Electrons for neutrinos

Lawrence Weinstein
Old Dominion University

NuFact 2018

Virginia Tech, August 2018

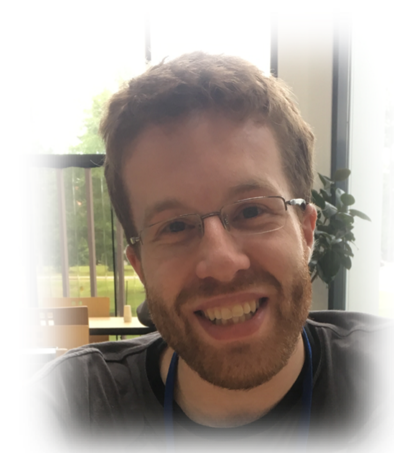
Collaboration

- Old Dominion University
- MIT
- Jefferson Lab
- Tel Aviv U
- Michigan State
- FermiLab
- Pitt
- York University, UK

Mariana Khachatryan
(ODU)

Afroditi Papdopolou
(MIT)

Adi Ashkenazi
(MIT)



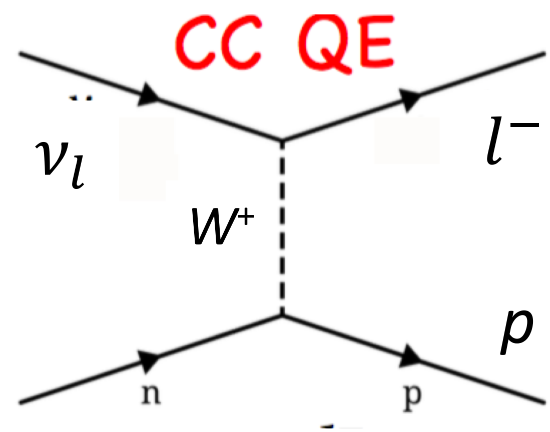
Florian Hauenstein
(ODU)

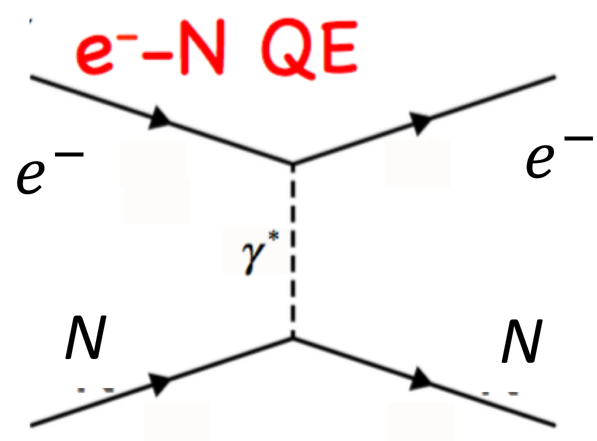
Outline

- Why electrons?
  - Nuclear Physics
- Current work
  - Jefferson Lab data analysis
  - Genie improvements
- Future plans

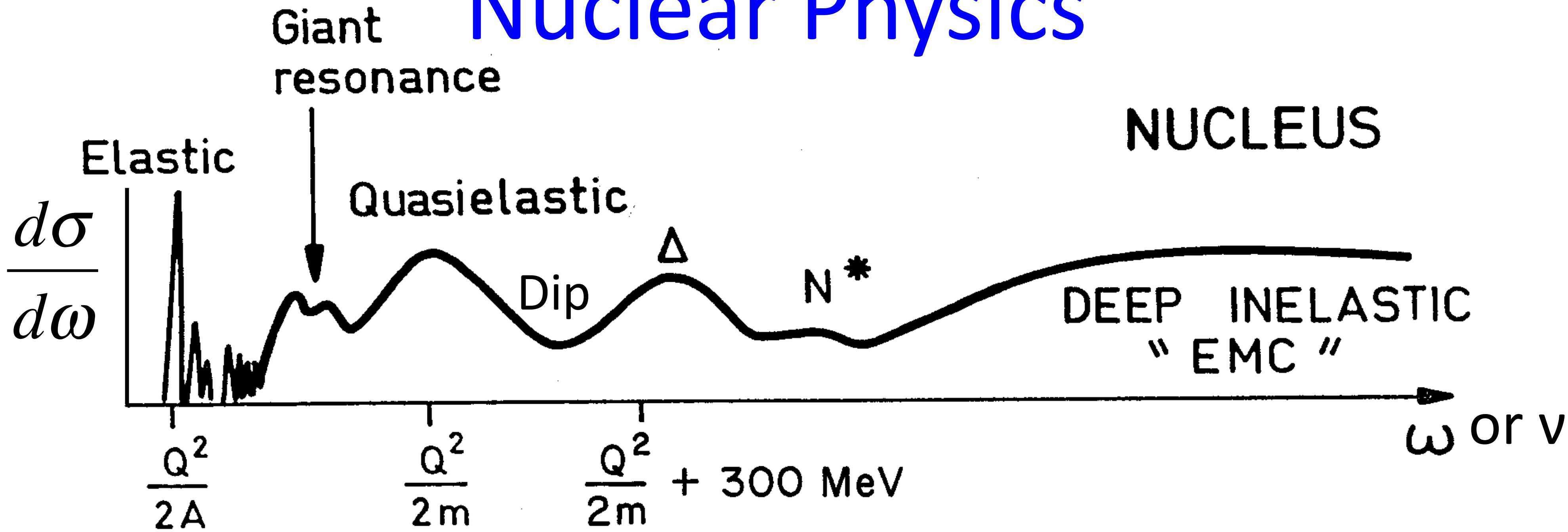
Why electrons?

- Known incident energy
- 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

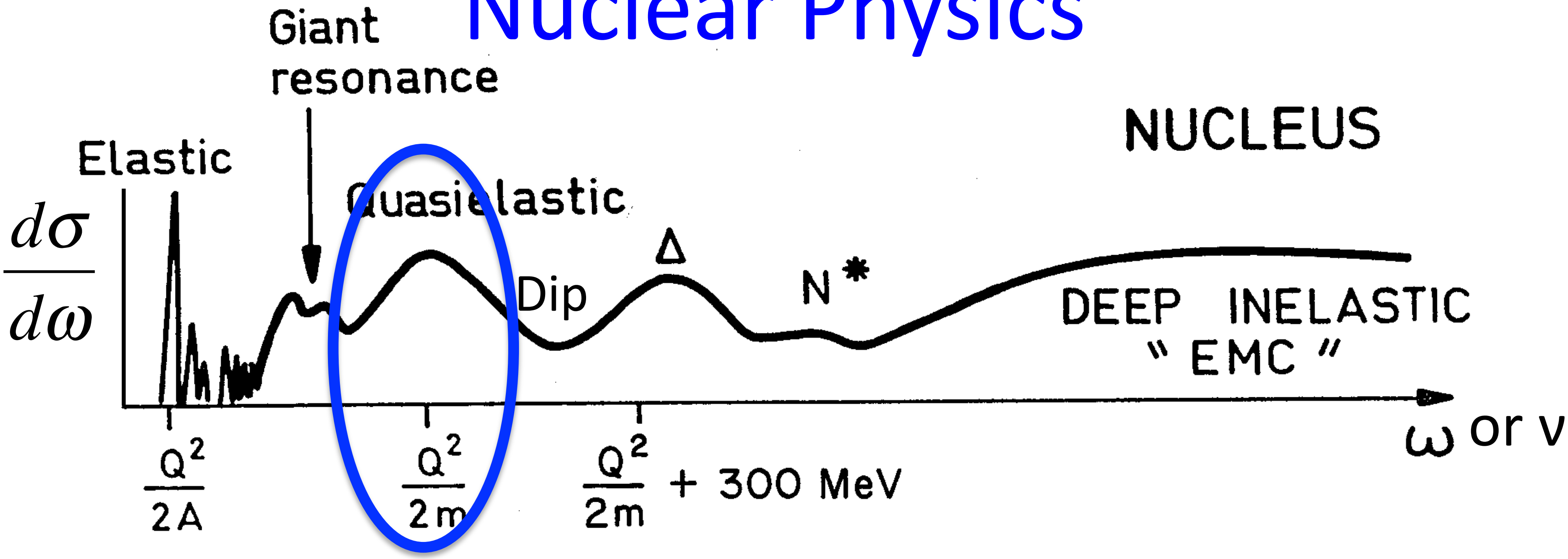




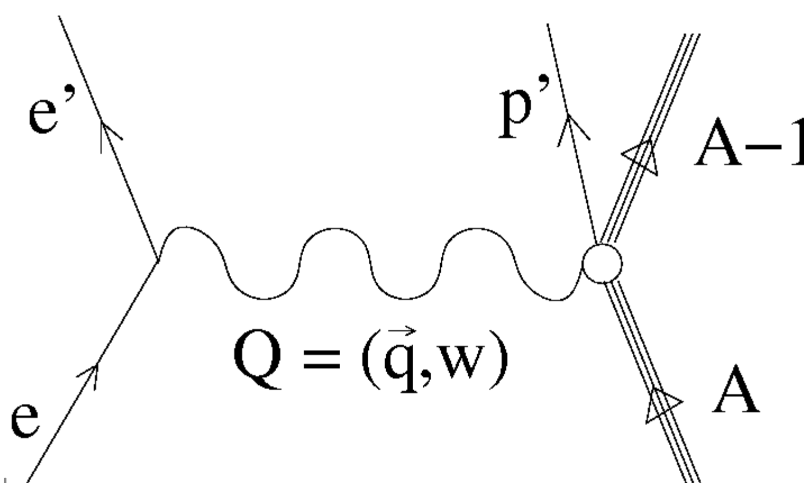
Nuclear Physics



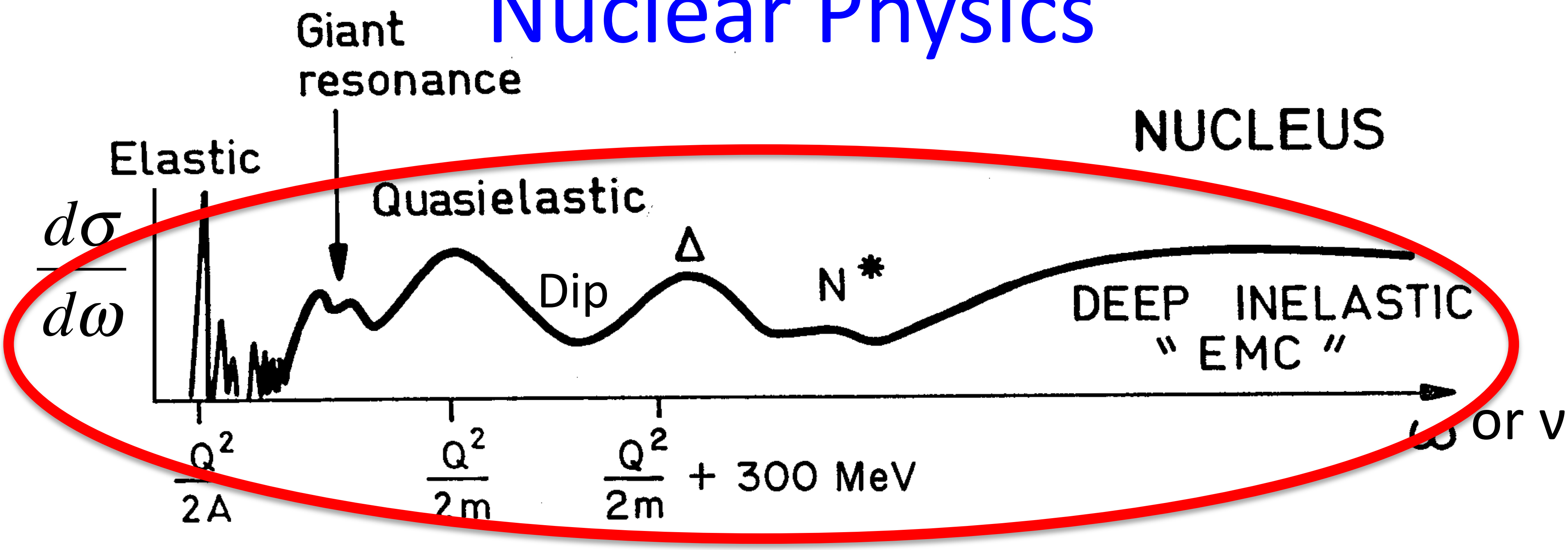
Nuclear Physics



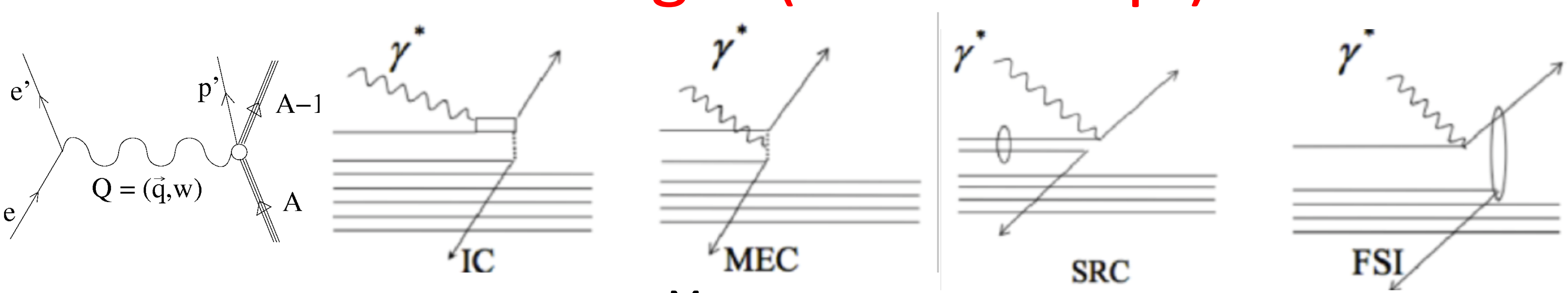
What neutrino expts want



Nuclear Physics



What we get (even for 0pi)



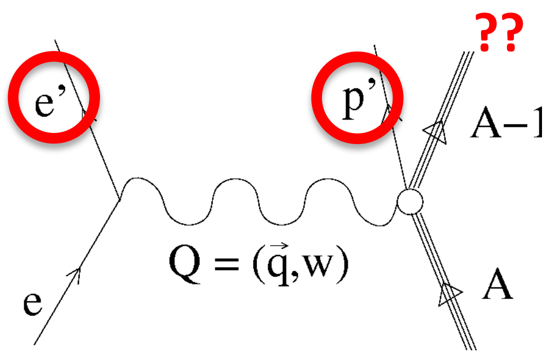
Resonance

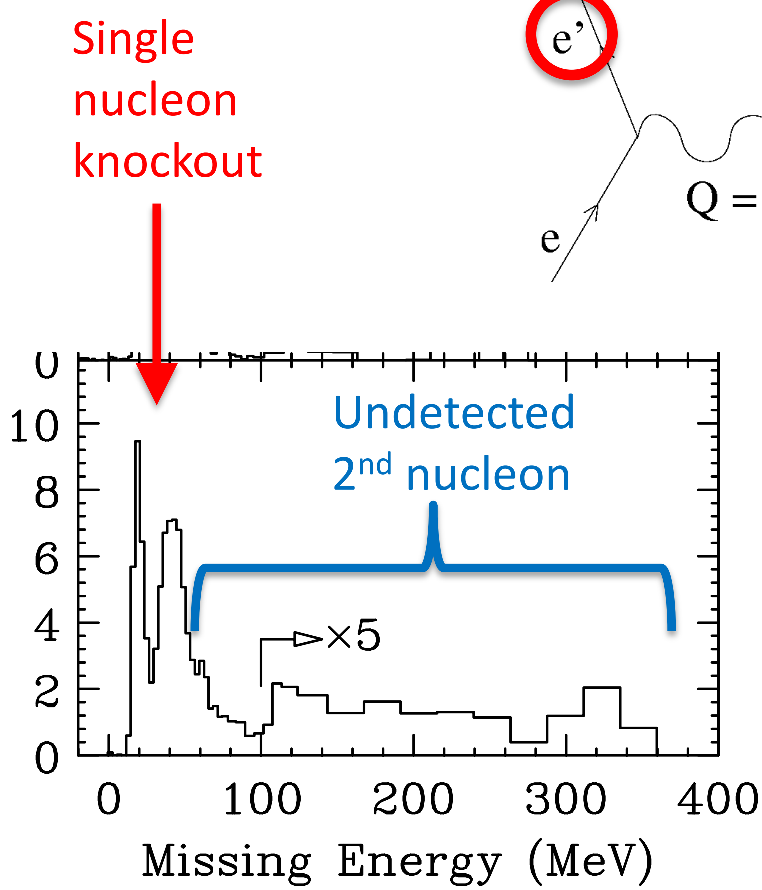
Meson Exchange Currents

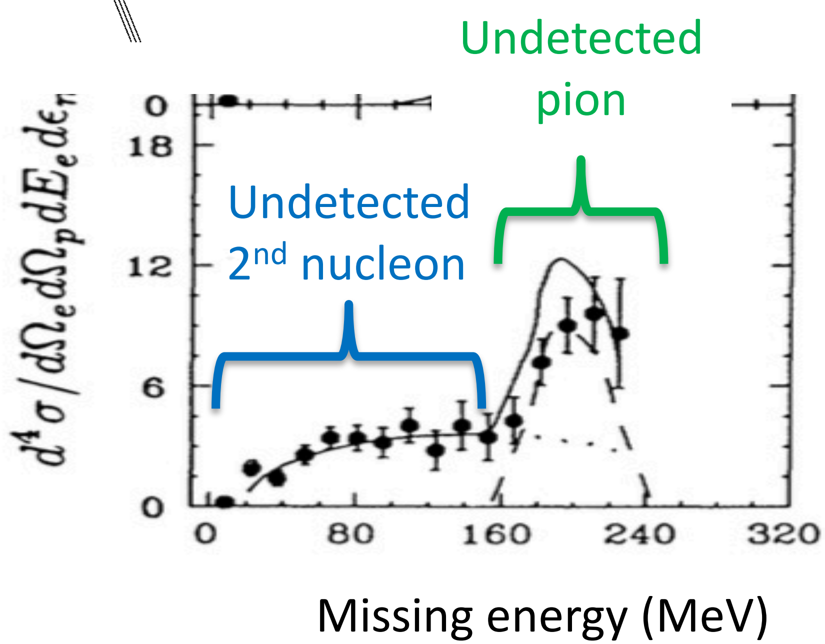
Short Range Correlations

Final State Interactions

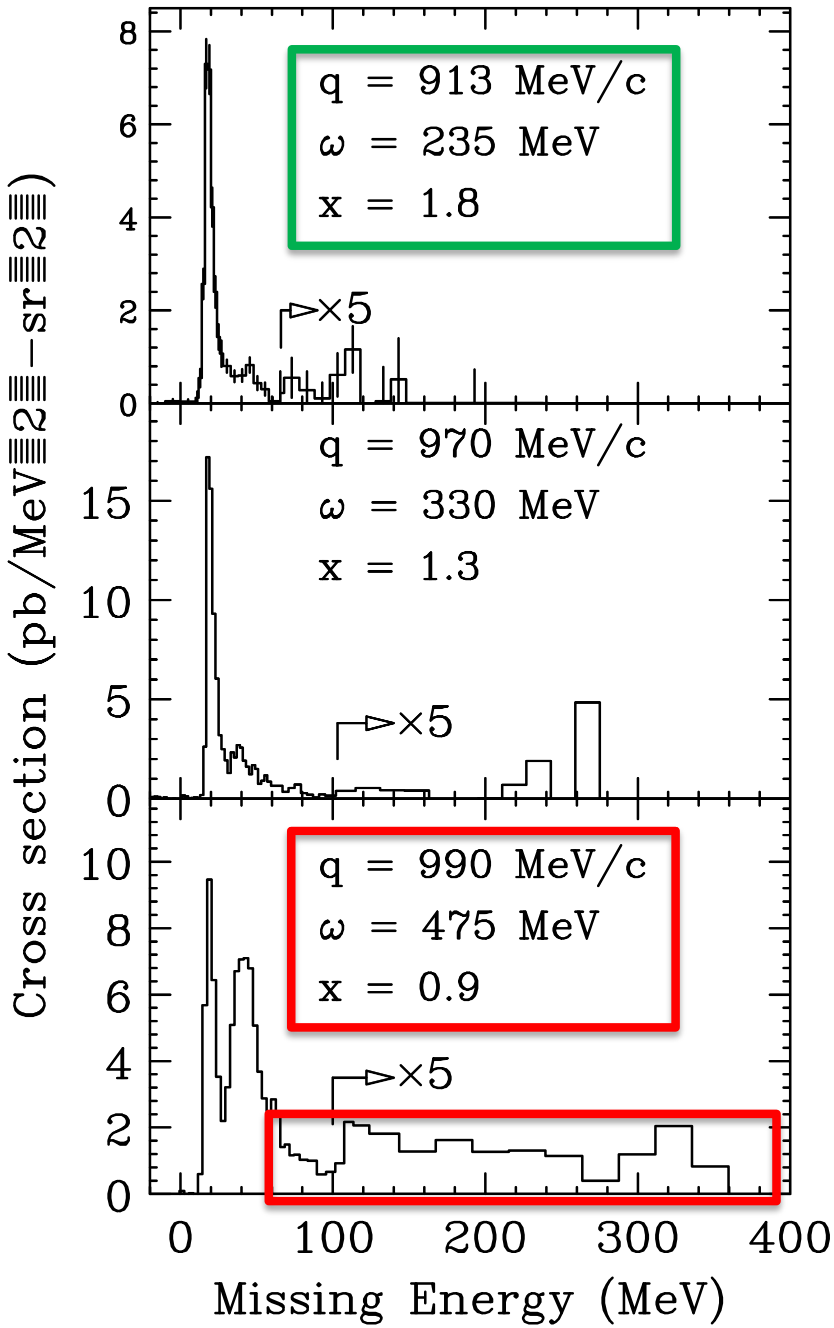
How do reaction mechanisms appear in (e,e'p)?

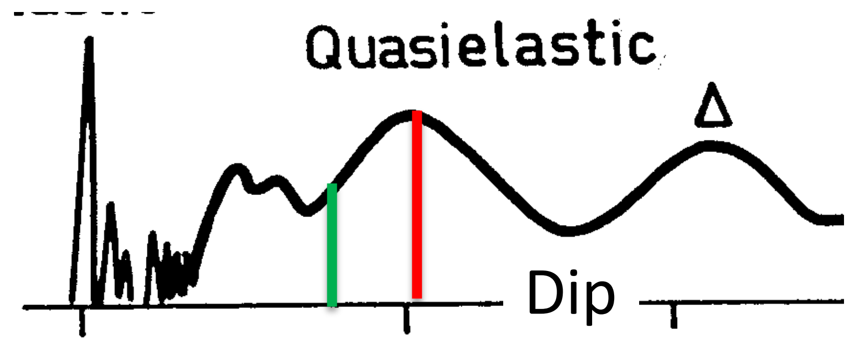






QE $^{12}C(e,e'p)$
q ~ 1 GeV/c



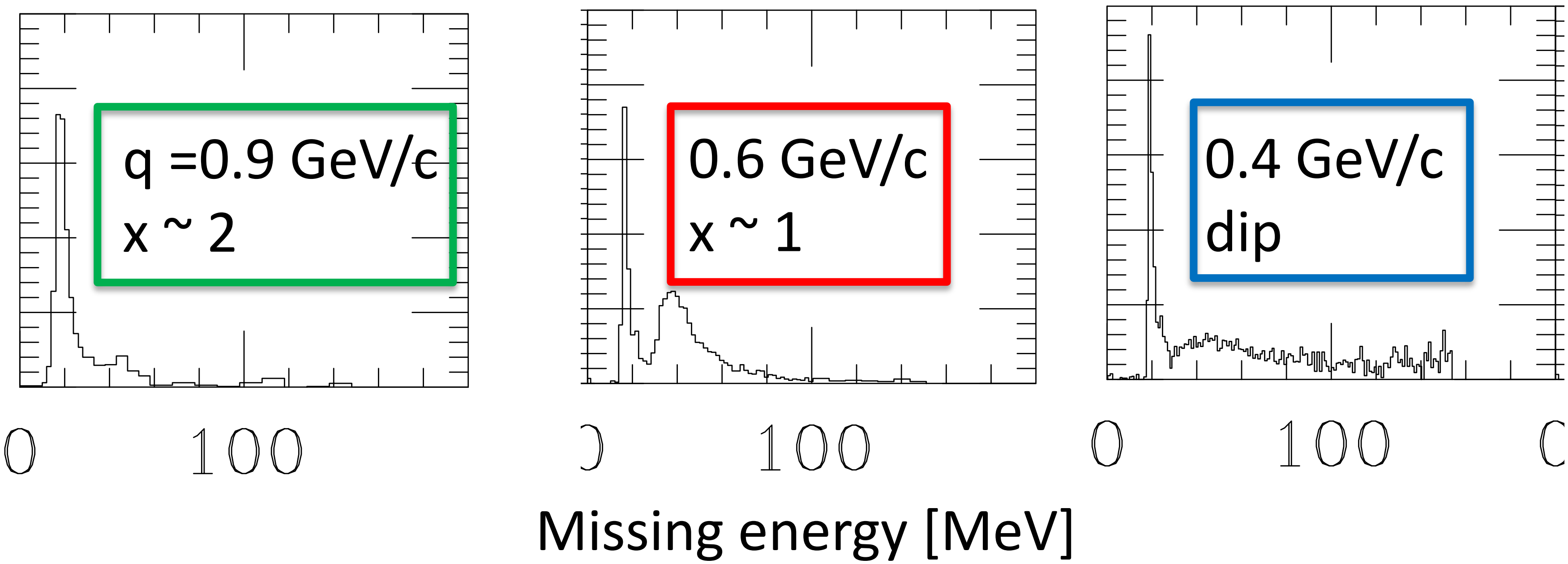


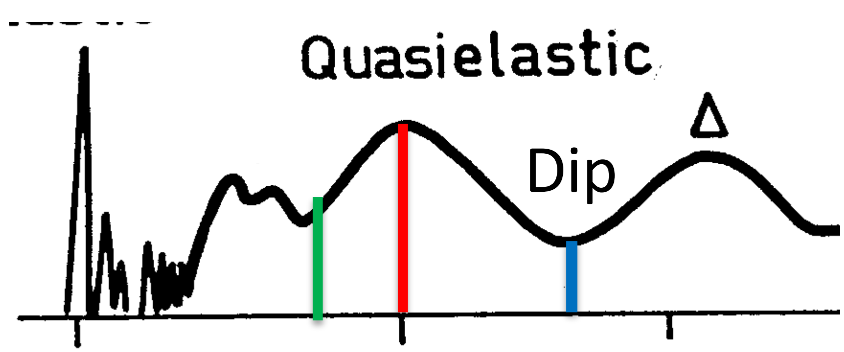
Non-QE reactions
increase with ω

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

S. Penn, unpublished
J. Morrison, PRC **59**, 221, (1999)

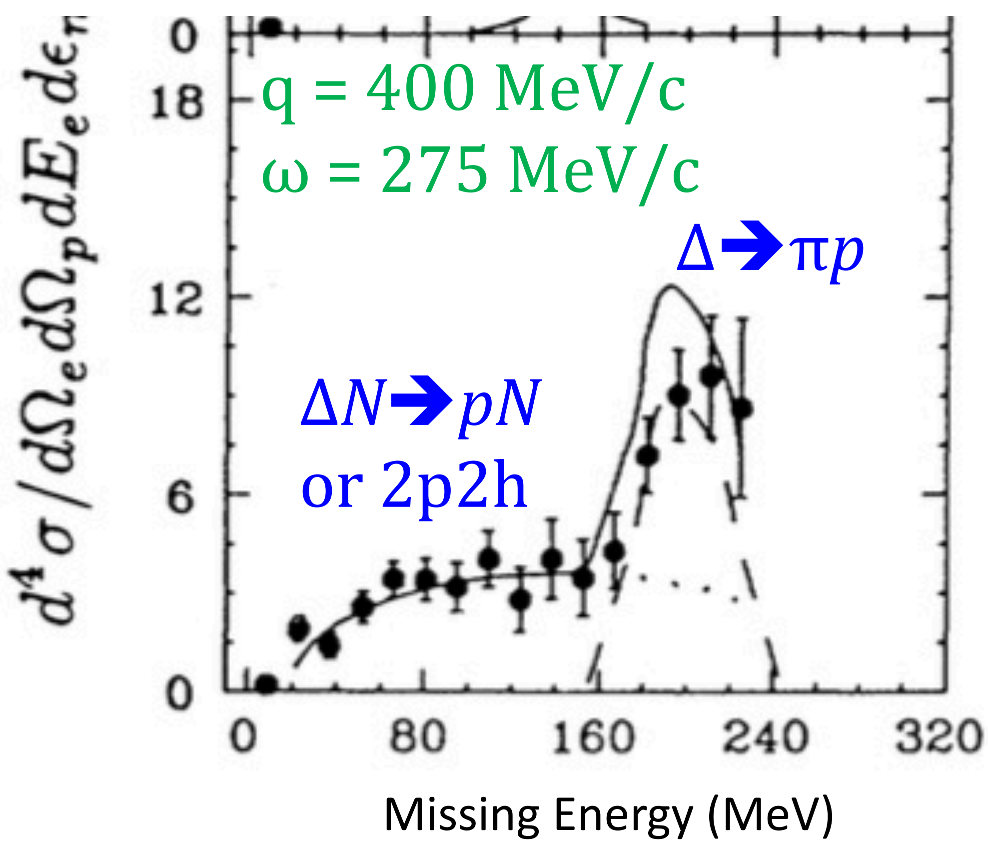
Fixed ω = 0.2 GeV, vary *q*

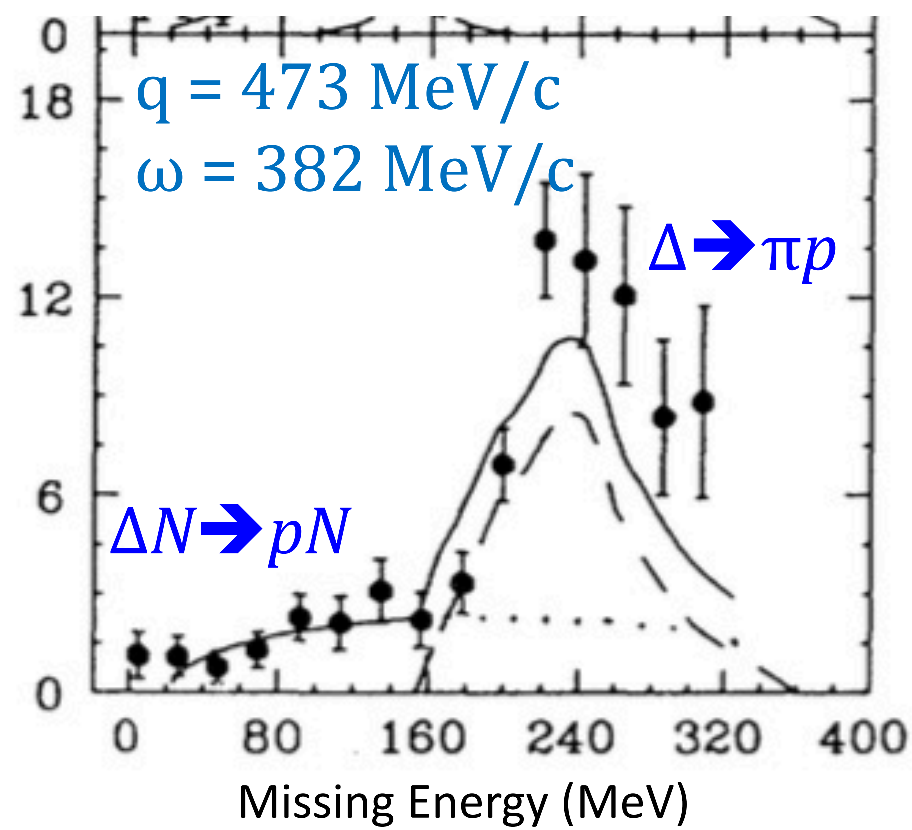


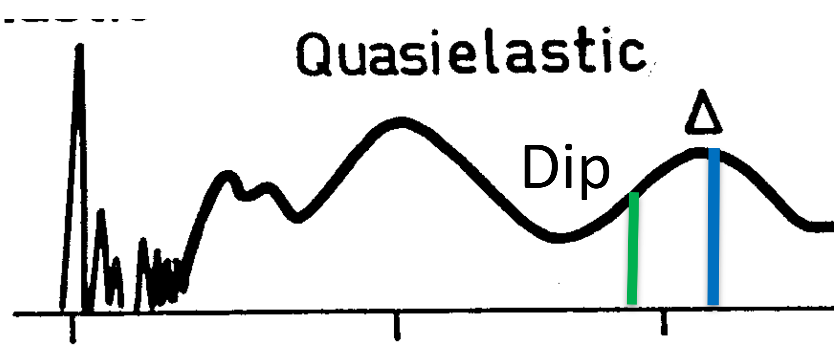


R. Lourie, PRL **56**, 2364 (1986)
L. Weinstein, PRL **64**, 1646 (1990)
S. Penn, unpublished

^{12}C(e,e'p) Delta Region





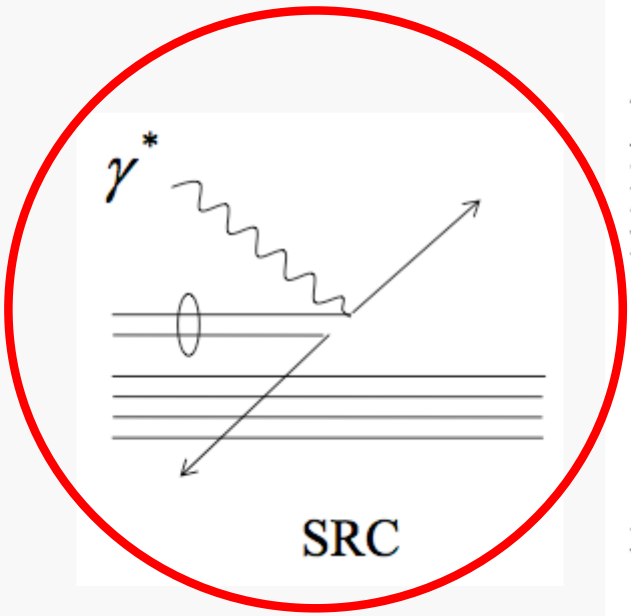


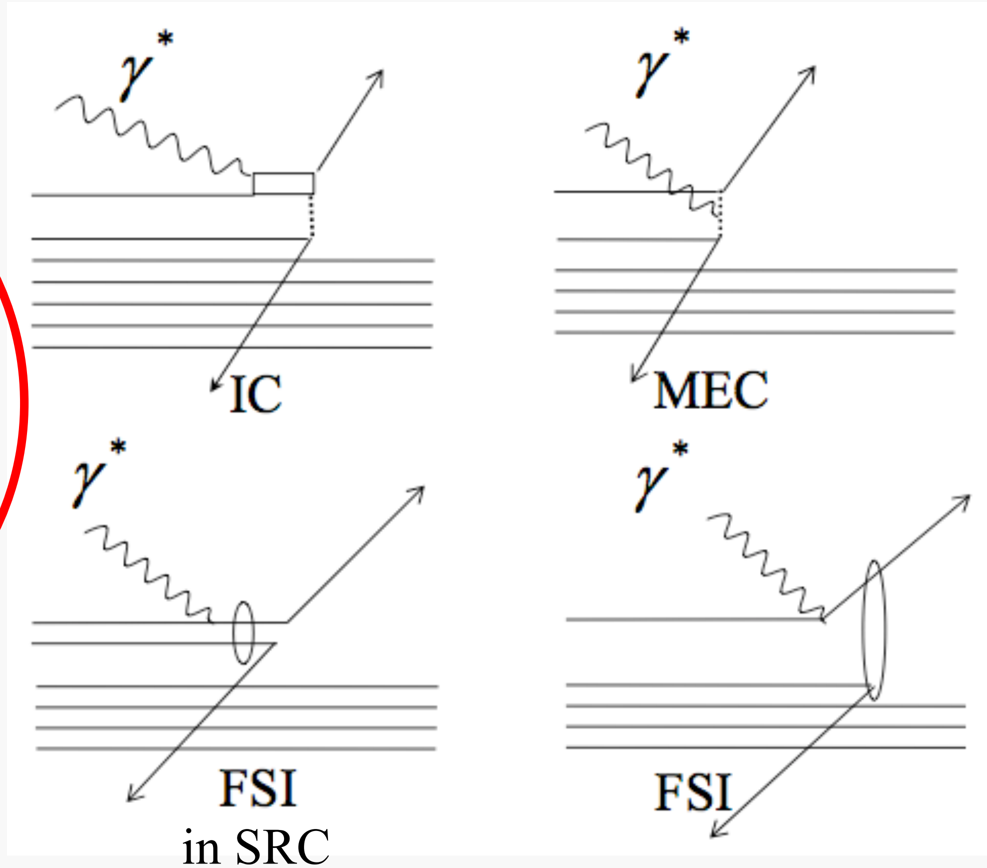
Baghaei, PRC **39**, 177 (1989)

What are correlations?

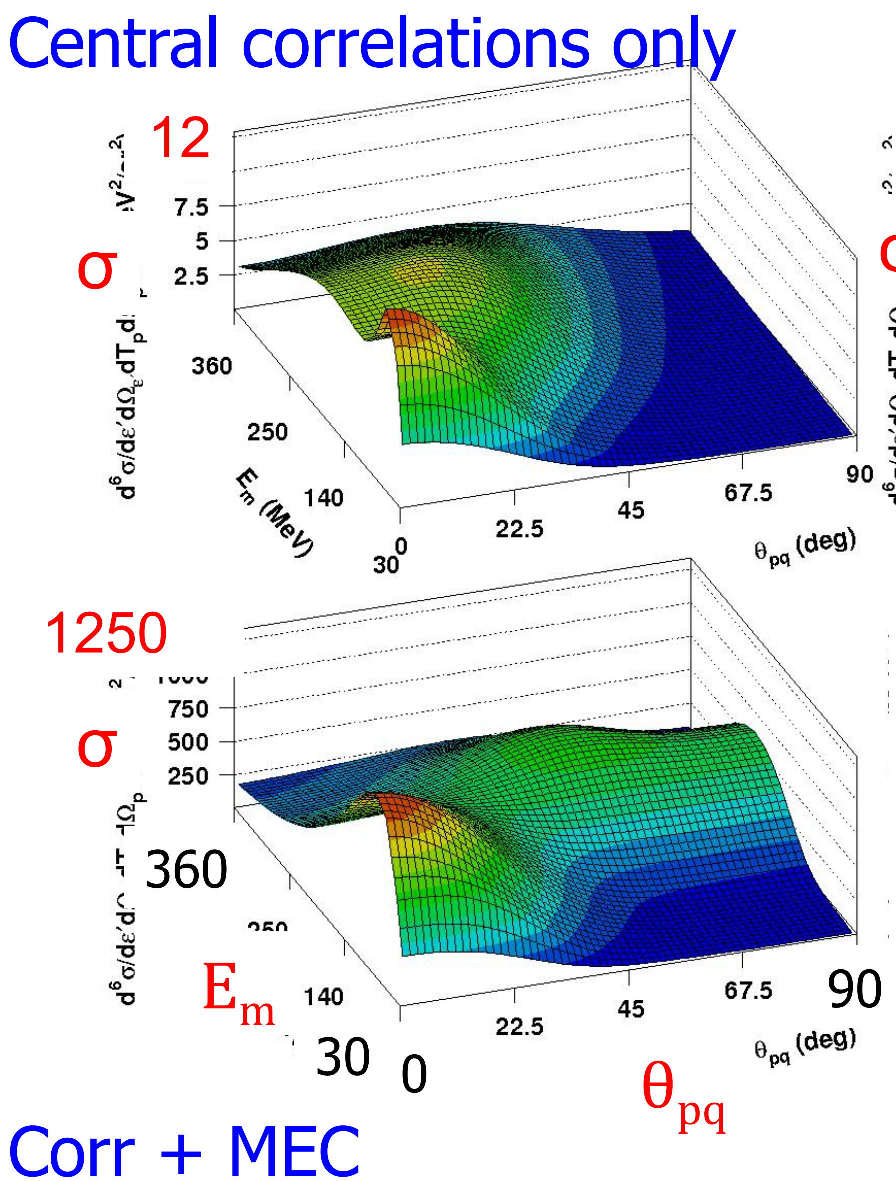
Average Two-Nucleon Properties in the Nuclear Ground State

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





2N currents enhance correlations



MEC and correlations add coherently

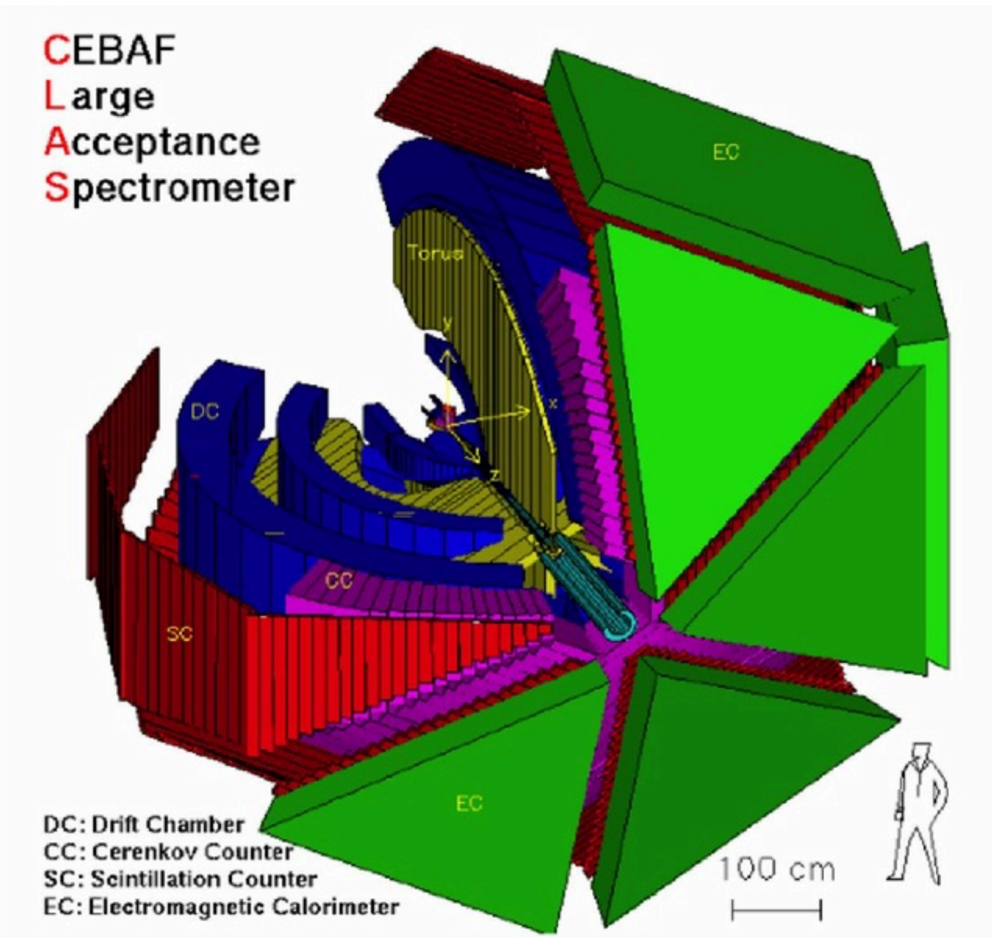
O(e,e'p) Ryckebusch
NP A672 (2000) 285

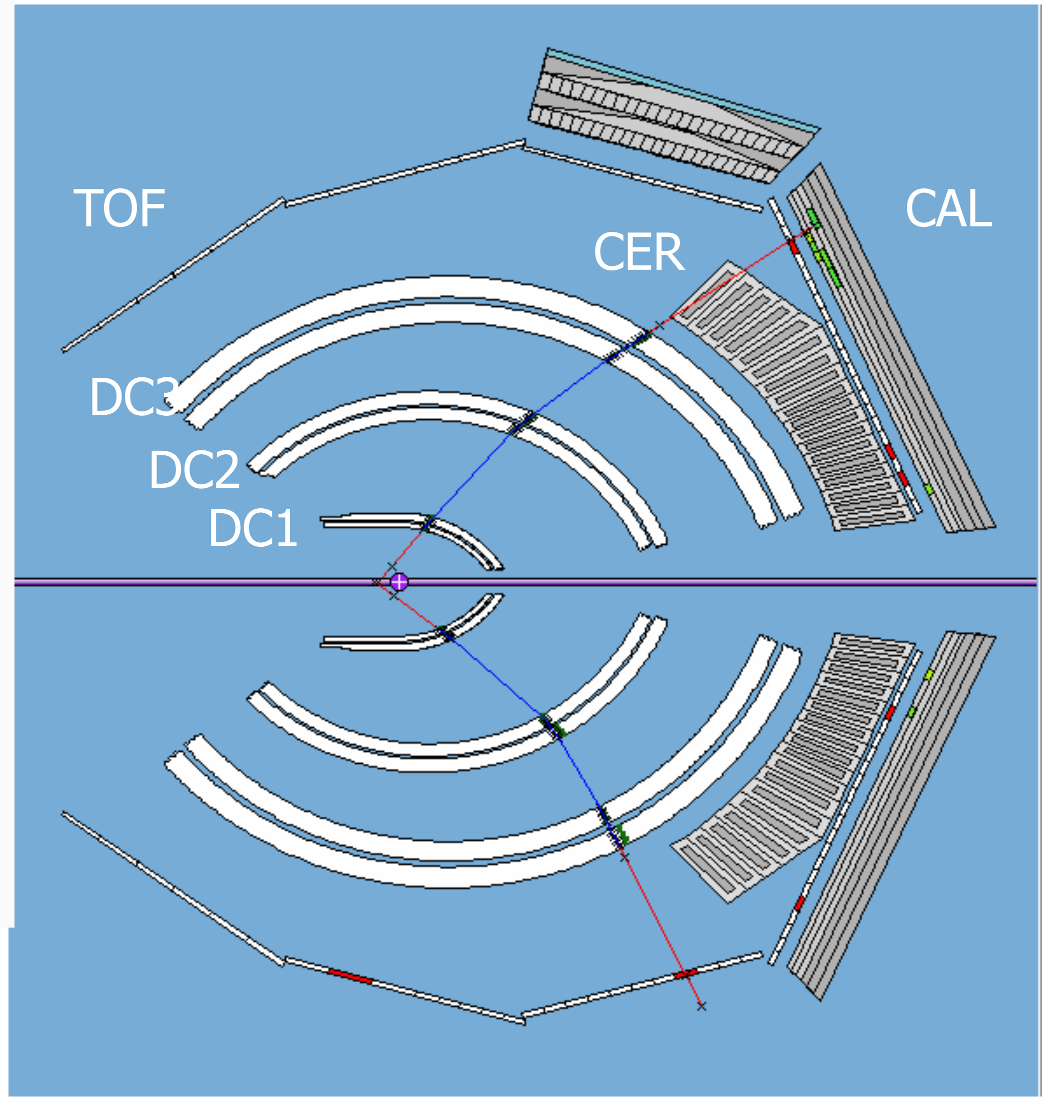
Physics Summary

- Electron scattering:
  - Monochromatic beam
  - Vector current only
  - Can choose kinematics to minimize “uninteresting” reaction mechanisms
  - Calculate cross sections after the fact
- Neutrino interactions
  - Continuous mixed beams
  - Vector plus axial current
  - Must include all reaction mechanisms
    - MEC, IC, SRC
    - FSI (not discussed here)
  - Need good models in event generators

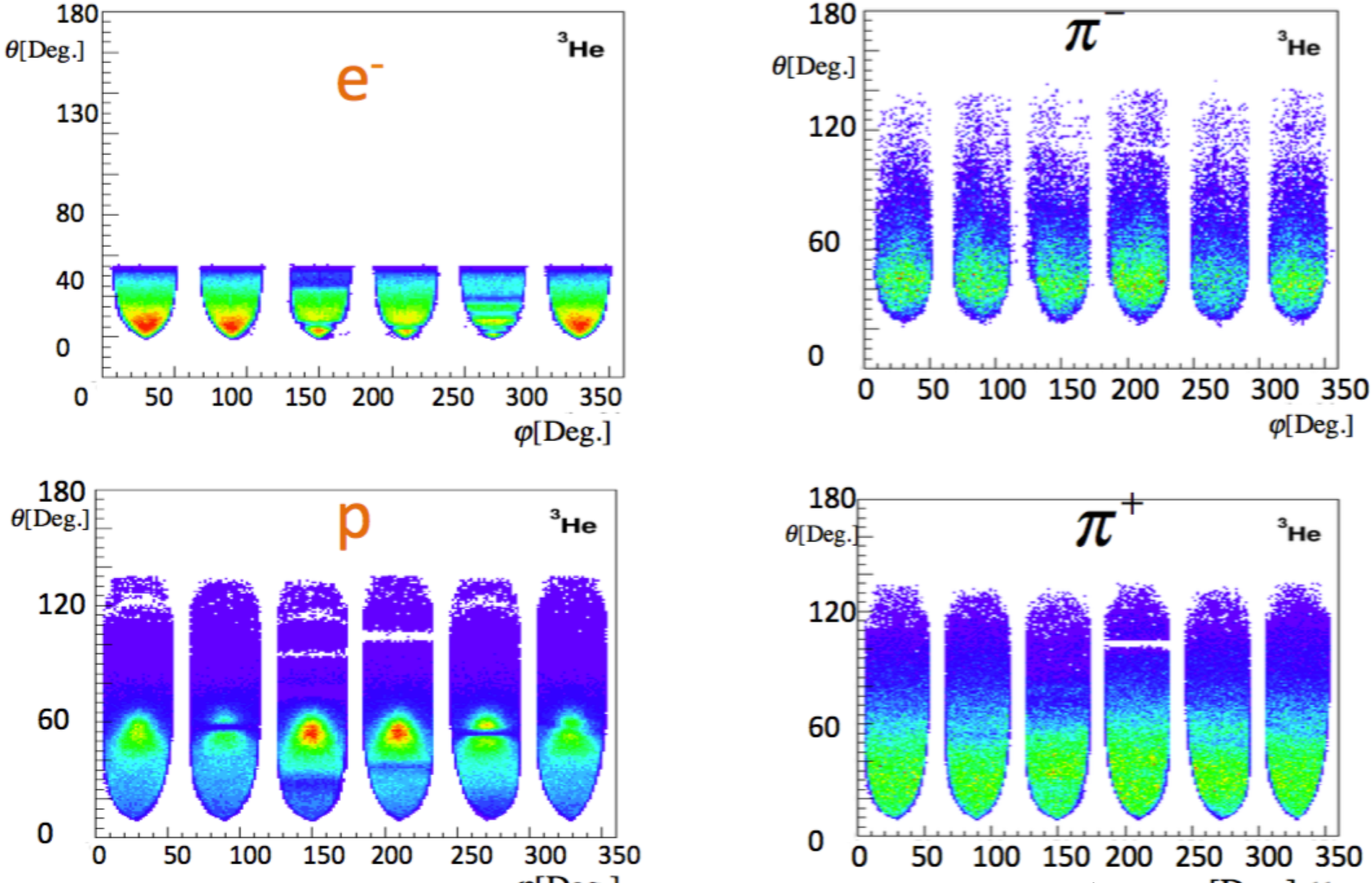
Jefferson Lab data

CLAS6: 1996-2015





CLAS6 coverage



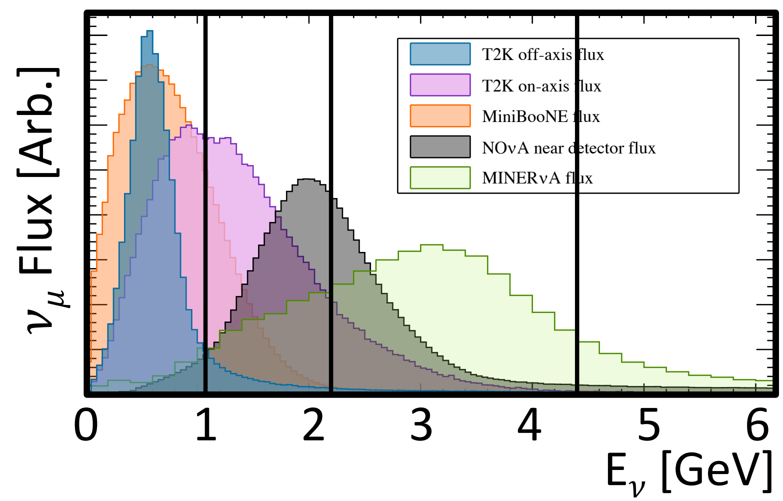
$p_{min} \approx 300$ MeV/c

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

CLAS6 Data (million events)

	1.1 GeV	2.2 GeV (e,e')	2.2 GeV (e,e'p)	4.4 GeV (e,e')	4.4 GeV (e,e'p)
3He	Not done	24	9	4	1
4He	Not done	46	17	8	3
12C	Not done	30	11	5	2
56Fe	Not done	1	0.5	0.4	0.1

E2a data only.
E2b has more 4.6 GeV 3He and 56Fe
Eg2 has 5 GeV d, C, Al, Fe, and Pb



Reconstructing the initial energy

- Choose 0π events to enhanced the QE sample
  - Subtract "undetected pions"
- Weight by $1/\sigma_{Mott}$ to account for photon propagator
- Reconstruct the incident lepton energy:
  - $E_{QE} = \frac{2M_N\epsilon+2M_NE_l-m_l^2}{2(M_N-E_l+k_l cos\theta_l)}$
    - ϵ: nucleon separation energy, M_N nucleon mass
    - $\{m_l, E_l, k_l, \theta_l\}$ scattered lepton mass, energy, momentum and angle
    - broadened by nucleon fermi motion
  - $E_{cal} = E_e + T_p + \epsilon$ [for (e,e'p)]

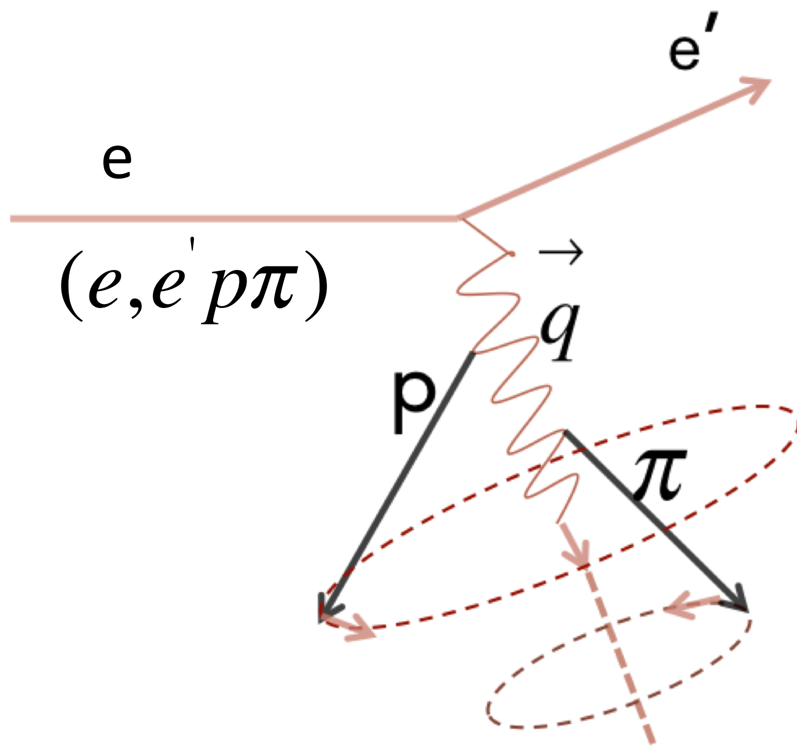
Background Subtraction

Non-QE interactions lead to multi hadron final states.

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

Data Driven Correction:

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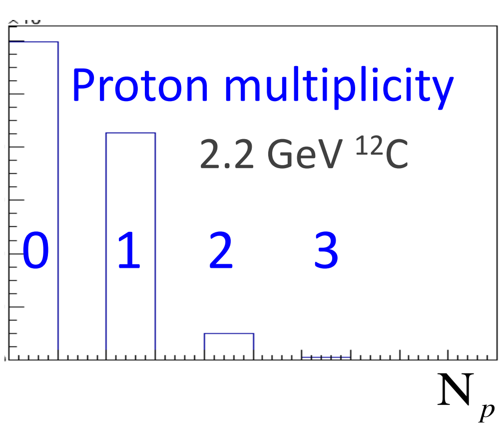
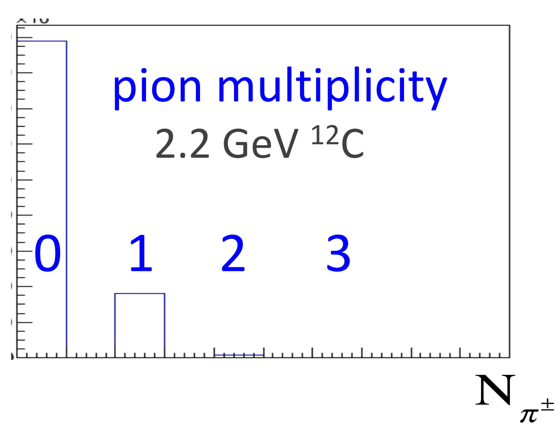
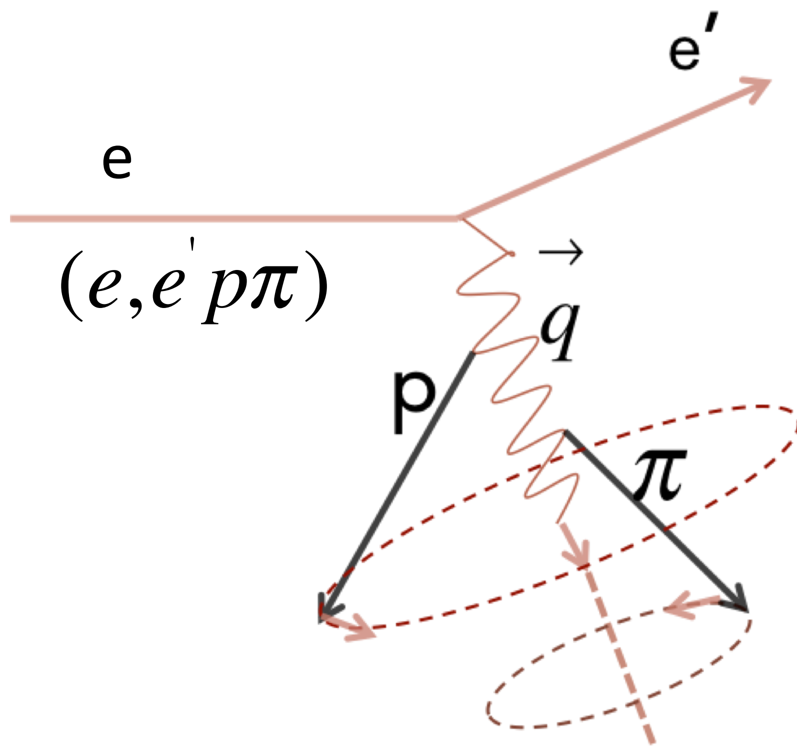
4. Do the same for 2p, 3p, 2p+ π etc.







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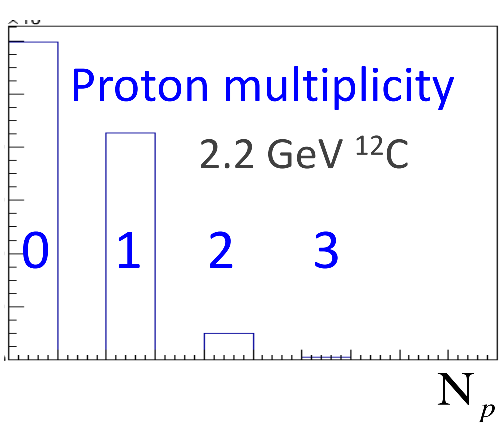
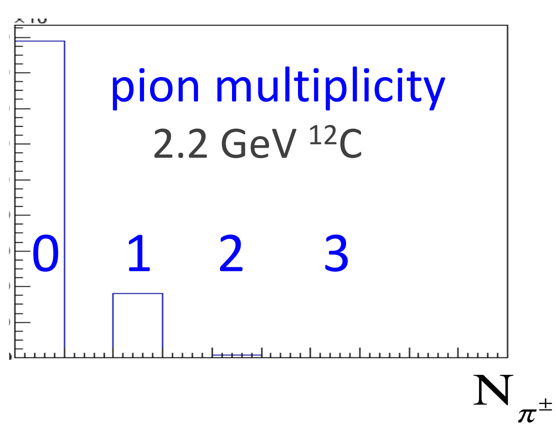
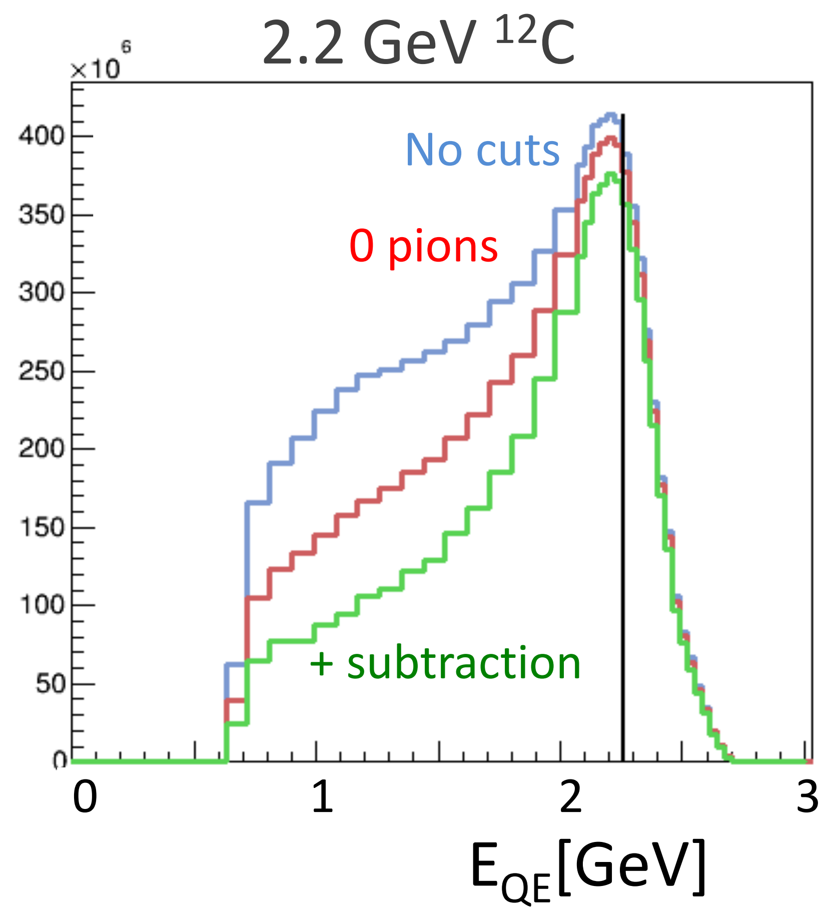
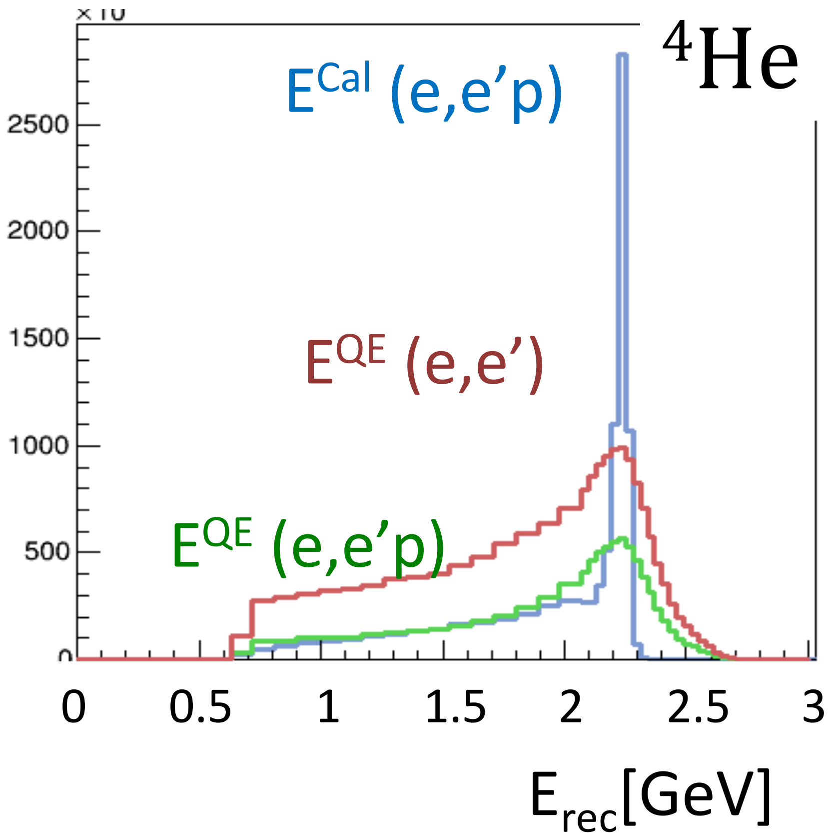


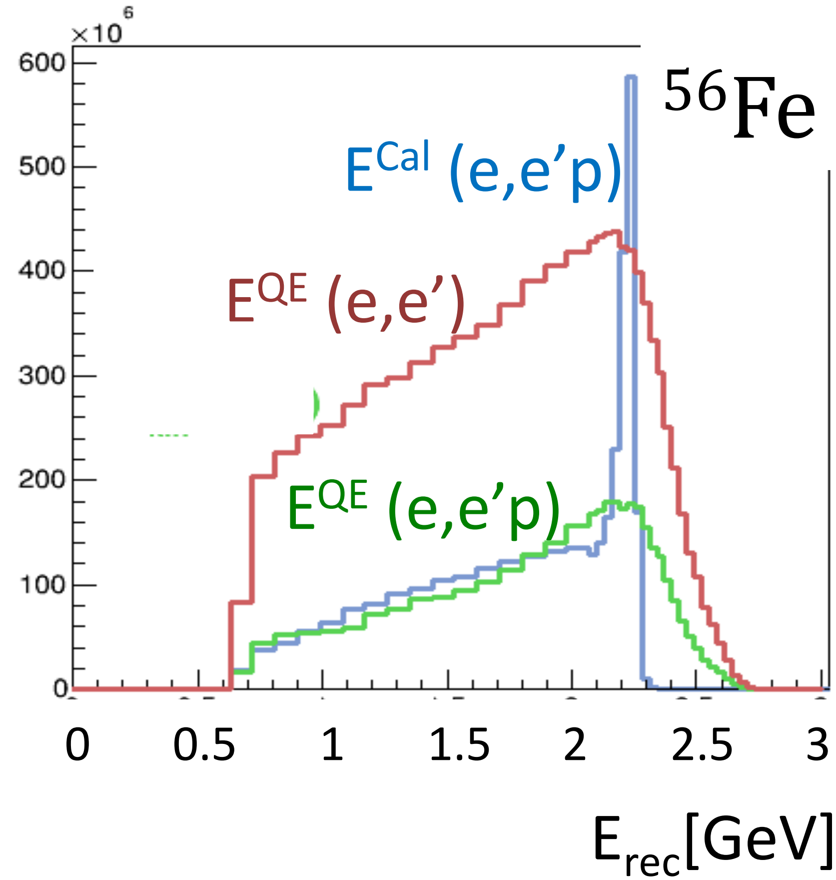




Energy Reconstruction Example

2.26 GeV beam   Zero pion events





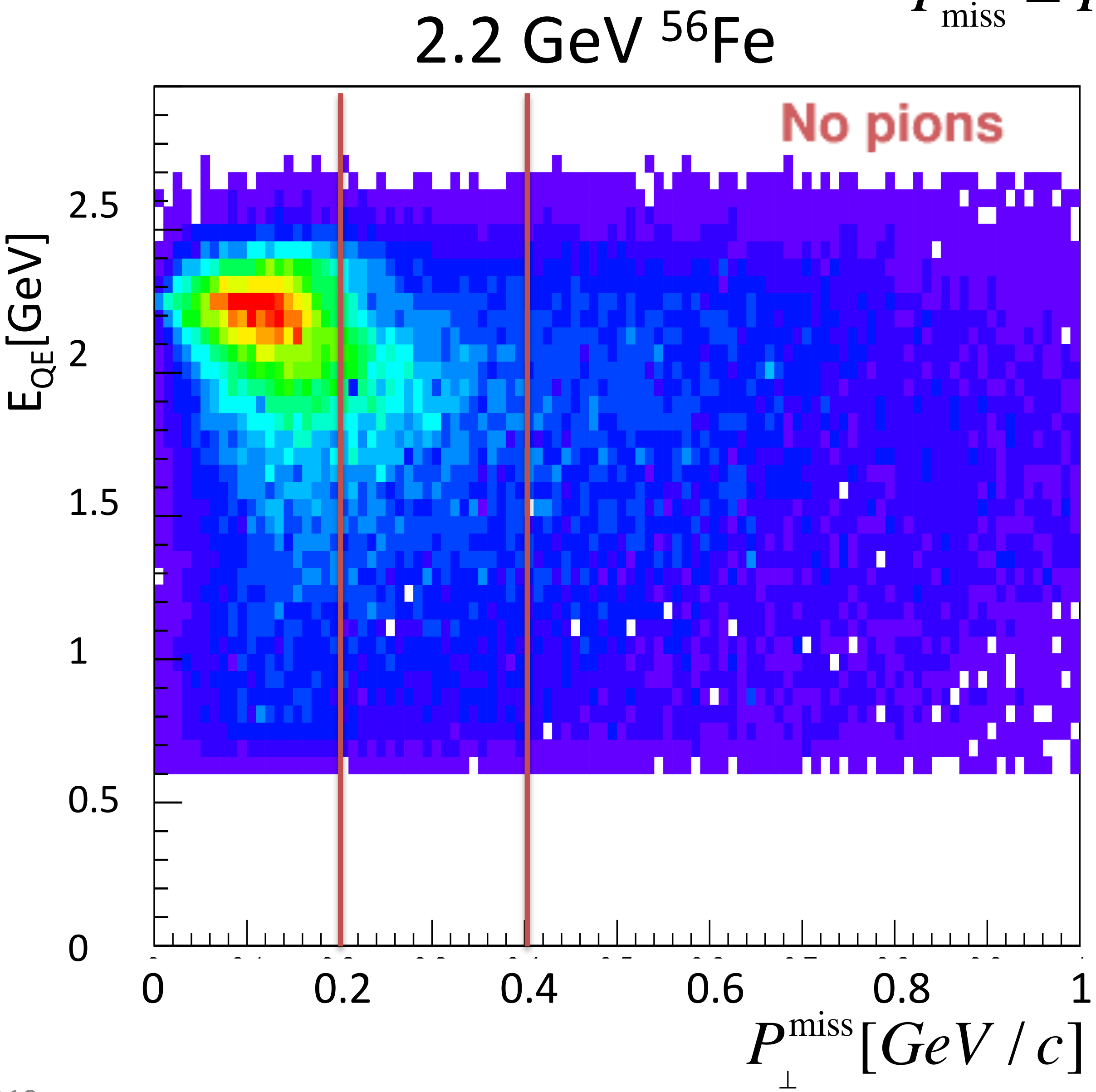
Even 0pi events have a LOT of non-QE events

Much bigger in Fe than ^{4}He

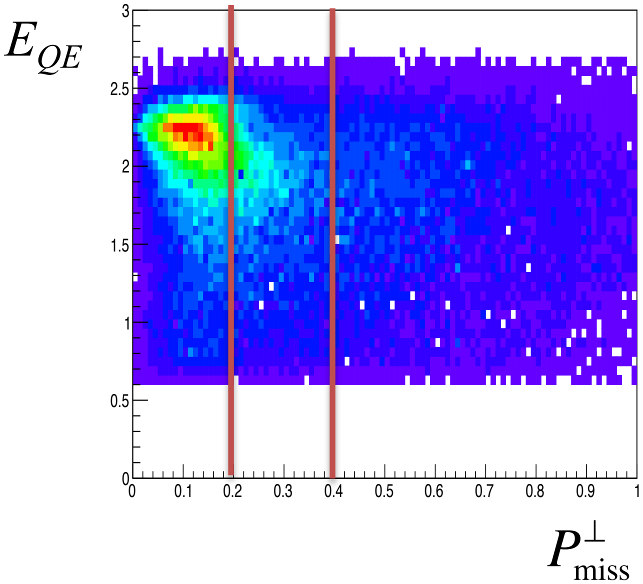
Larger at 4.4 GeV than 2.2 GeV

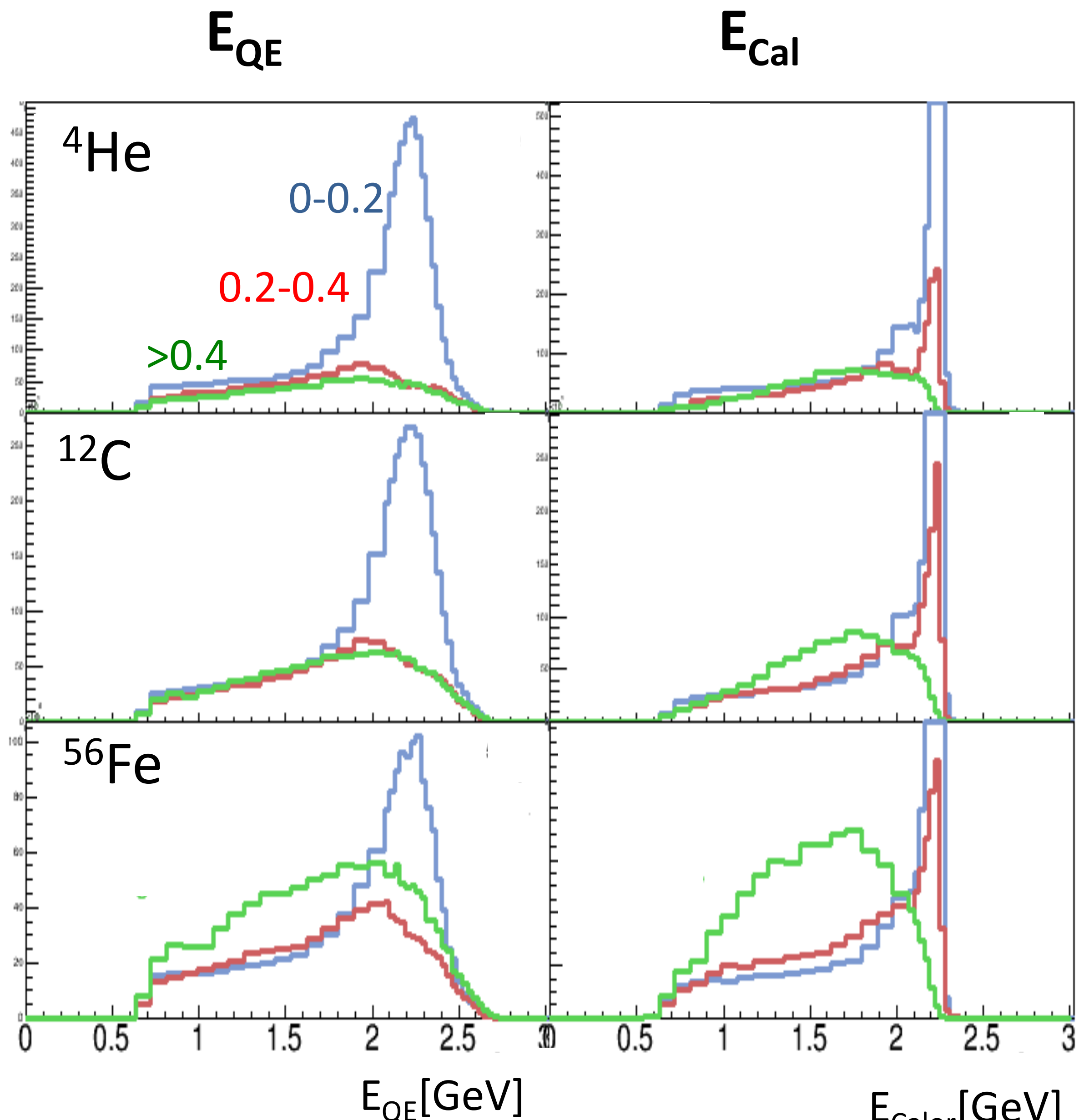
Perpendicular momentum (Data)

$$P^{\perp}_{\text{miss}} = P^{\perp}_{e^-} + P^{\perp}_{p} = P^{\perp}_{\text{init}}$$



$P_{\rm miss}^{\perp}$ slices

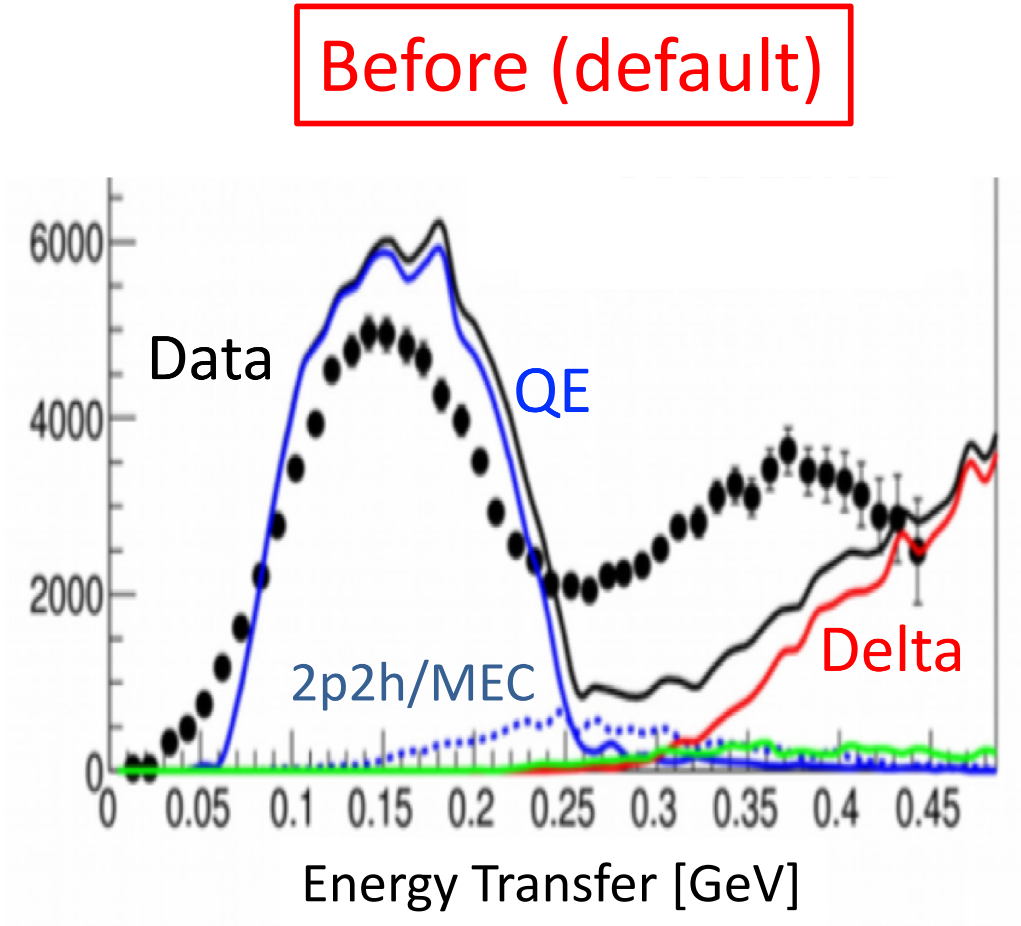


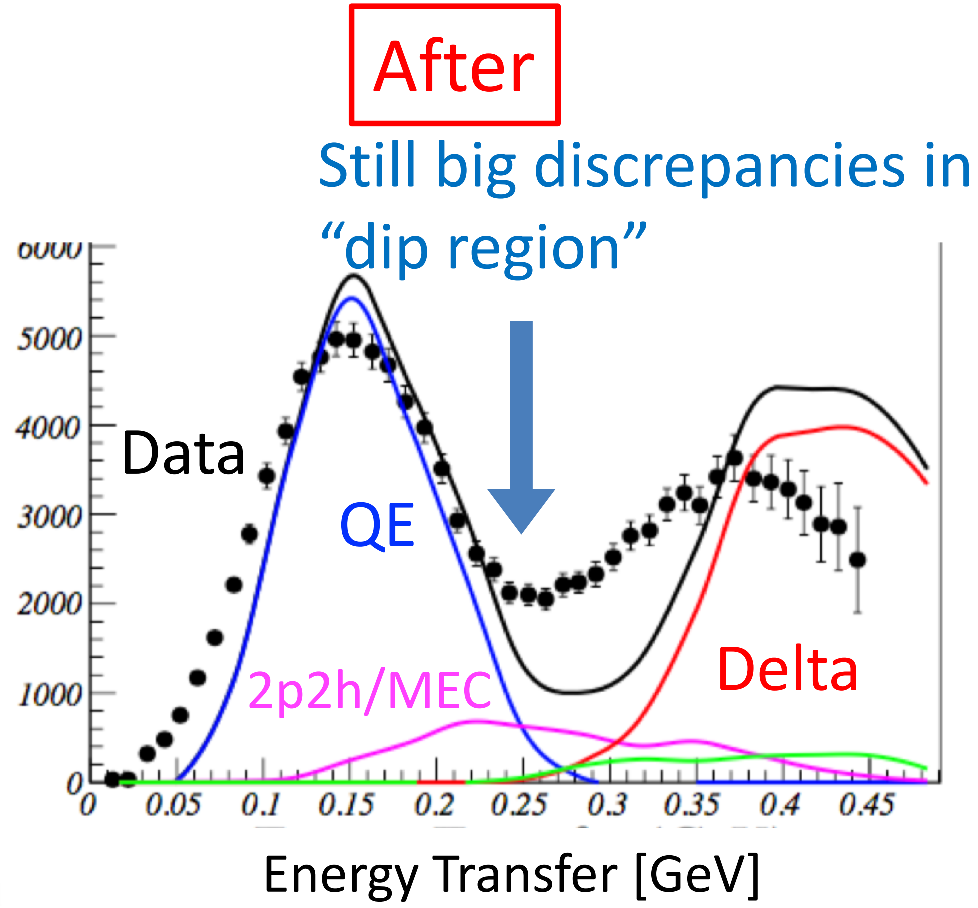


1. Worse peak resolution for E_{QE}
2. $E_{Reconstructed}$ worse for heavier targets
3. Large $P_{\rm miss}^{\perp}$ -> bad reconstruction

We're Also Improving Genie

$C(e,e') \text{ } 560 \text{ MeV } \theta = 60^{o}$





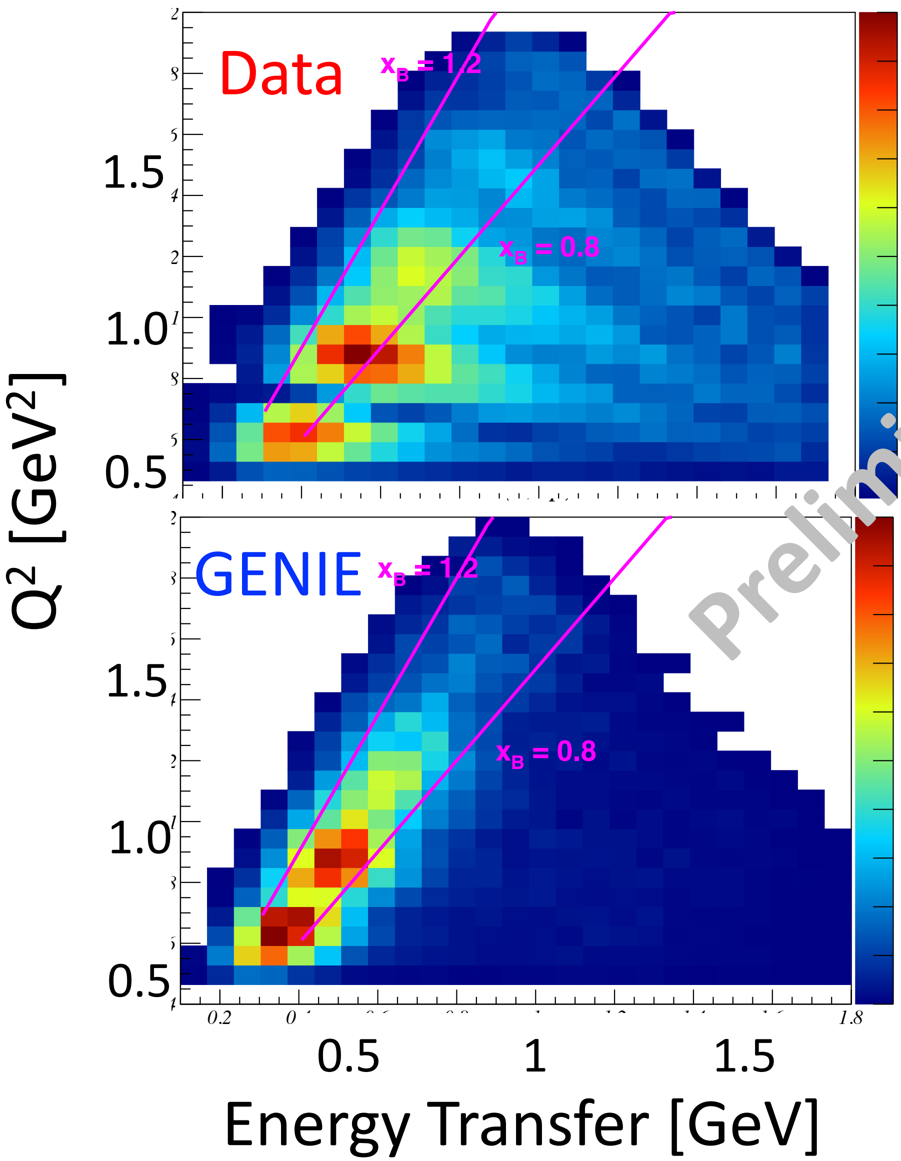
We're Also Improving Genie

1. Corrected expression for Mott cross section in QE
2. MEC/2p2h
   1. Added boost back to lab frame
   2. Corrected mass for cluster of particles
   3. Corrected Form Factors
3. Resonance
   1. Replaced old calculation with GSL Minimizer (now gives correct peak location)
   2. Switched to Berger-Seghal model
   3. Used corrected coupling constant for EM interactions
4. Nucleon momentum distributions
   1. Switched to Local Fermi Gas Model

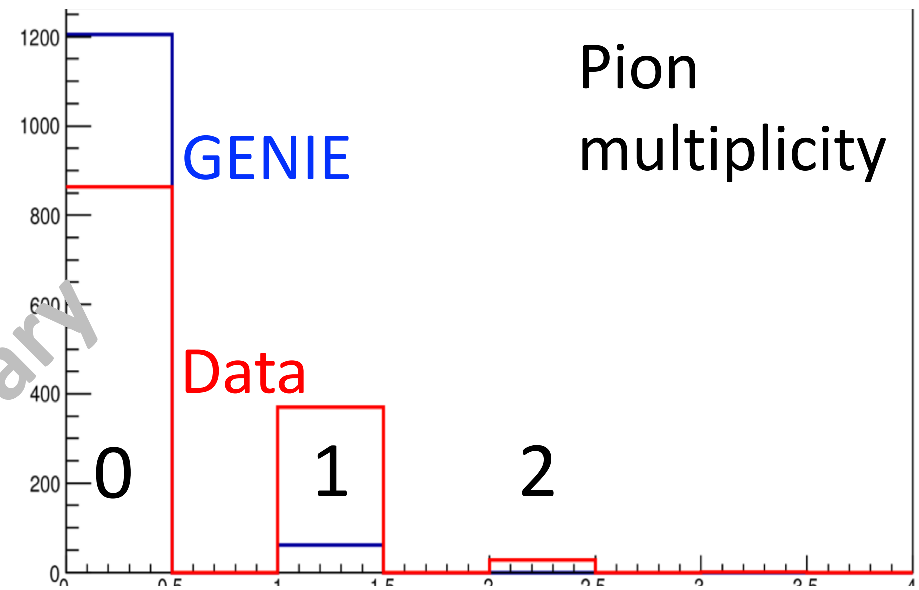
Beginning work on NuWro and GiBUU.
Consulting with the relevant experts on each code.

Data-Genie Comparisons

C(e,e'p) 2.26 GeV
No x or W cuts



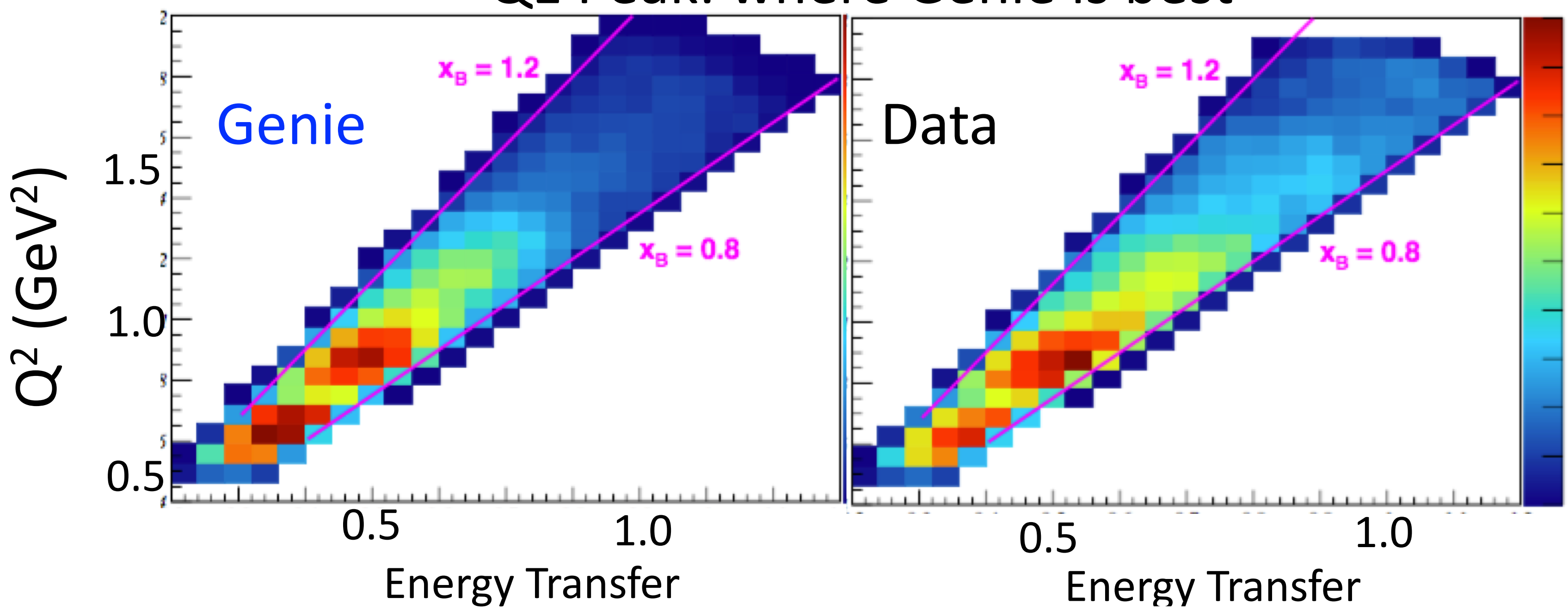
C(e,e'p) 4.46 GeV
0.8 < x < 1.2, W < 2 GeV

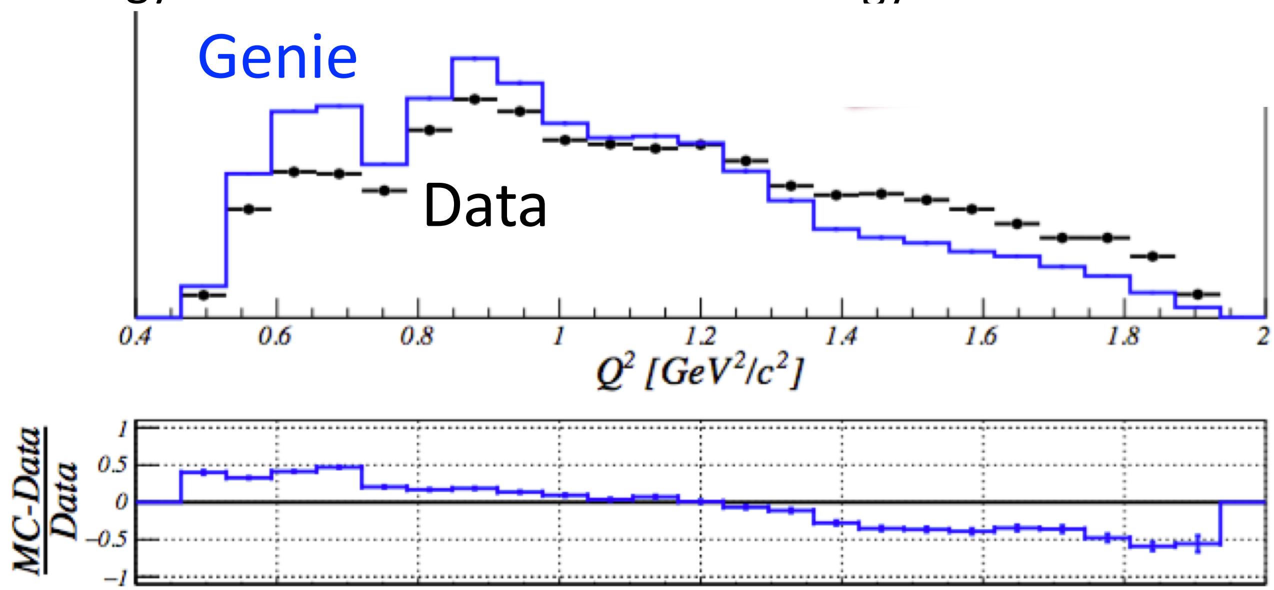


Data-Genie Comparisons

C(e,e'p) 2.26 GeV, $0.8 < x < 1.2$

QE Peak: where Genie is best

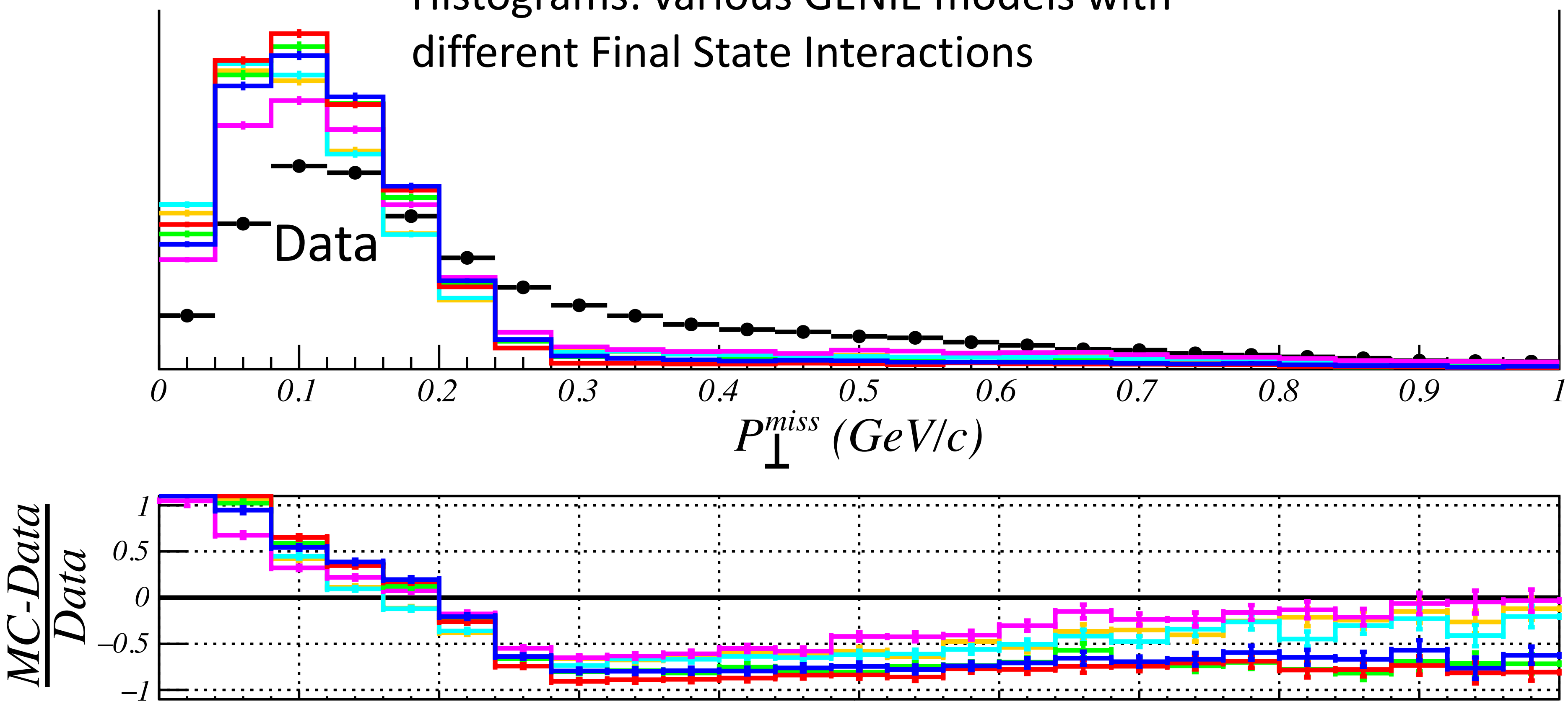




Data-Genie Comparisons

C(e,e'p) 2.26 GeV, $Q^2 > 0.5$ GeV^2, W < 2 GeV

Histograms: various GENIE models with different Final State Interactions

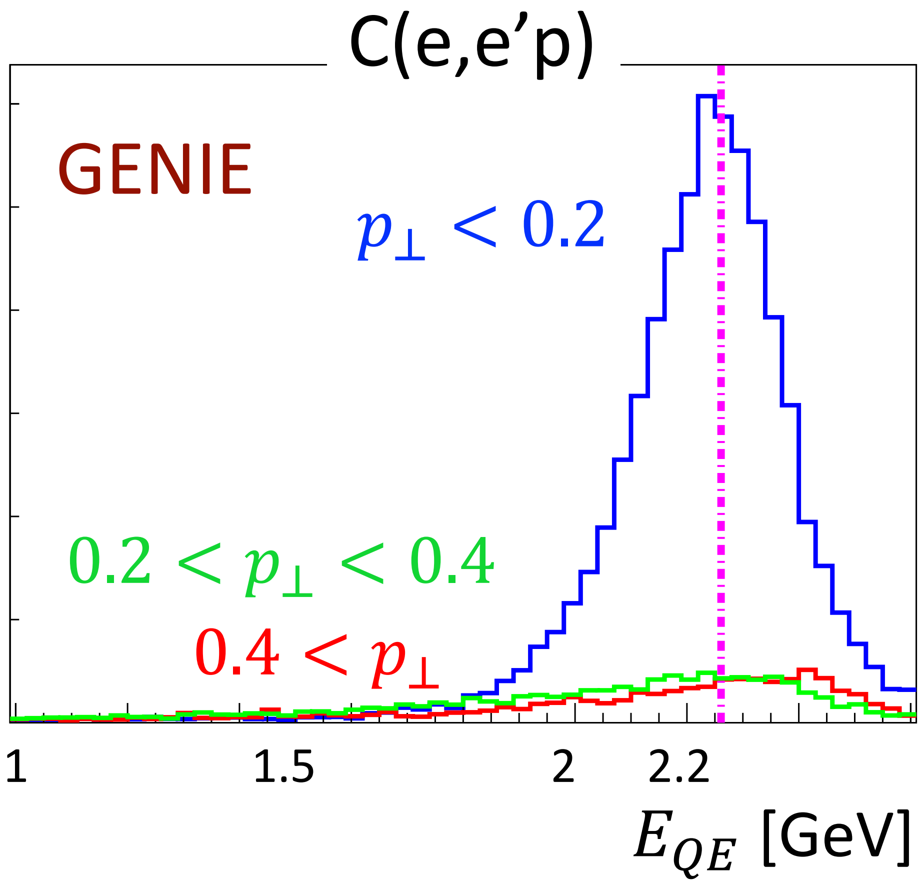


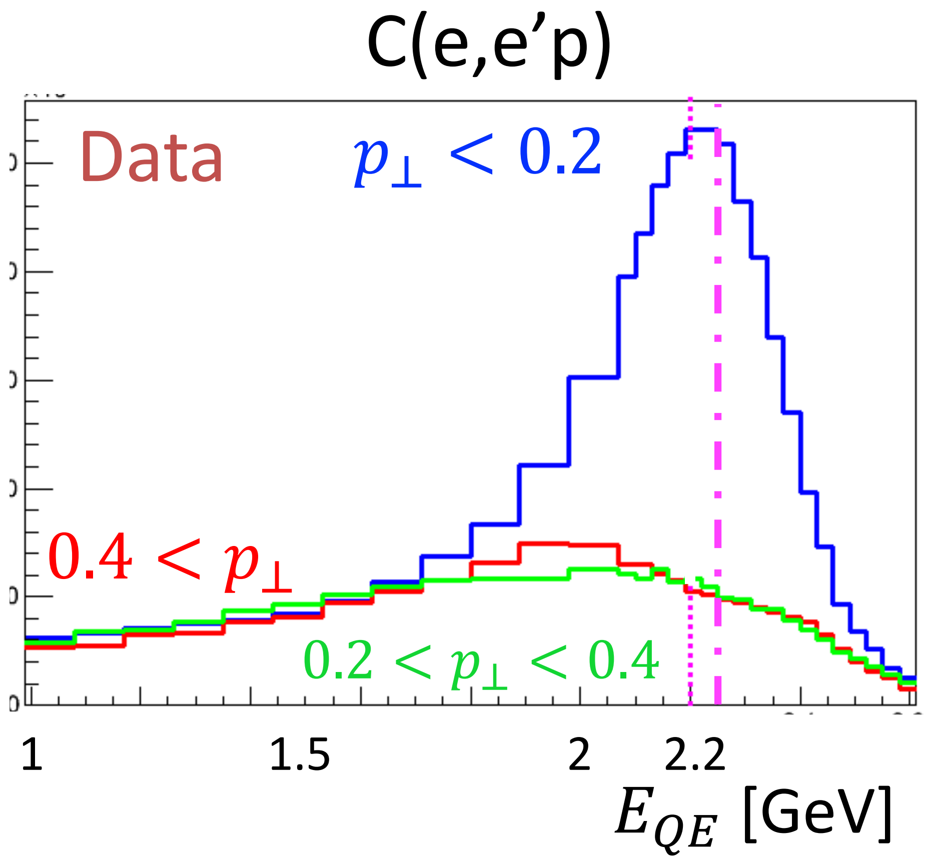
Significant differences at large $p_\perp$, none describe the data well

Data-Genie Comparisons

E_{beam} Reconstruction

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



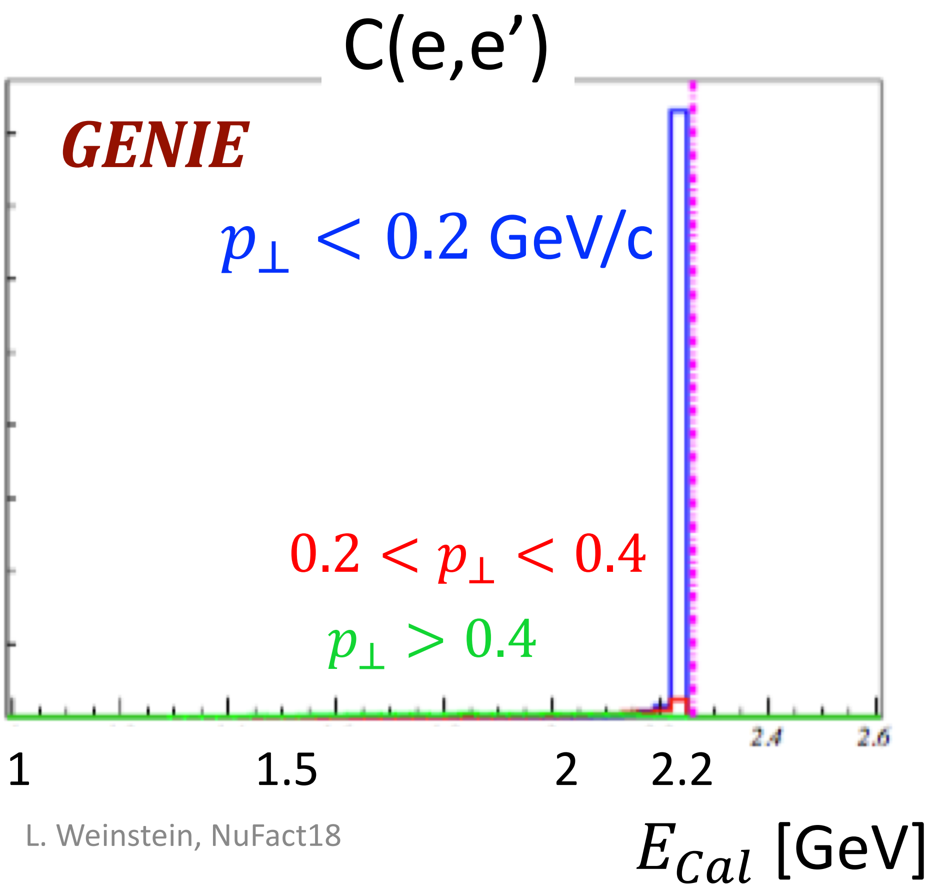


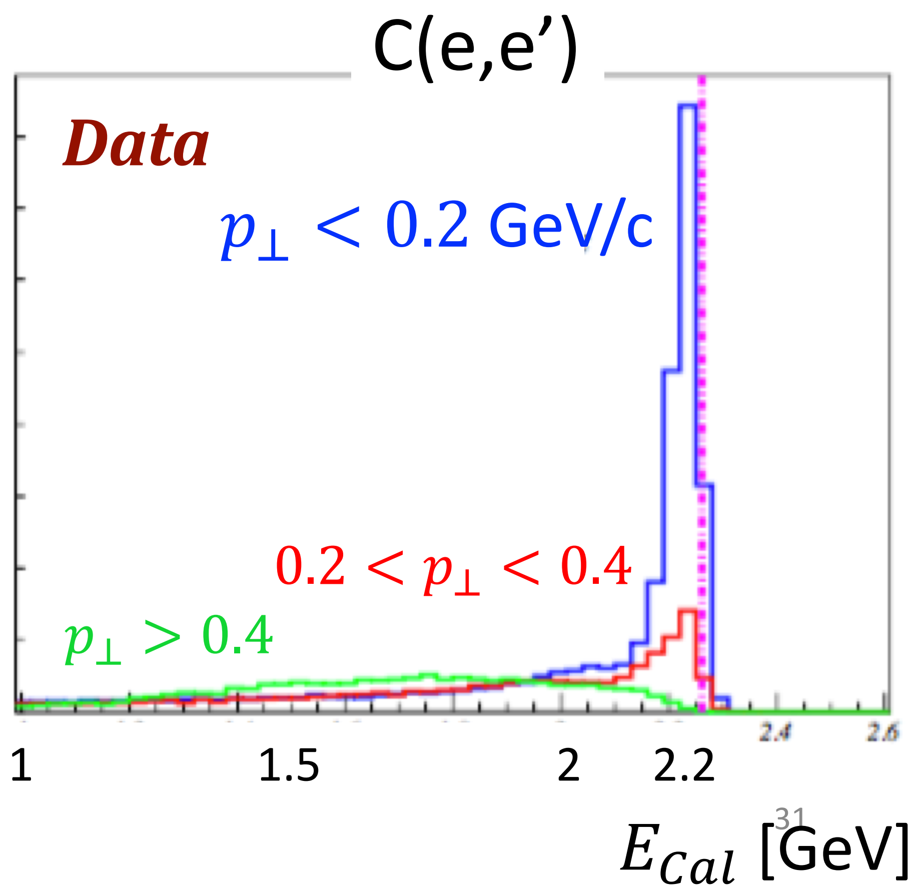
Peaks in same location

Data-Genie Comparisons

E_{beam} Reconstruction

$$E_{cal} = E_l + \Sigma E_p + \epsilon + \Sigma E_\pi$$



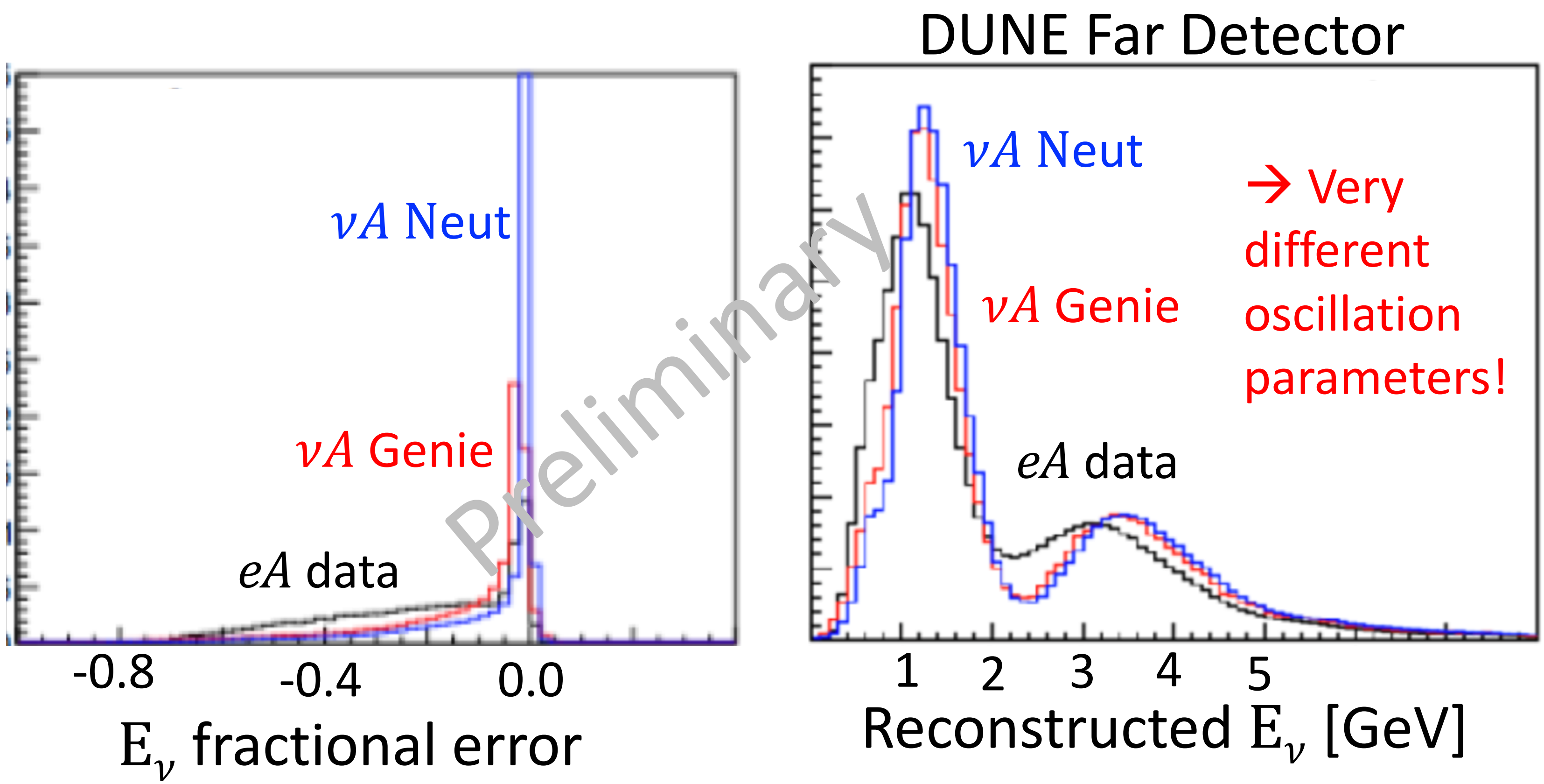


3. Comparing Data to Genie: E_{beam} Reconstruction

Fe	e^- Data	ν GENIE
2.2 GeV	26%	62%
4.4 GeV	14%	62%

Fraction of Fe$(e, e'p)$ and Fe$(\nu, \mu^- p)$ events with E_{Cal} within 5% of E_{beam}

Apply CLAS data to DUNE Oscillation



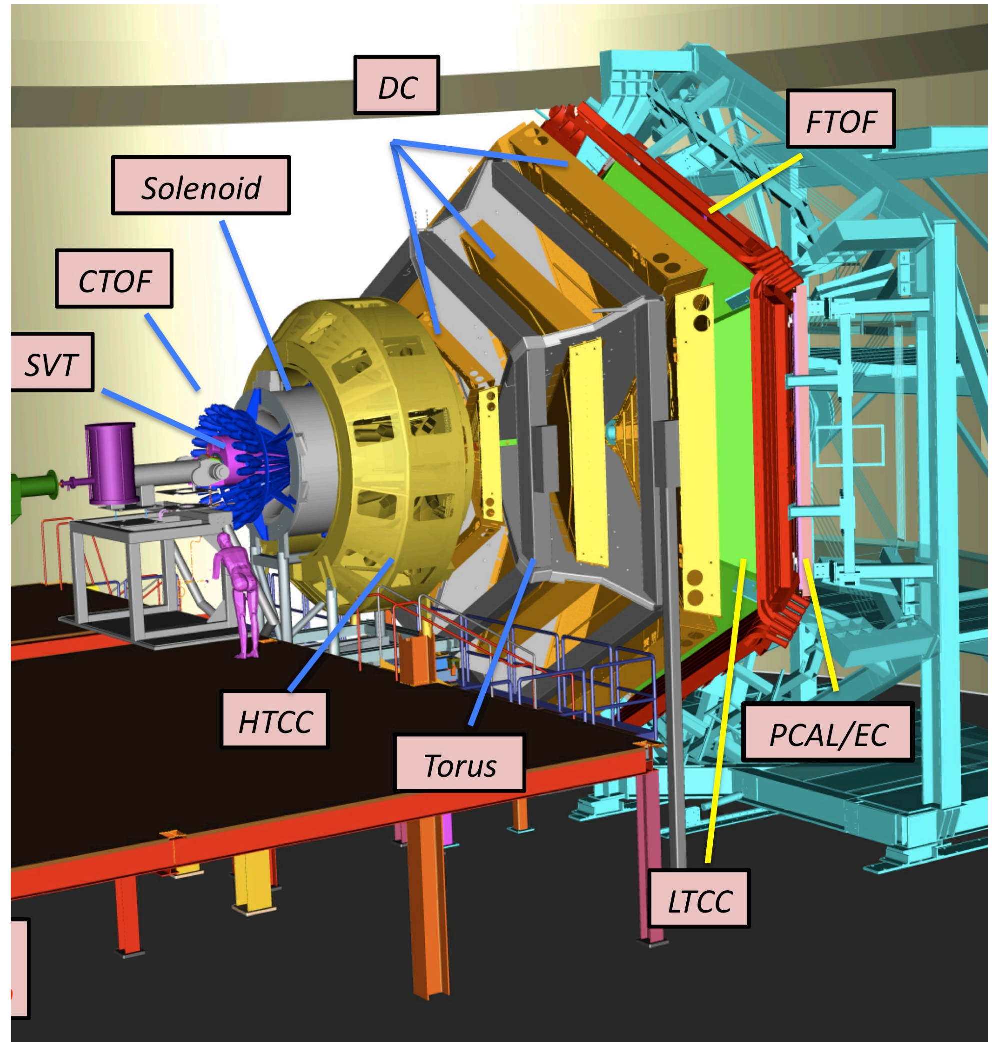
(Chris Marshall, LBNL)

- Proof of principle to show potential impact
- Threw events with νA Genie
    - Reconstructed with νA Neut or eA data
- Compared E_{rec} for eA to E_{rec} for νA
- Used 2.26 GeV eA E_{rec} for all incident energies

e4ν CLAS12

CLAS12

- forward detector (8 – 40°)
  - Toroidal magnetic field
  - $\frac{\delta p}{p}$ ~ 0.5—1%
  - Neutrons:
    - 50% effi for p > 1 GeV/c
    - $\frac{\delta p}{p}$ ~ 10-15% for 1 GeV/c
- Hermetic central detector (40 – 135°)
  - 5 T solenoidal field
  - Neutron effi ~ 10—15%
  - Neutron $\frac{\delta p}{p}$: 60 ps @ 0.3 m

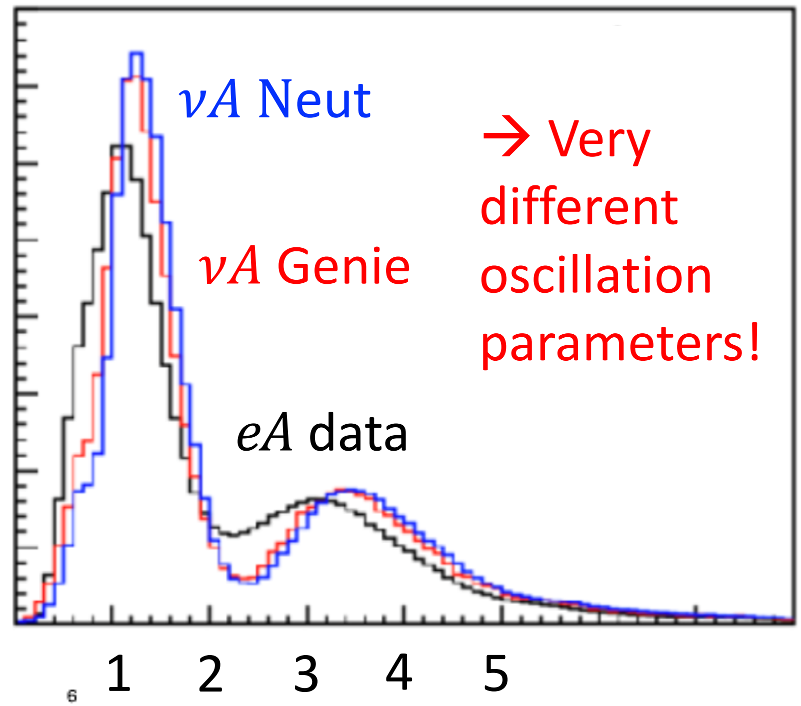


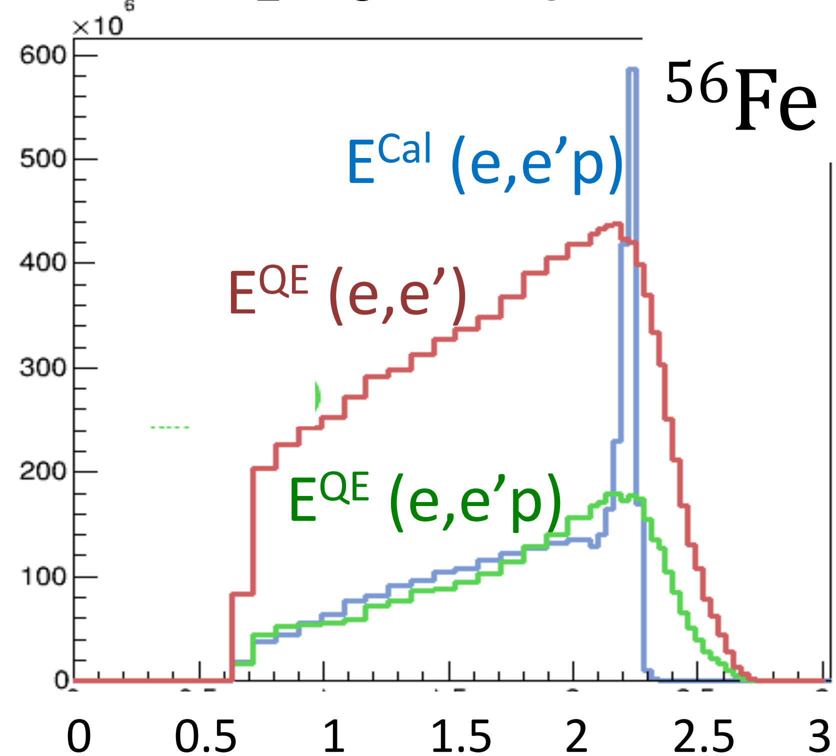
- 45 beam days approved with an A rating for
  - 1.1, 2.2, 4.4, and 6.6 GeV beam energies
  - d, He, C, O, Ar, and Sn targets

e4ν Goals

- We provide event yields and detector acceptance maps
  - Many beam energies
  - Many targets
  - Many event topologies
- Let experts use these to tune generators and understand energy reconstruction
- Can we use 40Ca or do we need 40Ar?
- What do you want to see??

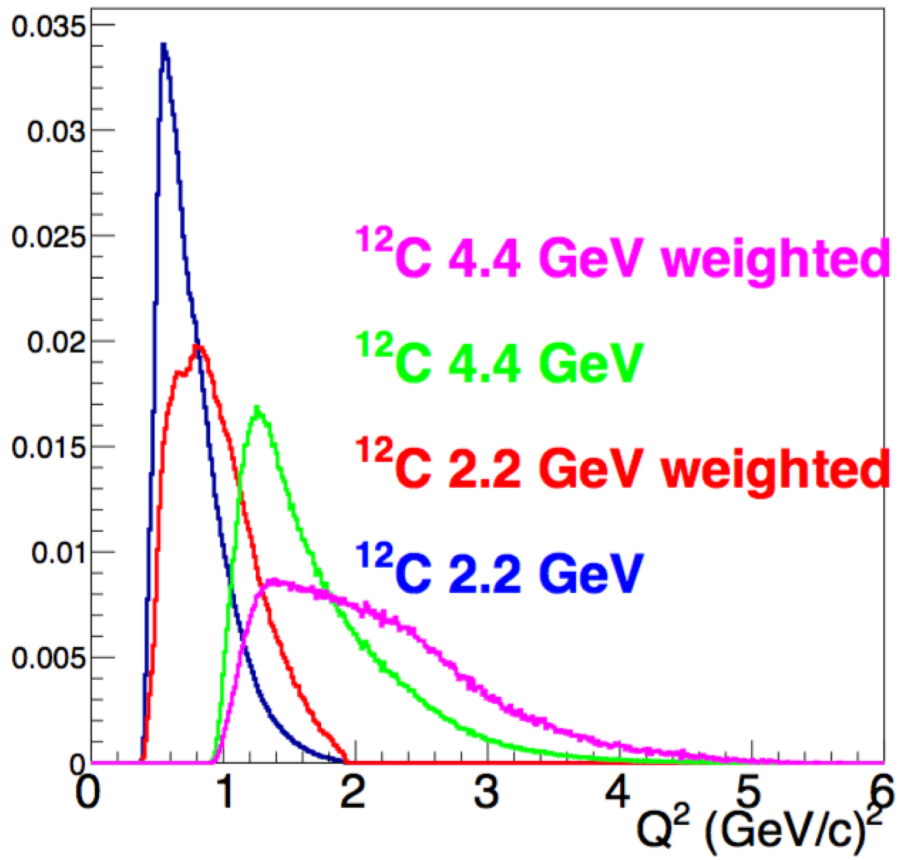
- Nuclear physics is complicated!
- Electron scattering can contribute dramatically to neutrino experiments
  - Similar physics
  - Lots of data available
  - Lots more to come
- We need guidance from the neutrino community



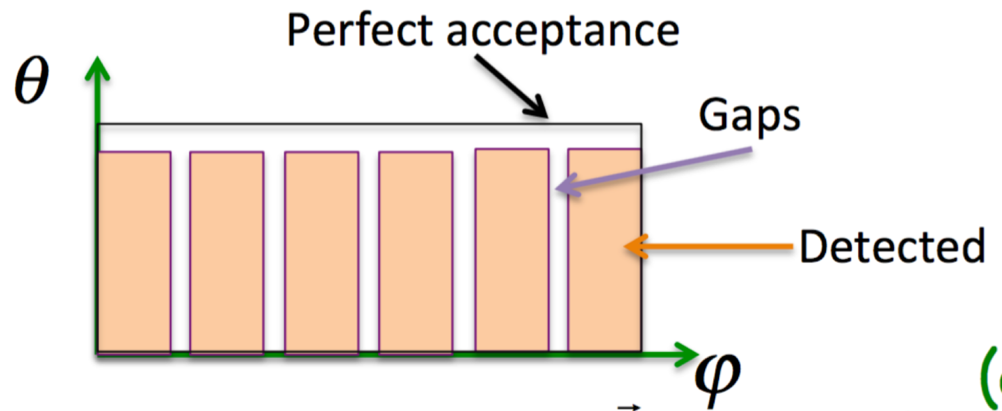


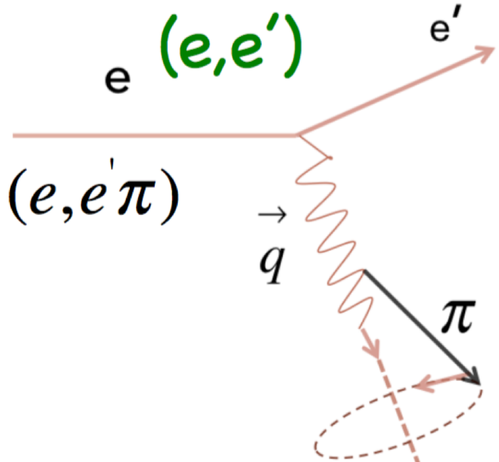
Backup slides

Mott weighting



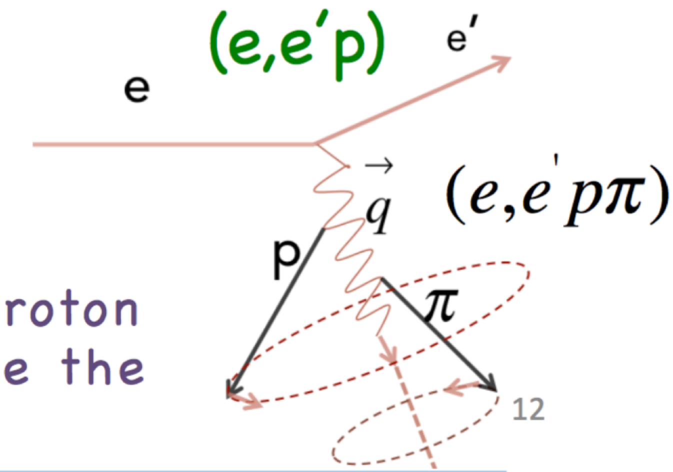
E2a ^{3}He 2.261 GeV



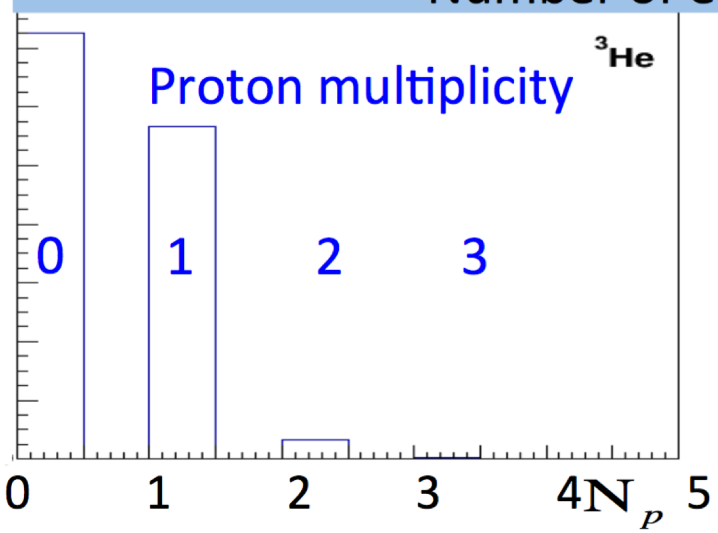


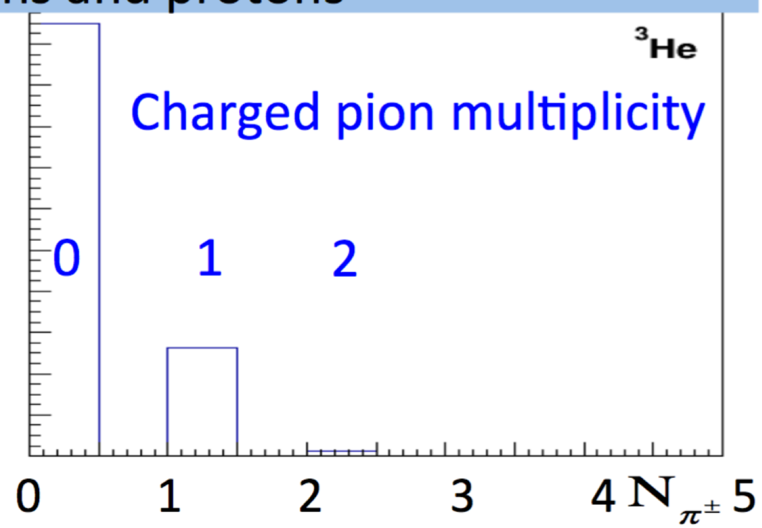
Rotate π around $\vec{q}$ to determine detection acceptance

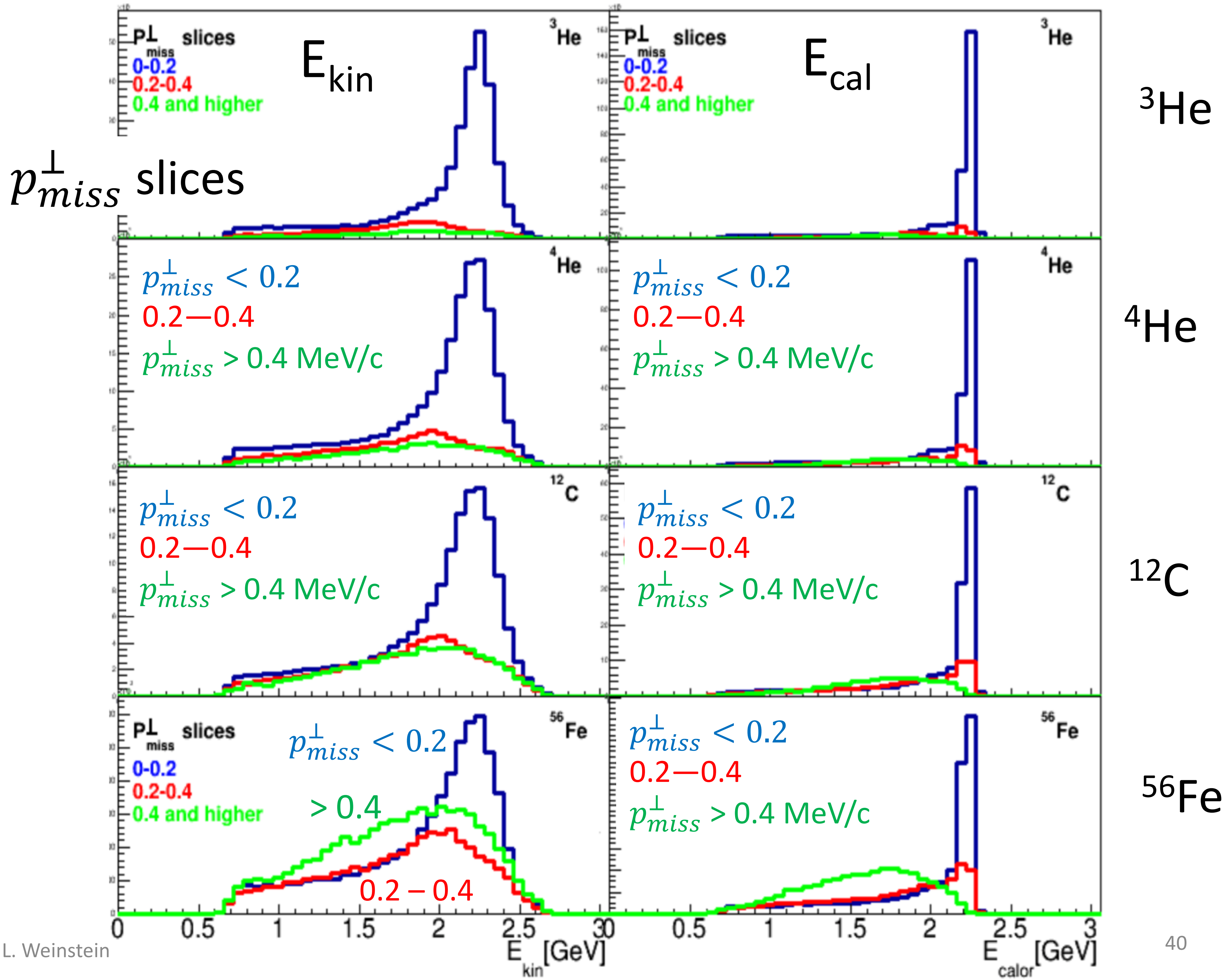
Subtracting undetected 2 proton events to get 1proton sample the similar way



Number of events with pions and protons



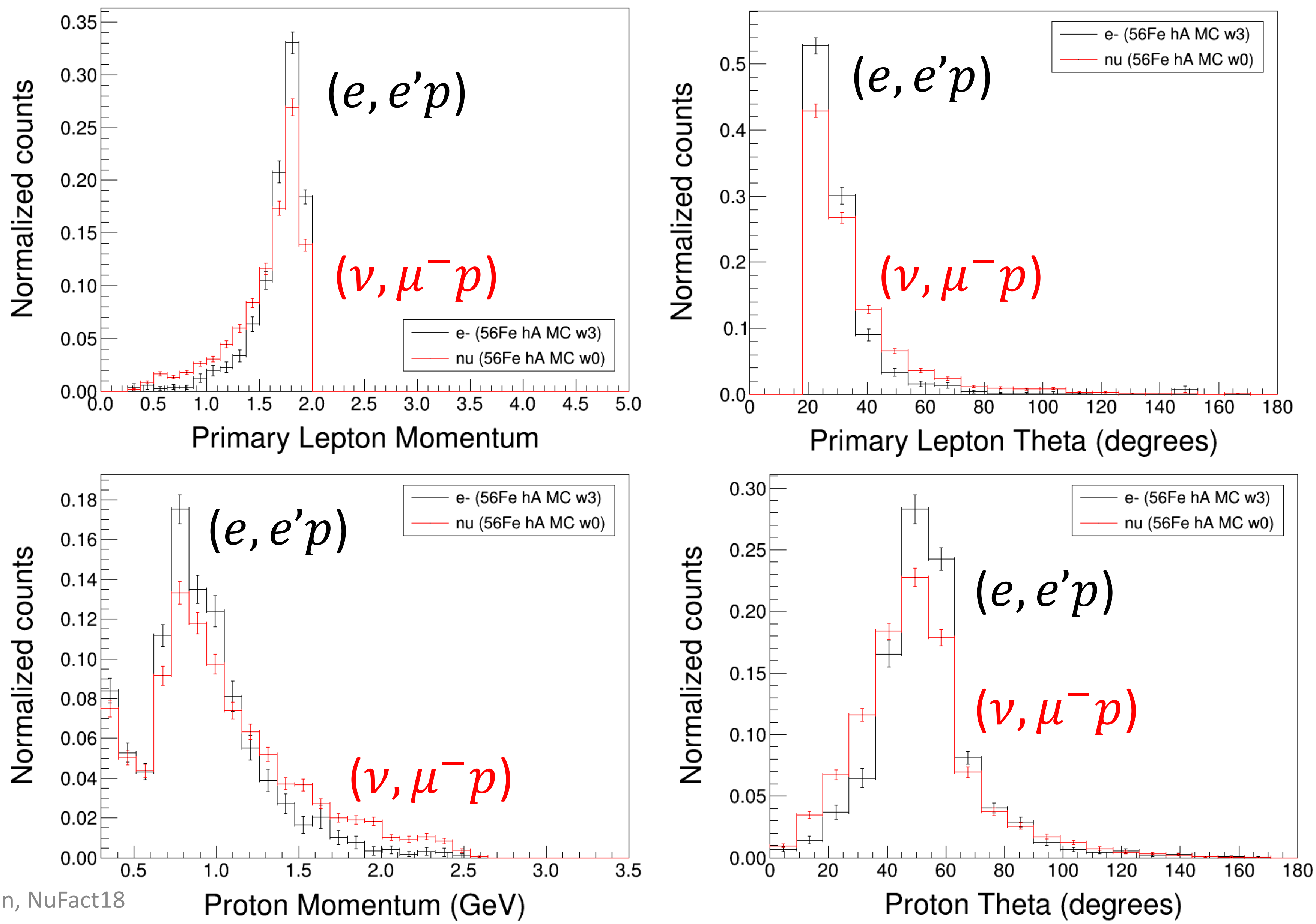




$p_{miss}^{\perp}$ slices
E_{kin}
E_{cal}
^3He
^4He
^{12}C
^{56}Fe
$p_{miss}^{\perp} < 0.2$
0.2—0.4
$p_{miss}^{\perp} > 0.4$ MeV/c
> 0.4
0.2 – 0.4
P⊥ miss slices
0-0.2
0.2-0.4
0.4 and higher
E_{kin} [GeV]
E_{calor} [GeV]

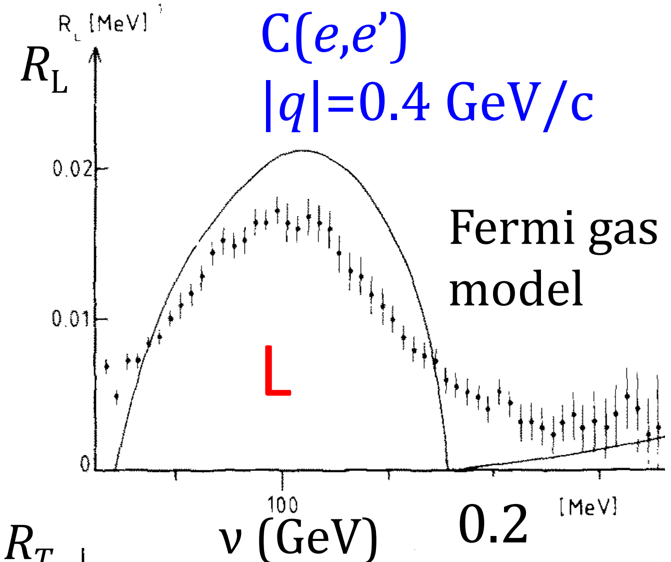
Similarity of electron and neutrino GENIE

2.2 GeV Fe, zero-pion. QE



How Quasielastic is the (e,e') QE peak?

$$\frac{d\sigma}{d\Omega d\nu} = \sigma_M \frac{E'}{E}\left[\frac{Q^4}{\vec{q}^{\,4}} R_L(Q^2,\nu) + \left(\frac{Q^2}{2\vec{q}^{\,2}} + \tan^2\frac{\theta}{2}\right) R_T(Q^2,\nu)\right]$$



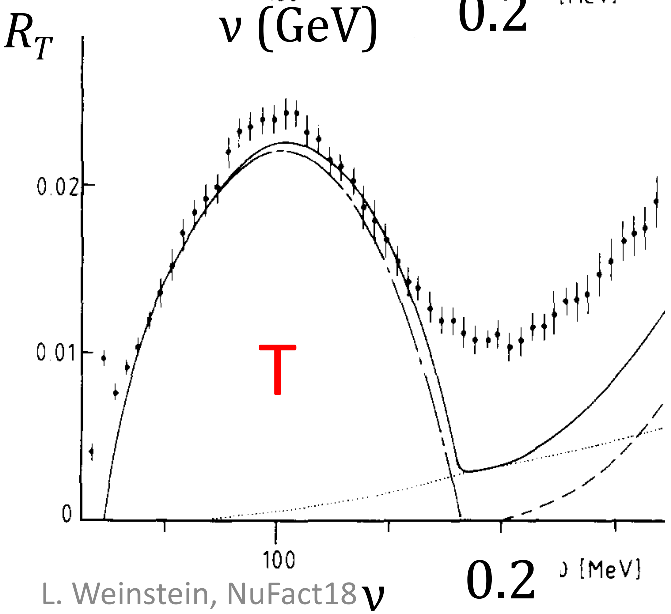
y = minimum initial nucleon momentum

= $m\nu/q - q/2$ (nonrelativistic only!)

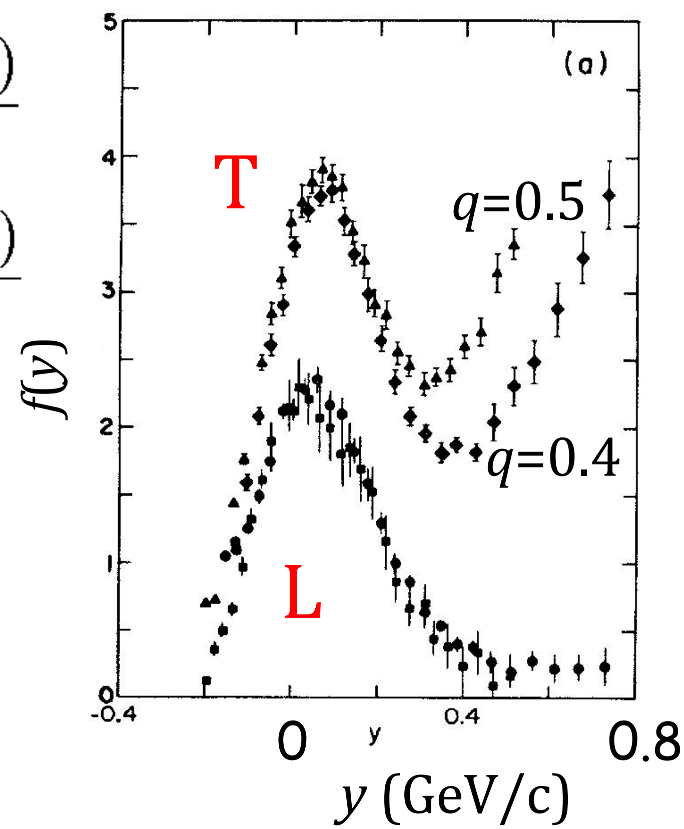
f = reduced response function

$$f_L(Q^2,\omega) \propto \frac{R_L(Q^2,\omega)}{\tilde{G}_E^2(Q^2)}$$

$$f_T(Q^2,\omega) \propto \frac{R_T(Q^2,\omega)}{\tilde{G}_M^2(Q^2)}$$

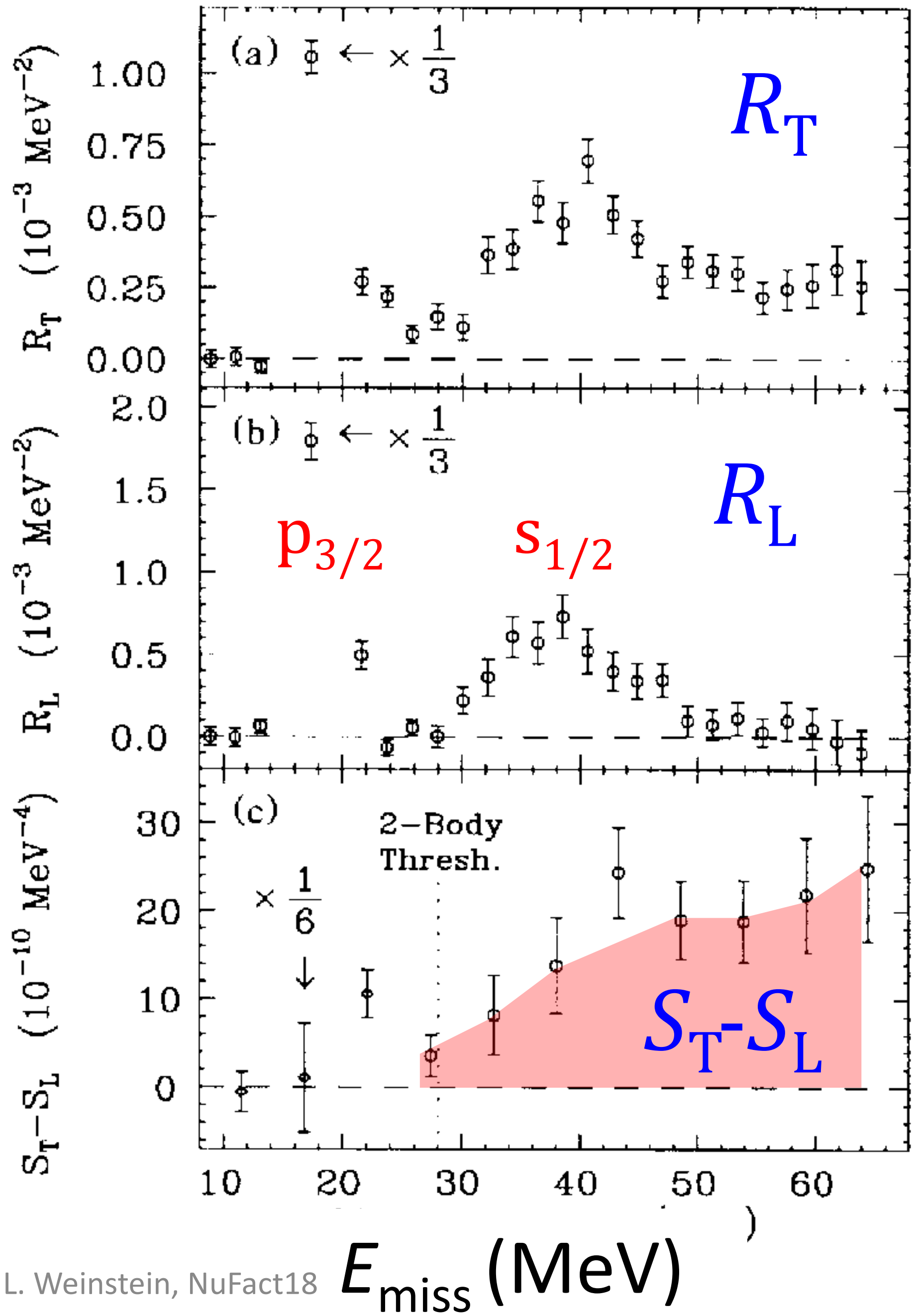


- L scales
- T scales
- T≠L!!



P. Barreau et al, NPA 402, 515 (1983)
Finn et al, PRC 29, 2230 (1984)

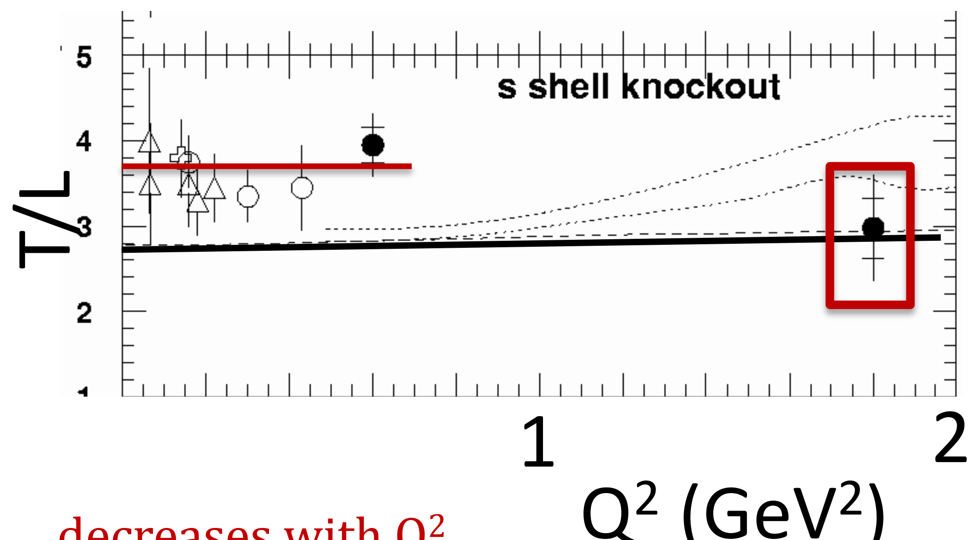
Extra Transverse even at the QE peak



$^{12}C(e,e'p)$

q=0.4 GeV and x=1

extra transverse strength starting at the 2N KO threshold



decreases with Q^2

Ulmer et al, PRL 59, 2259 (1987); Dutta et al, PRC 61, 061602 (2000)

The ideal electron experiment

- Identify contributing reaction mechanisms over a wide kinematic range
  - Full acceptance for all charged hadrons
  - High efficiency for neutrals
    - Neutrons
    - π^0
- Lots of targets
  - Neutrino detector materials: C, O, Ar, Fe
  - More nuclei to constrain models
- Enough beam energies to cover the full range of interesting momentum transfers

Why momentum transfer and not beam energy?

- The scattering cross section depends primarily on energy and momentum transfer
- For (e,e'p):
  - $\frac{d^6\sigma}{d\Omega_e d\Omega_p dE_p d\omega} = \sigma_{Mott}[v_L R_L + v_T R_T + v_{LT} R_{LT} cos\phi_{pq} + v_{TT} R_{TT} \cos 2\phi_{pq}]$
  - Kinematic factors v_i depend on $\{Q^2, \omega, \theta_e\}$
  - Response functions R_i depend on $\{Q^2, \omega, \theta_{pq}\}$
  - Only beam energy dependence comes from θ_e
- Need to account for boson propagator $\propto \frac{1}{Q^2+M^2}$
  - $\propto \frac{1}{M^2}$ for W exchange
  - $\propto \frac{1}{Q^2}$ for photon exchange (Mott Cross section)

How to use electron data for neutrino measurements

- Tune vector models in generators to data
  - Span a wide enough range in Q^2 and A to constrain models well
  - Constrain final state interaction (outgoing particle rescattering) models
- Tune remaining model elements to near detector data
- Guide event selection for "enhanced QE" samples, "Res" samples, etc

Standard Candle → Inclusive Analysis on ^{12}C