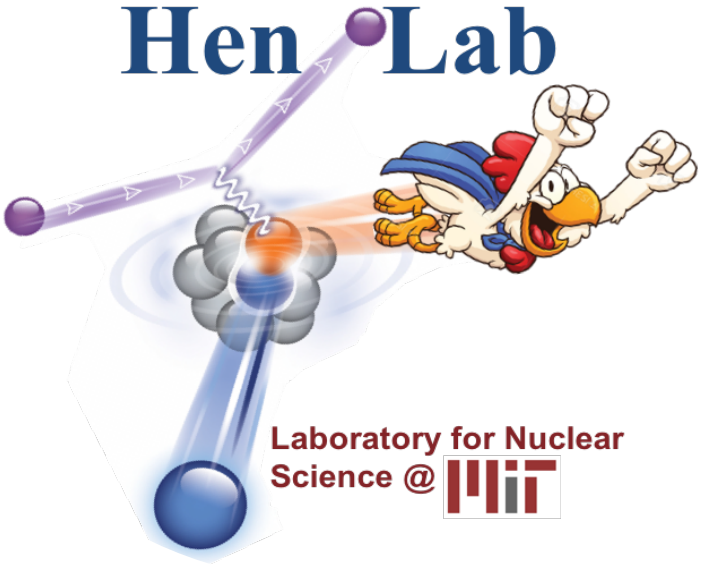
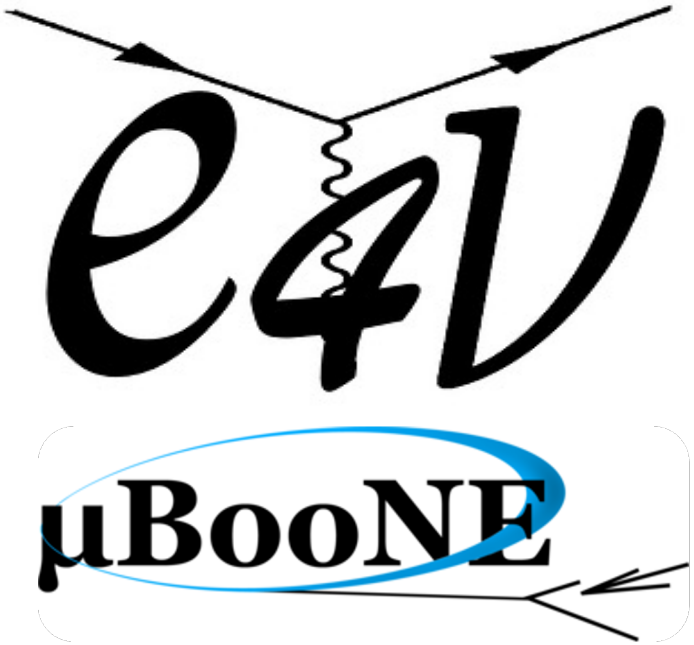
Electrons for Neutrinos: new results towards precision oscillation measurements

Or Hen (MIT)

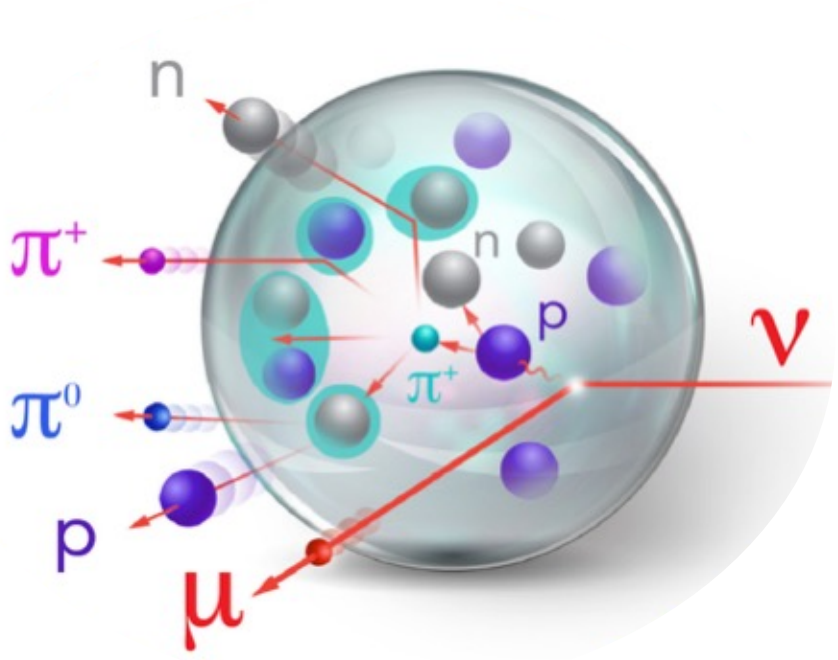




Measuring Oscillations

(/ Detecting Neutrinos)

Neutrinos are detected following their interaction with nuclei

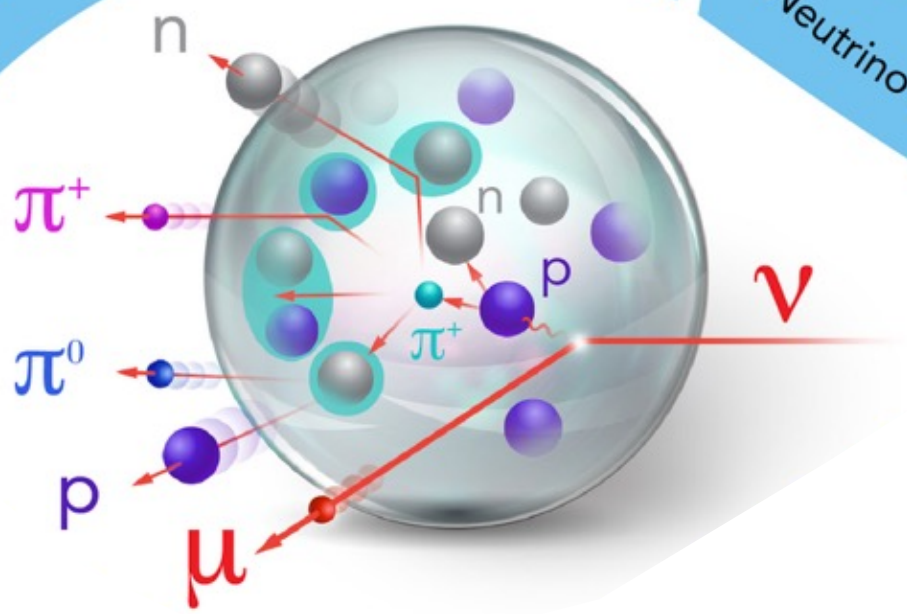


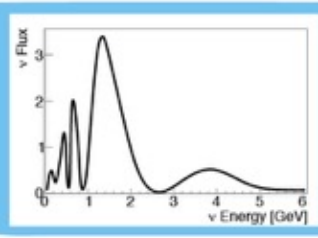
PHYSICS PROCESS

Particles shoot out

Interacts with the nucleus

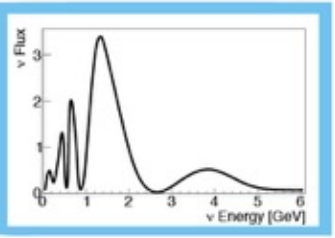
Neutrino comes in





PHYSICS PROCESS

Neutrino comes in



Interacts with the nucleus

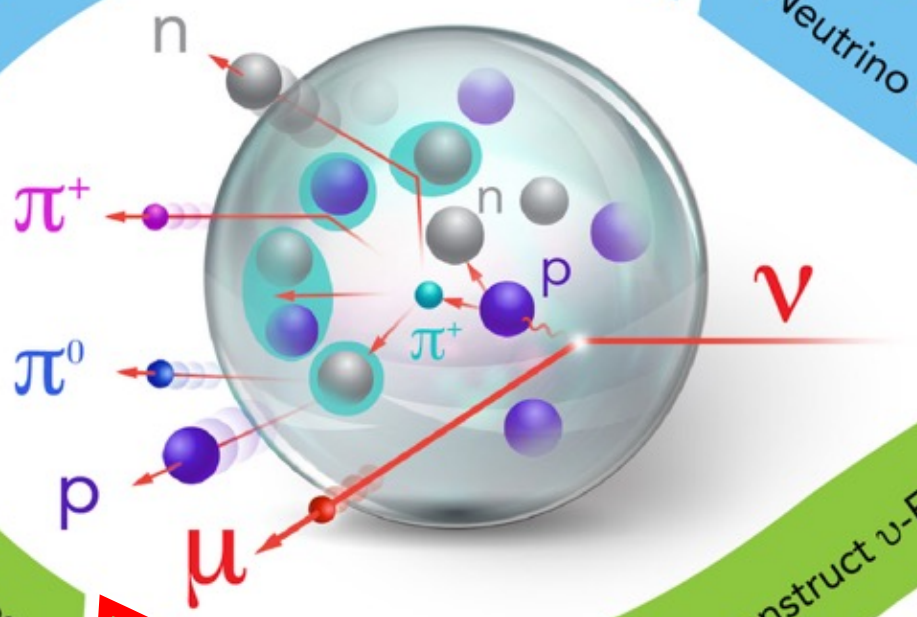
Particles shoot out

Measure Particles

Apply Interaction Model

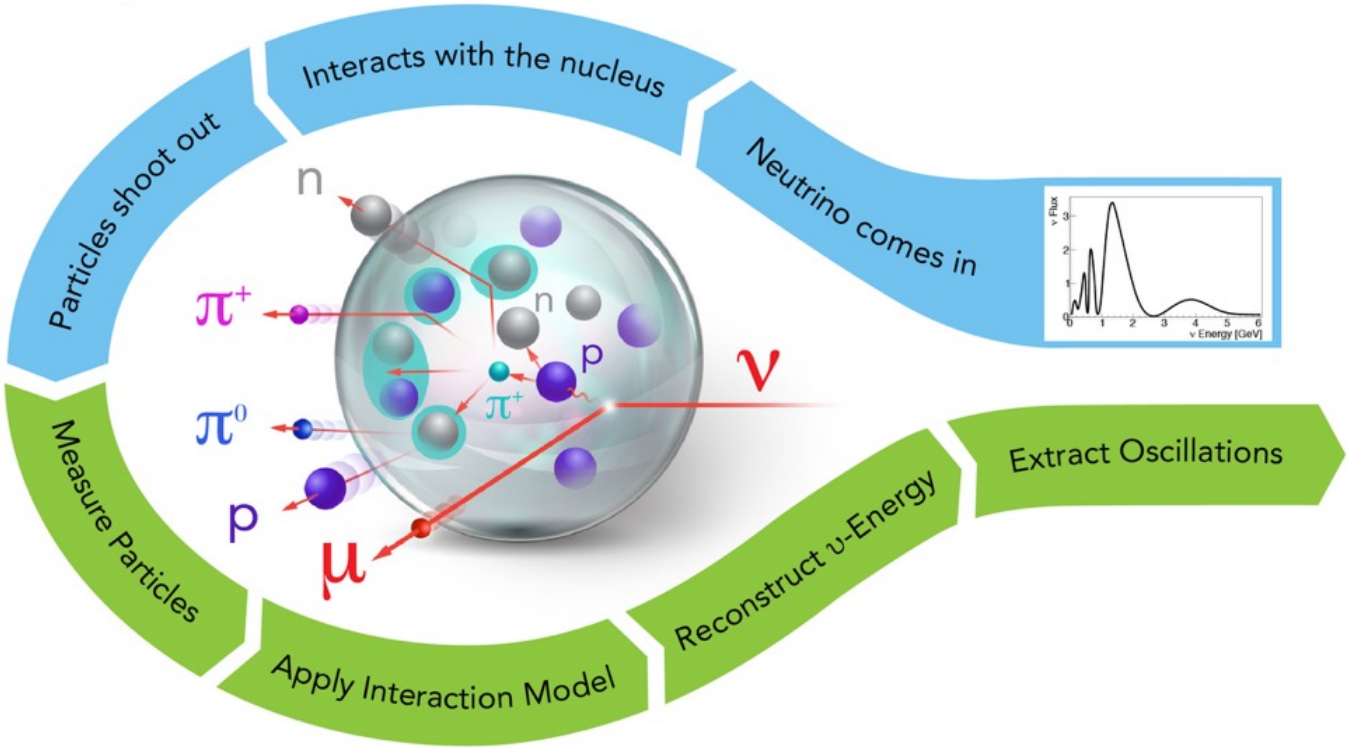
Reconstruct υ-Energy

Extract Oscillations



EXPERIMENTAL ANALYSIS

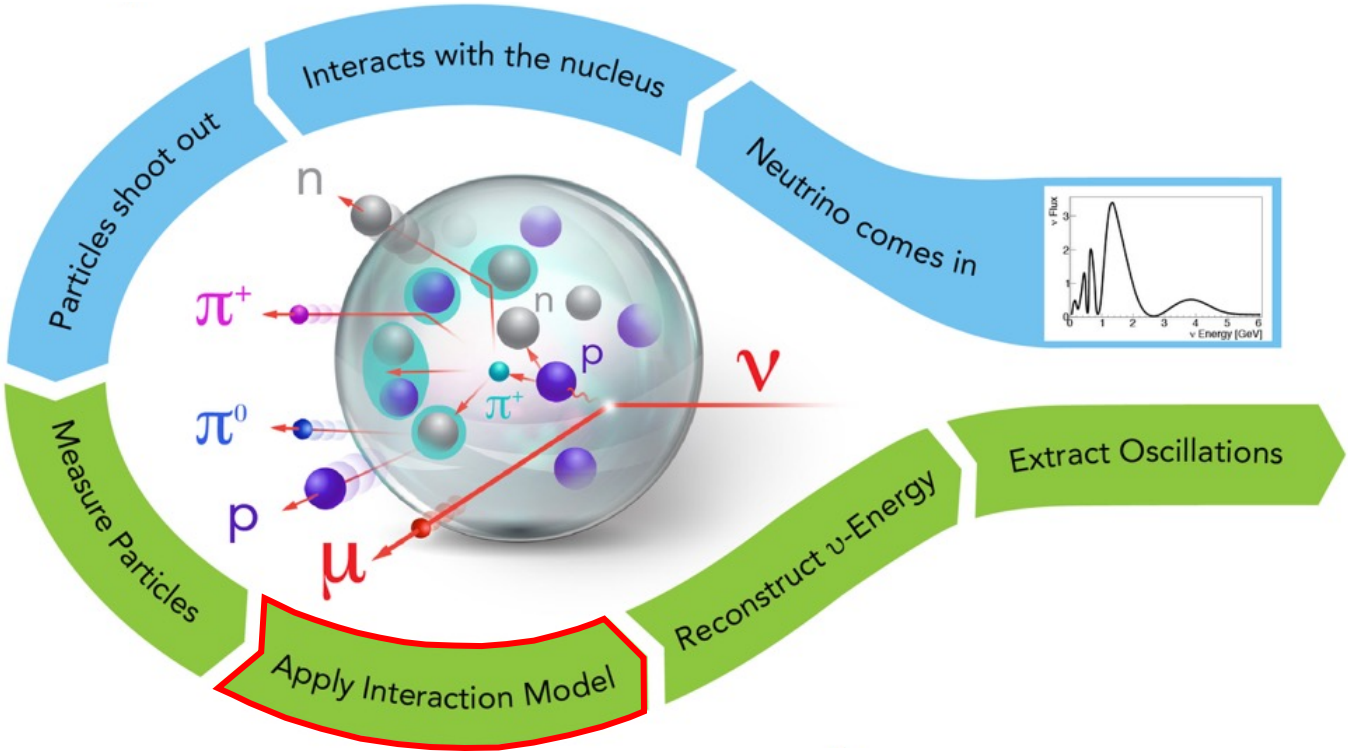
=> Experiments detect interaction and use theory to deconvolute the ν Flux.



=> Experiments detect interaction and use theory to deconvolute the ν Flux.

$$N_\alpha(E_{rec}, L) = \sum_i \int \Phi_\alpha(E, L)\sigma_i(E) f_{\sigma_i}(E, E_{rec}) dE$$

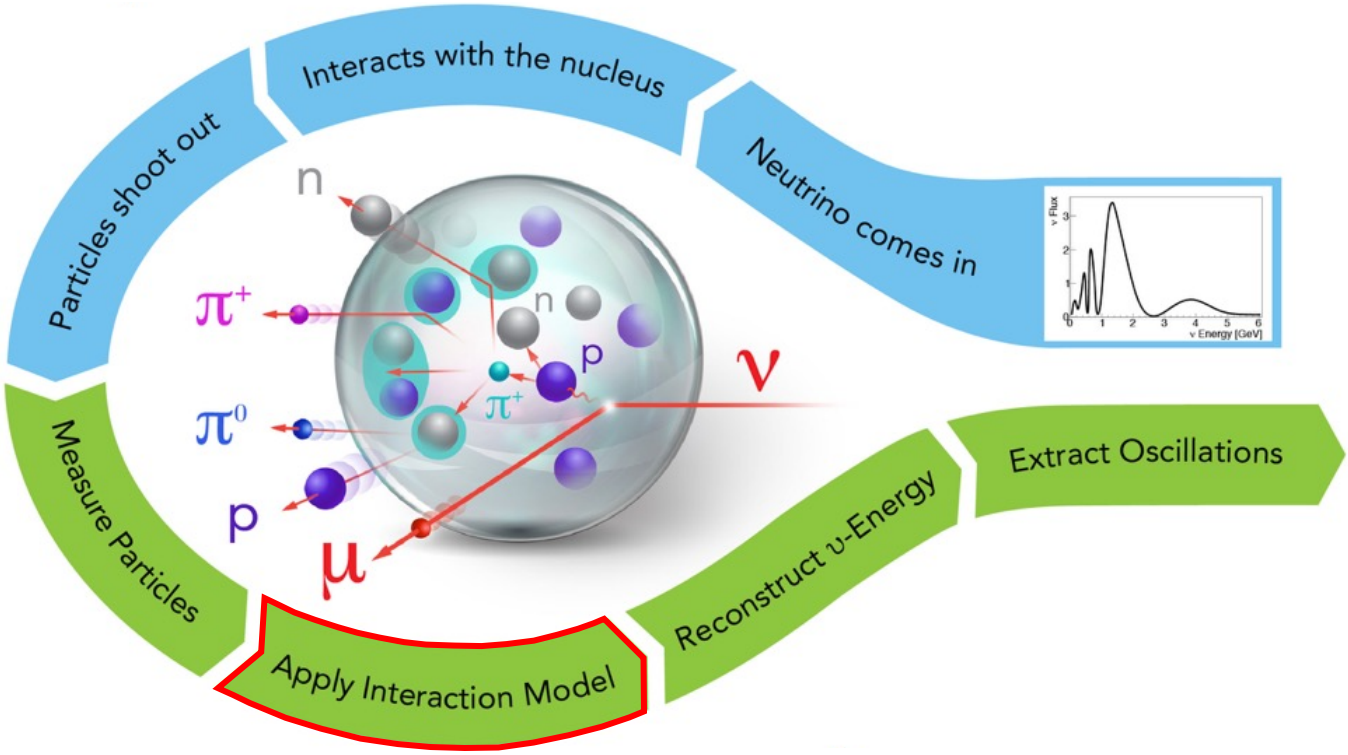
Measured



=> Experiments detect interaction and use theory to deconvolute the ν Flux.

$$N_\alpha(E_{rec}, L) = \sum_i \int \Phi_\alpha(E, L)\sigma_i(E) f_{\sigma_i}(E, E_{rec}) dE$$

Measured | Wanted | Theory Input



Constrain theory input?

No oscillations @ L=0:

➔ ϕ(E, L=0) known

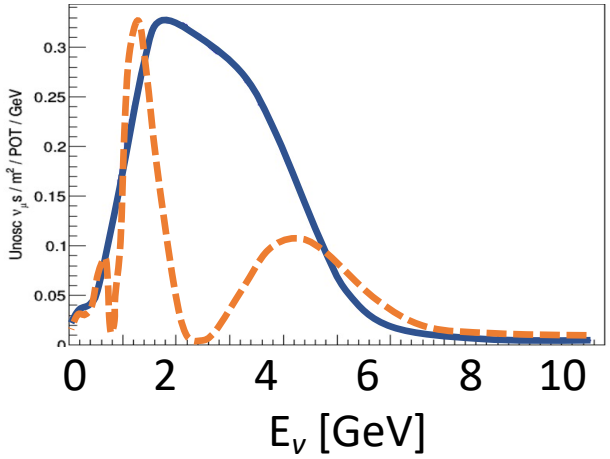
➔ using 'near detector' (@L=0) to constrain σ(E) & f_σ(E,E_{rec})

$$N_\alpha(E_{rec}, L) = \sum_i \int \Phi_\alpha(E, L)\sigma_i(E) f_{\sigma_i}(E, E_{rec}) dE$$

Measured — Wanted — Theory Input

Constrain theory input?

But… near detector offer integral constrain with a different flux from the far detector



$$N_\alpha(E_{rec}, L) = \sum_i \int \Phi_\alpha(E, L)\sigma_i(E)f_{\sigma_i}(E, E_{rec})dE$$

Measured — Wanted — Theory Input

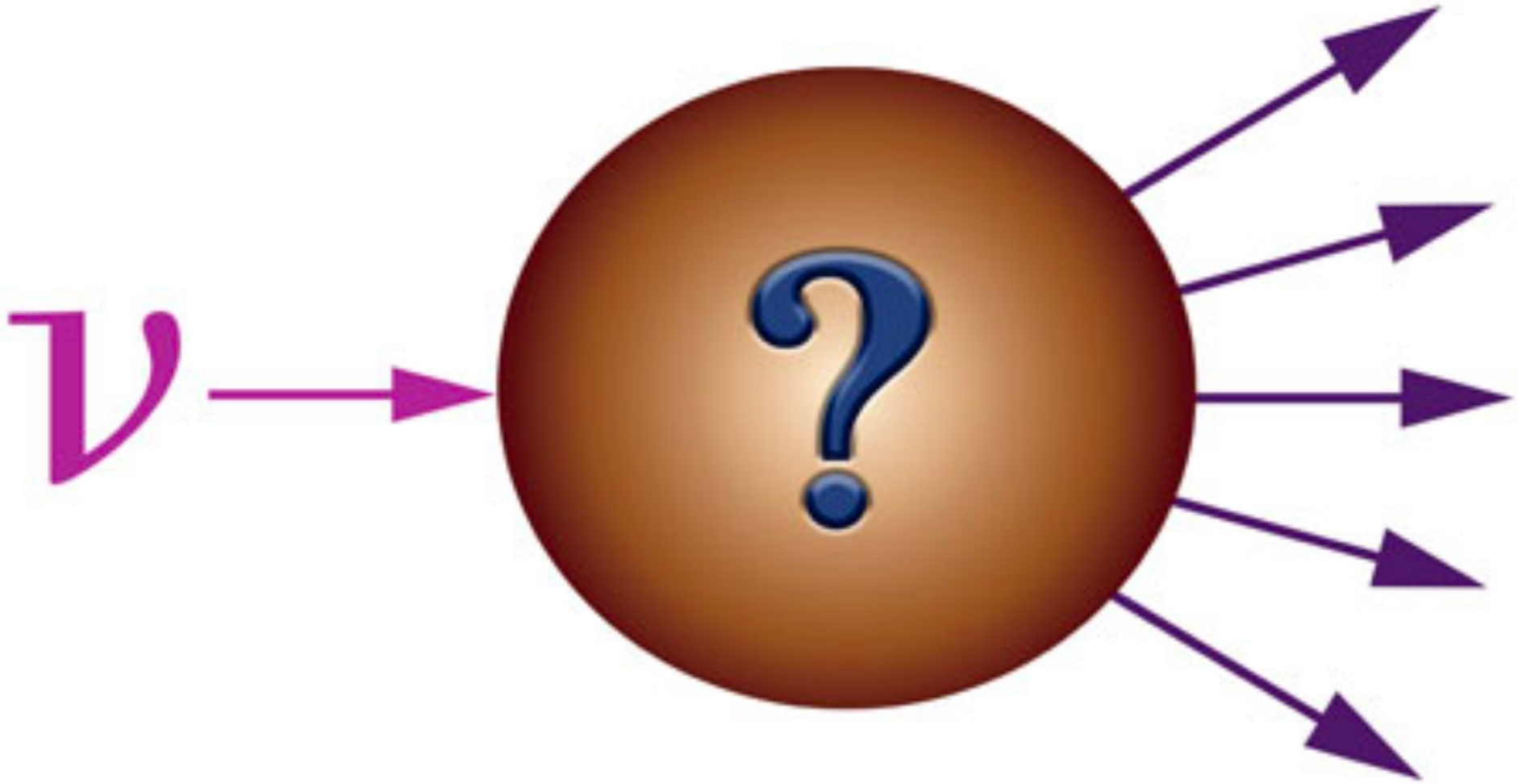
Interaction theory already main systematic!

TABLE III. Percentage change in the number of 1-ring neutrino mode and antineutrino mode μ-like events before the oscillation fit from 1σ systematic parameter variations, assuming the oscillation parameters $\sin^2 2\theta_{12} = 0.846$, $\sin^2 2\theta_{13} = 0.085$, $\sin^2 \theta_{23} = 0.528$, $\Delta m^2_{32} = 2.509 \times 10^{-3}$ eV^2/c^4, $\Delta m^2_{21} = 7.53 \times 10^{-5}$ eV^2/c^4, $\delta_{CP} = 0$ and normal hierarchy. The numbers in the parenthesis correspond to the number of parameters responsible for each group of systematic uncertainties.

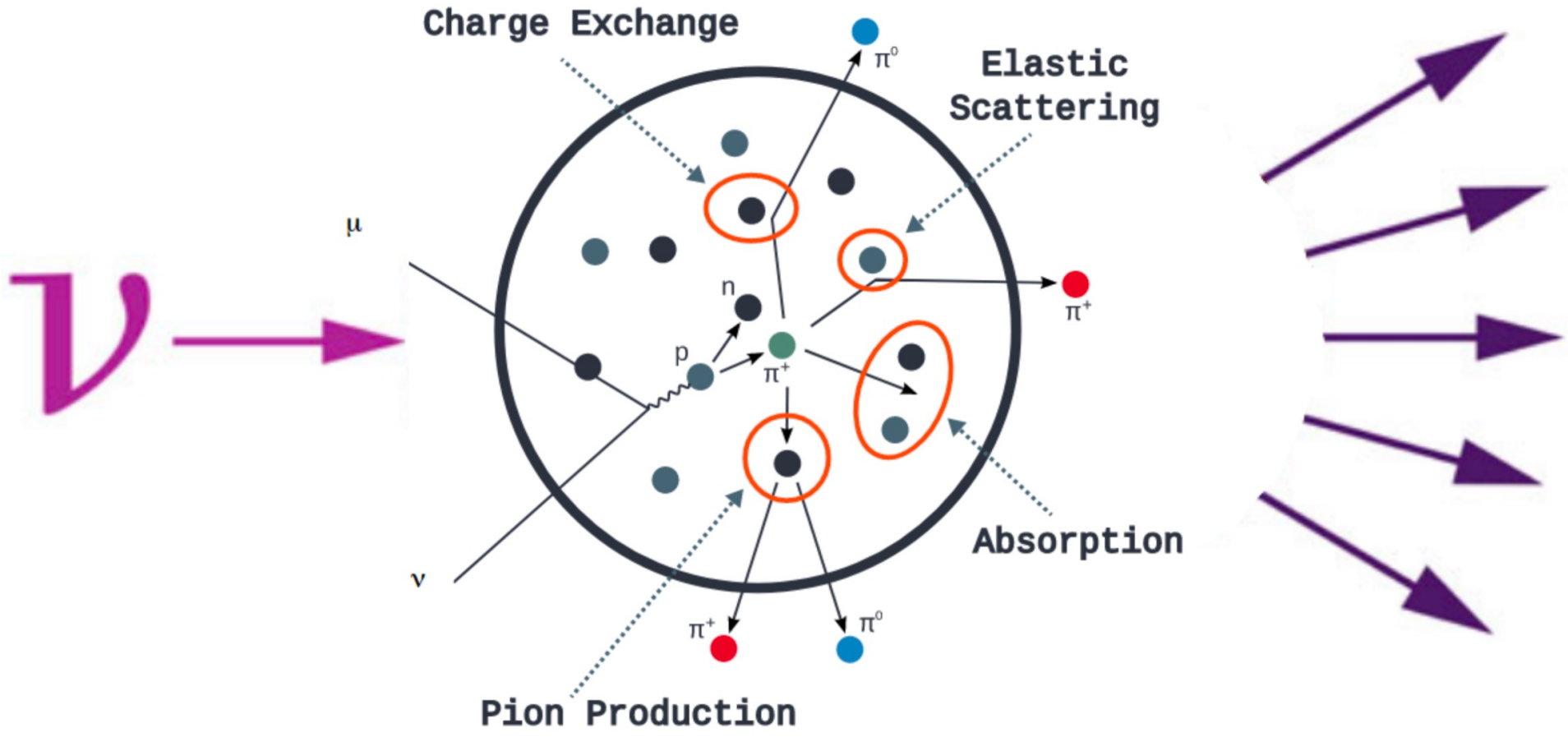
Source of uncertainty (number of parameters)	$\delta n^{\rm exp}_{\rm SK}/n^{\rm exp}_{\rm SK}$	
	neutrino mode	antineutrino mode
Flux+ ND280 constrained cross section (without ND280 fit result) (61)	10.81%	11.92%
Flux+ ND280 constrained cross section (using ND280 fit result) (61)	2.79%	3.26%
Flux+ all cross section (65)	2.90%	3.35%
Super-Kamiokande detector systematics (12)	3.86%	3.31%
Pion FSI and re-interactions (12)	1.48%	2.06%
Total (using ND280 fit result) (77)	5.06%	5.19%

T2K 2017, 18’

Why? Nuclear Interactions Are Complex!



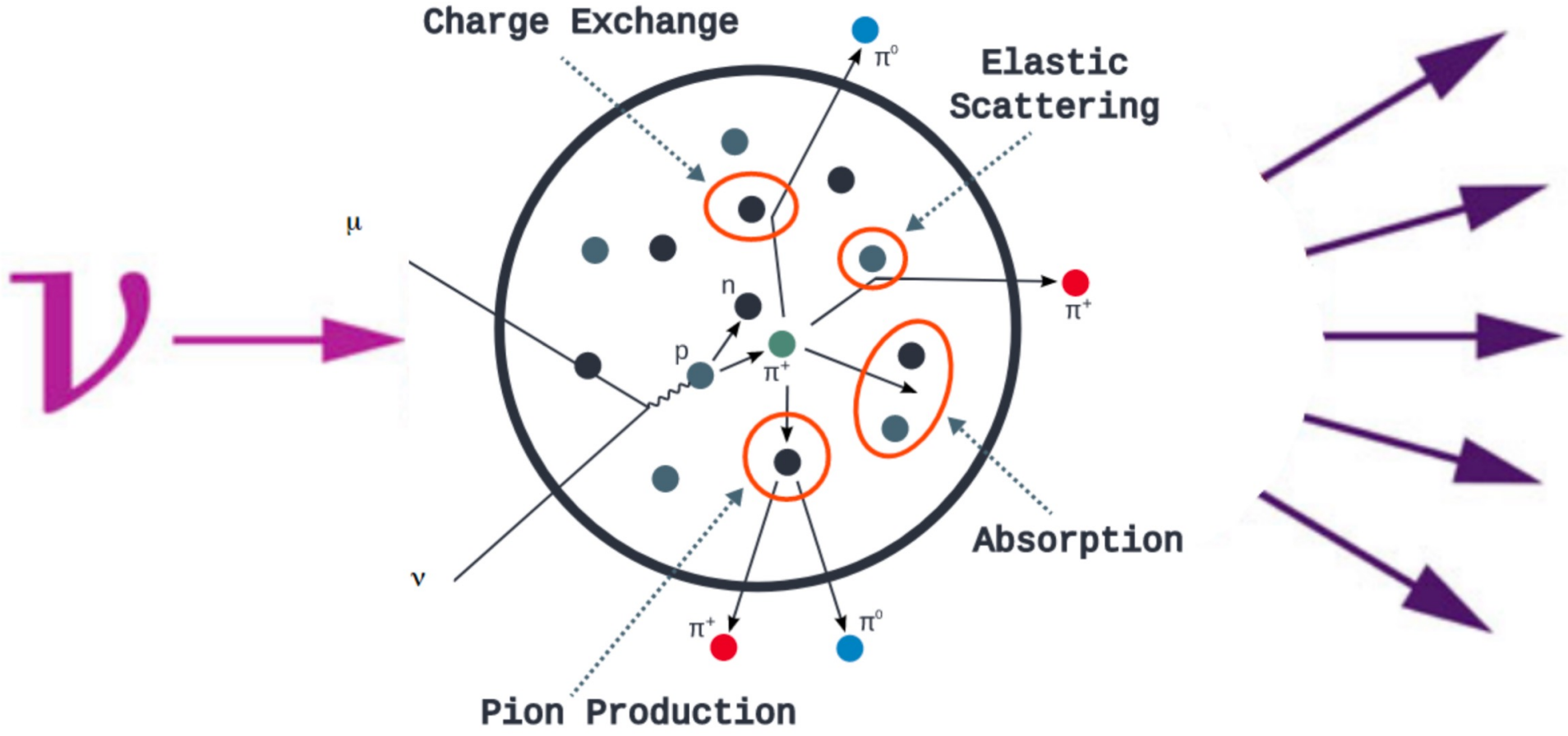
Why? Nuclear Interactions Are Complex!



Current event-generator models are often:

Effective. Often Empirical. Semi-Classical (no interference)

=> MUST TUNE TO DATA!



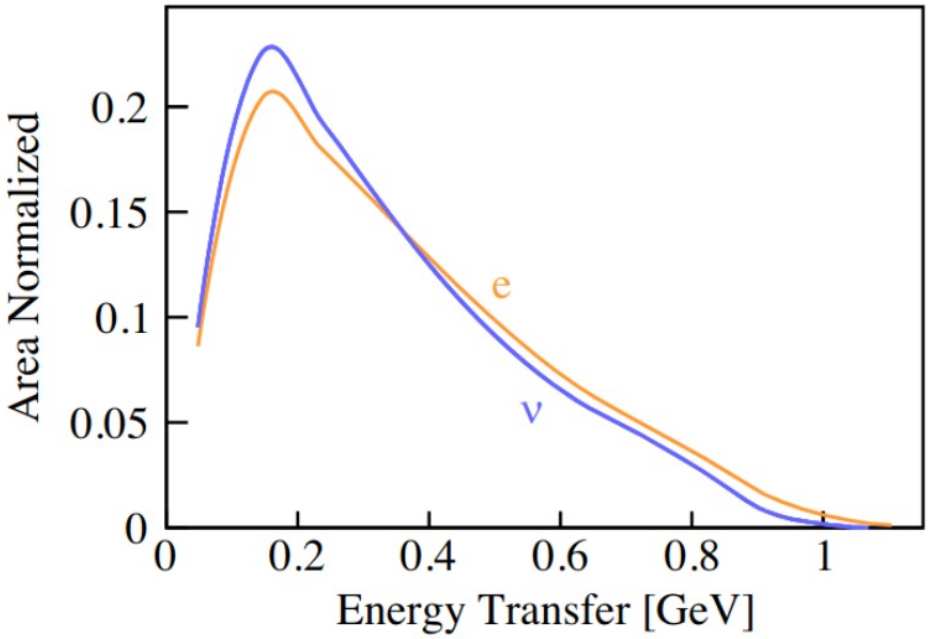
Constrain Using Electron Scattering!

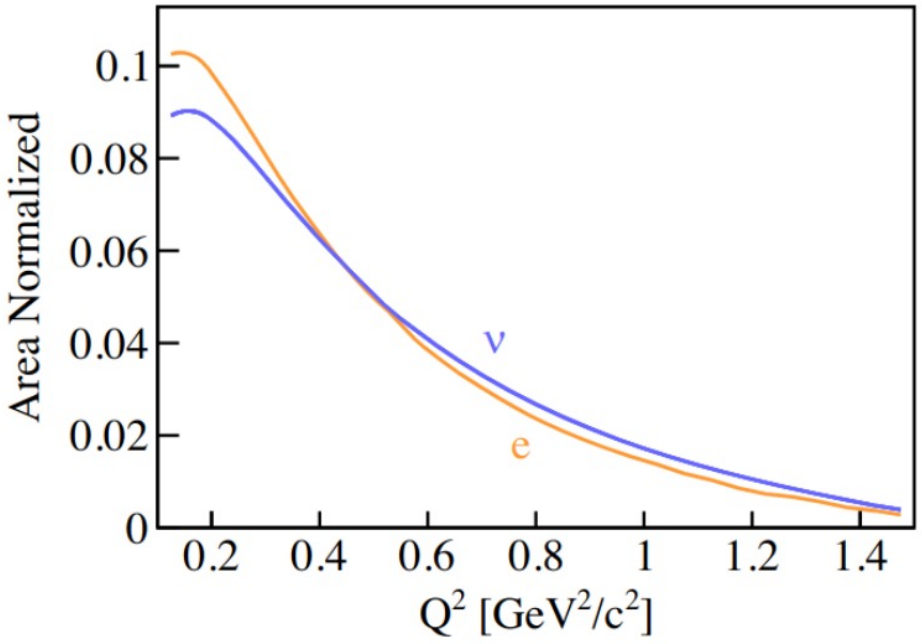
- e & ν interact similarly.
- Many nuclear effects identical (FSI, multi-N effects, …).
- e beam energy is known
- Test ν event generators by running in e-mode (turn off axial response).

Constrain Using Electron Scattering!

- ✓ e & ν interact similarly.
- Many nuclear effects identical (FSI, multi-N effects, …).
- e beam energy is known
- Test ν event generators by running in e-mode (turn off axial response).

e & ν interact similarly





2.26 GeV on ^{12}C.

$1p0\pi$ events,
$\theta_{lepton} > 15^{\circ}$.

Papadopoulou and Ashkenazi et al (e4ν collaboration) Phys. Rev. D **103**, 113003 (2021).

Constrain Using Electron Scattering!

- ✓ e & ν interact similarly.
- ✓ Many nuclear effects identical (FSI, multi-N effects, …)
- e beam energy is known
- Test ν event generators by running in e-mode (turn off axial response).

Constrain Using Electron Scattering!

- ✓ e & ν interact similarly.
- ✓ Many nuclear effects identical (FSI, multi-N effects, …)
- ✓ e beam energy is known
- Test ν event generators by running in e-mode (turn off axial response).

Constrain Using Electron Scattering!

- ✓ e & ν interact similarly.
- ✓ Many nuclear effects identical (FSI, multi-N effects, …)
- ✓ e beam energy is known

➔ Test ν event generators by running in e-mode (turn off axial response).

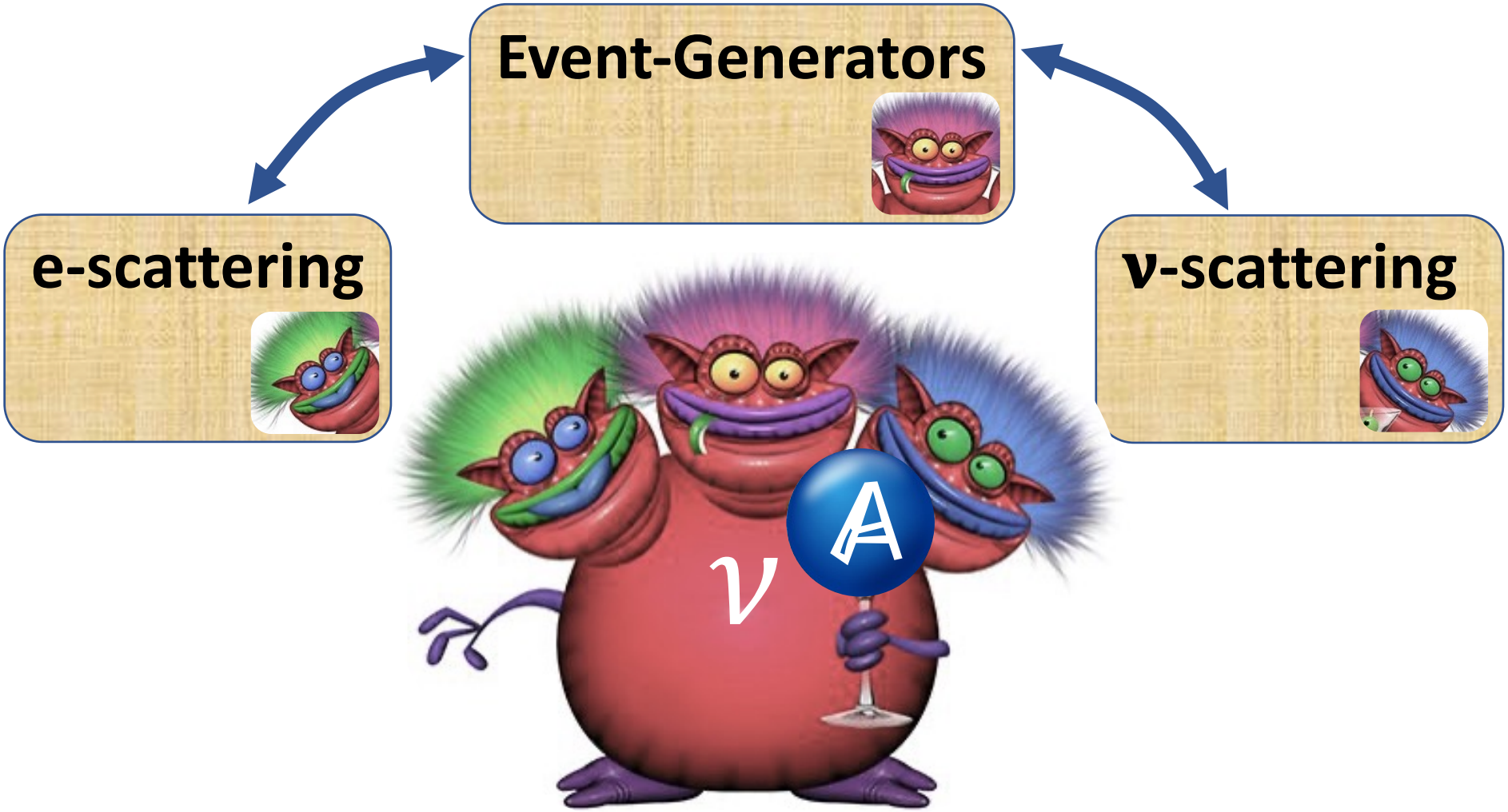
Constrain Using Electron Scattering!

Any model must work for electrons,
or it won't work for neutrinos !

- ✓ e
- ✓ Many nuclear effects identical
  (FSI, multi-N effects, …)
- ✓ e beam energy is known

➔ Test ν event generators by running in e-mode
(turn off axial response).

Attacking the Monster From All Sides

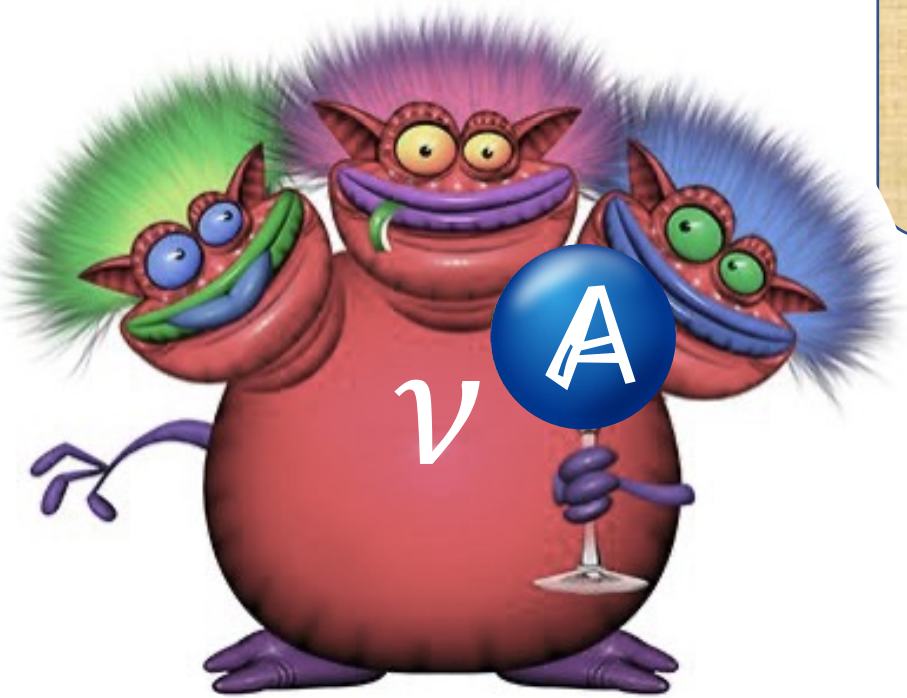


Attacking the Monster From All Sides

Event-Generators

e-scattering

ν-scattering



Monochromatic e^-:

- Vector currents
- Nuclear FSI
- Ground state
- …

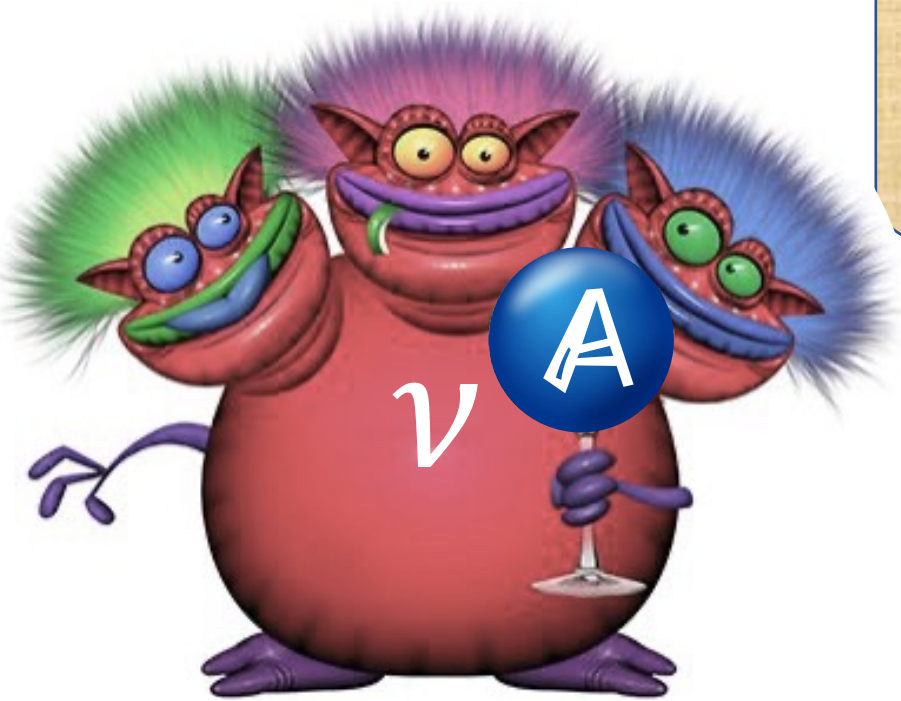
Attacking the Monster From All Sides

Event-Generators

e-scattering

Monochromatic e^-:

- Vector currents
- Nuclear FSI
- Ground state
- …



ν-scattering

ν near-detector:

- Axial & Vector-Axial currents
- Ultra-low Q^2
- …

Attacking the Monster From All Sides

Event-Generators

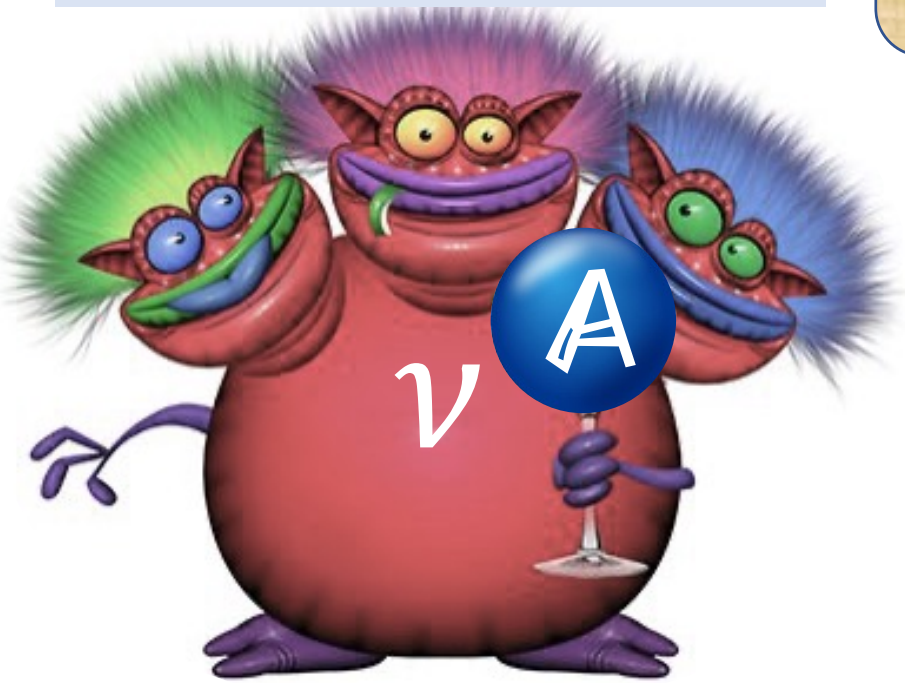
e-scattering

ν-scattering

Must reproduce e^- & ν data to extract oscillation parameters.

Monochromatic e^-:

- Vector currents
- Nuclear FSI
- Ground state
- …



ν near-detector:

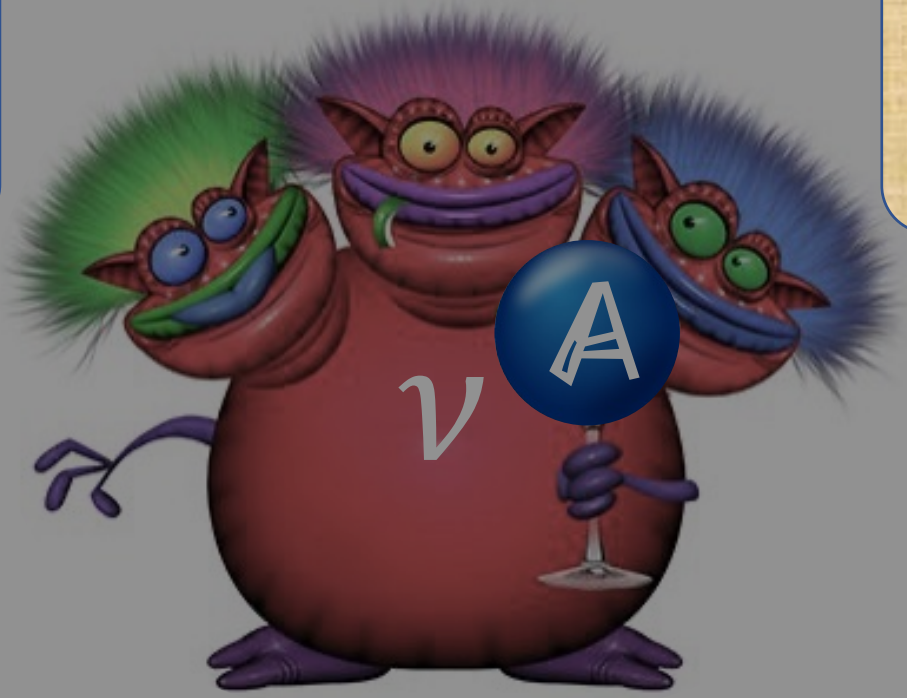
- Axial & Vector-Axial currents
- Ultra-low Q^2
- …

New Paradigm for *Precision* Oscillation Studies

Event-Generators

e-scattering

ν-scattering



“We’ve been throwing electrons at nuclei for over 40 years – why new data?”

General situation: lots of data, mostly irrelevant:

- A(e,e’): measured extensively; well described by scaling.
- A(e,e’p): measured primarily around the QE peak. Usually reported as ratio to theory.
- A(e,e’n), A(e,e’NN): Sparse data, especially @ GeV energies.
- Resonance production: lacking systematic data on nuclei and at large multiplicities.

“We’ve been throwing electrons at nuclei for over 40 years – why new data?”

General situation: lots of data, mostly irrelevant:

- A(e,e’): measured extensively; well described by scaling.
- A(e,e’p): measured primarily around the QE peak. Usually reported as ratio to theory.
- A(e,e’n), A(e,e’NN): Sparse data, especially @ GeV energies.
- Resonance production: lacking systematic data on nuclei and at large multiplicities.

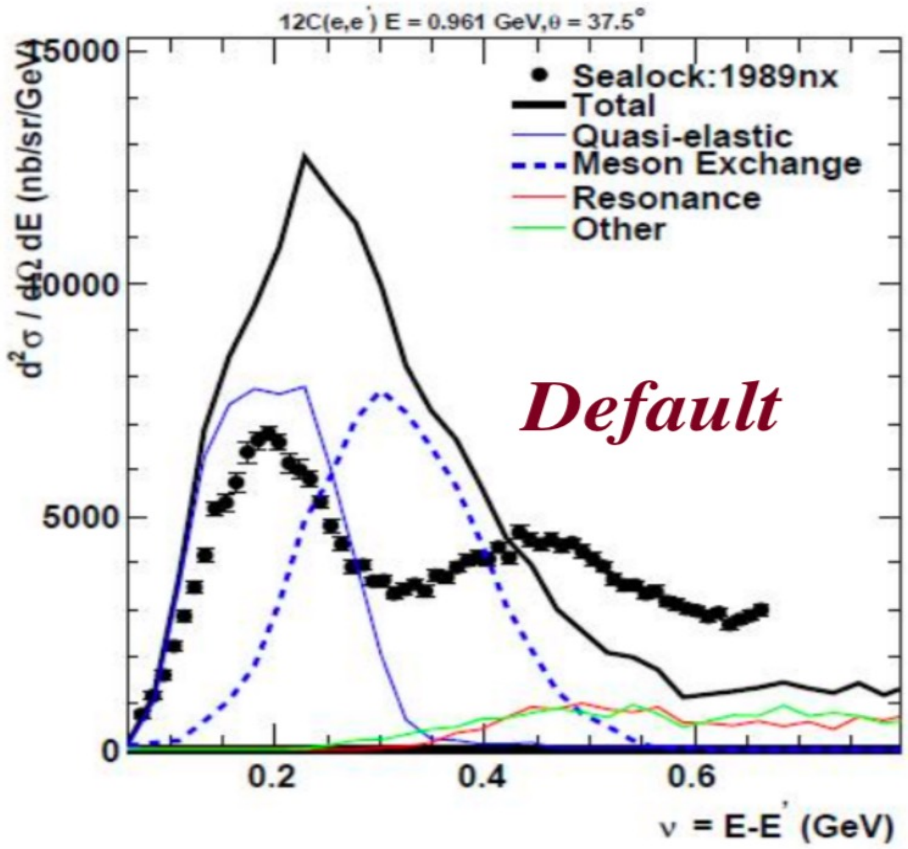
"We've been throwing electrons at nuclei for over 40 years – why new data?"

General situation: lots of data, mostly irrelevant:

- A(e,e'): measured extensively; overall well understood.
- A(e,e'p): measured primarily around the QE peak. Usually reported as ratio to theory.
- A(e,e'n), A(e,e'NN): Sparse data, especially @ GeV energies.
- Resonance production: lacking systematic data on nuclei and at large multiplicities.

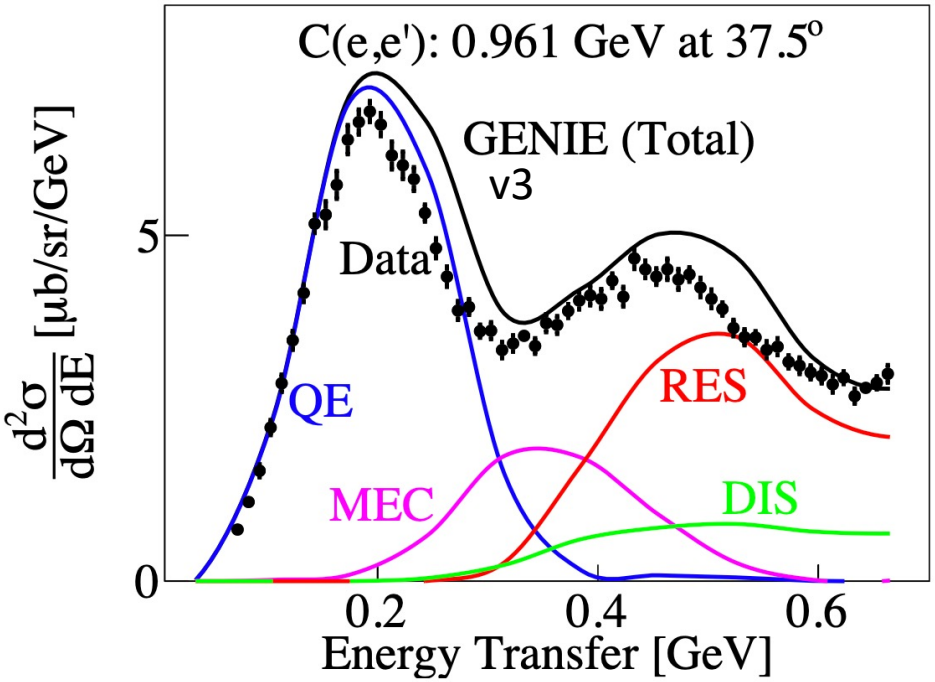
Generator vs. (e,e’)

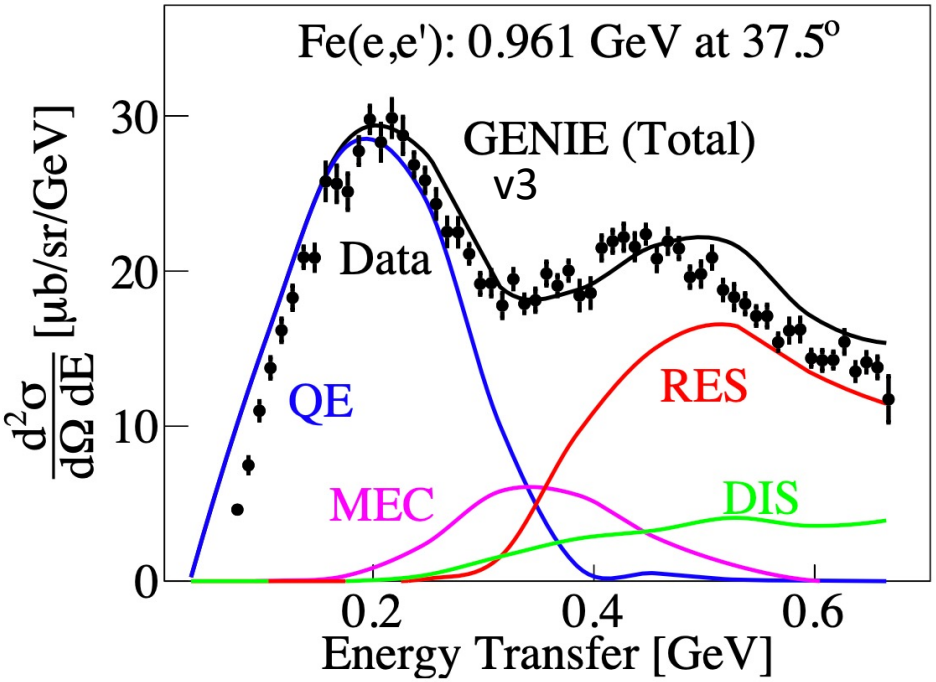
When we started…



Generator vs. (e,e’)

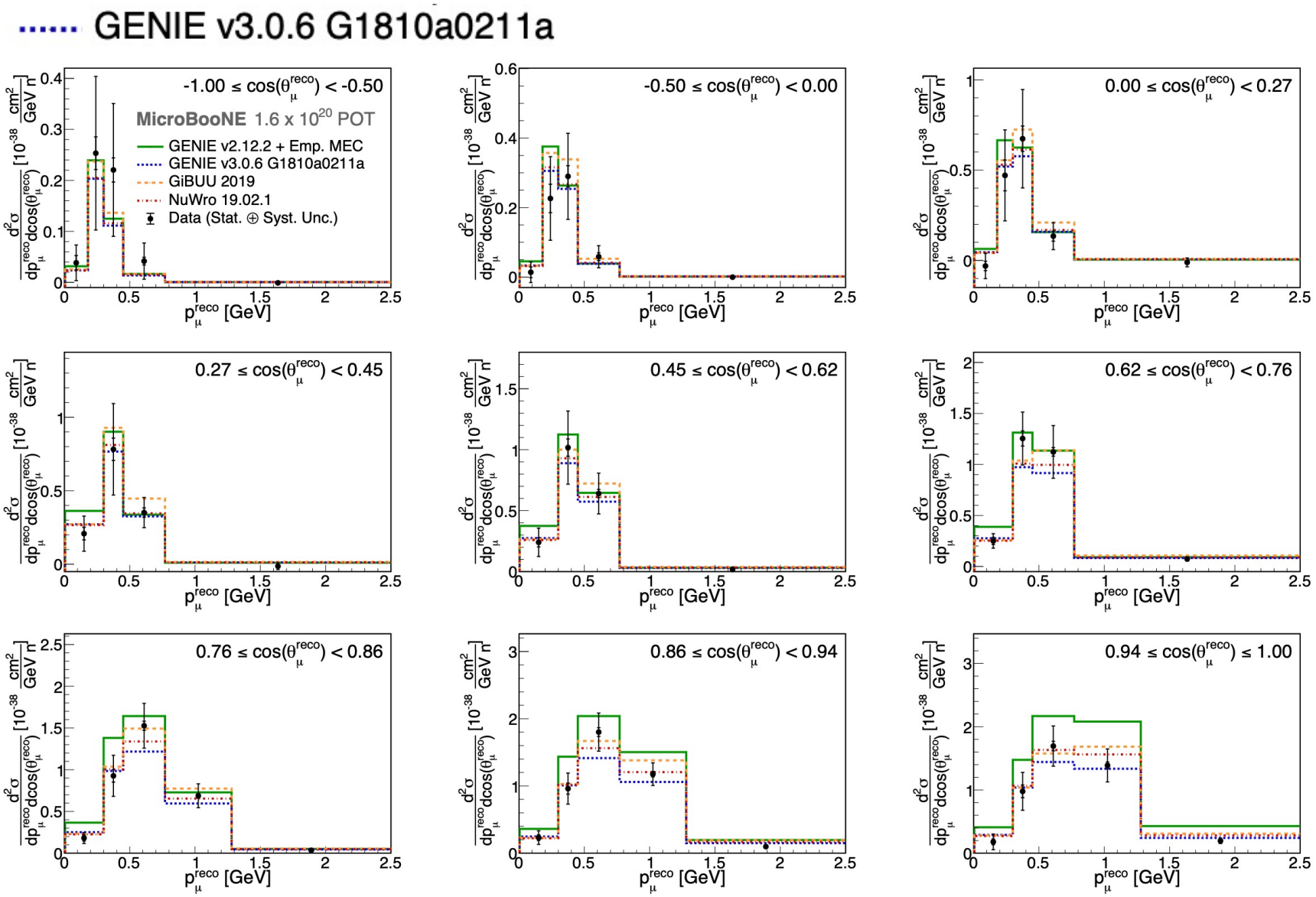
…Today





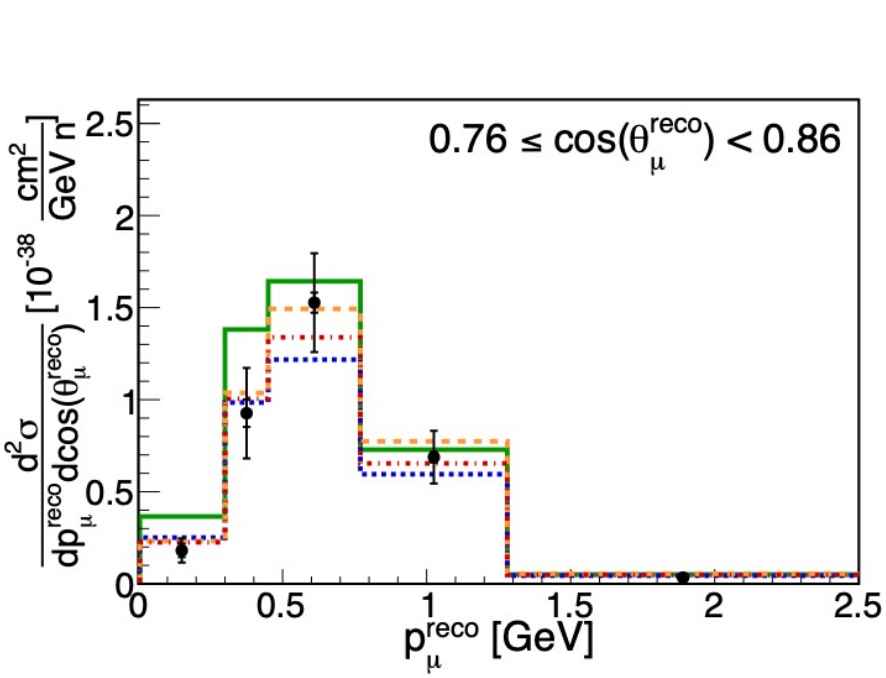
Papadopoulou and Ashkenazi et al (e4v collaboration) Phys. Rev. D **103**, 113003 (2021).

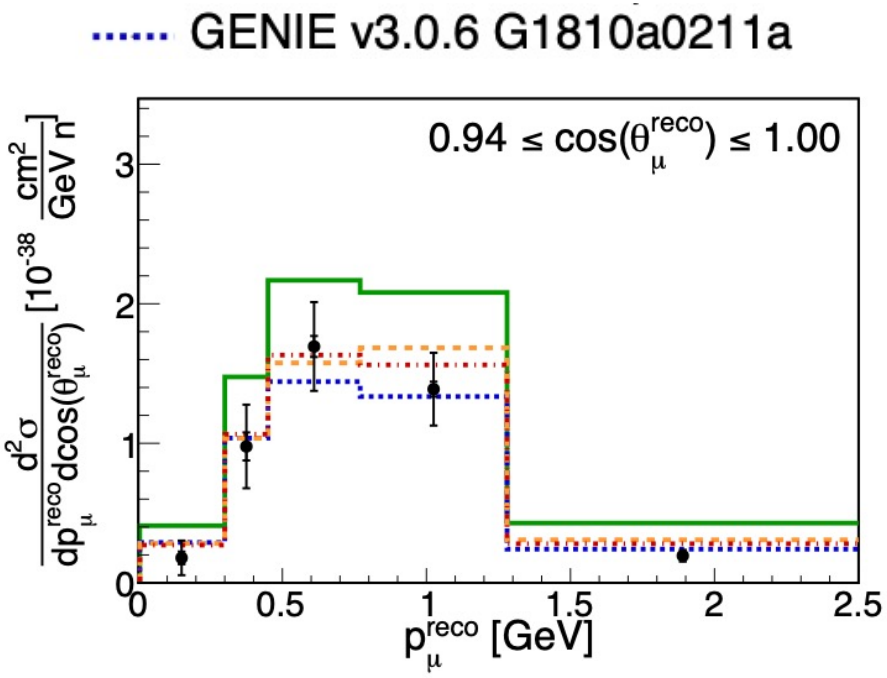
Also works for inclusive ν



MicroBooNE PRL **123**, 131801 (2019)

Also works for inclusive ν





MicroBooNE PRL **123**, 131801 (2019)

"We've been throwing electrons at nuclei for over 40 years – why new data?"

General situation: lots of data, mostly irrelevant:

- A(e,e'): measured extensively; well described by scaling.
- A(e,e'p): measured primarily around the QE peak. Usually reported as ratio to theory.
- A(e,e'n), A(e,e'NN): Sparse data, especially @ GeV energies.
- Resonance production: lacking systematic data on nuclei and at large multiplicities.

"We've been throwing electrons at nuclei for over 40 years – why new data?"

General situation: lots of data, mostly irrelevant:

- A(e,e'): measured extensively; well described by scaling.
- A(e,e'p): measured primarily around the QE peak. Usually reported as ratio to theory.
- A(e,e'n), A(e,e'NN): Sparse data, especially @ GeV energies.
- Resonance production: lacking systematic data on nuclei and at large multiplicities.

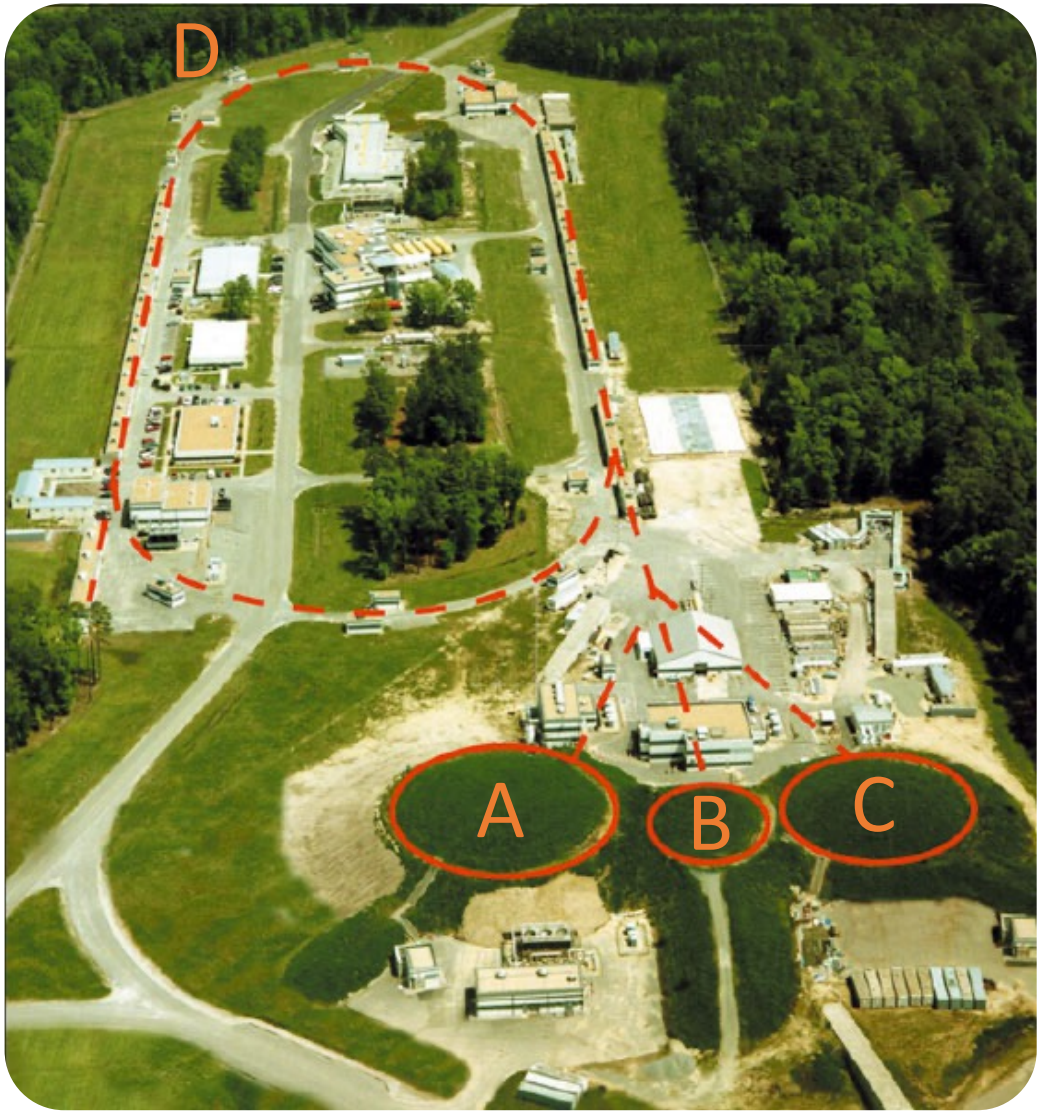
"We've been throwing electrons at nuclei for over 40 years – why new data?"

General situation: lots of data, mostly irrelevant:

- A(e,e'): measured extensively; well described by scaling.
- A(e,e'p): measured primarily around the QE peak. Usually reported as ratio to theory.
- A(e,e'n), A(e,e'NN): Sparse data, especially @ GeV energies.
- Resonance production: lacking systematic data on nuclei and at large multiplicities.

Need New Exclusive Data!

New Old Data!

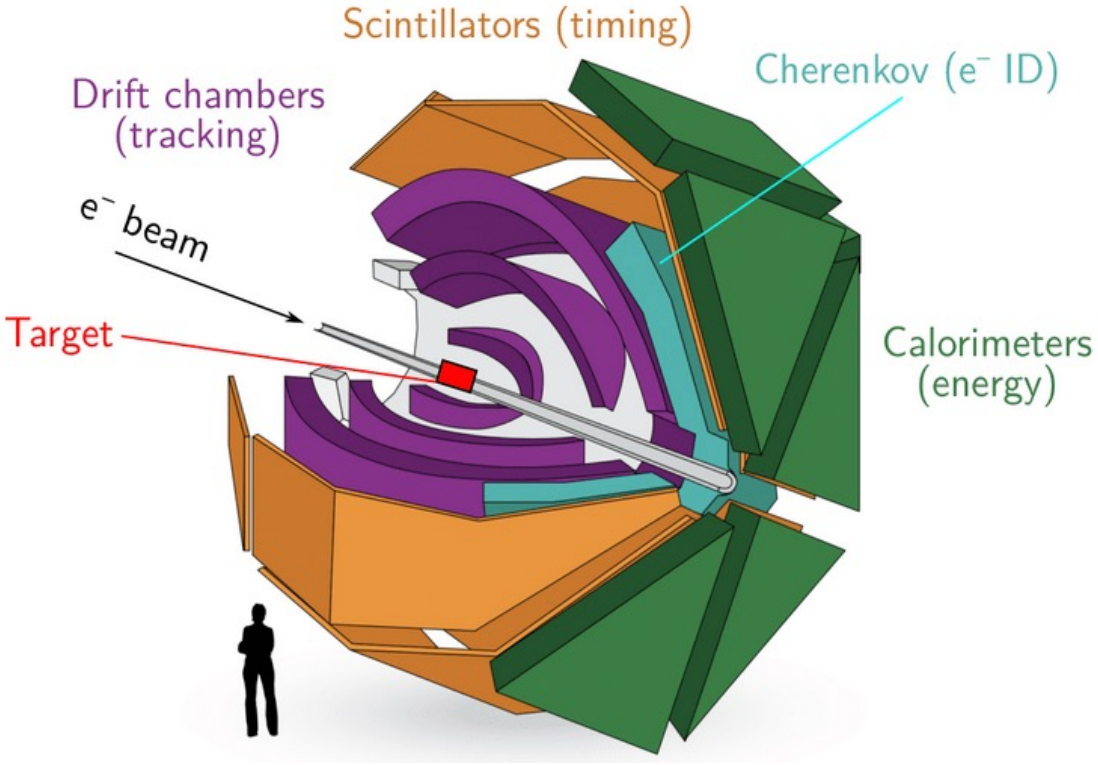


CLAS-6

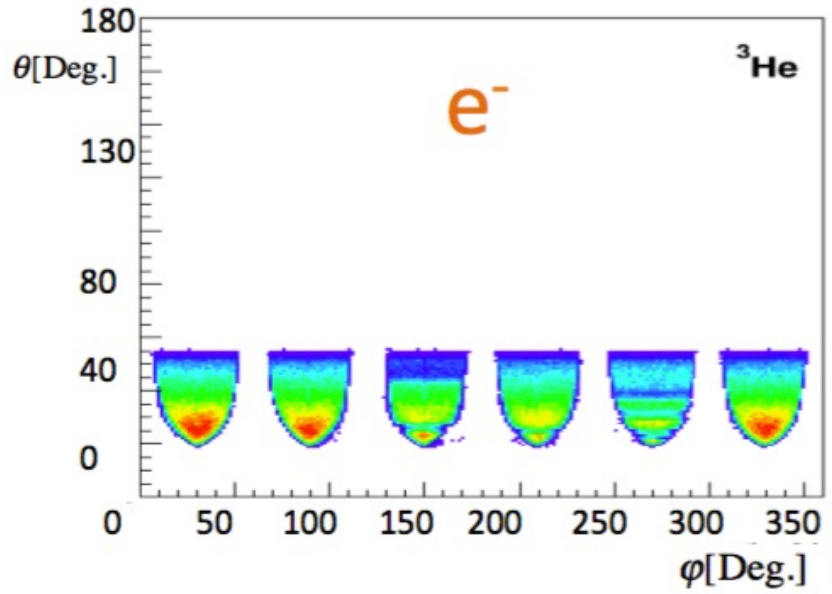
✧ ~4π acceptance (almost).

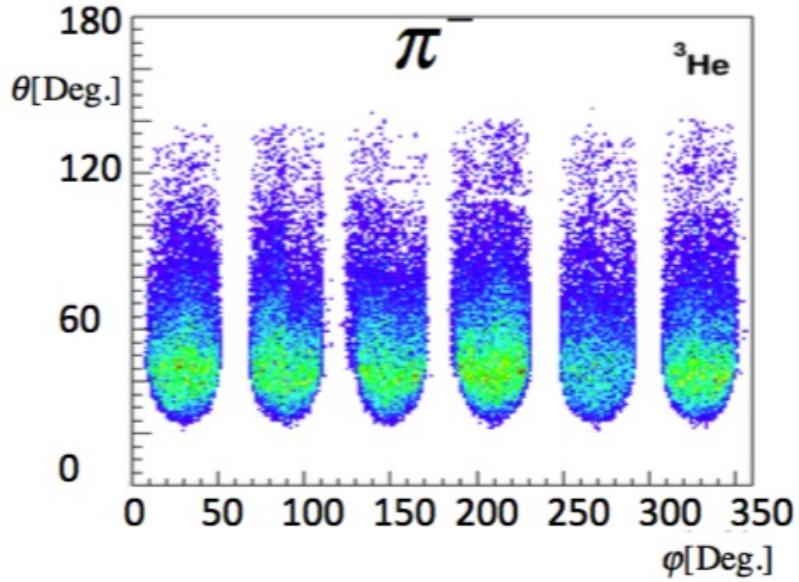
✧ Charged particles (8-143^o):
- P_p>300 MeV/c
- P_π >150 MeV/c

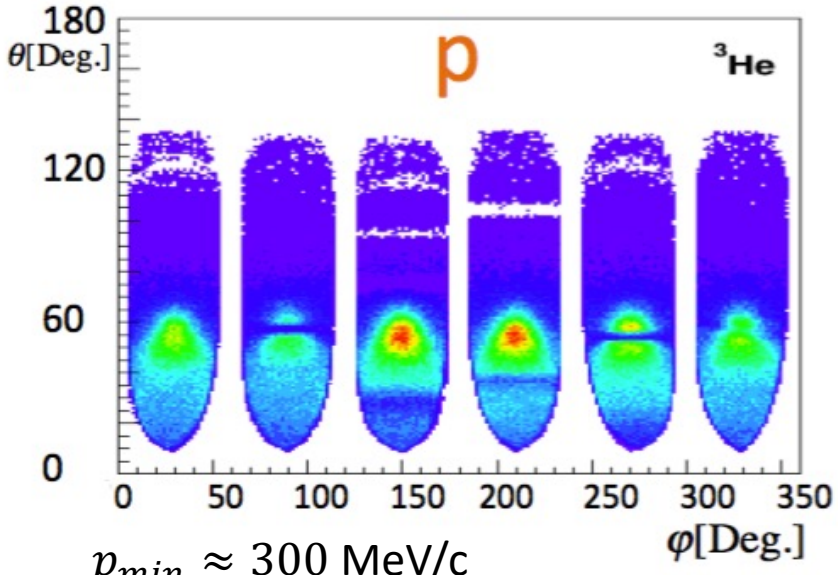
✧ Neutral particles:
- EM calorimeter (8-75^o)
- TOF (8-143^o)



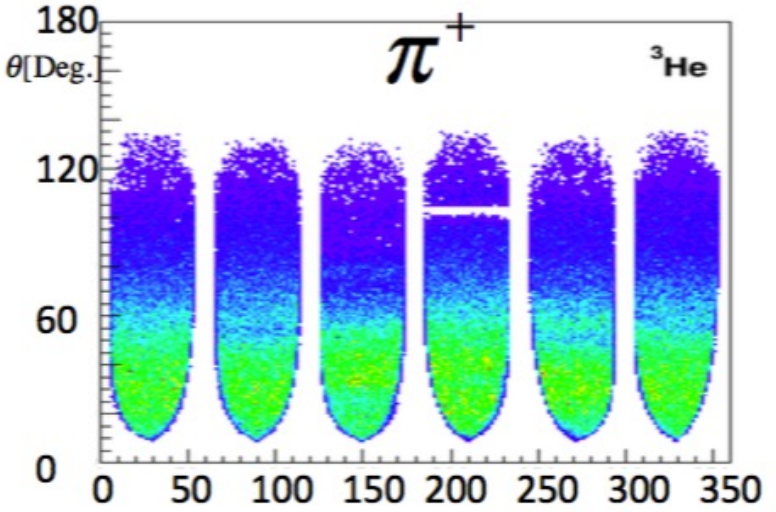
CLAS-6 Coverage







$p_{min} \approx 300$ MeV/c



$p_{min} \approx 150$ MeV/c

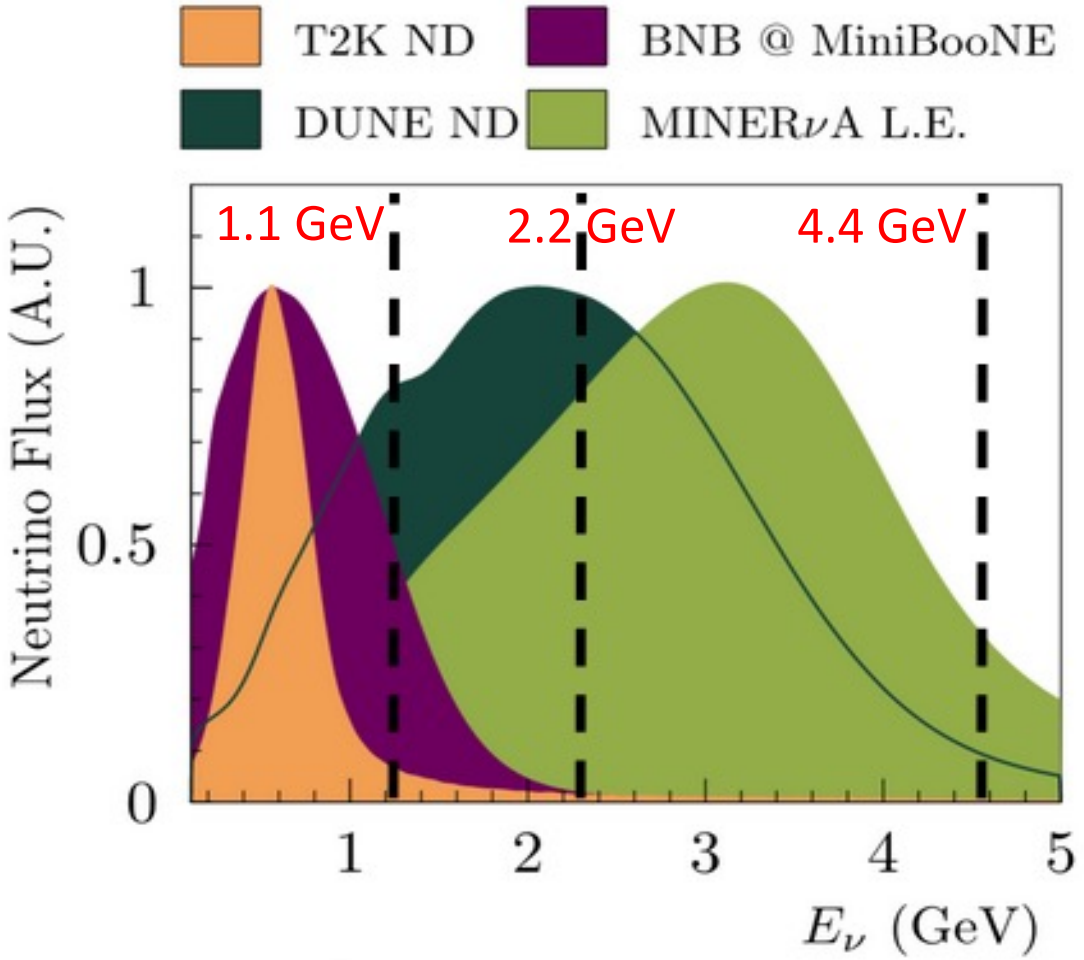
New '*Old*' Data: CLAS-6 @ JLab

Targets:

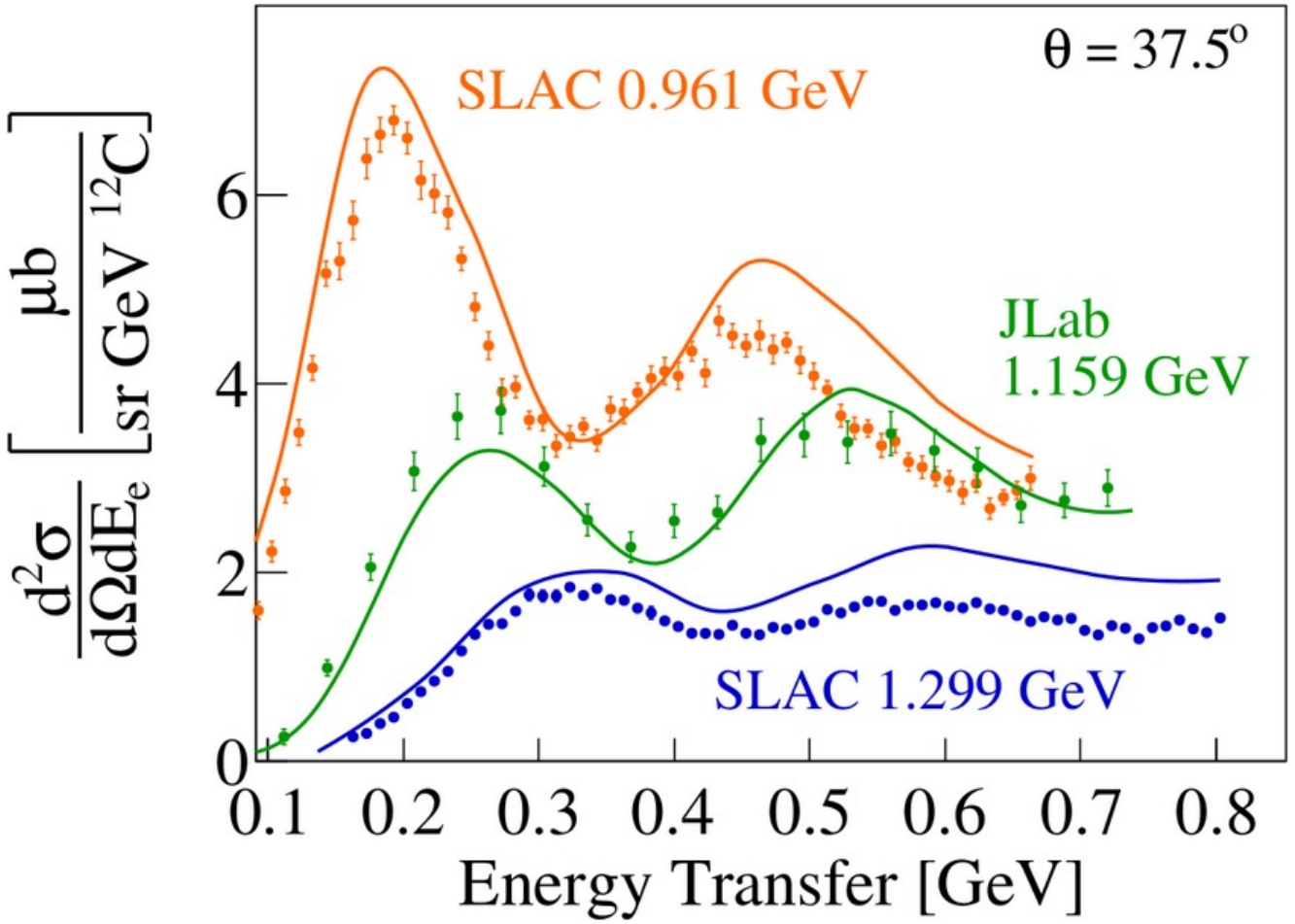
^{4}He, ^{12}C, & ^{56}Fe.

Energies:

4.4, 2.2 & 1.1 GeV.



Sanity Check: inclusive cross-sections



Playing the Neutrino Game

Goal: Use CLAS data to study E_{beam} reconstruction and vector-current cross-sections for different energies / nuclei.

Means (for QE study):

- Select 'clean' (e,e'p) events (no π, 2nd p, ...),
- Reweight by $\sigma_{e\text{-}N} / \sigma_{\nu\text{-}N}$ (Q^4),
- Analyze as 'neutrino data' (assume unknown E_{beam}),
- Reconstruct E_{beam} using different methods,
- Compare to theory (GENIE) predictions.

Playing the Neutrino Game

Goal: Use CLAS data to study E_{beam} reconstruction and vector-current cross-sections for different energies / nuclei.

Means (for QE study):

- Select 'clean' (e,e'p) events (no π, 2nd p, ...),
- Reweight by $\sigma_{e\text{-}N} / \sigma_{\nu\text{-}N}$ (Q^4),
- Analyze as 'neutrino data' (assume unknown E_{beam}),
- Reconstruct E_{beam} using different methods,
- Compare to theory (GENIE) predictions.

Playing the Neutrino Game

Goal: Use CLAS data to study E_{beam} reconstruction and vector-current cross-sections for different energies / nuclei.

Means (for QE study):

- Select 'clean' (e,e'p) events (no π, 2nd p, ...),
- Reweight by $\sigma_{e\text{-}N}$ / $\sigma_{\nu\text{-}N}$ (Q^4),
- Analyze as 'neutrino data' (assume unknown E_{beam}),
- Reconstruct E_{beam} using different methods,
- Compare to theory (GENIE) predictions.

Playing the Neutrino Game

Goal: Use CLAS data to study E_{beam} reconstruction and vector-current cross-sections for different energies / nuclei.

Means (for QE study):

- Select 'clean' (e,e'p) events (no π, 2nd p, ...),
- Reweight by $\sigma_{e\text{-}N}$ / $\sigma_{\nu\text{-}N}$ (Q^4),
- Analyze as 'neutrino data' (assume unknown E_{beam}),
- Reconstruct E_{beam} using different methods,
- Compare to theory (GENIE) predictions.

Playing the Neutrino Game

Goal: Use CLAS data to study E_{beam} reconstruction and vector-current cross-sections for different energies / nuclei.

Means (for QE study):

- Select 'clean' (e,e'p) events (no π, 2nd p, ...),
- Reweight by $\sigma_{e\text{-}N}$ / $\sigma_{\nu\text{-}N}$ (Q^4),
- Analyze as 'neutrino data' (assume unknown E_{beam}),
- Reconstruct E_{beam} using different methods,
- Compare to theory (GENIE) predictions.

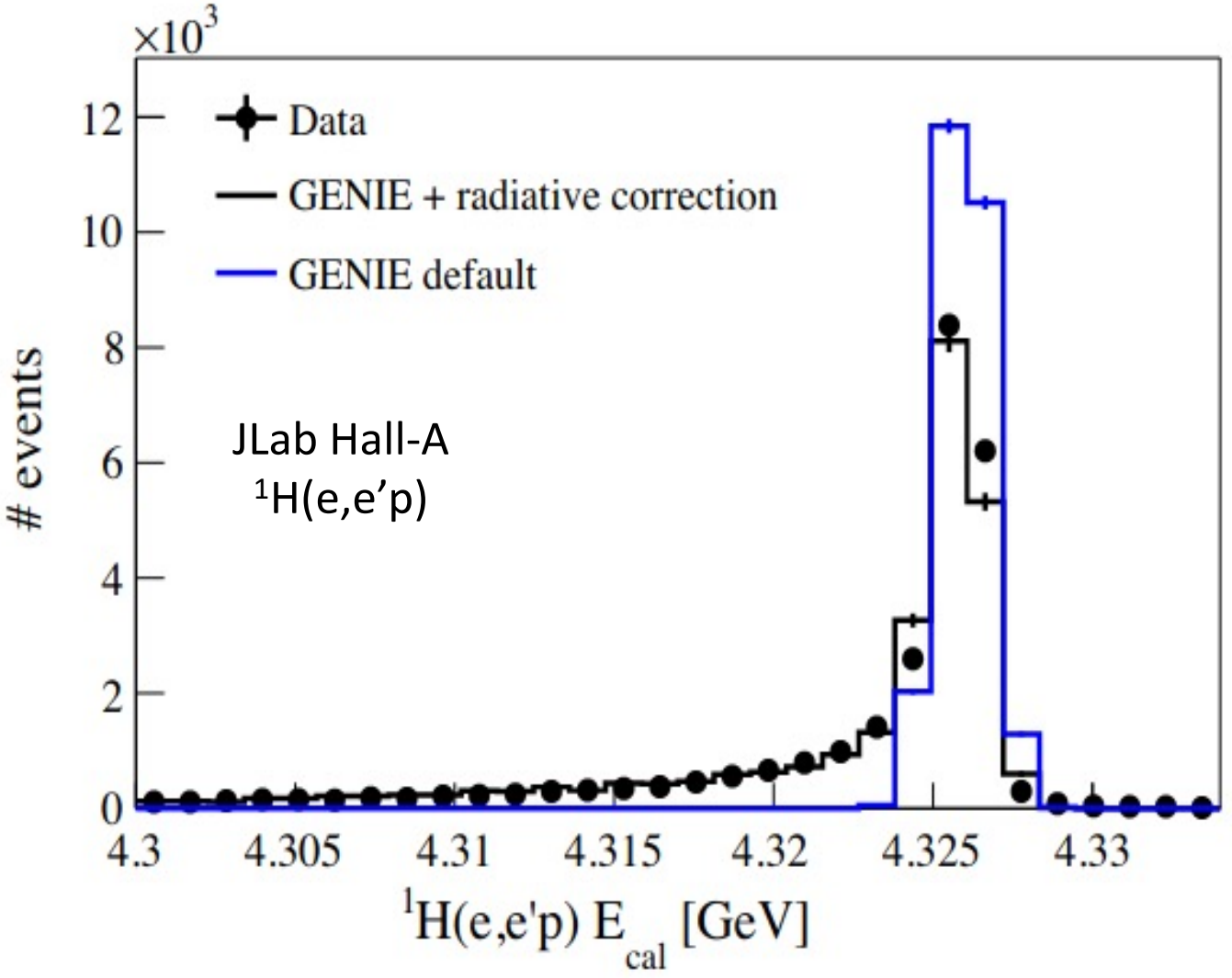
Playing the Neutrino Game

Goal: Use CLAS data to study E_{beam} reconstruction and vector-current cross-sections for different energies / nuclei.

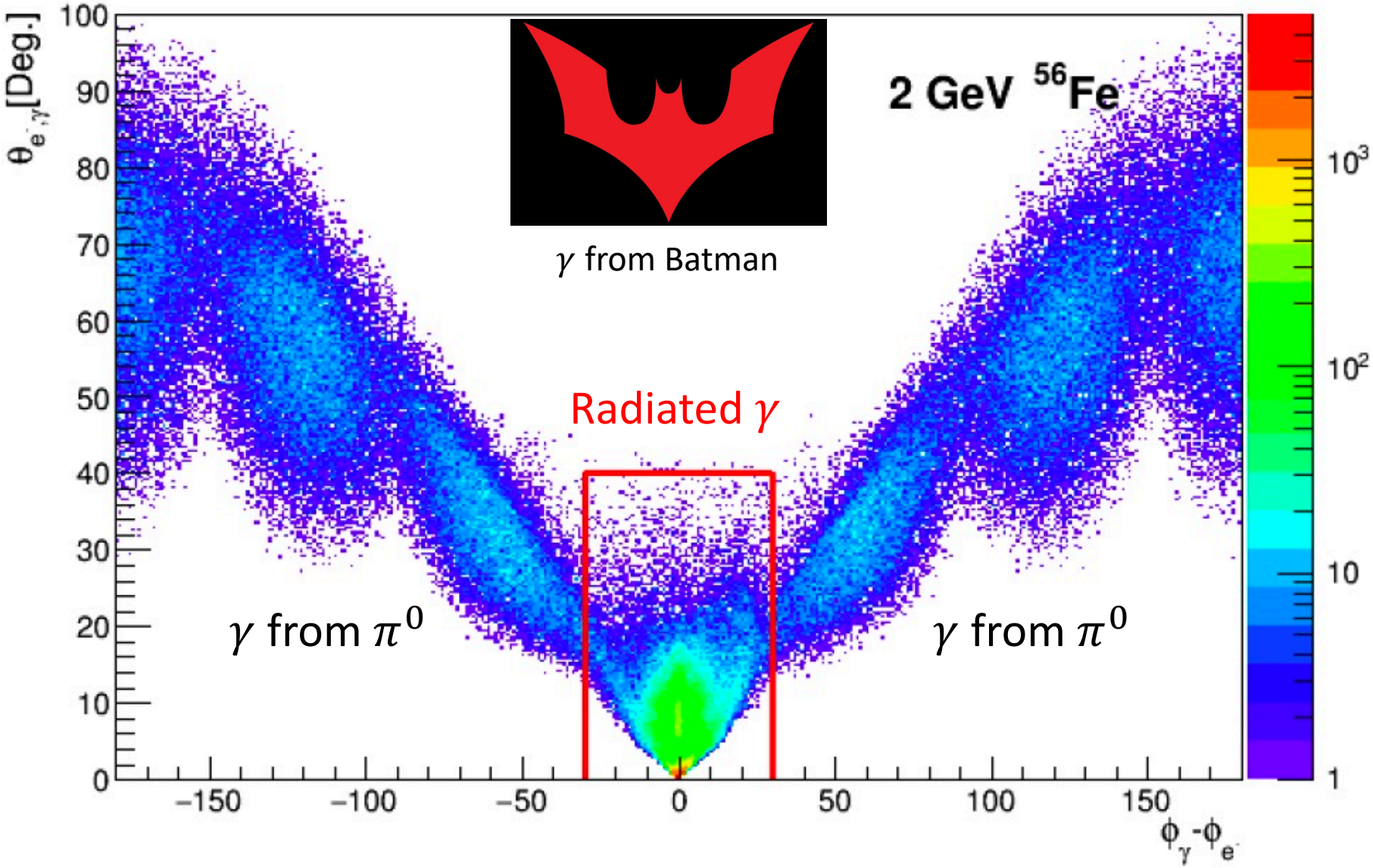
Means (for QE study):

- Select 'clean' (e,e'p) events (no π, 2nd p, ...),
- Reweight by $\sigma_{e\text{-}N}$ / $\sigma_{\nu\text{-}N}$ (Q^4),
- Analyze as 'neutrino data' (assume unknown E_{beam}),
- Reconstruct E_{beam} using different methods,
- Compare to theory (GENIE) predictions.

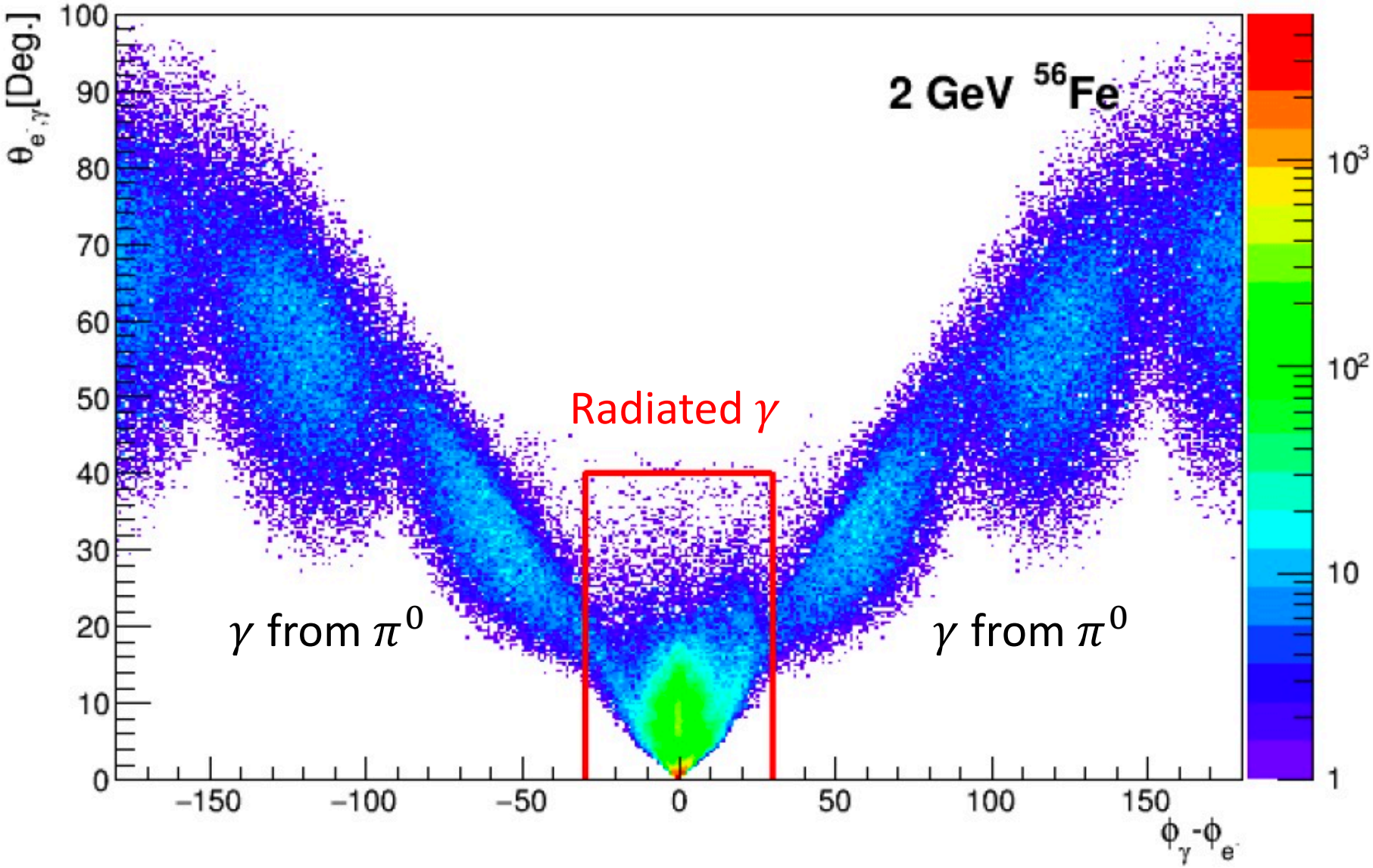
Adding Radiation to GENIE



Excluding Radiation in data



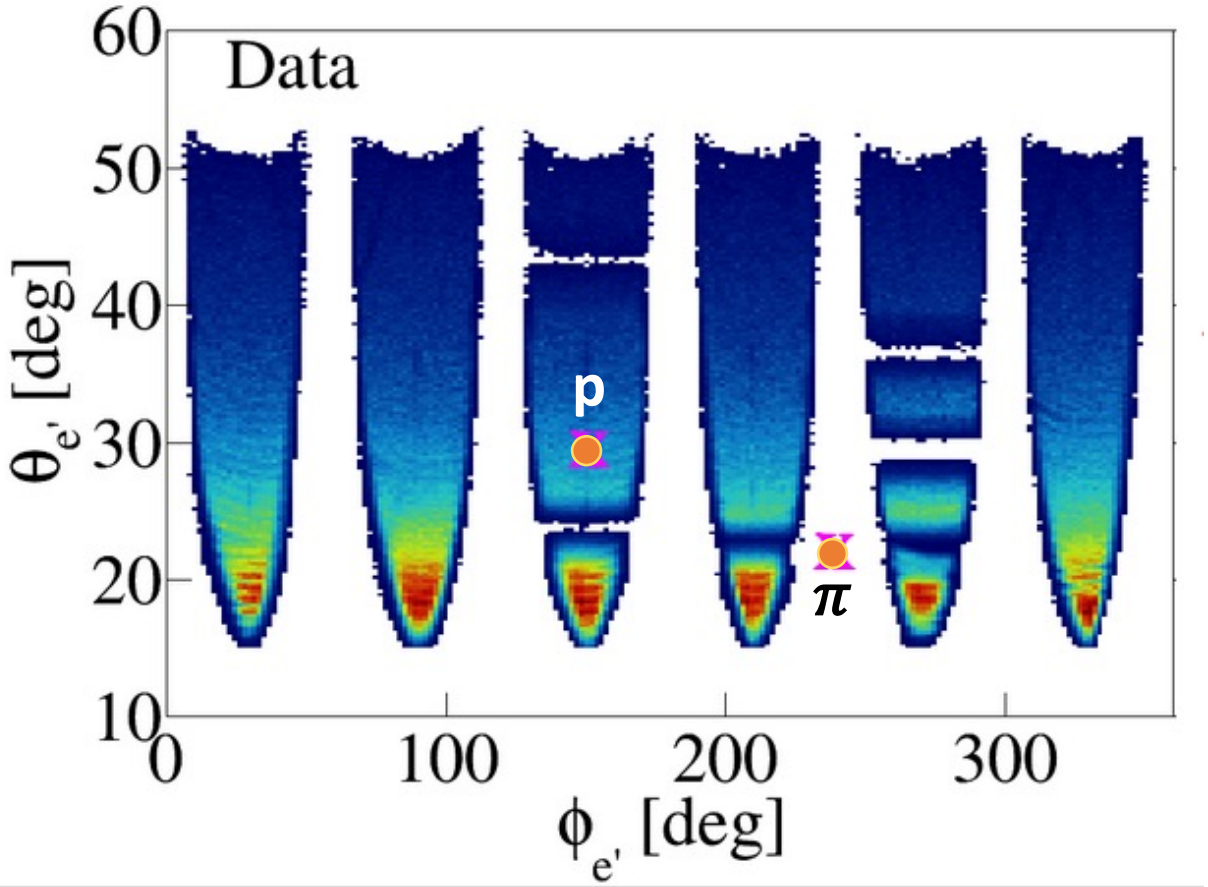
Excluding Radiation in data



Non-1p0π Background Subtraction

Non-QE interactions lead to multi hadron final states.

Gaps in CLAS acceptance will make them look like (e,e'p) events.



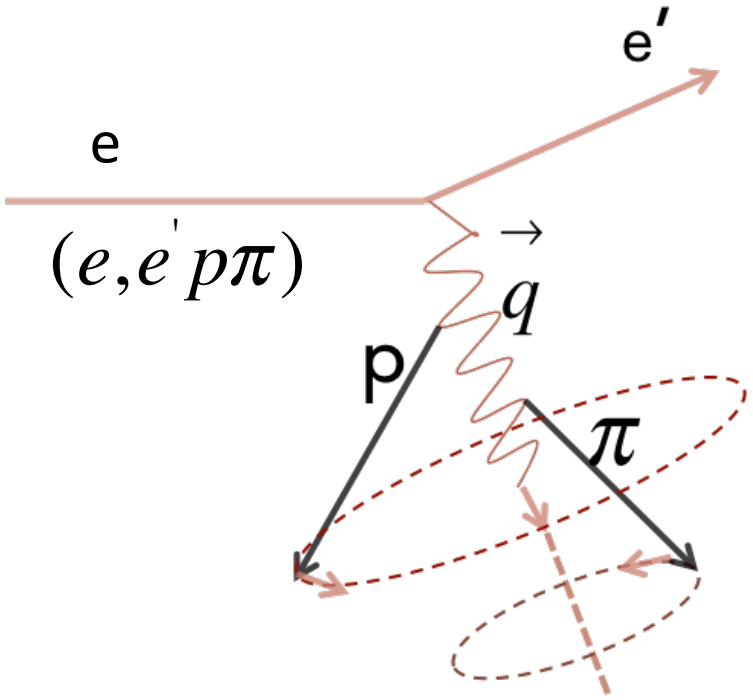
Non-1p0π Background Subtraction

Non-QE interactions lead to multi hadron final states.

Gaps in CLAS acceptance will make them look like (e,e'p) events.

<u>Data Driven Correction:</u>

1. Use measured (e,e'pπ) events,
2. Rotate π around q to determine its acceptance,
3. Subtract (e,e'pπ) contributions



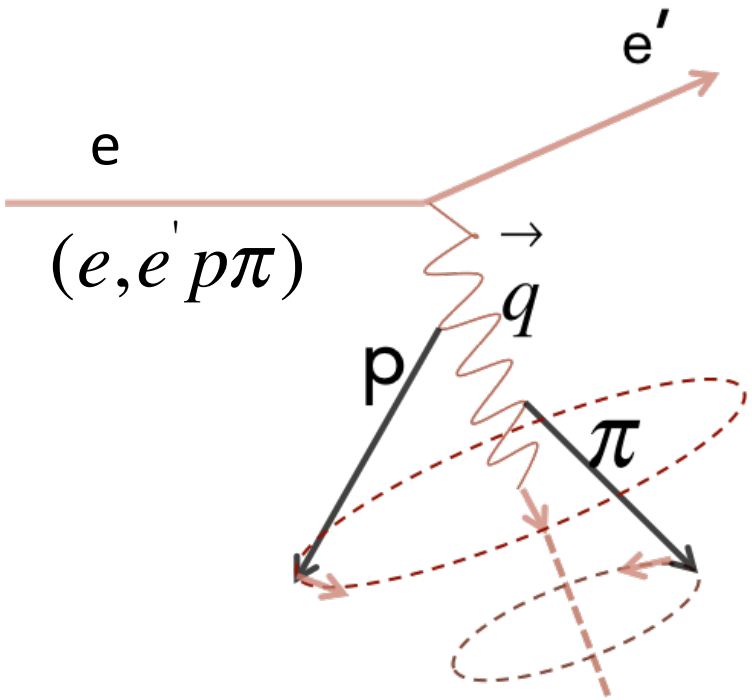
Non-1p0π Background Subtraction

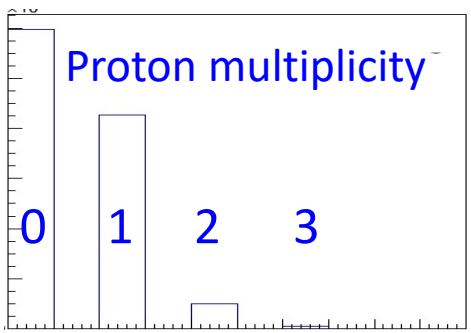
Non-QE interactions lead to multi hadron final states.

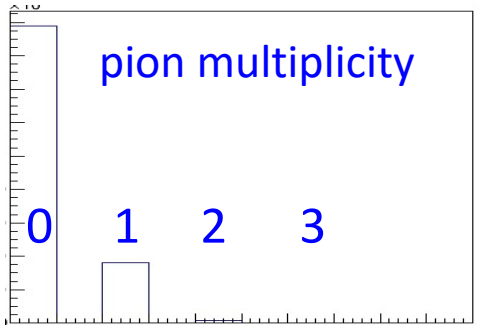
Gaps in CLAS acceptance will make them look like (e,e'p) events.

<u>Data Driven Correction:</u>

1. Use measured (e,e'pπ) events,
2. Rotate π around q to determine its acceptance,
3. Subtract (e,e'pπ) contributions
4. Do the same for 2p, 3p 2p+ π etc.







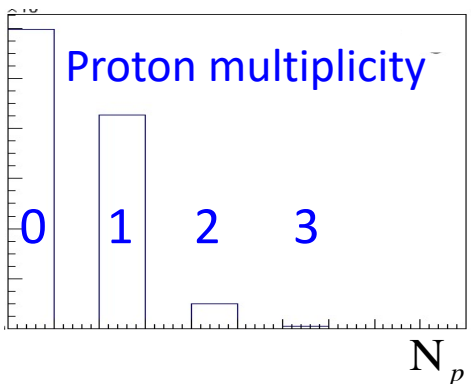
Non-1p0π Background Subtraction

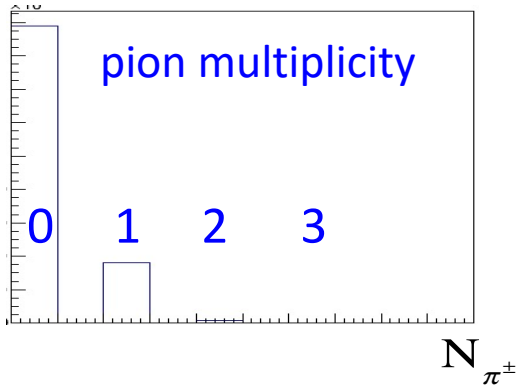
Non-QE interactions lead to multi hadron final states.

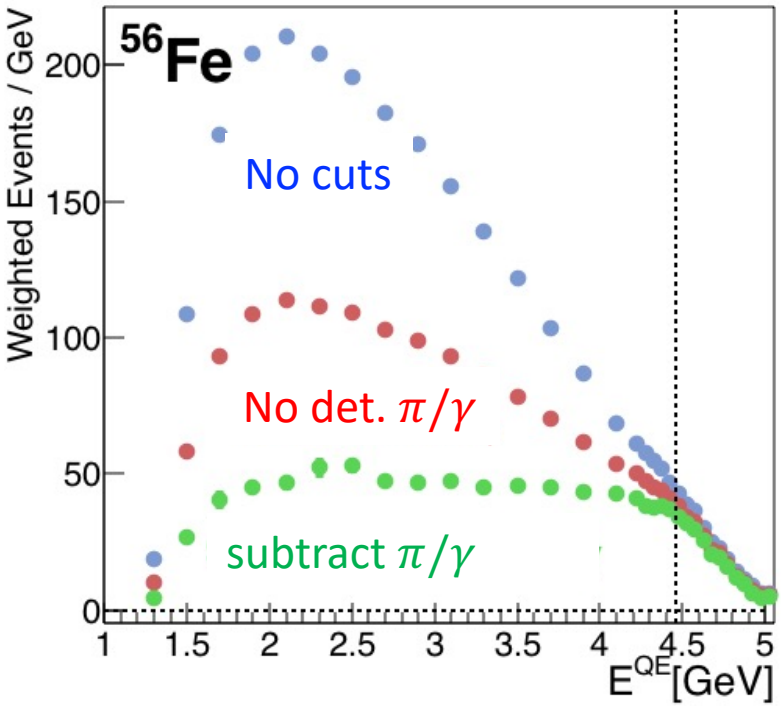
Gaps in CLAS acceptance will make them look like (e,e'p) events.

<u>Data Driven Correction:</u>

1. Use measured (e,e'pπ) events,
2. Rotate π around q to determine its acceptance,
3. Subtract (e,e'pπ) contributions
4. Do the same for 2p, 3p 2p+ π etc.

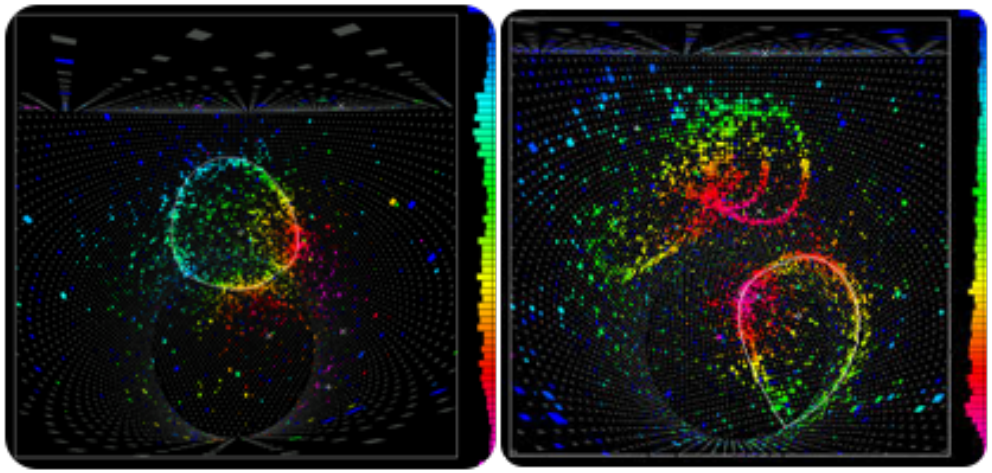






➡ True 0π event sample!

Energy Reconstruction



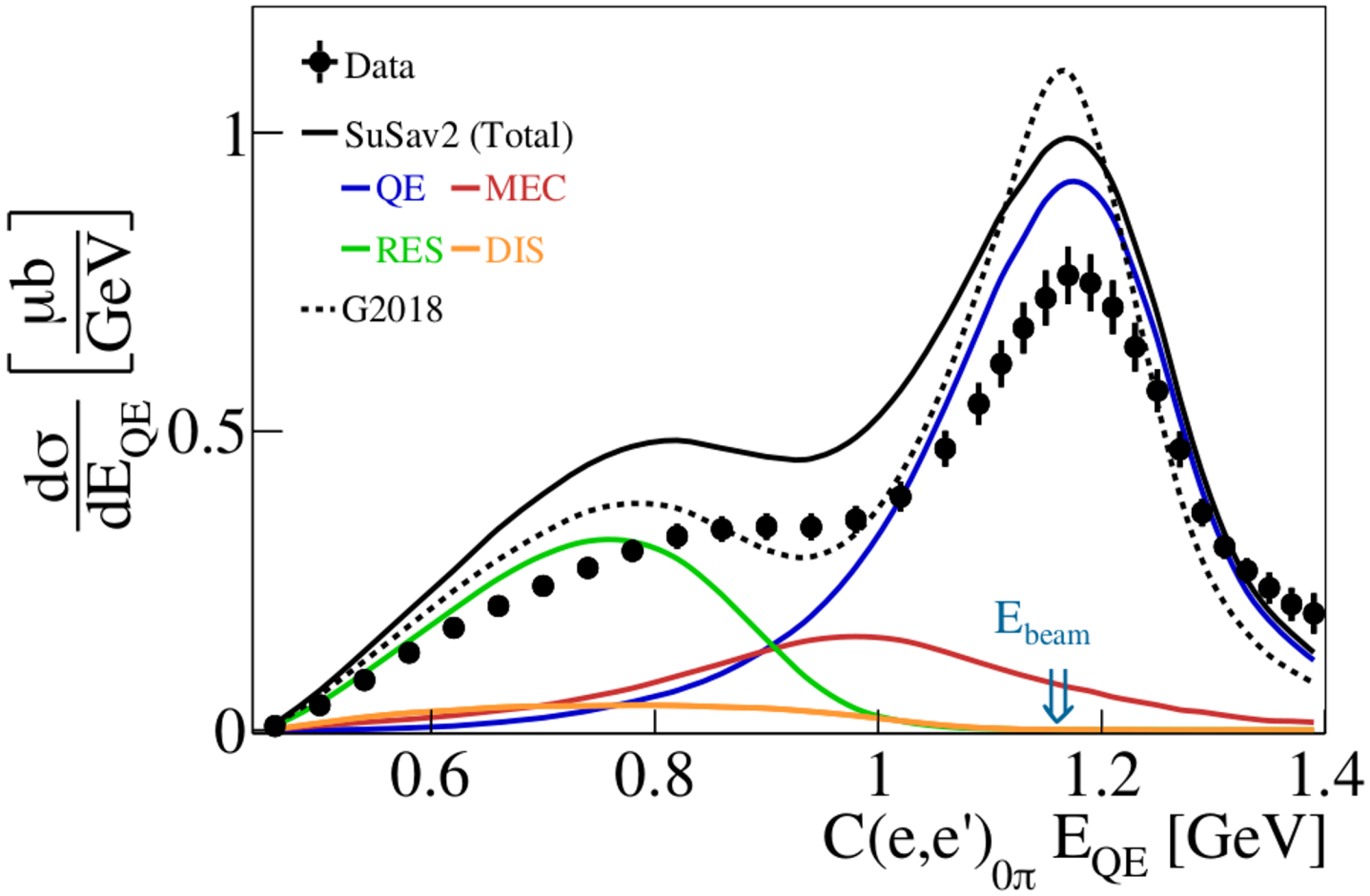
Cherenkov detectors:

Assuming QE interaction

Using solely the final state lepton

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

(e,e’) Data-Theory Disagreements



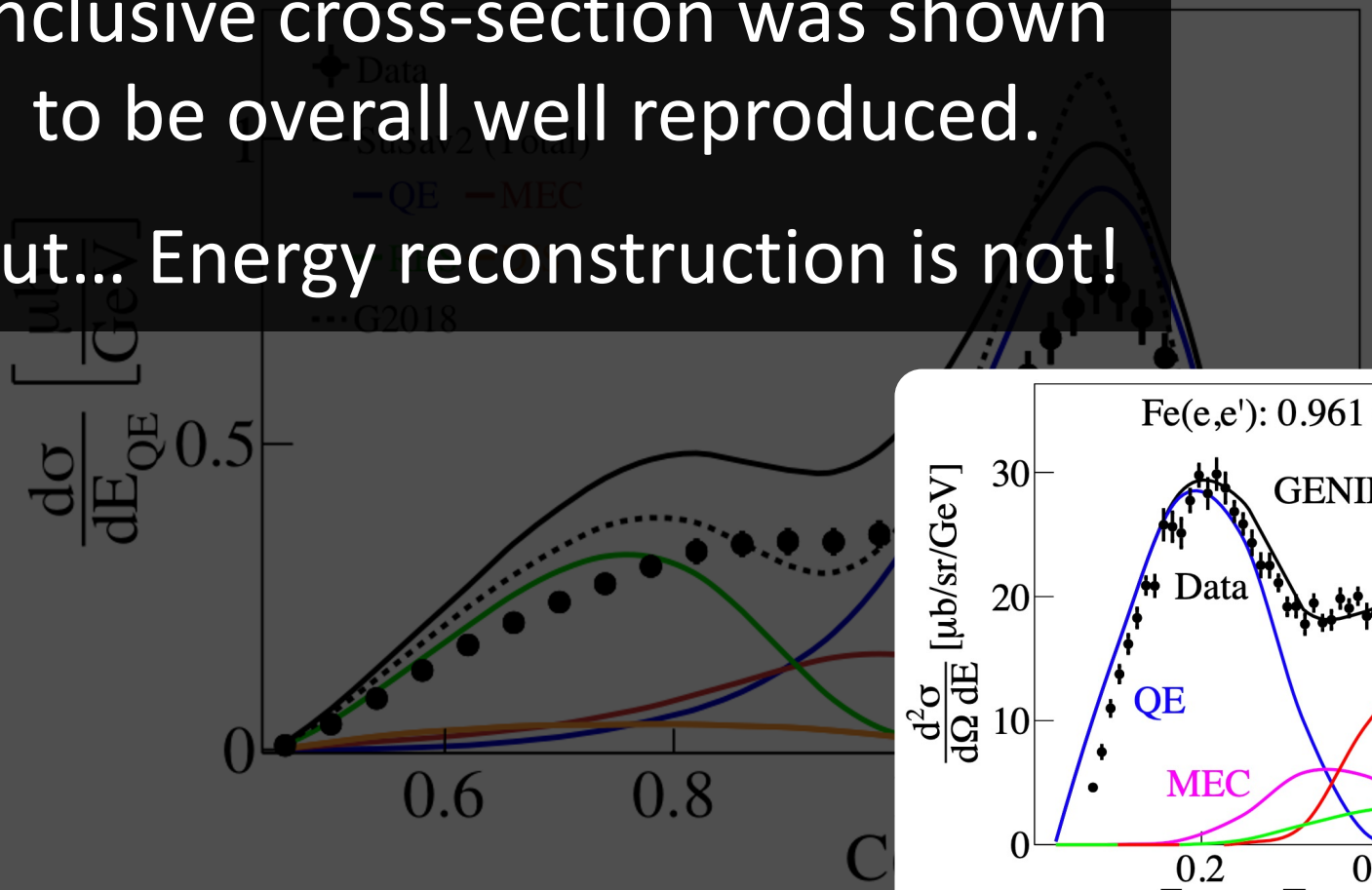
Khachatryan, Papadopoulou, and Ashkenazi et al. (CLAS & e4v collaborations), Nature **599**, 565 (2021).

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

(e,e’) Data-Theory Disagreements

Inclusive cross-section was shown to be overall well reproduced.

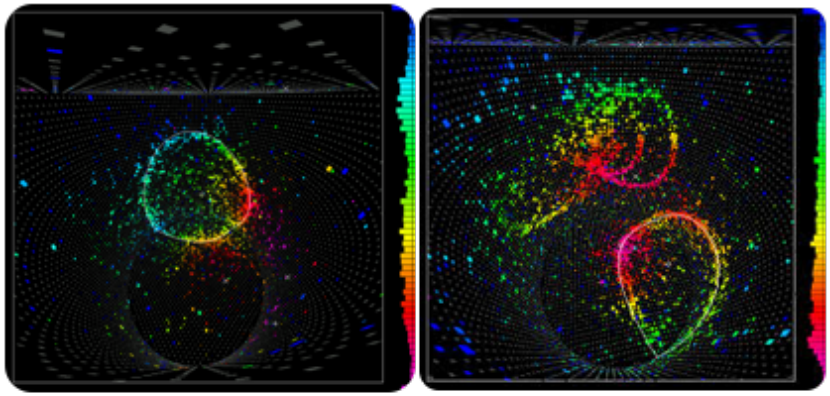
But… Energy reconstruction is not!



Khachatryan, Papadopoulou, and Ashkenazi et al. (CLAS & e4v collaborations), Nature **599**, 565 (2021).

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

Energy Reconstruction

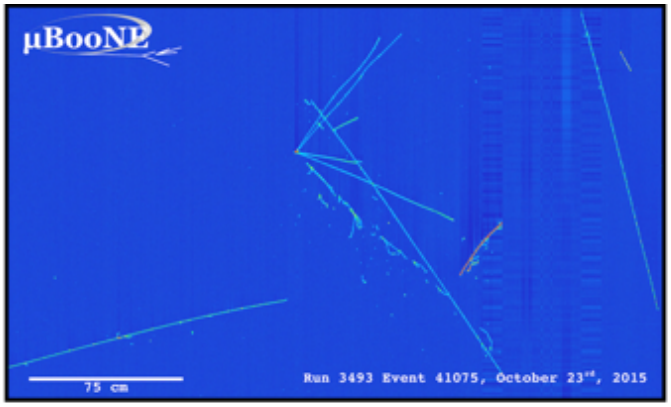


Cherenkov detectors:

Assuming QE interaction

Using solely the final state lepton

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

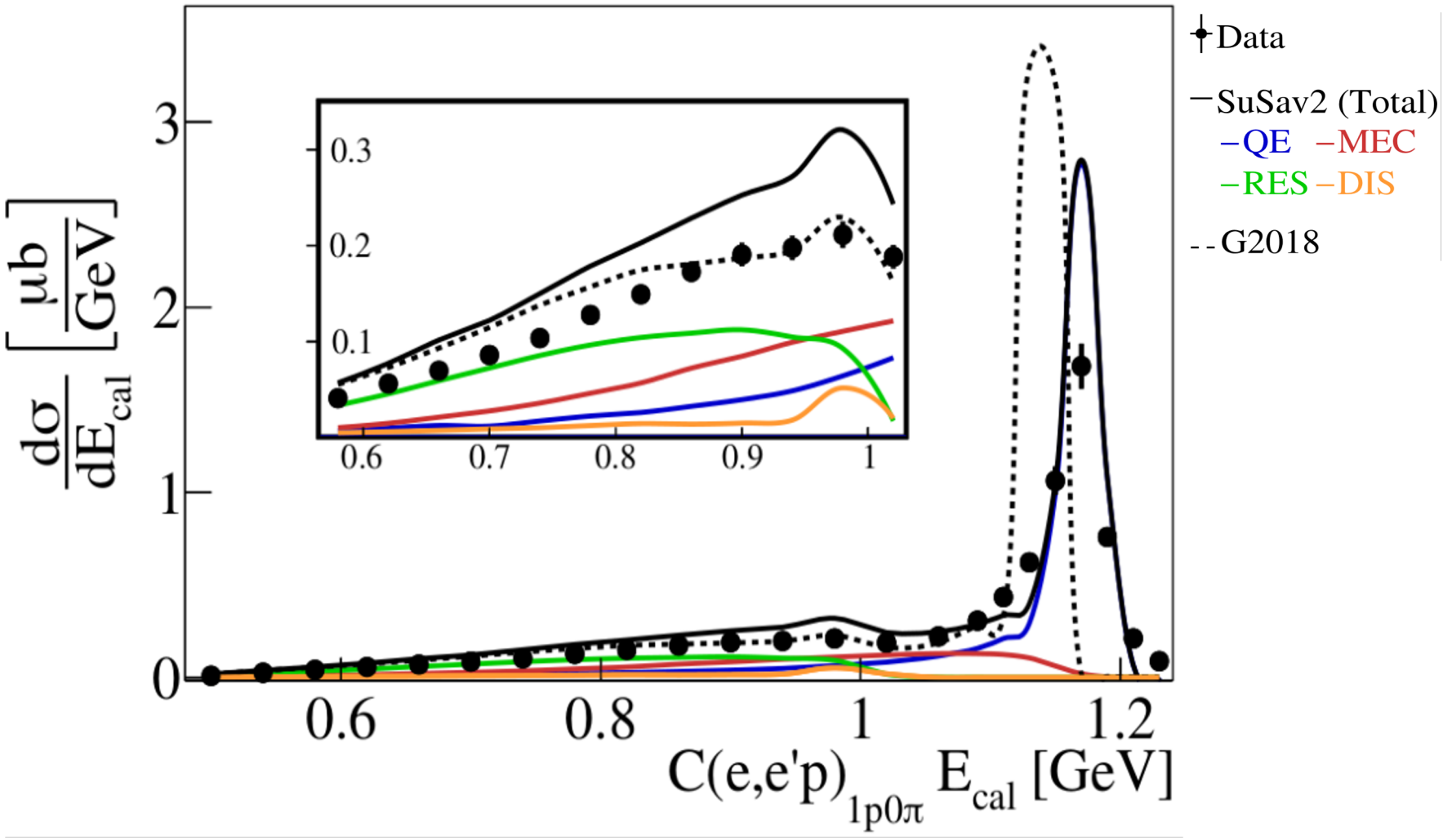


Tracking detectors:

Need good hadronic reconstruction

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

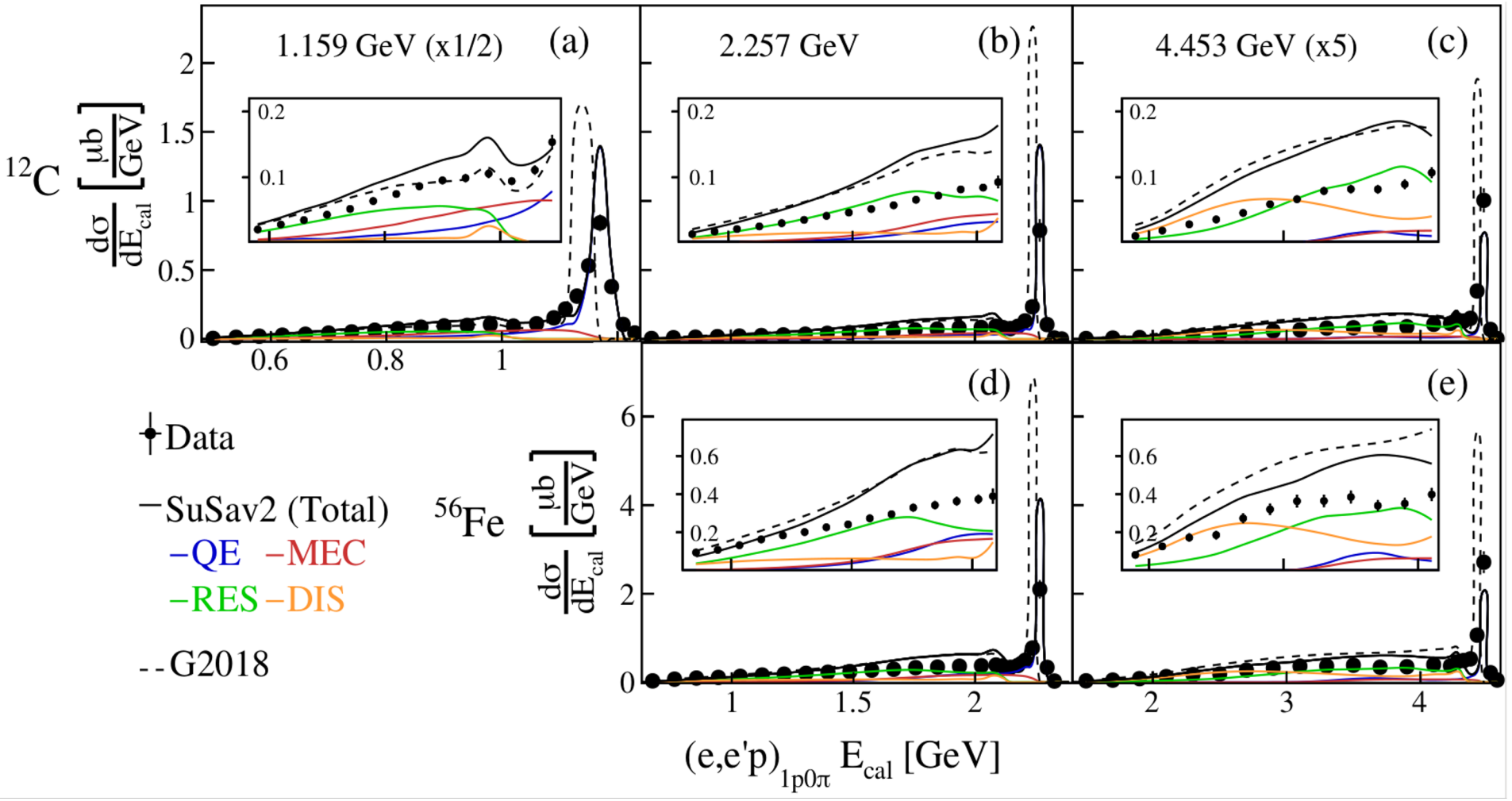
(e,e'p) Energy Reconstruction



Khachatryan, Papadopoulou, and Ashkenazi et al. (CLAS & e4v collaborations), Nature **599**, 565 (2021).

$$E_{cal} = E_l + T_p + \epsilon$$

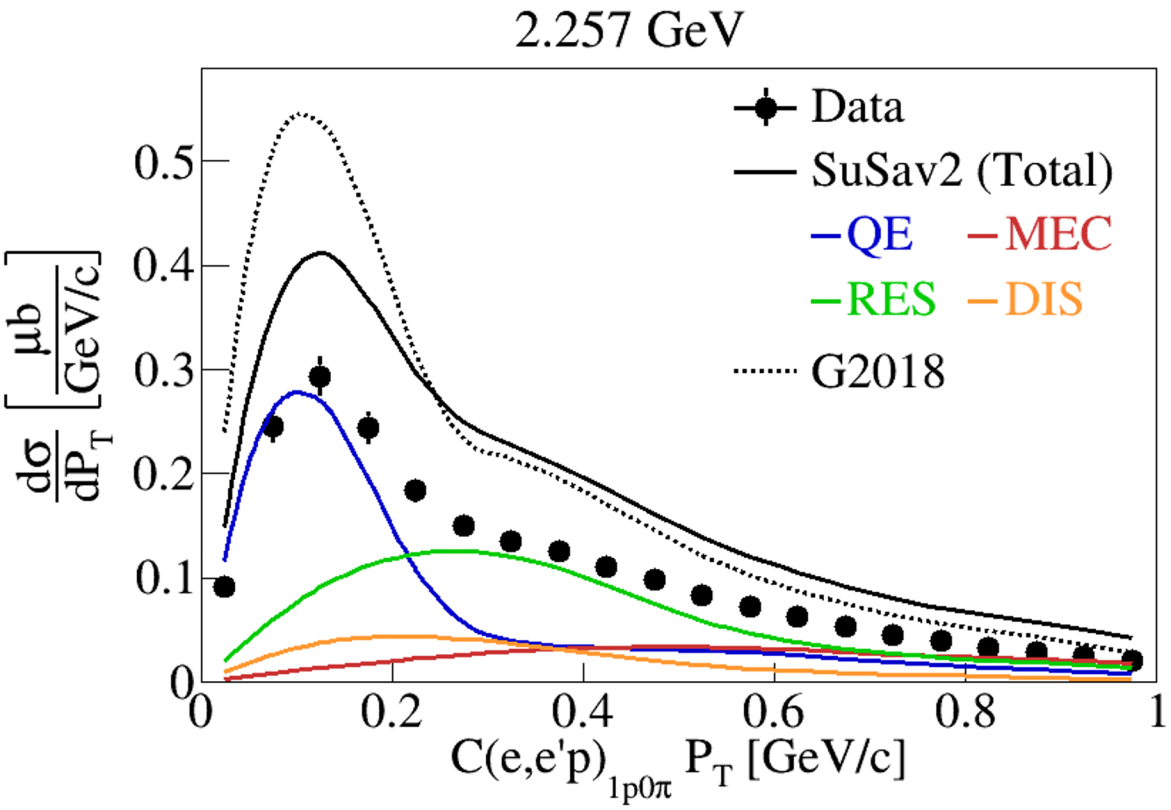
Gest worse as A & E increase…



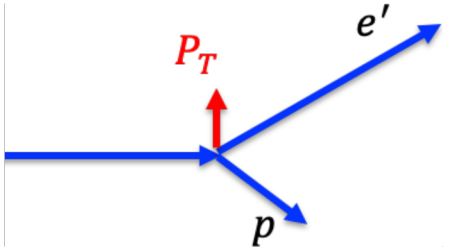
Khachatryan, Papadopoulou, and Ashkenazi et al. (CLAS & e4v collaborations), Nature **599**, 565 (2021).

$$E_{cal} = E_l + T_p + \epsilon$$

Transverse Constraints



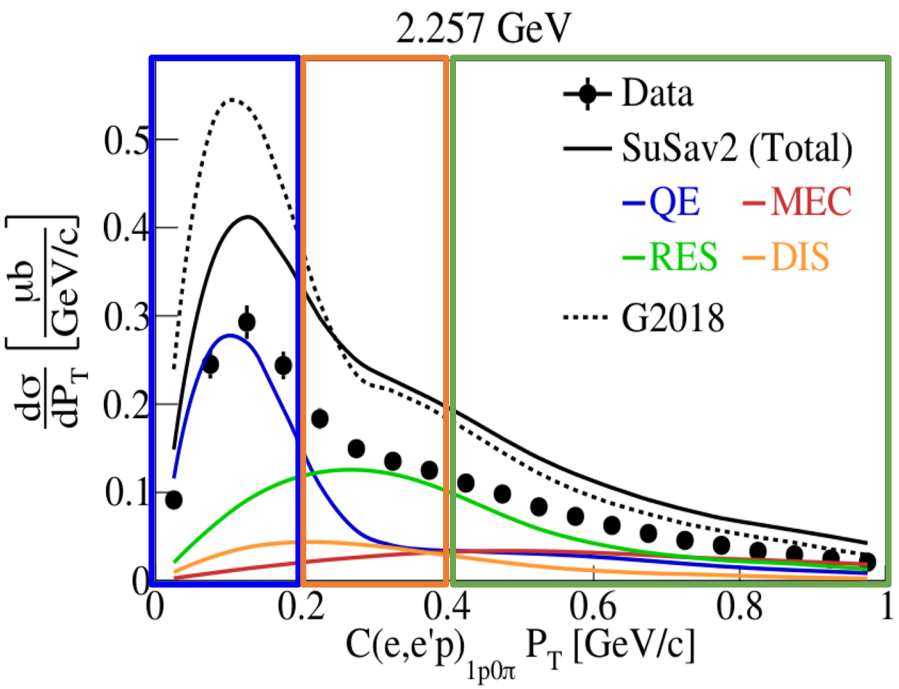
$$P_T = | \mathbf{P_T}^{e'} + \mathbf{P_T}^{p} |$$

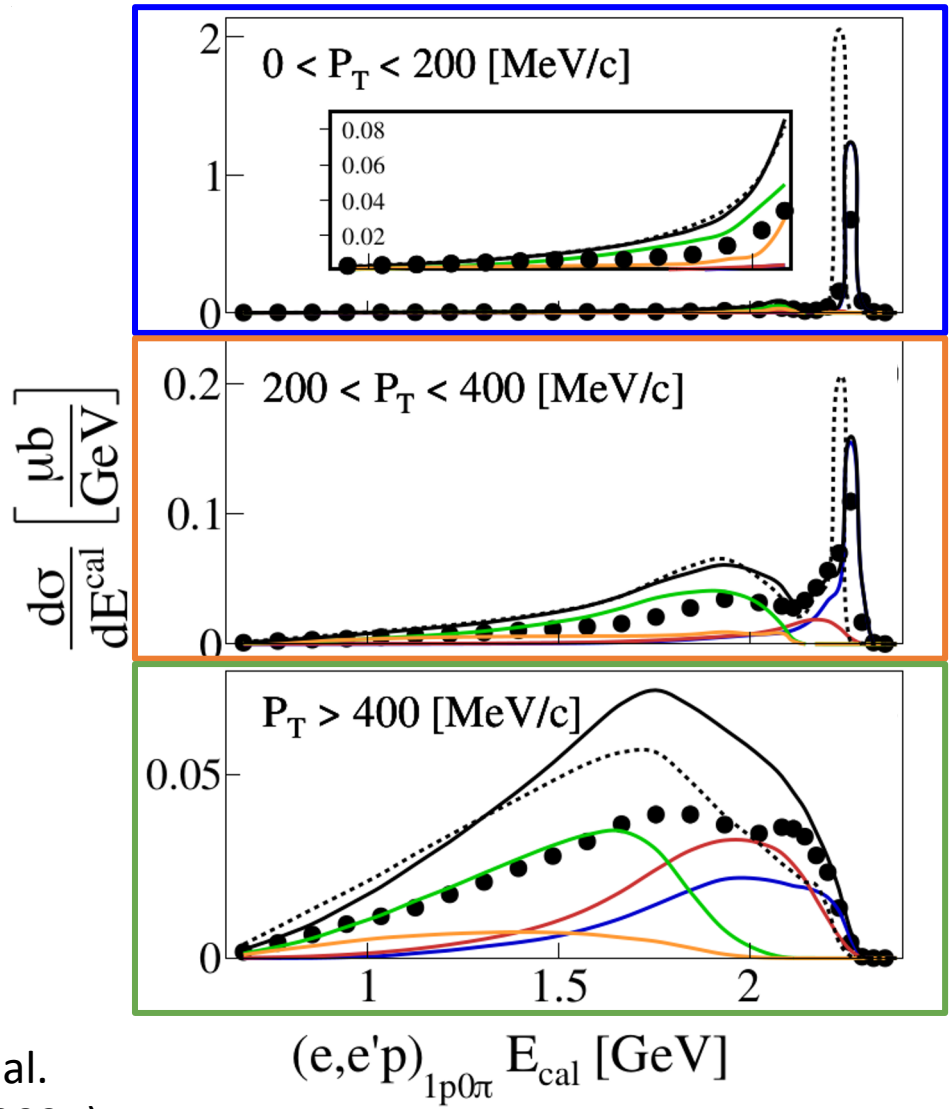


Overestimation of QE peak & RES tail

Khachatryan, Papadopoulou, and Ashkenazi et al. (CLAS & e4v collaborations), Nature **599**, 565 (2021).

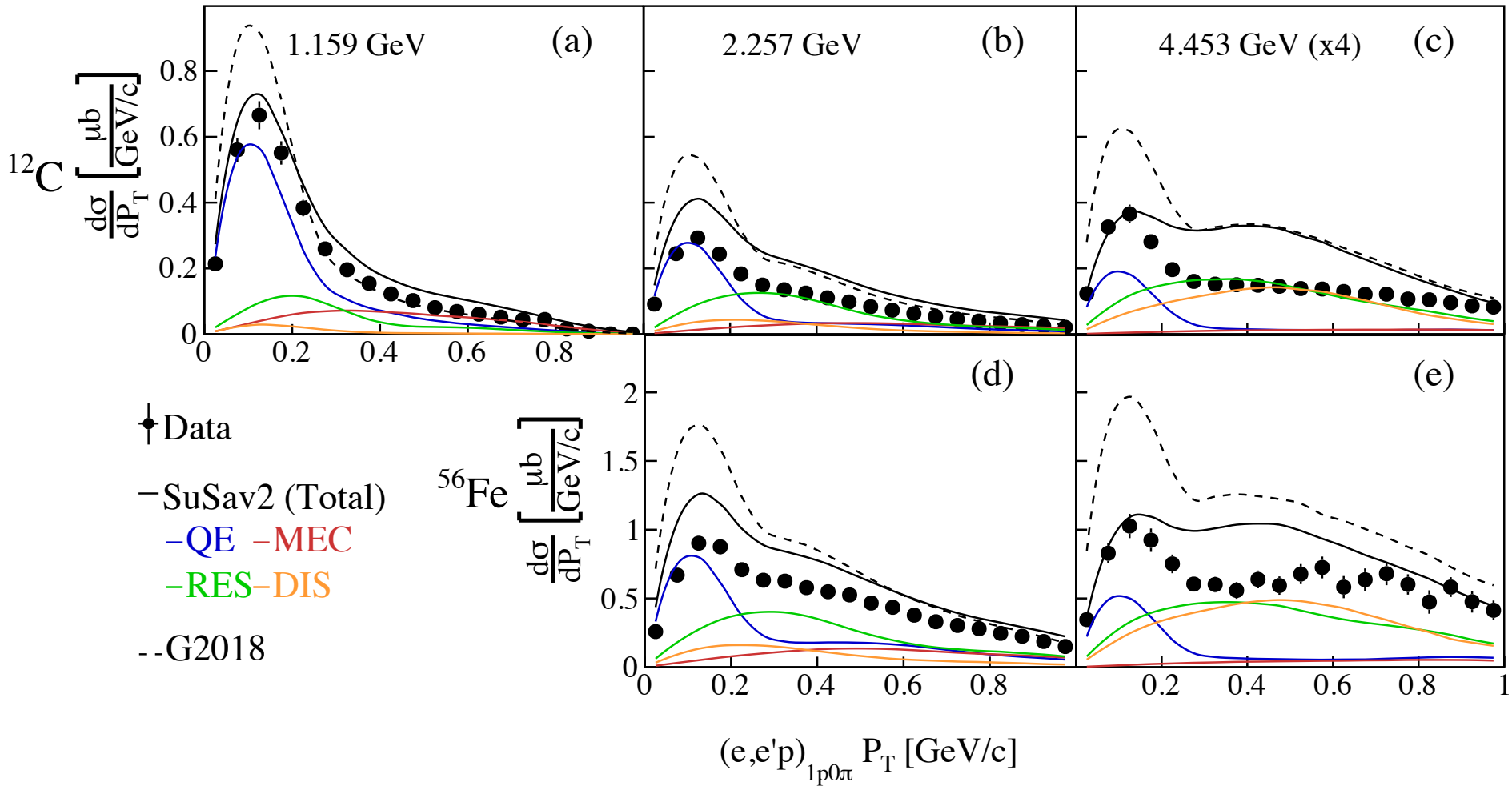
Transverse Constraints





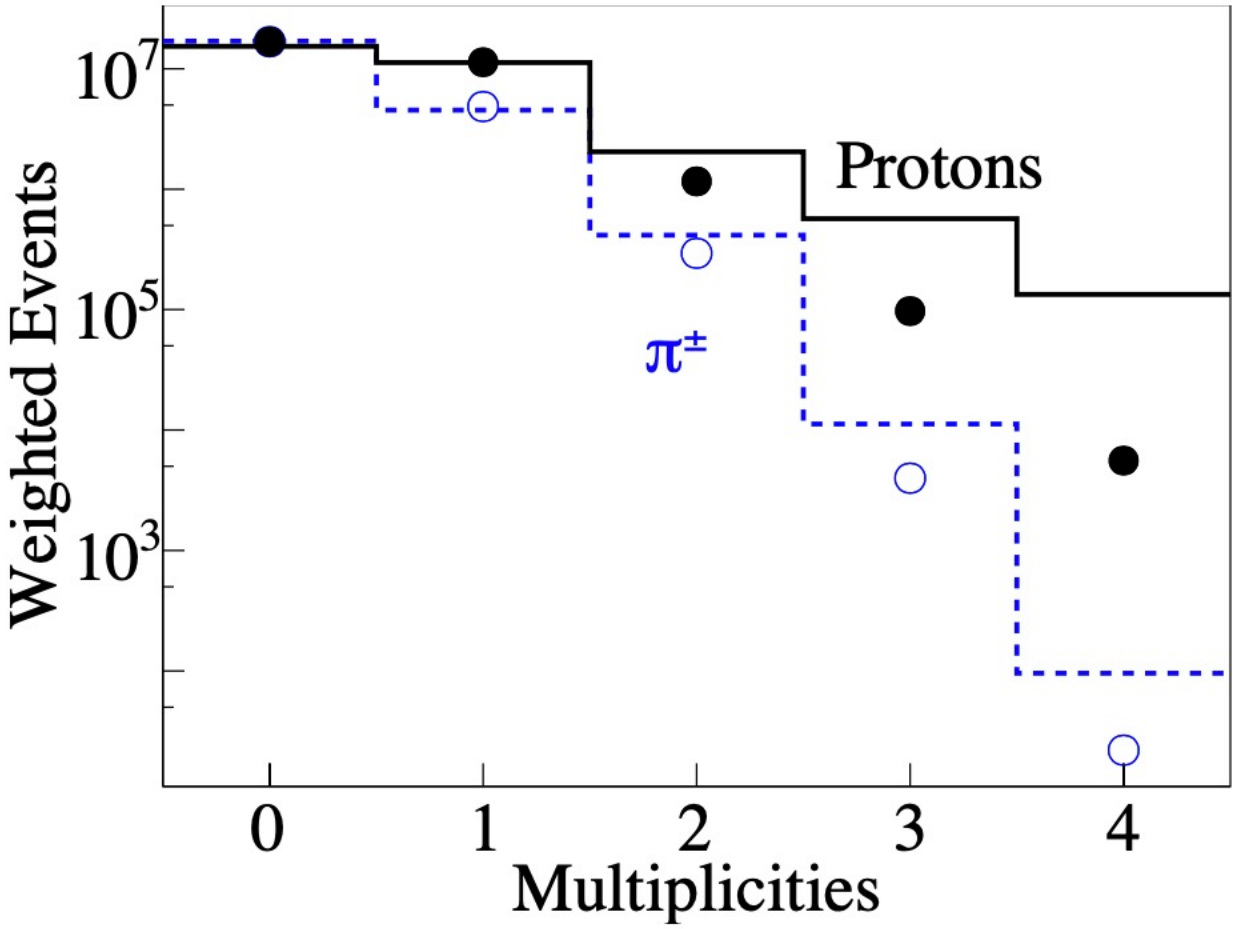
Khachatryan, Papadopoulou, and Ashkenazi et al. (CLAS & e4v collaborations), Nature **599**, 565 (2021).

Also… Issues @ high-energy!



Khachatryan, Papadopoulou, and Ashkenazi et al.
(CLAS & e4v collaborations), Nature **599**, 565 (2021).

Also… Issues \w Particle Multiplicities



Khachatryan, Papadopoulou, and Ashkenazi et al.
(CLAS & e4v collaborations), Nature **599**, 565 (2021).

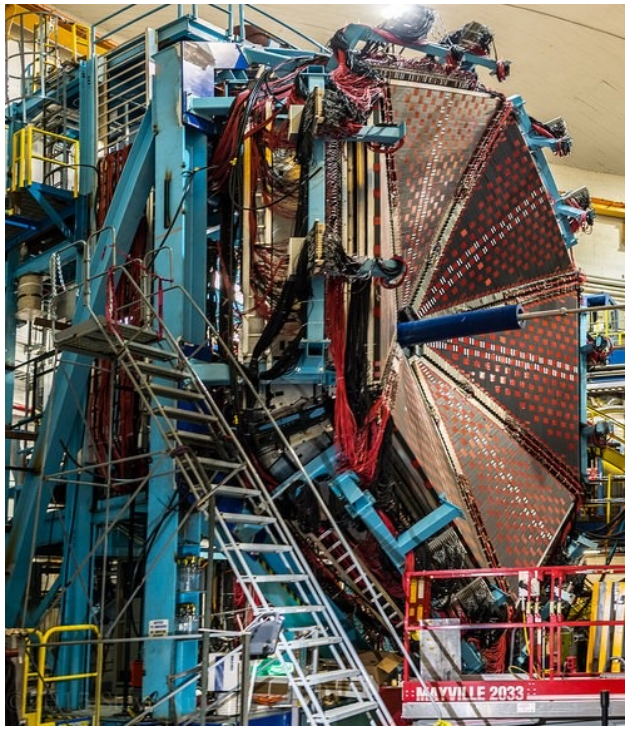
New CLAS-12 data

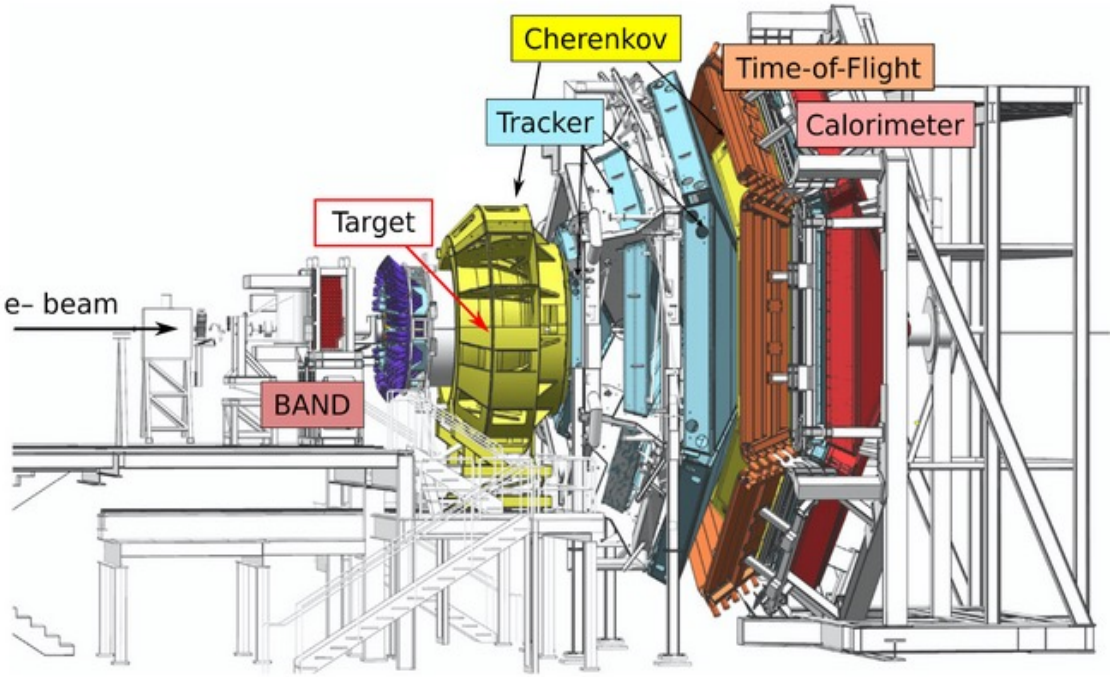
Targets:

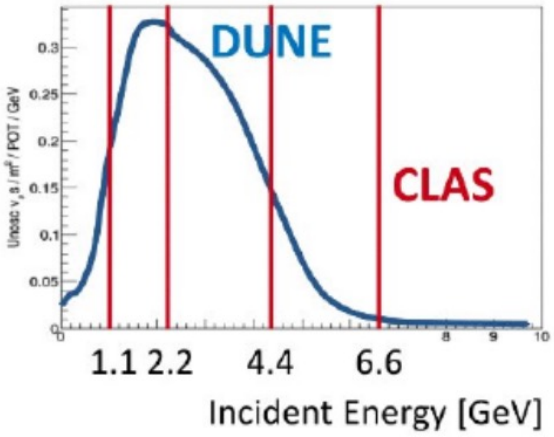
^{4}He, ^{12}C, ^{16}O, ^{40}Ar, ^{120}Sn

Beam Energies:

1.1, 2.2, 4.4, 6.6 GeV







New CLAS-12 data

Targets:

^{4}He, ^{12}C, ^{16}O, ^{40}Ar, ^{120}Sn

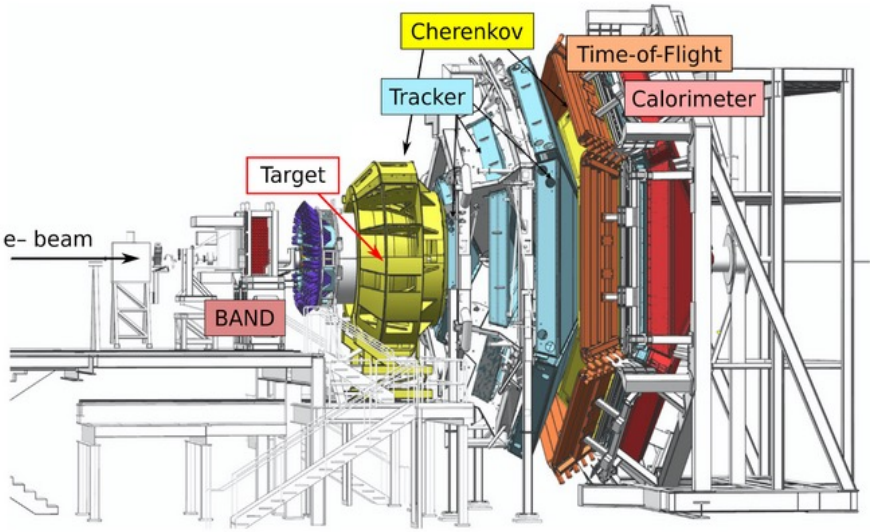
Beam Energies:

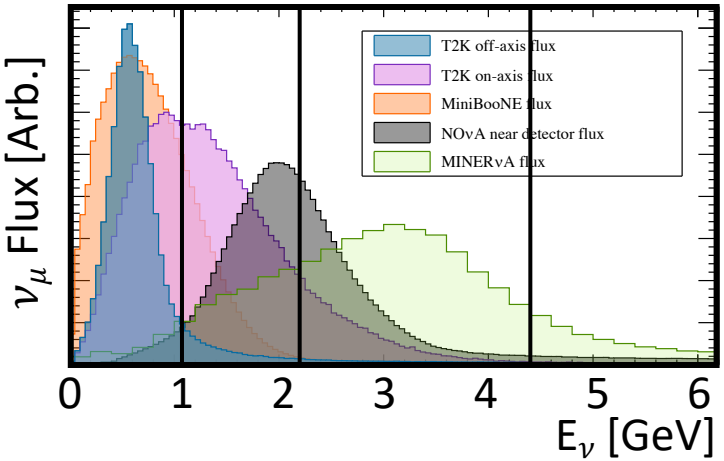
1.1, 2.2, 4.4, 6.6 GeV

CLAS12 Spectrometer:

- Luminosity: x10 higher than CLAS6
- Charged Particles: 5° – 120°
- Neutrons: 5° – 120° + 160° – 170°
- Threshold: ~300 MeV/c

=> High stat. semi-inclusive and exclusive data sets on multiple targets at multiple energies.





Unique hadronic models test!

Overwhelming Community Support

Fermilab

Hyper-Kamiokande

DUNE

IceCube
SOUTH POLE NEUTRINO OBSERVATORY

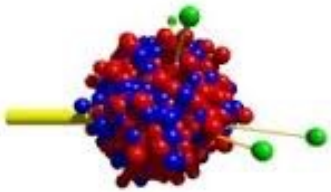
NOvA

MINERvA

T2K

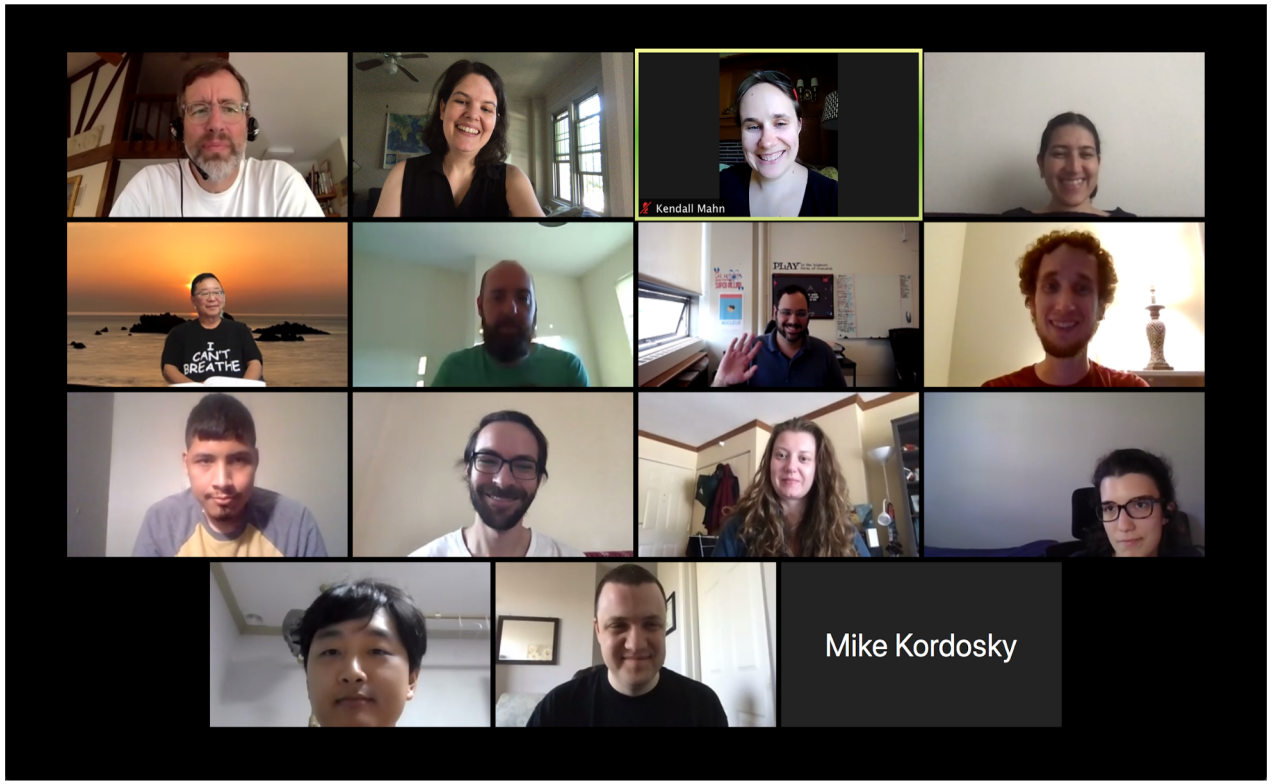
ANNIE
Accelerator Neutrino Neutron Interaction Experiment

μBooNE



GiBUU
The Giessen Boltzmann-Uehling-Uhlenbeck Project

Growing Collaboration!



e4v + ?

Join us!

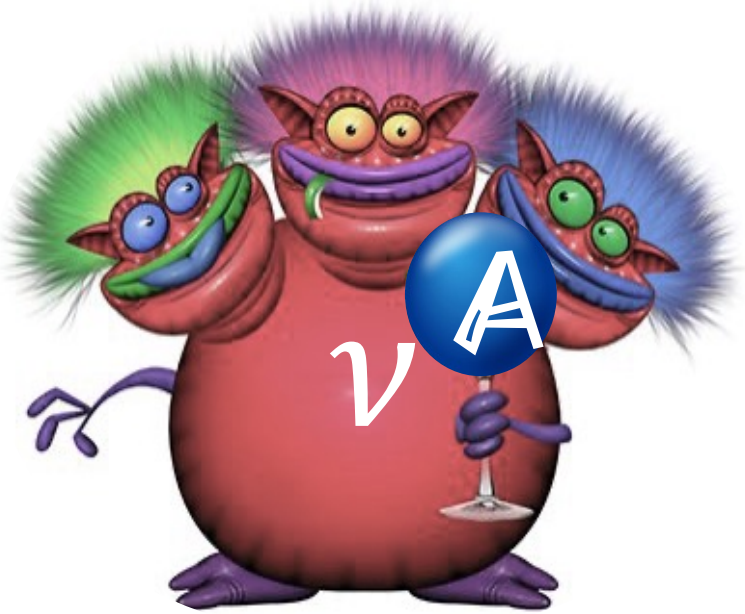
Jefferson Lab

UCL

CSIC
Consejo Superior de Investigaciones Científicas

WAIT….

This is all Vector (e)!
What about Axial (ν)?

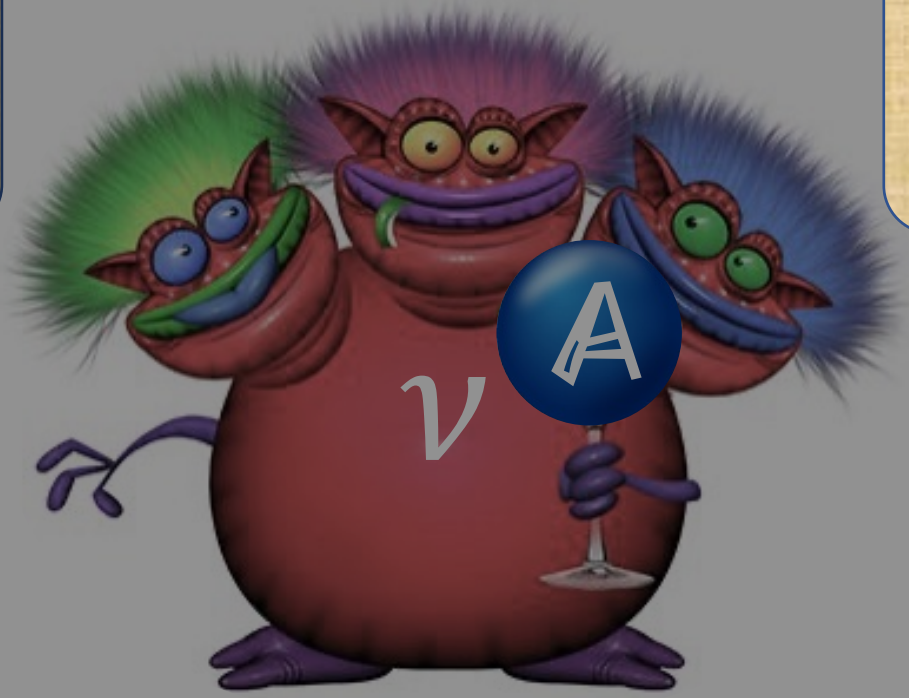


Attacking the Monster From All Sides

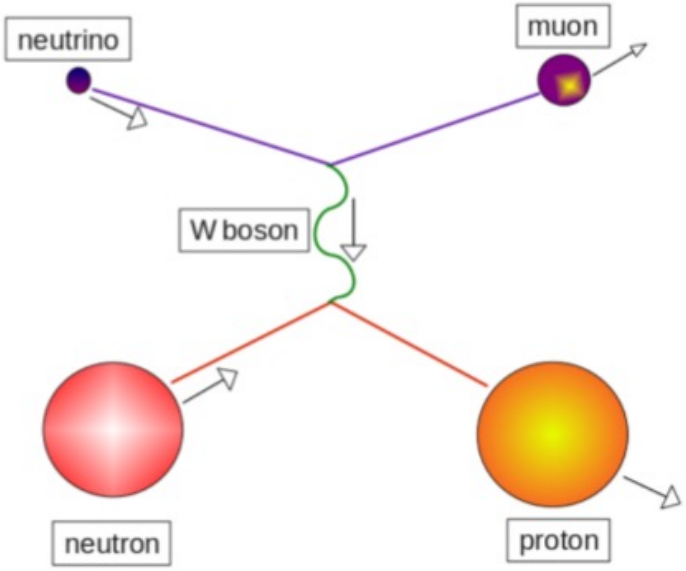
Event-Generators

e-scattering

ν-scattering



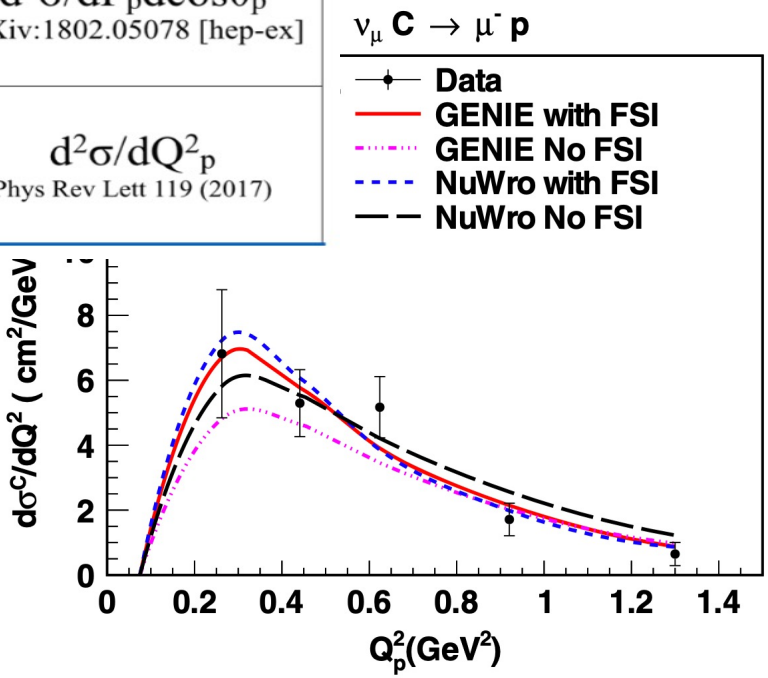
ν-Ar cross-section measurement @ μBooNE



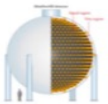
- Simplest nuclear process
- Dominant interaction at low energies
- "Good" neutrino energy reconstruction
- Allows high precision oscillation studies

World-Data is limited

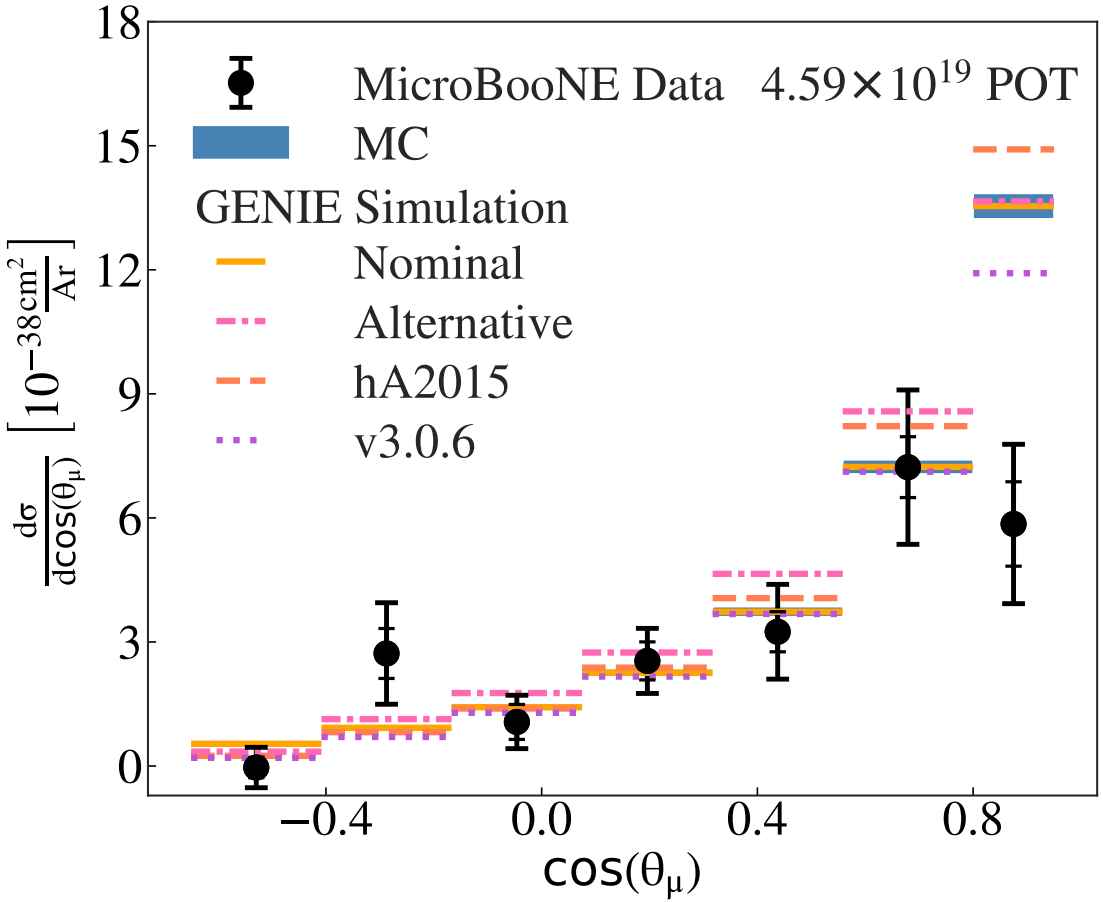
Experiment	Target	μ-dependence	p-dependence
SciBooNE	^{12}C	$d\sigma/dE_\nu$ doi: 10.1063/1.3661556	
MiniBooNE Detector	^{12}C	$d^2\sigma/dP_\mu d\cos\theta_\mu$ Phys Rev D88 (2013)	
T2K	^{12}C, ^{16}O	$d\sigma/d\theta_\mu$ Phys Rev D92 (2015) $d^2\sigma/dP_\mu d\cos\theta_\mu$ PhysRevD.98.0124004	$d^2\sigma/dP_p d\cos\theta_p$ arXiv:1802.05078 [hep-ex]
MINERvA	^{12}C, ^{56}Fe, ^{208}Pb	$d^2\sigma/dP_\parallel dP_T$ Phys Rev D97.052002	$d^2\sigma/dQ^2_p$ Phys Rev Lett 119 (2017)



World-Data is limited

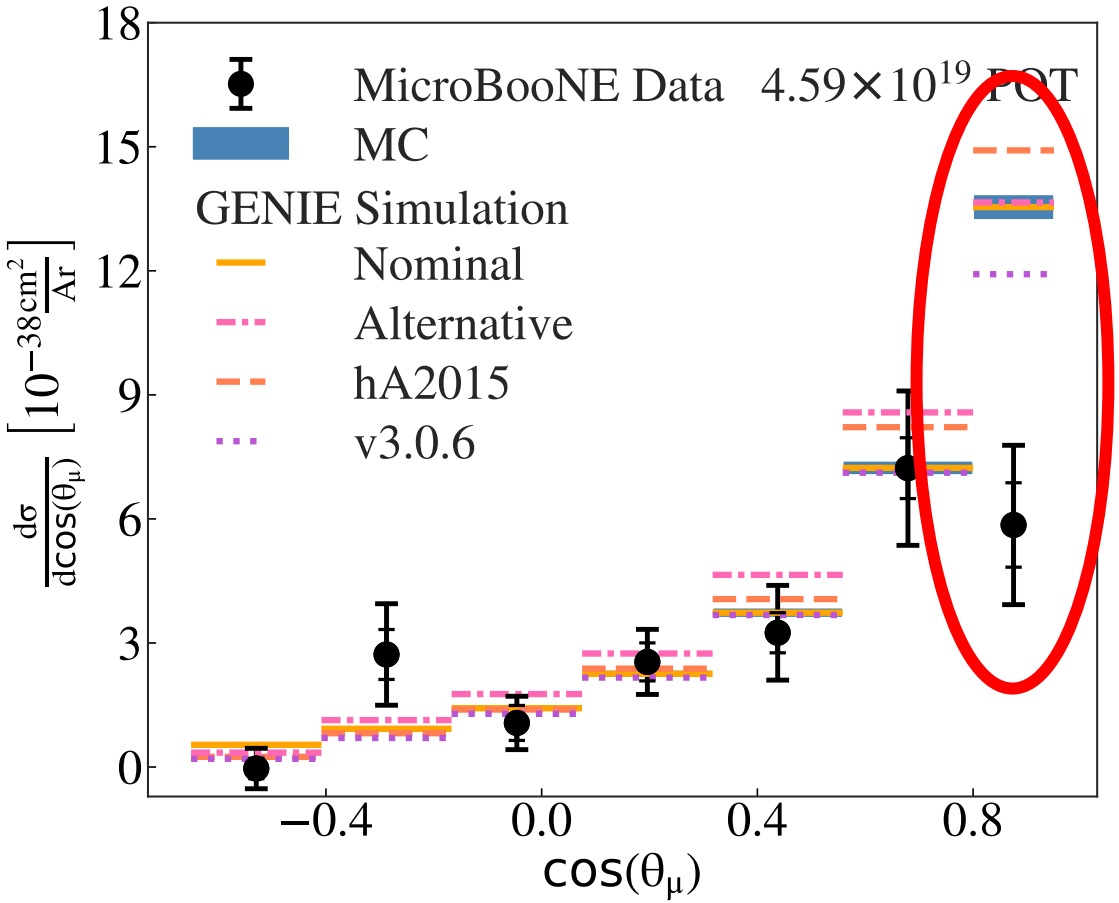
Experiment	Target	μ-dependence	p-dependence
SciBooNE	^{12}C	$d\sigma/dE_\nu$ doi: 10.1063/1.3661556	
MiniBooNE Detector 	^{12}C	$d^2\sigma/dP_\mu d\cos\theta_\mu$ Phys Rev D88 (2013)	
T2K	^{12}C, ^{16}O	$d\sigma/d\theta_\mu$ Phys Rev D92 (2015) $d^2\sigma/dP_\mu d\cos\theta_\mu$ PhysRevD.98.0124004	$d^2\sigma/dP_p d\cos\theta_p$ arXiv:1802.05078 [hep-ex]
MINERvA 	^{12}C, ^{56}Fe, ^{208}Pb	$d^2\sigma/dP_{\|} dP_T$ Phys Rev D97.052002	$d^2\sigma/dQ^2_p$ Phys Rev Lett 119 (2017)
μBooNE	^{40}Ar	$d\sigma/dP_\mu$, $d\sigma/d\cos\theta_\mu$, $d\sigma/d\varphi_\mu$	$d\sigma/dP_p$, $d\sigma/d\cos\theta_p$, $d\sigma/d\varphi_p$

First Exclusive Cross-section Measurements



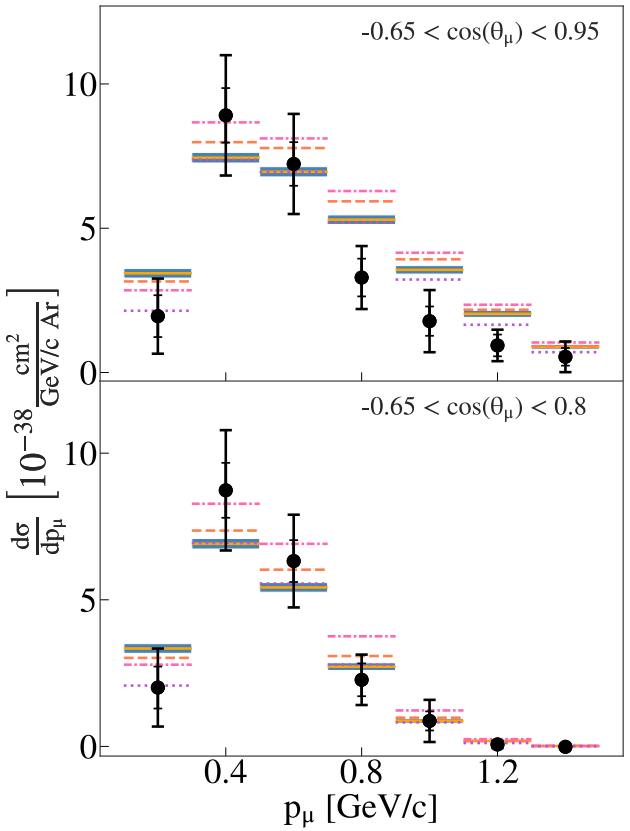
MicroBooNE PRL (2020).

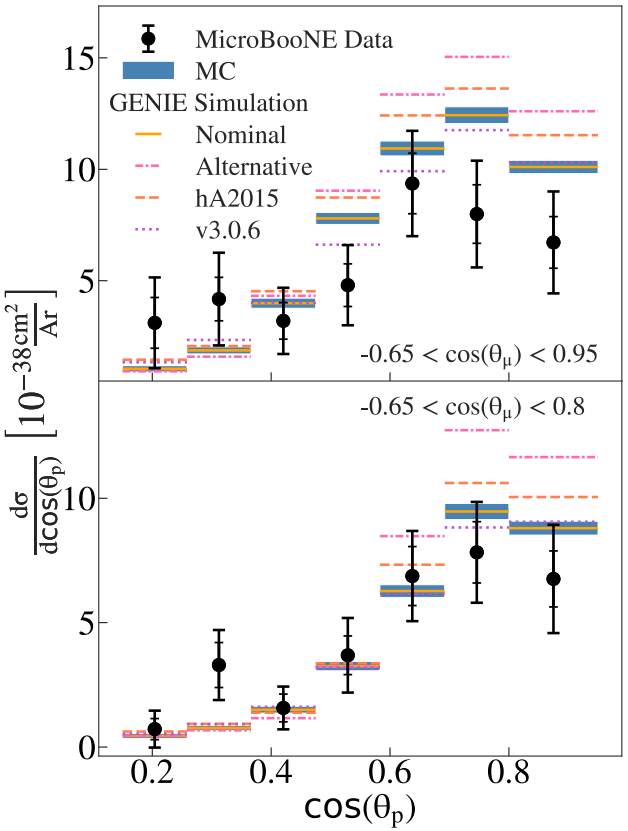
Issues at forward angles

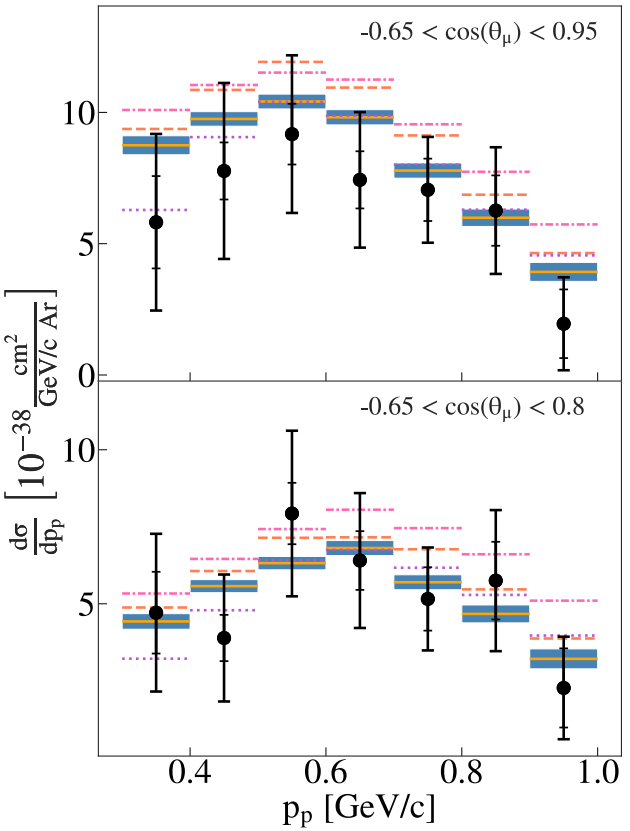


MicroBooNE PRL (2020).

Overall good agreement with theory outside small angle region

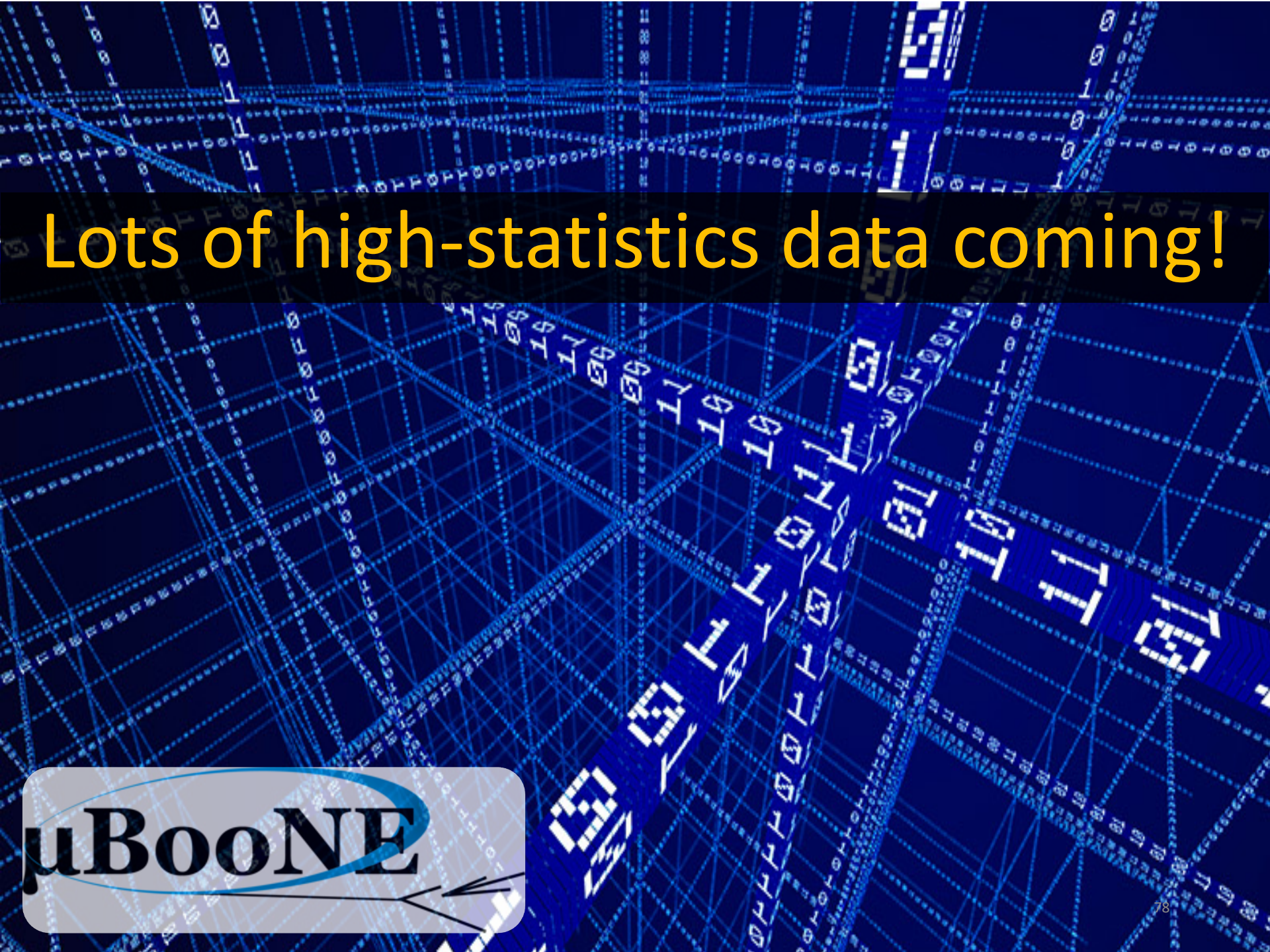






GENIE	Differential Cross Section χ^2/d.o.f	
	$-0.65 < \cos(\theta_\mu) < 0.95$	$-0.65 < \cos(\theta_\mu) < 0.8$
Nominal	63.2/28	30.1/27
hA2015	56.5/28	25.4/27
Alternative	51.2/28	33.7/27
v3.0.6	34.6/28	21.4/27

MicroBooNE PRL (2020).


Lots of high-statistics data coming!
μBooNE

MITAU MicroBooNE Group

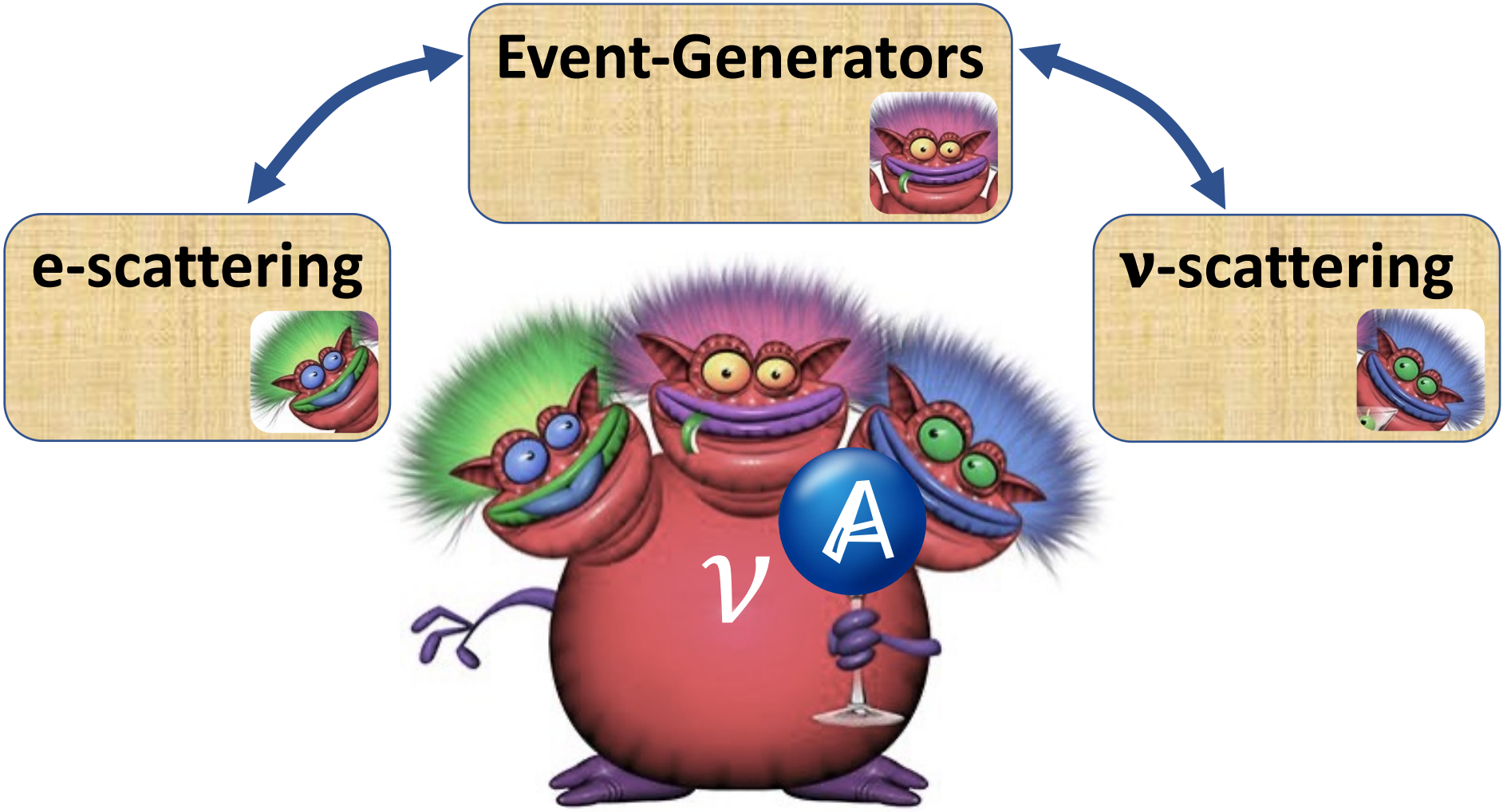
Dr. Adi Ashkenazi

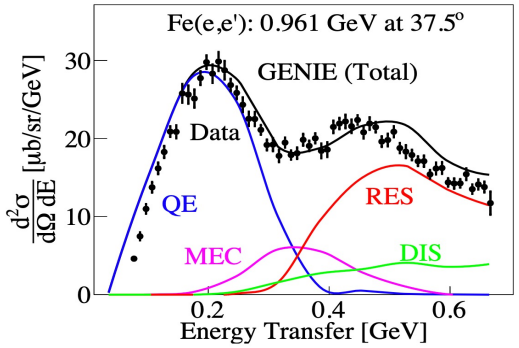
Afroditi Papadopoulou

Dr. Josh Barrow

μBooNE

New Paradigm for *Precision* Oscillation Studies





PRD (2021)

Event-Generators

Nature (2021)

e-scattering

PRL (2020)

ν-scattering