Electron-scattering constraints for neutrino-nucleus interactions

Lawrence Weinstein
Old Dominion University

APS April Meeting
Denver, CO, April 2019

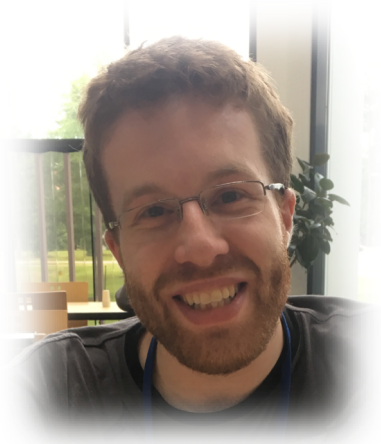
Collaboration

- 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)



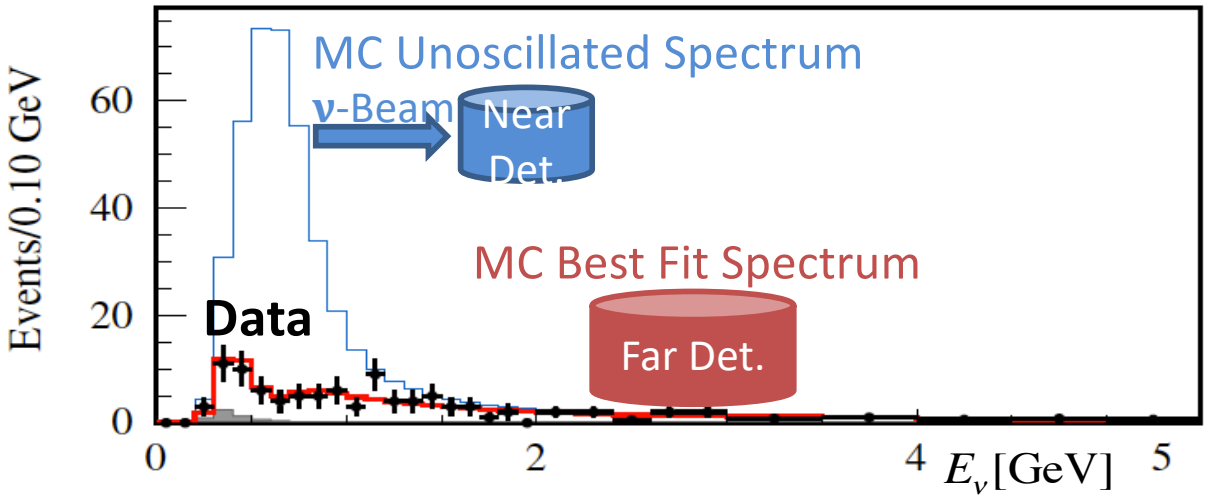
Florian Hauenstein
(ODU)

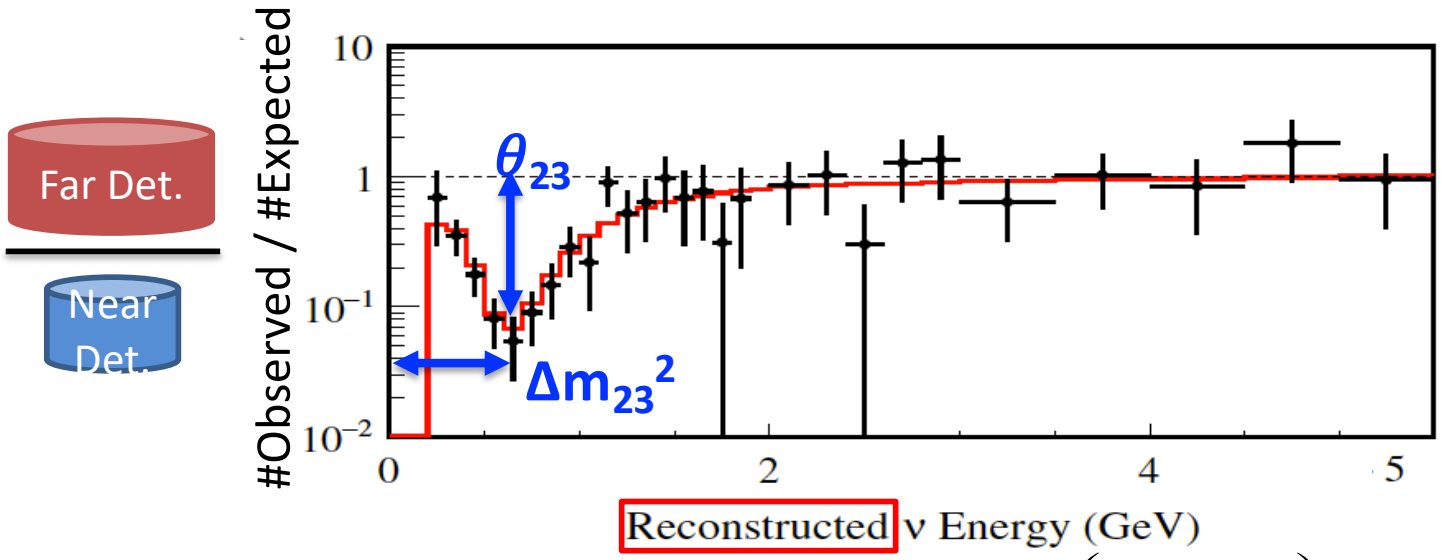
Outline

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

Measuring Neutrino Oscillations

T2K experiment L=295km





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

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

Event Generators and Neutrino Oscillations

Measure neutrino-nucleus reaction products in detector

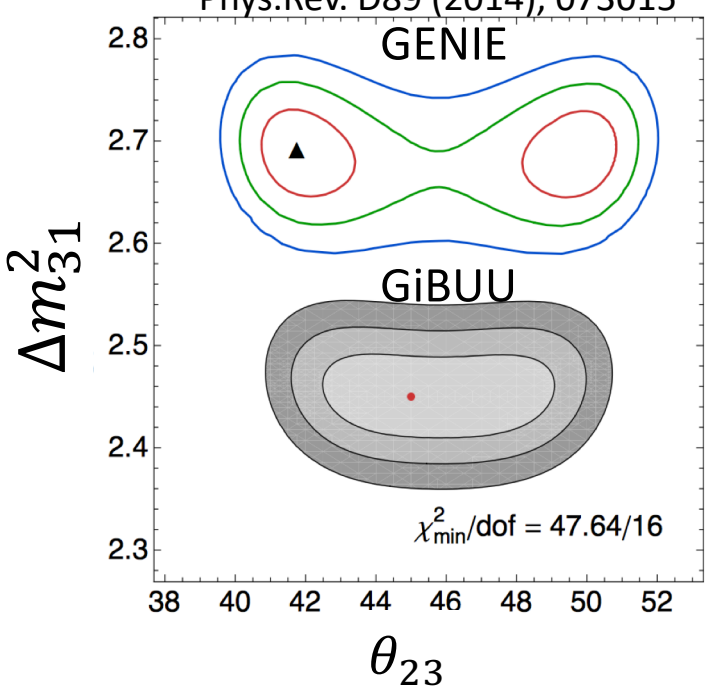
- Reconstruct incident neutrino energy for each event

From the measured incident neutrino energy distribution

- Use a neutrino event generator (GENIE, NUWRO, GIBUU …) to determine the actual neutrino beam energy distribution

- Create events with GiBUU
- Reconstruct events with GiBUU and GENIE.

Phys.Rev. D89 (2014), 073015



=> Incorrect neutrino-nucleus interaction modeling will bias the extracted oscillation parameters

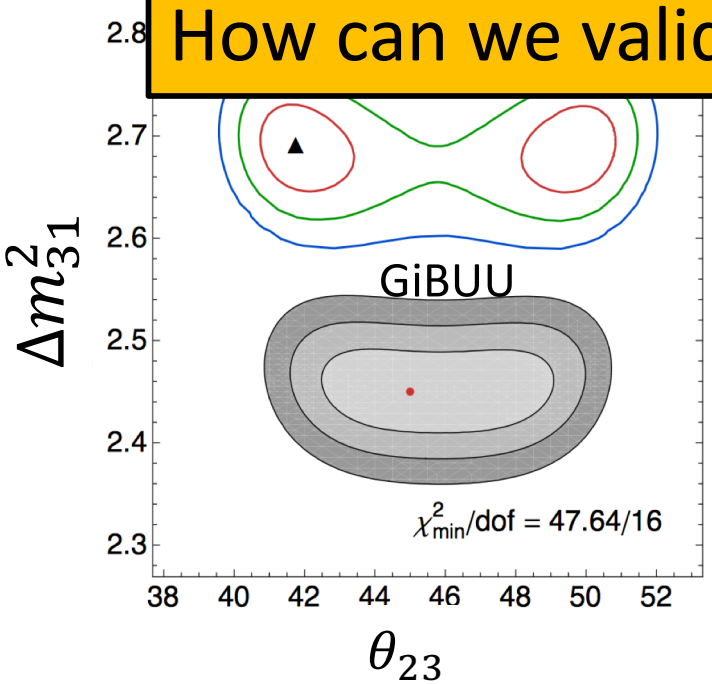
Event Generators and Neutrino Oscillations

How do we reconstruct:

- The energy of each incident neutrino
- The number of incident neutrinos

from the neutrino-nucleus reaction products measured in the detectors?

How can we validate these reconstructions?



Events created with GiBUU and reconstructed with GiBUU and GENIE.

=> Incorrect neutrino-nucleus interaction modeling will bias the extracted oscillation parameters

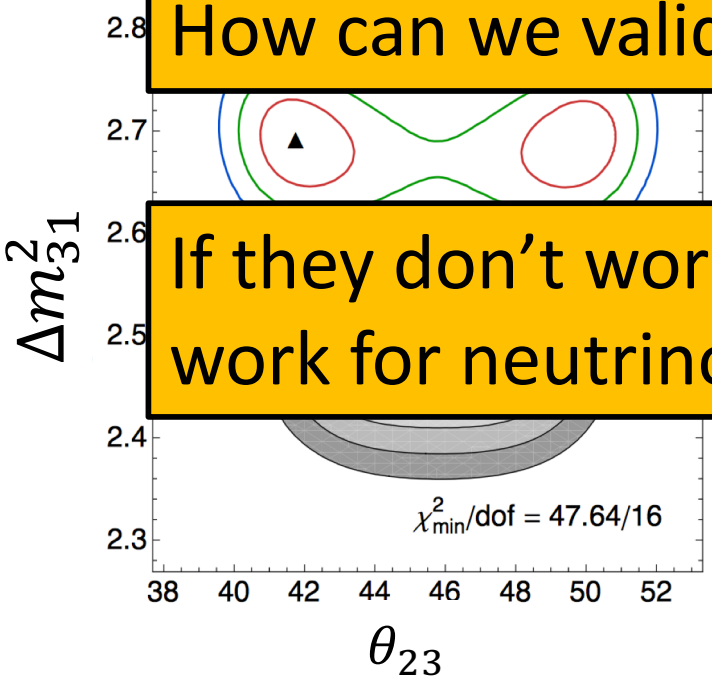
Event Generators and Neutrino Oscillations

How do we reconstruct:

- The energy of each incident neutrino
- The number of incident neutrinos

from the neutrino-nucleus reaction products measured in the detectors?

How can we validate these reconstructions?



Events created with GiBUU and

If they don't work for electrons, they won't work for neutrinos!

U ...) to

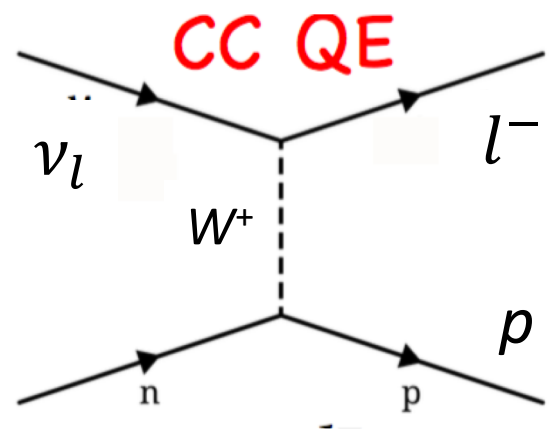
on

trino-

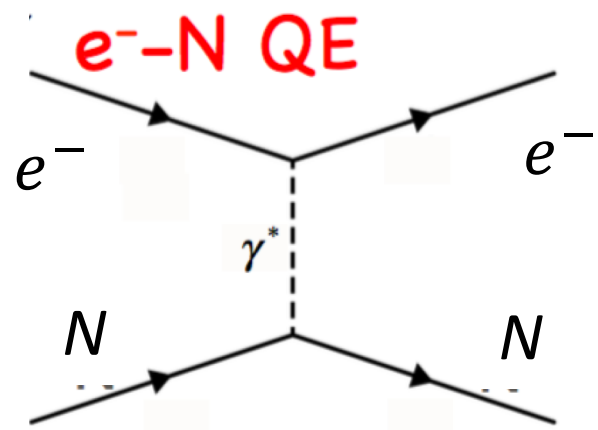
on

s the extracted oscillation parameters

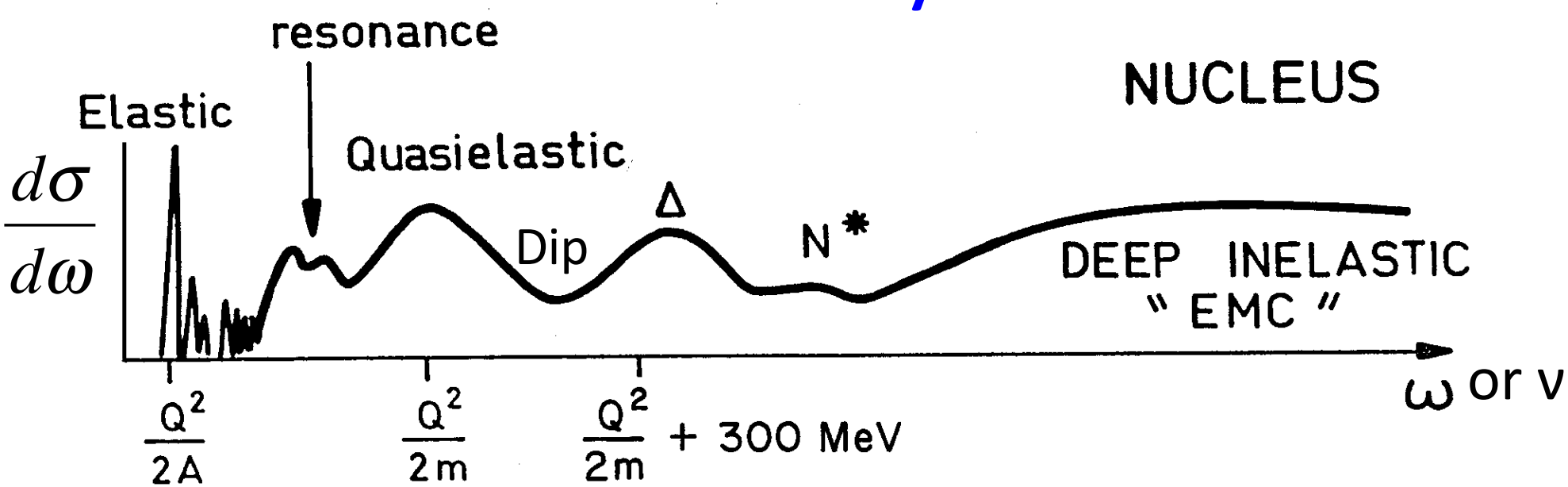
Why electrons?



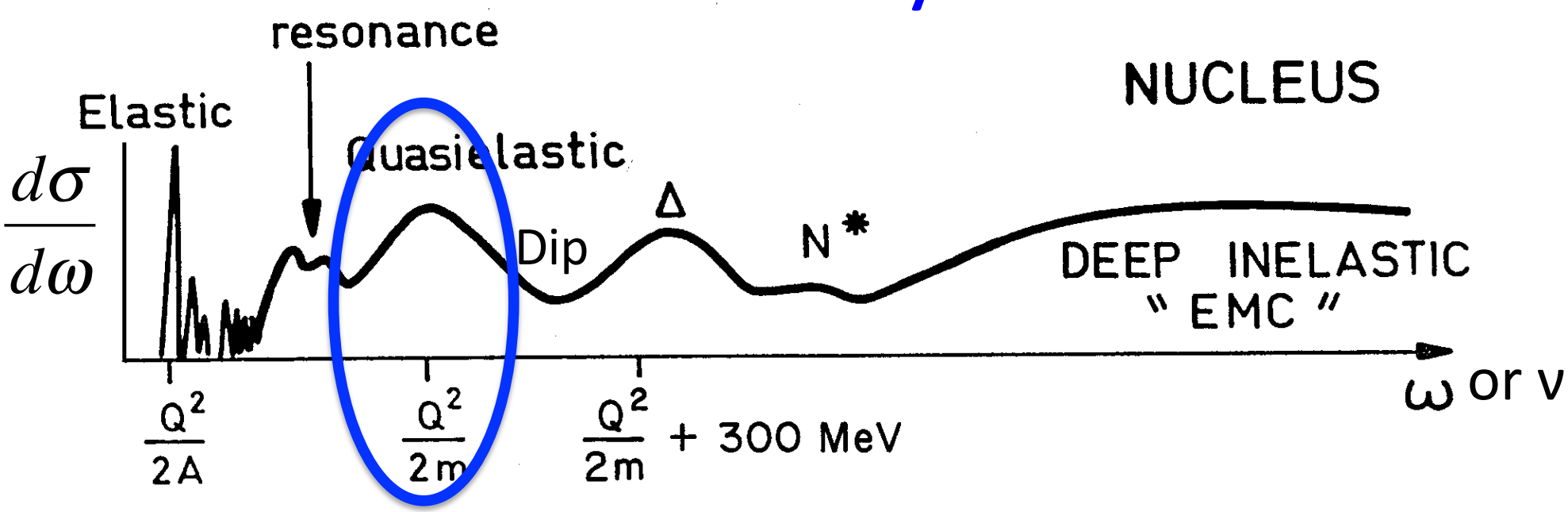
- Known incident energy
- High intensity
- Similar interaction with nuclei
  - Single boson exchange
  - CC Weak current [vector plus axial]
    - $j_\mu^\pm = \bar{u}\frac{-ig_W}{2\sqrt{2}}(\gamma^\mu - \gamma^\mu\gamma^5)u$
  - EM current [vector]
    - $j_\mu^{em} = \bar{u}\,\gamma^\mu u$
- Similar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



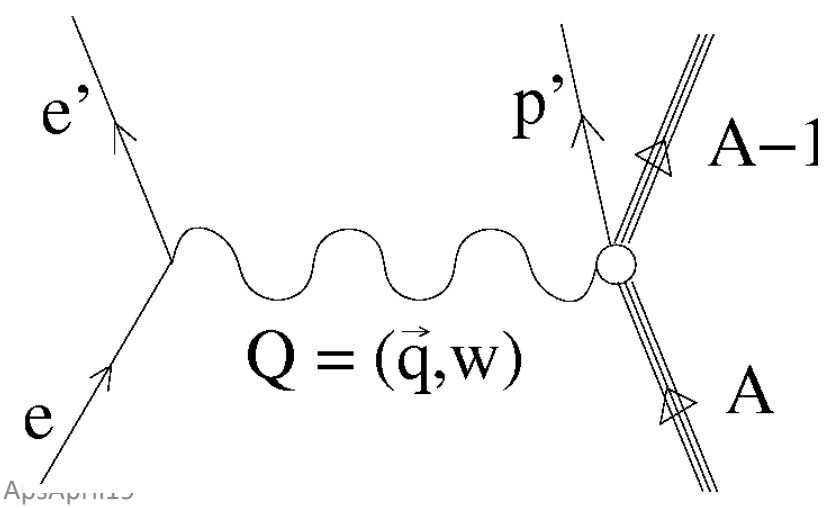
Nuclear Physics



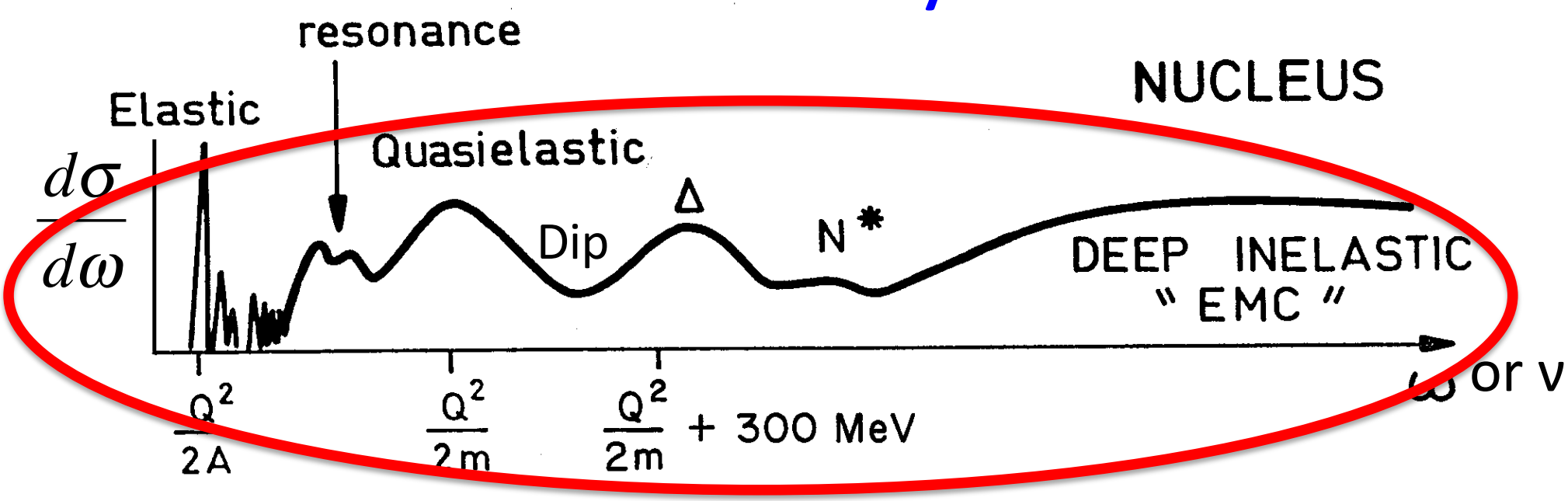
Nuclear Physics



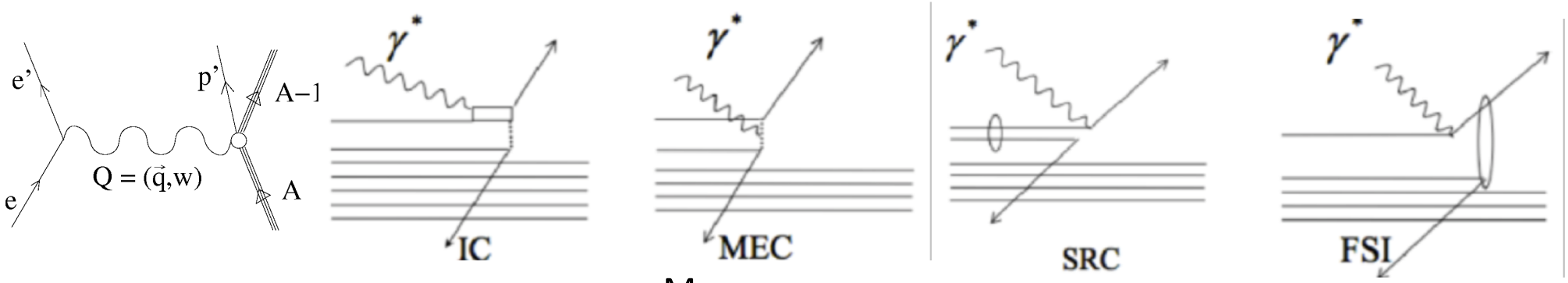
What neutrino expts want



Nuclear Physics



What we get (even for 0pi)



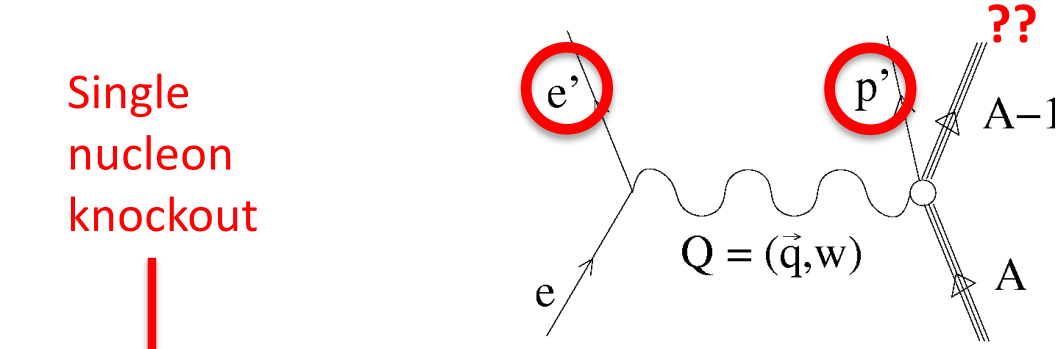
Resonance

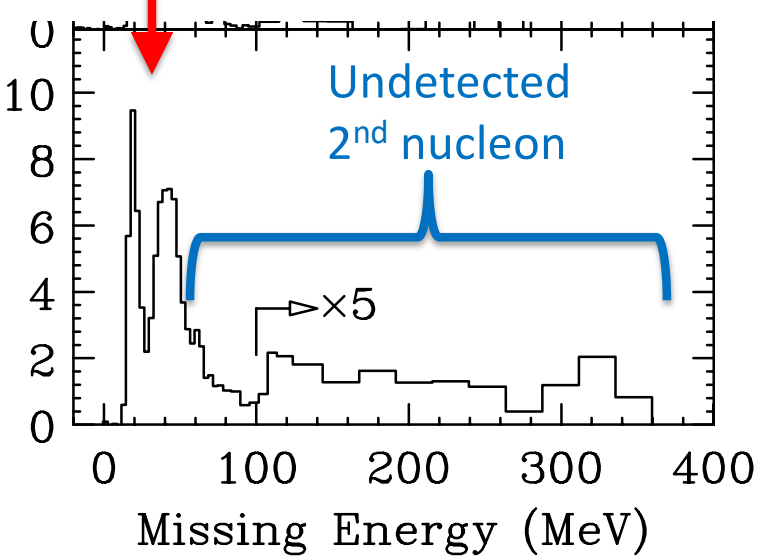
Meson Exchange Currents

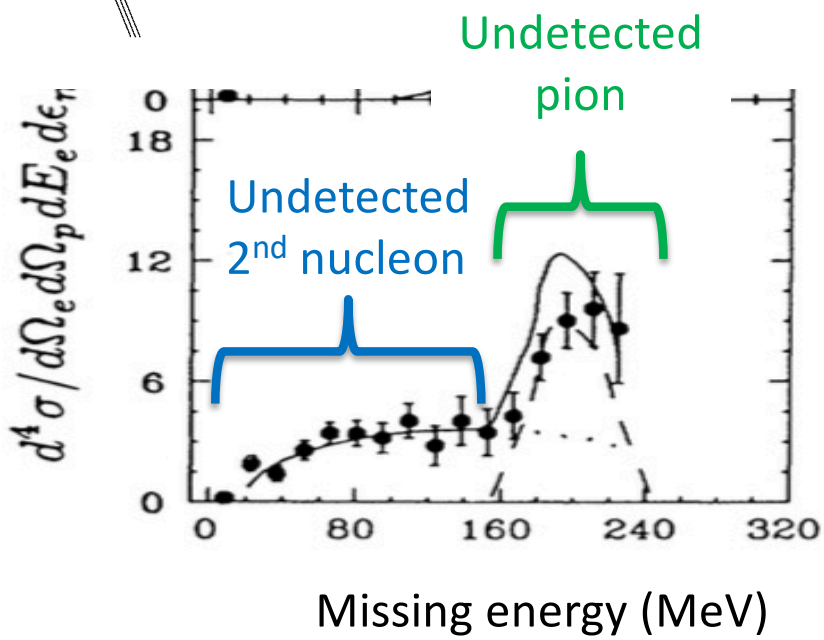
Short Range Correlations

Final State Interactions

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

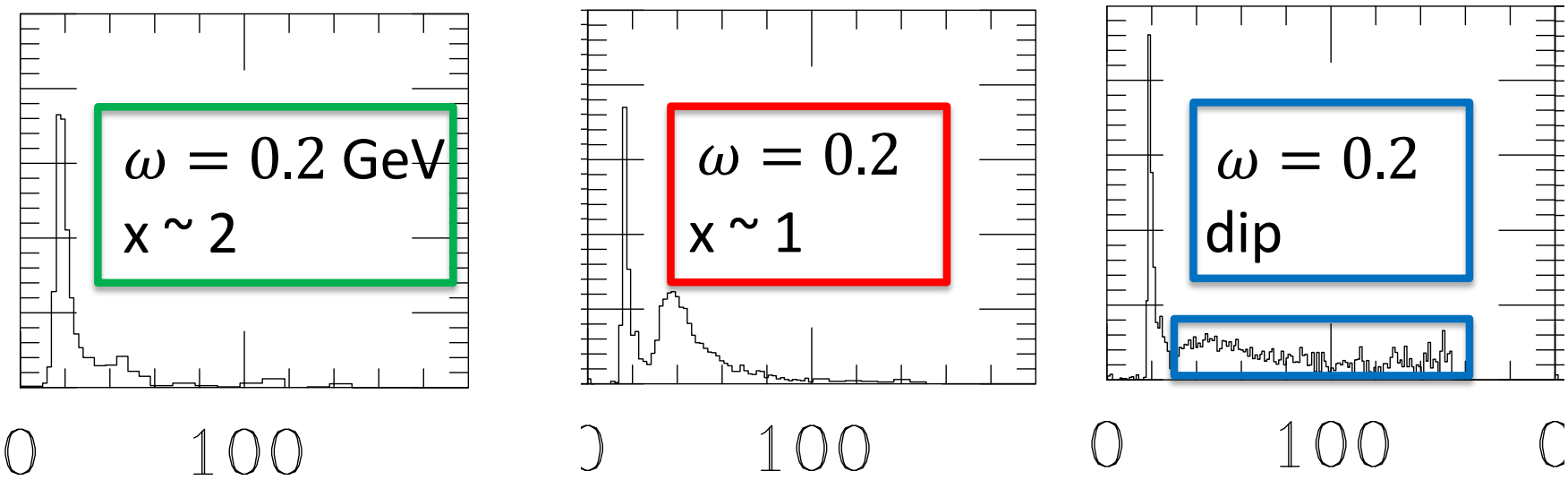




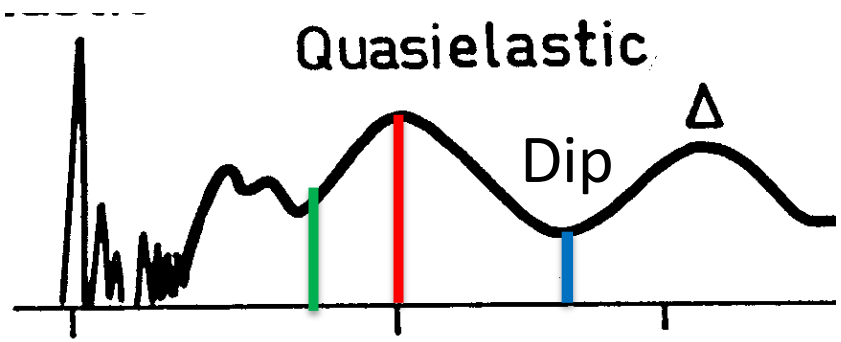


From QE to "dip"

C(e,e'p)



Missing energy [MeV]



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

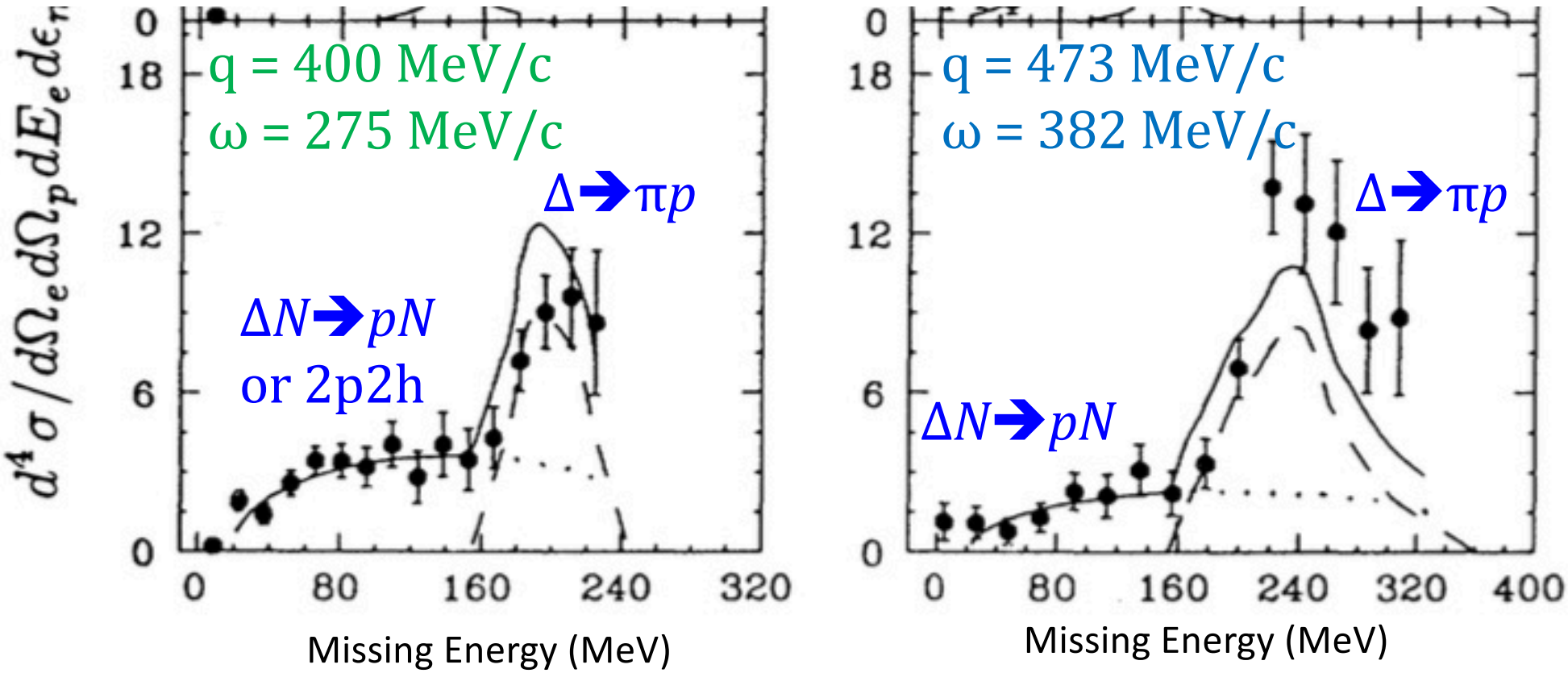
R. Lourie, PRL **56**, 2364 (1986)

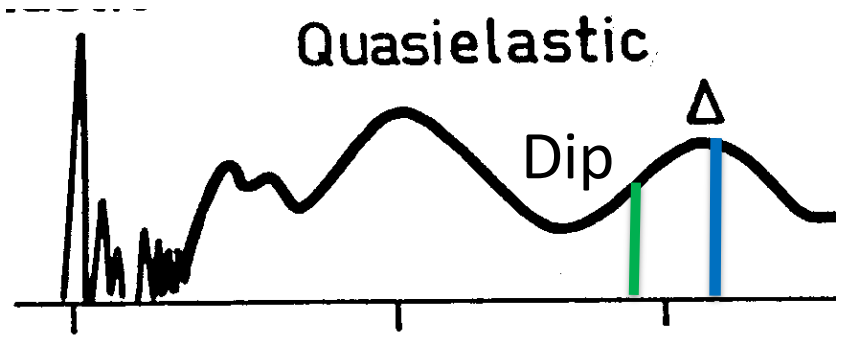
L. Weinstein, PRL **64**, 1646 (1990)

S. Penn, unpublished

From Dip to Delta Region

C(e,e'p)





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

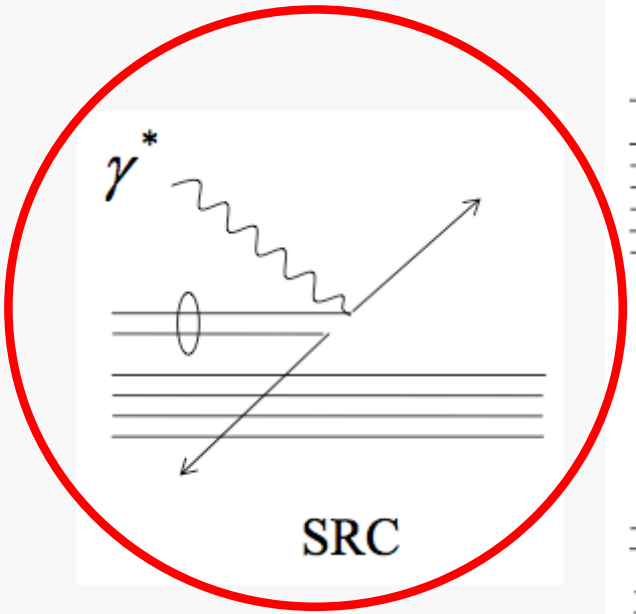
What are correlations?

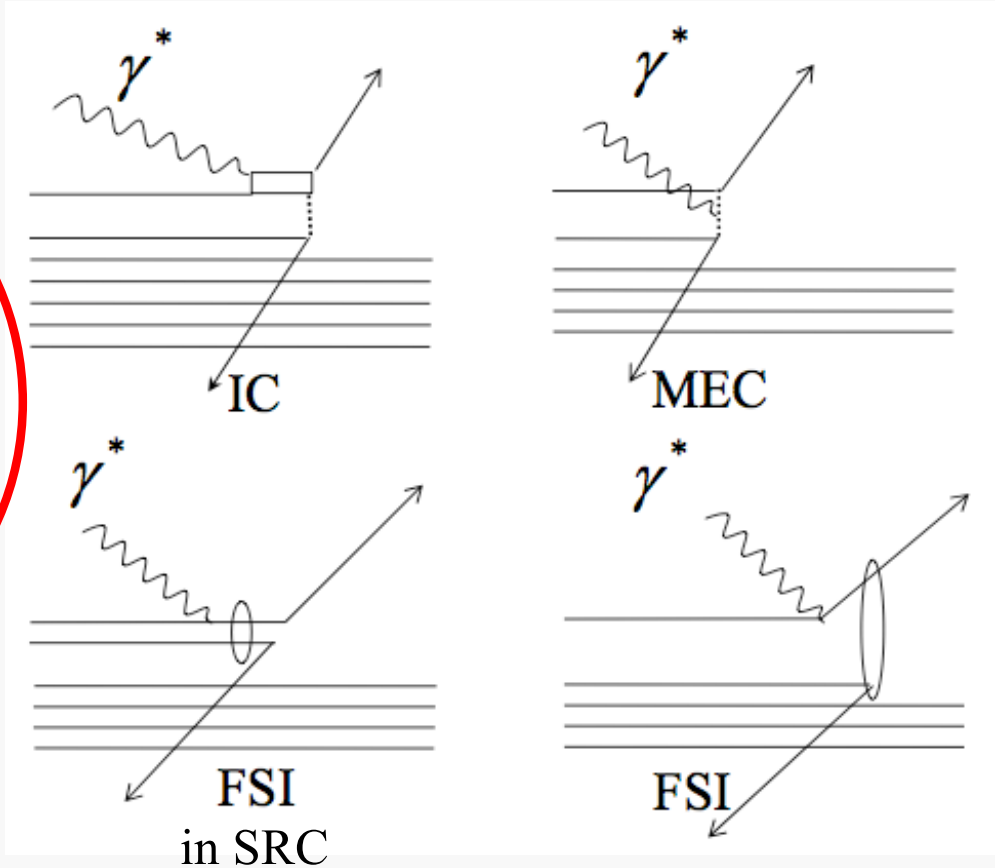
Average Two-Nucleon Properties in the Nuclear Ground State

Responsible for the high momentum part of of the Nuclear WF

Two-body currents are not Correlations

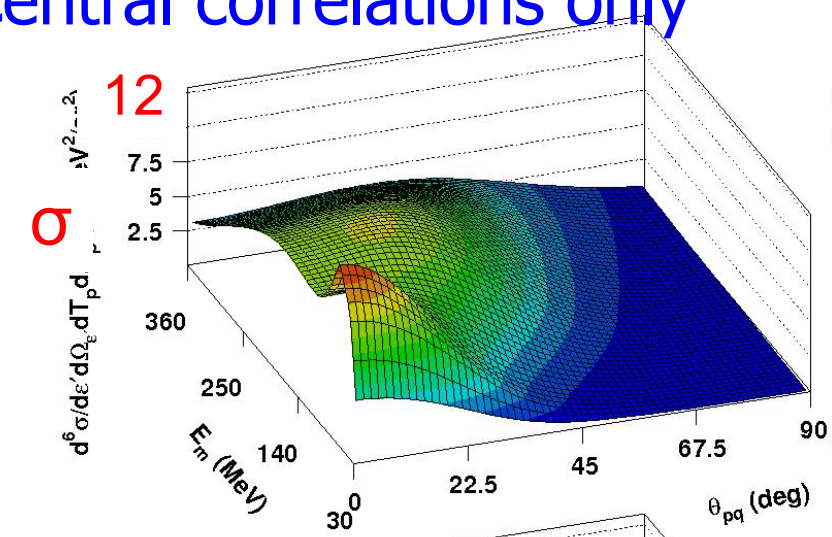
(but everything adds coherently)



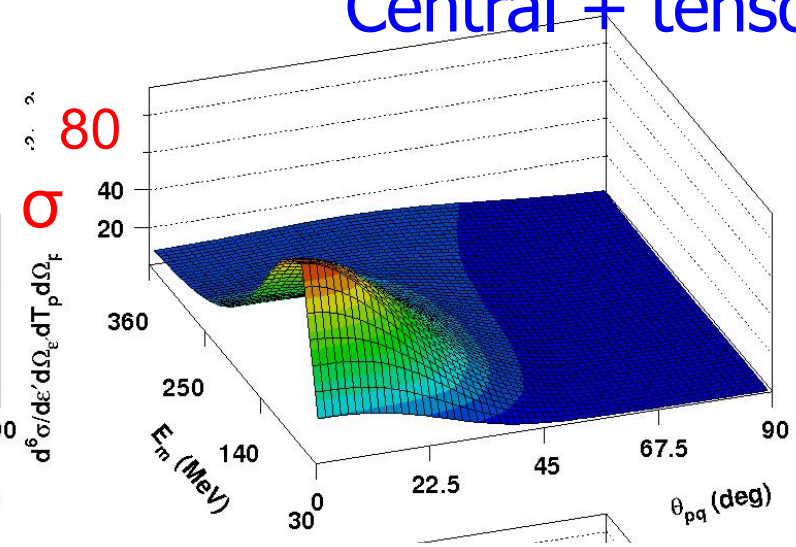


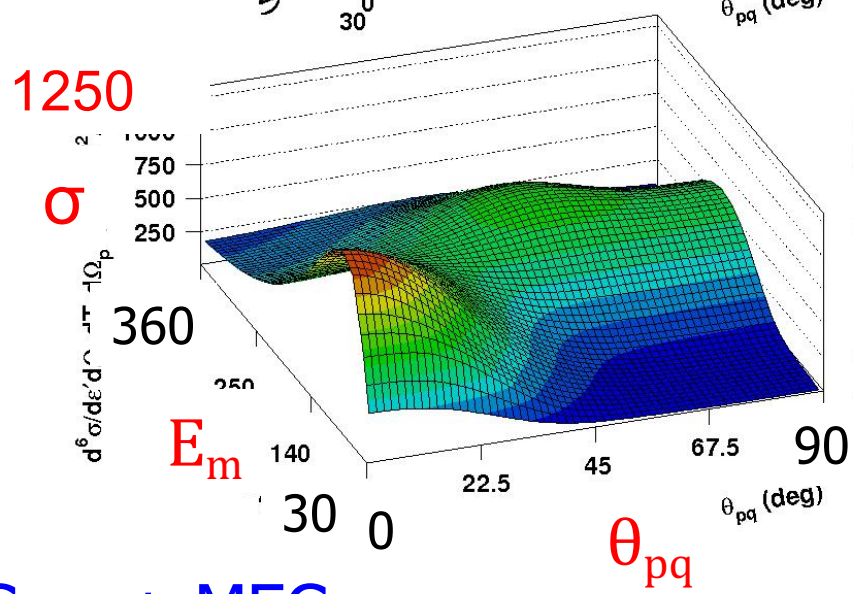
2N currents enhance correlations

Central correlations only



Central + tensor corr





MEC and correlations add coherently

$\rightarrow 2p2h$

Corr + MEC

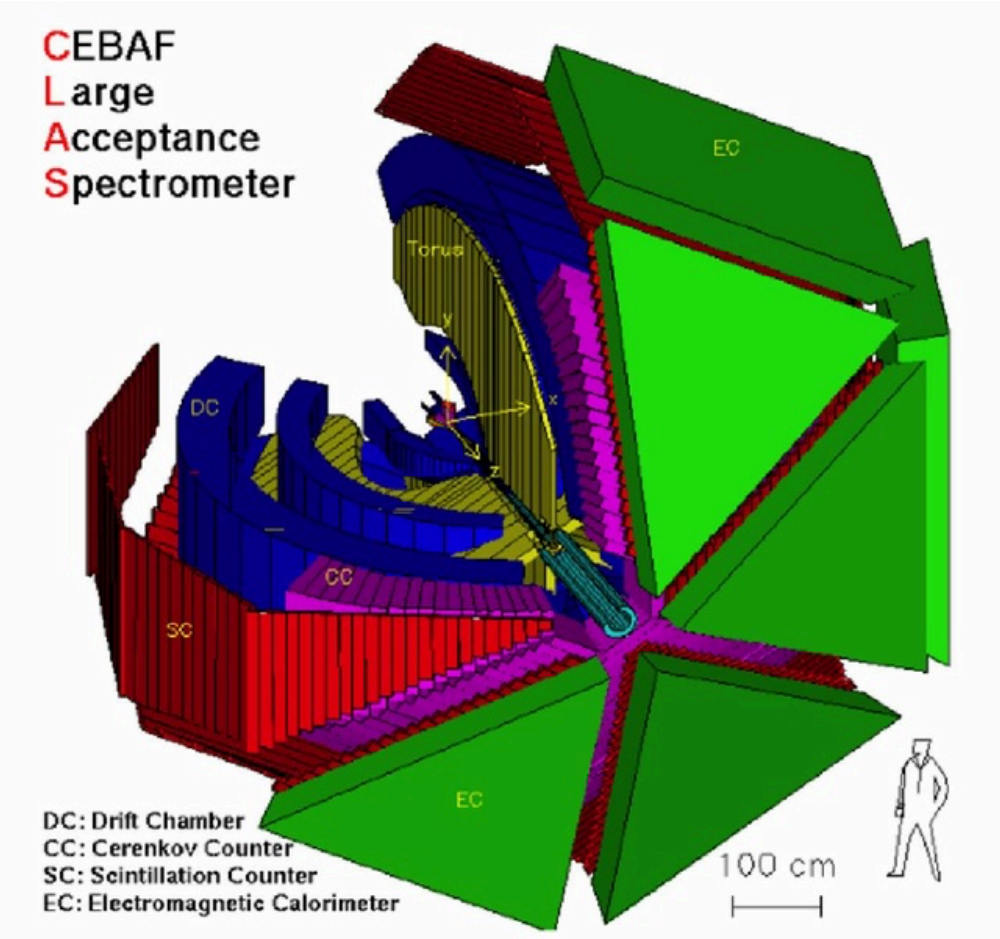
O(e,e'p) Ryckebusch
NP A672 (2000) 285

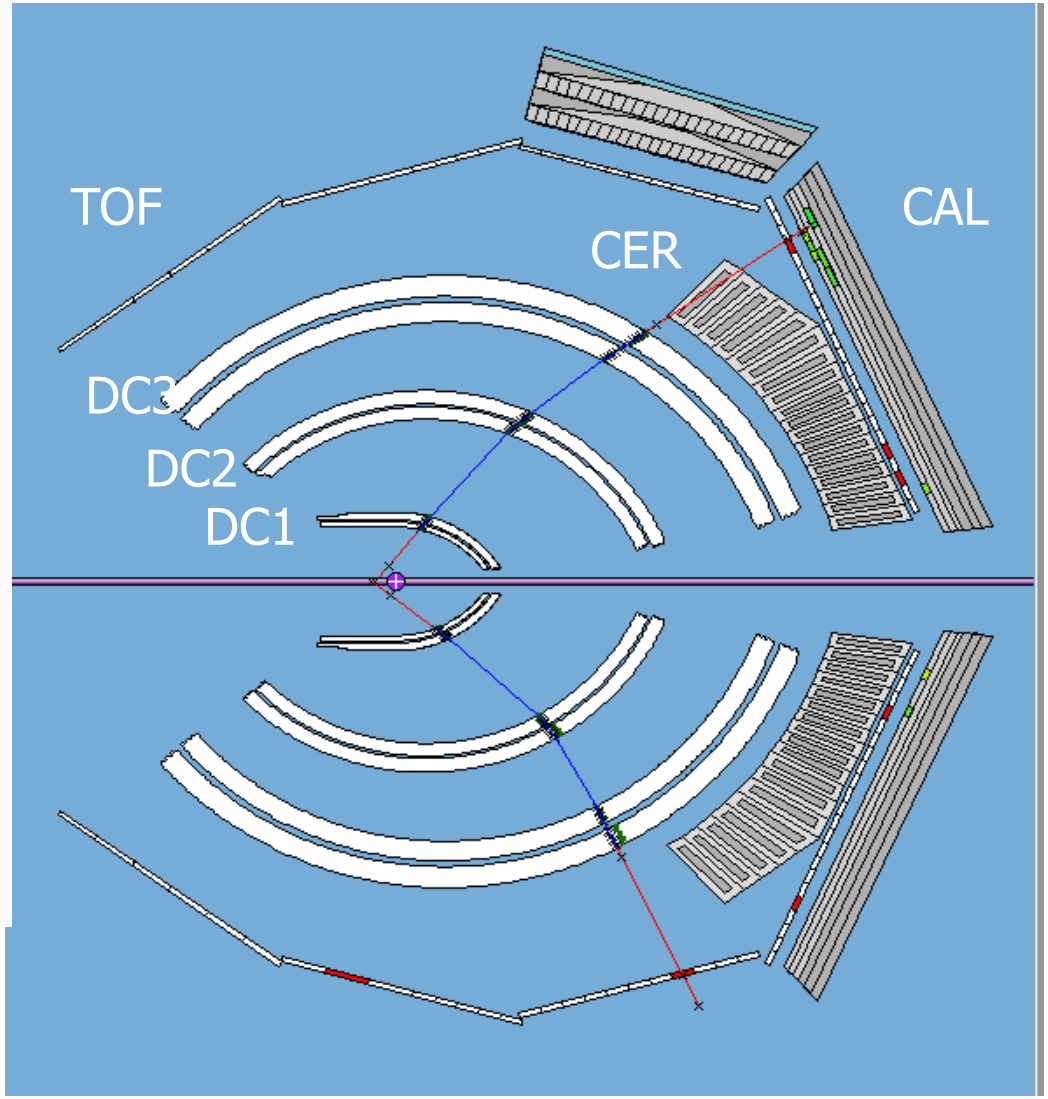
Physics Summary

- 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, correlations, Delta, …
    - FSI (not discussed here)
  - Need good models in event generators

Jefferson Lab data

CLAS6: 1996-2015

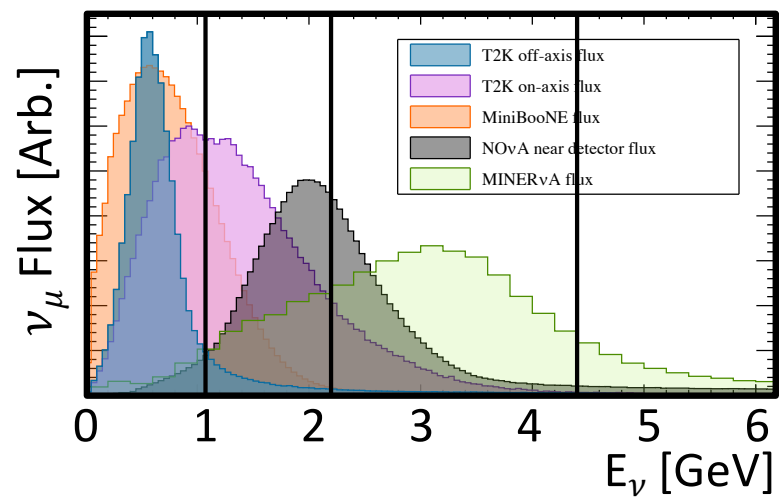




CLAS6 Data (million events)

	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

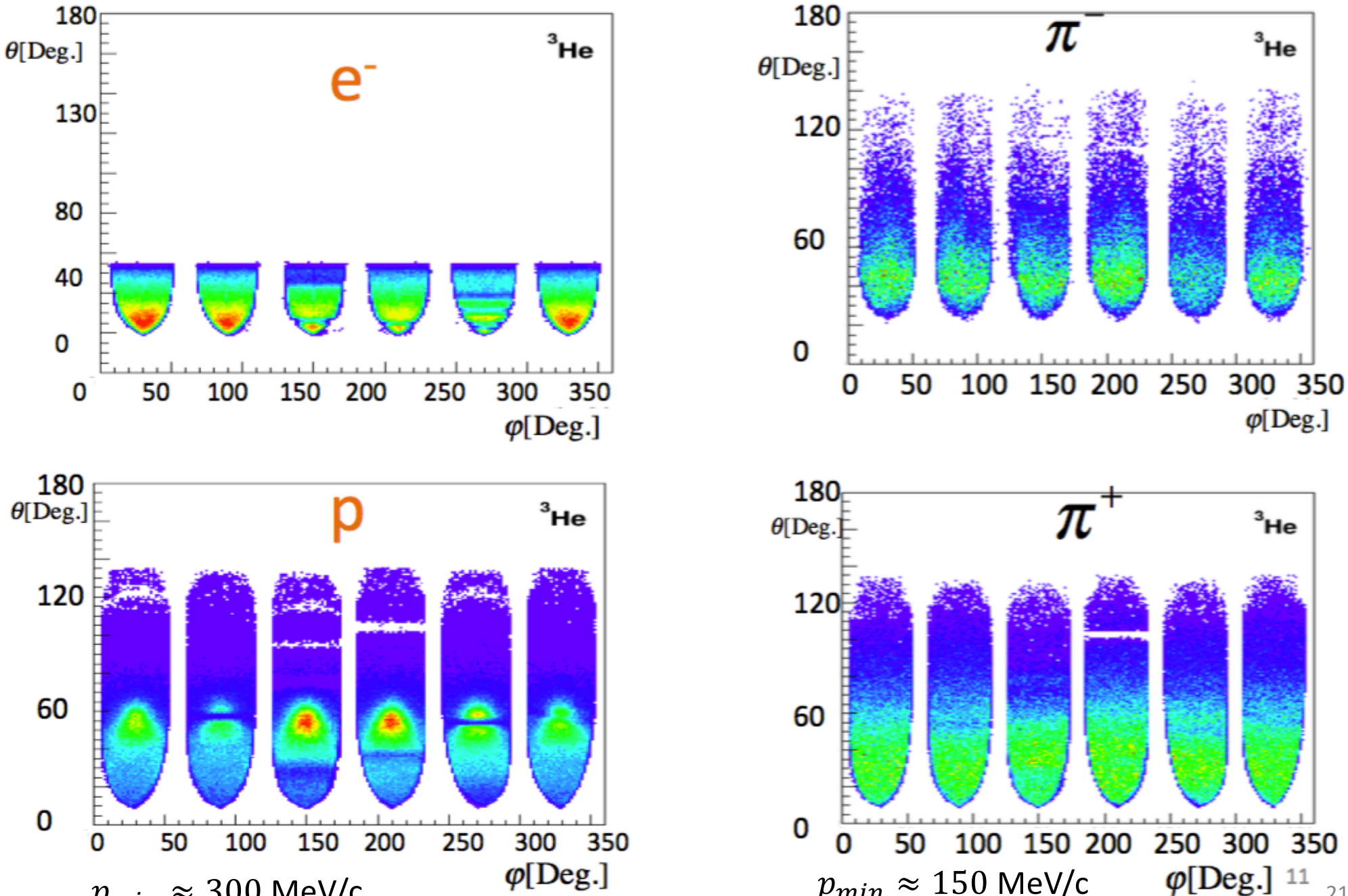
E2a data only.
E2b has more 4.6 GeV 3He and 56Fe
Eg2 has 5 GeV d, C, Al, Fe, and Pb



Reconstructing the initial energy

- Choose 0π events to enhance the QE sample
  - Subtract undetected pions and photons
- Weight by $1/\sigma_{Mott}$ to account for photon propagator
- Reconstruct the incident lepton energy:
  - $E_{QE} = \frac{2M_N\epsilon + 2M_N E_l - m_l^2}{2(M_N - E_l + k_l cos\theta_l)}$
    - 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)]

CLAS6 coverage



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

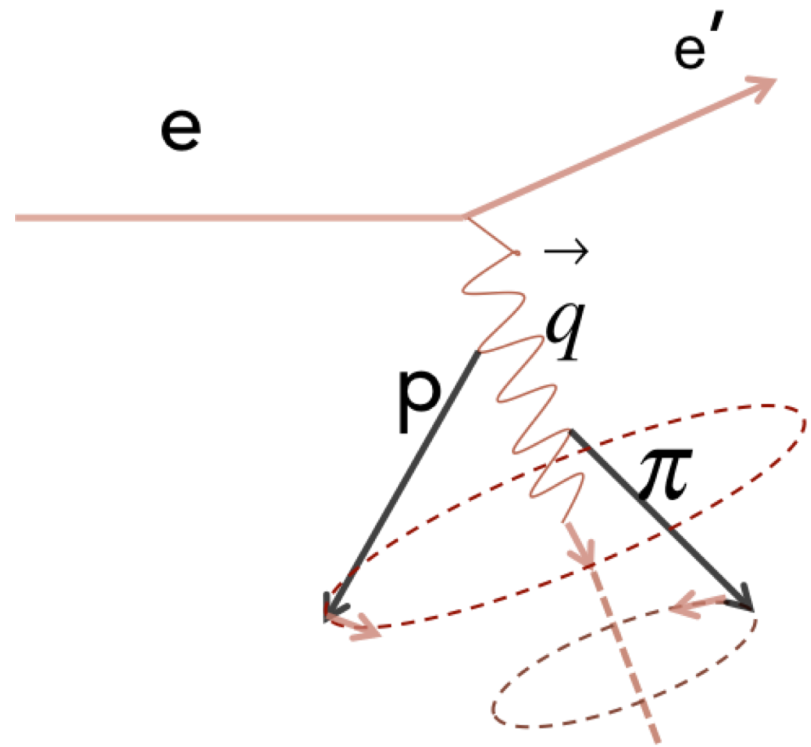
$p_{min} \approx 150$ MeV/c

Background Subtraction

Want 0π event sample
(e,e') background: undetected pions (and photons)
(e,e'p) background: undetected pions and extra protons

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

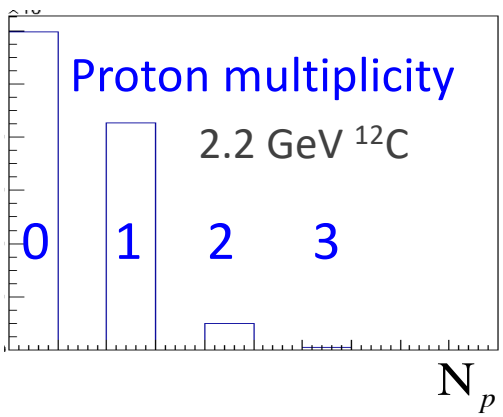


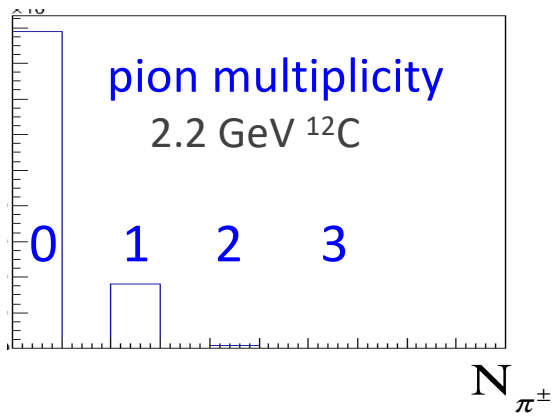
Background Subtraction

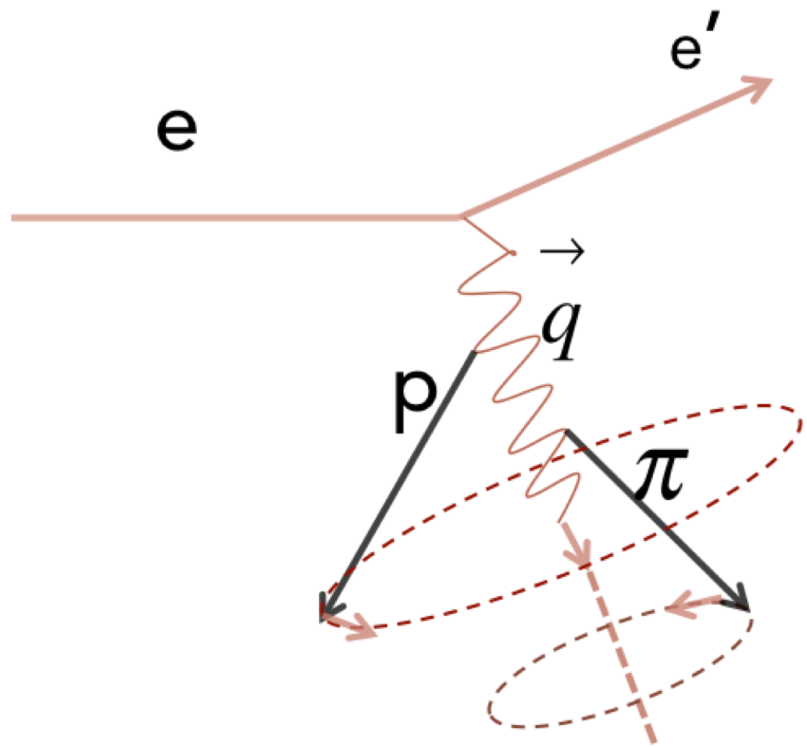
Want 0π event sample
(e,e') background: undetected pions (and photons)
(e,e'p) background: undetected pions and extra protons

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







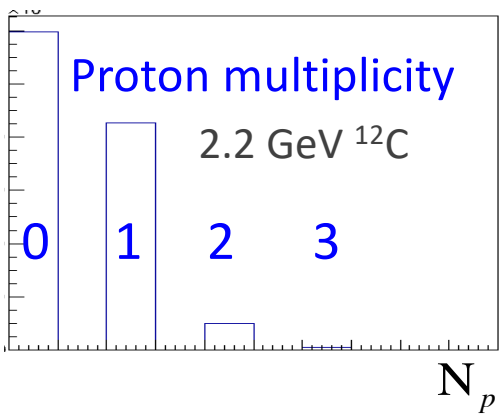
Background Subtraction

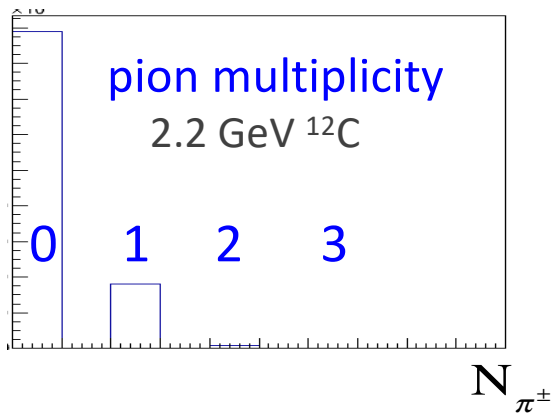
Want 0π event sample
(e,e') background: undetected pions (and photons)
(e,e'p) background: undetected pions and extra protons

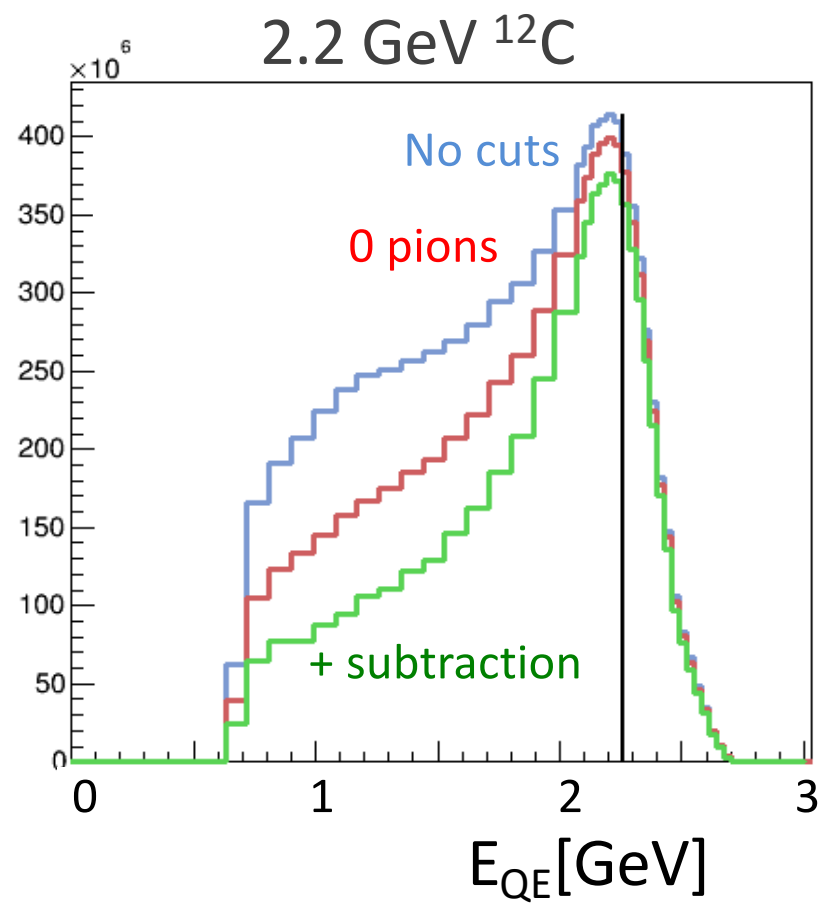
Data Driven Correction:

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

- γ subtraction in progress

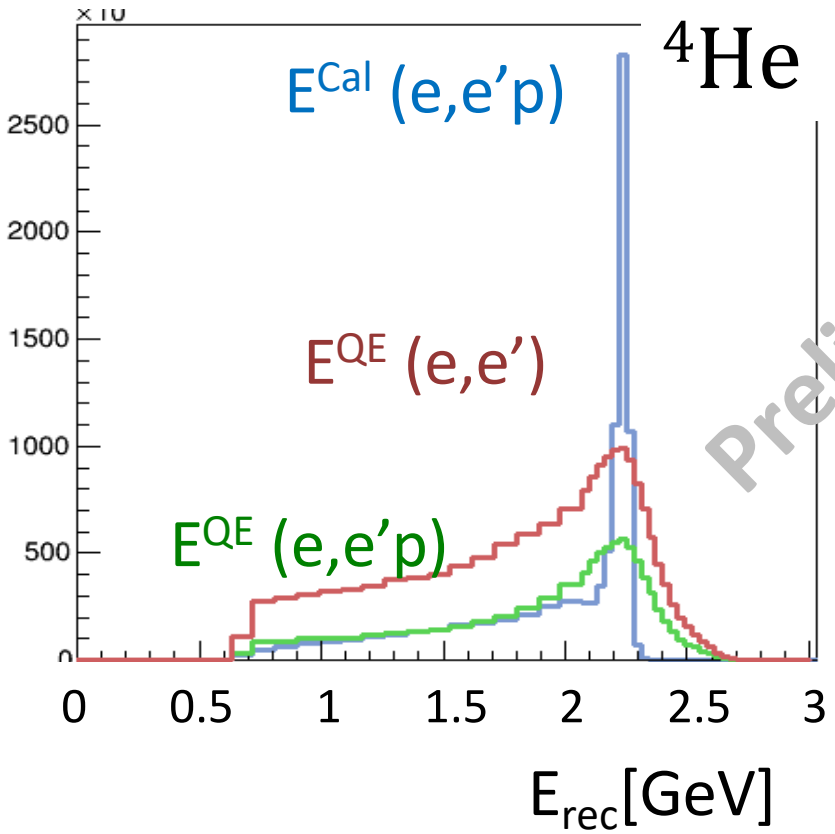


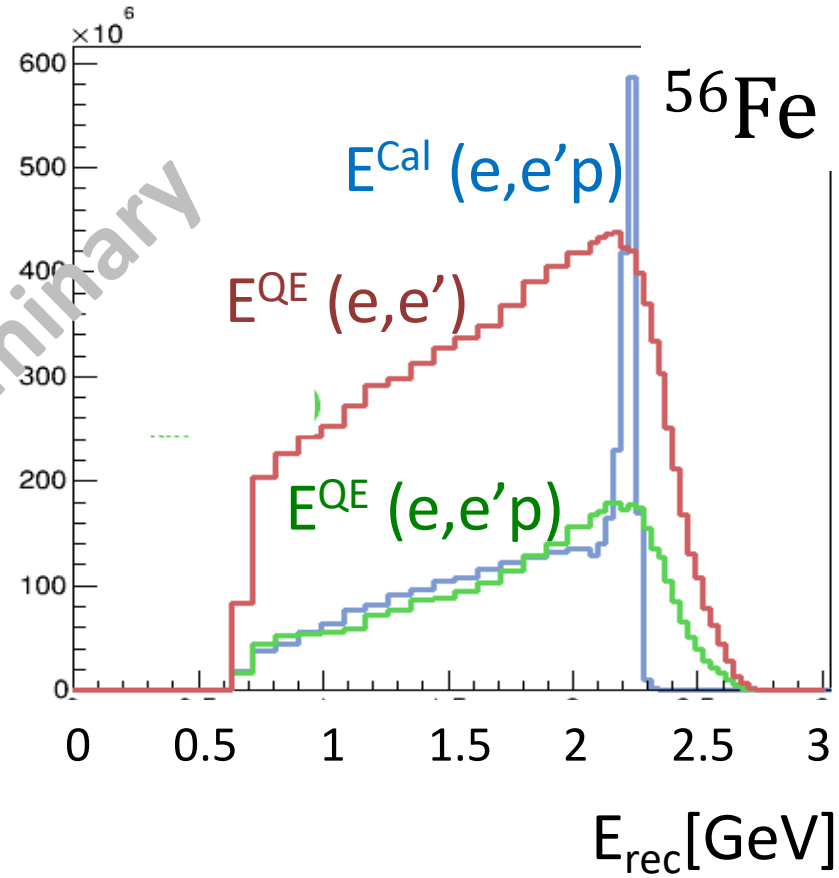




Energy Reconstruction: A dependence

2.26 GeV beam Zero pion events

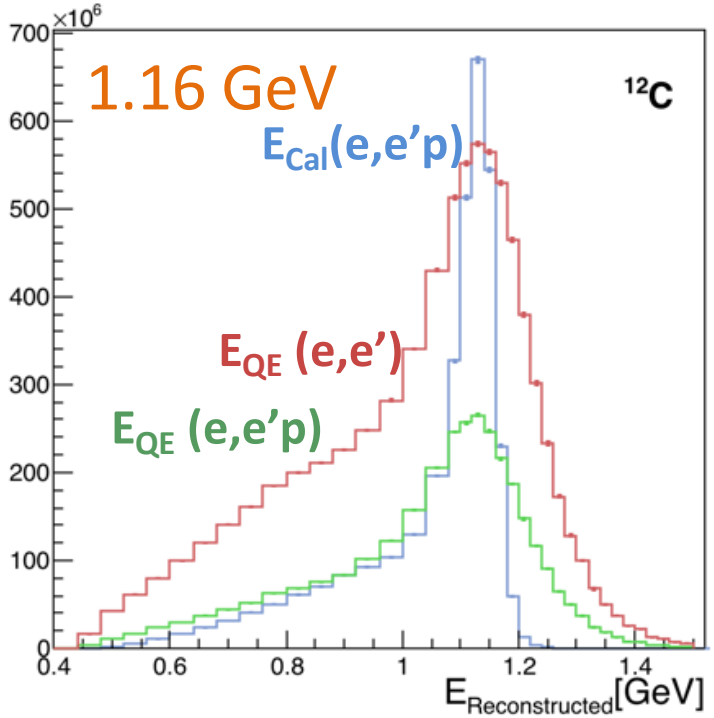




Even 0pi events have a LOT of non-QE events

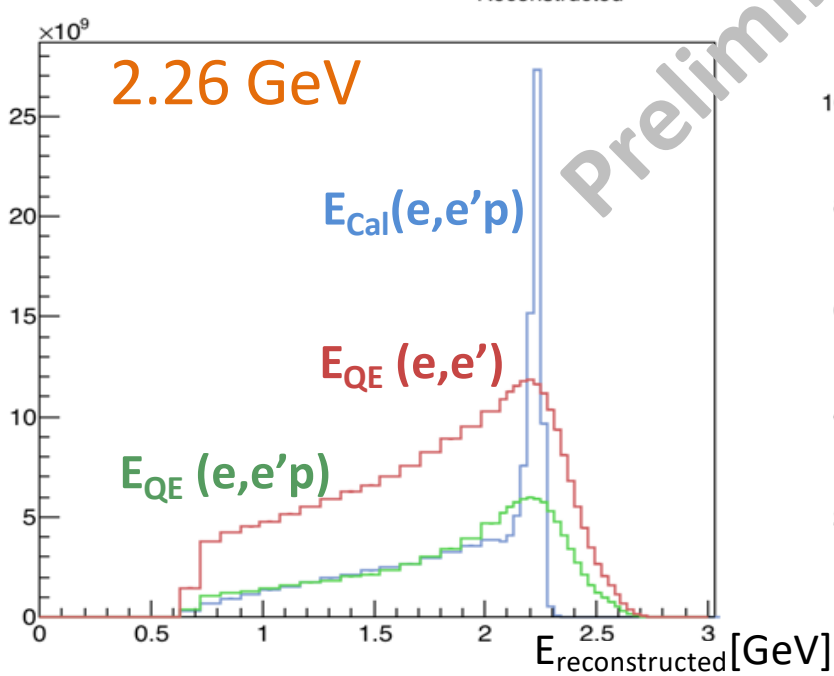
Much bigger in Fe than ^{4}He

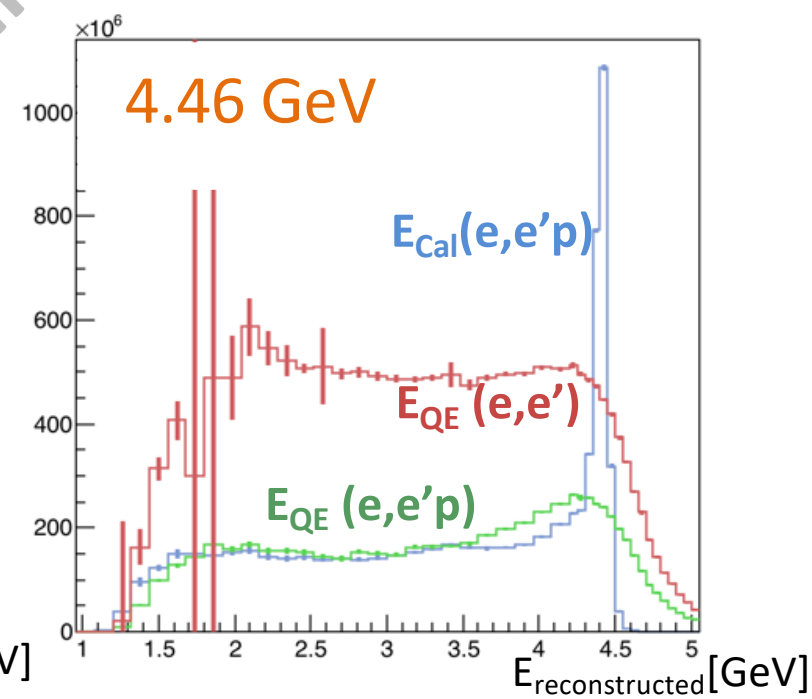
Energy Reconstruction: E dependence



^{12}C

Non-QE events increase with E

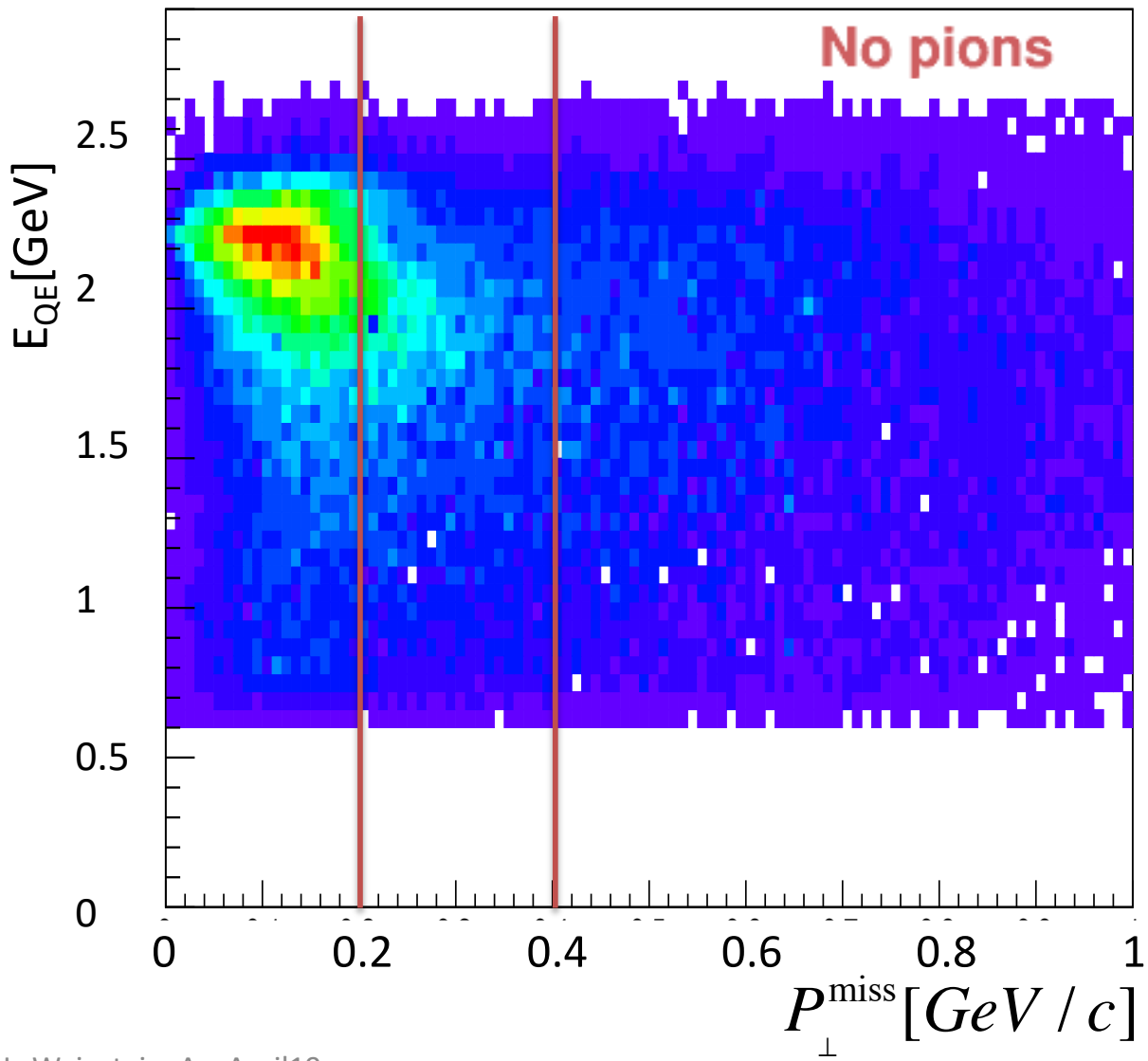




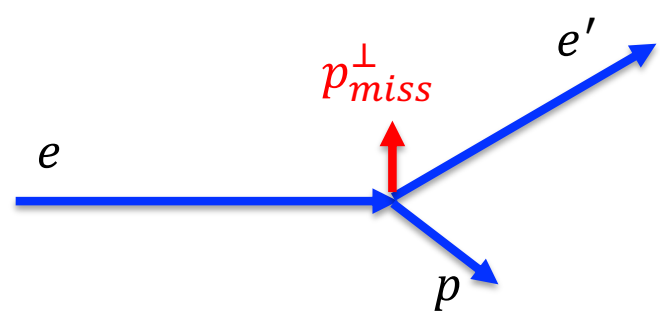
Preliminary

Can we select QE events?

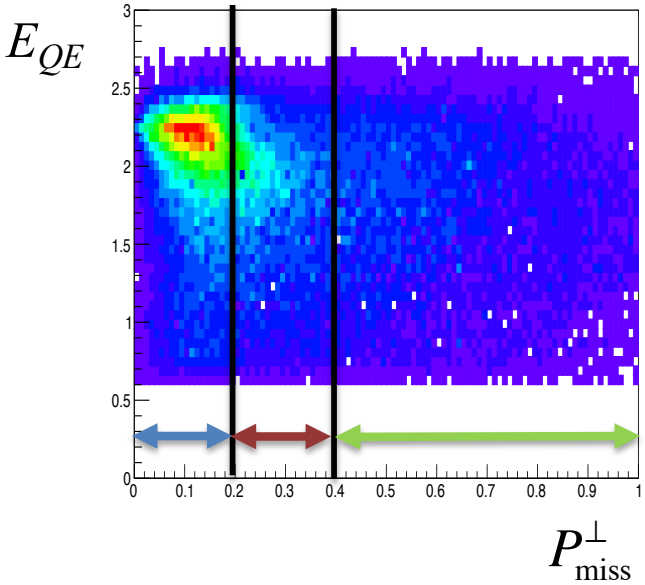
2.2 GeV ^{56}Fe

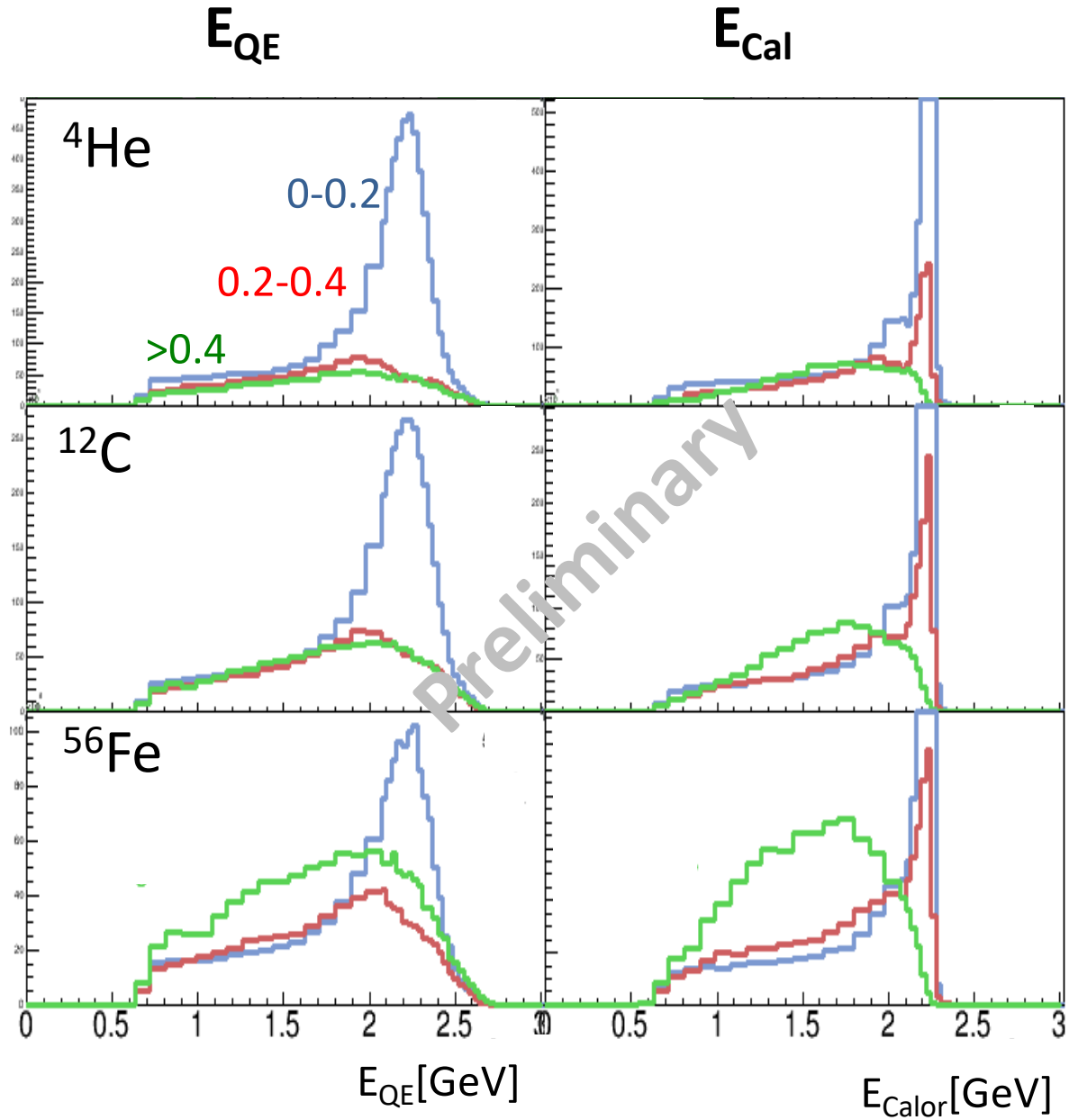


$$P_{\text{miss}}^{\perp} = P_{e^-}^{\perp} + P_{p}^{\perp} \approx P_{\text{init}}^{\perp}$$



$P^{\perp}_{\text{miss}}$ slices

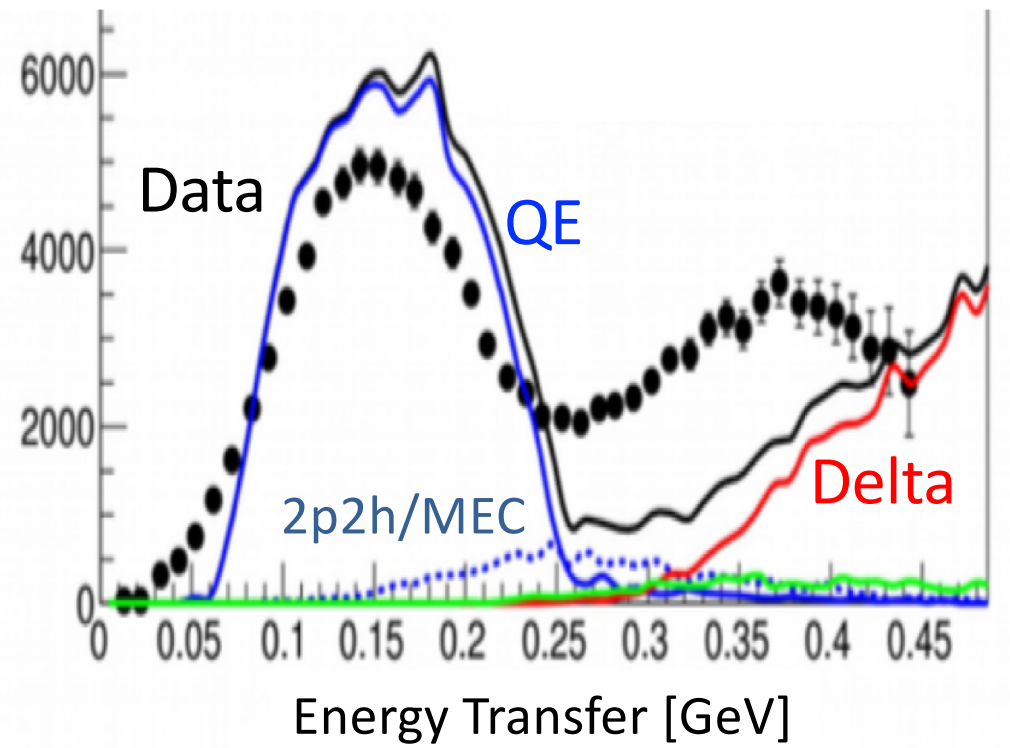




We're Also Improving Genie

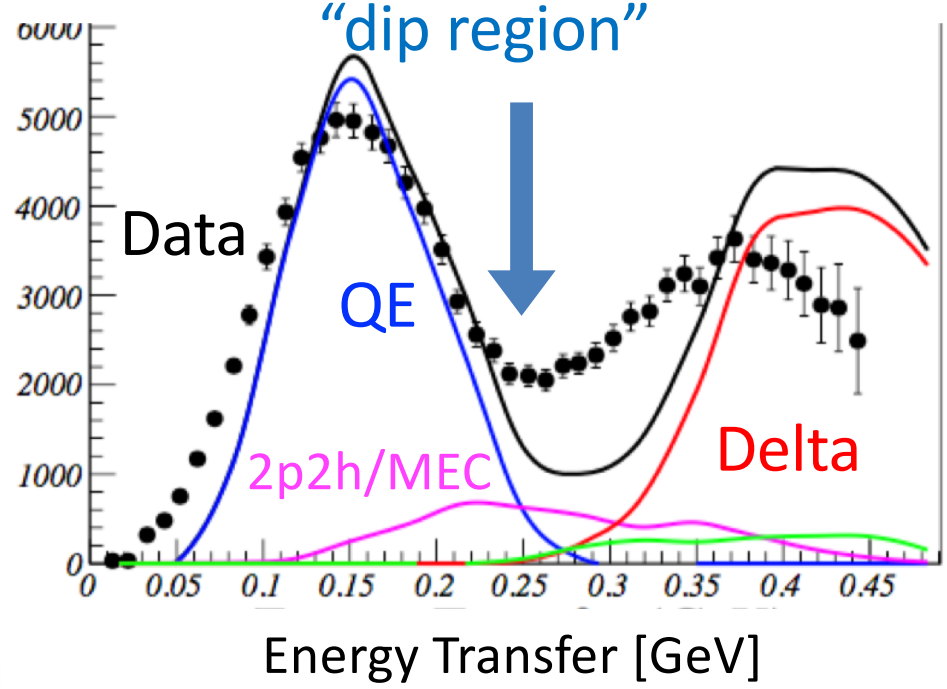
$$\mathrm{C(e,e')\ 560\ MeV}\ \theta = 60^o$$

Before (default)



After

Still big discrepancies in "dip region"



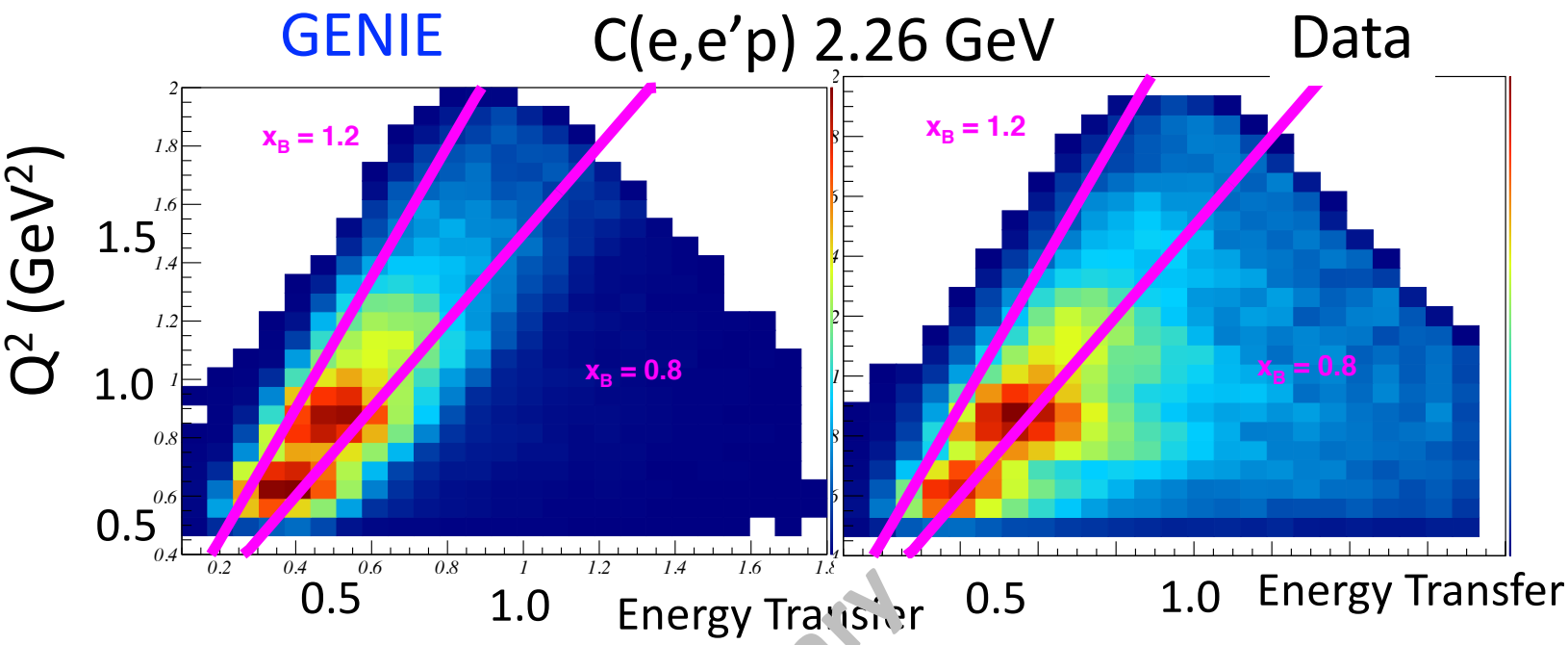
See M. Betancourt's talk, session J

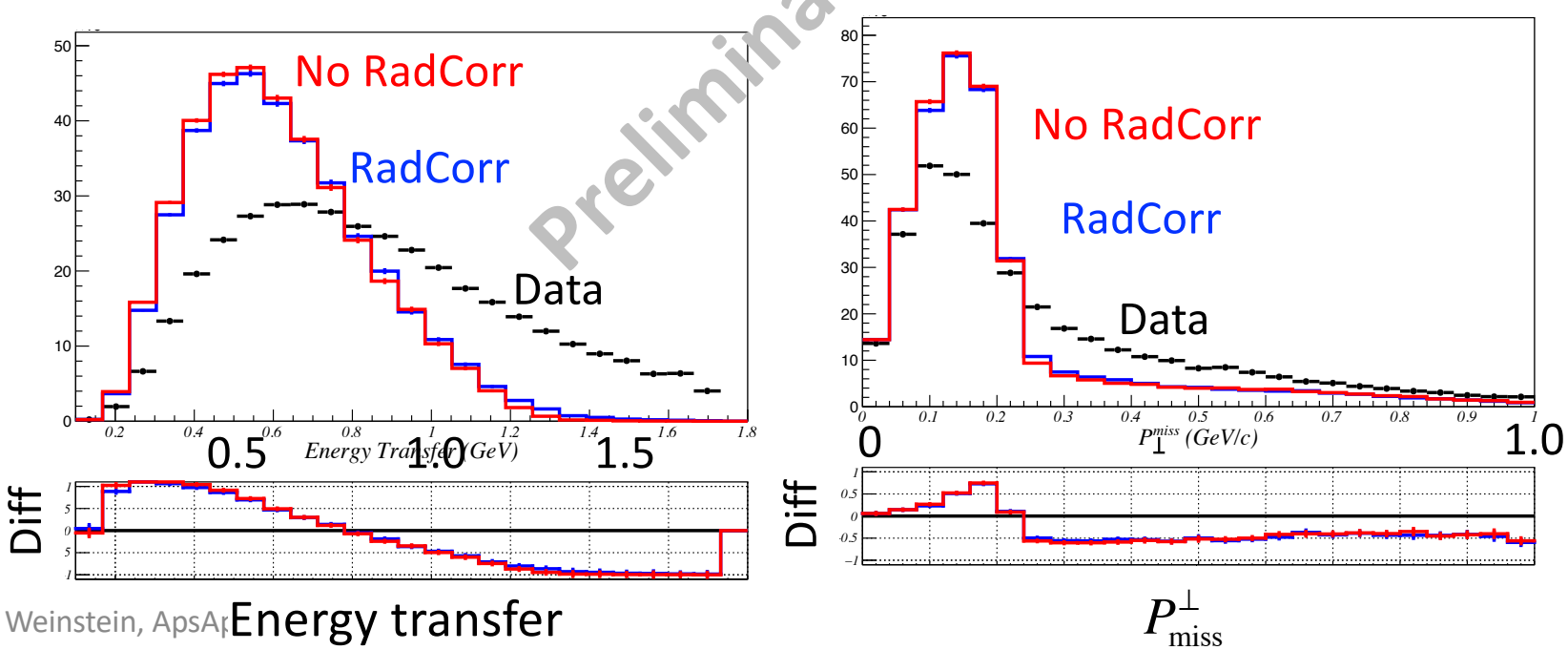
We're Also Improving Genie

1. Corrected lots of errors in electron GENIE
2. Made electron-GENIE more similar to neutrino-GENIE
    1. Lewellyn-Smith cross section for electrons
3. MEC/2p2h
4. Resonance
    1. Replaced old calculation with GSL Minimizer (now gives correct peak location)
    2. Switched to Berger-Seghal model
5. Nucleon momentum distributions
    1. Switched to Local Fermi Gas Model
    2. Implemented Correlated Fermi Gas with high-momentum tail
6. Added radiative effects

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

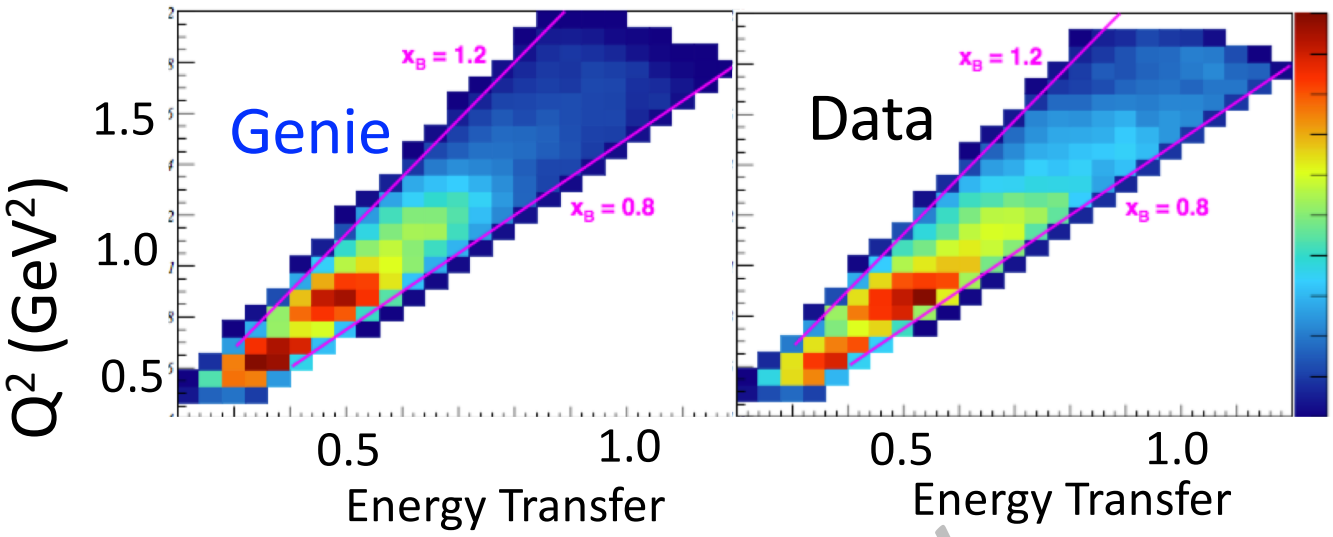
0π Data vs Genie: everywhere

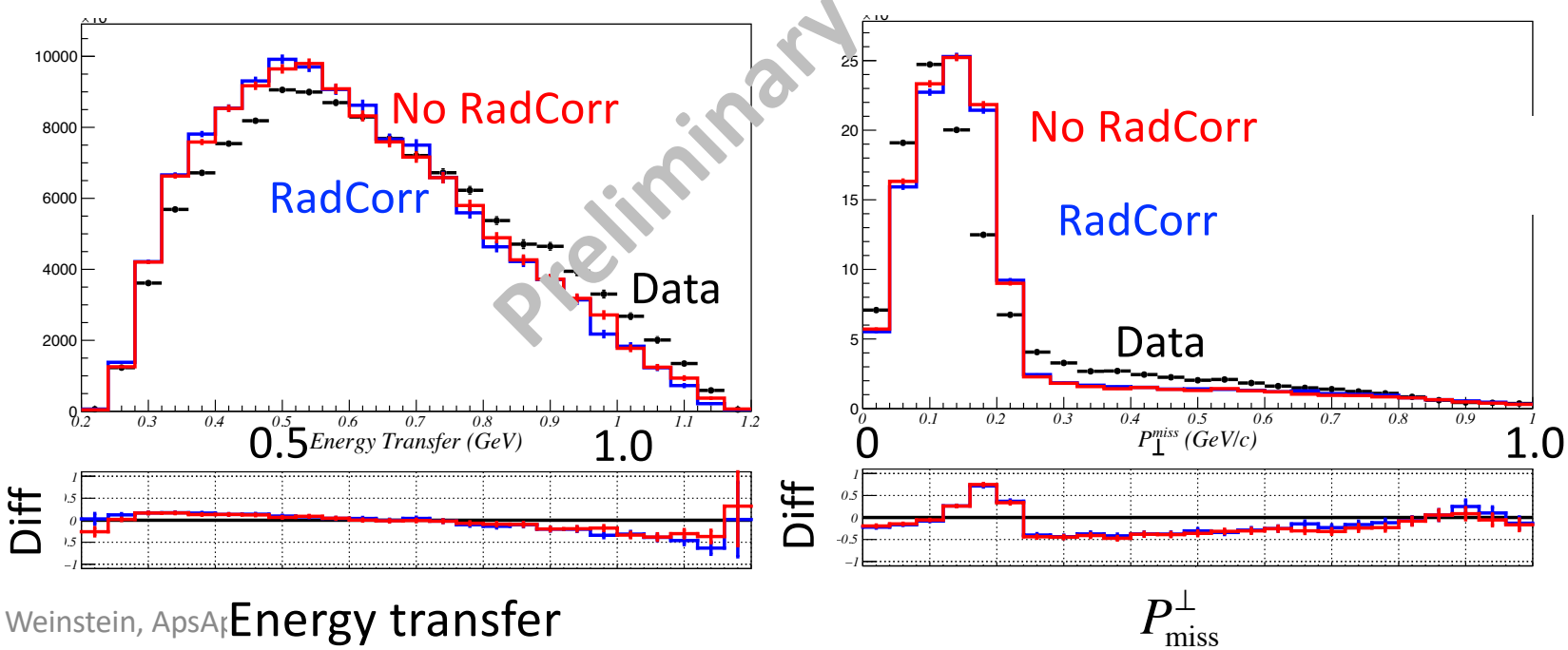




0π Data vs Genie: QE Peak

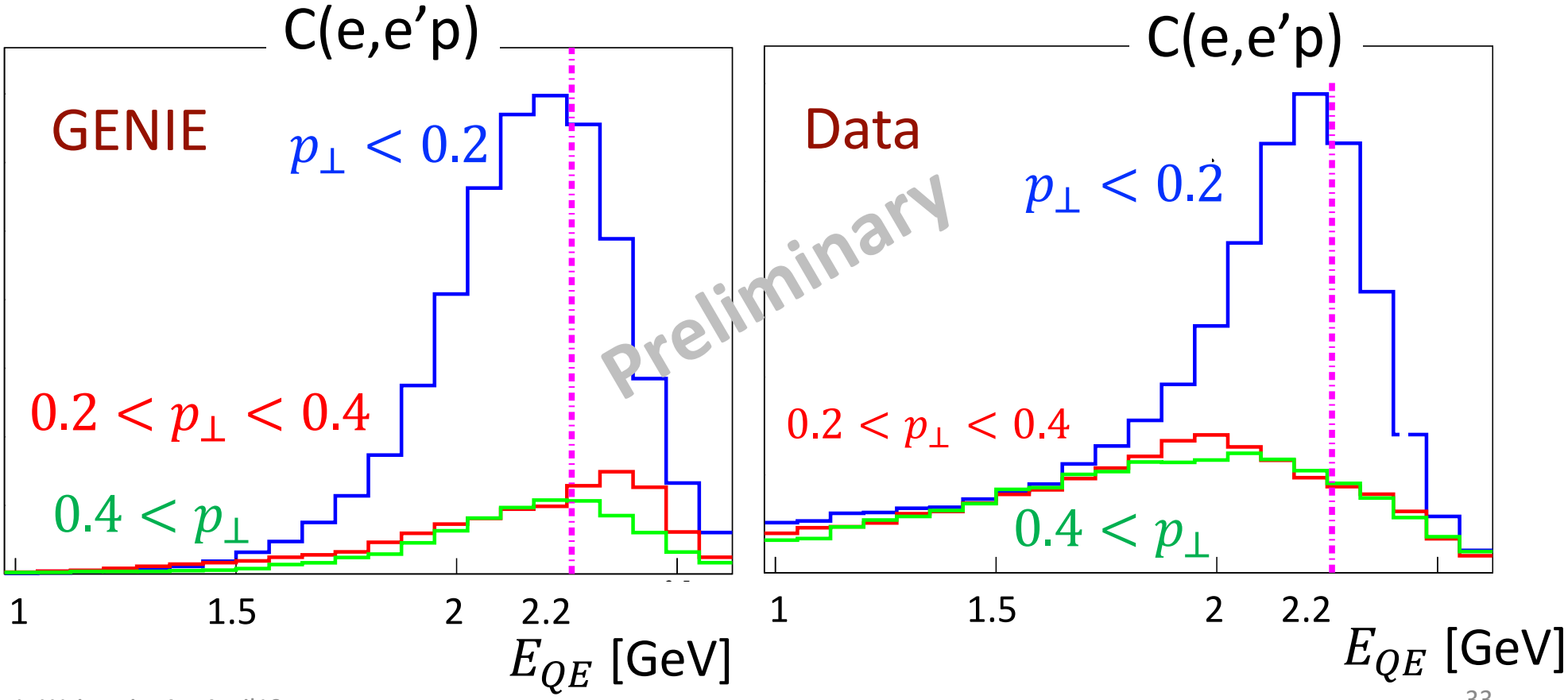
C(e,e'p) 2.26 GeV, 0.8 < x < 1.2





Data vs Genie: E_{beam} Reconstruction

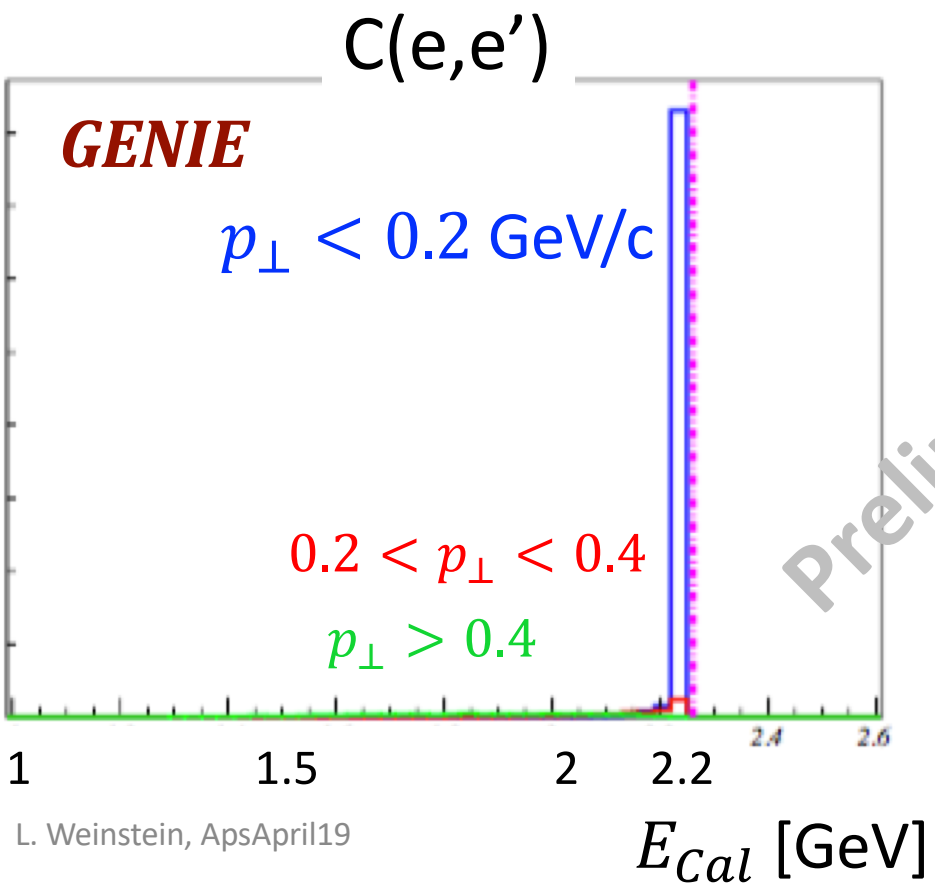
$$E_{QE} = \frac{2ME_l + 2M\varepsilon - m_l^2}{2(M - E_l + |k_l|\cos\theta)}$$

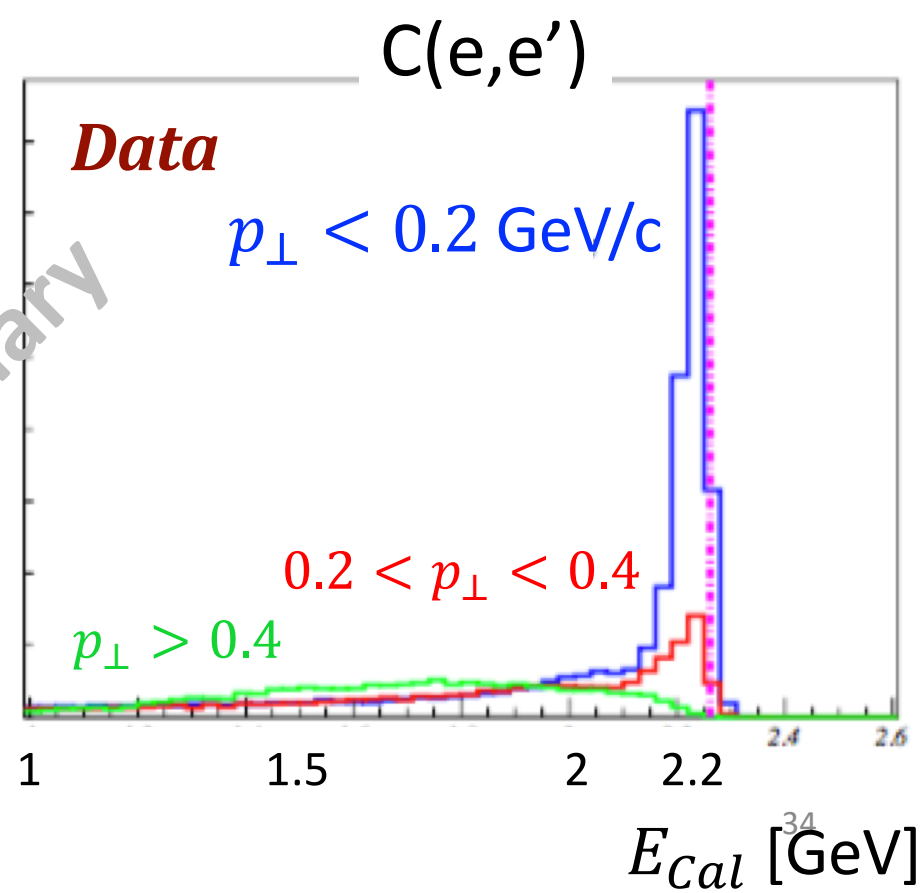


Peaks in same location

Data vs Genie: E_{beam} Reconstruction

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





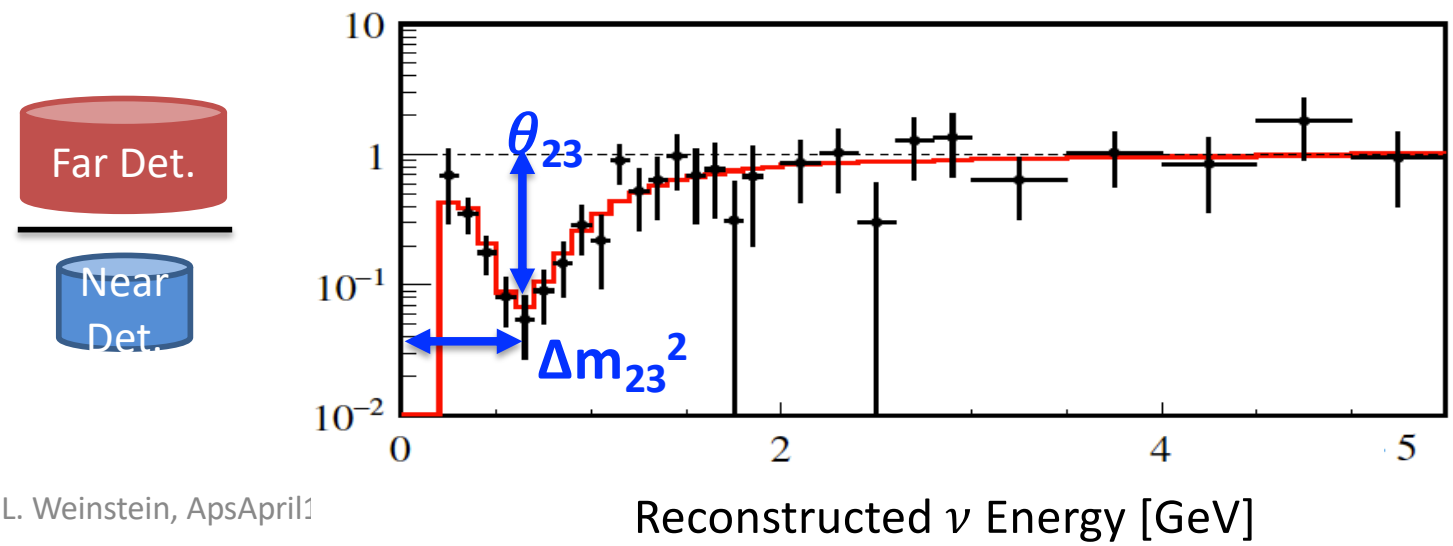
Preliminary

Data vs Genie: E_{beam} Reconstruction

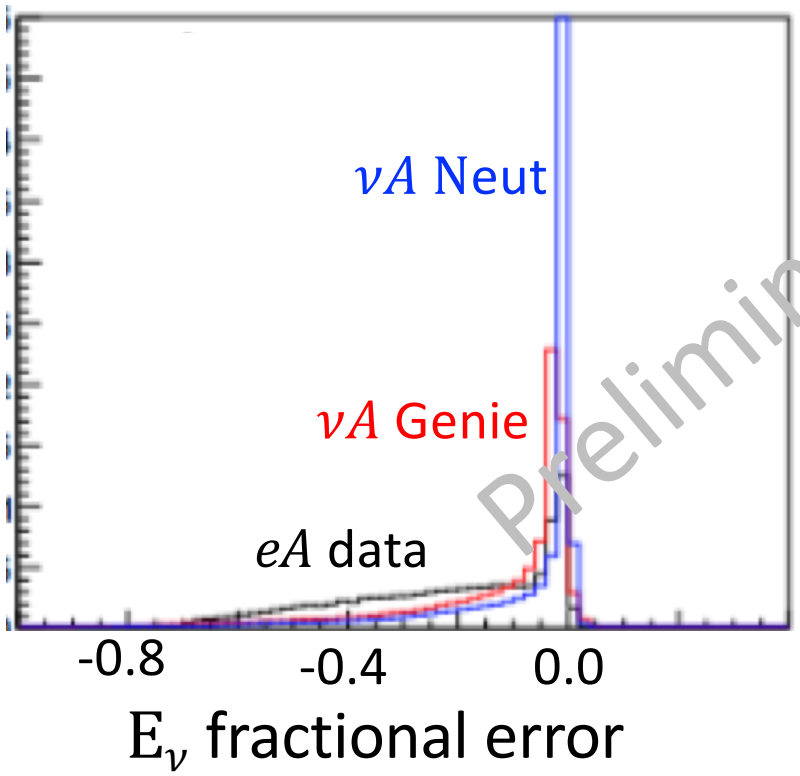
Fe	e⁻ Data	e GENIE	ν GENIE
2.2 GeV	25%	67%	66%
4.4 GeV	16%	68%	66%

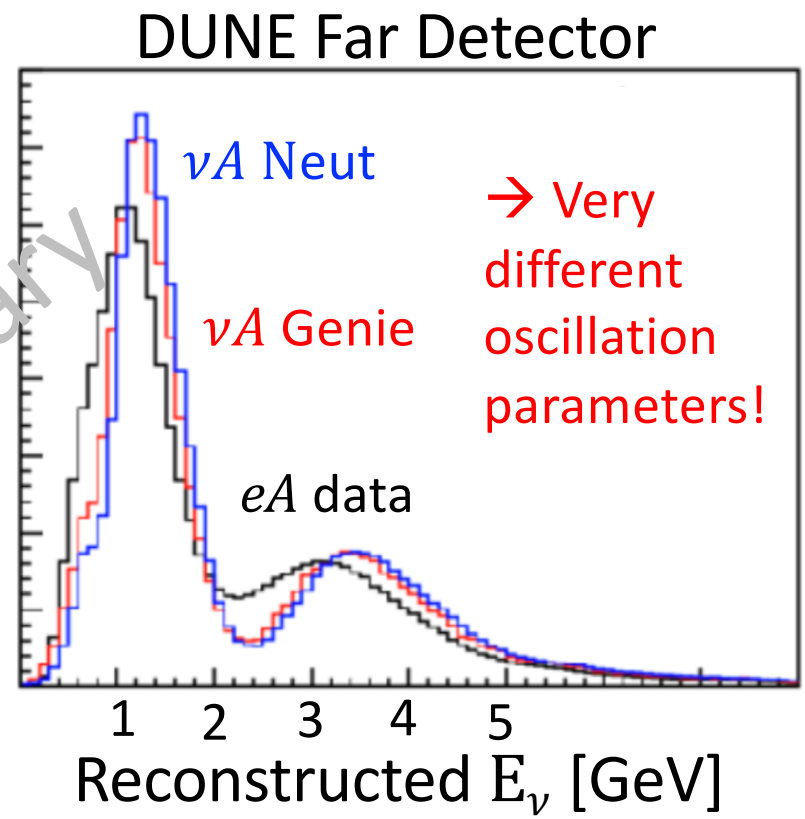
Fraction of Fe$(e, e'p)$ and Fe$(\nu, \mu^- p)$ events with E_{Cal} within 5% of E_{beam}

Errors affect both θ_{23} and Δm^2_{23}



Apply CLAS data to DUNE Oscillation





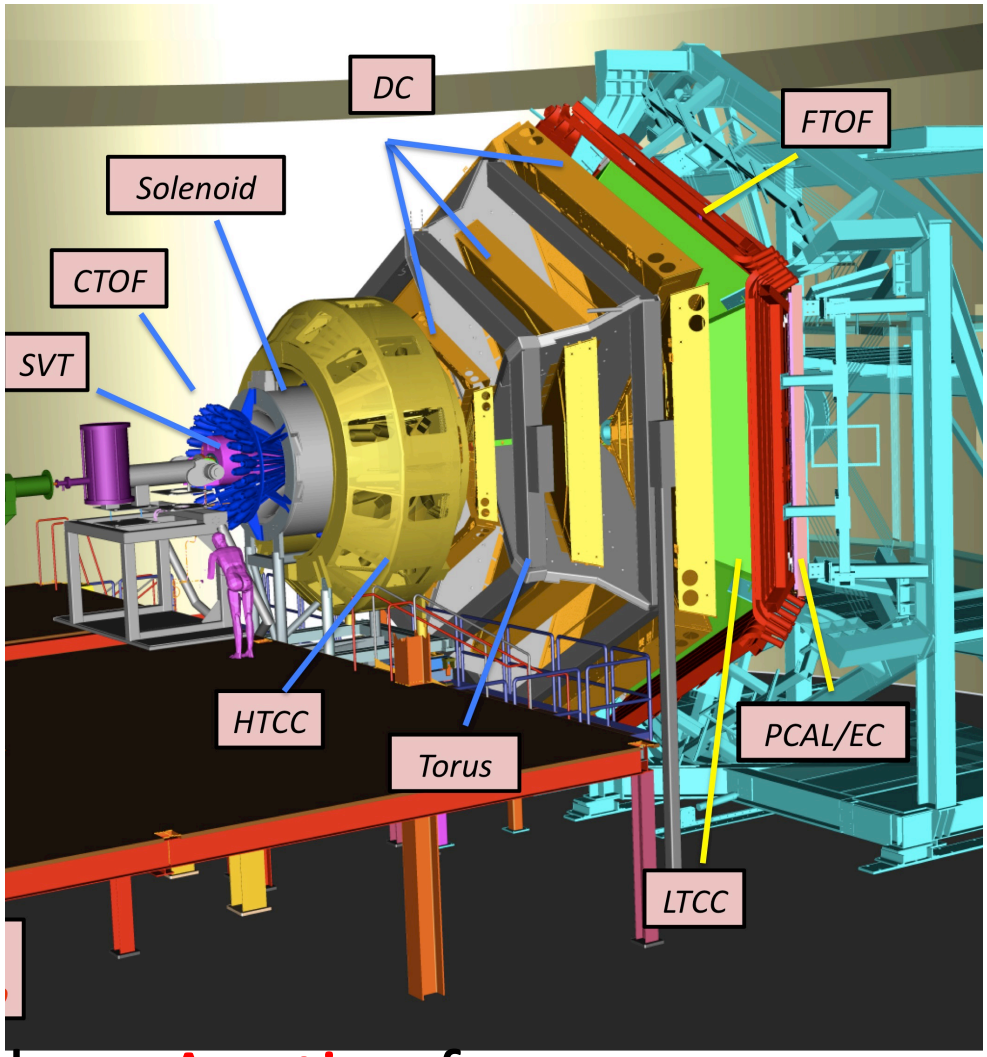
(Chris Marshall, LBNL)

- 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

CLAS12

CLAS12

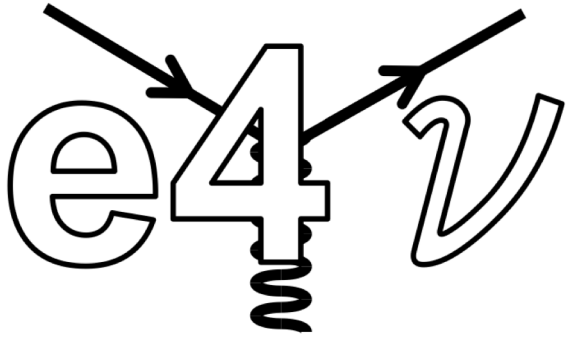
- forward detector (8 – 40°)
  - Toroidal magnetic field
  - $\frac{\delta p}{p}$ ~ 0.5—1%
  - Neutrons:
    - 50% effi for p > 1 GeV/c
    - $\frac{\delta p}{p}$ ~ 10-15% for 1 GeV/c
- Hermetic central detector (40 – 135°)
  - 5 T solenoidal field
  - Neutron effi ~ 10—15%
  - Neutron $\frac{\delta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



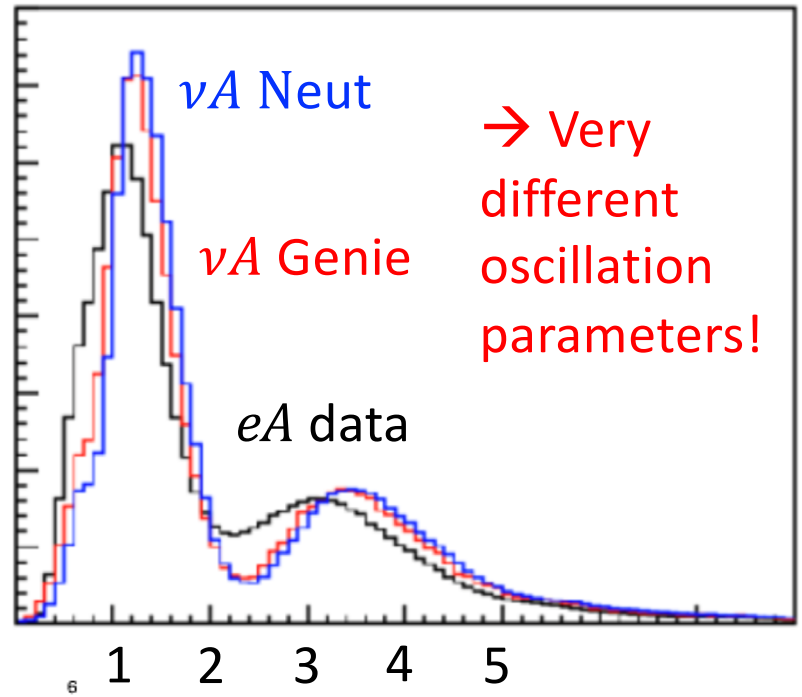
- 45 beam days approved with an A rating for
  - 1.1, 2.2, 4.4, and 6.6 GeV beam energies
  - d, He, C, O, Ar, Sn and SRC targets

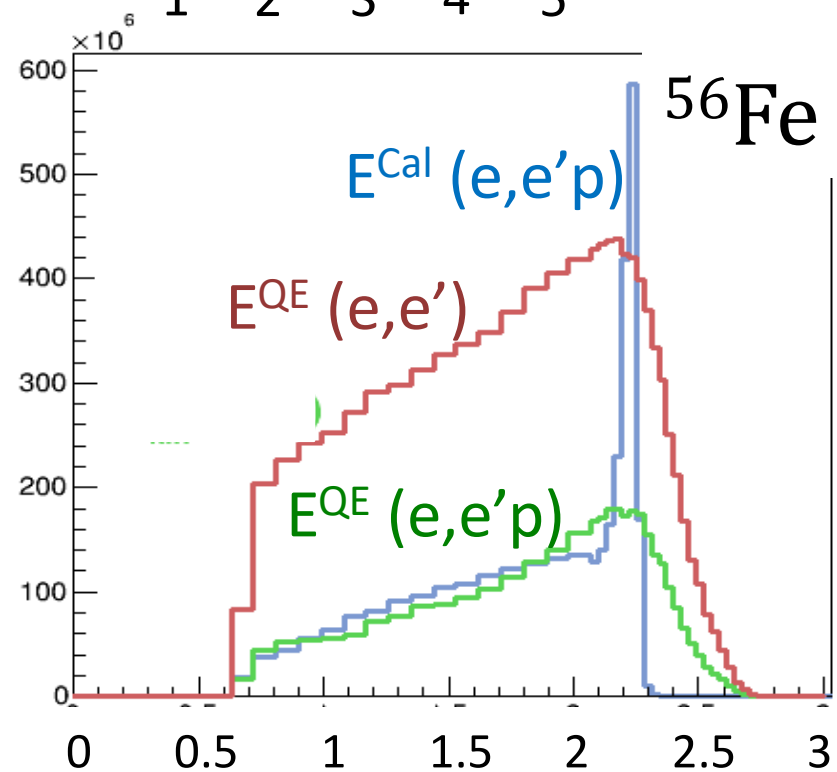
e4ν Goals

- 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
- Neutrino community input is welcome



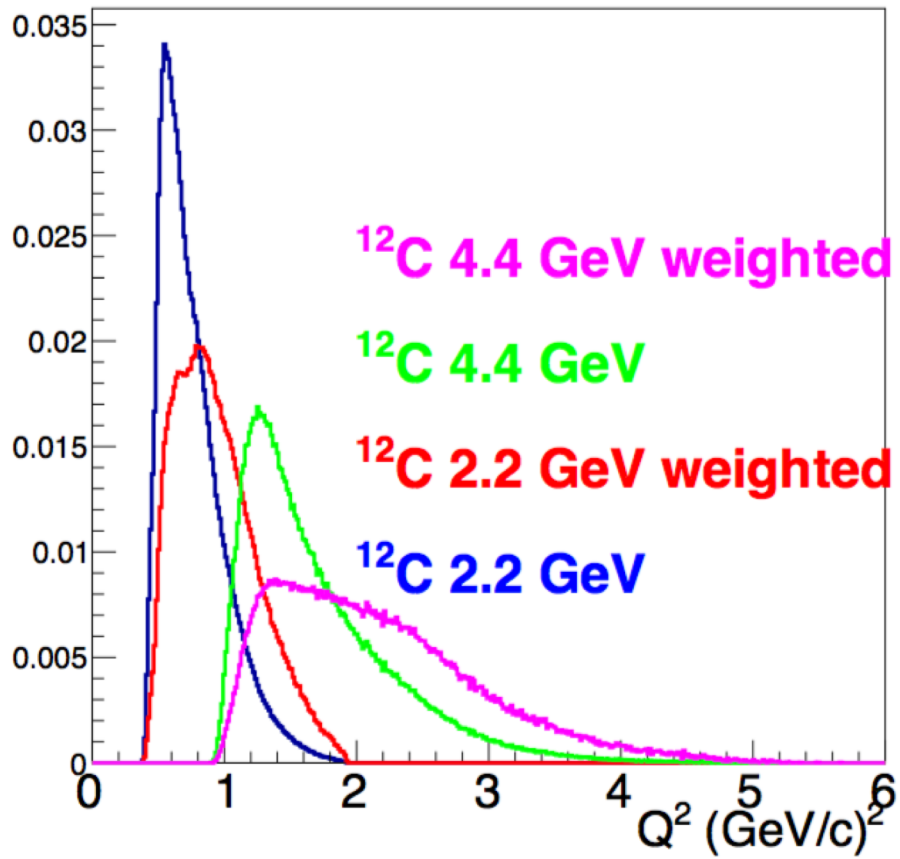
- Nuclear physics is complicated!
- Electron scattering can contribute dramatically to neutrino experiments
  - Similar physics
  - Lots of data available
  - Lots more to come
- Neutrino community input is welcome



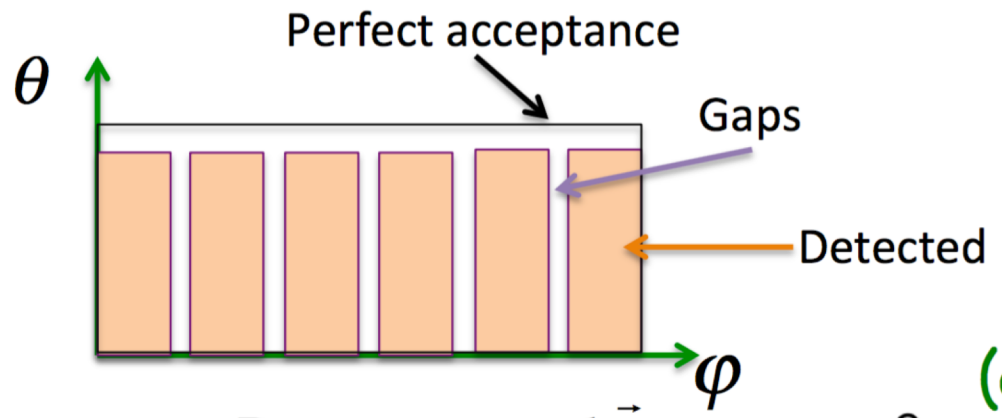


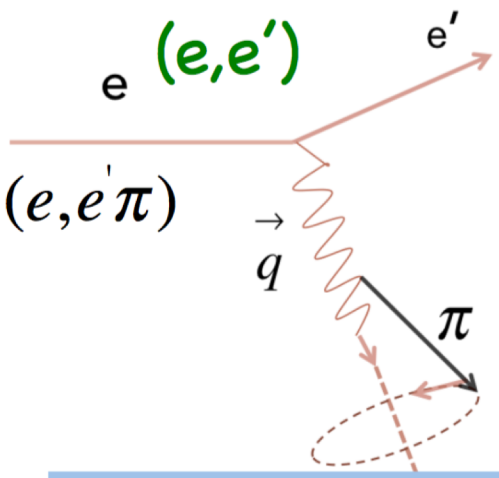
Backup slides

Mott weighting

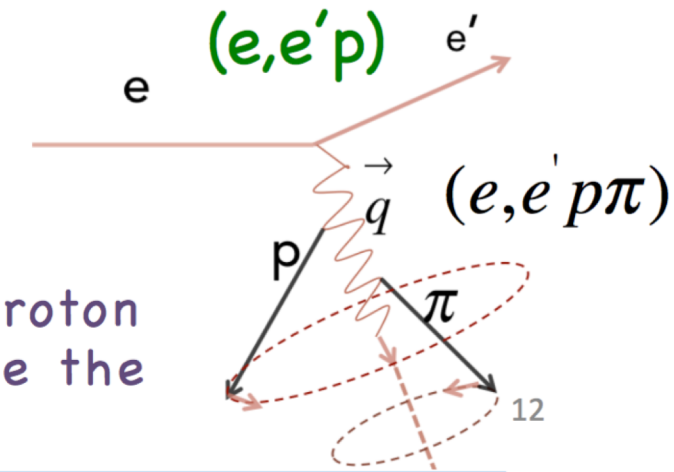


E2a ^{3}He 2.261 GeV





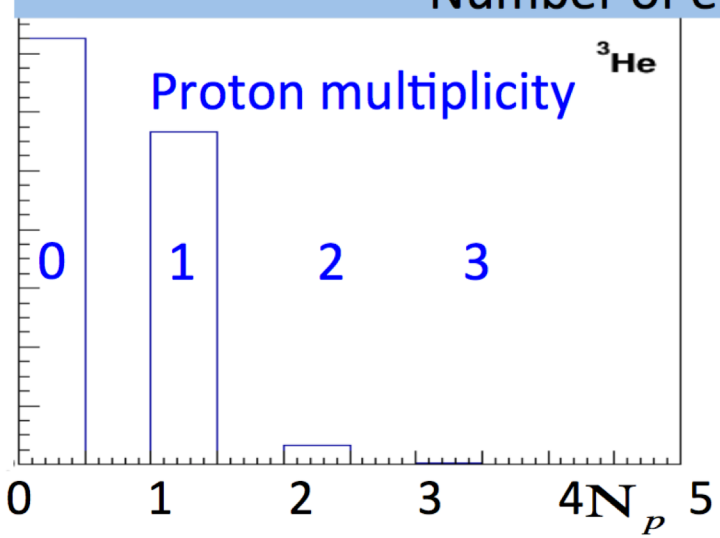
Rotate π around $\vec{q}$ to determine detection acceptance

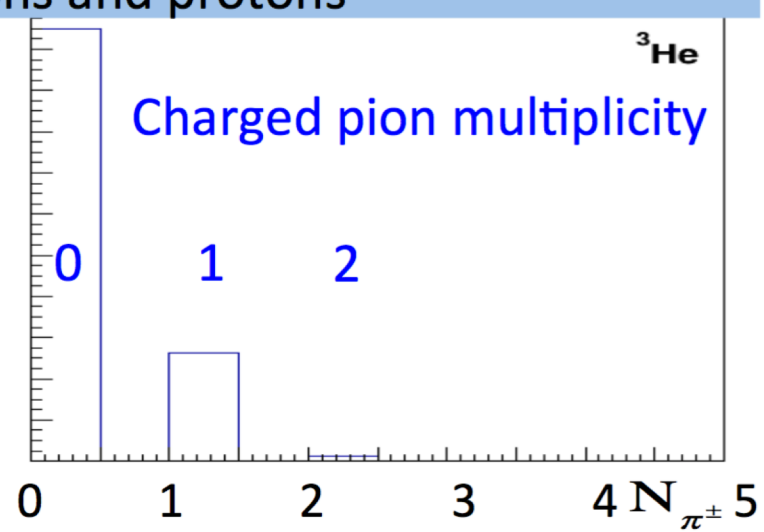


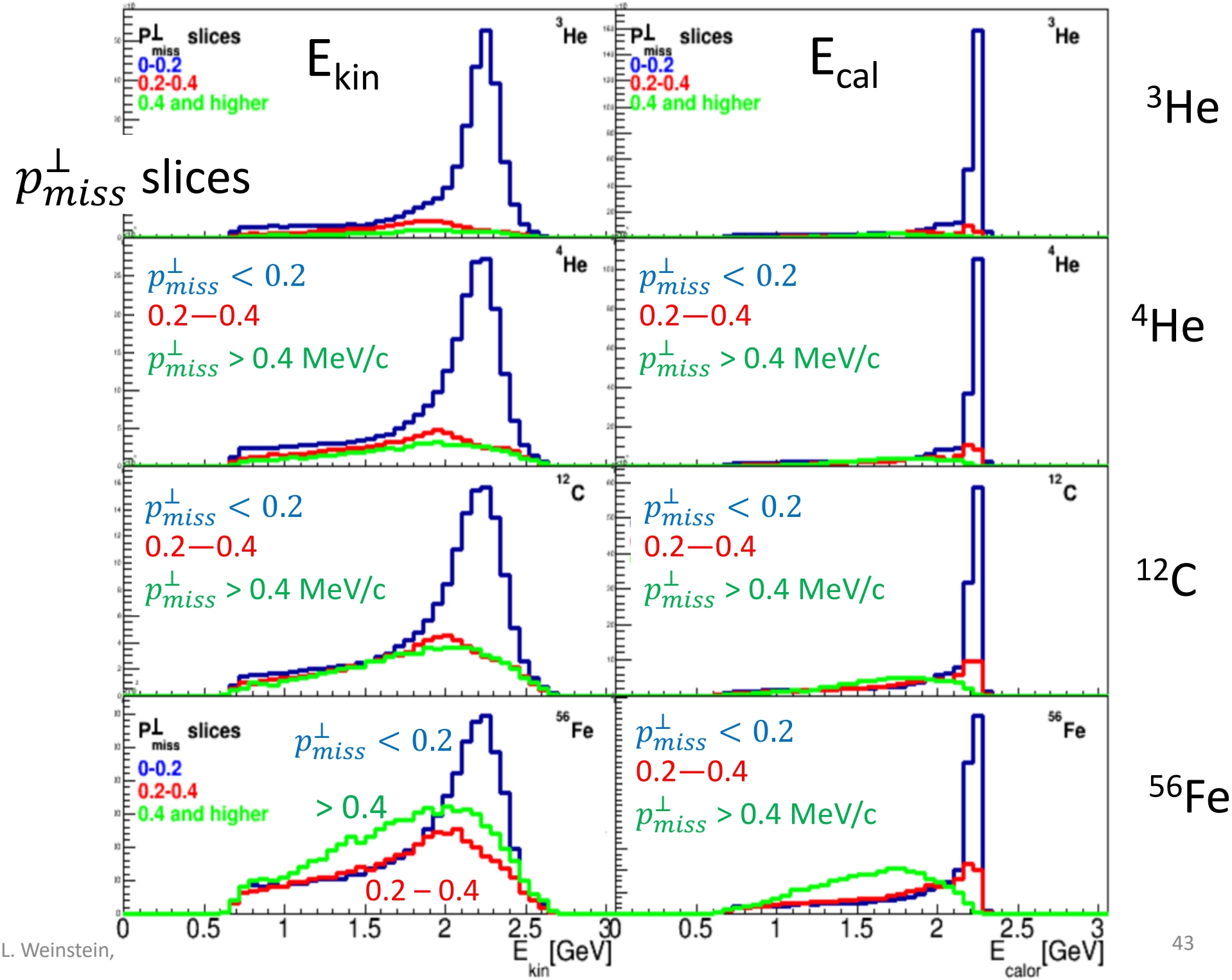
Subtracting undetected 2 proton events to get 1proton sample the similar way

12

Number of events with pions and protons

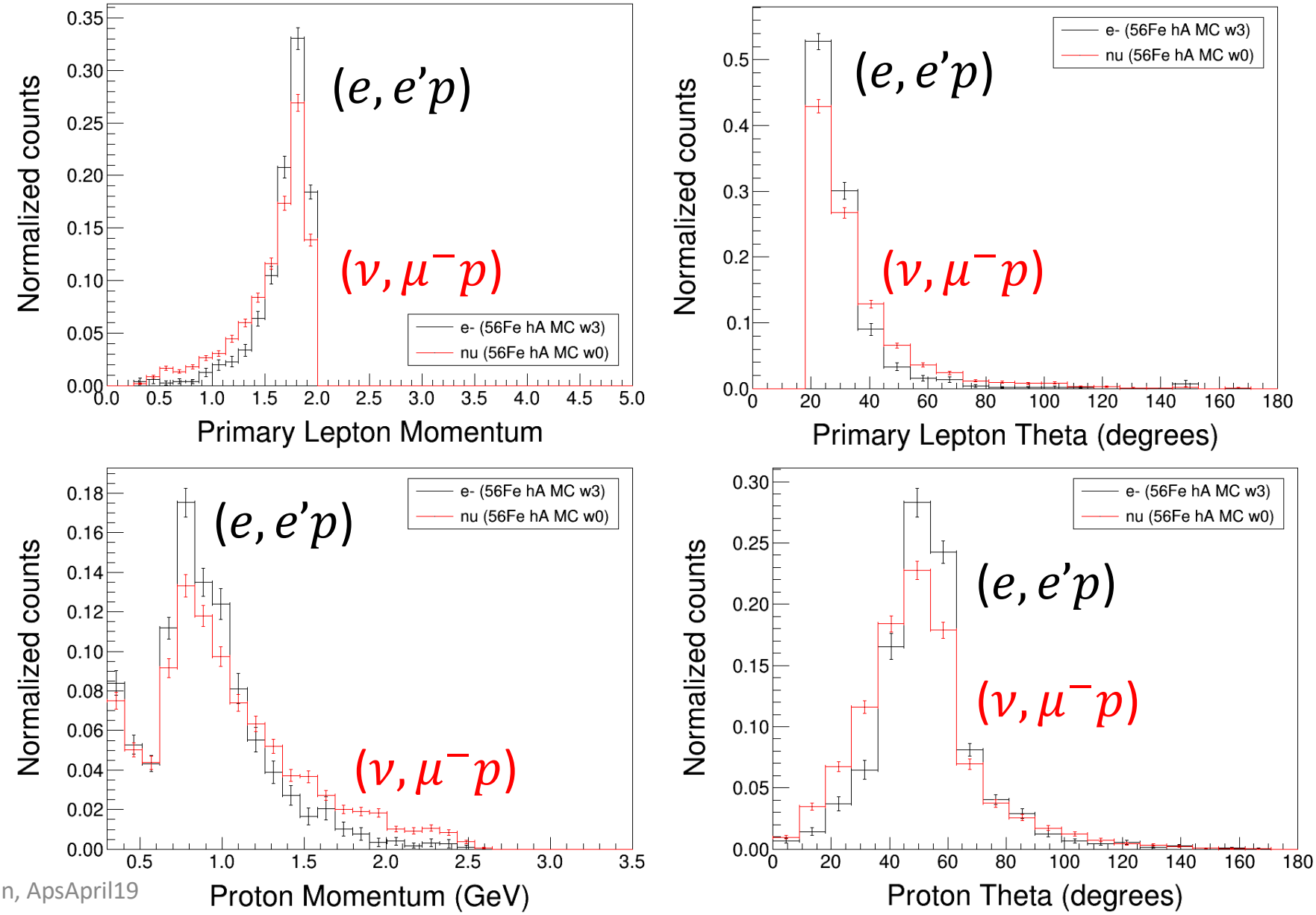





$p^{\perp}_{miss}$ slices
E_{kin}
E_{cal}
^{3}He
^{4}He
^{12}C
^{56}Fe
$p^{\perp}_{miss}$ slices
0-0.2
0.2-0.4
0.4 and higher
$p^{\perp}_{miss} < 0.2$
0.2—0.4
$p^{\perp}_{miss}$ > 0.4 MeV/c
> 0.4
0.2 – 0.4
E_{kin} [GeV]
E_{calor} [GeV]

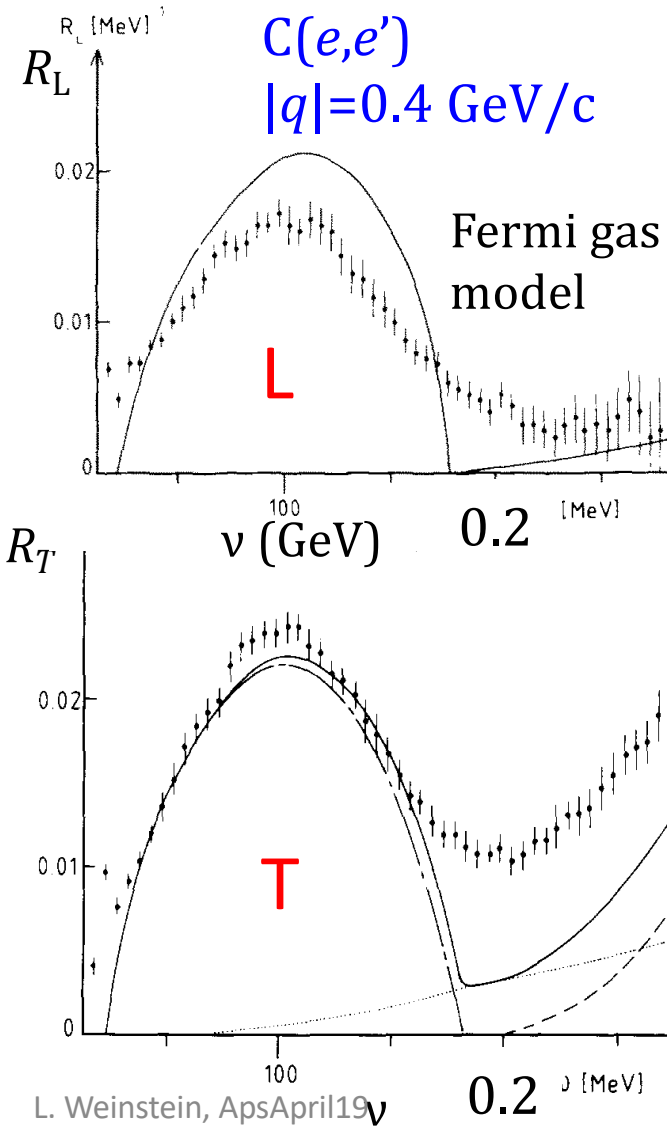
Similarity of electron and neutrino GENIE

2.2 GeV Fe, zero-pion. QE



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

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

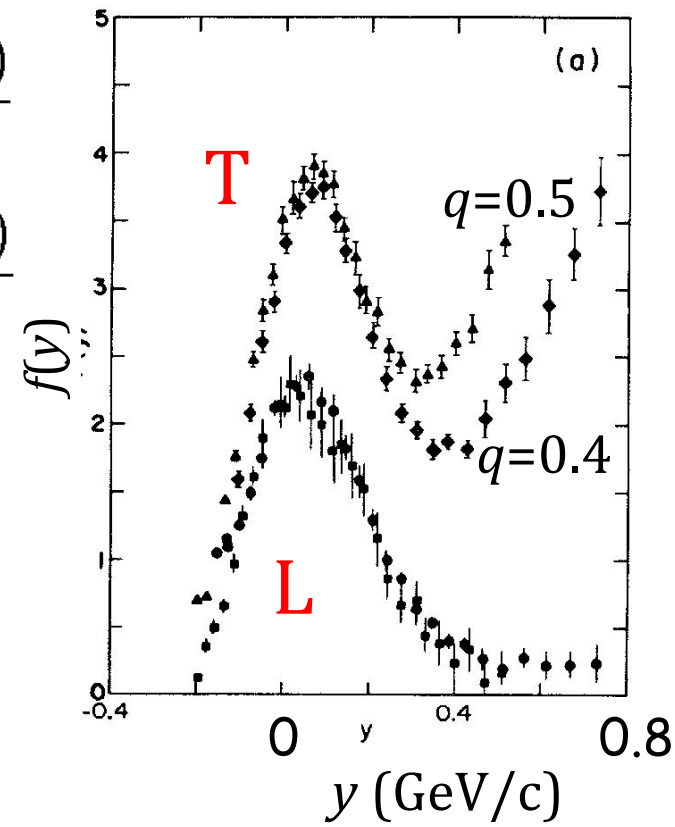


y = minimum initial nucleon momentum
= $m\nu/q - q/2$ (nonrelativistic only!)
f = reduced response function

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

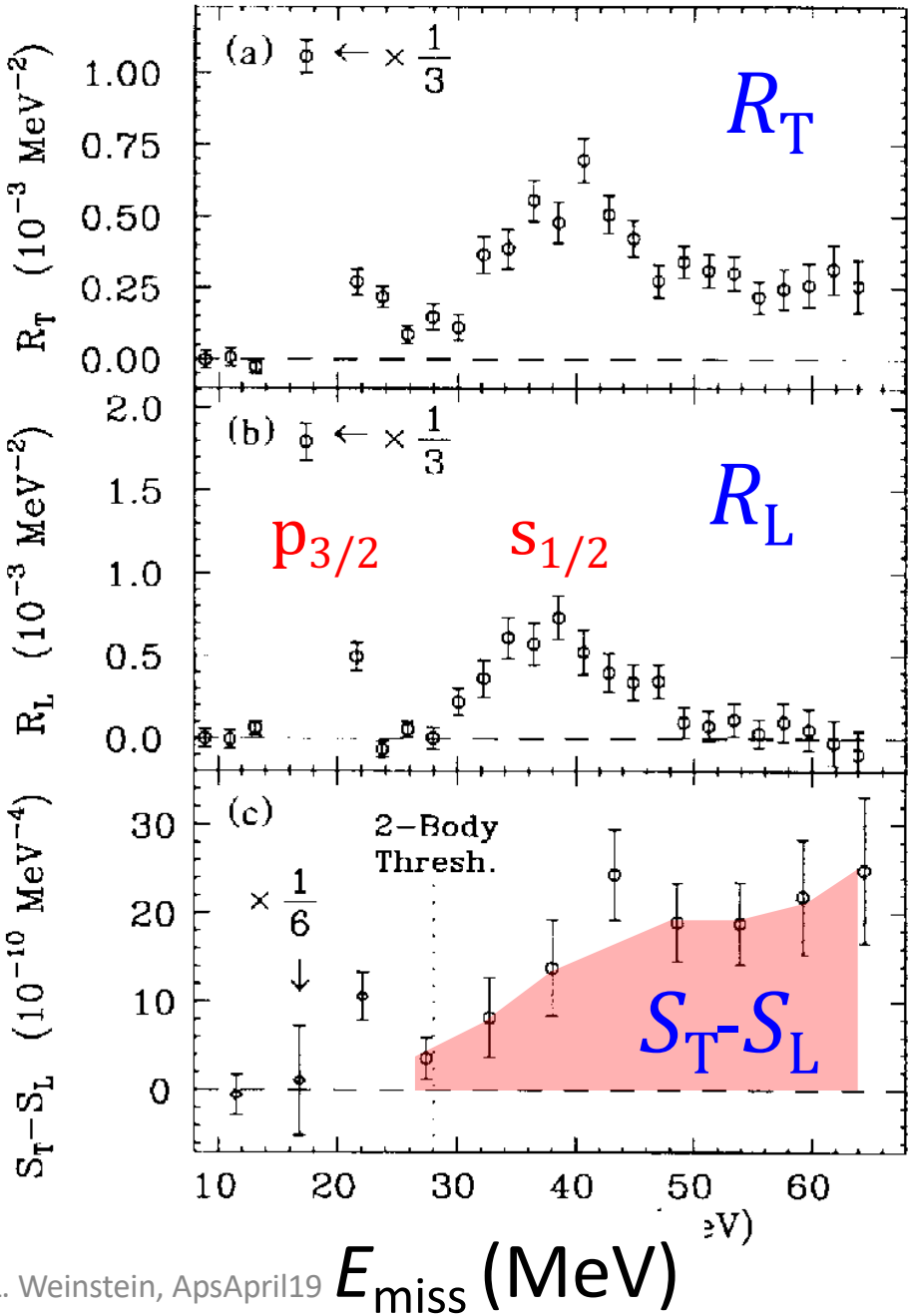
$$f_T(Q^2,\omega) \propto \frac{R_T(Q^2,\omega)}{\tilde{G}_M^2(Q^2)}$$

- L scales
- T scales
- T≠L!!



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

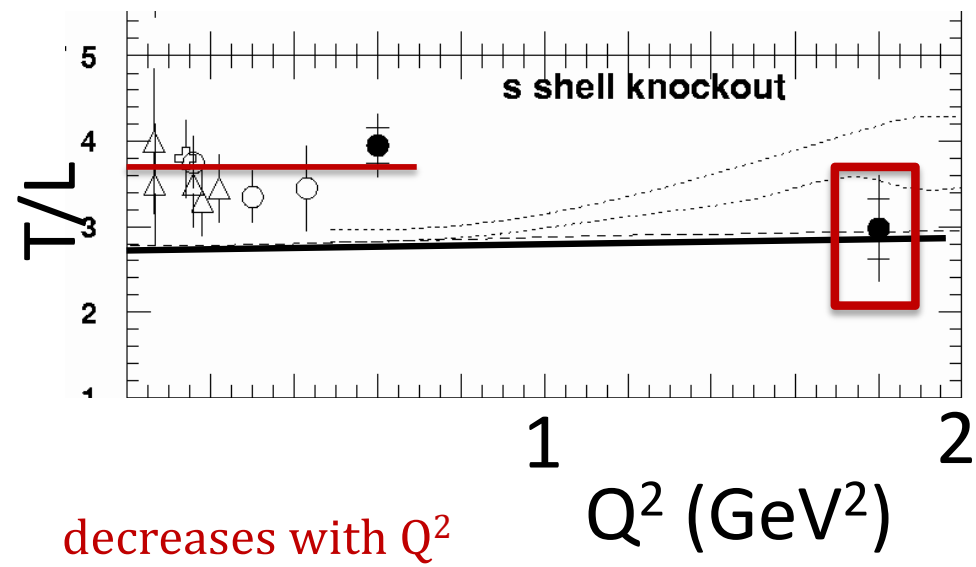
Extra Transverse even at the QE peak



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

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?

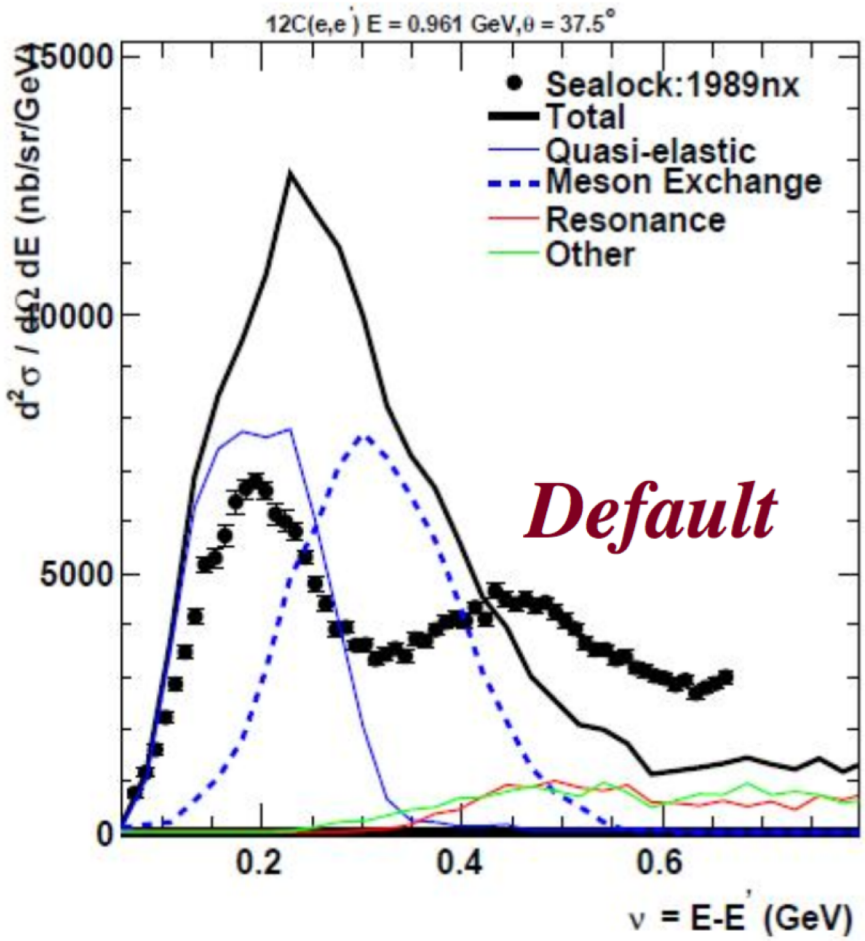
- The scattering cross section depends primarily on energy and momentum transfer
- For (e,e'p):
  - $\frac{d^6\sigma}{d\Omega_e d\Omega_p dE_p d\omega} = \sigma_{Mott}[v_L R_L + v_T R_T + v_{LT} R_{LT} cos\phi_{pq} + v_{TT} R_{TT} \cos 2\phi_{pq}]$
  - Kinematic factors v_i depend on $\{Q^2, \omega, \theta_e\}$
  - 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)

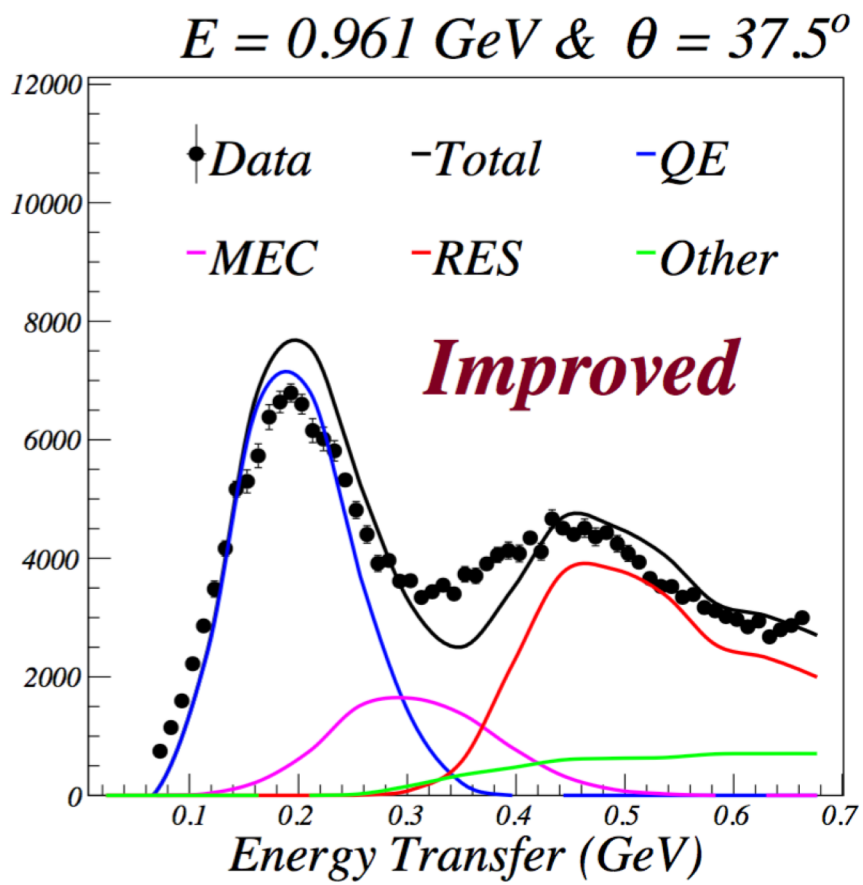
How to use electron data for neutrino measurements

- 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

GENIE Development

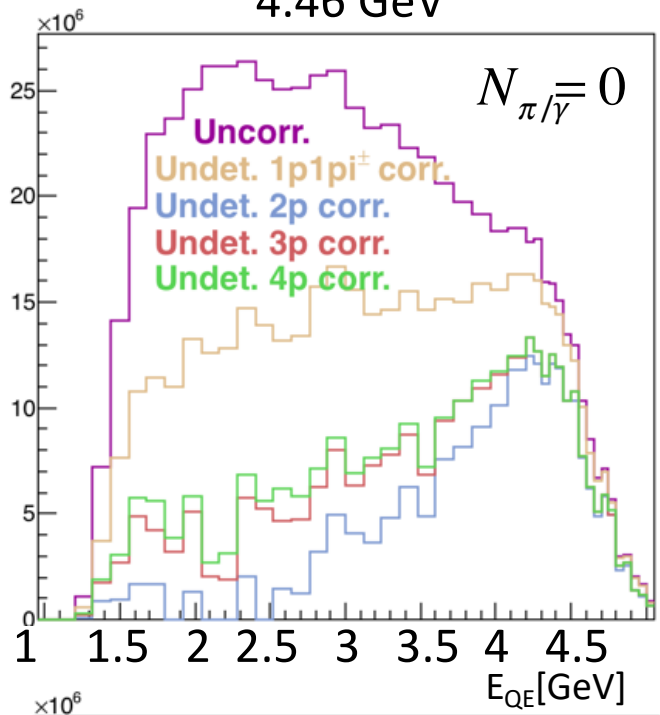
Standard Candle → Inclusive Analysis on ^{12}C

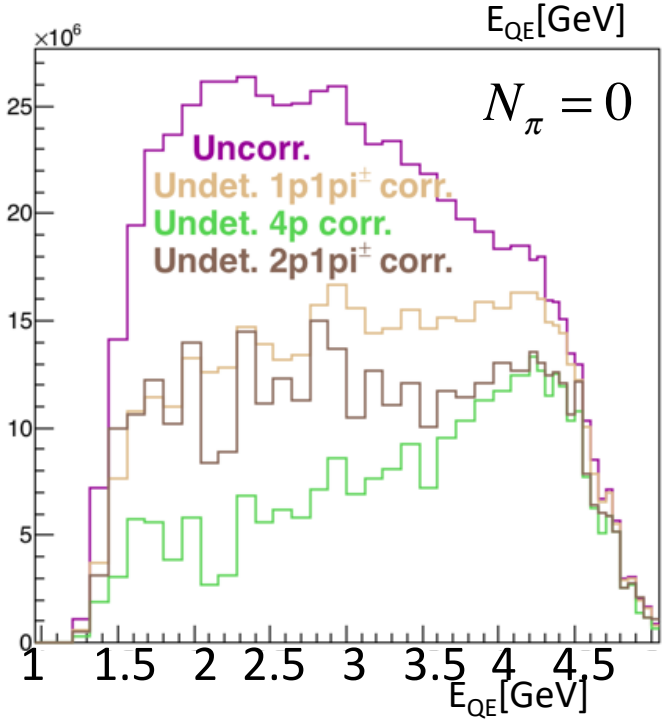


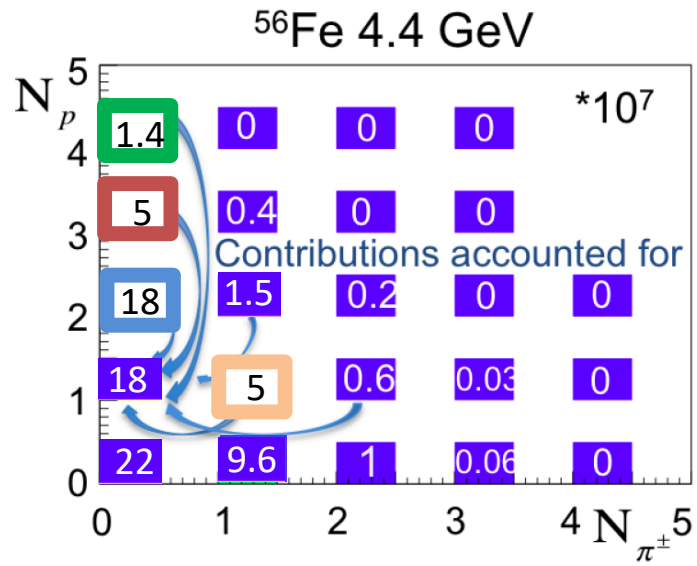


Proton subtraction

^{56}Fe (e,e'p) 4.46 GeV







Subtraction converges

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.