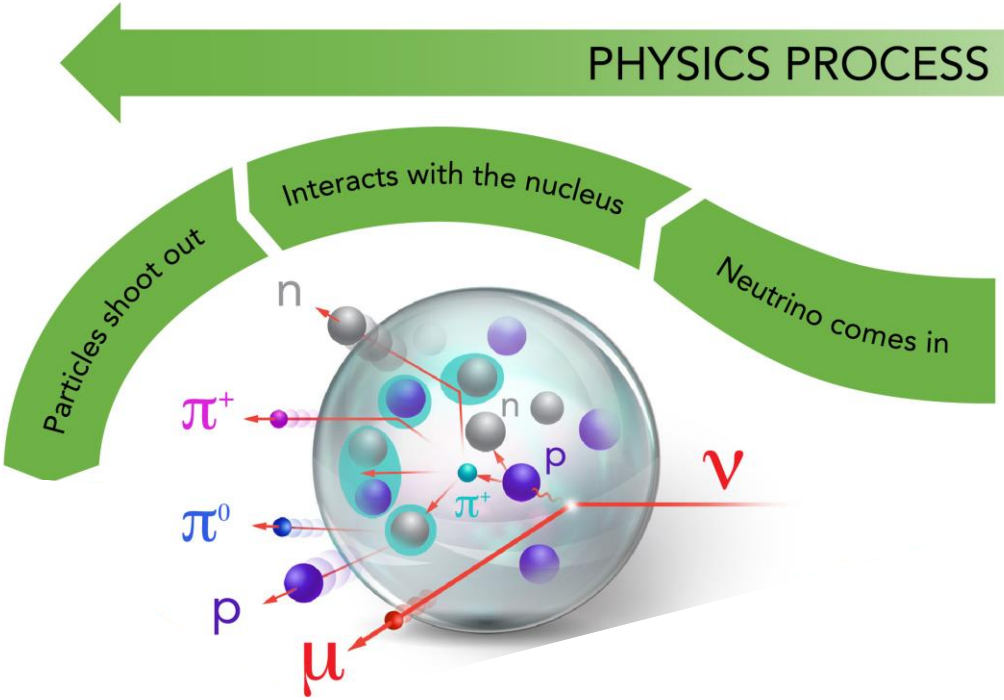
How precision lepton scattering (especially electrons) can help precision LBL neutrino measurements

Lawrence Weinstein

(for Adi Ashkenazi)

Old Dominion University

INT 2023

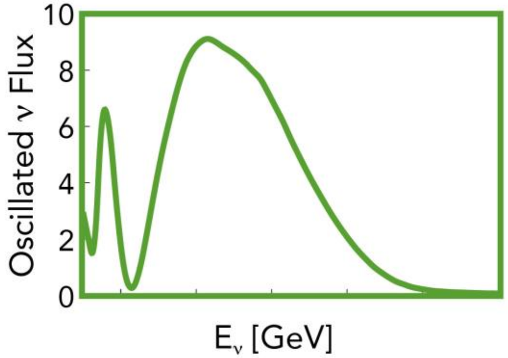


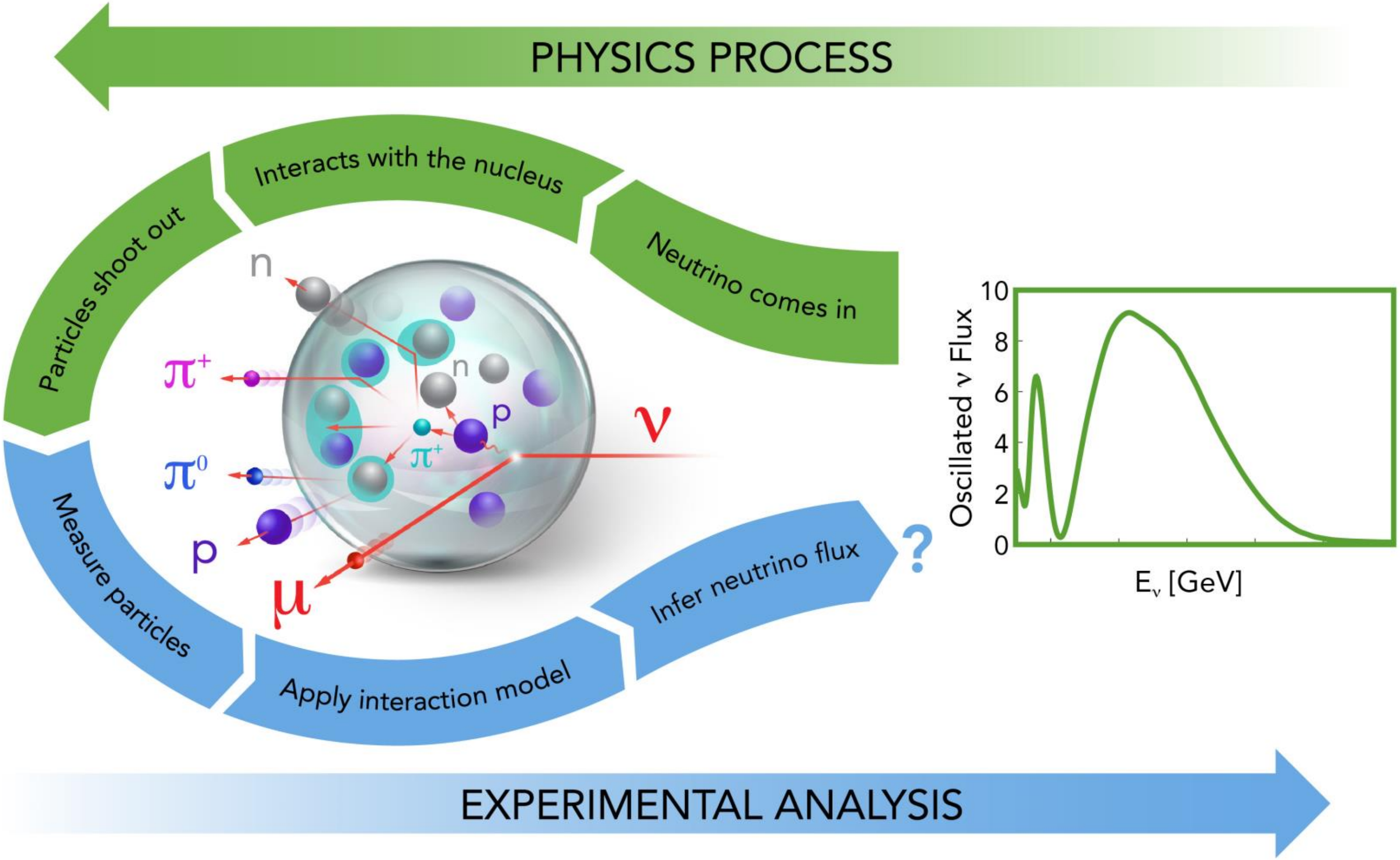
PHYSICS PROCESS

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

Infer neutrino flux

EXPERIMENTAL ANALYSIS

Measure counts

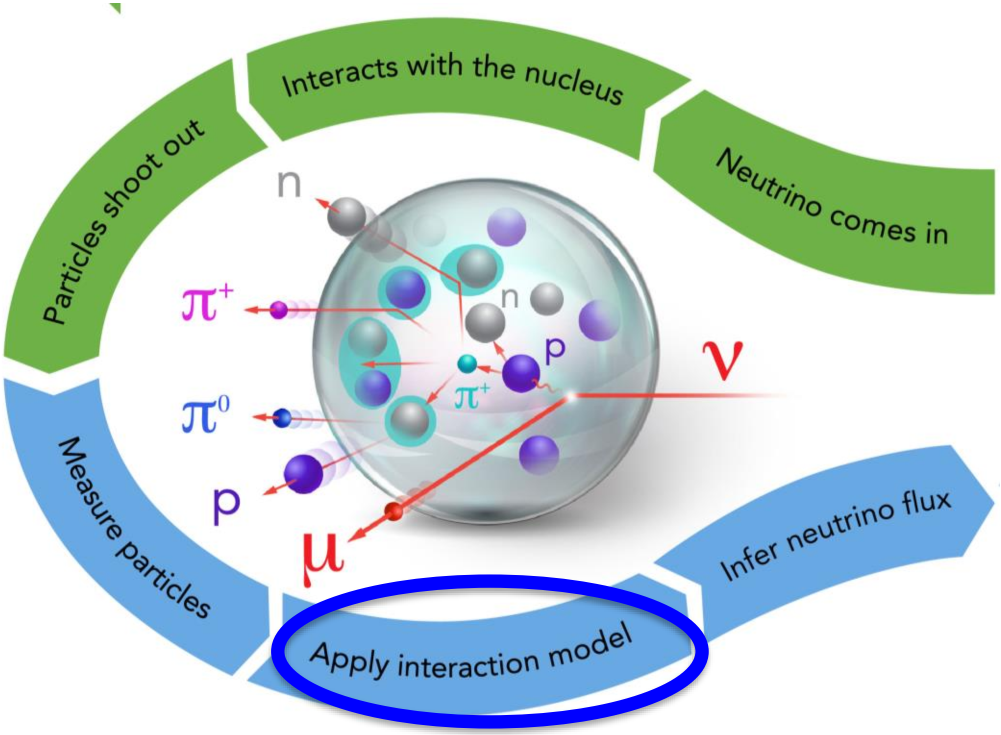
Use an interaction model to deconvolute the ν Flux.

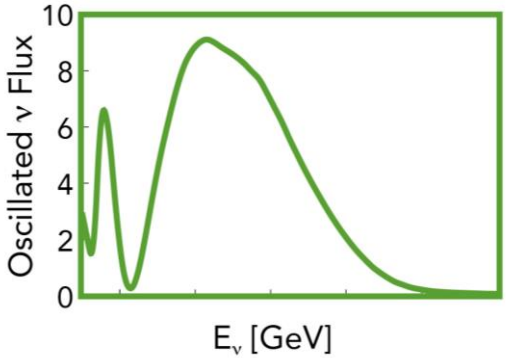
$$N_\alpha(E_{rec},L)=\sum_i \int \Phi_\alpha(E,L)\,\sigma_i(E)\,f_{\sigma_i}(E,E_{rec})\,dE$$

measured

ν Flux

interaction model





Measure counts

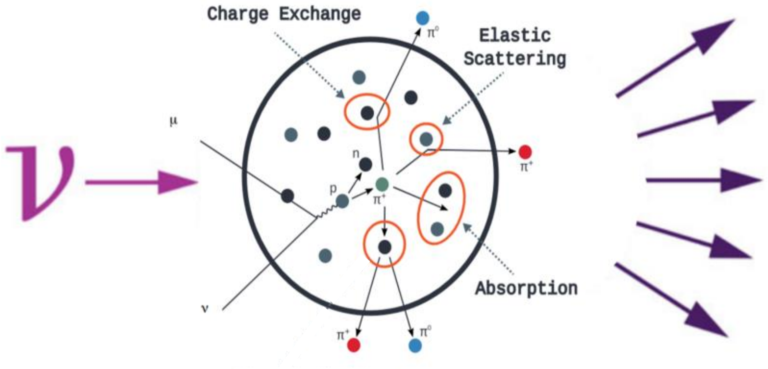
Use an interaction model to deconvolute the ν Flux.

$$\underbrace{N_\alpha(E_{rec},L)}_{\text{measured}}=\sum_i \int \underbrace{\Phi_\alpha(E,L)}_{\nu\text{ Flux}}\,\underbrace{\sigma_i(E) f_{\sigma_i}(E,E_{rec})}_{\text{interaction model}}\,dE$$

Lots of complicated strong interaction nuclear physics

- Quasielastic scattering
- Meson exchange currents
- Resonance production
- Deep inelastic scattering
- Rescattering and absorption

No good complete theories



Use effective, empirical, semi-classical (no interference) models in **Neutrino Event Generators**

Measure counts

Use an interaction model 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 $\quad$ ν Flux $\quad$ interaction model

<u>Event Generators</u>: theory models, e data, ν ND data, …

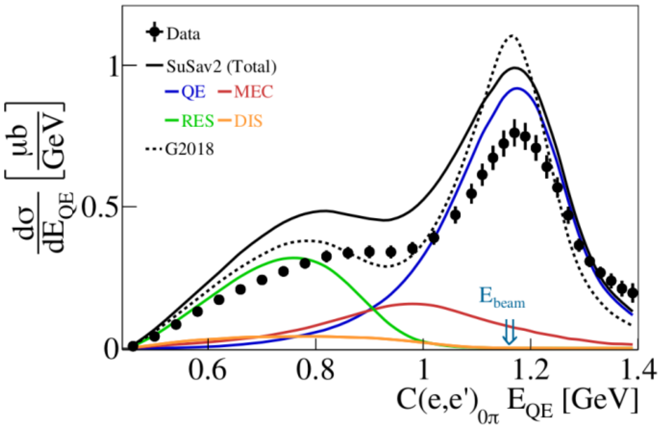
<u>ν Near Detector data</u>:

Measure $N_\alpha(E_{rec},0)$

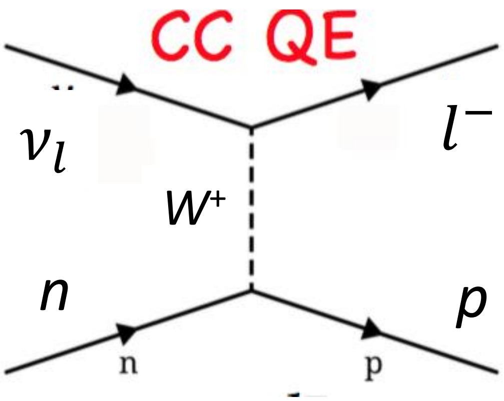
$\Longrightarrow$ integrated constraint on $\sigma_i(E)$ and $f_{\sigma_i}(E,E_{rec})$

<u>Electron Data</u>

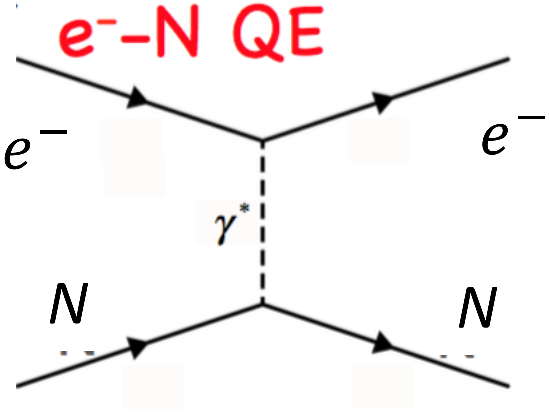
e4ν $\quad$ clas



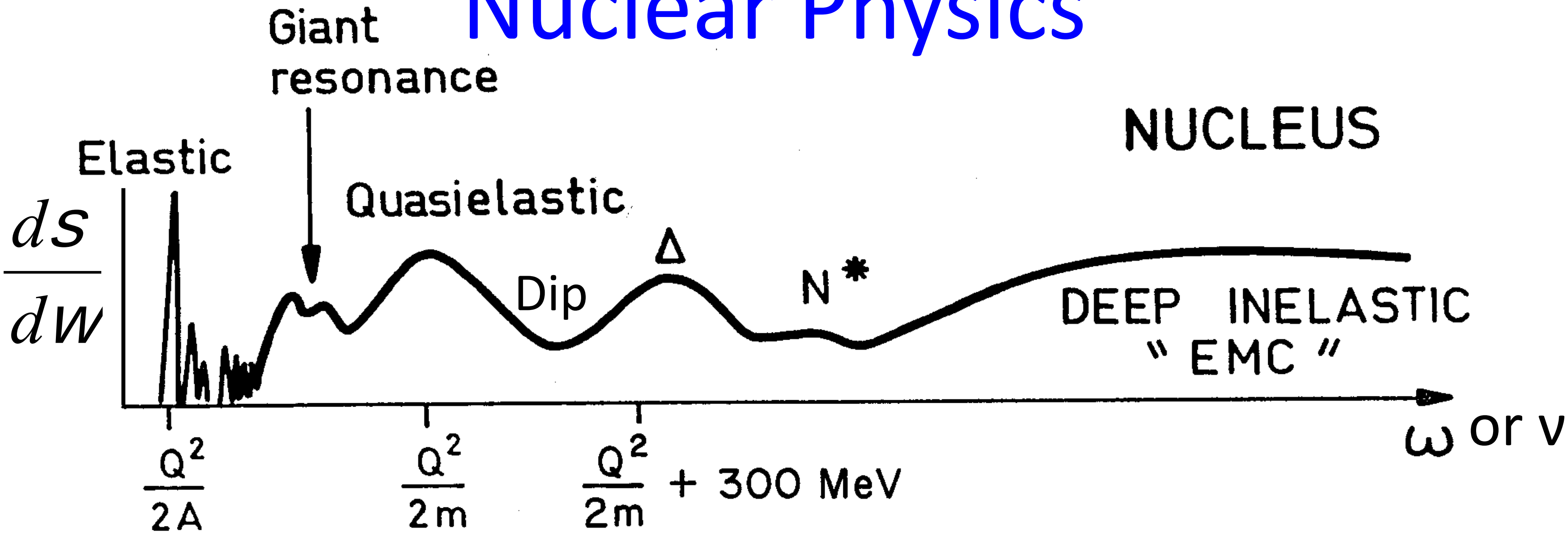
Why electrons?



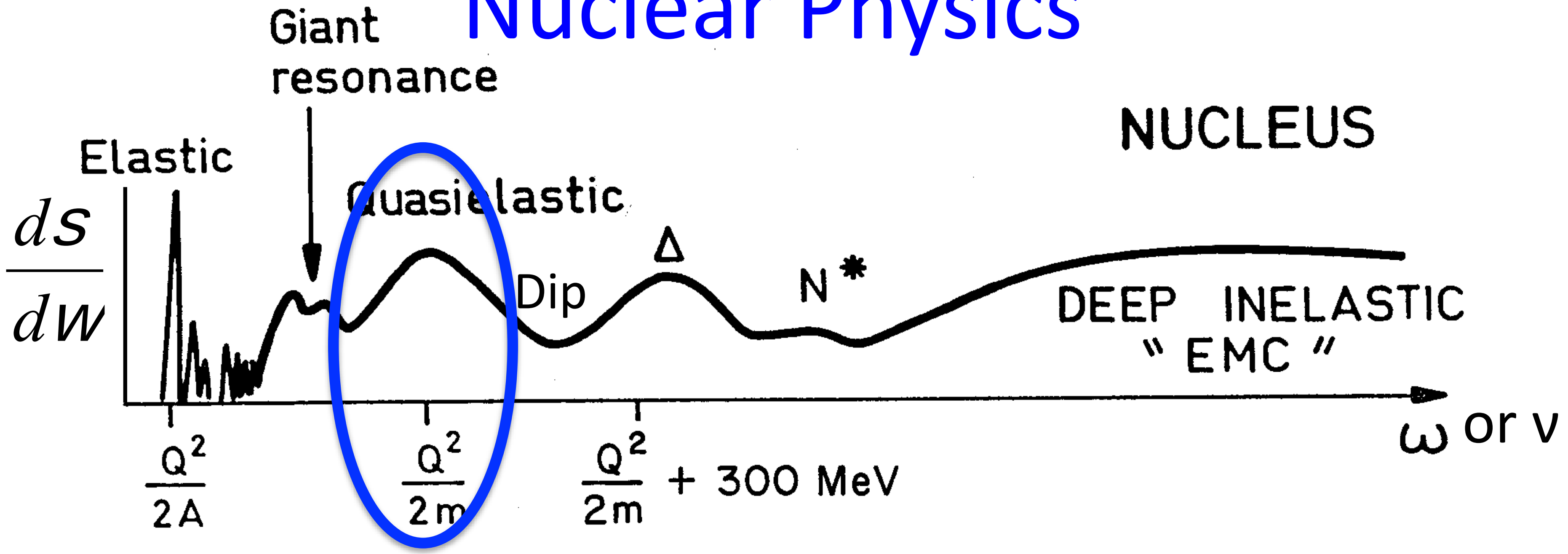
- Monoenergetic
- High intensity
- Similar interaction with nuclei
  - Single boson exchange
  - CC Weak current [vector plus axial]
    - $j_\mu^\pm = \bar{u}\frac{-ig_W}{2\sqrt{2}}(\gamma^\mu - \gamma^\mu\gamma^5)u$
  - EM current [vector]
    - $j_\mu^{em} = \bar{u}\,\gamma^\mu u$
- Similar nuclear physics



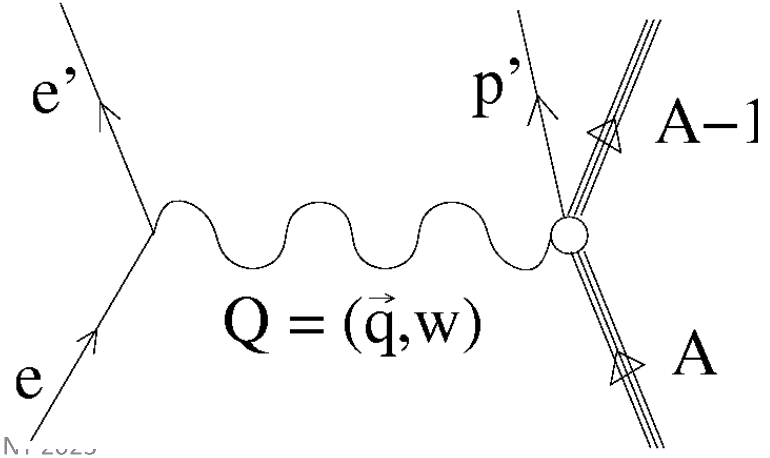
Nuclear Physics



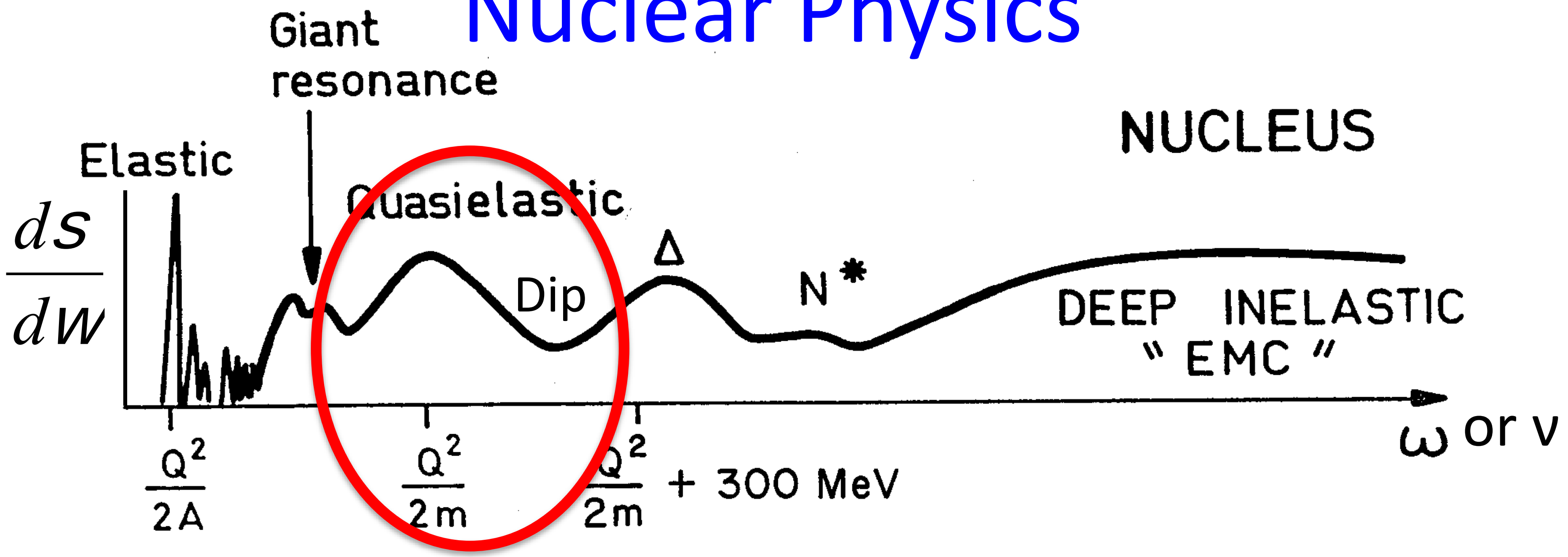
Nuclear Physics



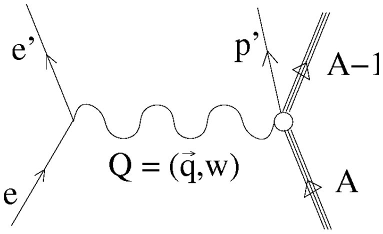
What neutrino expts want

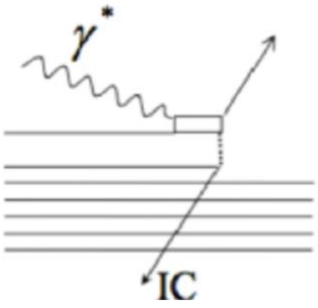


Nuclear Physics

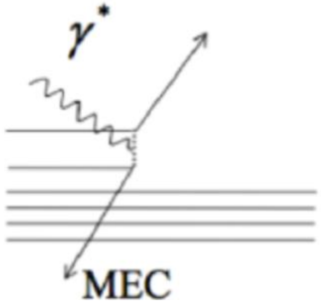


What we get (even for 0pi)

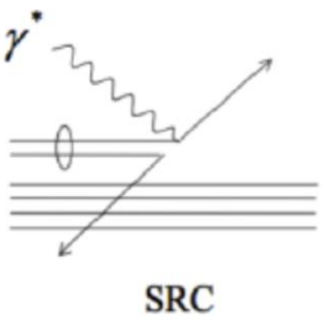




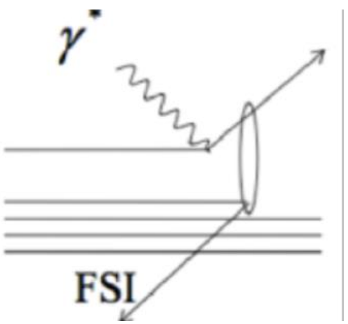
Resonance



Meson Exchange Currents

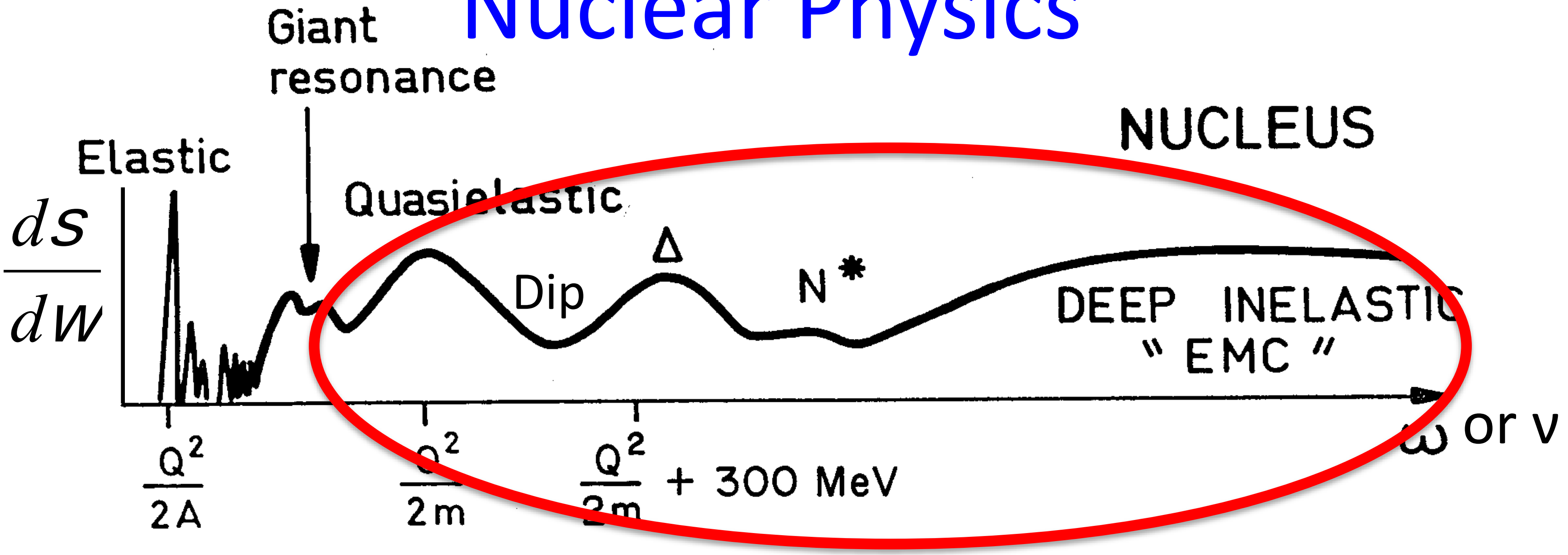


Short Range Correlations

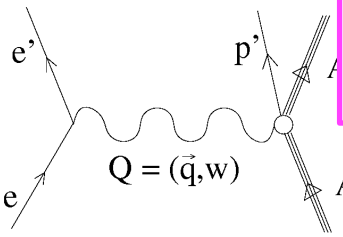


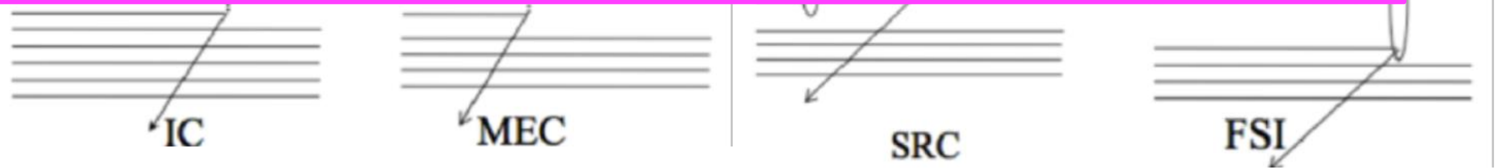
Final State Interactions

Nuclear Physics



Now add pion production through resonances, DIS, etc!





Resonance

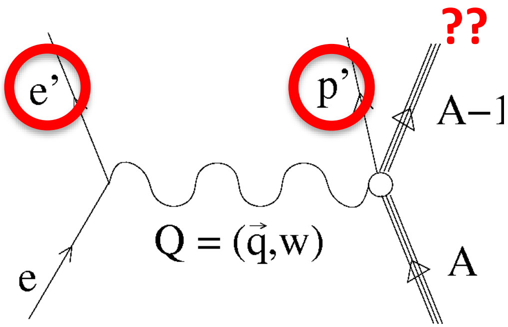
Meson Exchange Currents

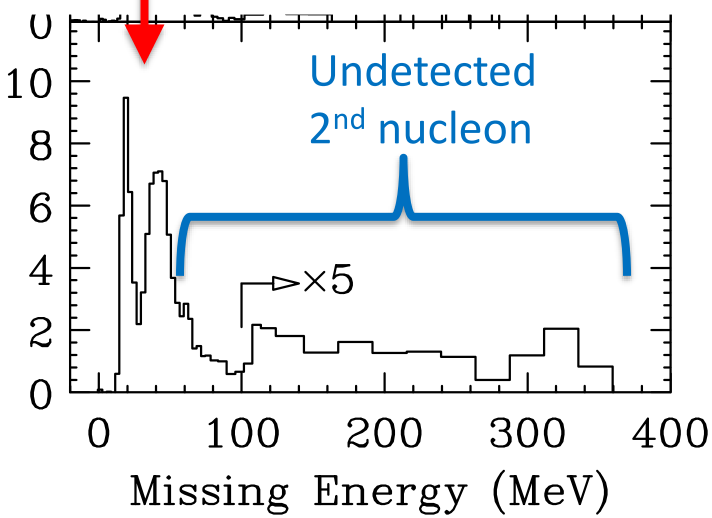
Short Range Correlations

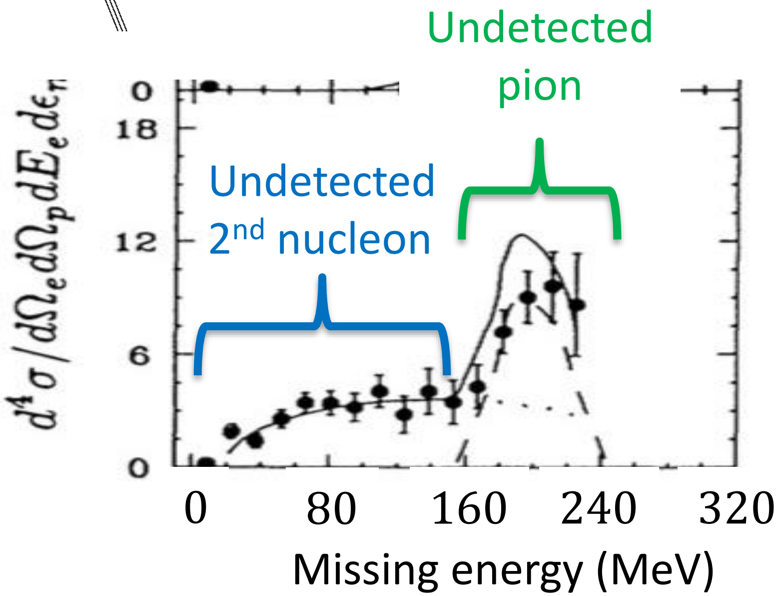
Final State Interactions

How do reaction mechanisms appear in A(e,e’p)?

Single nucleon knockout





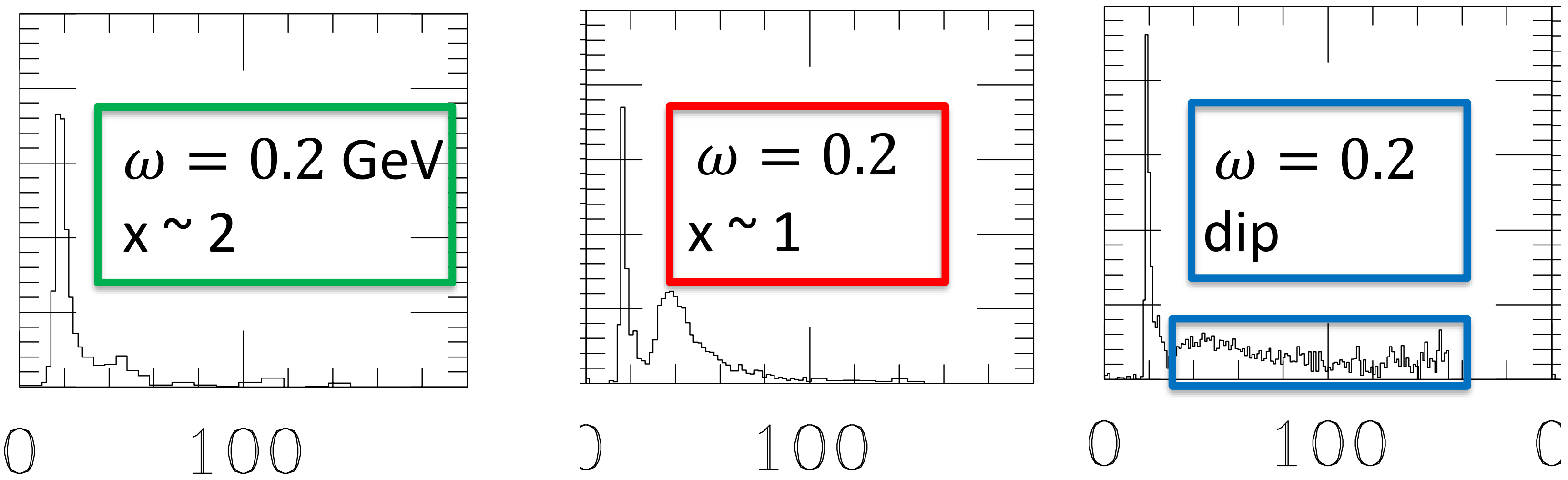


$$E_{miss} = \omega - T_p$$

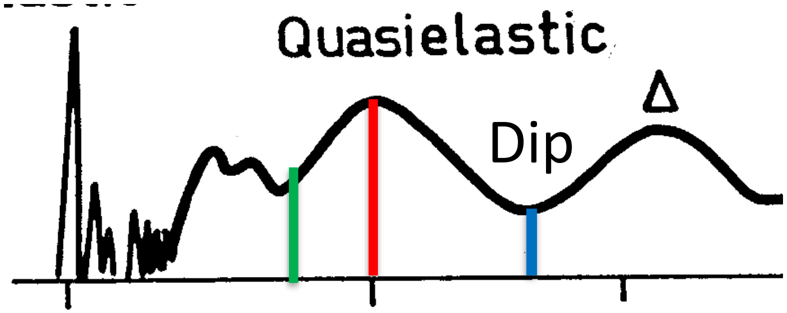
$$\omega = E - E'$$

From QE to “dip”

C(e,e’p)



Missing energy [MeV]



$$x = \frac{Q^2}{2m\omega}$$

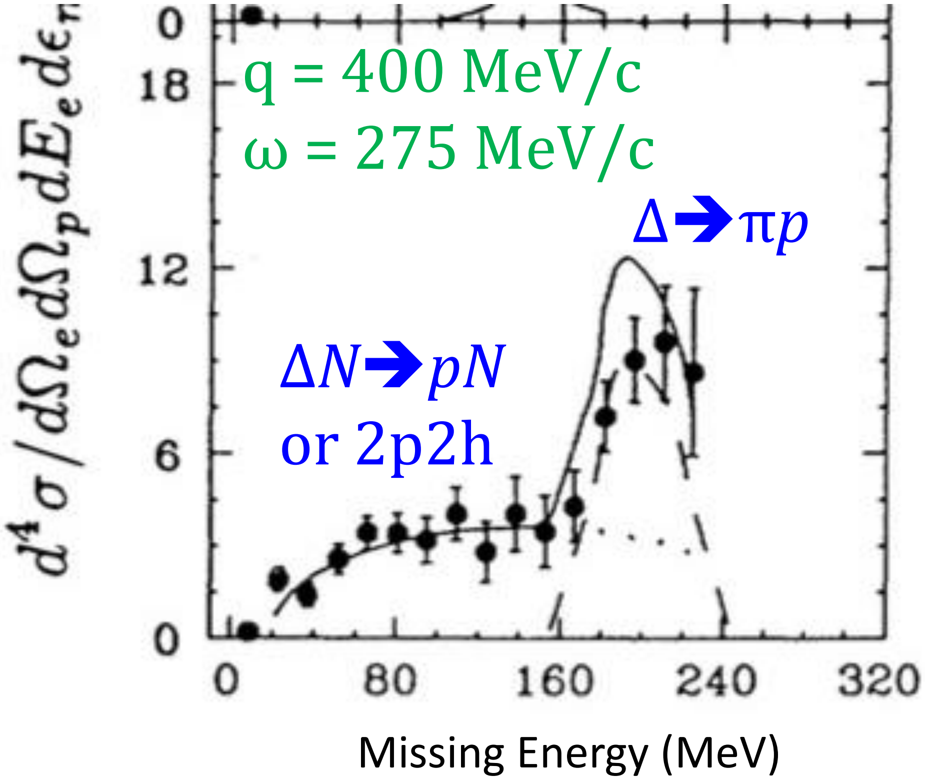
R. Lourie, PRL **56**, 2364 (1986)

L. Weinstein, PRL **64**, 1646 (1990)

S. Penn, PhD thesis, MIT

From Dip to Delta Region

C(e,e’p)

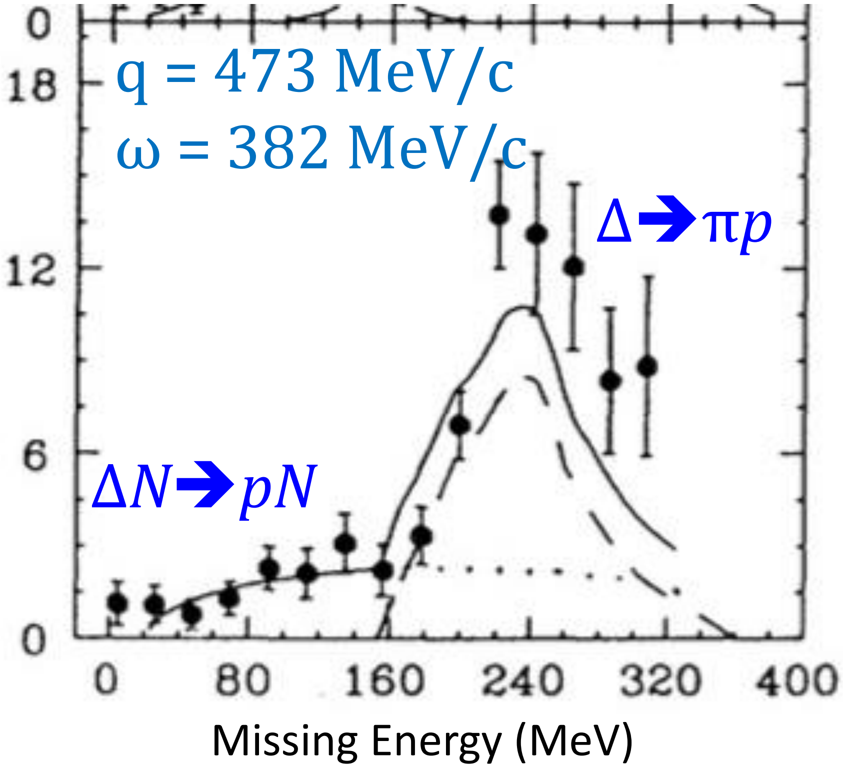


q = 400 MeV/c
ω = 275 MeV/c

$\Delta \rightarrow \pi p$

$\Delta N \rightarrow pN$
or 2p2h

Missing Energy (MeV)

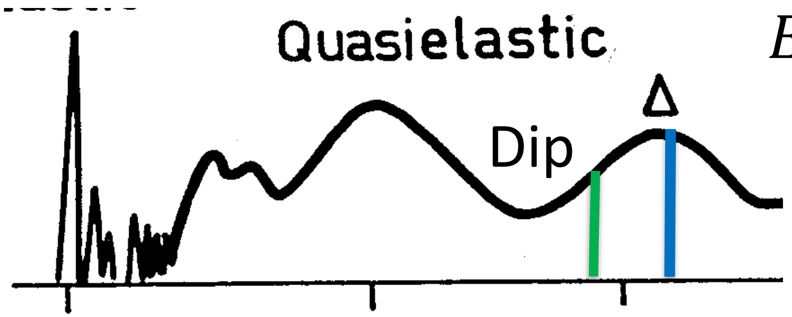


q = 473 MeV/c
ω = 382 MeV/c

$\Delta \rightarrow \pi p$

$\Delta N \rightarrow pN$

Missing Energy (MeV)



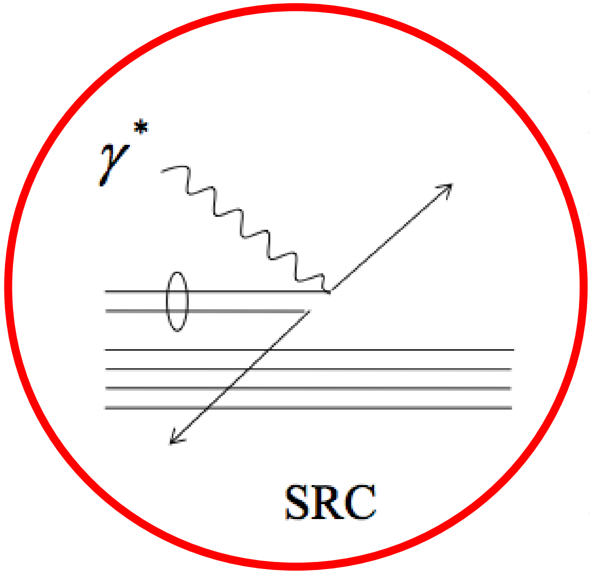
$$E_{miss} = \omega - T_p$$

Baghaei, PRC **39**, 177 (1989)

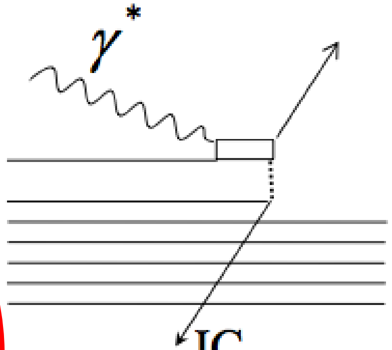
What are correlations?

Average Two-Nucleon Properties in the Nuclear Ground State

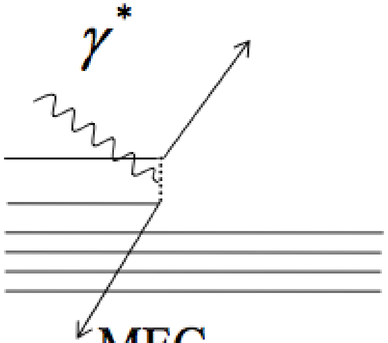
Two-body currents are not Correlations
(but everything adds coherently)



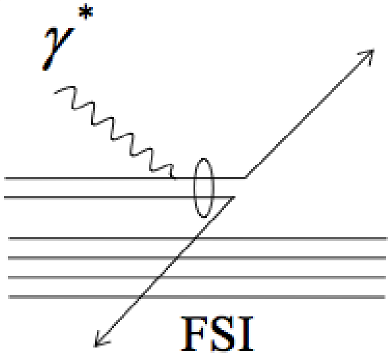
SRC



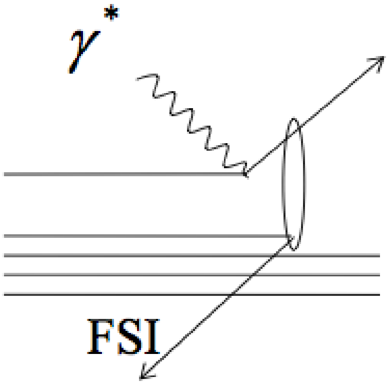
IC



MEC



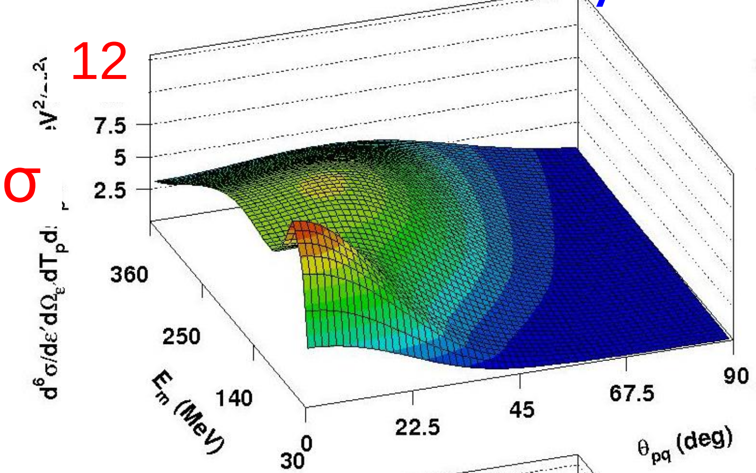
FSI
in SRC



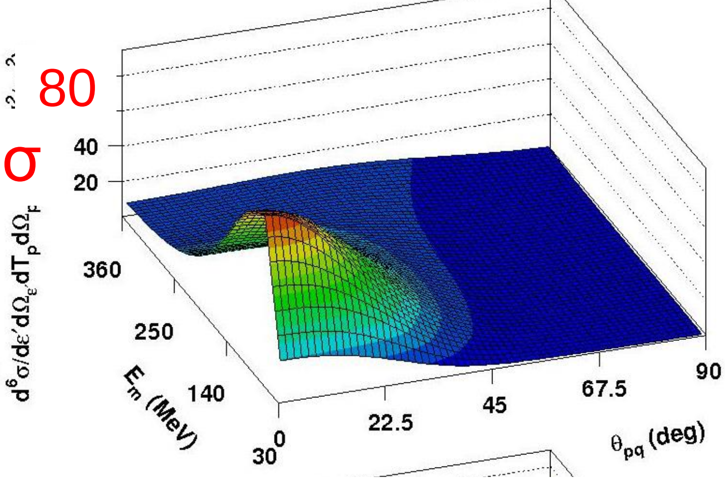
FSI

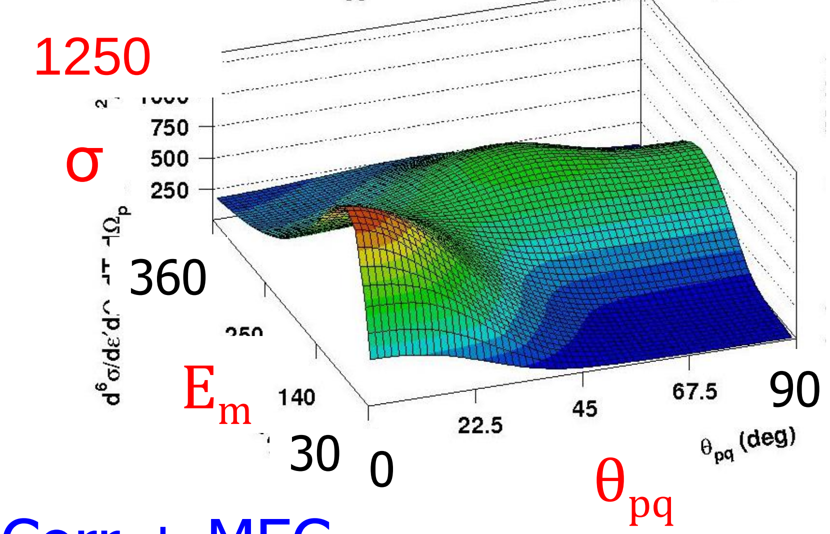
2N currents enhance correlations

Central correlations only



Central + tensor corr





Corr + MEC

MEC and correlations add coherently

$\rightarrow 2p2h$

O(e,e'p) Ryckebusch
NP A672 (2000) 285

Physics Summary

Nuclei are complicated

- Neutrino interactions
  - Continuous mixed beams
  - Vector plus axial current
  - Includes all reaction mechanisms
    - MEC, IC, correlations, Delta, …
    - Final state interactions
  - Need cross sections to extract oscillation parameters from data
- Electron scattering can help!
  - Monochromatic beam
  - Vector current only
  - Can choose kinematics and event topologies to select reaction mechanisms
  - Use data to measure cross sections

But!

How to use $\boldsymbol{eA}$ data to better describe $\boldsymbol{\nu A}$ interactions?

Papadopoulou et al, PRD 103, 113003 (2021)
arXiv:2106.09381

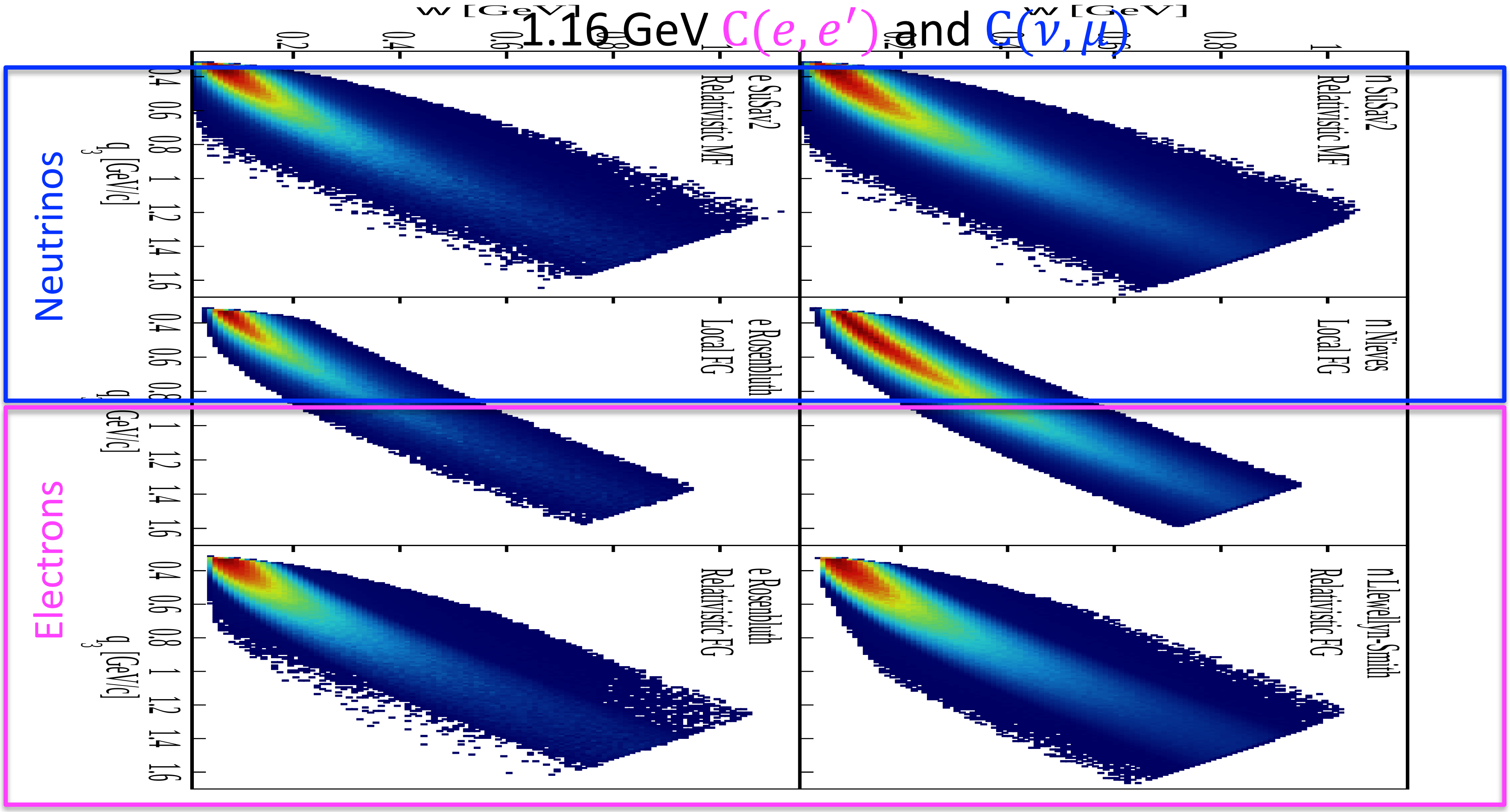
- GENIE v3
  - Unified eA and νA code

Test:

- Cross sections
- Hadronization
- Final State Interactions

eA vs νA similarities

1.16 GeV C(e, e') and C(ν, μ)



PRD 103, 113003 (2021)

Electron events weighted by Q^4

Electron Data

Present

- Jefferson Lab
  - Small aperture spectrometers (Hall A)
    - (e,e’) and (e,e’p) data at fixed angles and energies
  - Large Acceptance Spectrometer (CLAS)
    - 1, 2, and 4 GeV beams
    - All channels (e,e’), (e,e’p), (e,e’pπ), …
    - He, C, Fe targets
  - Large Acceptance Spectrometer (CLAS12)
    - (1), 2, 4, and 6 GeV beams
    - All channels (e,e’), (e,e’p), (e,e’pπ), …
    - D, He, C, (O), Ar, Ca40, Ca48 and Sn targets

Future

- Mainz (O and Ar gas jet targets)
- SLAC (LDMX, arXiv:1912.06140)

Inclusive (e,e’) cross sections

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

Now: selected target, energy, angle combinations

Sparse coverage, little to no O or Ar data

In progress: use large acceptance CLAS12 data

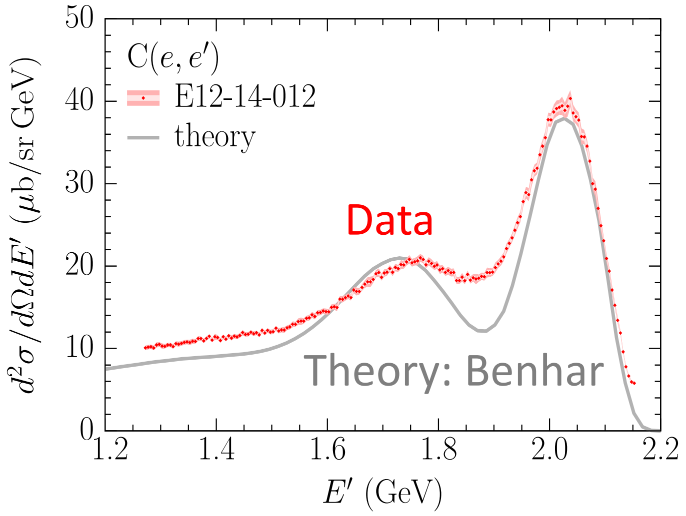
a) H, D, C, (O), Ar targets
b) (1), 2, 4 and 6 GeV at
c) $8 \leq \theta_e \leq 35°$

→ Continuous q, ω coverage

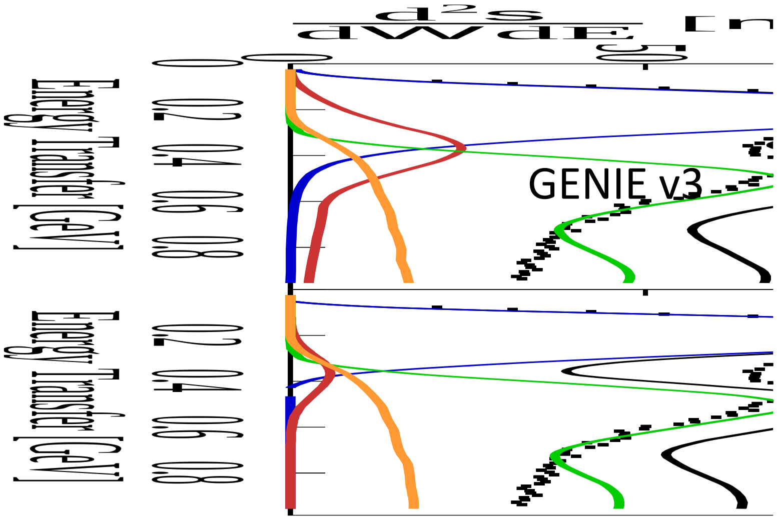
(M. Goldberg and A. Ashkenazi, Tel Aviv U)

Inclusive (e,e’) cross sections

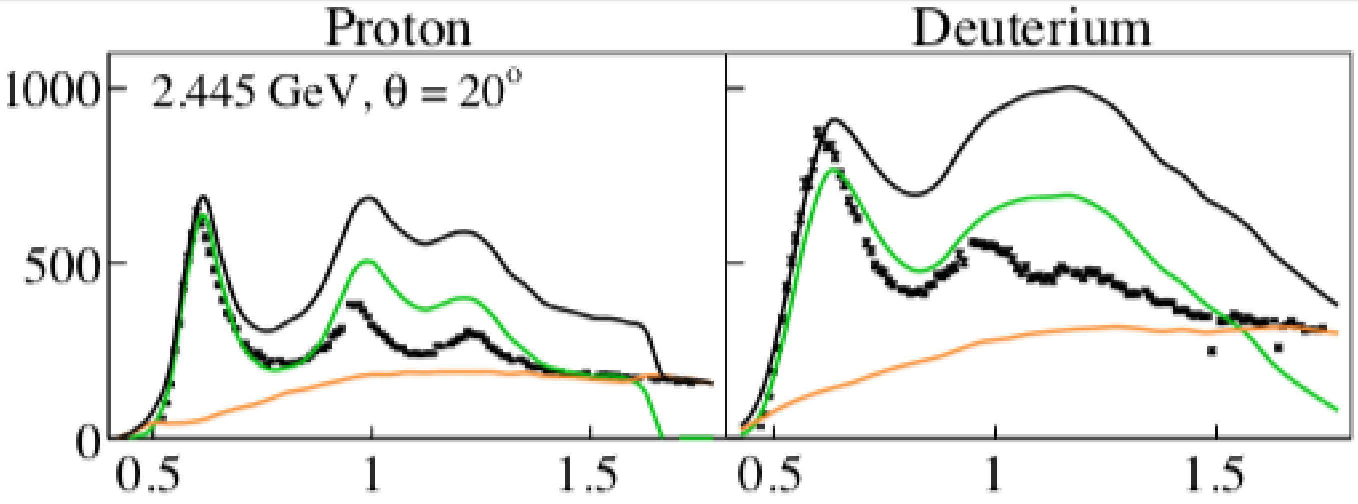
Jefferson Lab Hall A: C, Ti and Ar (e,e’) 2.2 GeV 15.5°



PRC 98, 014617; 99 054608; 100 054606



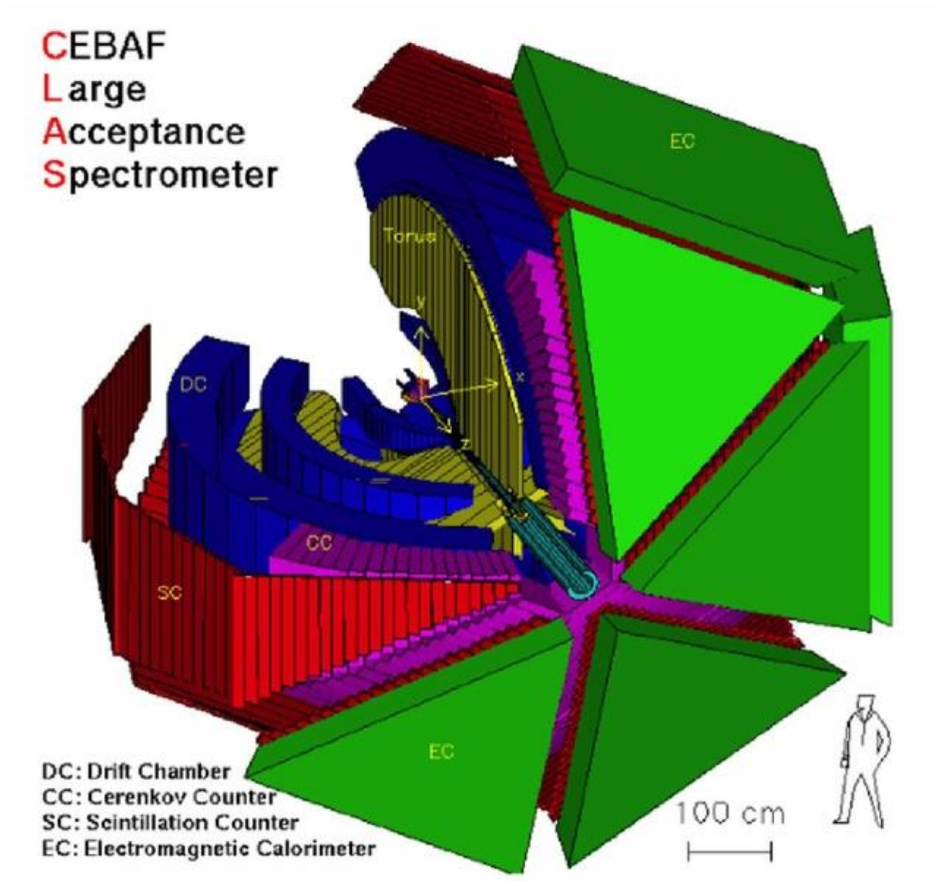
PRD 103, 113003 (2021)

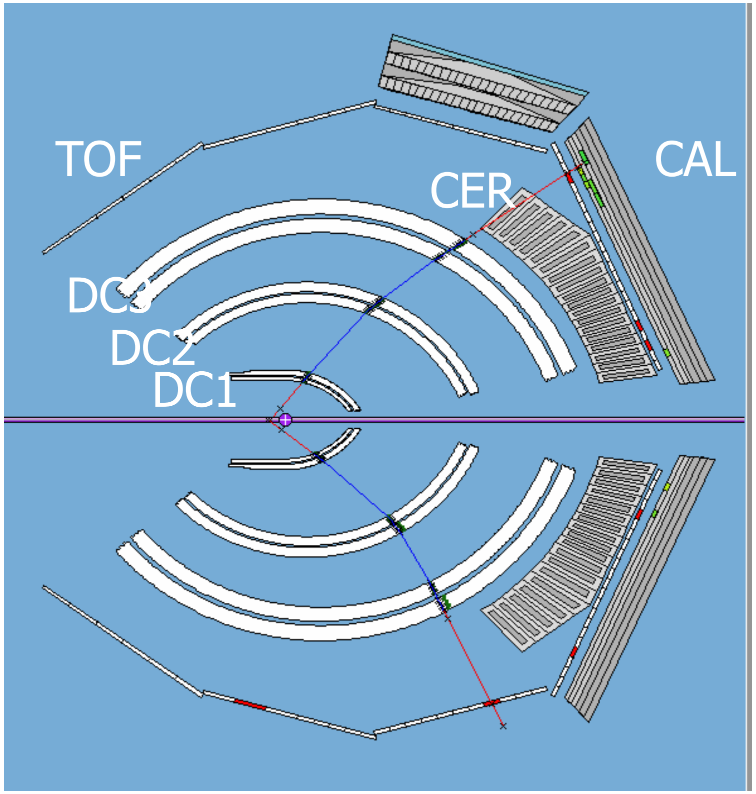


PRD 103, 113003 (2021)

Jefferson Lab CLAS

CLAS: 1996-2015

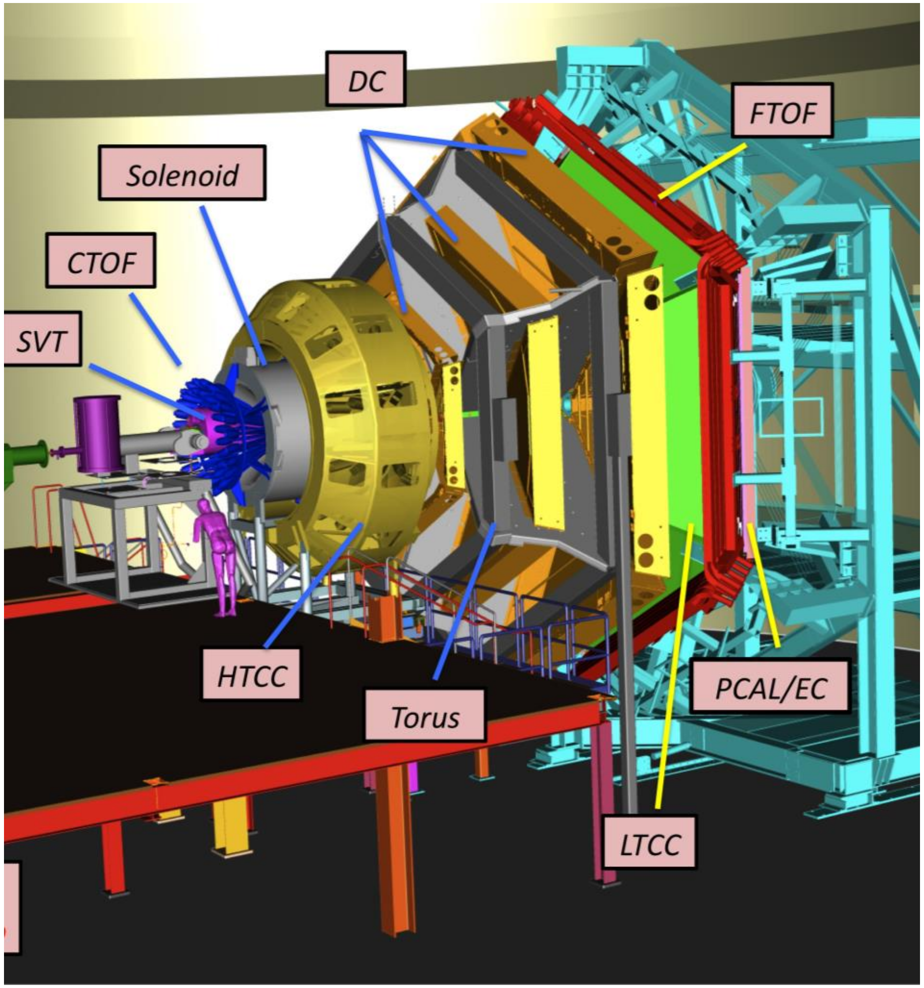




Large acceptance for $\theta_e > 15°$
1, 2, and 4 GeV
He, C, and Fe
Charged particle thresholds similar to neutrino tracking detectors

e4ν CLAS12

- forward detector (5 – 40^{o})
  - Luminosity ~10^{35} $s^{-1}cm^{-2}$
  - $\frac{\delta p}{p}$ ~ 0.5—1%
  - Neutrons:
    - 50% effi for p > 1 GeV/c
- Hermetic central detector (40 – 135^{o})
  - 5 T solenoidal field
  - $p_p > 350$ MeV/c
  - Neutron effi ~ 10—15%
- Data taken 21/22
  - (1), 2, 4, and 6 GeV
  - d, He, **C, (O), Ar**, ^{40}Ca, ^{48}Ca, Sn

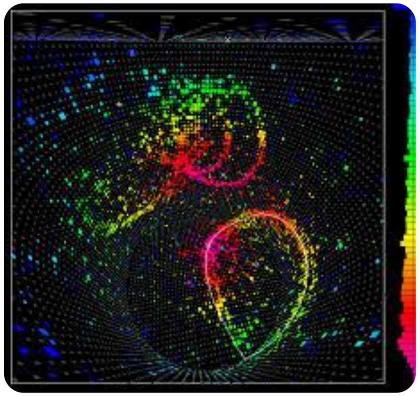


Emphasize QE – A(e,e'p) 0π

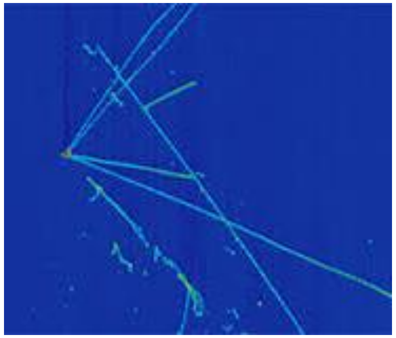
- Choose 0π events to enhance the QE sample
  - Subtract undetected pions and photons
- Weight by Q^4 to account for photon propagator

Reconstruct the incident lepton energy:

- Cherenkov detectors:
  - $E_{QE} = \frac{2M_N\epsilon + 2M_N E_l - m_l^2}{2(M_N - E_l + k_l \cos\theta_l)}$
    - Use lepton kinematics
    - assuming QE



- Tracking detectors
  - $E_{cal} = E_e + T_p + \epsilon$
    - calorimetry



Background Subtraction

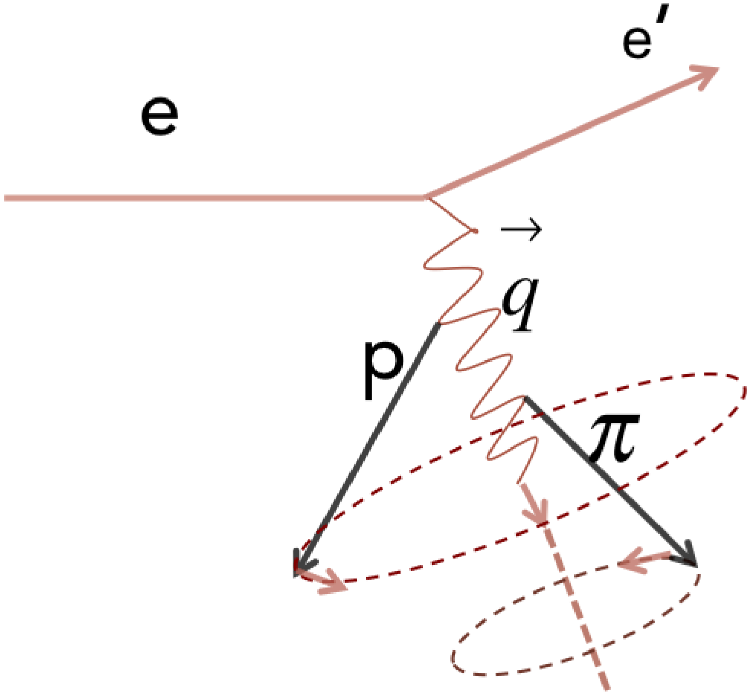
Want 0π event sample

(e,e') background: undetected pions and photons

(e,e'p) background: undetected pions, photons and extra protons

Data Driven Correction:

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



Background Subtraction

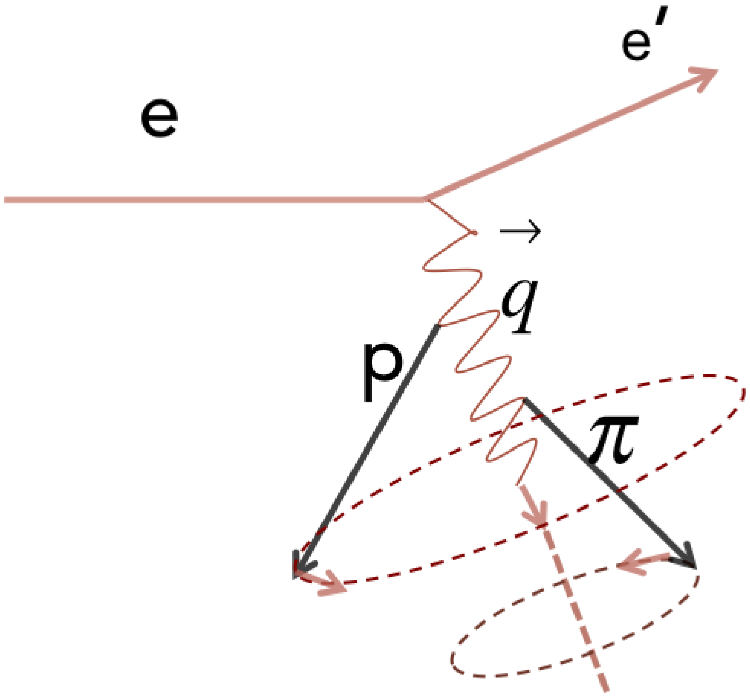
Want 0π event sample

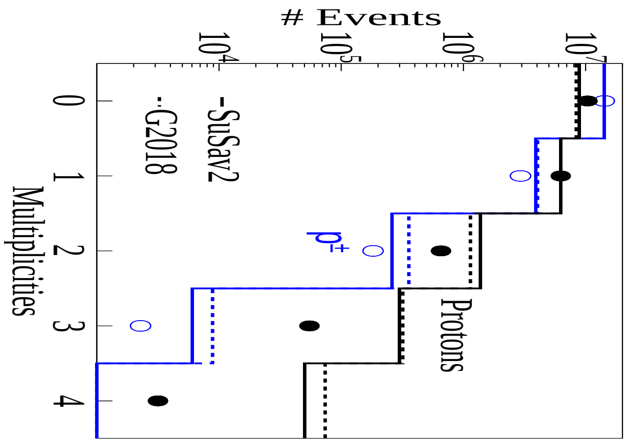
(e,e’) background: undetected pions and photons

(e,e’p) background: undetected pions, photons and extra protons

Data Driven Correction:

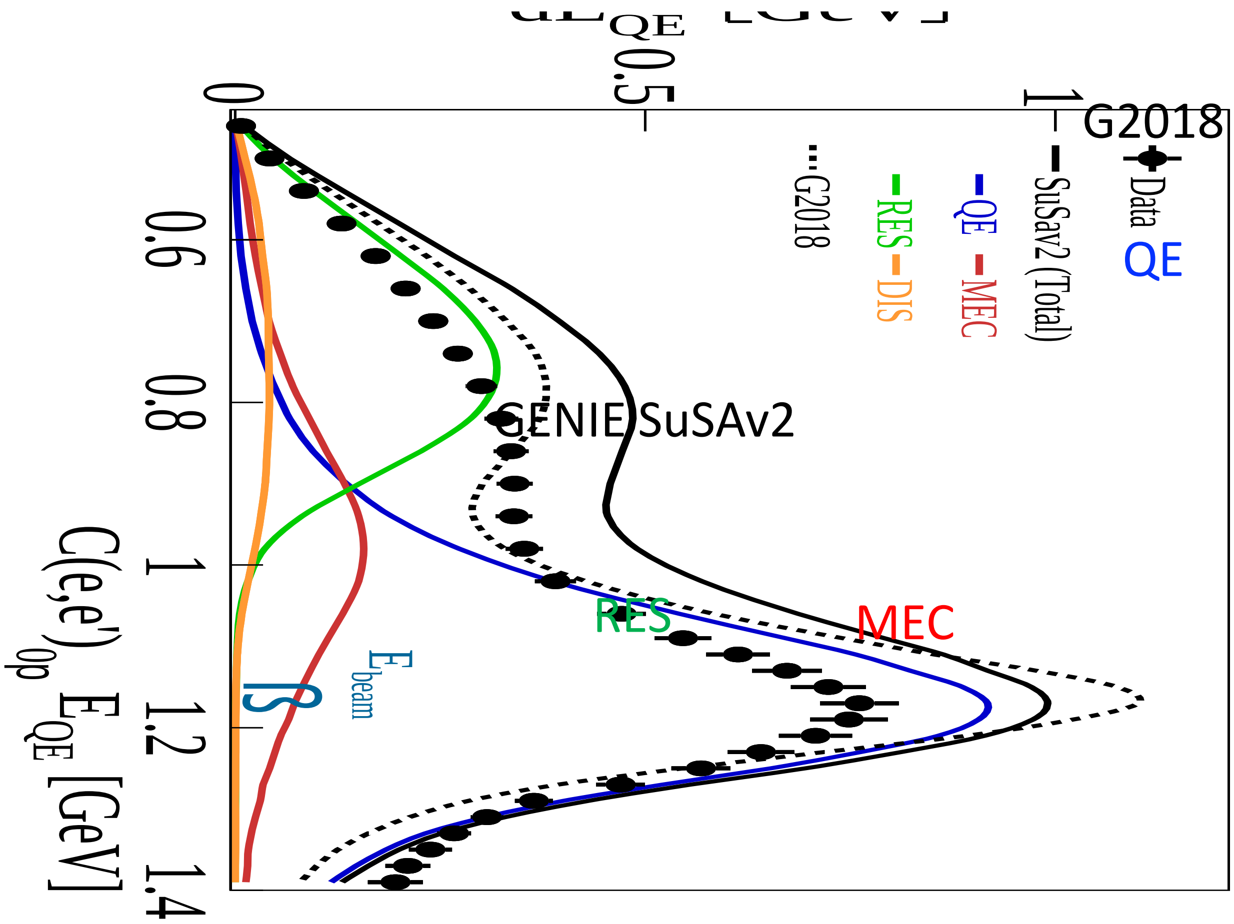
1. Use measured (e,e’pπ/γ) events,
2. Rotate π or γ around **q** to determine its acceptance,
3. Subtract (e,e’pπ/γ) contributions
4. Do the same for 2p, 3p, 2p+ π etc.





Caution: π^0 threshold ~ 600 MeV

QE-like C(e,e’)$_{0\pi}$ Cross Sections

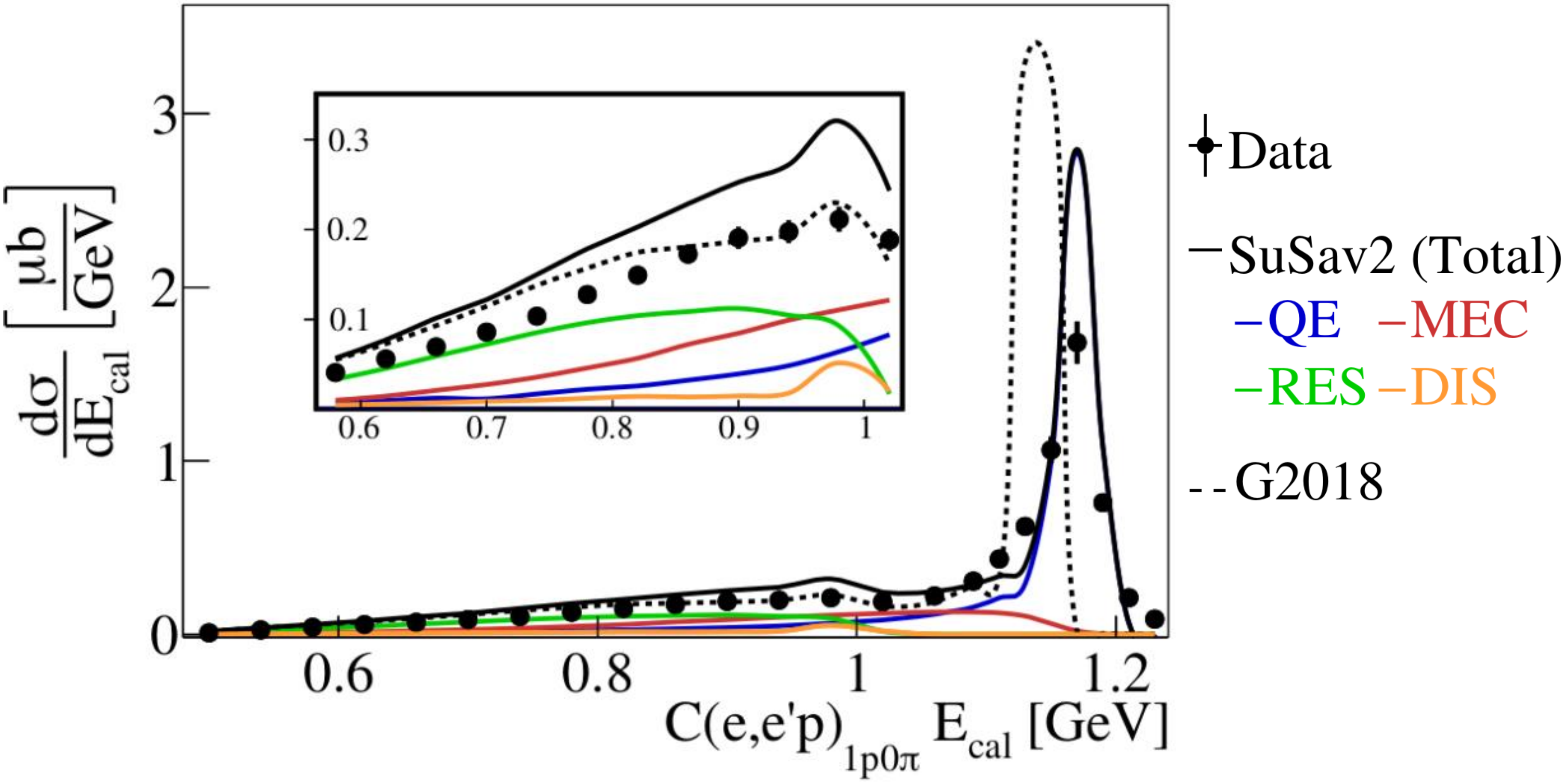


QE and MEC: SuSAv2 vs G2018 (Local Fermi Gas + Dytman)

RES and DIS: Berger-Sehgal + Bodek- Yang

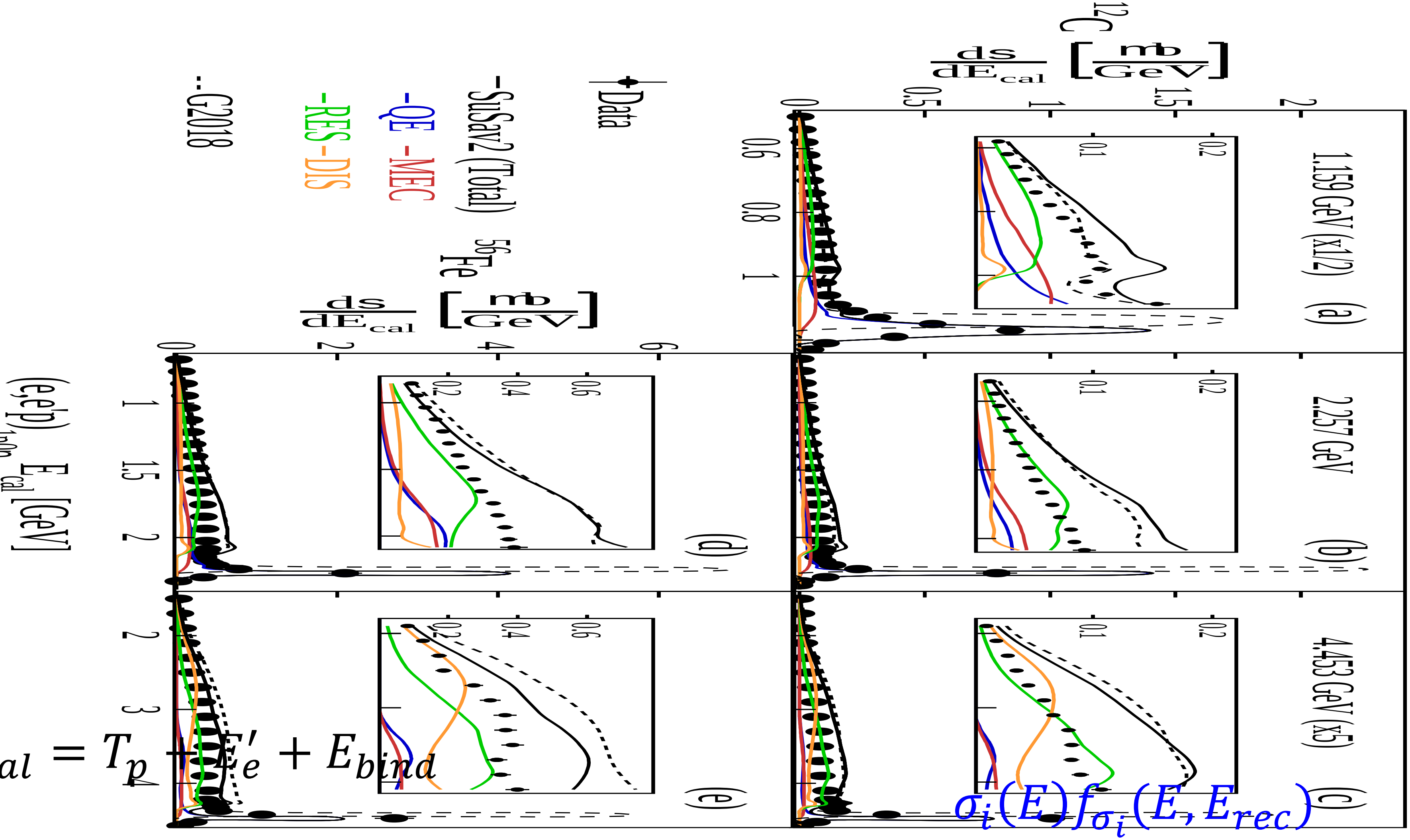
Khachatryan, Papadopoulou et al, Nature, 2021

Absolute QE-like $C(e,e'p)_{0\pi}$ Cross Sections



Khachatryan, Papadopoulou et al, Nature, 2021

A and *E* dependence

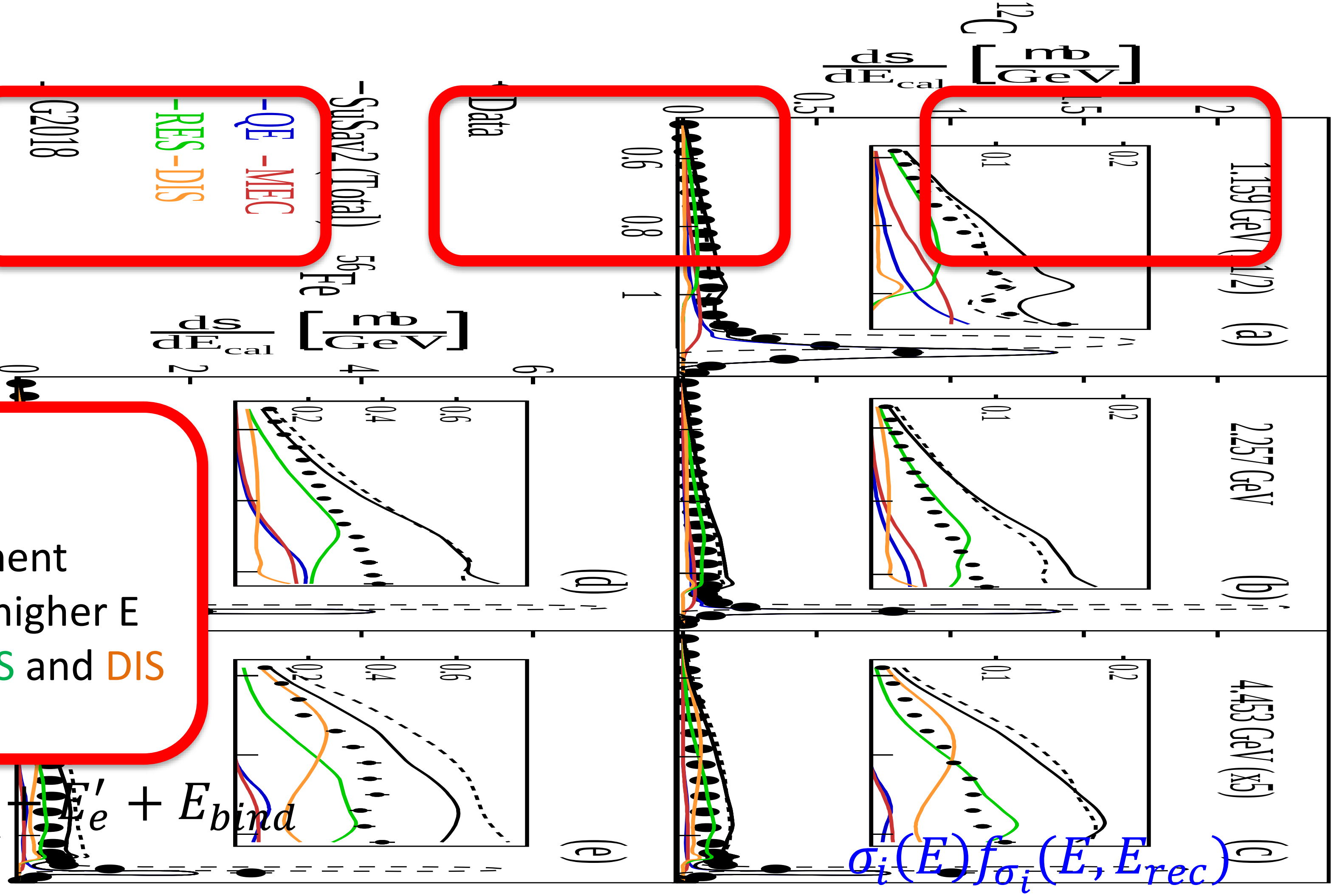


$$E_{cal} = T_p + E'_e + E_{bind}$$

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

Khachatryan, Papadopoulou et al, Nature, 2021

A and *E* dependence



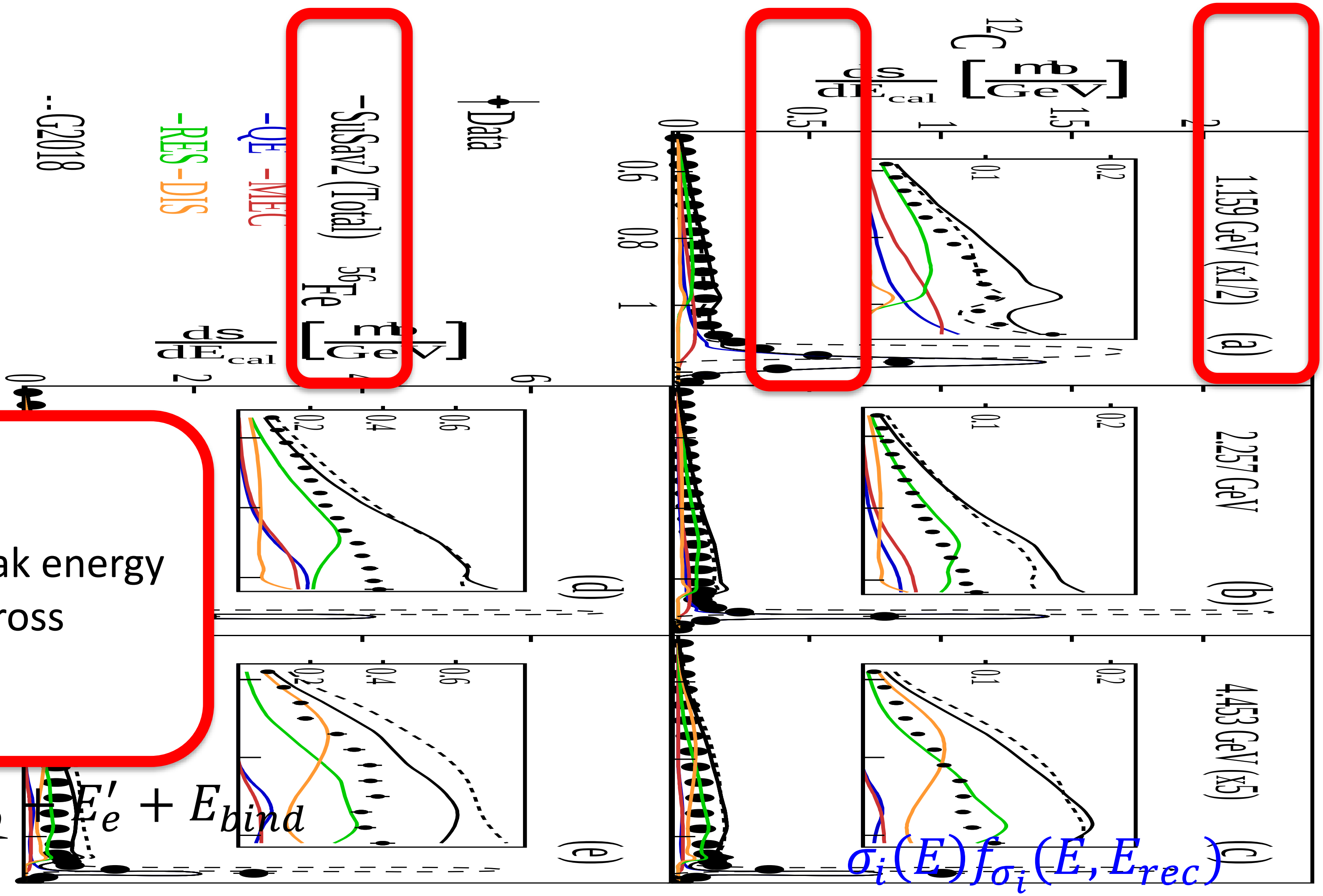
- Data/MC disagreement
- Worse at higher E
- Due to RES and DIS

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

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

Khachatryan, Papadopoulou et al, Nature, 2021

A and *E* dependence



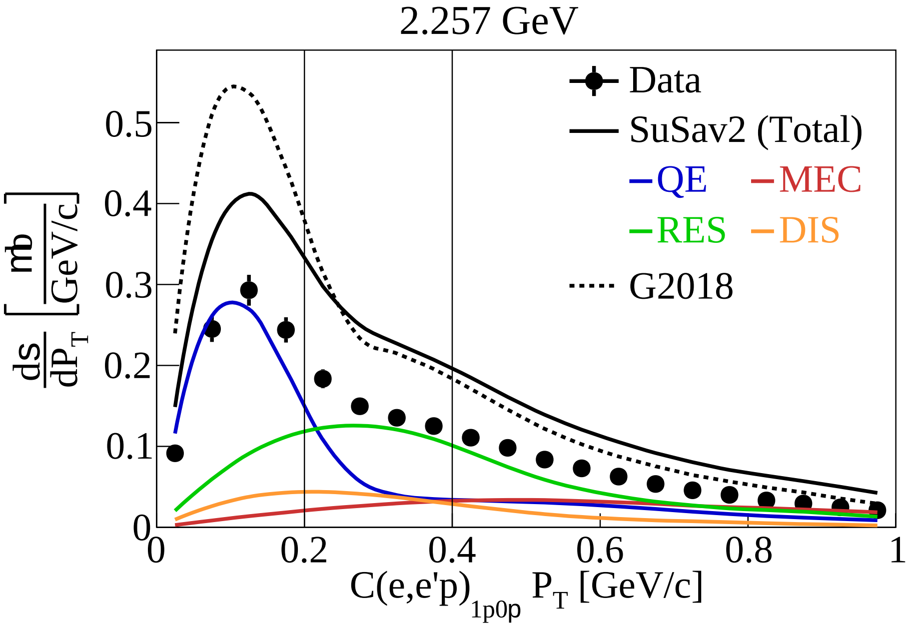
SuSAv2
* Correct peak energy
* Incorrect cross section

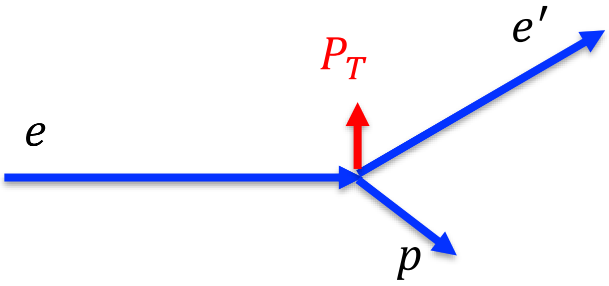
$$E_{cal} = T_p + E'_e + E_{bind}$$

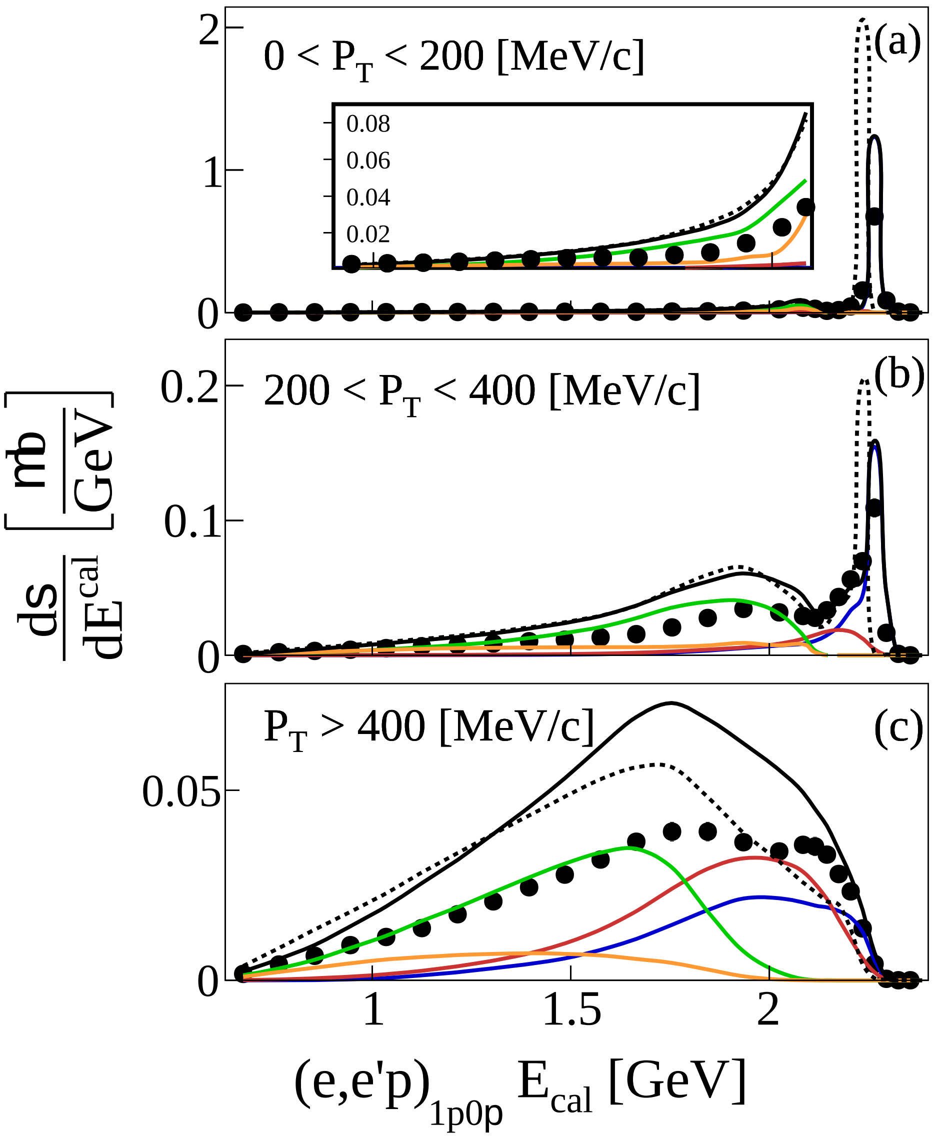
$$\sigma_i(E) f_{\sigma_i}(E, E_{rec})$$

Khachatryan, Papadopoulou et al, Nature, 2021

Single Transverse Variables (P_T)





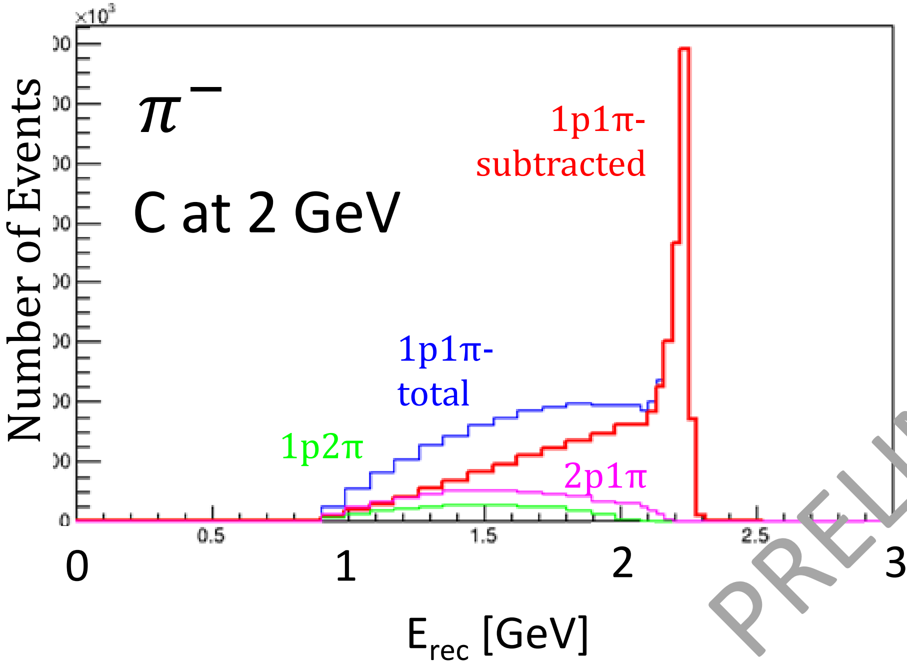


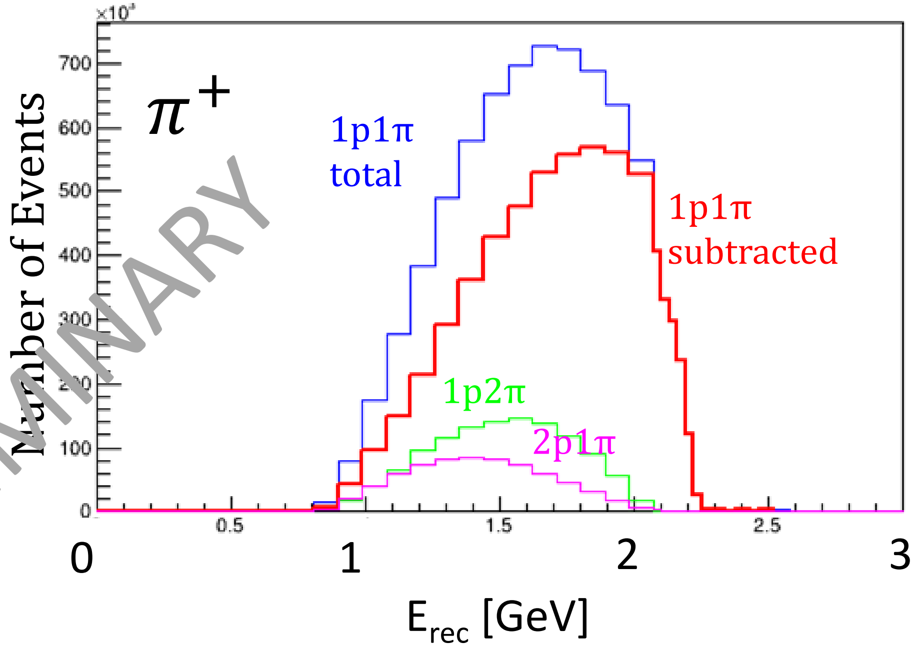
$$E_{cal} = T_p + E'_e + E_{bind}$$

Khachatryan, Papadopoulou et al, Nature, 2021

$A(e,e'p\pi^\pm)$

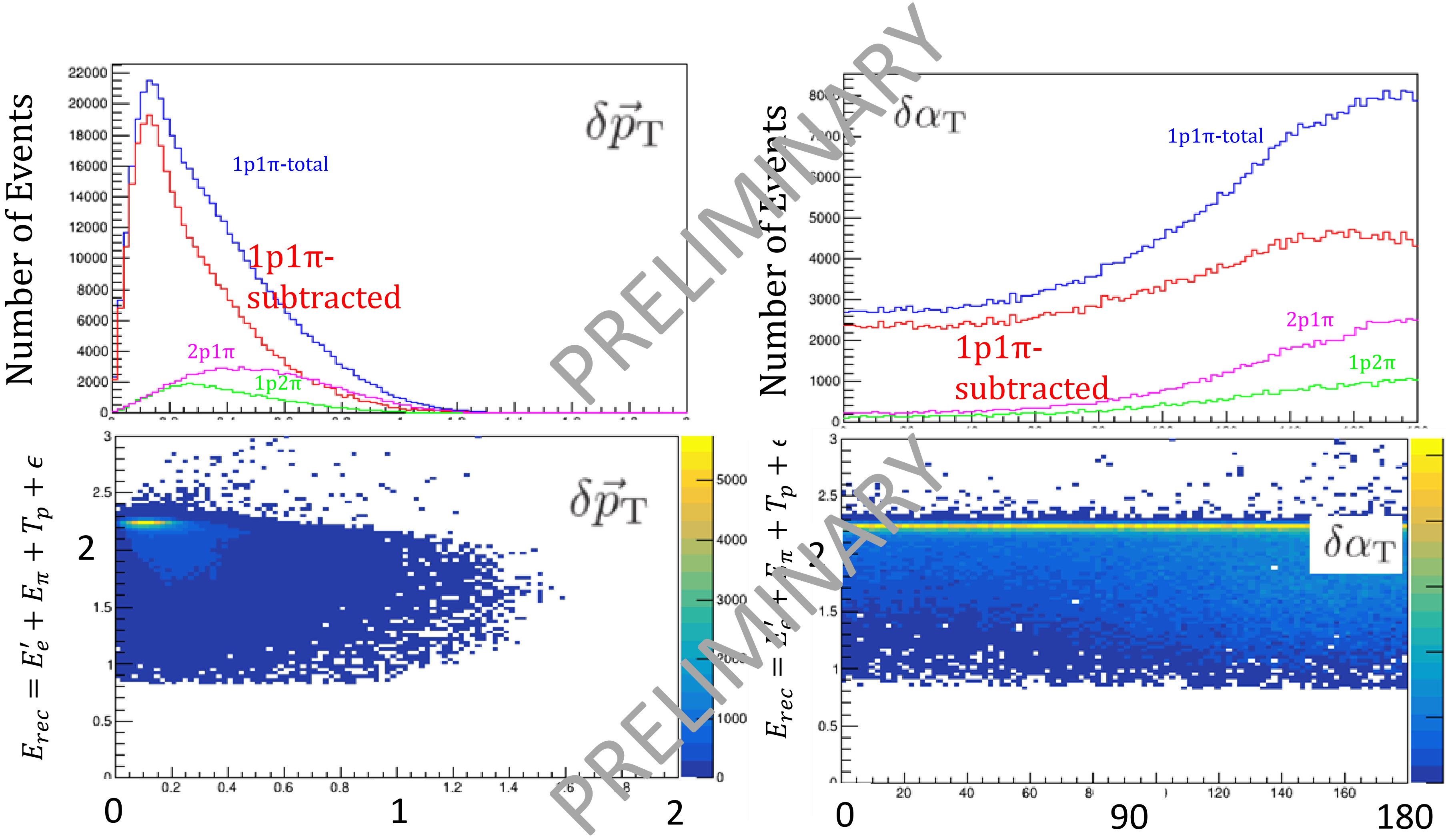
- Focus on resonance and DIS
  - More important for DUNE
- Subtract higher multiplicity backgrounds





$$E_{rec} = E'_e + E_\pi + T_p + \epsilon$$

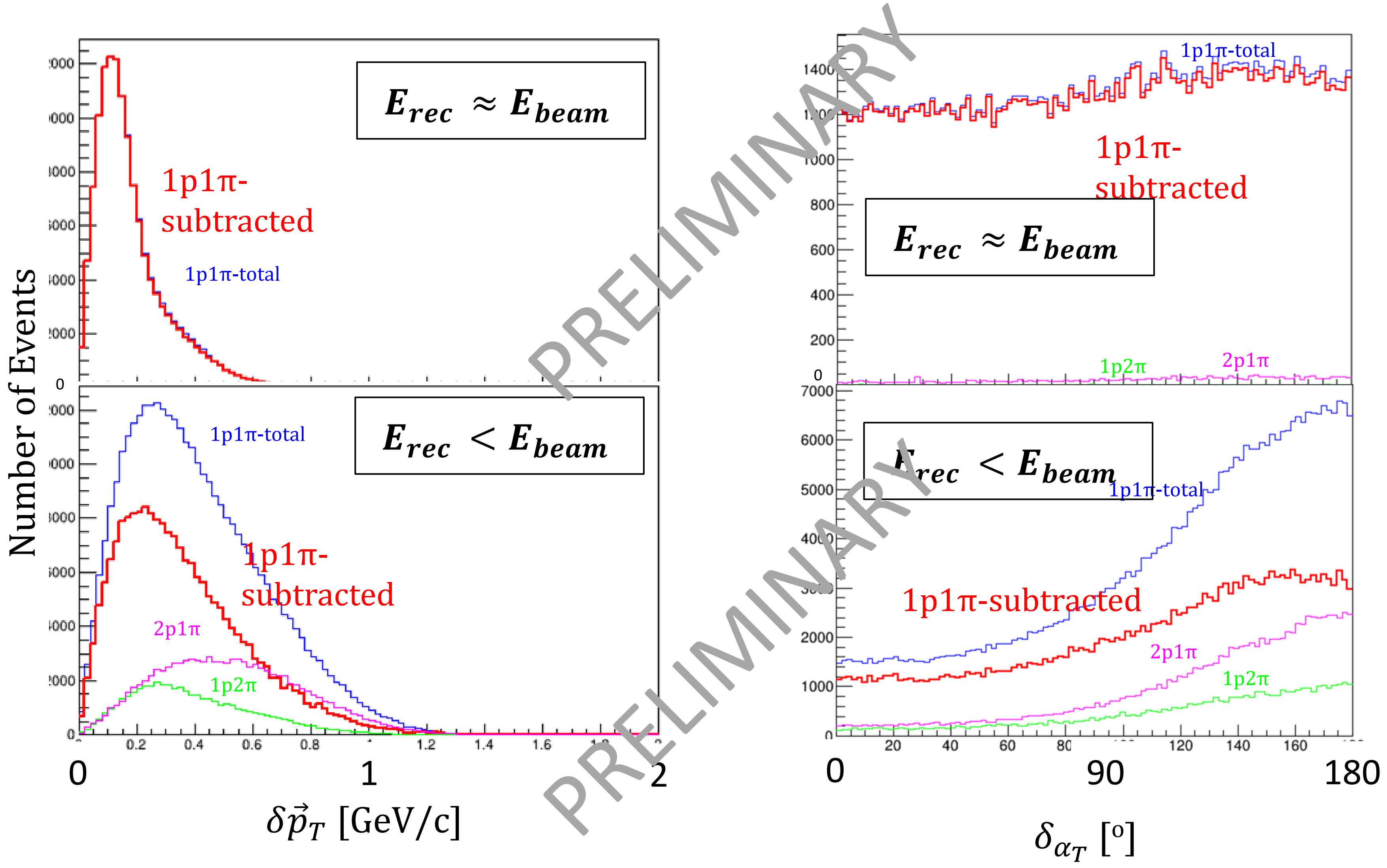
C$(e, e'p\pi^-)$ at 2.2 GeV



$\delta\vec{p}_T = \vec{p}_T^{\,e} + \vec{p}_T^{\,p} + \vec{p}_T^{\,\pi}$ [GeV]

$$\delta\alpha_T \equiv \arccos\frac{-\vec{p}_T^{\,\ell'}\cdot\delta\vec{p}_T}{p_T^{\ell'}\delta p_T}$$

$C(e,e'p\pi^-)$ at 2.2 GeV



Analysis by A. Mand (ODU) and J. Tena Vidal (TAU)
Available data: 3He, 4He, C, Fe at 1.1, 2.2 and 4.4 GeV

Proton Transparency

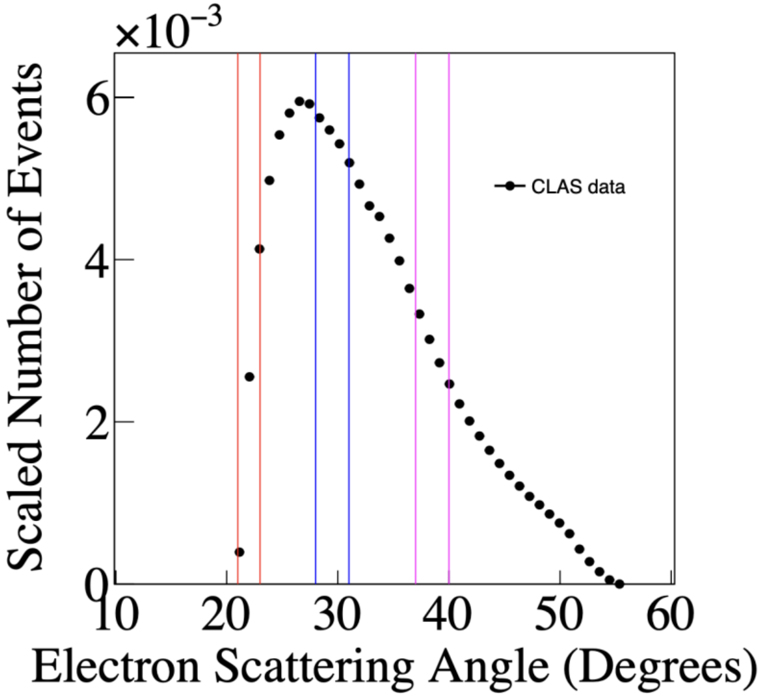
- Measure final state interactions (rescattering) of struck particles to constrain event generator models
- Methods
  - Ratio of A(e,e’p) cross sections to PWIA models
  - (new) fraction of quasielastic A(e,e’) events with a detected proton
    - CLAS6 data He, C, and Fe at 2 and 4 GeV
    - N. Steinberg, S. Dytman, M. Betancourt, in preparation

Proton Transparency

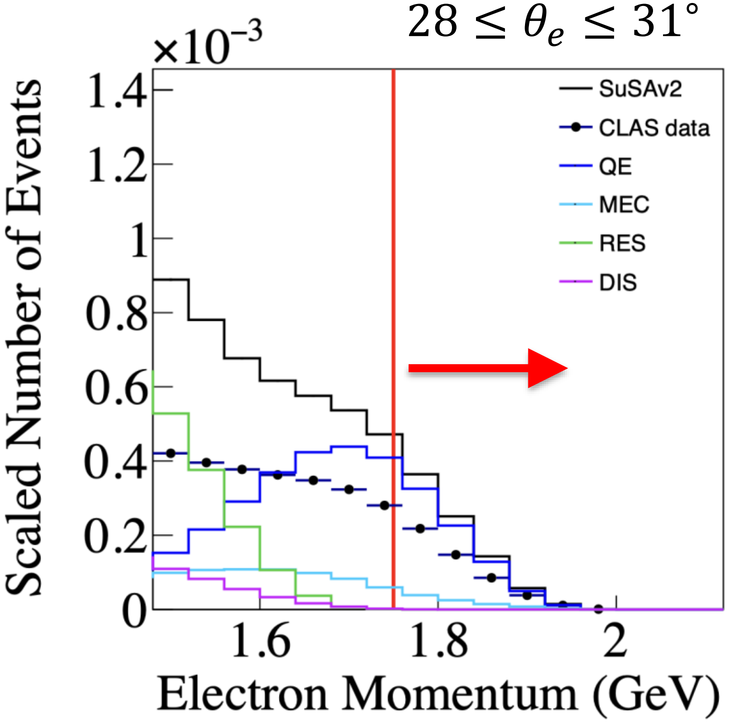
Data analysis

(e,e’) events (denominator)

- Select bins of θ_e
- Choose $E'_{min}(\theta_e)$ to reject non-quasielastic (RES and MEC) events
  - Correct for remaining non-QE fraction (GENIE)



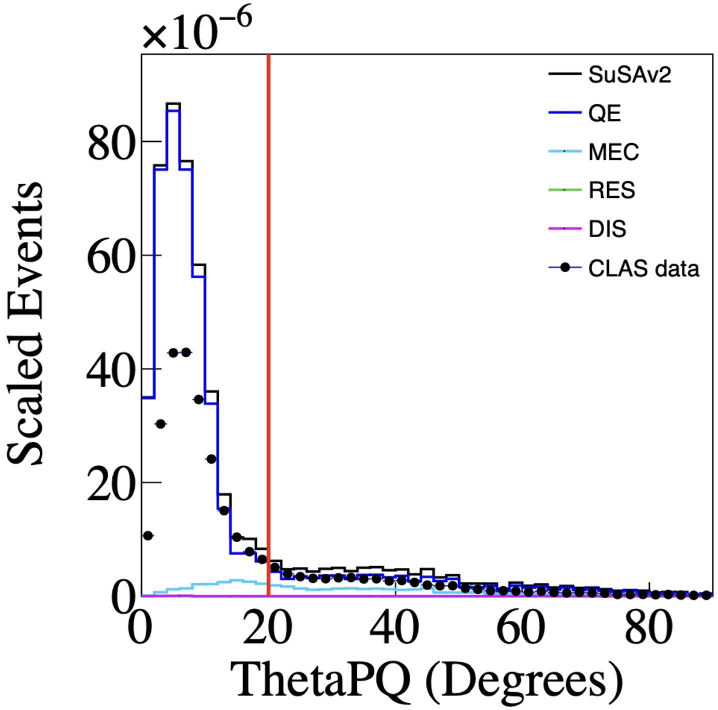
$28 \le \theta_e \le 31^\circ$



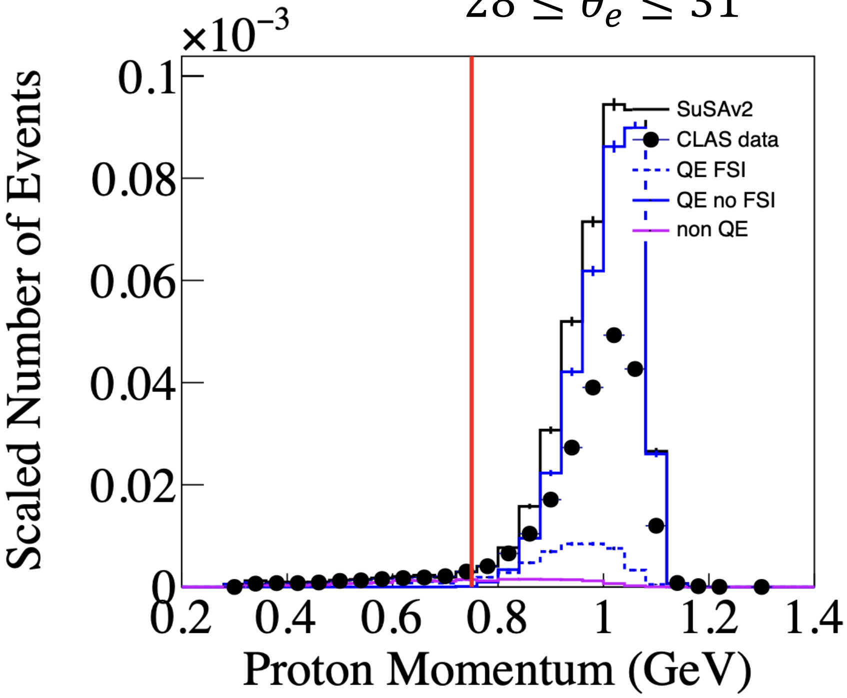
Proton Transparency: (e,e’p)/(e,e’) ratio

(e,e’p) events (numerator)

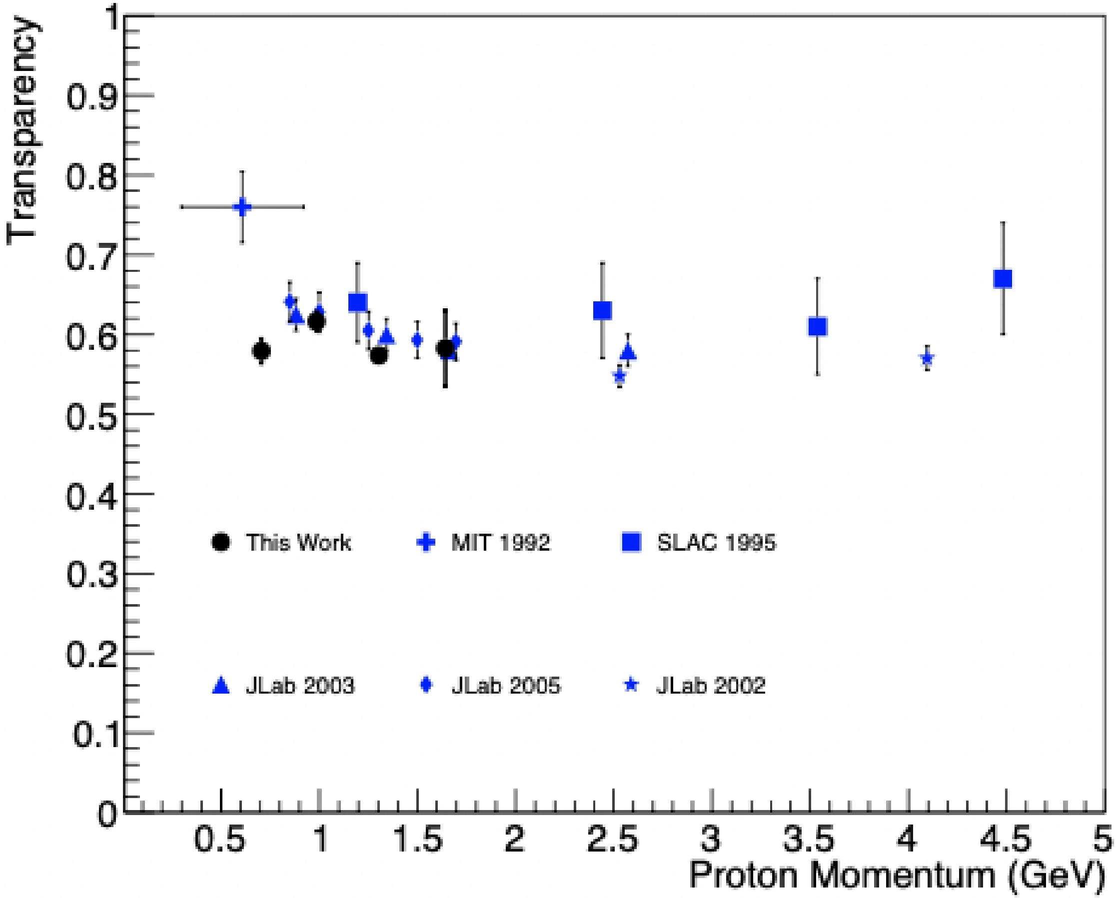
- Start with (e,e’) events
- Select non-rescattered protons:
    - ○ θ_{pq}^{max} and p_p^{min} cuts
- Purely data ratio corrected for non-QE electron events and for (e,e’n)



$28 \leq \theta_e \leq 31°$



Proton Transparency: comparison to previous data

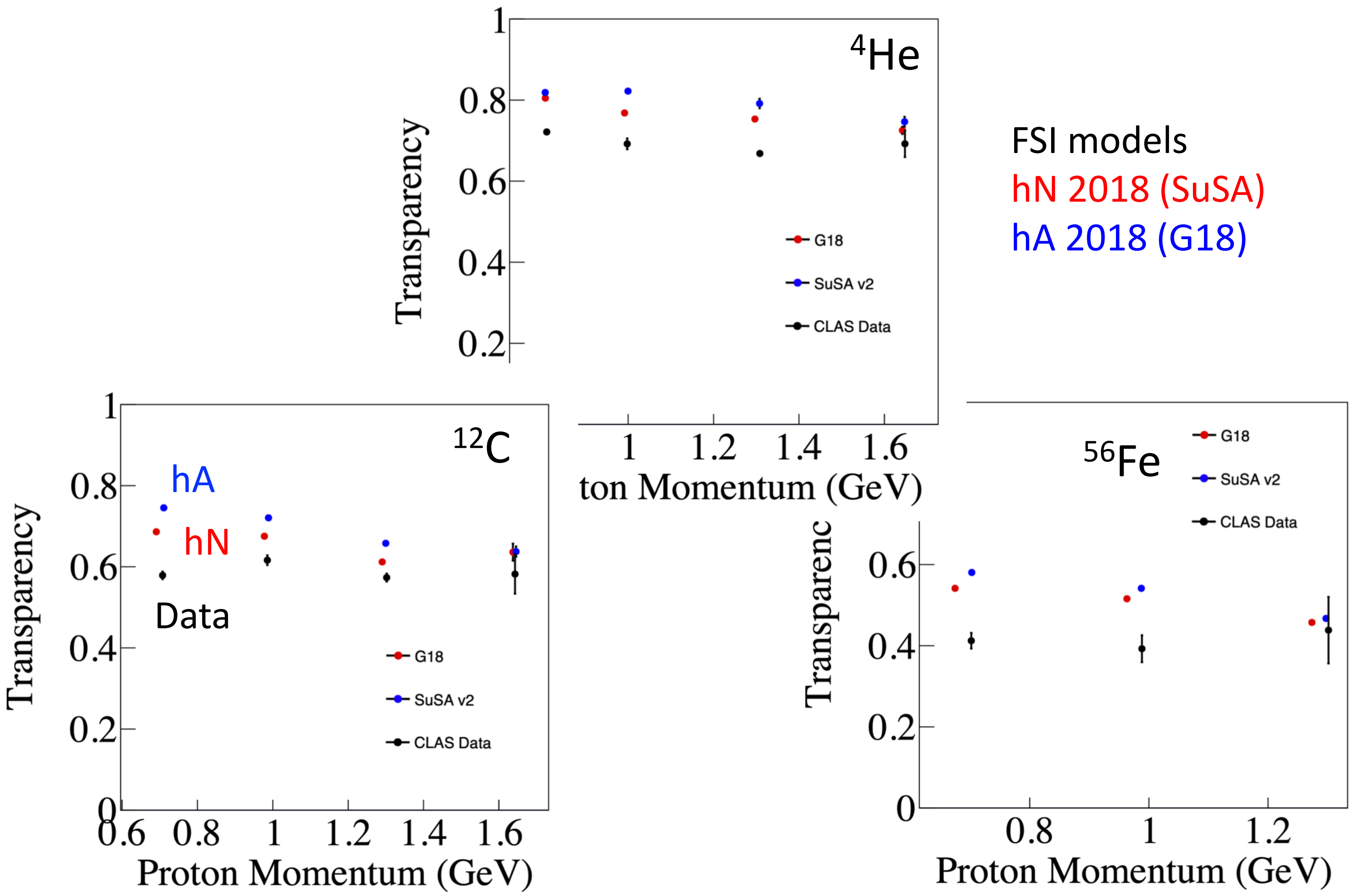


Jlab:
Dutta, PRC 68, 064603 (2003),
Garrow, PRC 66, 044613 (2002)
Rohe, PRC 72, 054602 (2005)

SLAC: O'Neill, PLB 351, 87 (1995)
MIT/Bates: Garino, PRC 45, 780 (1992)

Slide added after talk

Proton Transparency: (e,e’p)/(e,e’) ratio

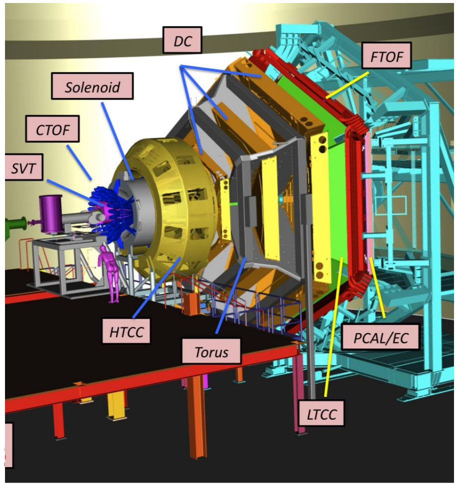


FSI models

hN 2018 (SuSA)

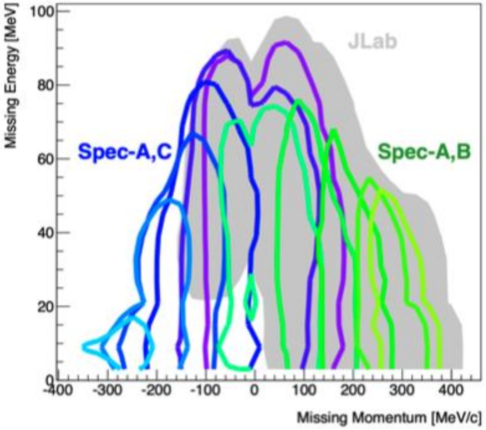
hA 2018 (G18)

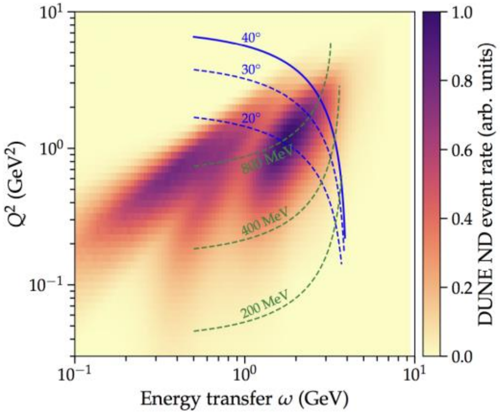
Electron Data



Present

- Jefferson Lab
  - Small aperture spectrometers (Hall A)
    - (e,e’) and (e,e’p) data at fixed angles and energie
  - Large Acceptance Spectrometer (CLAS)
    - Wide angular and momentum acceptance
    - 1, 2, and 4 GeV beams
    - All channels (e,e’), (e,e’p), (e,e’pπ), …
    - He, C, Fe targets
  - Large Acceptance Spectrometer (CLAS12)
    - Wide angular and momentum acceptance
    - (1), 2, 4 and 6 GeV beams
    - H, D, He, C, (O), Ar, Ca40, Ca48, Sn
- Mainz (O and Ar gas jet targets)
- SLAC (LDMX arXiv:1912.06140)



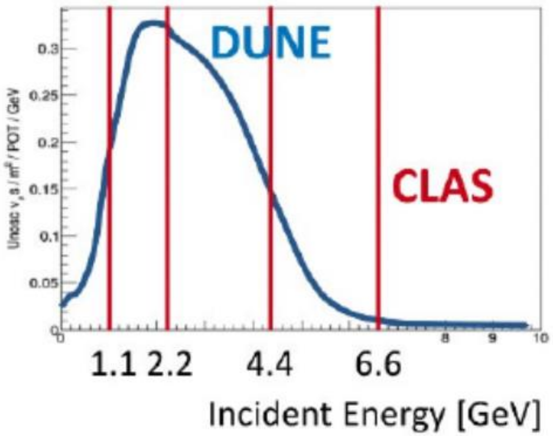


So how do use this wealth of eA data?

e4ν Working Groups

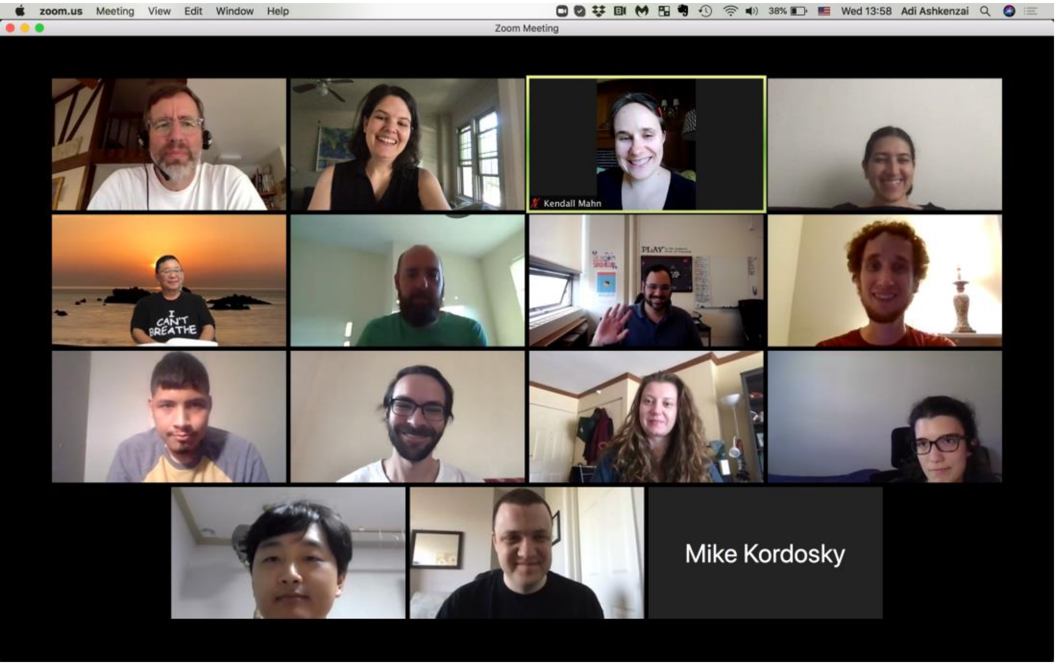
- Electron Data analysis
- Modeling development
- GENIE tuning
- Implications for neutrinos

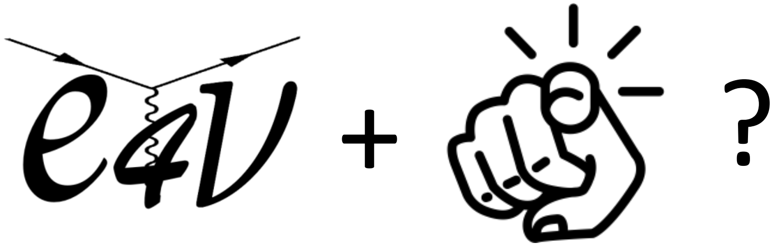
e4ν Goals



- lots of data taken and to come
  - Many beam energies and targets
  - Many event topologies
    - Inclusive scattering to constrain cross sections
    - 0π events to constrain QE
      - pp and pn events to constrain MEC and FSI
    - 1π events to constrain resonance and SIS/DIS
    - Proton transparency measurements to constrain FSI
- Use these to tune generators to understand cross sections and energy reconstruction $\sigma_i(E) f_{\sigma_i}(E, E_{rec})$

Unique hadronic models test!





Join us!

Jefferson Lab

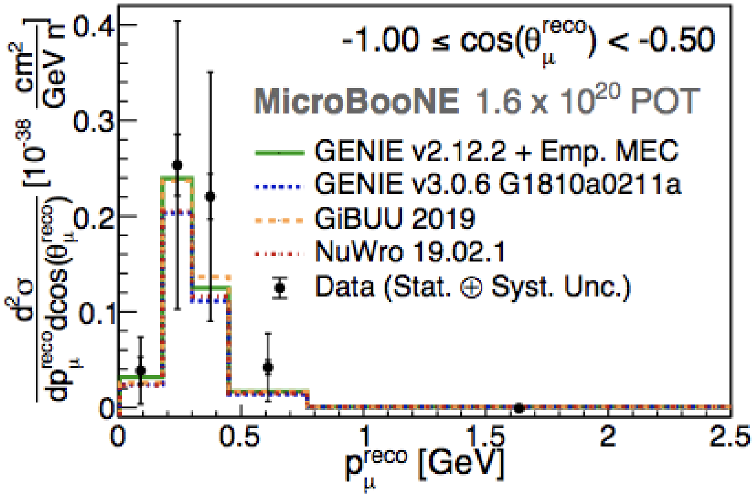
CSIC
CONSEJO SUPERIOR DE INVESTIGACIONES CIENTÍFICAS

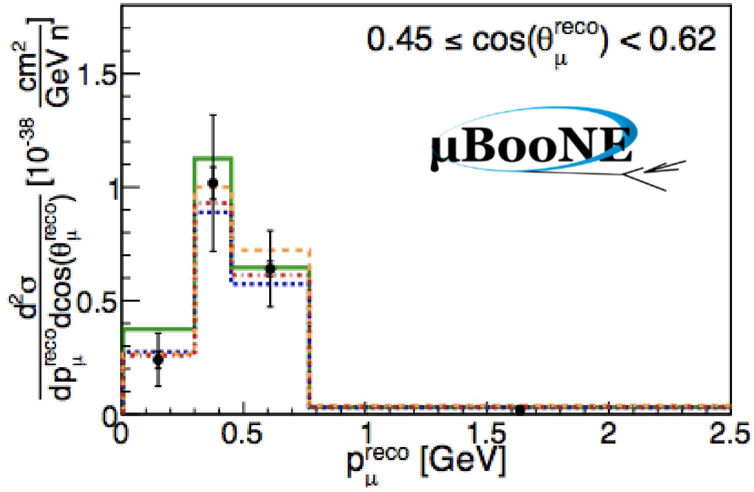
UCL

BERKELEY LAB

Backup slides

GENIE reproduced ν inclusive data

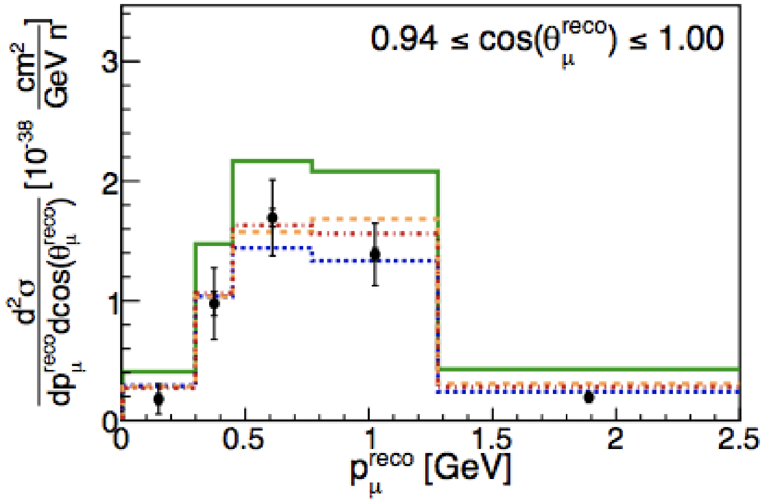




Genie

⋯ v3.0.6 tune G18_10a_02_11a

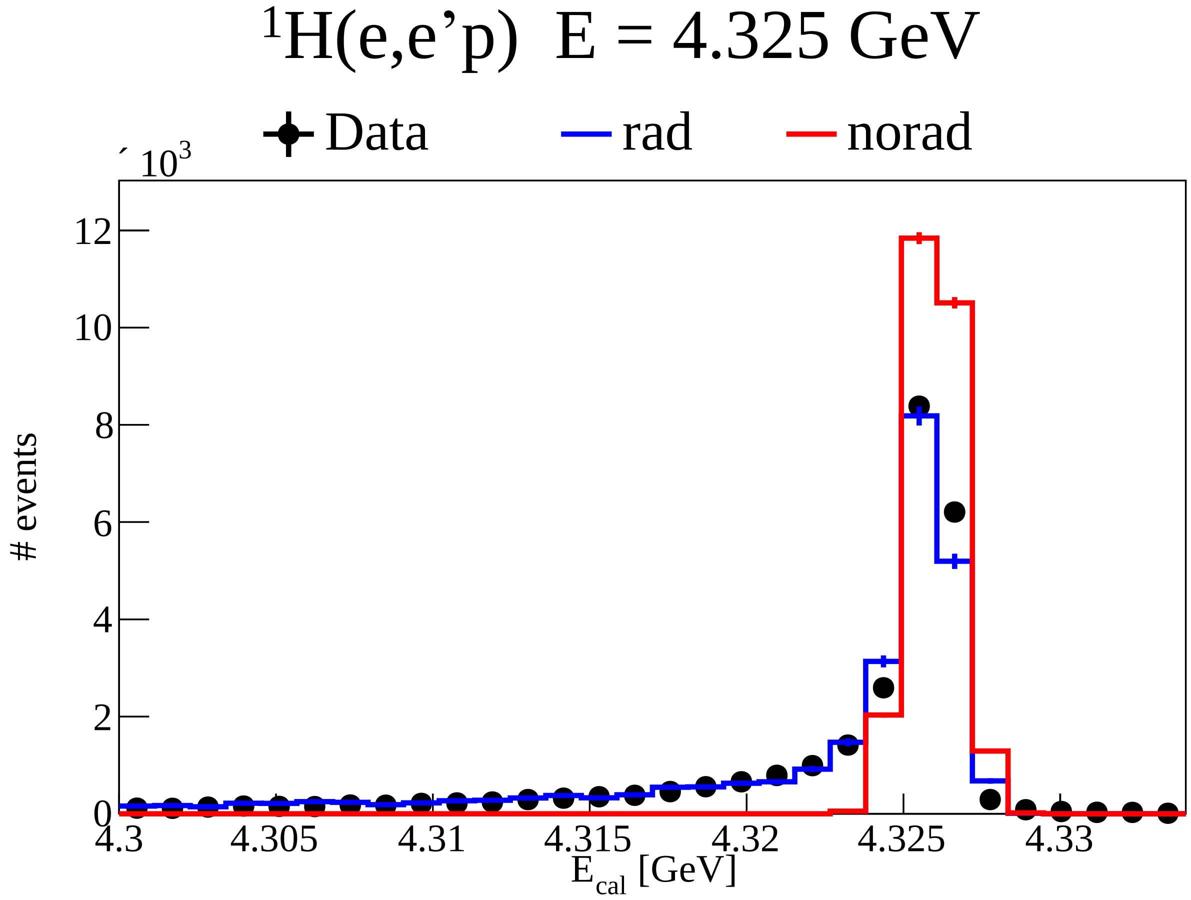
For more details see backup slides



Phys. Rev. Lett. 123, 131801 (2019)
See talk from Kirsty Duffy next session

From A. Ashkenazi, Neutrino 2020

Adding radiative effects



[Mo and Tsai]

Genie v3.0.6 tune G18_10a_02_11a

From A. Ashkenazi, Neutrino 2020