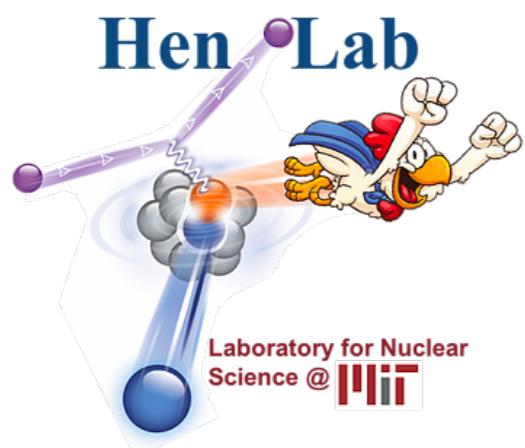


ELECTRONS FOR NEUTRINO 2020



Adi Ashkenazi (MIT)
on behalf of the $e4\nu$ collaboration



06/23/2020

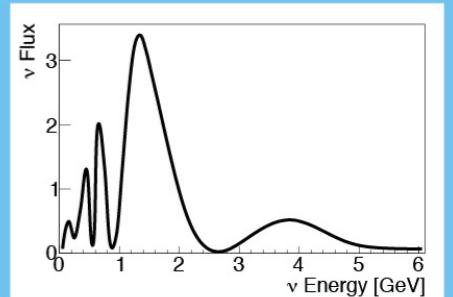


PHYSICS PROCESS

Particles shoot out

Interacts with nucleus

Neutrino comes in

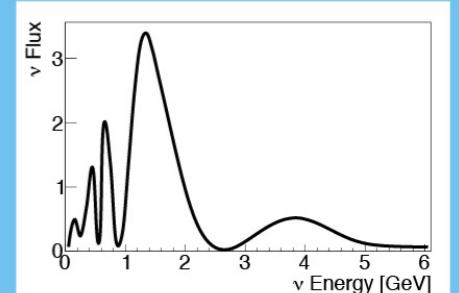


PHYSICS PROCESS

Particles shoot out

Interacts with nucleus

Neutrino comes in



Measure Particles

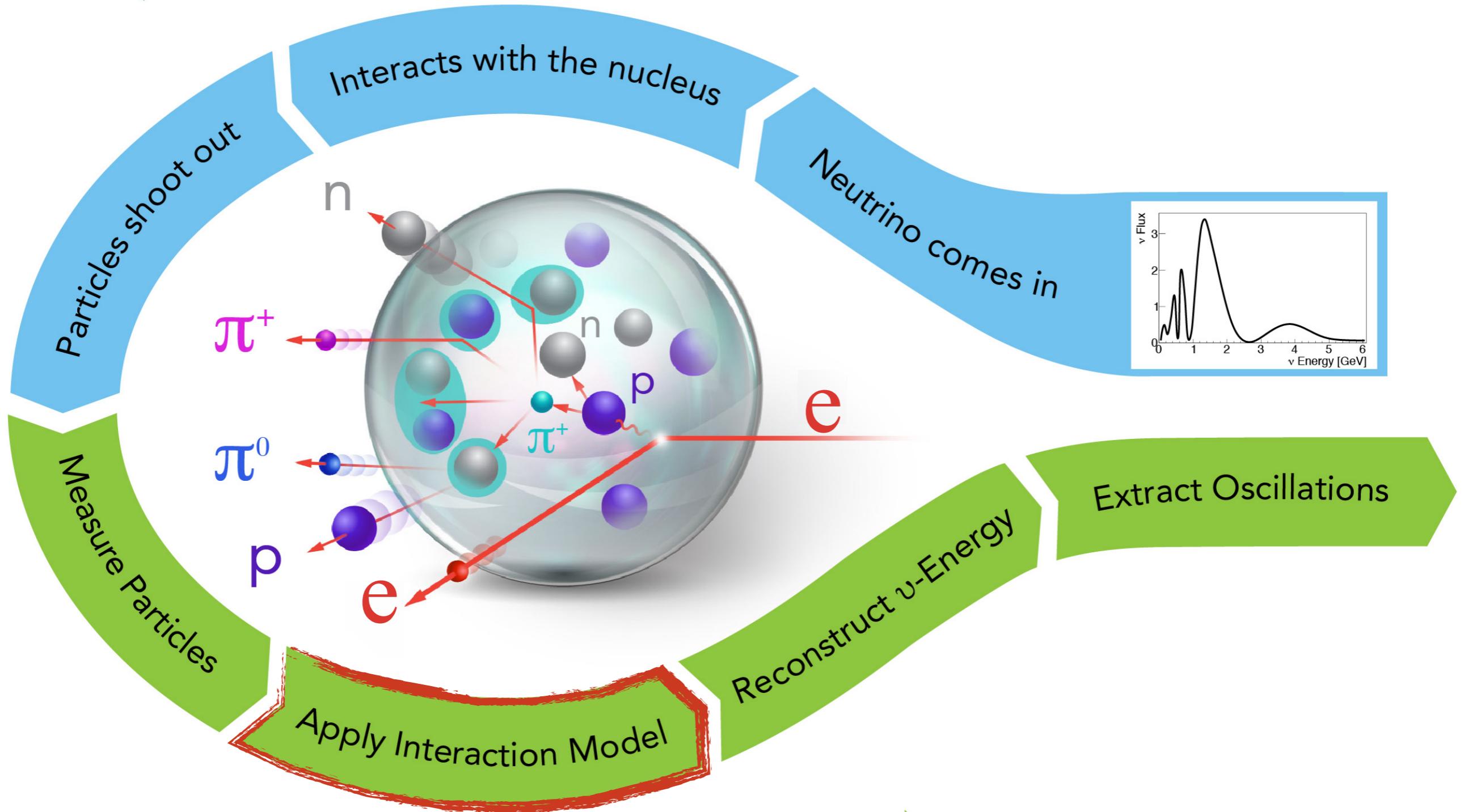
Apply Interaction Model

Reconstruct ν -Energy

Extract Oscillations

EXPERIMENTAL ANALYSIS

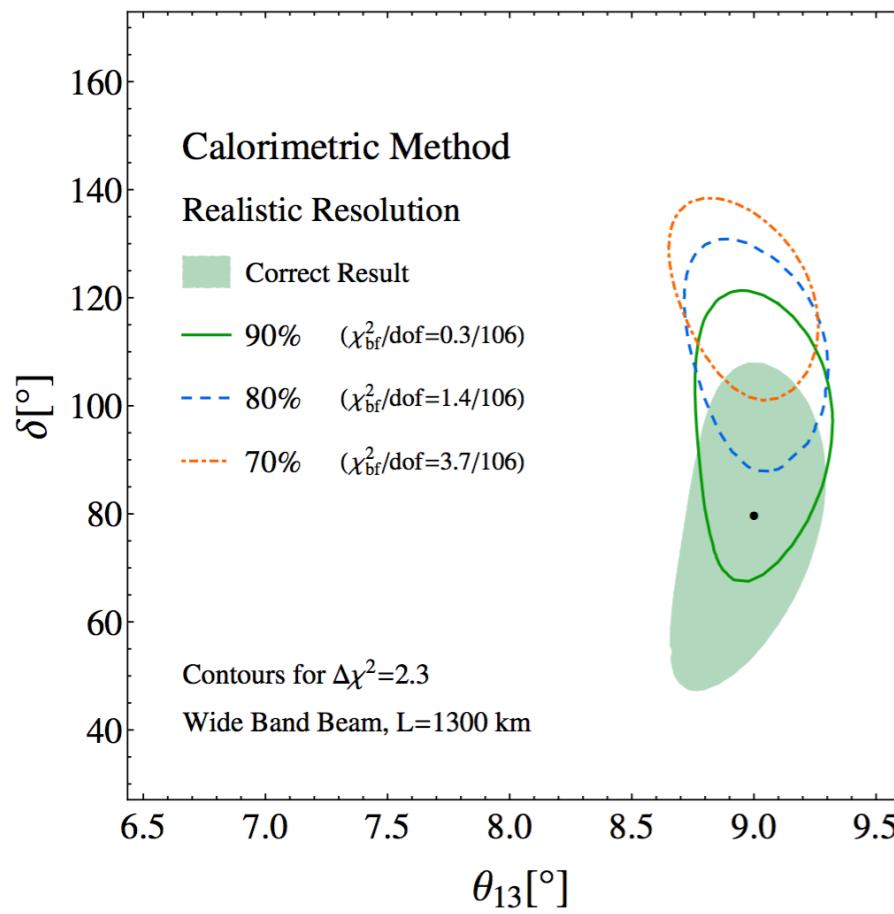
PHYSICS PROCESS



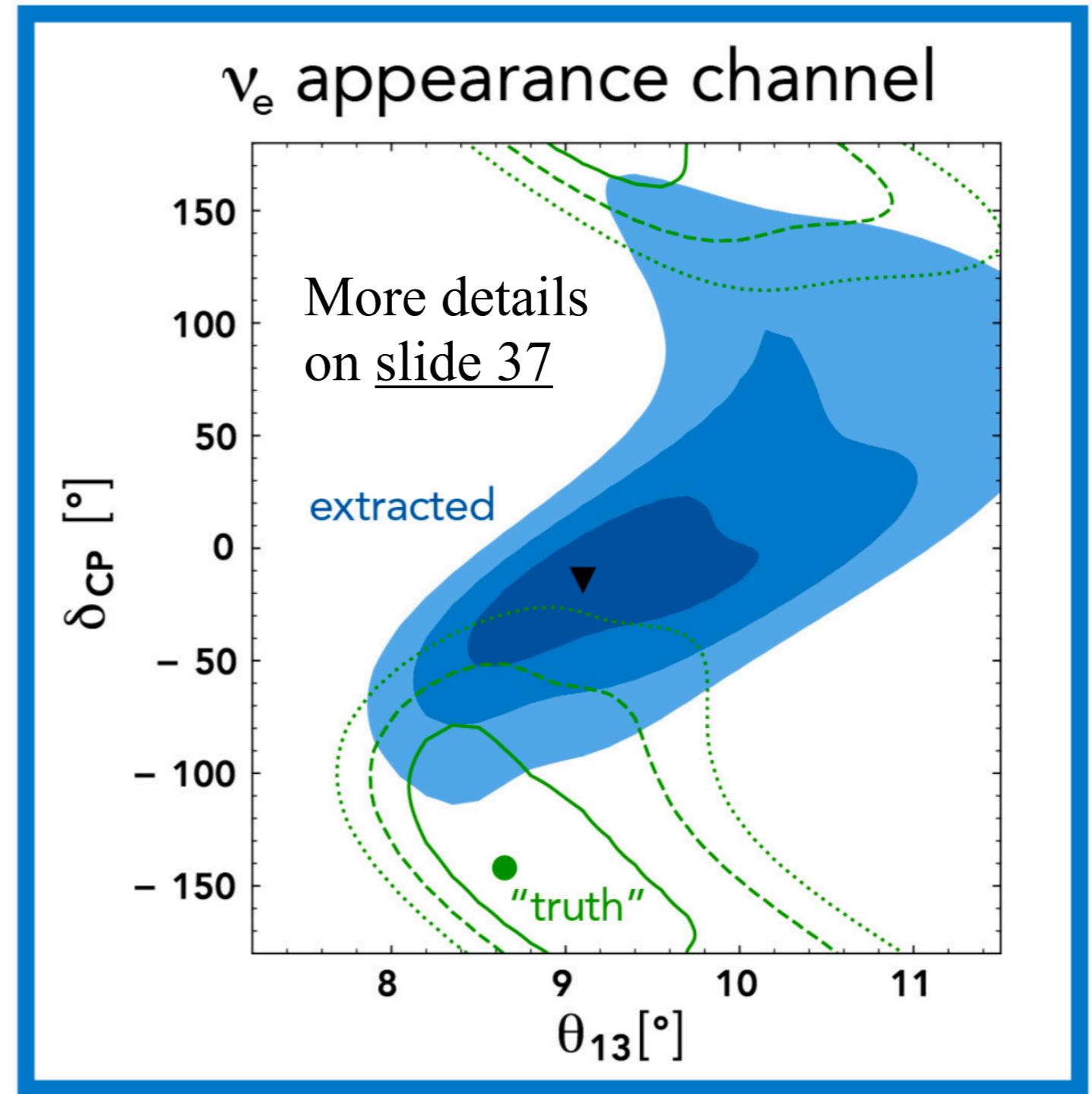
EXPERIMENTAL ANALYSIS

Miss-modelling might impact mixing parameters

Extract Oscillations

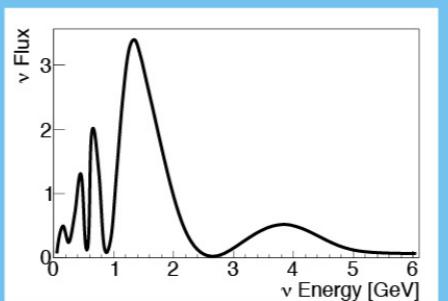


Phys. Rev. D 92, 091301 (2015)



The Challenge

Neutrino comes in



Reconstruct ν -Energy

Extract Oscillations

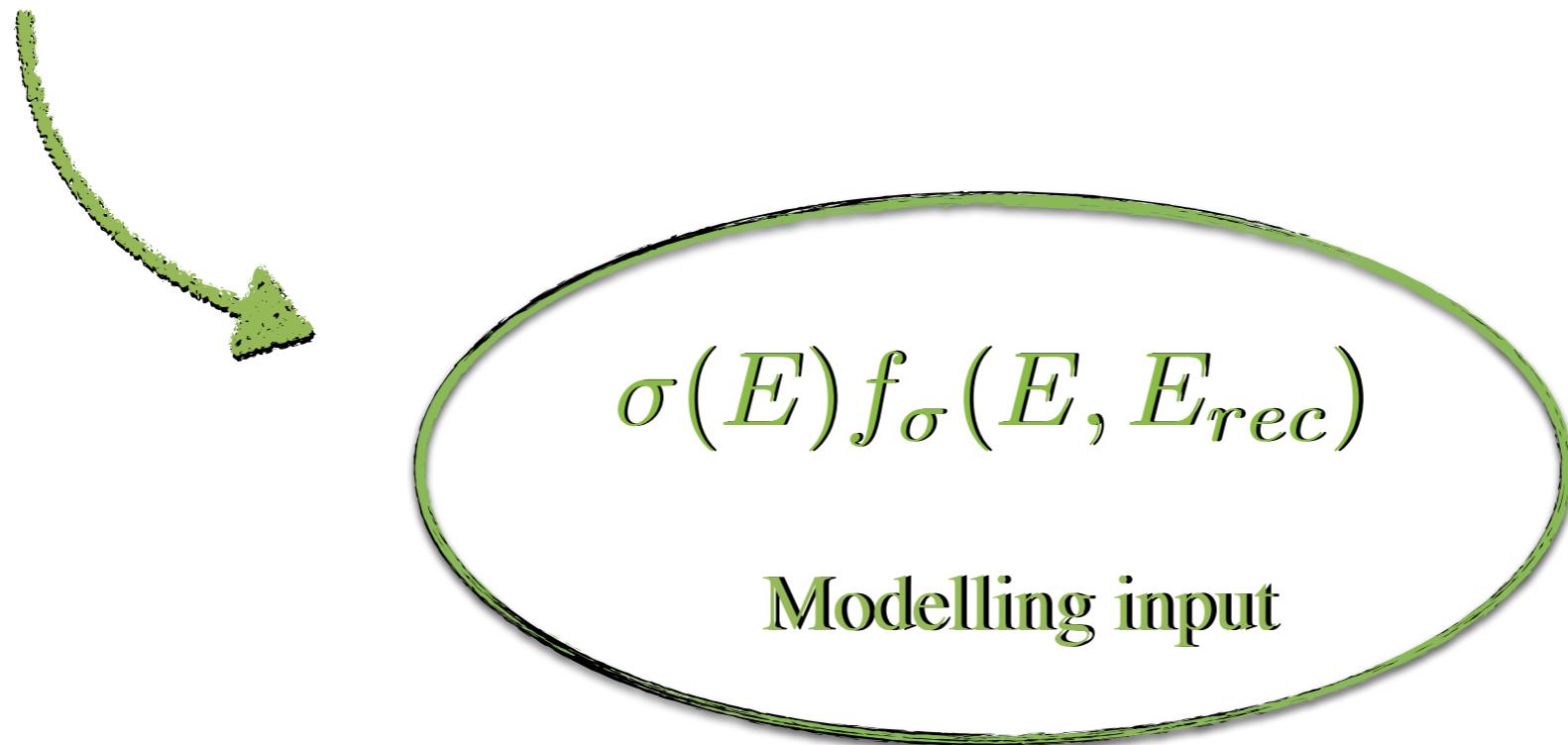
$$N(E_{rec}, L) \propto \int \Phi(E, L) \sigma(E) f_\sigma(E, E_{rec}) dE$$

Measurement

Incoming true flux Modelling input

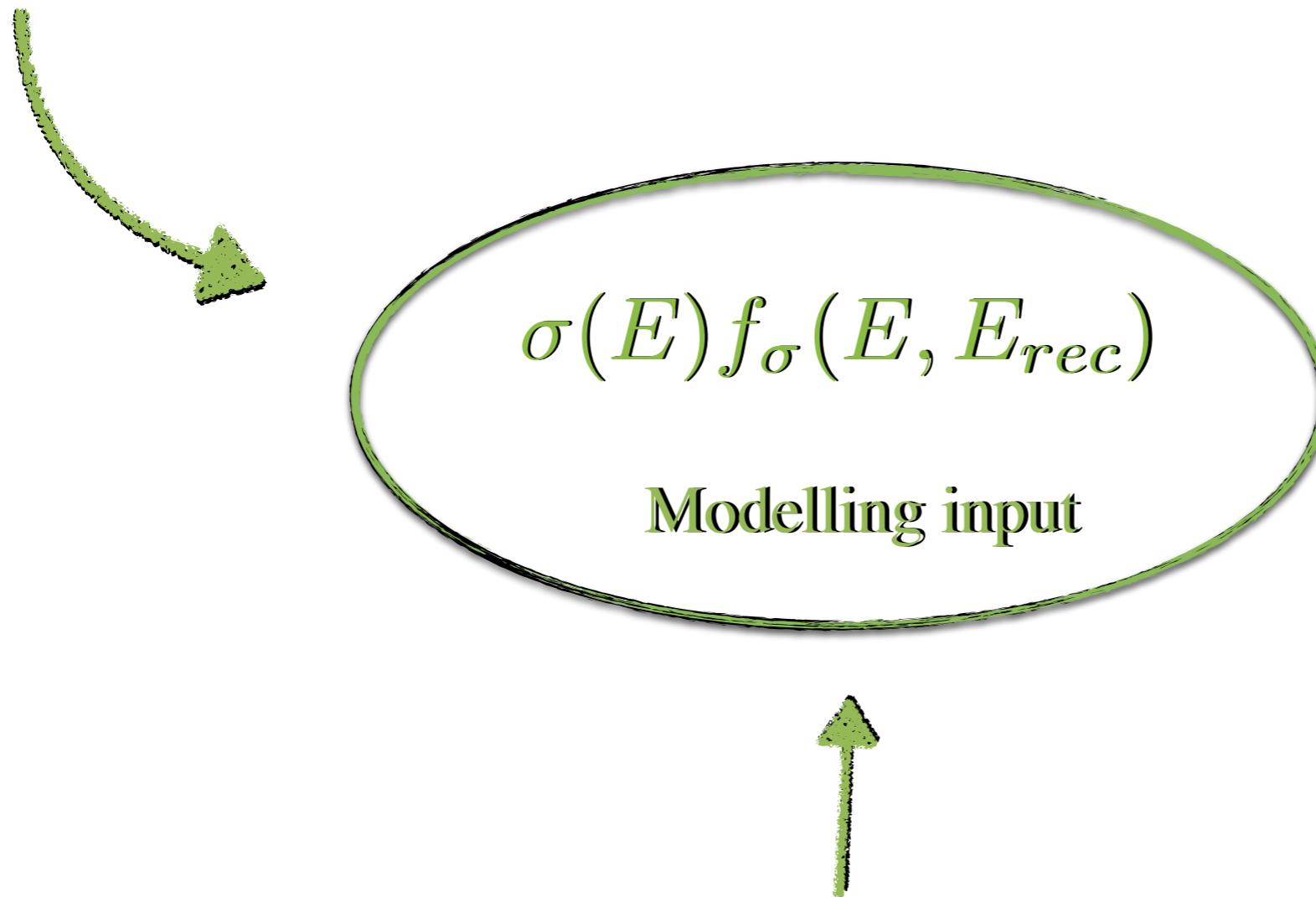
How to improve modelling?

Improve theory



How to improve modelling?

Improve theory

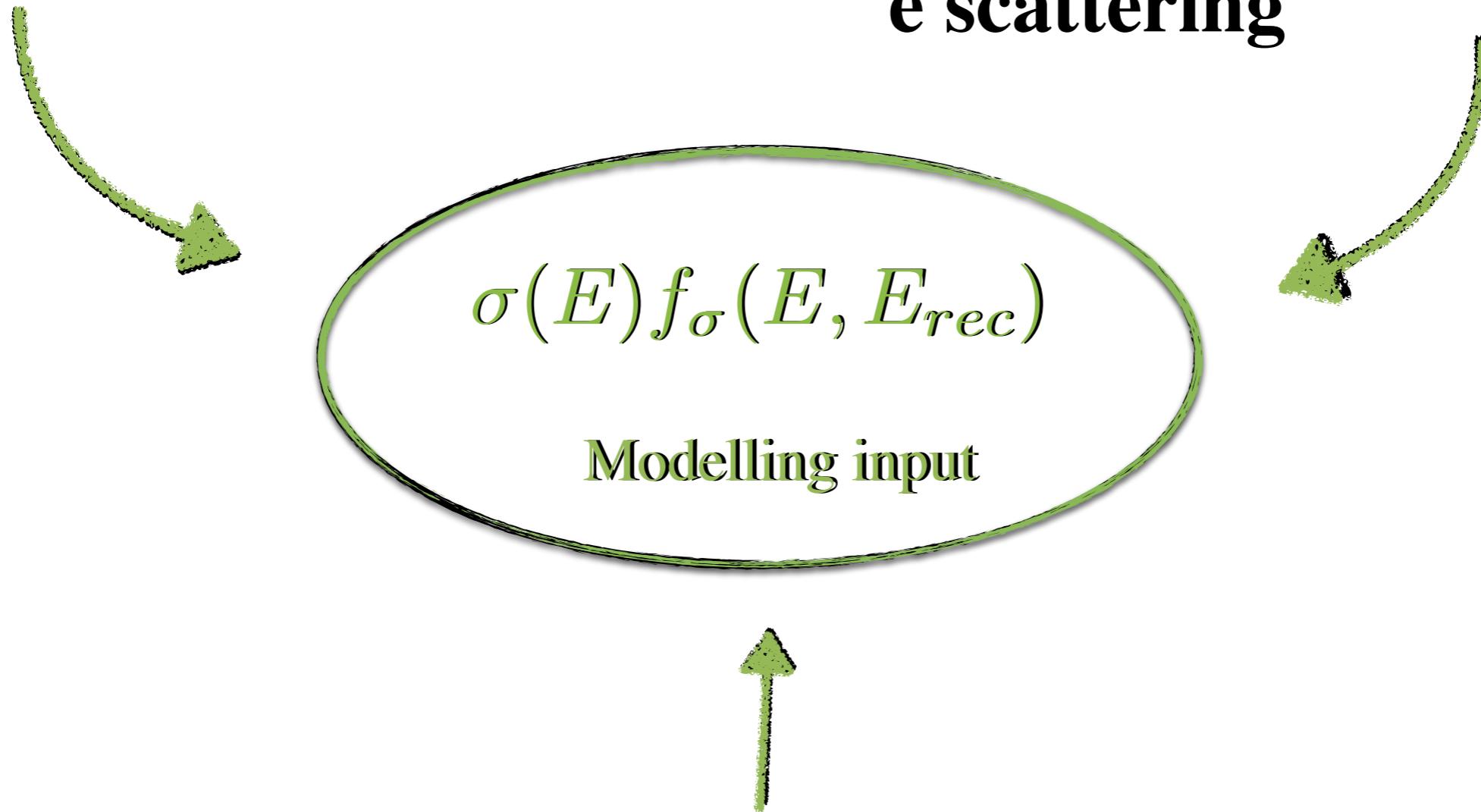


Use near detector

How to improve modelling?

Improve theory

Use external constraints
e scattering

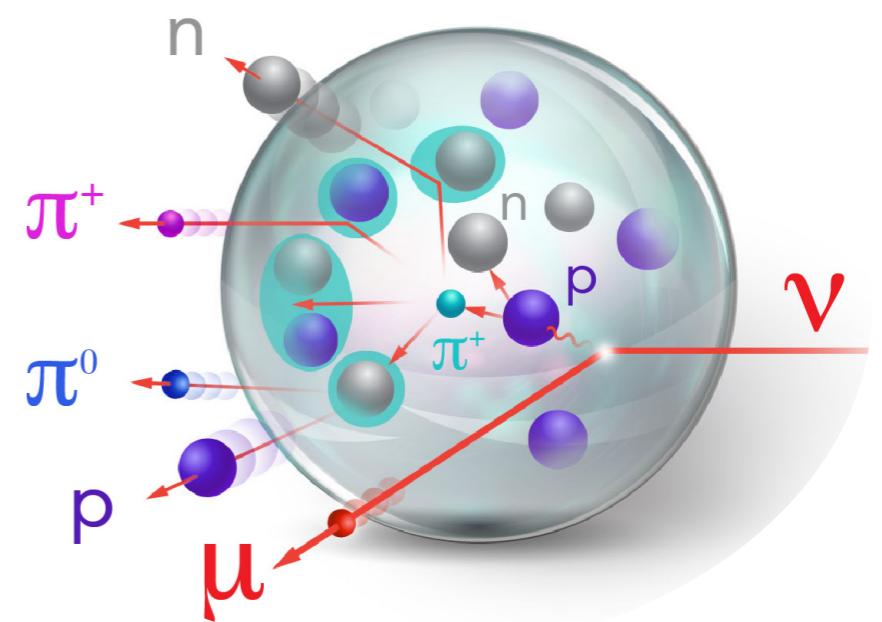


Use near detector

Why Electrons?

- Electrons and Neutrinos have:
 - Similar interactions
 - Vector vs. Vector + Axial Vector
- Many identical nuclear effects
 - Ground state (spectral function)
 - Final state interactions

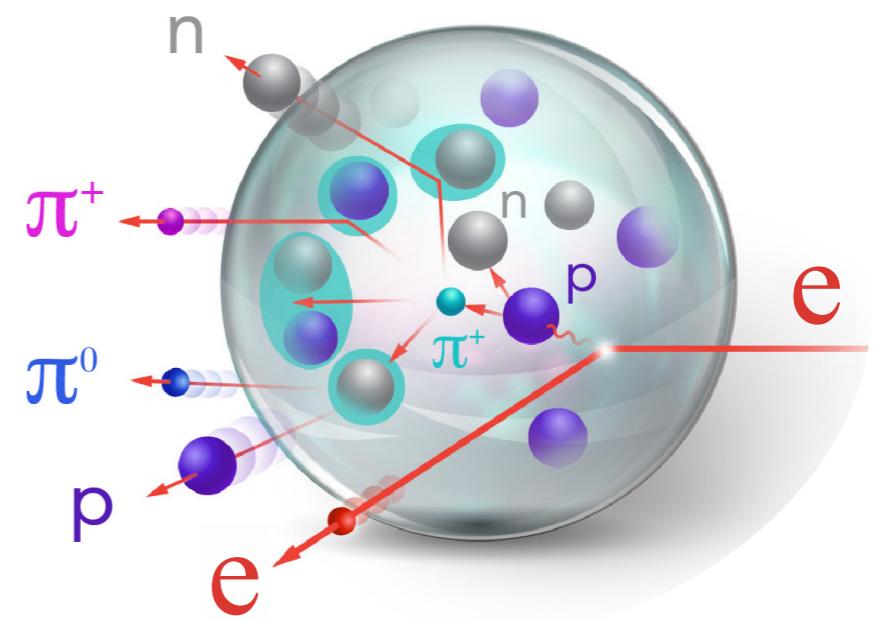
Electron beams have known energy



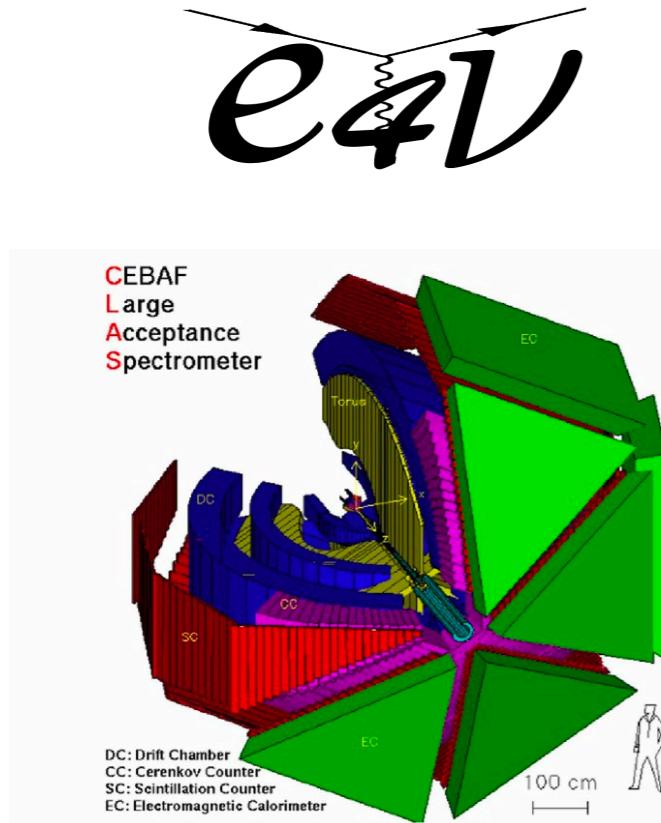
Why Electrons?

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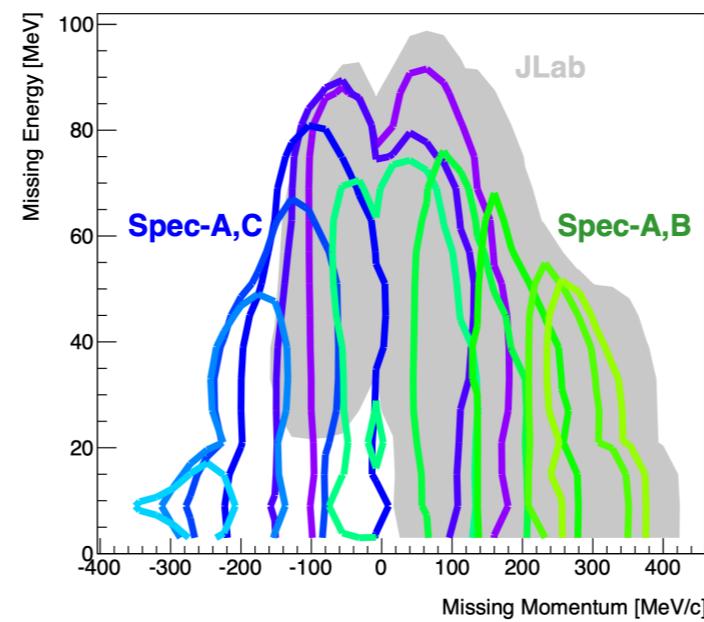


Possible electron facilities

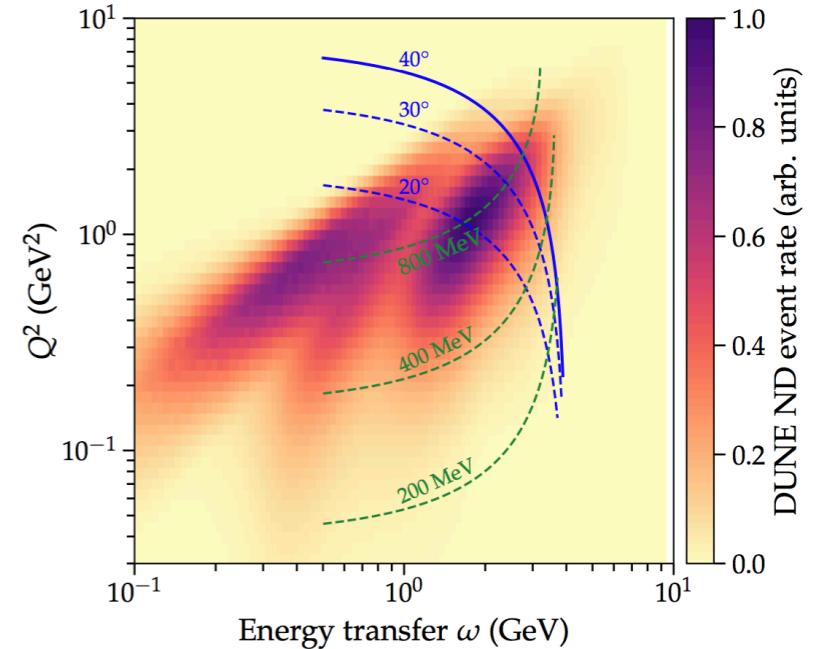


Jefferson Lab

Mainz MAMI
accelerator testing
their sensitivity



Lepton-Nucleus σ
Measurements with
LDMX



SLAC

CLAS6 Detector

Electron beam with energies up to 6 GeV

Large acceptance

Charged particles above detection threshold:

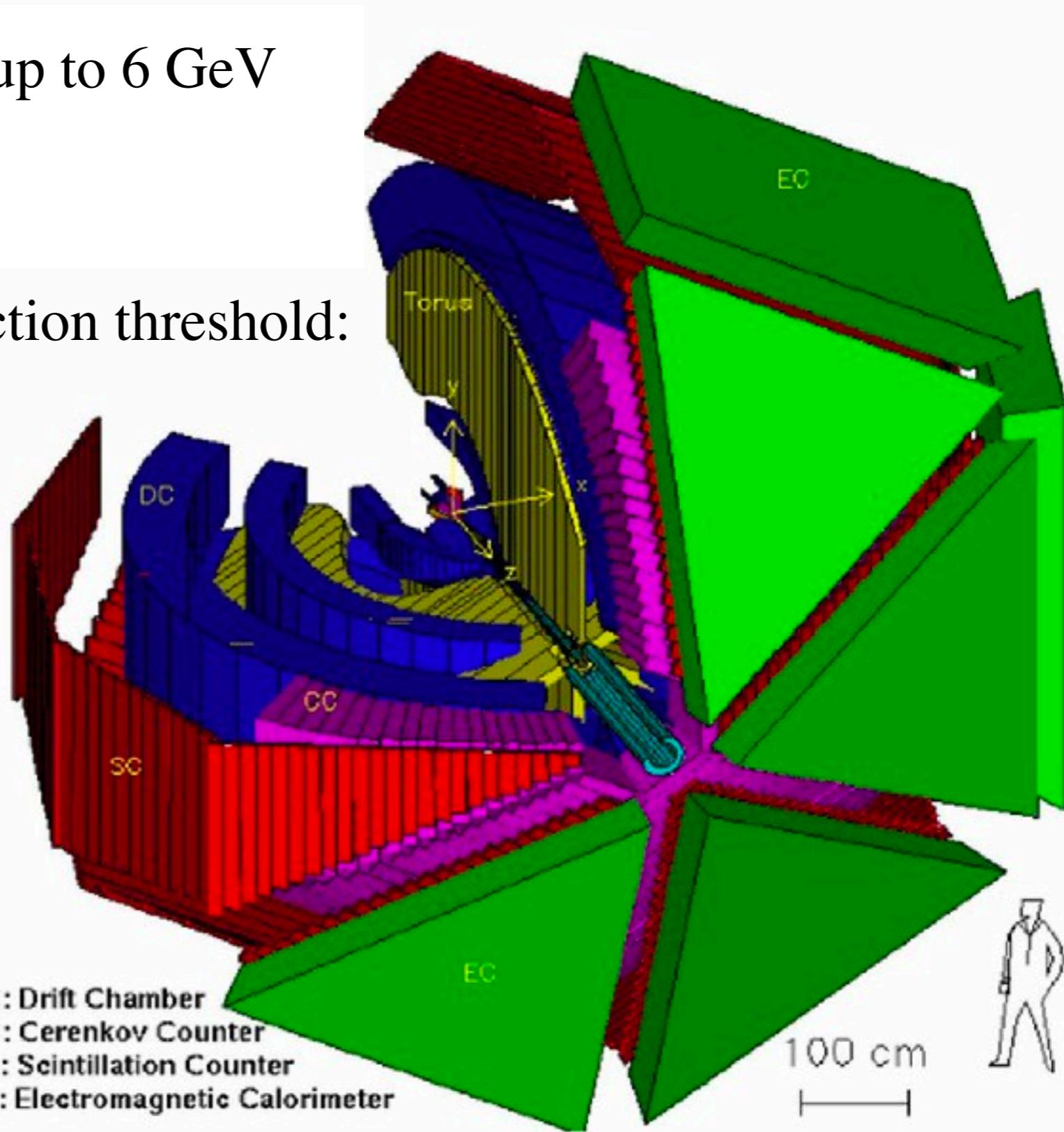
$$\theta_e > 15^\circ$$

$$P_p > 300 \text{ MeV}/c$$

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

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

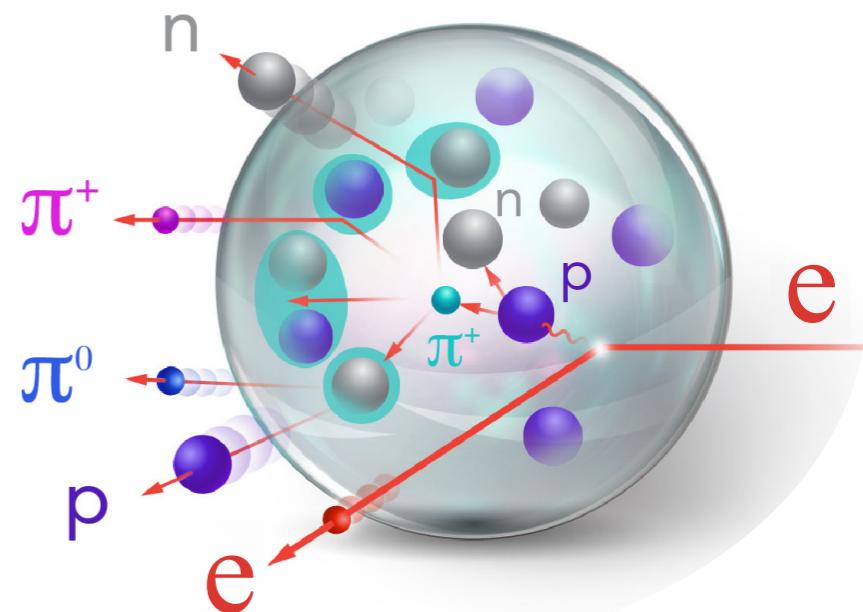
Open Trigger



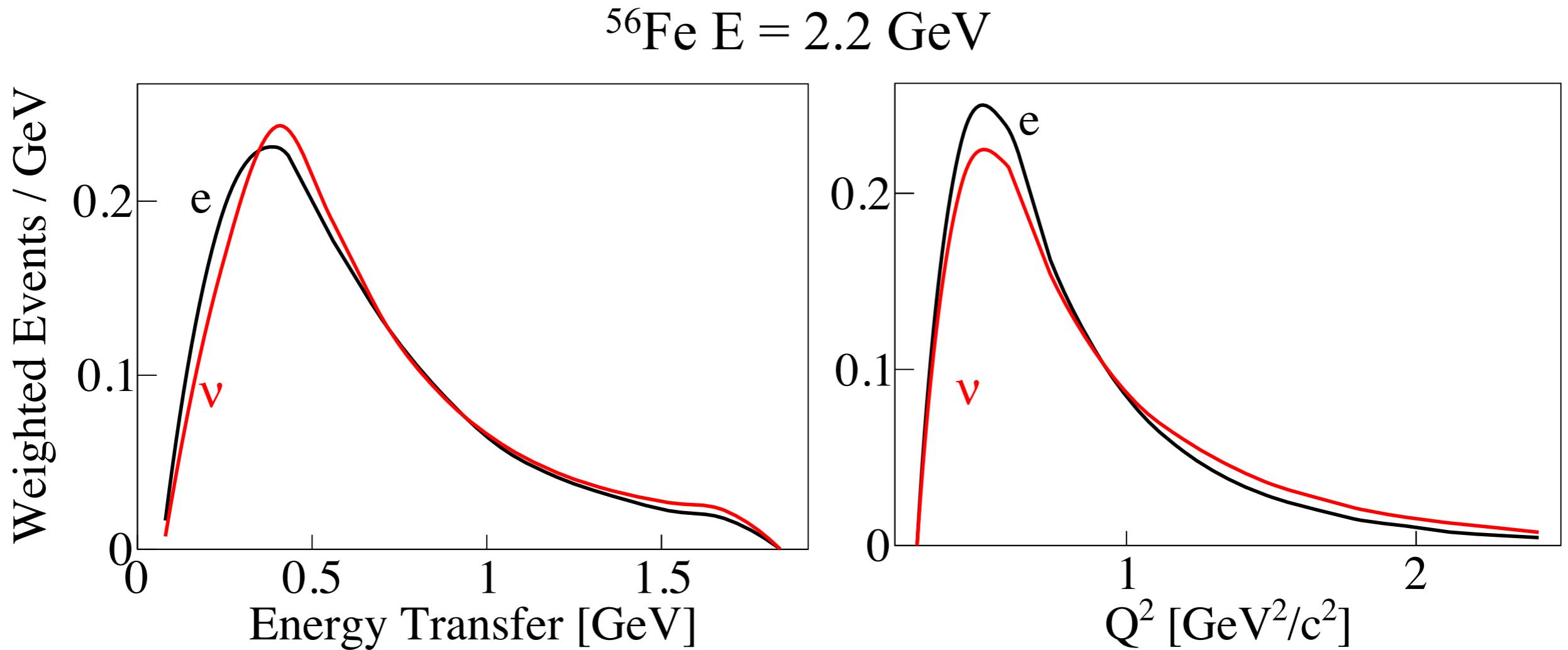
$e4V$: Playing the Neutrino game

Analyse electron data as neutrino data

- Select lepton + proton final state ($1p0\pi$)
- Scale by $\sigma_{\nu N}/\sigma_{e N} \propto 1/Q^4$
- Reconstruct incoming lepton energy
- Benchmark neutrino event generators

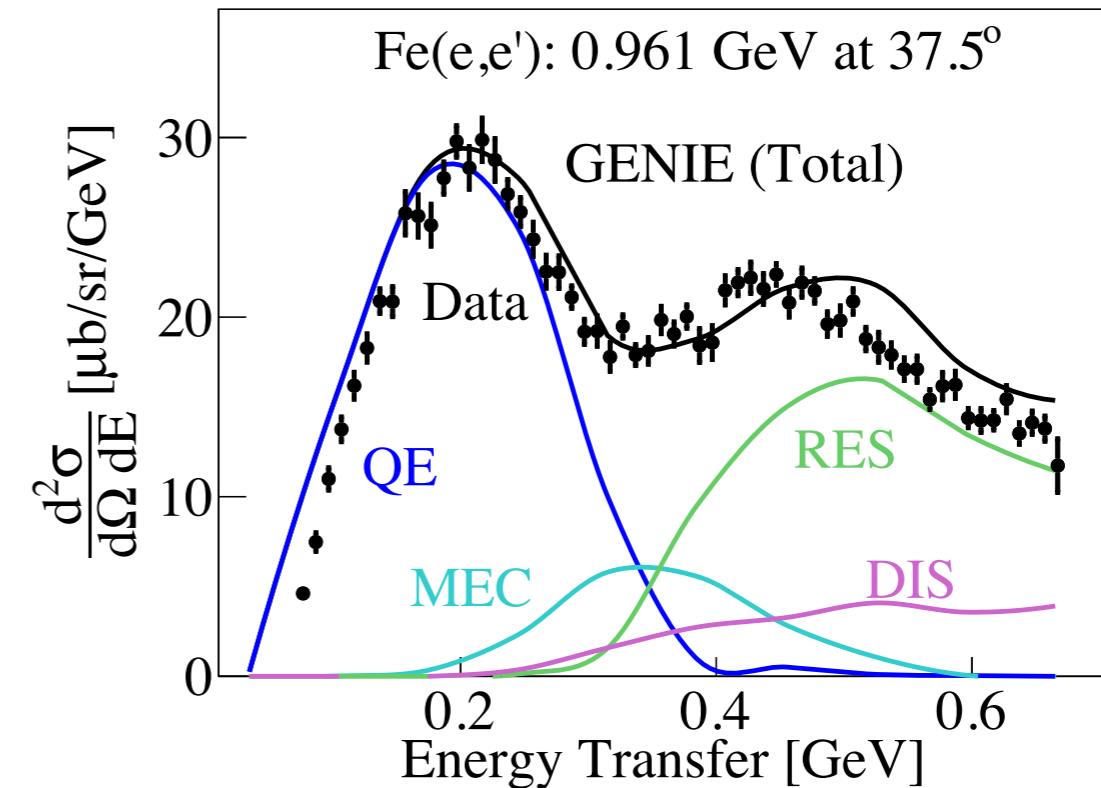
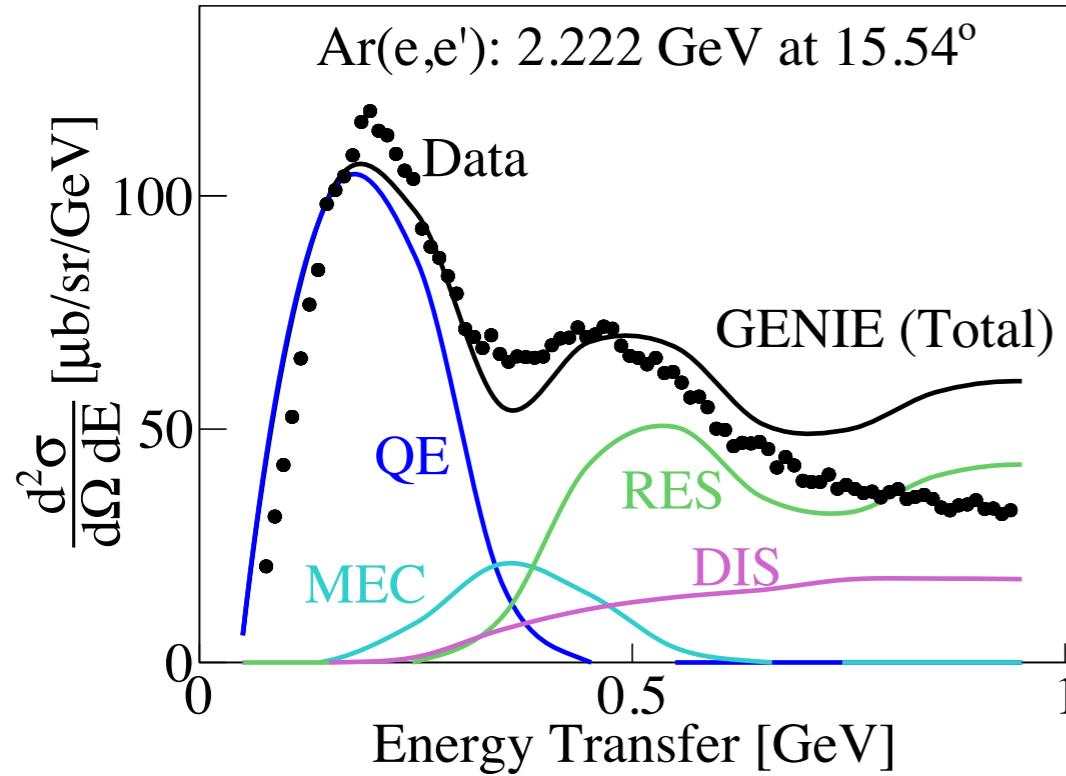


1p0 π electrons vs. neutrinos

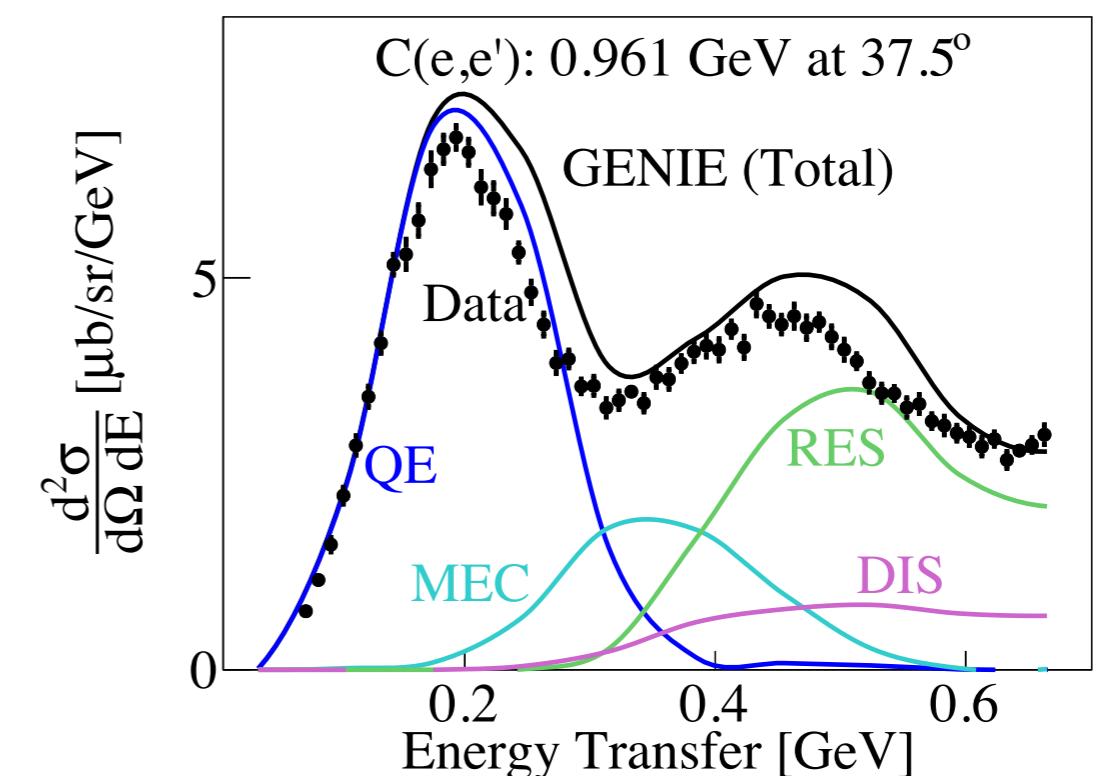


Genie v3.0.6 tune G18_10a_02_11a Electron were weighted by $1/Q^4$

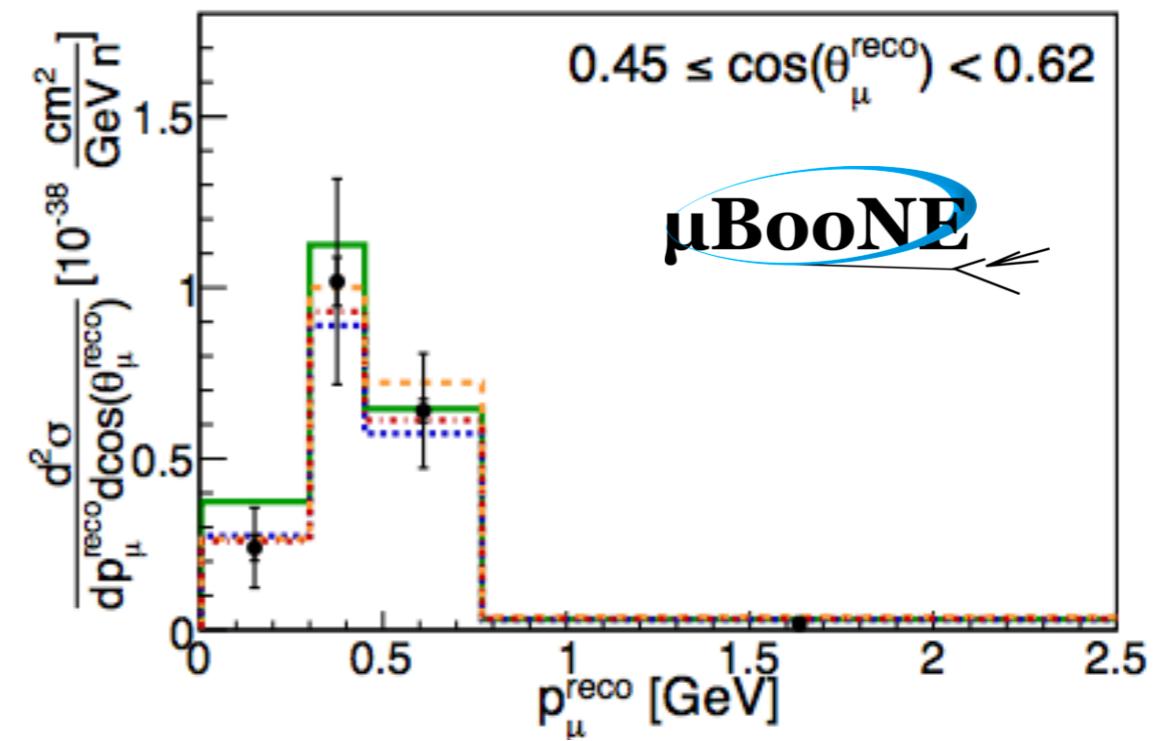
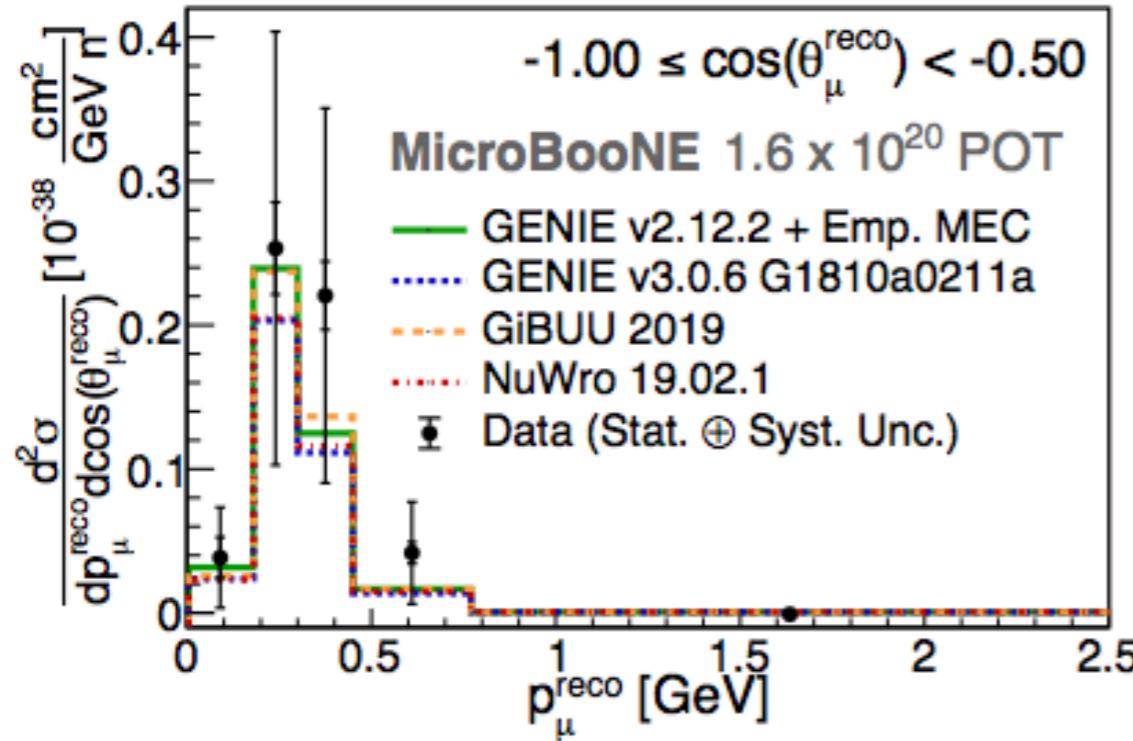
GENIE reproduced e inclusive data



Genie
— v3.0.6 tune G18_10a_02_11a
For more details see backup slides



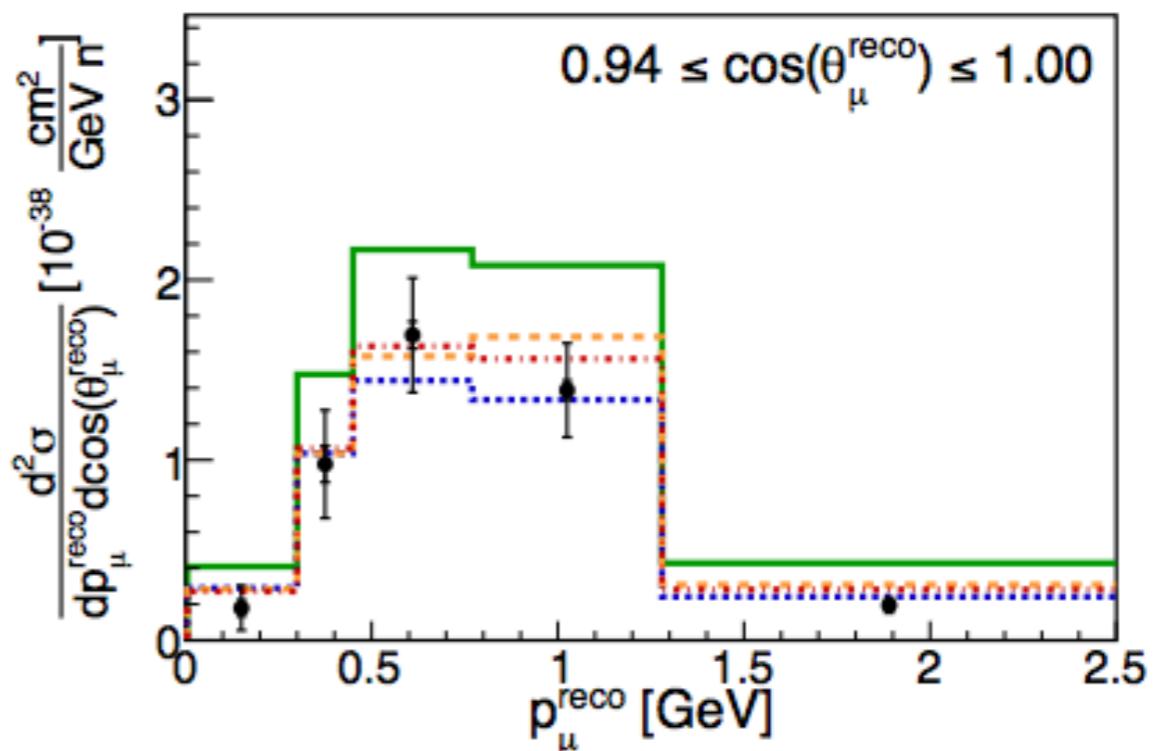
GENIE reproduced ν inclusive data



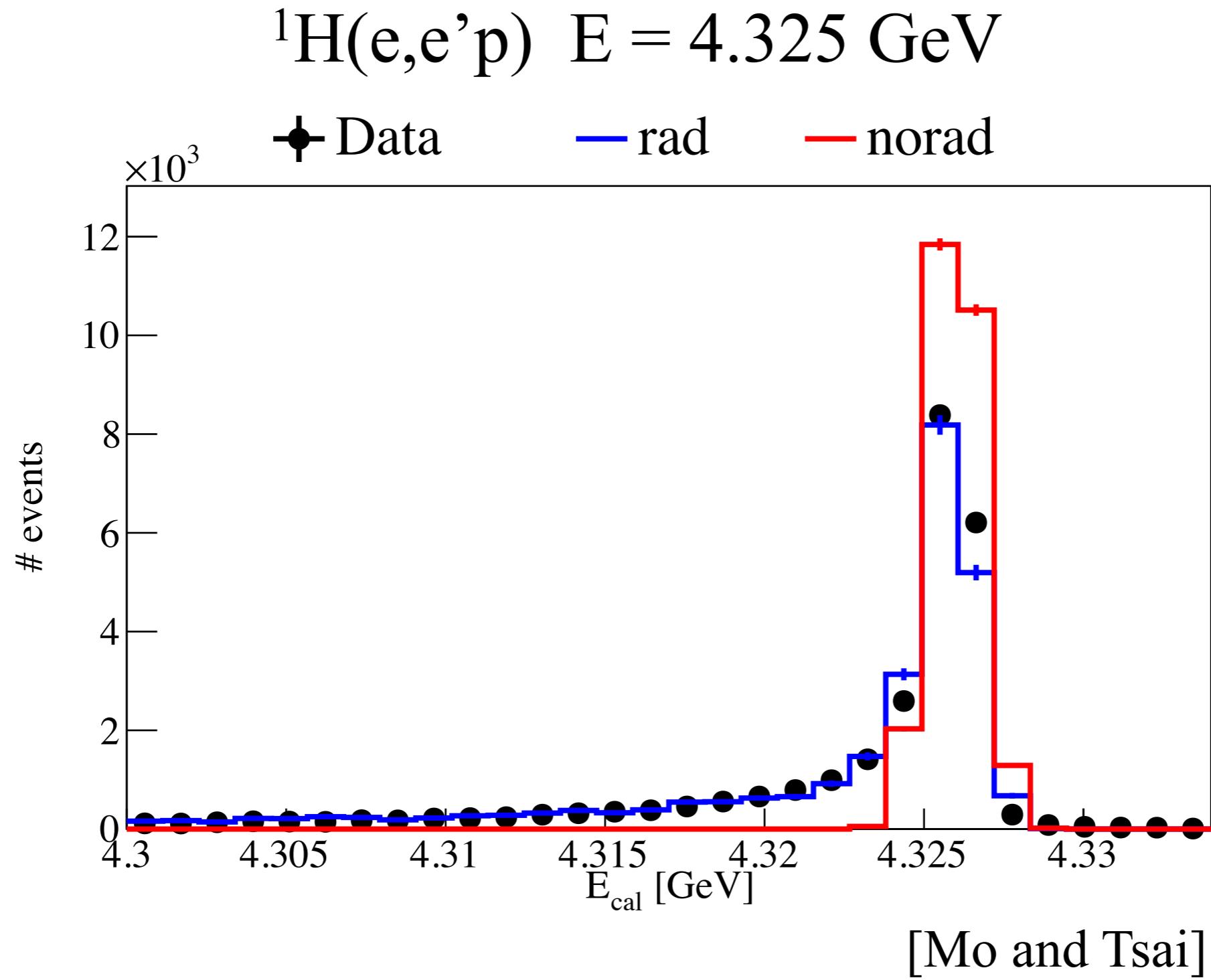
Genie

.... v3.0.6 tune G18_10a_02_11a

For more details see backup slides



Adding radiative effects



e4V 1p0 π Event Selection

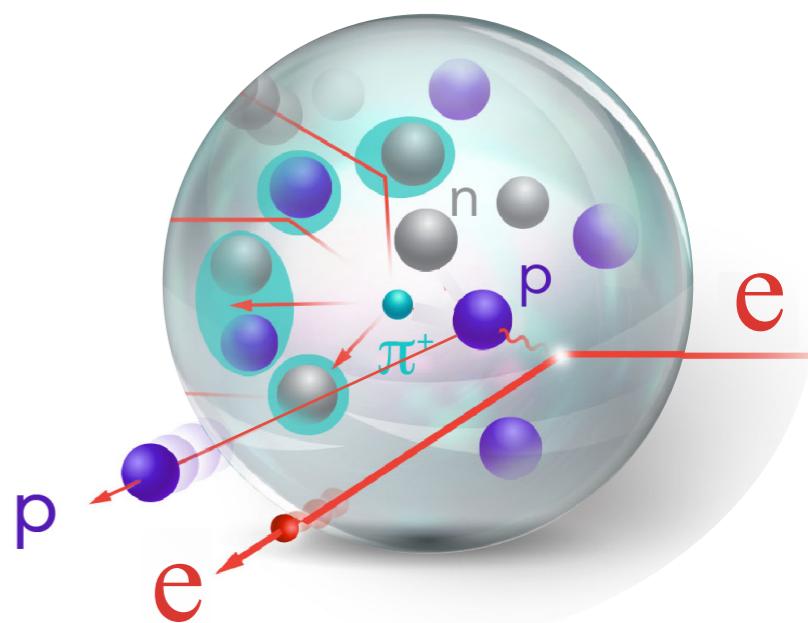
Focus on Quasi Elastic events:

1 proton above 300 MeV/c

no additional hadrons above threshold:

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

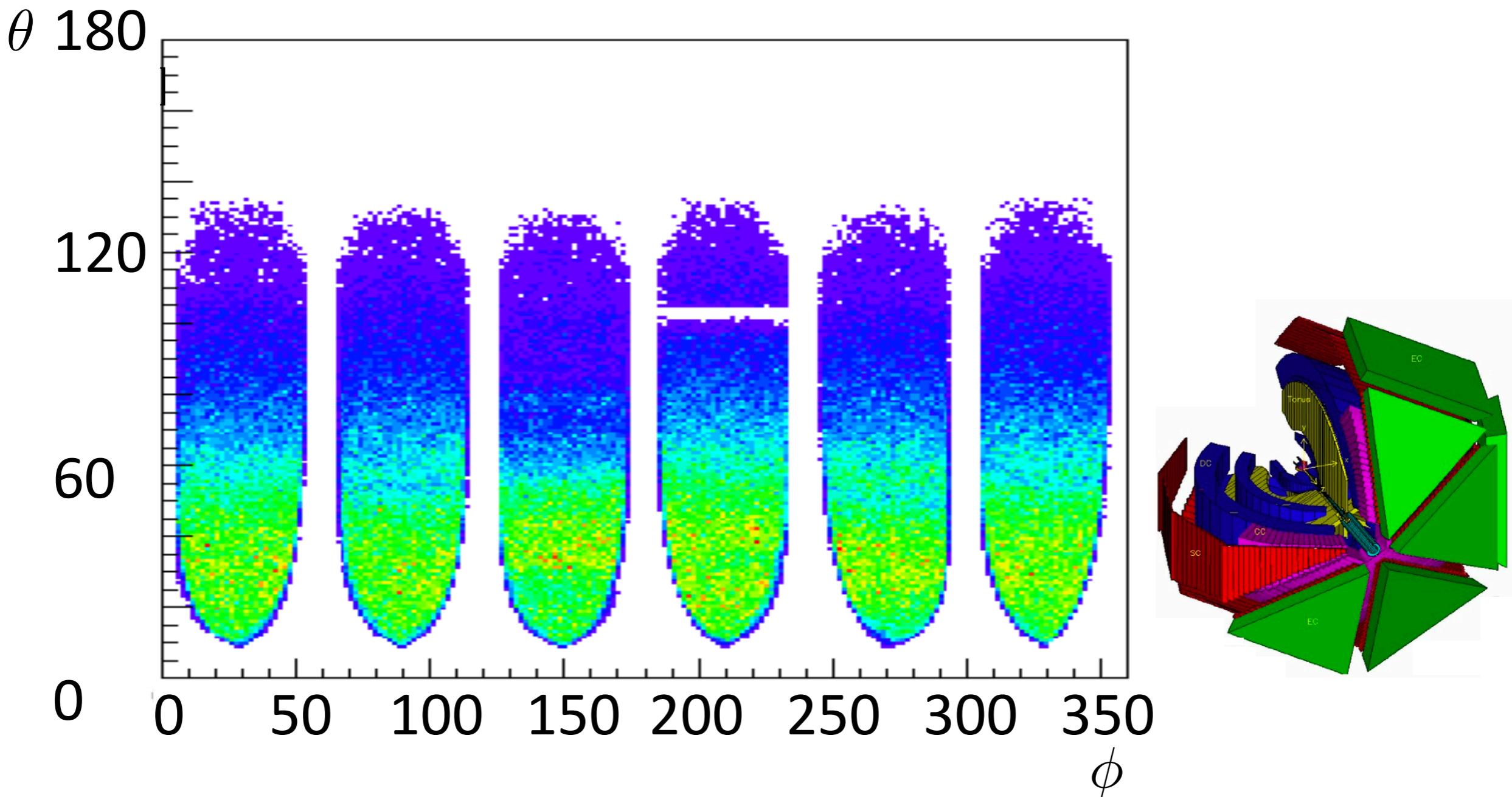
$P_{\pi^0} > 500 \text{ MeV}/c$



Background Subtraction

Different interaction lead to multi-hadron final states

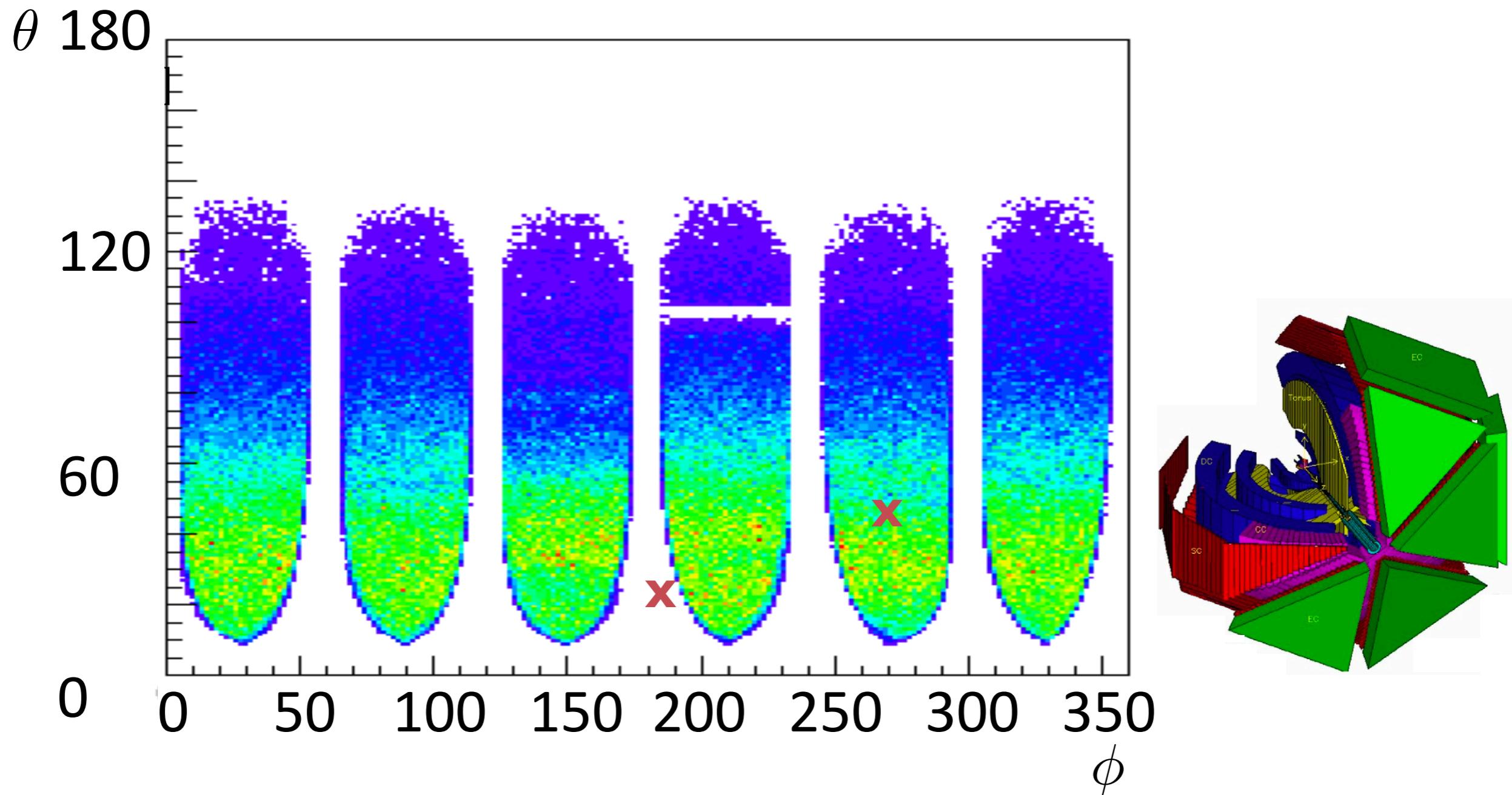
Gaps can make them look like QE-like events with outgoing $1\mu 1p$



Background Subtraction

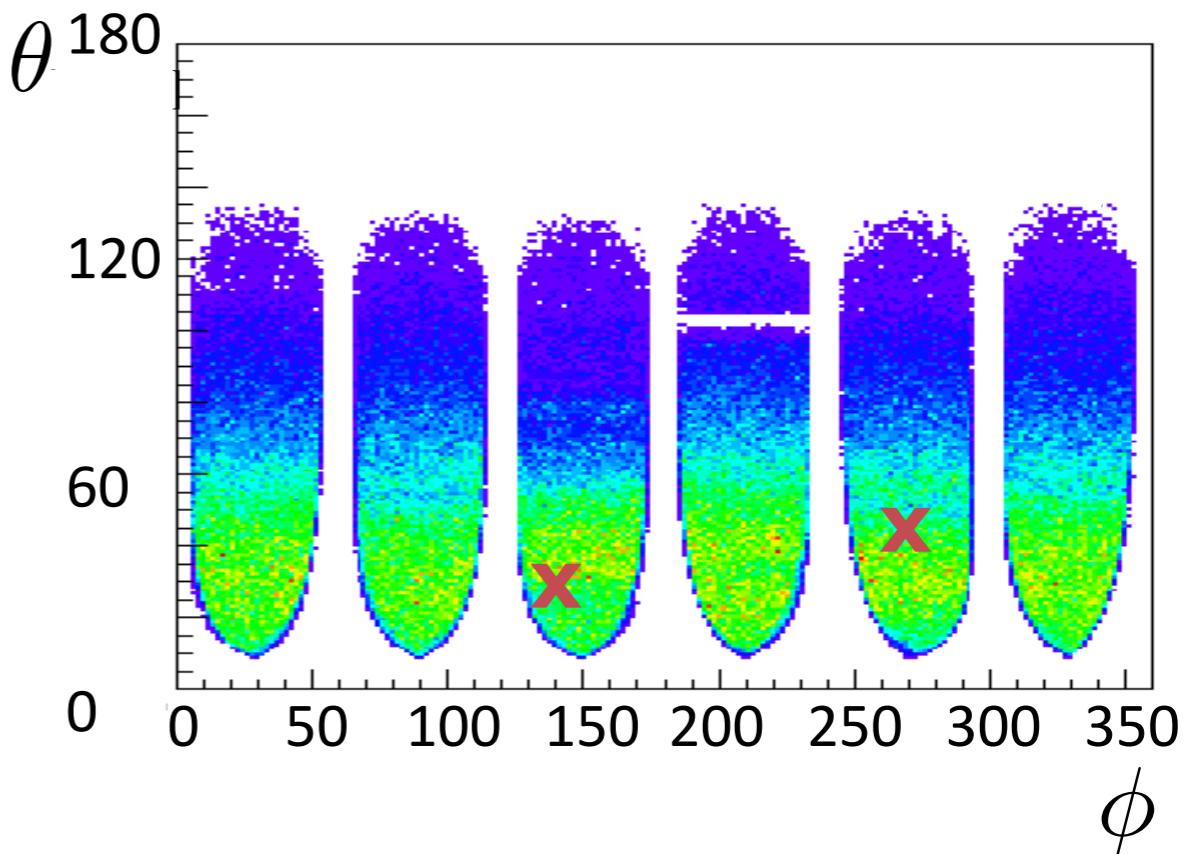
Different interaction lead to multi-hadron final states

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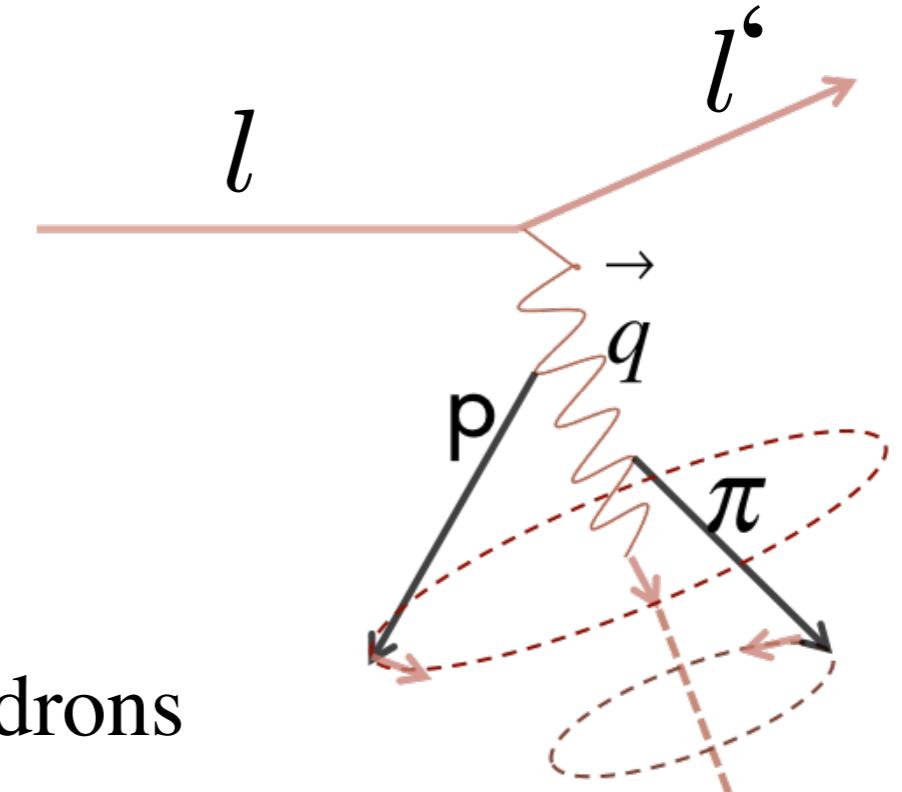
Data driven Background Subtraction

Using events with two detected hadrons

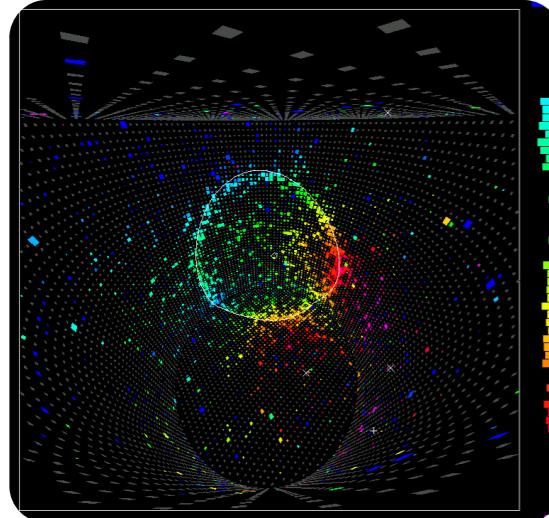


- Rotating p, π around q
- Determining π detection efficiency
- Subtracting contribution to QE-like

Same for final states with more than 2 hadrons



Incoming Energy Reconstruction



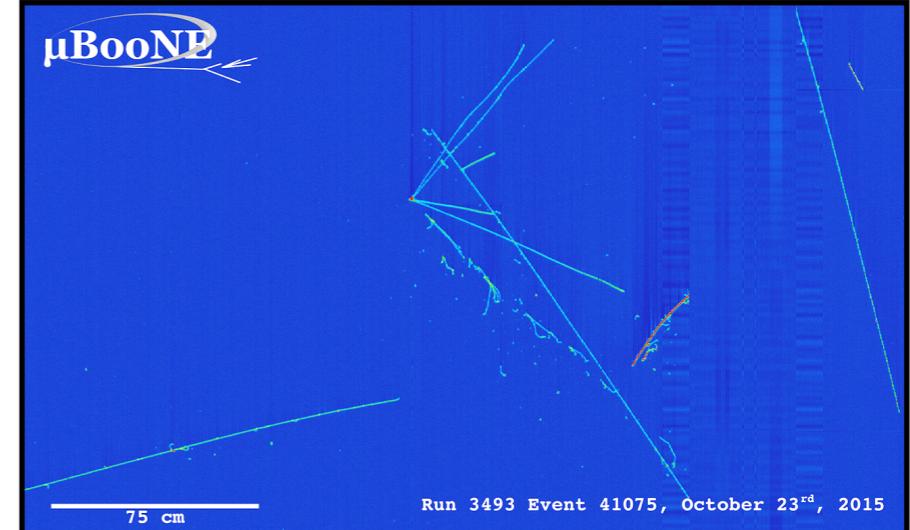
Cherenkov detectors:



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



Data

CLAS6 A(e,e'p) Data

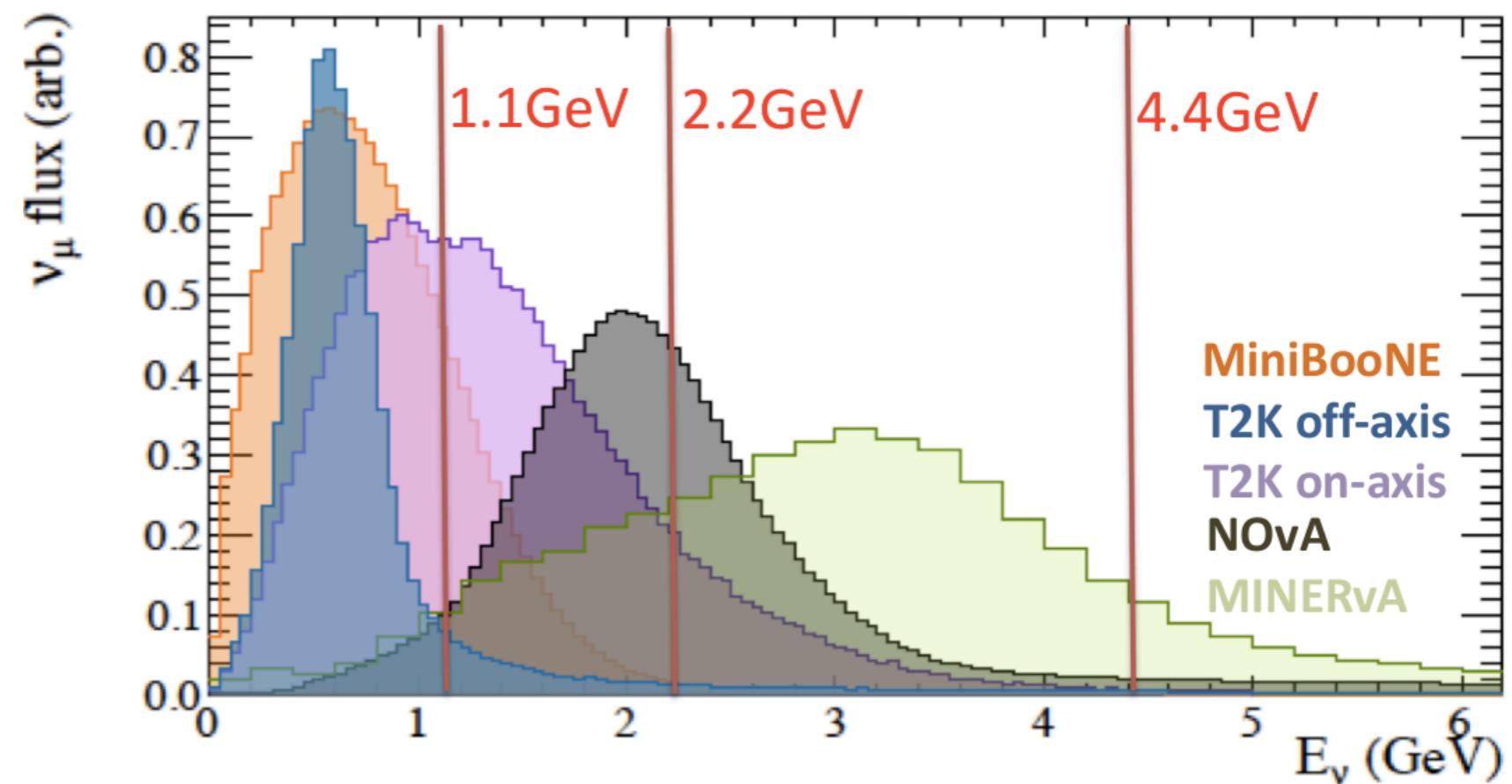
Targets:

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

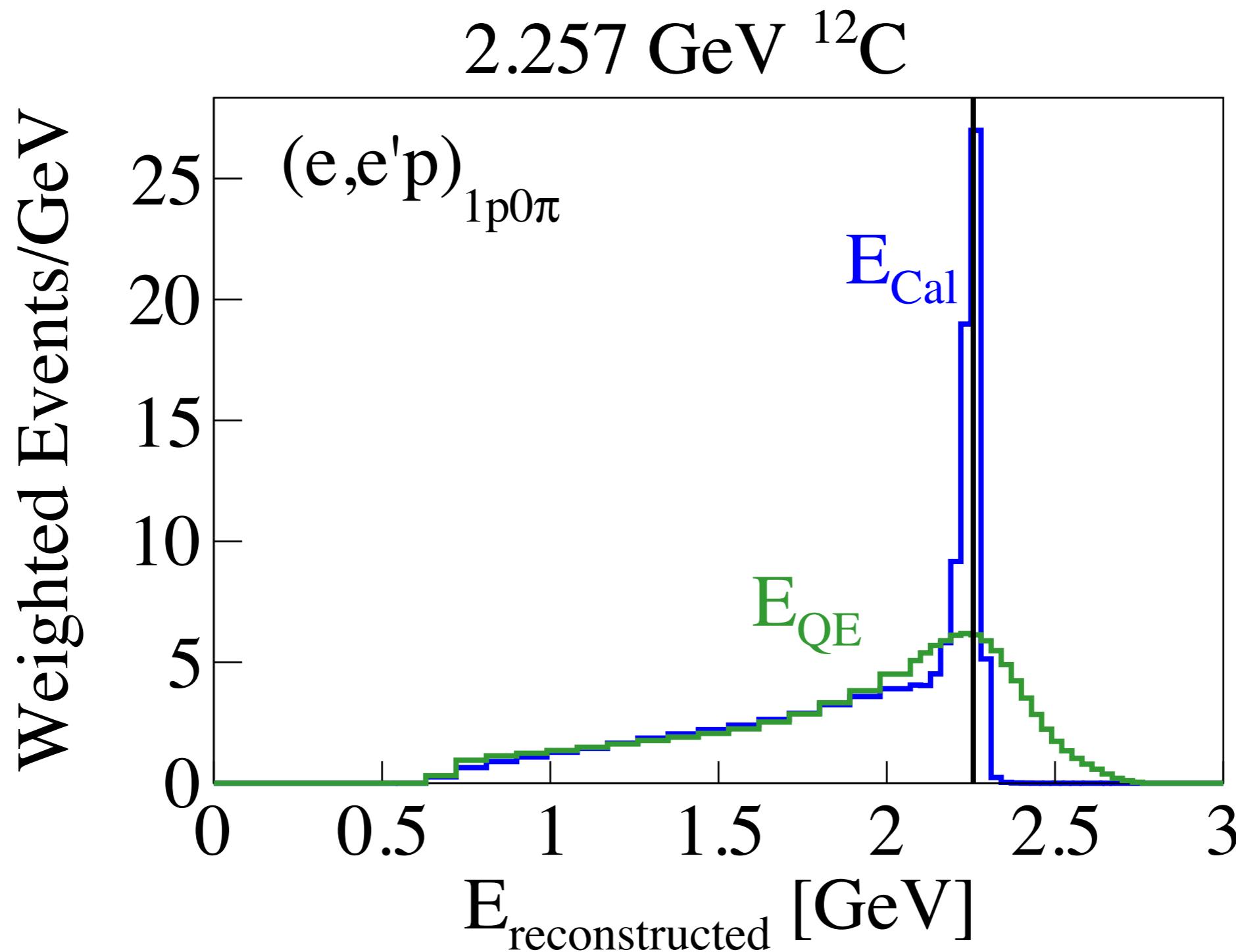


Energies around:

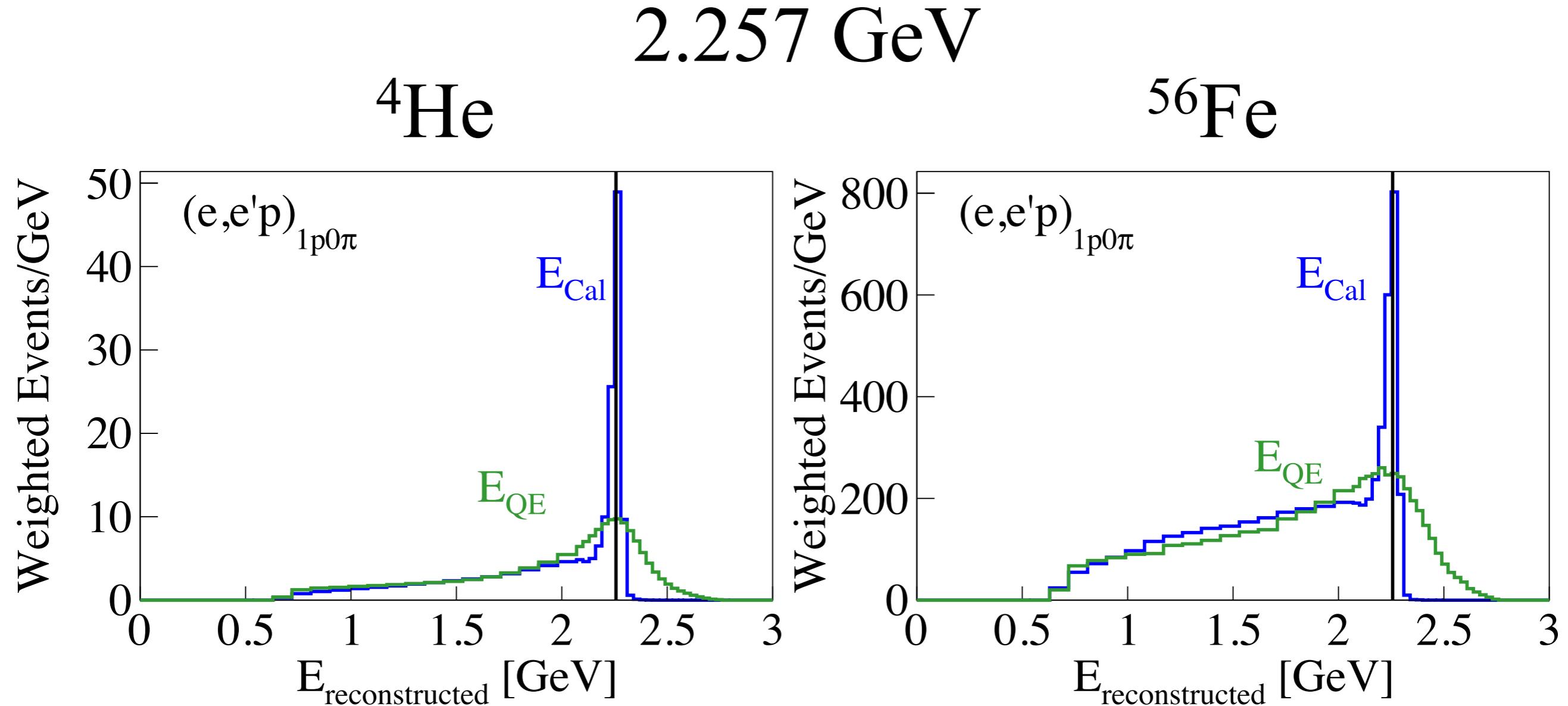
1,2,4 GeV



Testing the incoming energy reconstruction



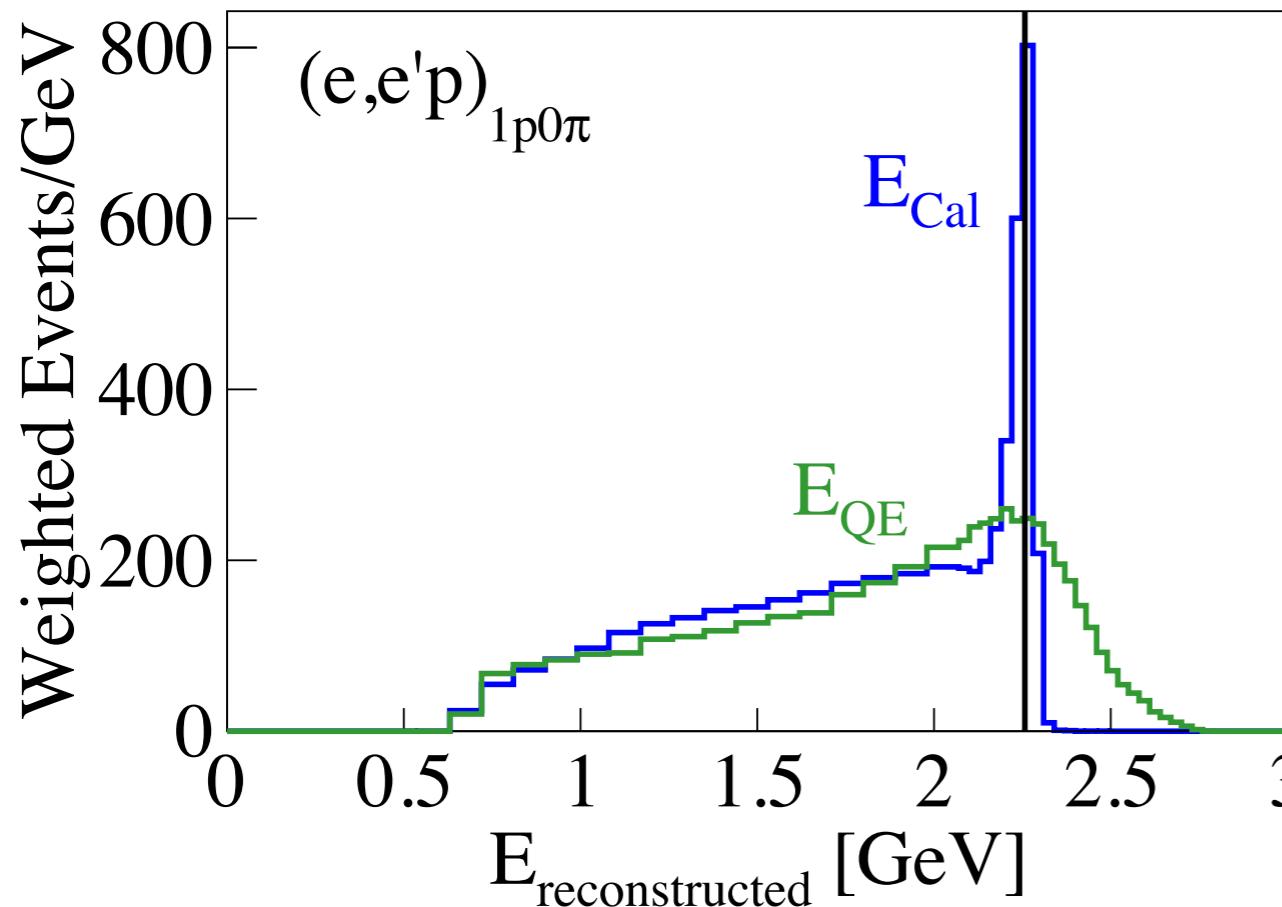
E_{rec} Worse with Higher Mass



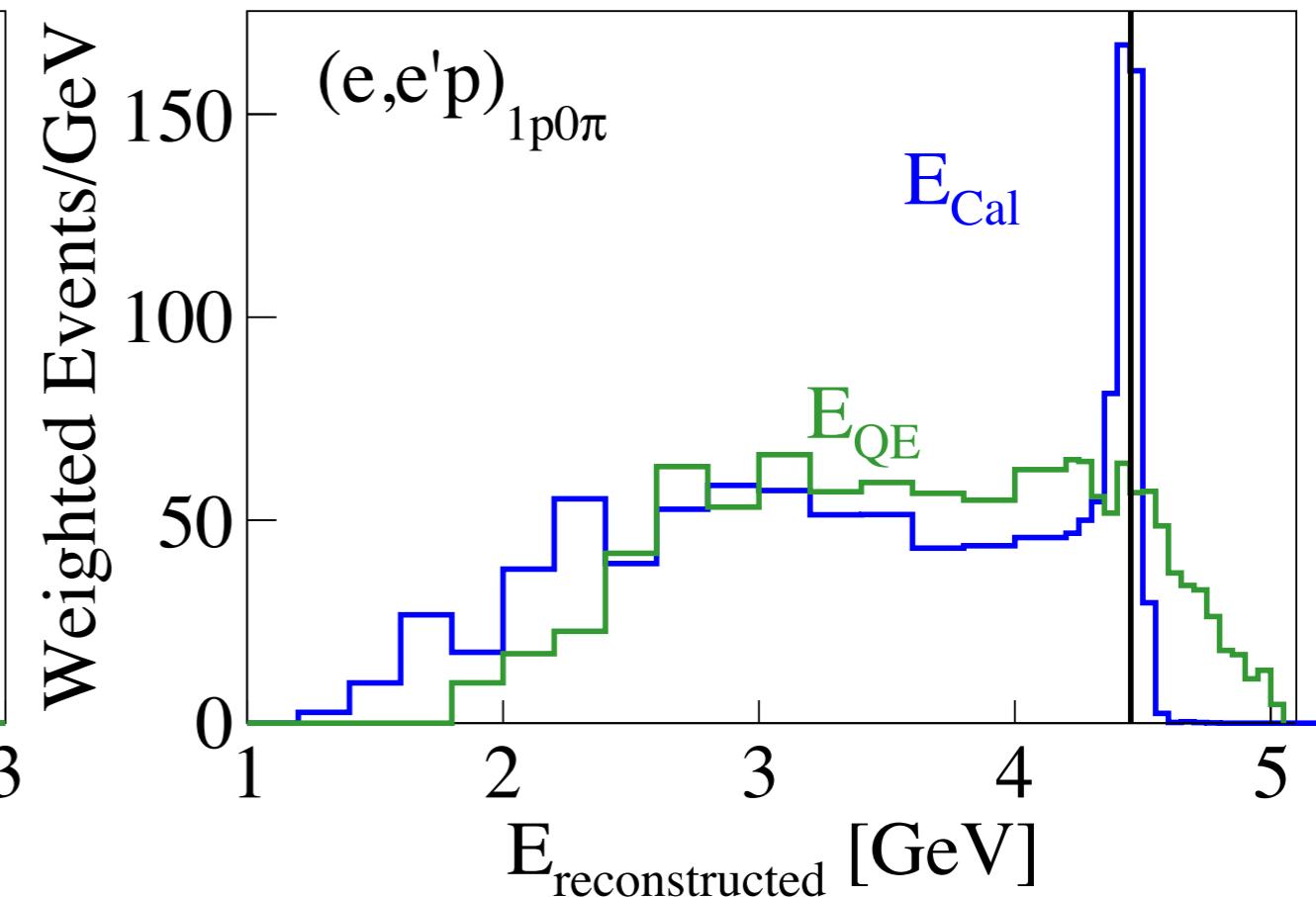
E_{rec} Worse with Higher Energy

^{56}Fe

2.257 GeV



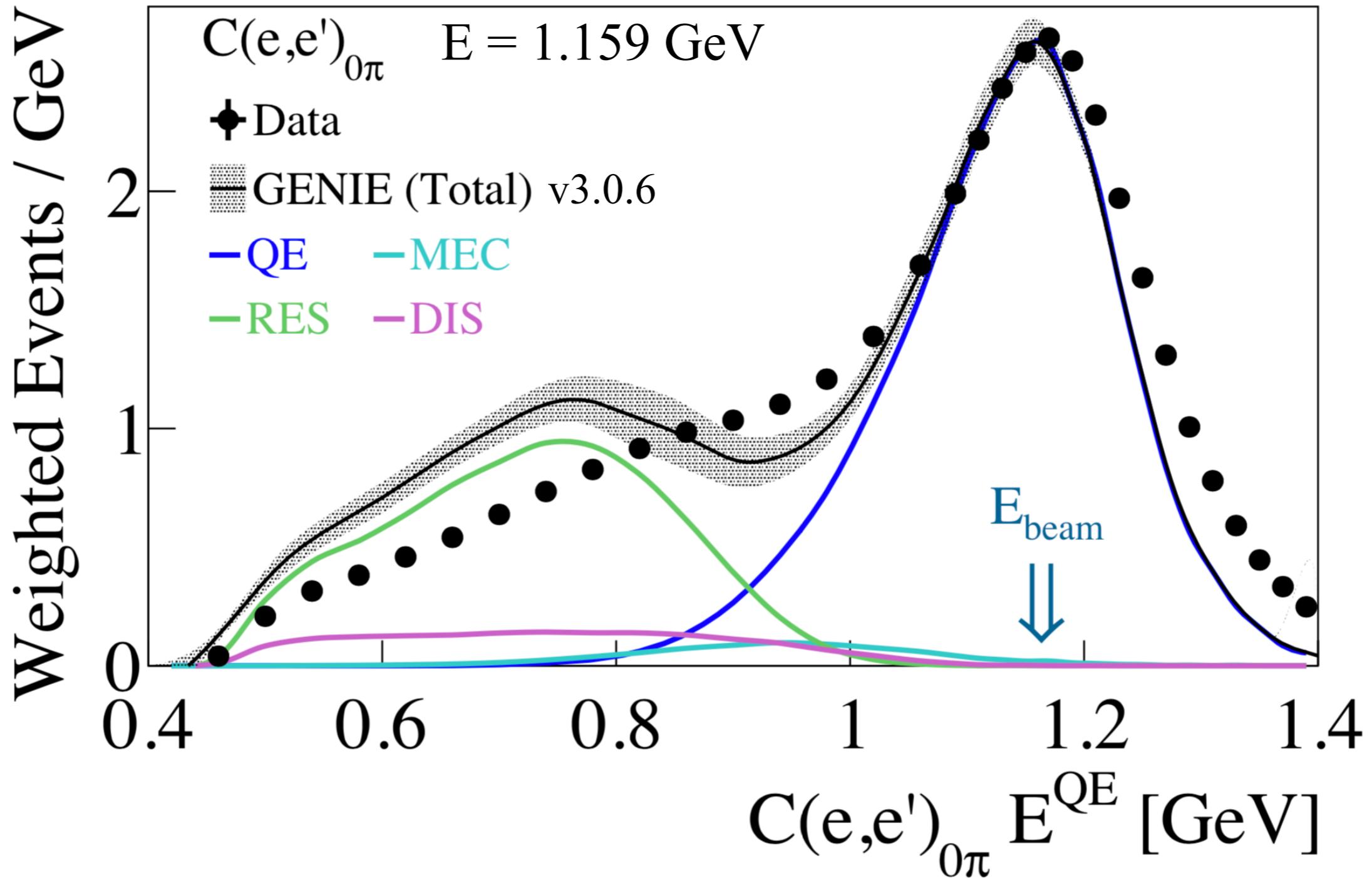
4.453 GeV





Data vs. Simulation

Disagreements between Data and MC

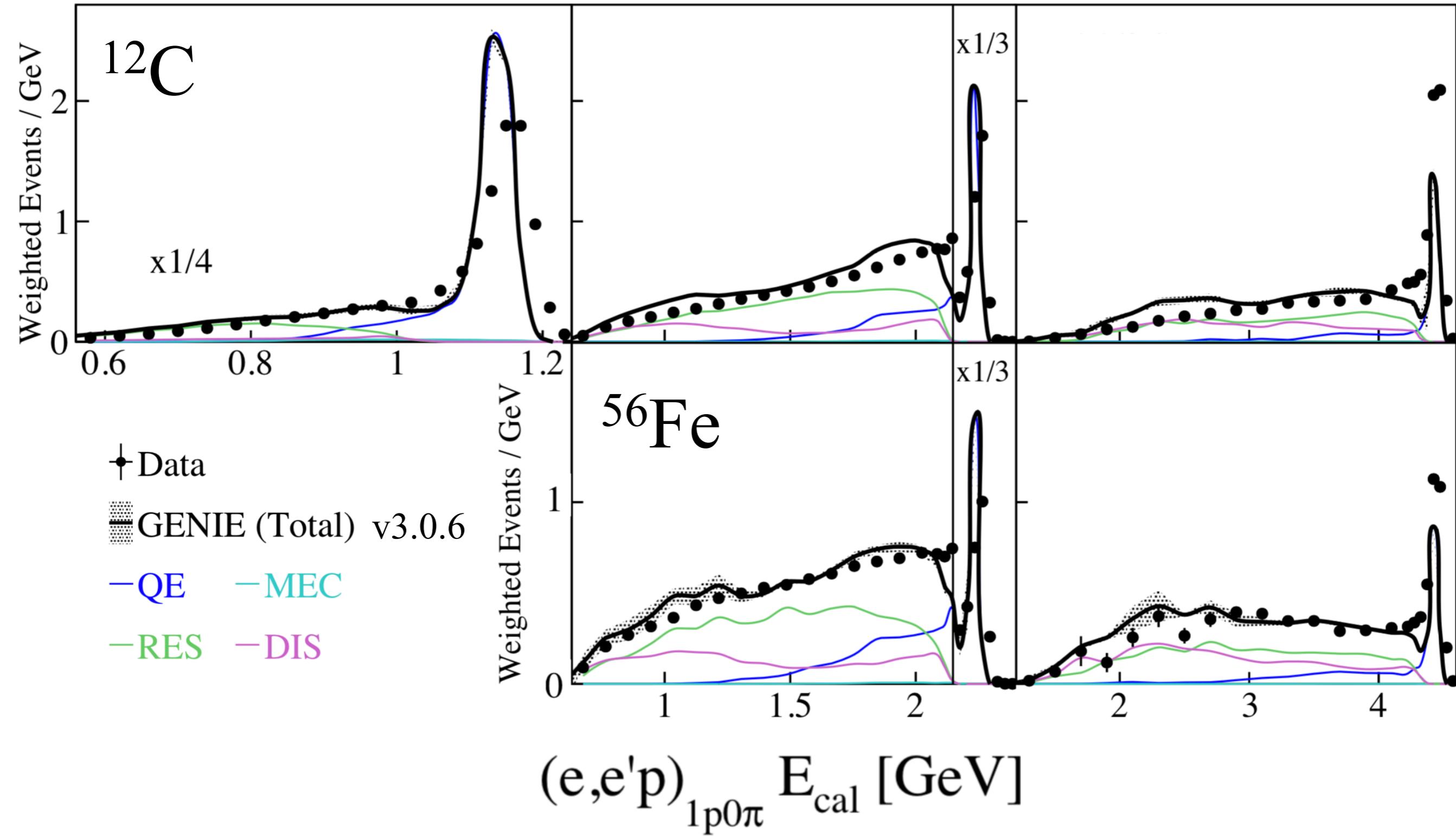


Disagreements between Data and MC

1.159 GeV

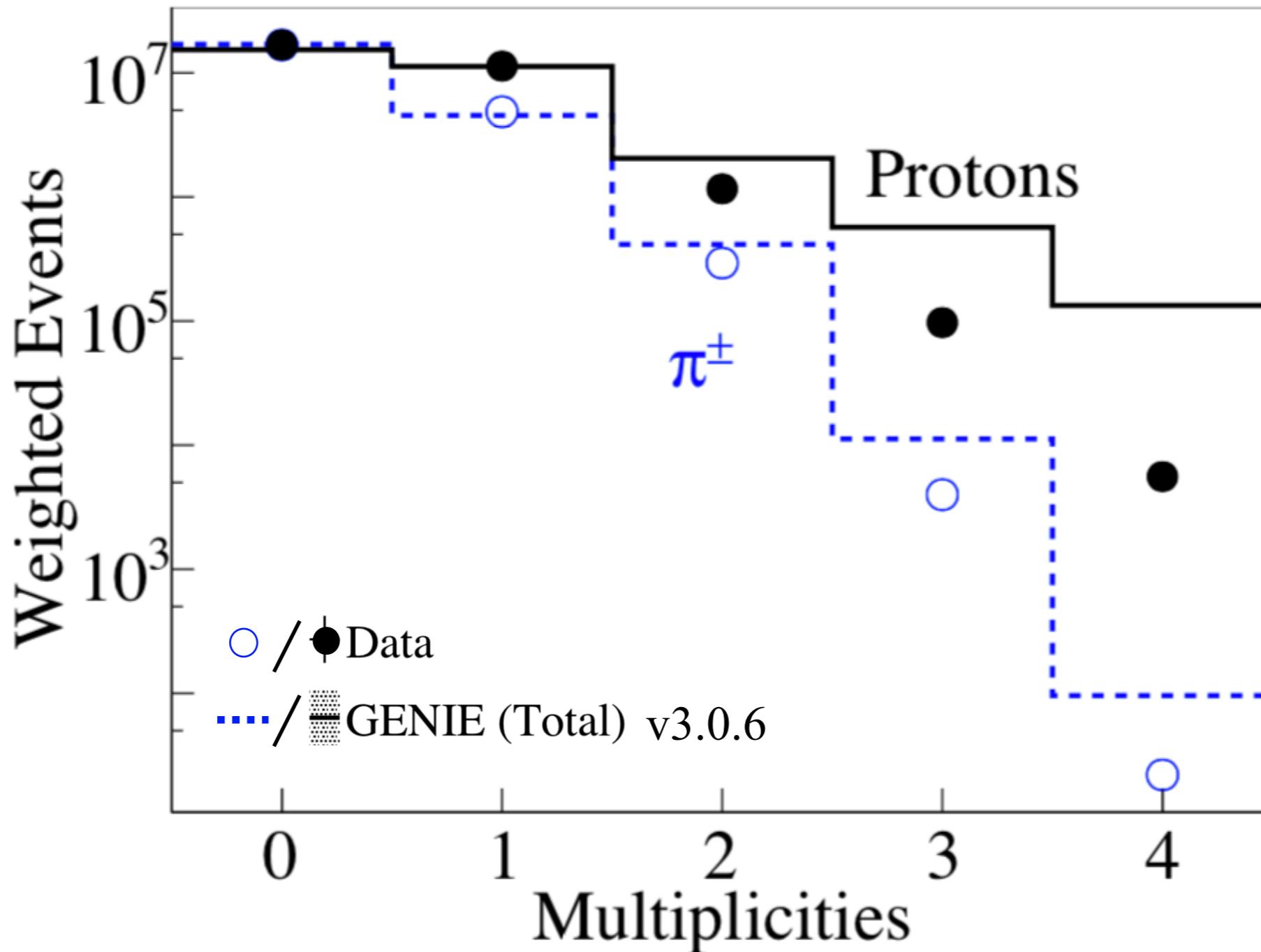
2.257 GeV

4.453 GeV

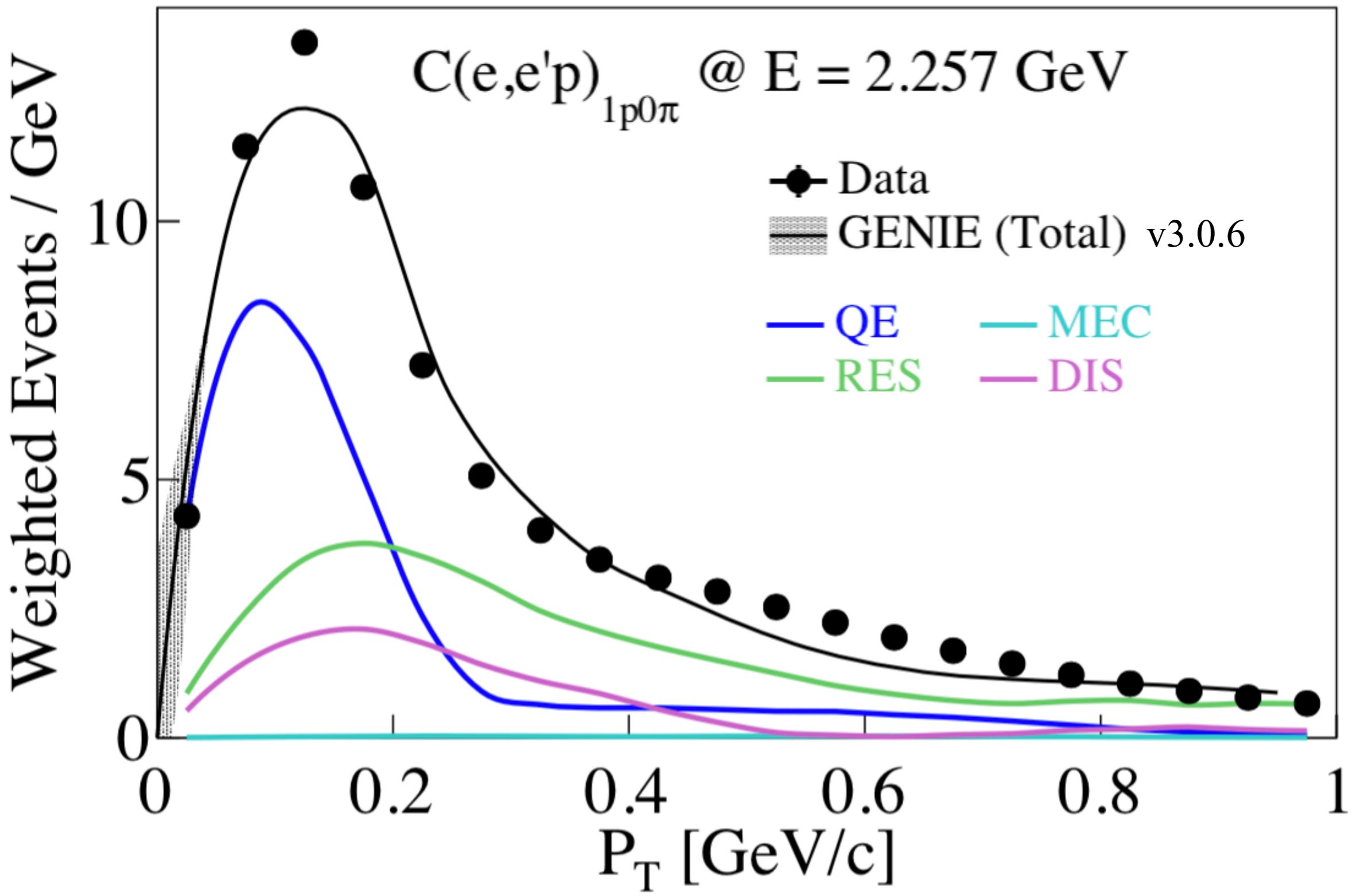
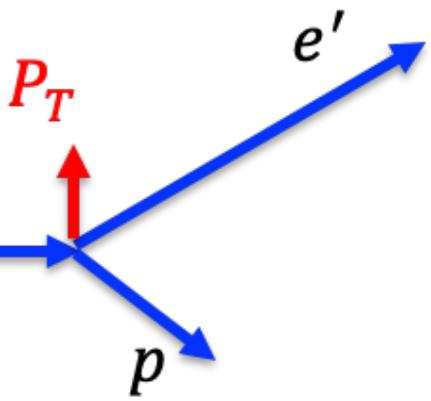


Multiplicities

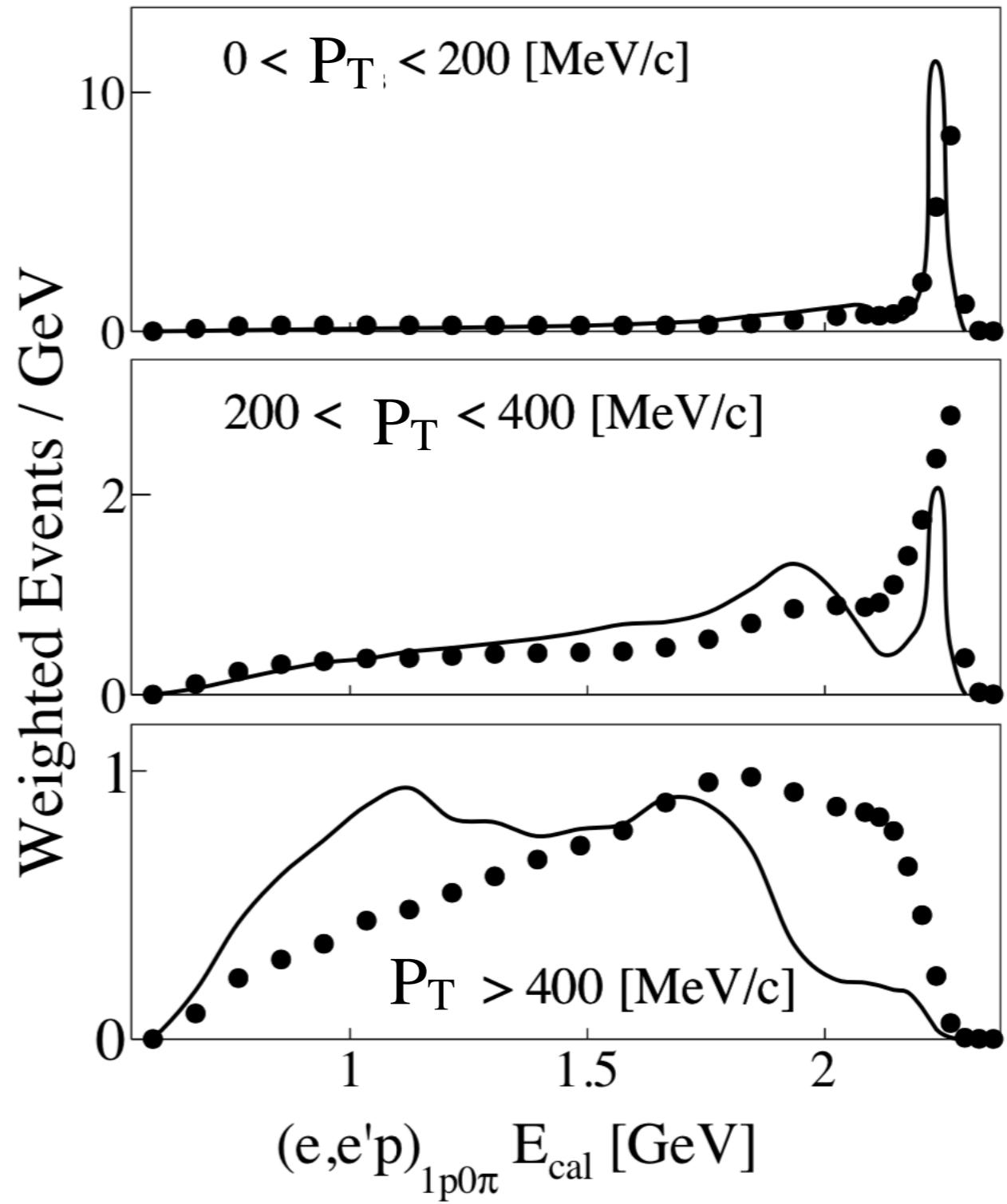
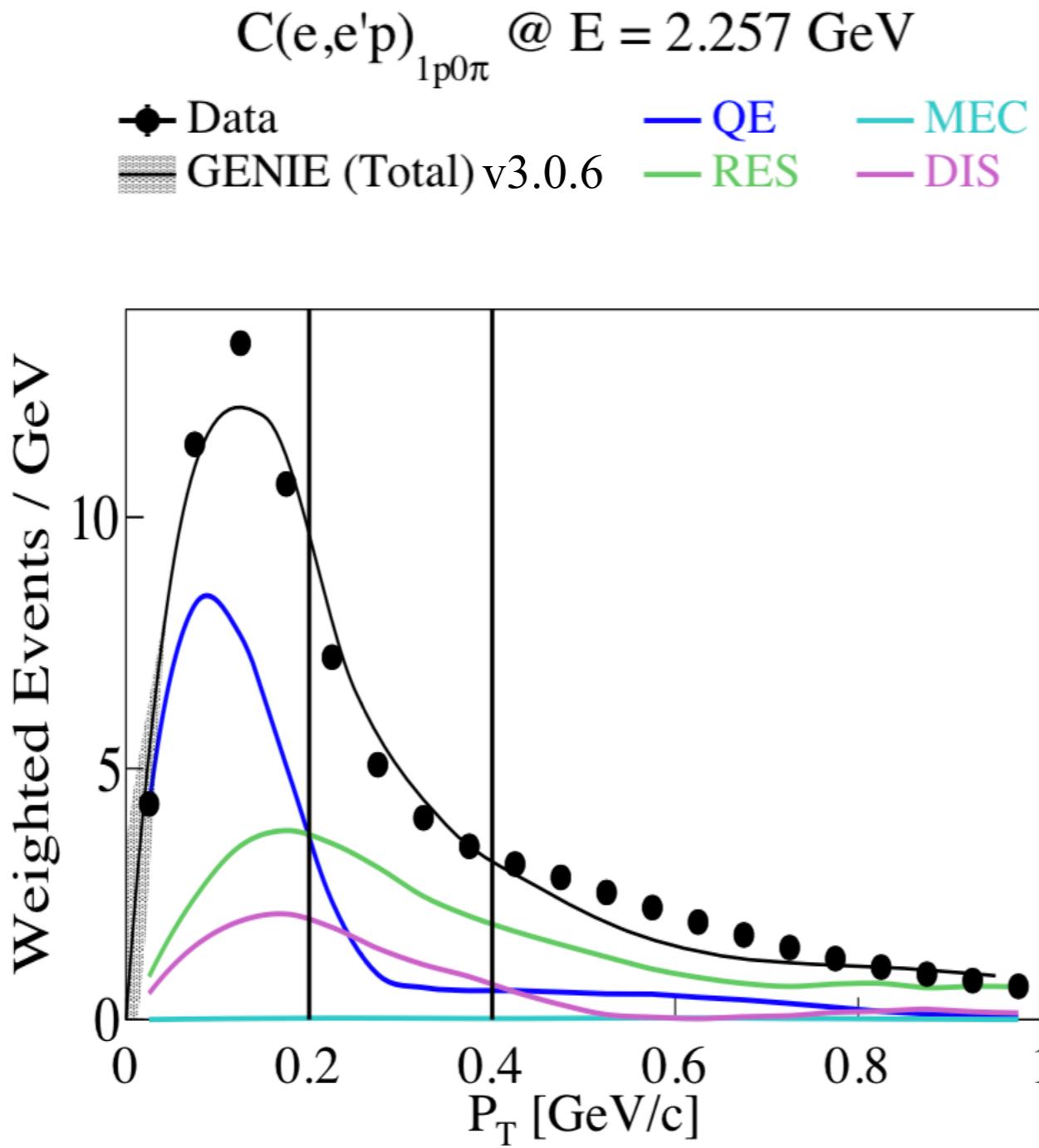
$E = 2.257 \text{ GeV}$ ^{12}C



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



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



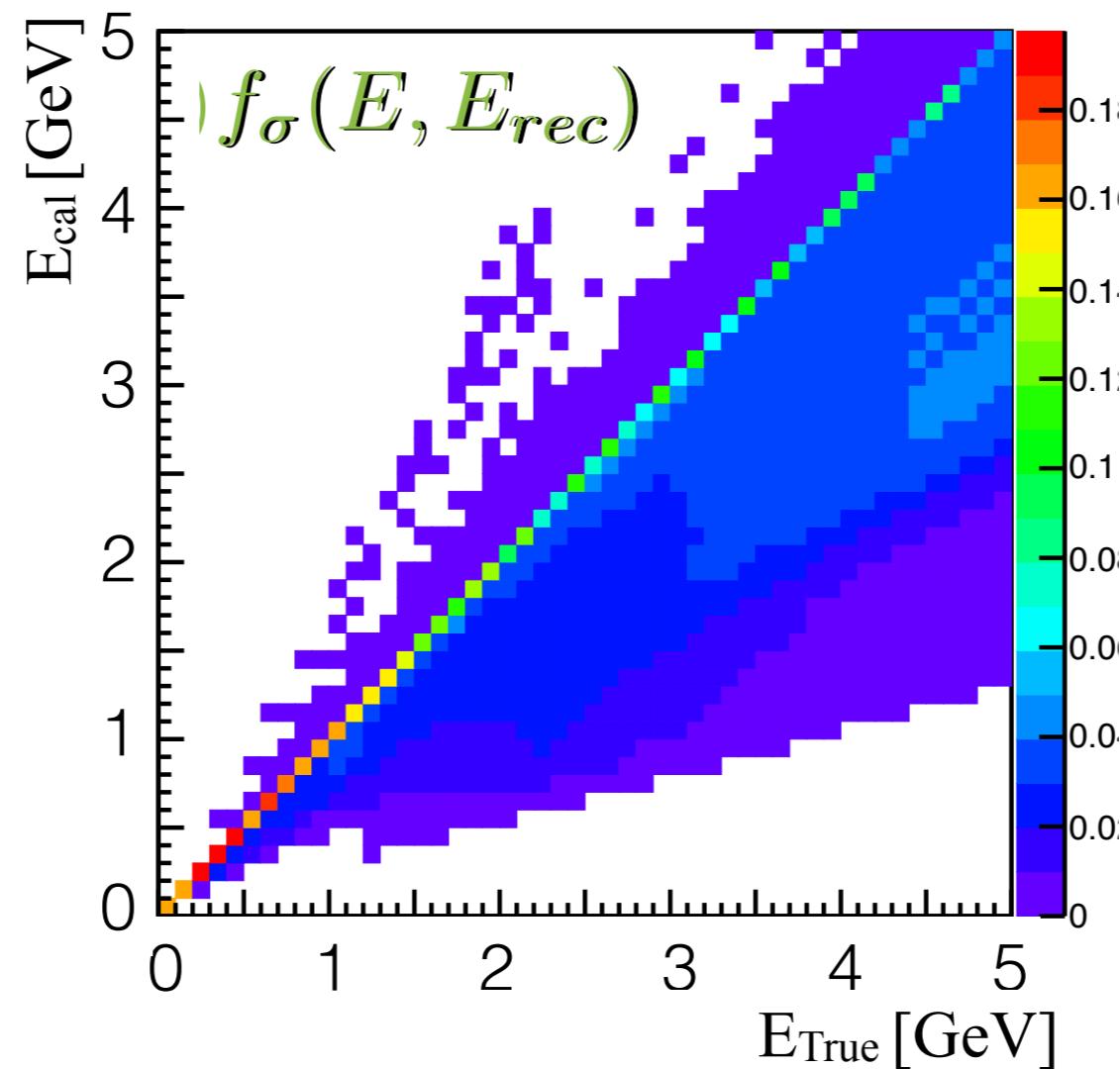


Implications and future plans

Potential implication on analysis

Extracting Data and Simulation smearing matrices

Based on electron scattering on ^{12}C with 3 known energies

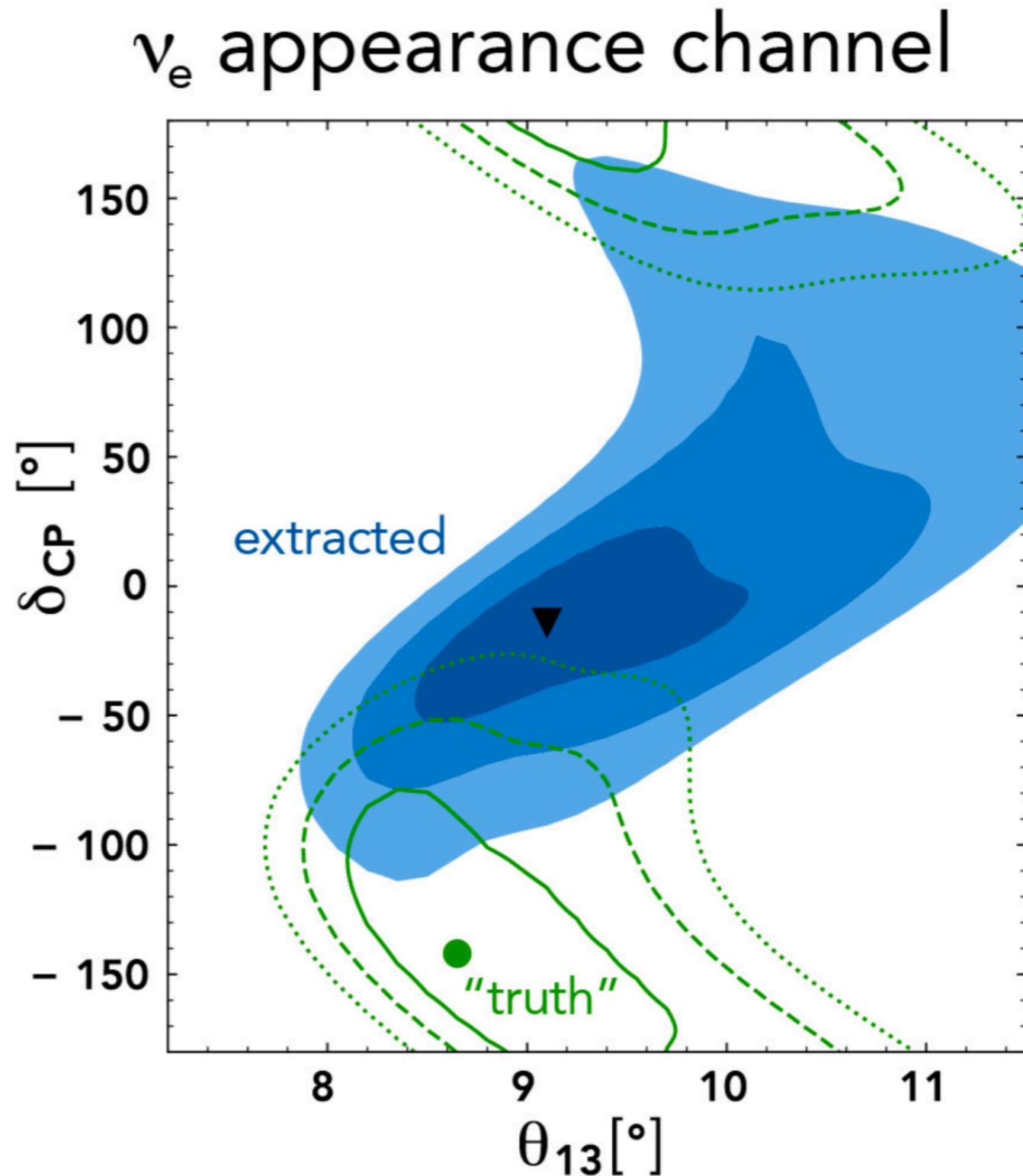


$$N(E_{rec}, L) \propto \int \Phi(E, L) \sigma(E) f_\sigma(E, E_{rec}) dE$$

Potential implication on DUNE analysis

The fit considers:

- ν_e appearance channel (all inclusive)
- Exposure of 168 kt MW yr on ^{12}C
- Corresponds to 3.5 years data taking on DUNE like experiment
- Using existing parameter constraints from reactors + others experiments
- Smearing matrices based on:
 - 1e1p selection
 - $\theta_e > 15^\circ$
 - $P_p > 300 \text{ MeV}/c$
 - No $P_{\pi^{+/-}} > 150 \text{ MeV}/c$



e4V The team



Mariana Khachatryan

ODU @ JLab



Afroditi Papadopoulou

MIT @ FNAL



Jefferson Lab



MIT



CSIC
CONSEJO SUPERIOR DE INVESTIGACIONES CIENTÍFICAS



Future Plans -Approved run for CLAS12

Acceptance down to 5° $Q^2 > 0.04 \text{ GeV}^2$

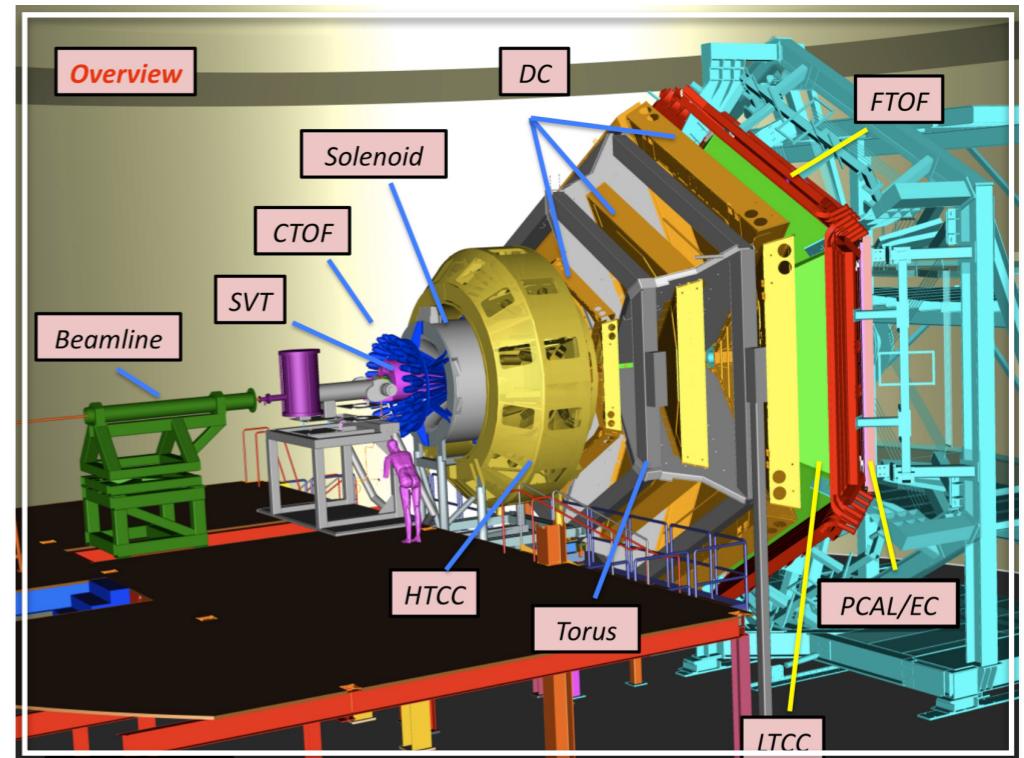
x10 luminosity [10³⁵ cm⁻²s⁻¹]

Keep low thresholds

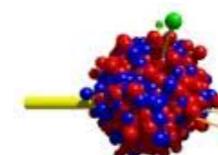
Targets: ²D, ⁴He, ¹²C, ¹⁶O, ⁴⁰Ar, ¹²⁰Sn

1 - 7 GeV (relevant for DUNE)

Running planned for 2021

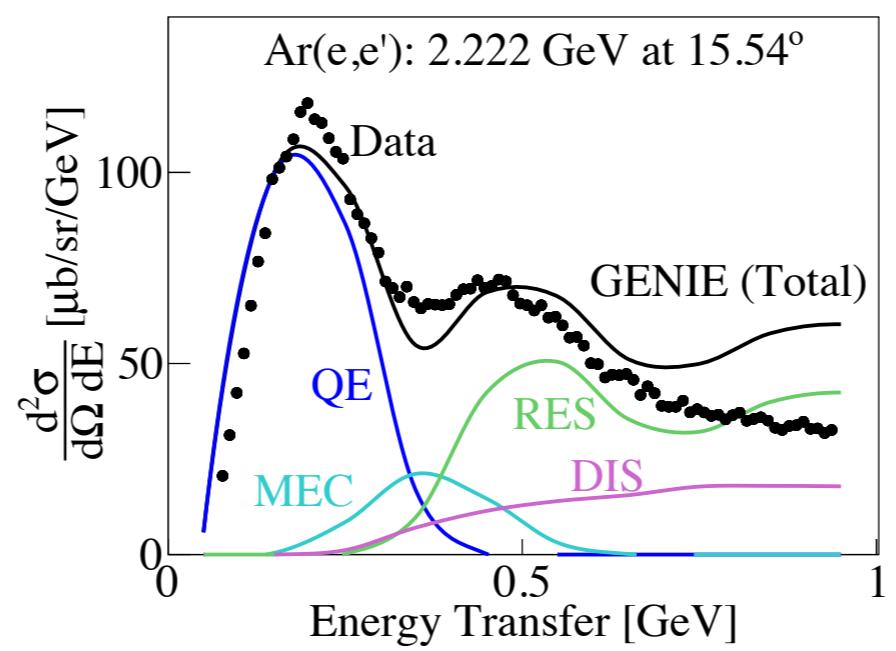


Overwhelming support from:



GiBUU
The Giessen Boltzmann-Uehling-Uhlenbeck Project





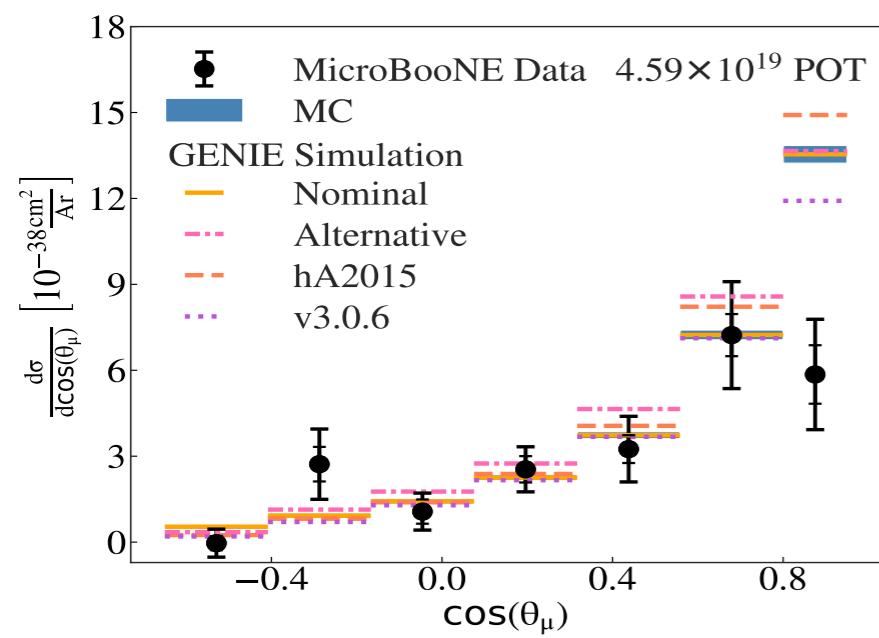
Event Generators

ν scattering

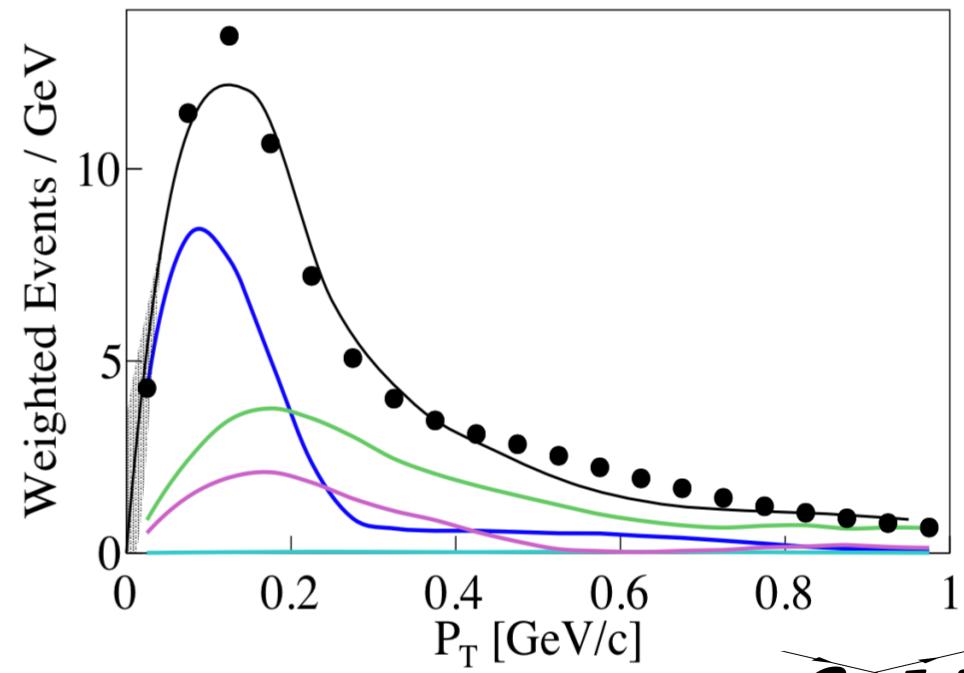
e scattering

$$\sigma(E)f_\sigma(E, E_{rec})$$

Modelling input



arXiv: 2006.00108 [hep-ex] (2020)
See talk from Kirsty Duffy

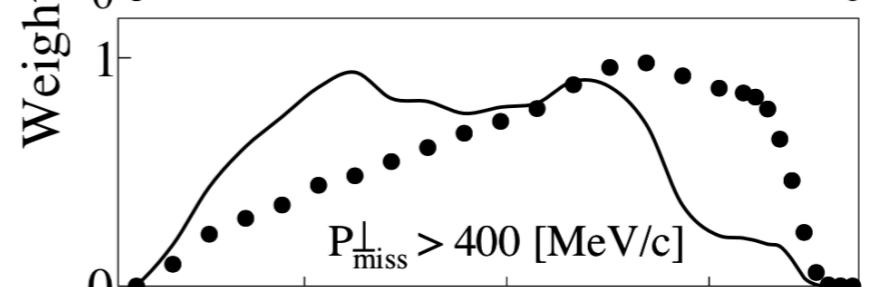
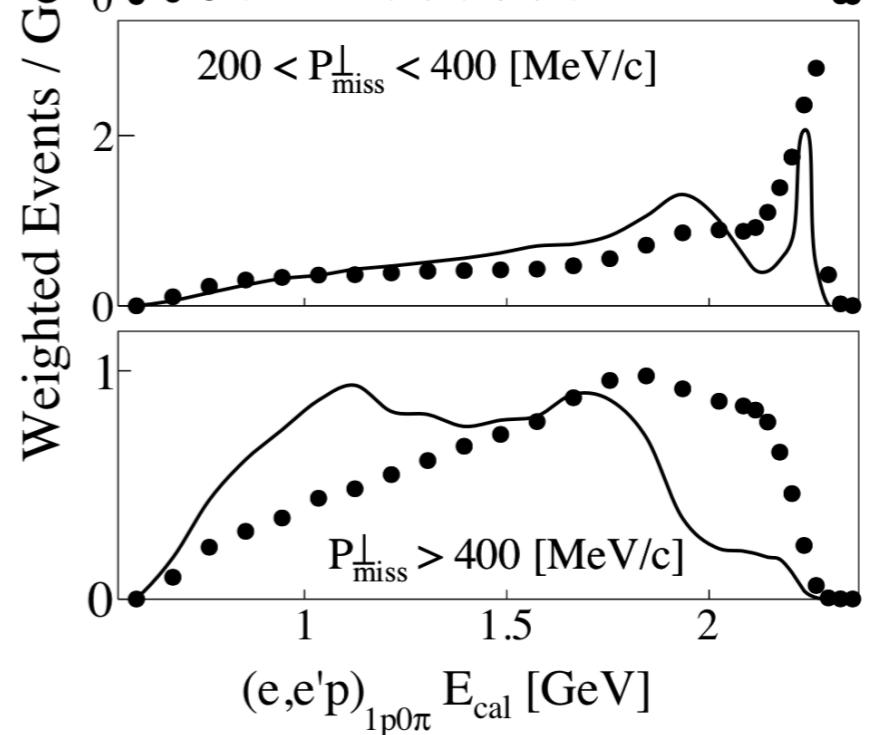
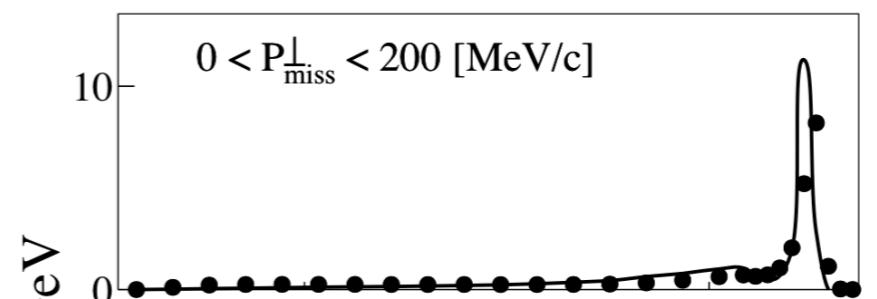
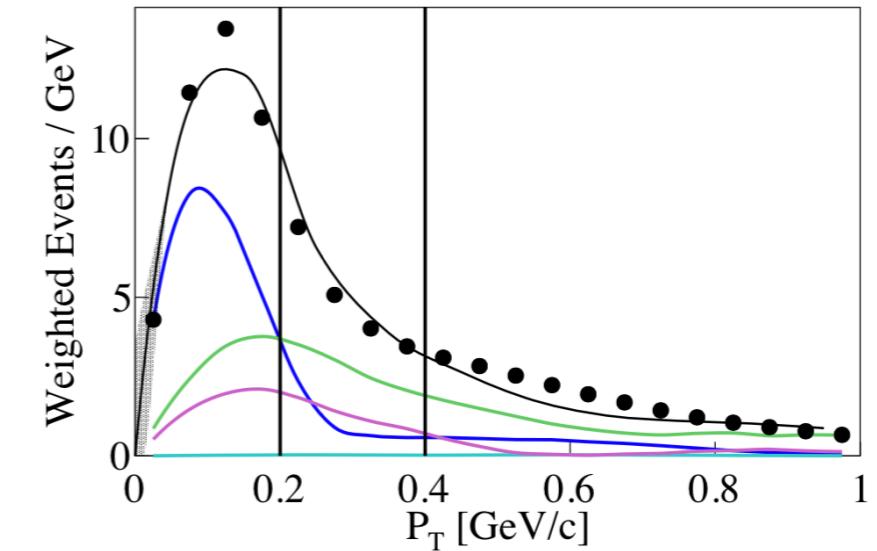


$e \bar{\nu}$

Summary

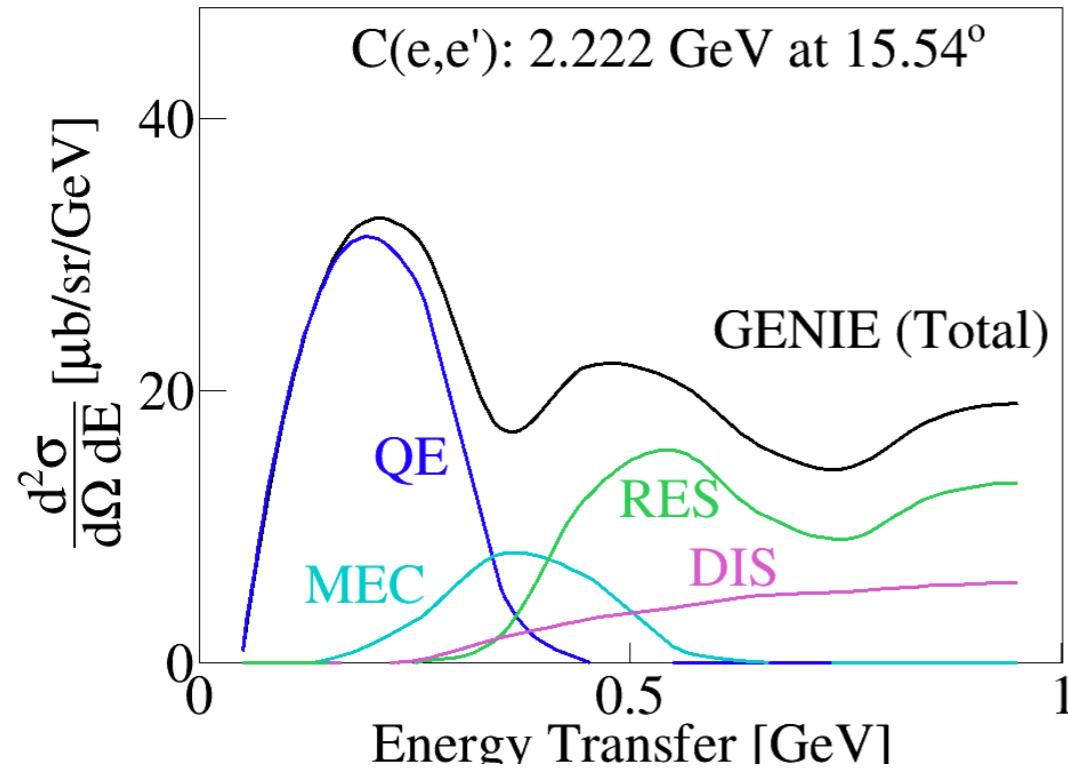
e4l

- Testing vA 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

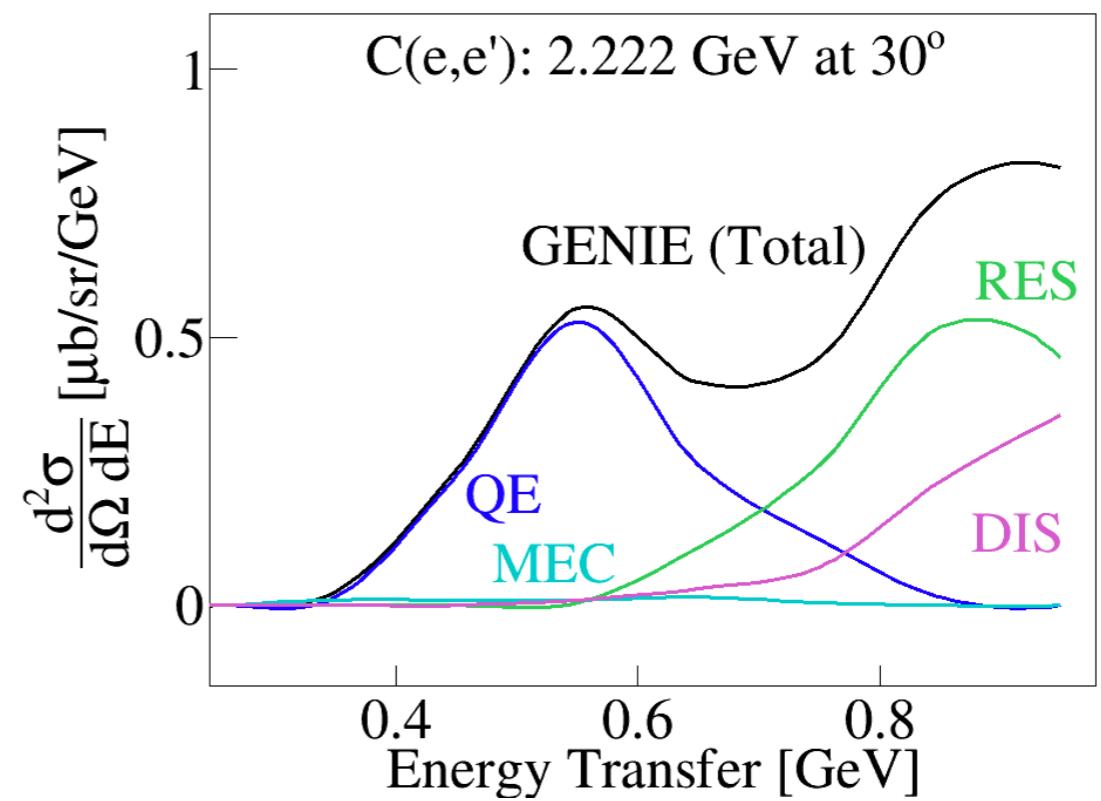
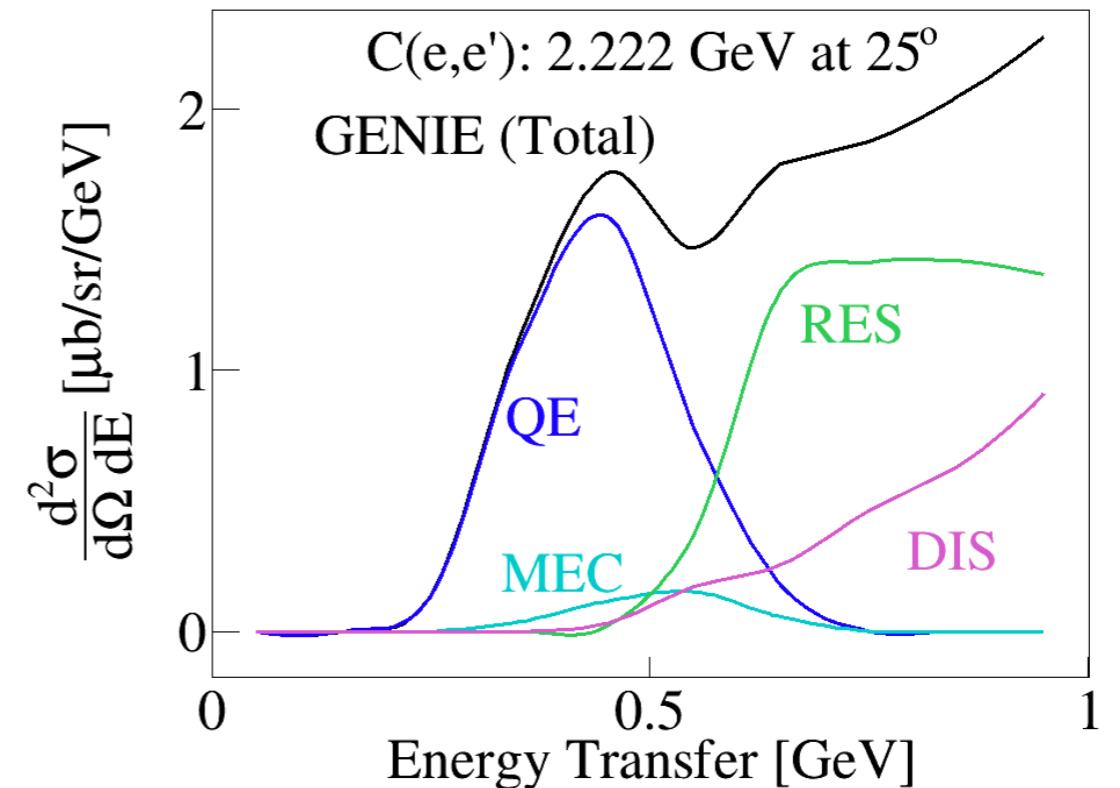


Thank you for your attention

Where did the MEC go?



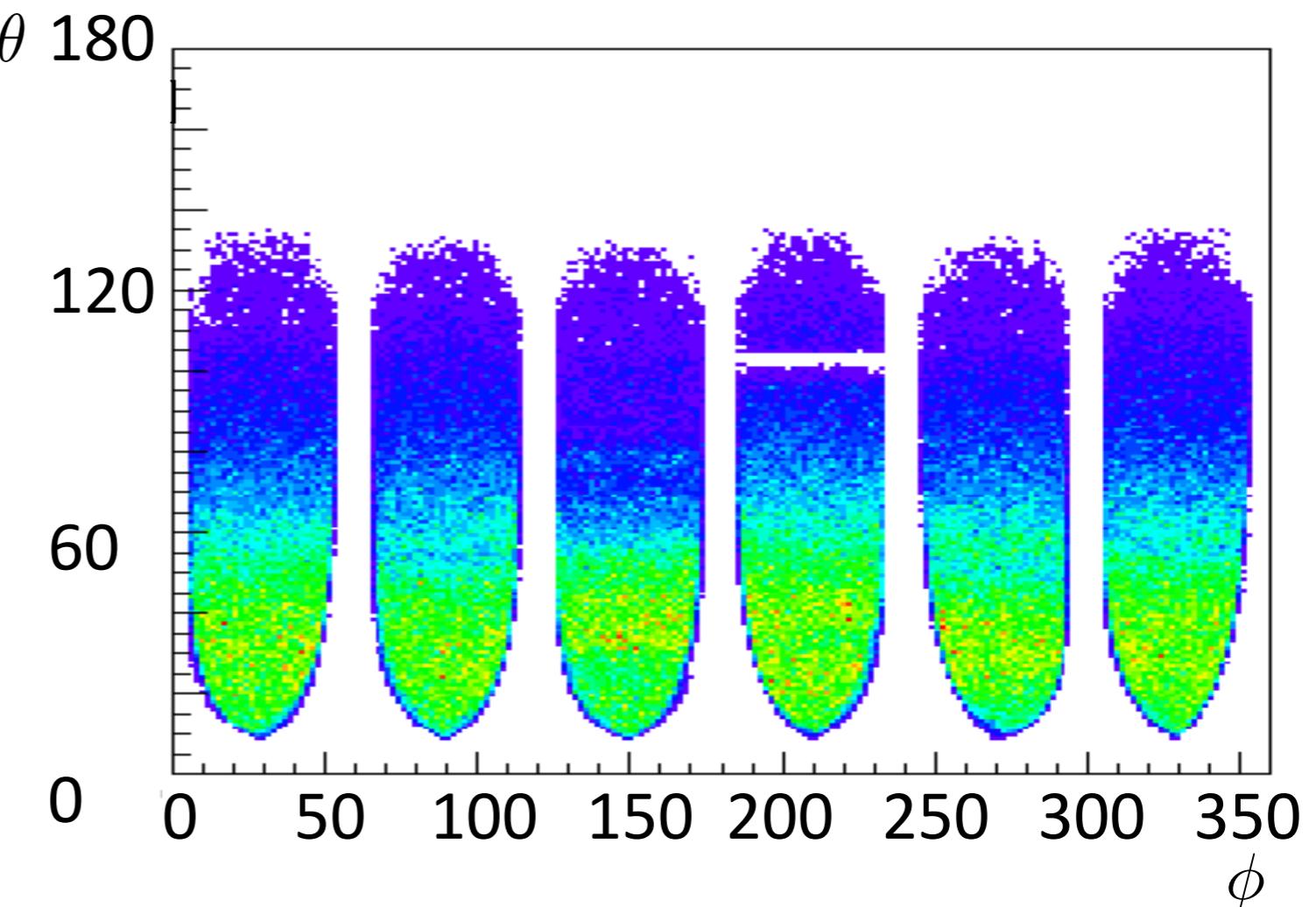
CLAS6: $15^\circ < \theta_e < 45^\circ$



CLAS6: Acceptance maps available

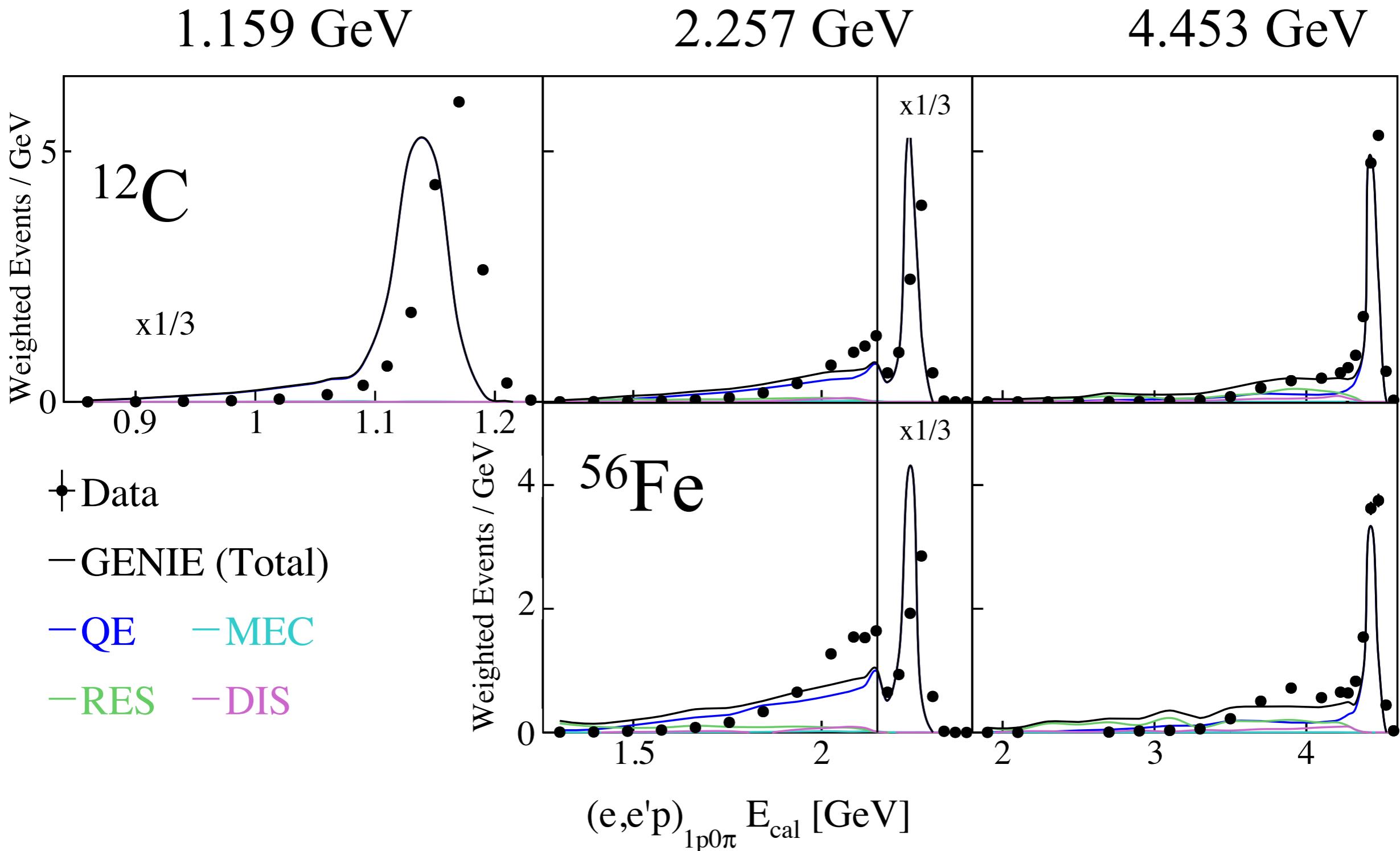
CLAS6 has a different efficiency, which we will publish as acceptance maps for public use for each:

- Target
- Particle type
- Particle momentum

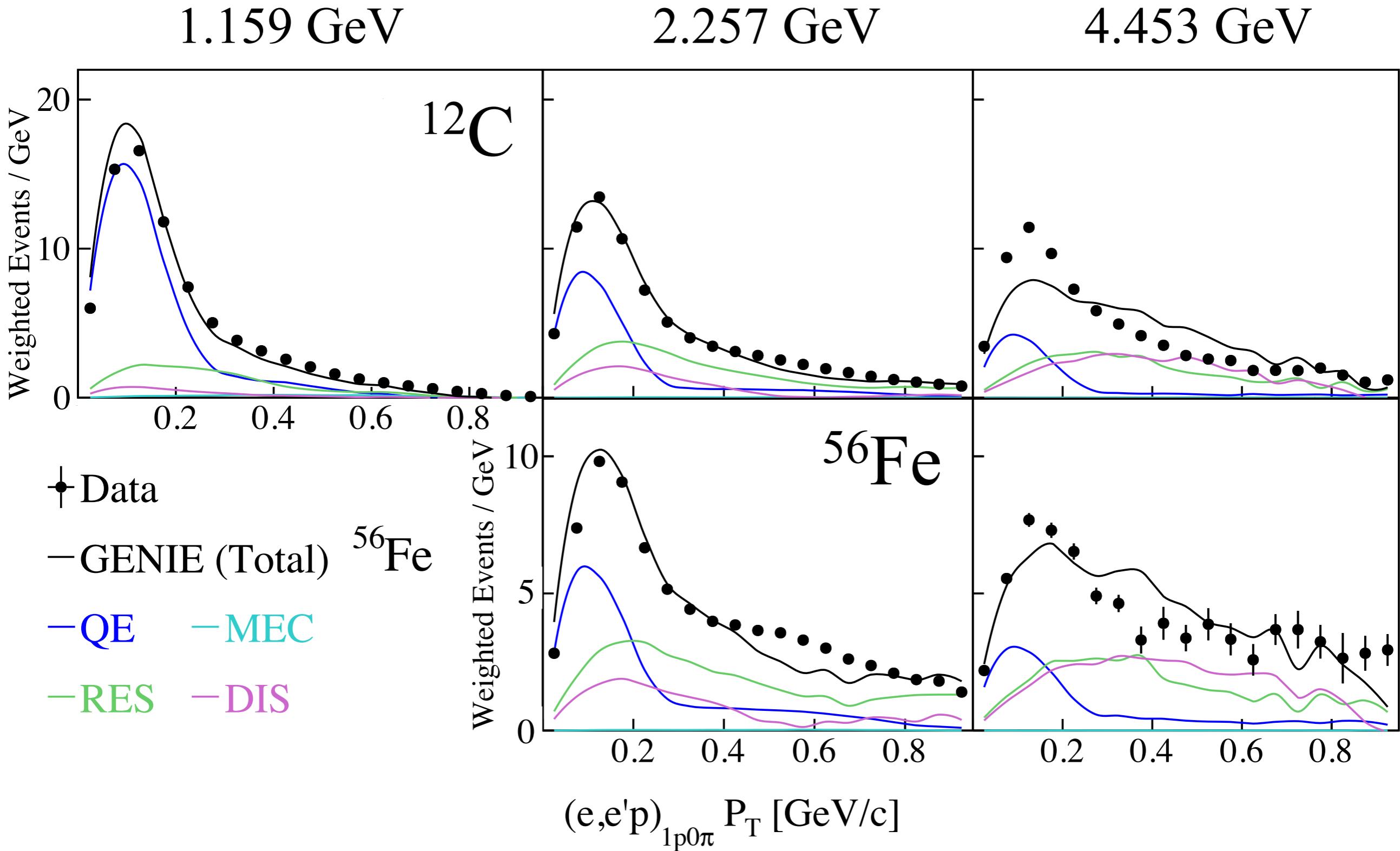


Axel Schmidt, Reynier Cruz Torres, Barak Schmookler, Adin Hrnjic

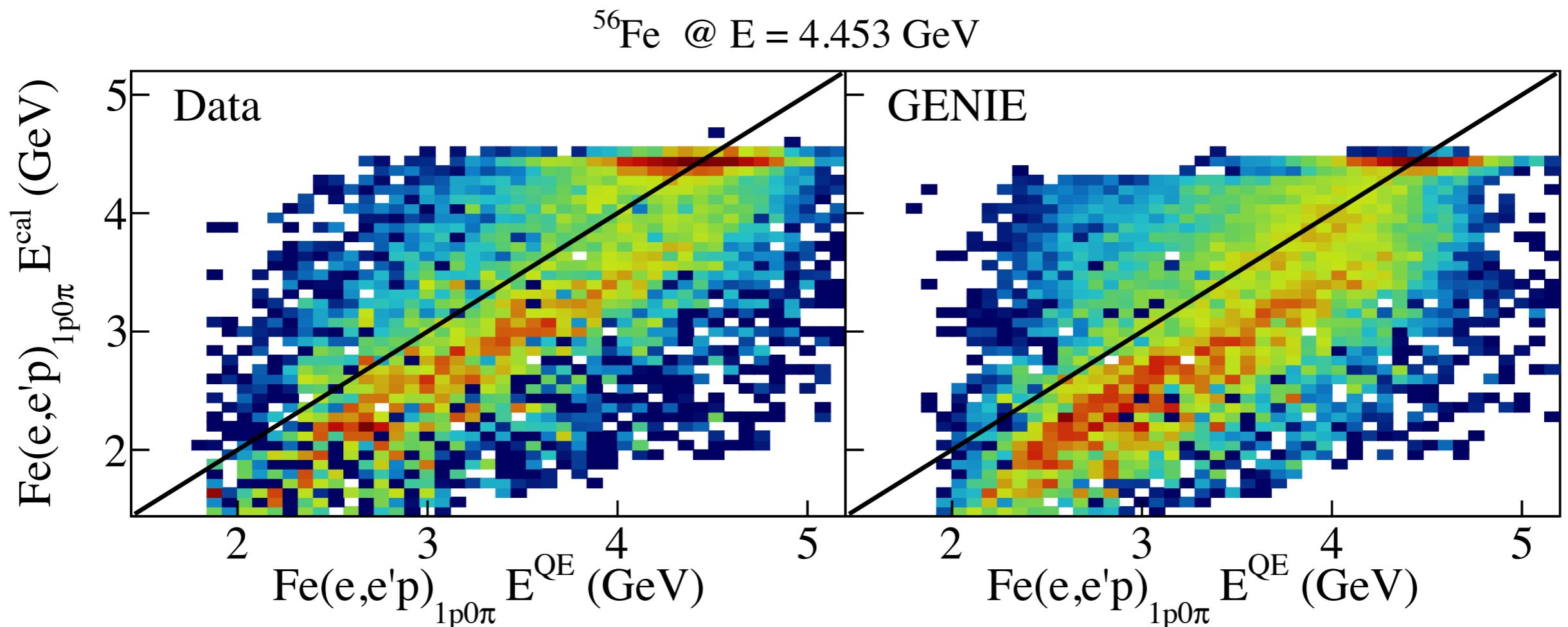
Ecal around the QE peak $0.8 < X_B < 1.2$



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



Systematic Uncertainties



Systematic Uncertainties - Data side

1. Background subtraction:
 1. Assuming no $\phi_{q\pi}$ dependency when rotating hadrons system around q vector. $H(e, e' p\pi)$ cross sections measured dependency affected the subtracted spectra by about 1%.
 2. Varying the CLAS ϕ acceptance in each sector reduced by 10–20%. 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 $\pm 0.25\sigma$. 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.

No normalisation uncertainties, as simulation was scaled to data.

GENIE Simulation

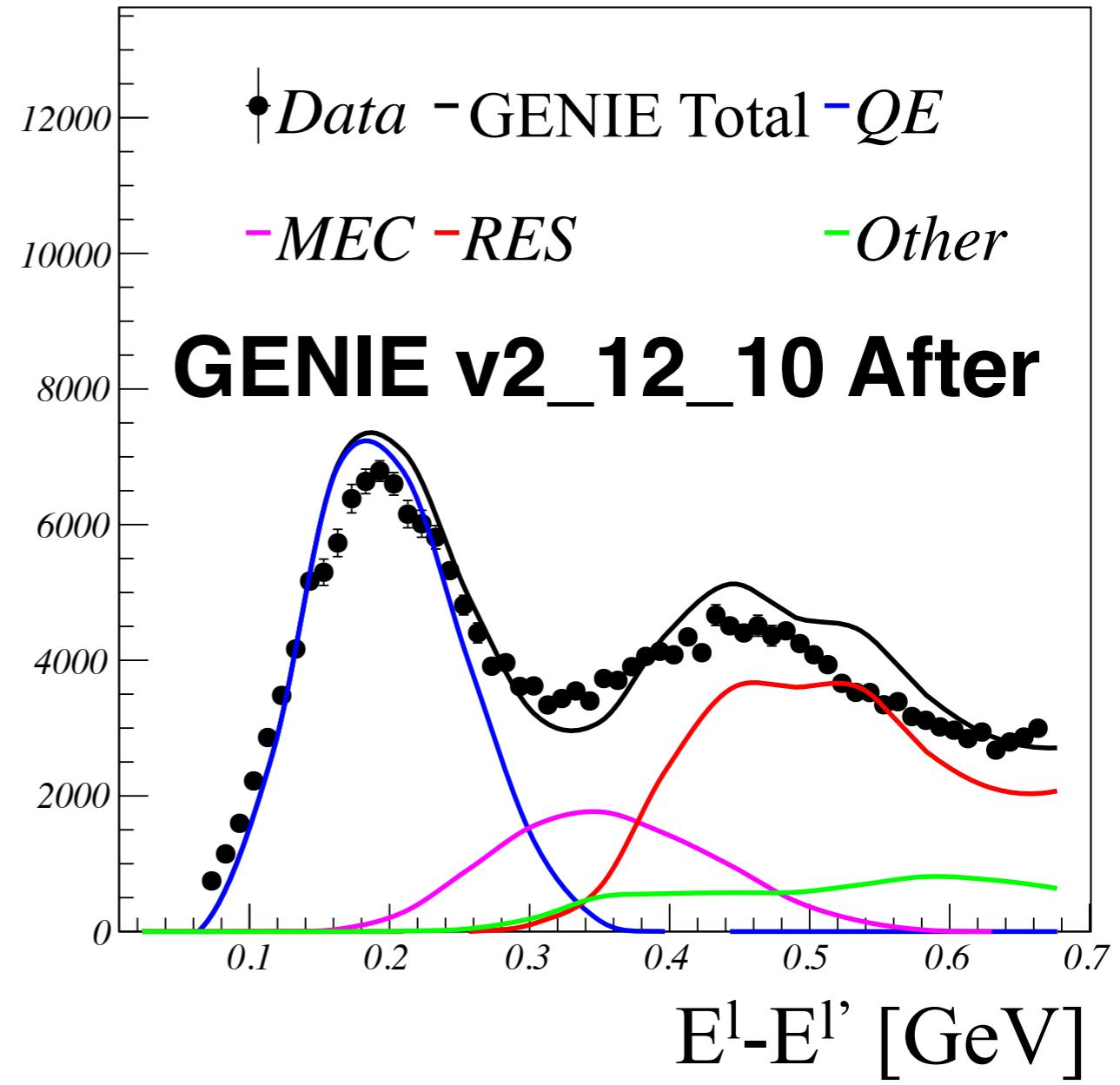
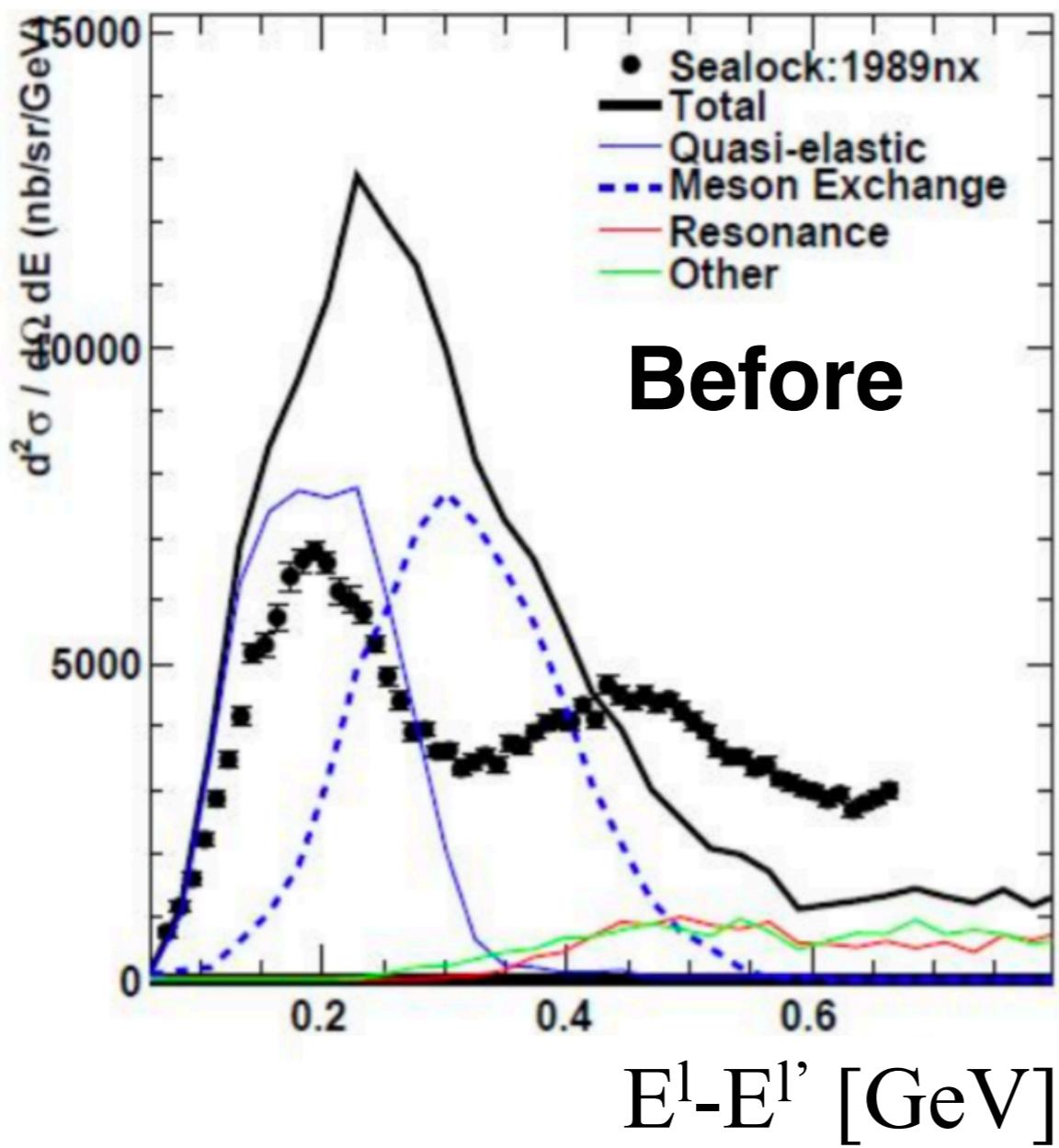
Genie

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		
FSI		hA2018
Others	Adding radiative correction	

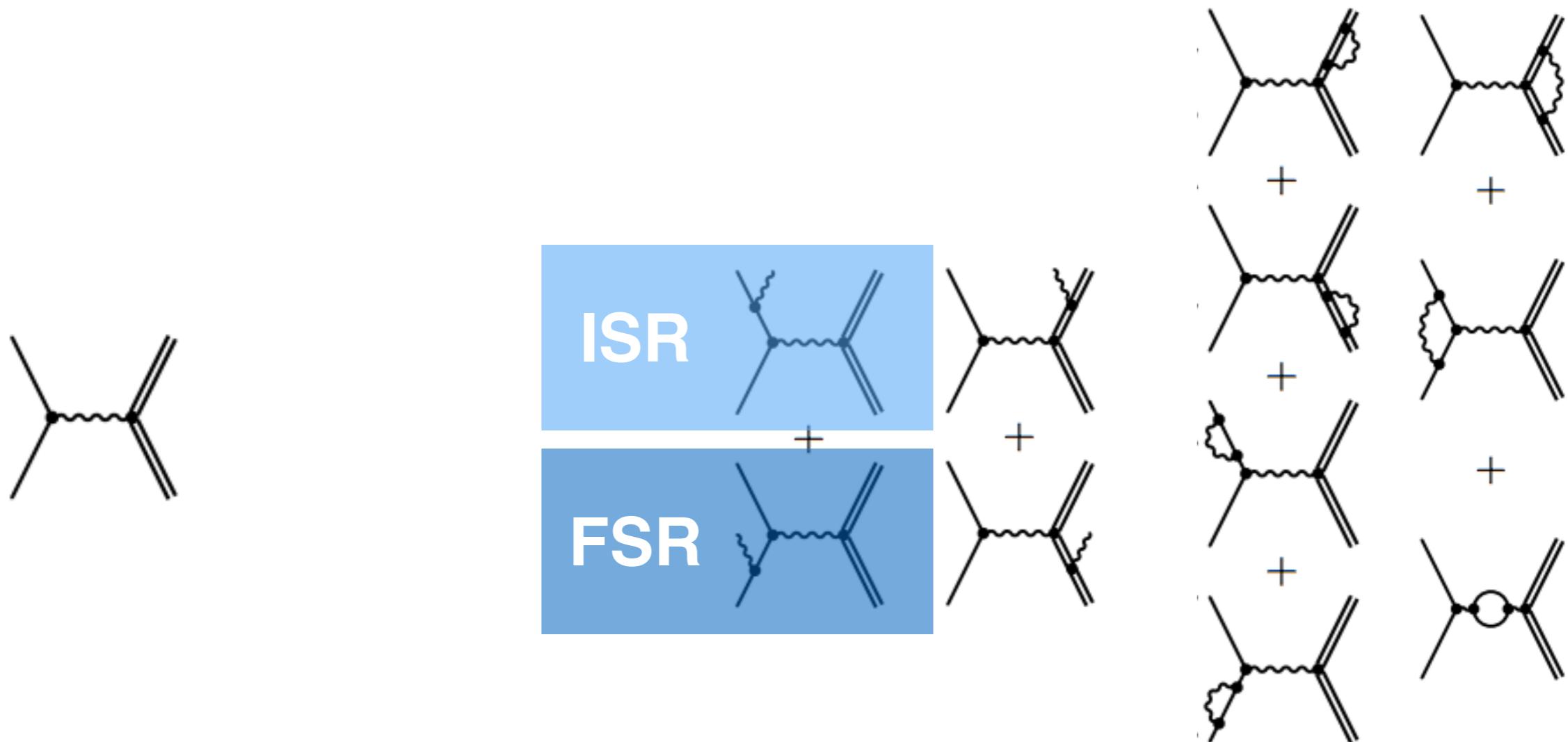
Testing neutrino generators with inclusive electron scattering data

$^{12}\text{C}(\text{e},\text{e}') \quad E = 0.961 \text{ GeV} \quad \theta = 37.5^\circ$



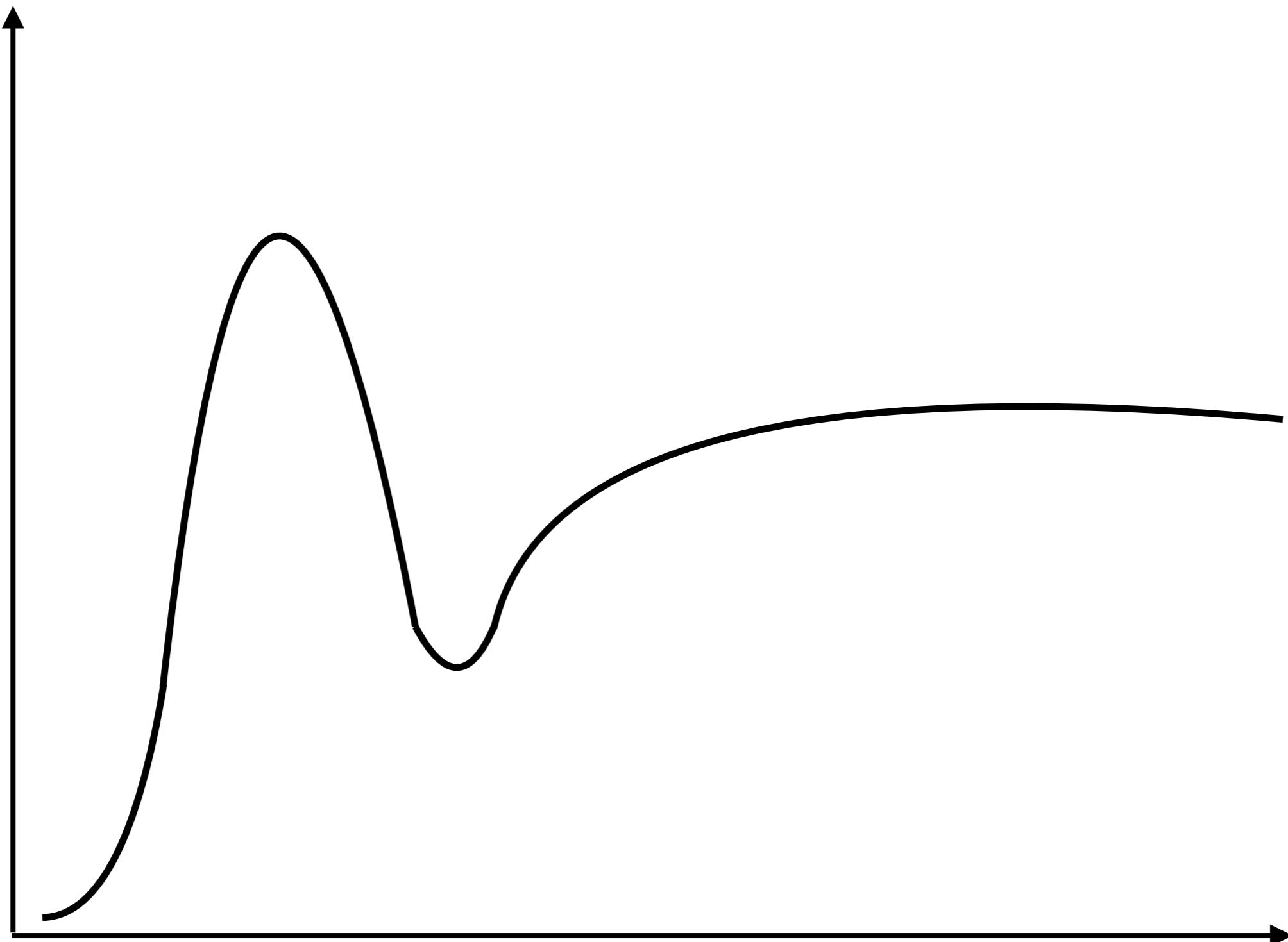
Radiative Correction

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

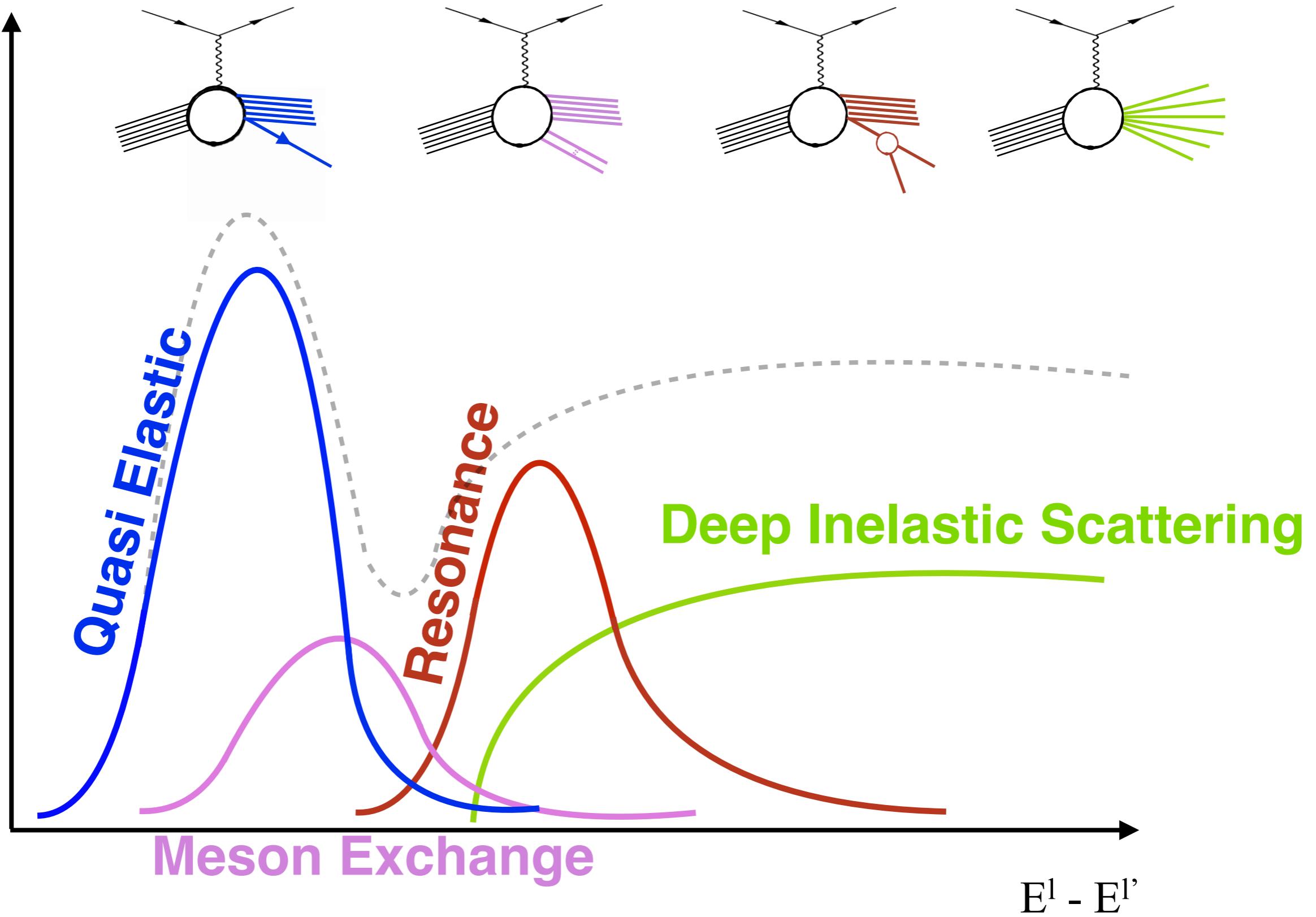


Based on Mo and Tsai calculation

E_ν Reco Requires Interaction Modelling

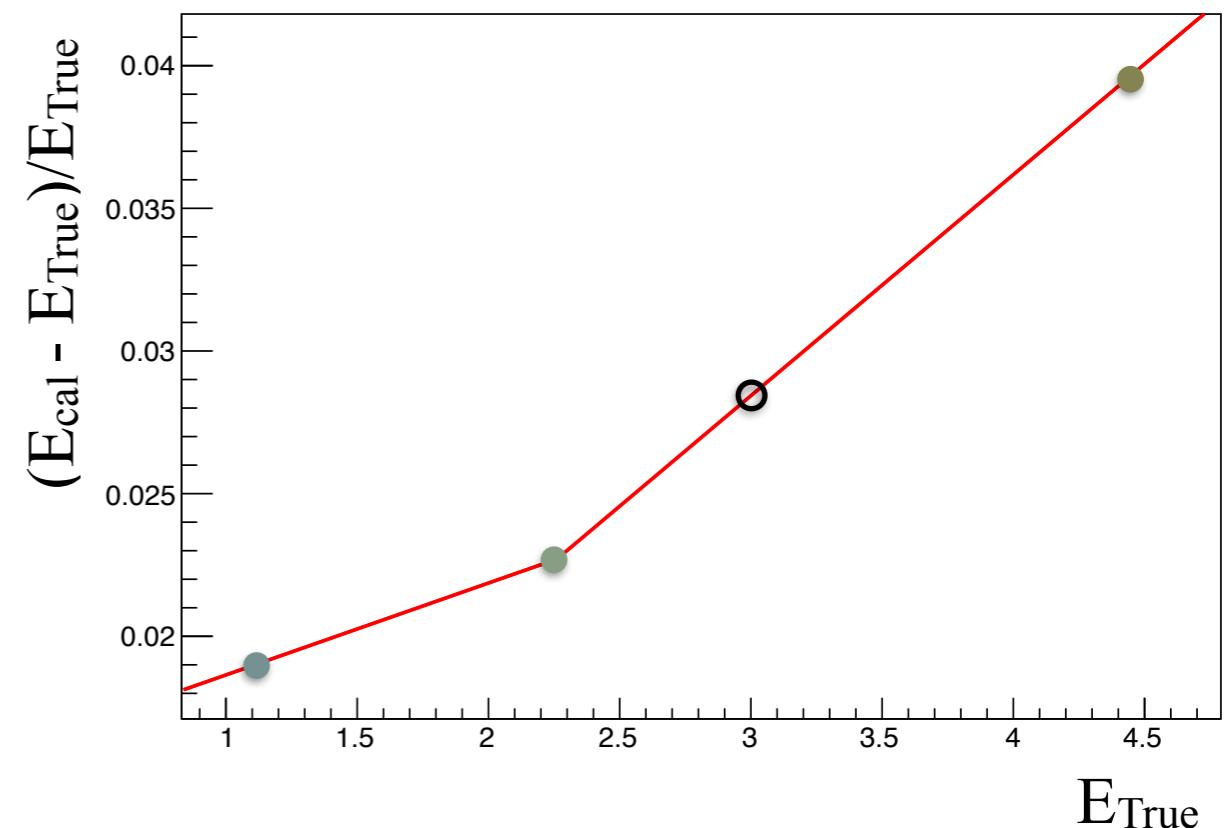
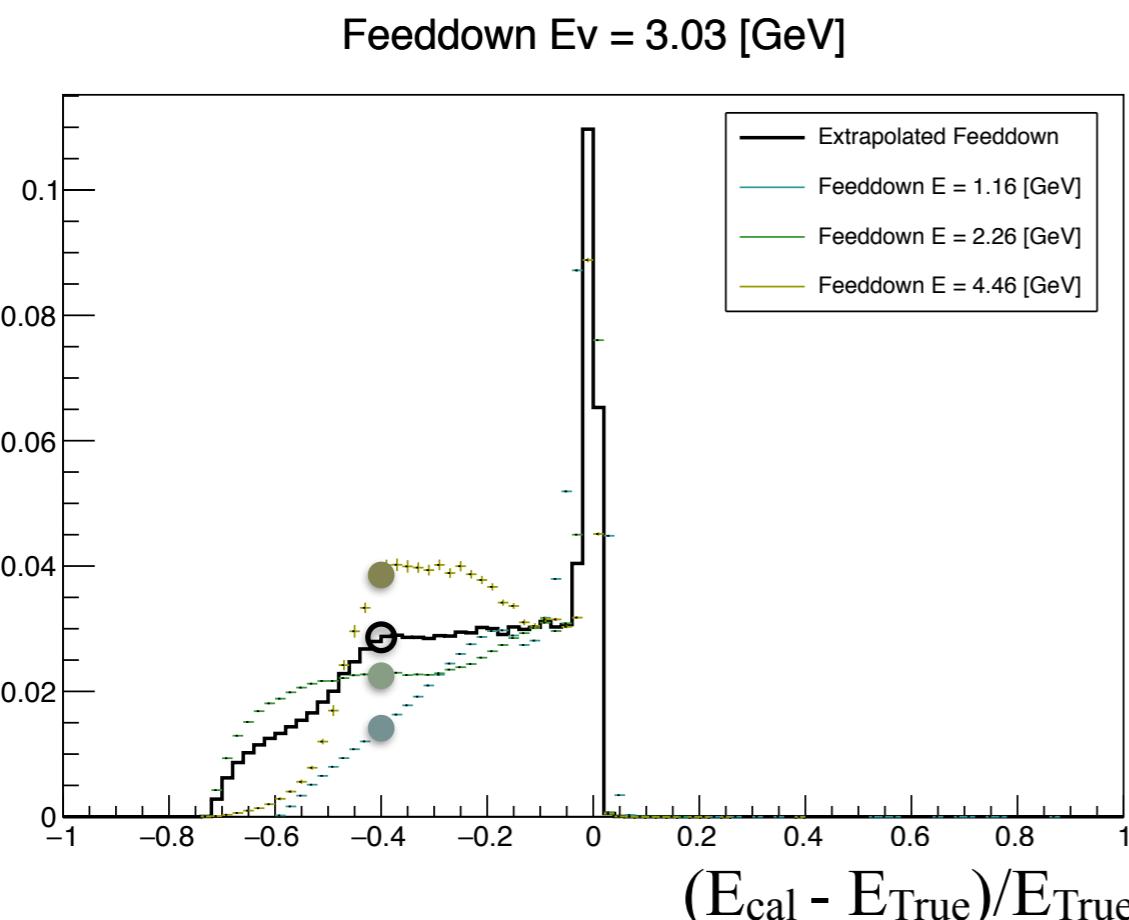


E_ν Reco Requires Interaction Modelling

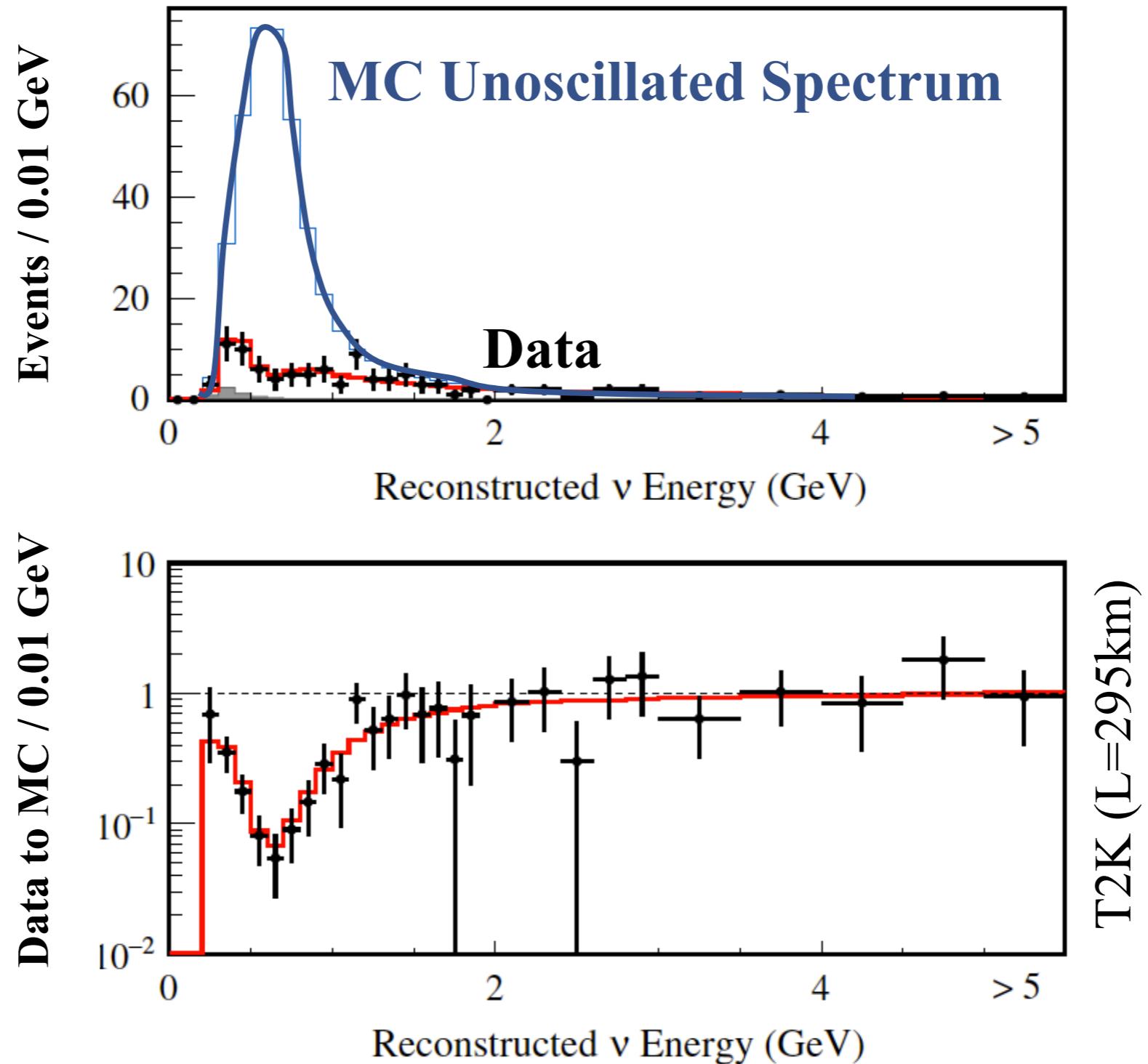


Potential implication on analysis

The expected energy at DUNE far detector as reconstructed using the energy feed down from $A(e,e'p)$ data and simulation

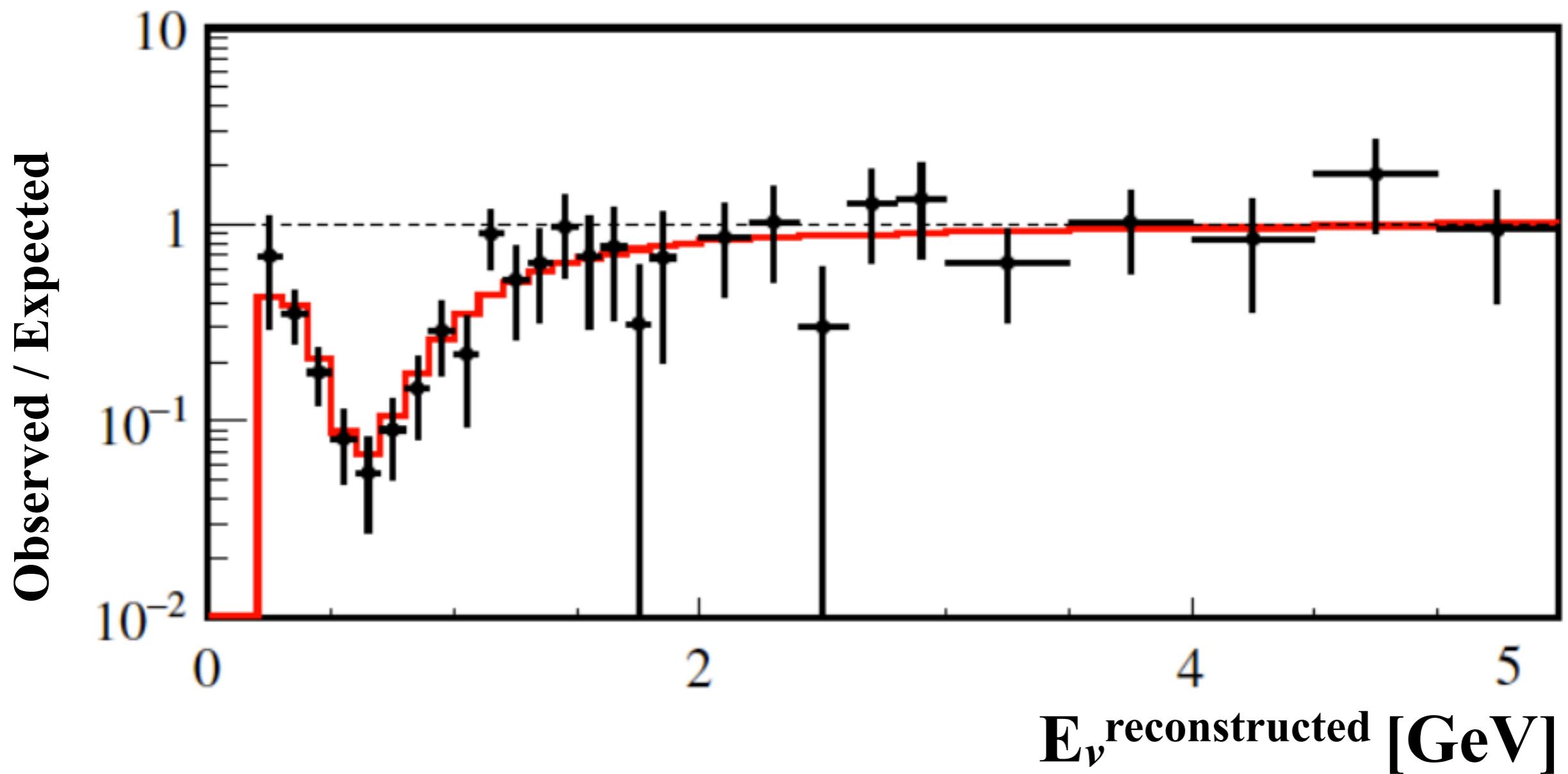


Oscillations Require E_ν Reconstruction



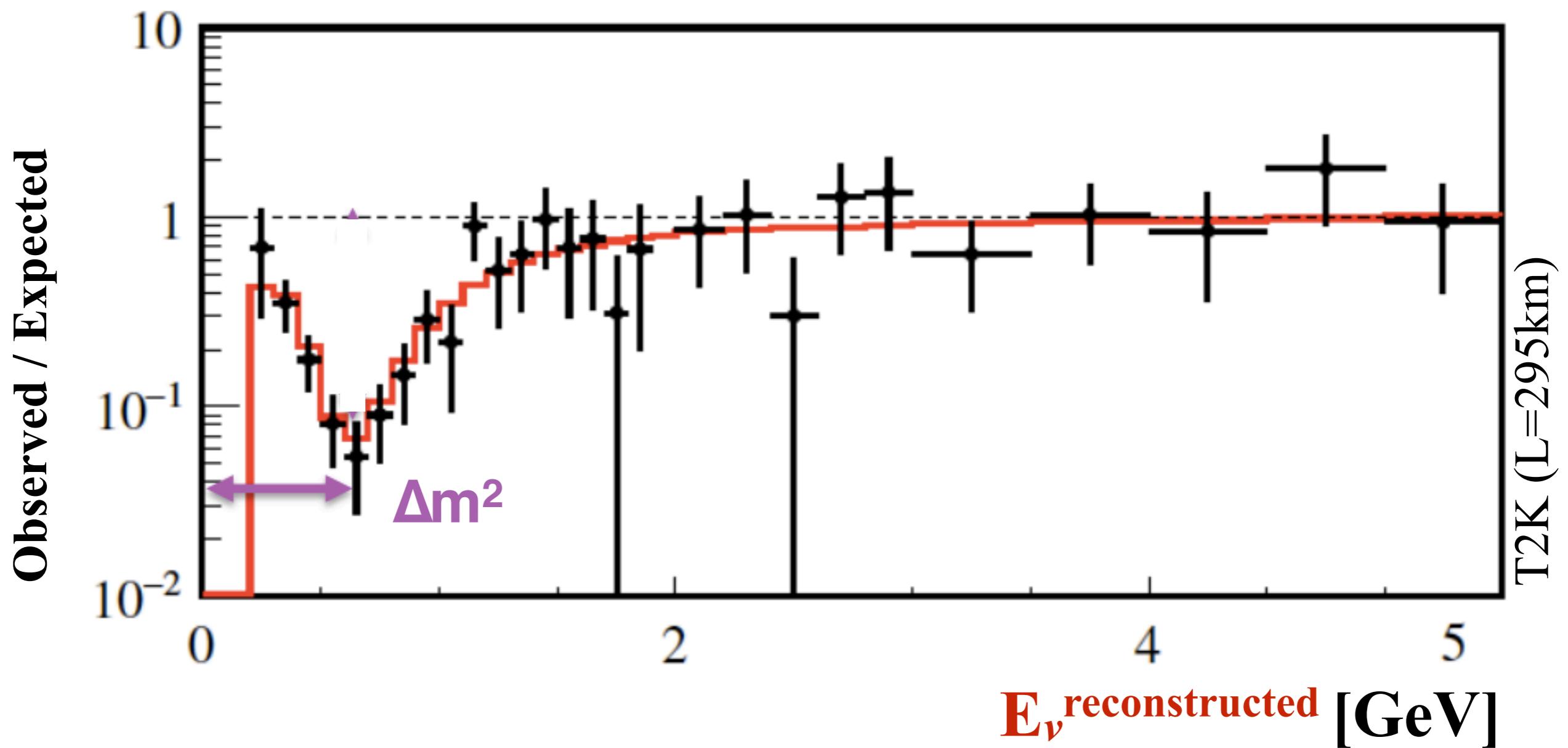
Oscillations Require E_ν Reconstruction

$$P(\nu_\mu \rightarrow \nu_x) = \sin^2(2\theta) \times \sin^2\left(\frac{\Delta m^2 L}{4E_\nu}\right)$$



Oscillations Require E_ν Reconstruction

$$P(\nu_\mu \rightarrow \nu_x) = \sin^2(2\theta) \times \sin^2\left(\frac{\Delta m^2 L}{4E_\nu^{real}}\right)$$



Oscillations Require E_ν Reconstruction

$$P(\nu_\mu \rightarrow \nu_x) = \sin^2(2\theta) \times \sin^2\left(\frac{\Delta m^2 L}{4E_\nu^{real}}\right)$$

