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# Nuclear Aspects of Neutrino Interactions

(or why should we care for neutrinos in DIS2022)

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TEL AVIV UNIVERSITY

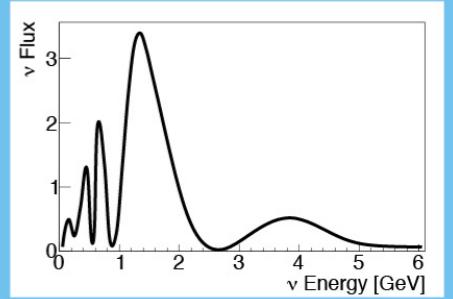
adishka@tauex.tau.ac.il

# PHYSICS PROCESS

Particles shoot out

Interacts with nucleus

Neutrino comes in

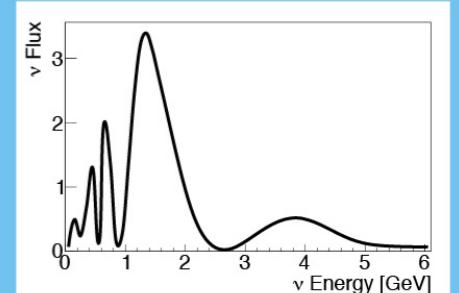


# PHYSICS PROCESS

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Interacts with nucleus

Neutrino comes in



Measure Particles

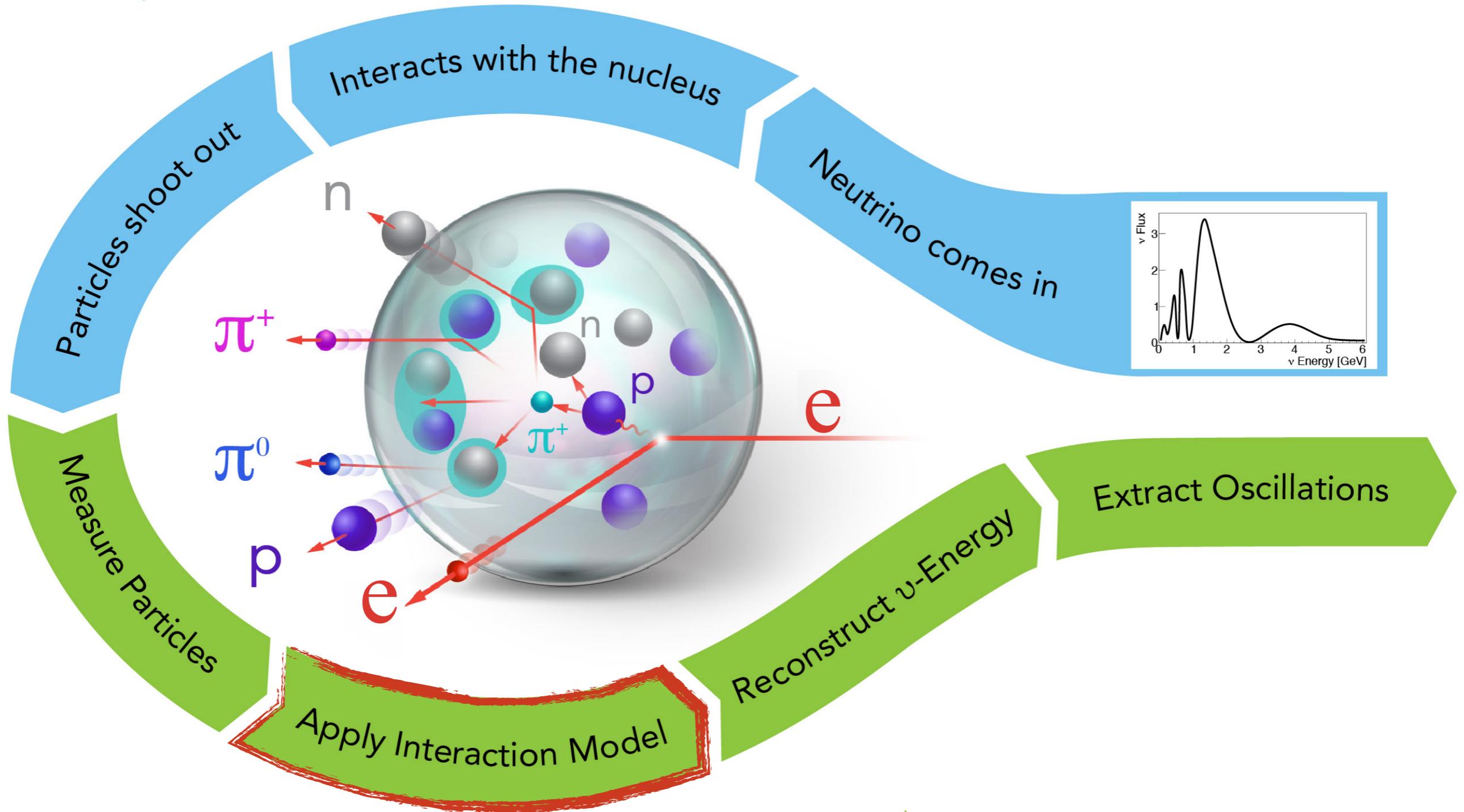
Apply Interaction Model

Reconstruct  $\nu$ -Energy

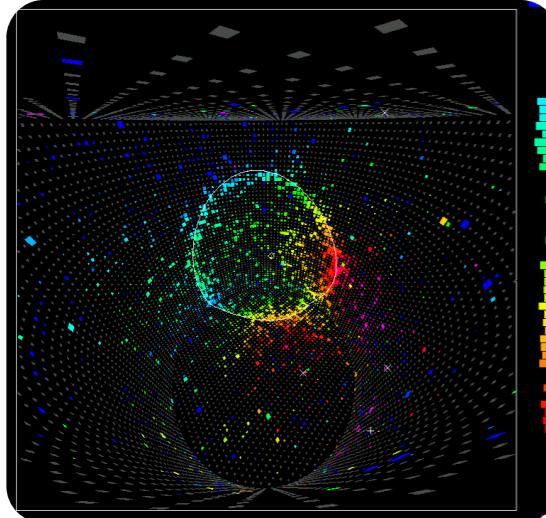
Extract Oscillations

# EXPERIMENTAL ANALYSIS

# PHYSICS PROCESS



# Incoming Energy Reconstruction



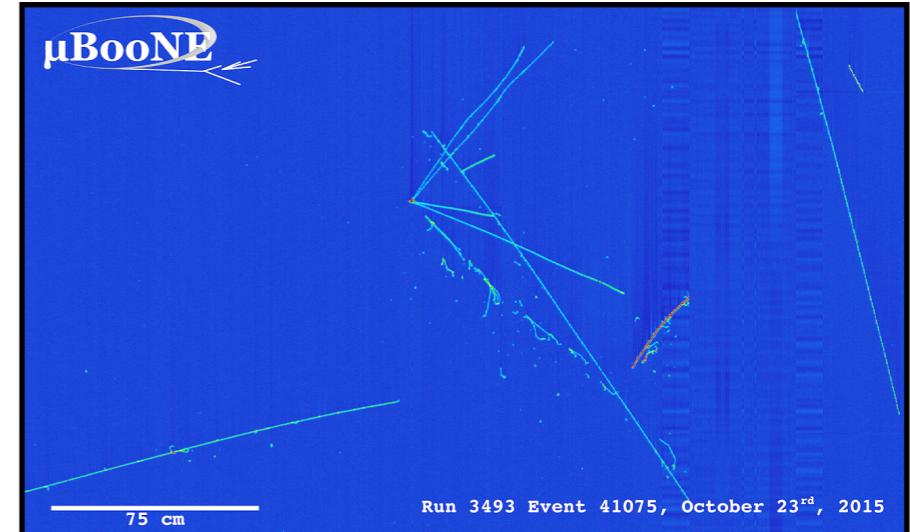
Cherenkov detectors:



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

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

$\epsilon$  is the nucleon separation energy  $\sim 20$  MeV

# The challenge - next generation high precision

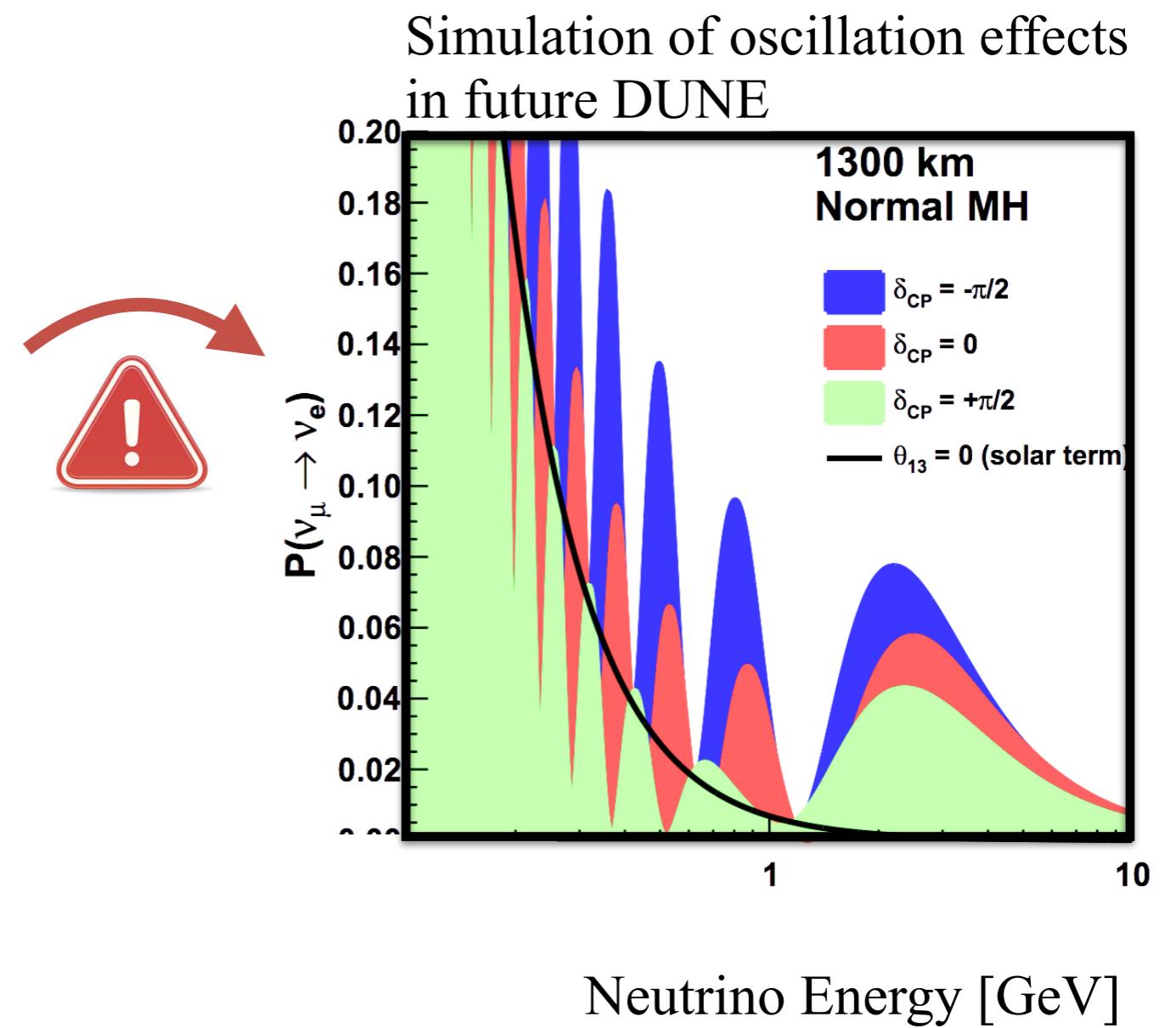
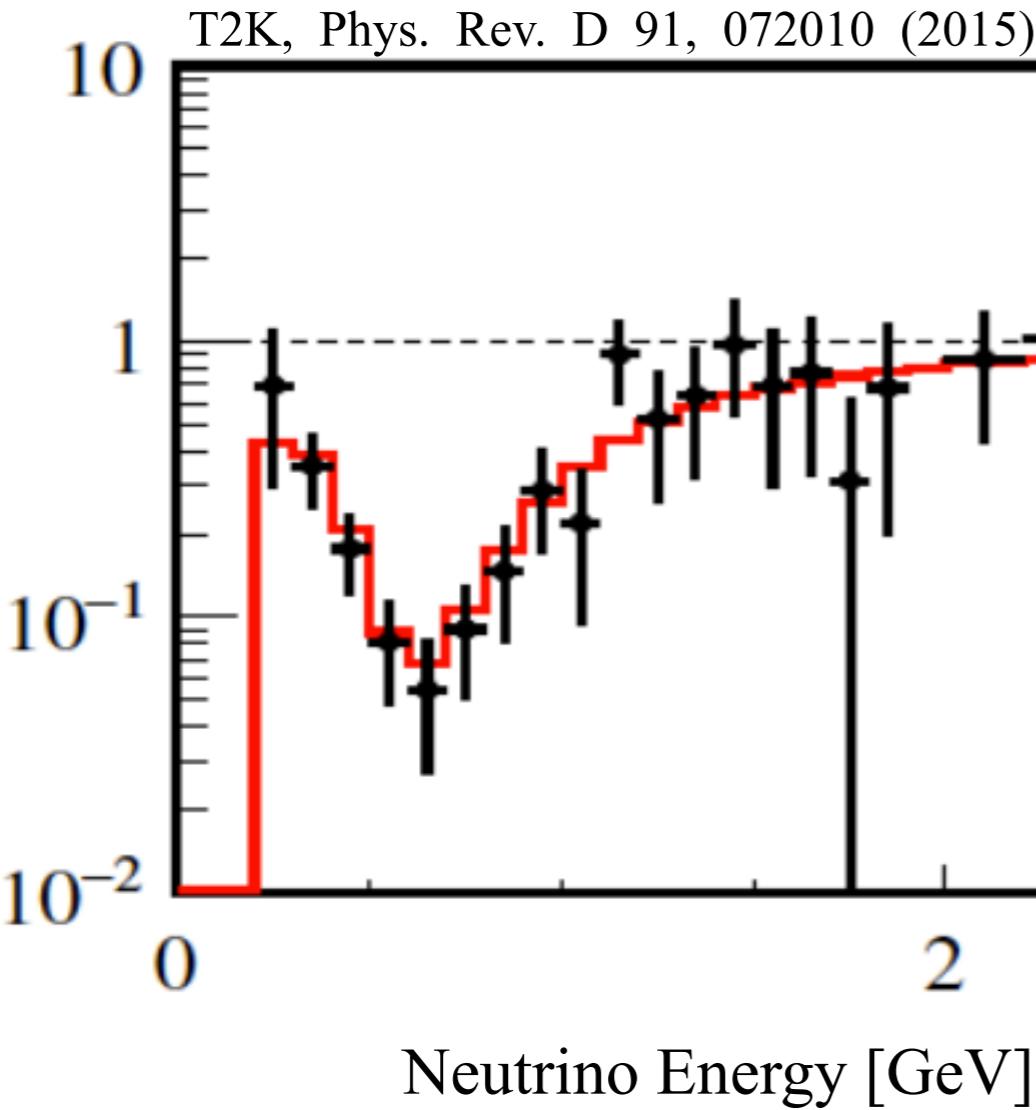
$$N(E_{rec}, L) \propto \int \Phi(E, L) \sigma(E) f_\sigma(E, E_{rec}) dE$$

Measurement

Incoming true flux Modelling input

# The challenge - next generation high precision

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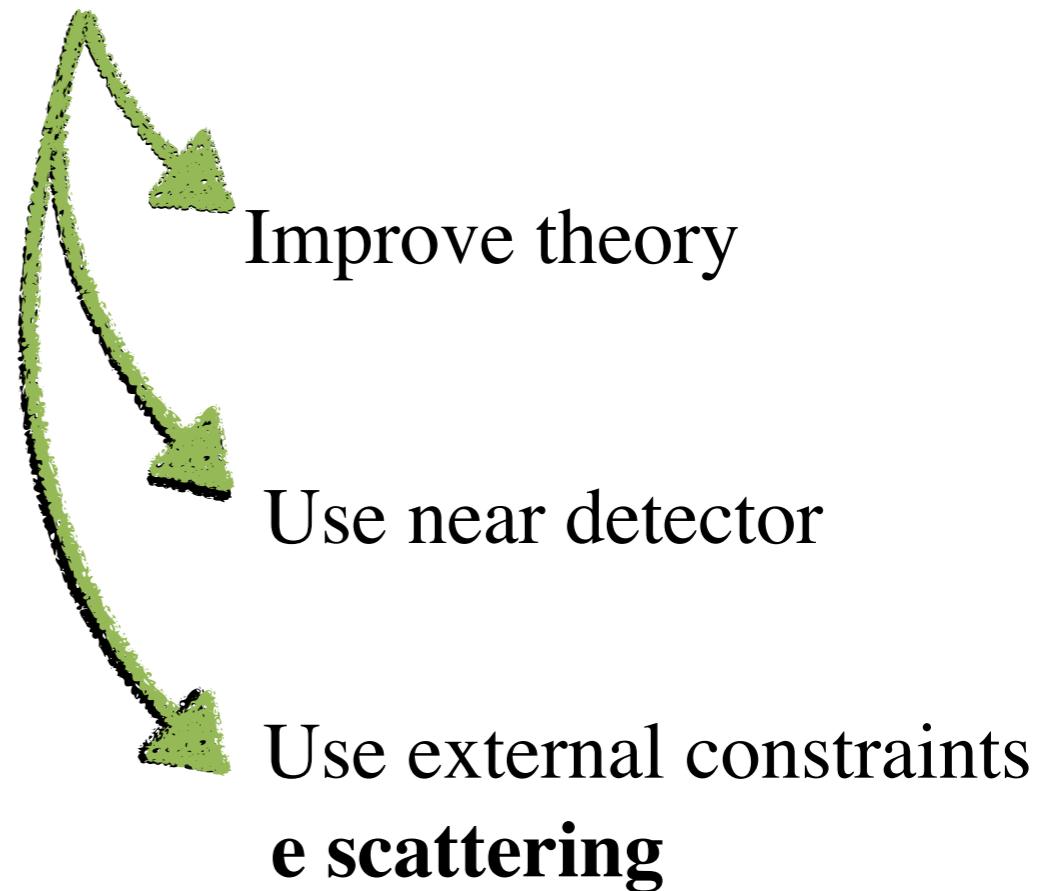


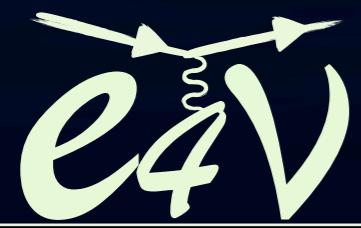
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Measurement

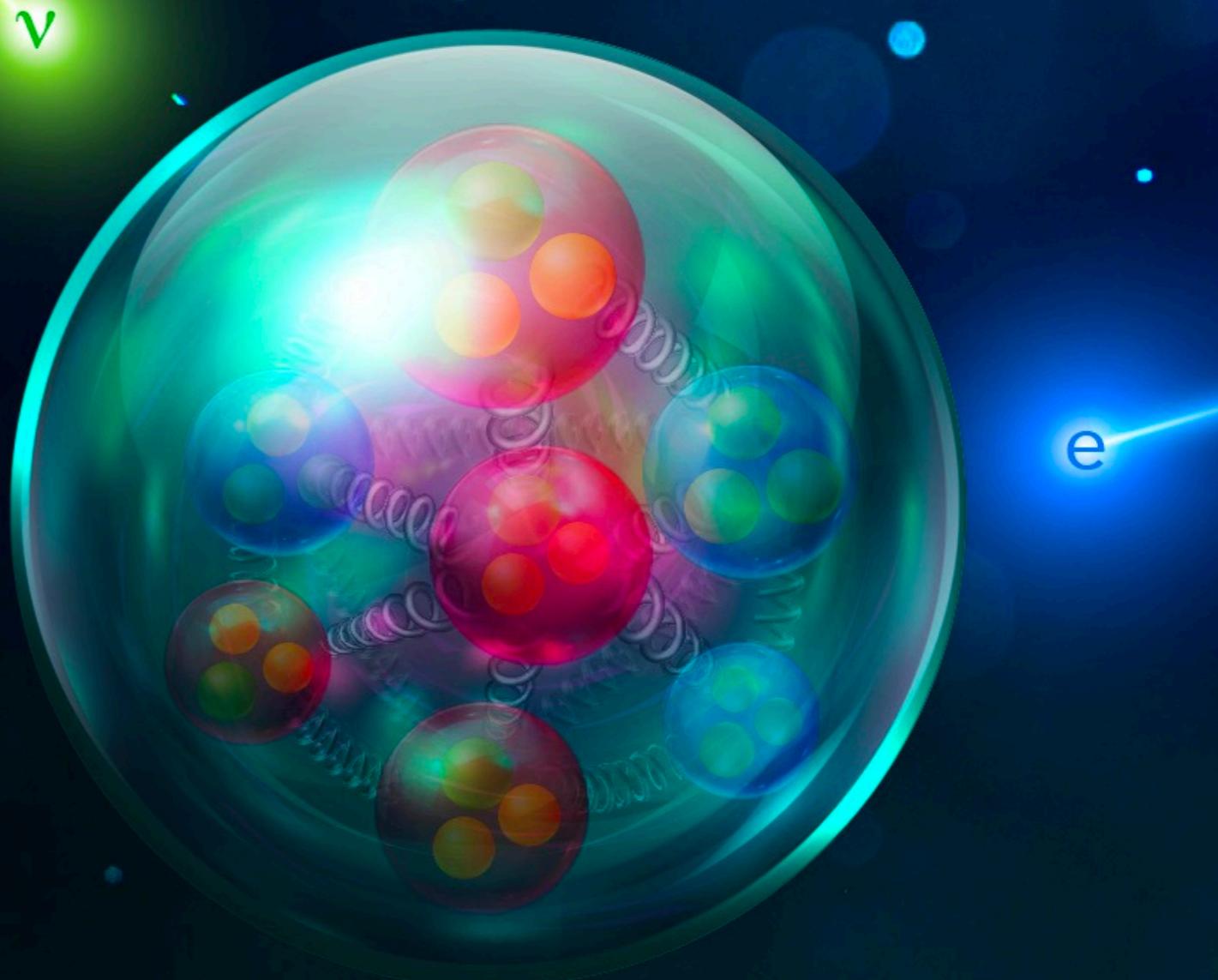
Incoming true flux Modelling input





# Electrons for Neutrinos

Using wide phase space  
electron scattering data  
for constraining  
neutrino-nuclei  
interaction models

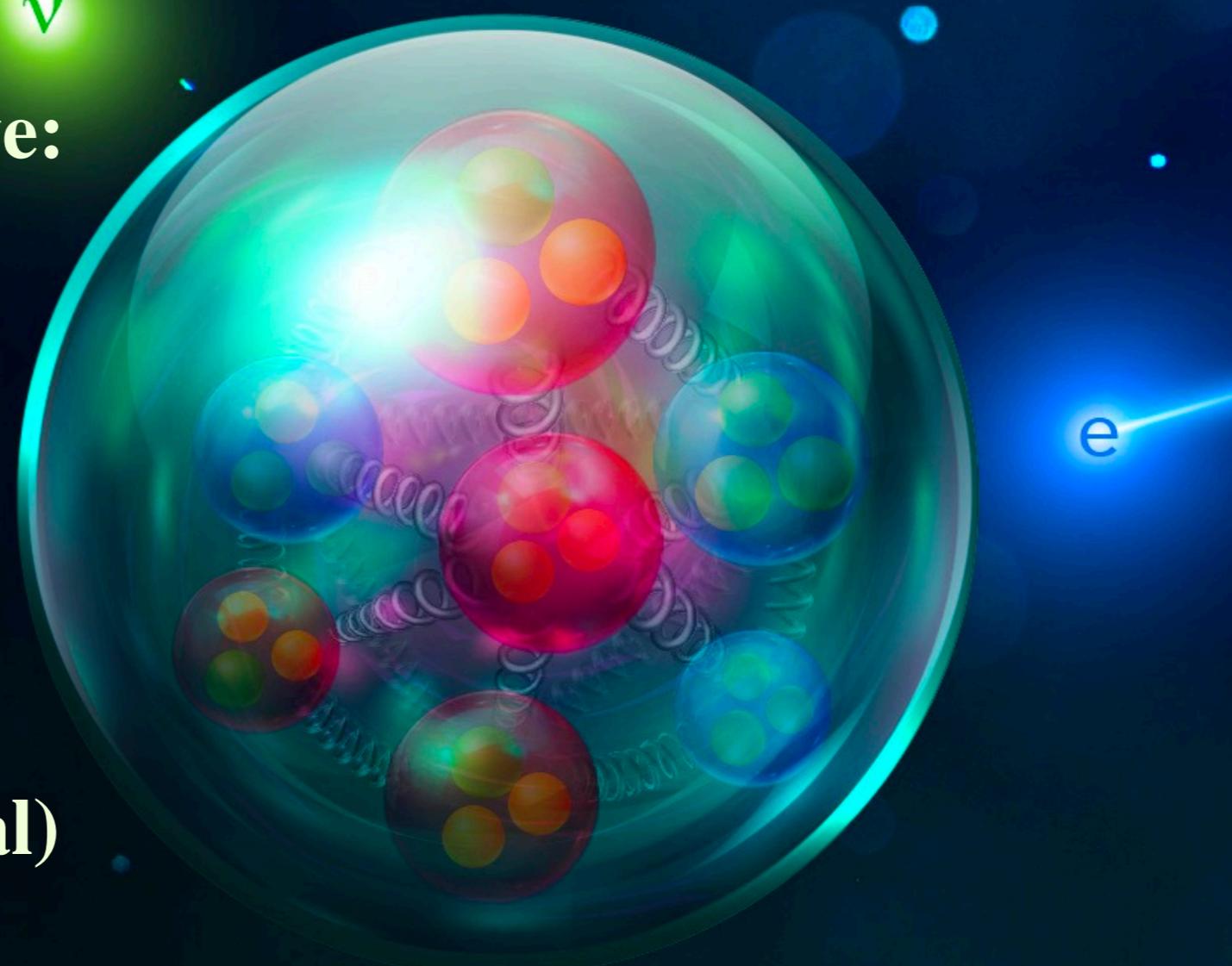


visit: [www.e4nu.com](http://www.e4nu.com)

# *e4N*: Why use electrons?

Electrons and Neutrinos have:

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

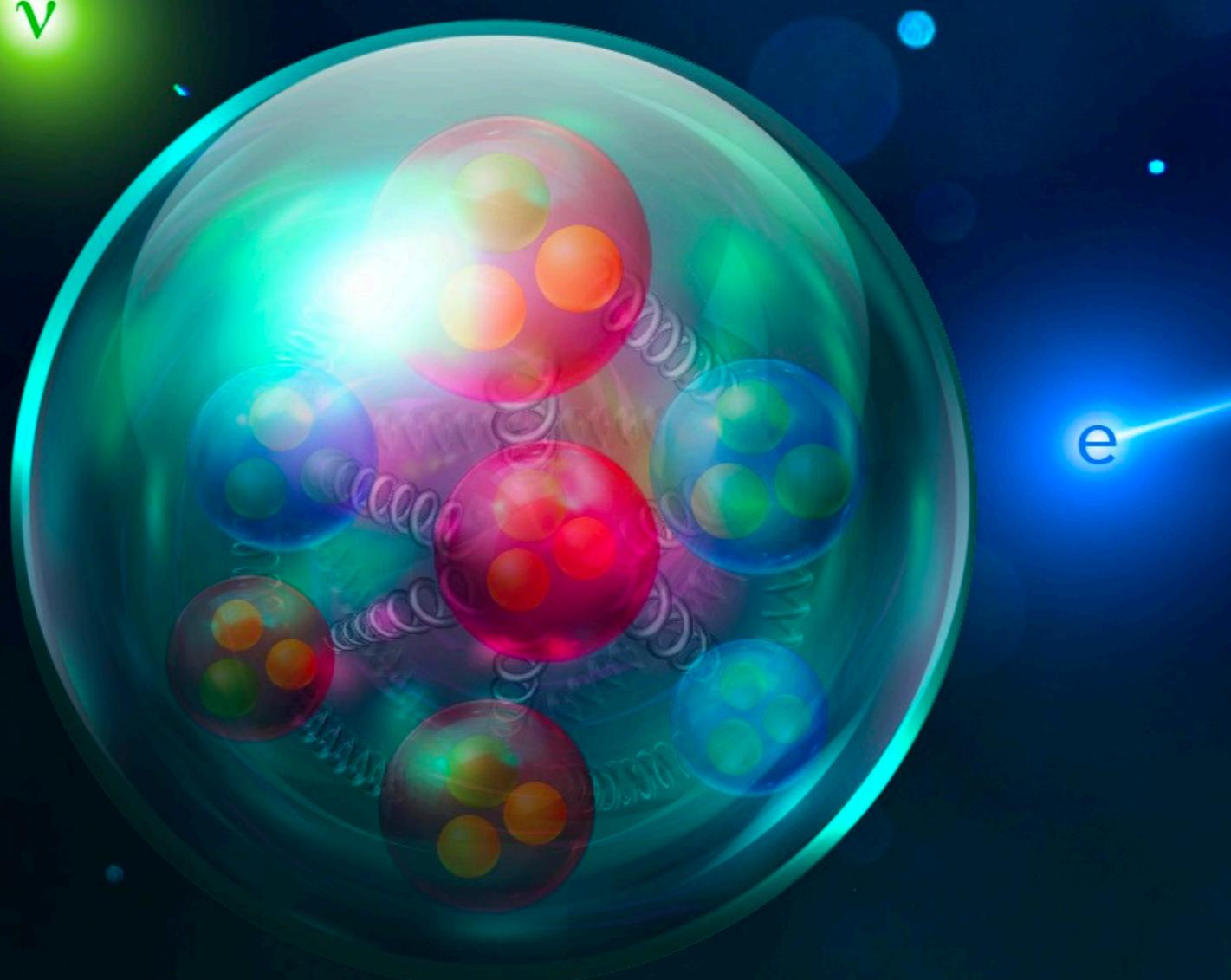


**Electron beams have known and precise energy**

# $e4\nu$ : Playing the Neutrino game

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

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



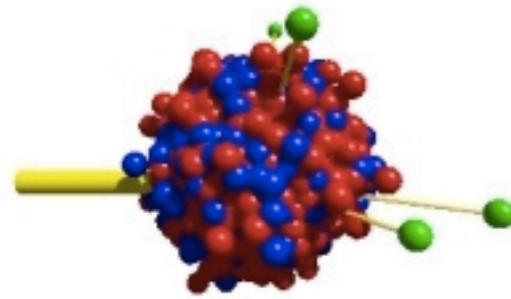
# vA Interaction Modelling

Neutrino event generators are used to simulate a vA interaction

Among those:



*Genie*



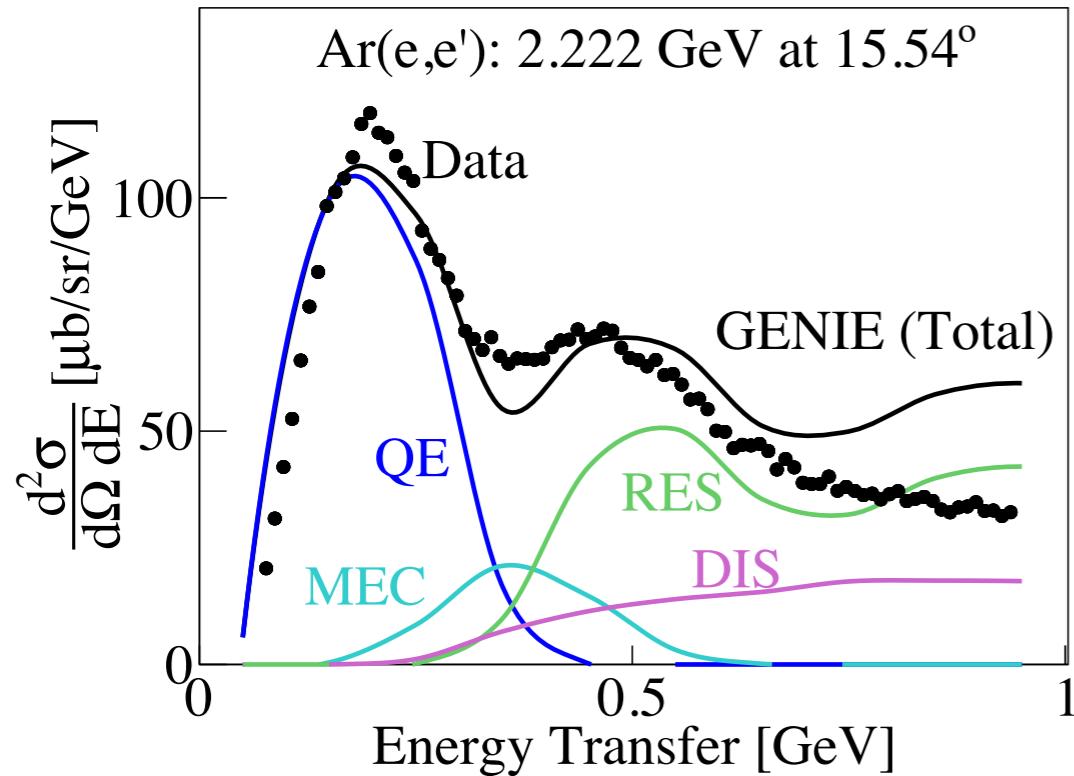
**GiBUU**

The Giessen Boltzmann-Uehling-Uhlenbeck Project

and more

# **GENIE reproduced e inclusive data**

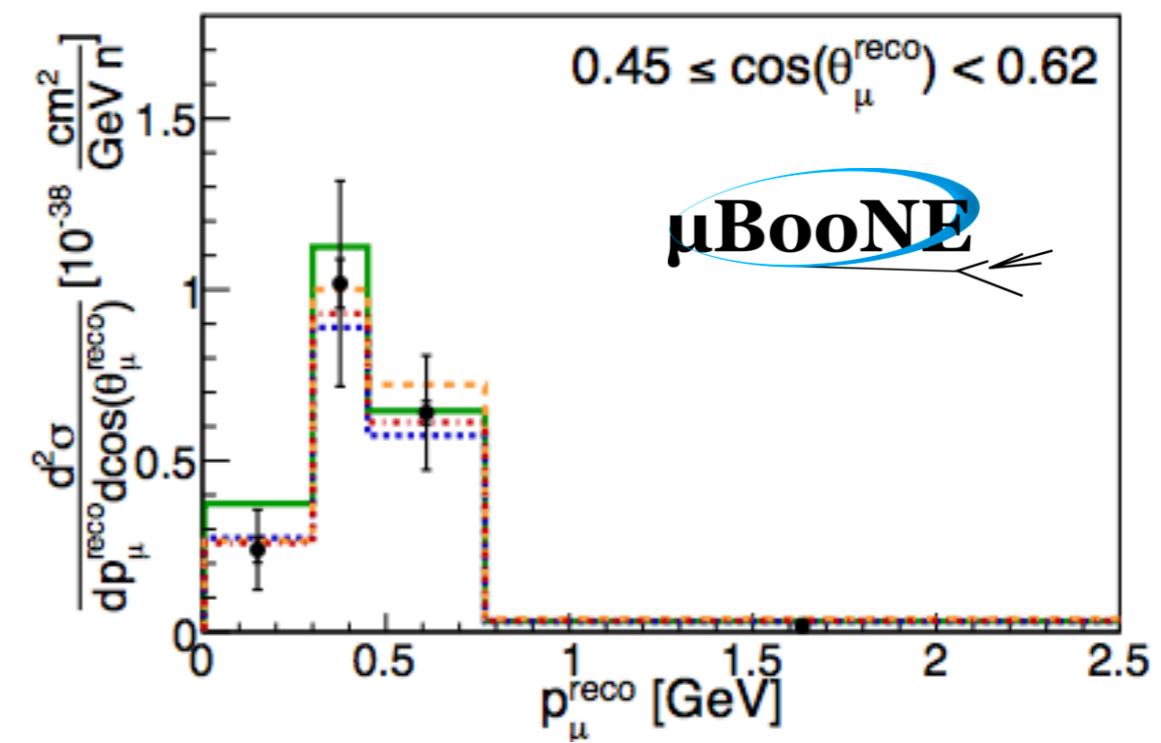
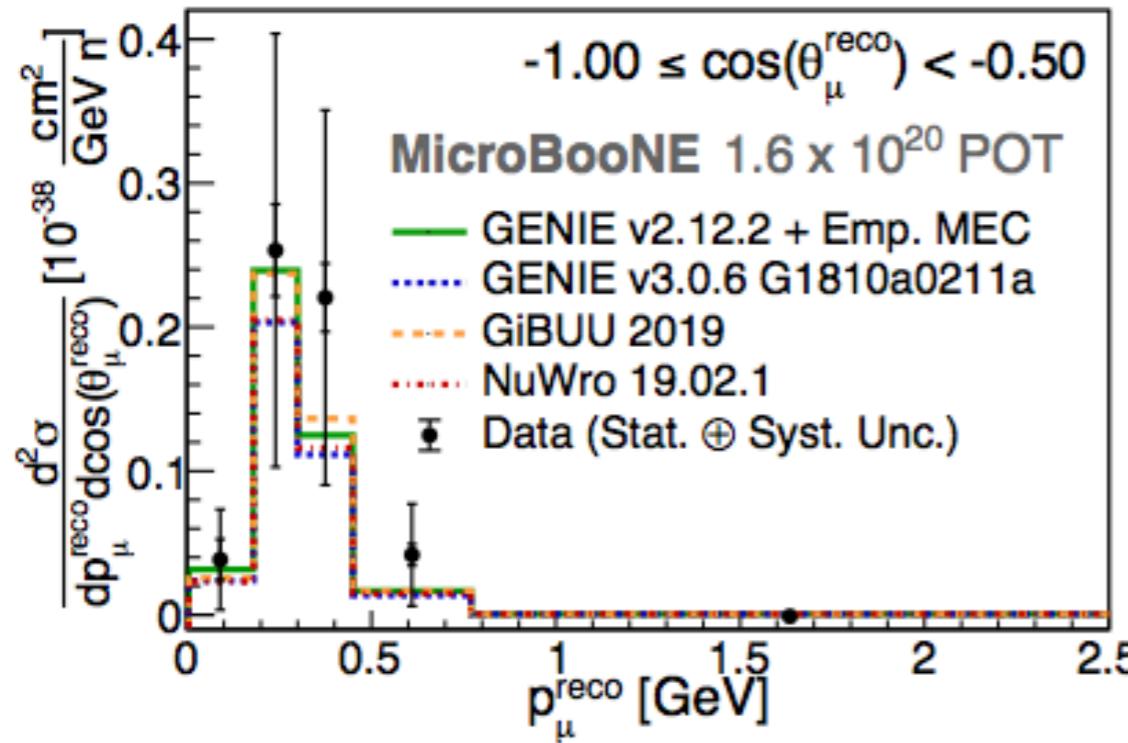
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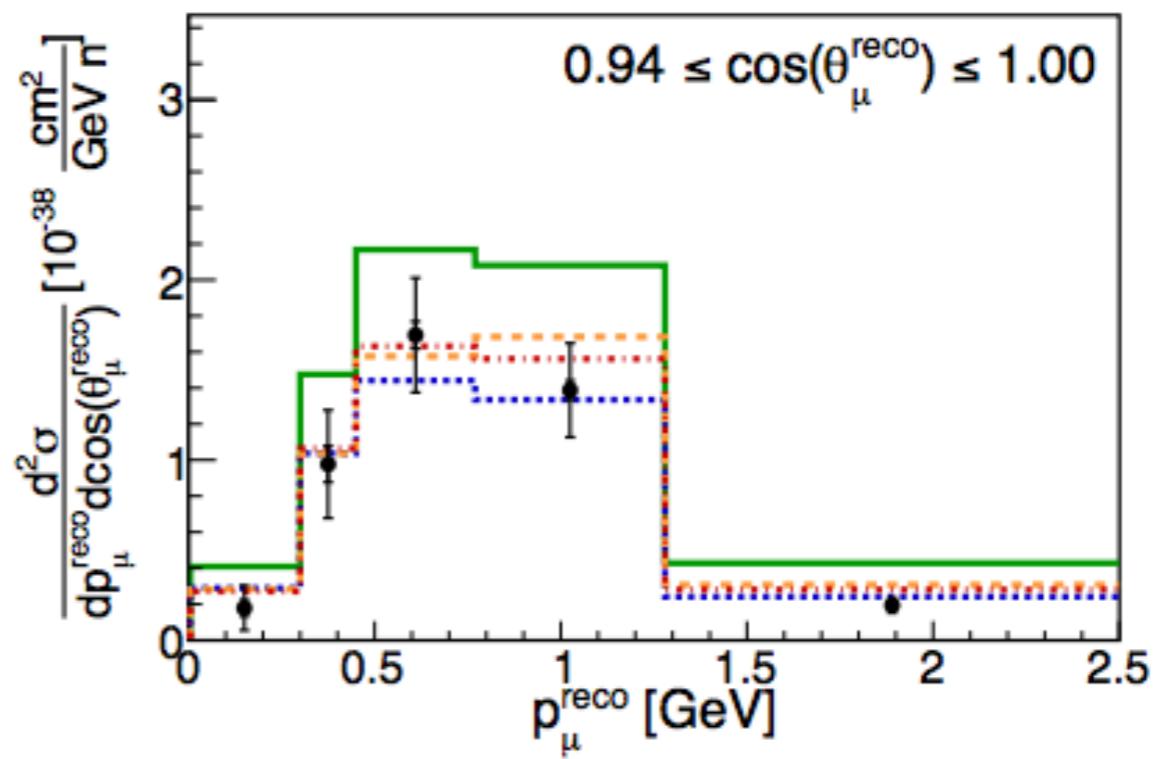
*Genie*

- v3.0.6 tune G18\_10a\_02\_11a

# GENIE reproducing $\nu$ inclusive data



*Genie*  
.... v3.0.6 tune G18\_10a\_02\_11a



# $e\bar{e}V$ @ the CLAS Detector

Electron beam with energies up to 6 GeV

Large acceptance

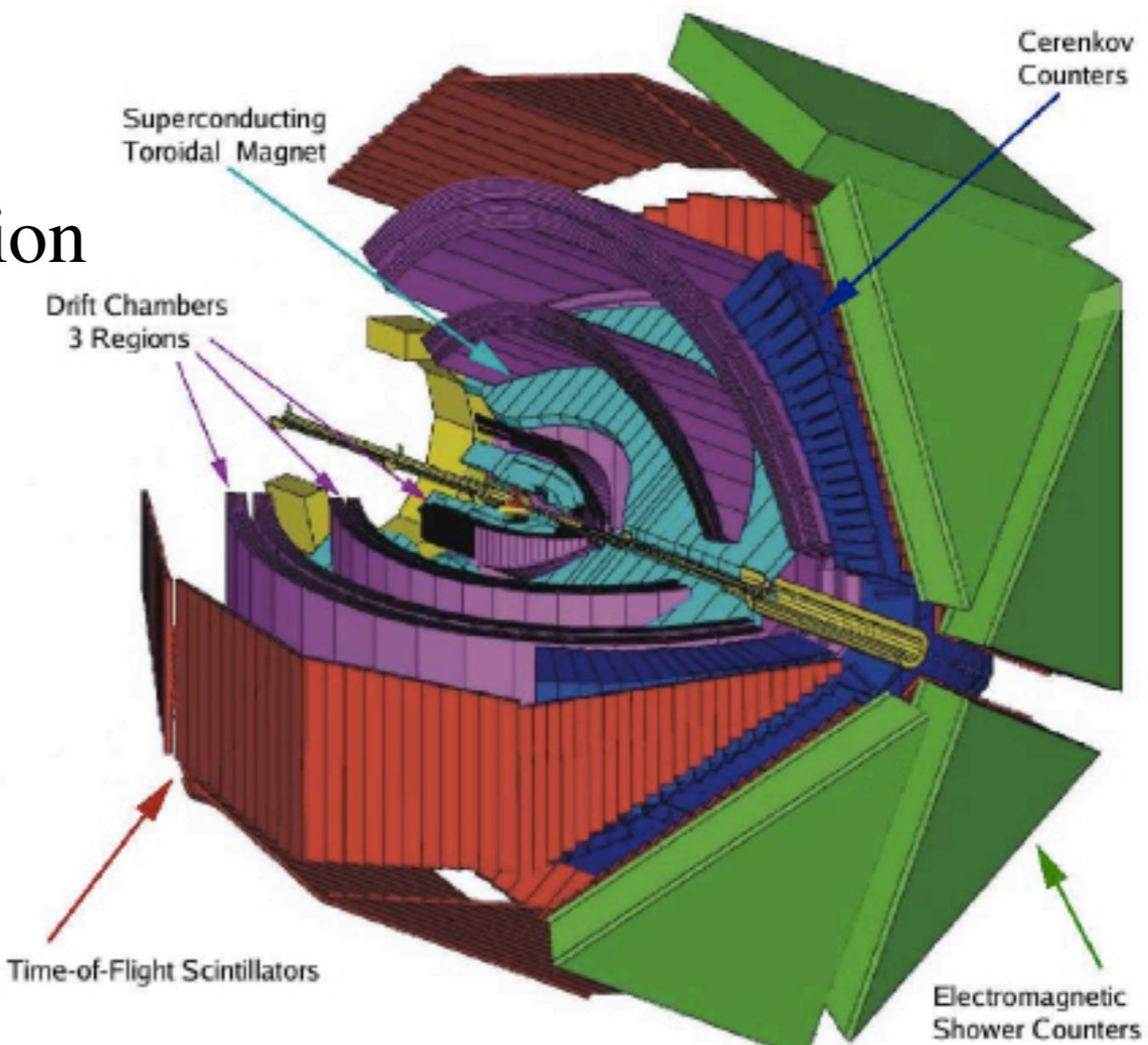
Charged particles above detection

threshold:

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

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

**Open Trigger**



# CLAS A(e,e'p) Data

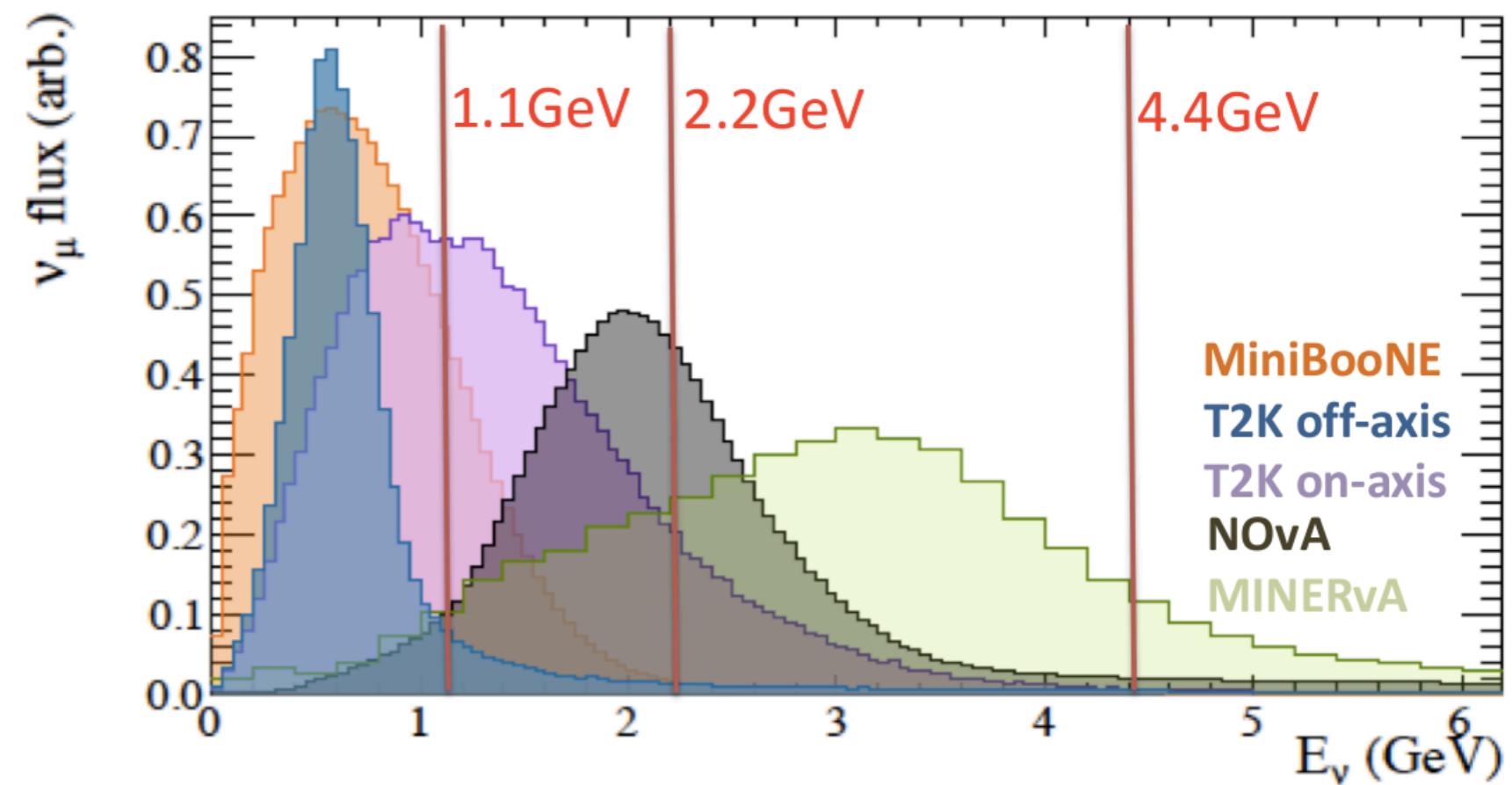
Targets:

$^4\text{He}$ ,  $^{12}\text{C}$ ,  $^{56}\text{Fe}$



Energies:

1.1, 2.2, 4.4 GeV



# $e\bar{e} \rightarrow 1p0\pi$ Event Selection

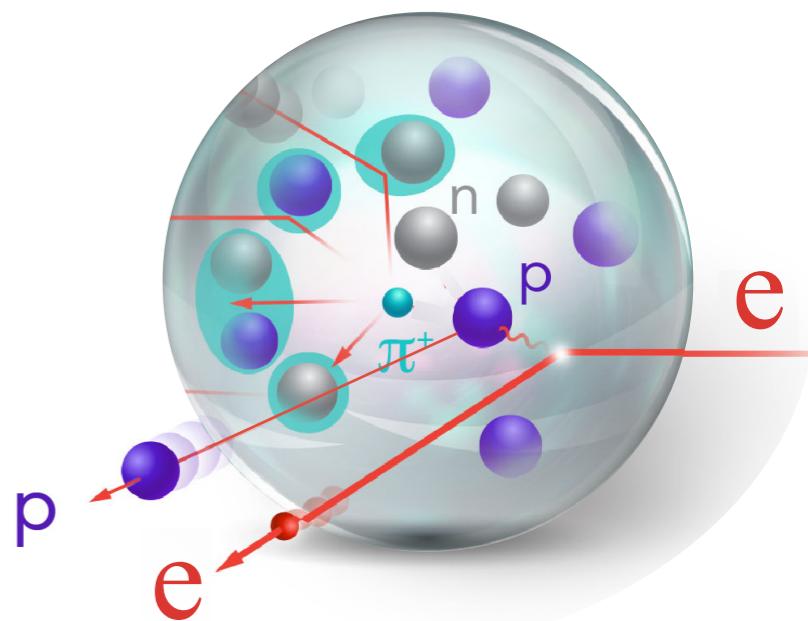
Focus on Quasi Elastic events:

1 proton above 300 MeV/c

no additional hadrons above threshold:

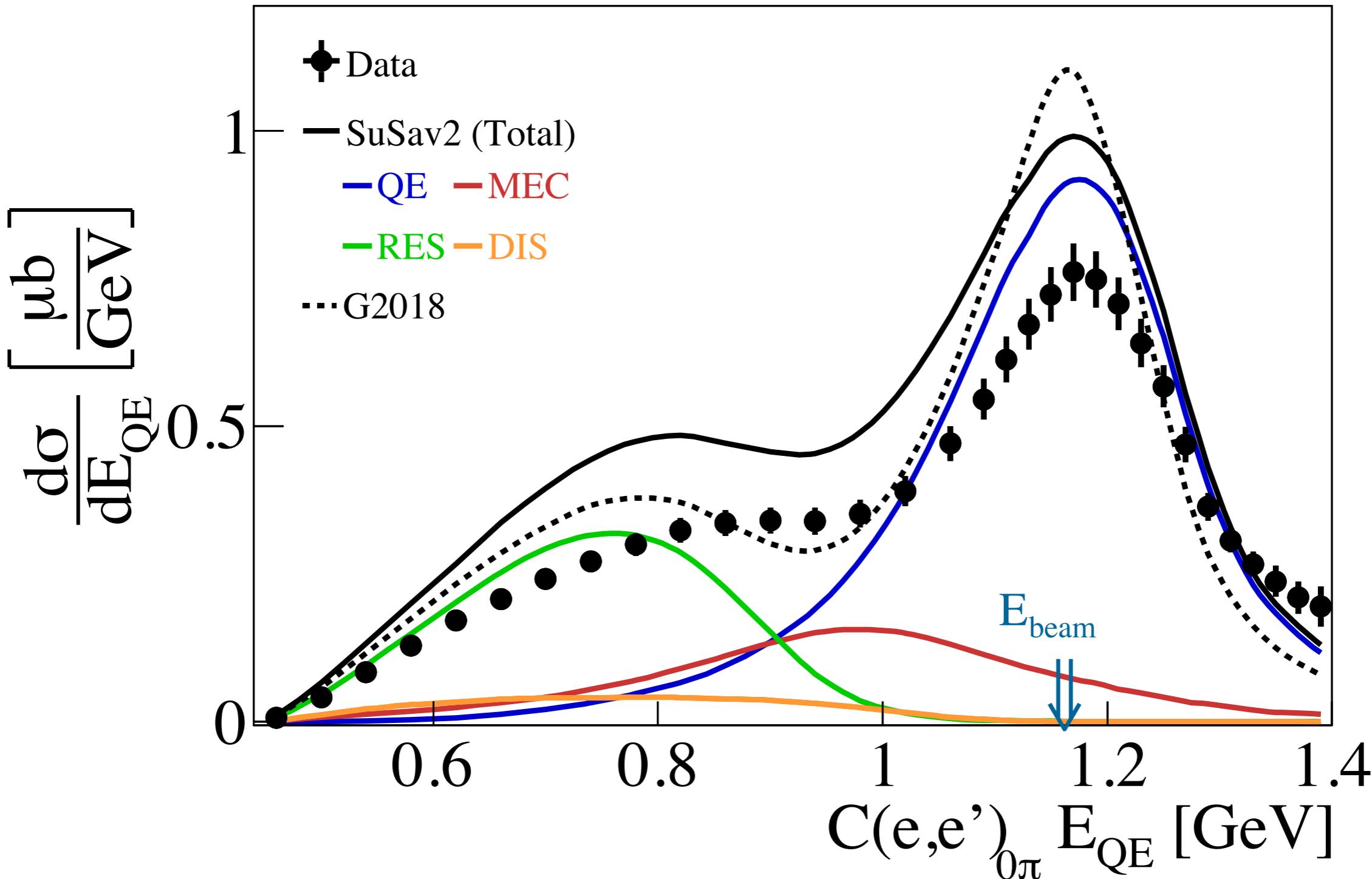
$$P_{\pi^{+/-}} > 150 \text{ MeV/c}$$

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



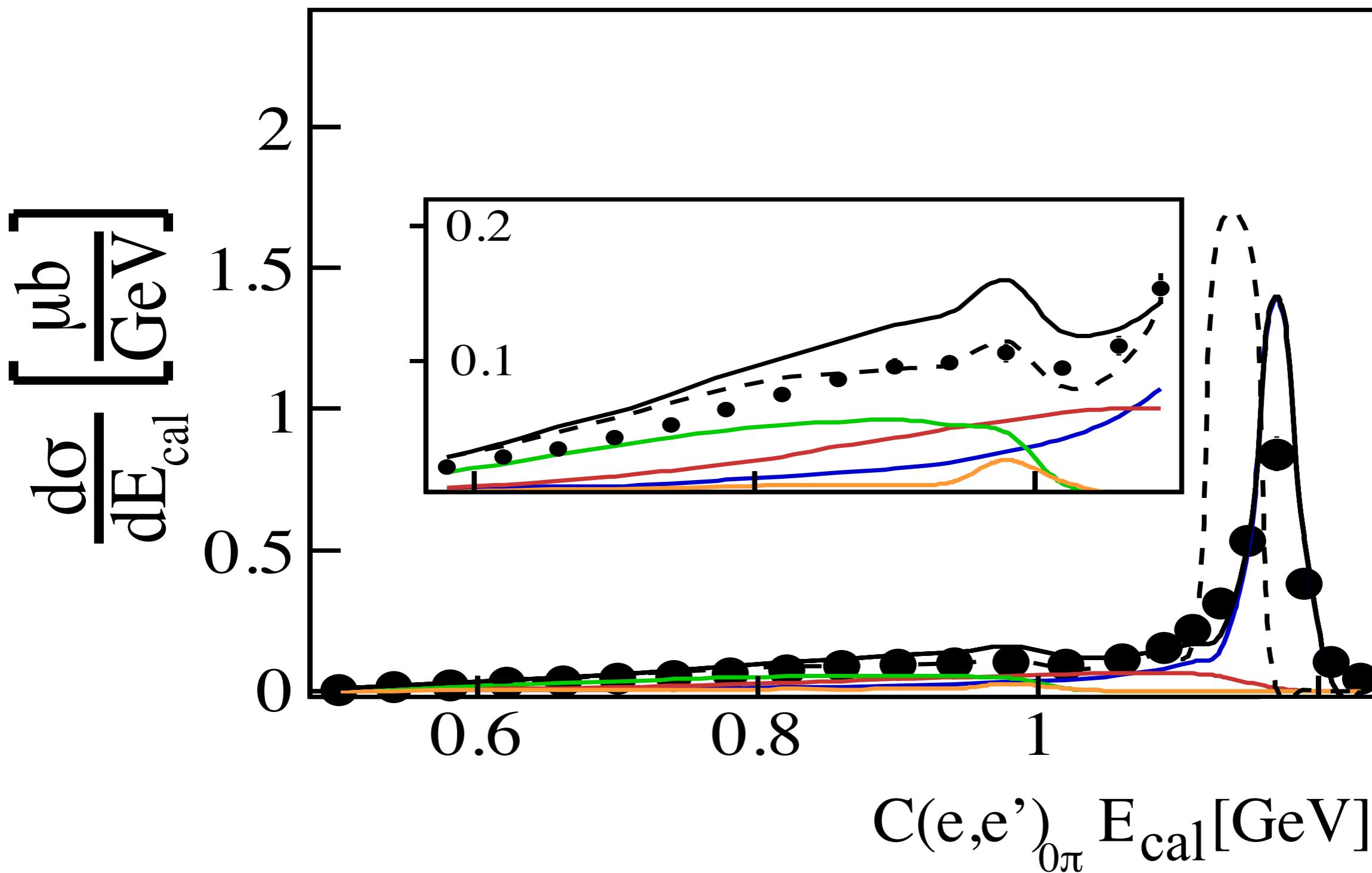
# Disagreements between Data and MC

$E = 1.159 \text{ GeV}$



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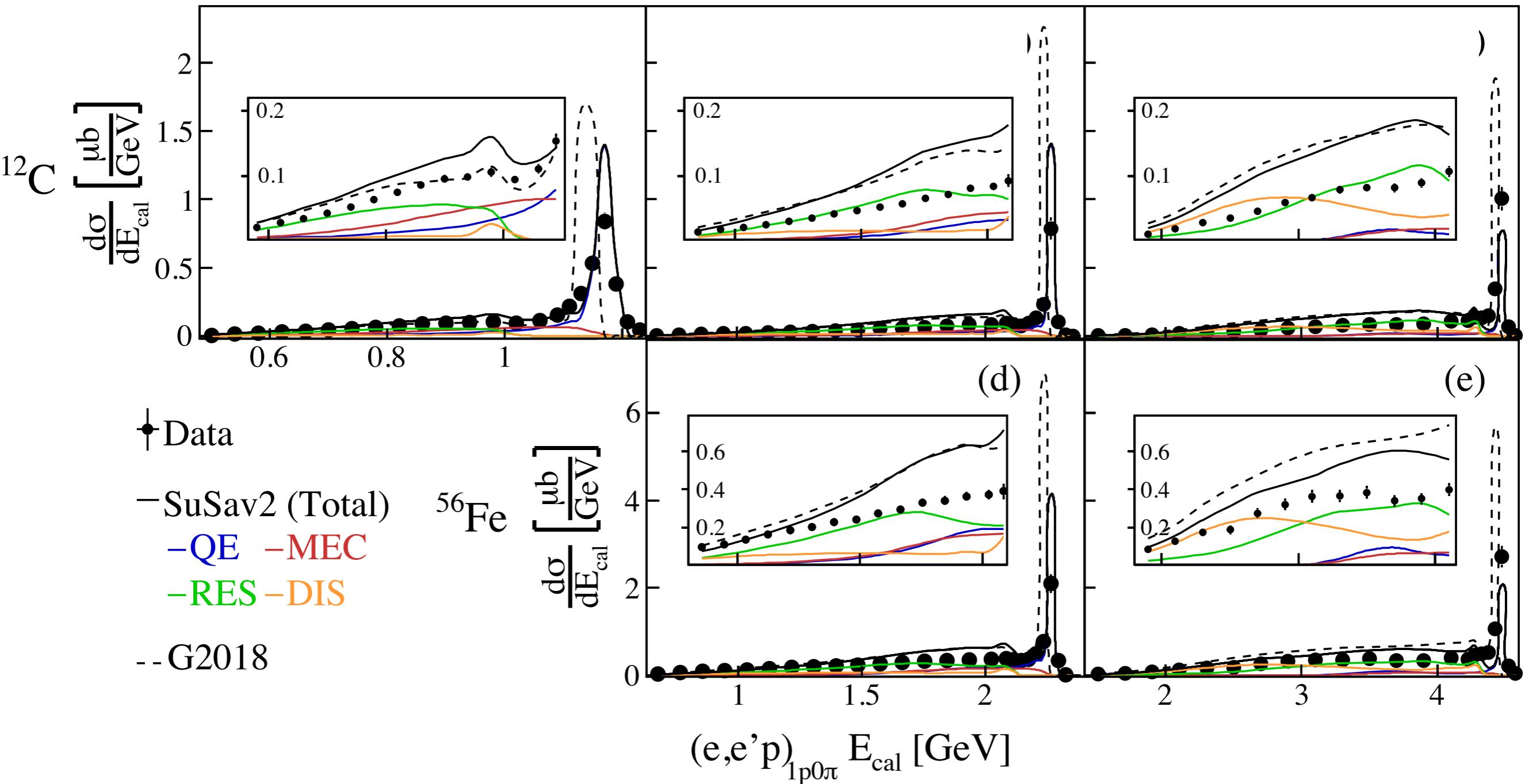


# Disagreements between Data and MC

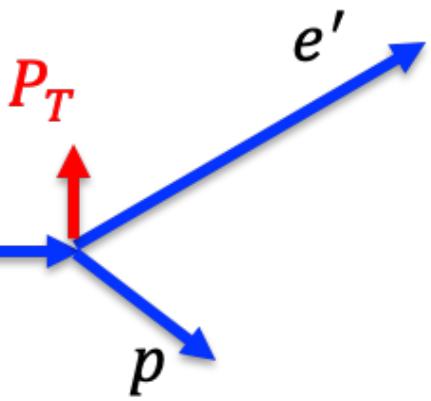
1.159 GeV

2.257 GeV

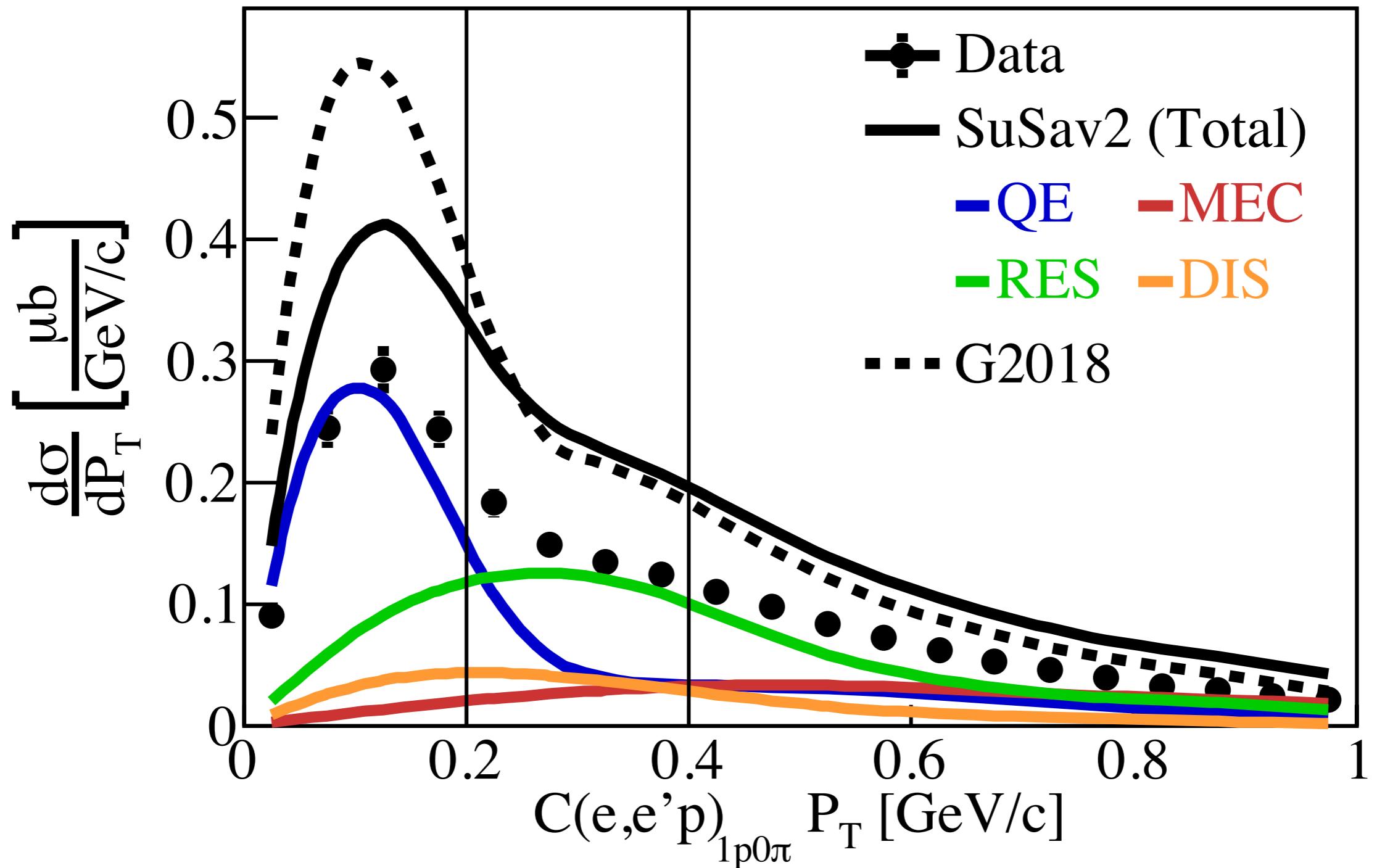
4.453 GeV



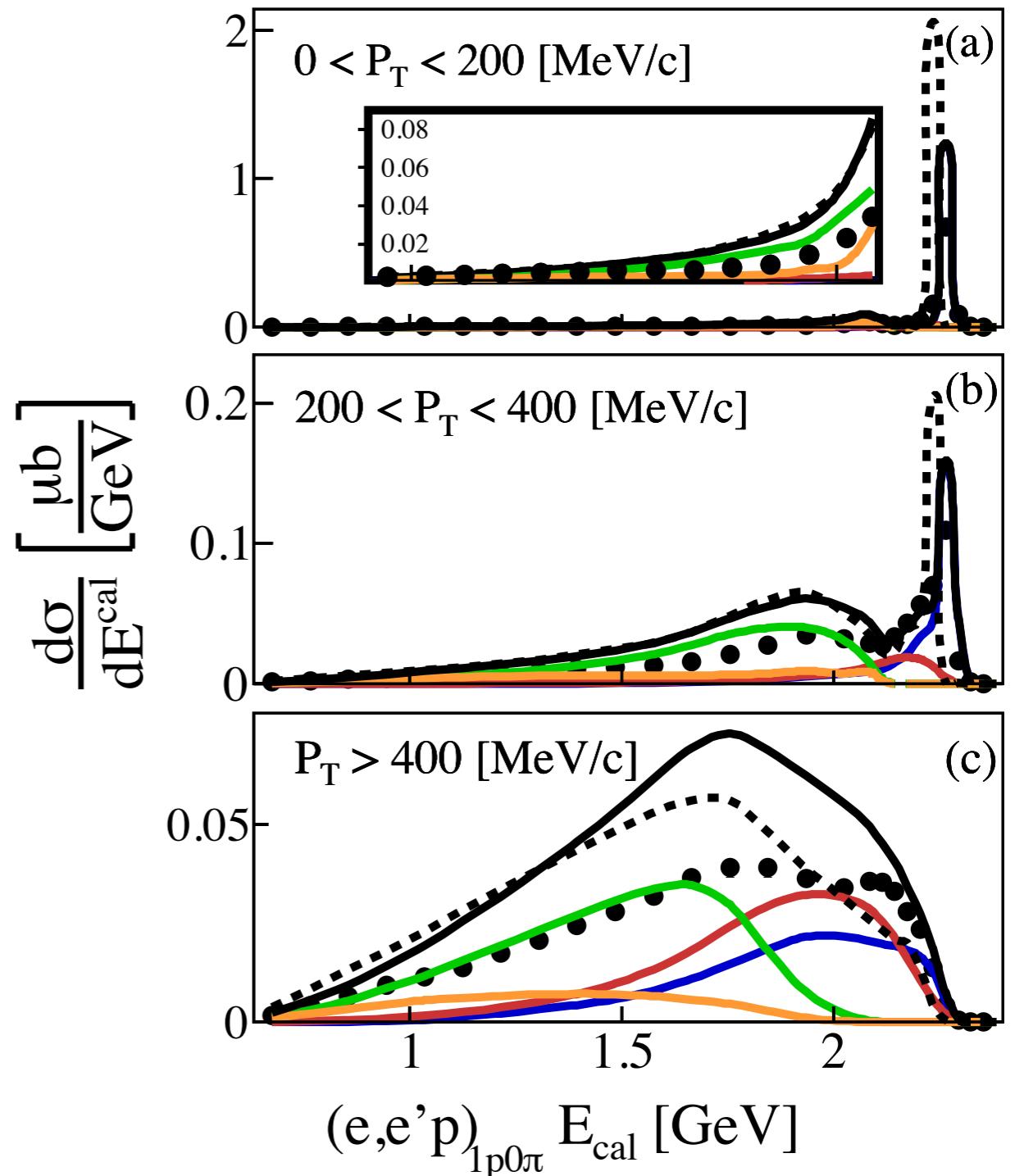
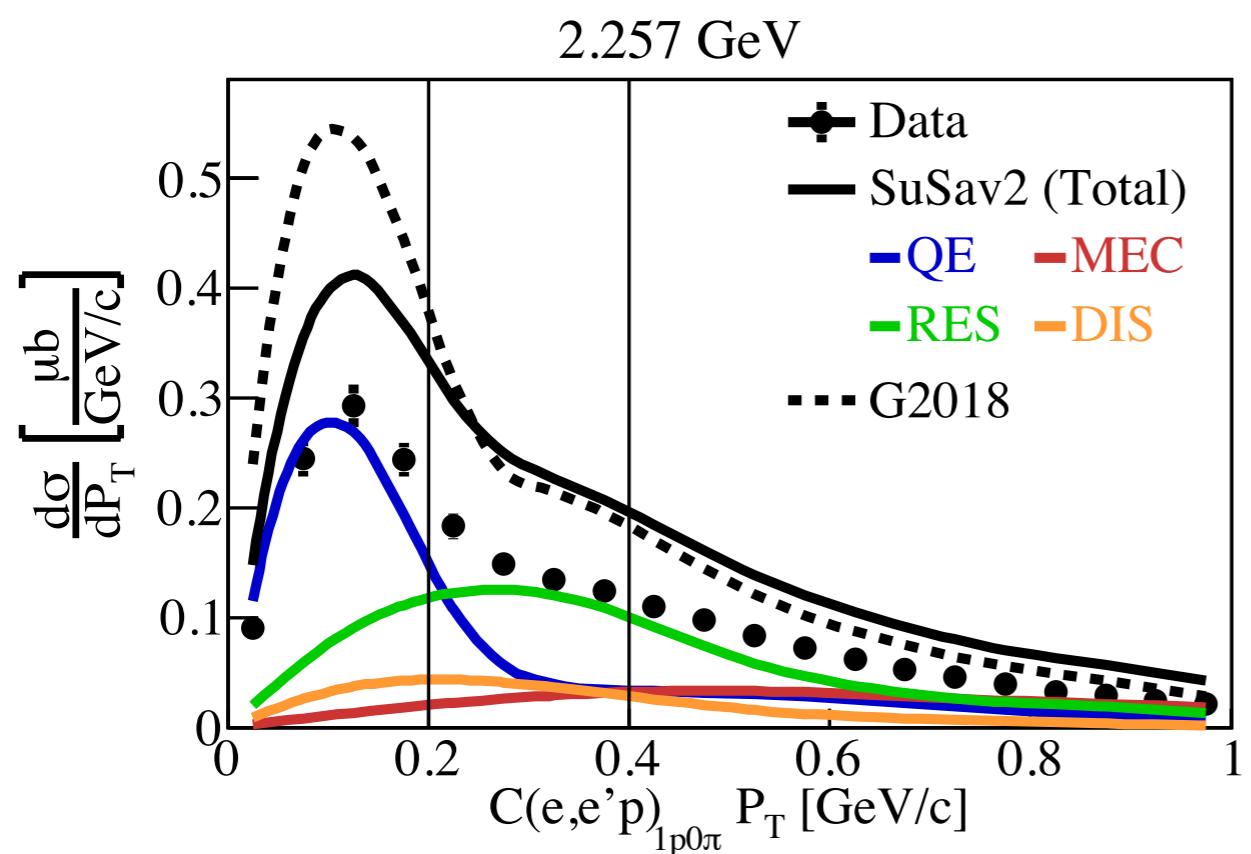
MC vs. (e,e'p) Data:  $\vec{P}_T = \vec{P}_T^{e'} + \vec{P}_T^p$



2.257 GeV



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



# New Data from CLAS12

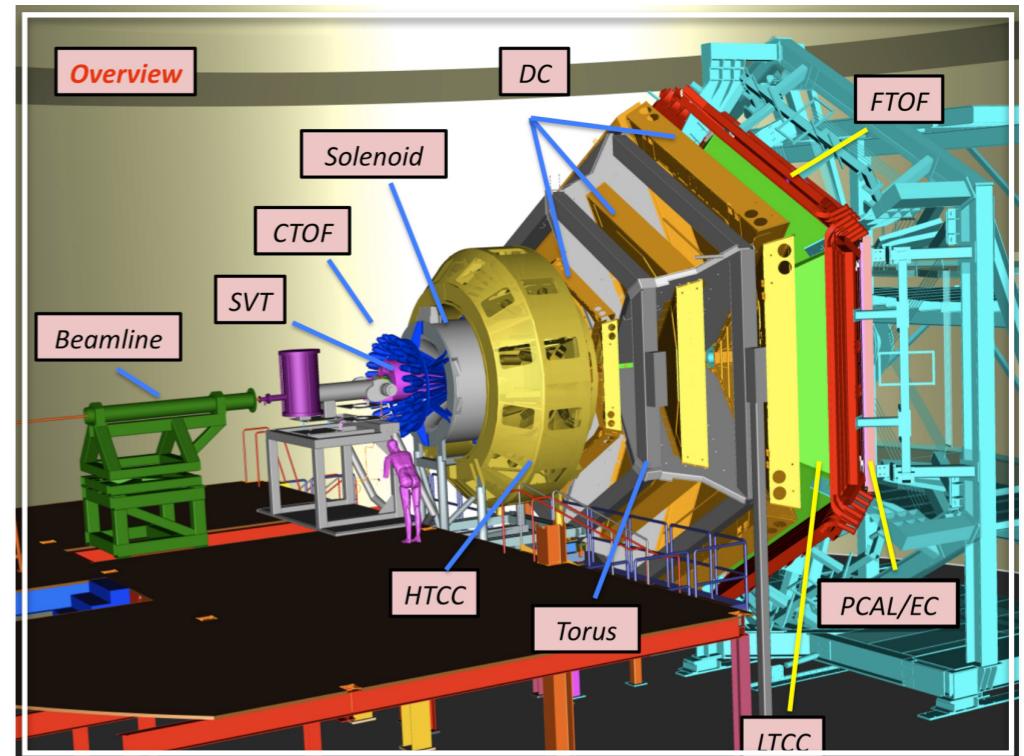
Acceptance down to  $5^\circ$     $Q^2 > 0.04 \text{ GeV}^2$

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

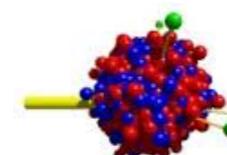
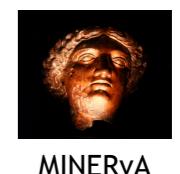
Keep low thresholds

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

2, 4, 6 GeV (relevant for DUNE)



Overwhelming support from:



GiBUU  
The Giessen Boltzmann-Uehling-Uhlenbeck Project



# The *e4ν* Collaboration

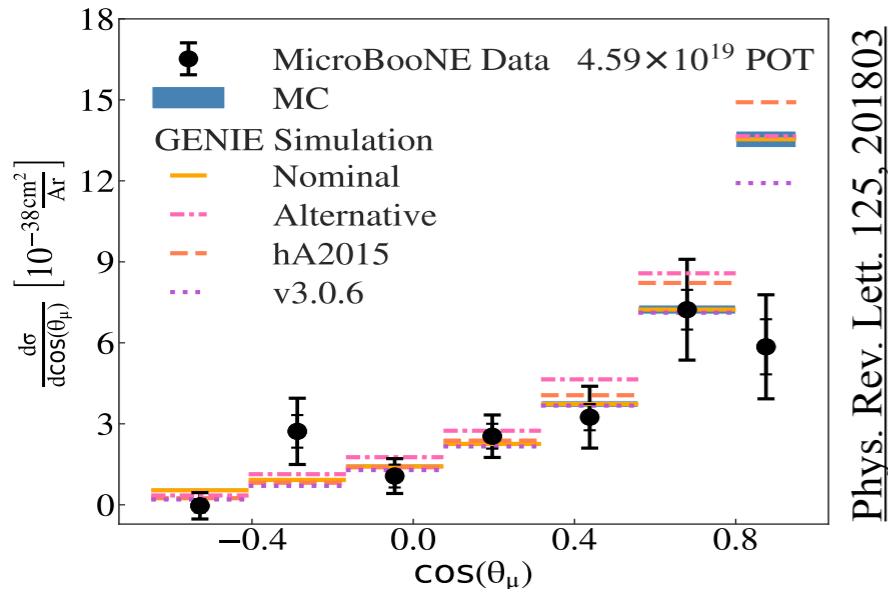


Join us! visit [www.e4nu.com](http://www.e4nu.com)

Contact: Minerba [betan009@fnal.gov](mailto:betan009@fnal.gov), Adi [adishka@tauex.tau.ac.il](mailto:adishka@tauex.tau.ac.il)

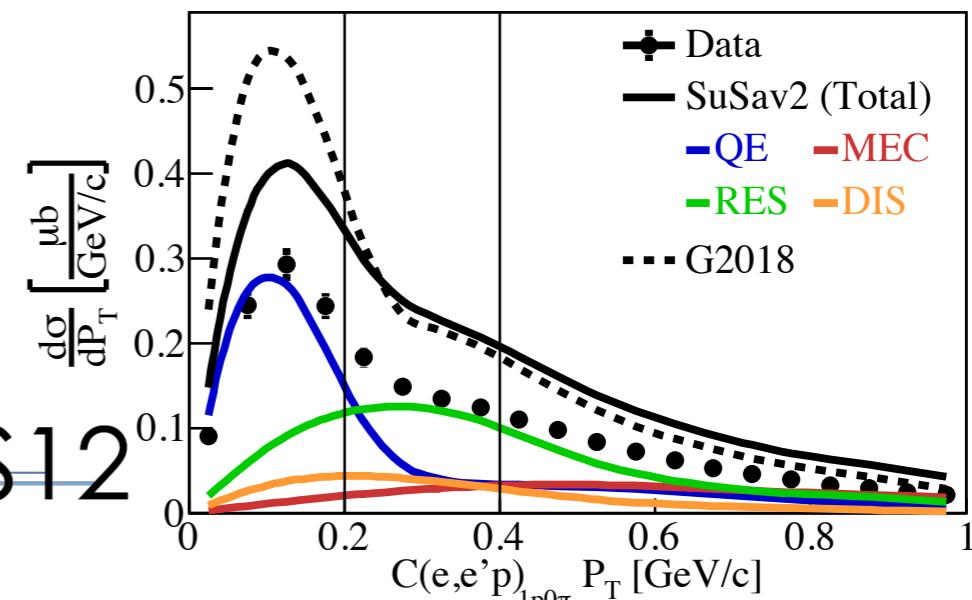
# Improving modelling input

## $\nu$ scattering



Phys. Rev. Lett. 125, 201803

## $e\nu$ e scattering



Nature 599, pages 565–570 (2021)

- Cross section measurements
- $\mu 4\nu$  using cosmic rays inside MicroBooNE

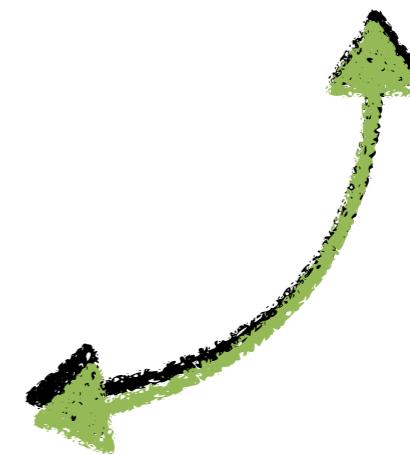
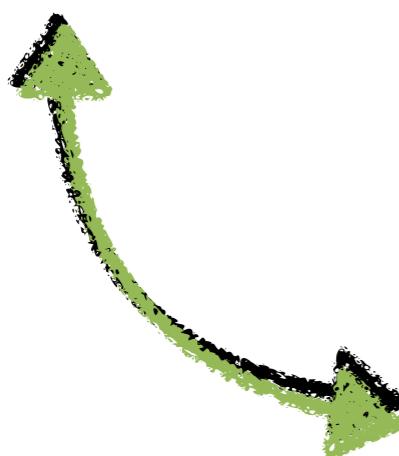
- Scanning inclusive spectra
- more exclusive channels (1n1p0 $\pi$ , 1p1 $\pi$  and more)

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

Modelling input

## Event Generators

Phys. Rev. D 103, 113003



# Summary

- Testing vA Models using wide phase-space eA
- Data-MC disagreements for QE-like events especially for high  $p_T$
- Adding vA cross section measurements
- Tuning models free parameters



Understanding the nuclear initial state is crucial

Accelerator based neutrino oscillation experiments reaching new energy regime:

- DIS becoming even more important
- New neutrino experiments could be useful for DIS studies see R. Petty talk
- In the future, (with your help) vA generators could be useful for DIS studies

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Thank you for your attention

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