Electron-scattering constraints for neutrino-nucleus interactions

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Elba 2019

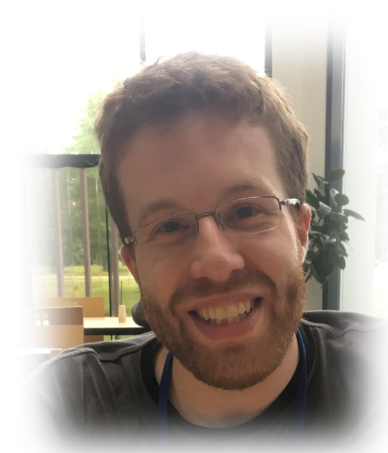
Collaboration

- 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)



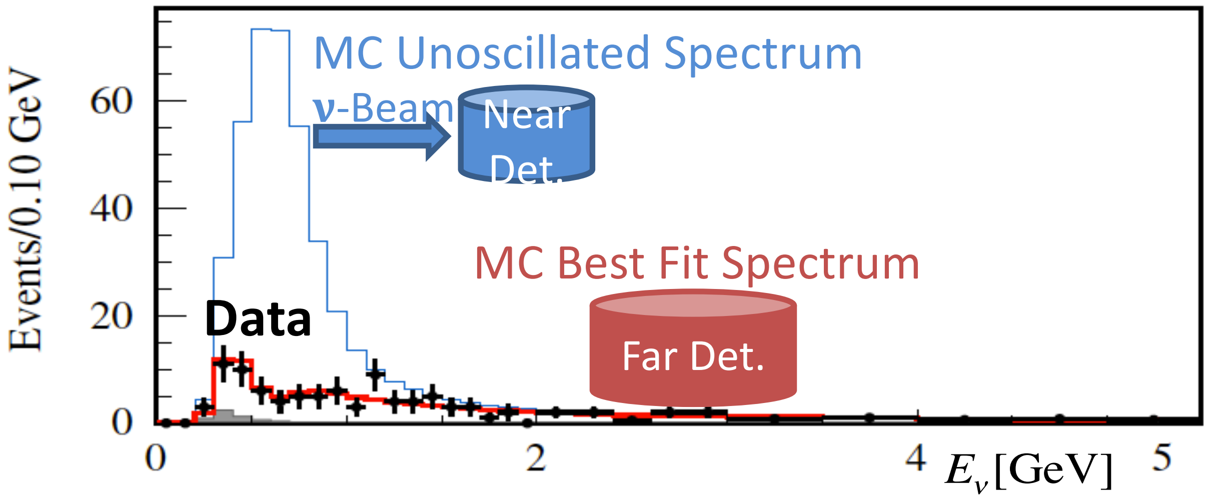
Florian Hauenstein (ODU)

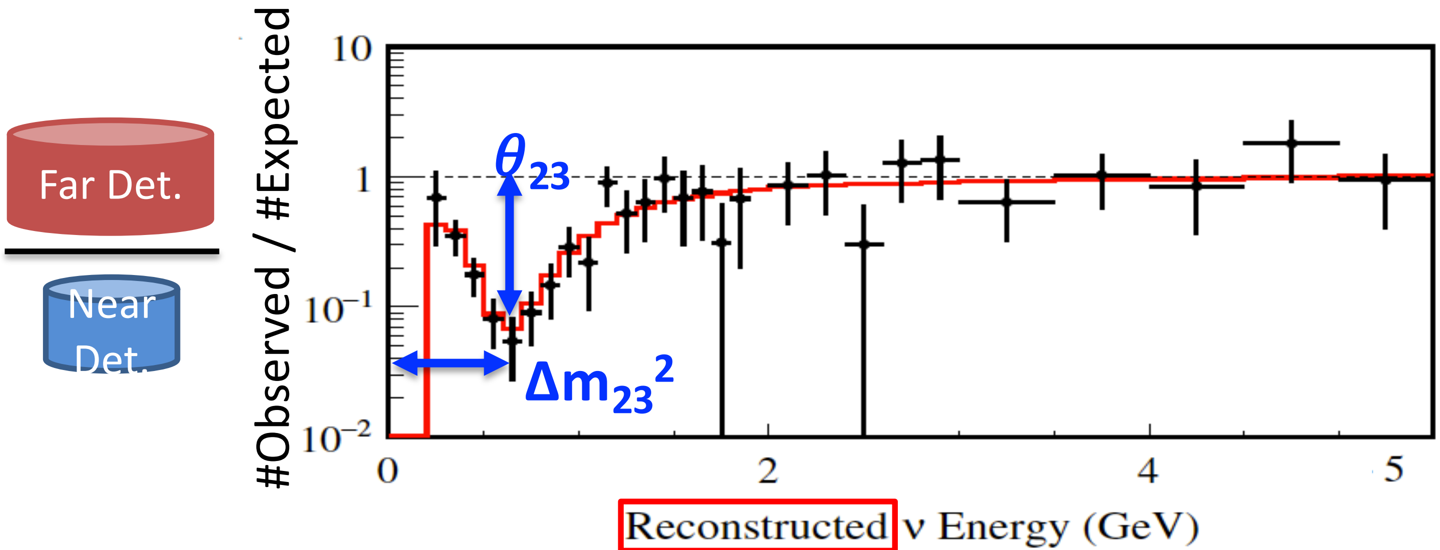
Outline

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

Measuring Neutrino Oscillations

T2K experiment L=295km





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

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

Event Generators and Neutrino Oscillations

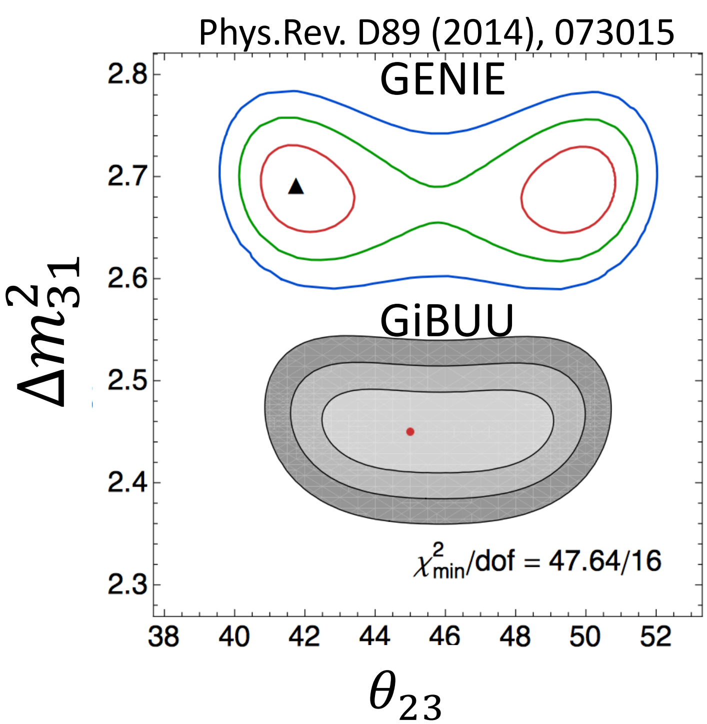
Measure neutrino-nucleus reaction products in detector

- 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.



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

Event Generators and Neutrino Oscillations

M

•

Fr n

• U ...) to

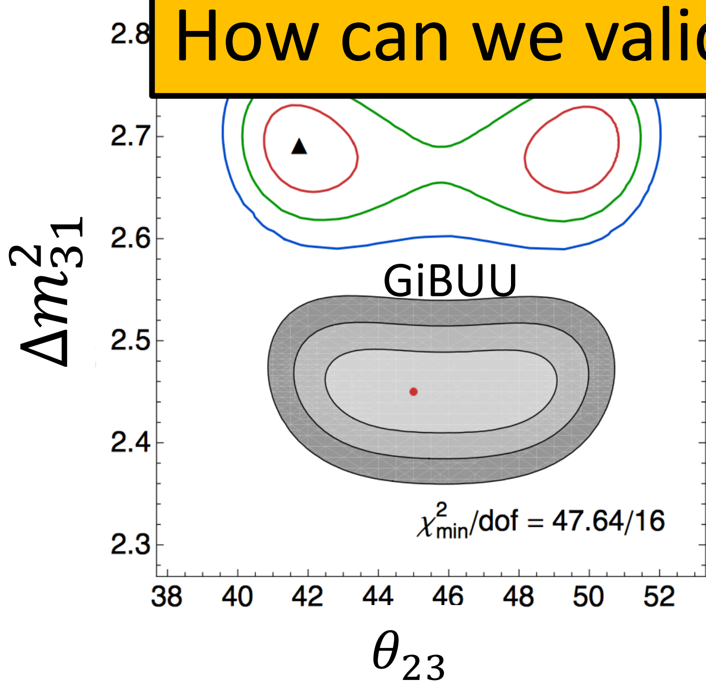
on

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

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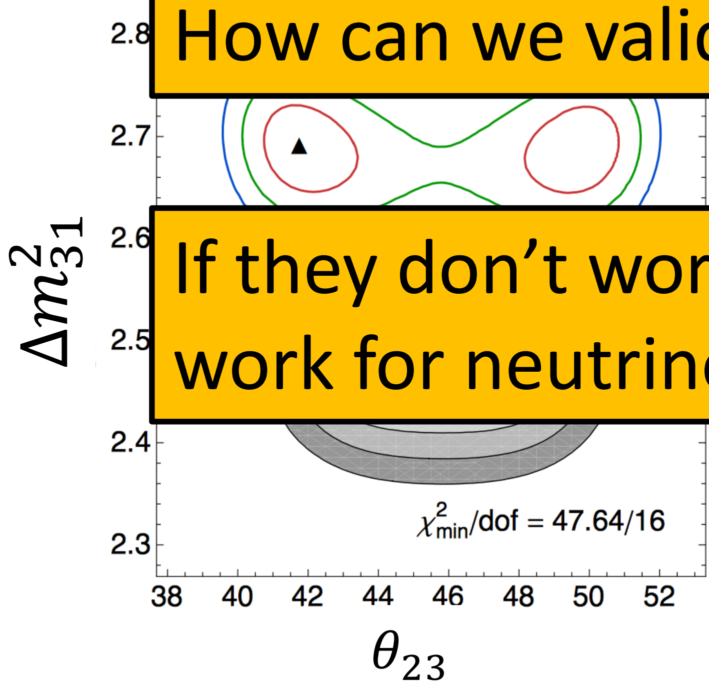


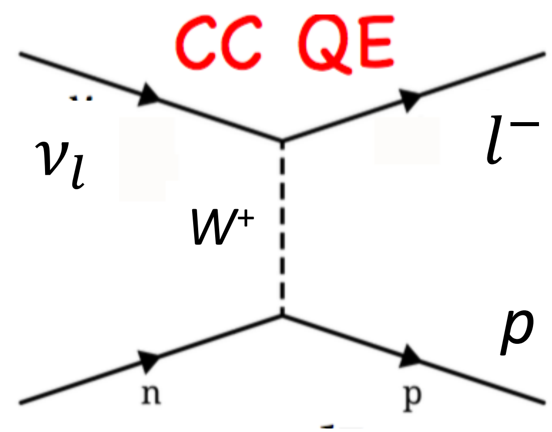
Events created with GiBUU and

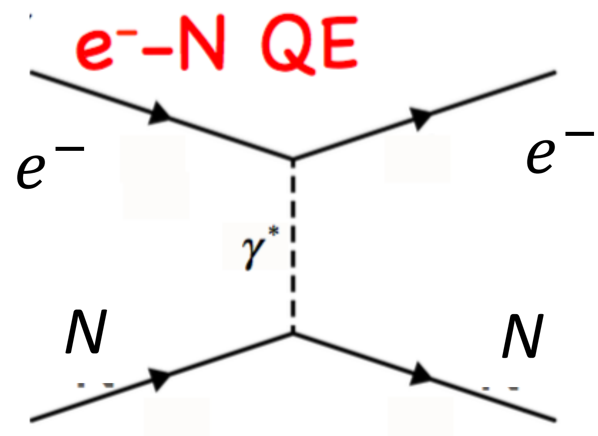
… trino- … on … s the extracted oscillation parameters

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

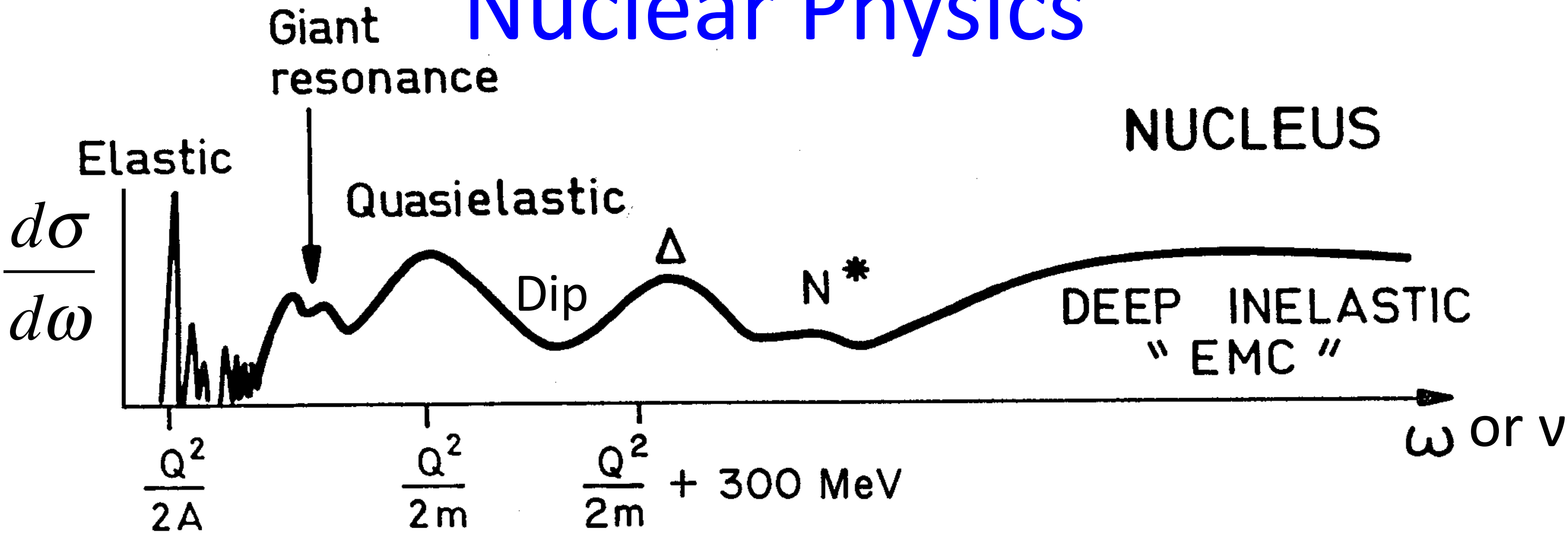
Why electrons?

- 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



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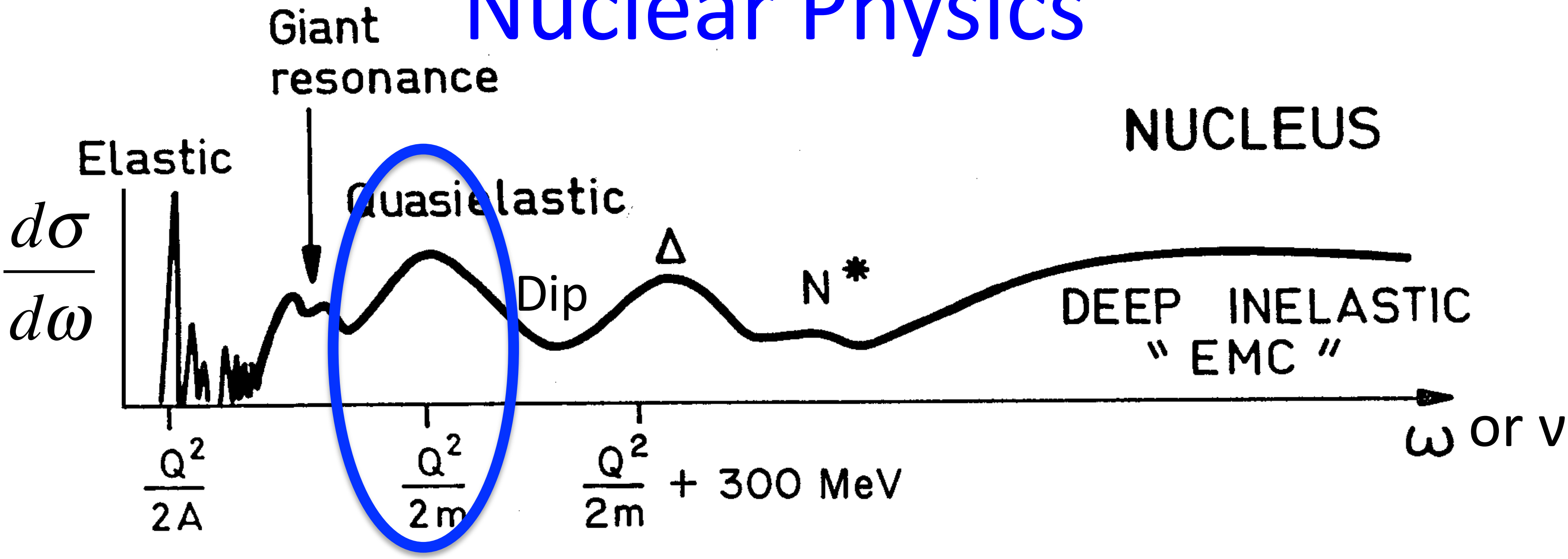
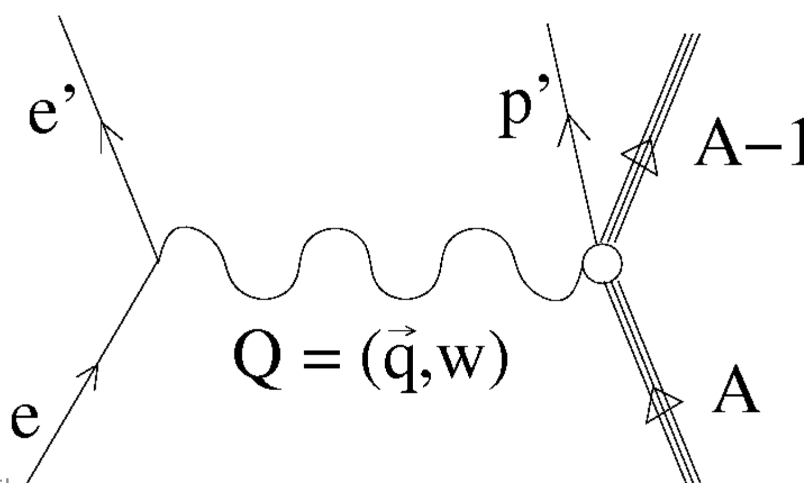
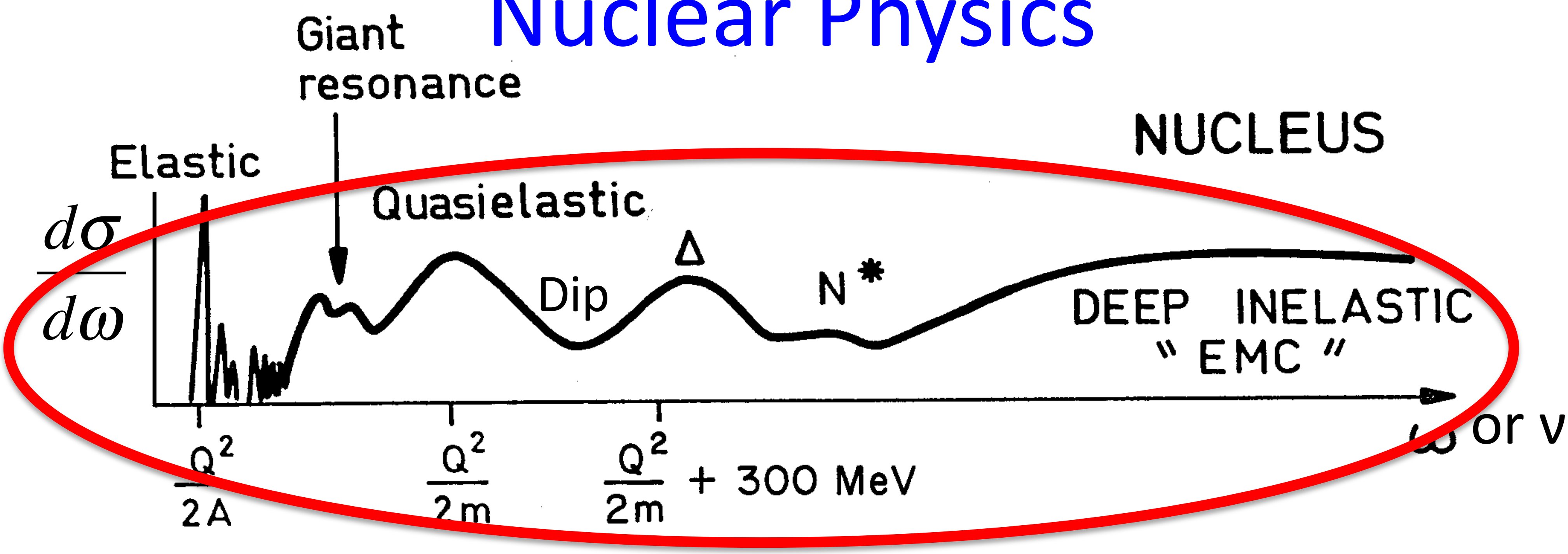


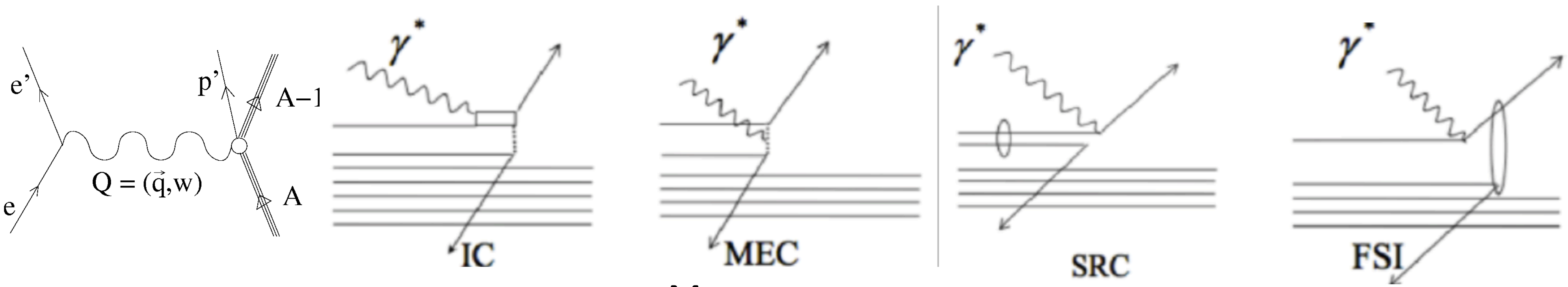
What neutrino expts want



Nuclear Physics



What we get (even for 0pi)



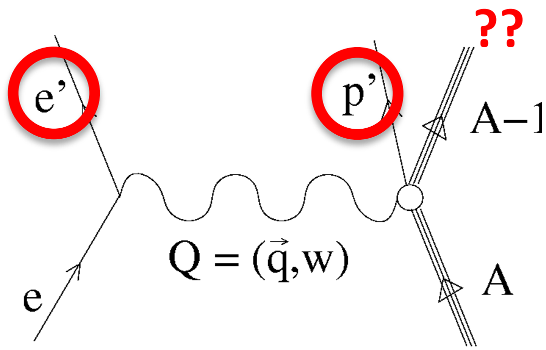
Resonance

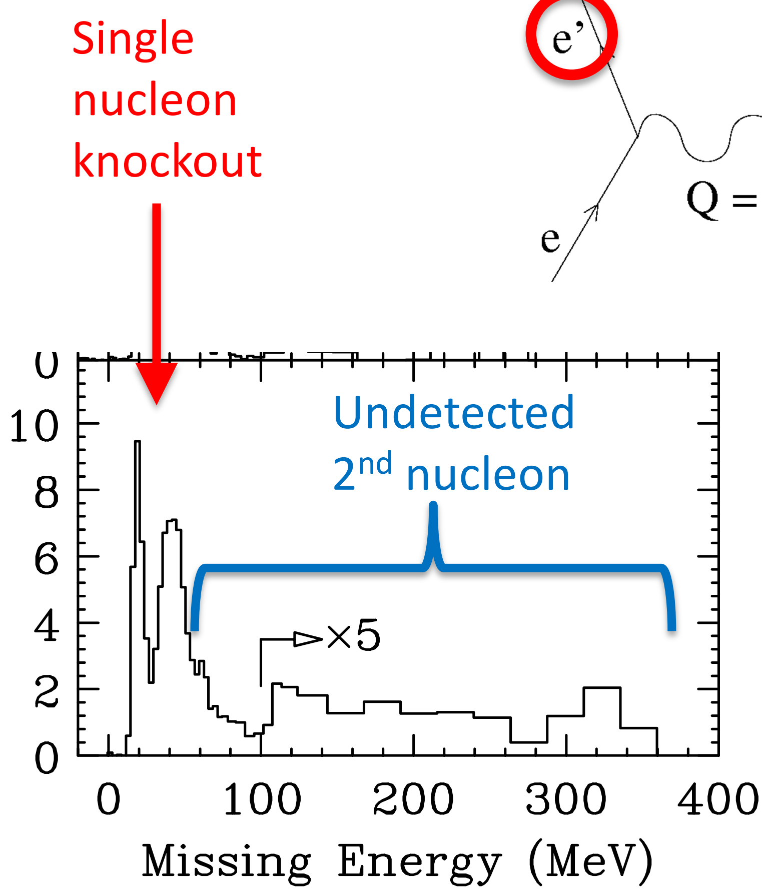
Meson Exchange Currents

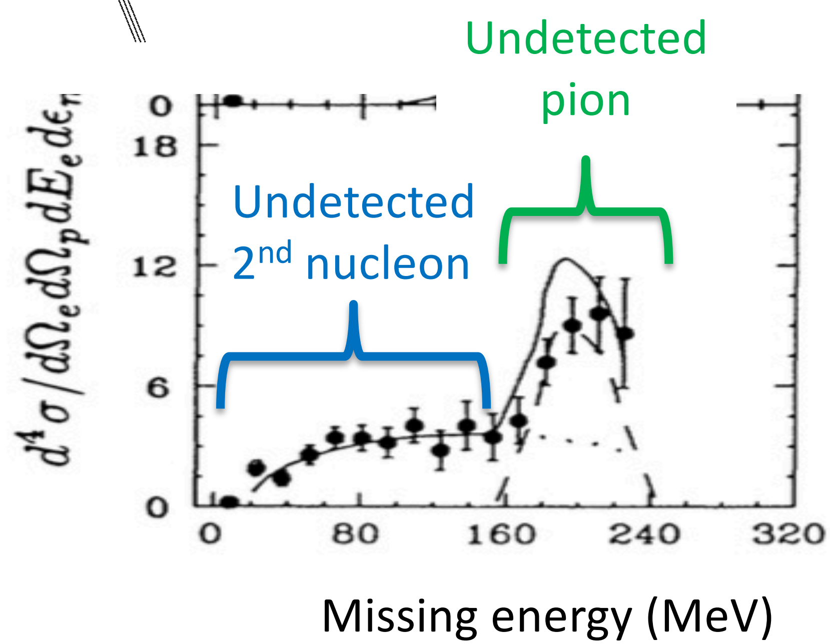
Short Range Correlations

Final State Interactions

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

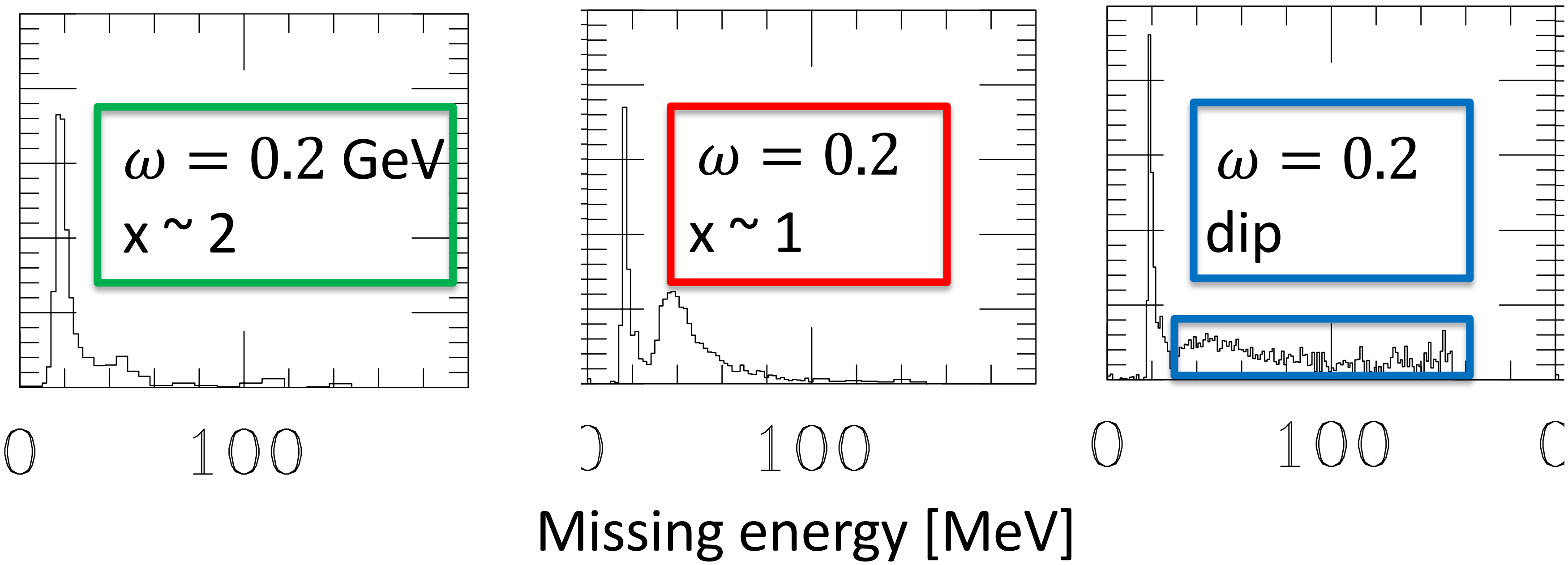


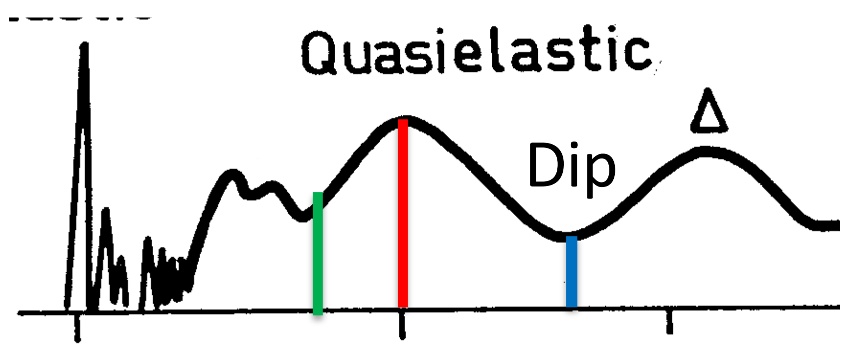




From QE to “dip”

C(e,e’p)



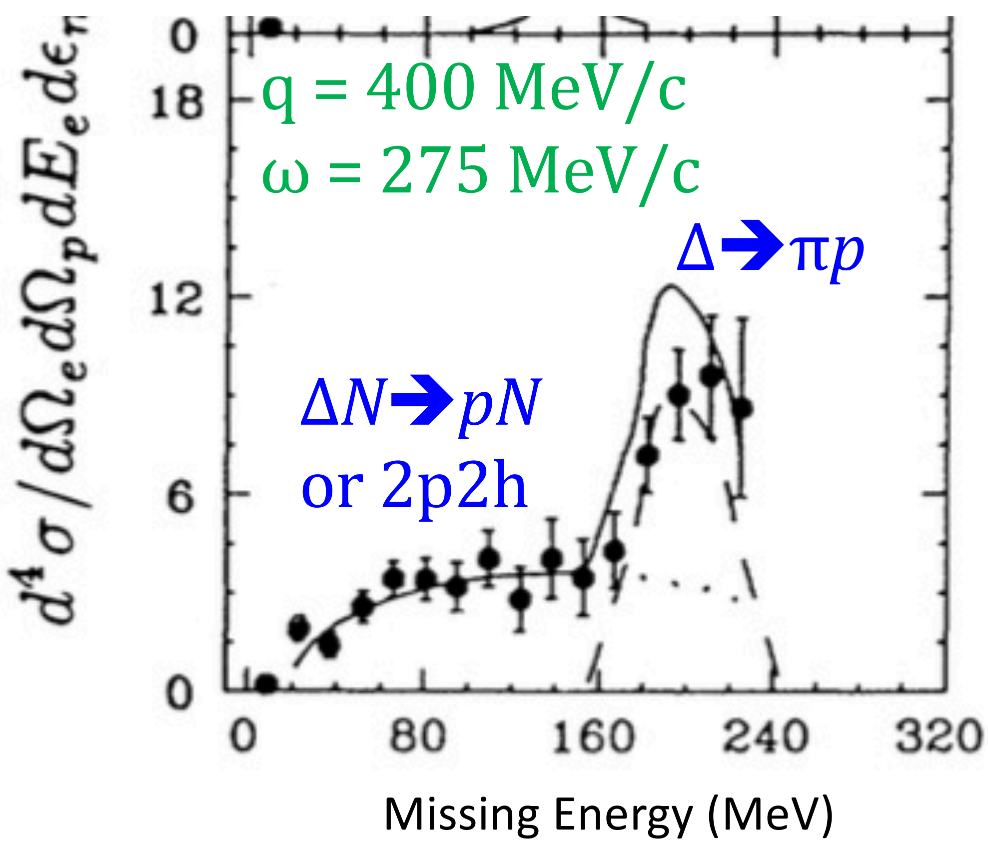


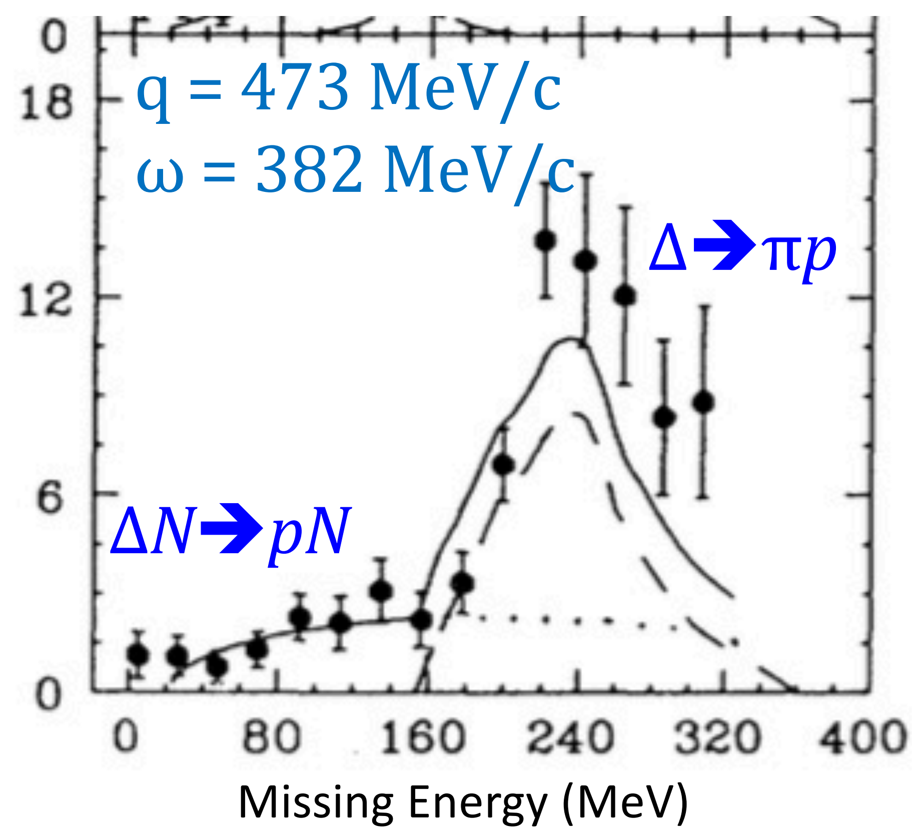
$$x = \frac{Q^2}{2m\omega}$$

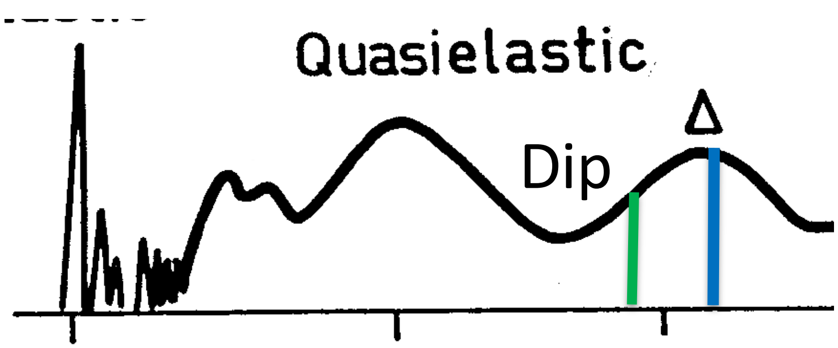
R. Lourie, PRL **56**, 2364 (1986)
L. Weinstein, PRL **64**, 1646 (1990)
S. Penn, PhD thesis, MIT

From Dip to Delta Region

C(e,e'p)







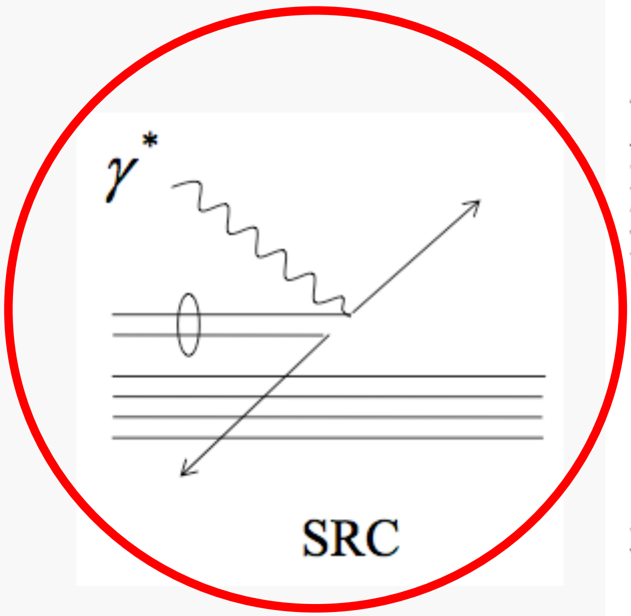
Baghaei, PRC **39**, 177 (1989)

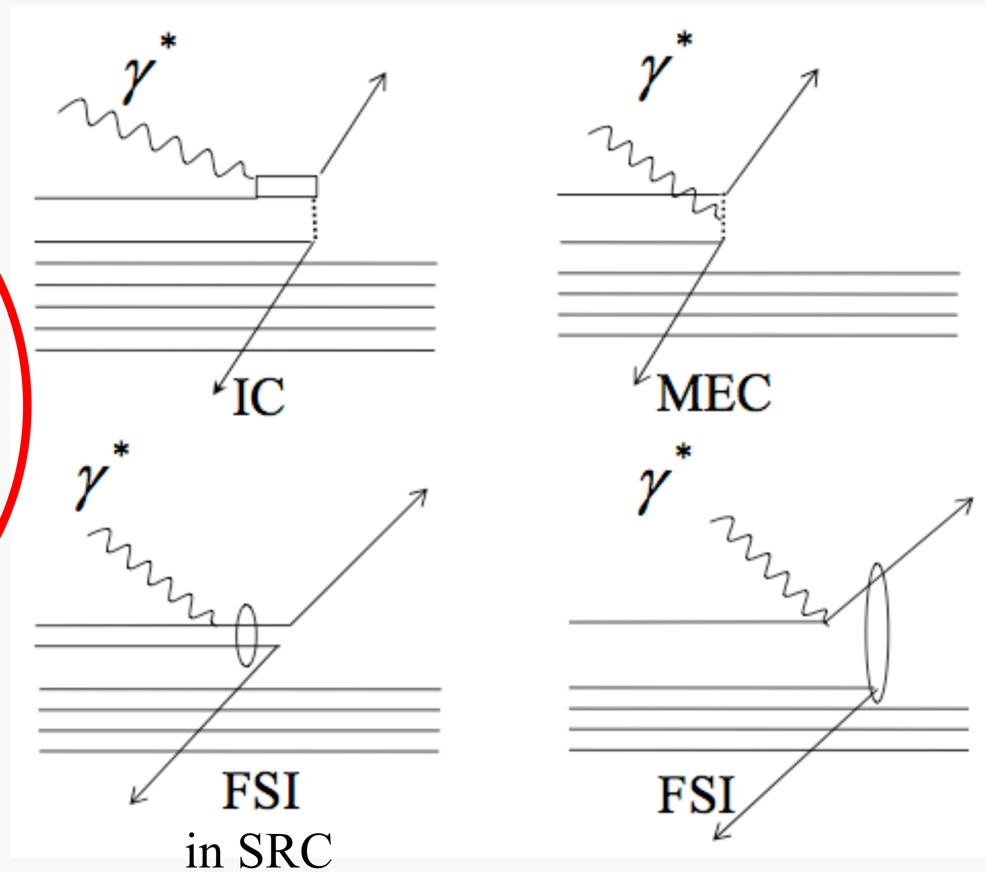
What are correlations?

Average Two-Nucleon Properties in the Nuclear Ground State

Responsible for the high momentum part of of the Nuclear WF

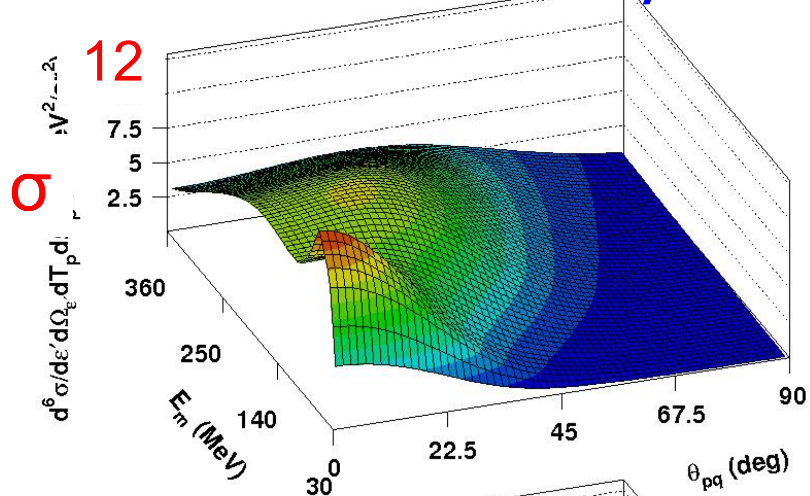
Two-body currents are not Correlations
(but everything adds coherently)



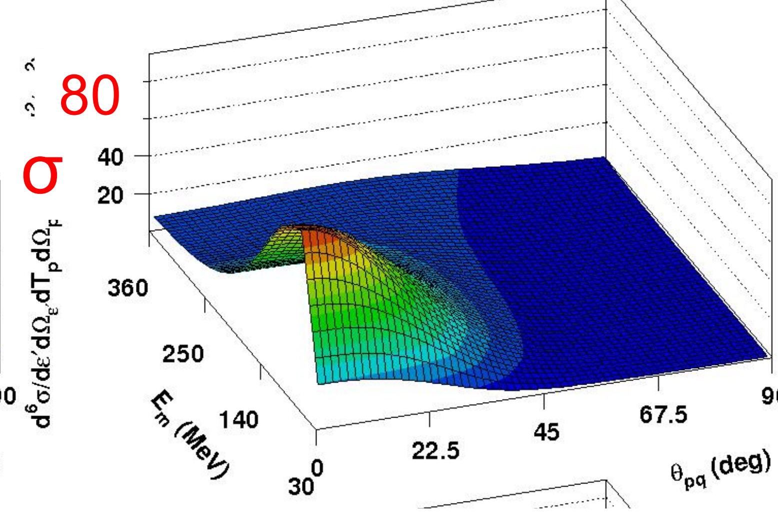


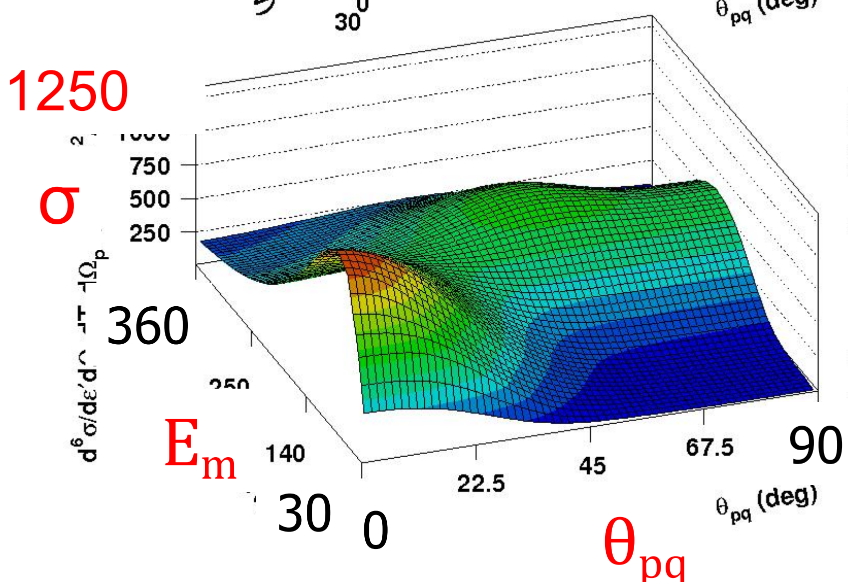
2N currents enhance correlations

Central correlations only



Central + tensor corr





Corr + MEC

MEC and correlations add coherently

$\rightarrow 2p2h$

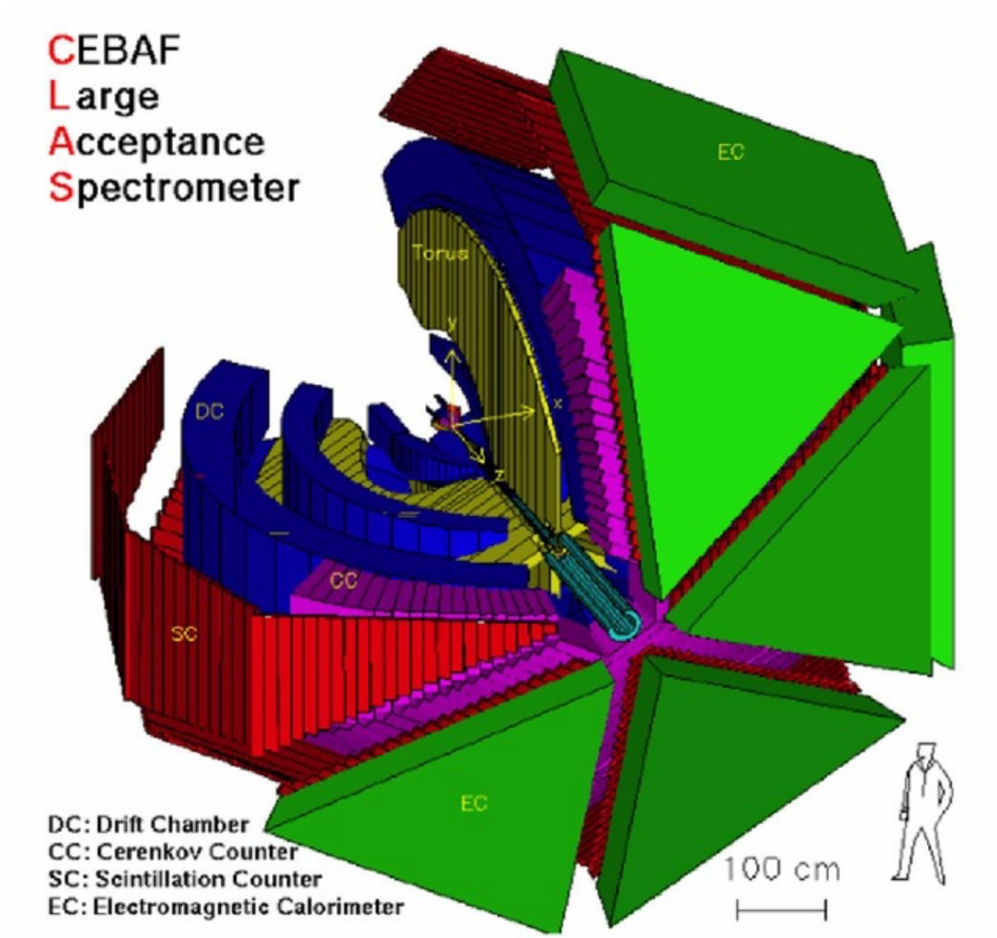
O(e,e’p) Ryckebusch
NP A672 (2000) 285

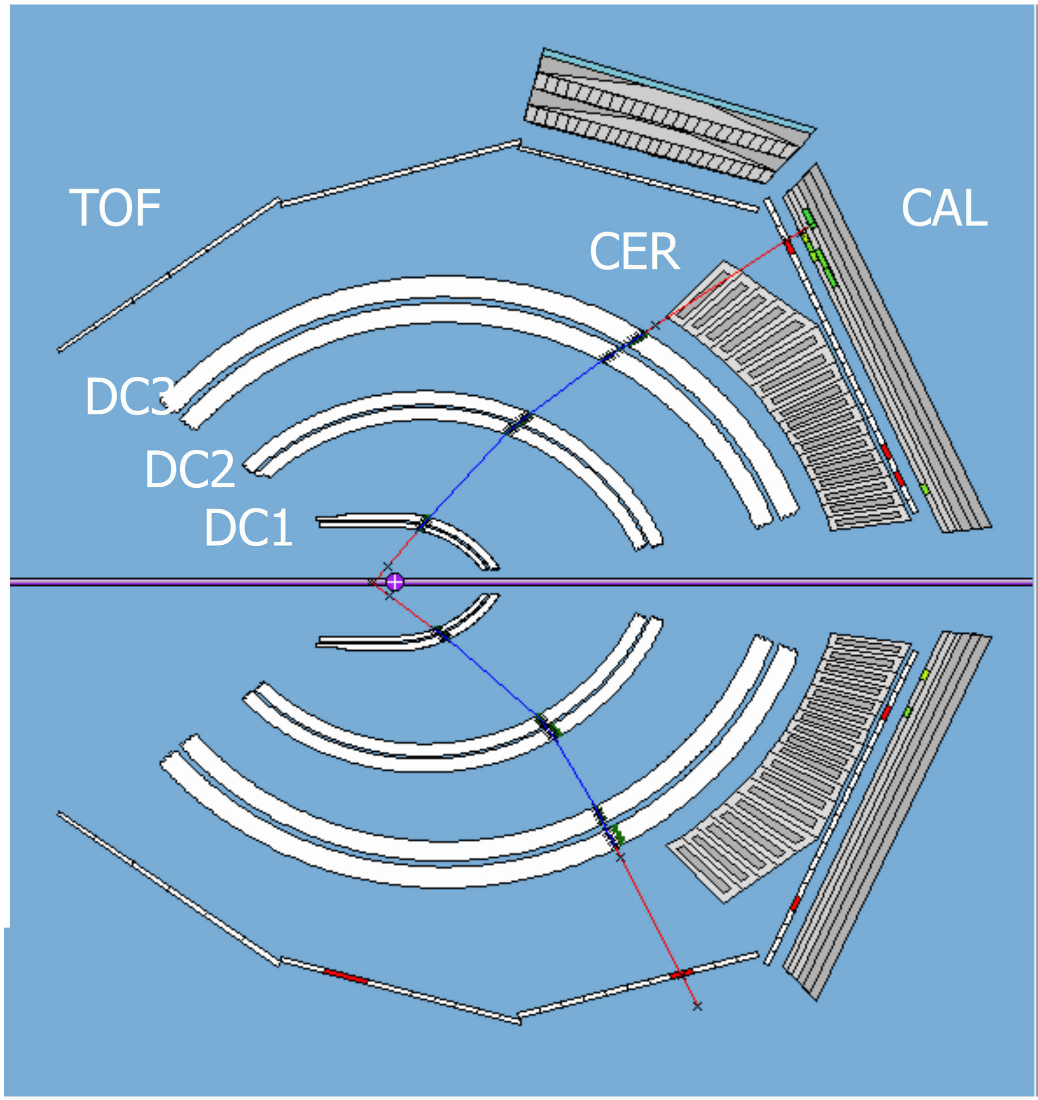
Physics Summary

- 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

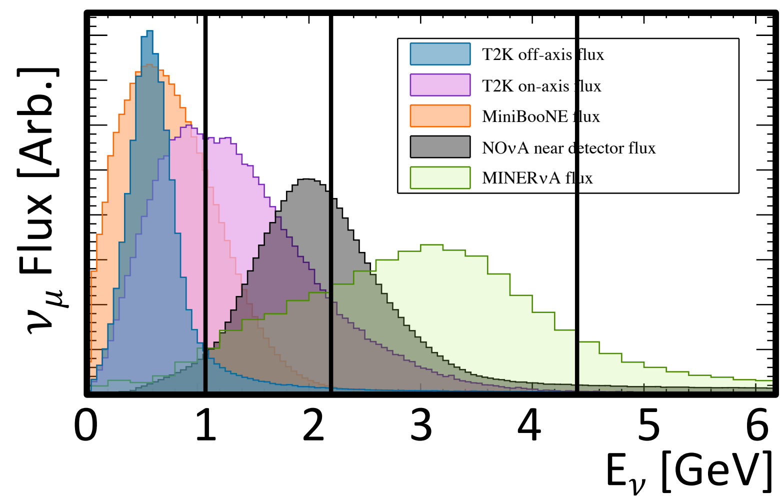




CLAS6 (e,e'p) Data (million events)

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

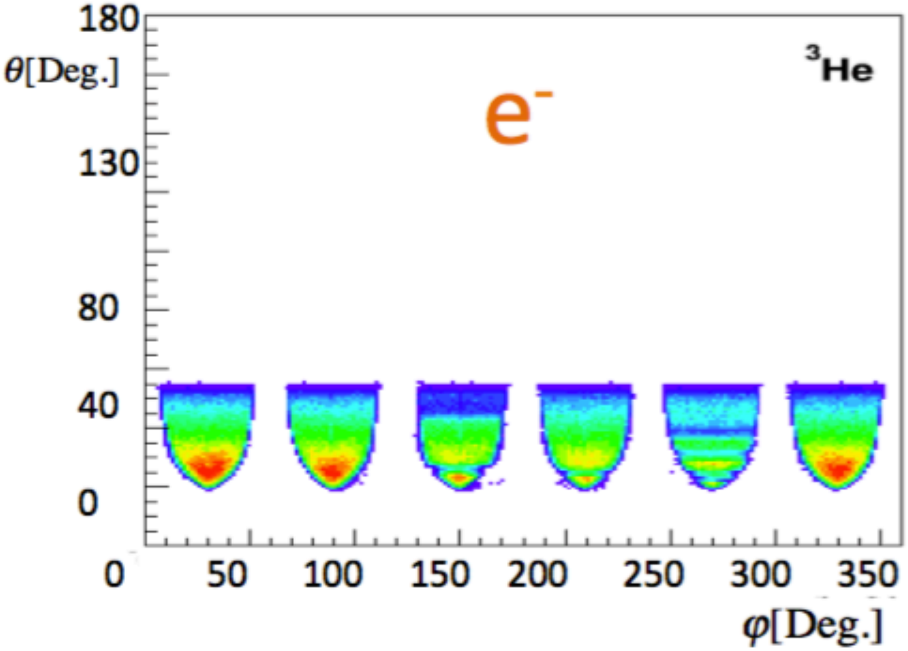
E2a data only.
E2b has more 4.6 GeV 3He and 56Fe
Eg2 has 5 GeV d, C, Al, Fe, and Pb

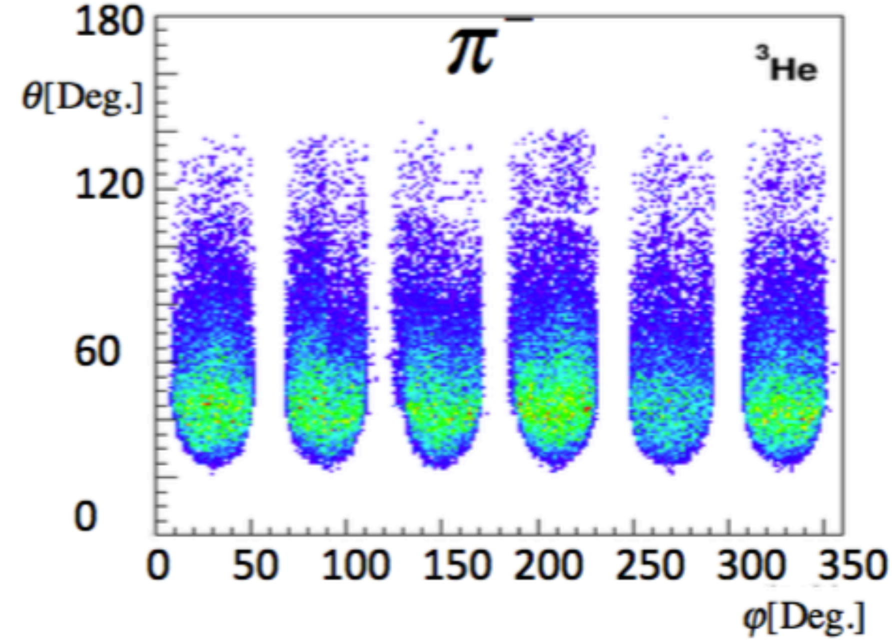


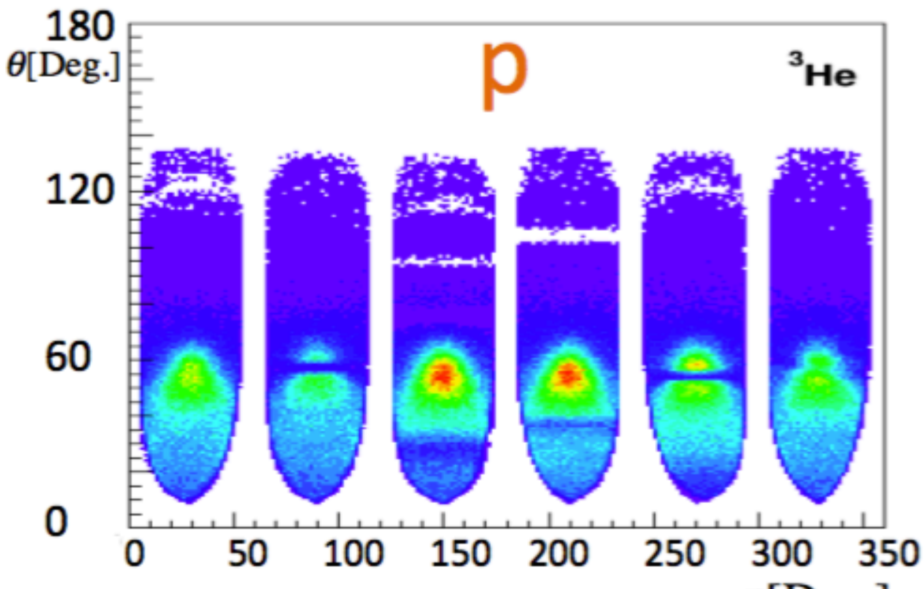
Reconstructing the initial energy

- 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)]

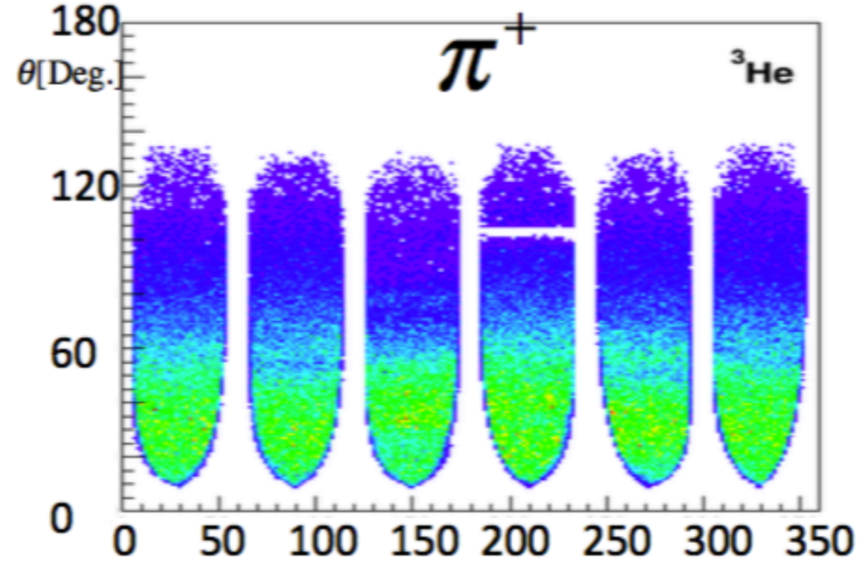
CLAS6 coverage





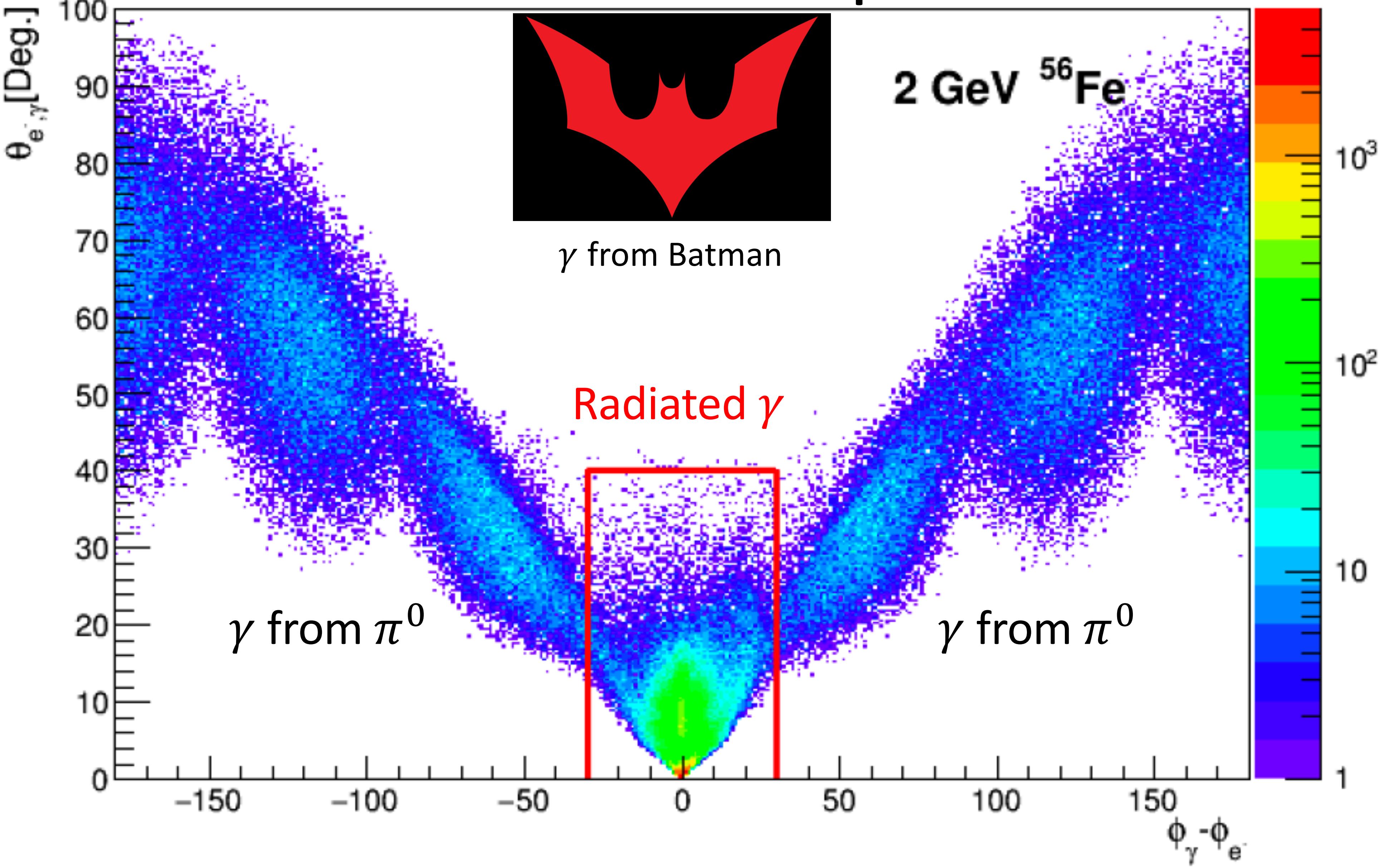


$p_{min} \approx 300$ MeV/c



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

Exclude radiated photons



L. Weinstein, Elba 2019

Background Subtraction

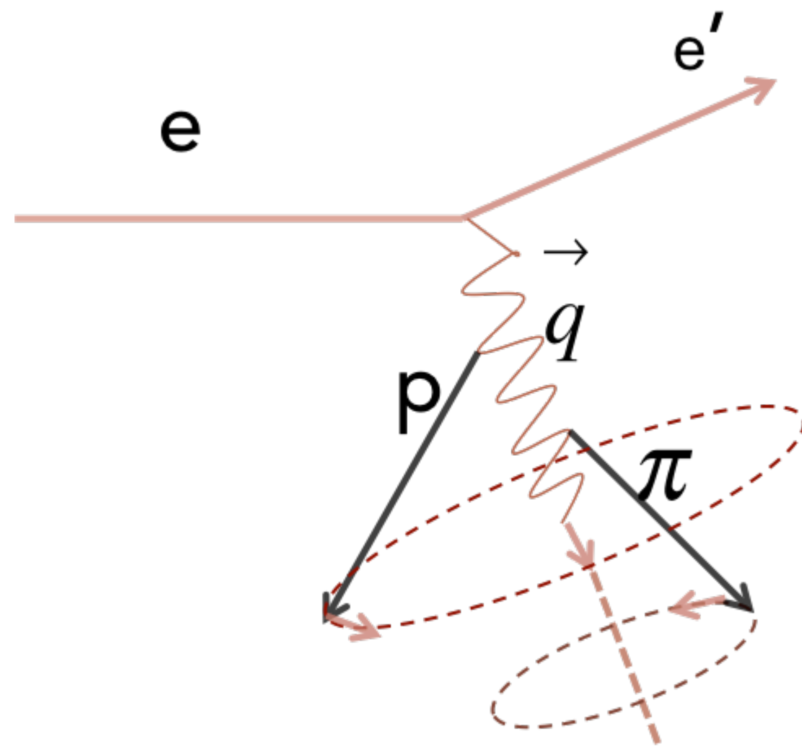
Want 0π event sample

(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



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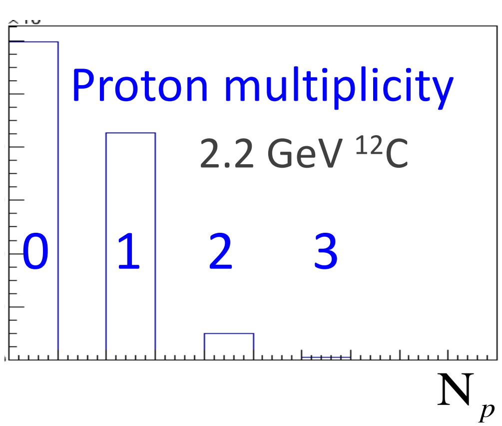
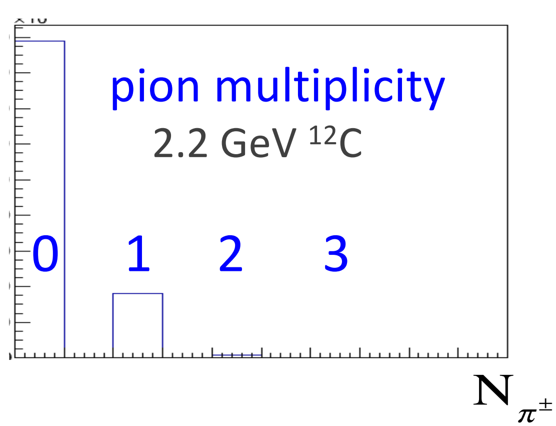
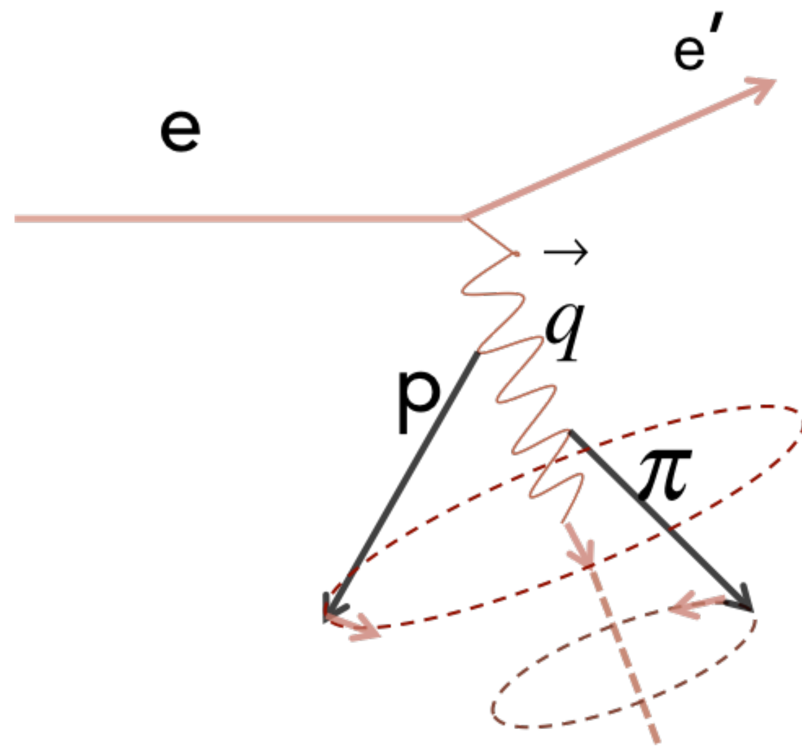
4. Do the same for 2p, 3p, 2p+ π etc.







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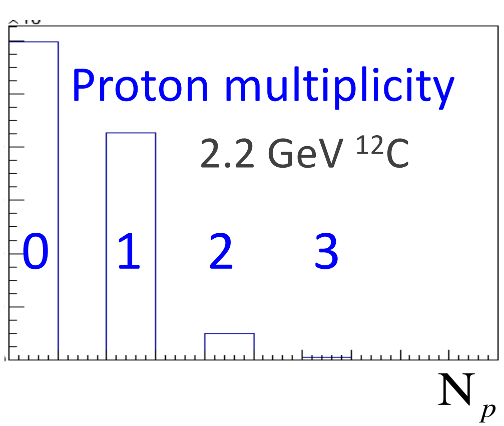

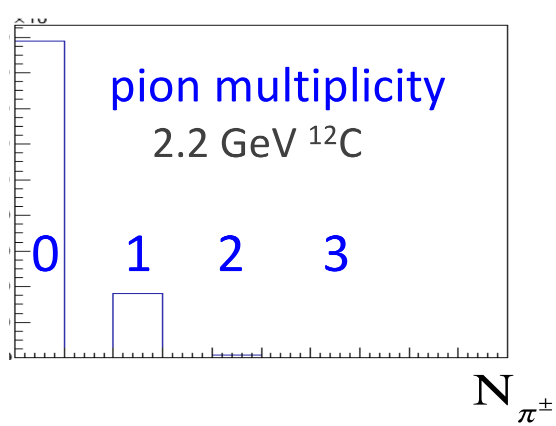

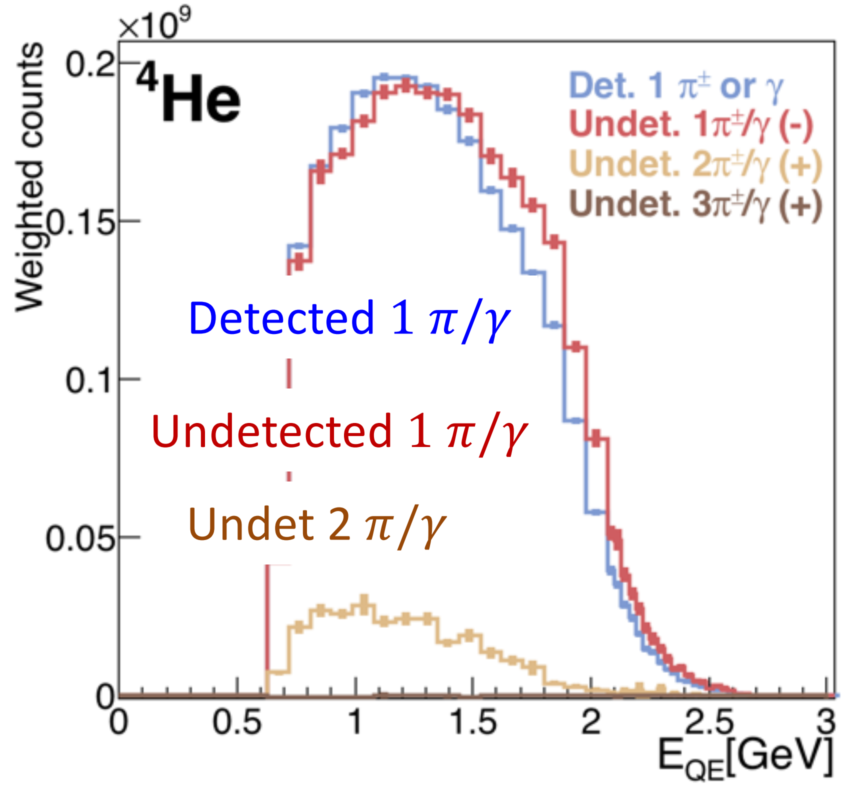

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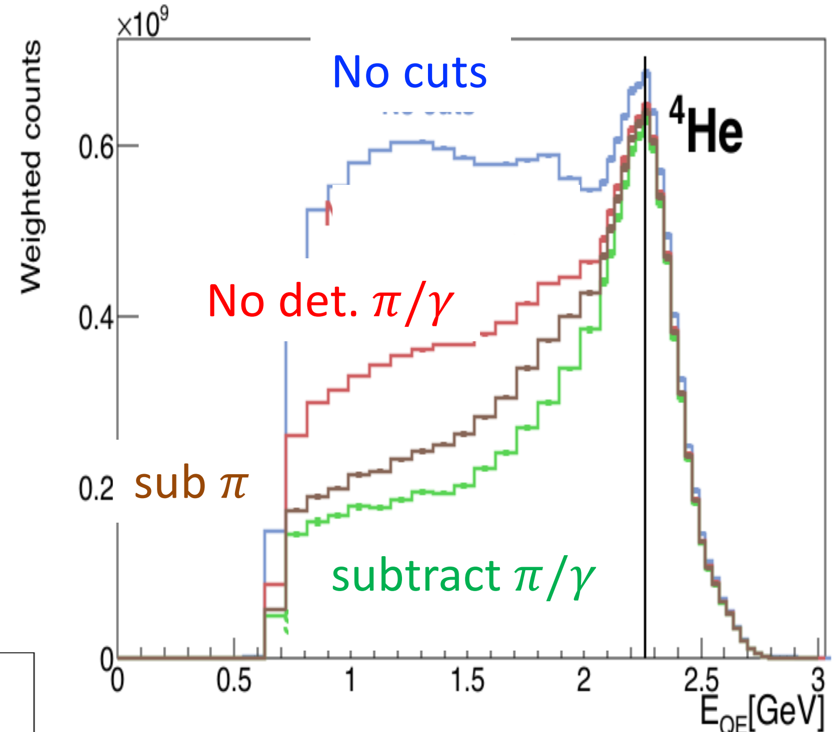
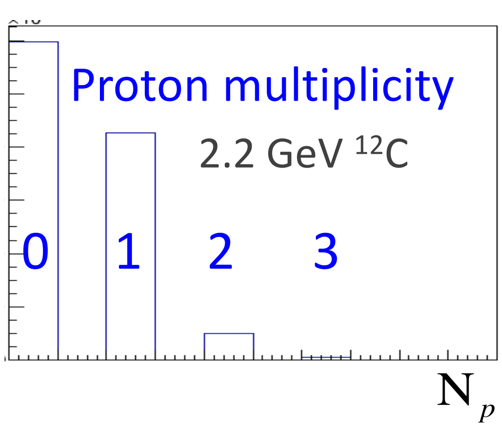
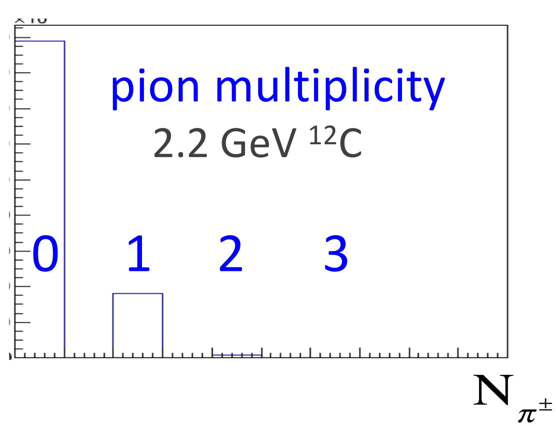


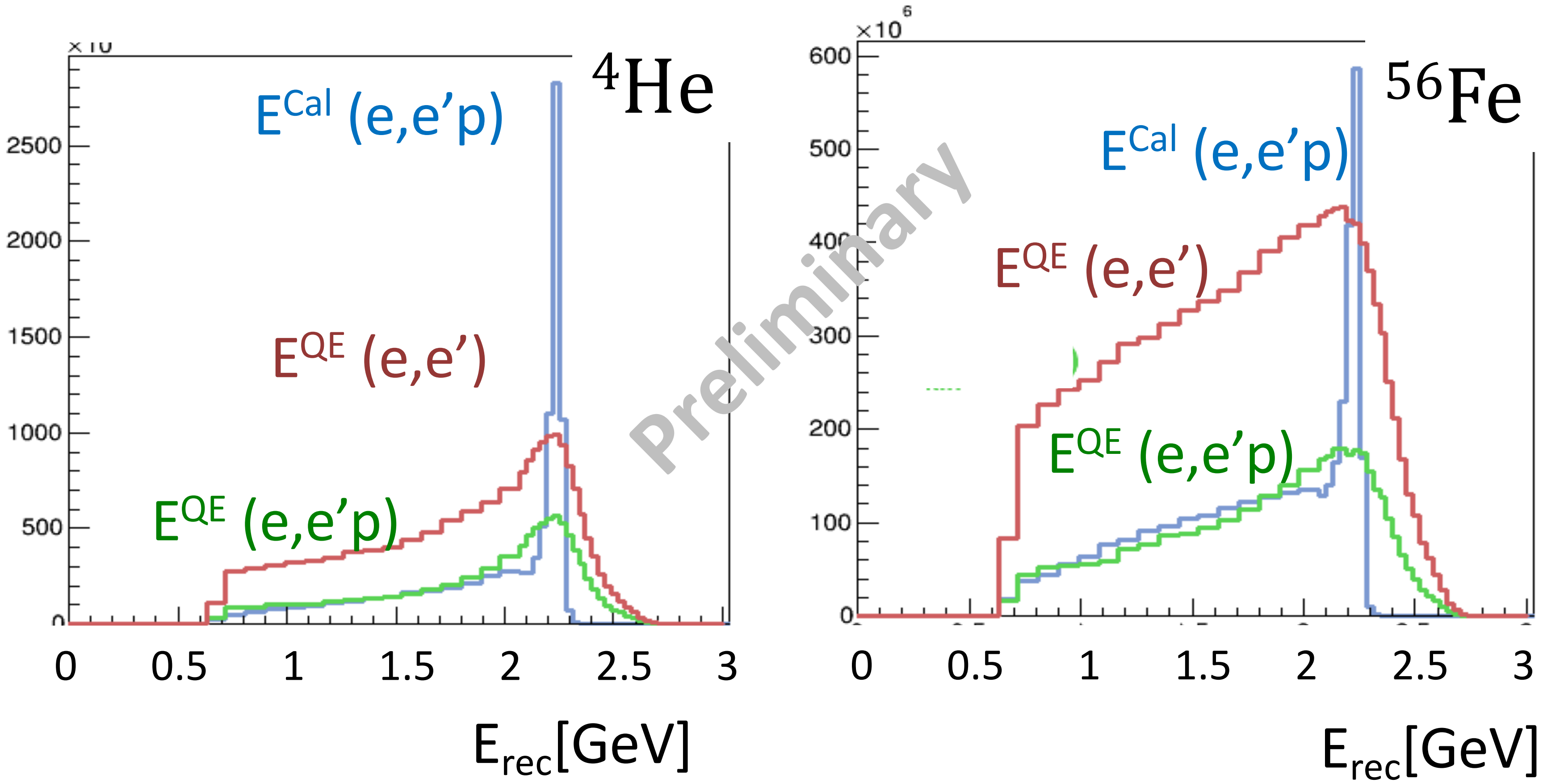




→ True 0π event sample!

Energy Reconstruction: A dependence

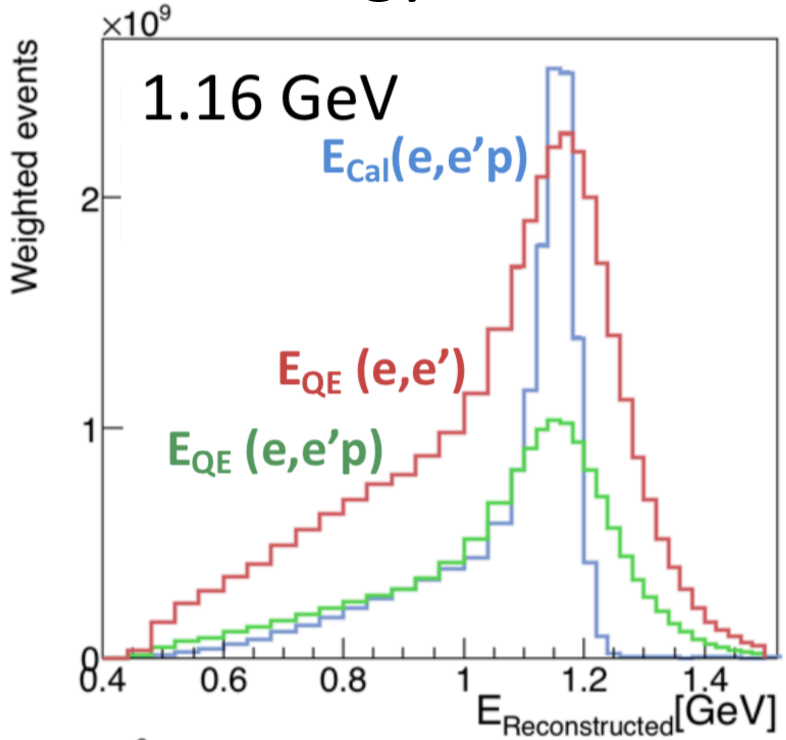
2.26 GeV beam   Zero pion events



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

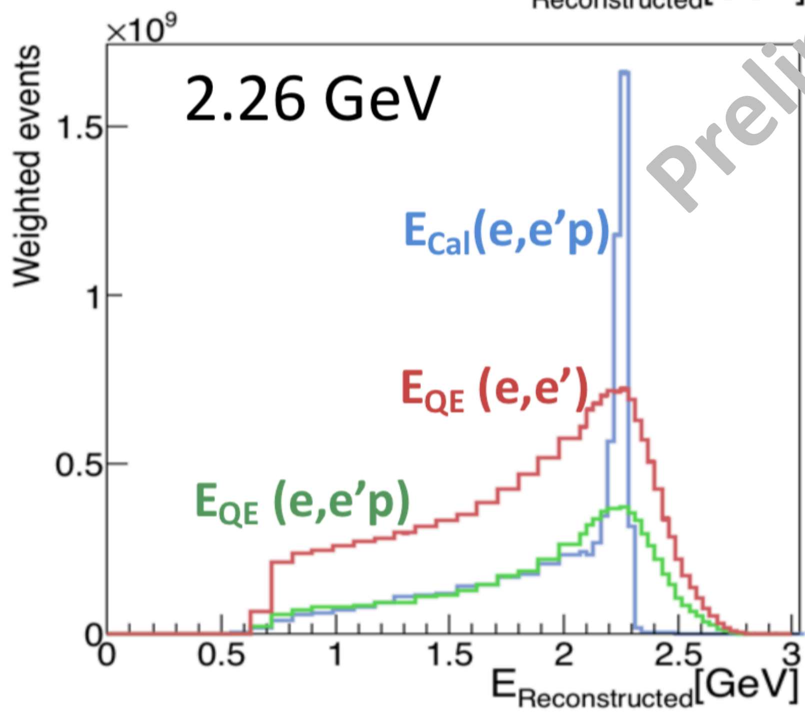
Much bigger in Fe than ^{4}He

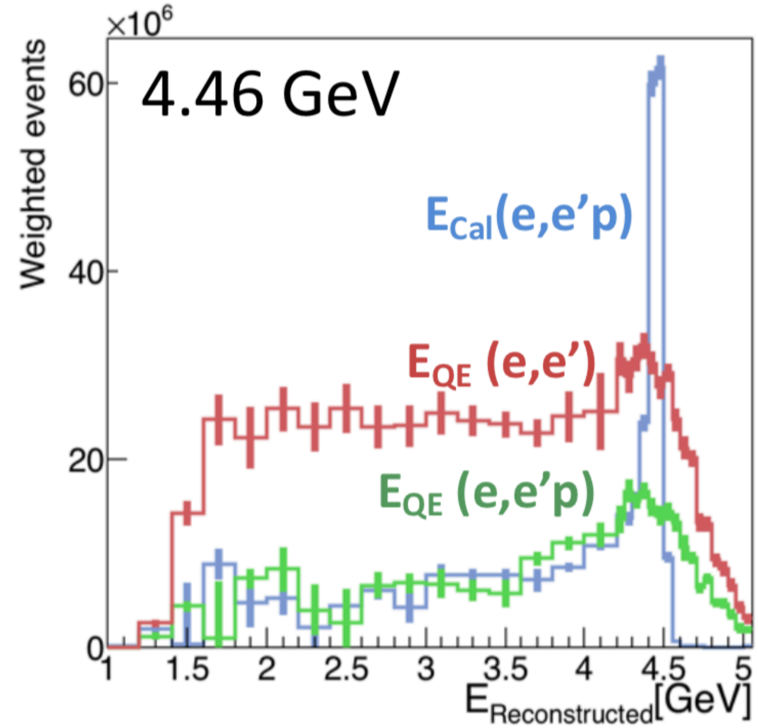
Energy Reconstruction: E dependence



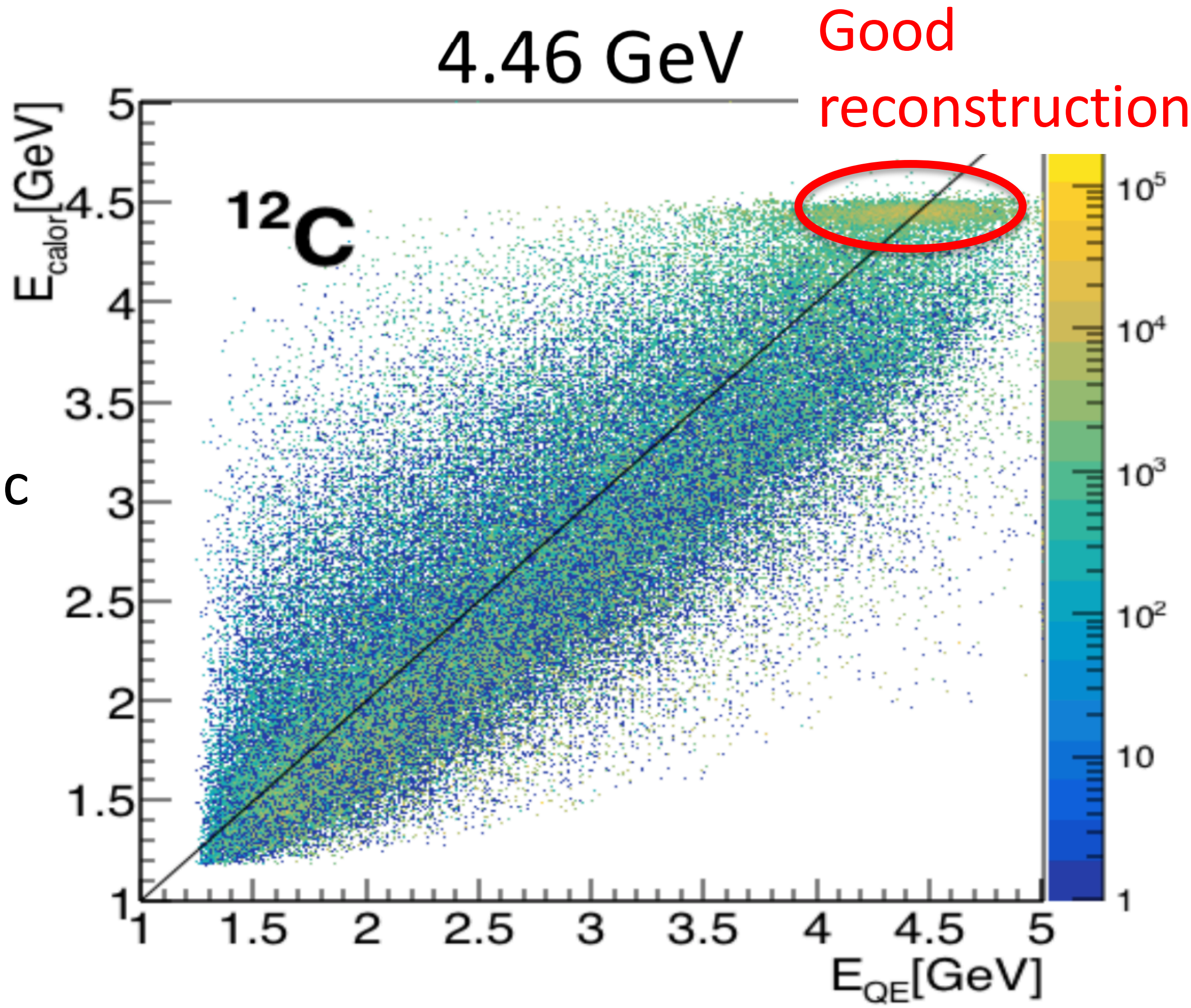
^{12}C

Non-QE events increase with E





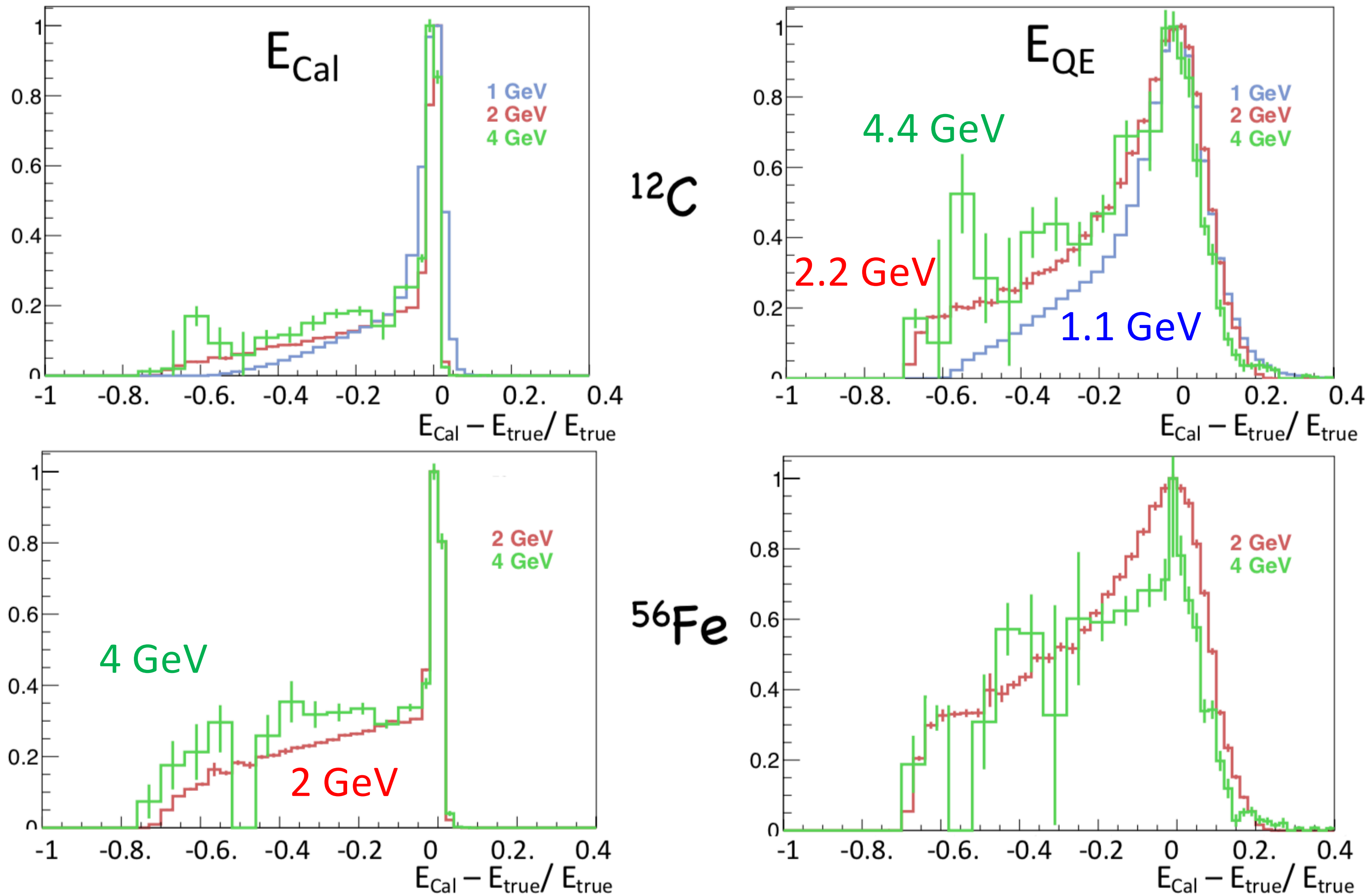
Agreement between methods does not guarantee correctness



Calorimetric method

QE (lepton only) method

Fractional Energy Feeddown



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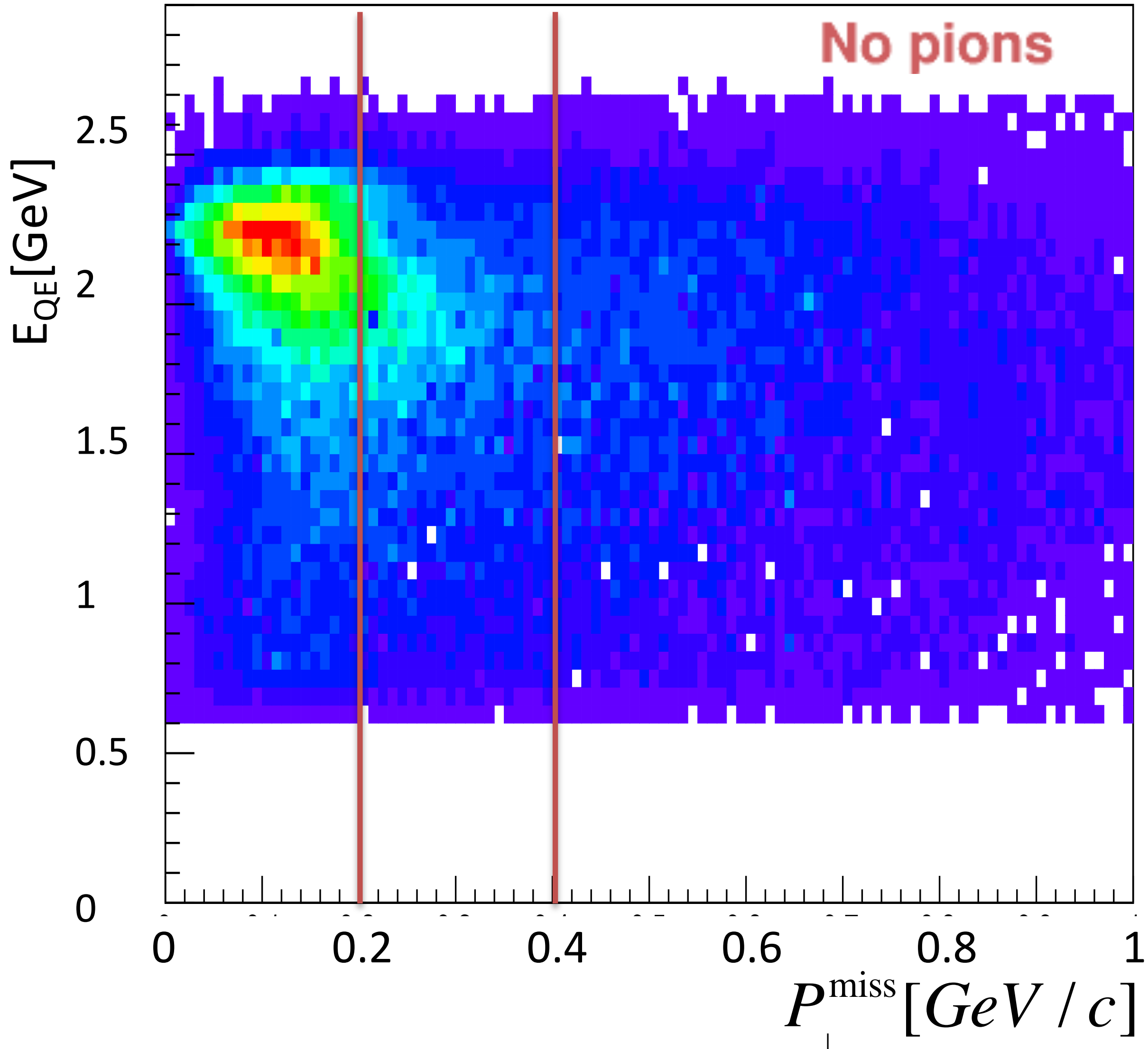
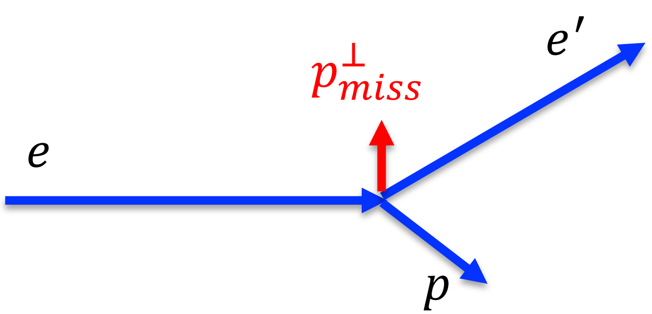
Can we select QE events?

2.2 GeV ^{56}Fe



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



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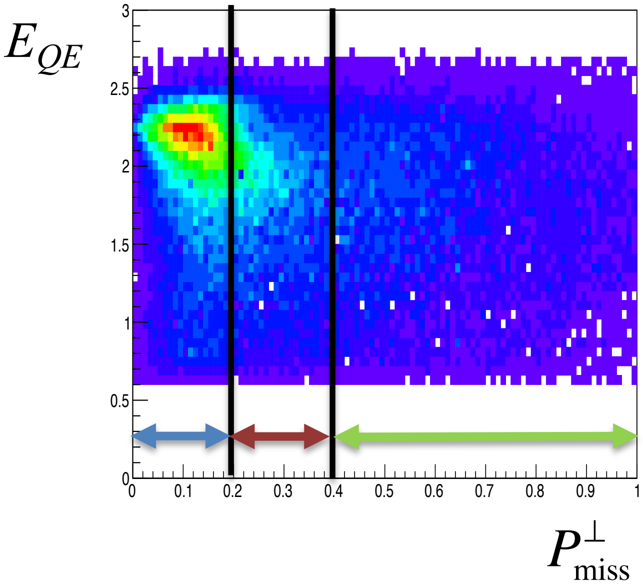
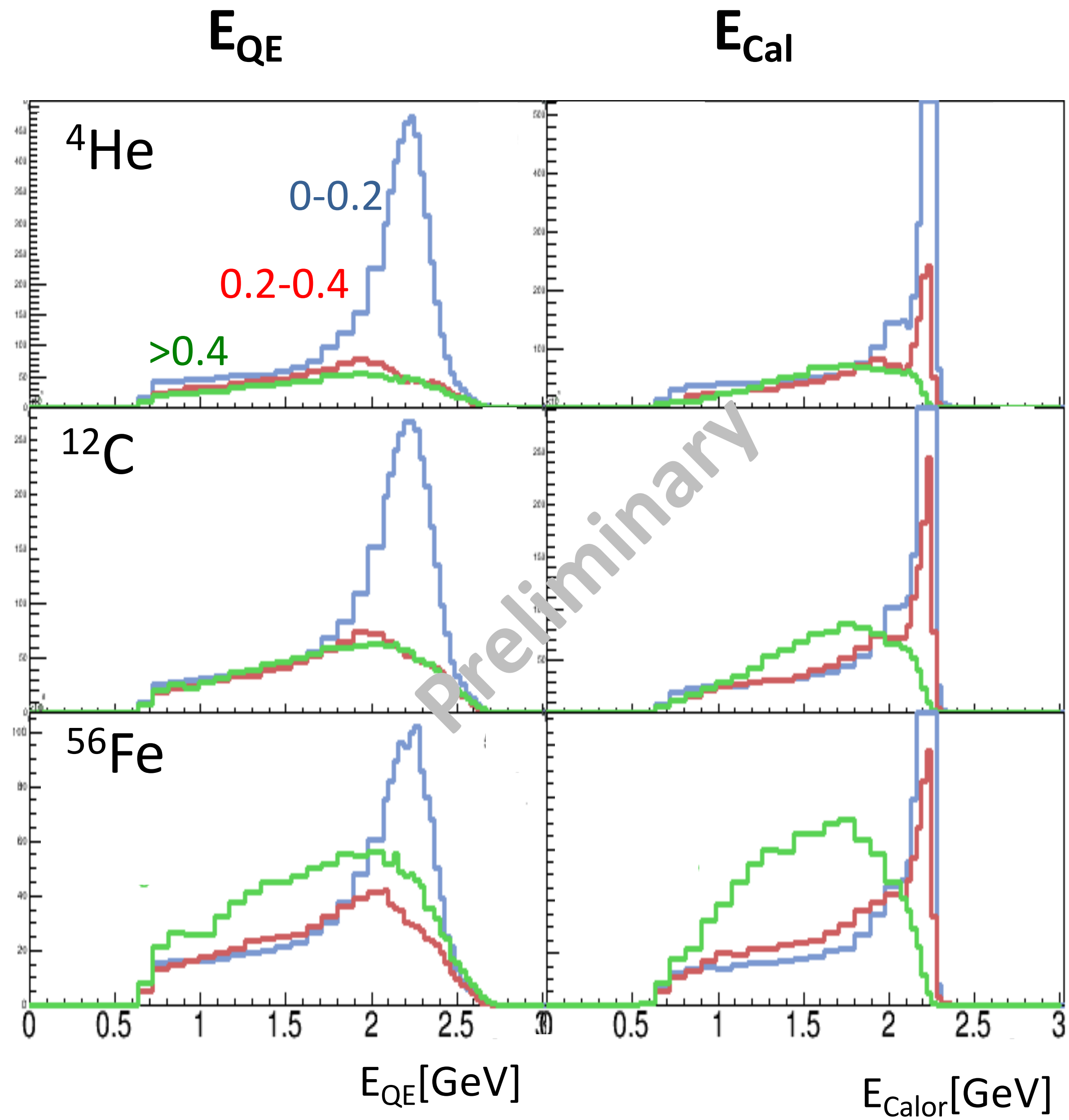
$P_{\text{miss}}^{\perp}$ slices



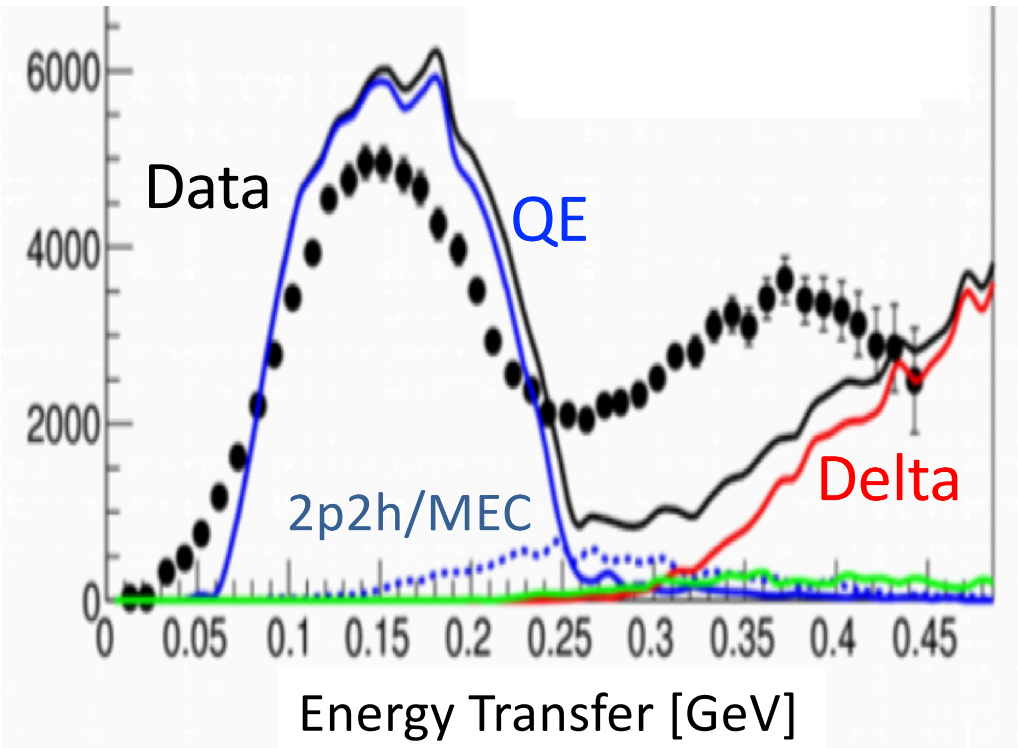


High $p_{miss}^{\perp}$
→ wrong energy!

We're Also Improving Genie

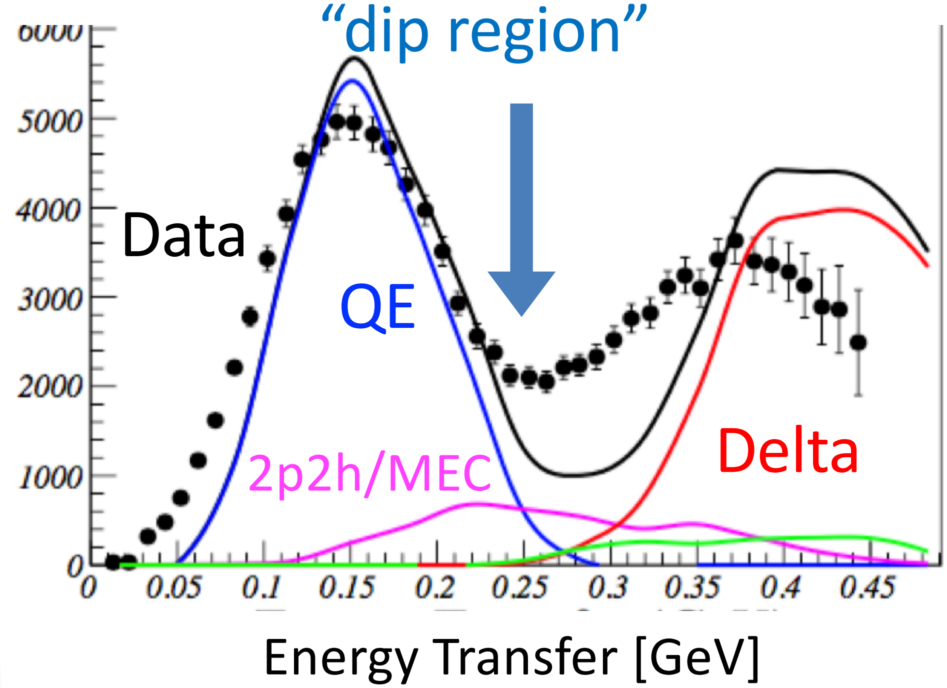
$C(e,e') \ 560 \text{ MeV } \theta = 60^{o}$

Before (default)



After

Still big discrepancies in "dip region"

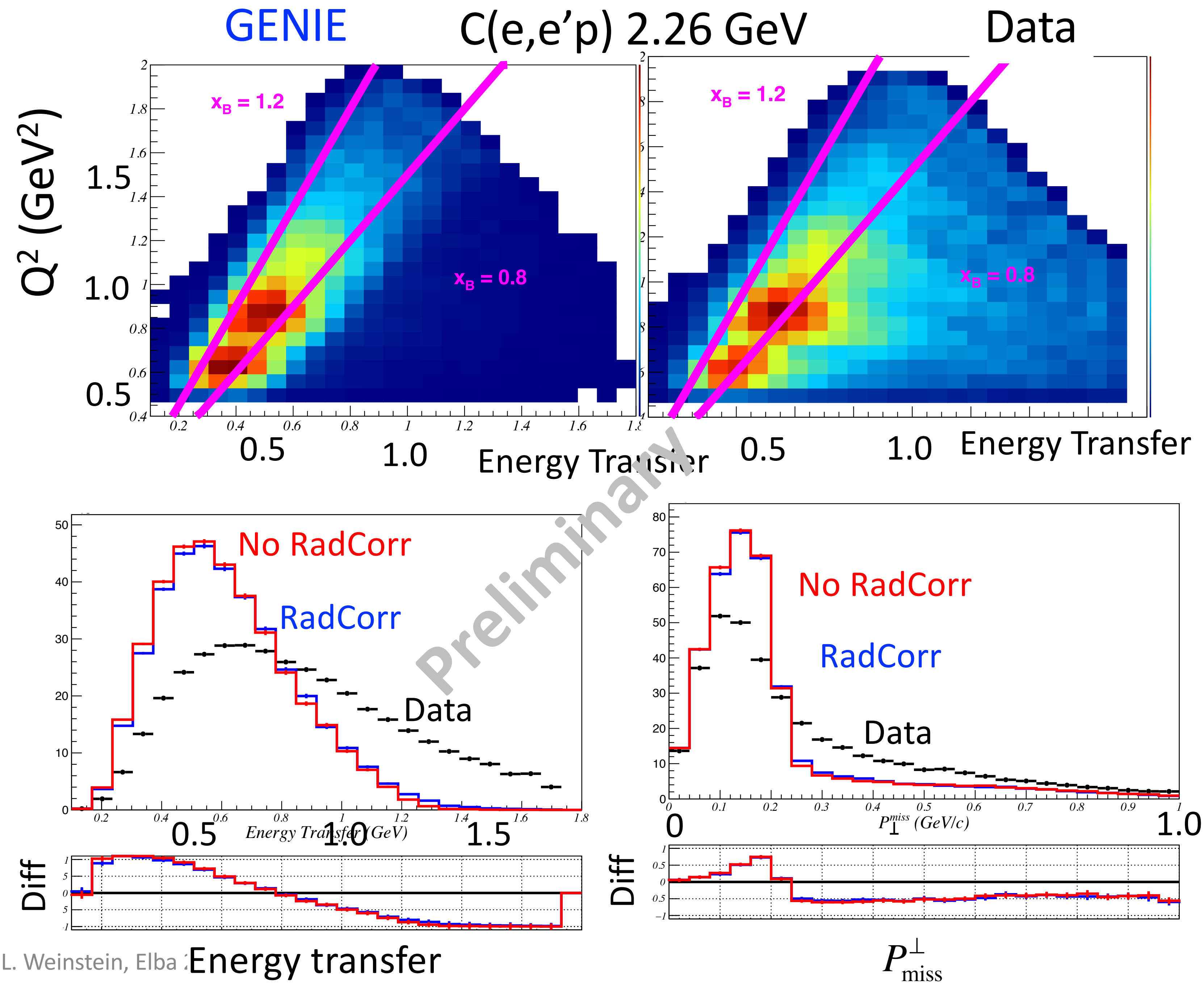


We're Also Improving Genie

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

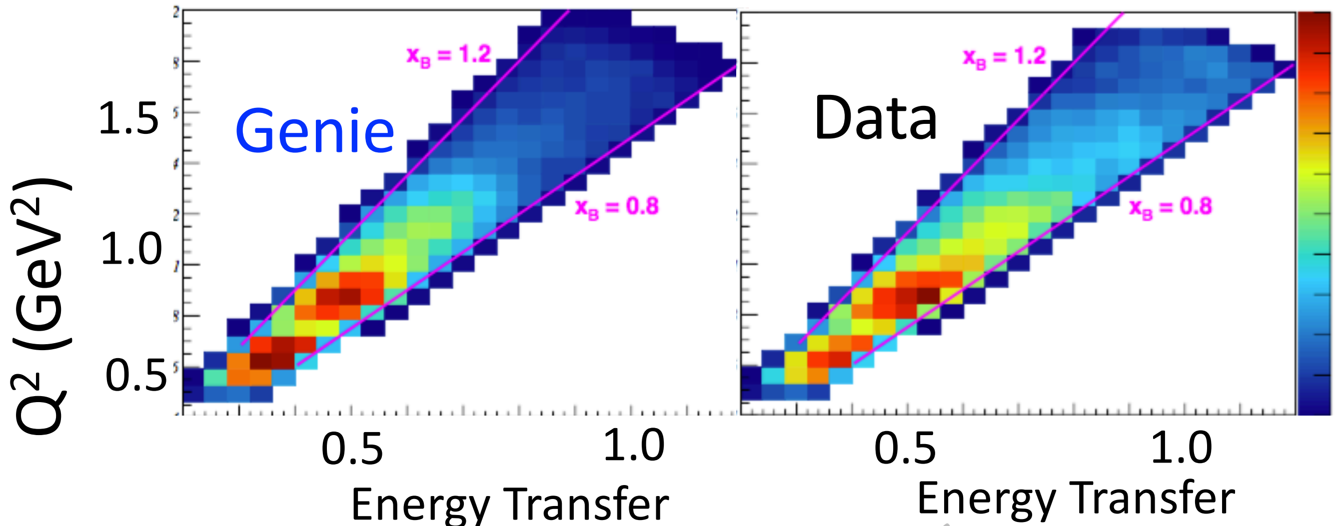
Beginning work on NuWro and GiBUU.
Consulting with the relevant experts on each code.

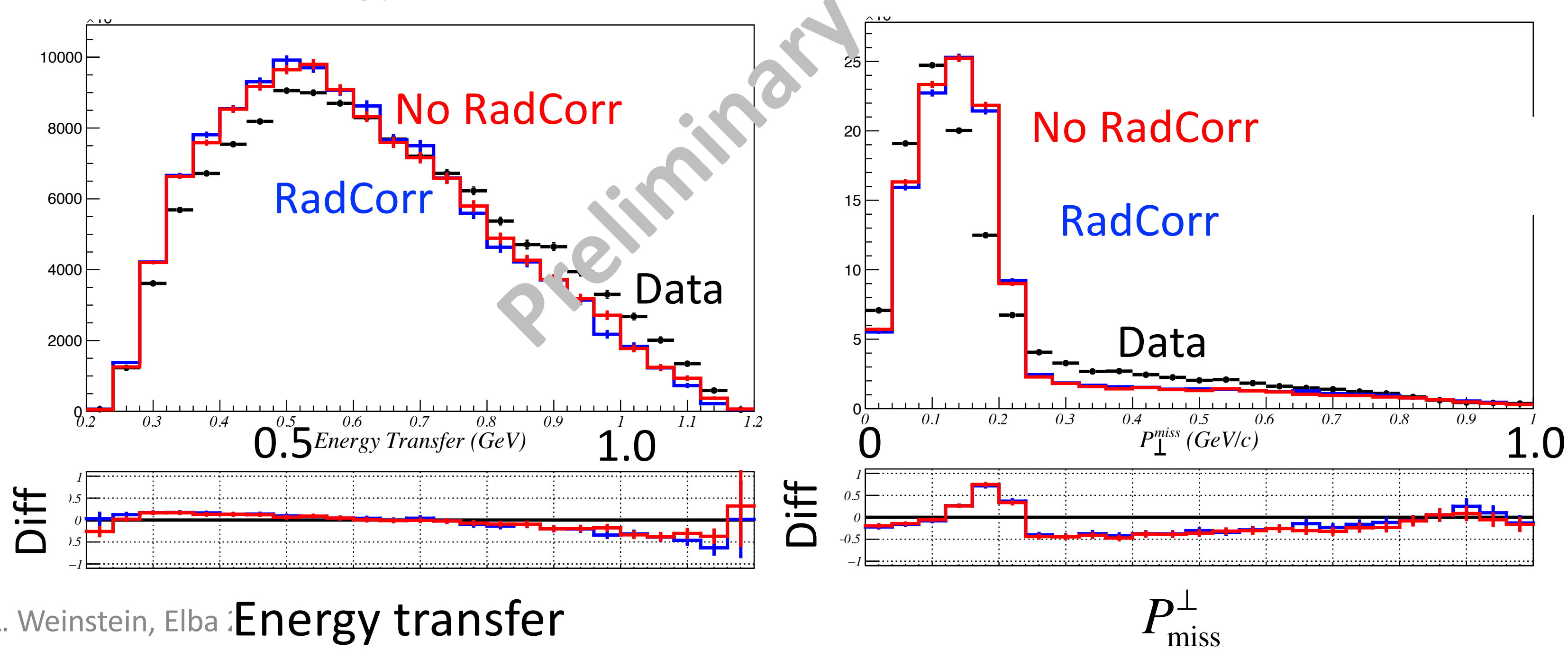
0π Data vs Genie: everywhere



0π Data vs Genie: QE Peak

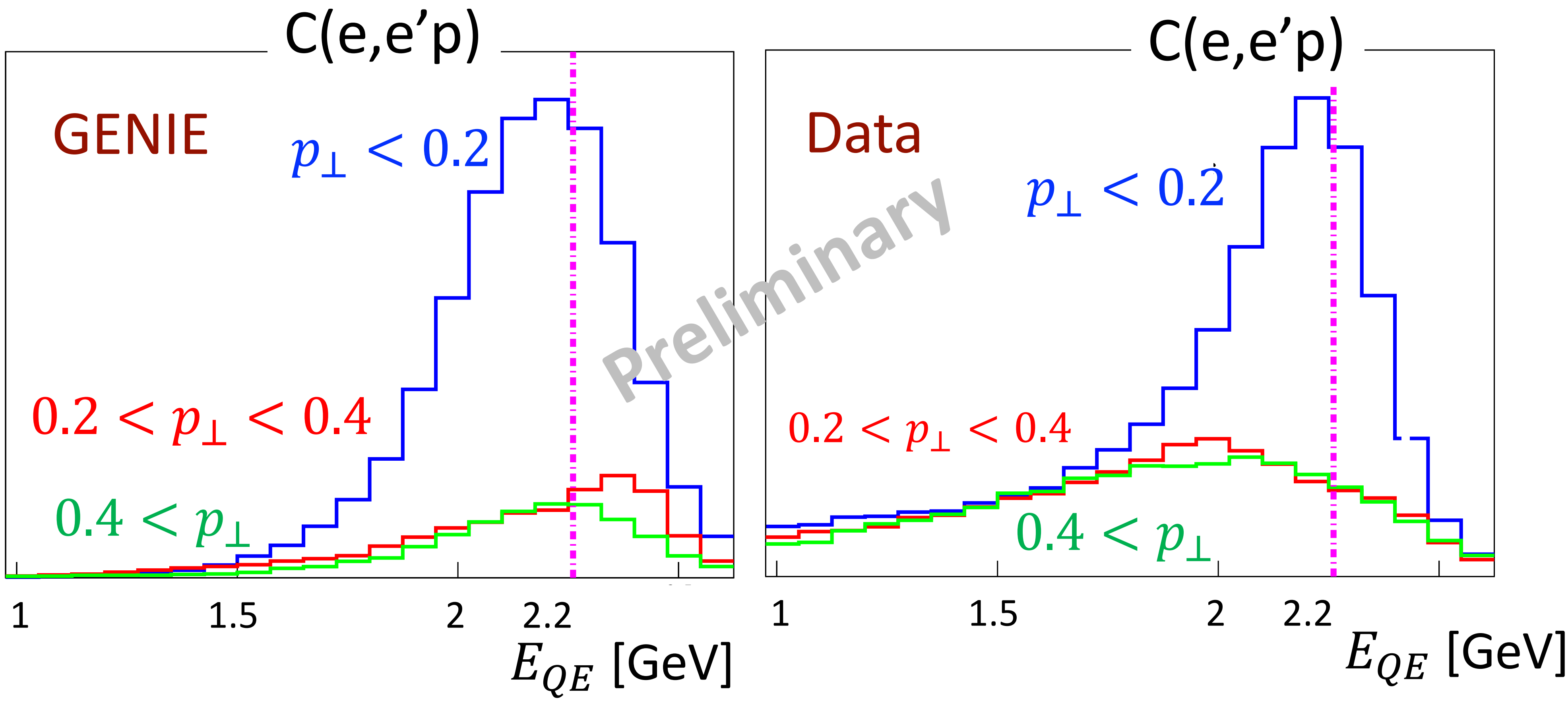
C(e,e'p) 2.26 GeV, 0.8 < x < 1.2





Data vs Genie: E_{beam} Reconstruction

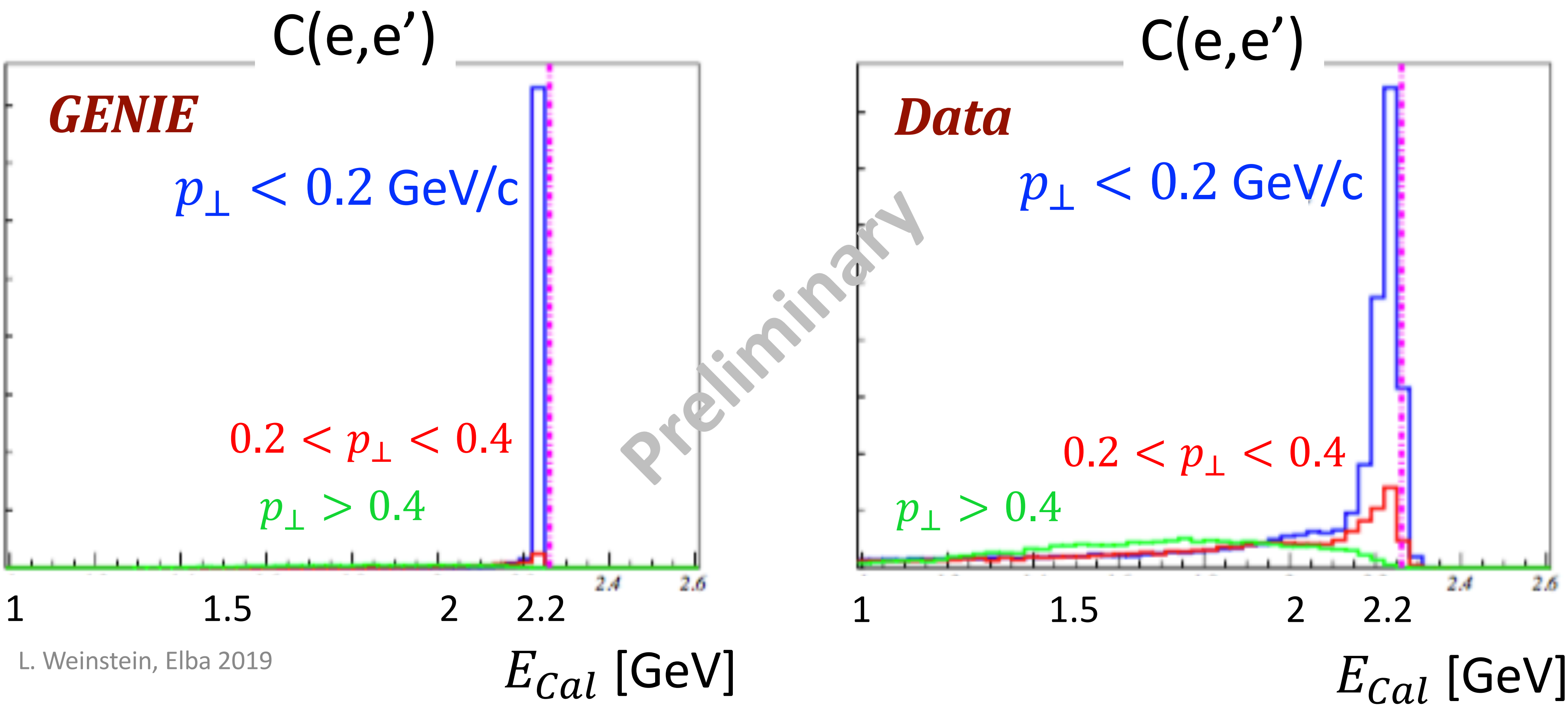
$$E_{QE} = \frac{2ME_l + 2M\varepsilon - m_l^2}{2(M - E_l + |k_l|\cos\theta)}$$



Peaks in same location

Data vs Genie: E_{beam} Reconstruction

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

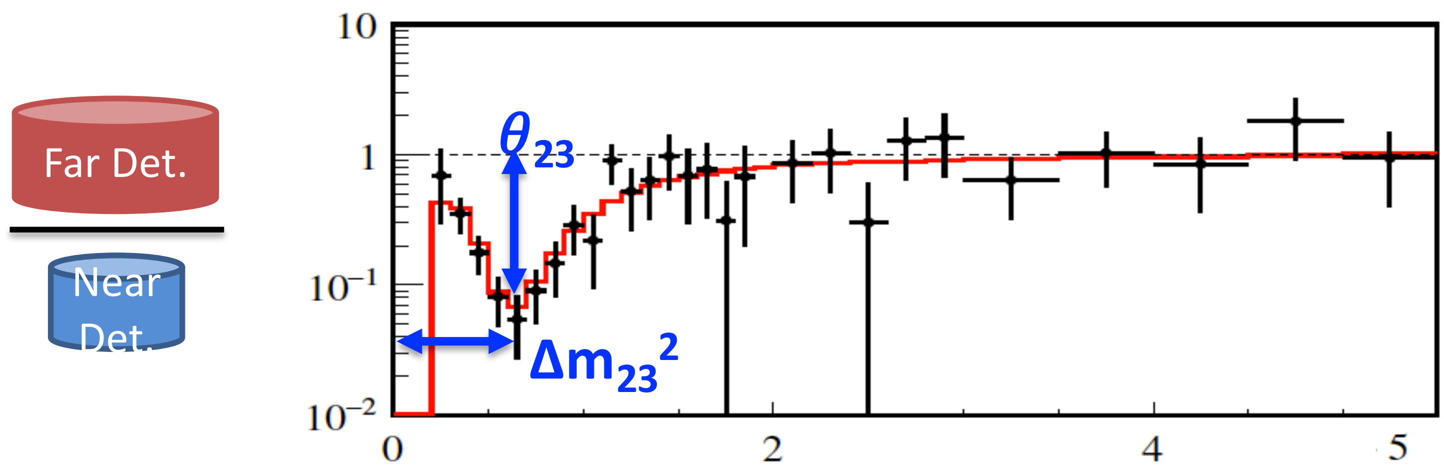


Data vs Genie: E_{beam} Reconstruction

Fe	e^- Data	e GENIE	ν GENIE
2.2 GeV	28%	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}

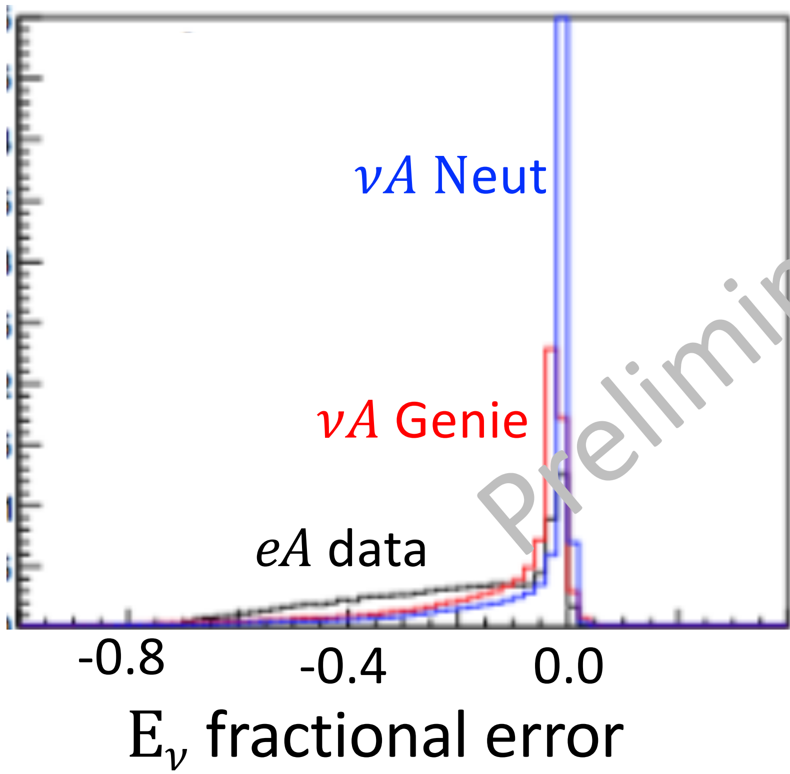
Errors affect both θ_{23} and Δm^2_{23}

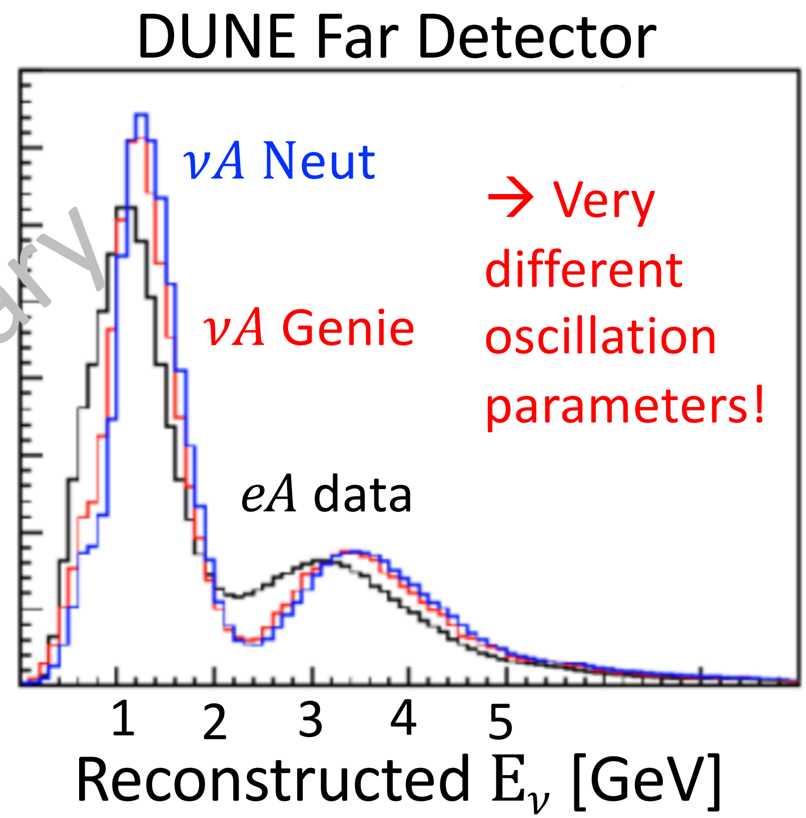


Reconstructed ν Energy [GeV]

L. Weinstein, Elba 201

Apply CLAS data to DUNE Oscillation





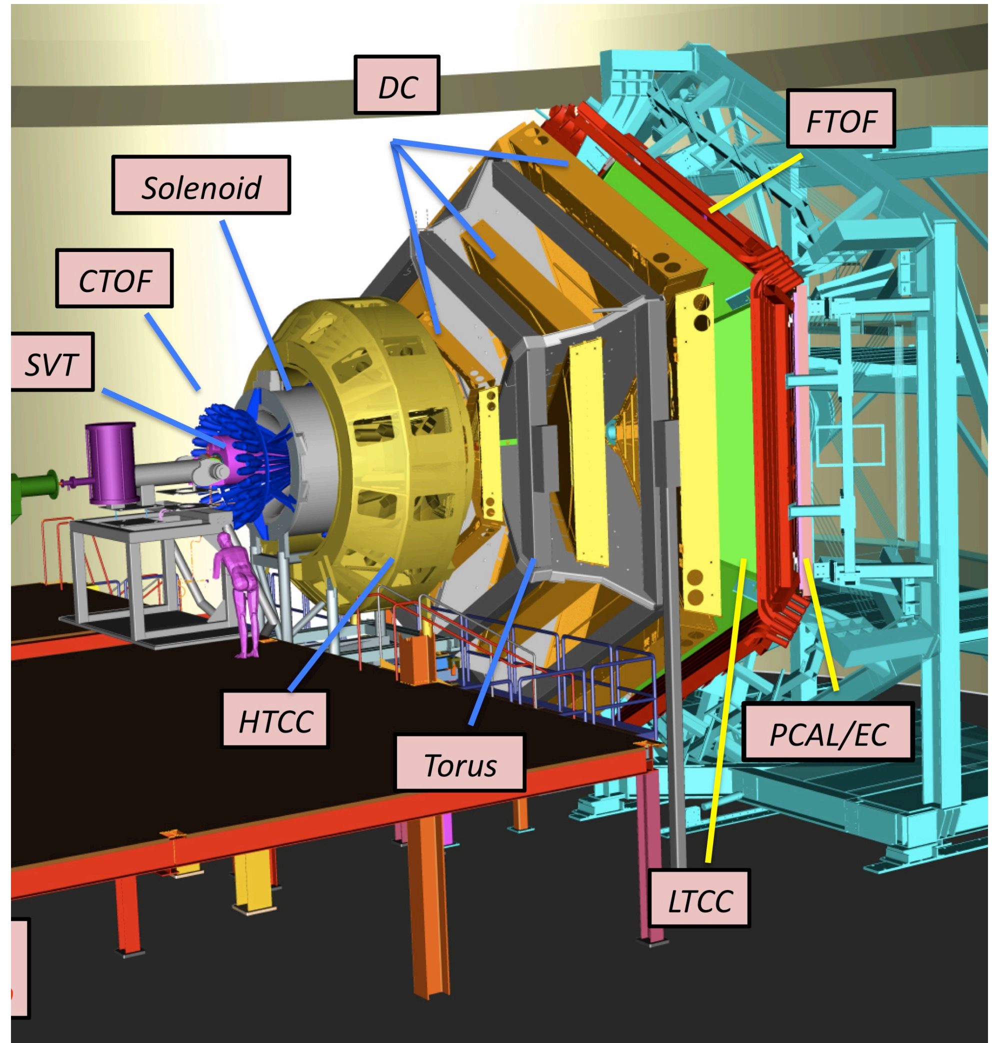
(Chris Marshall, LBNL)

- 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 (5 – 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

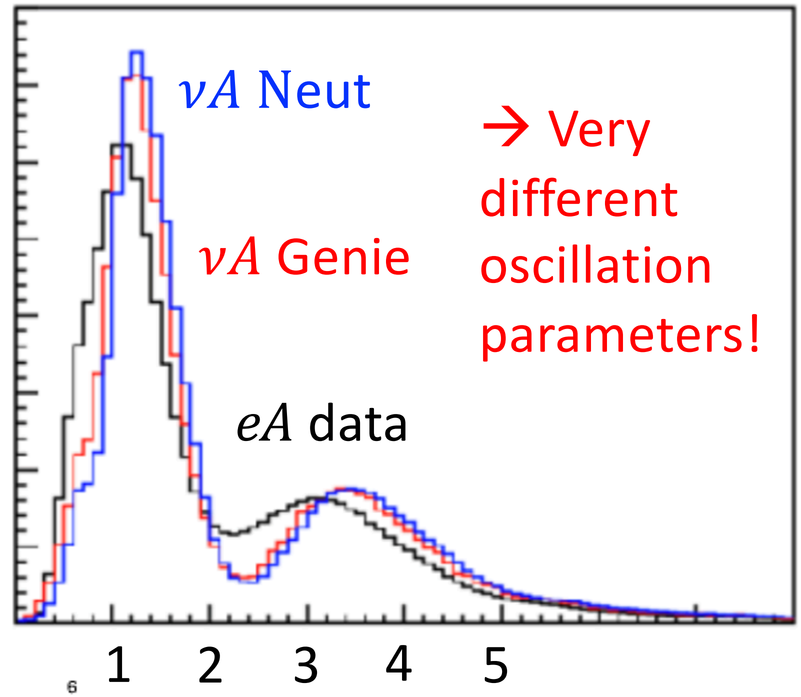


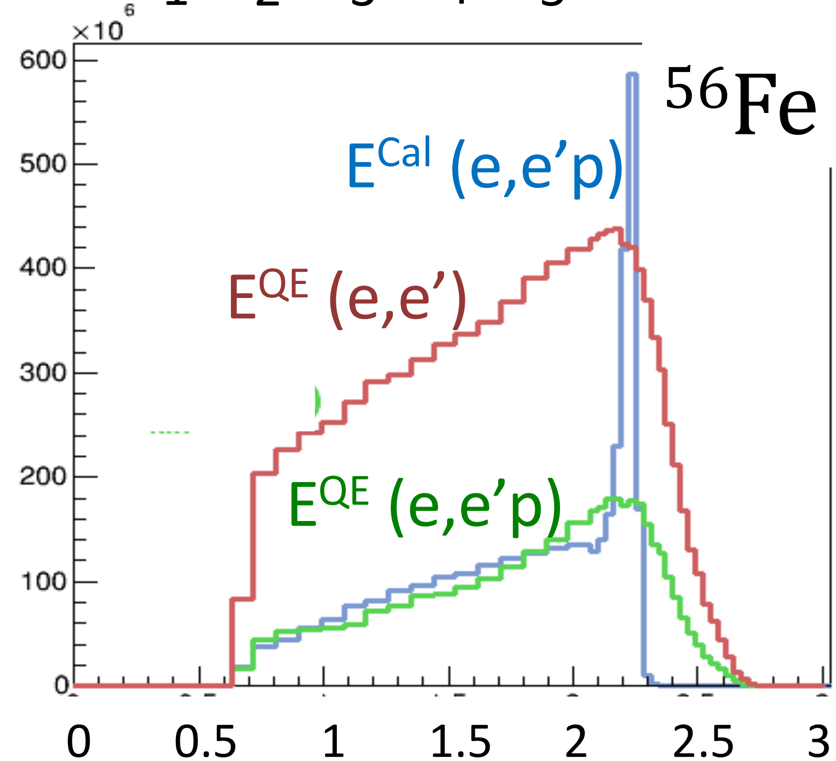
- 45 beam days approved with an A rating for
  - 1.1, 2.2, 4.4, and 6.6 GeV beam energies
  - d, He, C, O, Ar, Sn and SRC targets

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

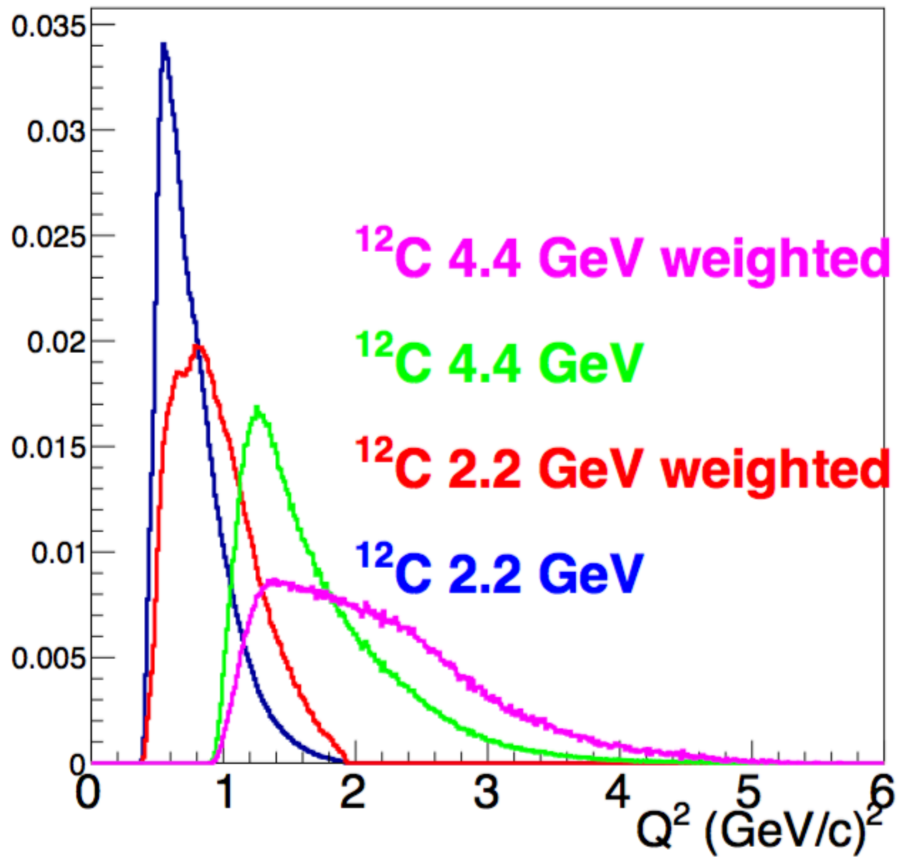
- Nuclear physics is complicated!
- Electron scattering can contribute dramatically to neutrino experiments
  - Similar physics
  - Lots of data available
  - Lots more to come
- Neutrino community input is welcome





Backup slides

Mott weighting



Similarity of electron and neutrino GENIE

2.2 GeV Fe, zero-pion. QE