

Electrons for neutrinos

Lawrence Weinstein
Old Dominion University
Neutrino Cross Section Strategy
Workshop
FermiLab, March 2018

Collaboration

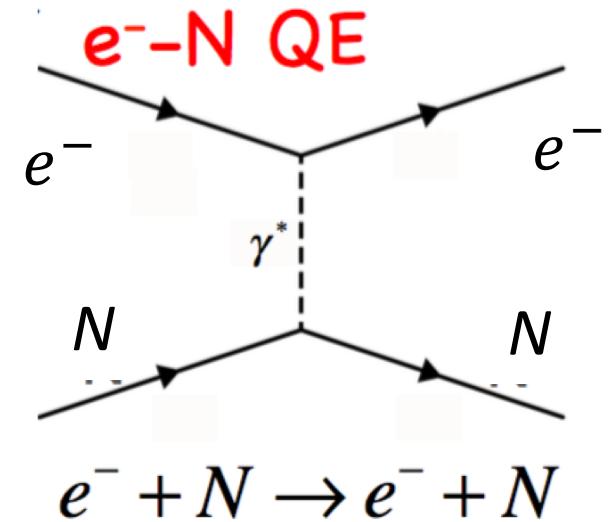
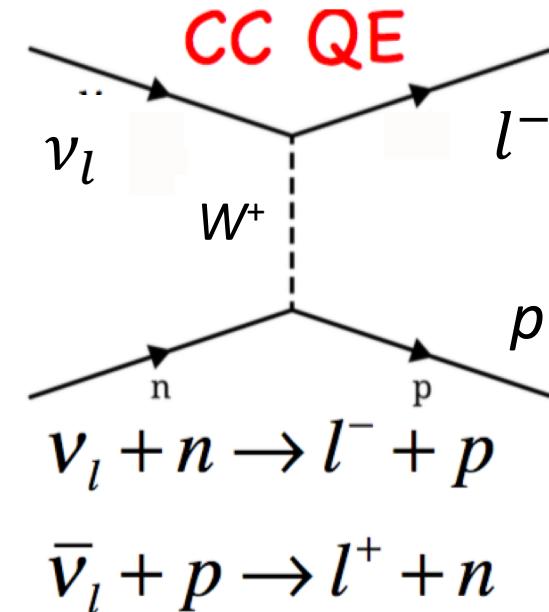
- Old Dominion University
 - Larry Weinstein
 - Florian Hauenstein (PD)
 - Mariana Khachatryan (grad)
- Michigan State
 - Kendall Mahn
 - Luke Pickering
- MIT
 - Or Hen
 - Adi Ashkenazi (PD)
 - Afroditi Papdolopou (grad)
- FermiLab
 - Minerba Betancourt (PD)
- Pitt
 - Steve Dytman
- Jefferson Lab
 - Stepan Stepanyan
- Tel Aviv U
 - Eli Piasetky

Outline

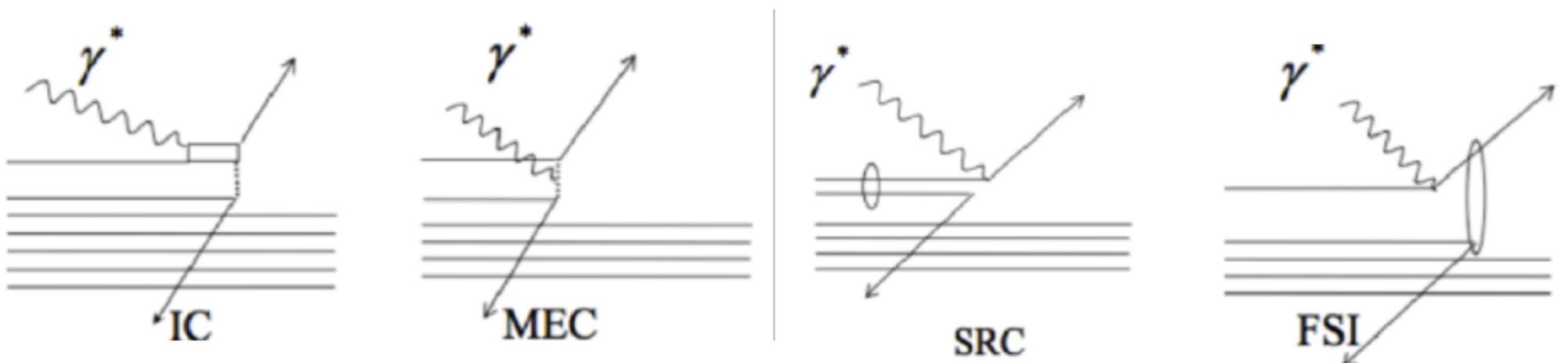
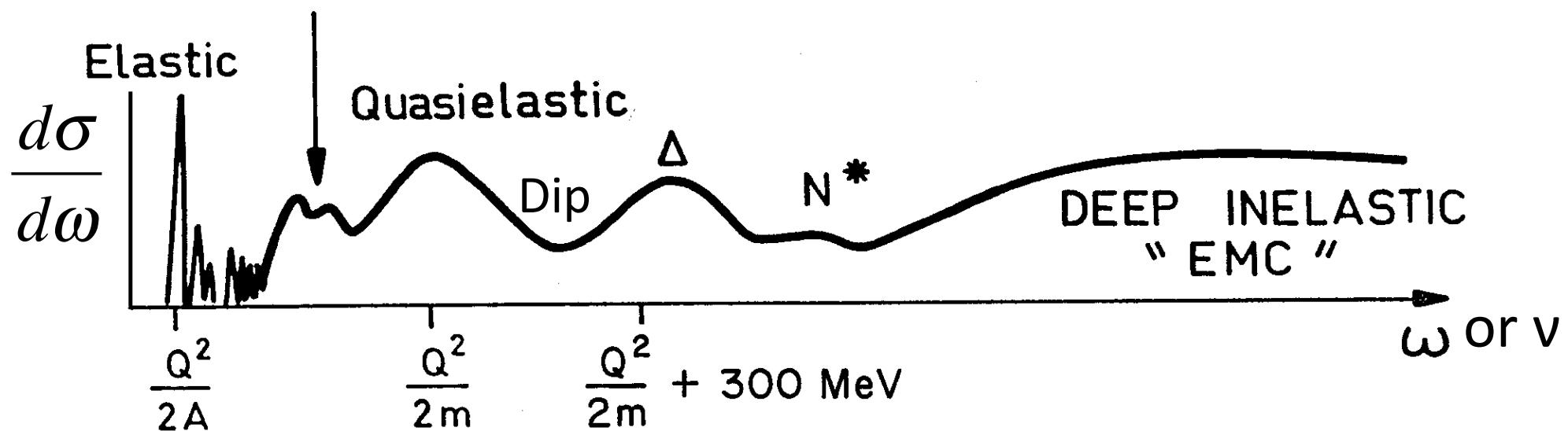
- Why electrons?
 - Nuclear Physics
- The “ideal” electron experiment
- How to use electron data to reduce neutrino uncertainties
- Current results
- Future plans

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
- $Q^2 = \vec{q}^2 - \omega^2$
- Energy transfer: ω or ν



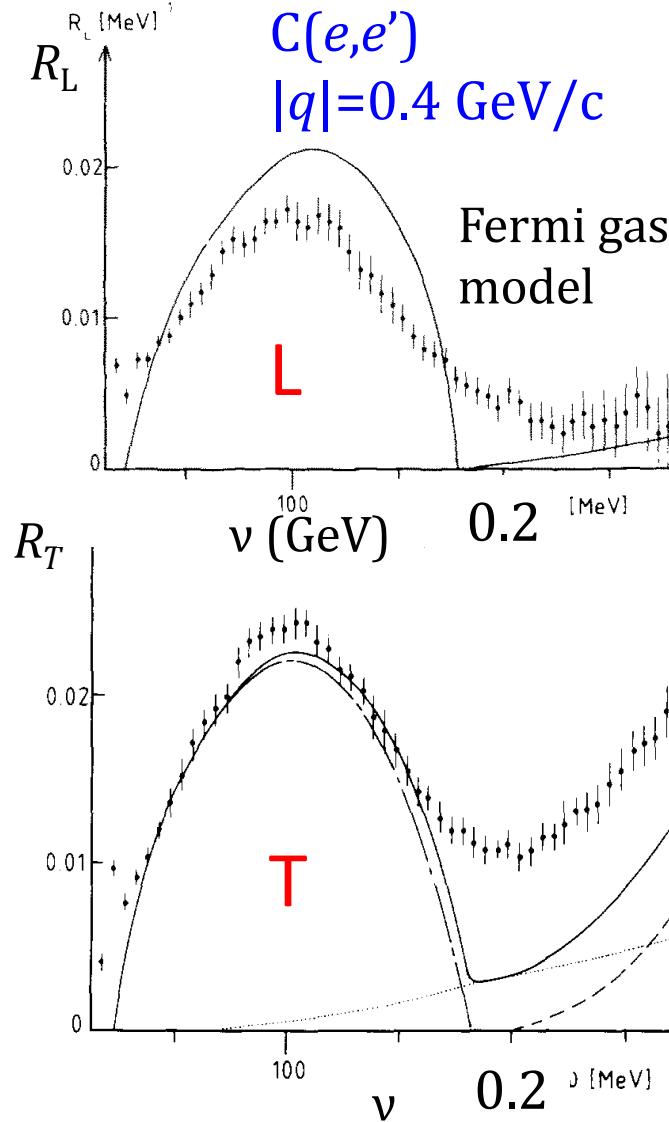
Nuclear Physics



Two body reaction mechanisms

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

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

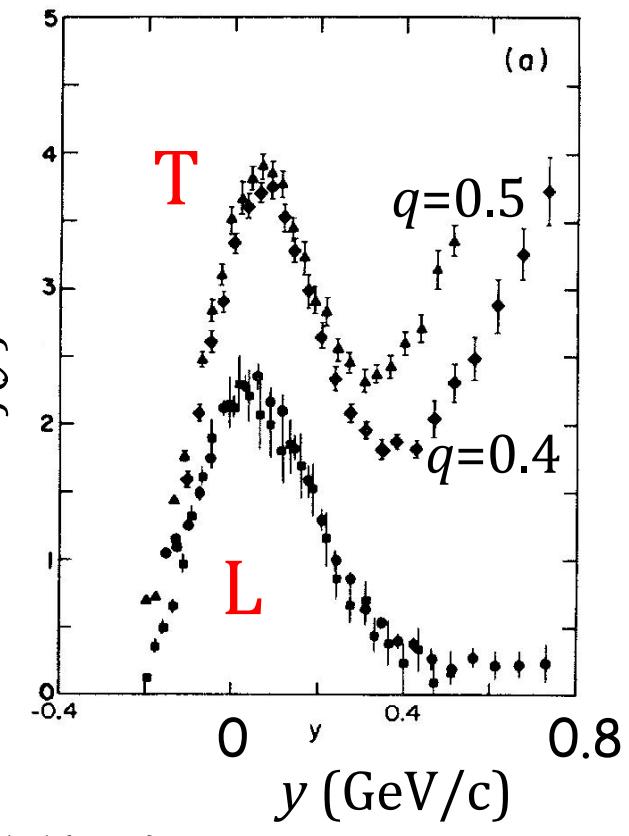


y = minimum initial nucleon momentum
 $= mv/q - q/2$ (nonrelativistic only!)
 f = reduced response function

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

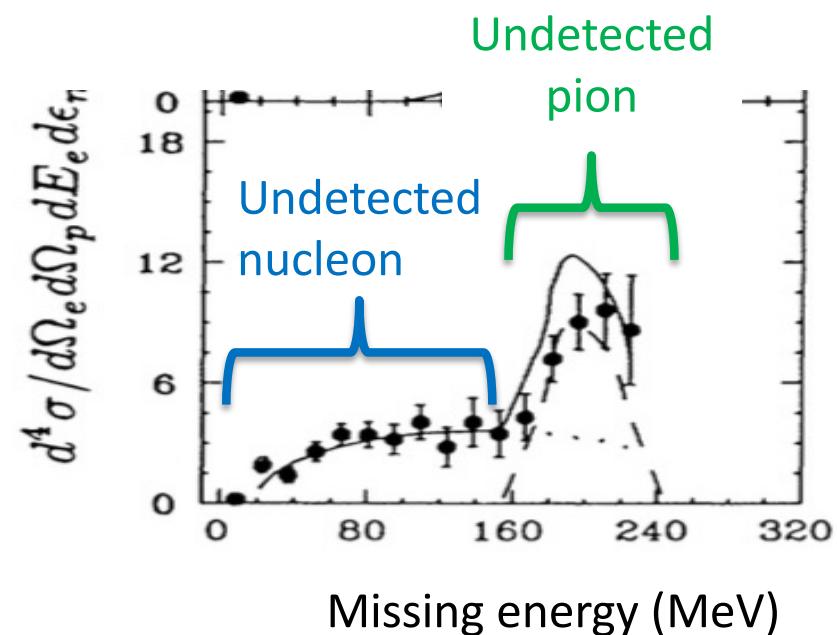
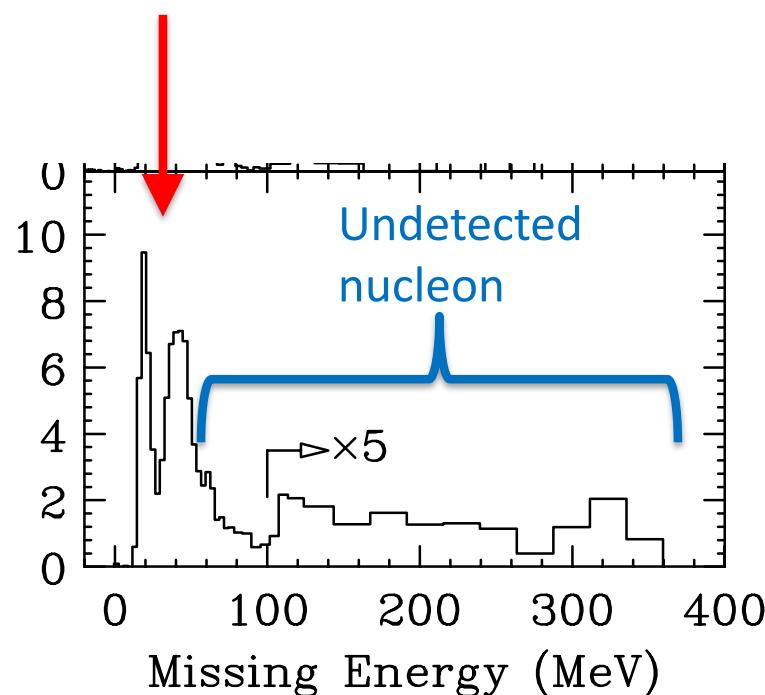
$$f_T(Q^2, \omega) \propto \frac{R_T(Q^2, \omega)}{\tilde{G}_M^2(Q^2)}$$

- L scales
- T scales
- $T \neq L!!$

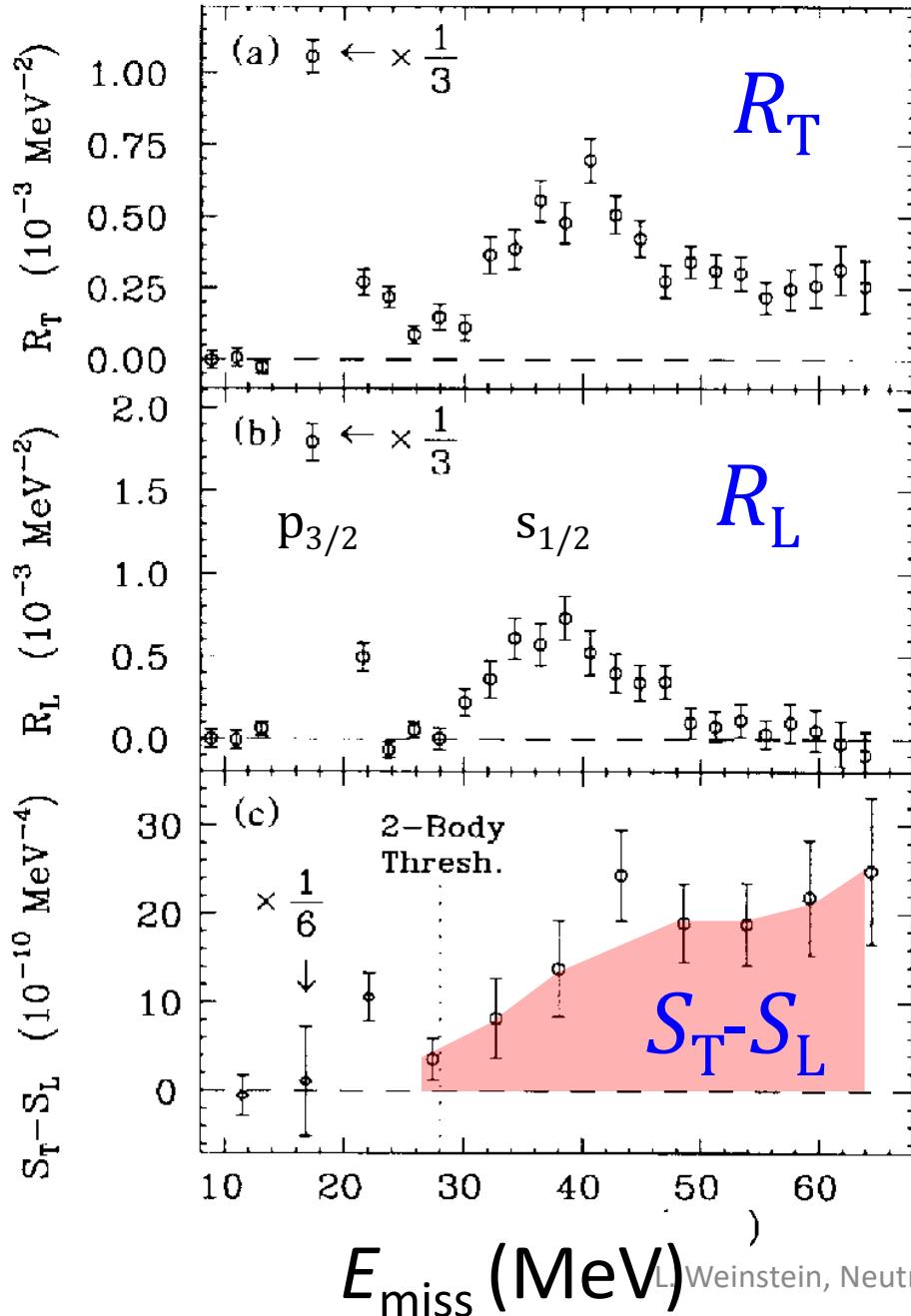


How to read an (e,e'p) spectrum

Single
nucleon
knockout

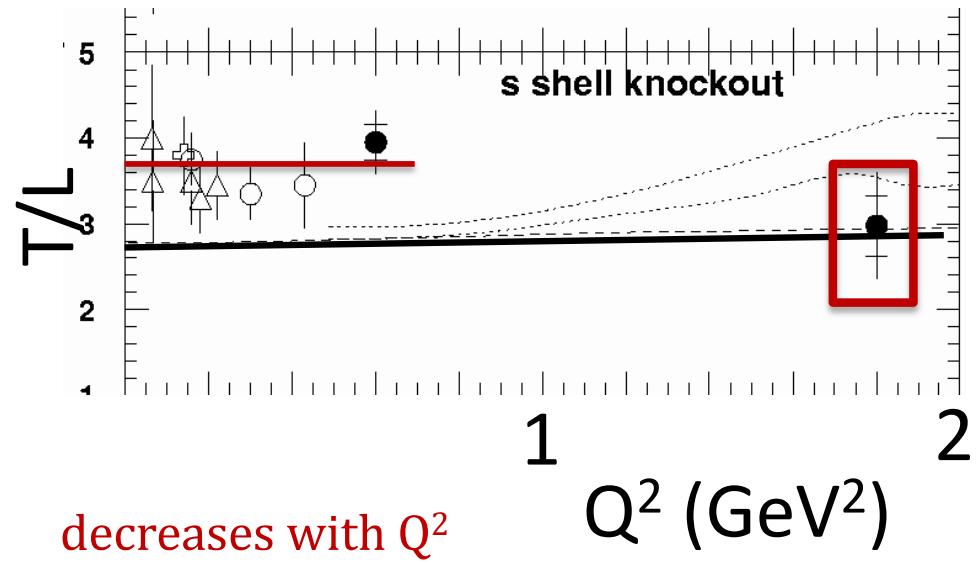


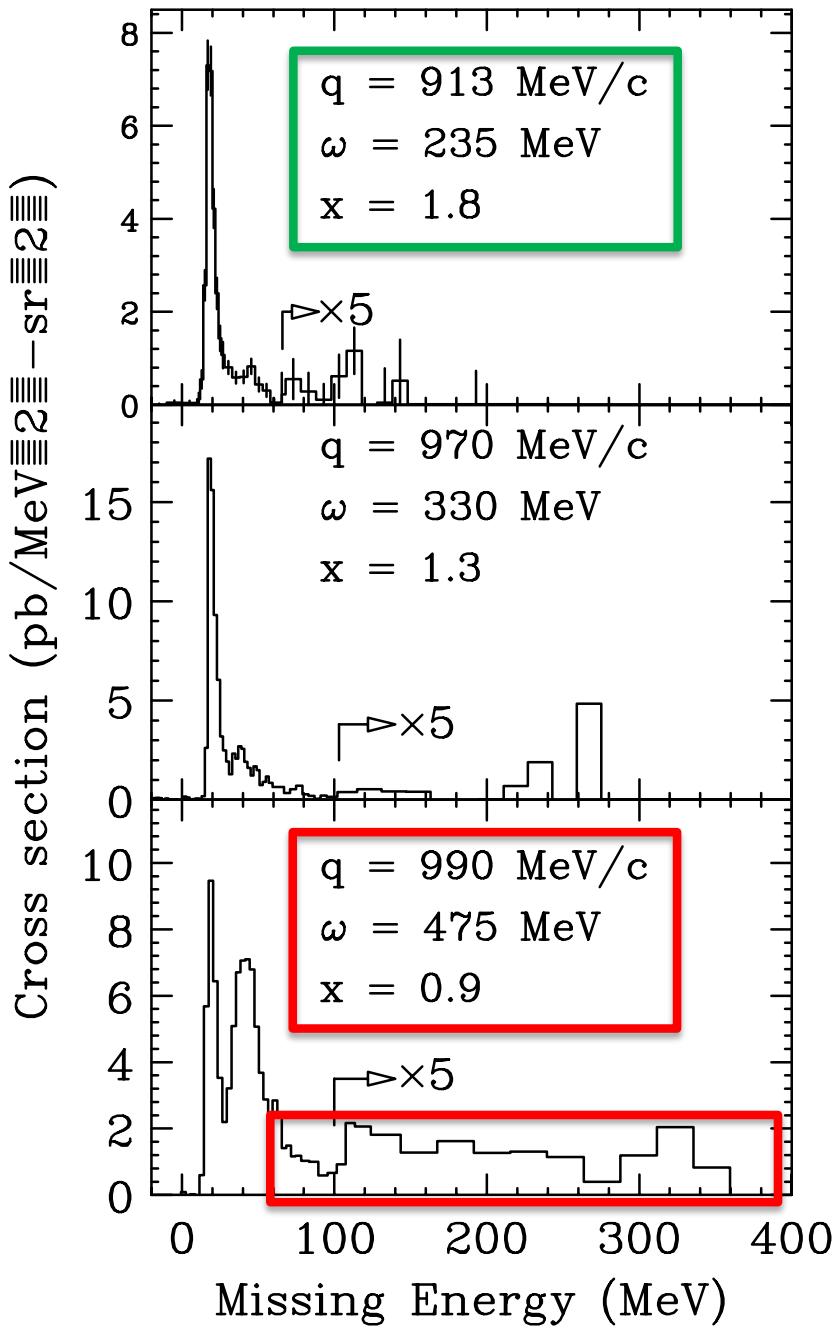
Extra Transverse even at the QE peak



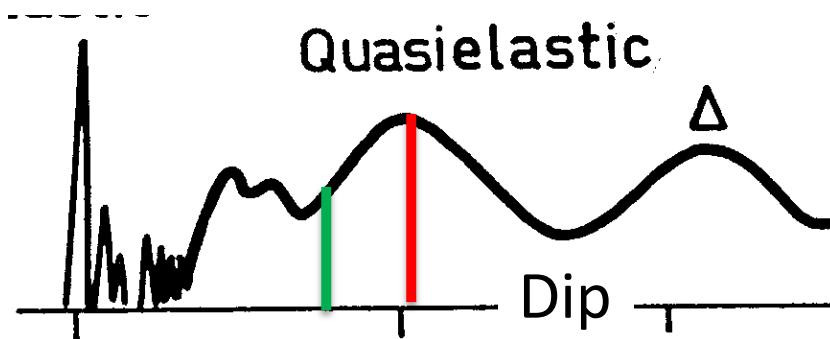
$^{12}\text{C}(e,e'p)$
 $q=0.4 \text{ GeV}$ and $x=1$

extra transverse strength starting at the
2N KO threshold





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

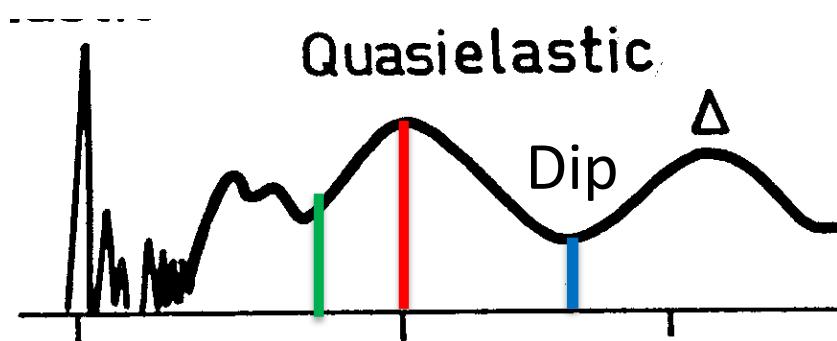
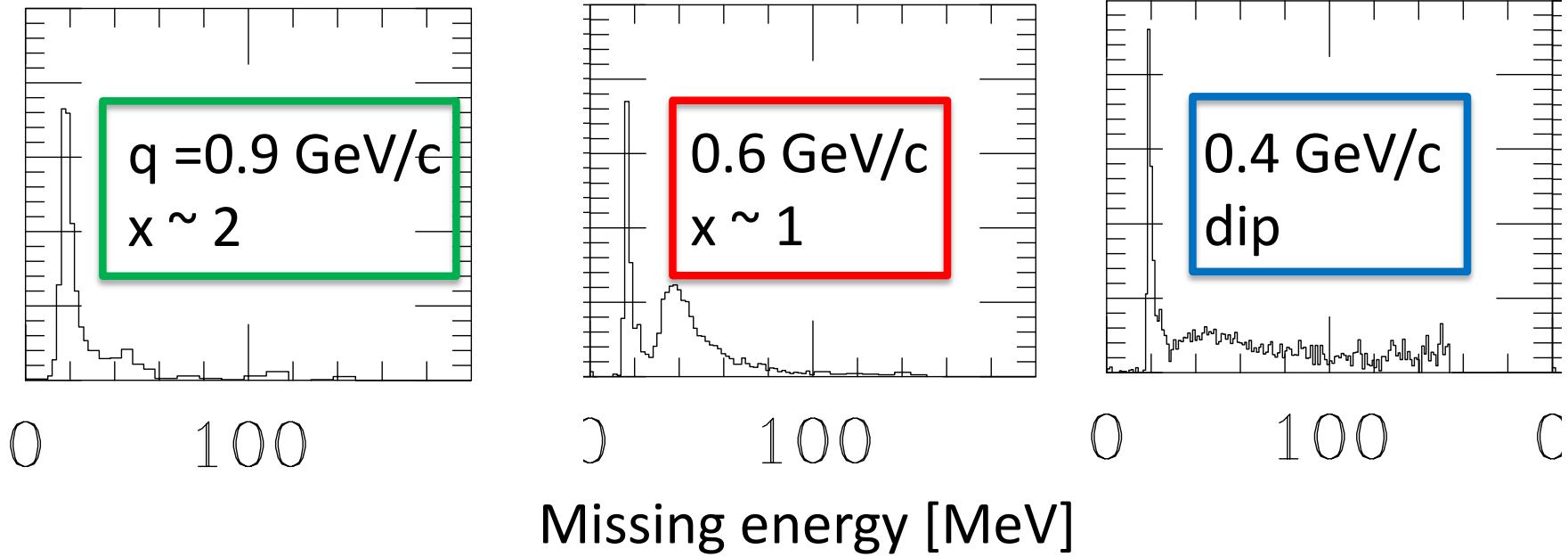


Non-QE reactions
increase with ω

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

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

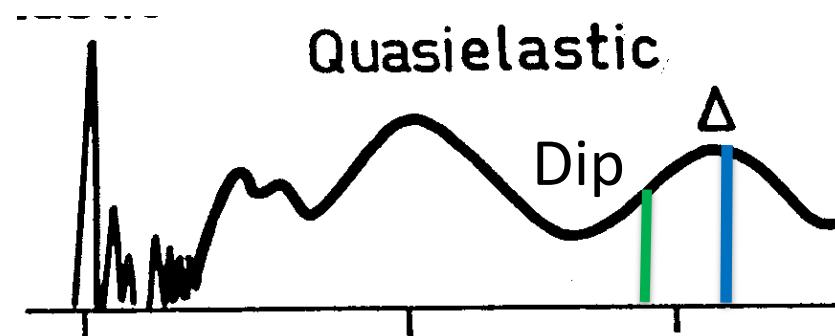
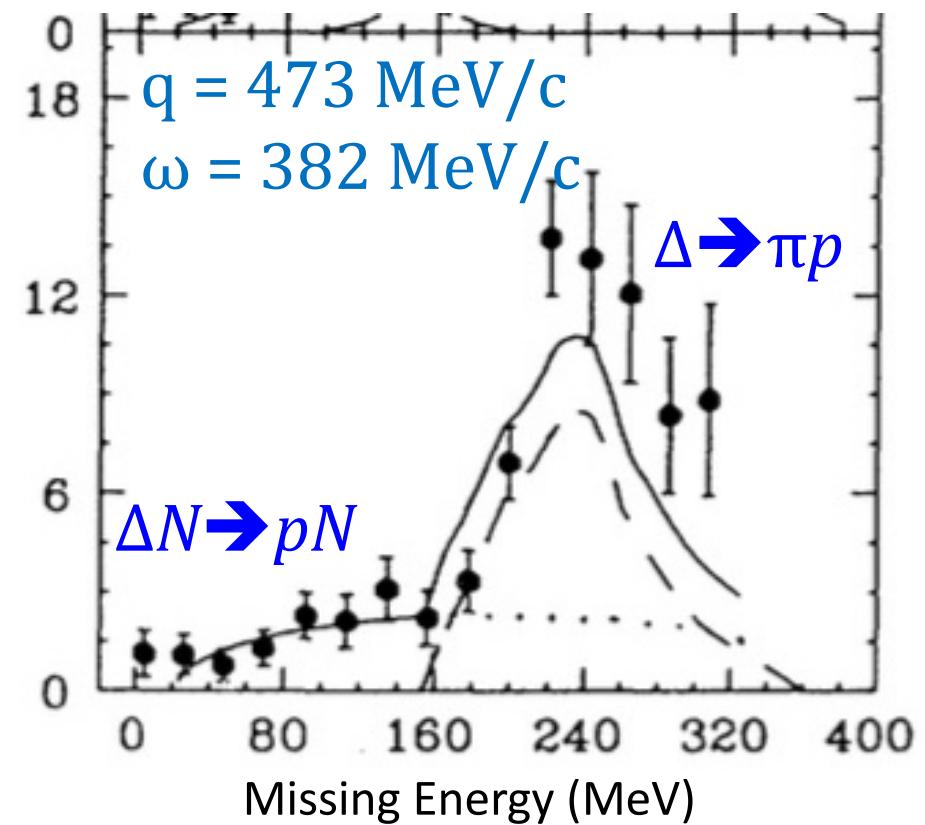
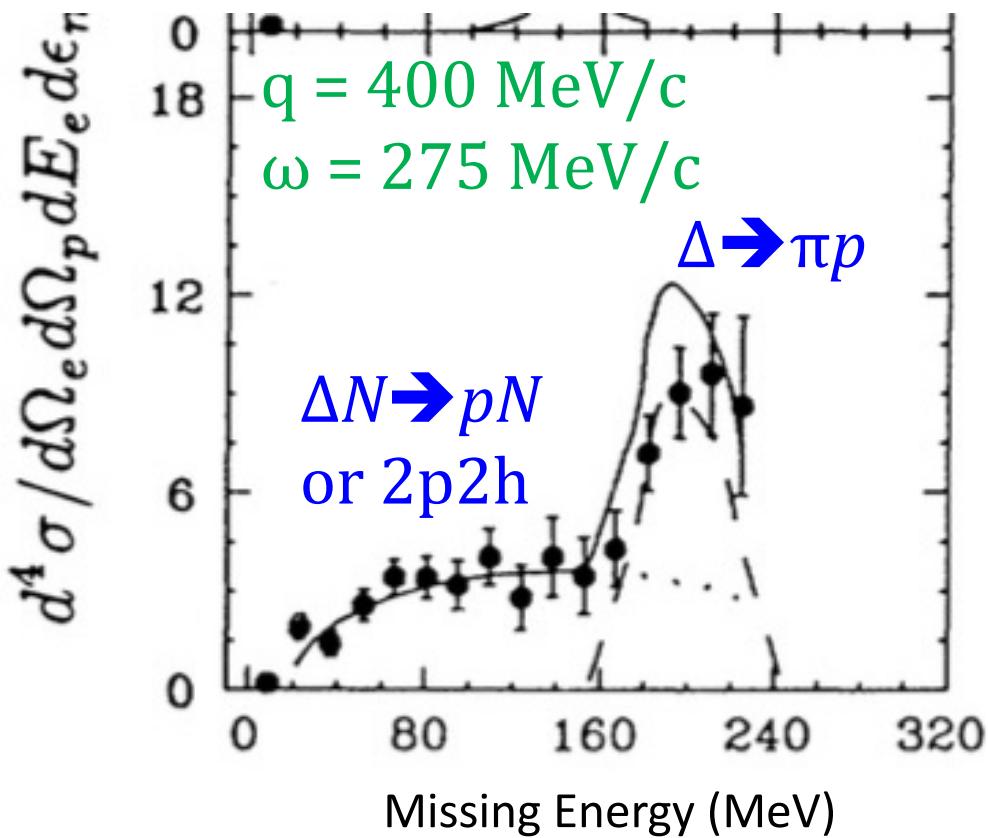
Fixed $\omega = 0.2$ GeV, vary q



From **QE** to **dip**:
S-shell decreases
Non-QE strength increases

R. Lourie, PRL 56, 2364 (1986)
L. Weinstein, PRL 64, 1646 (1990)
L. Weinstein, Neutrino Cross Sections 2018
S. Penn, unpublished

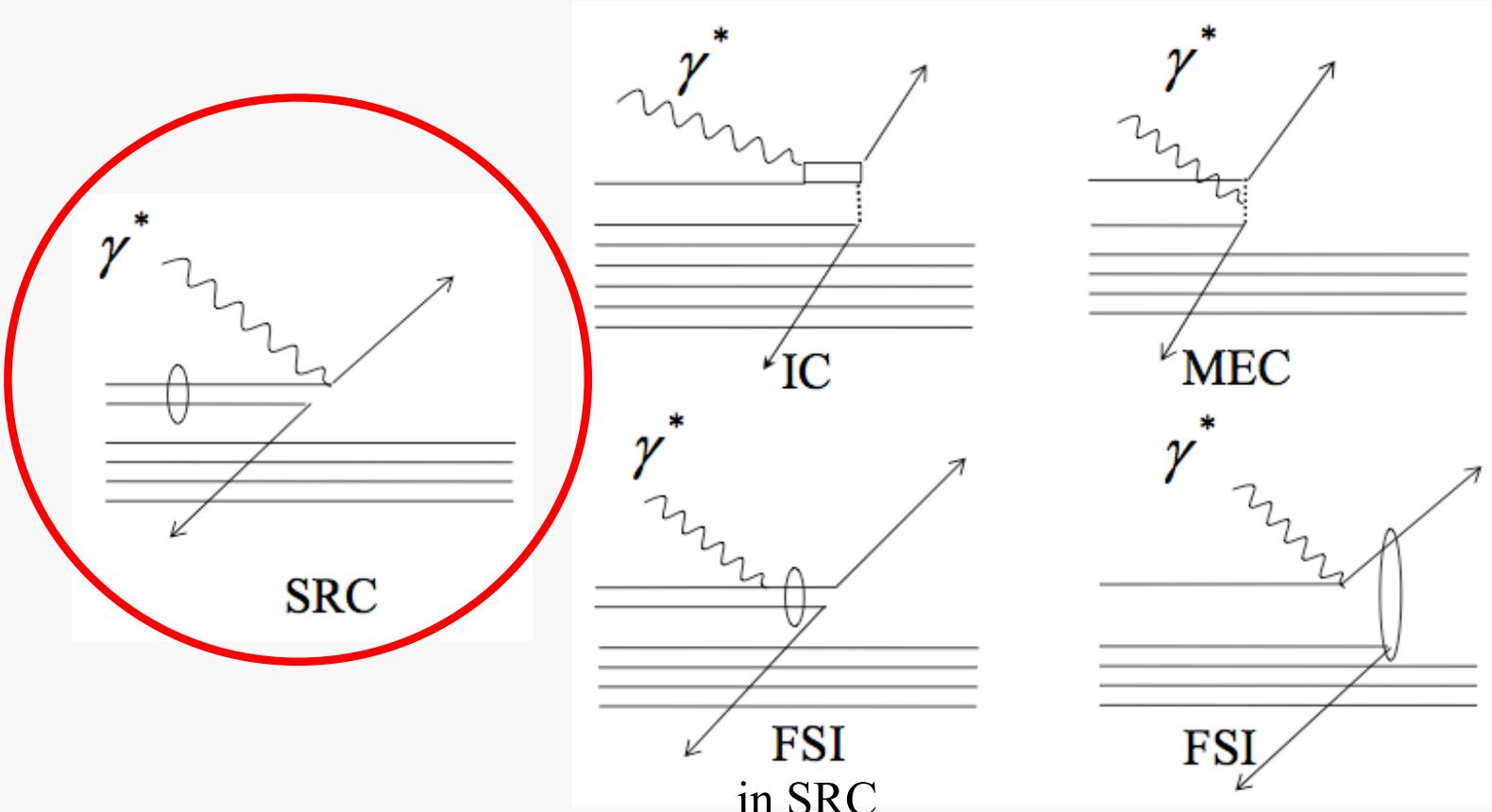
$^{12}\text{C}(\text{e},\text{e}'\text{p})$ Delta Region



What are correlations?

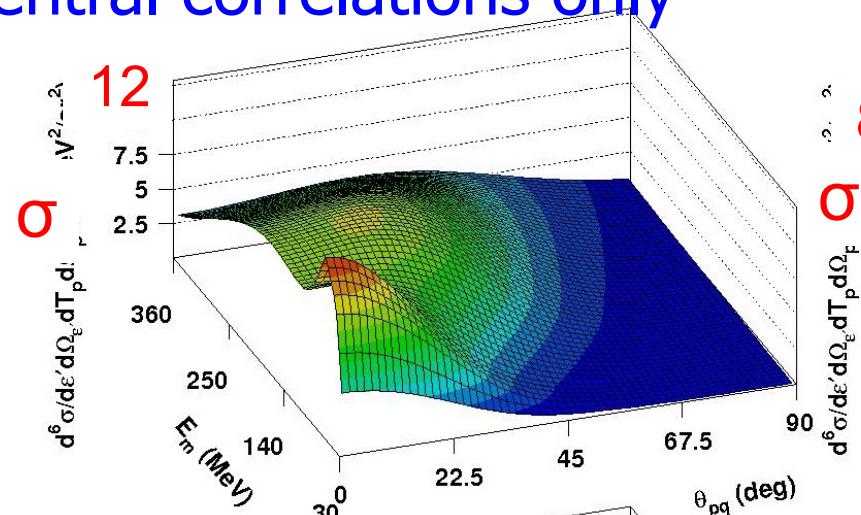
Average Two-Nucleon Properties in the Nuclear Ground State

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

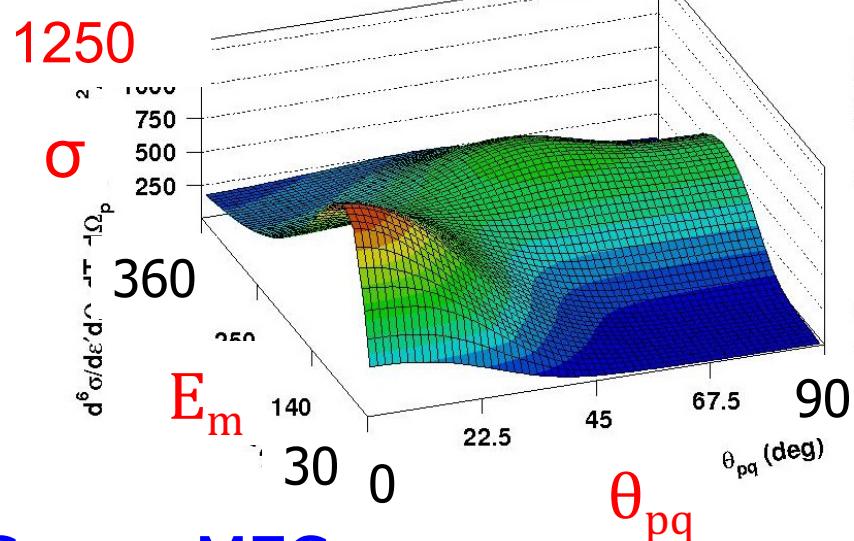
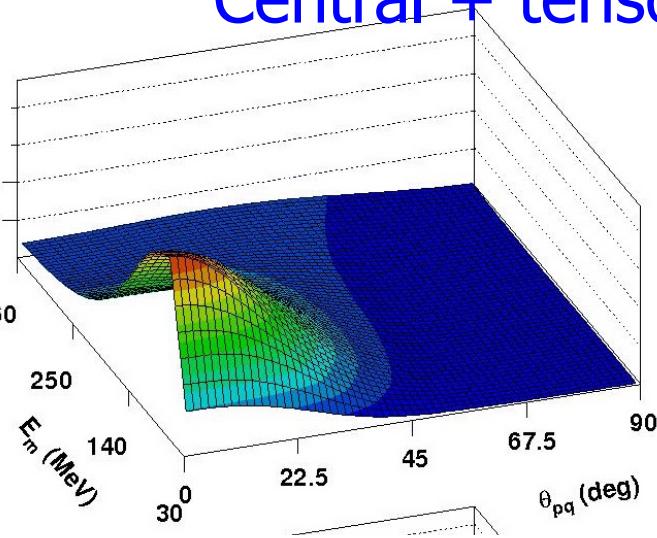


2N currents enhance correlations

Central correlations only



Central + tensor corr



Corr + MEC

MEC changes the magnitude
of the cross section,
not the distribution in E_{miss} vs
 Θ_{pq}

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

Physics Summary

- Electron scattering:
 - Intense monochromatic beams
 - Can choose kinematics to minimize “uninteresting”(i.e., complicated) reaction mechanisms
 - Calculate cross sections after the fact
- Neutrino interactions
 - Continuous mixed beams
 - Must include all reaction mechanisms
 - Need good models in event generators
 - Correct initial state
 - MEC, IC
 - FSI (not discussed here)

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):
 - $\frac{d^6\sigma}{d\Omega_e d\Omega_p dE_p d\omega} = \sigma_{Mott} [\nu_L R_L + \nu_T R_T + \nu_{LT} R_{LT} \cos\phi_{pq} + \nu_{TT} R_{TT} \cos 2\phi_{pq}]$
 - Kinematic factors ν_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)

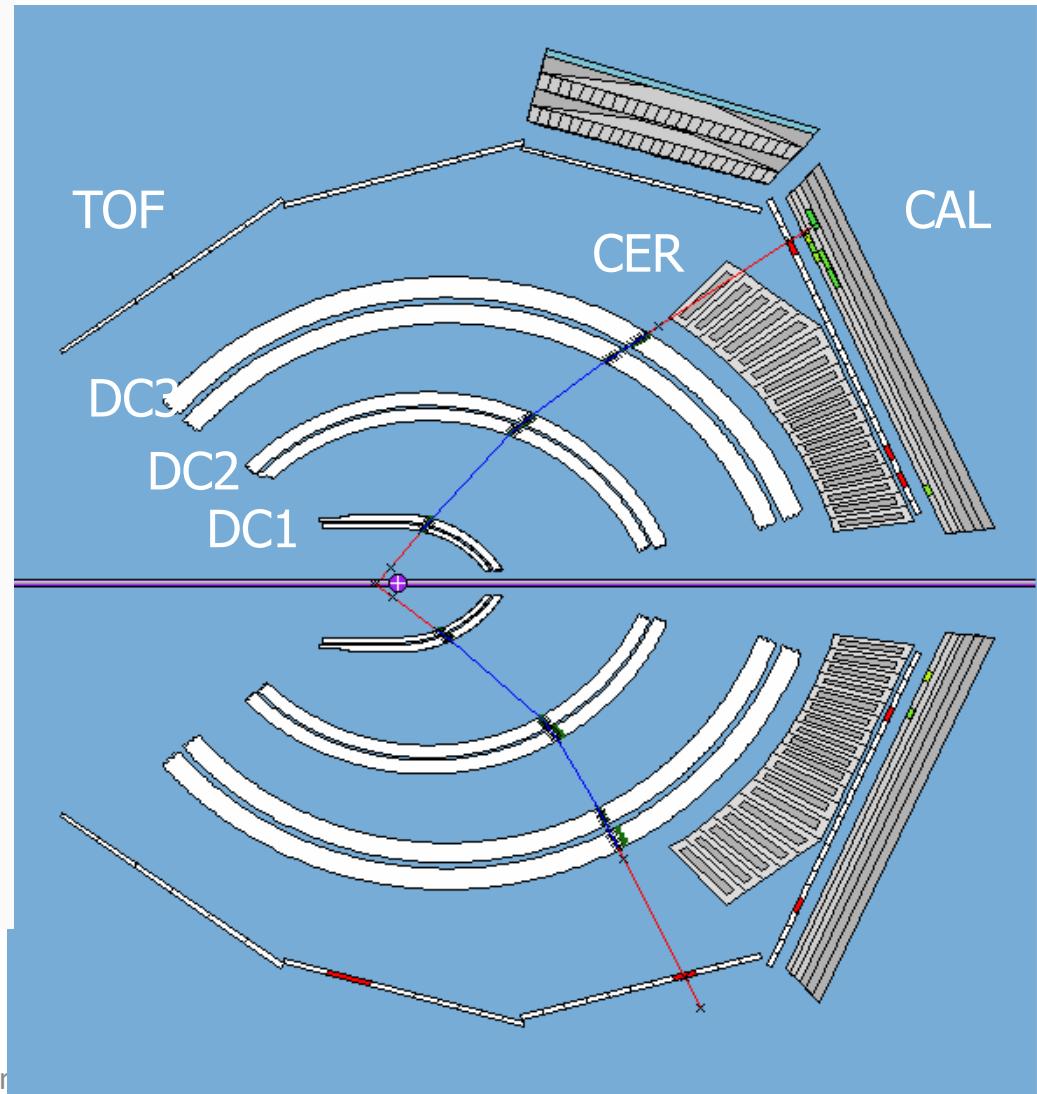
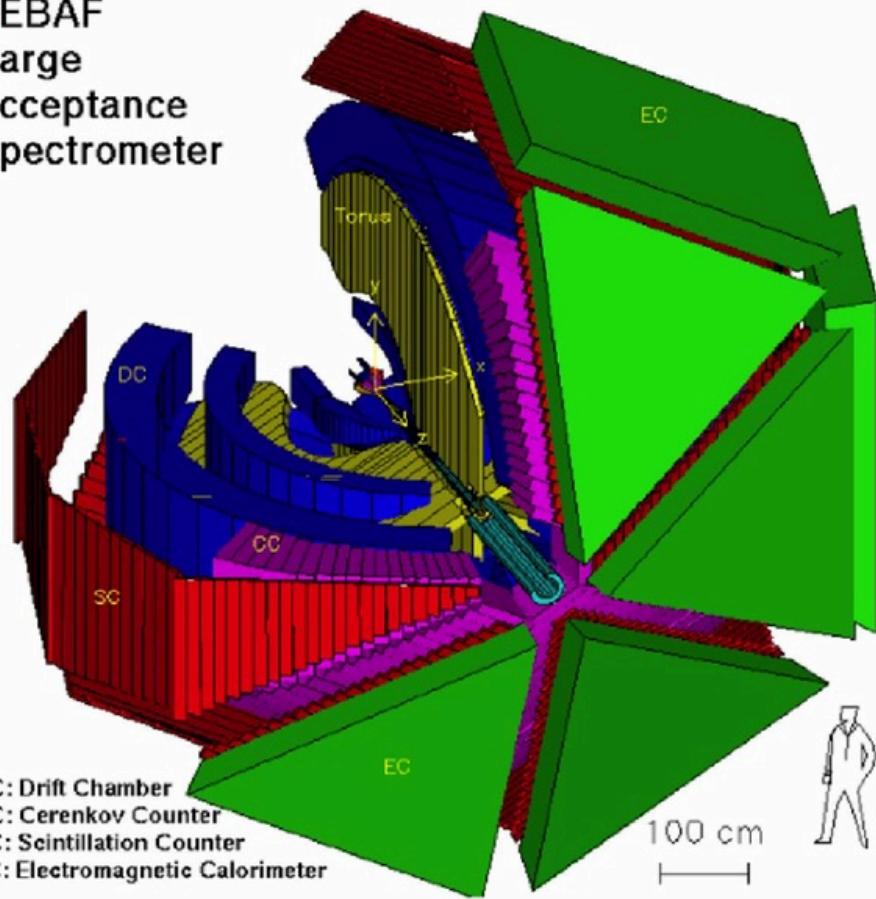
How to use electron data for neutrino measurements

- Tune vector models in generators to data, especially the Q^2 and A dependence
 - 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

A real electron experiment

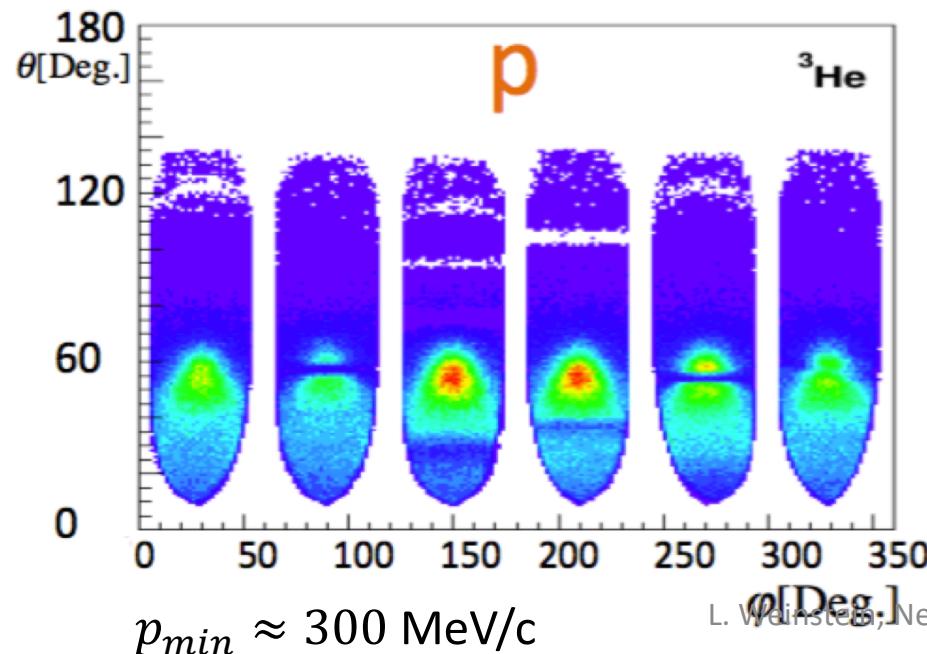
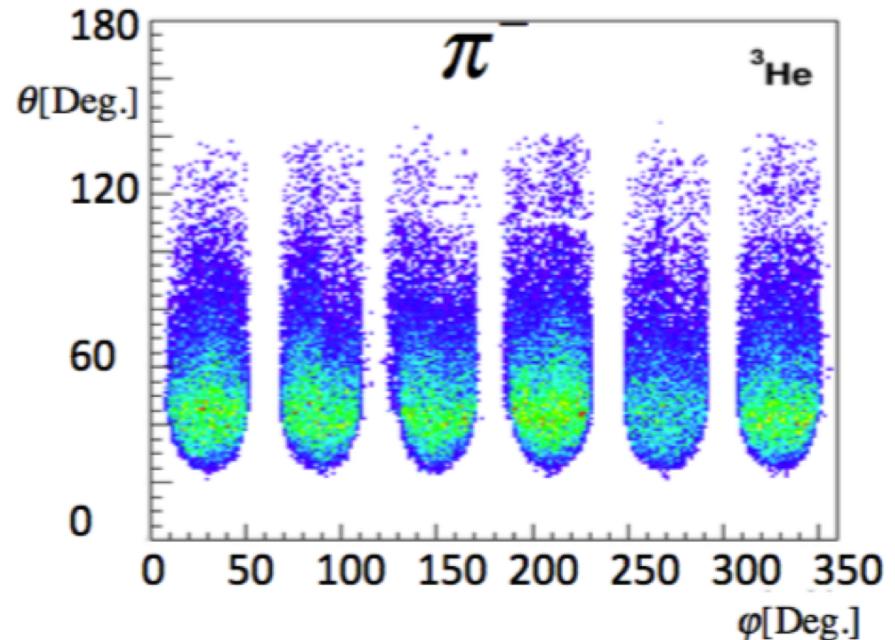
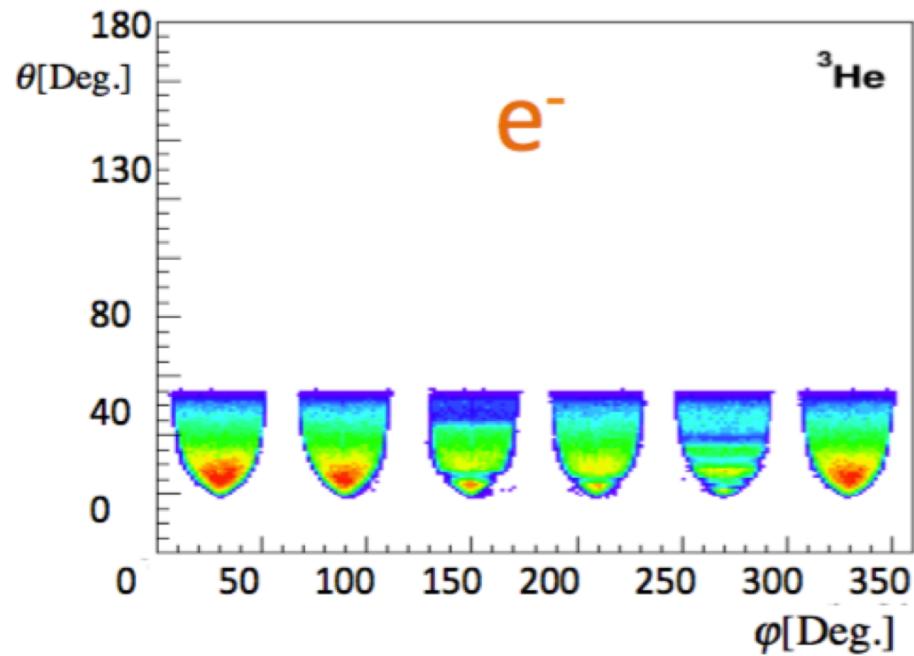
CLAS6: 1996-2015

CEBAF
Large
Acceptance
Spectrometer

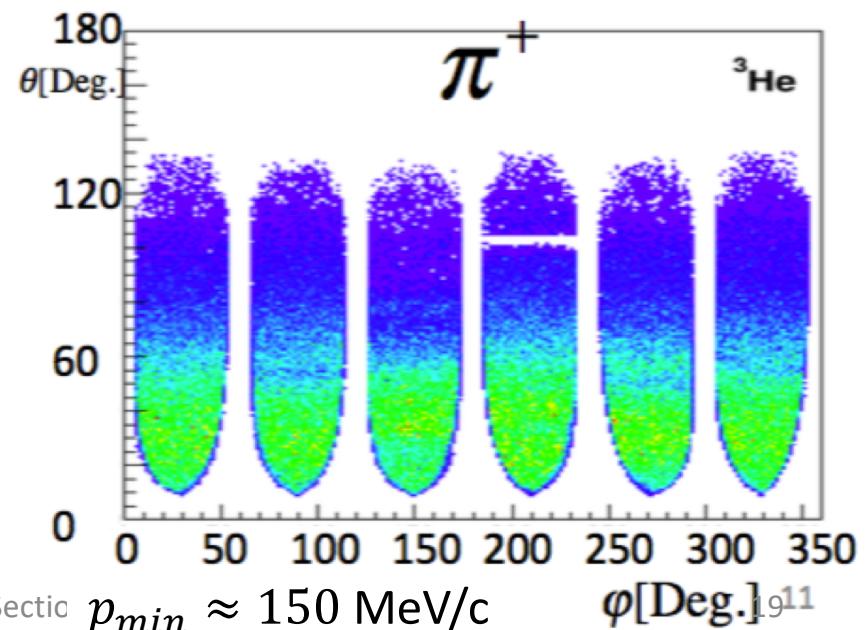


L. Weinstein, Neutrino

CLAS6 coverage



L. Weinstein, Neutrino Cross Sectio



¹⁹¹¹

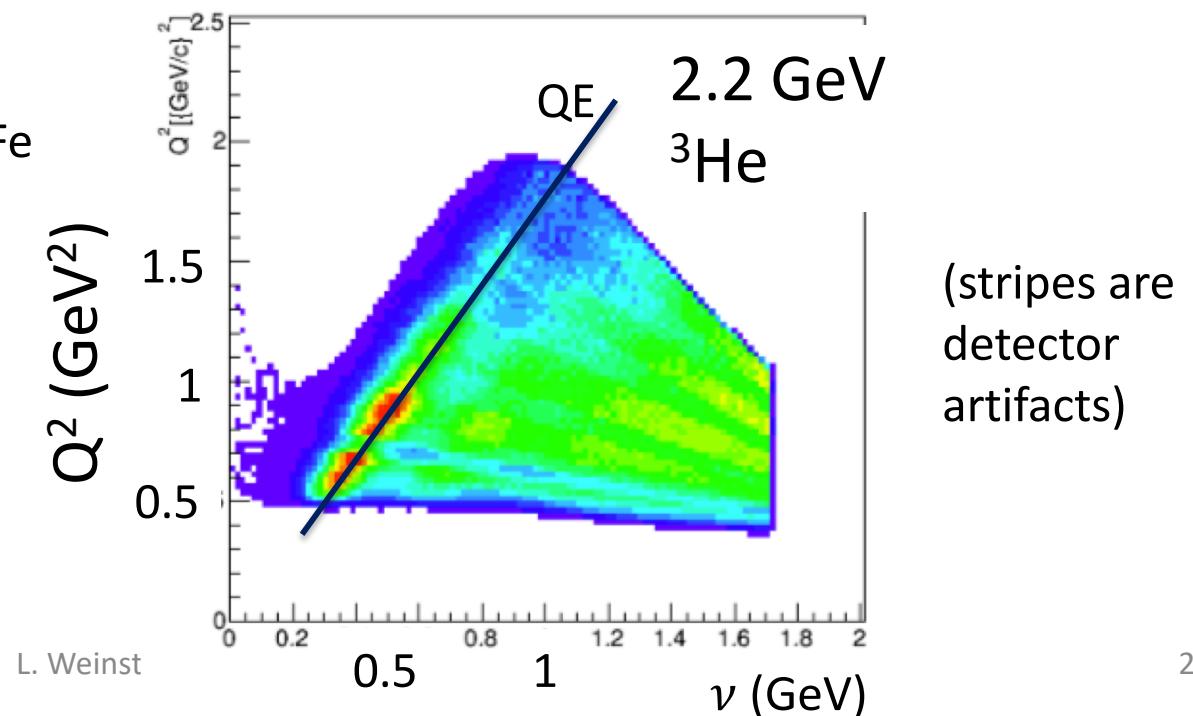
CLAS6 Data (million events)

	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	29	12	4	1
4He	Not done	46	17	8	3
12C	Not done	19	11	5	2
56Fe	Not done	1	1	0.4	0.1

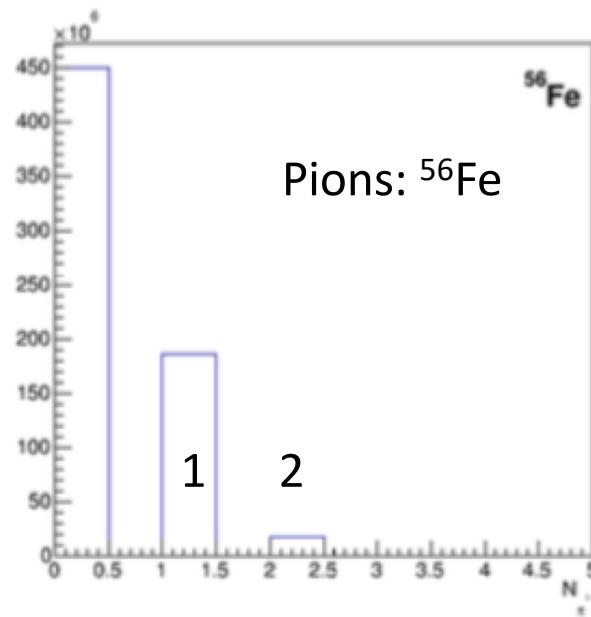
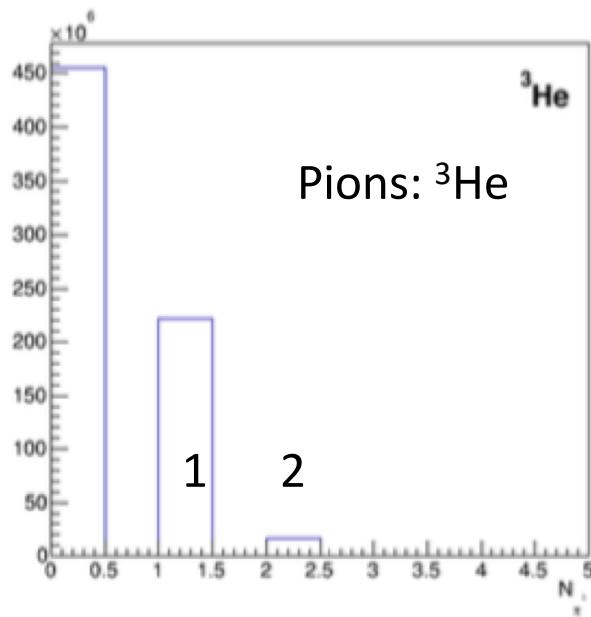
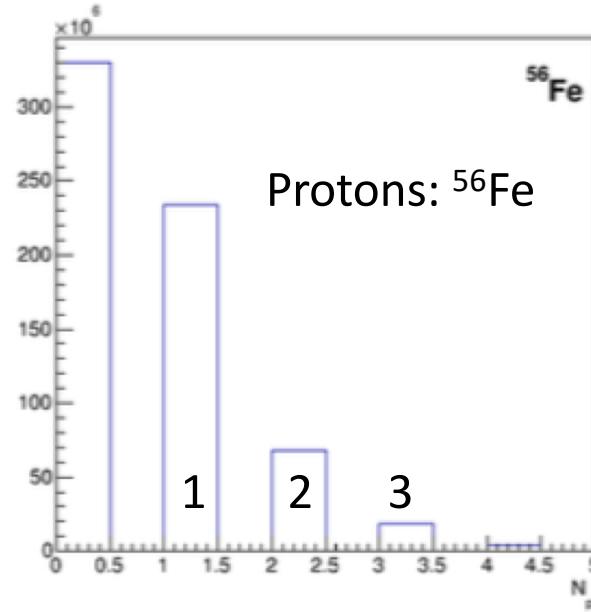
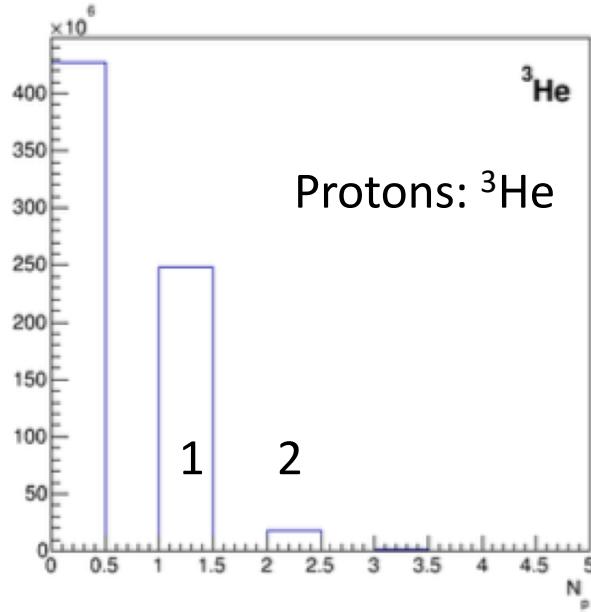
E2a data only.

E2b has more 4.6 GeV 3He and 56Fe

Eg2 has 5 GeV d, C, Al, Fe, and Pb

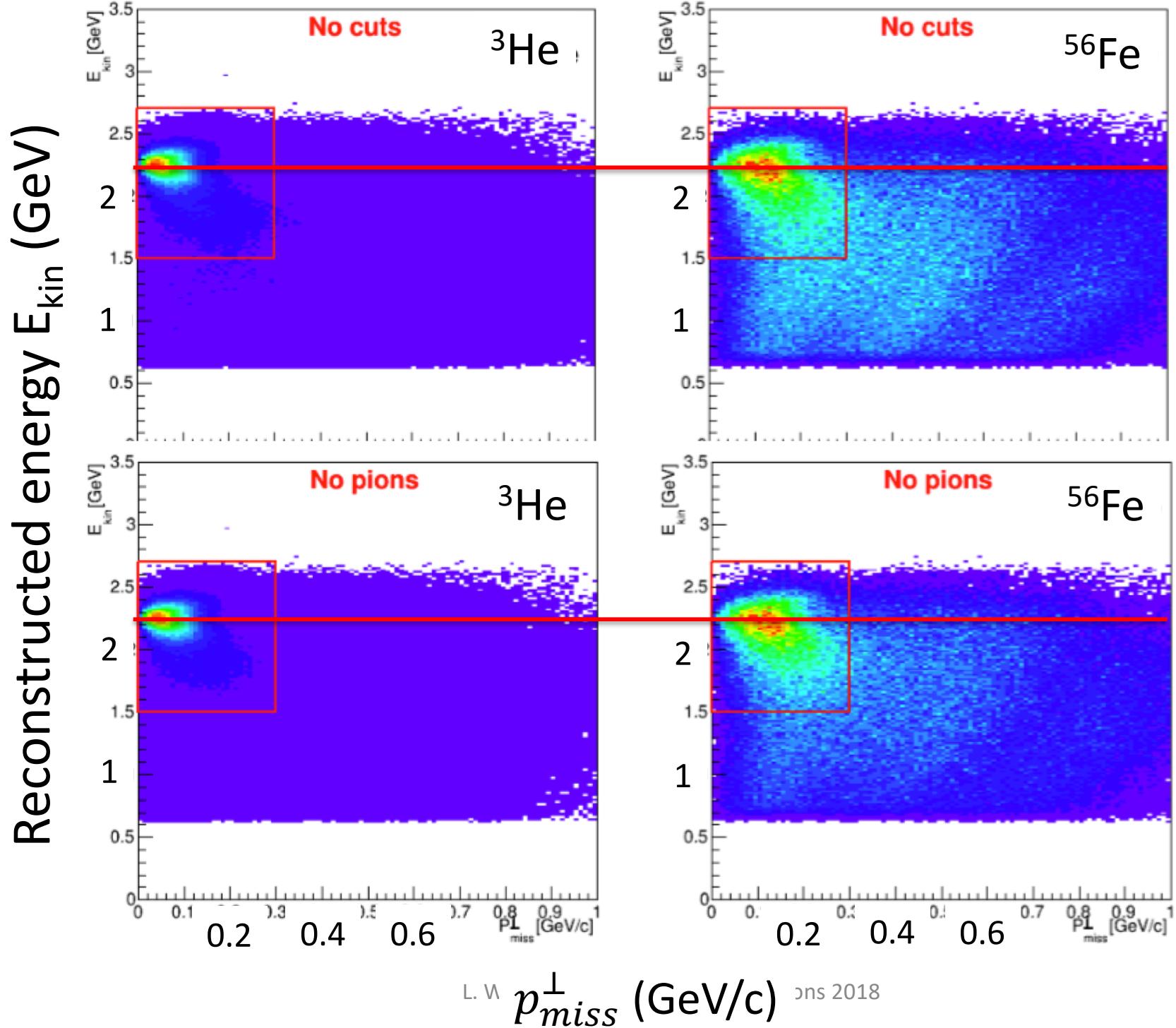


4 GeV charged particle multiplicity



Reconstructing the initial energy

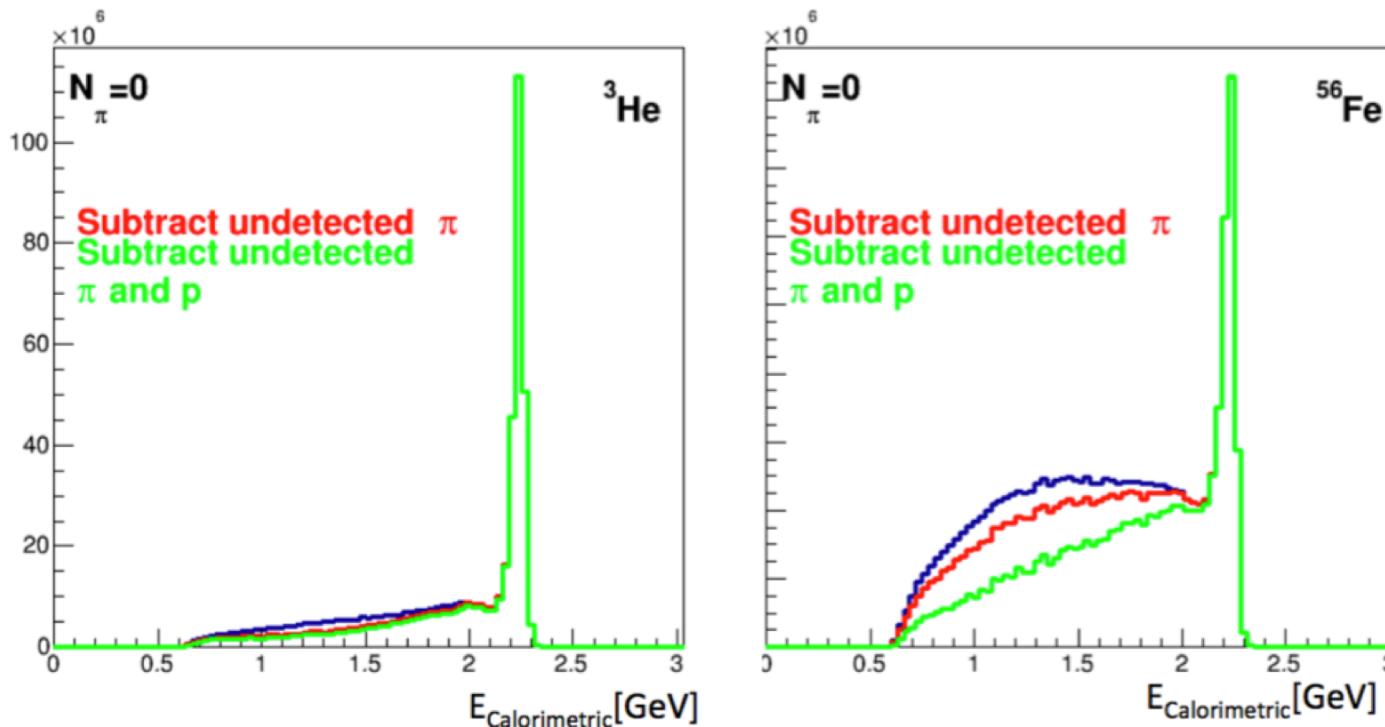
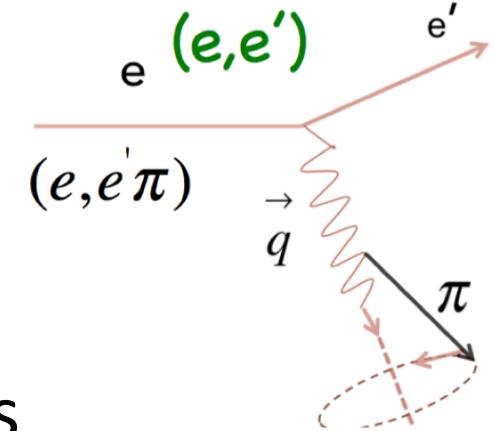
- Select an enhanced QE sample using
 - Zero pion events
 - $p_{miss}^\perp = p_p^\perp + p_l^\perp$ cuts for (e,e'p) and (e,e'X) events
- Reconstruct the incident lepton energy:
 - $E_{kin} = \frac{2M_N\epsilon + 2M_NE_l - m_l^2}{2(M_N - E_l + k_l \cos\theta_l)}$
 - ϵ single nucleon separation energy
 - 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)]



2.2 GeV
(e,e'p)
events

Form “pure” $0\pi 1p$ ($e, e' p$) spectrum: Subtract undetected pi and proton

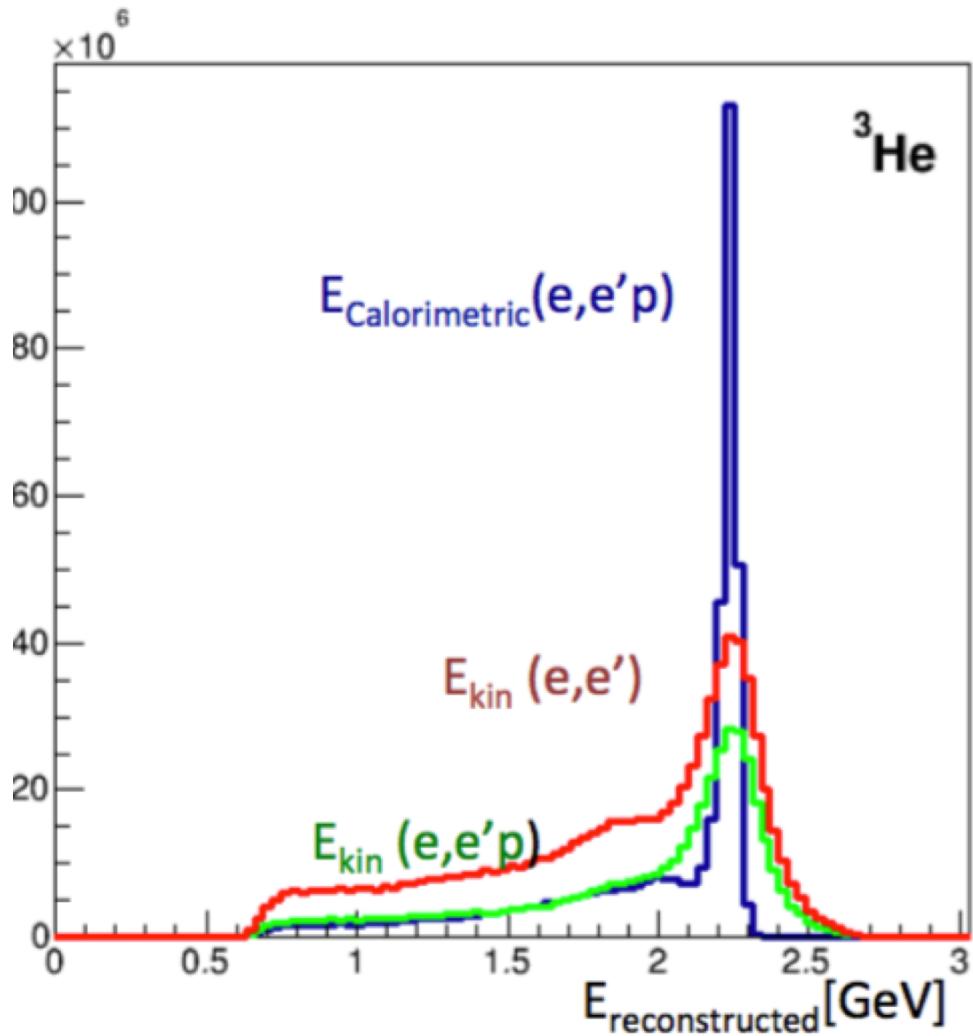
- For ($e, e' p$ pi) events:
 - Rotate pions around q
 - Determine pion acceptance for that event
 - Subtract undetected pions
- Repeat for undetected two proton events



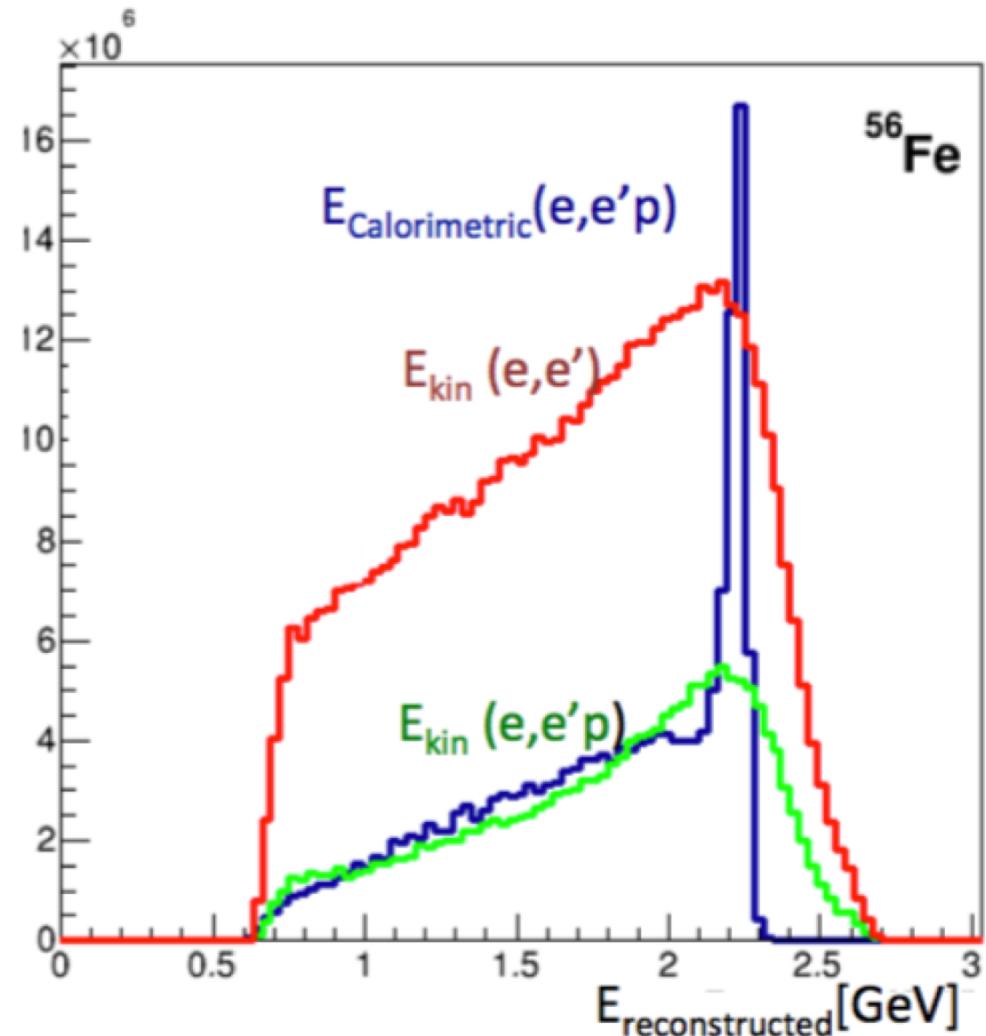
$$E_{\text{cal}} = E_l + T_p$$

(all events weighted
by $1/\sigma_{Mott}$ to
account for the
different
propagators)

Compare E_{kin} and E_{cal}



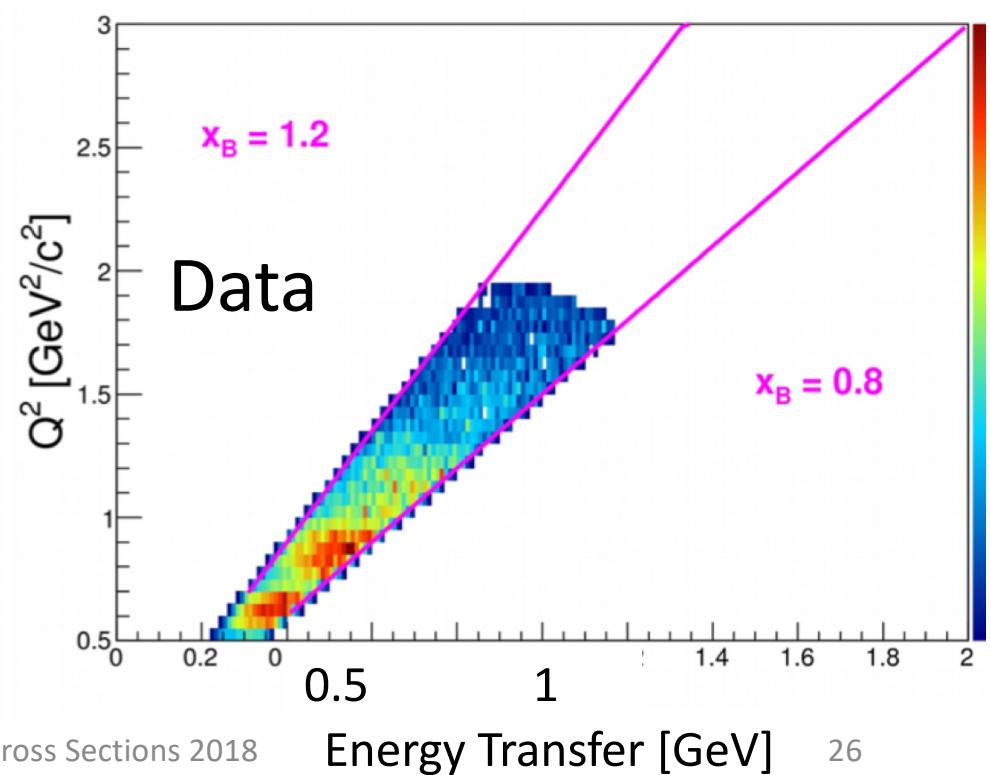
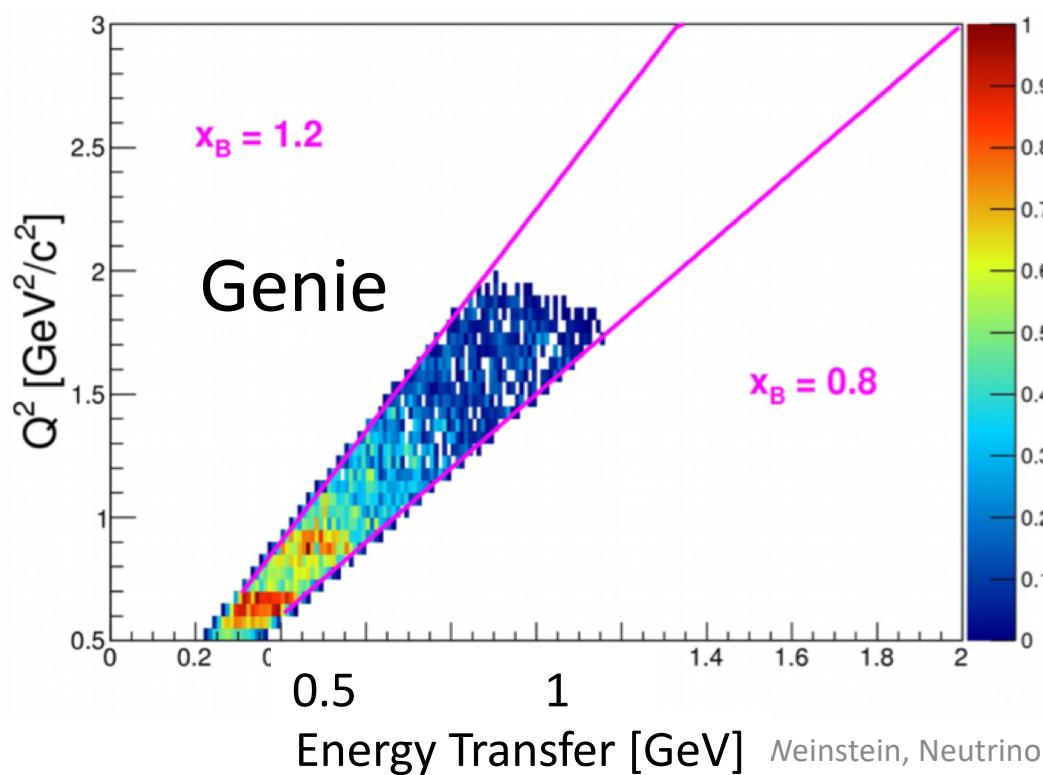
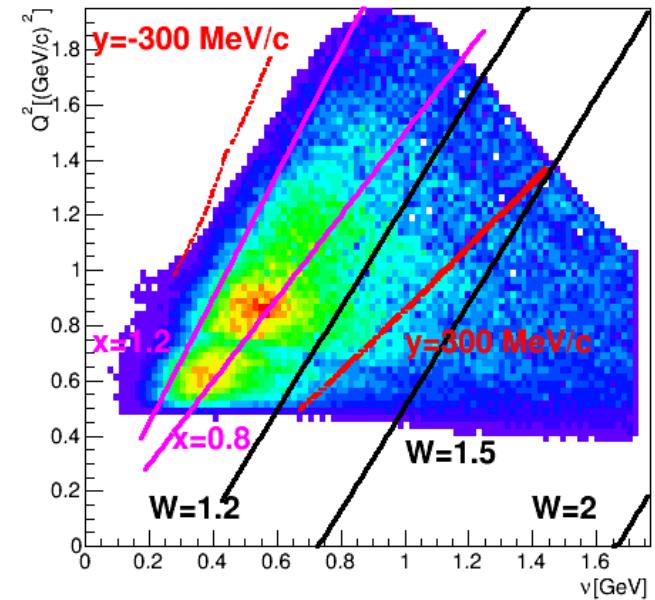
${}^3\text{He}$: low density, primarily 1-body

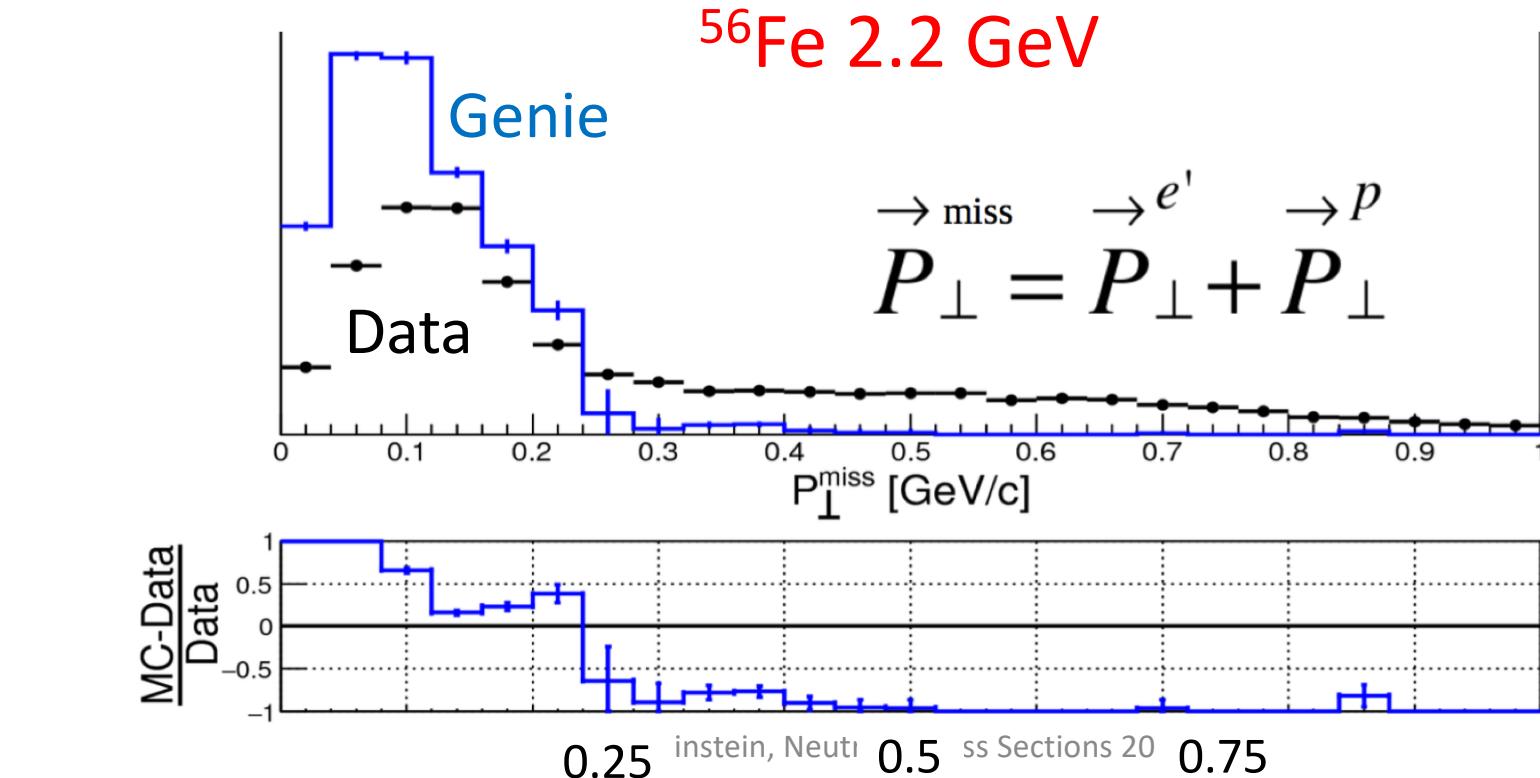
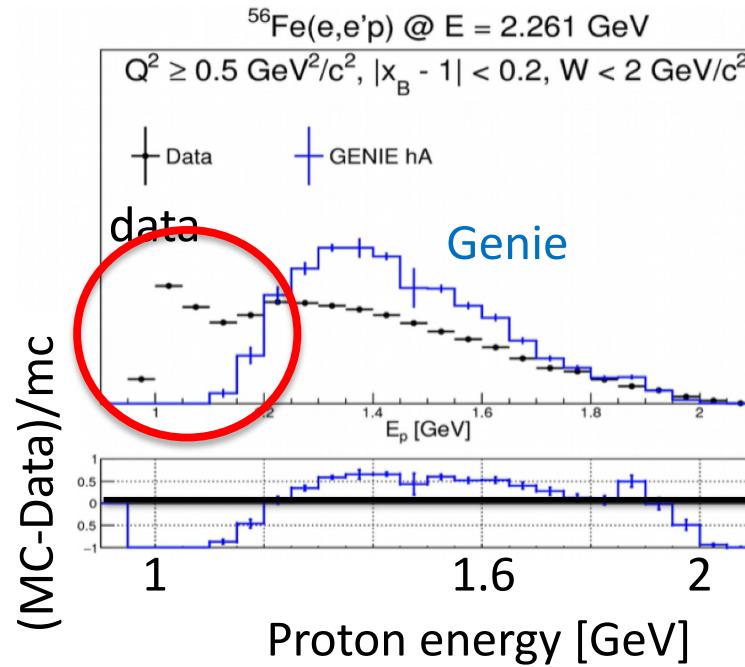
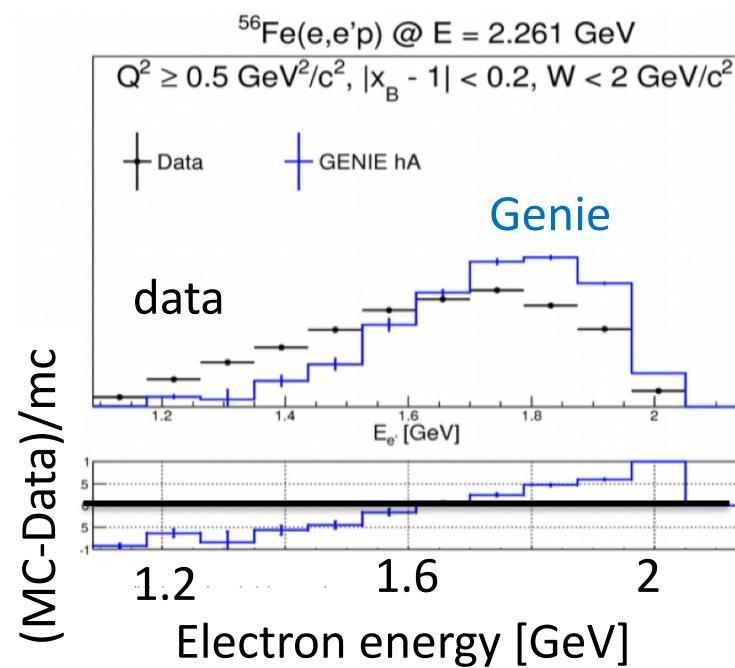


${}^{56}\text{Fe}$: typical density, more complicated

Compare to generators

- Genie for electrons
 - QE and 2p2h mechanisms
- Focus on peak of QE
 - Physics should be well described
 - $x = \frac{Q^2}{2m\omega} = 1 \pm 0.2$





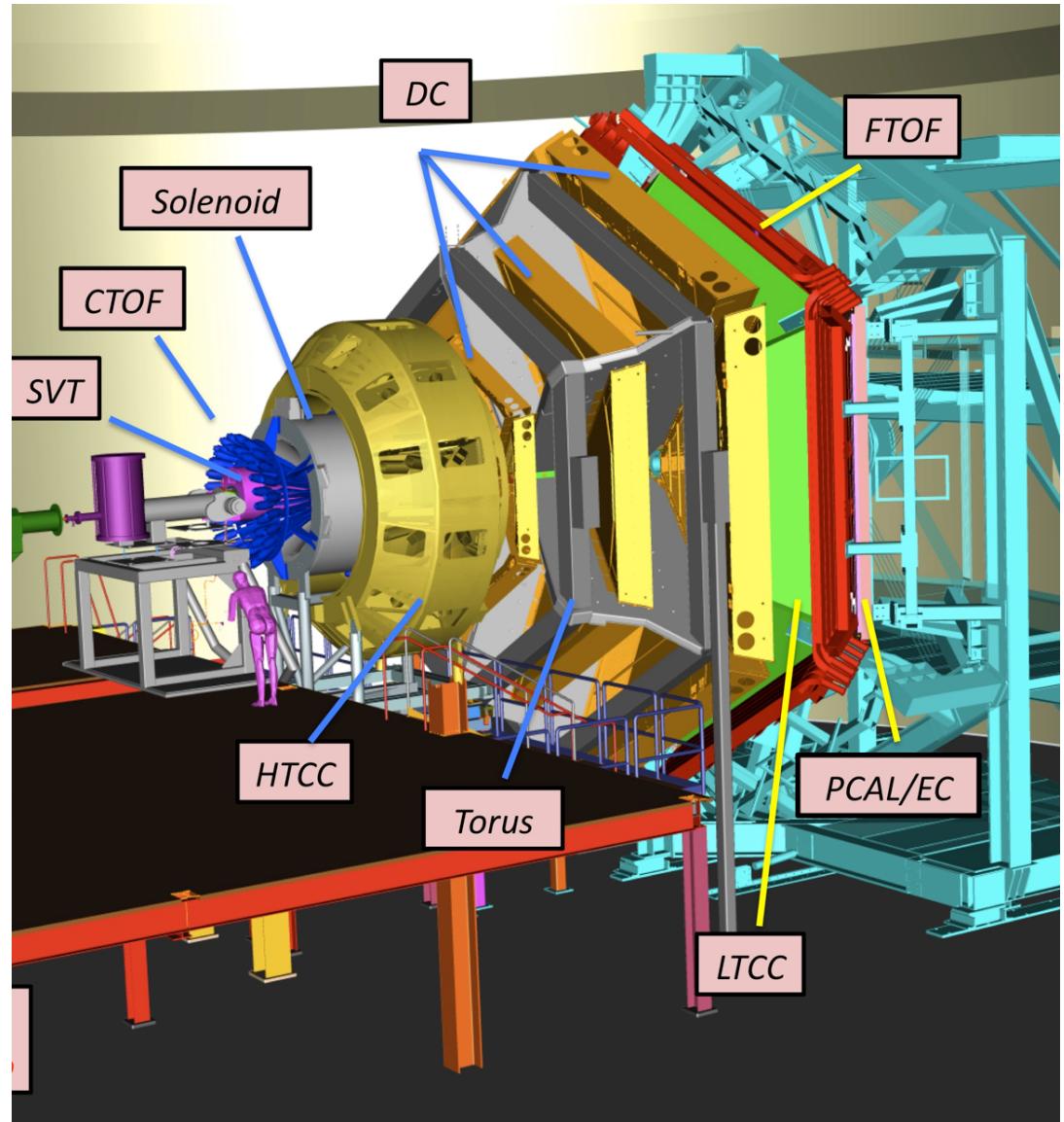
Near term next steps

- Add more reaction mechanisms to electron-Genie
 - Resonance production
 - $\Delta \rightarrow N\pi$
 - $\Delta N \rightarrow NN$
 - Electron radiation
- See effect on neutrino model parameters
 - Tune models
 - Use beam energy reconstructions directly
- Analyze the 1π reaction channel ($e, e' p\pi$)
- Resubmit a proposal to take more data

Electrons for neutrinos proposal

CLAS12

- 6-sector forward detector ($8 - 40^\circ$)
 - Toroidal magnetic field
 - $\frac{\delta p}{p} \sim 0.5 - 1\%$
 - 50% neutron detection efficiency for $p > 1 \text{ GeV}/c$ (Pb/scint cal)
 - 200 ps @ 5 m $\rightarrow \frac{\delta p}{p} \sim 10\%$ at $1 - 1.5 \text{ GeV}/c$
- Hermetic central detector ($40 - 135^\circ$)
 - 5 T solenoidal field, 30 cm radius
 - 10–15% neutron detection efficiency (scintillator)
 - 60 ps @ 0.3 m



Electrons for neutrinos proposal

- CLAS12
 - 6-sector forward detector ($8 - 40^\circ$)
 - Toroidal magnetic field
 - 50% neutron detection efficiency for $p > 1 \text{ GeV}/c$ (Pb/scint cal)
 - $200 \text{ ps} @ 5 \text{ m} \rightarrow \frac{\delta p}{p} \sim 10 - 15\%$ at $1 - 1.5 \text{ GeV}/c$
 - Hermetic central detector ($40 - 135^\circ$)
 - 5 T solenoidal field, 30 cm radius
 - 10–15% neutron detection efficiency (scintillator)
 - 60 ps @ 0.3 m
- 37.5 beam days requested for
 - 1.1, 2.2, 4.4, 6.6 and 8.8 GeV beam energies
 - H, He, C, O, Ar, and Pb
- Conditionally approved by Jlab PAC45
 - Need to return and optimize beam time request

Goals

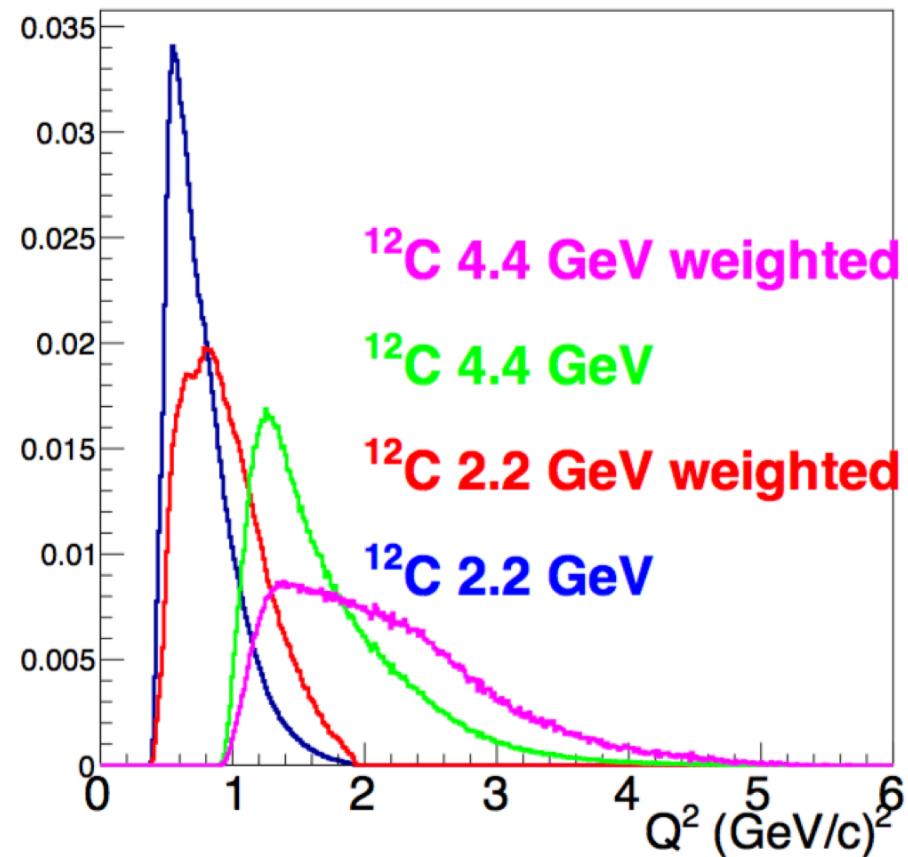
- We provide event yields and detector acceptance maps
 - Many beam energies
 - Many targets
 - Many event topologies
- Let experts use these to tune generators
- What do you want to see??
 - Targets
 - Energies
 - Event topologies
 - Distributions
- Proposal update due April 30 to CLAS!

Summary

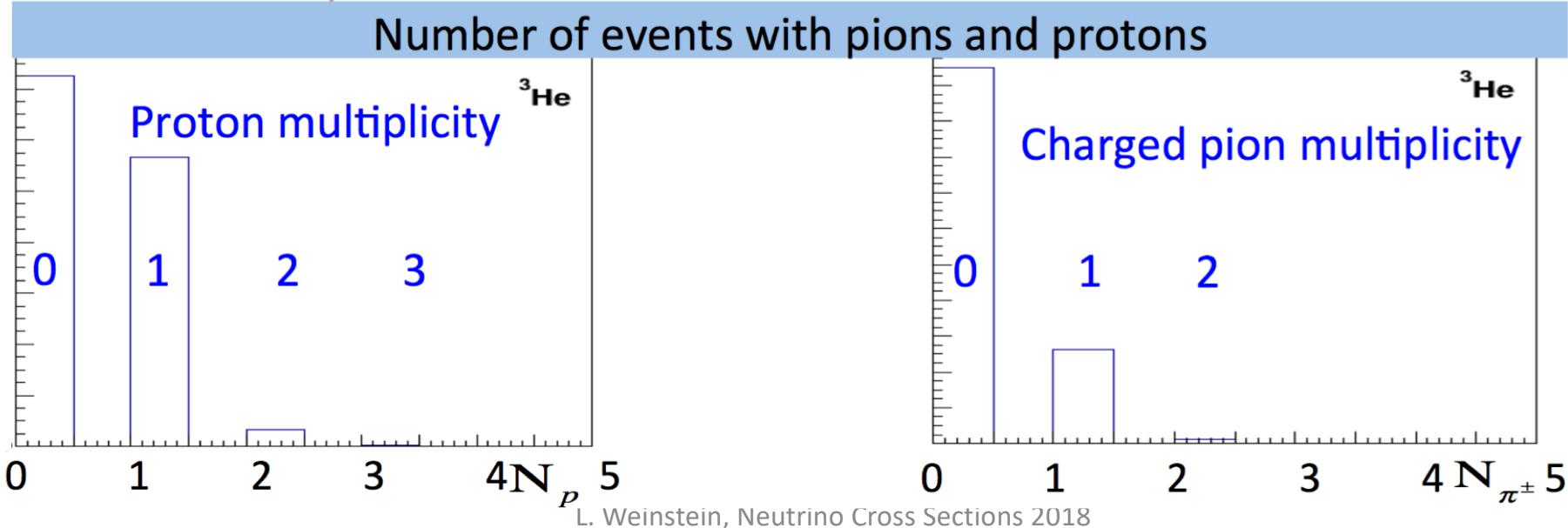
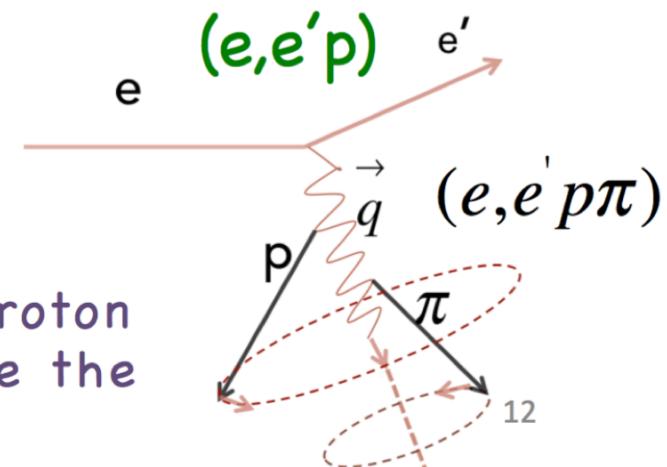
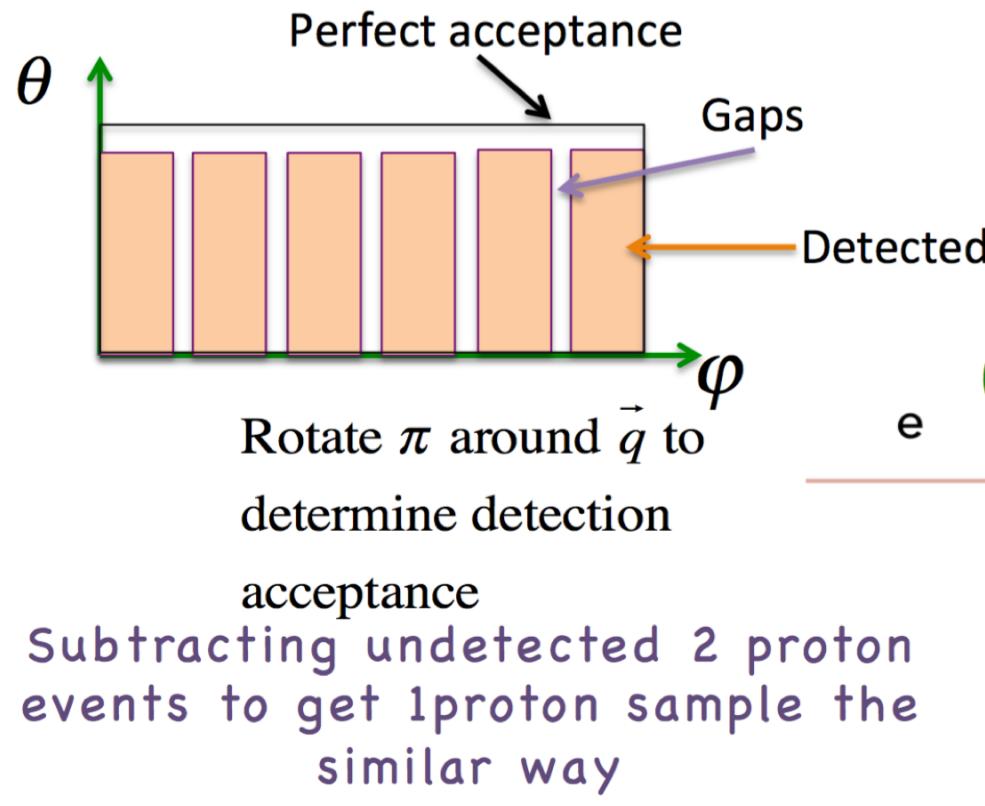
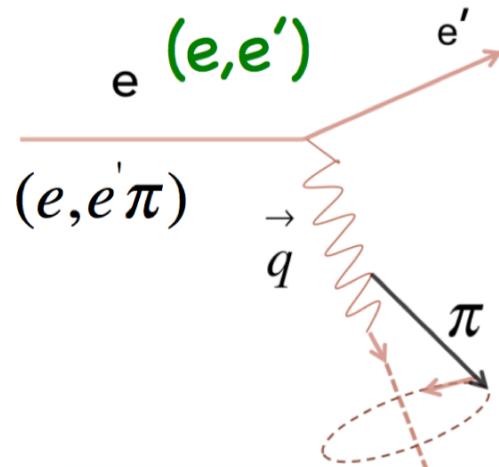
- Electron scattering can contribute dramatically to neutrino experiments
- We need guidance from the neutrino community
- We'll provide data, you figure out what it means

Backup slides

Mott weighting



E2a ${}^3\text{He}$ 2.261 GeV



Energy (GeV)	H	^4He	^{12}C	^{16}O	^{40}Ar	Pb	Total
1	0.2	0.5	0.5	0.5	0.5	0.5	2.5
2.2	0.2	1	1	1	1	1	5
4.4	0.2	1	1	1	1	1	5
6.6	0.2	2	2	0	2	2	8
8.8	0.2	4	4	0	4	4	16
Total (days)	1	8.5	8.5	2.5	8.5	8.5	37.5

