
Nuclear Aspects of Neutrino Interactions

(or why should we care for neutrinos in DIS2022)



Adi Ashkenazi



TEL AVIV UNIVERSITY

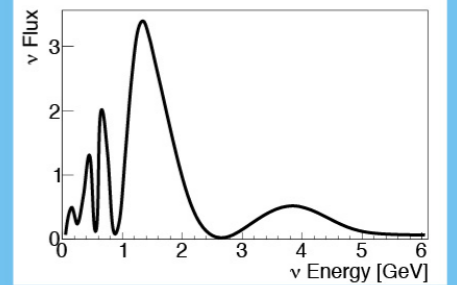
adishka@tauex.tau.ac.il

PHYSICS PROCESS

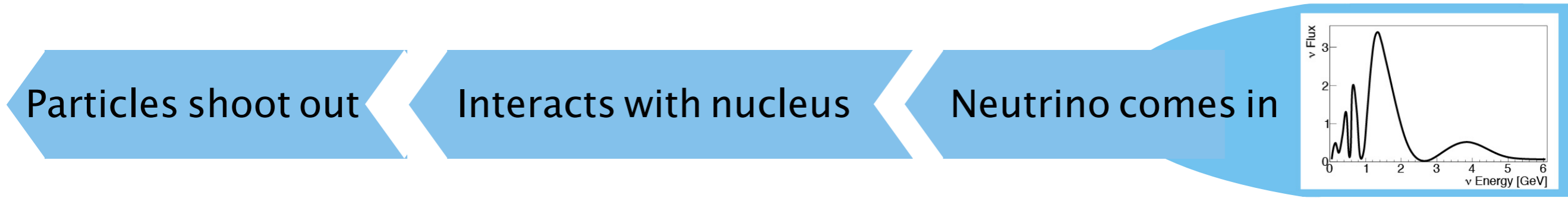
Particles shoot out

Interacts with nucleus

Neutrino comes in

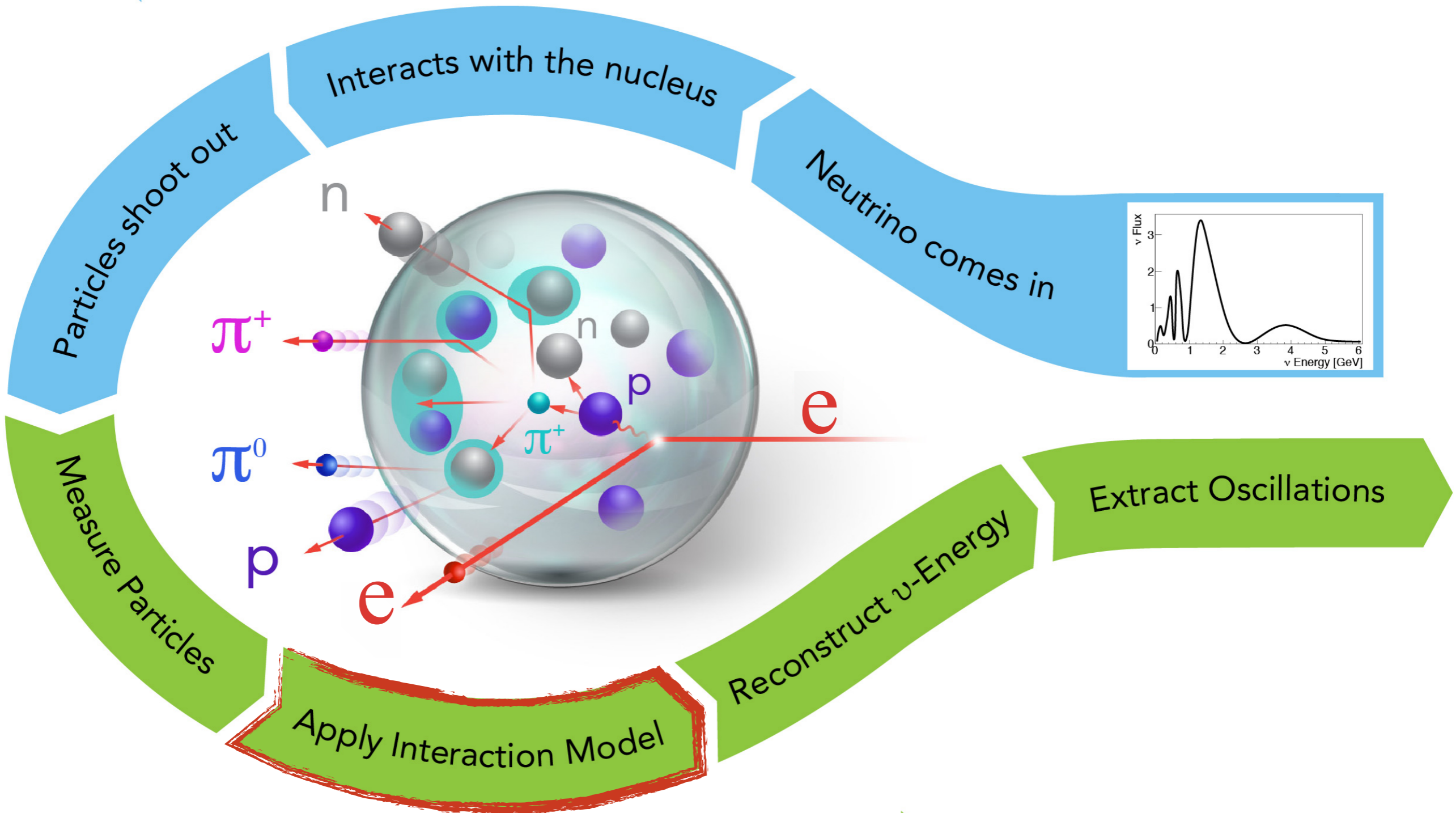


PHYSICS PROCESS



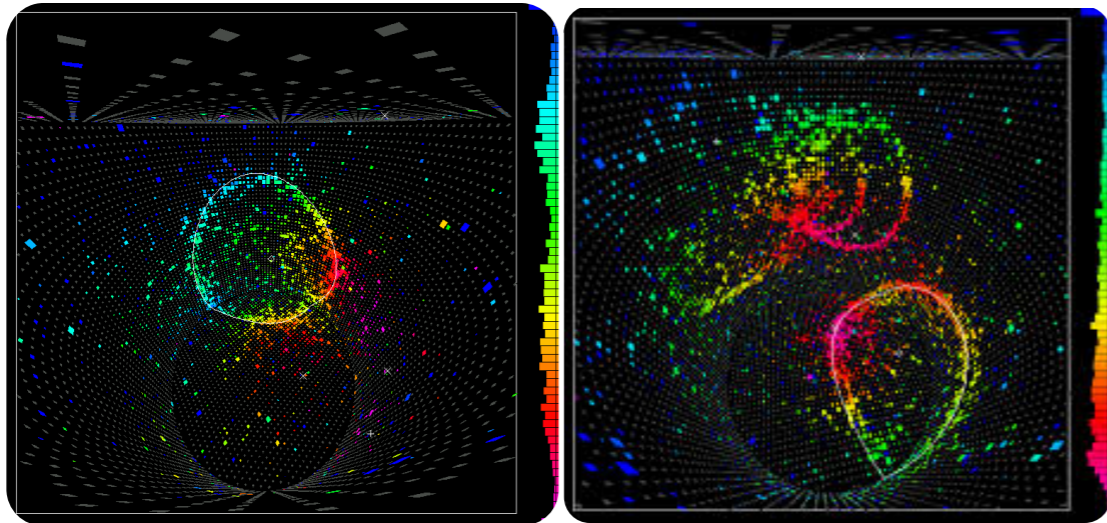
EXPERIMENTAL ANALYSIS

PHYSICS PROCESS



EXPERIMENTAL ANALYSIS

Incoming Energy Reconstruction

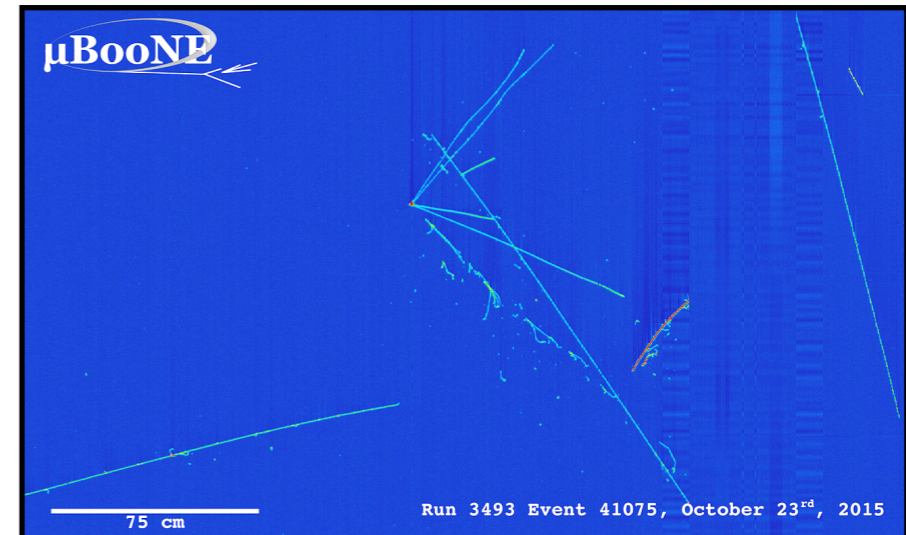


Cherenkov detectors:

Assuming QE interaction

Using lepton only

$$E_{QE} = \frac{2M\epsilon + 2ME_l - m_l^2}{2(M - E_l + |k_l| \cos \theta_l)}_{[0\pi]}$$



Tracking detectors:

Calorimetric sum

Using All detected particles

$$E_{cal} = E_l + E_p^{kin} + \epsilon_{[1p0\pi]}$$

ϵ is the nucleon separation energy ~ 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

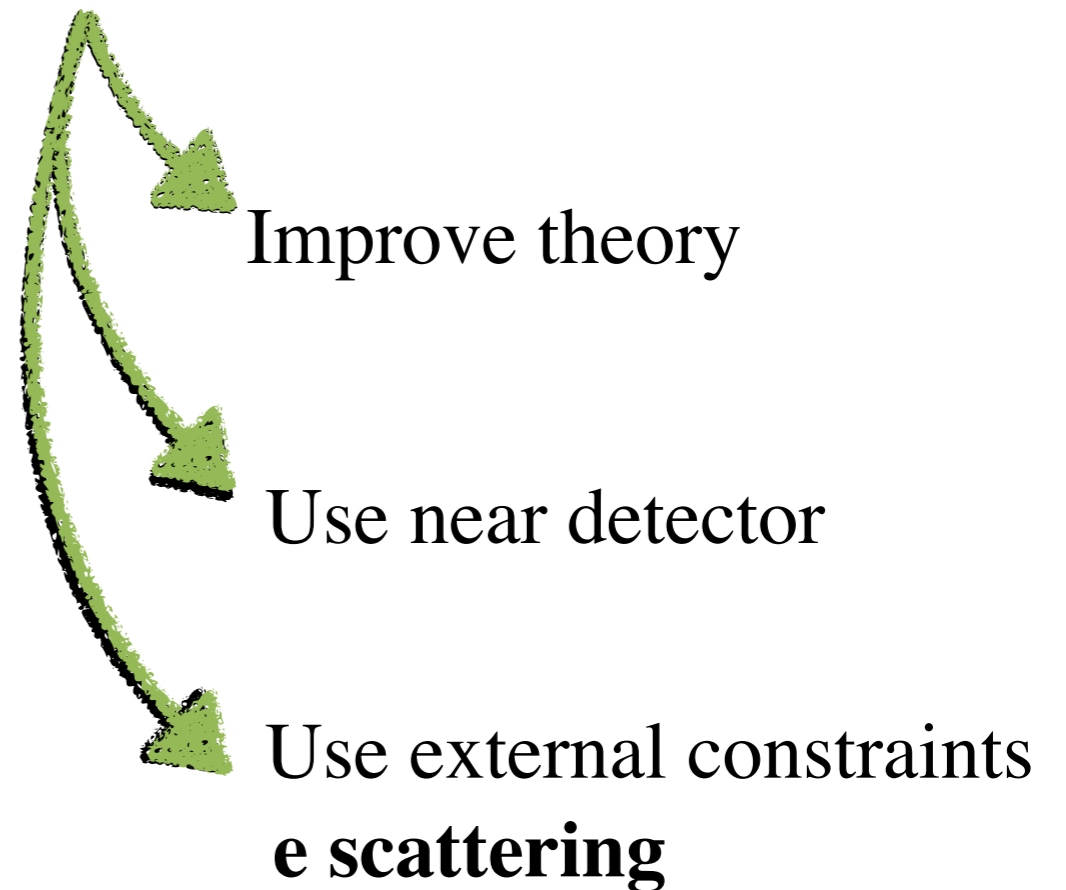
Incoming true flux Modelling input

The challenge - next generation high precision

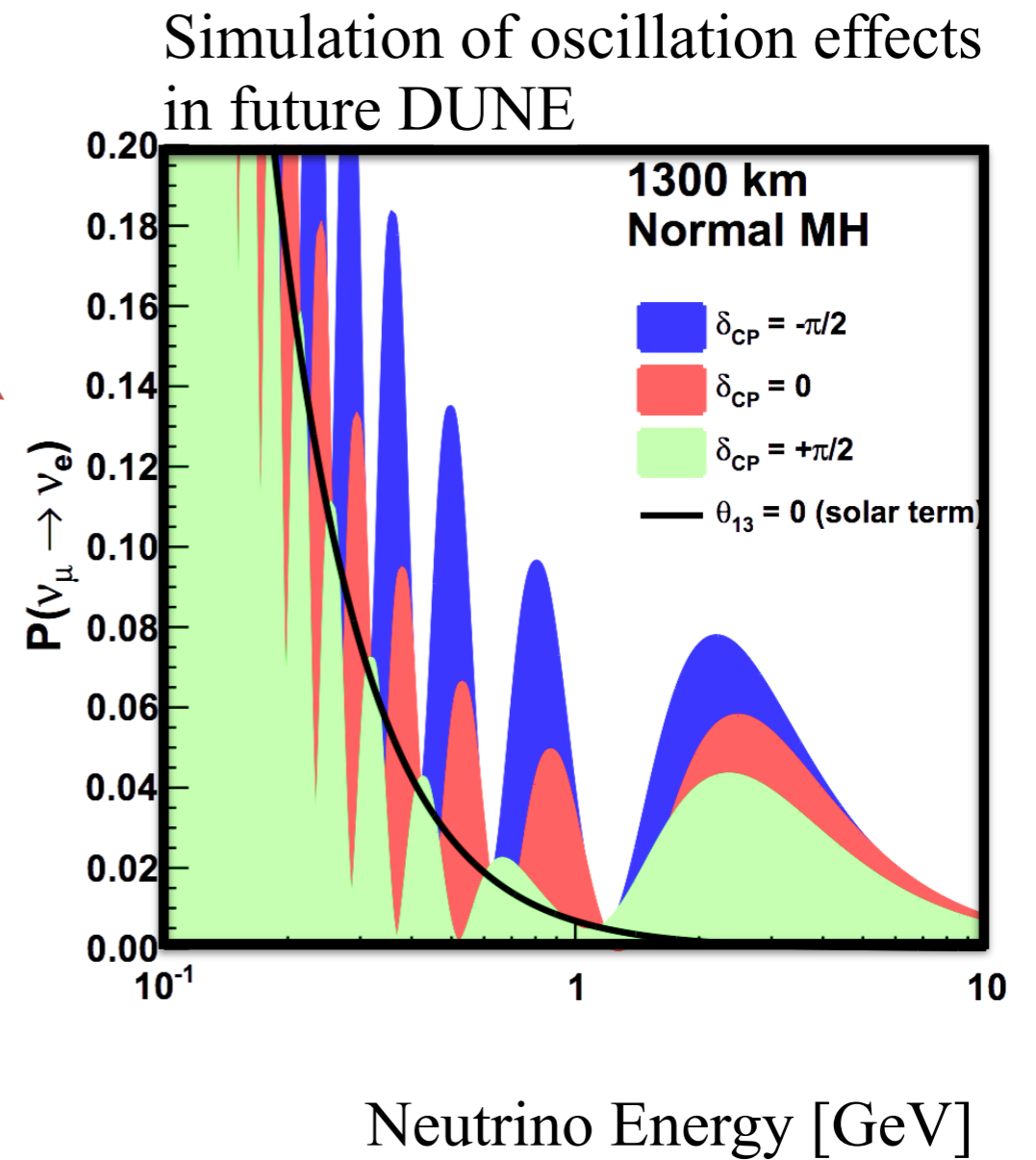
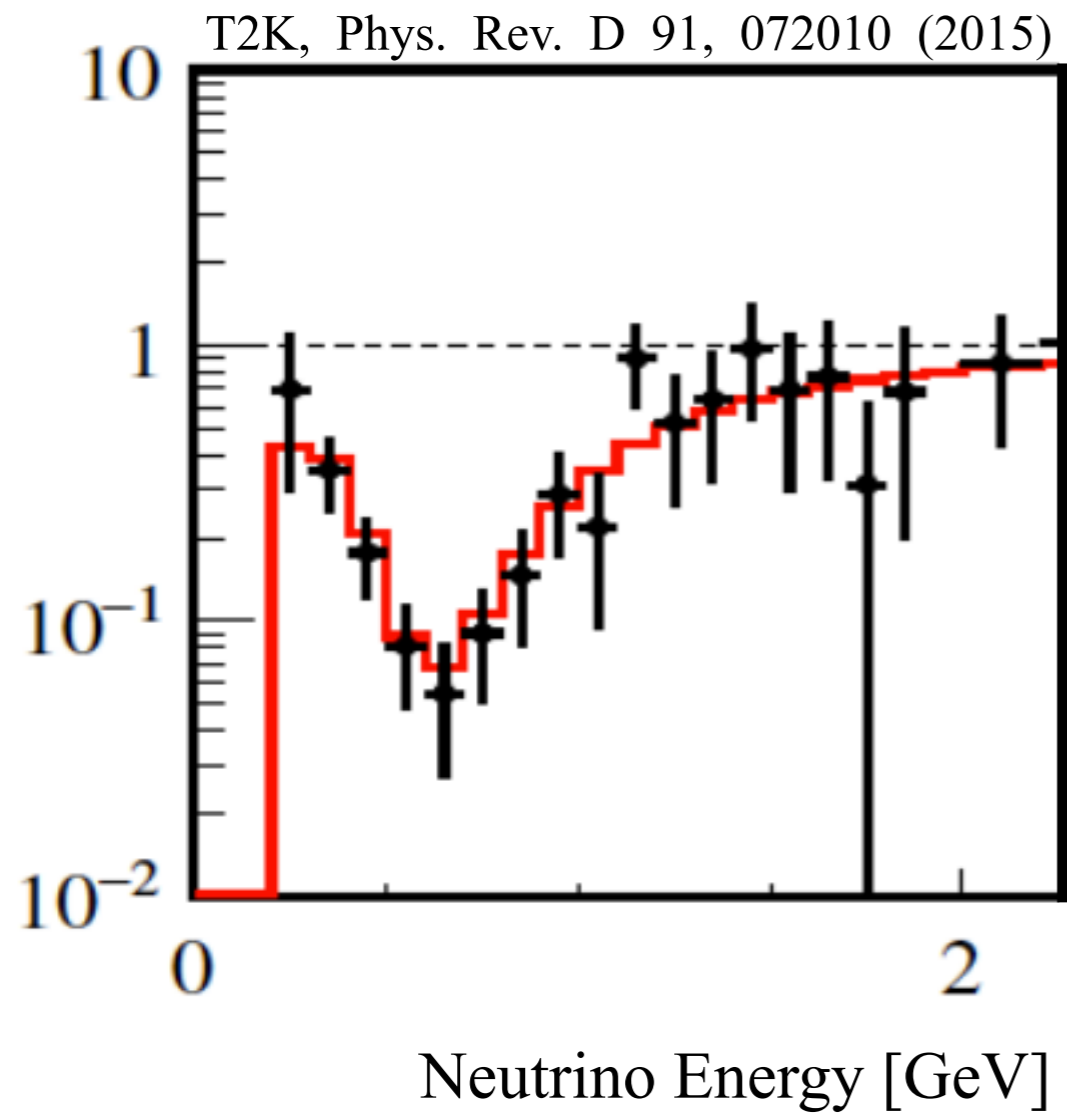
$$N(E_{rec}, L) \propto \int \Phi(E, L) \sigma(E) f_{\sigma}(E, E_{rec}) dE$$

Measurement

Incoming true flux Modelling input



The challenge - next generation high precision





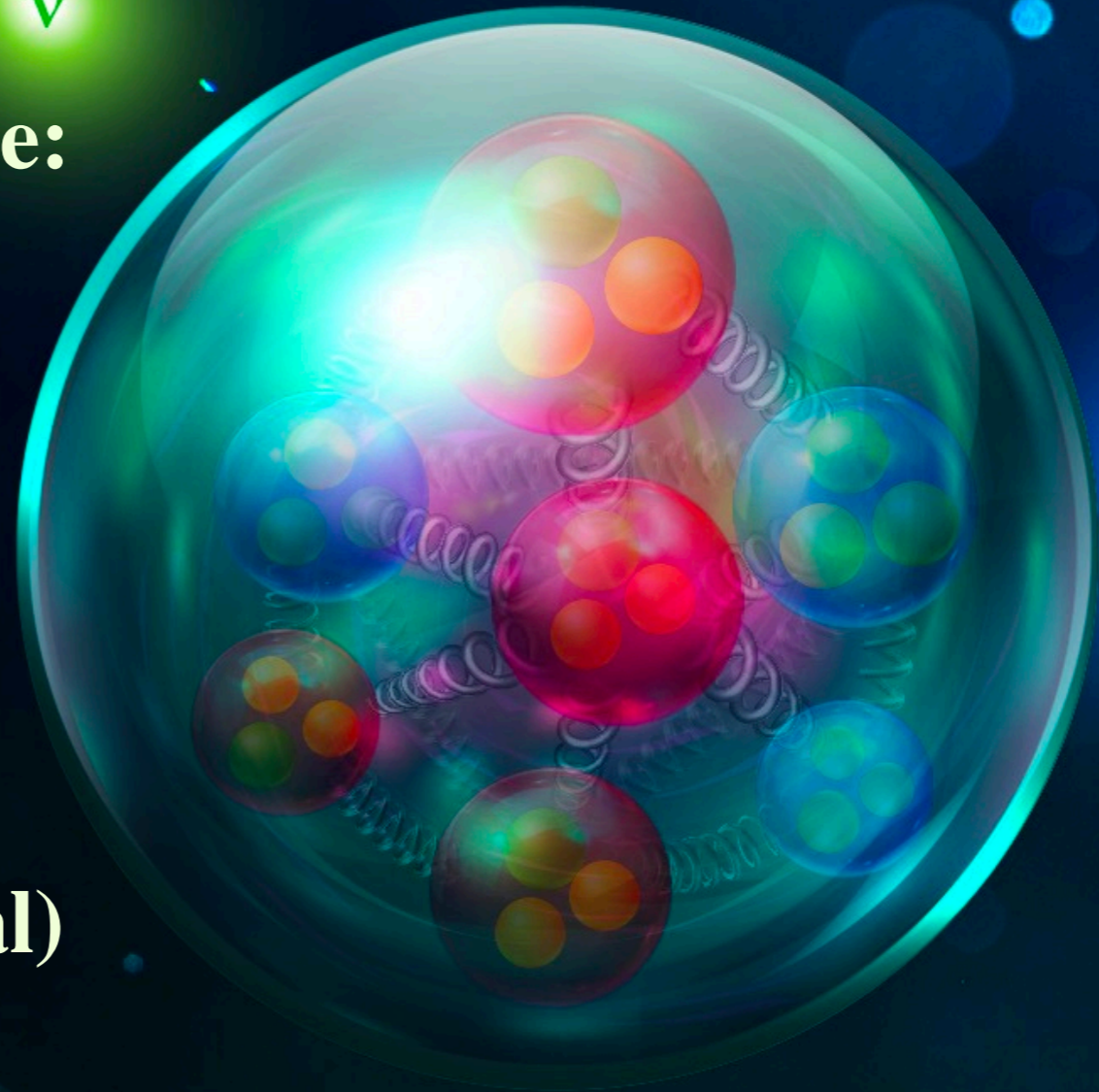
Electron for neutrinos

visit: www.e4nu.com

ν

Electrons and Neutrinos have:

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

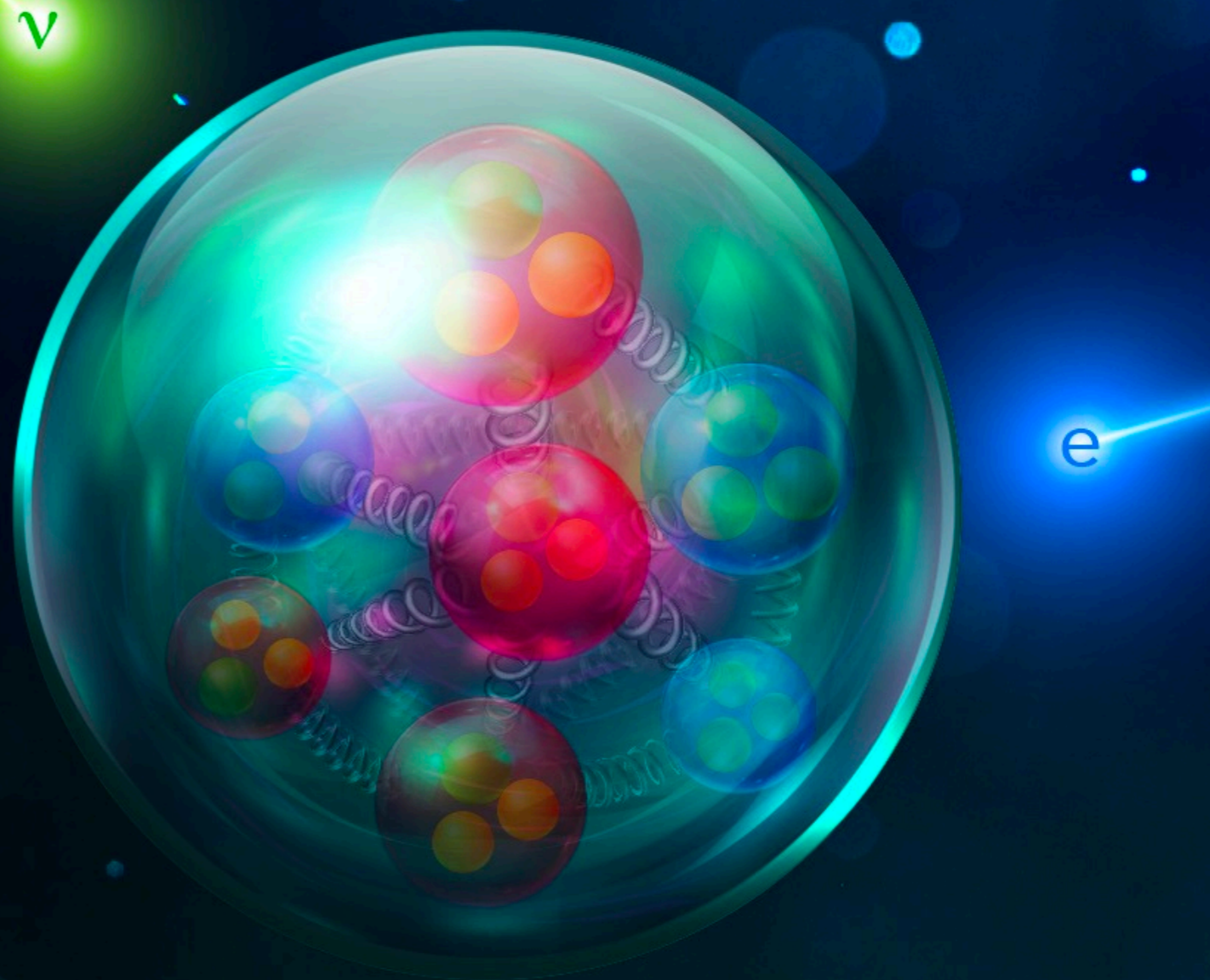


Electron beams have known and precise energy

$e4\nu$: 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



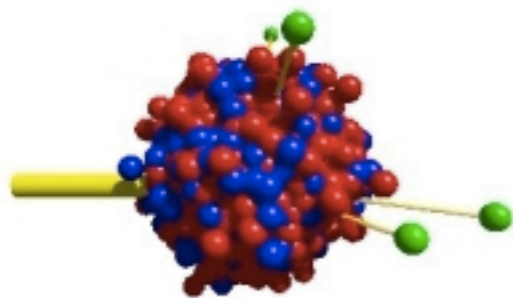
ν A Interaction Modelling

Neutrino event generators are used to simulate a ν A interaction

Among those:



Genie

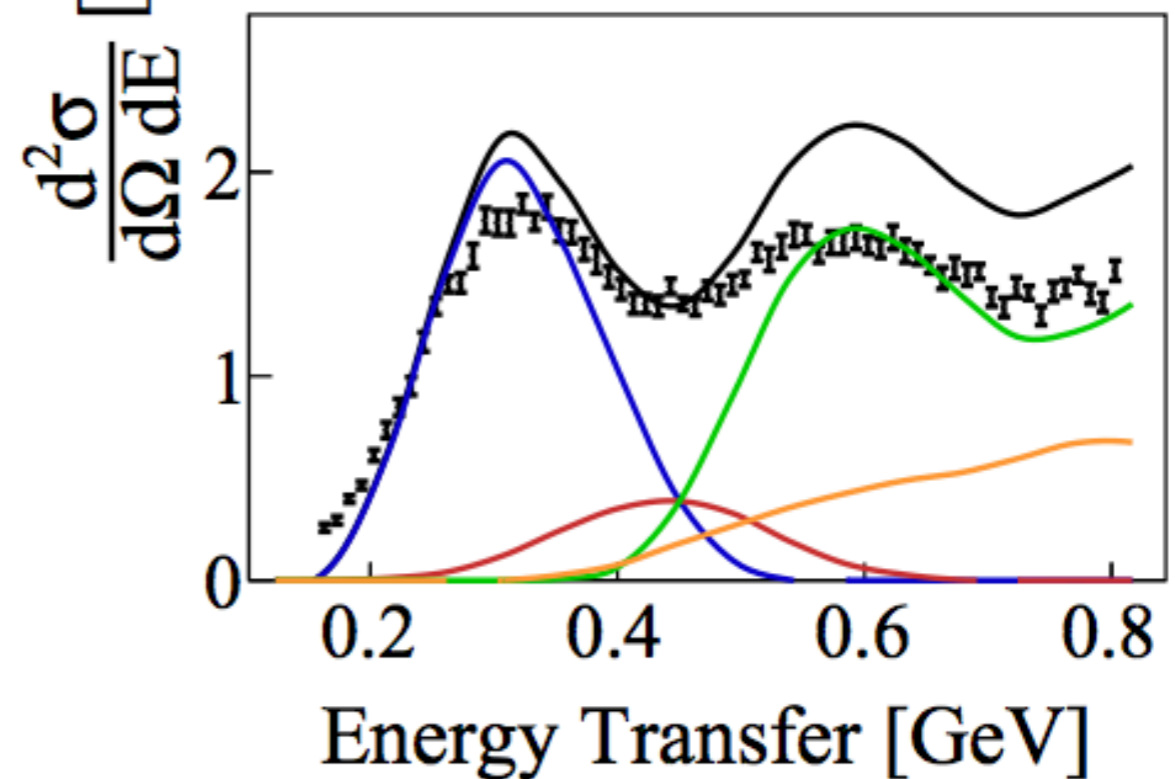
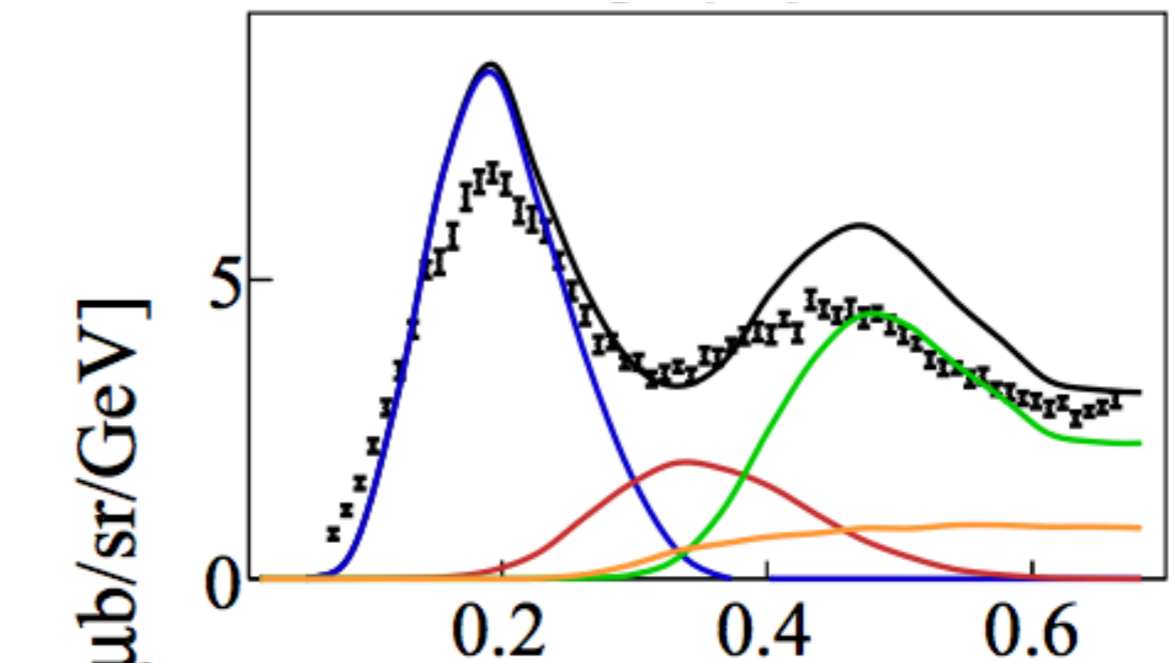
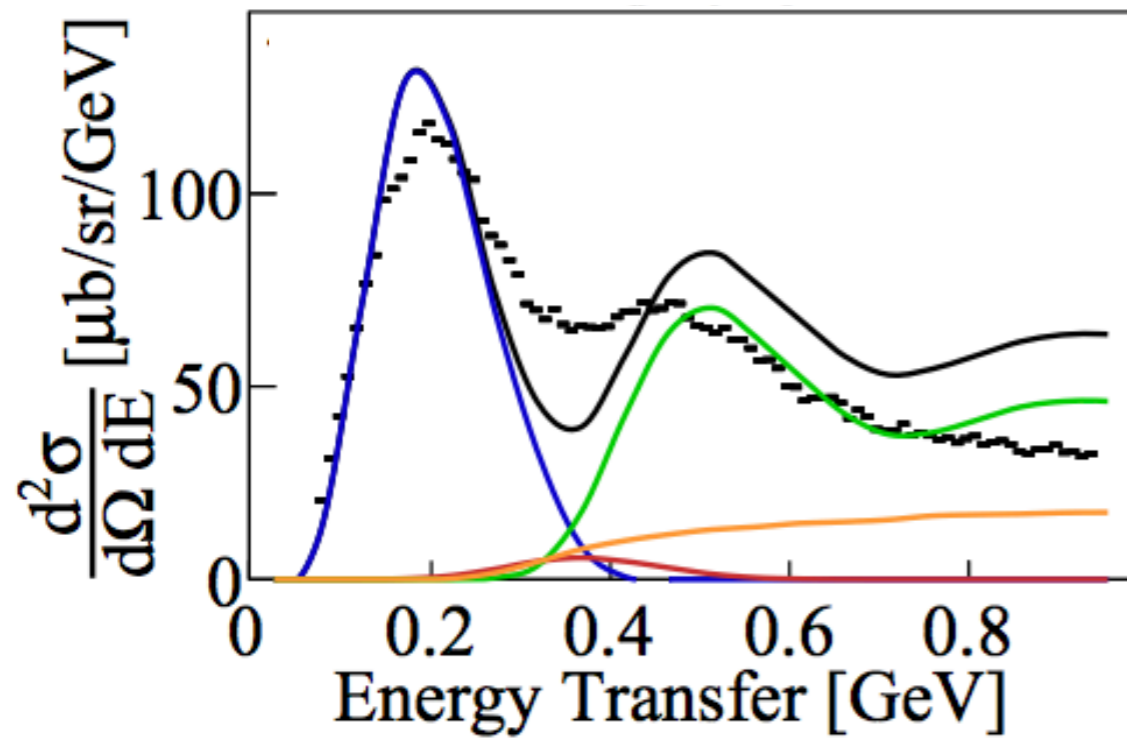


GiBUU

The Giessen Boltzmann-Uehling-Uhlenbeck Project

and more

GENIE reproducing e inclusive data

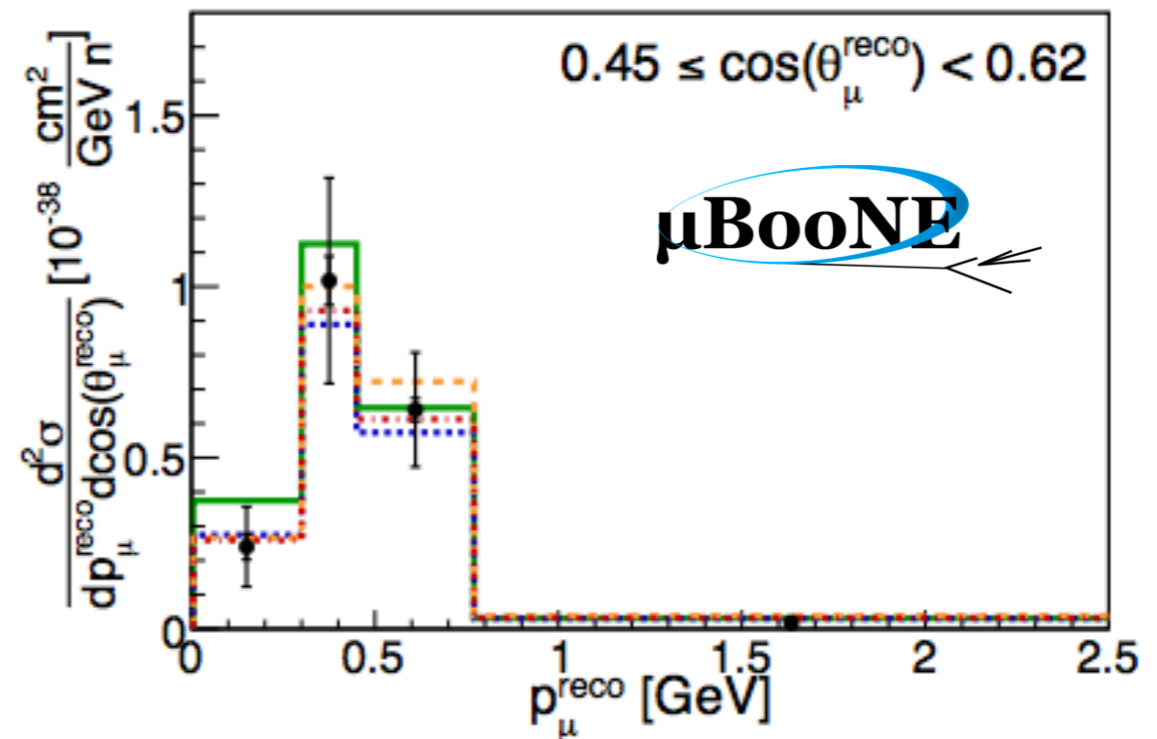
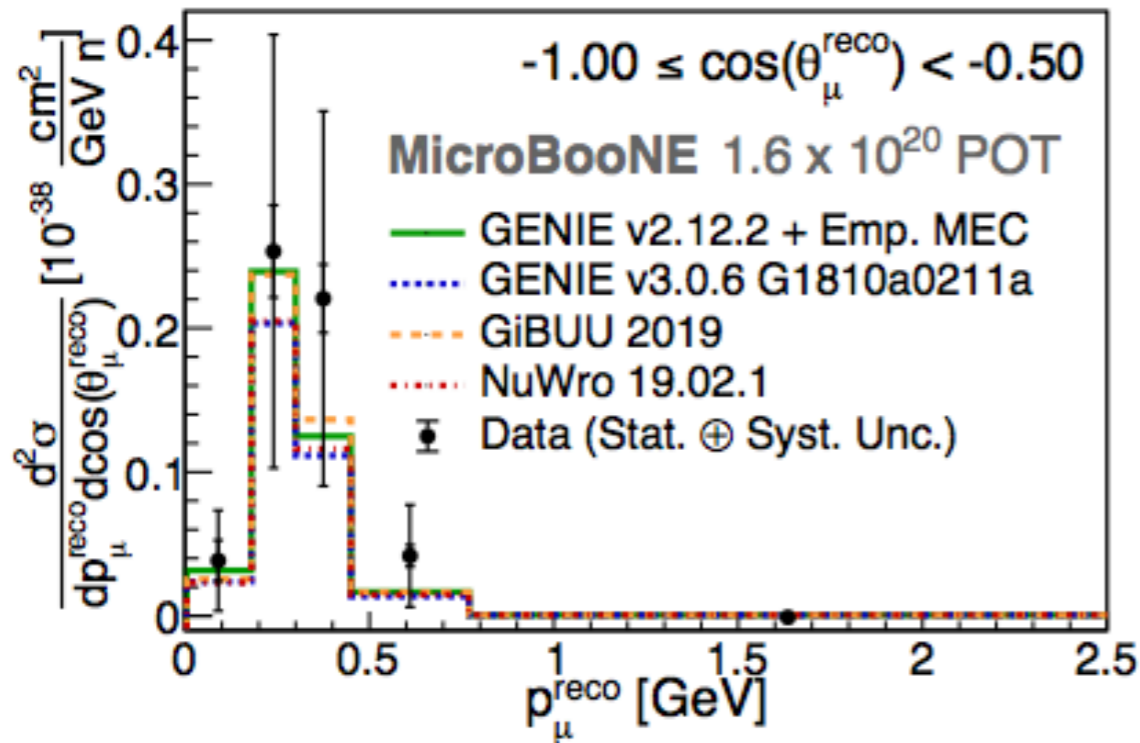


Genie

— v3.0.6 tune G18_10a_02_11a

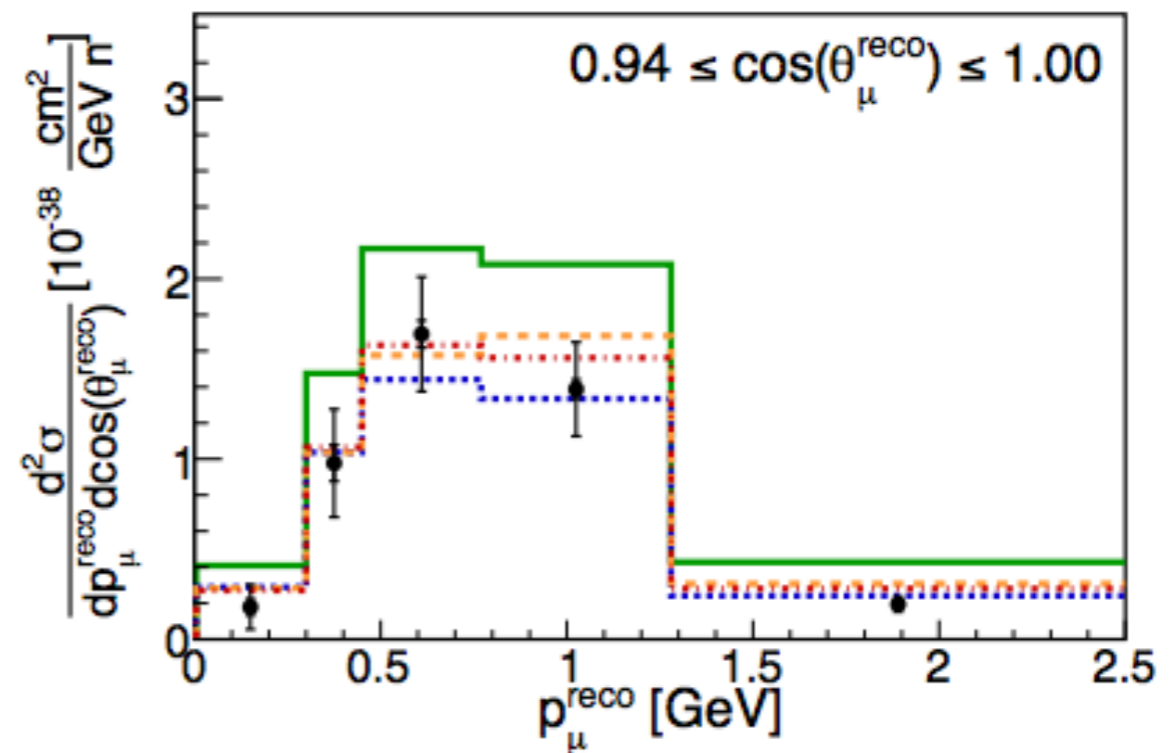
Phys.Rev.D 103 (2021) 113003

GENIE reproducing ν inclusive data



Genie

···· v3.0.6 tune G18_10a_02_11a



$e4V$ @ the CLAS Detector

Electron beam with energies up to 6 GeV

Large acceptance

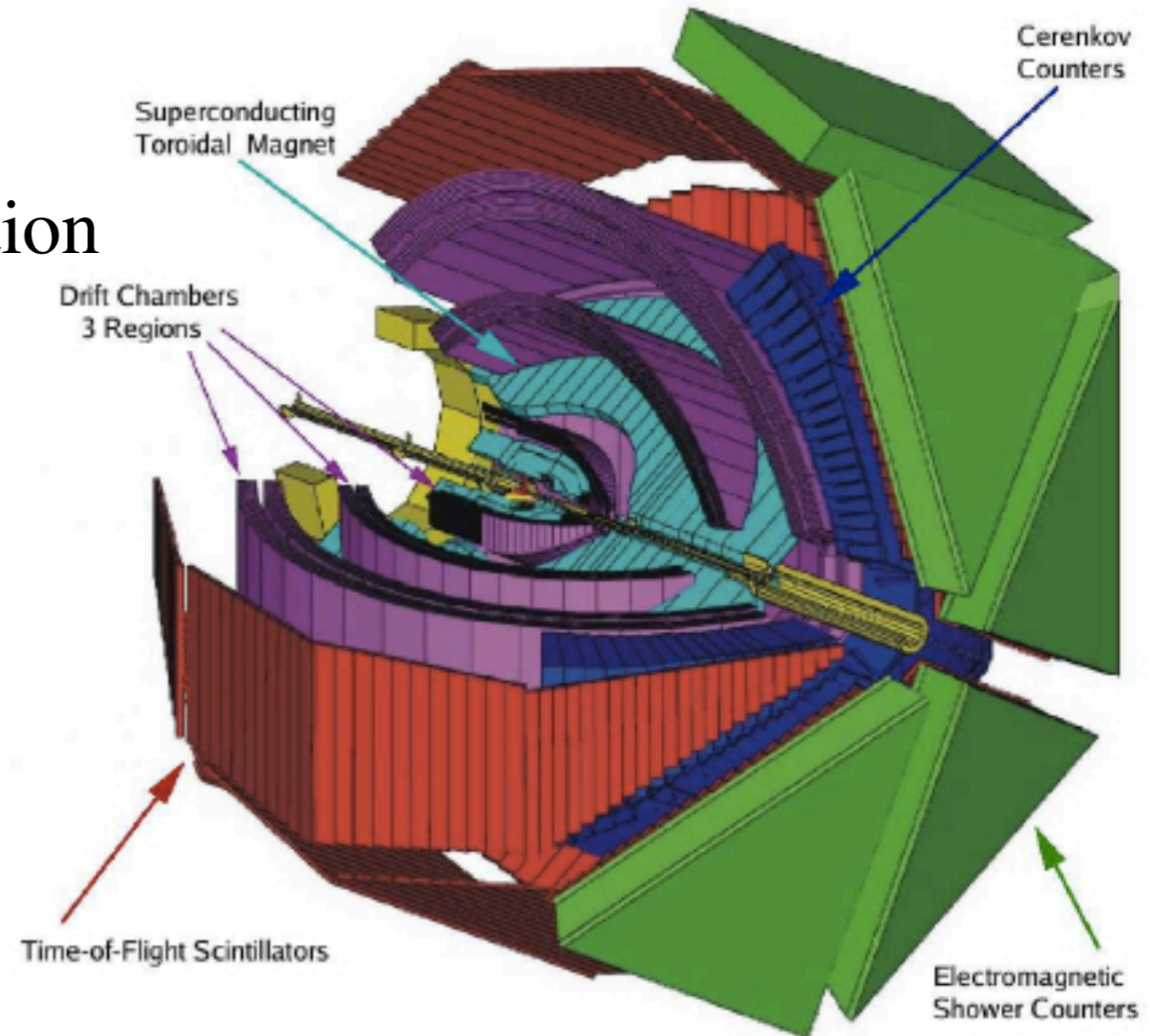
Charged particles above detection

threshold:

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

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

Open Trigger



CLAS A(e,e'p) Data

Targets:

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



H_2O



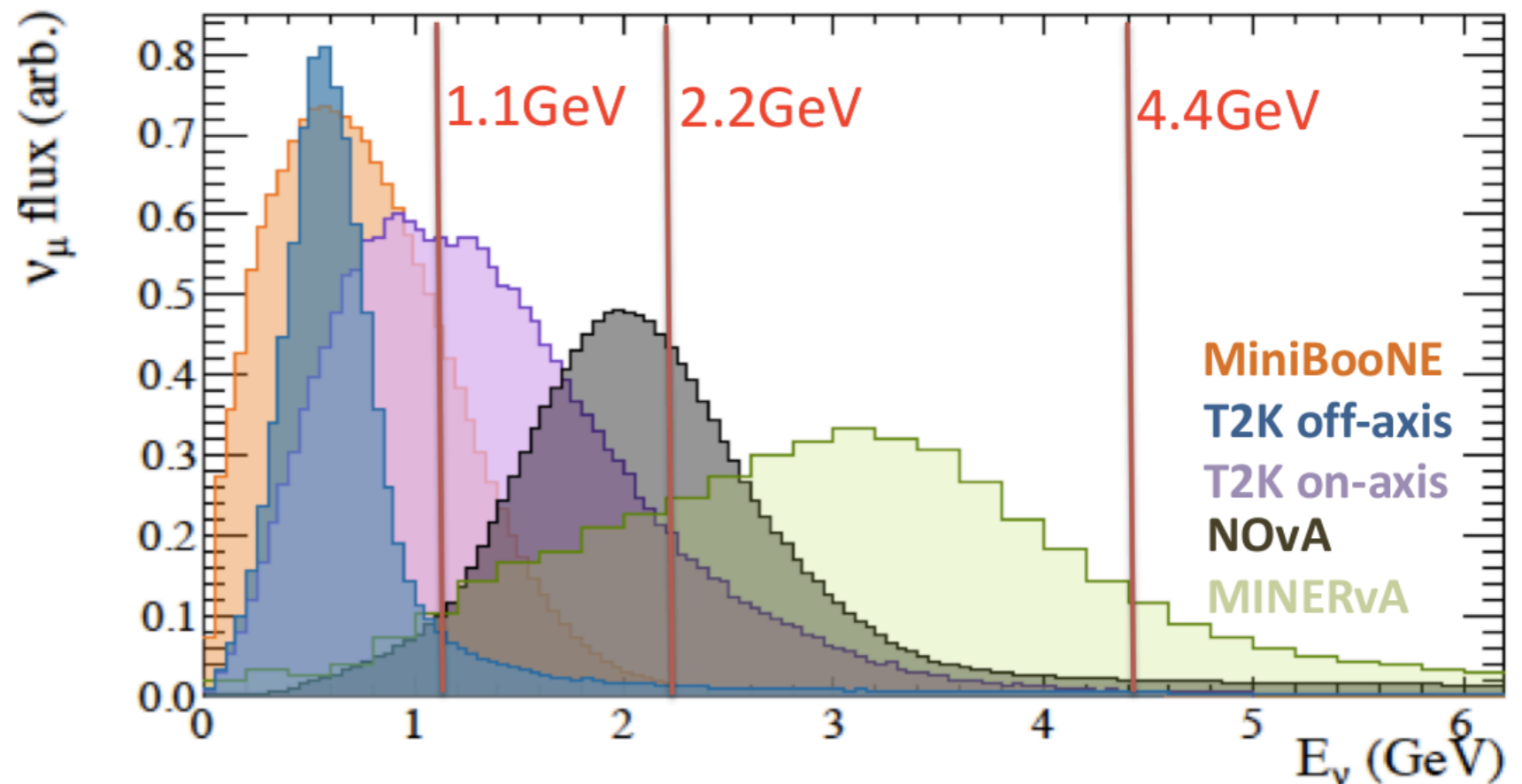
CH



Ar

Energies:

1.1, 2.2, 4.4 GeV



$e4V$ $1p0\pi$ Event Selection

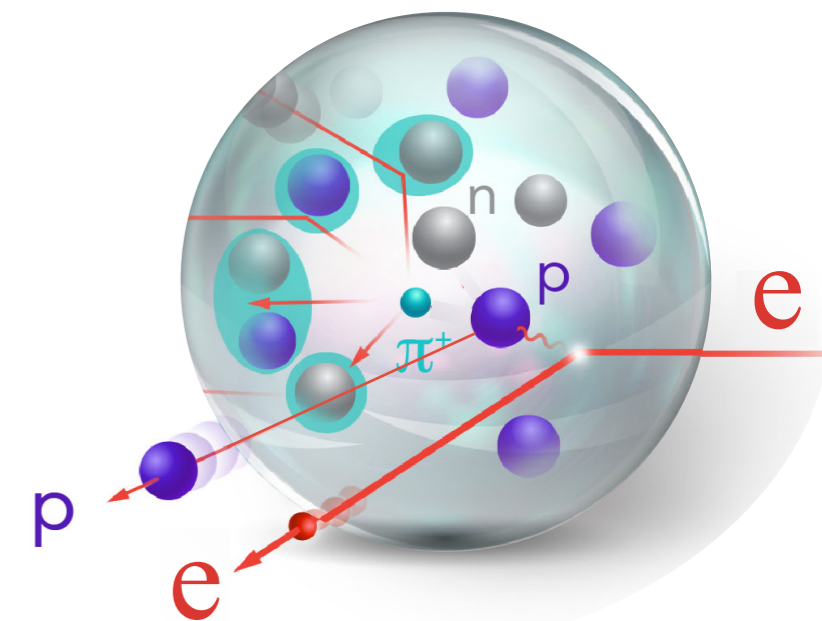
Focus on Quasi Elastic events:

1 proton above 300 MeV/c

no additional hadrons above threshold:

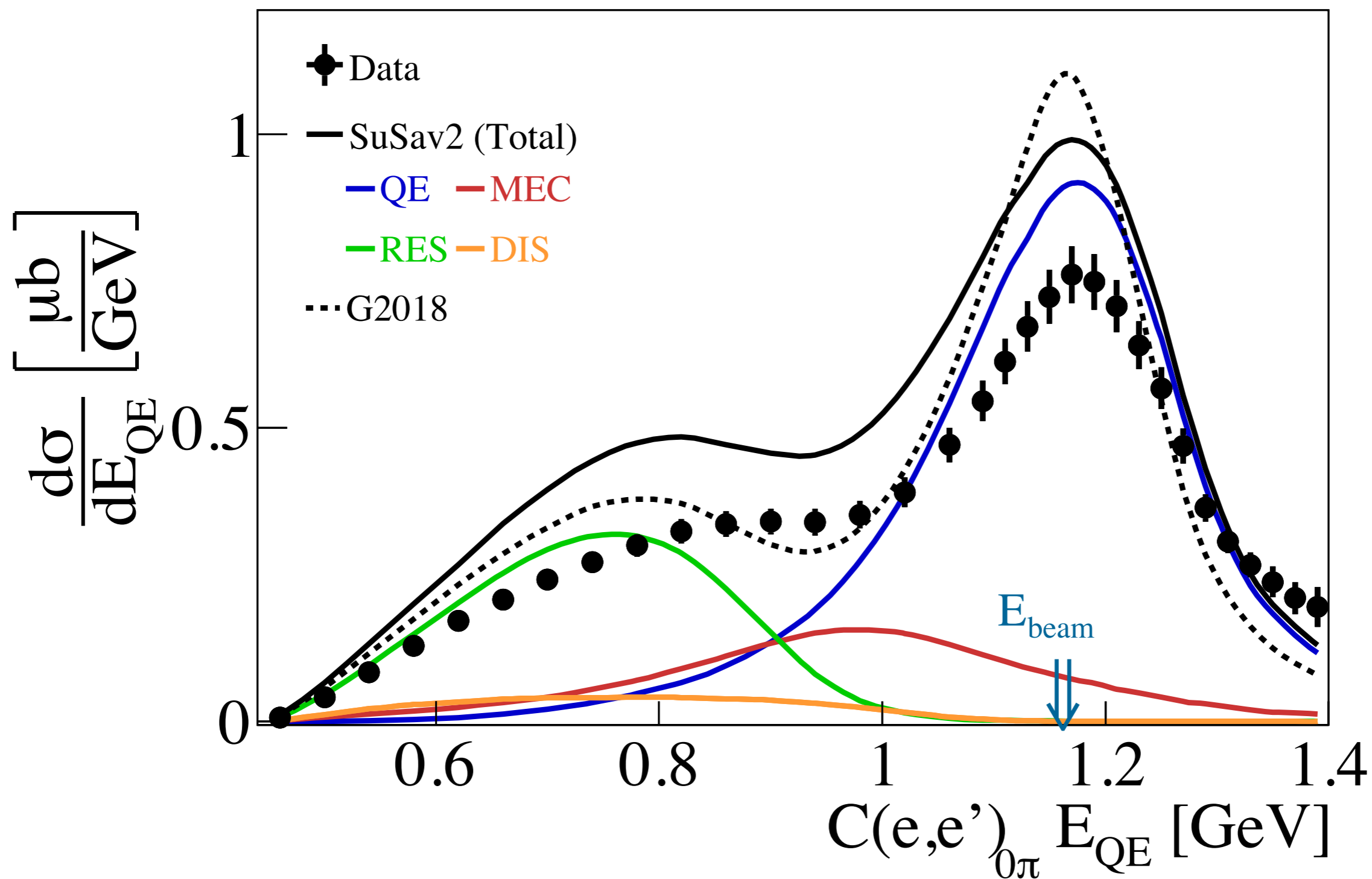
$$P_{\pi^{+/-}} > 150 \text{ MeV/c}$$

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



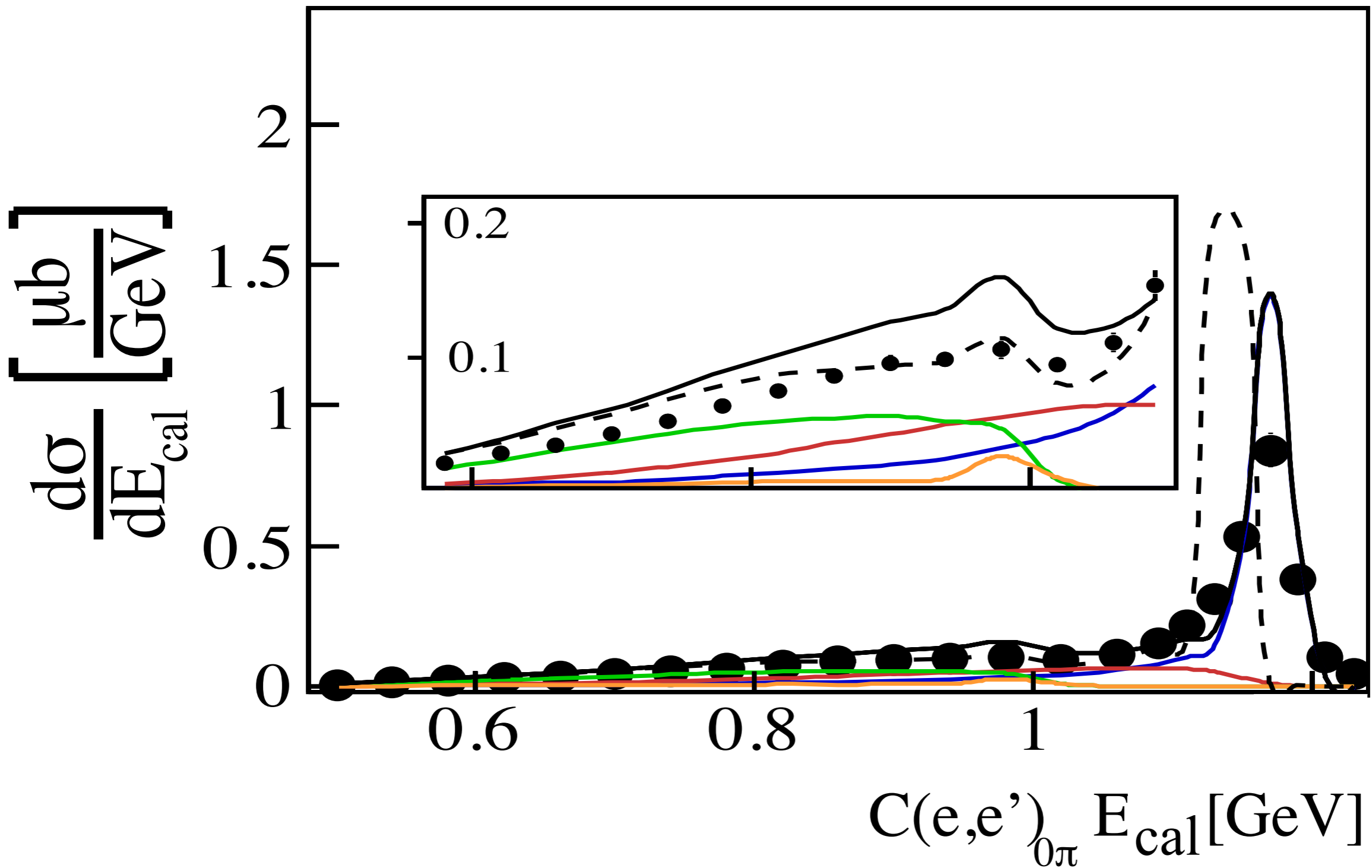
Disagreements between Data and MC

$E = 1.159 \text{ GeV}$



Disagreements between Data and MC

$E = 1.159 \text{ GeV}$

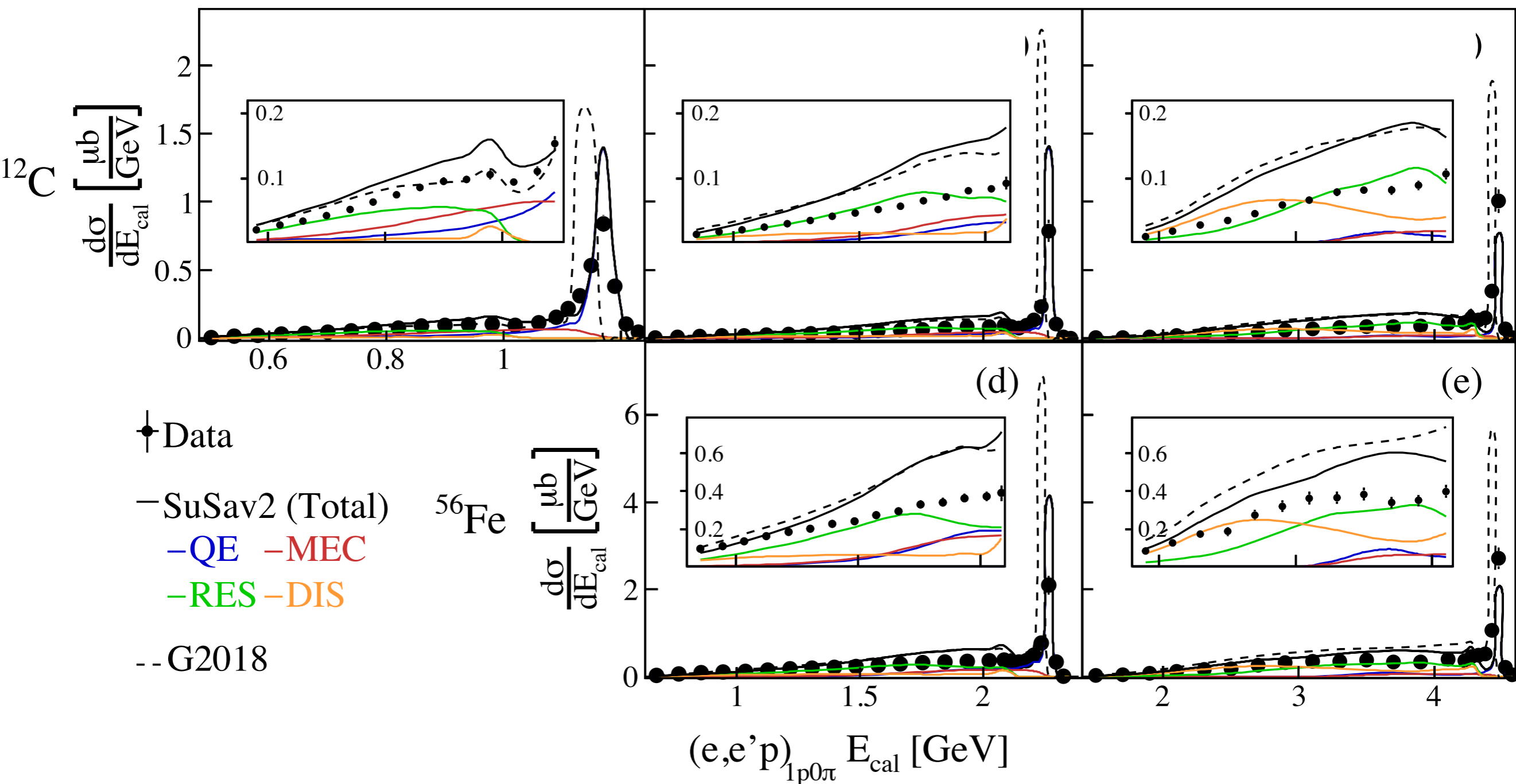


Disagreements between Data and MC

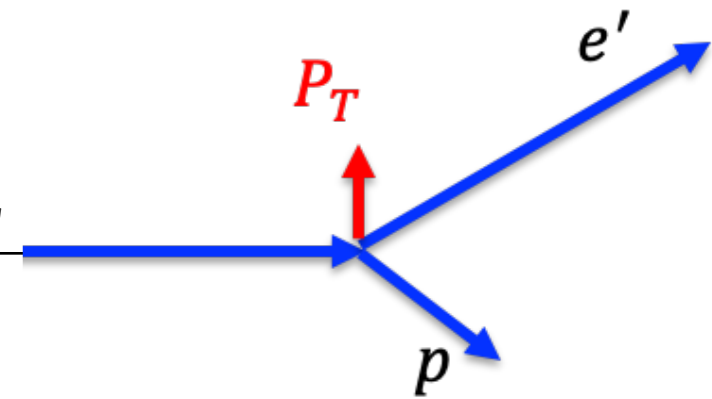
1.159 GeV

2.257 GeV

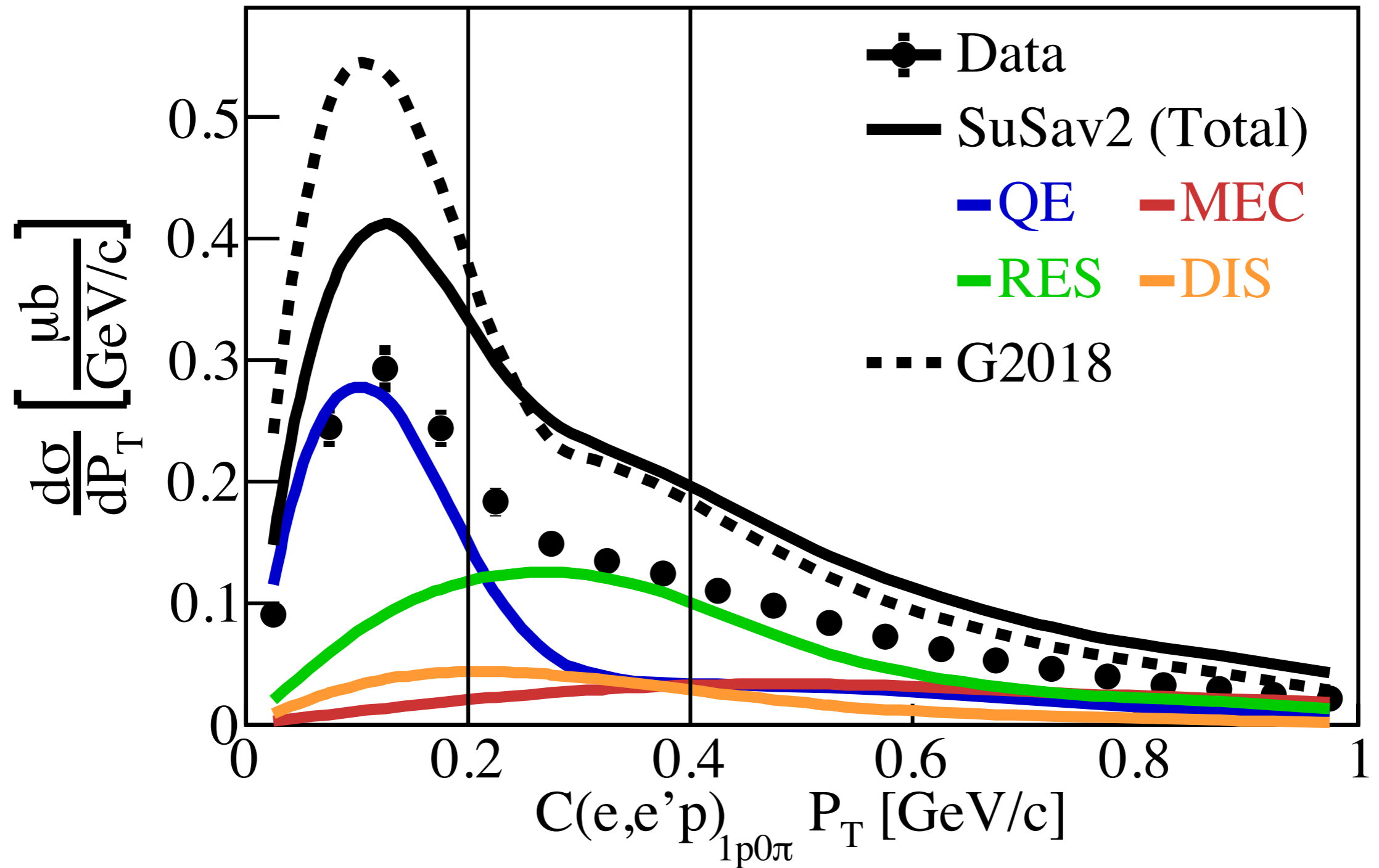
4.453 GeV



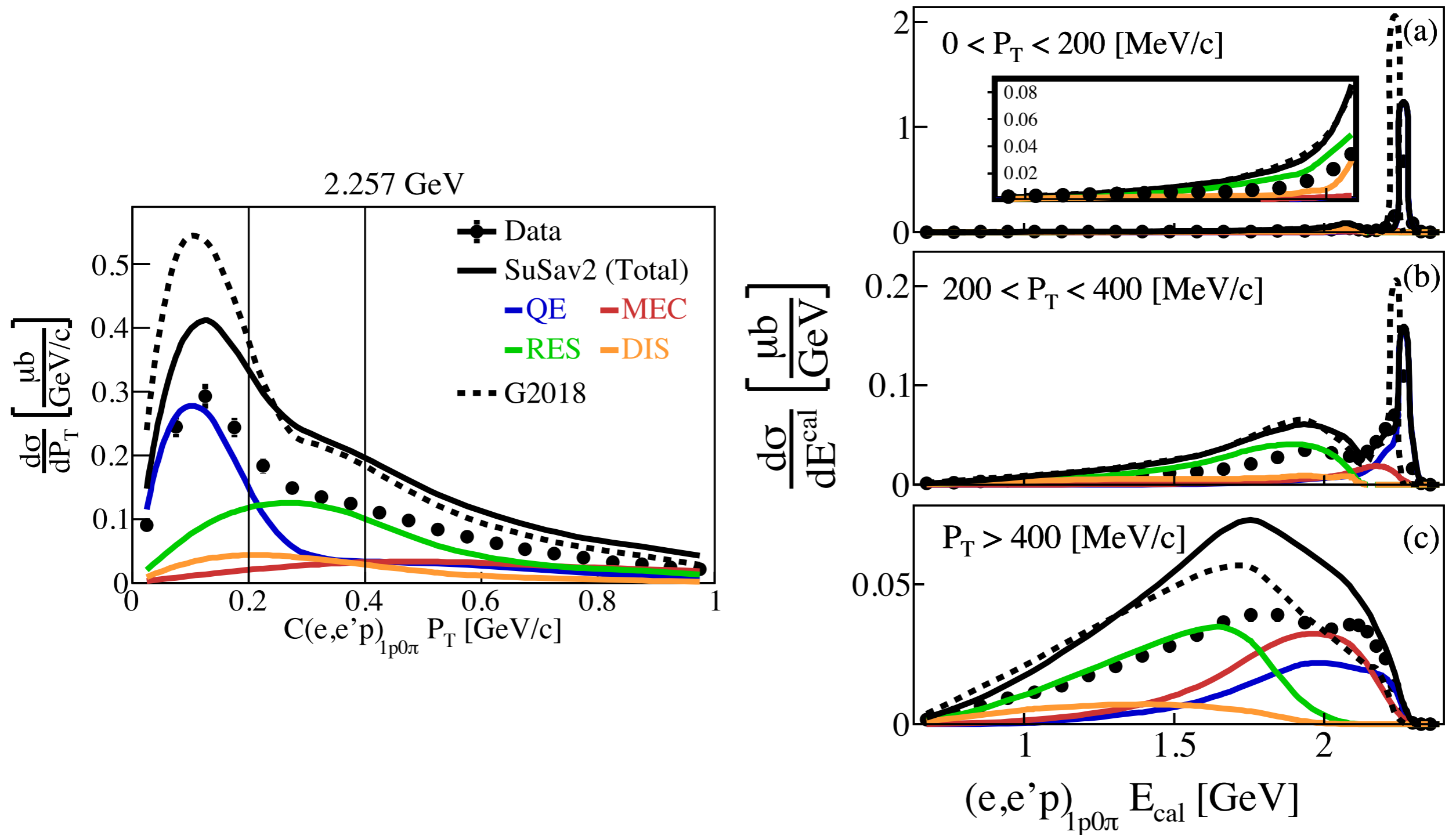
MC vs. (e,e'p) Data: $\vec{P}_T = \vec{P}_T^{e'} + \vec{P}_T^p$



2.257 GeV



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



New Data from @CLAS12

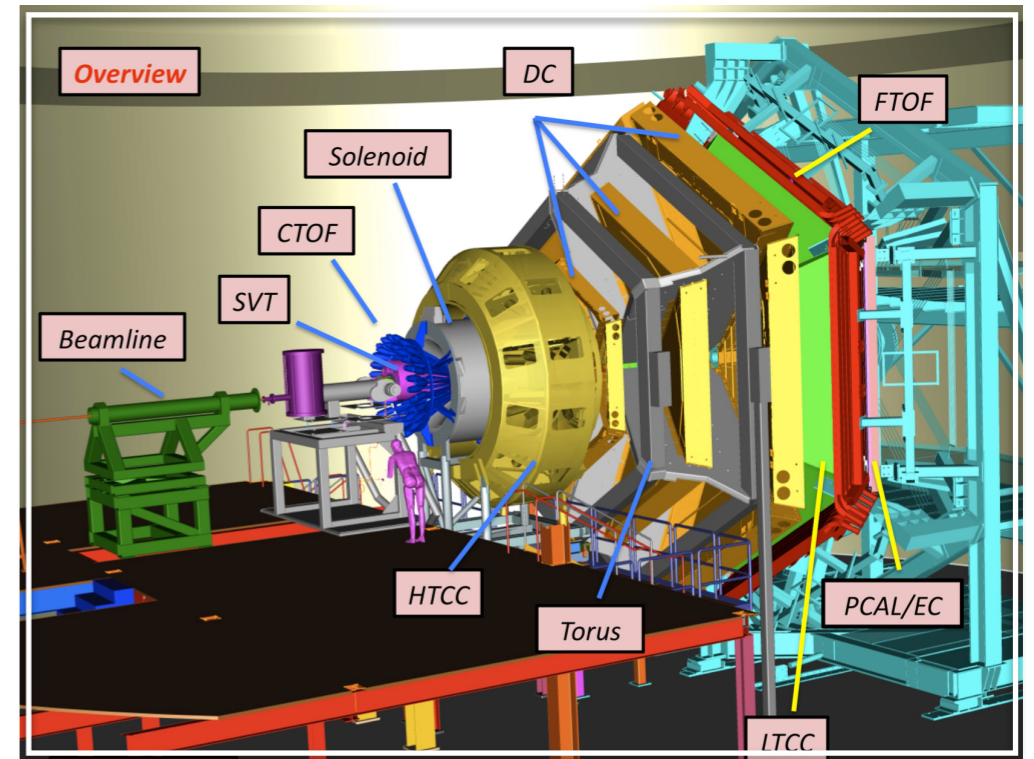
Acceptance down to 5° $Q^2 > 0.04 \text{ GeV}^2$

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

Keep low thresholds

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

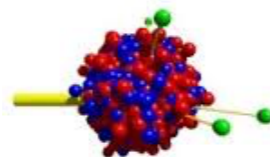
2, 4, 6 GeV (relevant for DUNE)



Overwhelming support from:



MINERVA



GiBUU
The Giessen Boltzmann-Uehling-Uhlenbeck Project



Genie



The *e4ν* Collaboration

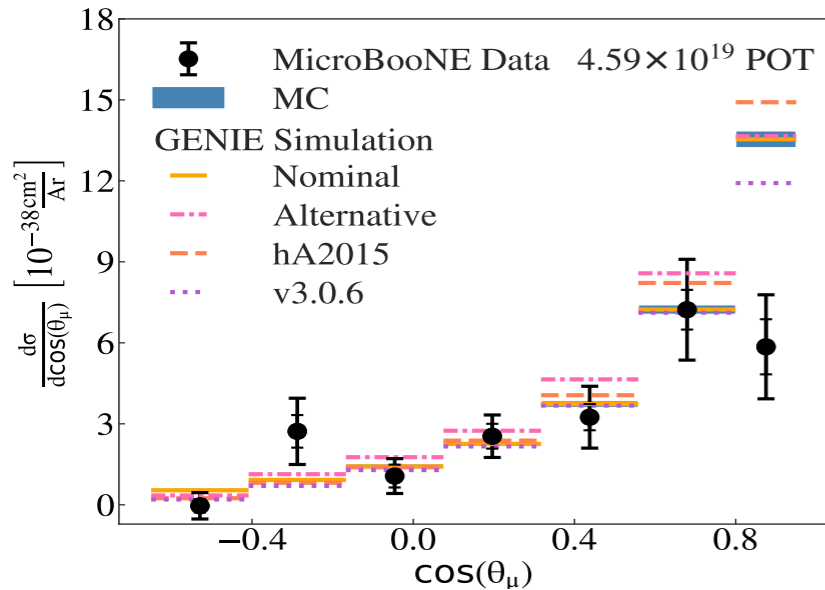


Join us! visit www.e4nu.com

Contact: Minerba betan009@fnal.gov, Adi adishka@tauex.tau.ac.il

Improving modelling input

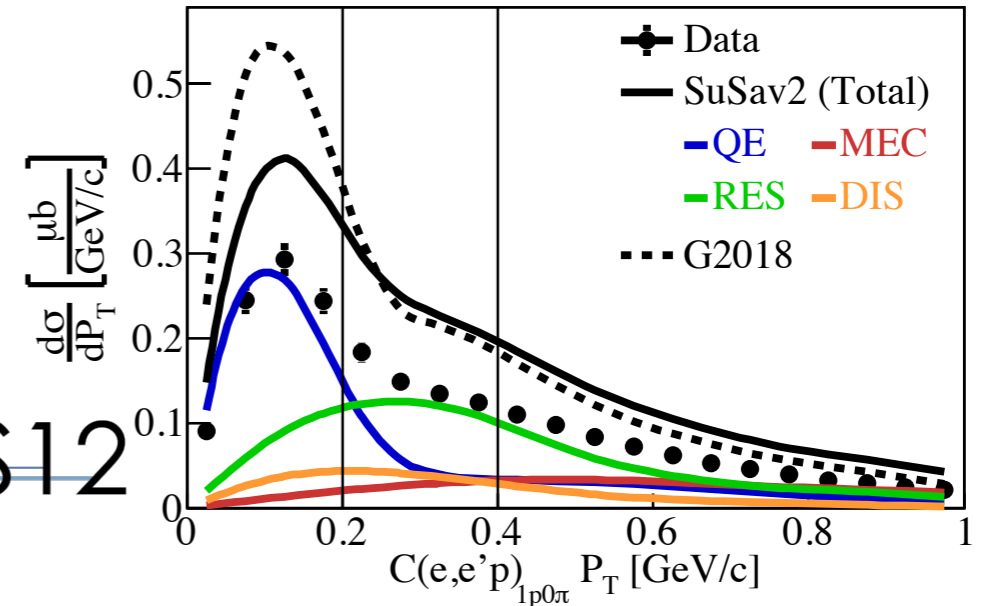
ν scattering



Phys. Rev. Lett. 125, 201803

μBooNE ← **CLAS12**

$e4\nu$ e scattering



Nature 599, pages565–570 (2021)

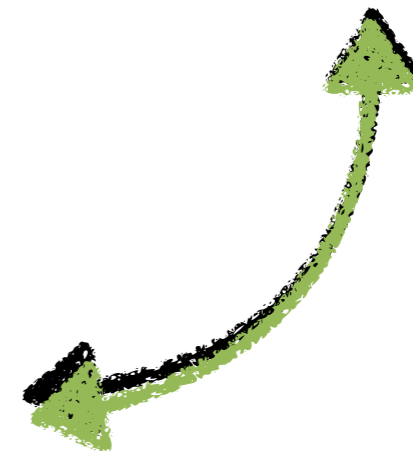
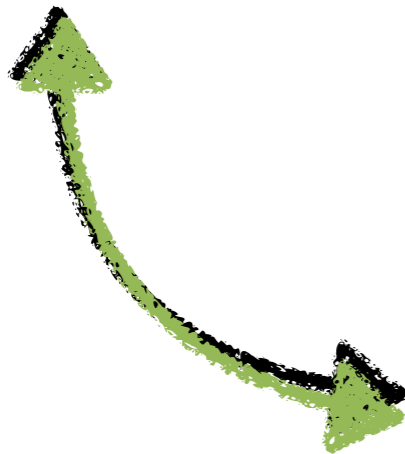
- Cross section measurements
- $\mu 4\nu$ using cosmic rays inside MicroBooNE

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

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

Event Generators

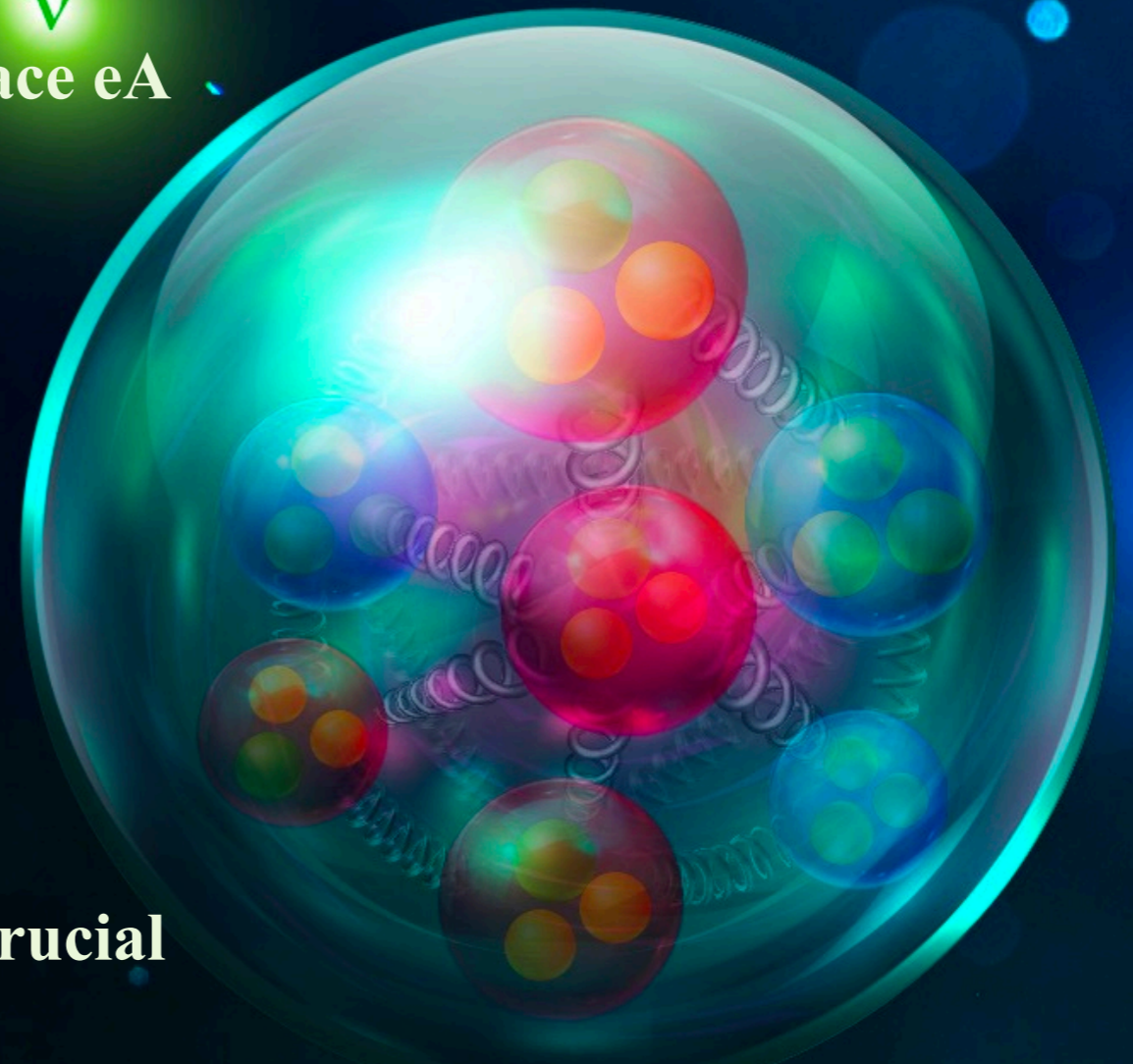
Phys. Rev. D 103, 113003



Summary

ν

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



Understanding the nuclear initial state is crucial

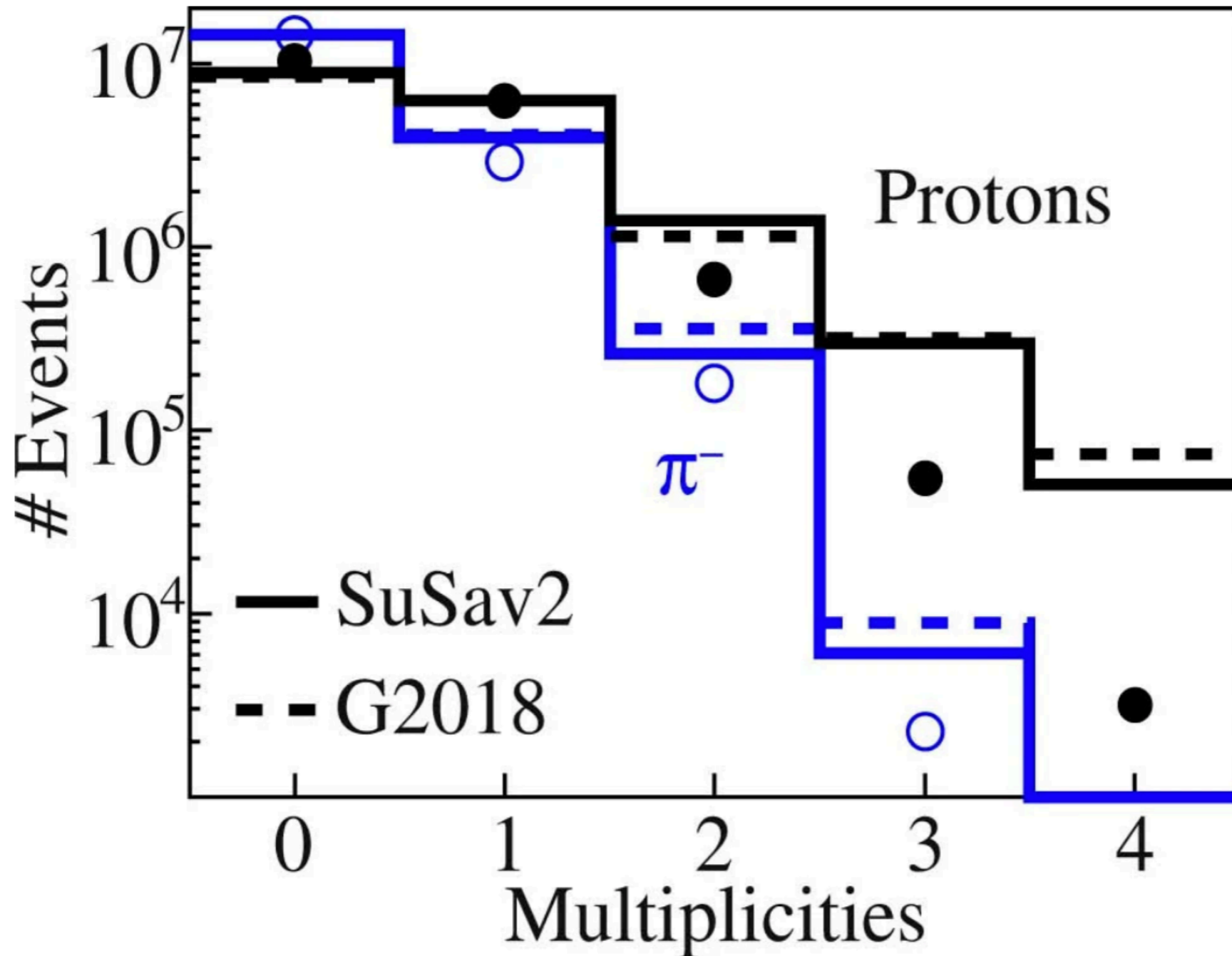
Accelerator based neutrino oscillation experiments reaching new energy regime:

- DIS becoming even more important
- New neutrino experiments could be useful for DIS studies see R. Petty talk
- One day (also with your help) νA generators could be useful for

Thank you for your attention

Multiplicities

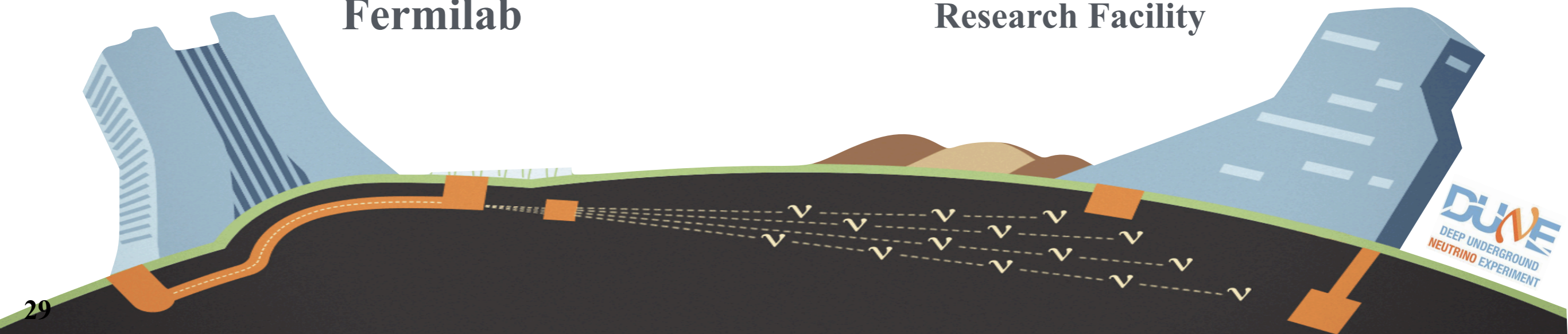
$$E = 2.257 \text{ GeV } ^{12}\text{C}$$



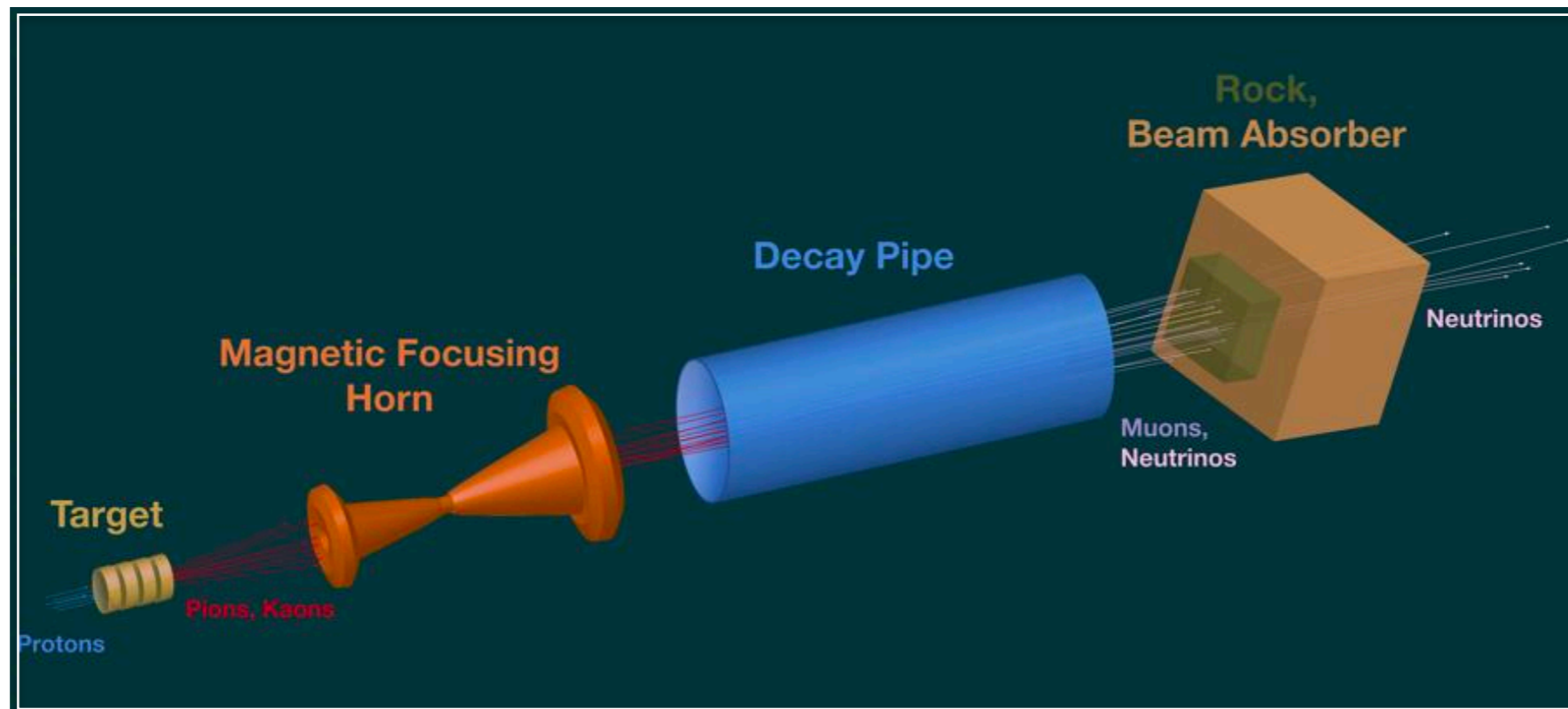
Accelerator-Based Neutrino Oscillations Exp

Fermilab

Sanford Underground
Research Facility



Introduction to Neutrino Oscillations



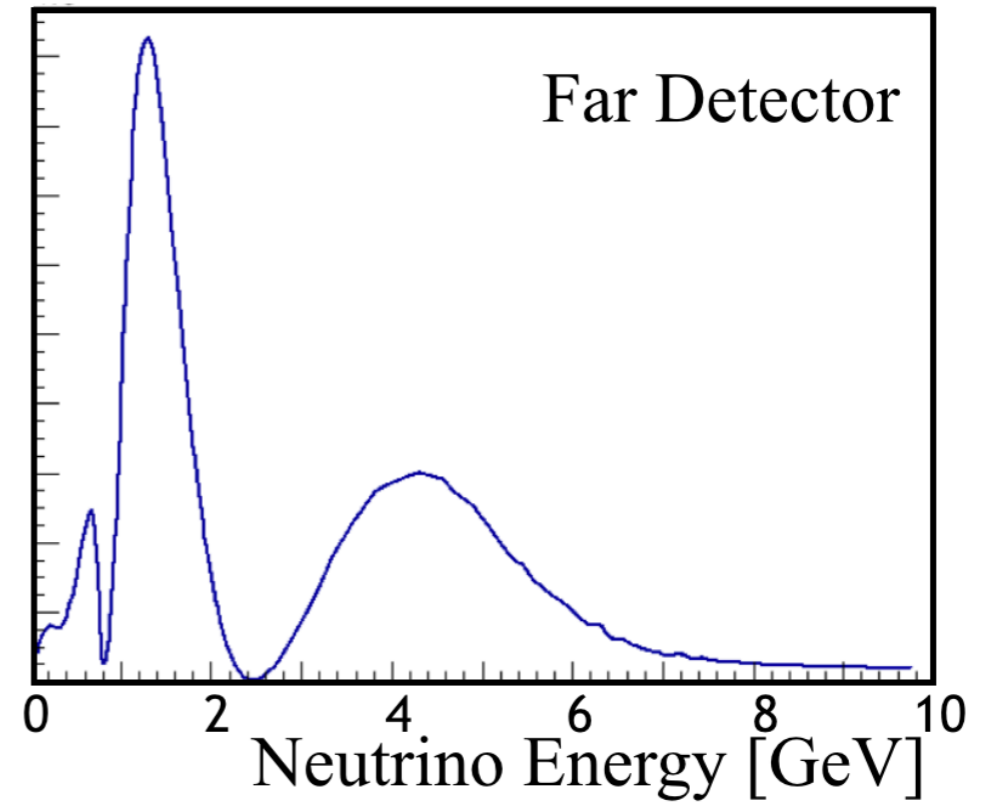
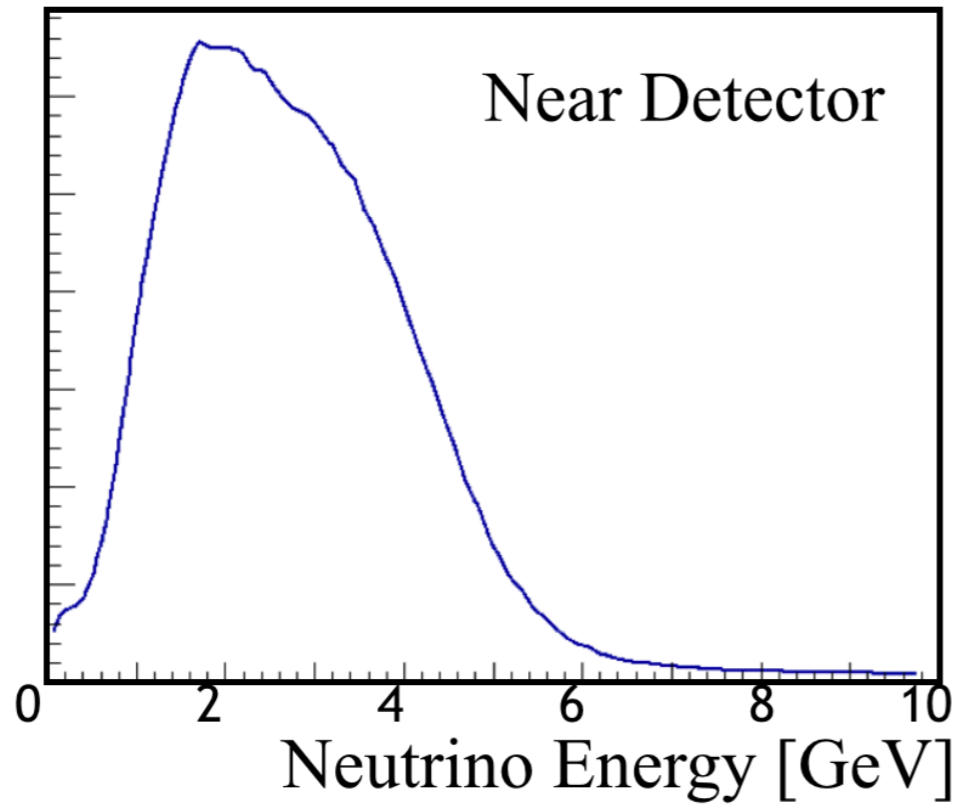
Fermilab

Sanford Underground
Research Facility

DUNE
DEEP UNDERGROUND
NEUTRINO EXPERIMENT

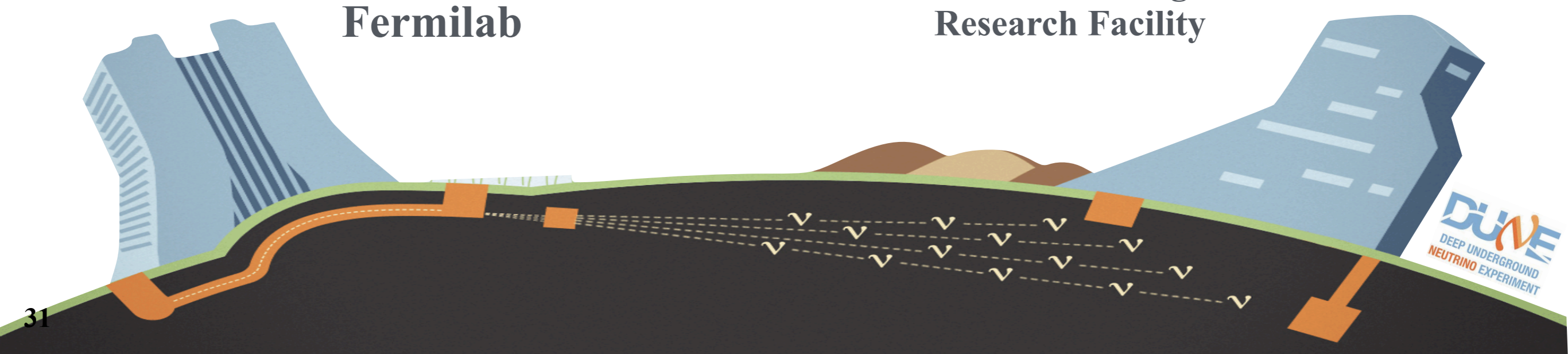
Accelerator-Based Neutrino Oscillations Exp

ν flux



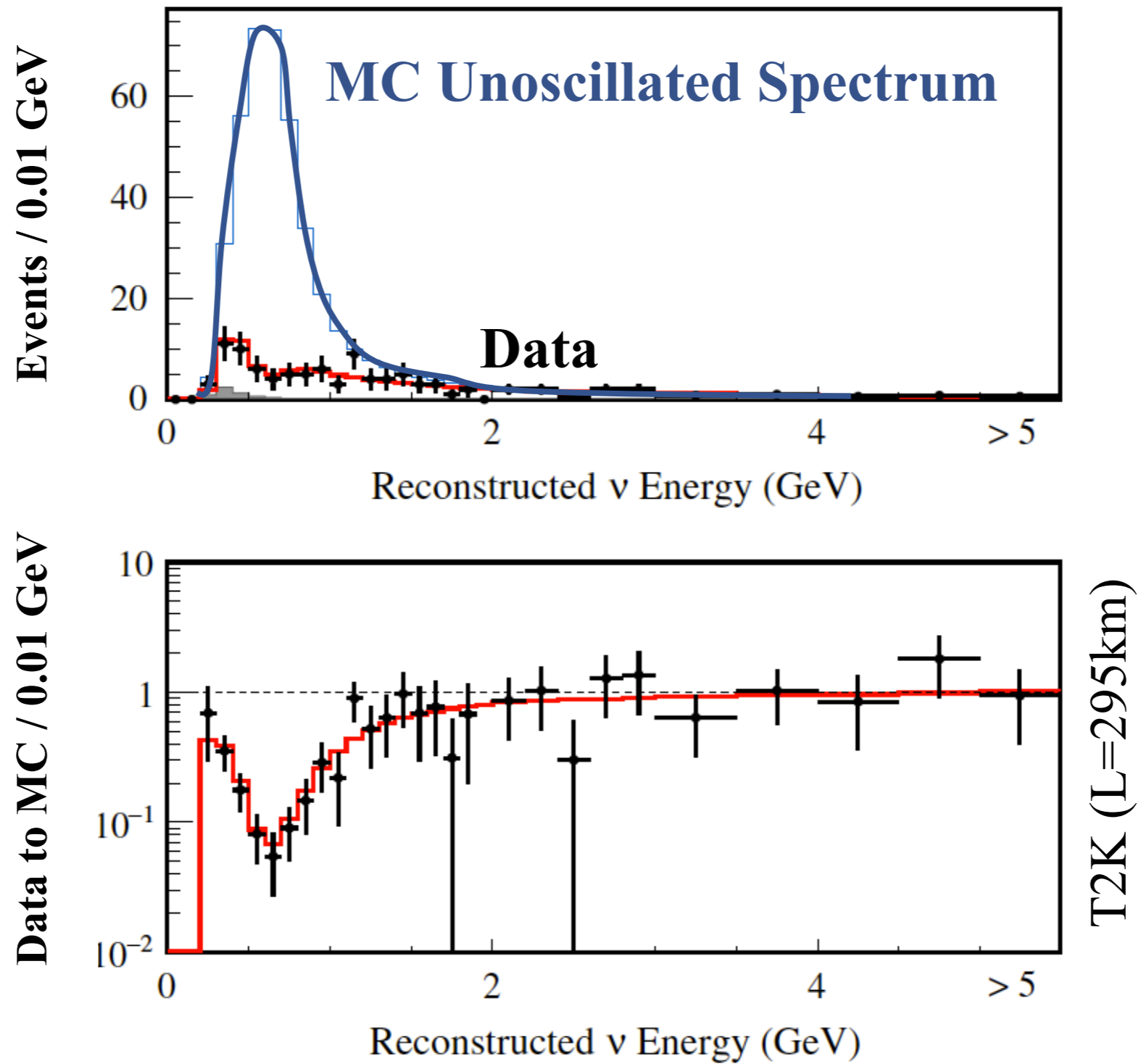
Fermilab

Sanford Underground
Research Facility



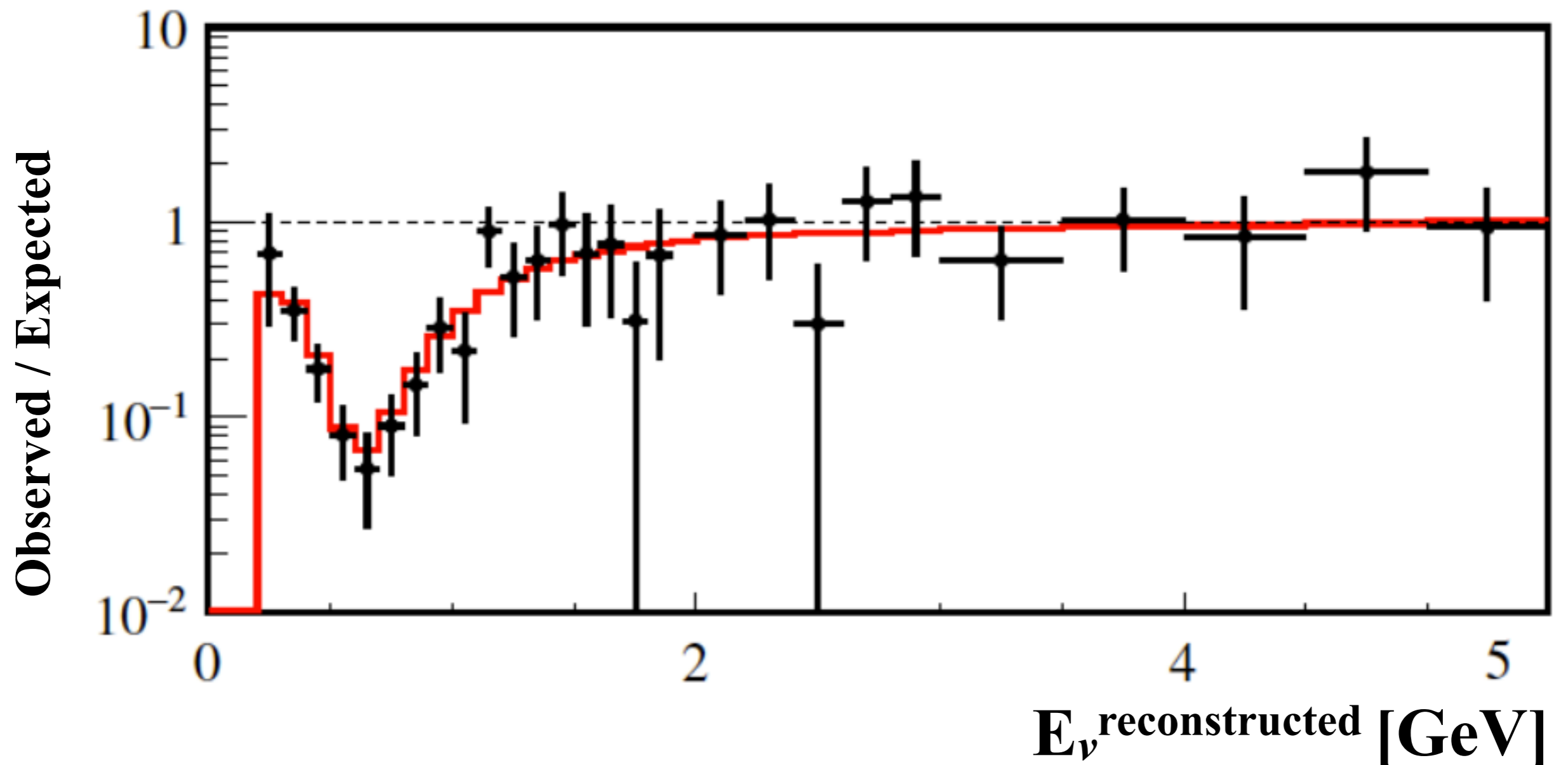
DUNE
DEEP UNDERGROUND
NEUTRINO EXPERIMENT

Oscillations Require incoming E_ν Reconstruction



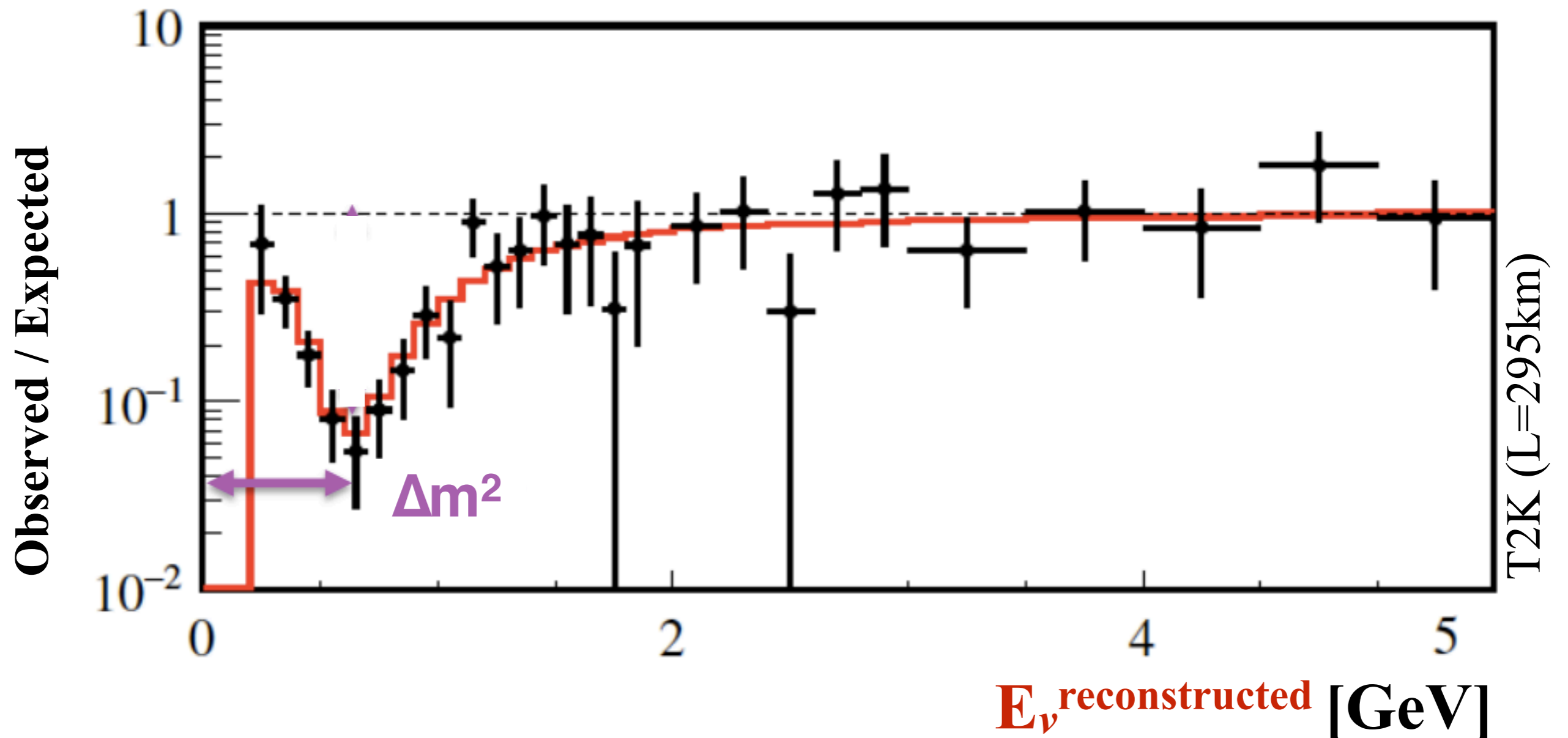
Oscillations Require incoming E_ν Reconstruction

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



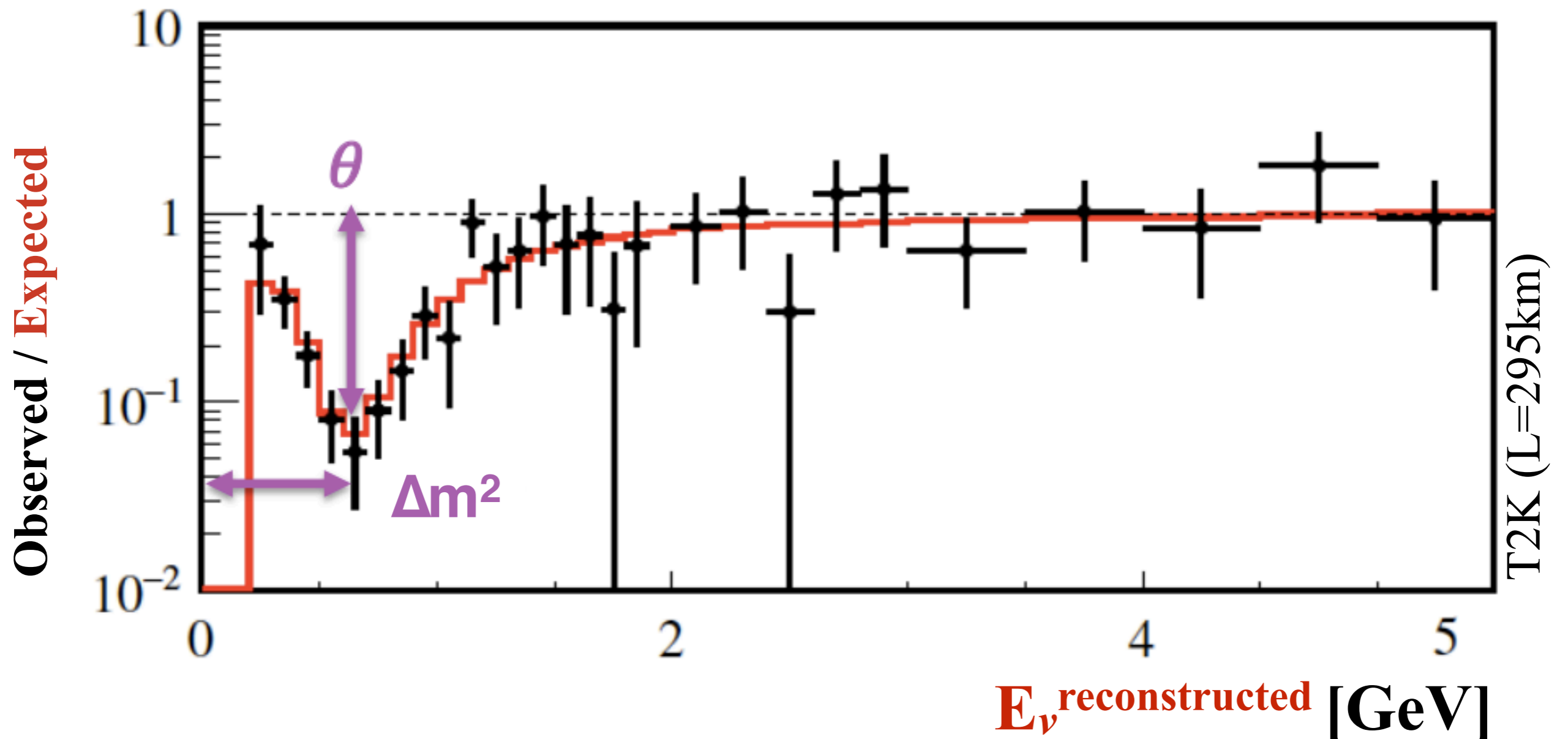
Oscillations Require incoming E_ν Reconstruction

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








Oscillations Require incoming E_ν Reconstruction

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



Complementary Efforts

Collaborations	Kinematics	Targets	Scattering
E12-14-012 (JLab) (Data collected: 2017) 	$E_e = 2.222$ 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) 	$E_e = 1, 2, 4, 6$ 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) 	$E_e = 4.0$ GeV $\theta_e < 40$		(e, e') e, p, n, π in the final state
A1 (MAMI) 	$E_e = 1.6$ GeV	H, D, He C, O, Al Ca, Ar, Xe	(e, e') 2 additional charged particles
eALBA (Planned) 	$E_e = 500$ MeV - few GeV	C, CH Be, Ca	(e, e')

Taken from Electron Scattering and Neutrino Data Whitepaper [arXiv:2203.06853\[hep-ex\]](https://arxiv.org/abs/2203.06853)

Modelling Consistency

Genie

v3.0.6

tune G18_10a_02_11a

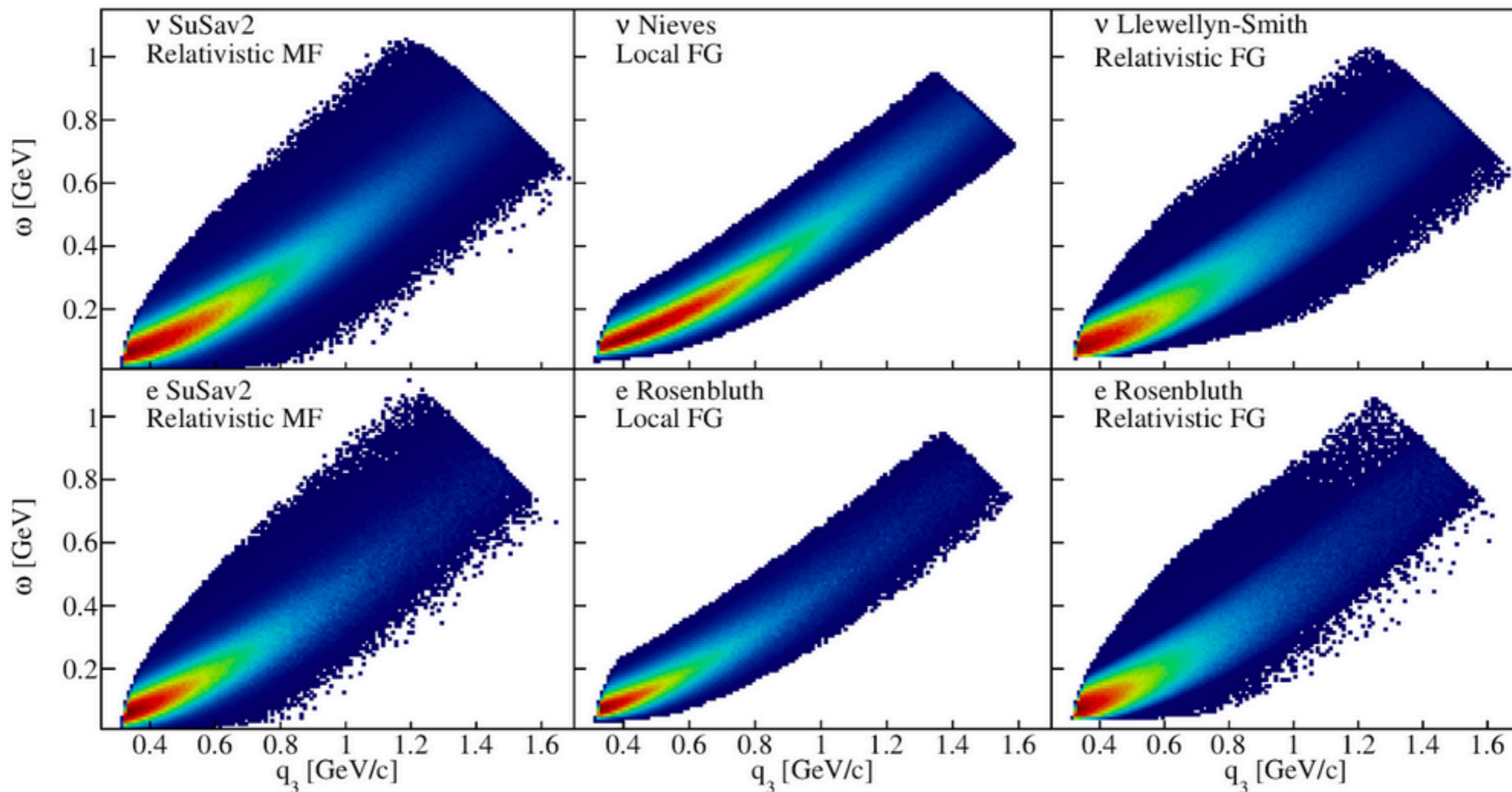
tune GTEST19 (SuSAv2)

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

	electrons	neutrinos
	Relativistic Mean Field	
	SuSAv2	
	SuSAv2	
	Berger Sehgal	
	AGKY	
	hA2018	
	Radiative effects	

Modelling Consistency

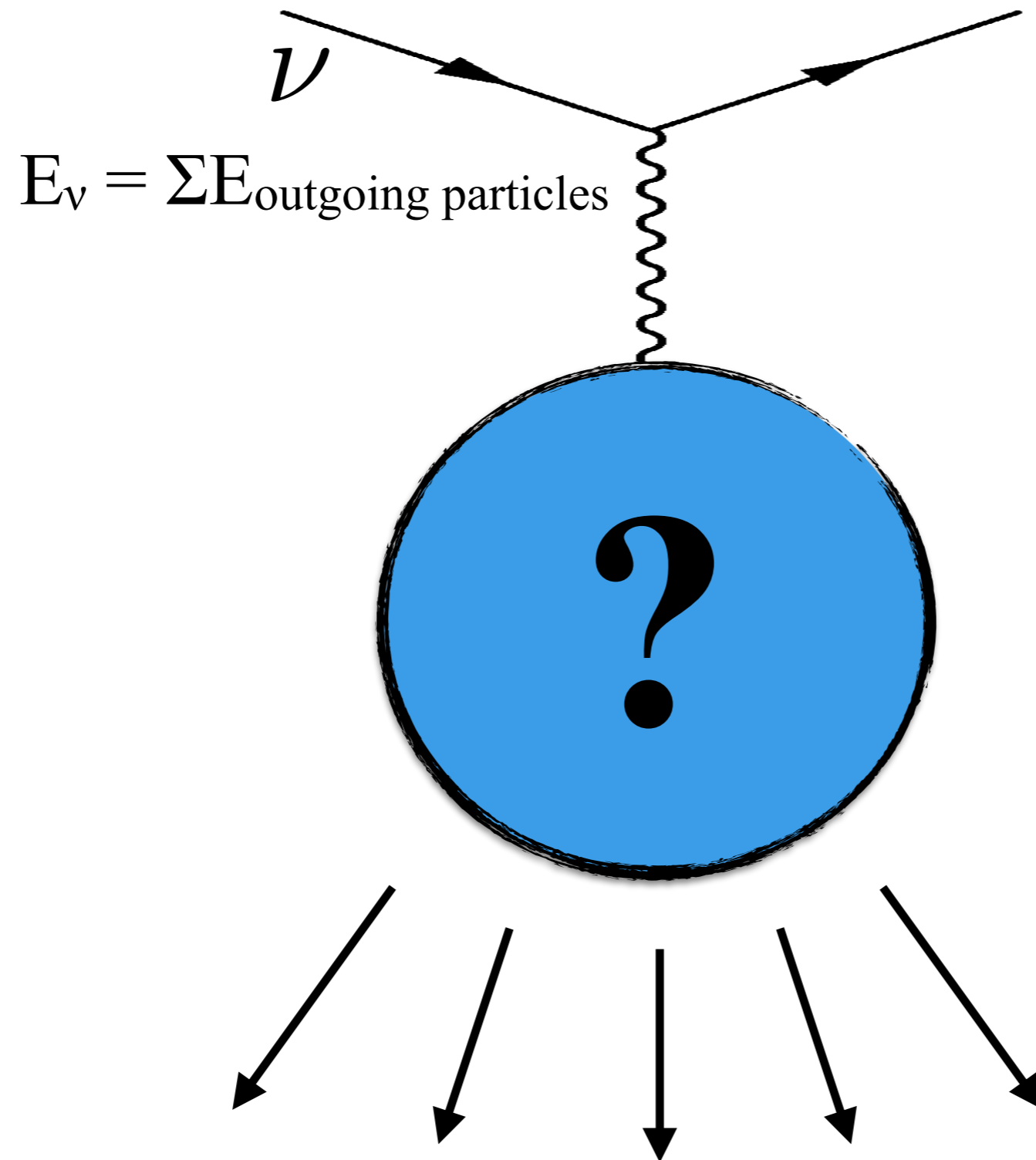
Test on $1p0\pi$ event selection



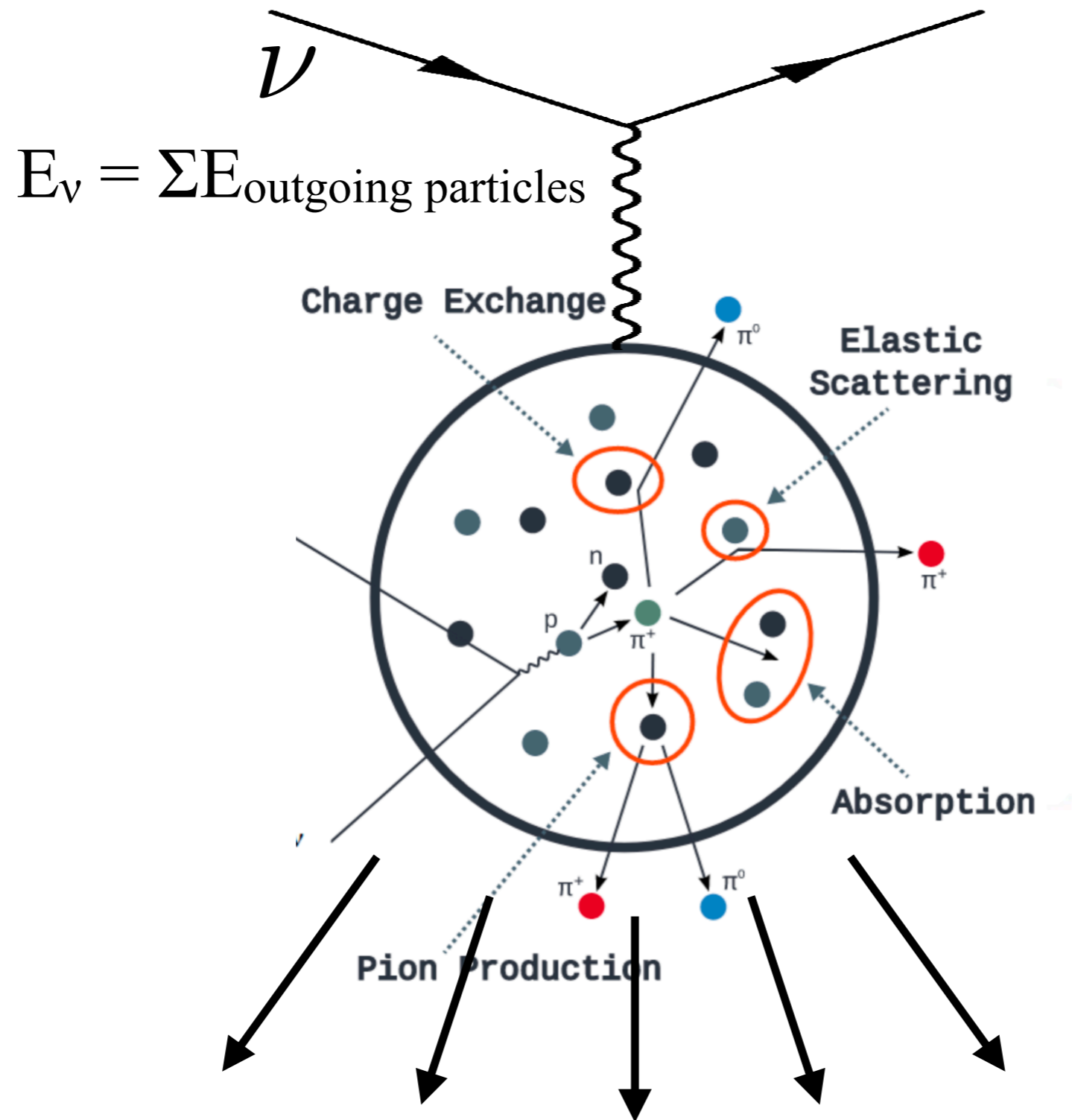
Electron were weighted by $1/Q^4$

Genie

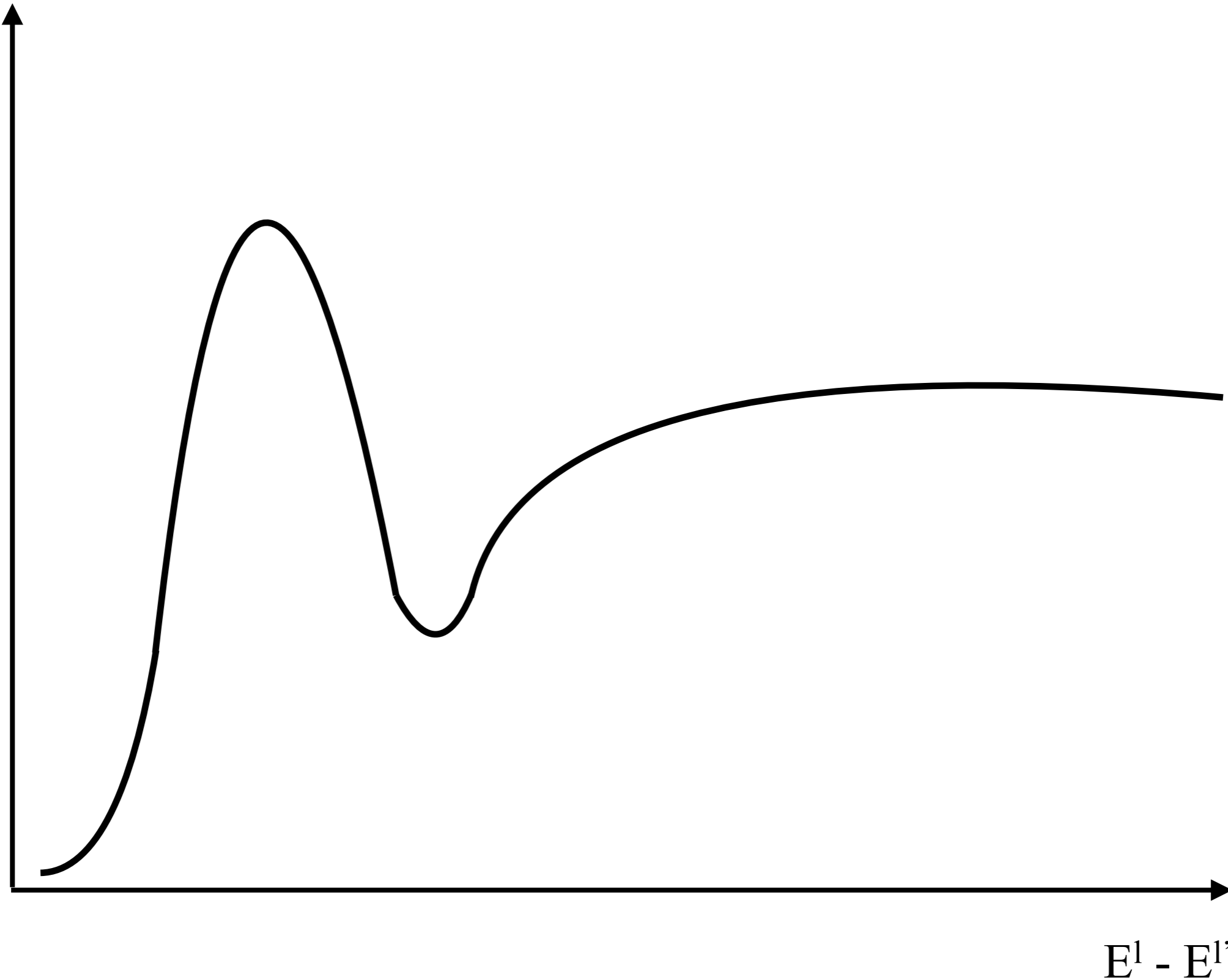
E_ν Reconstruction



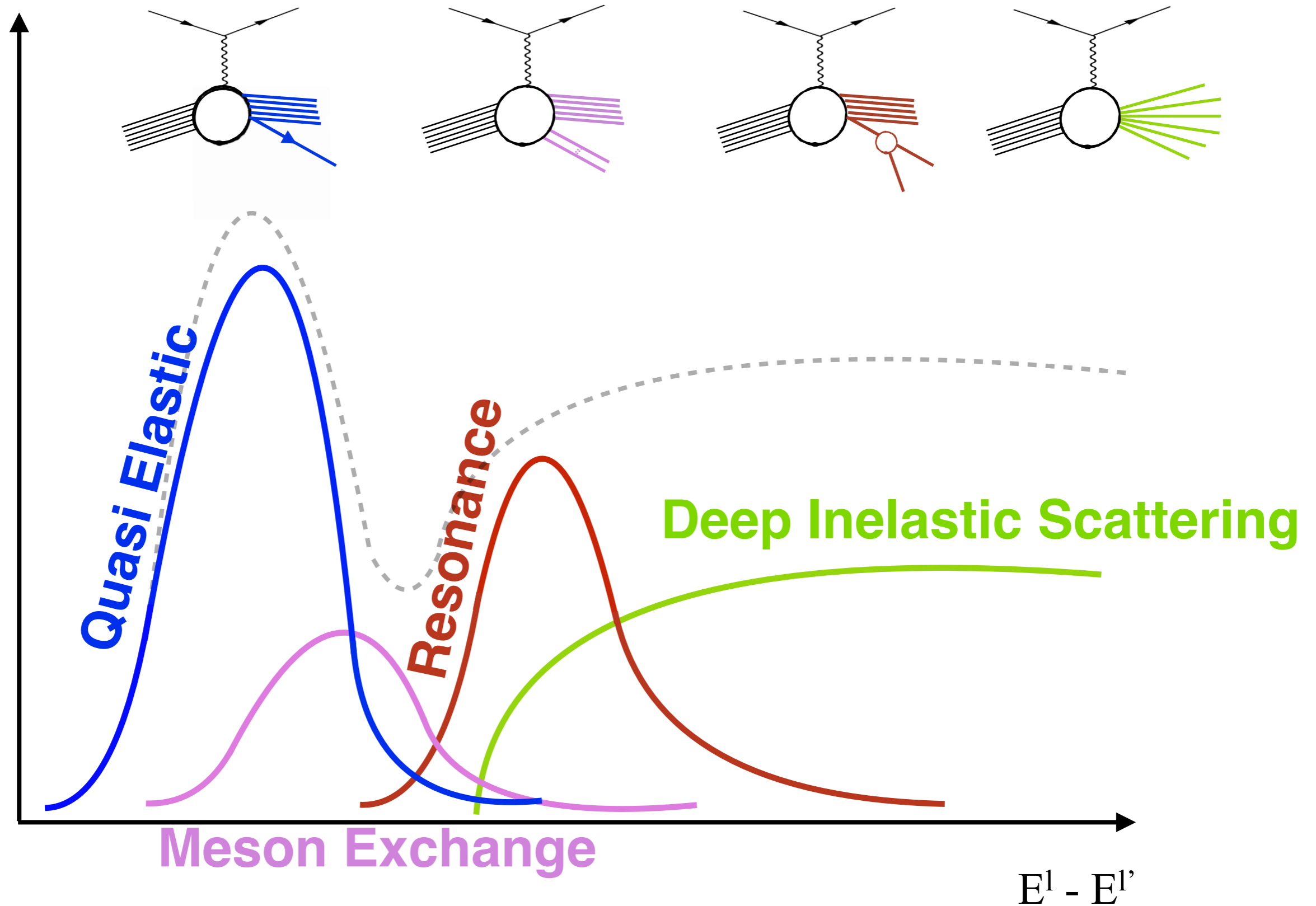
E_ν Reconstruction



E Reconstruction Requires Interaction Modelling



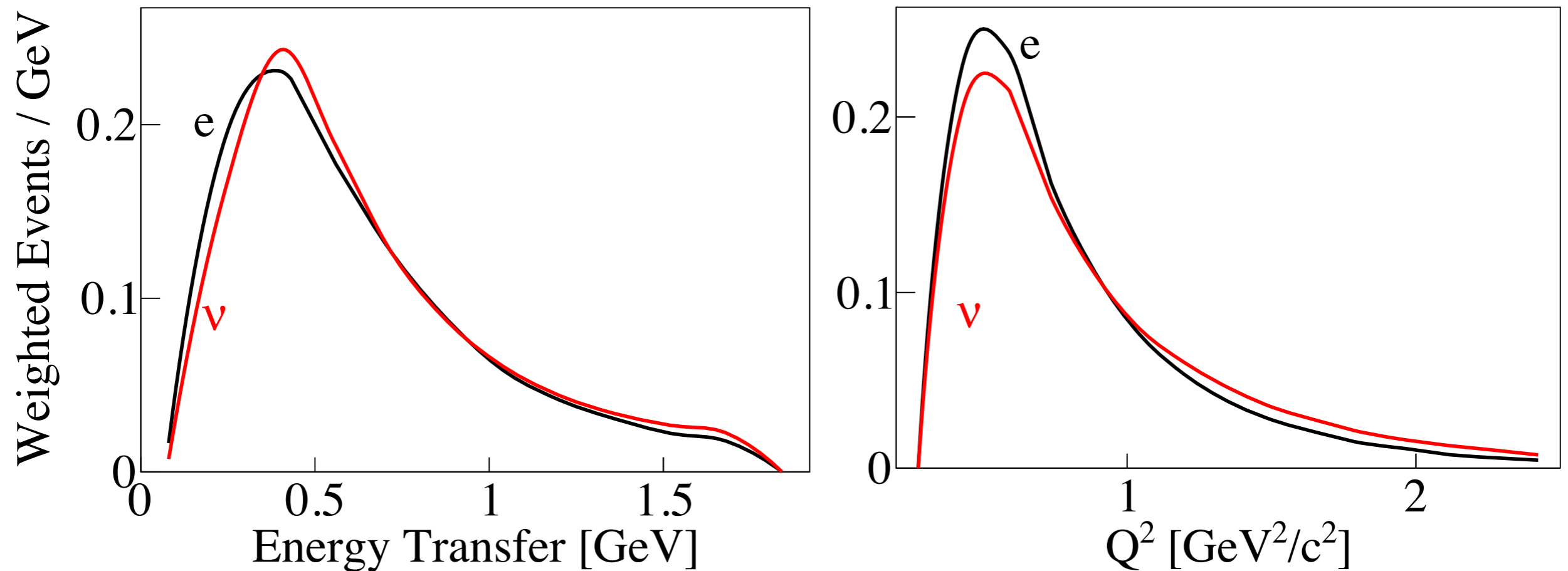
E Reconstruction Requires Interaction Modelling



Modelling Consistency

Test on $1p0\pi$ event selection

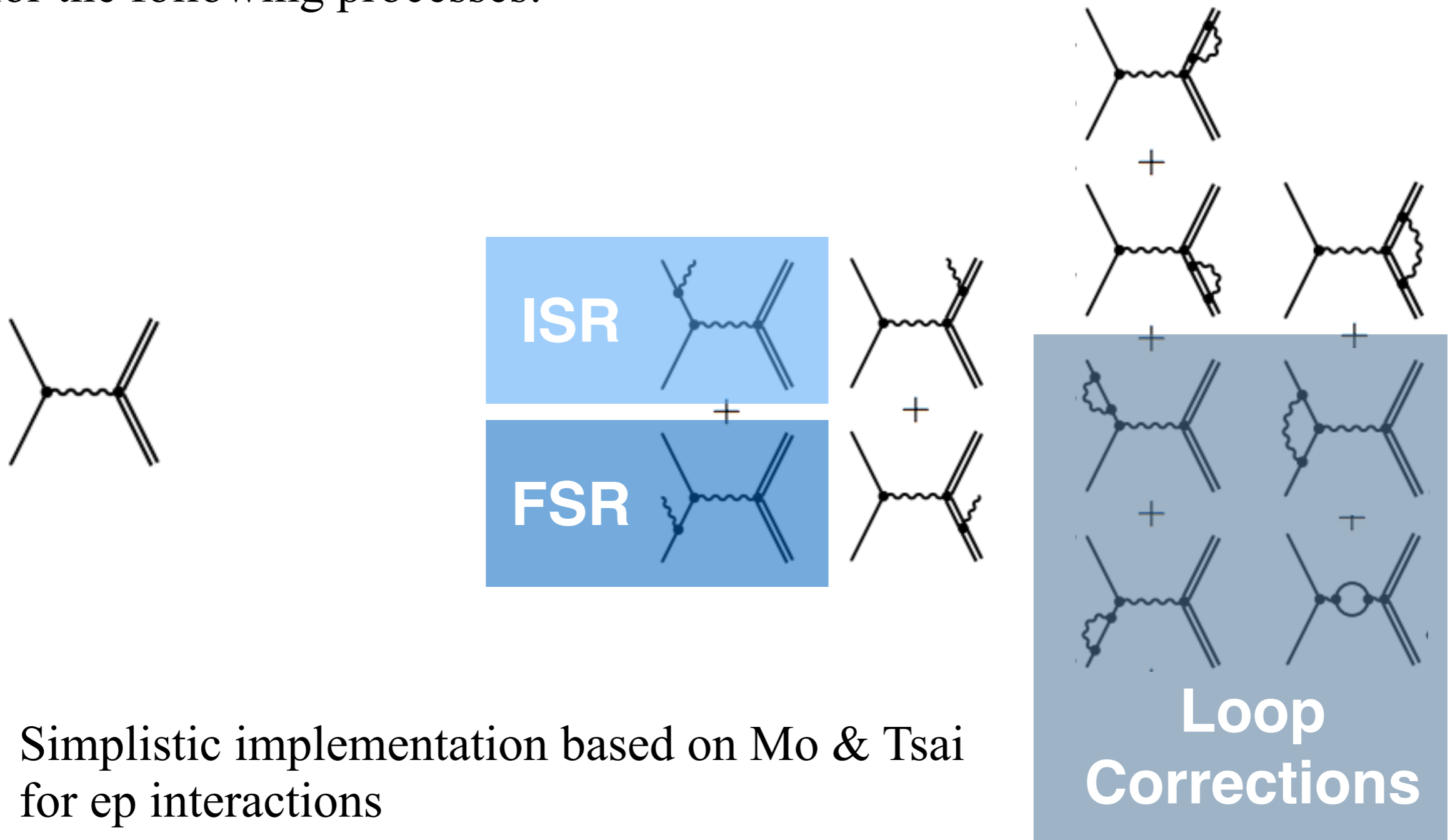
^{56}Fe $E = 2.2$ GeV



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

Radiative effects

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

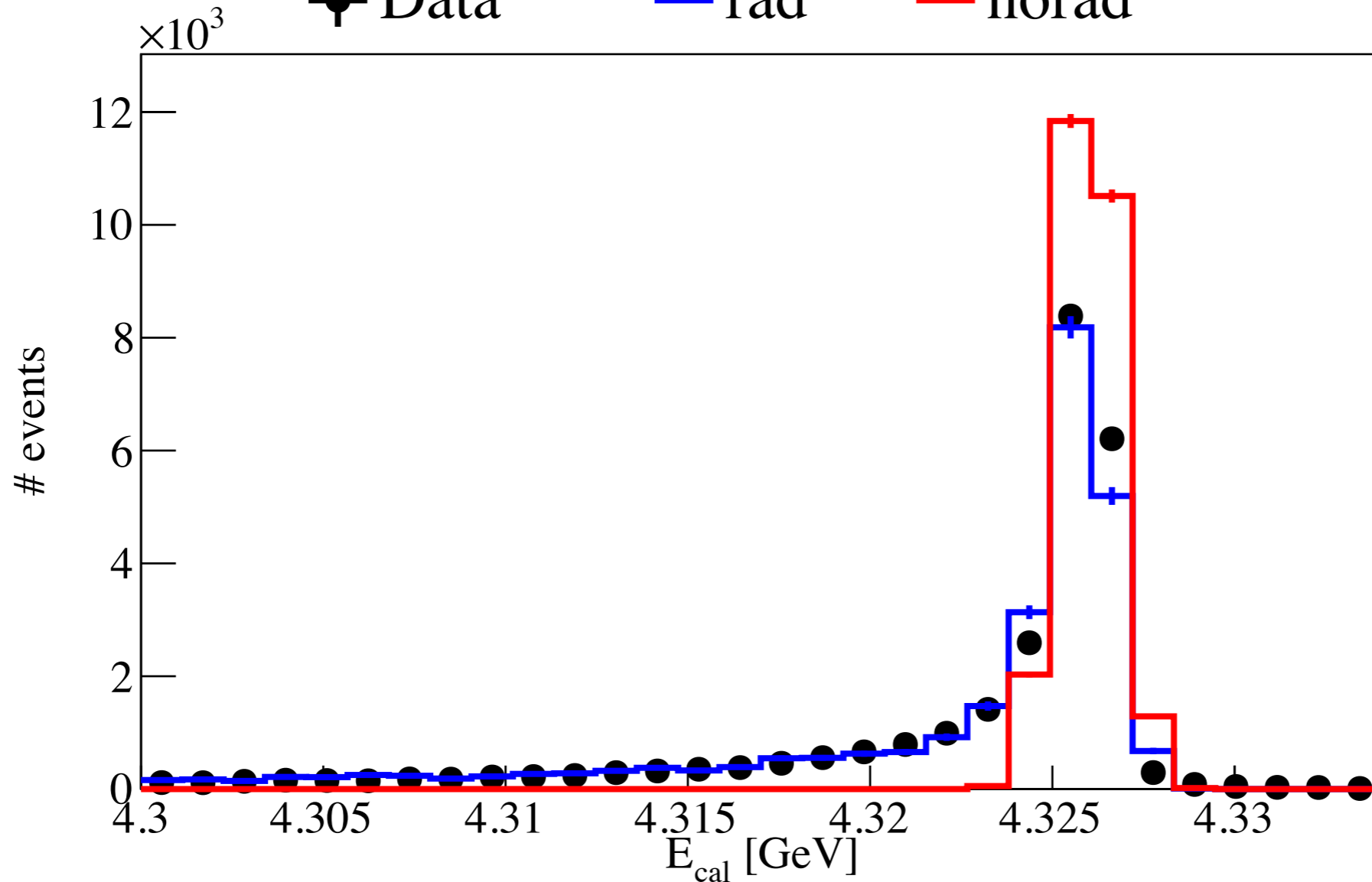


Simplistic implementation based on Mo & Tsai for ep interactions

Adding radiative effects

$^1\text{H}(e,e'p)$ $E = 4.325$ GeV

•+ Data — rad — norad



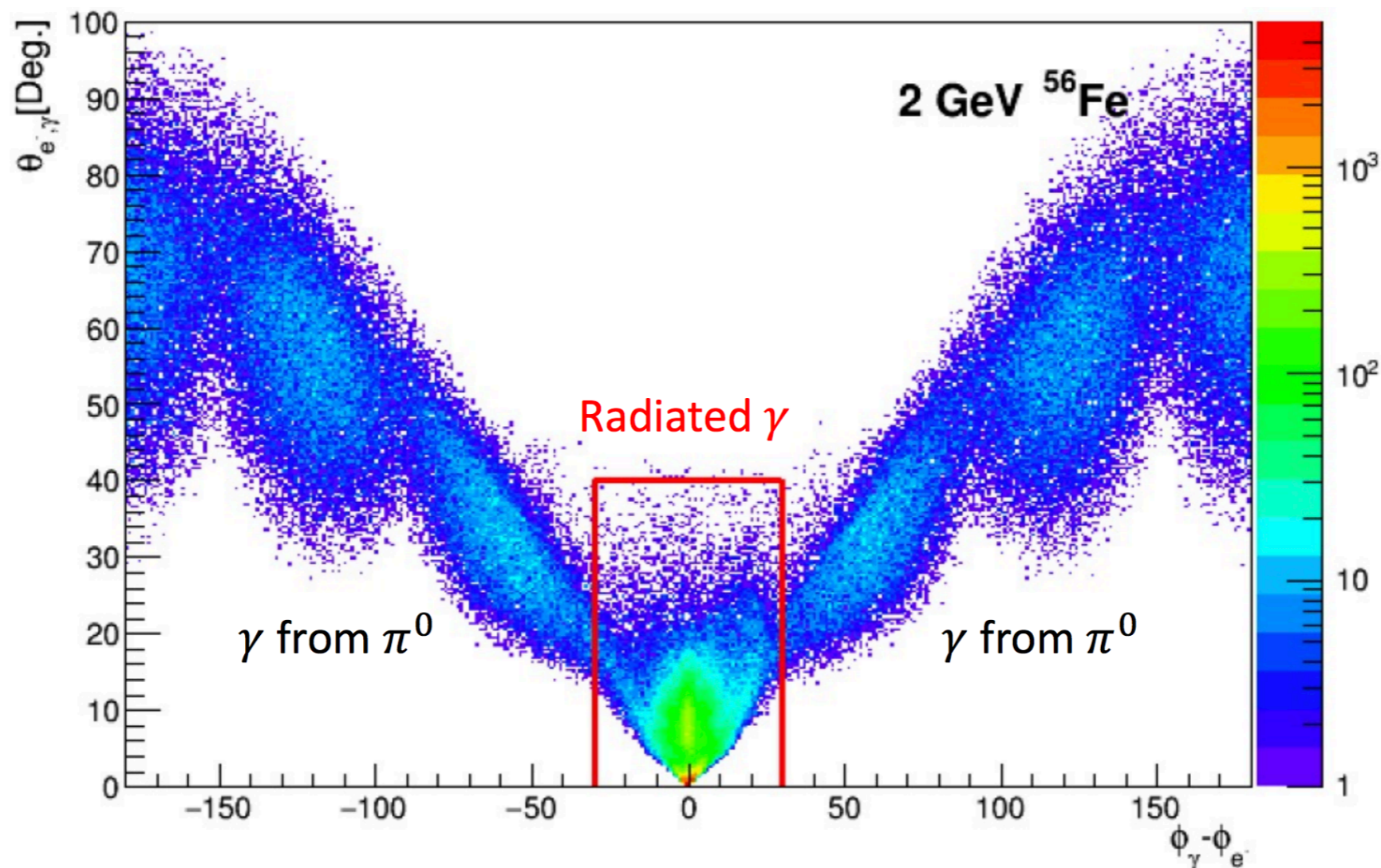
[Mo and Tsai]

Genie v3.0.6 tune G18_10a_02_11a

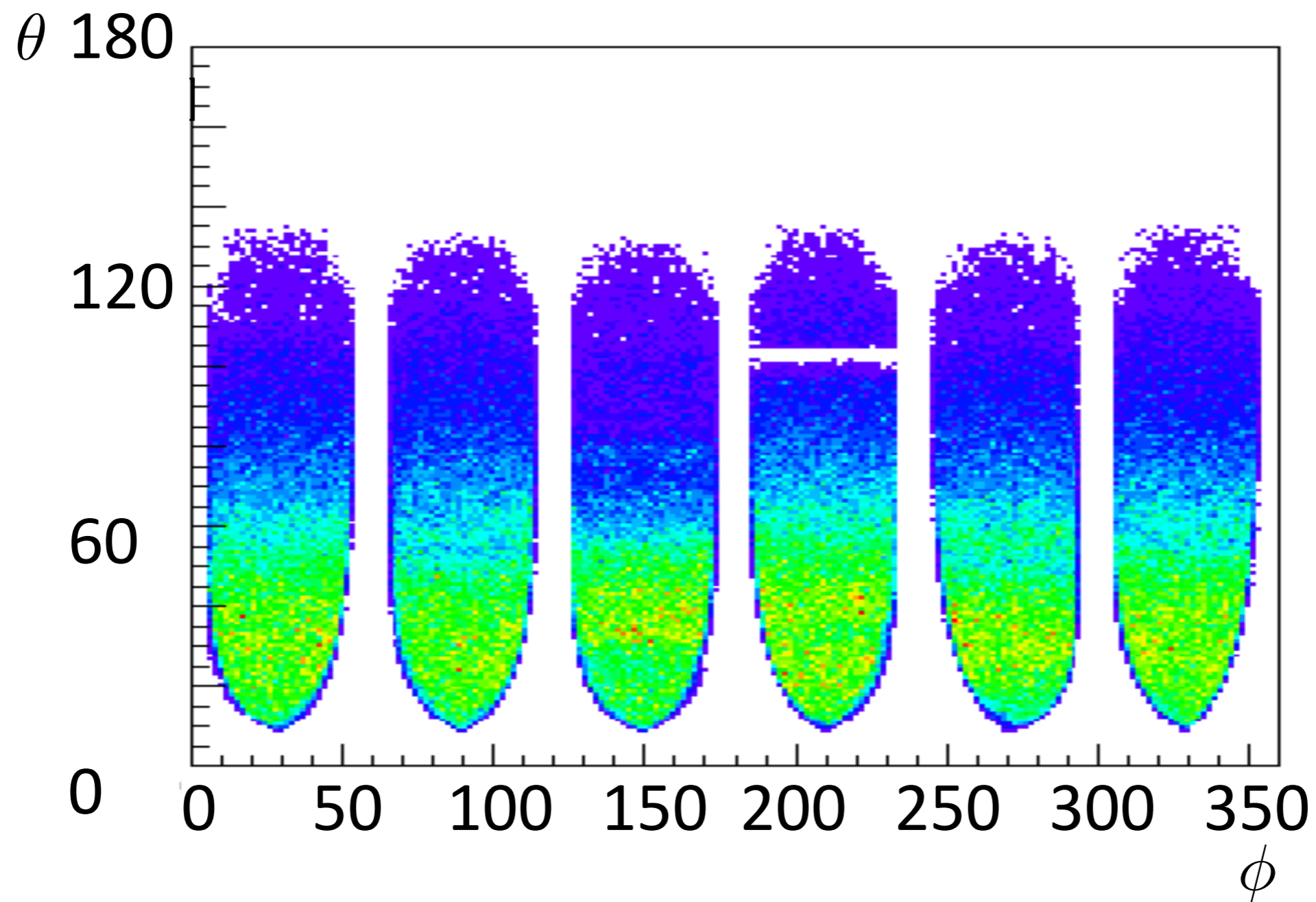
Coping with radiative effects

In addition we're ignoring events with:

- A photon in close proximity to the final state electron
- $E_1' < 0.25 E_1$



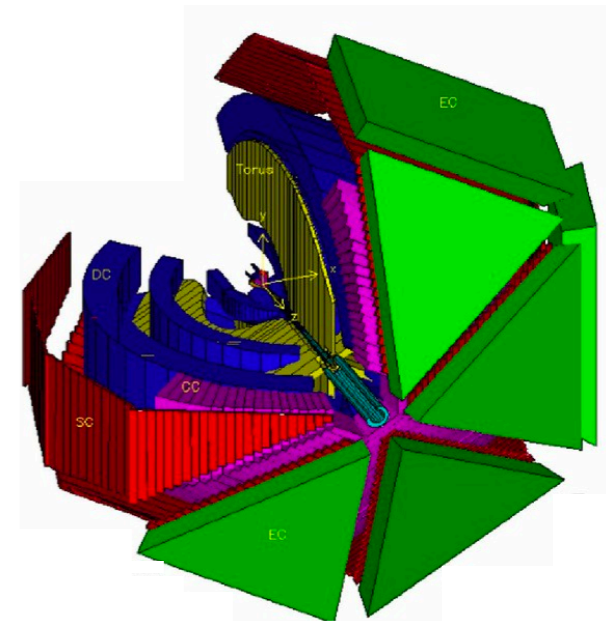
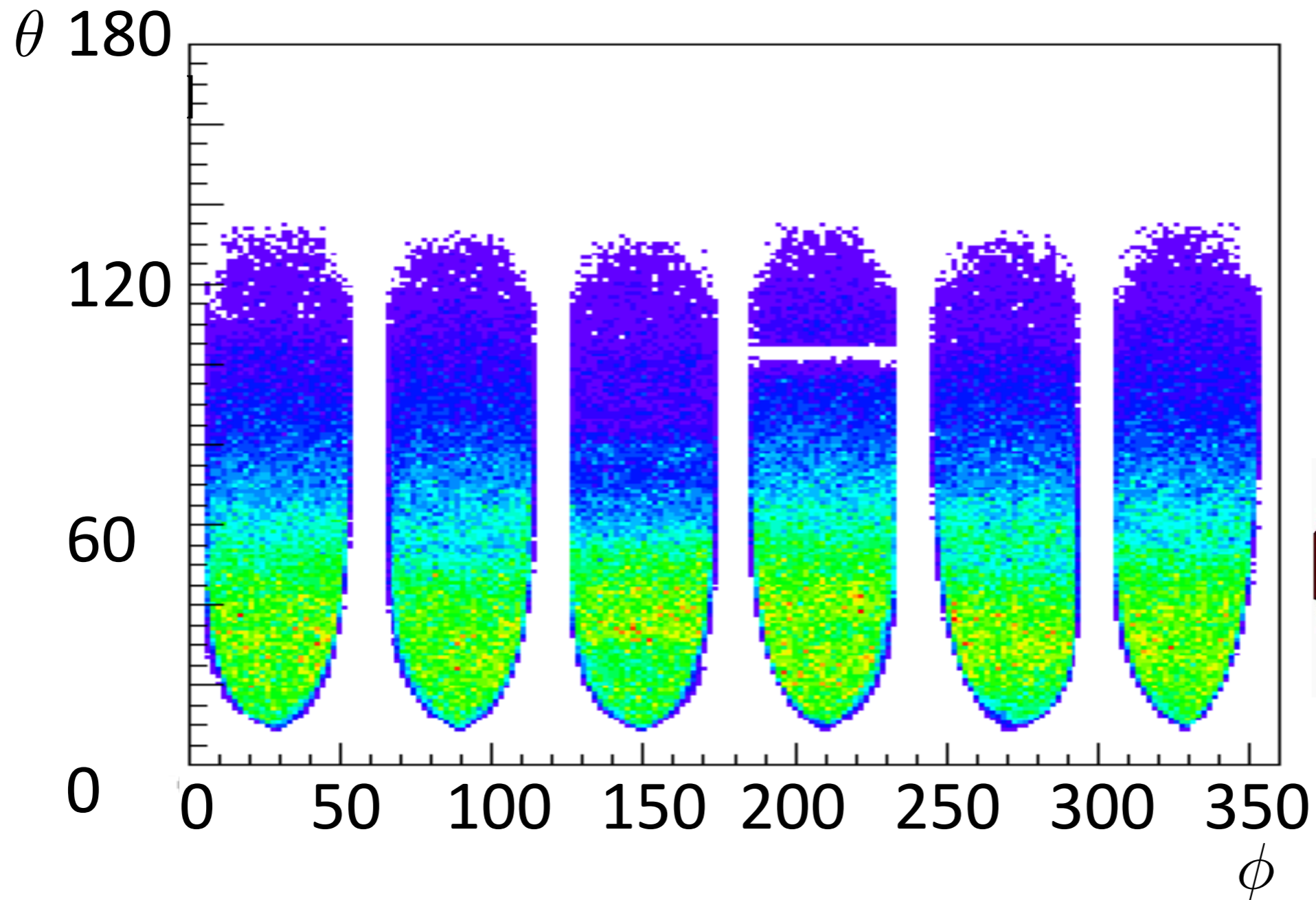
Wide Phase Space



Background Subtraction

Different interaction lead to multi-hadron final states

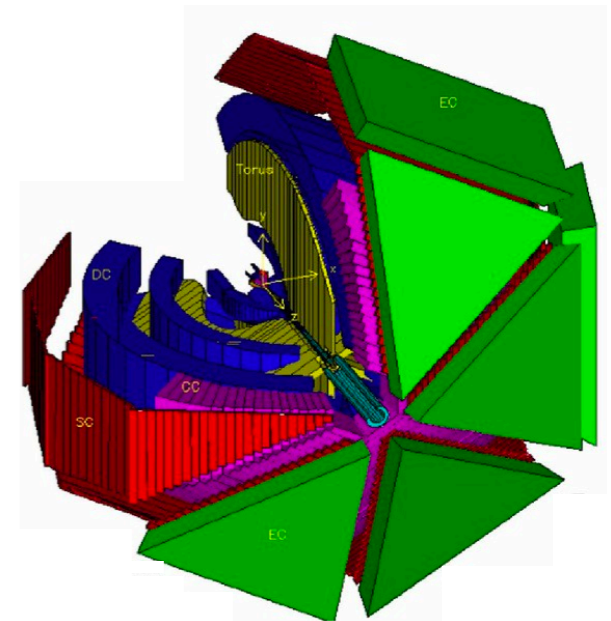
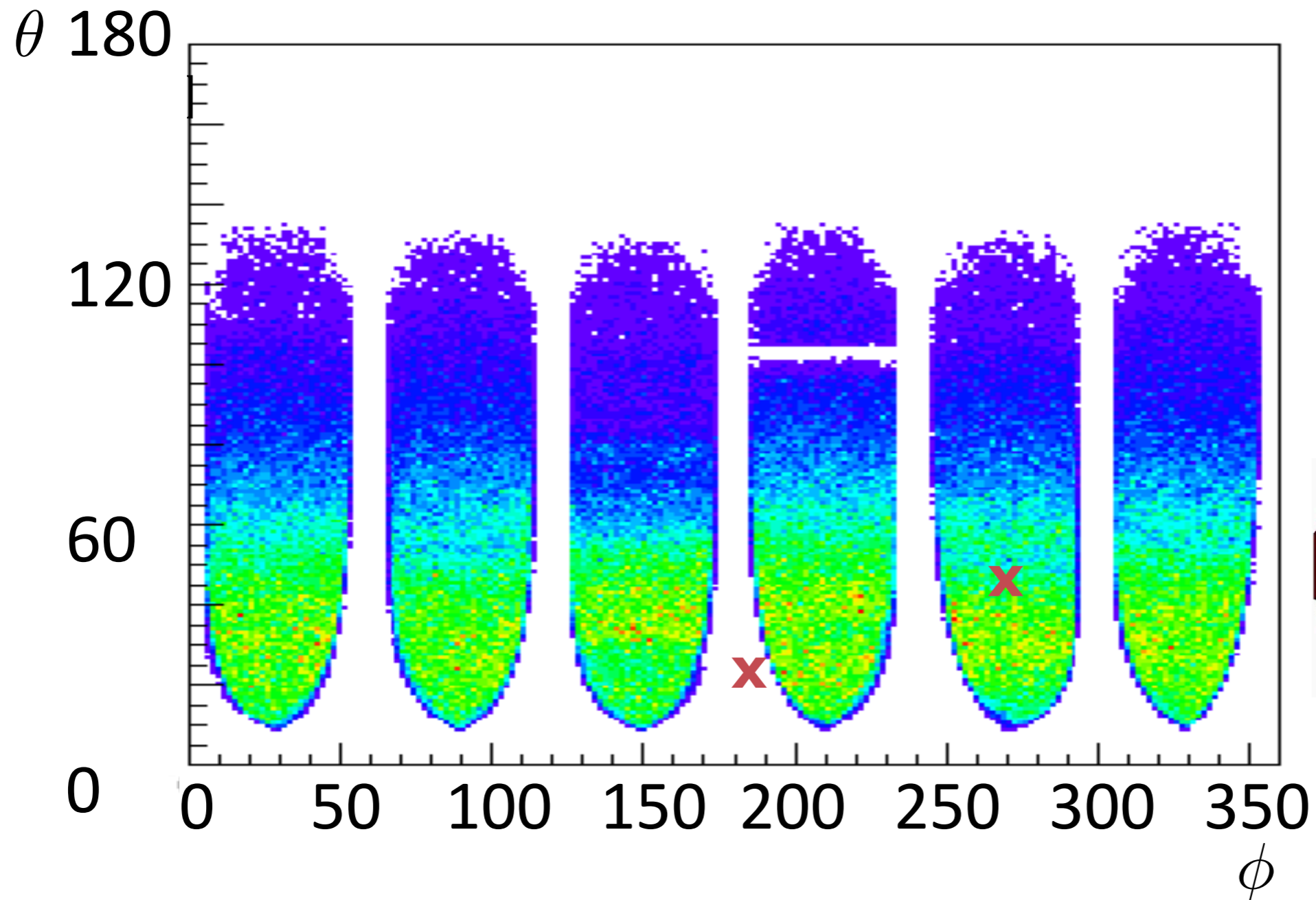
Gaps can make them loop like QE-like events with outgoing $1\mu 1p$



Background Subtraction

Different interaction lead to multi-hadron final states

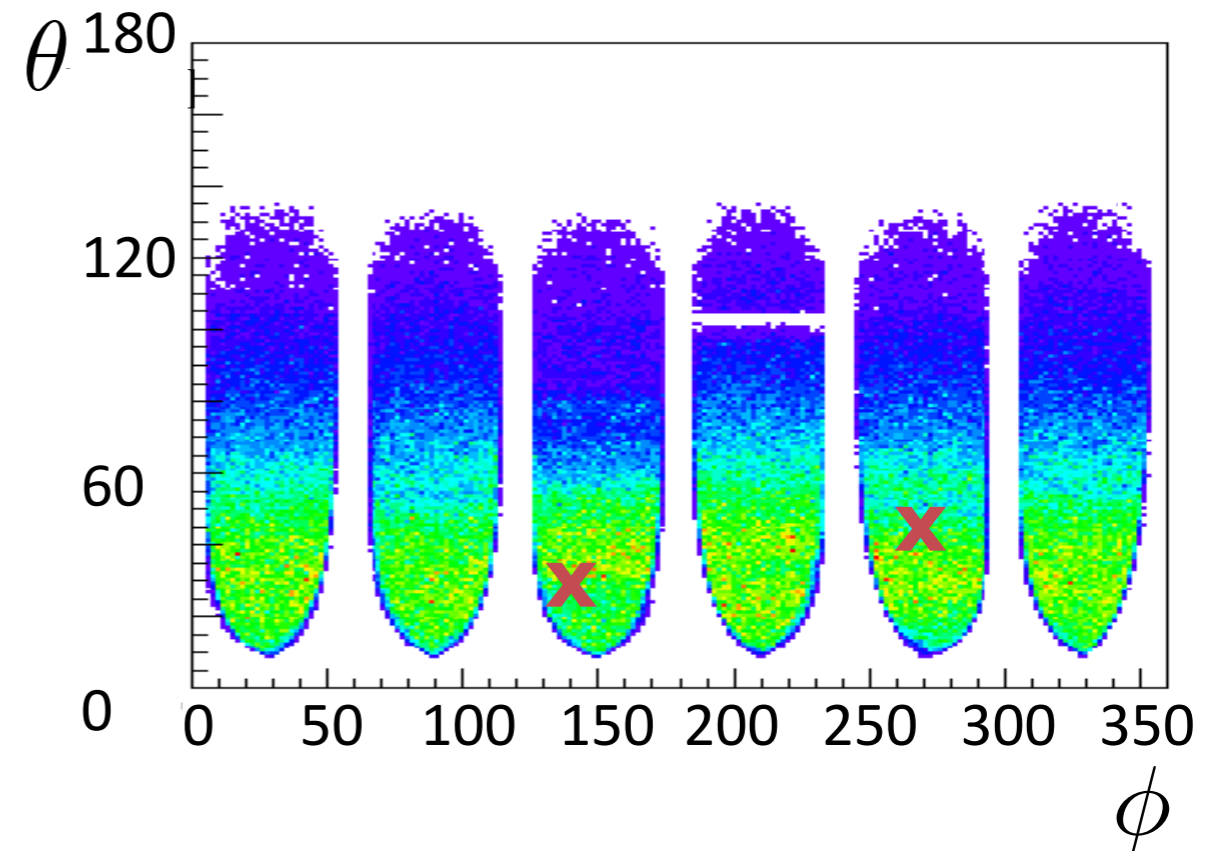
Gaps can make them loop like QE-like events with outgoing $1\mu 1p$



Data driven Background Subtraction

Using events with two detected hadrons

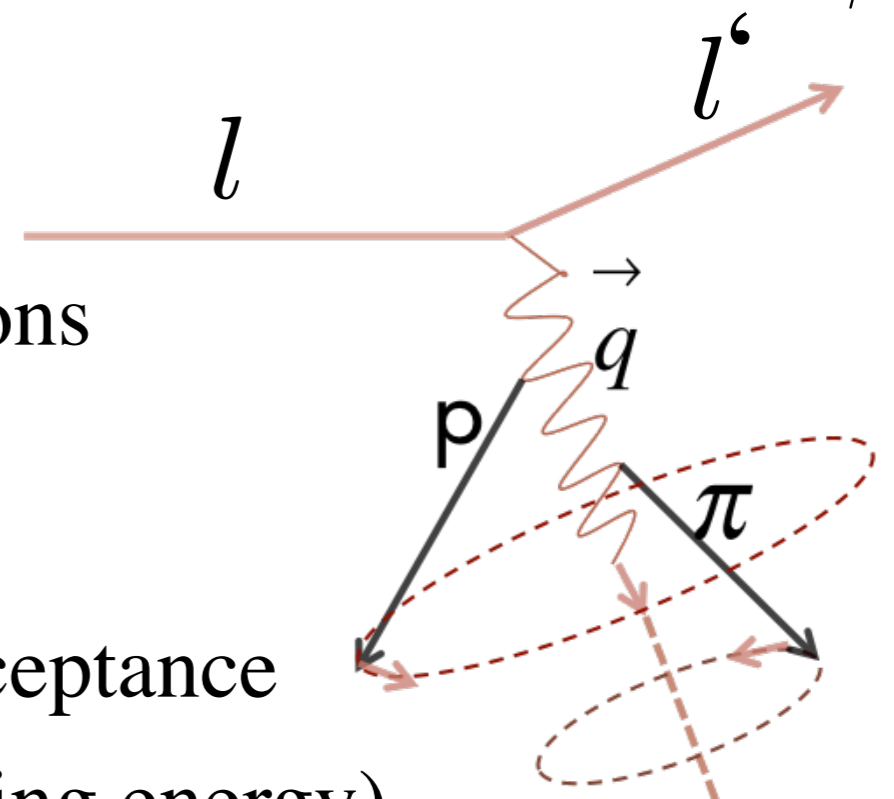
- Rotating p, π around q
- Determine event acceptance
- Subtract contribution to QE-like



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

