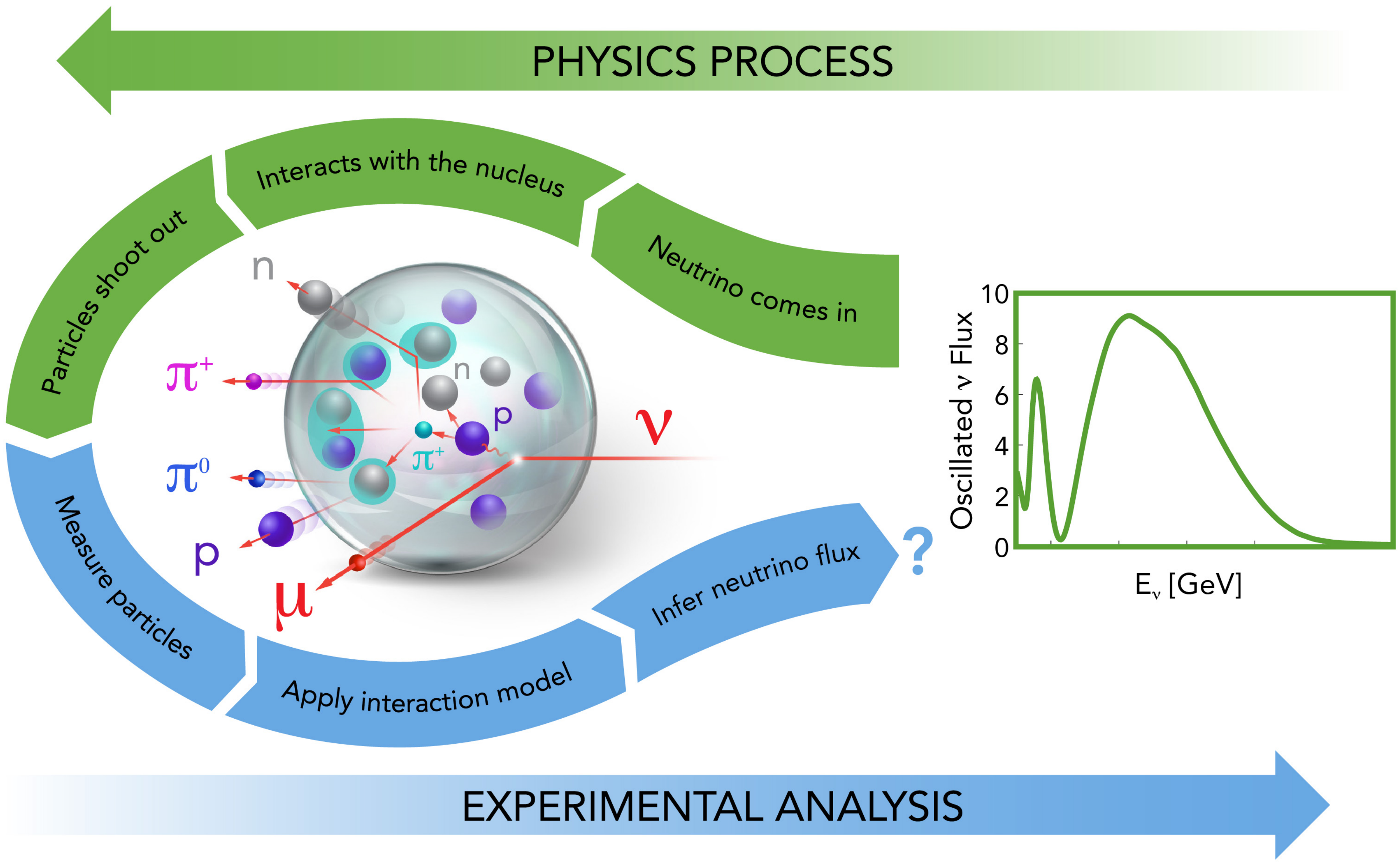
Electron for Neutrinos

Minerba Betancourt on behalf of the e4ν collaboration
PANIC 2021, Particles and Nuclei International Conference
08 September 2021

How to Extract Neutrino Physics



Measure counts

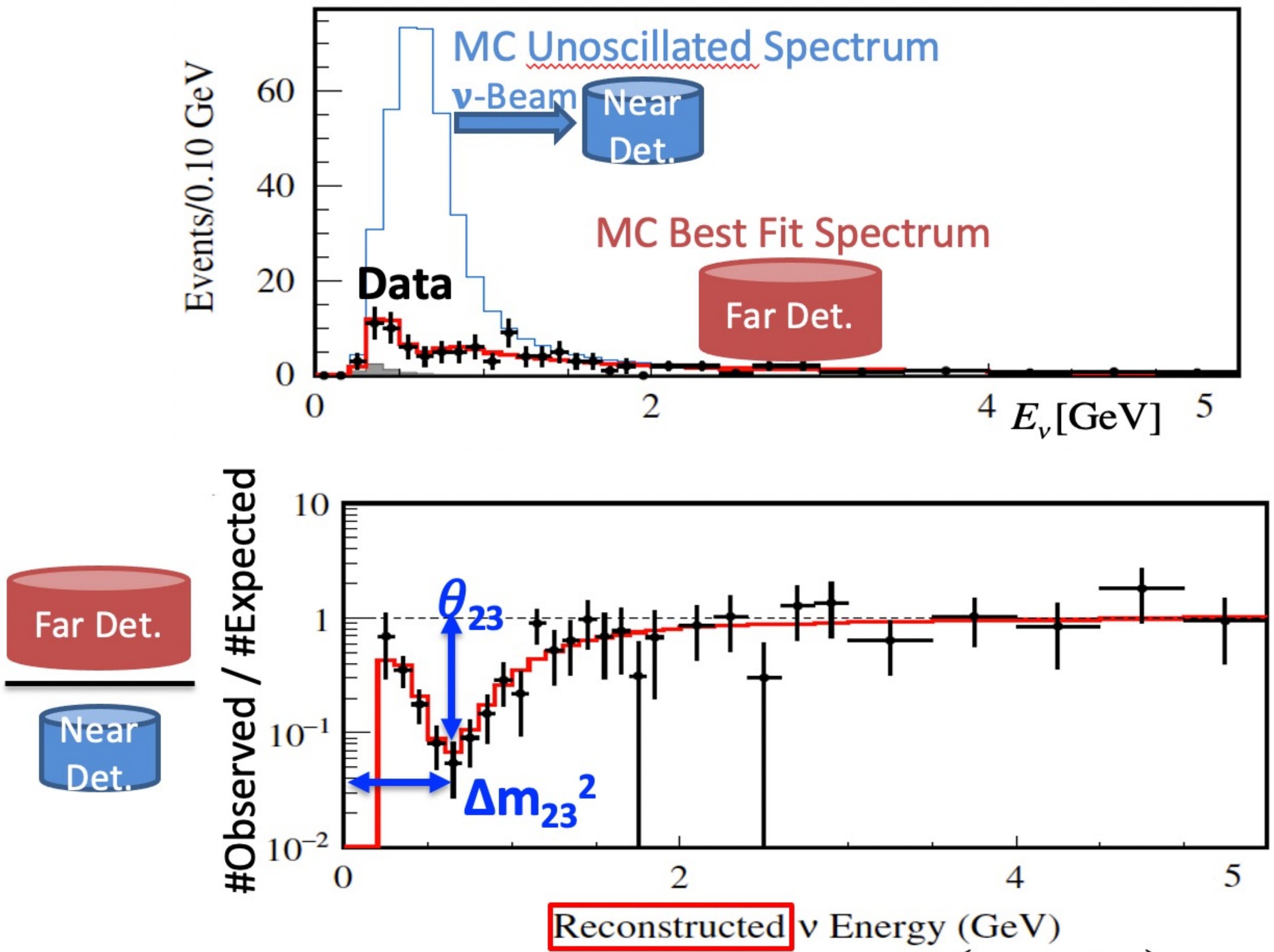
Use an interaction model to deconvolute the neutrino flux

$$N_{\alpha}(E_{rec},L)=\sum_{i}\int\Phi_{\alpha}(E,L)\sigma_{i}(E)f_{\sigma_{i}}(E,E_{rec})dE$$

measured — ν Flux — interaction model

Measuring Neutrino Oscillations

T2K experiment L=295km



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

T2K, Phys. Rev. D 91, 072010 (2015)

Interaction Uncertainty will limit future Oscillation Experiment

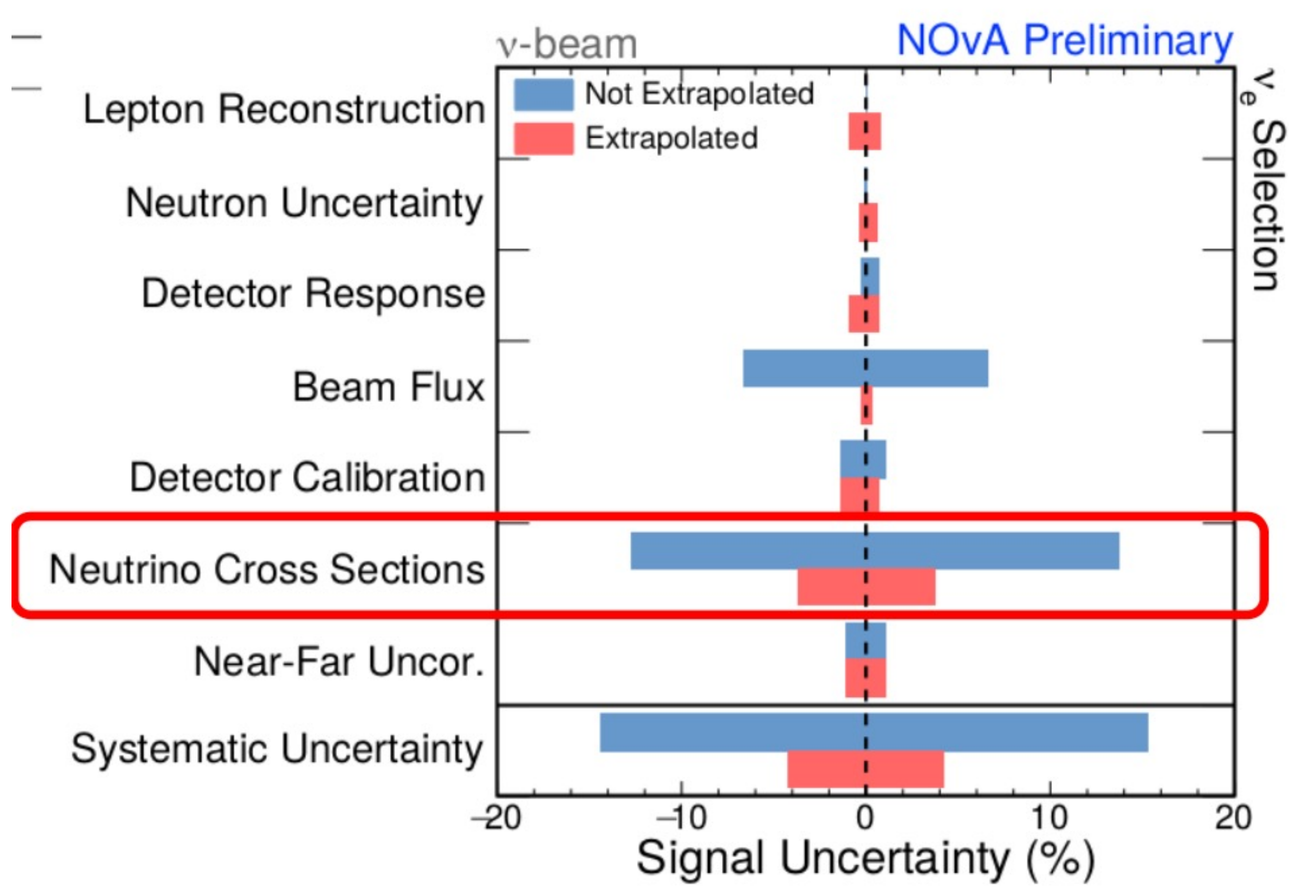
T2K

T2K *Nature* **580**, 339–344 (2020)

Type of Uncertainty	$\nu_e/\bar{\nu}_e$ Candidate Relative Uncertainty (%)
Super-K Detector Model	1.5
Pion Final State Interaction and Rescattering Model	1.6
Neutrino Production and Interaction Model Constrained by ND280 Data	2.7
Electron Neutrino and Antineutrino Interaction Model	3.0
Nucleon Removal Energy in Interaction Model	3.7
Modeling of Neutral Current Interactions with Single γ Production	1.5
Modeling of Other Neutral Current Interactions	0.2
Total Systematic Uncertainty	6.0

5% out of 6%!

NOvA



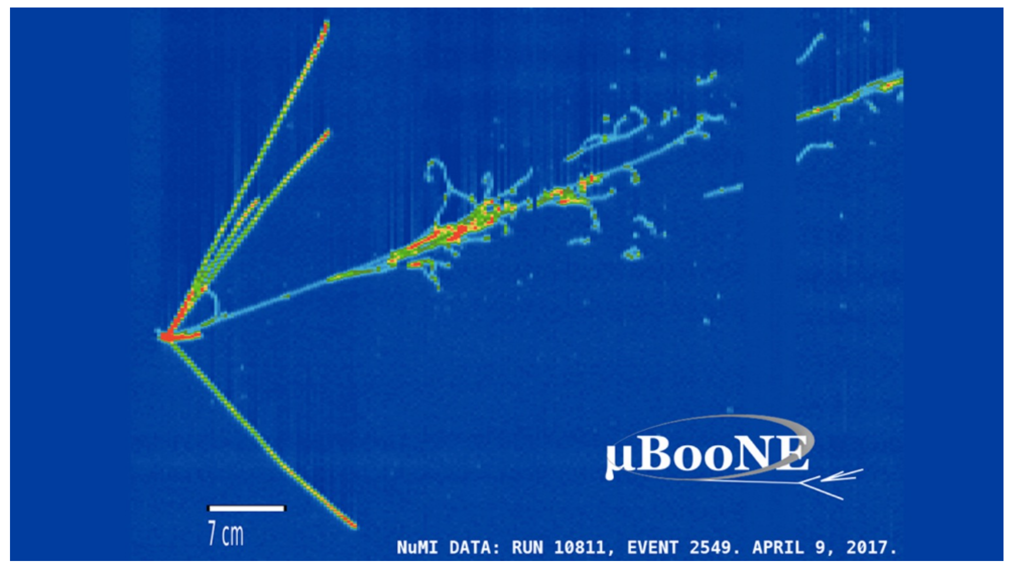
Alex Himmel, Neutrino 2020

Fermilab

Neutrino-Nucleus Scattering is complicated

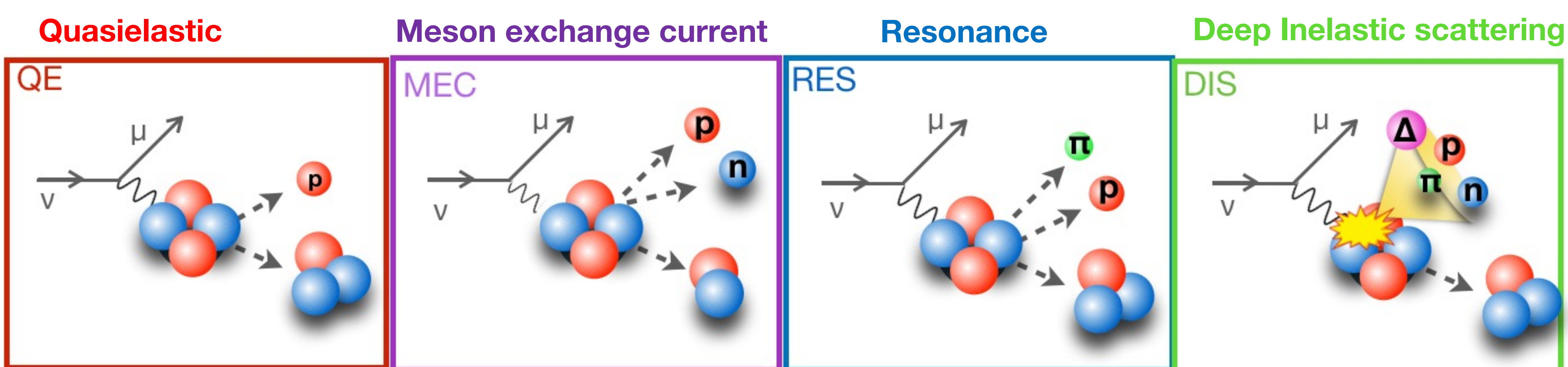
Initial nuclear state

- Nucleon motion
- Long range correlations
- Short range correlations
- Nucleon removal energies
- Form factors



Final state interactions

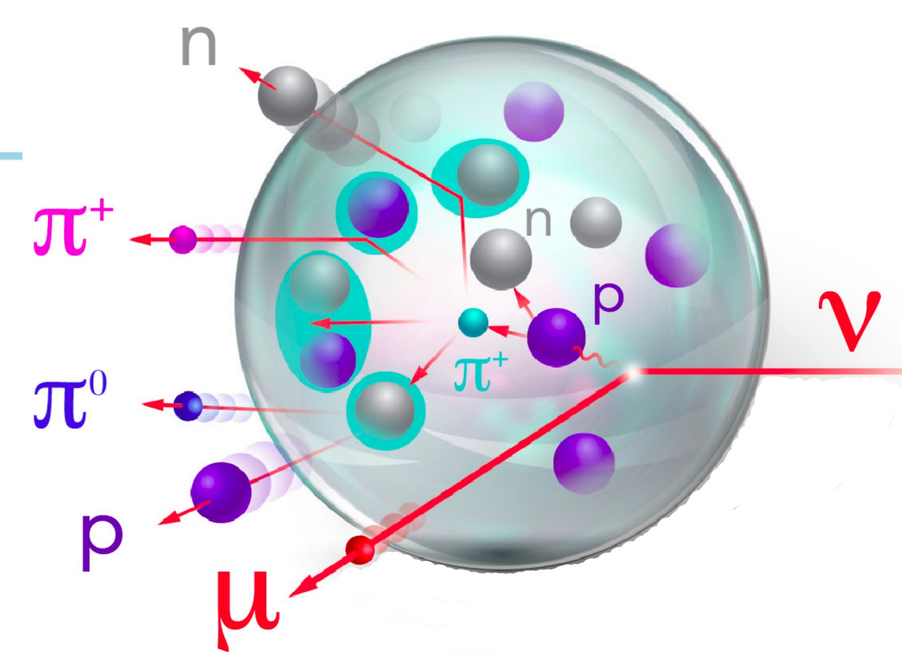
- Reinteractions of outgoing particles
- Knockout of new particles

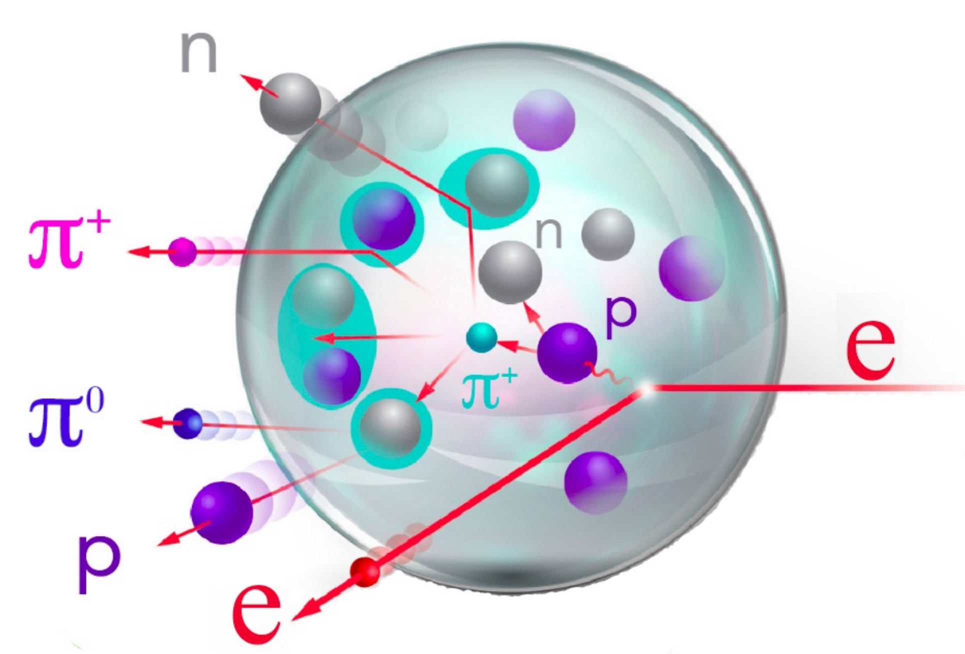


Credit: Noemi Rocco

Why Electron Scattering?

- e & ν interact similarly
  - Single boson exchange
  - CC Weak current [vector plus axial]
    - $j_{\mu}^{\pm} = \bar{u} \frac{-i g_W}{2\sqrt{2}} (\gamma^{\mu} - \gamma^{\mu}\gamma^{5}) u$
  - EM current [vector]
    - $j_{\mu}^{em} = \bar{u}\, \gamma^{\mu} u$
- Many nuclear effects identical
  - Final State Interaction (FSI)
  - Initial state, reaction mechanism, …
- e beam energy is known
- → can test energy reconstruction





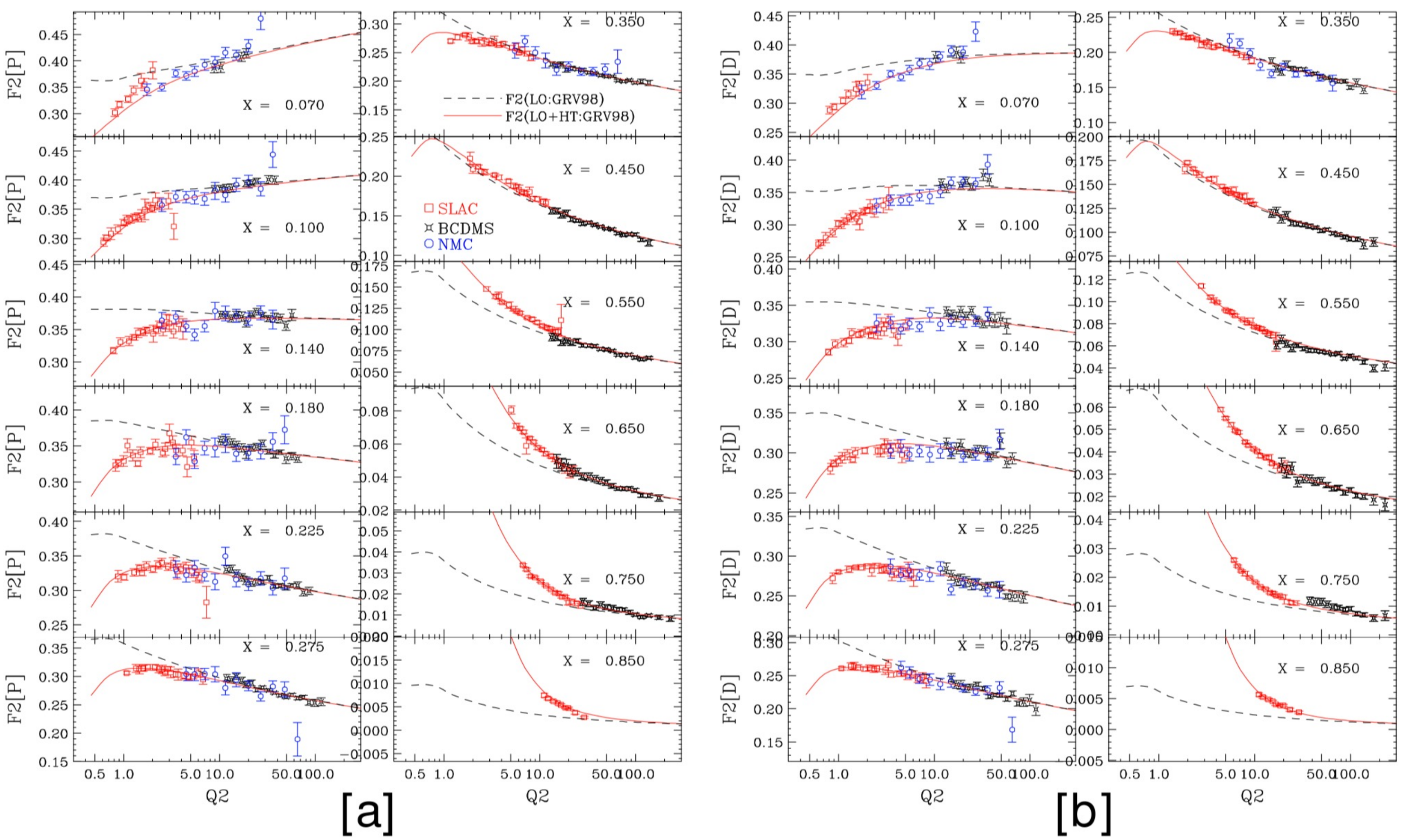
Why Electron Scattering?

- For Quasi-elastic process we use a free nucleon CCQE formalism to determine the cross section

$$\frac{d\sigma}{dq^2} \propto (F_1, F_2, F_A)$$

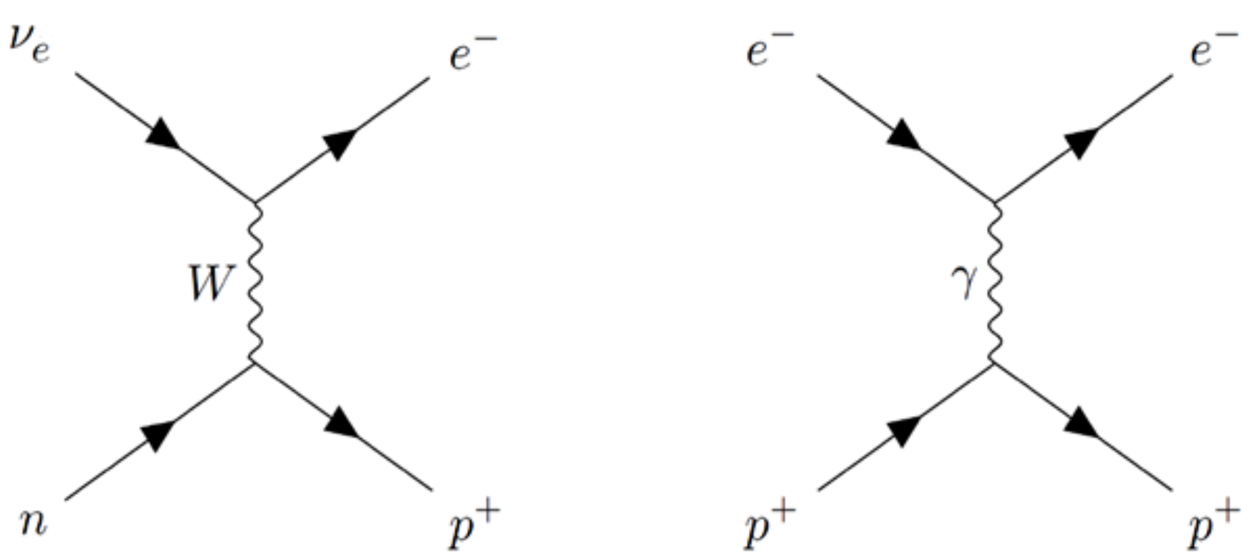
- The vector form factor F1 and F2 are known from electron-nucleon scattering
- The DIS term of the inelastic differential cross section is expressed in terms of the differential cross section predicted by Boded-Yang model, which has been tuned to lepton scattering data
  https://arxiv.org/pdf/hep-ex/0210024.pdf

Electron and muon F2 data



Electrons for Neutrinos (e4ν)

- Use monochromatic electron beams and large acceptance CLAS and CLAS12 detectors
- Measure exclusive final states
  - constrain nuclear effects
  - constrain vector part of interaction
- Improve event generators (GENIE)
  - Updated e-GENIE to be as similar as possible to ν-GENIE
  - E4ν working groups:
    - Data Analysis
    - Modeling development
    - Implications on neutrino studies
    - Tuning



Attacking the Monster From All Sides

Event-Generators

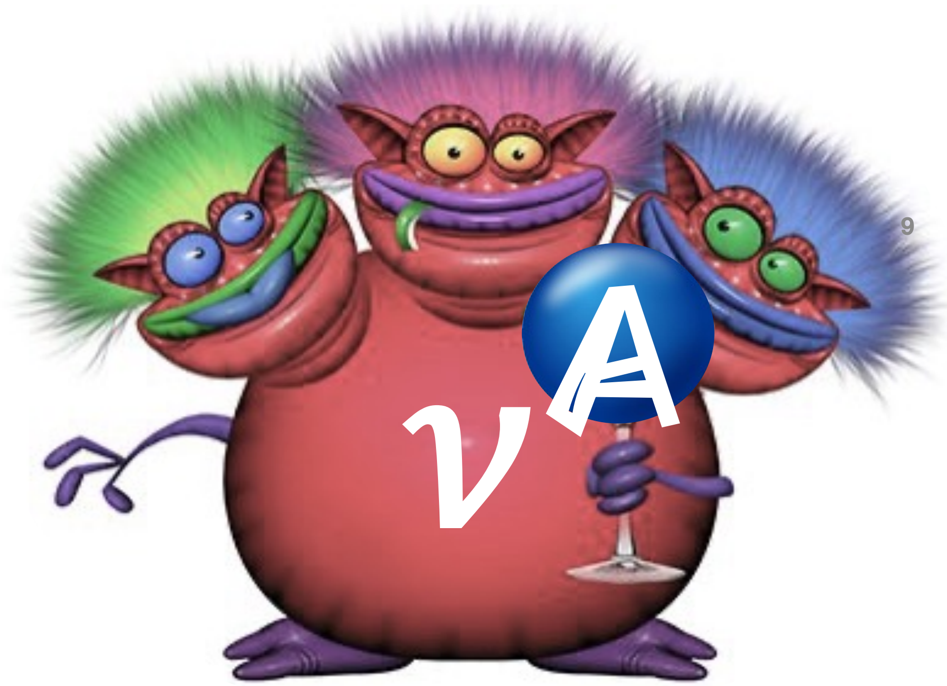
e-scattering

ν-scattering

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

Monochromatic e⁻:

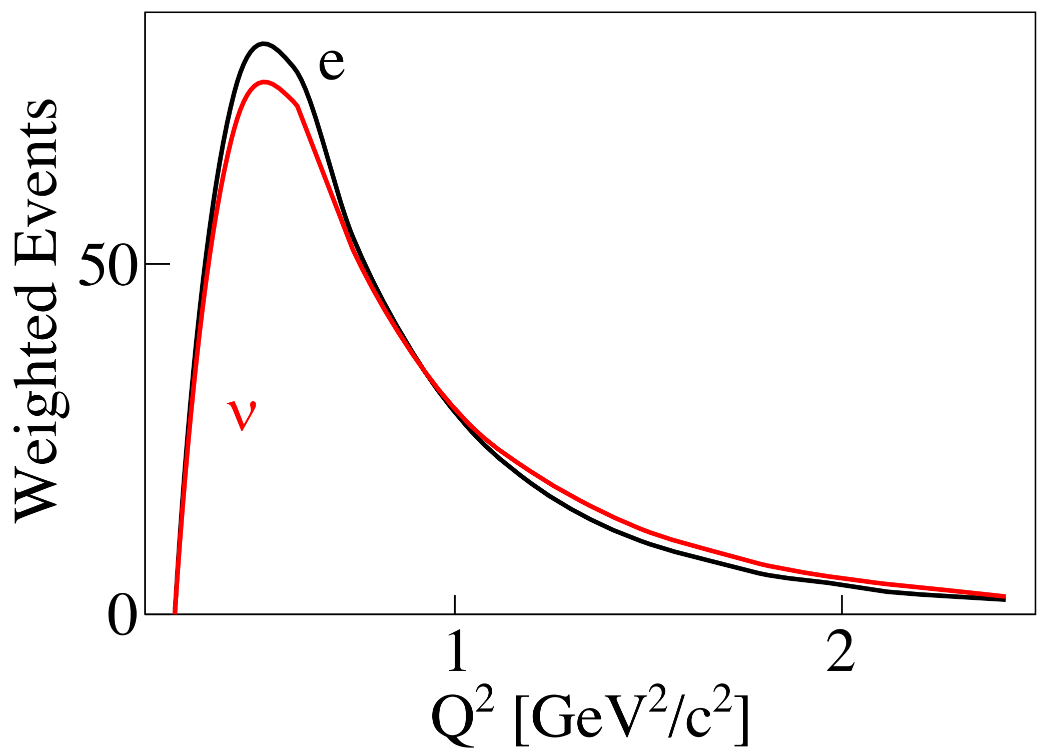
- Vector currents
- Same initial nucleus
- Similar interactions
- Same final state interactions
- …

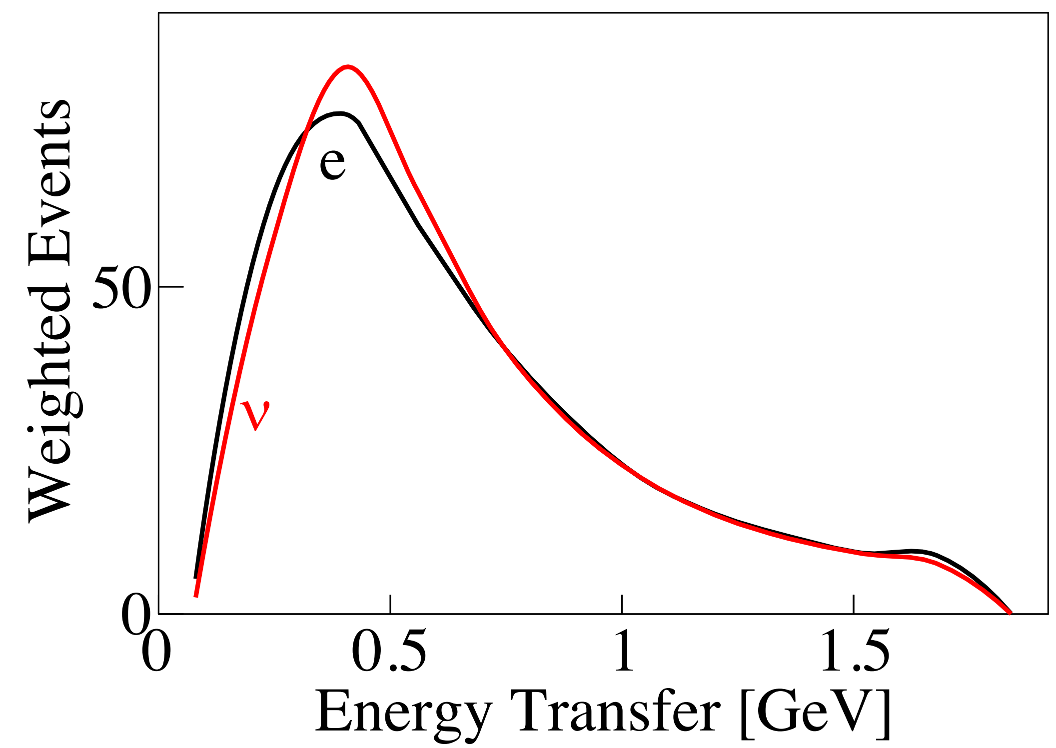


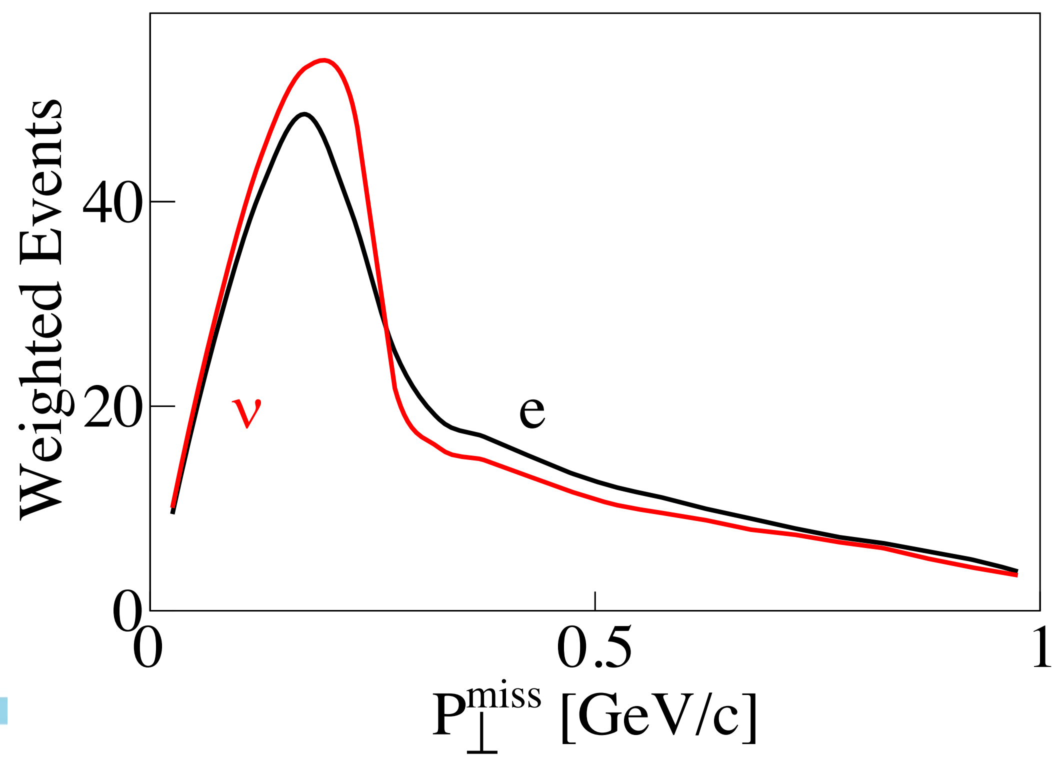
ν near-detector:

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

ν & e⁻ are very similar!



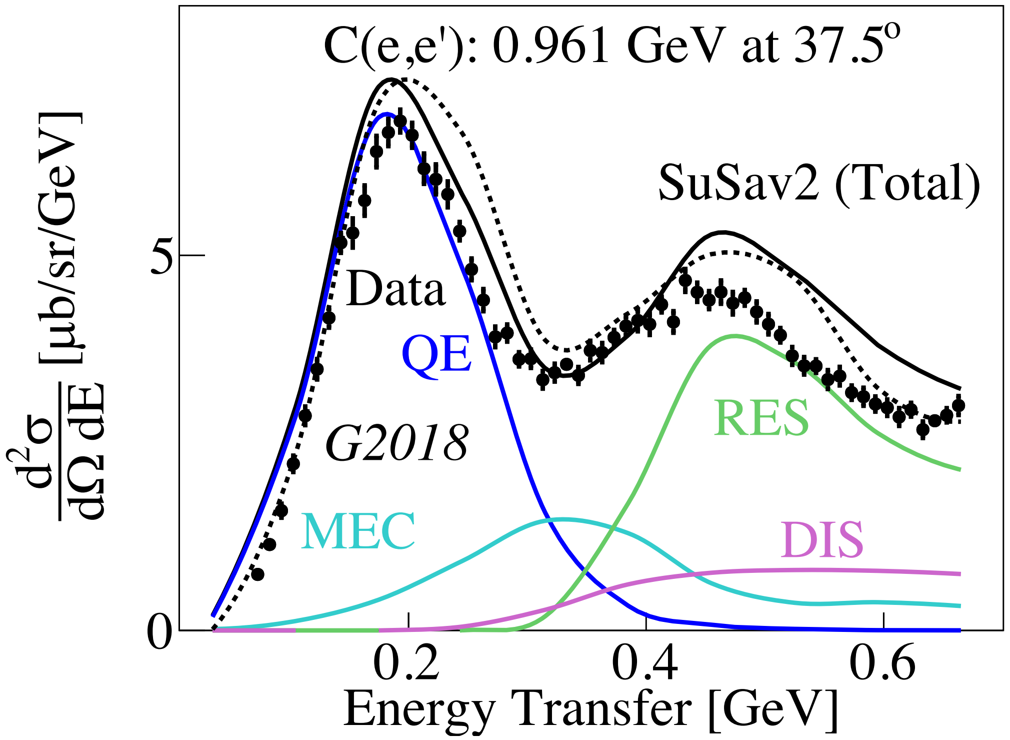


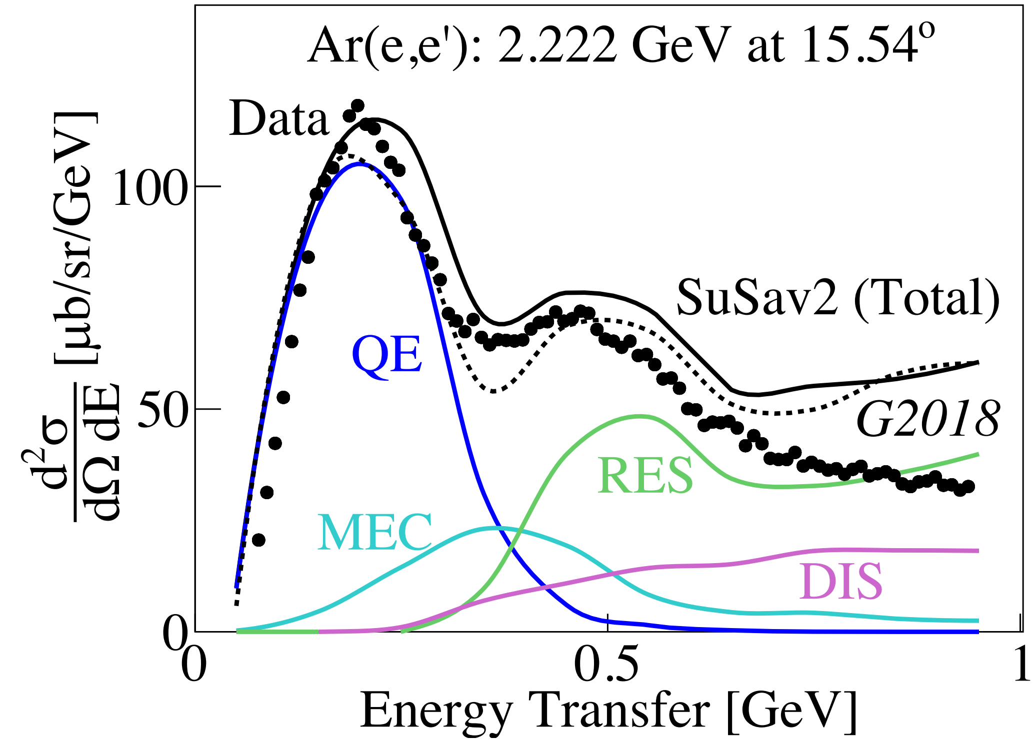


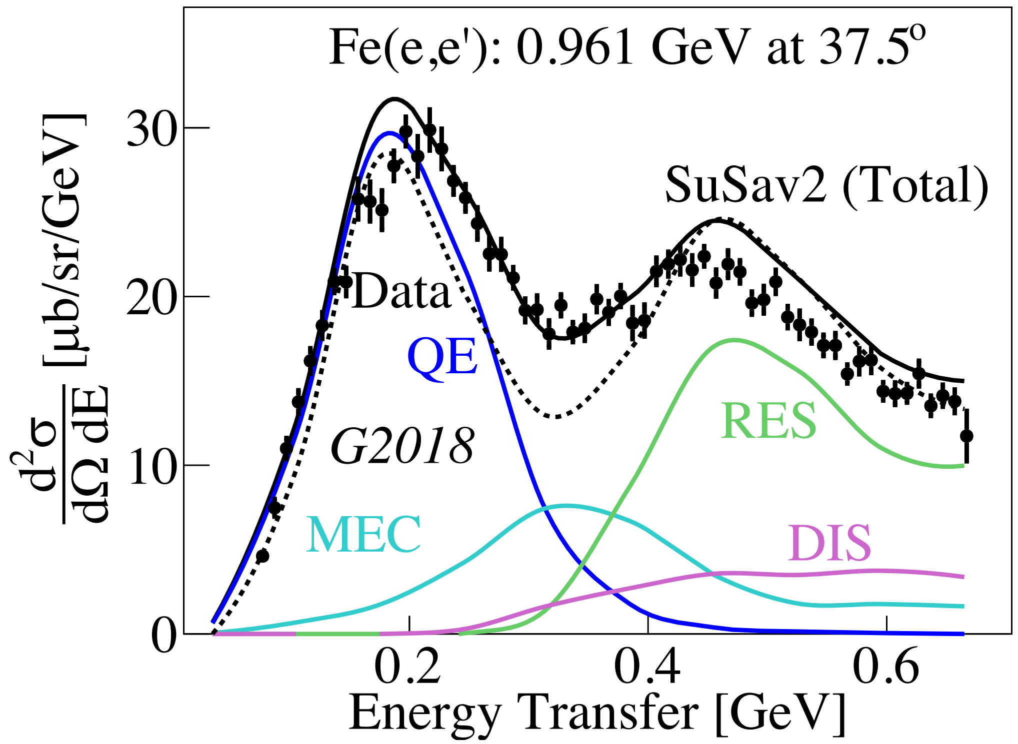
2.26 GeV on ^{12}C

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

Inclusive electron scattering



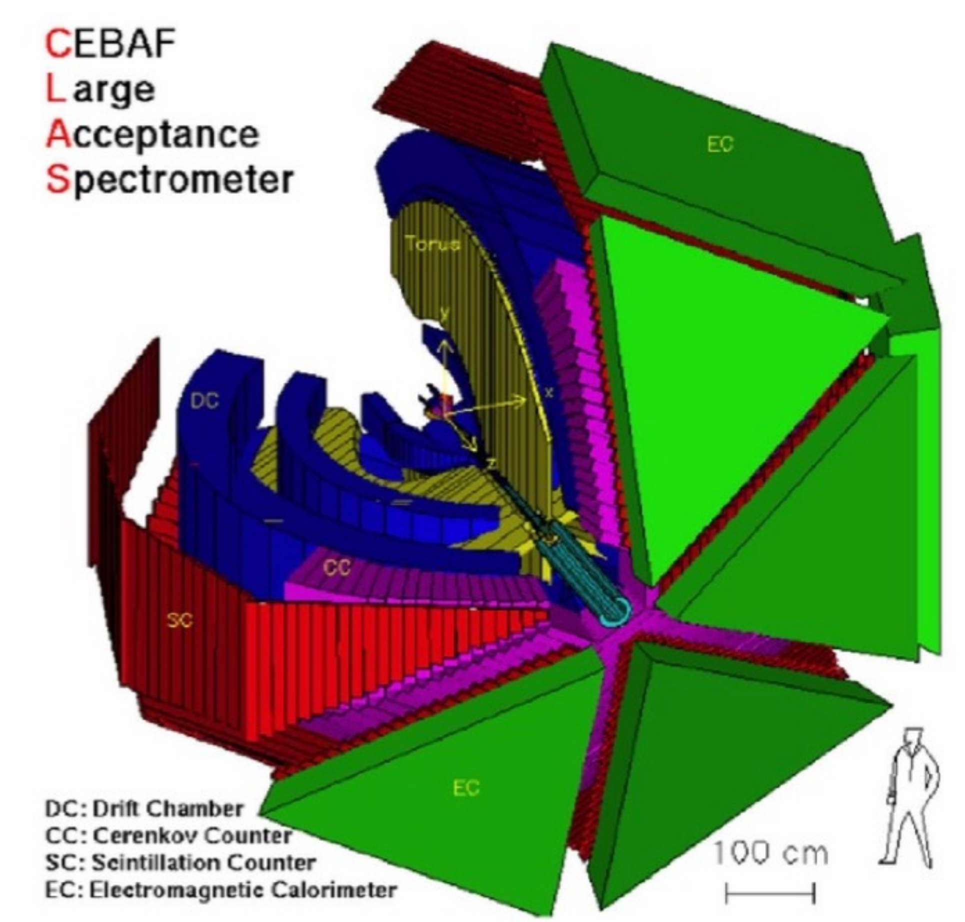




Room for improvements

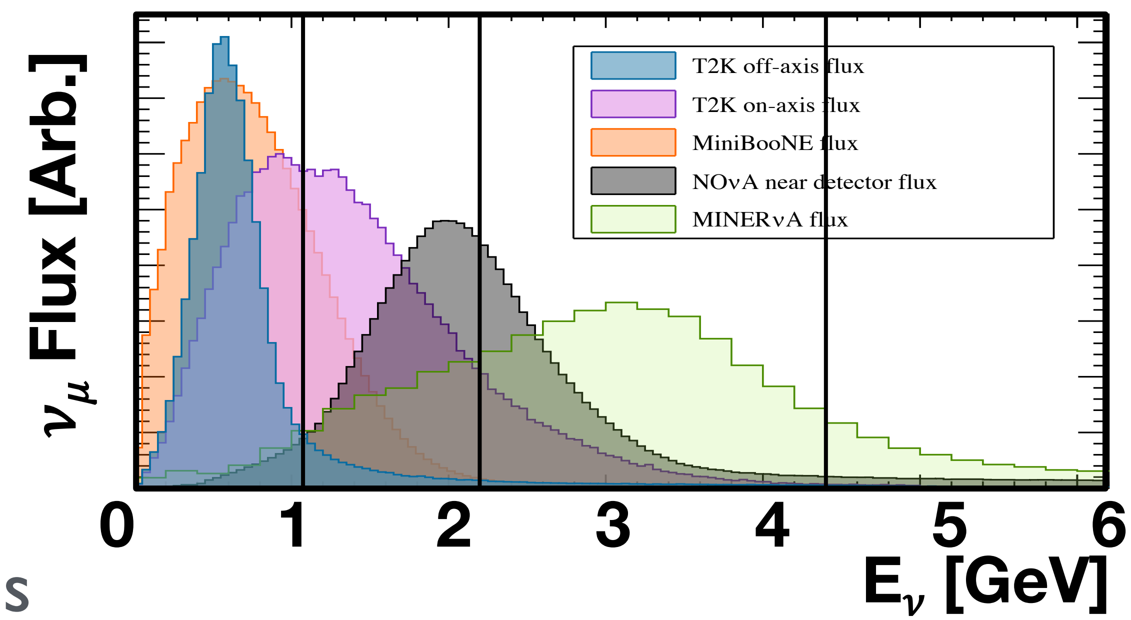
Phys. Rev. D103, 113003, 2021

Electron Scattering with CLAS at JLab



CLAS6 (e,e'p) Data (million events)

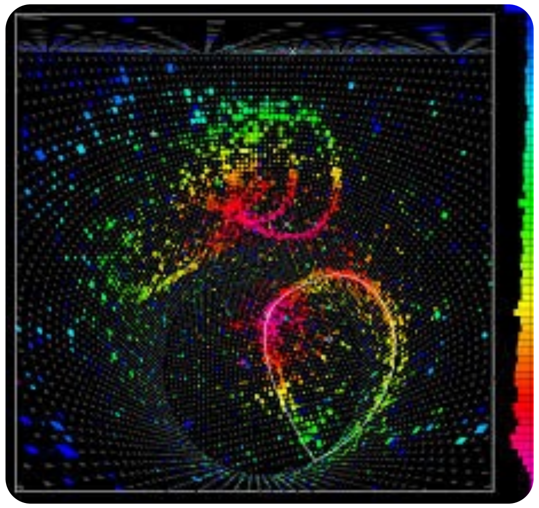
	1.1 GeV	2.2 GeV	4.4 GeV
3He	4	9	1
4He		17	3
12C	3	11	2
56Fe		0.5	0.1



- First exclusive measurements for neutrinos
- Moderate detector thresholds, $p_\pi > 150$ MeV/c, $p_p > 300$ MeV/c
- $\theta_e > 15^o$

First Test of Lepton Energy Reconstruction

- Choose 0π events to enhance the QE sample
  - Reconstruct the incident lepton energy
    - Cherenkov detectors:

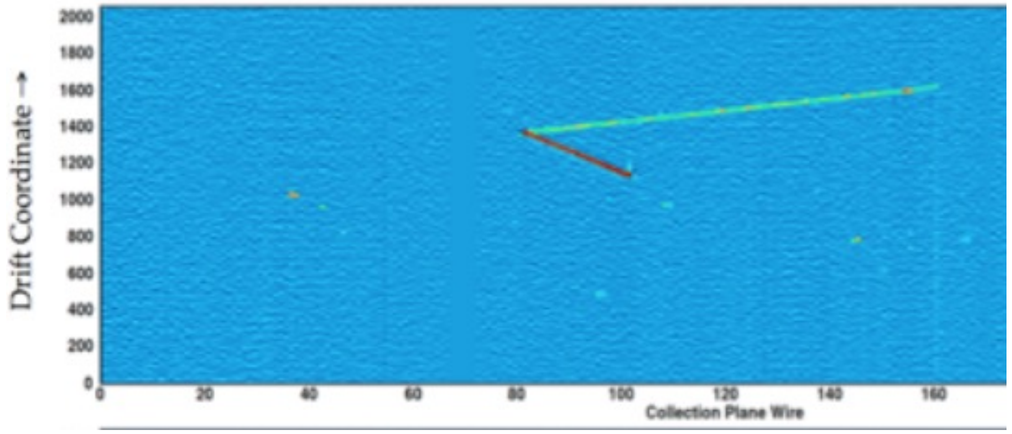


$$E_{QE} = \frac{2M\epsilon + 2ME_l - m_l^2}{2(M - E_l + |k_l|\cos\theta_l)}$$

- Using lepton and assuming QE hypothesis
  - Tracking detectors

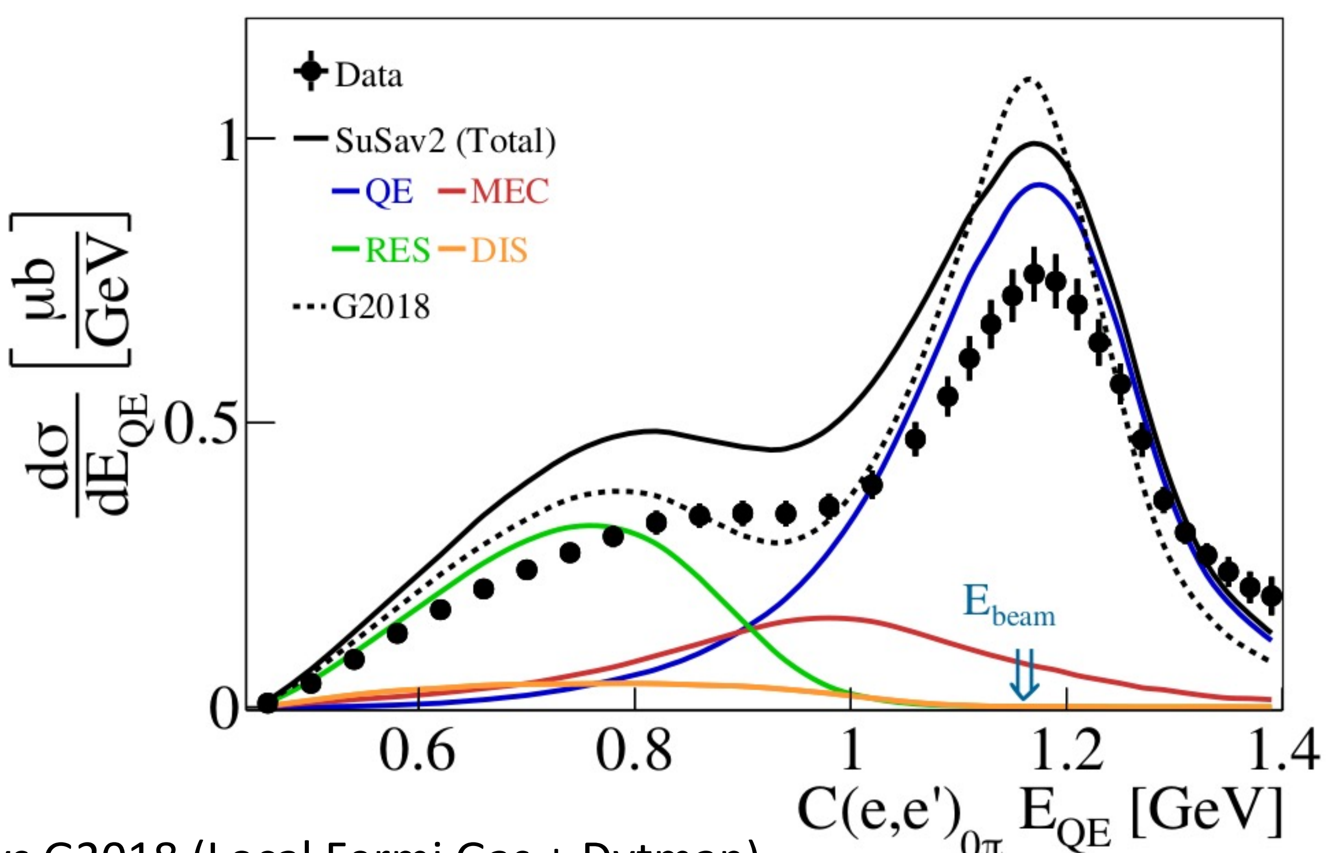
$$E_{cal} = E'_e + T_p + E_{bind}$$

  - Calorimetry



Absolute QE-like C(e,e')0π Cross Section

- Analyze electron data as neutrino data
  - $(e, e'), 0\pi$
    - Correct for events with undetected other particles
  - Scale by Q^4 to compare with neutrinos
  - Reconstruct incoming lepton energy



E_{QE} reconstructed from lepton only

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

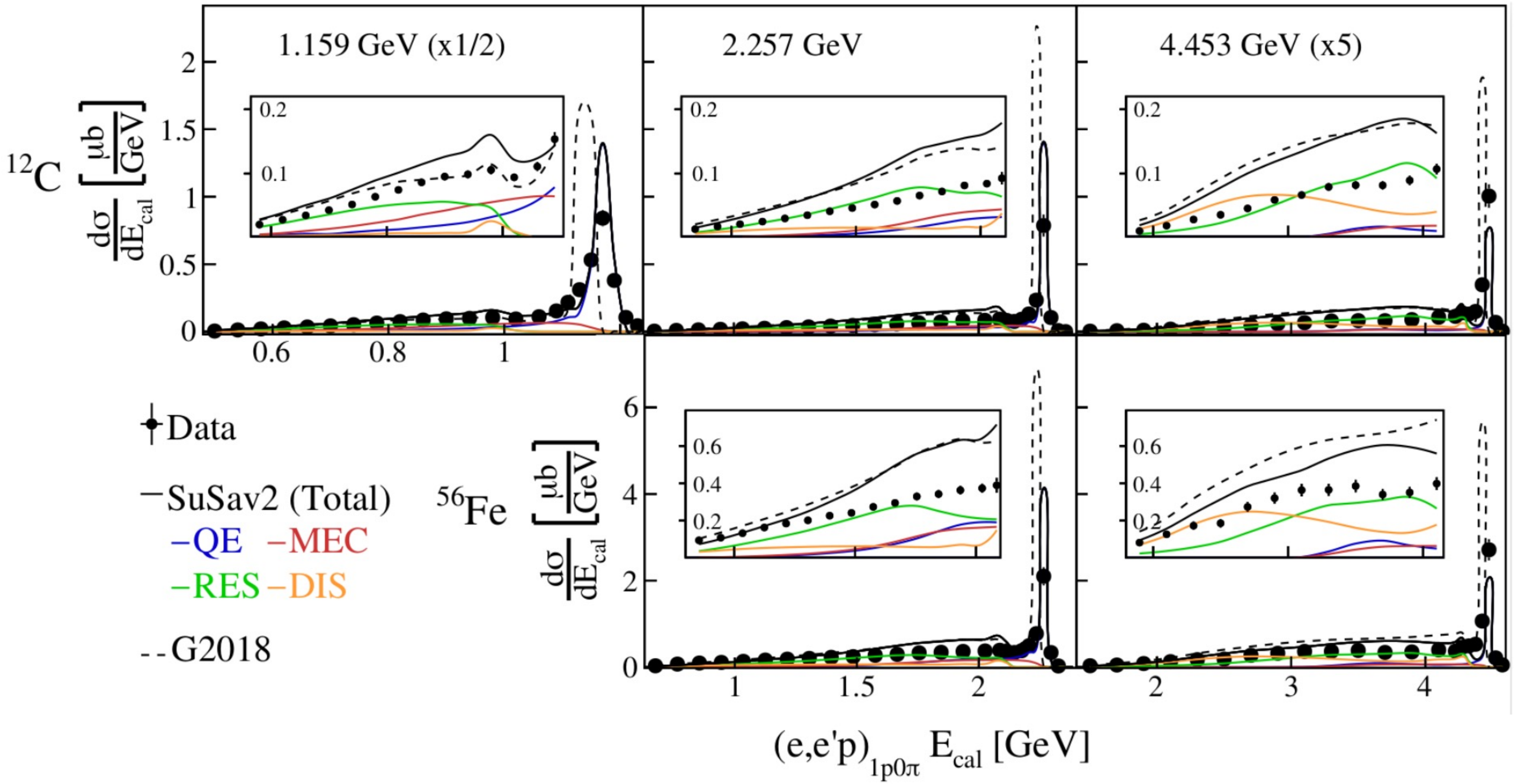
Khachatryan, Papadopoulou et al, Nature, in press

QE and MEC: SuSAv2 vs G2018 (Local Fermi Gas + Dytman)
RES and DIS: Berger-Sehgal + Bodek and Yang

Overestimation of QE peak and RES tail

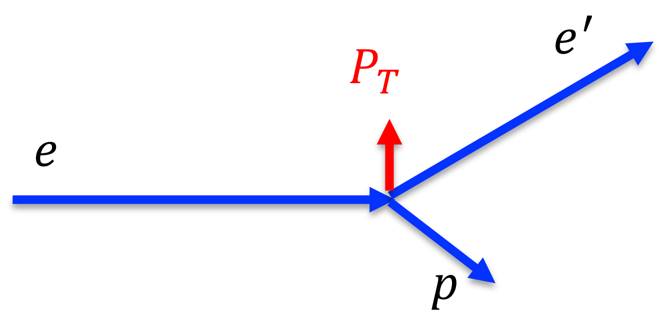
Absolute QE-Like (e,e'p) Cross Sections

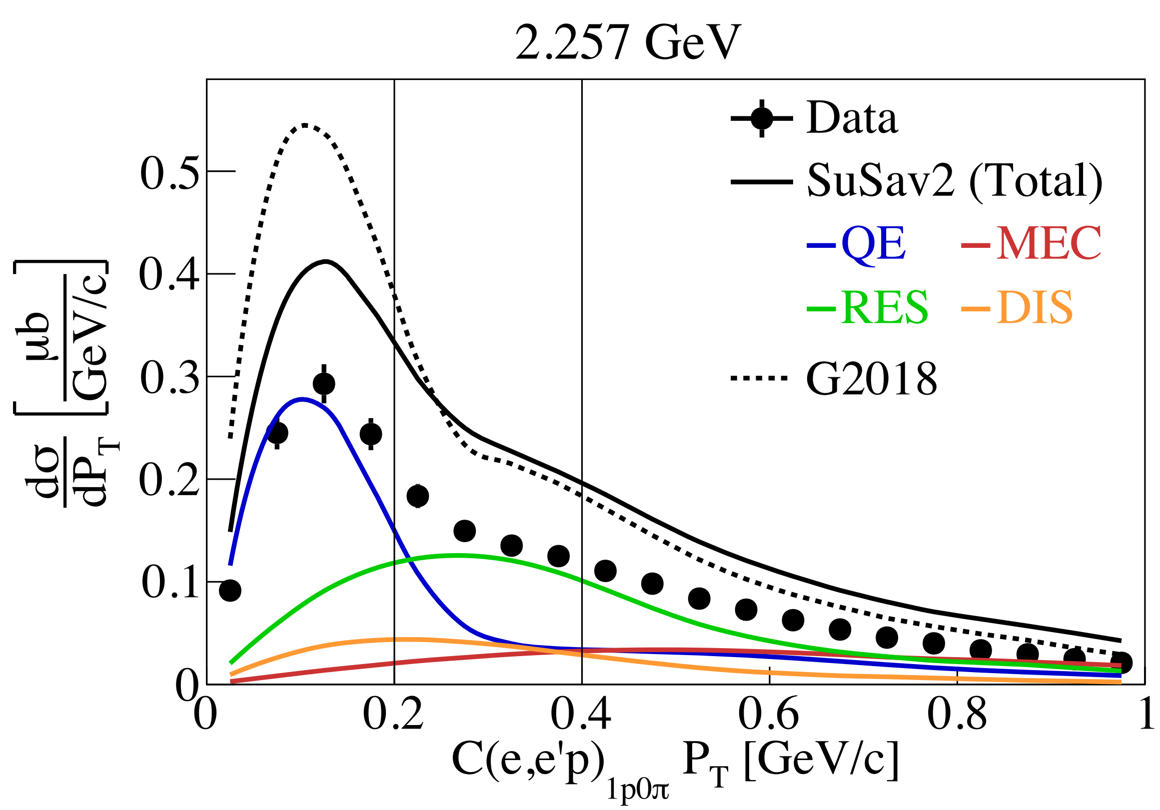
$$E_{cal} = E'_e + T_p + E_{bind}$$

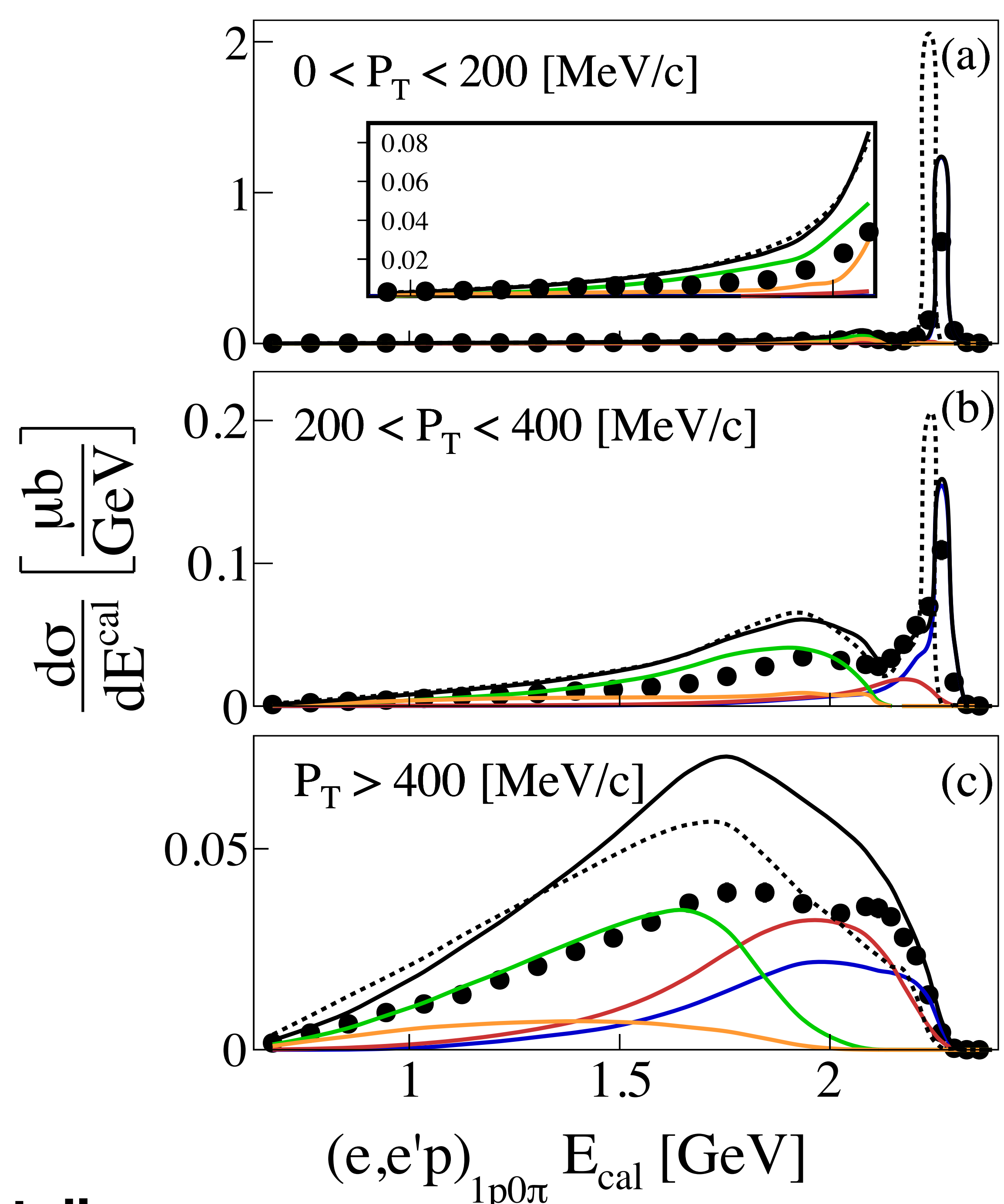


Khachatryan, Papadopoulou et al, Nature, in press

Transverse Missing Momentum



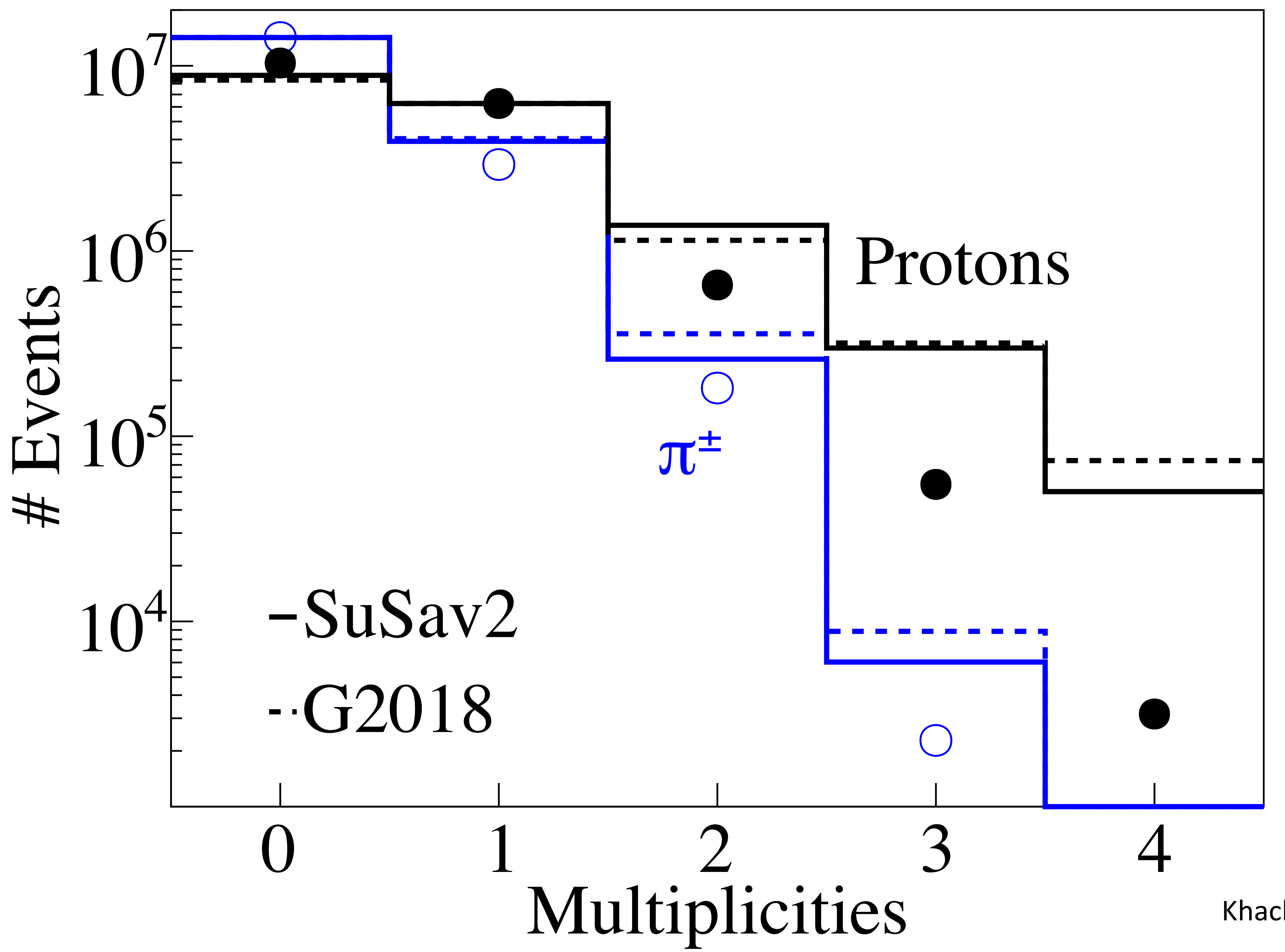




Overestimation of QE peak and RES tail

Khachatryan, Papadopoulou et al, Nature, in press

Hadron Multiplicities



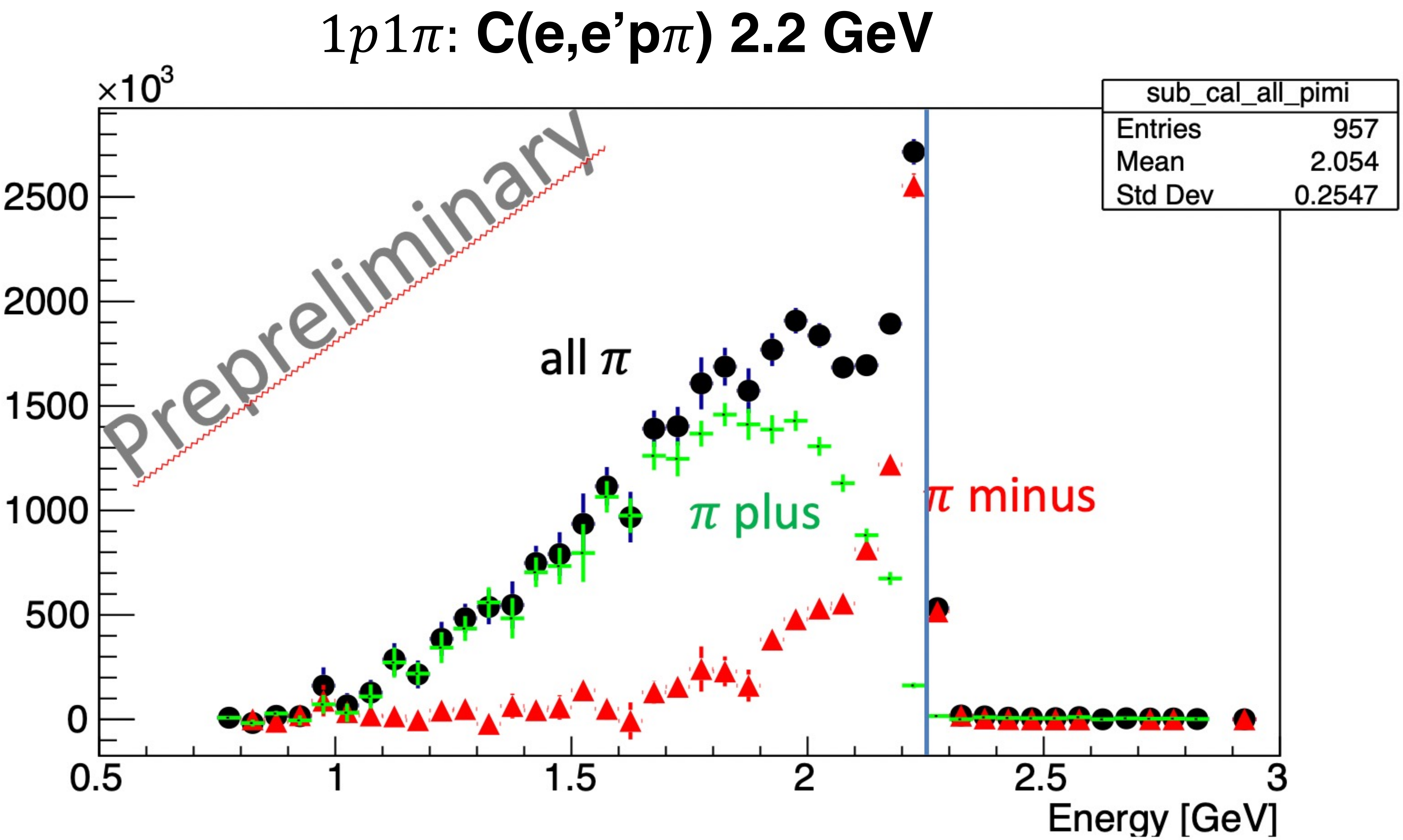
^{12}C @ 2.2 GeV

$P_p > 300$ MeV/c
$P_\pi > 150$ MeV/c

GENIE overpredicts hadron multiplicities

Khachatryan, Papadopoulou et al, Nature, in press

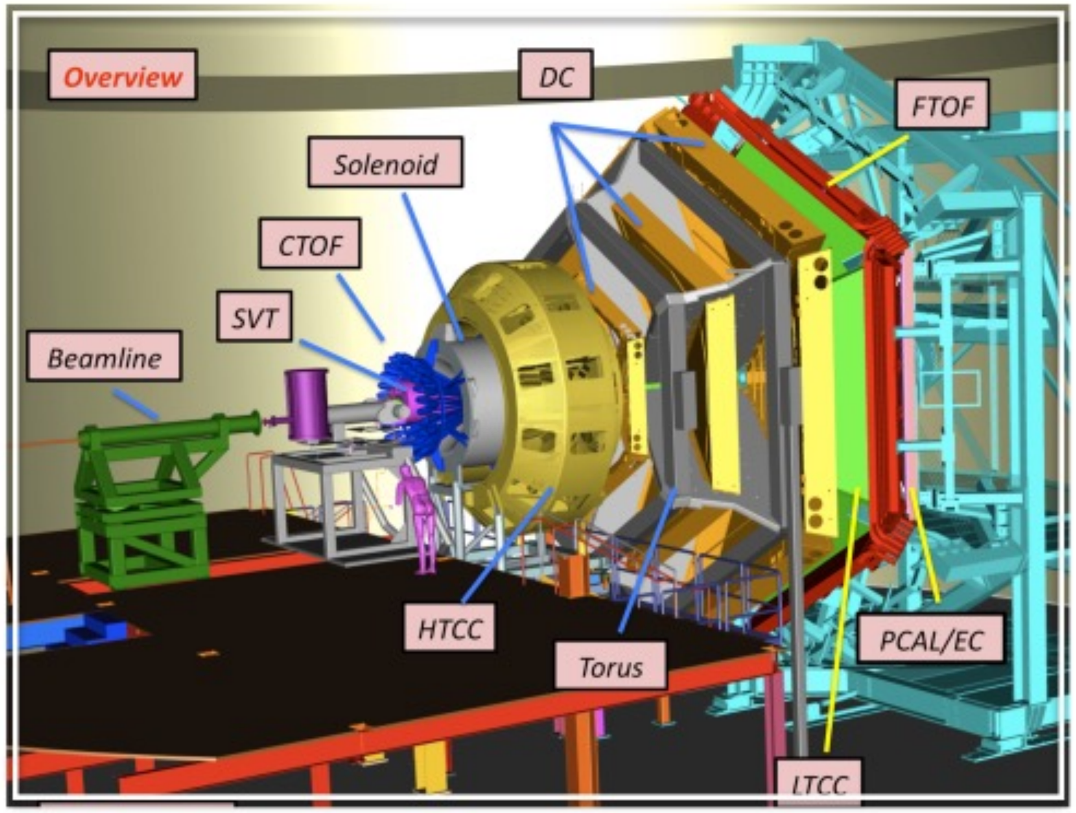
Measuring pions

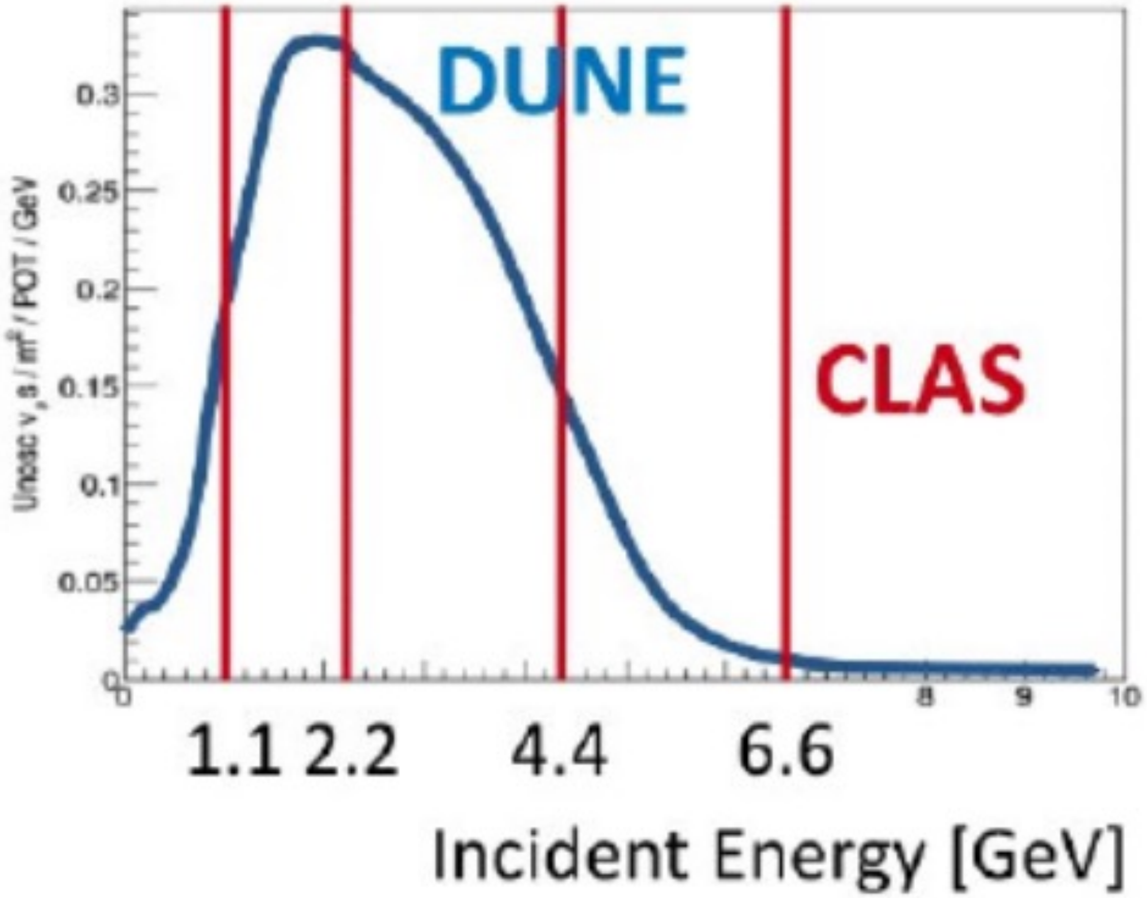


Calorimetric energy: $E = E_e' + E_\pi + T_p$

Coming Fall 2021: New Data with CLAS12

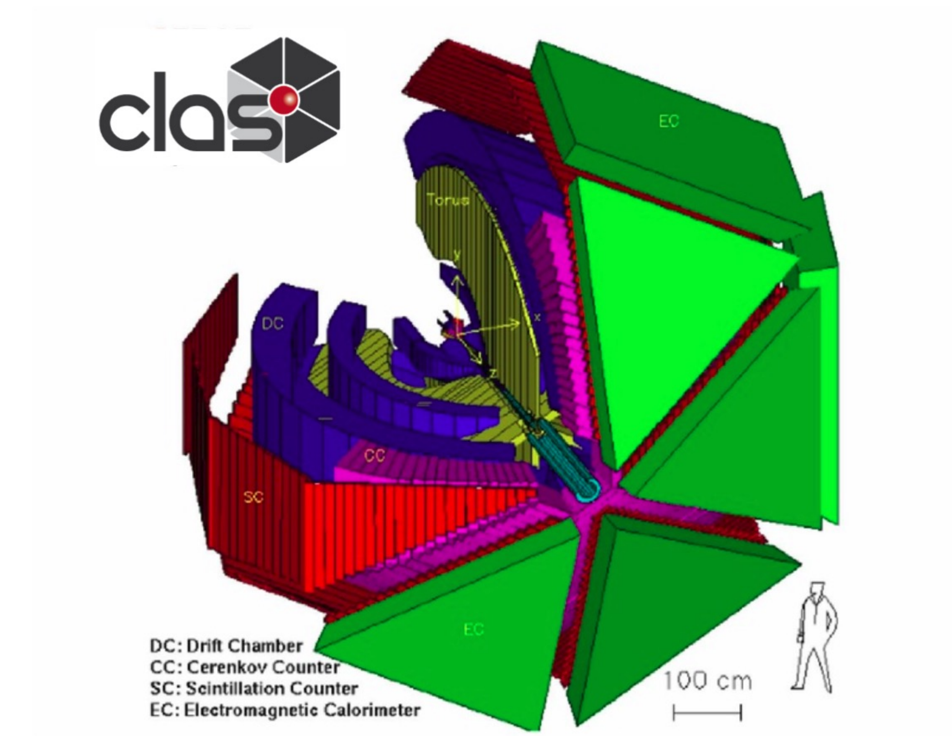
- Acceptance down to 5
- x10 luminosity [10^{35} cm^{-2} s^{-1}]
- Targets:
  - ^{2}D, ^{4}He, ^{12}C, ^{16}O, **^{40}Ar**, ^{120}Sn
  - 1-7 GeV beam energies
  - Better neutron & gamma directions

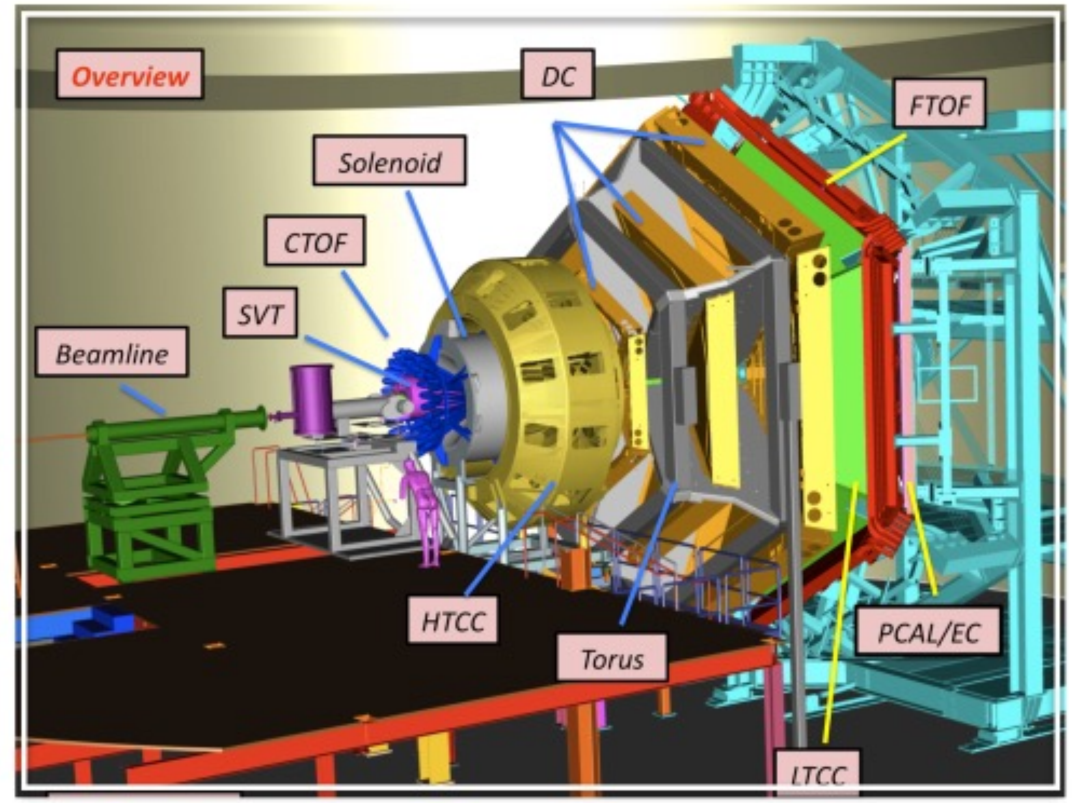




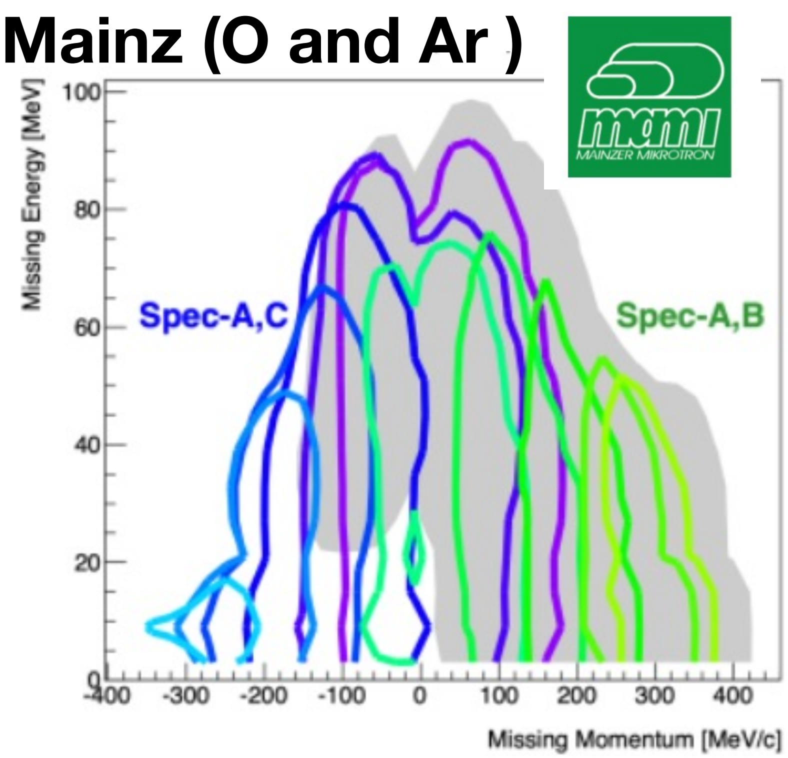
Parallel Efforts

e4V @ Jefferson Lab
Thomas Jefferson National Accelerator Facility

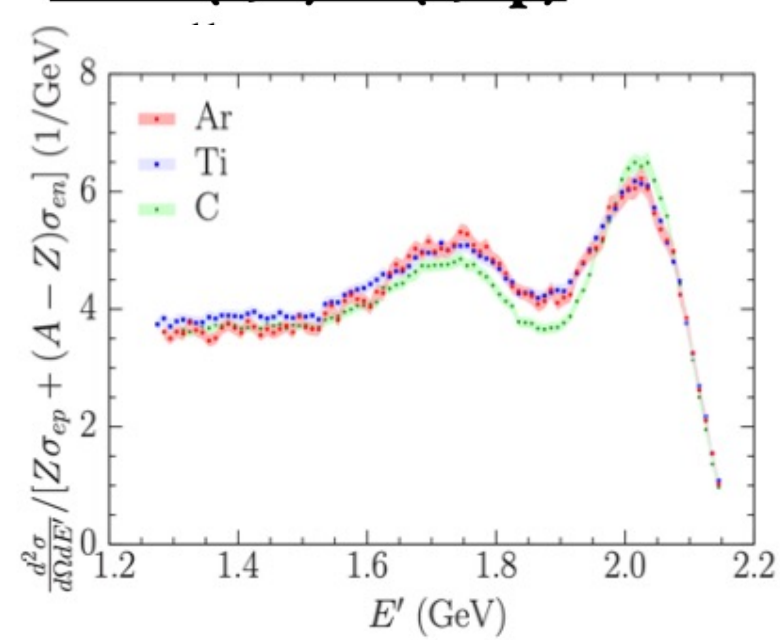




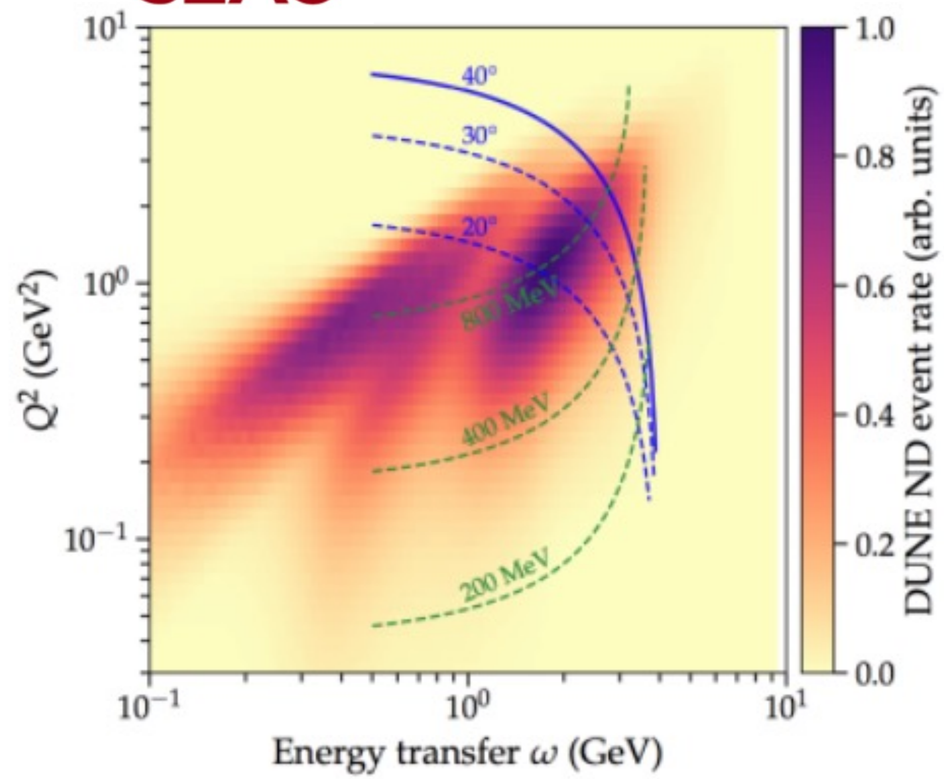
Mainz (O and Ar)



ArTi (e,e') & (e,e'p) JLab



SLAC arXiv:1912.06140



Summary

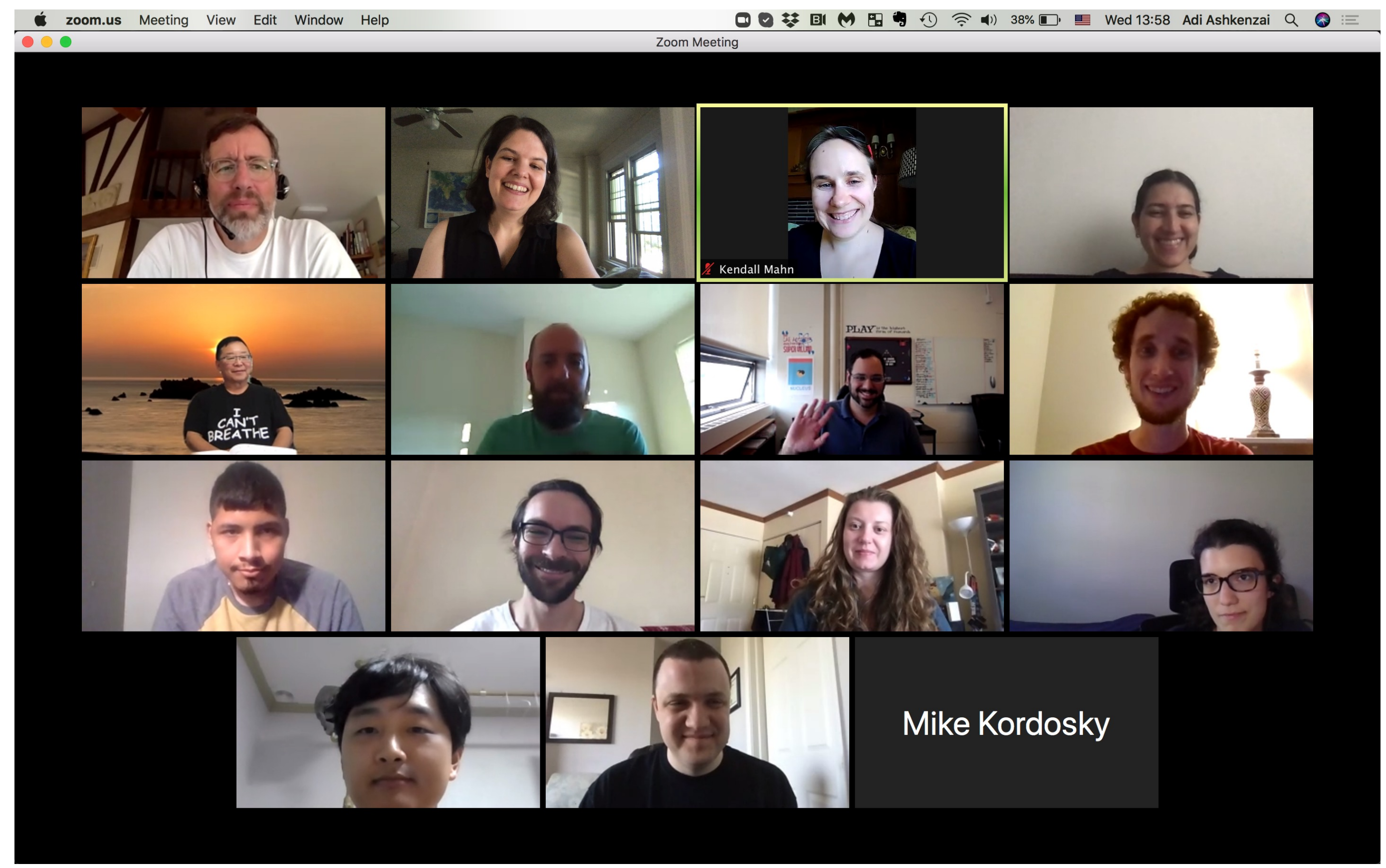
- Neutrino nucleus scattering uncertainties will limit next generation oscillation experiment
- First measurement of wide space phase electron data with CLAS to improve neutrino-nucleus scattering model
  - Most events do not reconstruct the correct beam energy
  - Data/model disagreements will guide model improvements, including QE-like and Resonance
- Collecting more electron data

e4ν Collaboration

- Old Dominion University
- MIT
- Jefferson Lab
- Tel Aviv U
- Michigan State
- Fermilab
- U Pittsburgh
- York University, UK

Join us!

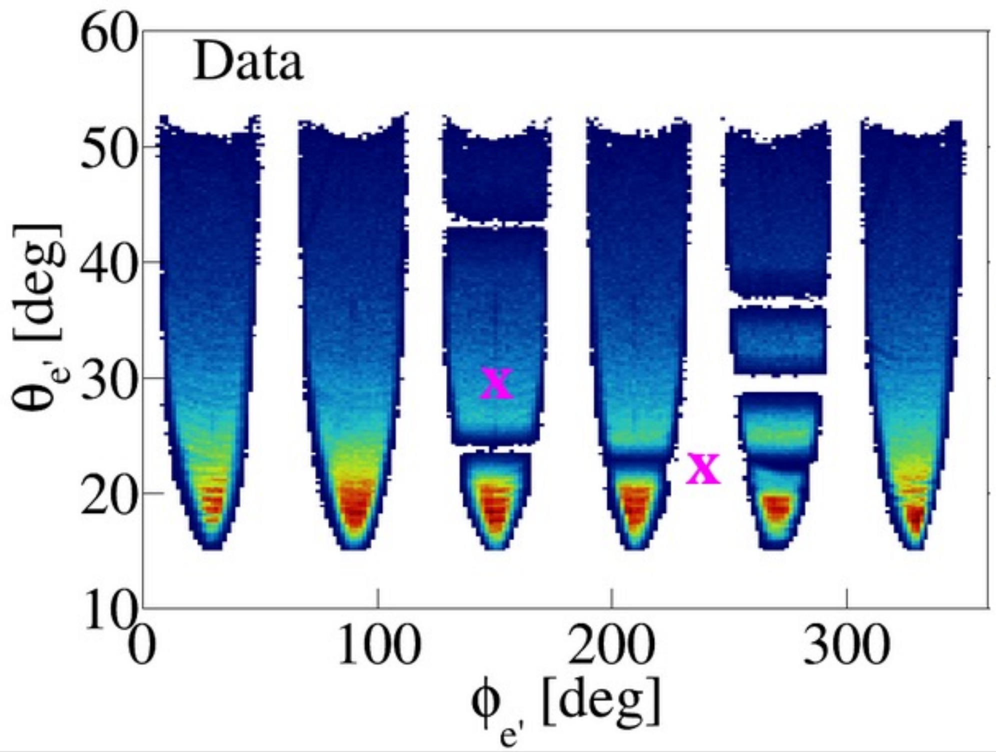
- New collaborators from:
  - UCL,
  - College of William & Mary,
  - U of Texas,
  - Arlington,
  - Rutgers U,
  - U of Maine
  - LBL

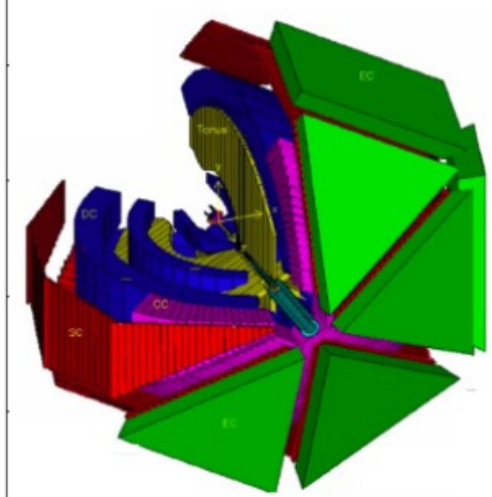


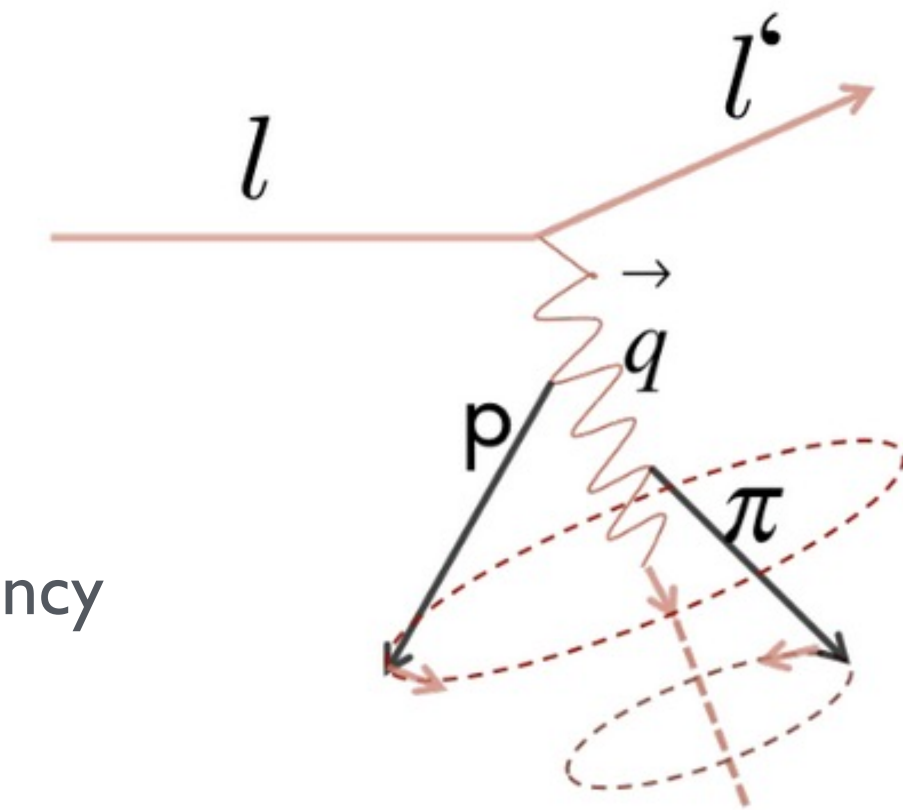
Jefferson Lab MIT CSIC CONSEJO SUPERIOR DE INVESTIGACIONES CIENTÍFICAS

Data Driven Correction

- Non-QE interactions lead to multi-hadron final states
- Gaps make them look like QE-like events







- Use measure (e,e’pπ) events
- Rotate p, π around q to determine π detection efficiency
- Subtract undetected (e,e’pπ)
- Repeat for higher hadron multiplicities