe

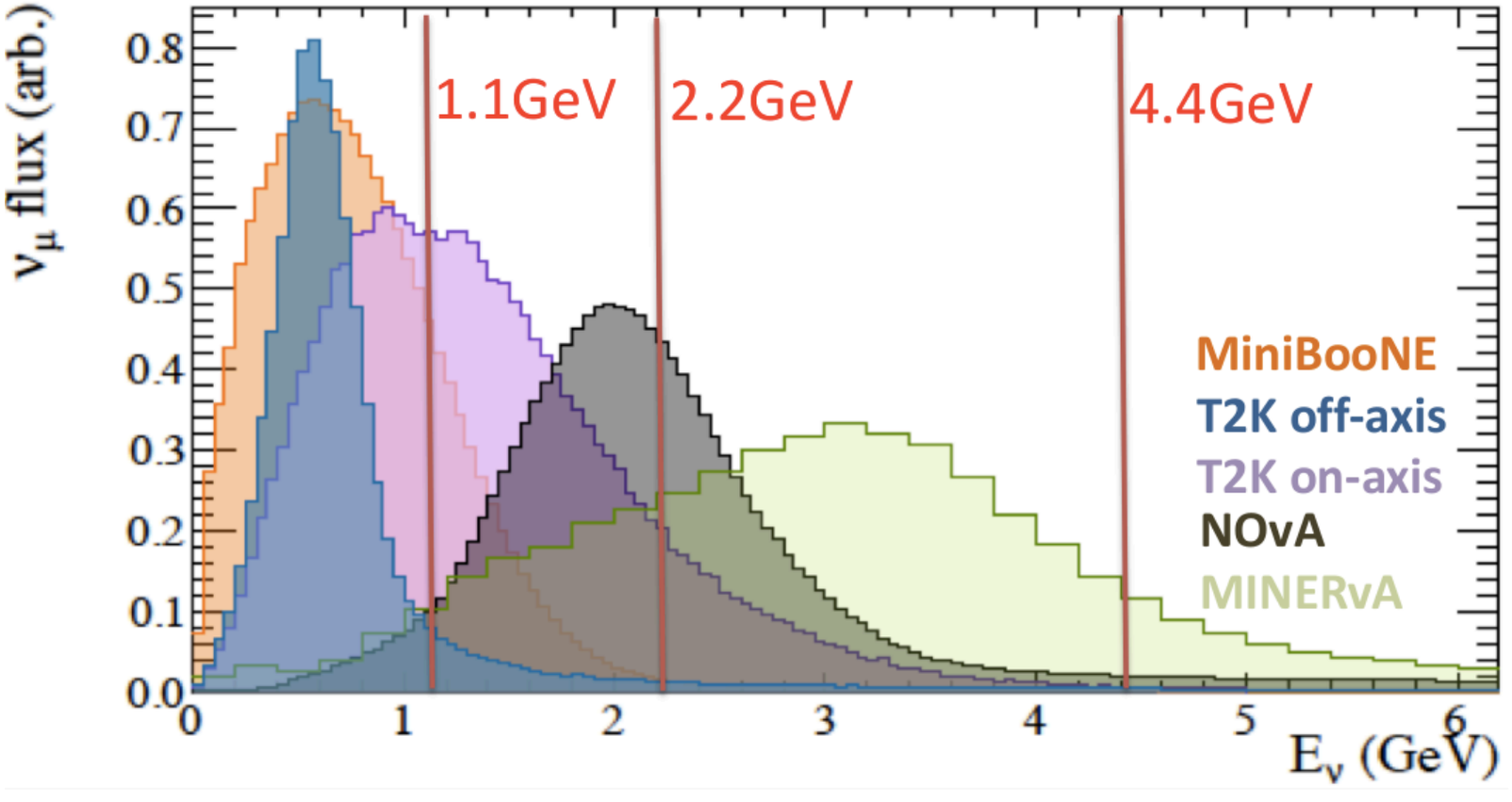
H_2O

CH

Ar

Energies:

1.1, 2.2, 4,4 GeV



e4ν Requirements and Limitations

- Consistency between electron and neutrino modes
- Test Inclusive distributions
- Account for differences such as radiative effects

Modelling Consistency

Genie v3.0.6 tune G18_10a_02_11a

	electrons	neutrinos
Nuclear model	Local fermi gas model	
QE	Rosenbluth CS	Nieves model
MEC	Empirical model	Nieves model
Resonances	Berger Sehgal	
DIS	AGKY	
FSI	hA2018	
Others	Adding radiative correction	

Modelling Consistency

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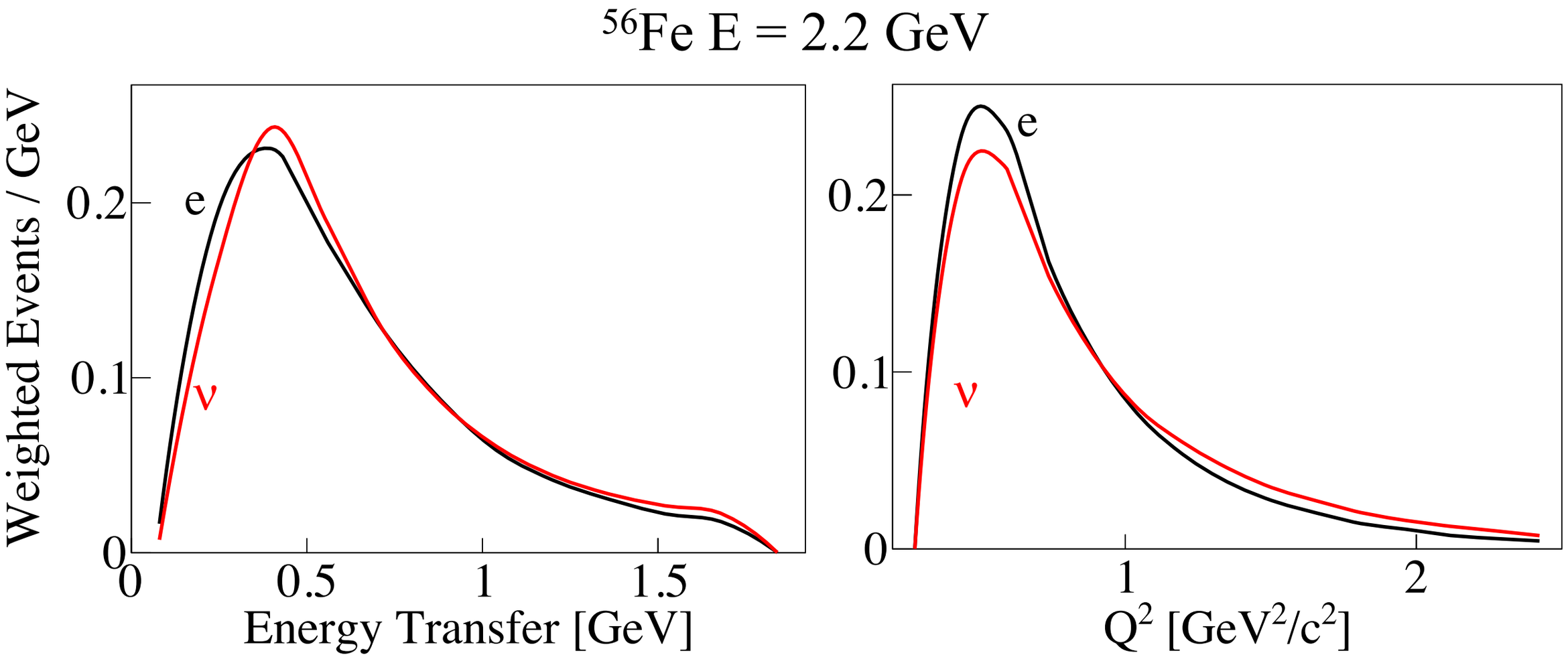
tune GTEST19 (SuSAv2)

electrons	neutrinos
Fermi gas model	
SuSAv2	
SuSAv2	
Berger Sehgal	
AGKY	
hA2018	
Radiative effects	

Modelling Consistency

Test on 1p0π event selection



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

Modelling Consistency

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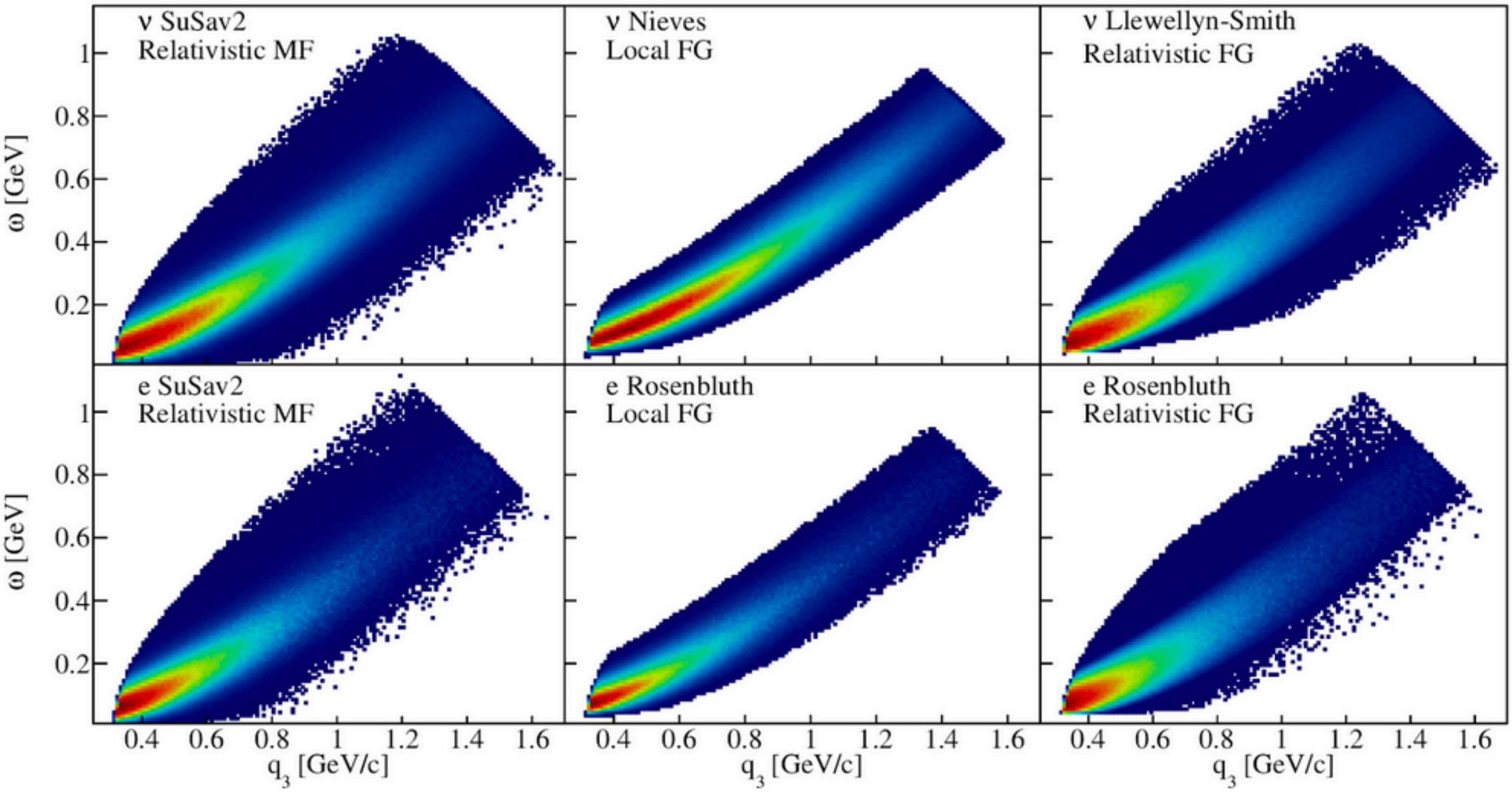

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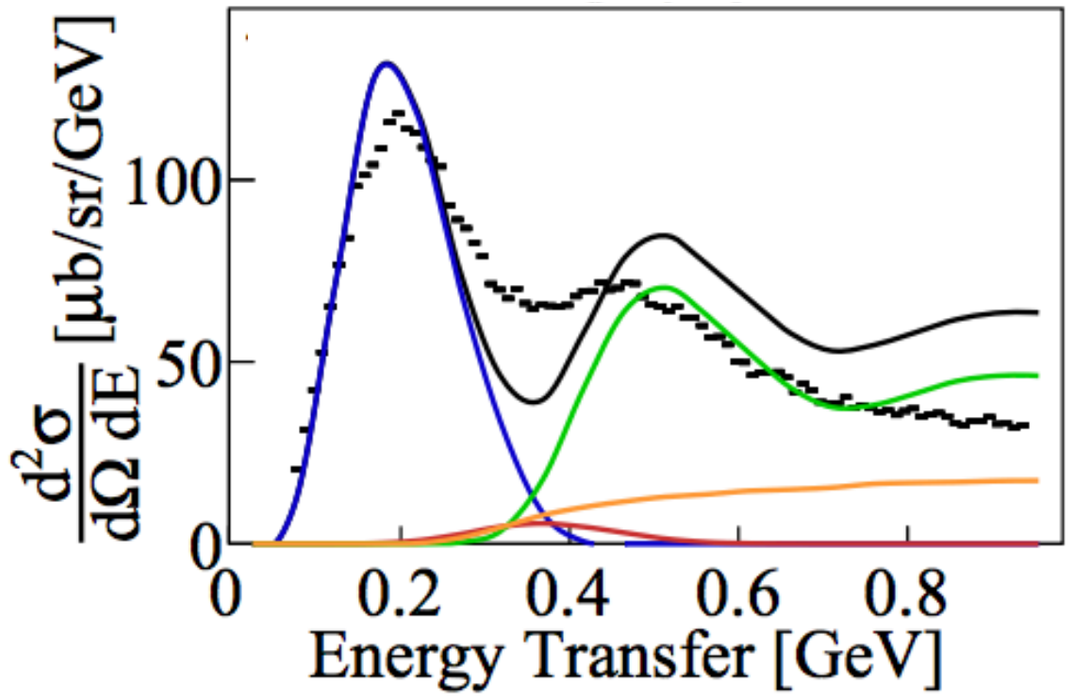
Genie

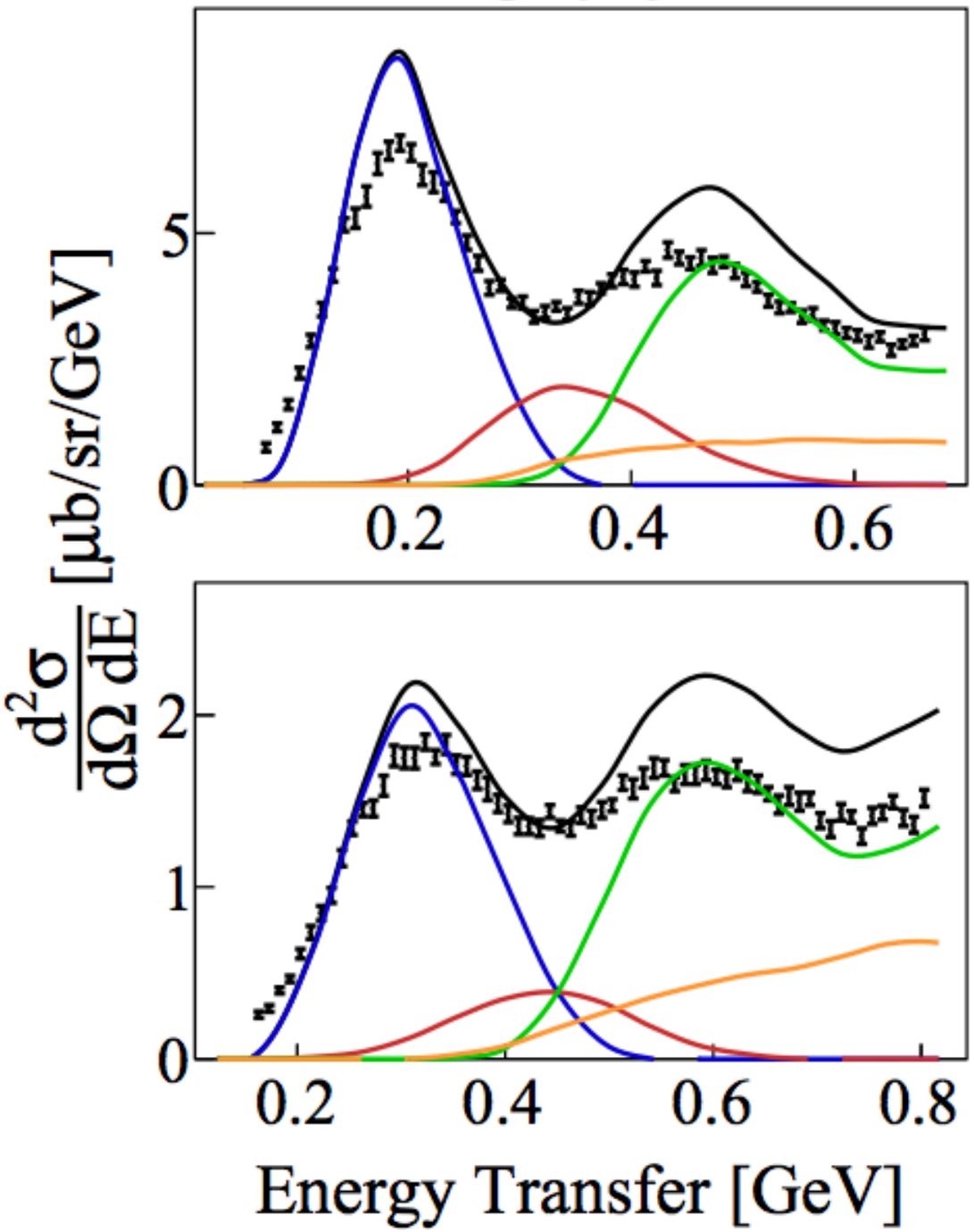
Phys.Rev.D 103 (2021) 113003

GENIE reproduced e inclusive data



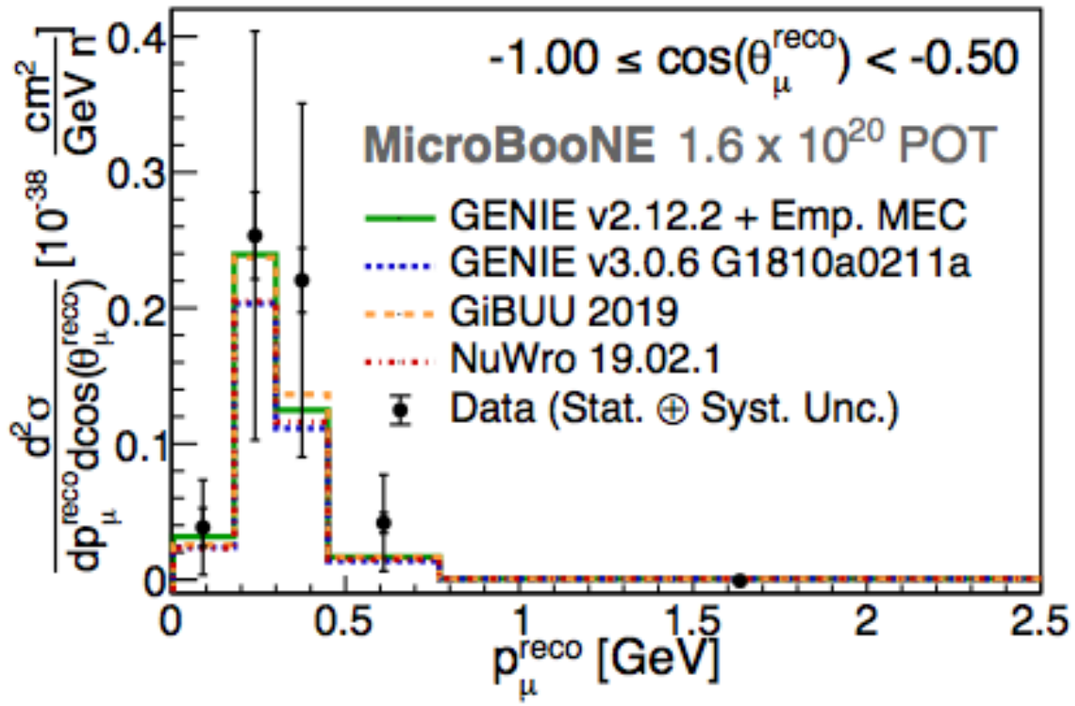
Genie

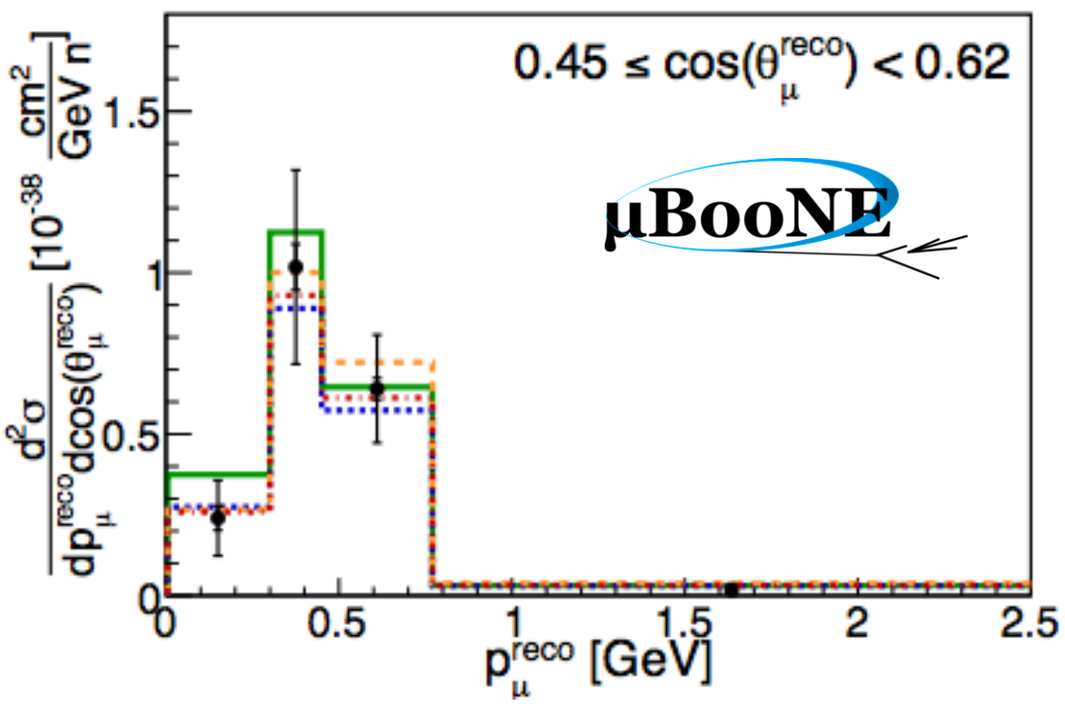
— v3.0.6 tune G18_10a_02_11a



Phys.Rev.D 103 (2021) 113003

GENIE reproduced ν inclusive data





Genie

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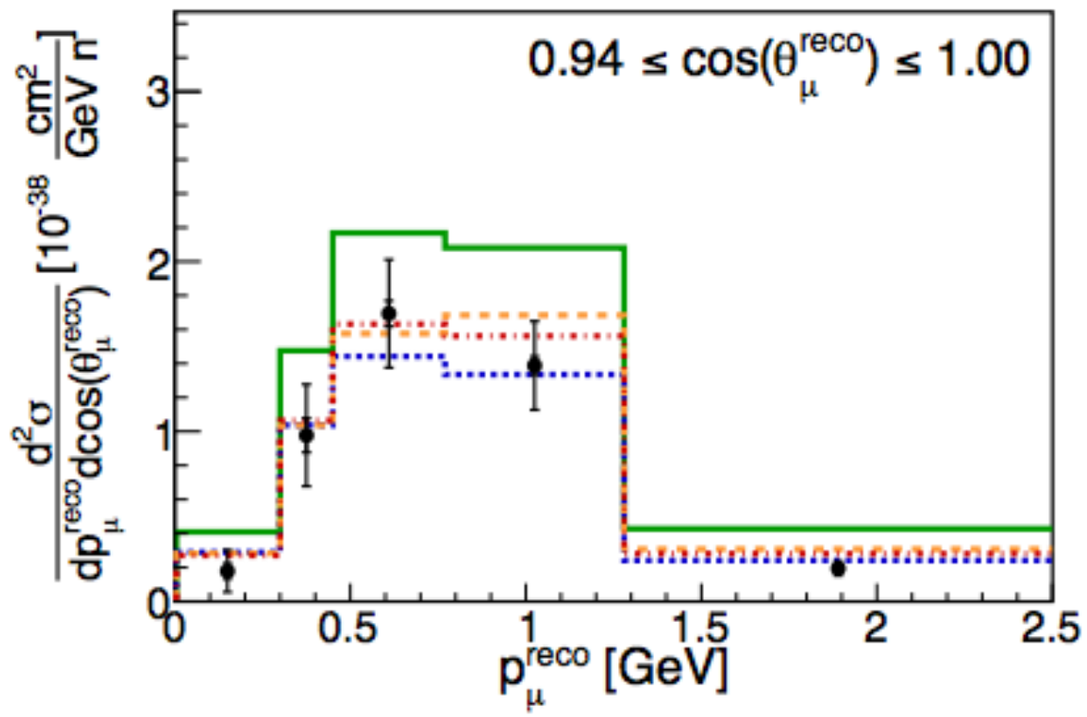
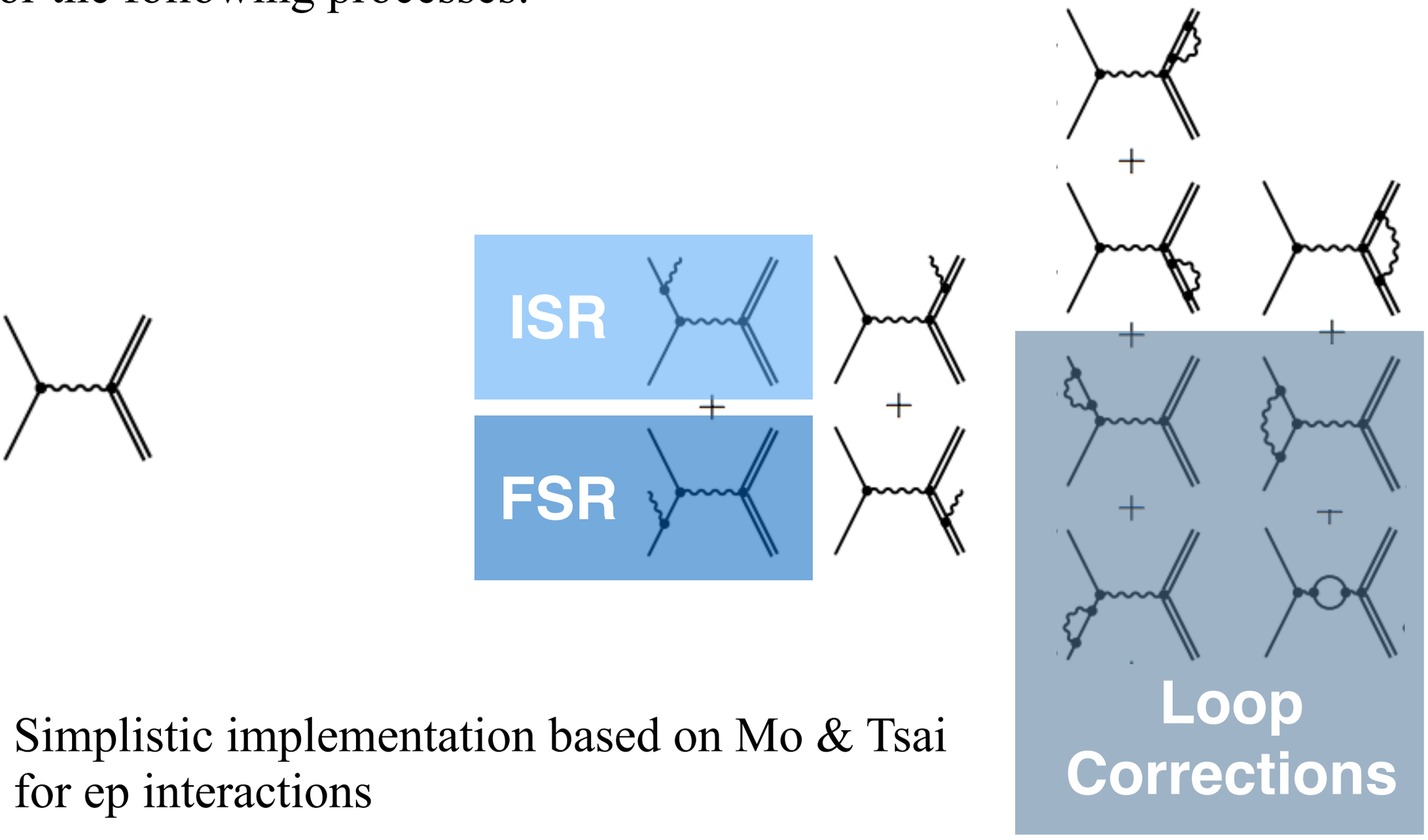


Phys. Rev. Lett. 123, 131801 (2019)

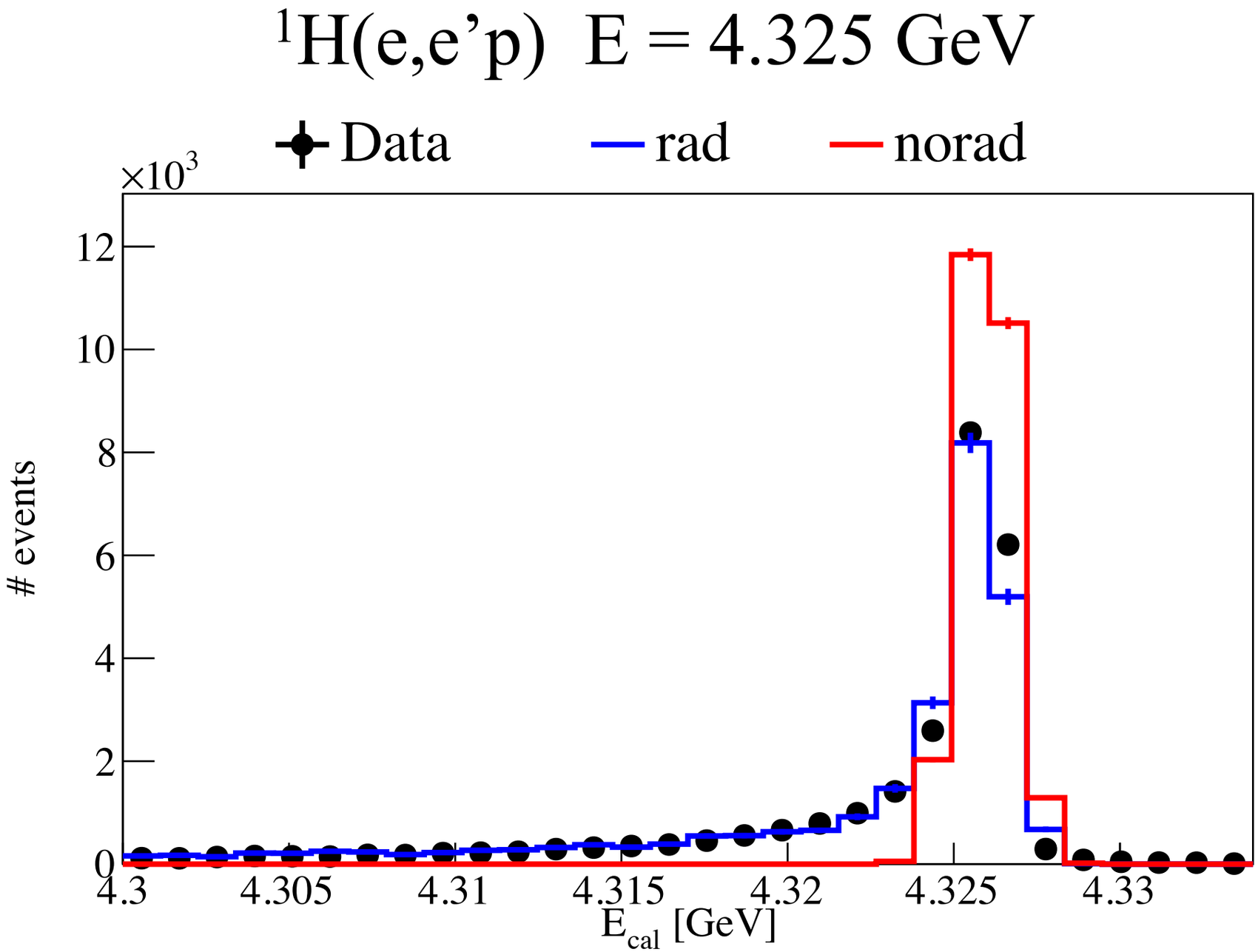
Radiative effects

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



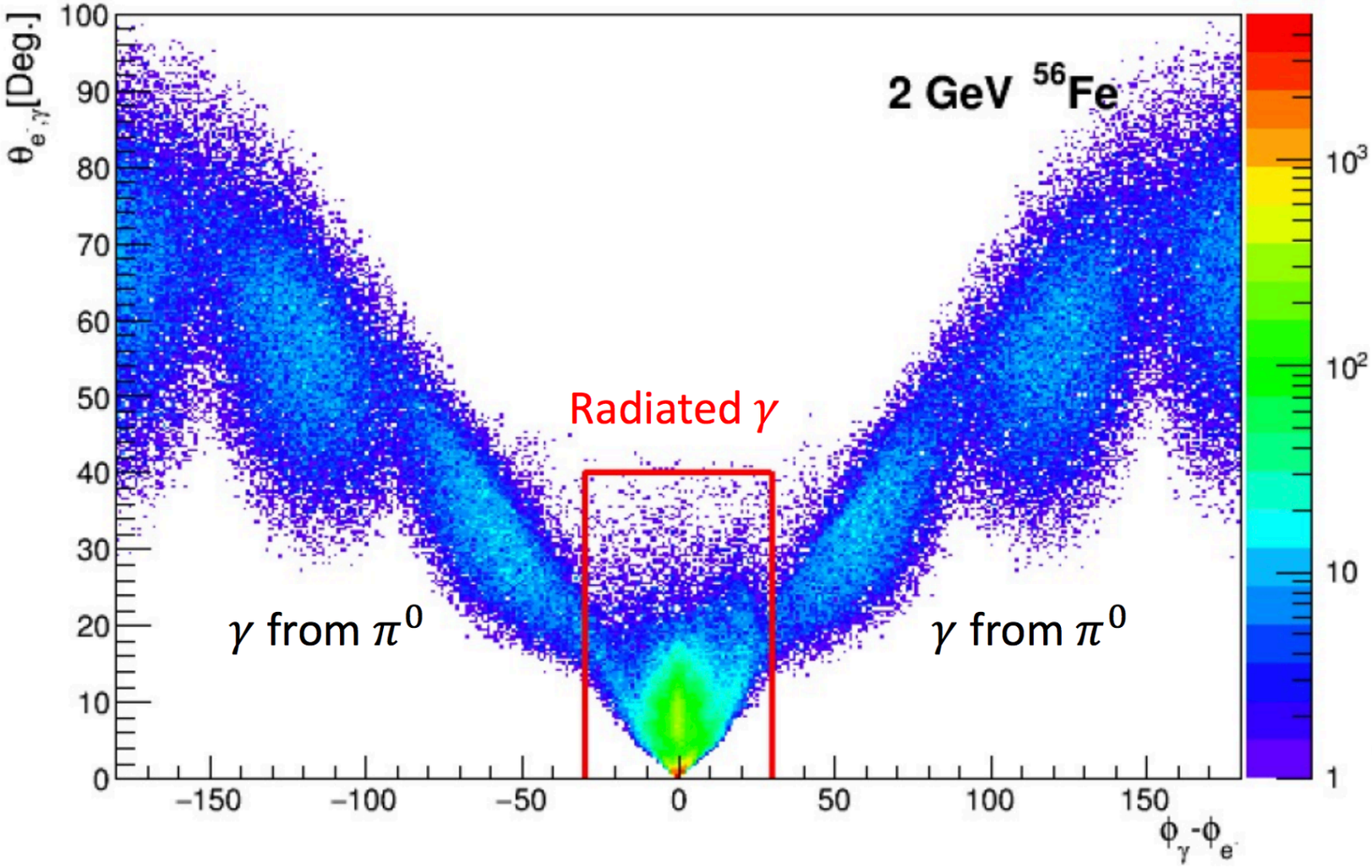
[Mo and Tsai]

Genie v3.0.6 tune G18_10a_02_11a

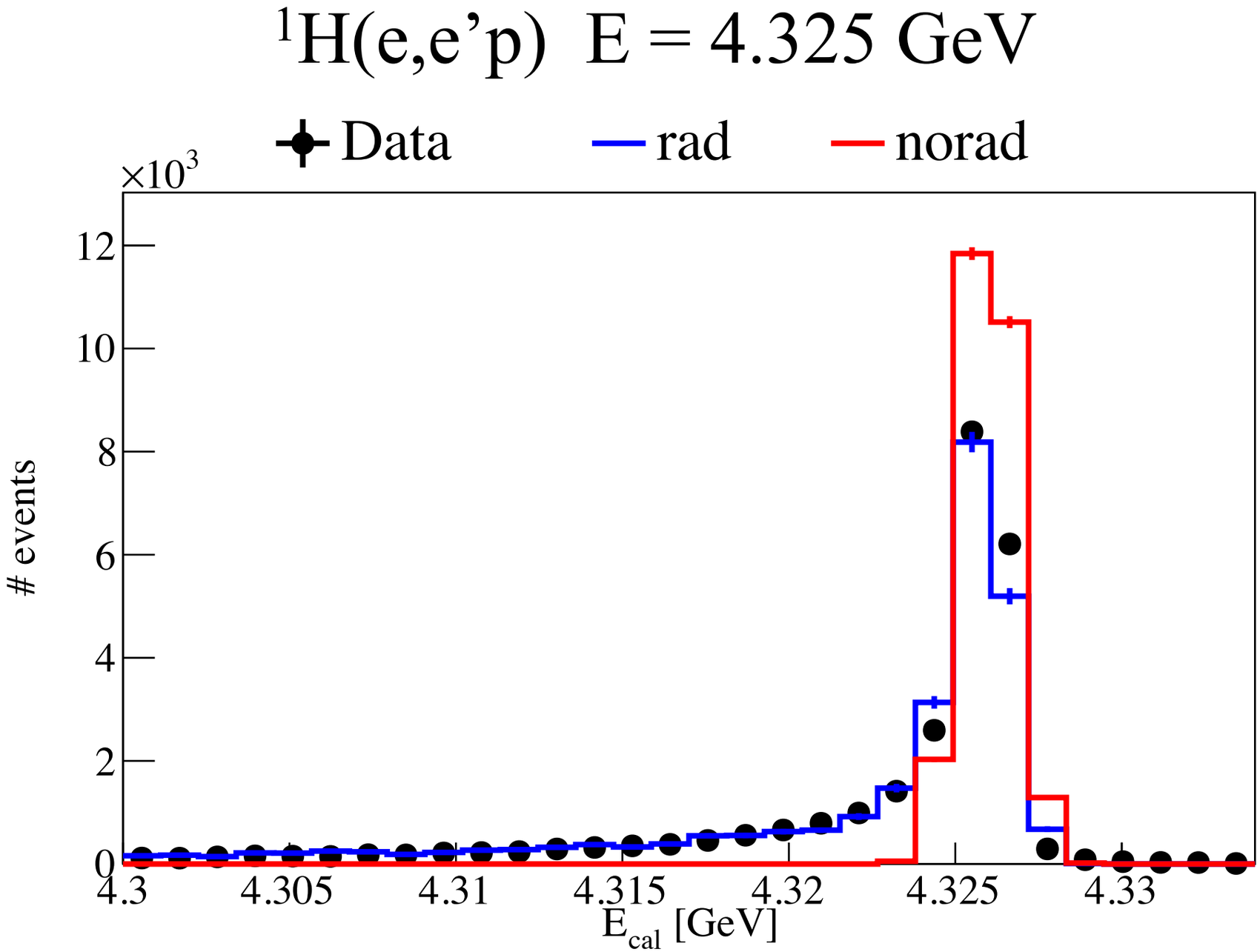
Coping with radiative effects

In addition we're ignoring events with:

- A photon in close proximity to the final state electron
- $E_l' < 0.25\ E_l$



Adding radiative effects to GENIE



[Mo and Tsai]

Genie v3.0.6 tune GTEST19

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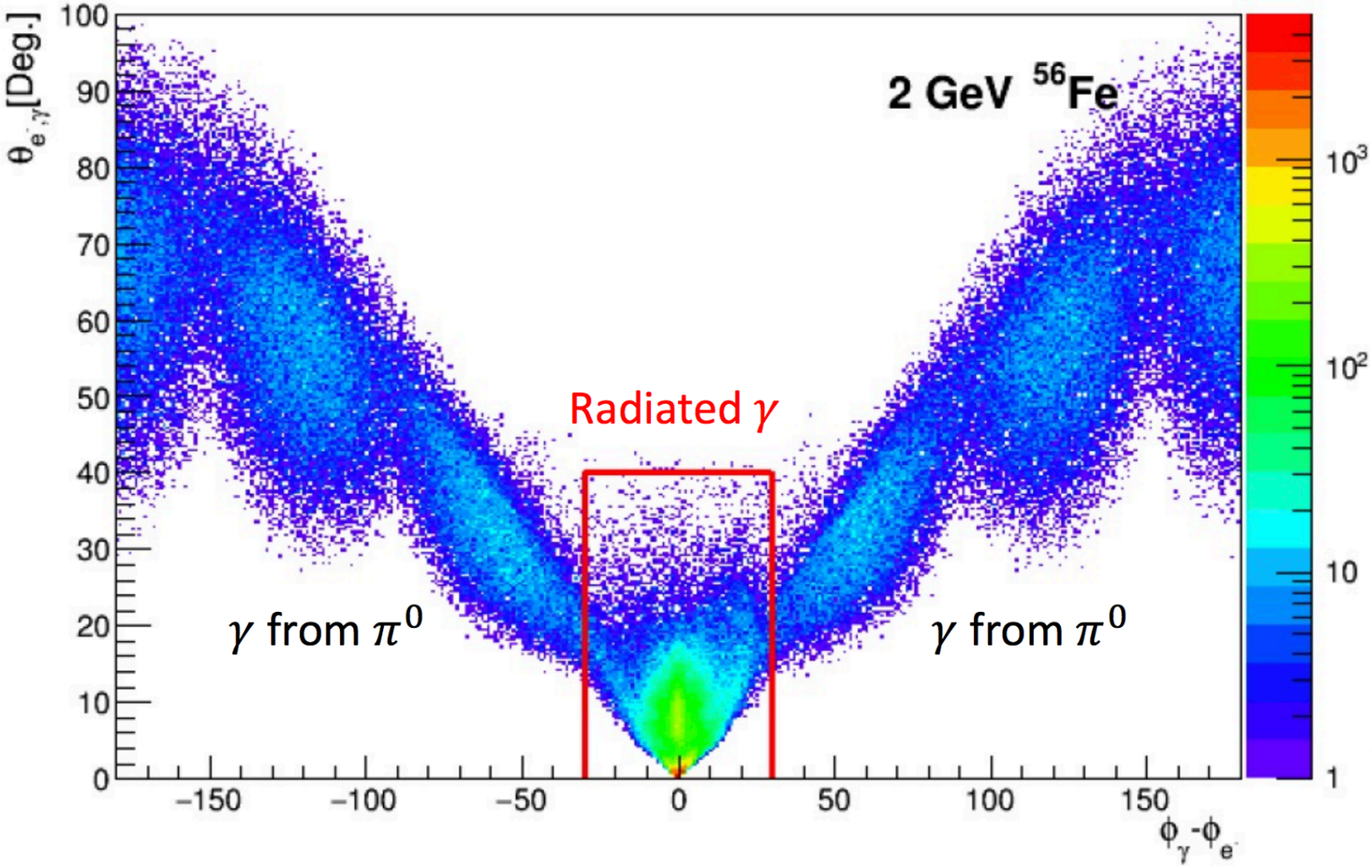


e4ν 1p0π Event Selection

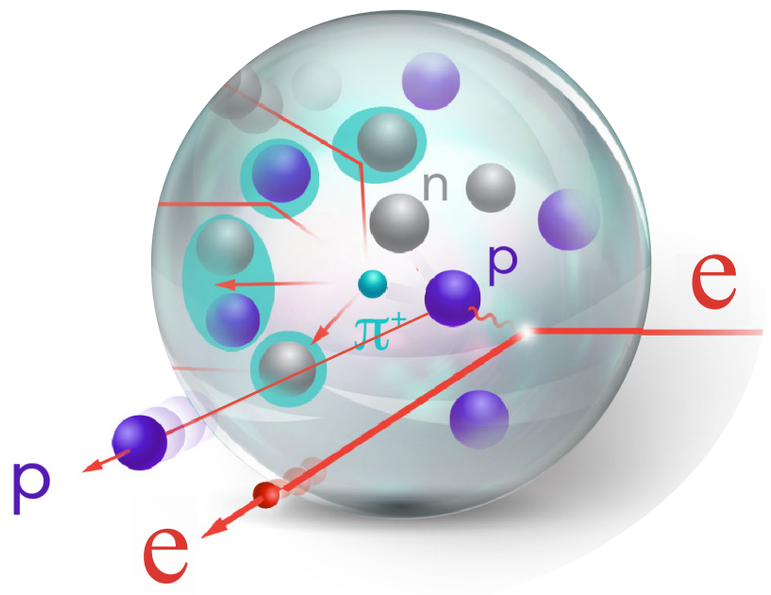
Focus on Quasi Elastic events:

1 proton above 300 MeV/c

no additional hadrons above threshold:

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

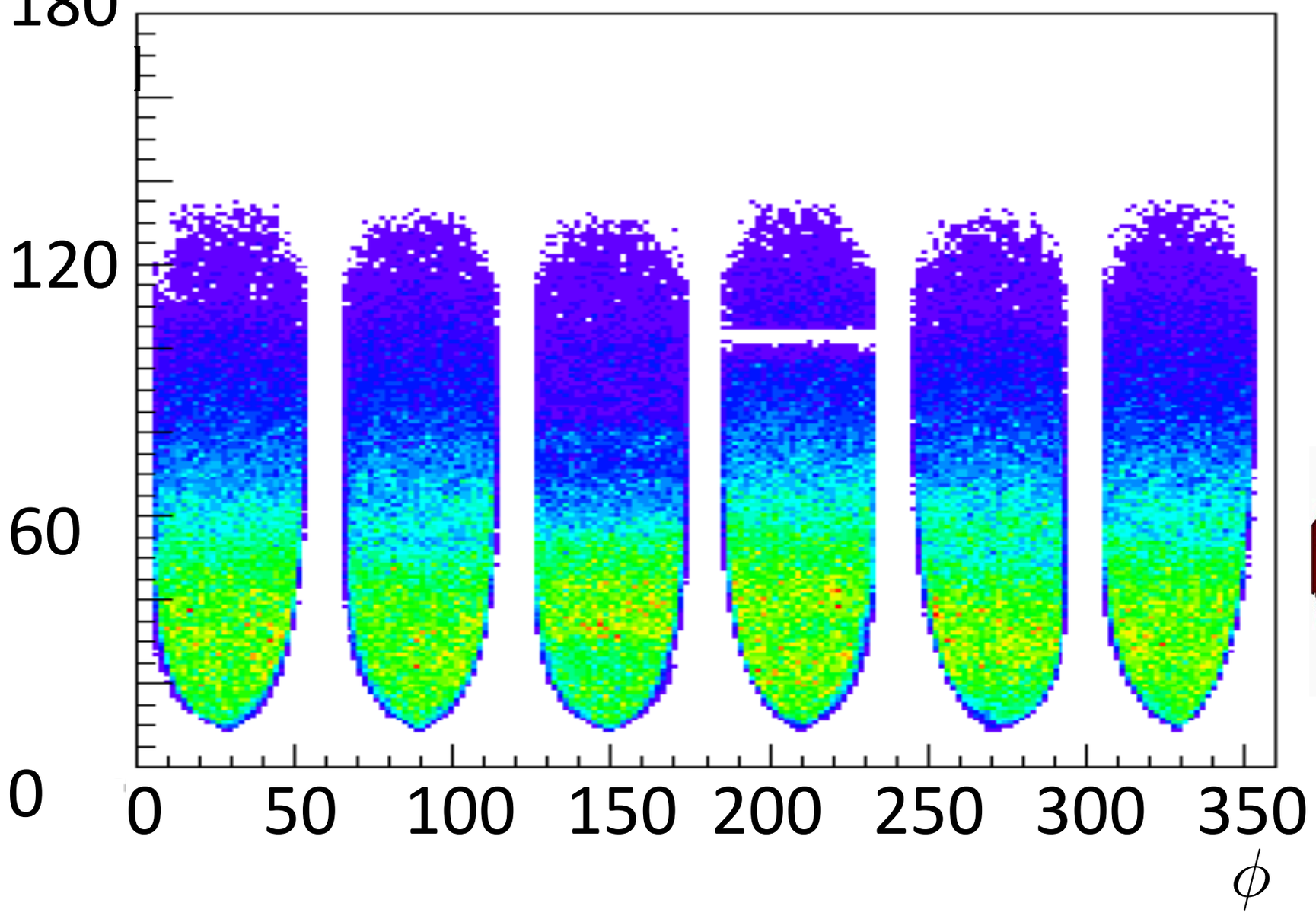
$P_{\pi^0} > 500$ MeV/c

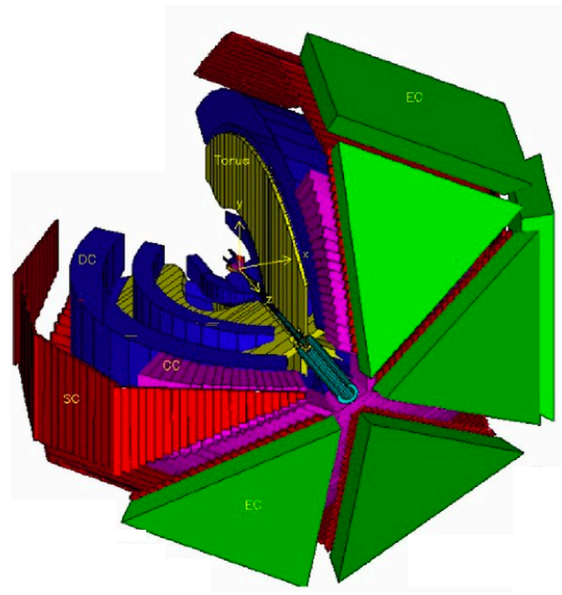


Background Subtraction

Different interaction lead to multi-hadron final states

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





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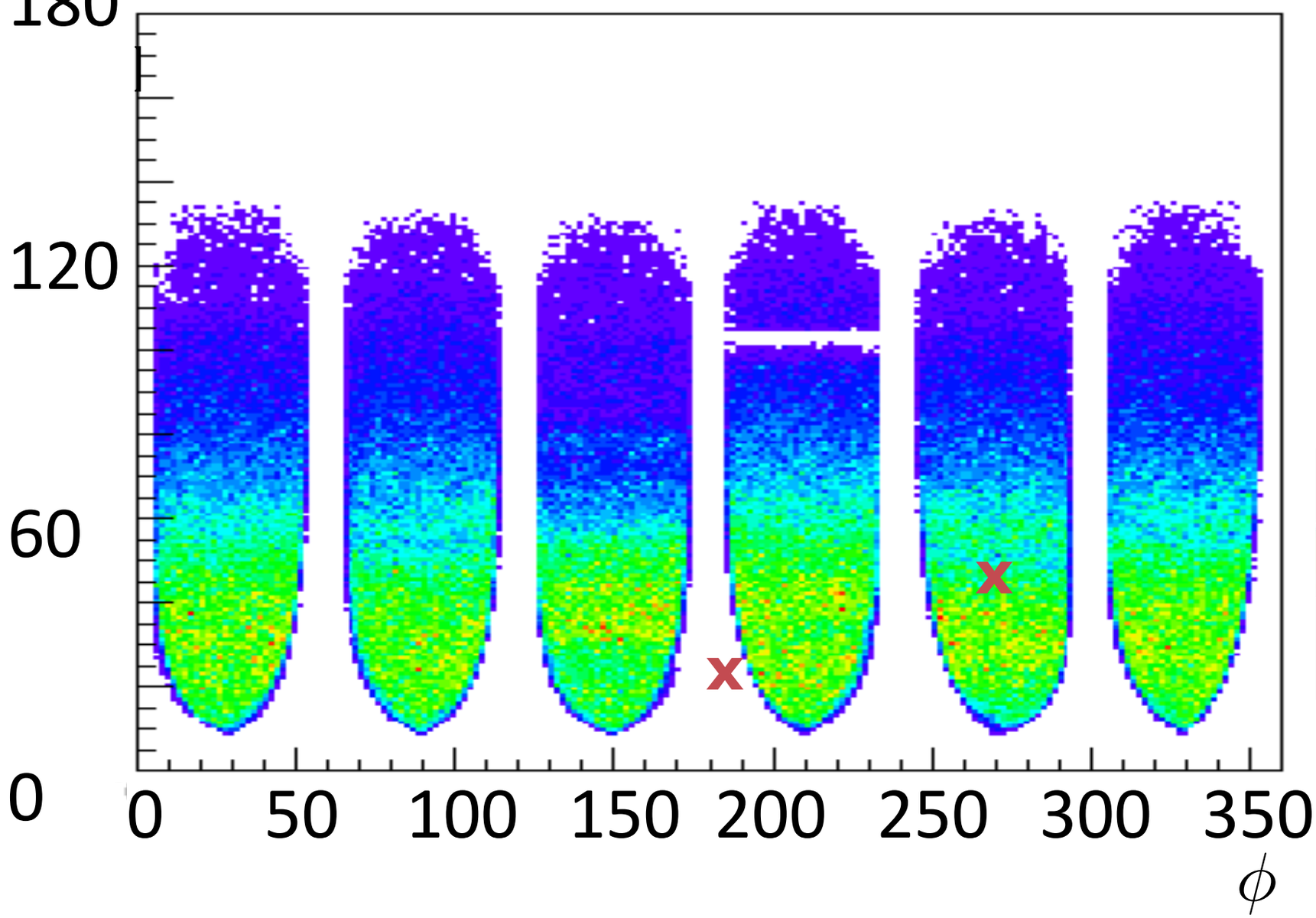
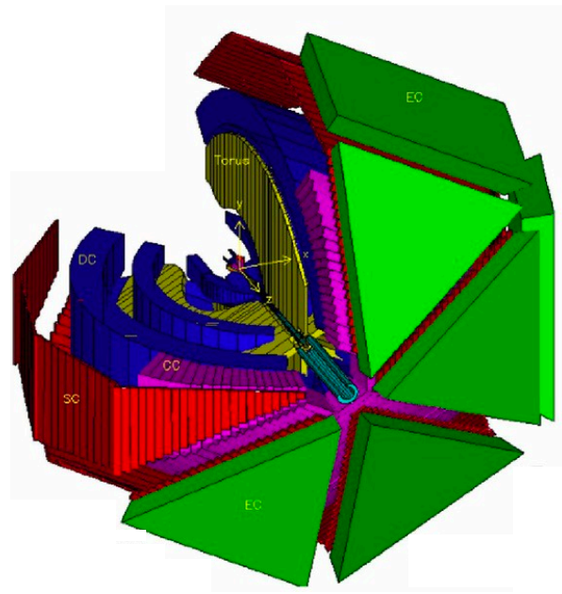
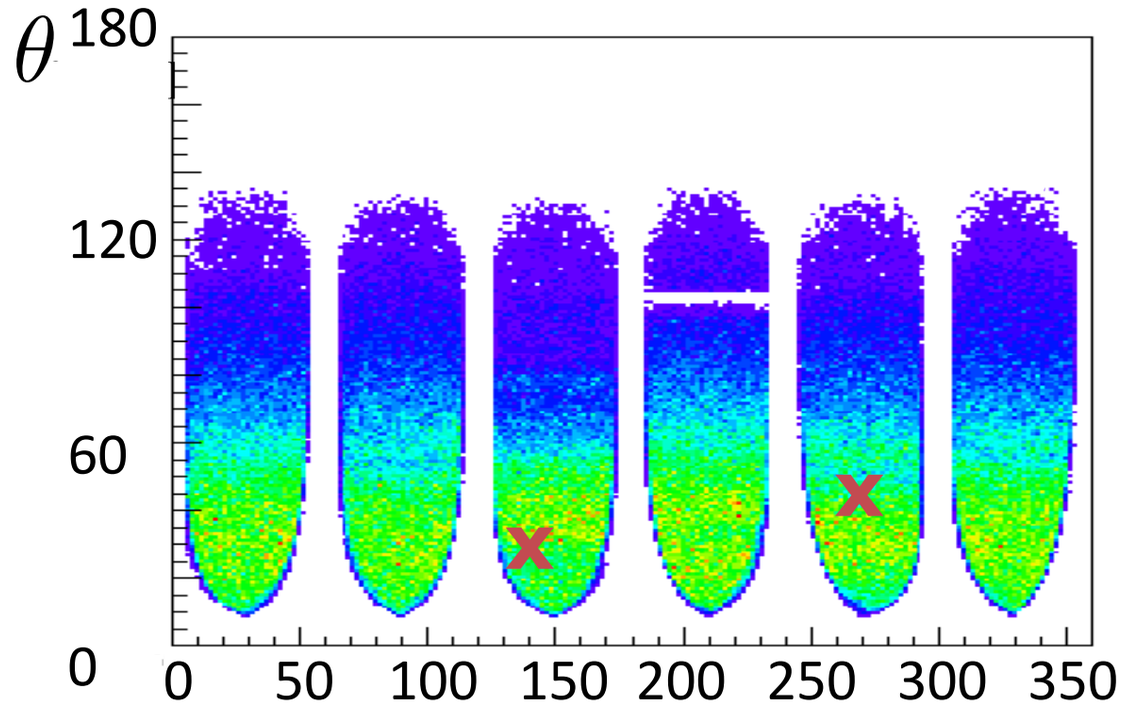


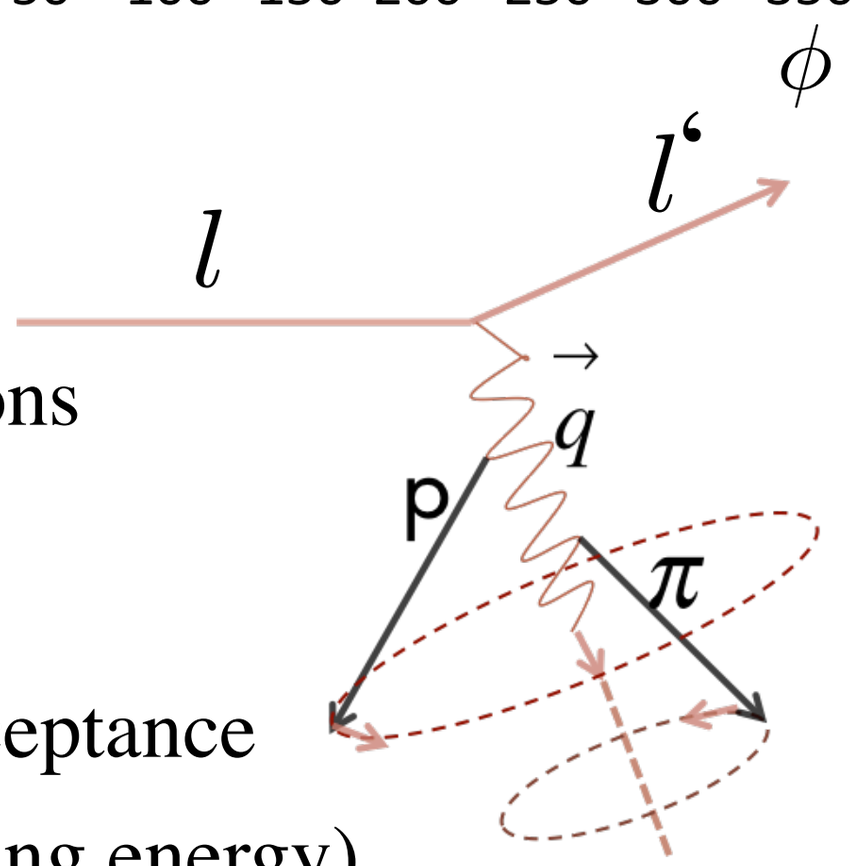


Data driven Background Subtraction

Using events with two detected hadrons



- Rotating p,π around q
- Determine event acceptance
- Subtract contribution to QE-like



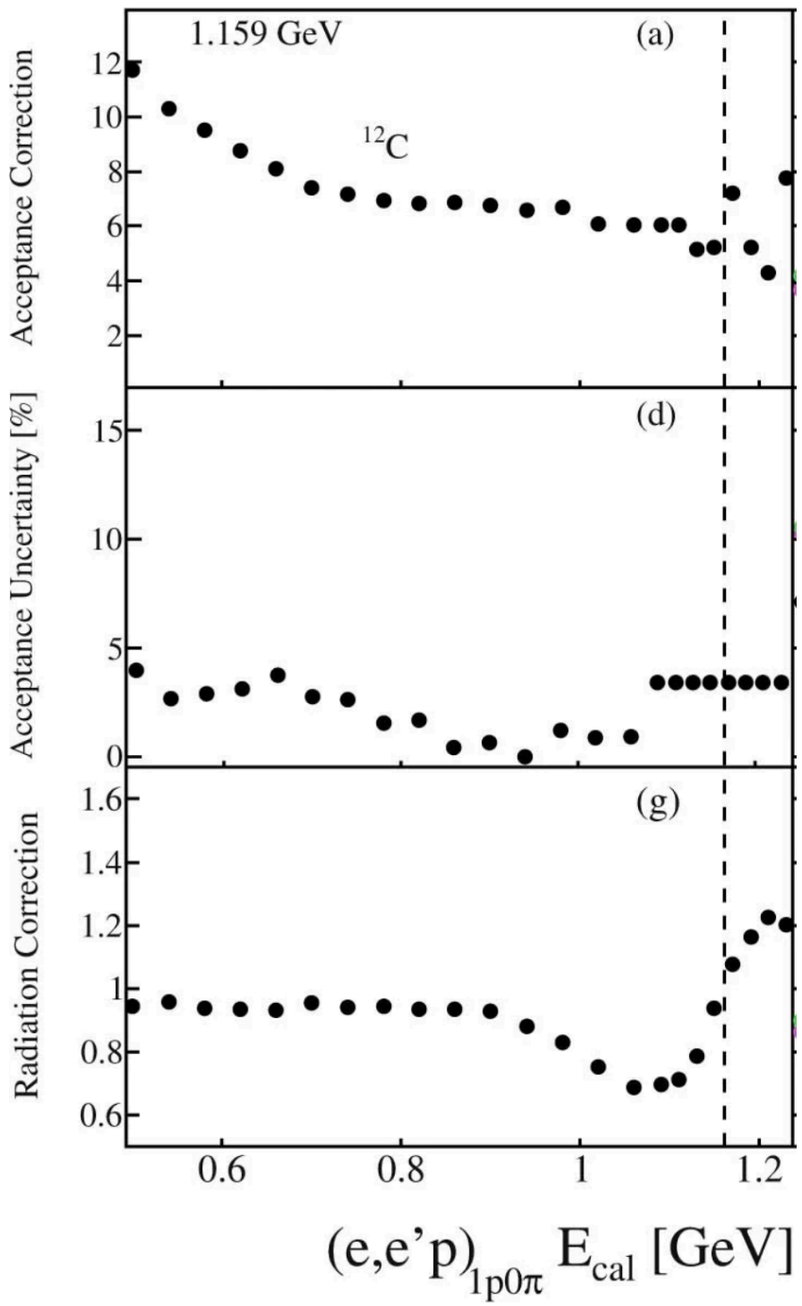
Same for final states with more than 2 hadrons

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

Unfolding

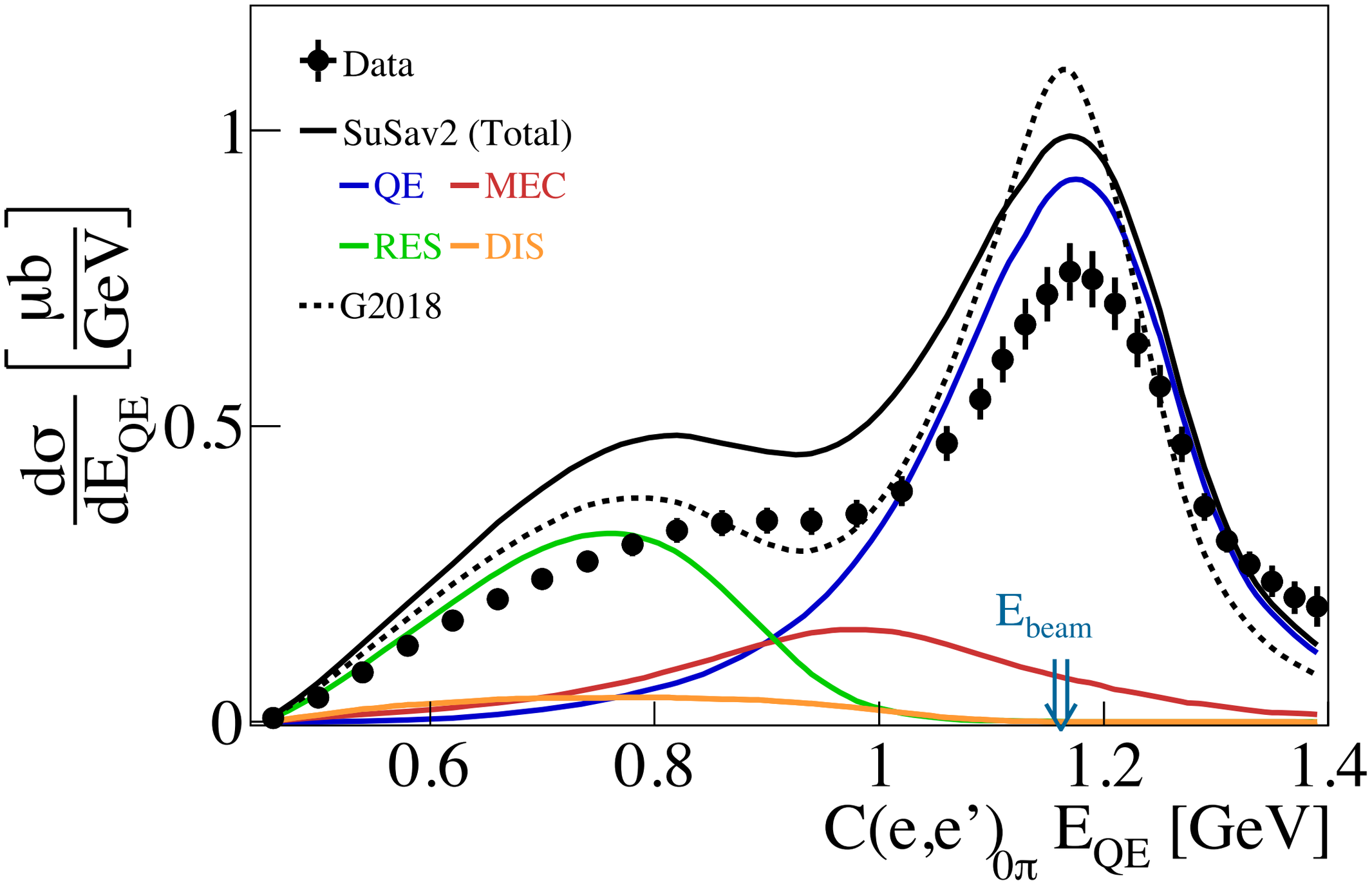
- Background subtracted distributions from data normalised by Luminosity
- Applying acceptance corrections and radiative corrections

Resulting distributions are comparable to calculated / simulated cross section predictions



Data

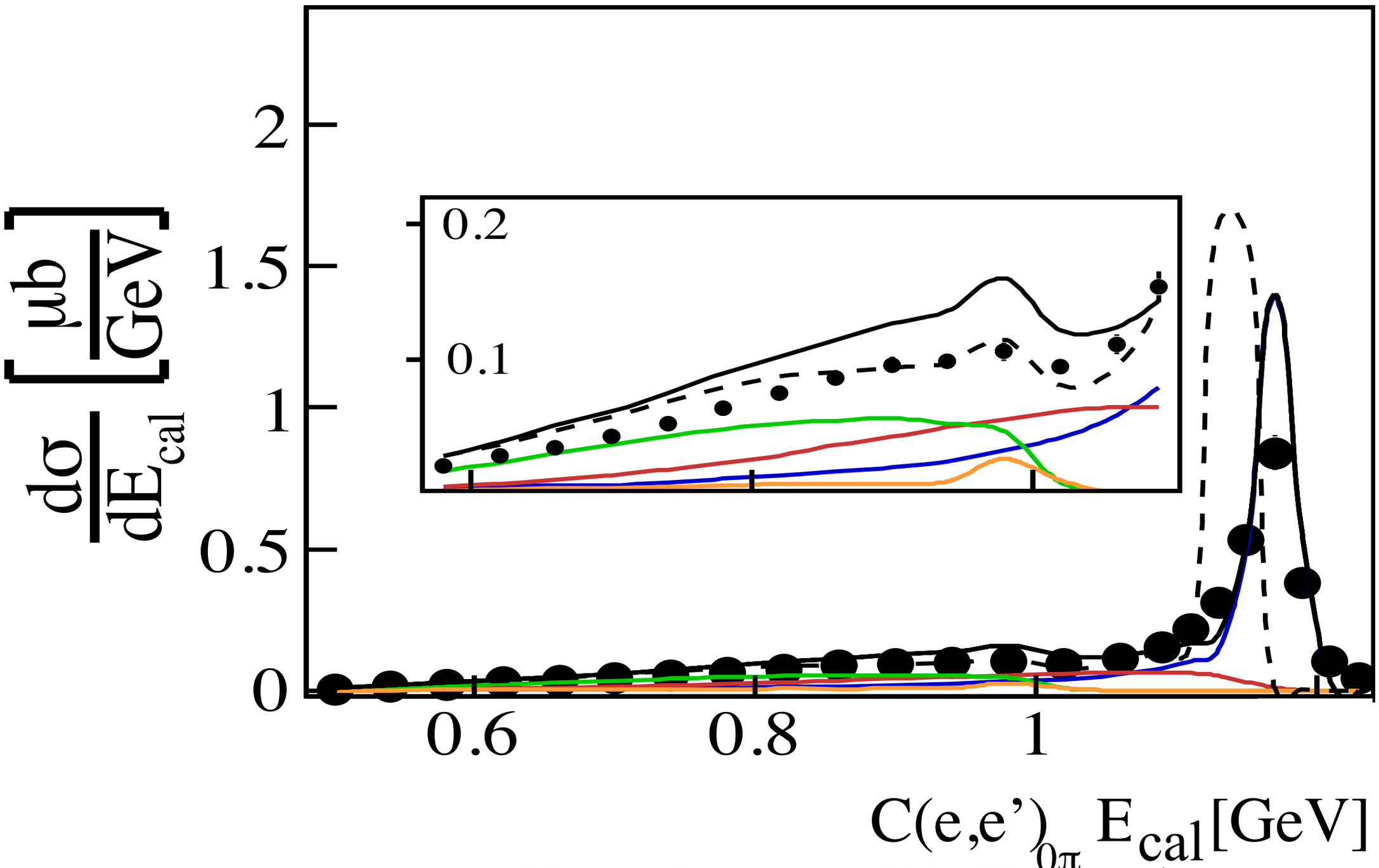
Disagreements between Data and MC



Nature **599**, pages565–570 (2021)

Disagreements between Data and MC

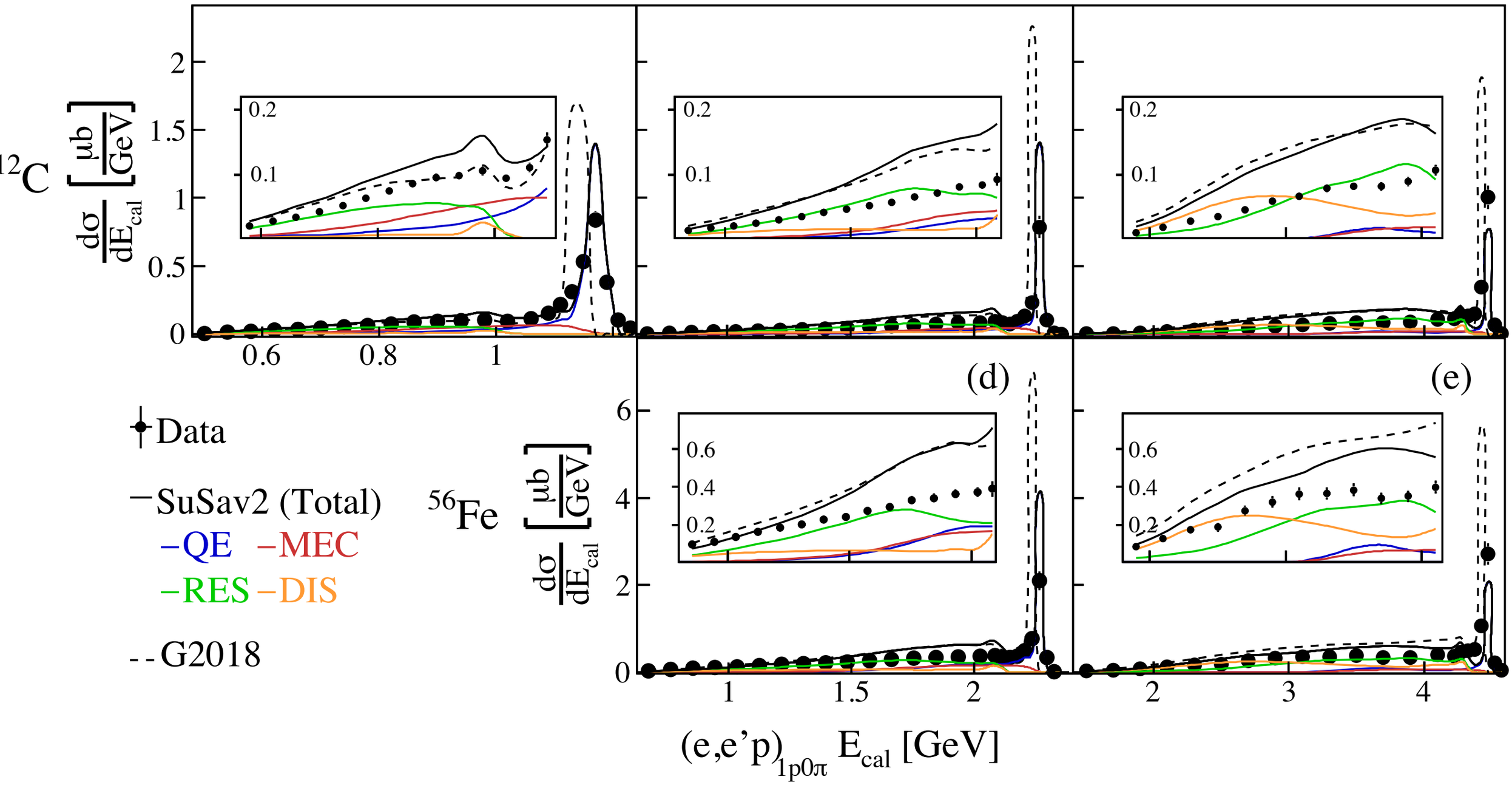
E = 1.159 GeV



Nature **599**, pages565–570 (2021)

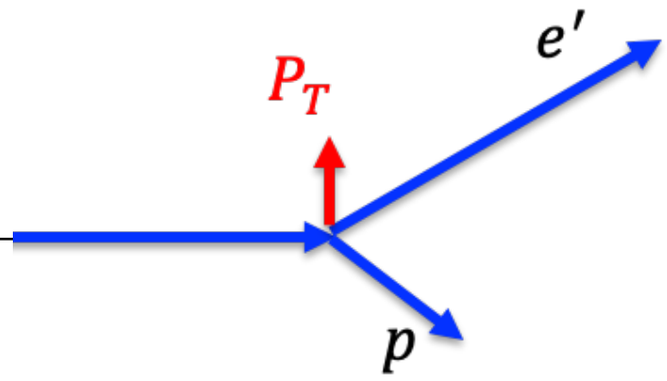
Disagreements between Data and MC

1.159 GeV 2.257 GeV 4.453 GeV

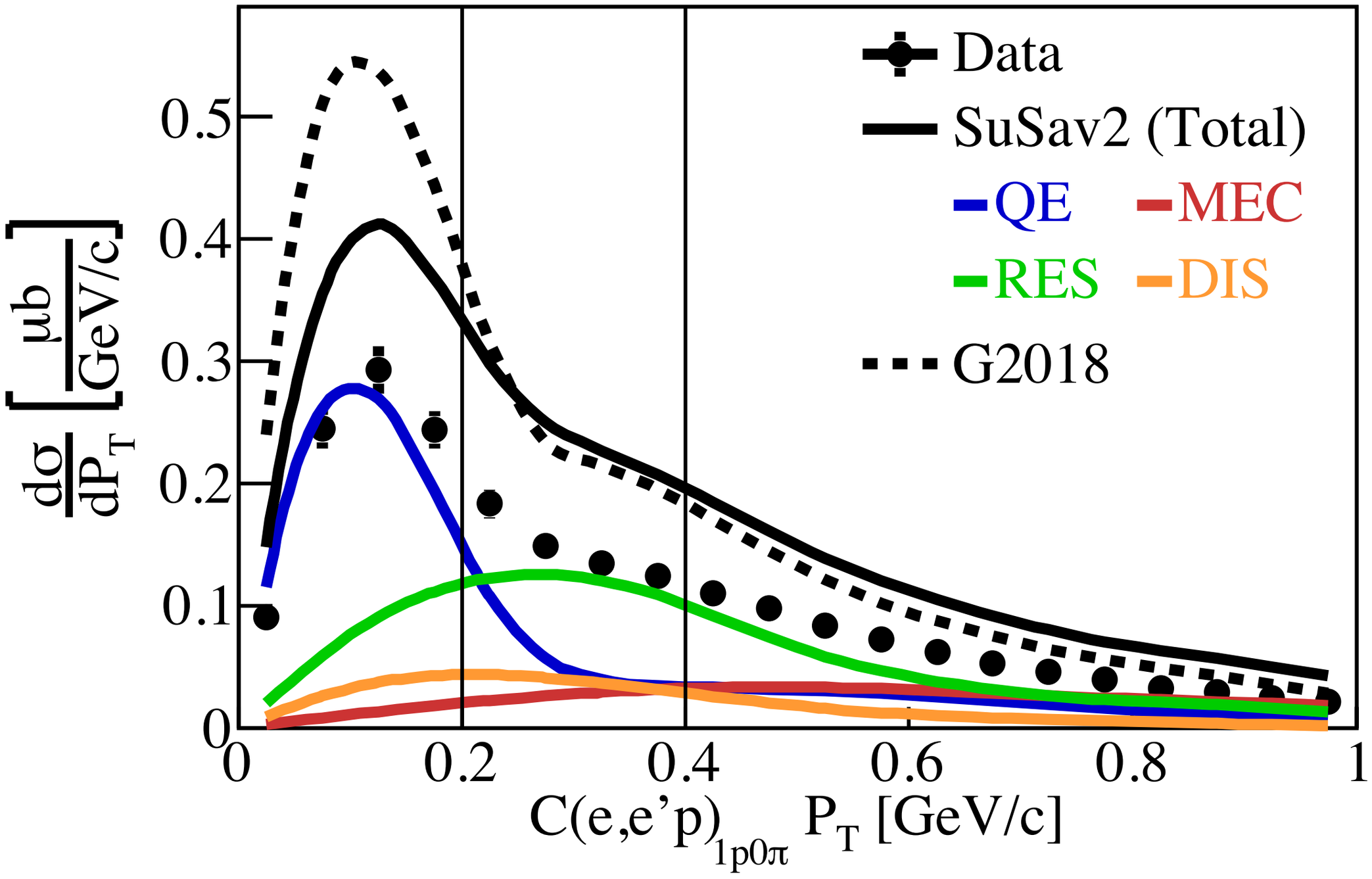


Nature **599**, pages565–570 (2021)

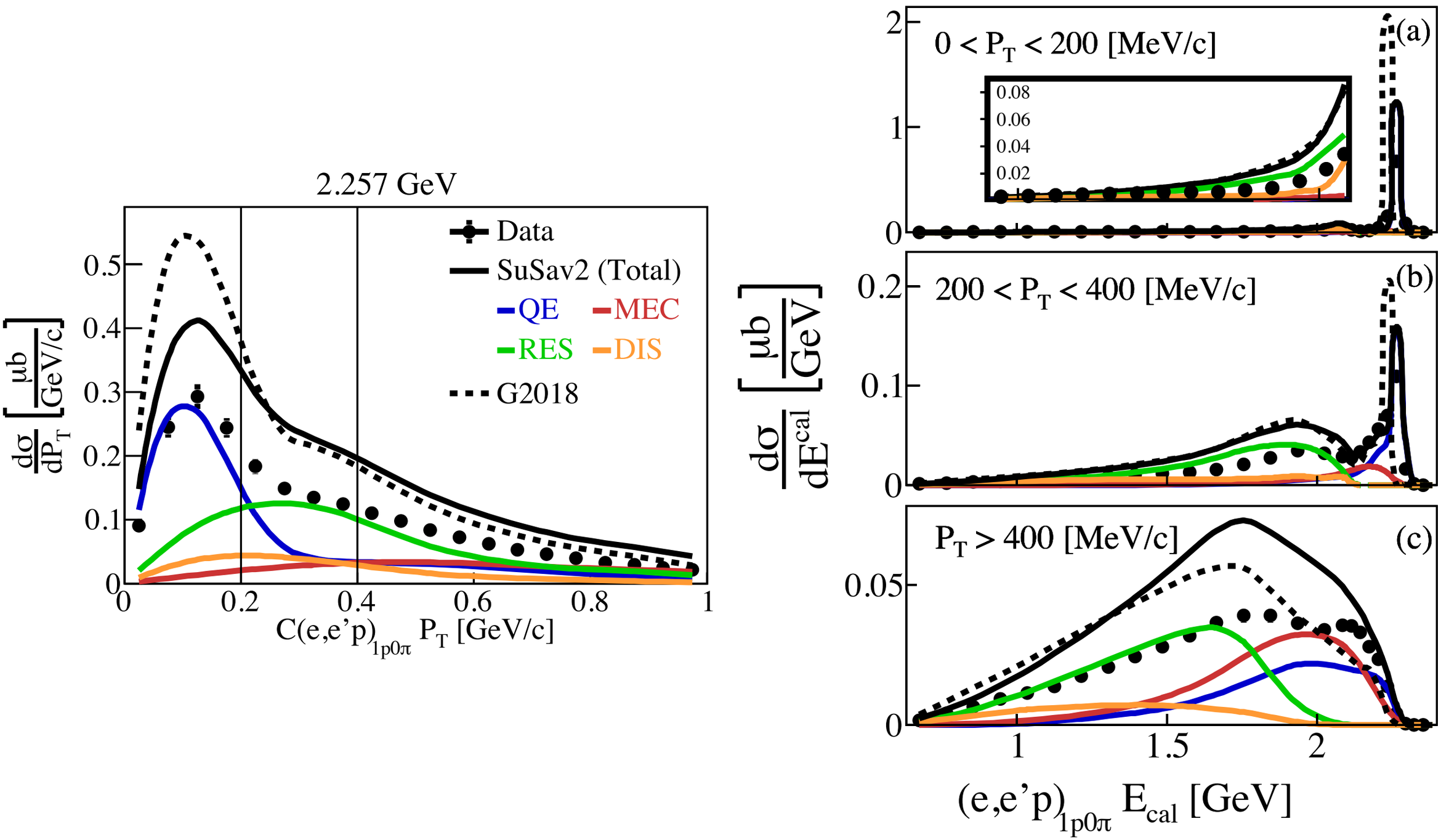
MC vs. (e,e'p) Data: $\vec{P}_T = \vec{P}_T^{e'} + \vec{P}_T^{p}$



2.257 GeV



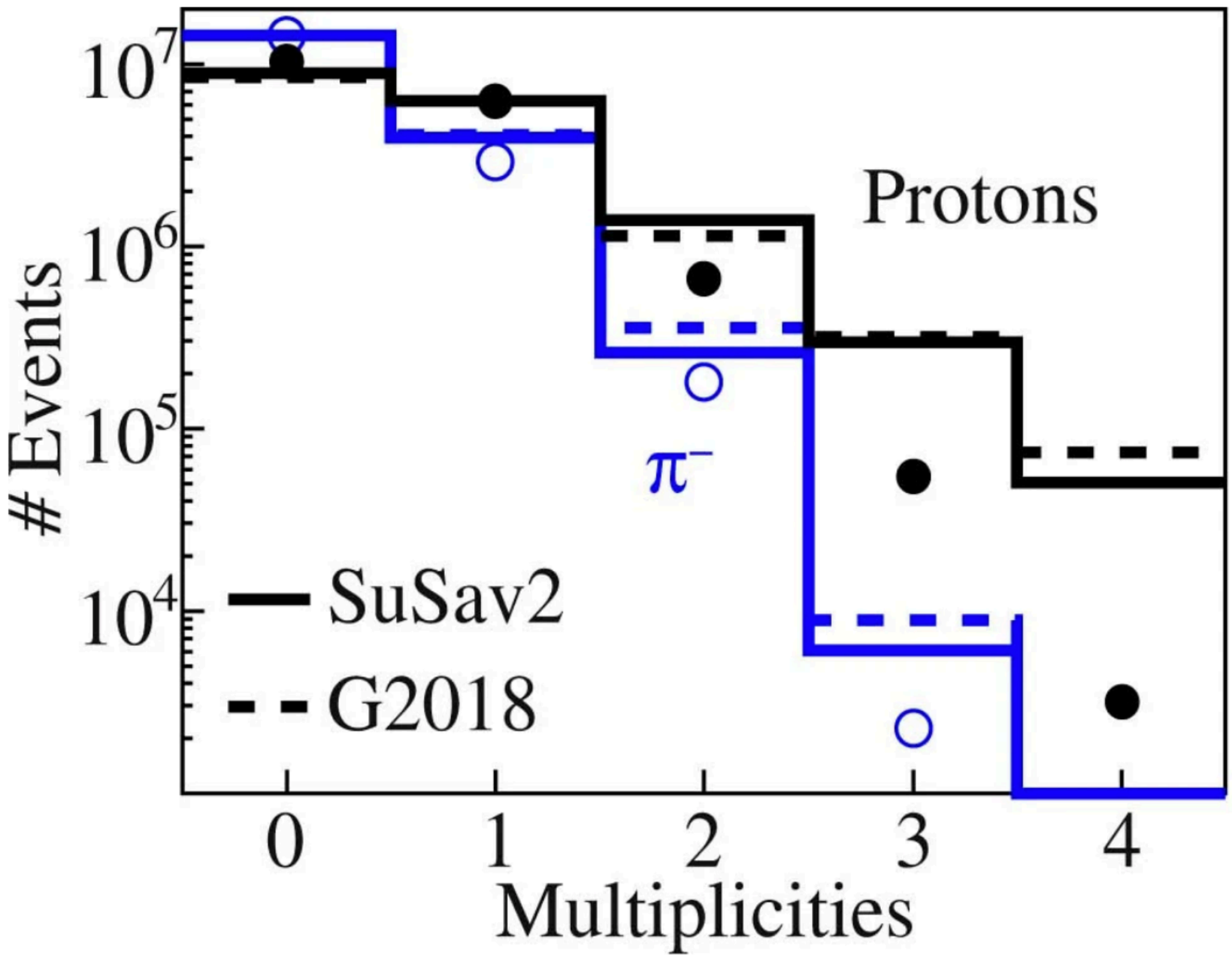
MC vs. (e,e'p) Data: $\vec{P}_T = \vec{P}_T^{e'} + \vec{P}_T^{p}$



Nature **599**, pages565–570 (2021)

Multiplicities

$E = 2.257$ GeV ^{12}C



Nature **599**, pages565–570 (2021)

Future Plans -Approved run for CLAS12

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

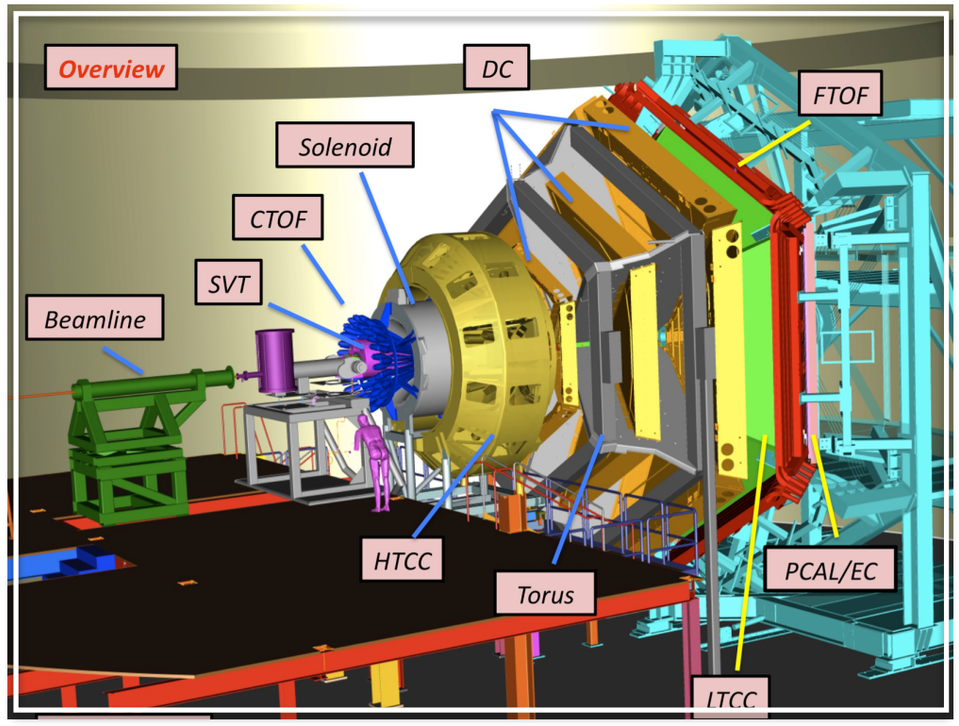
x10 luminosity [10^{35} cm^{-2}s^{-1}]

Keep low thresholds

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

2, 4, 6 GeV (relevant for DUNE)

Data was taken by January 2022



Overwhelming support from:

Summary

- Testing νA Models using wide phase-space eA data.

- Data-MC disagreements for QE-like lepton+proton events
  - Especially for high transverse momentum.
  - Large potential impact on DUNE

- Our data will help improve models

- More data coming very soon

Complementary efforts

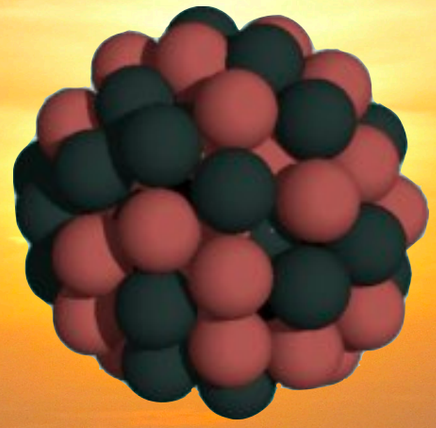
Collaborations	Kinematics	Targets	Scattering
E12-14-012 (JLab) (Data collected: 2017) Jefferson Lab	$E_e = 2.222$ GeV $\theta_e =$ 15.5, 17.5, 20.0, 21.5 $\theta_p =$ -39.0, -44.0, -44.5, -47.0 -50.0	Ar, Ti Al, C	(e, e') $(e, e'p)$
e4nu/CLAS (JLab) (Data collected: 1999, 2022) Jefferson Lab	$E_e =$ 1, 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
LDMX (SLAC) SLAC	$E_e = 4.0$ GeV $\theta_e < 40$		(e, e') e, p, n, π in the final state
A1 (MAMI) mami MAINZER MIKROTRON	$E_e = 1.6$ GeV	H, D, He C, O, Al Ca, Ar, Xe	(e, e') 2 additional charged particles
eALBA (Planned) ALBA	$E_e =$ 500 MeV - few GeV	C, CH Be, Ca	(e, e')

Table 5: Current and planned electron scattering experiments.

Taken from the Electron Scattering white paper draft

This time we'll have to be remote

Next time in Tel Aviv



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Thank you for your attention