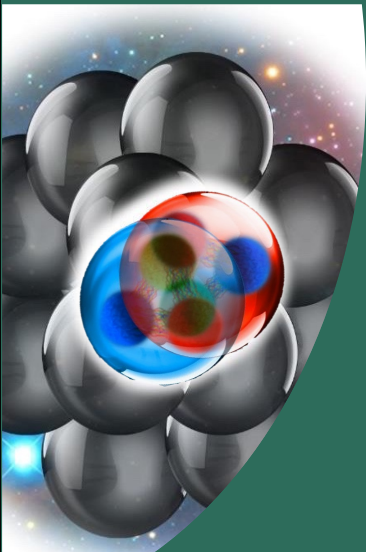
Electrons-for-Neutrinos: Trailblazing precision oscillation measurements

Or Hen (MIT)

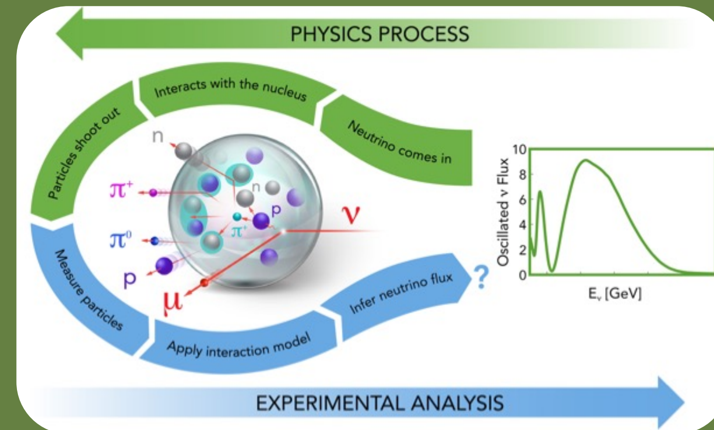
Hen Lab
Laboratory for Nuclear Science @ MIT

e4ν
μBooNE

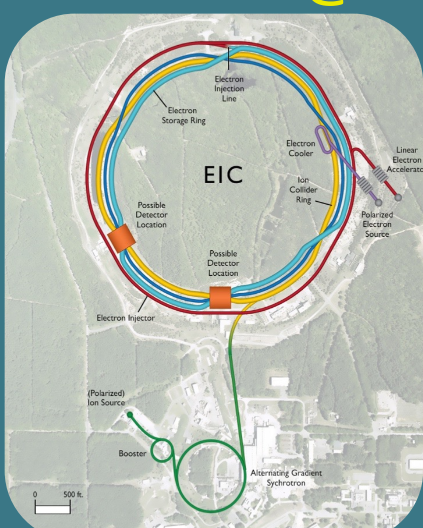
Correlations & Hadron structure @ JLab

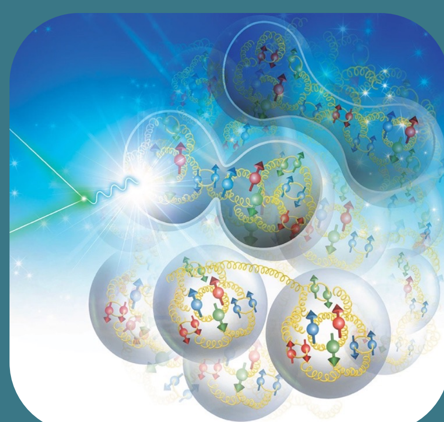


Neutrino-Nucleus Interactions @ FNAL & JLab

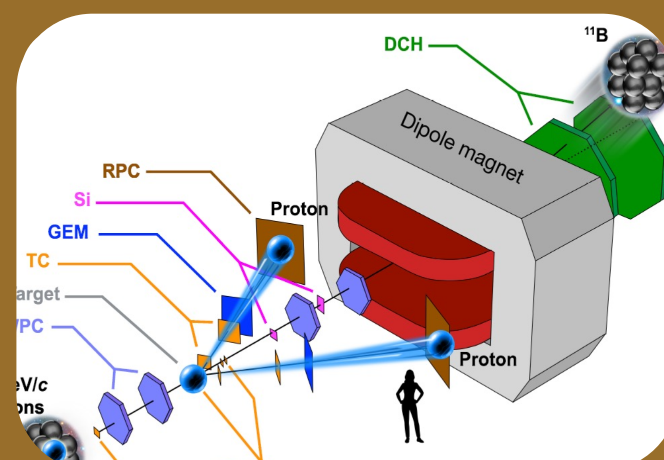


Electron-Ion Collider @ BNL





Hadronic Radioactive Matter @ GSI & JINR



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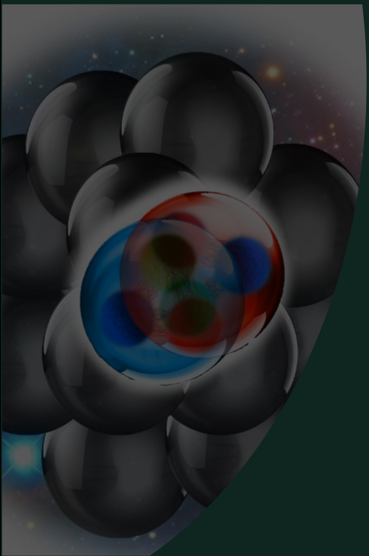

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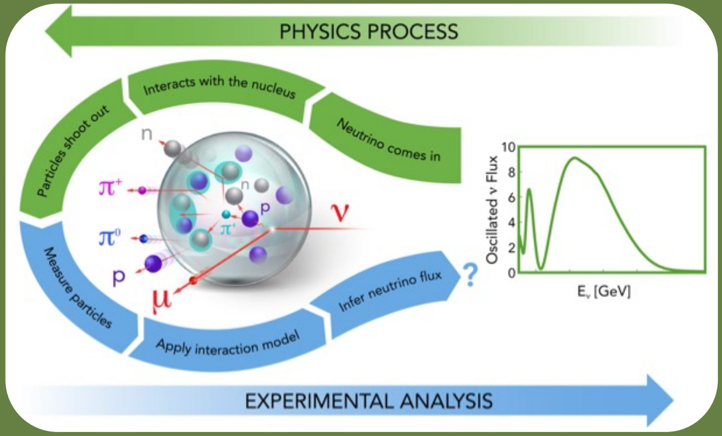

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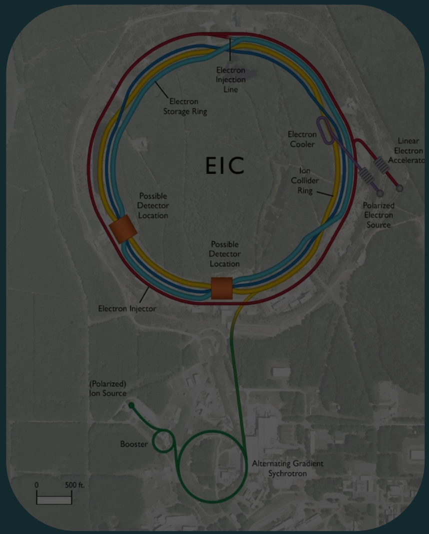

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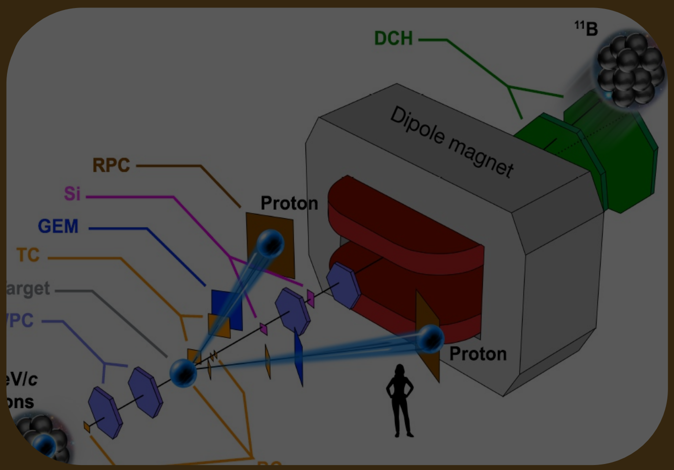
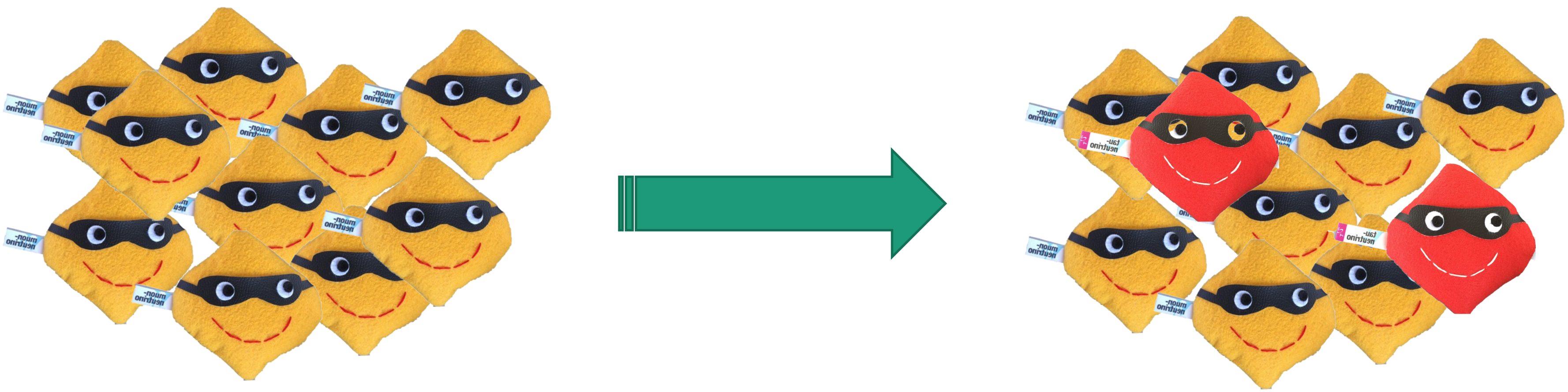
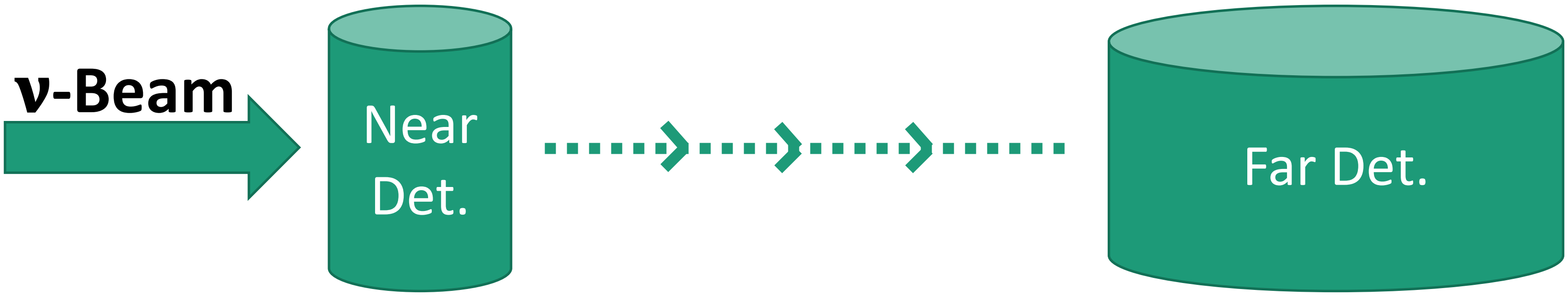
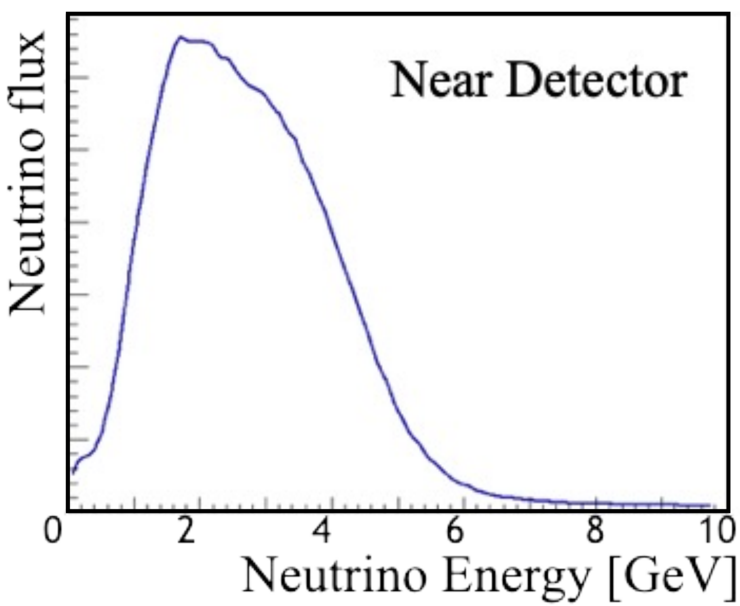


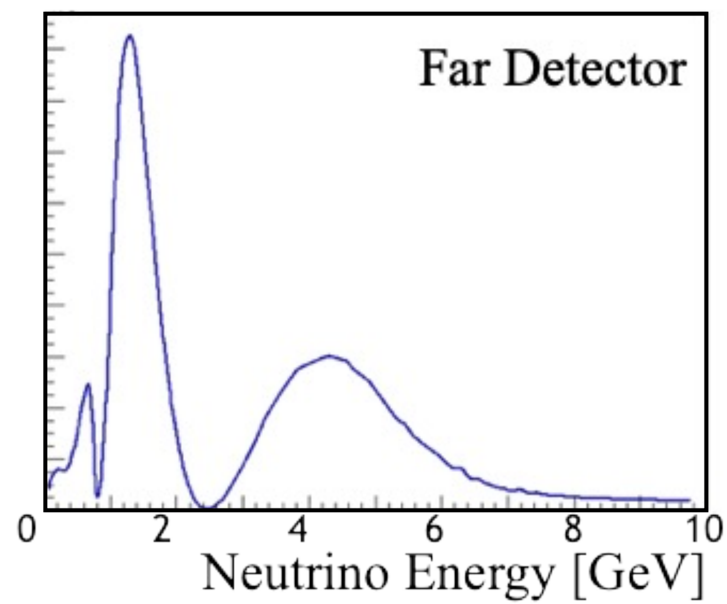
Neutrinos oscillate between flavor states when propagating through space



To observe, 'simply' measure neutrino flux at two locations

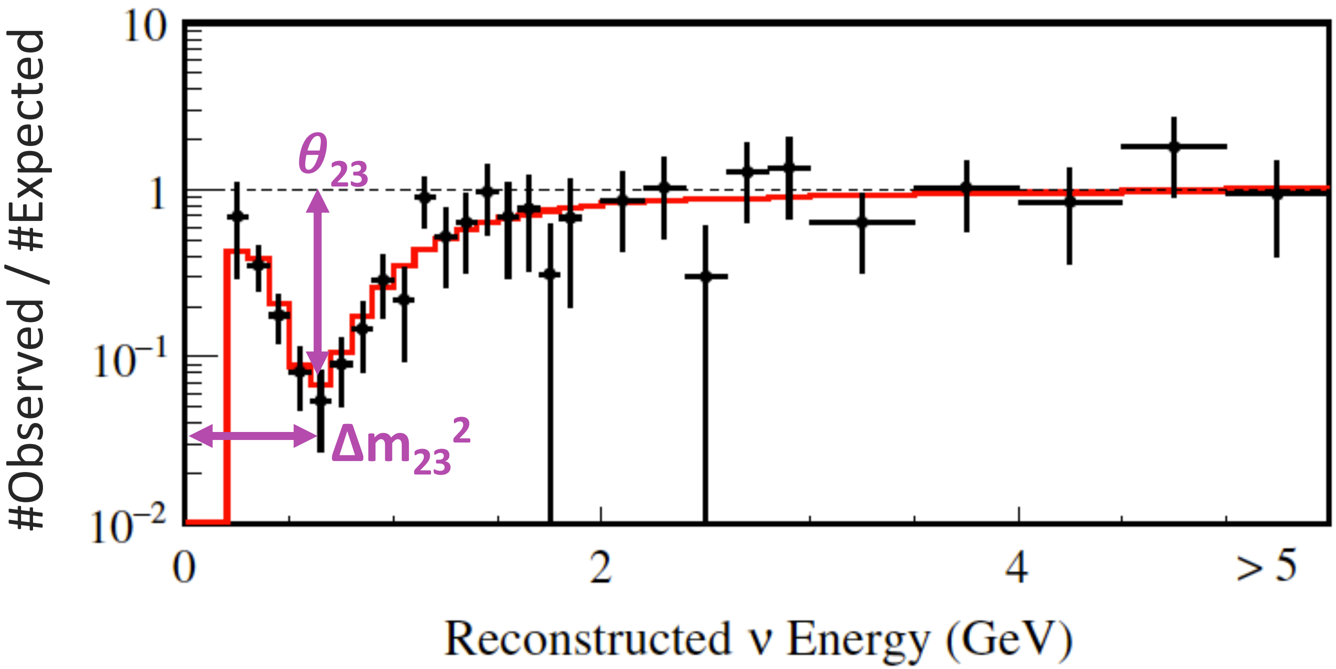






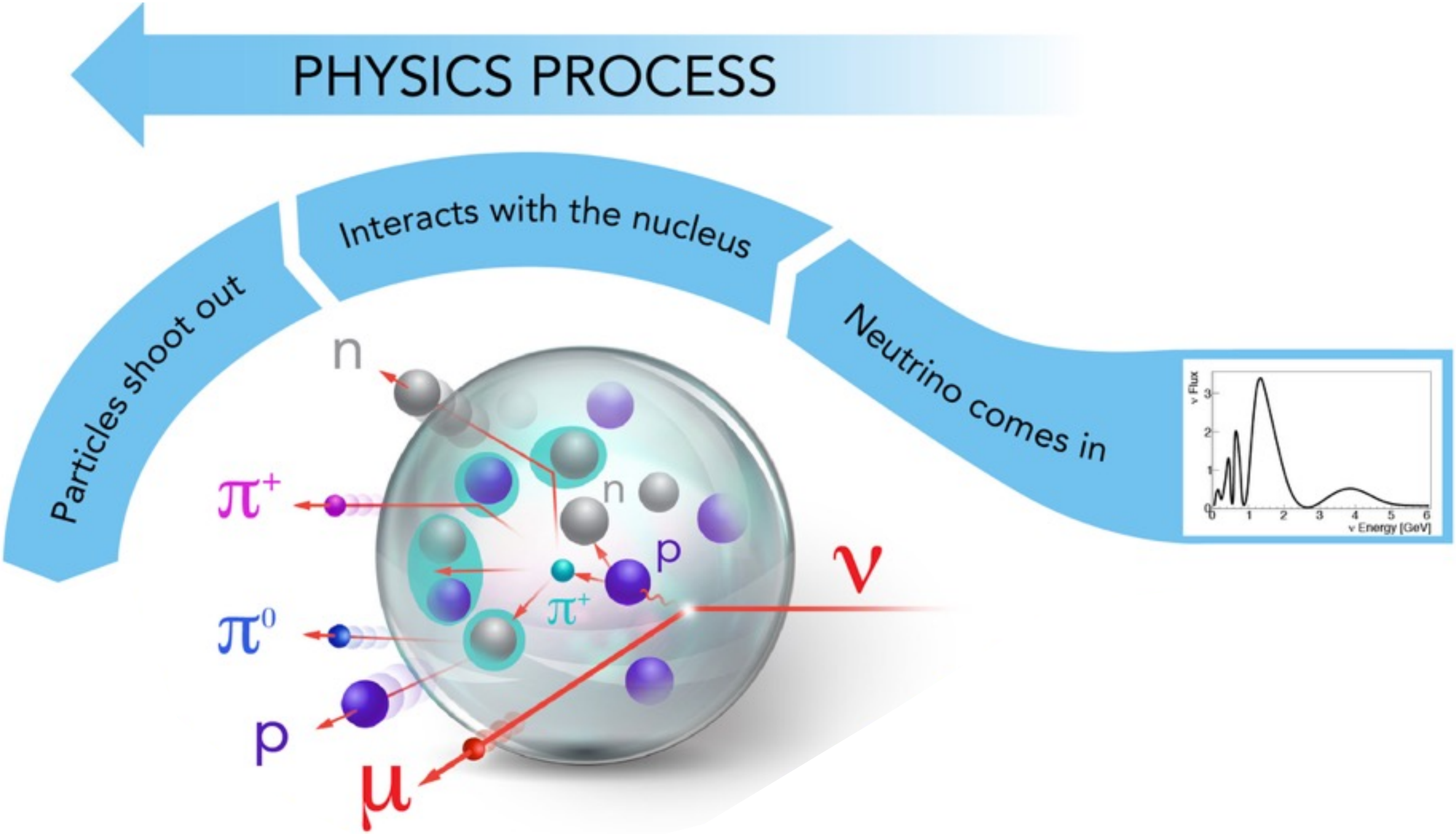
Deviation from the ‘no oscillation’ hypothesis measures the oscillation parameters

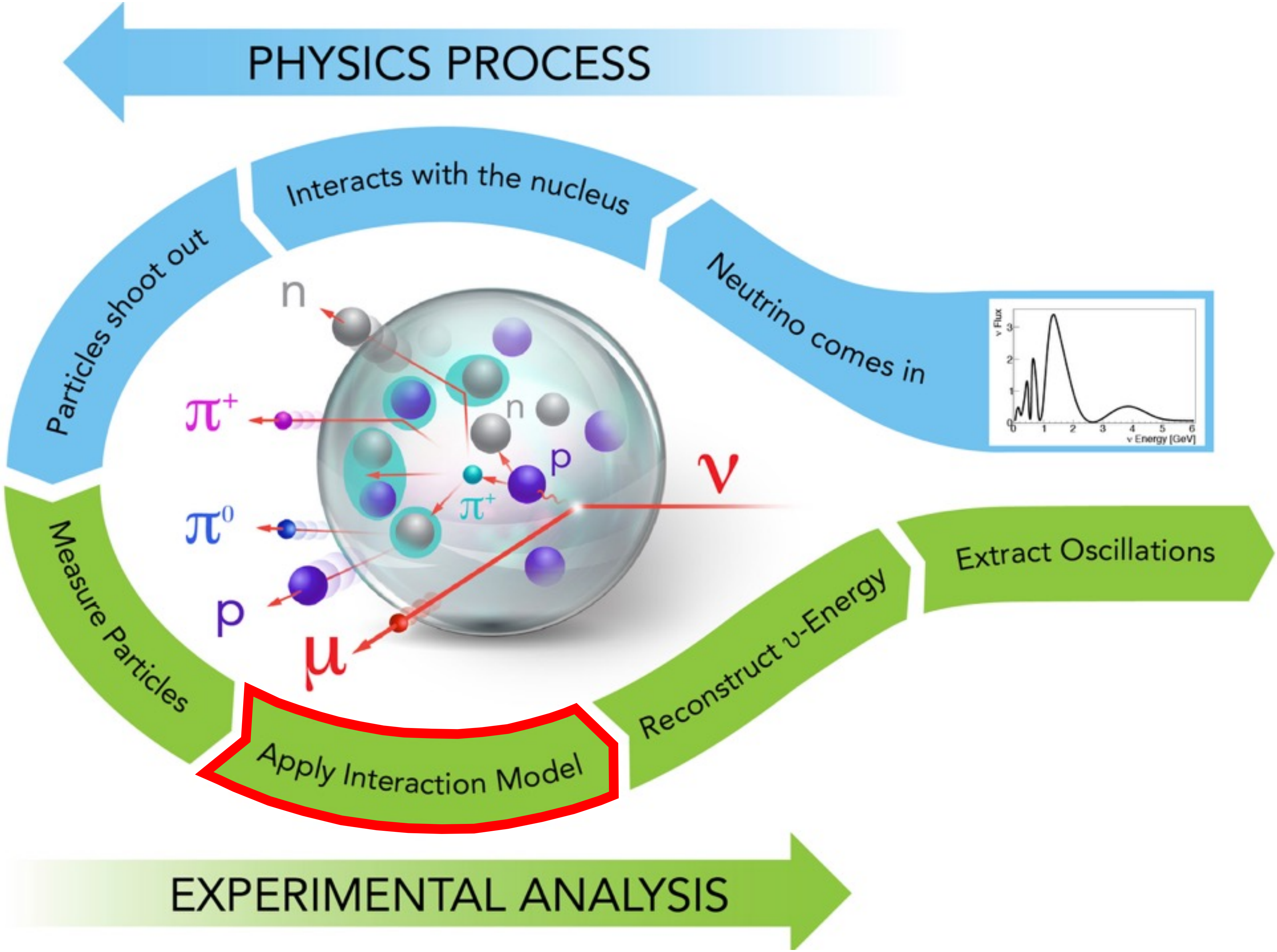
$$P(\nu_\mu \to \nu_\mu) = \sin^2(2\theta_{23}) \times \sin^2\left(\frac{\Delta m_{32}{}^2 L}{4E_\nu}\right)$$



T2K PRD (2015)

Detecting Neutrinos: The Nuclear Reality of Oscillation Measurements


PHYSICS PROCESS
Particles shoot out
Interacts with the nucleus
Neutrino comes in
ν Flux
ν Energy [GeV]
n
π+
π0
p
μ
ν
π+
p
n



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Interacts with the nucleus
Particles shoot out
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ν Flux
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n
n
p
p
π+
π+
π0
ν
μ
Measure Particles
Apply Interaction Model
Reconstruct υ-Energy
Extract Oscillations
EXPERIMENTAL ANALYSIS

=> 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

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

$$\underbrace{N_\alpha(E_{rec}, L)}_{\text{Measured}} = \sum_i \int \underbrace{\Phi_\alpha(E, L)}_{\text{Wanted}} \underbrace{\sigma_i(E) f_{\sigma_i}(E, E_{rec})}_{\text{Theory Input}} dE$$

Near Detector Constraints:

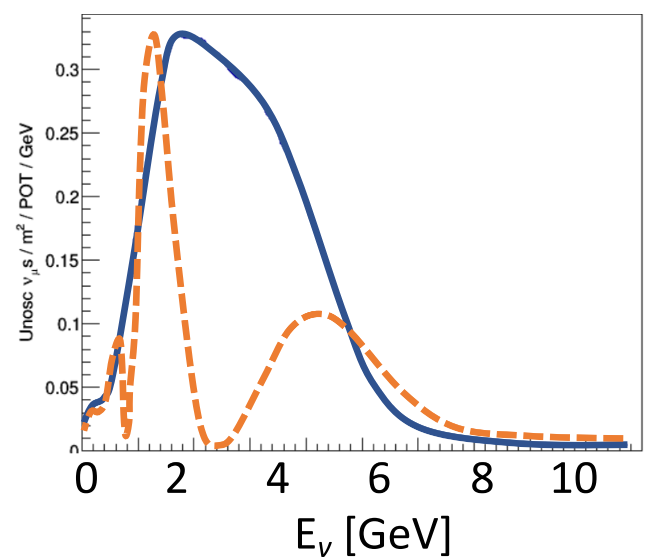
- ➔ No oscillations @ L=0
- ➔ ϕ(E, L=0) known
- ➔ use to constrain σ(E) & $f_\sigma(E,E_{rec})$

=> 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

WARNING: near detector offers integral constrain with different flux from far detector



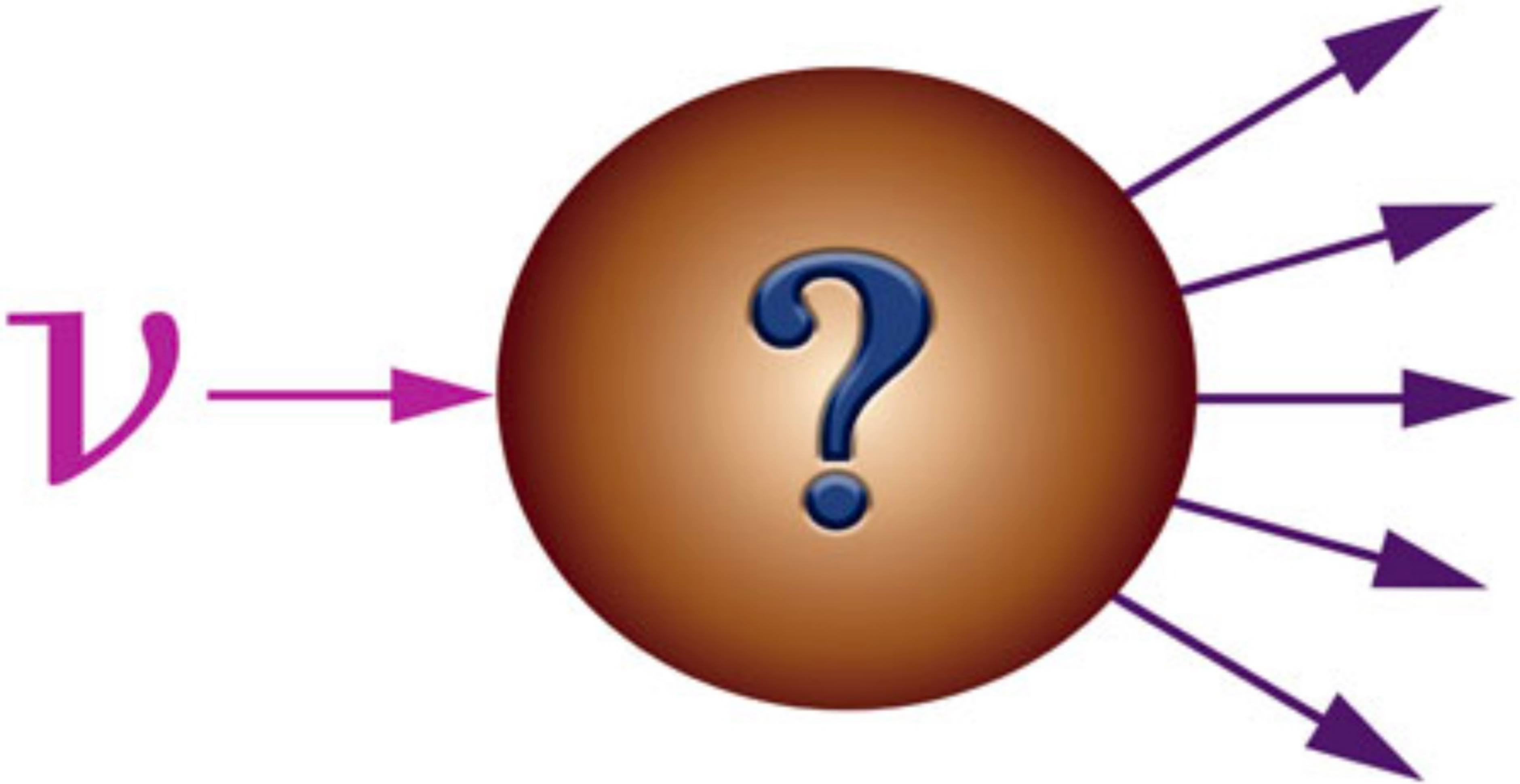
Interaction theory already main systematic!

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)	$\delta n^{\mathrm{exp}}_{\mathrm{SK}} / n^{\mathrm{exp}}_{\mathrm{SK}}$ neutrino mode	$\delta n^{\mathrm{exp}}_{\mathrm{SK}} / n^{\mathrm{exp}}_{\mathrm{SK}}$ 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!



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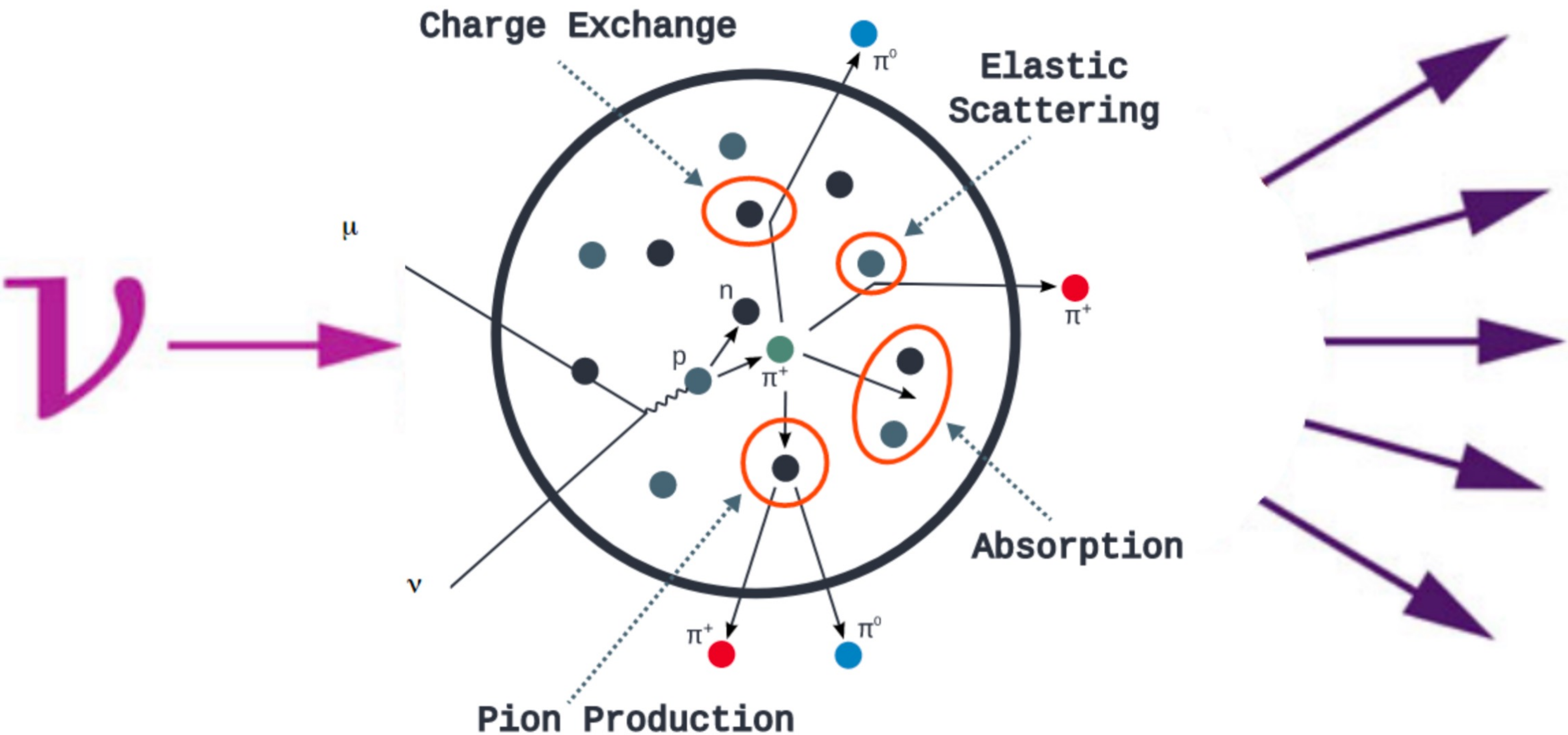
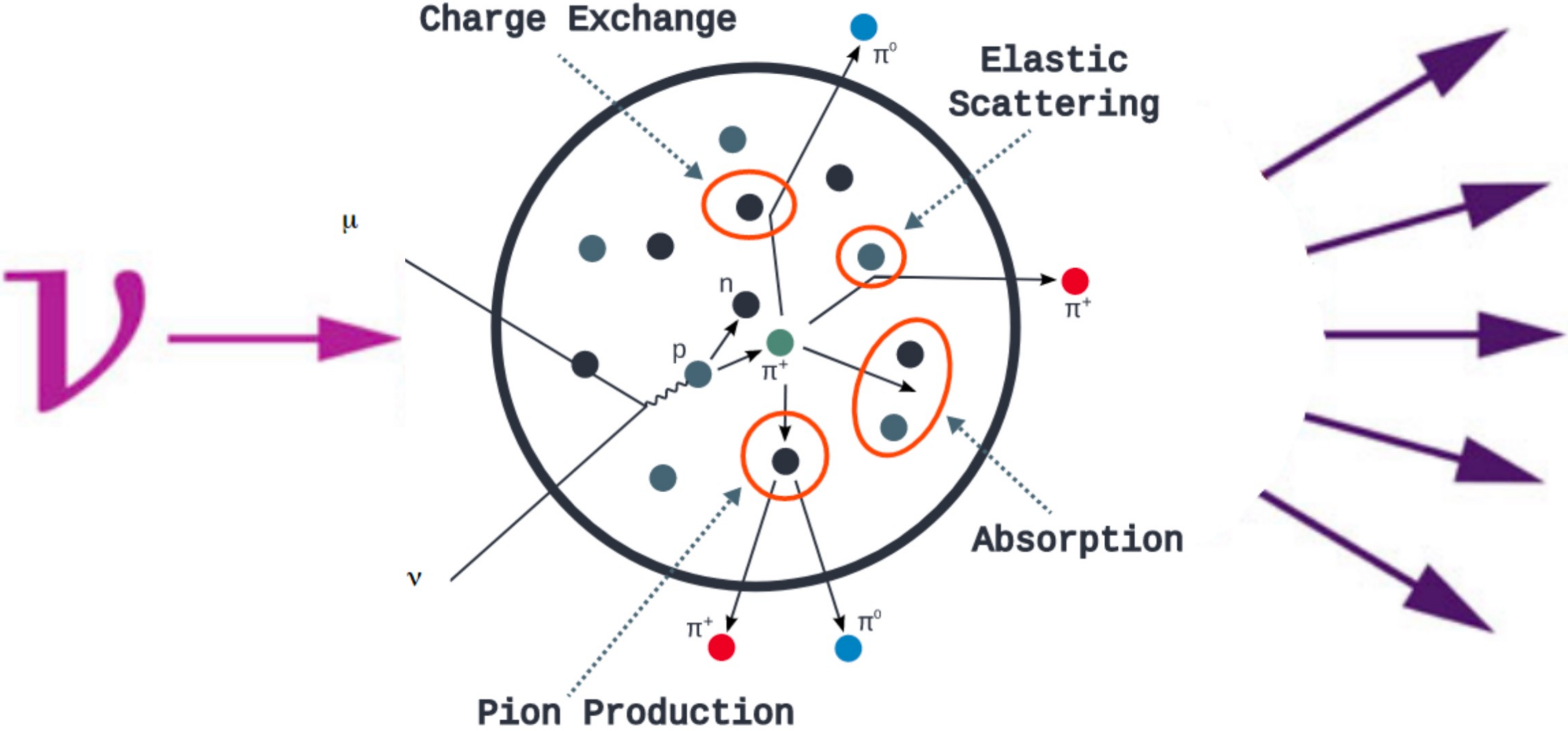


Current event-generator models are often:

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).

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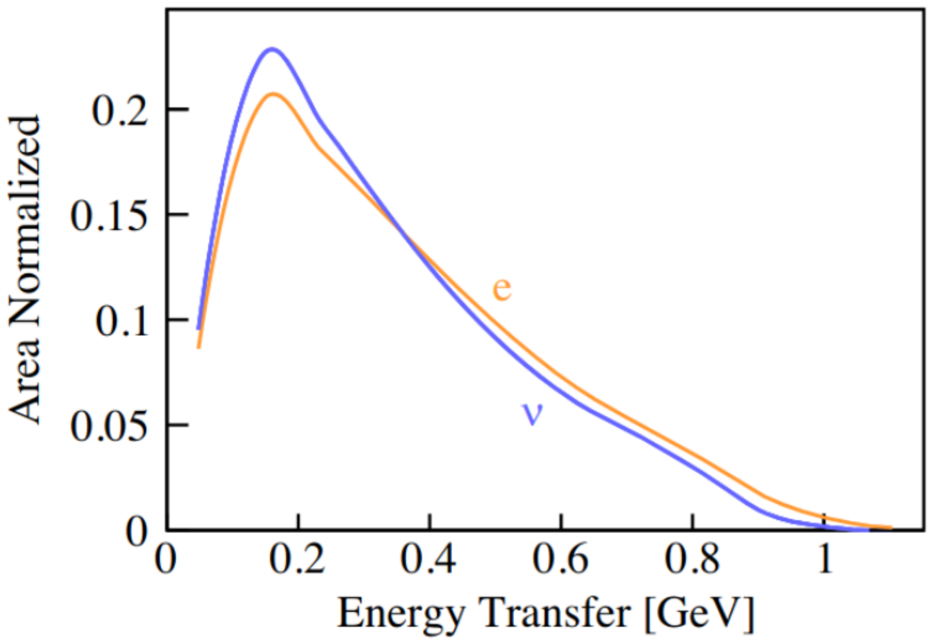

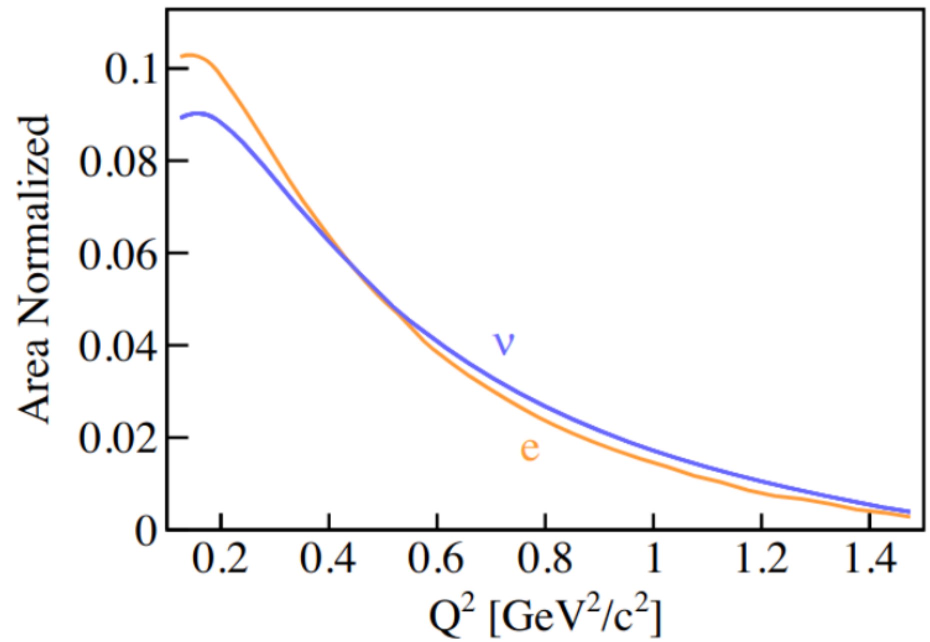

2.26 GeV on ^{12}C.

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

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

*e$^-$ scaled by Q^4

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Constrain Using Electron Scattering!

- ✓ e

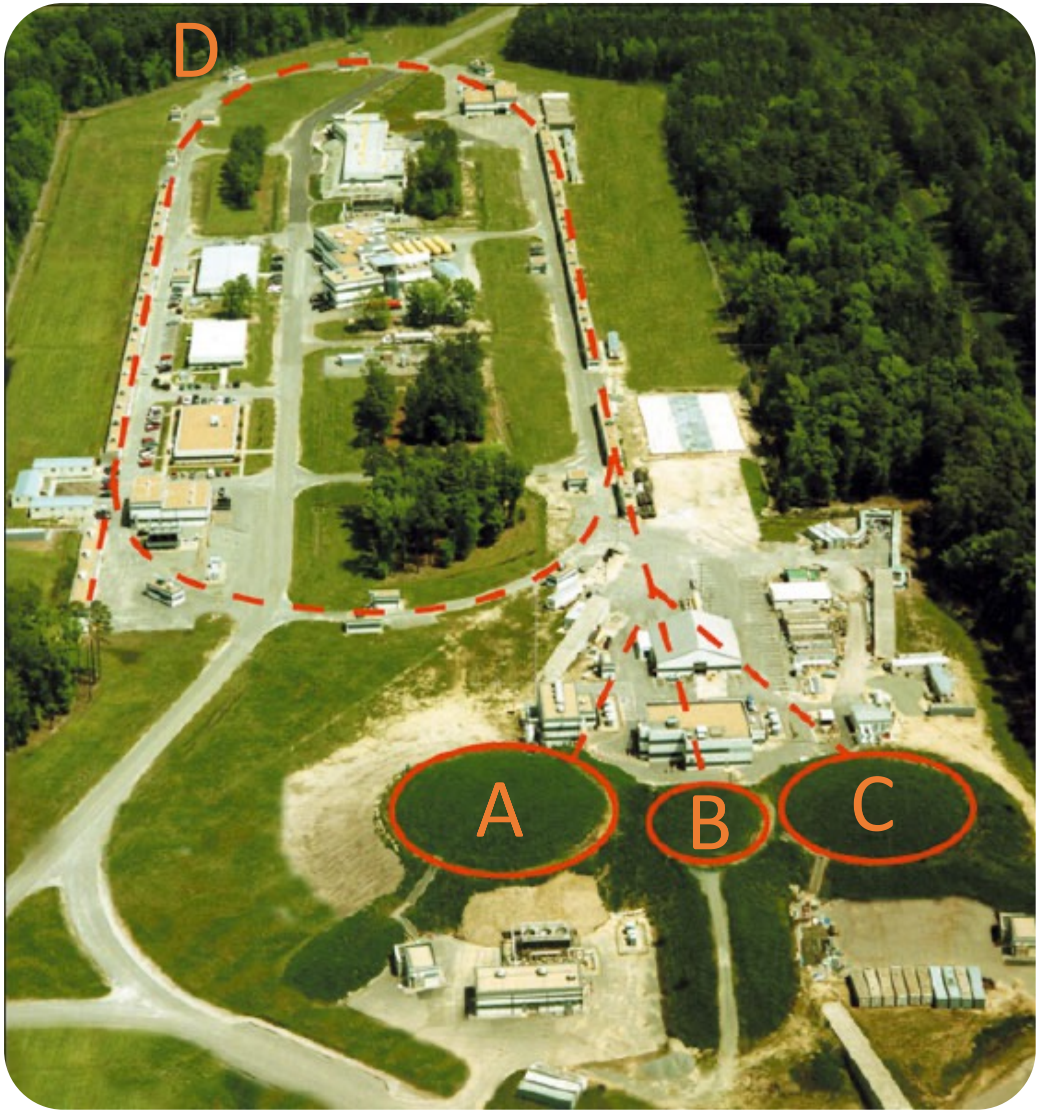
Any model must work for electrons, or it won't work for neutrinos !

- ✓ M
  (F

- ✓ e beam energy is known

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

New Old Data!

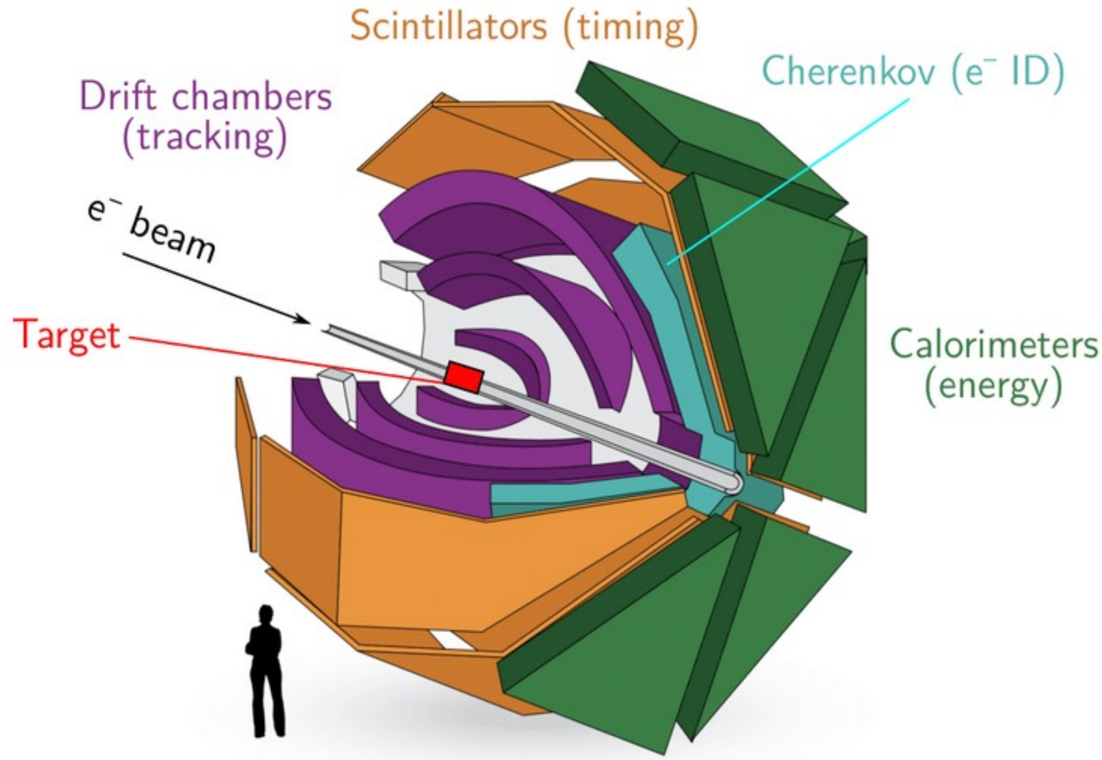


CLAS-6

✧ ~4π acceptance (almost).

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

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



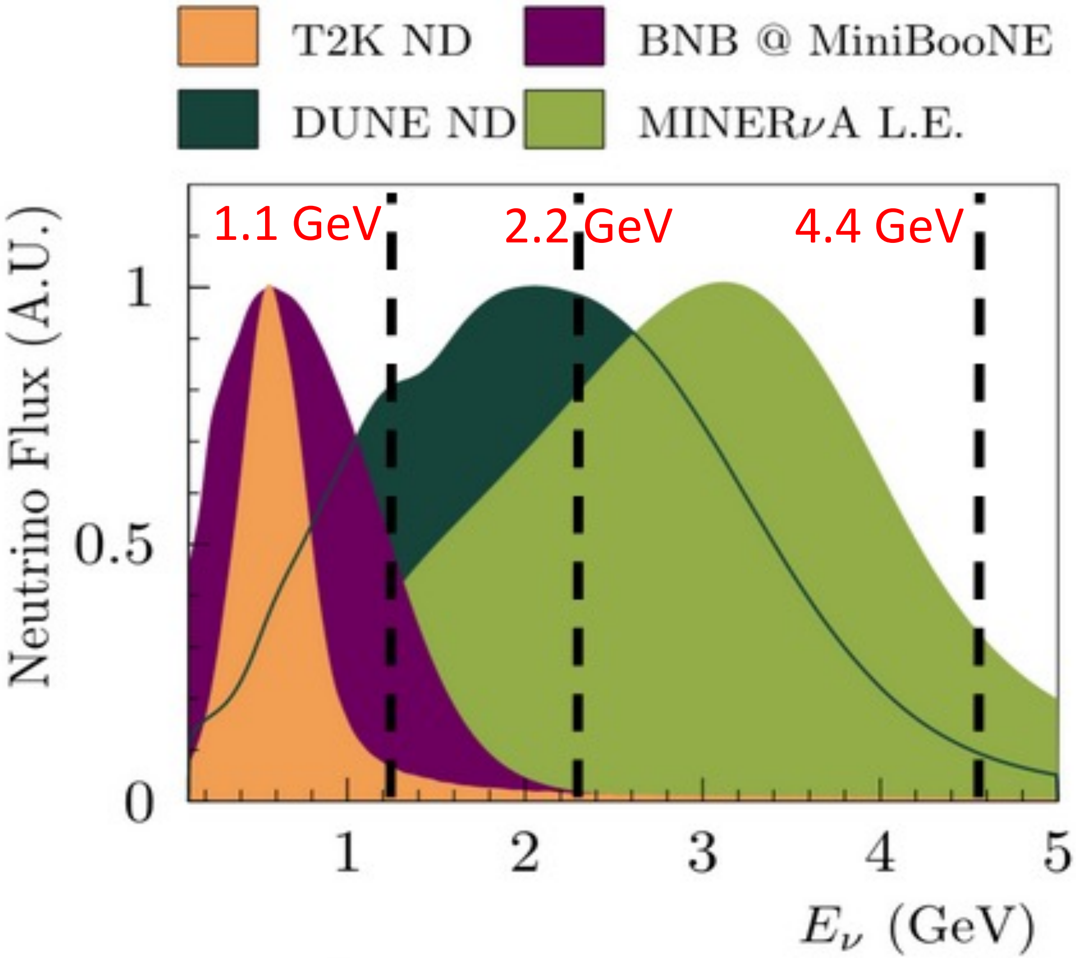
New '*Old*' Data: CLAS-6 @ JLab

Targets:

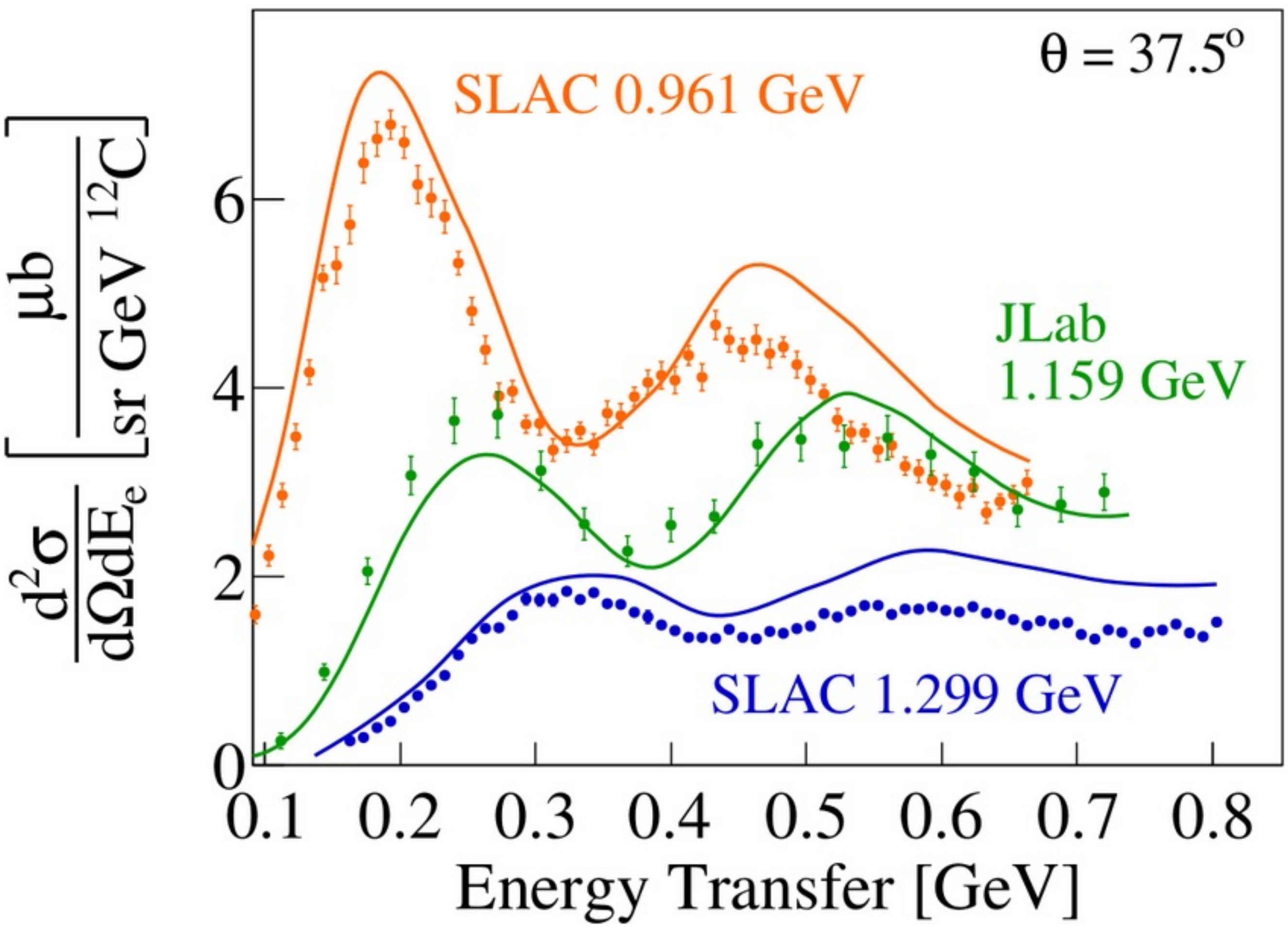
^{4}He, ^{12}C, & ^{56}Fe.

Energies:

4.4, 2.2 & 1.1 GeV.



Sanity Check: inclusive cross-sections



Playing the Neutrino Game

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

<u>Means (for QE study):</u>

- 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}),
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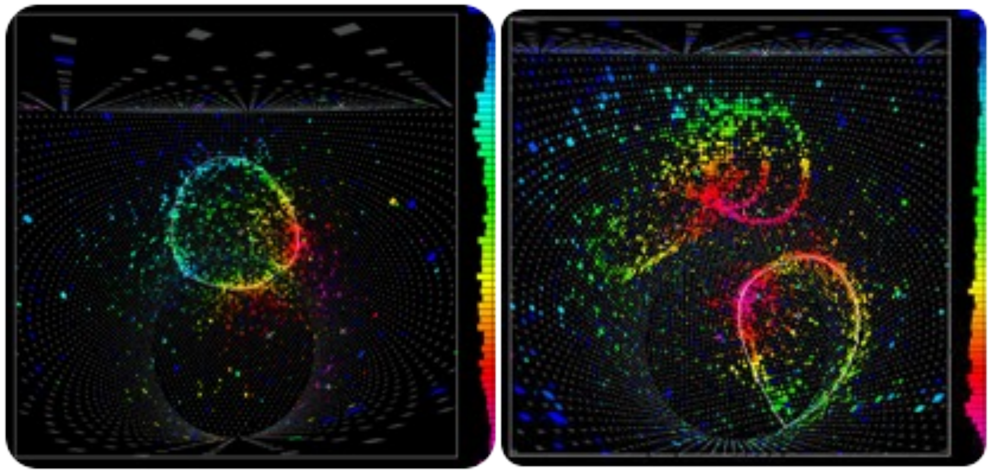
Energy Reconstruction



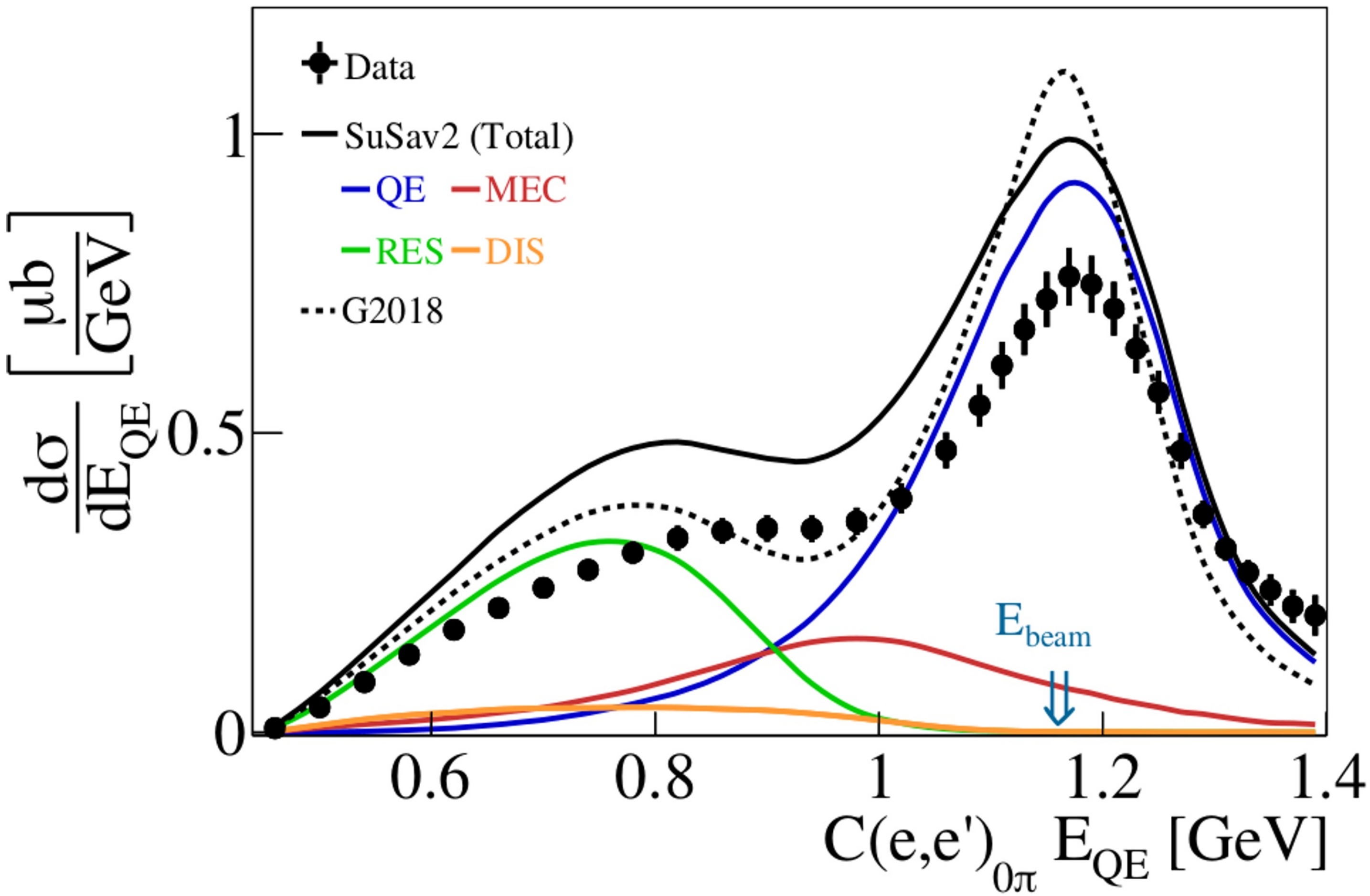
Cherenkov detectors:

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).

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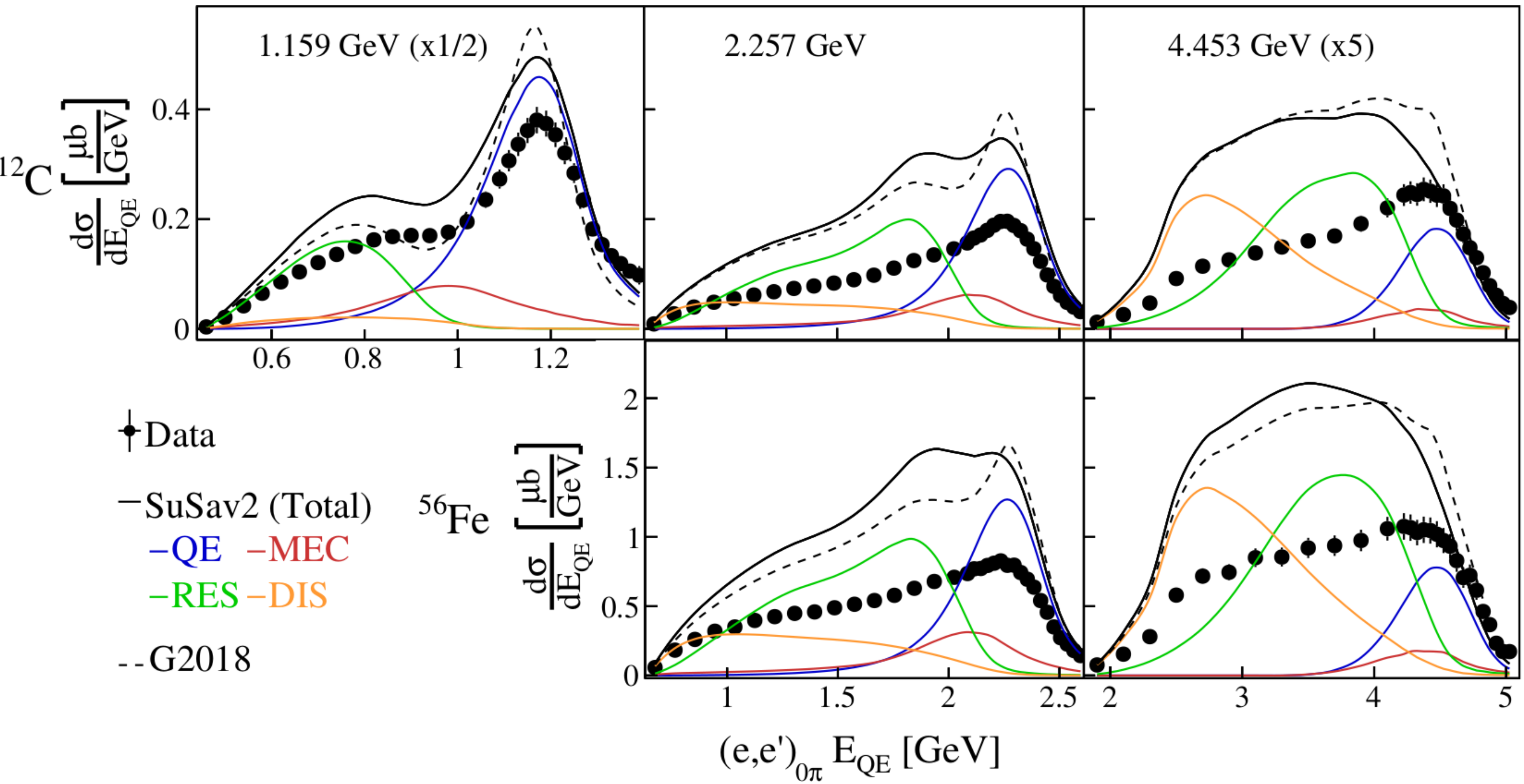

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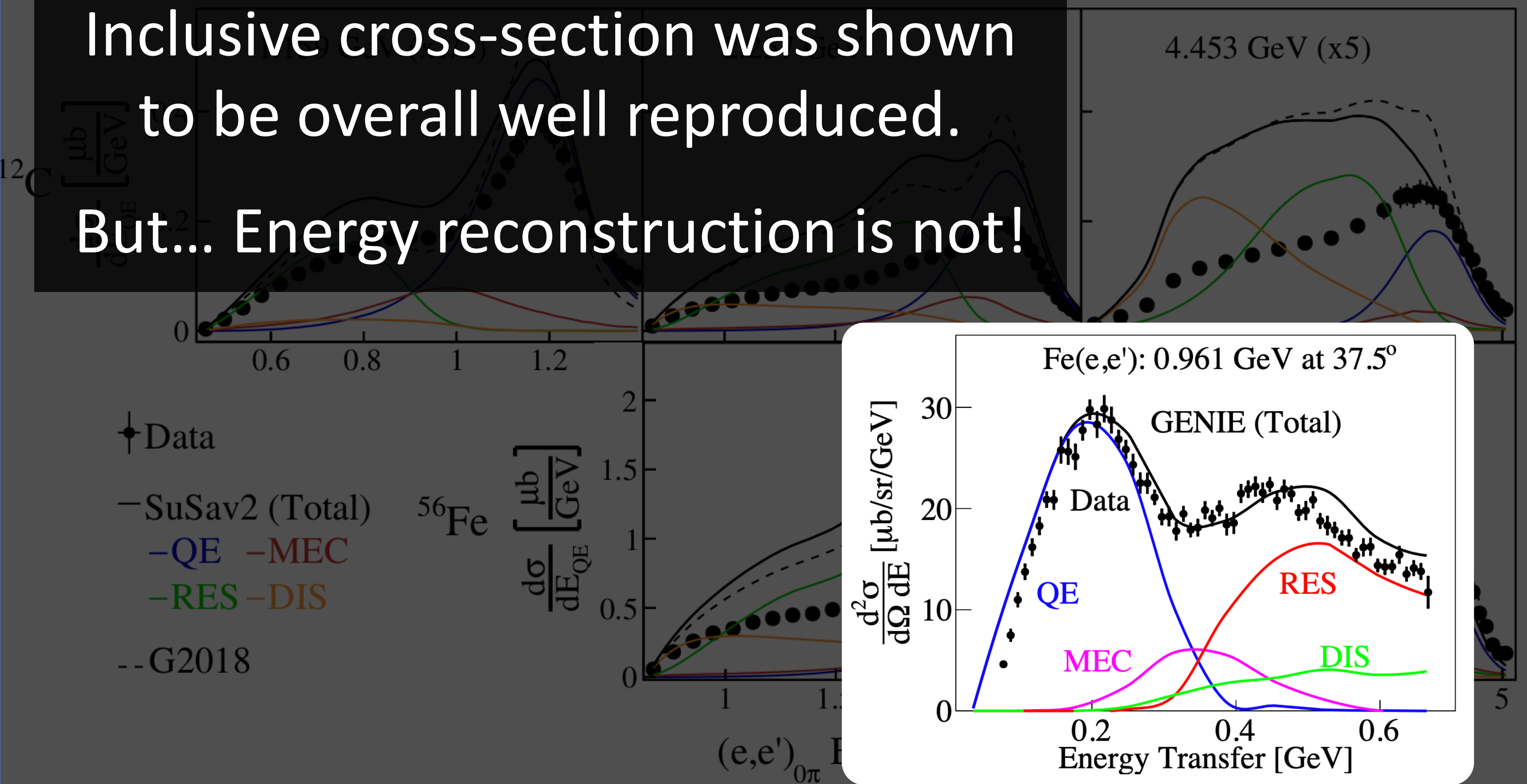
(e,e') Data-Theory Disagreements

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

But… Energy reconstruction is not!



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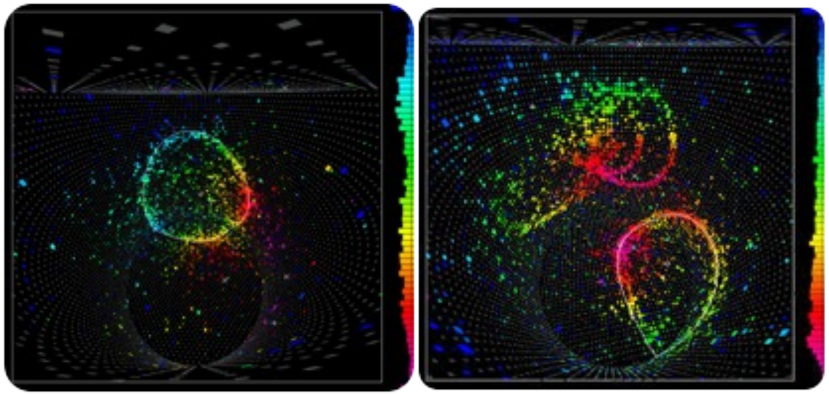

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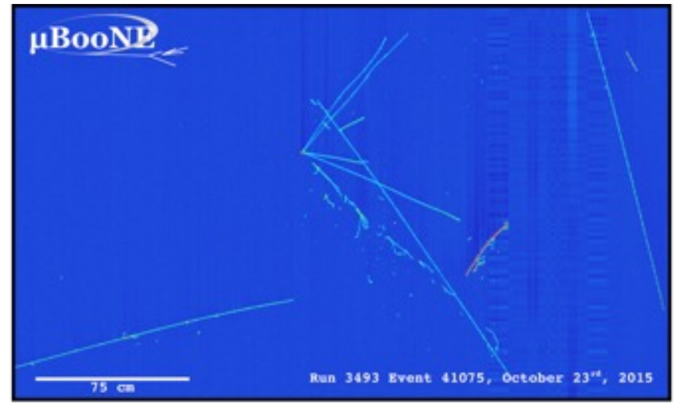
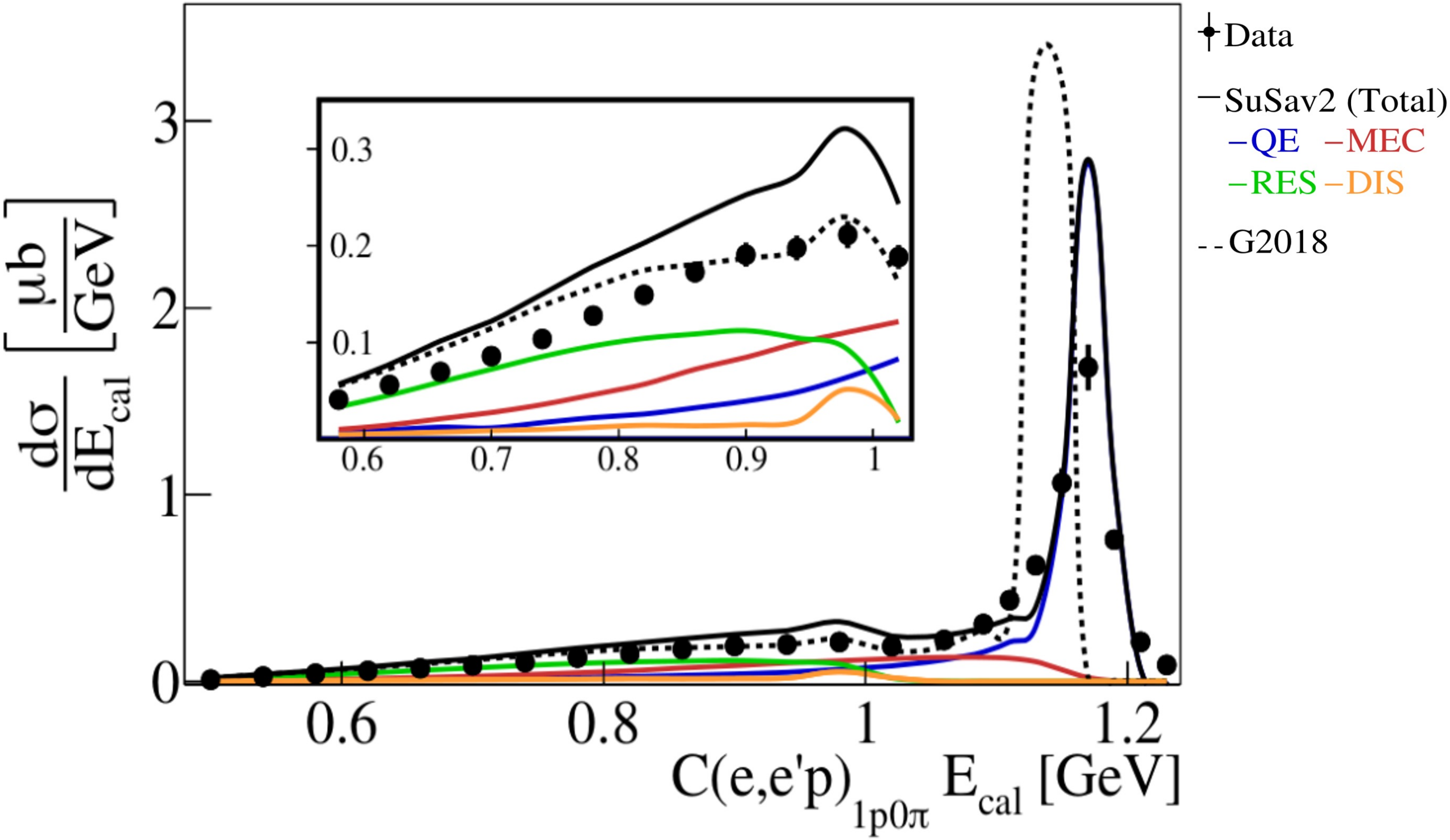


Tracking detectors:

Need good hadronic reconstruction

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

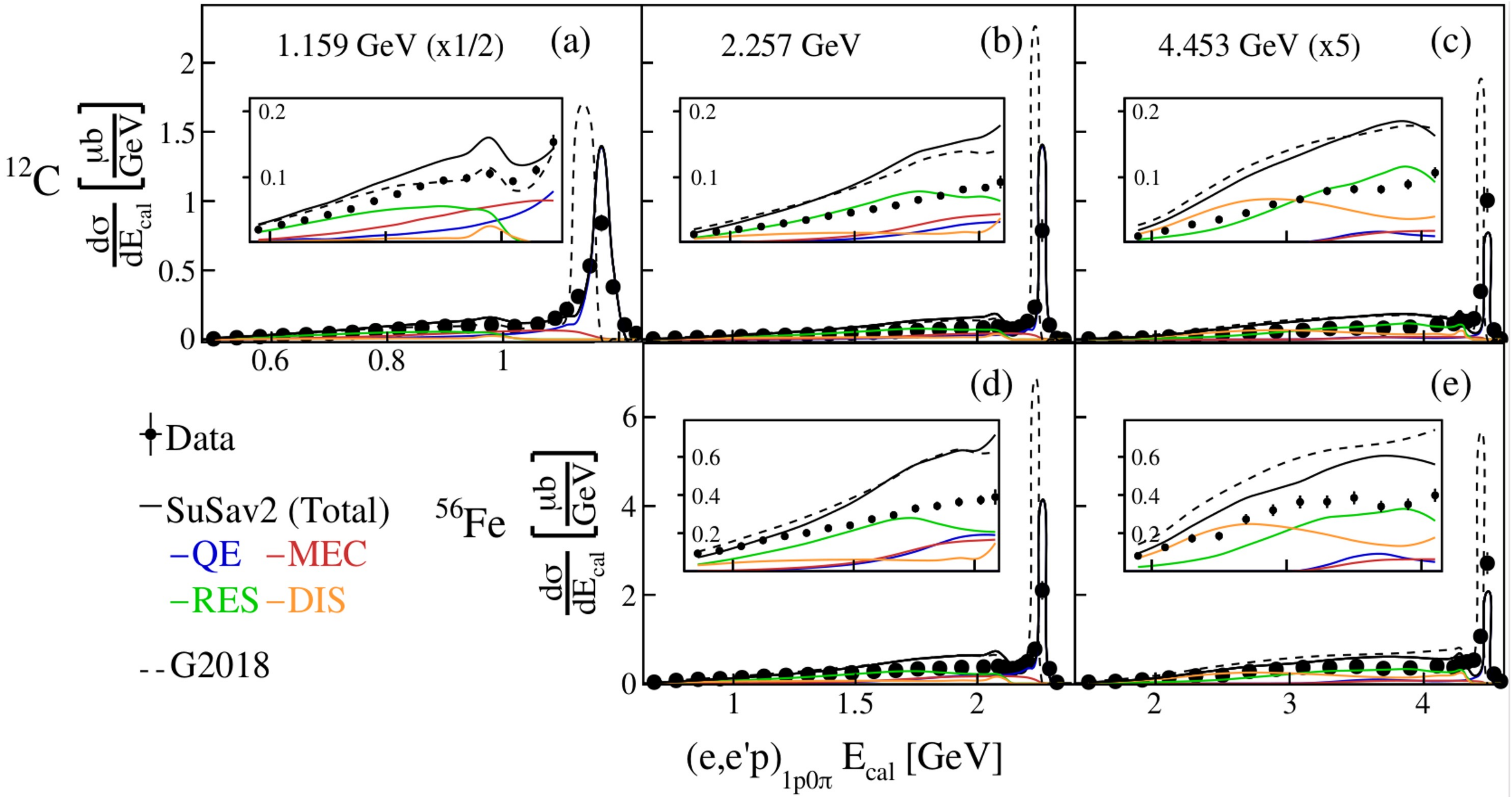
(e,e'p) Energy Reconstruction



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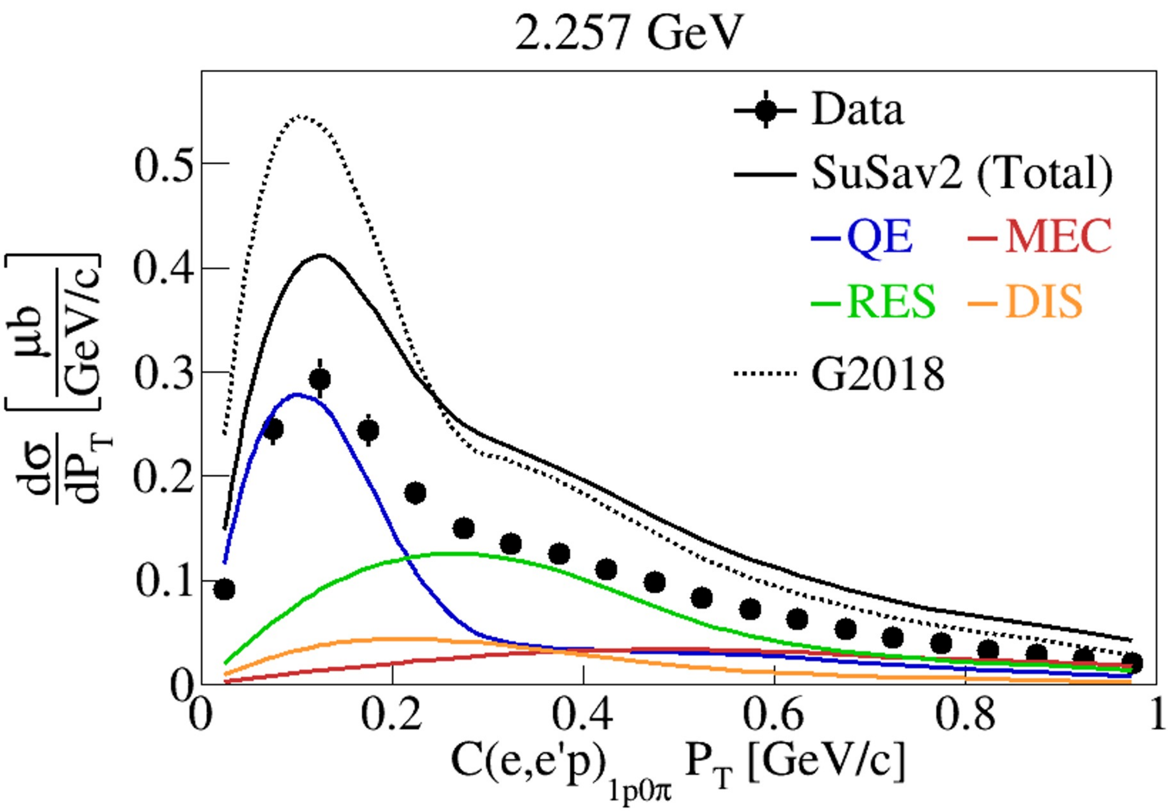
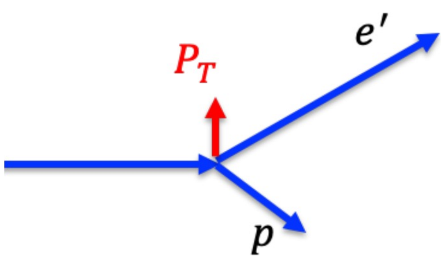
$$E_{cal} = E_l + T_p + \epsilon$$

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).

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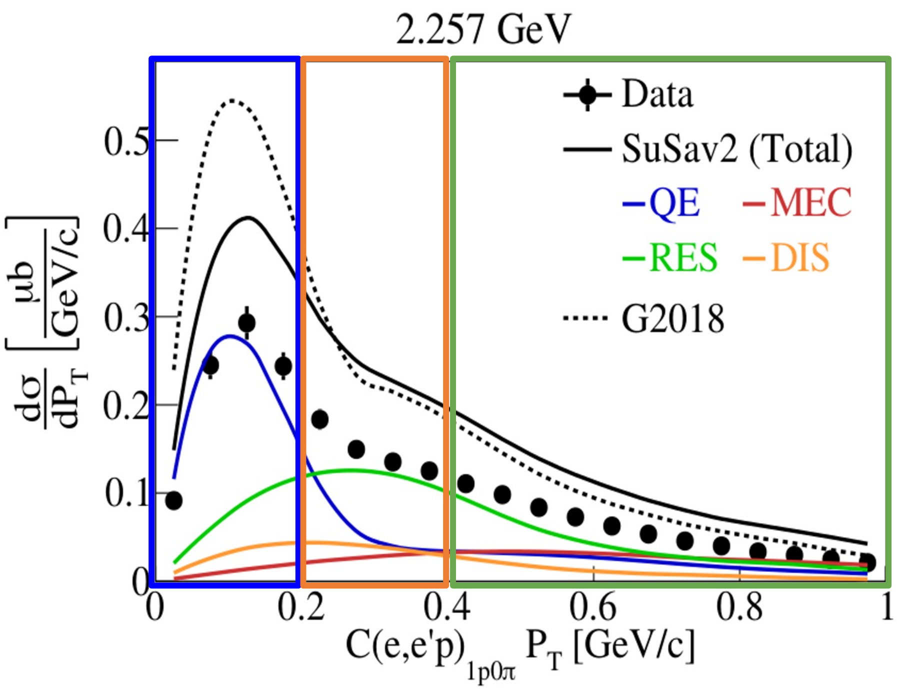
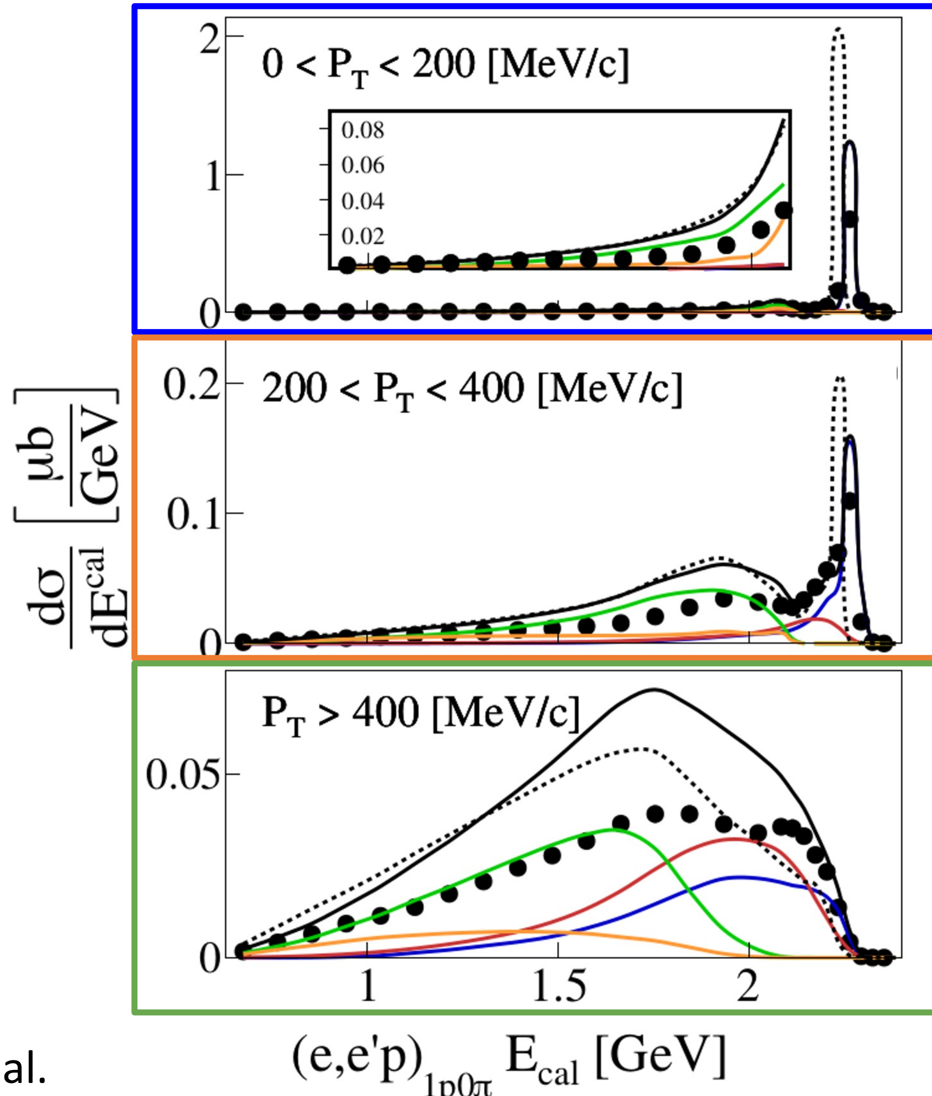
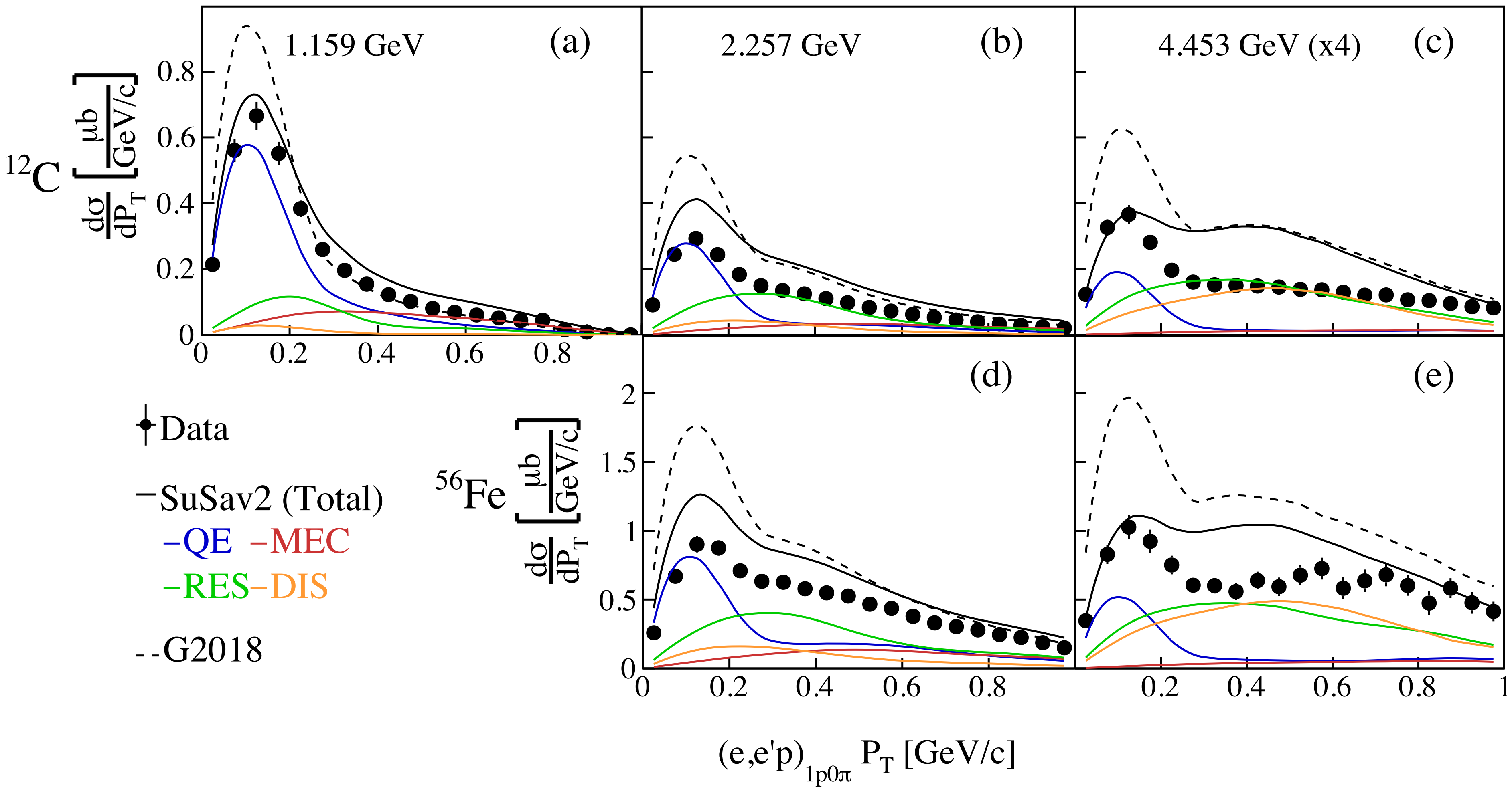




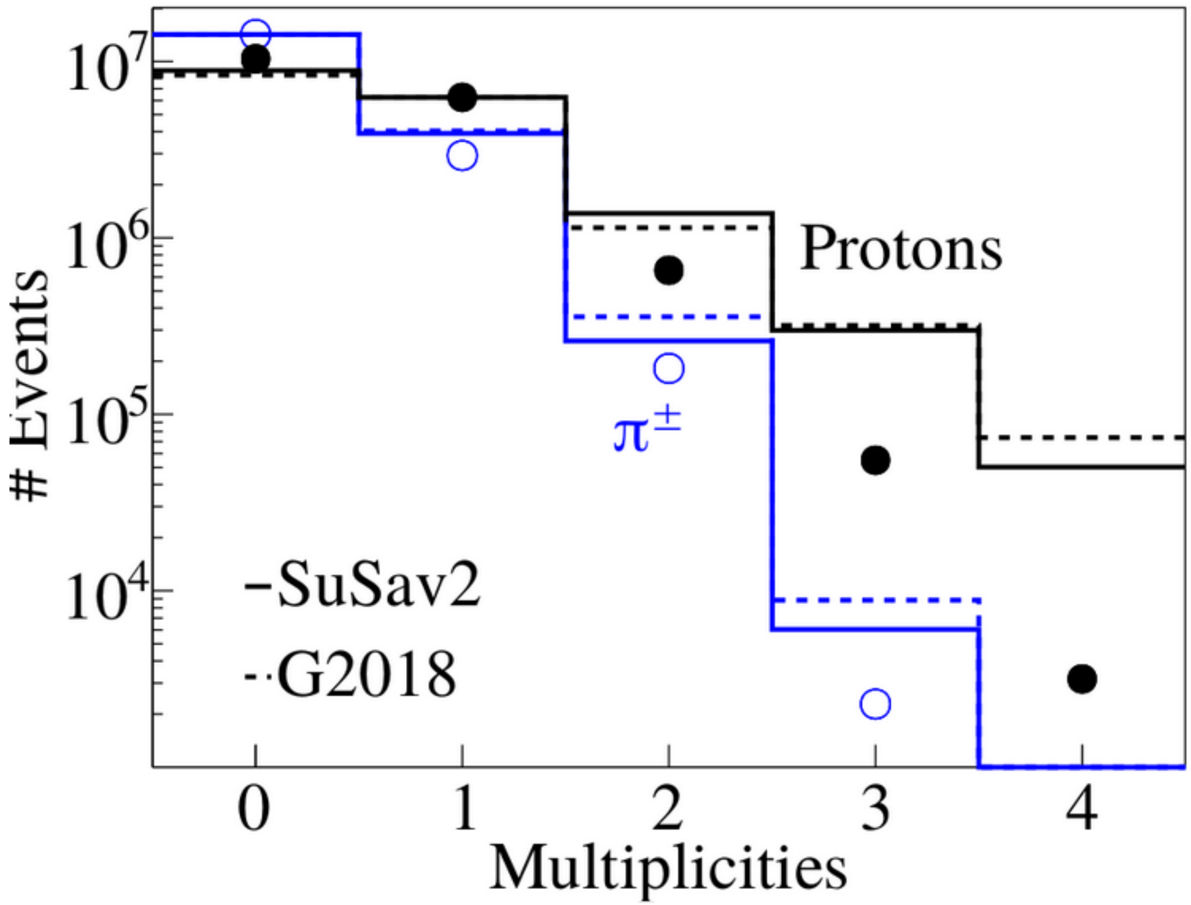
Khachatryan, Papadopoulou, and Ashkenazi et al. (CLAS & e4v collaborations), Nature **599**, 565 (2021).

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).

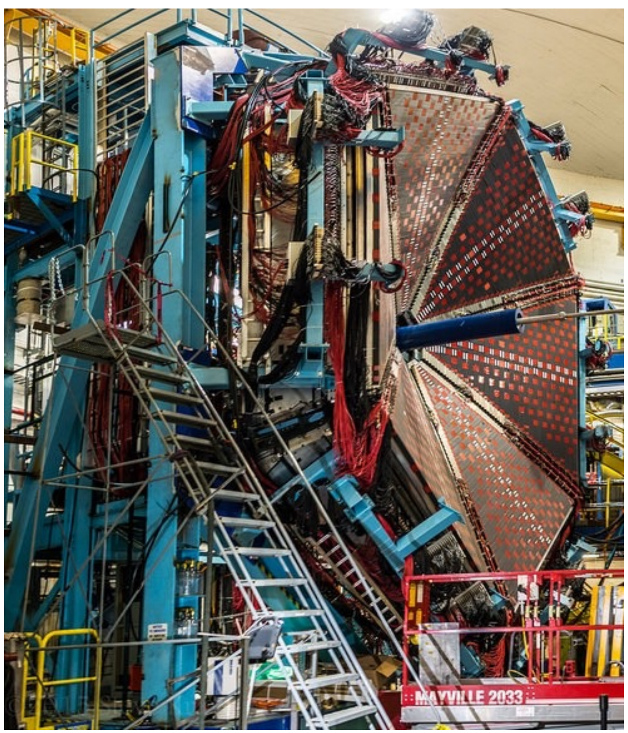
Newly Measured CLAS-12 data

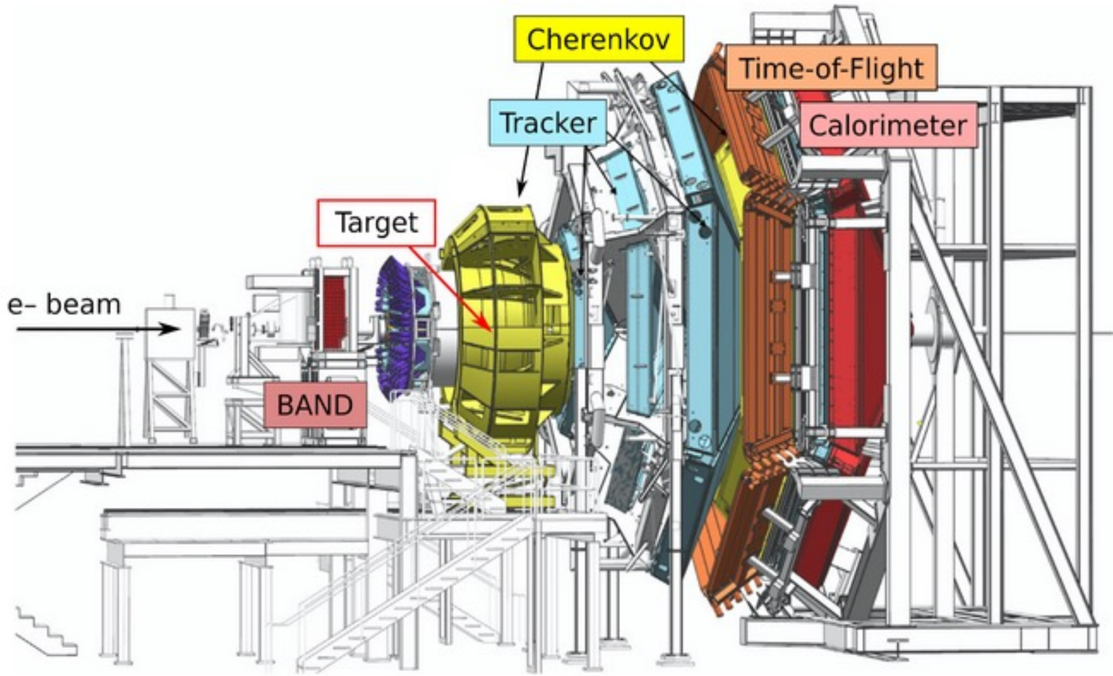
Targets:

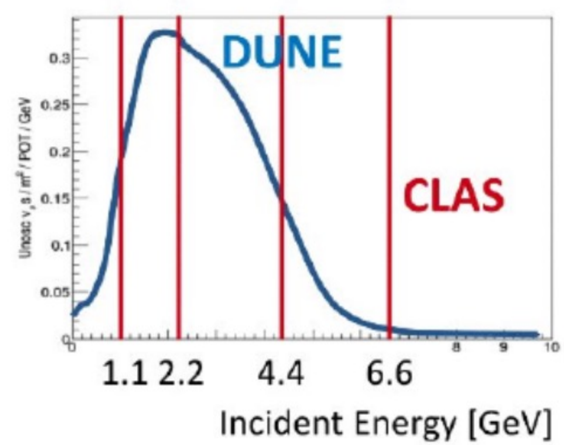
^{4}He, ^{12}C, ^{16}O, ^{40}Ar, ^{120}Sn

Beam Energies:

1.1, 2.2, 4.4, 6.6 GeV





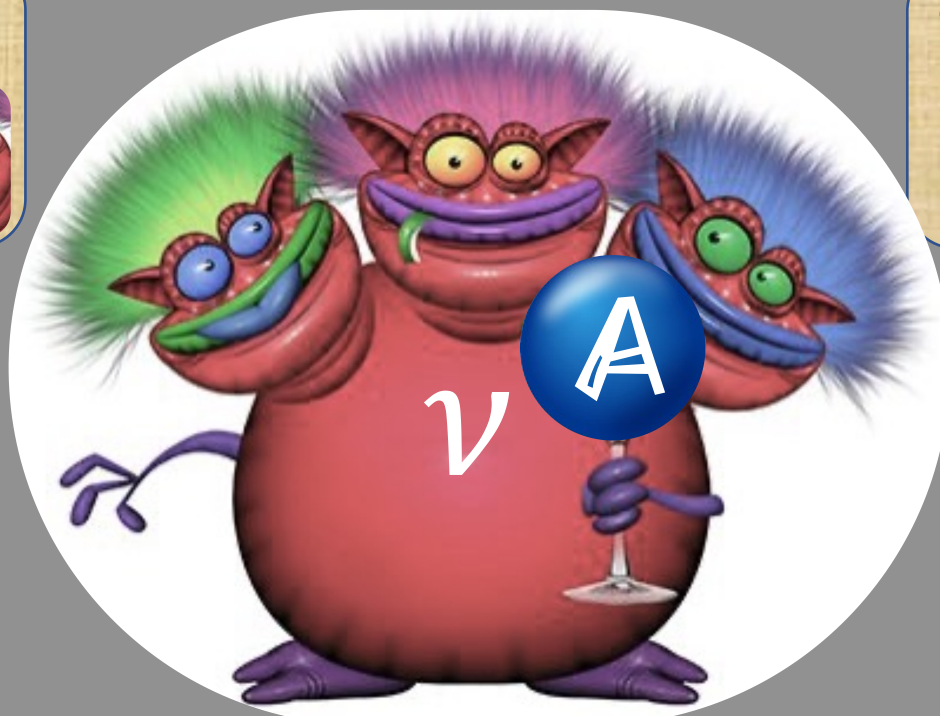


New Paradigm for Precision Oscillation Studies

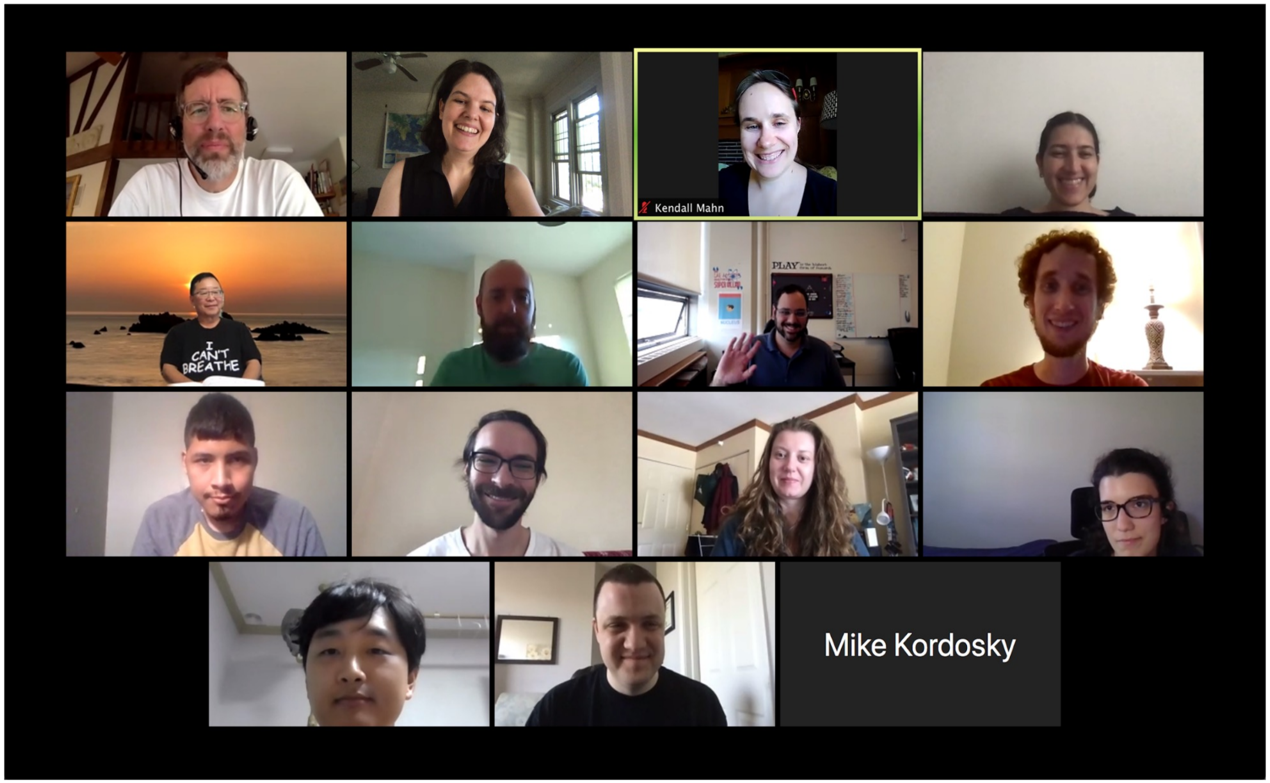
Event-Generators

e-scattering

ν-scattering



Growing Collaboration!



e4V +  ?

Join us!

Overwhelming Community Support

Fermilab

Hyper-Kamiokande

DUNE

ICECUBE
SOUTH POLE NEUTRINO OBSERVATORY

NOvA

MINERvA

T2K

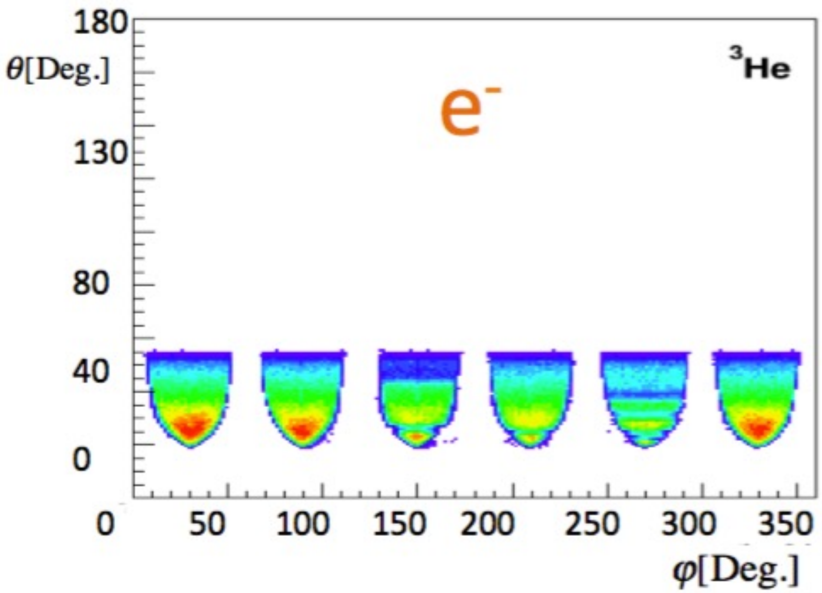
ANNIE
Accelerator Neutrino Neutron Interaction Experiment

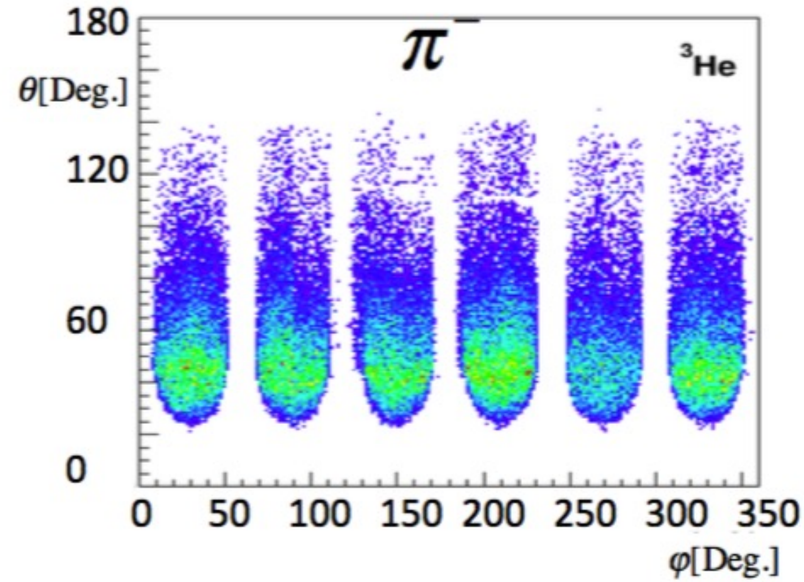
μBooNE
LArTPC

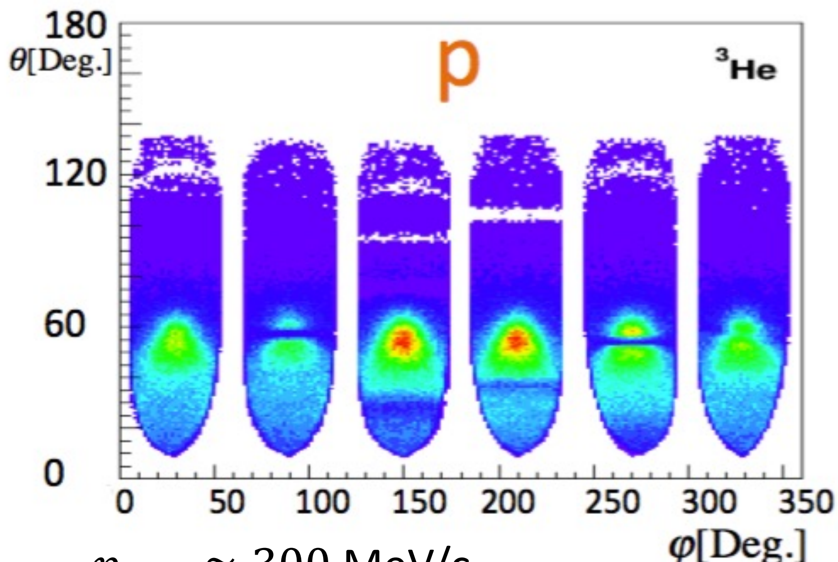
GiBUU
The Giessen Boltzmann-Uehling-Uhlenbeck Project

Backup

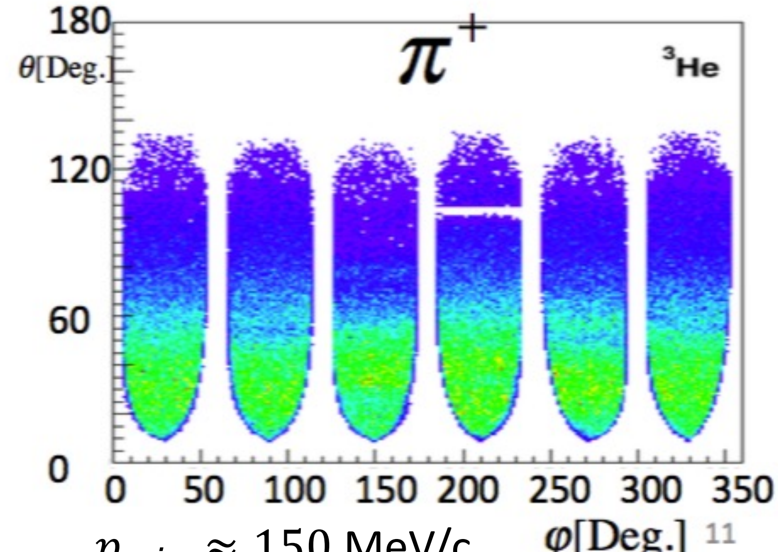
CLAS-6 Coverage





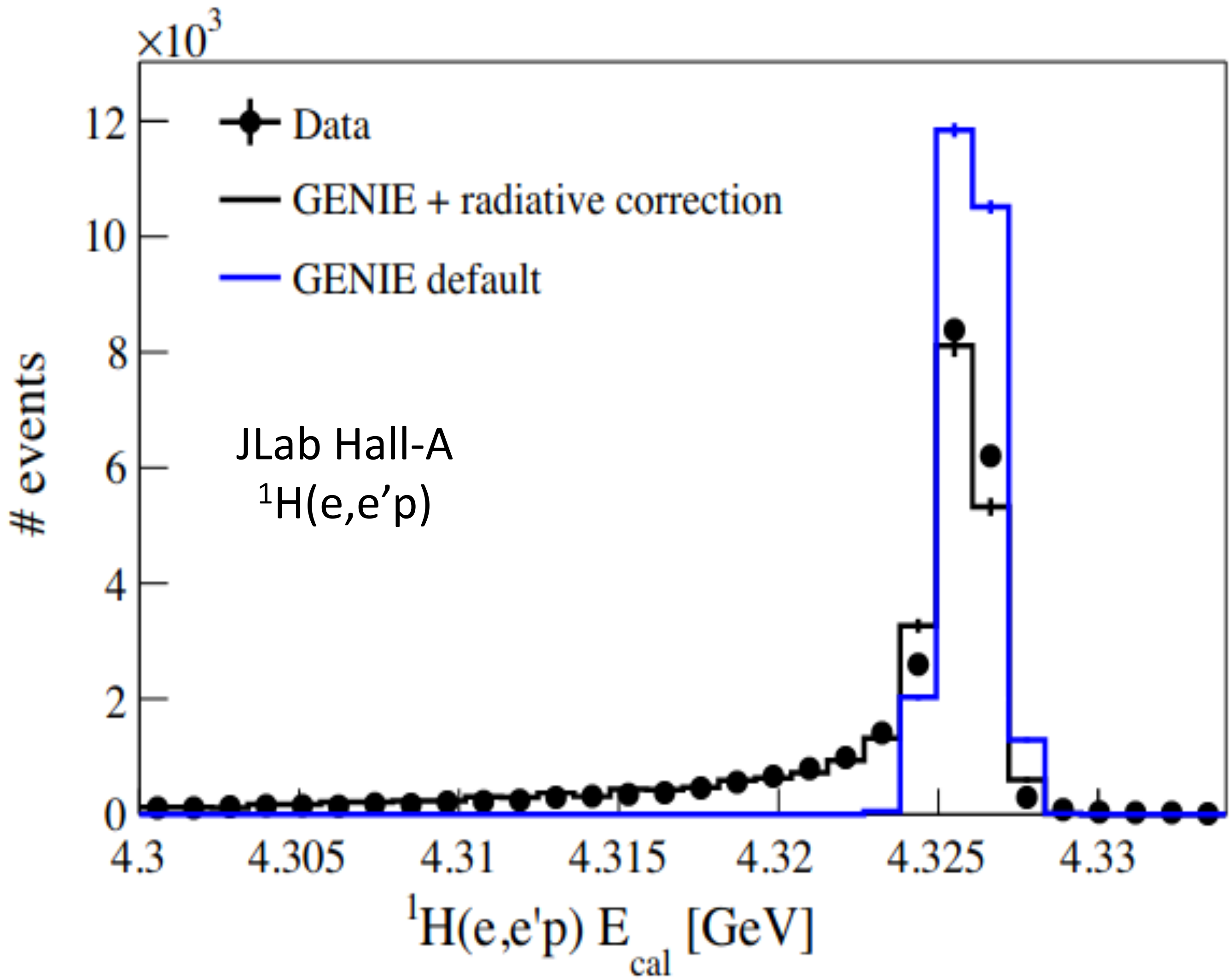


$p_{min} \approx 300$ MeV/c

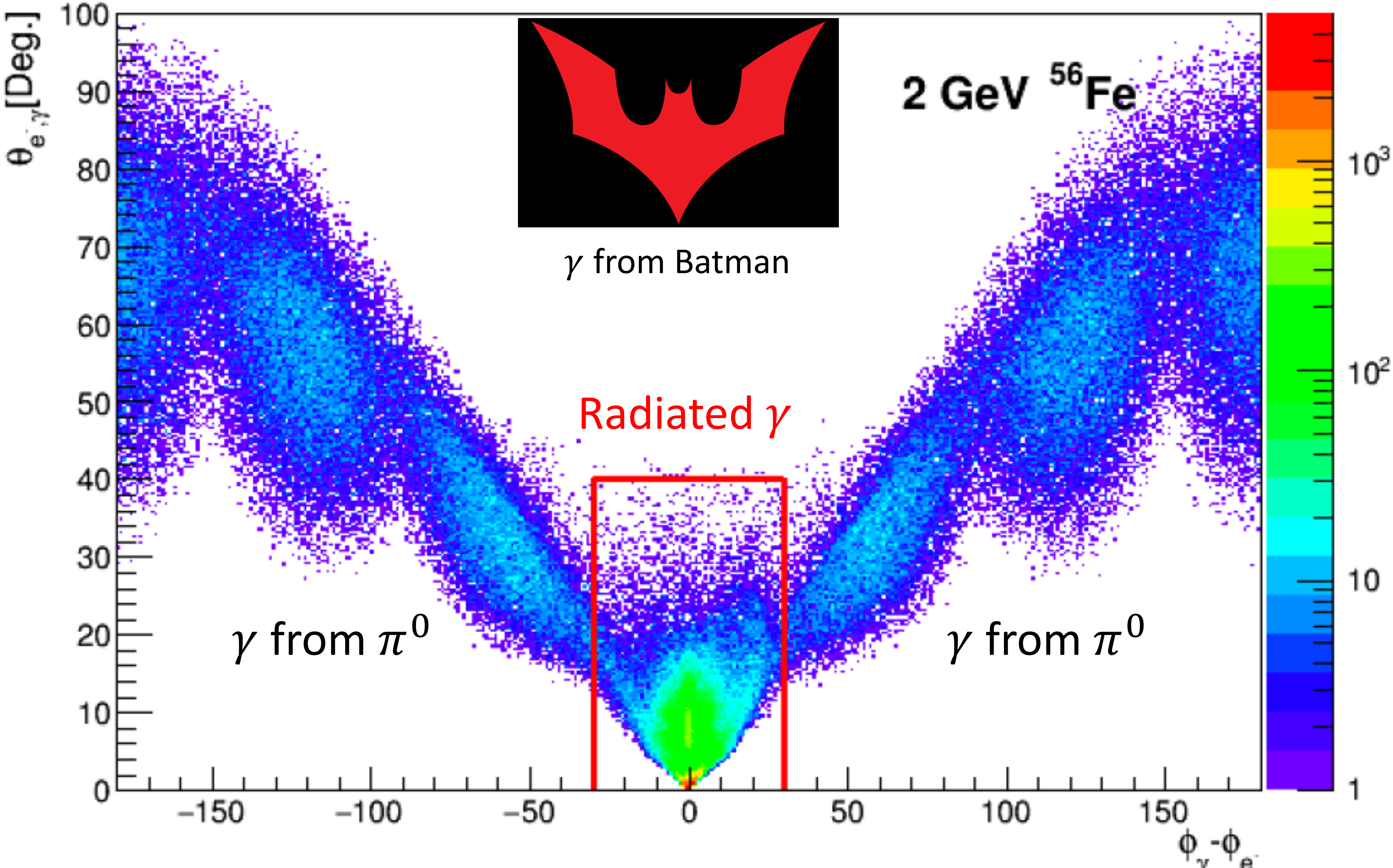


$p_{min} \approx 150$ MeV/c

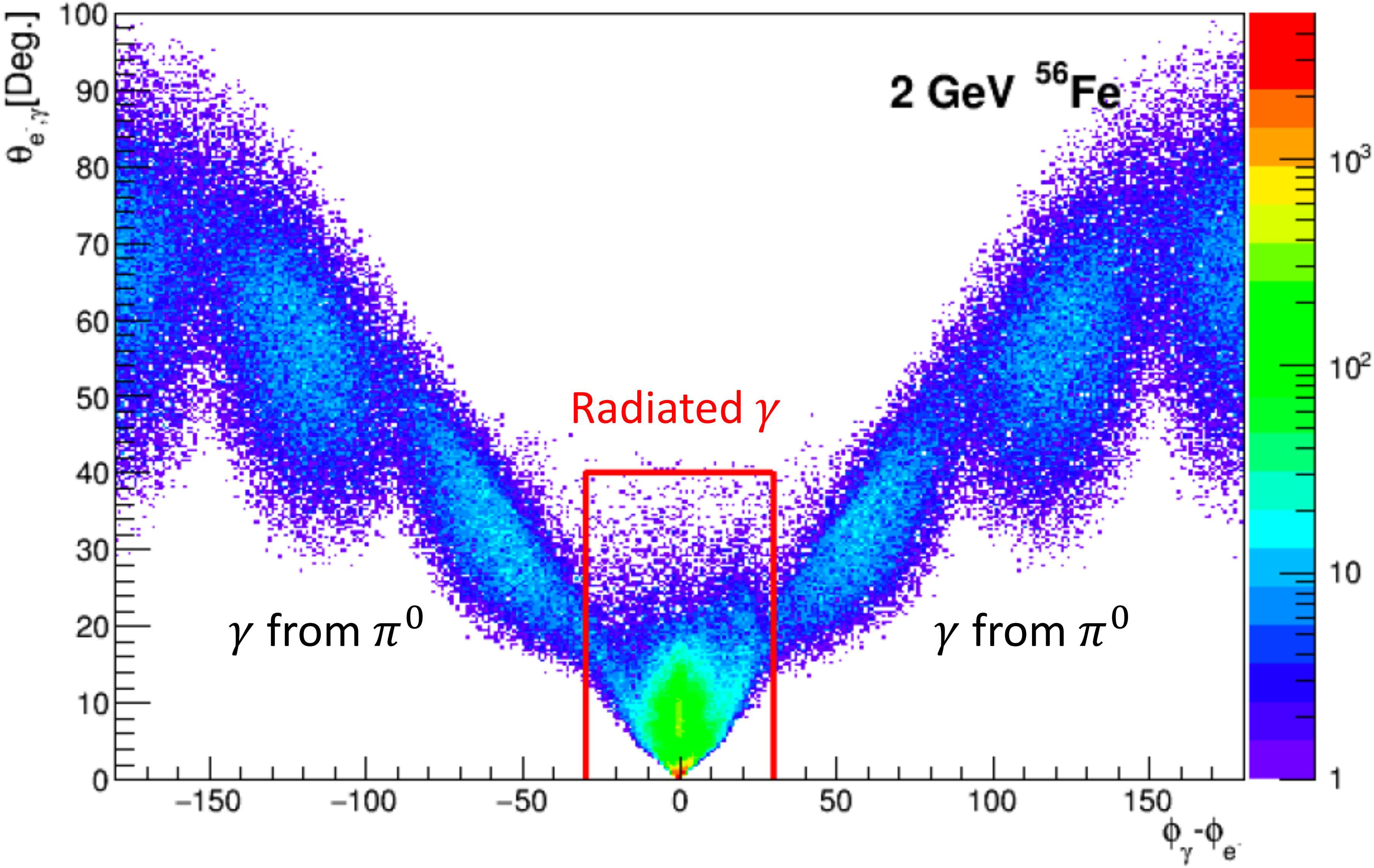
Adding Radiation to GENIE



Excluding Radiation in data



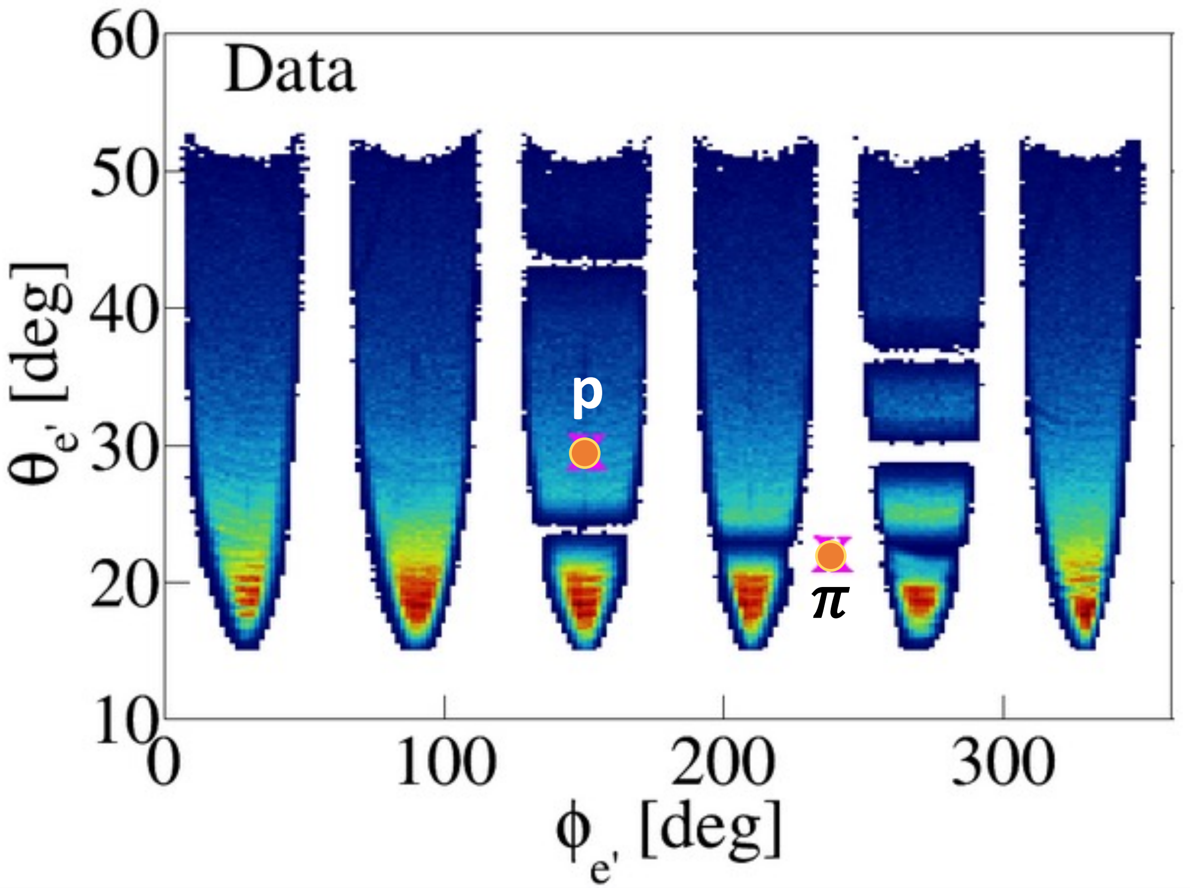
Excluding Radiation in data



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.



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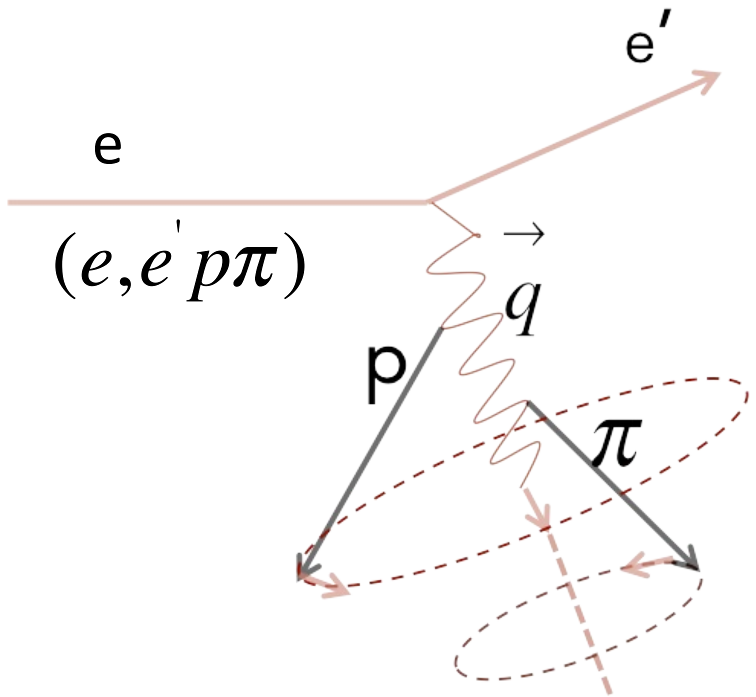
<u>Data Driven Correction:</u>

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



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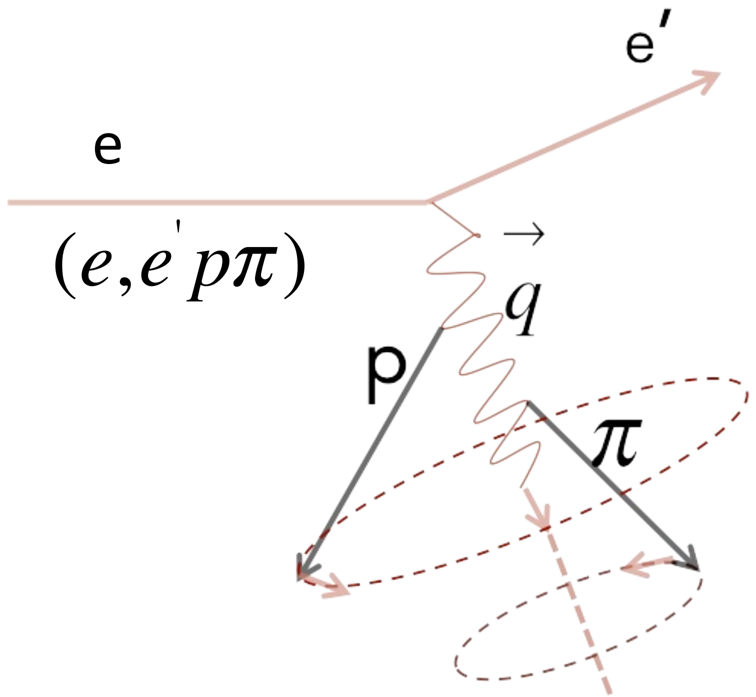
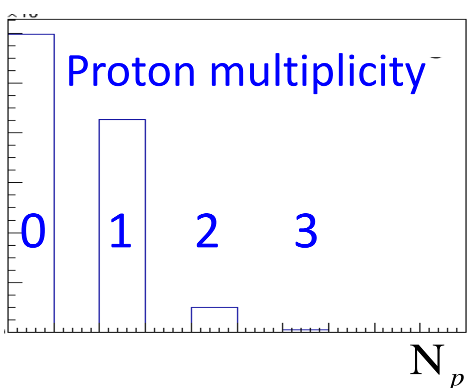
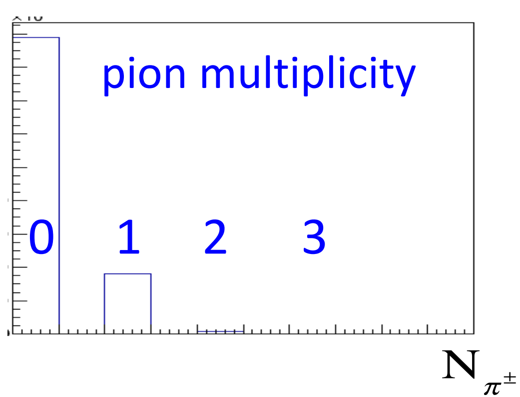
4. Do the same for 2p, 3p 2p+ π etc.







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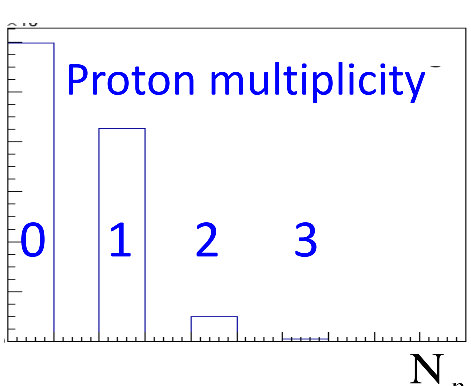
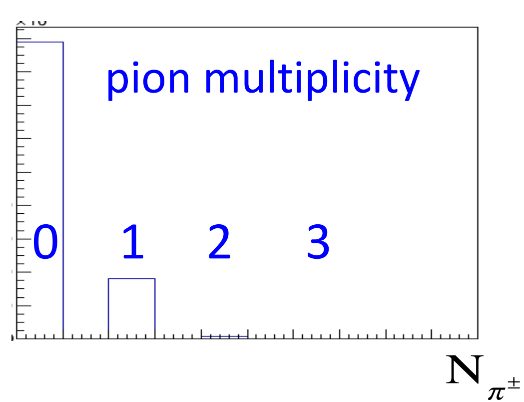
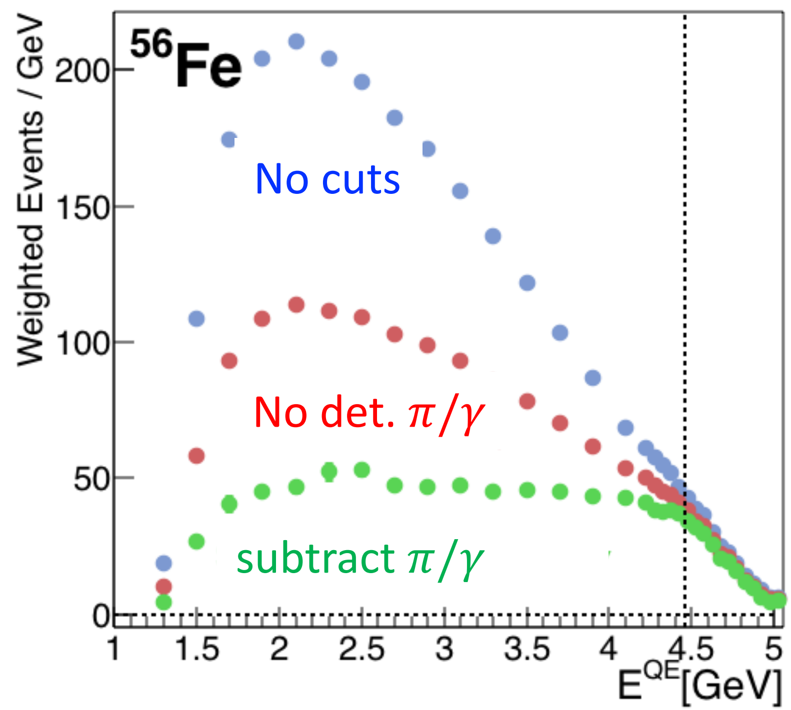






True 0π event sample!

Systematics

Source	Uncertainty (%)
Detector acceptance Identification cuts $\varphi_{q\pi}$ cross section dependence Number of rotations	2,2.1,4.7 (@ 1.1,2.2,4.4 GeV)
Sector dependence	6
Acceptance correction	2-15
Overall normalization	3
Electron inefficiency	2

Attacking the Monster From All Sides

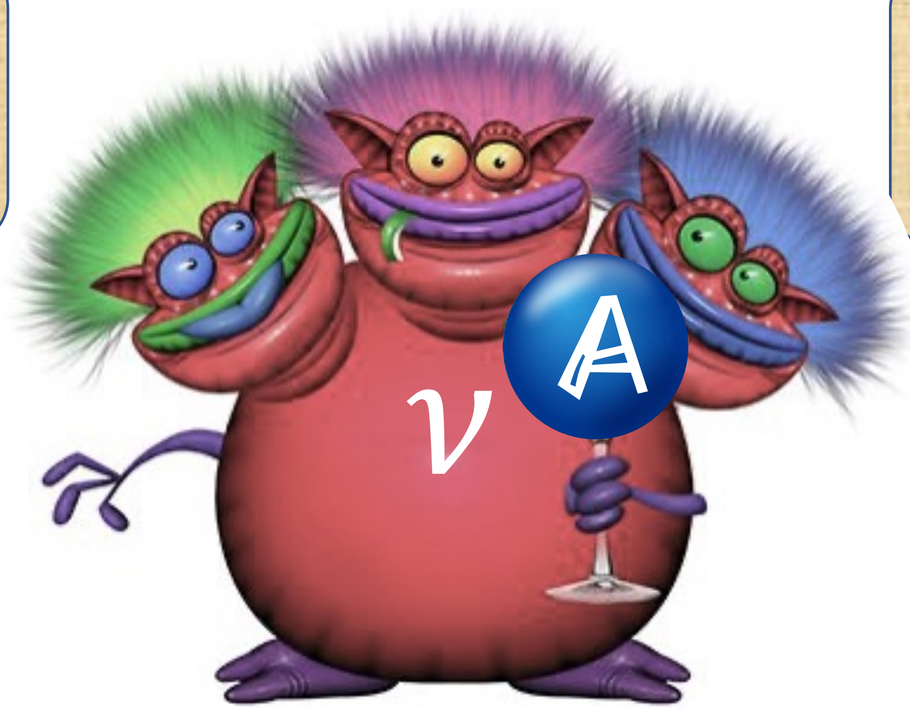
Event-Generators

e-scattering

ν-scattering

Monochromatic e⁻:

- Vector currents
- Nuclear FSI
- Ground state
- …

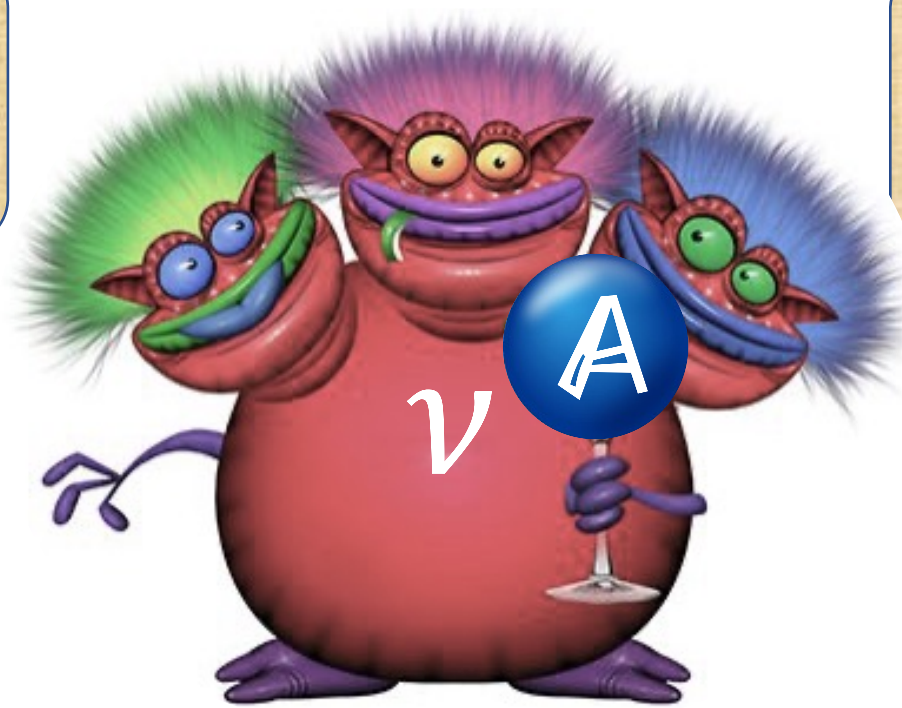


Attacking the Monster From All Sides

Event-Generators

e-scattering

ν-scattering



Monochromatic e^-:

- Vector currents
- Nuclear FSI
- Ground state
- …

ν near-detector:

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

Attacking the Monster From All Sides

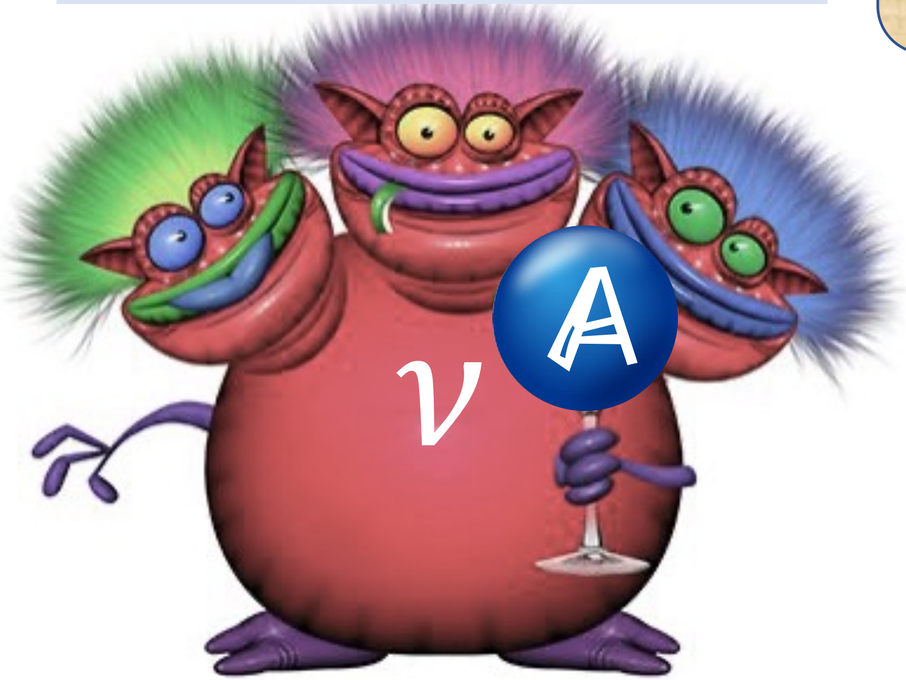
Event-Generators

e-scattering

Must reproduce e⁻ & ν data to extract oscillation parameters.

ν-scattering

Monochromatic e^-:
- Vector currents
- Nuclear FSI
- Ground state
- …



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- …