Constraining neutrino-nucleus interactions with electron scattering data

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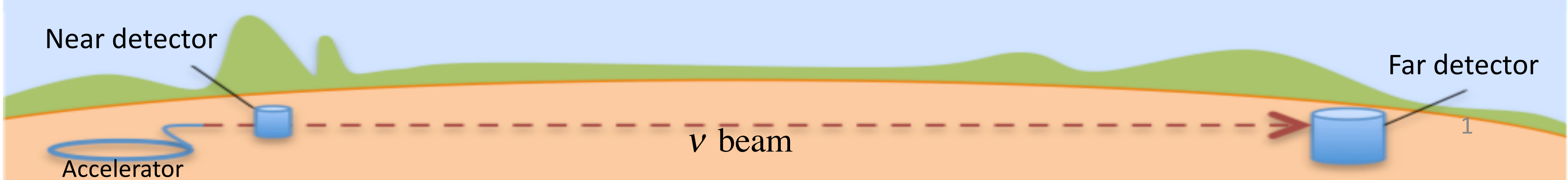
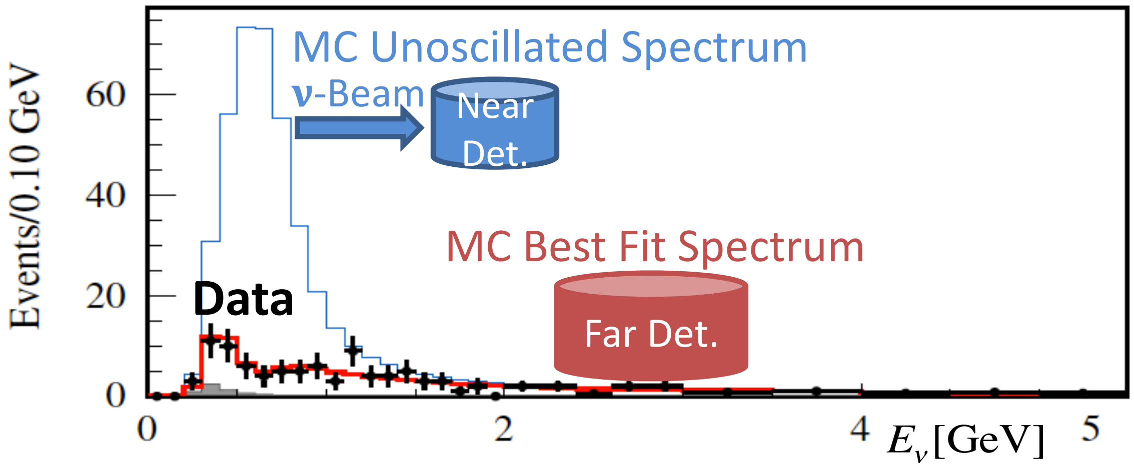


Outline

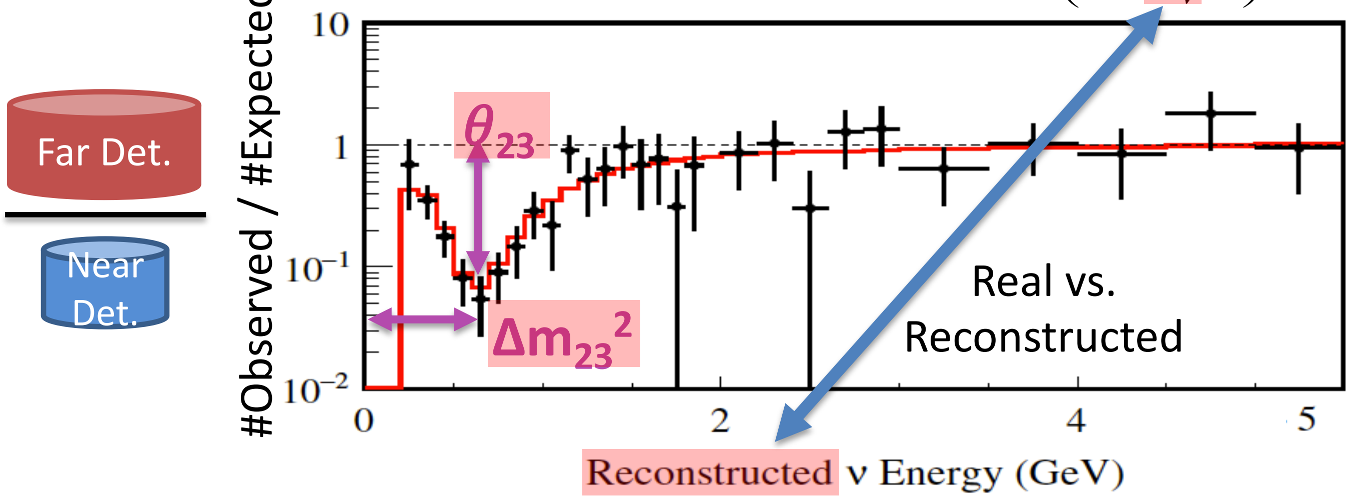
- The importance of energy reconstruction in neutrino oscillation experiments.
- What can we learn from e- scattering studies?
- Testing neutrino beam energy reconstruction methods with electron scattering JLab CLAS data.

(Long Baseline) Oscillation Challenge

T2K experiment L=295km



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

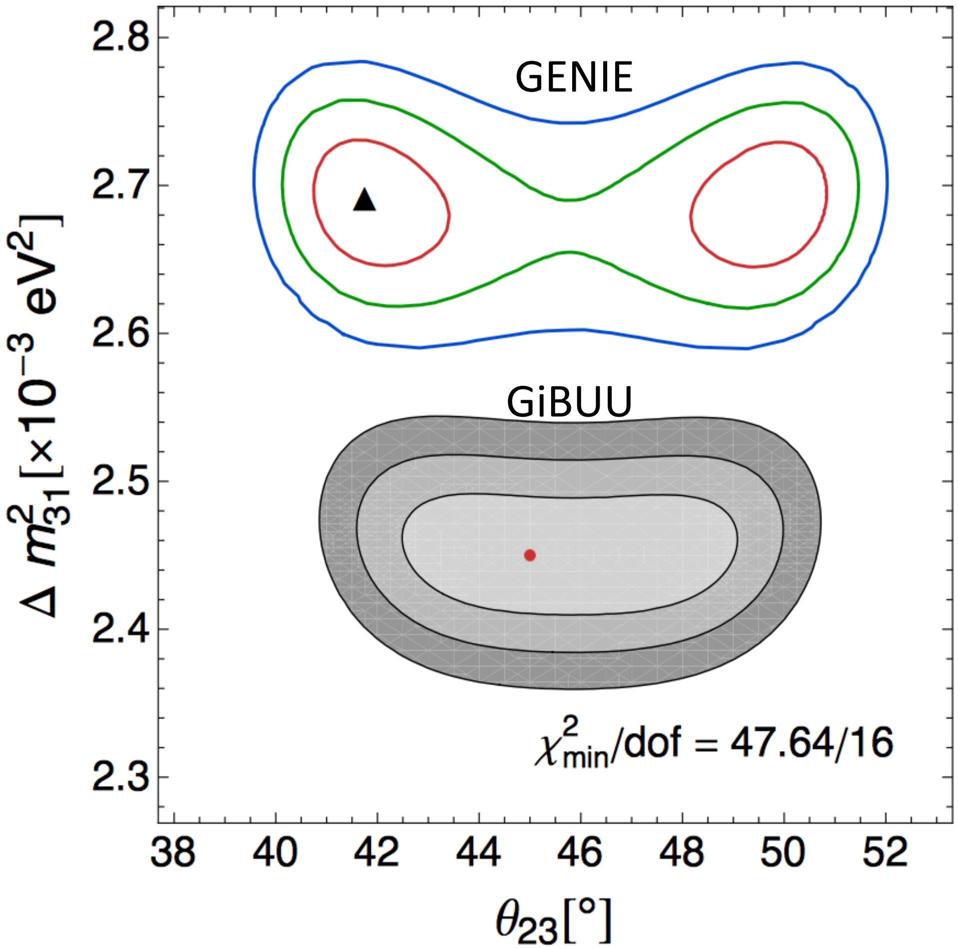


T2K, Phys. Rev. D 91, 072010 (2015)

Neutrino-nucleus interaction modeling

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

Phys.Rev. D89 (2014), 073015



Events created with GiBUU and reconstructed with GiBUU and GENIE.

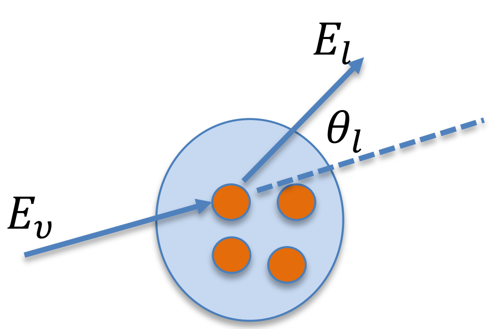
Energy Reconstruction for QE reactions

(1) Cherenkov detectors:
- Detect: leptons & pions
- Miss: protons and neutrons

(2) Tracking detectors:
- Detect: Charged particles + π^0
- Miss: Neutrons and charged particles below threshold.

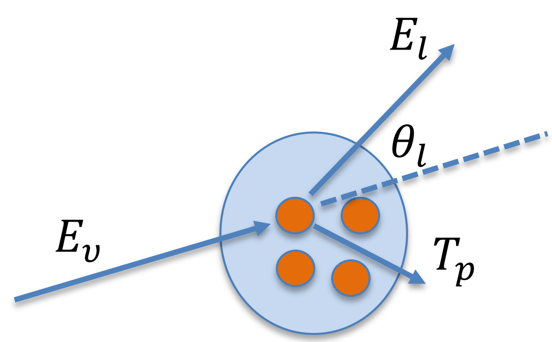
Use Lepton kinematics
Assuming QE interaction

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



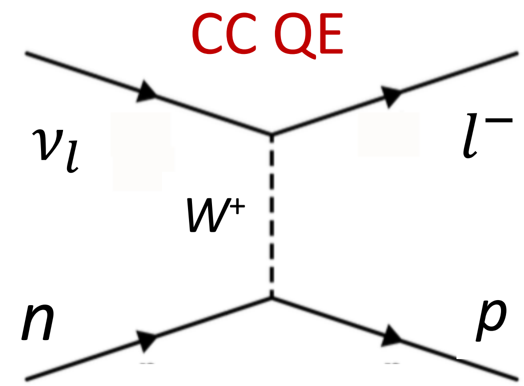
Use Final-State Calorimetry
Assuming low residual excitations

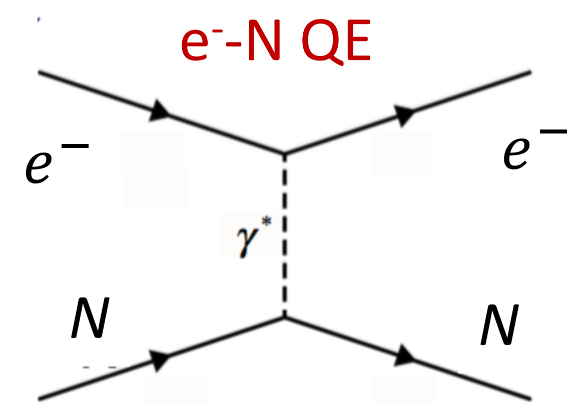
$$E_{Cal} = E_l + T_p + \varepsilon$$



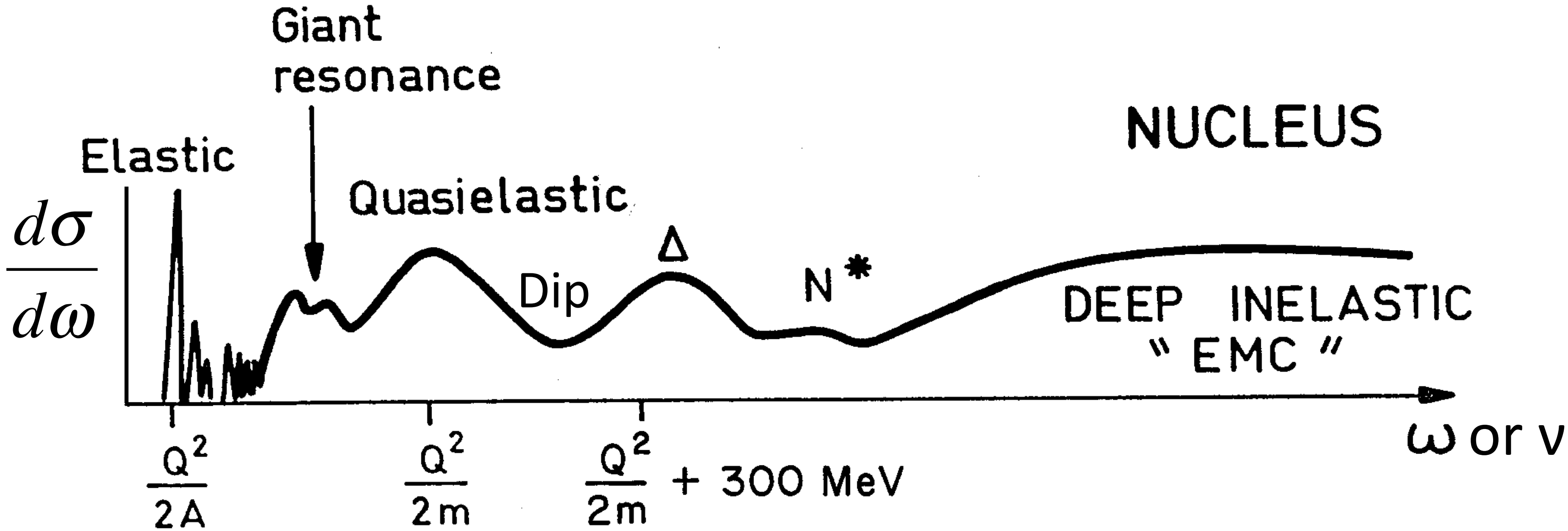
Why electrons?

- 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

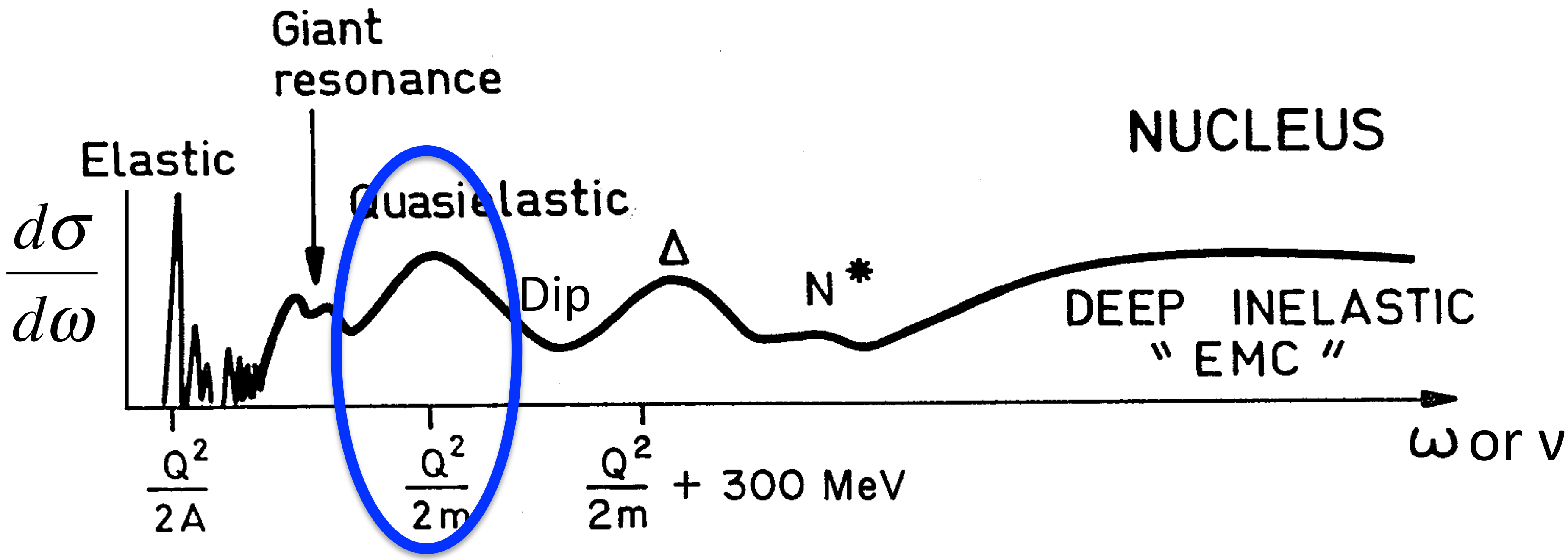




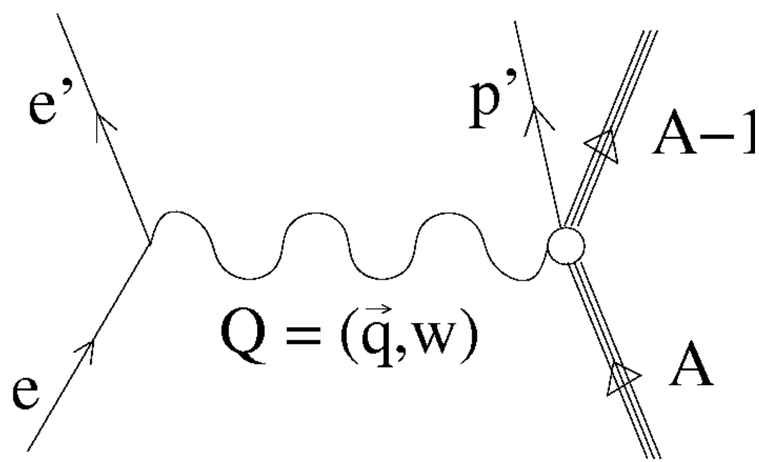
Nuclear Physics



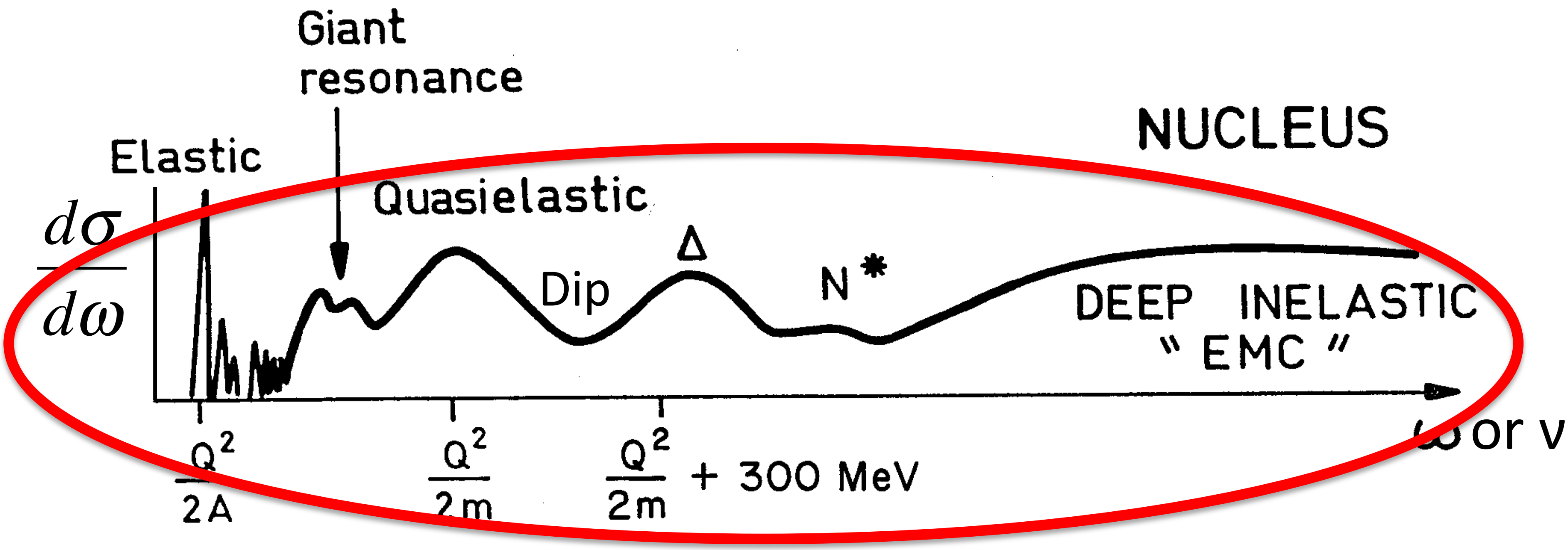
Nuclear Physics



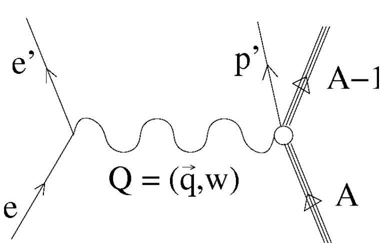
What neutrino expts want

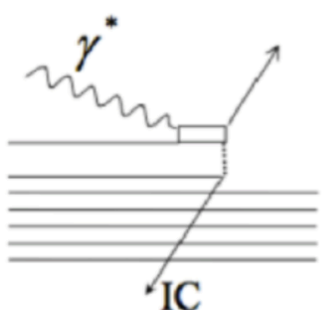


Nuclear Physics

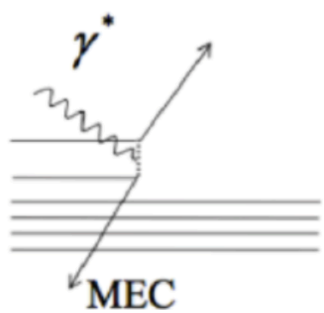


What we get (even for 0pi)

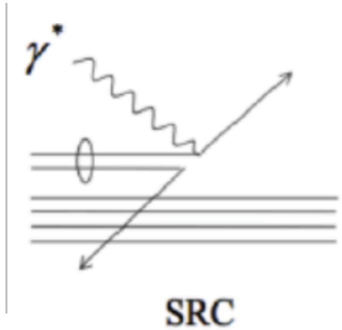




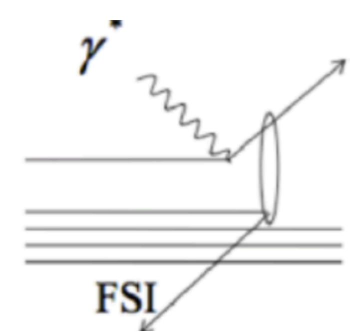
Resonance



Meson Exchange Currents



Short Range Correlations



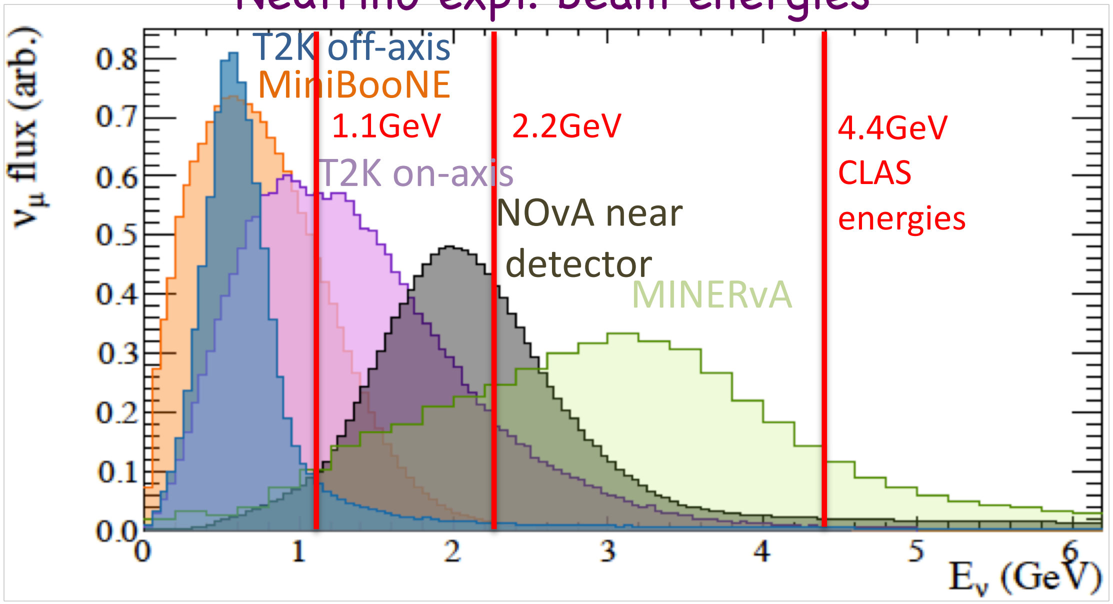
Final State Interactions

E2a experiment

Targets:

<u>CLAS: ^{3}He , ^{4}He, ^{12}C, ^{56}Fe</u>
T2K: CH, H_2O
Minerva: ^{3}He, ^{4}He, C, Fe, H_2O
Microboone: Ar
Miniboone: mineral oil (C, H, O)
Nova: $C_6H_3(CH_3)_3$
DUNE: Ar

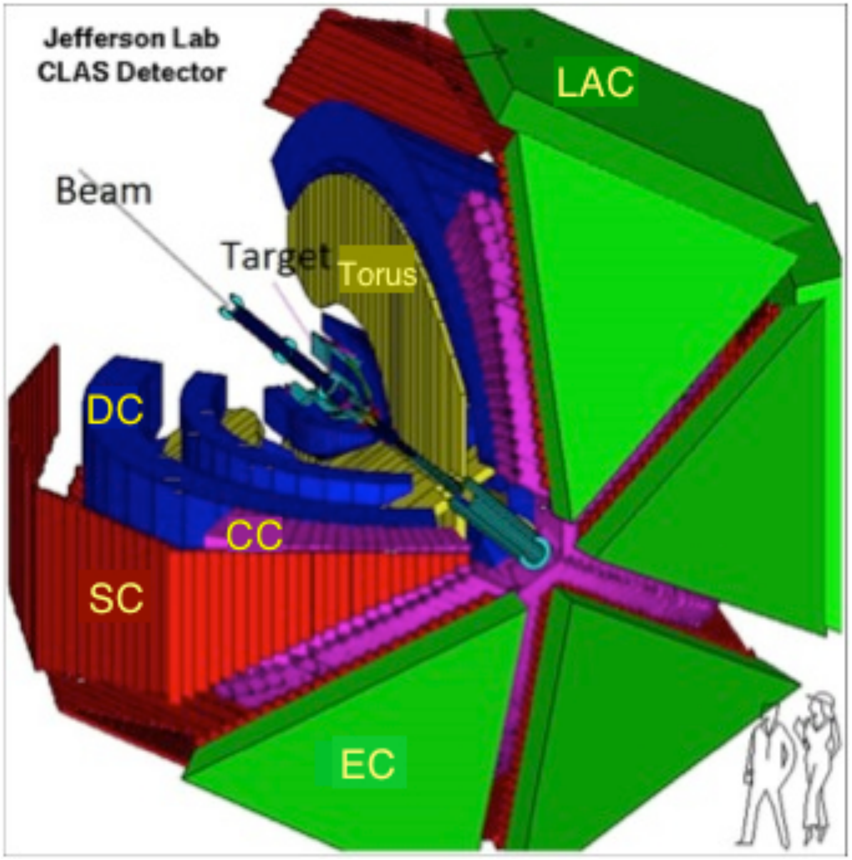
Neutrino expt. beam energies



Scale the electron scattering data with $1/\sigma_{Mott}$
to have 'neutrino like' data!

CLAS detector package

3D view



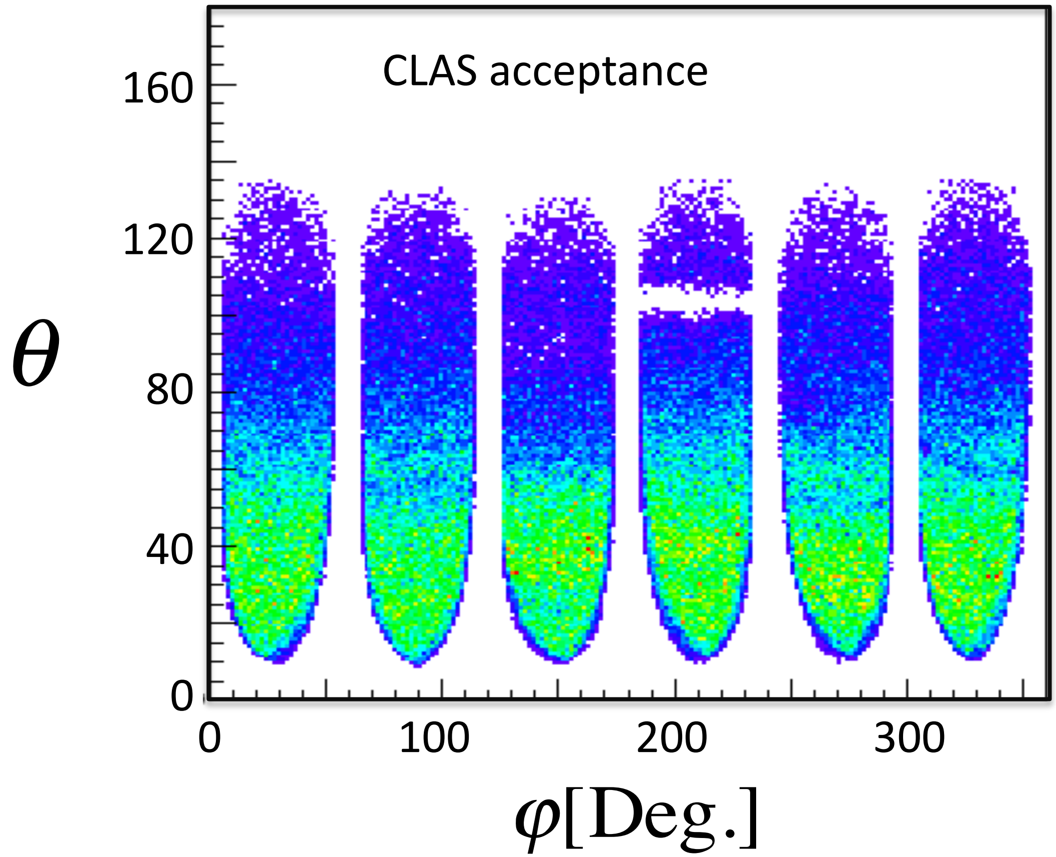
- ✧ 4π acceptance (almost).
- ✧ Charged particles (8-143°):
  - P_p >300 MeV/c
  - P_π >150 MeV/c
- ✧ Neutral particles:
  - EM calorimeter (8-45°)

As close to QE as one can get:

- Scattered electron,
- Knockout proton,
- Zero pion,
- Zero γ in the EC.

Background Subtraction

Want 0π (e,e') and (e,e'p) events.
Need to account for undetected π, γ and extra protons.



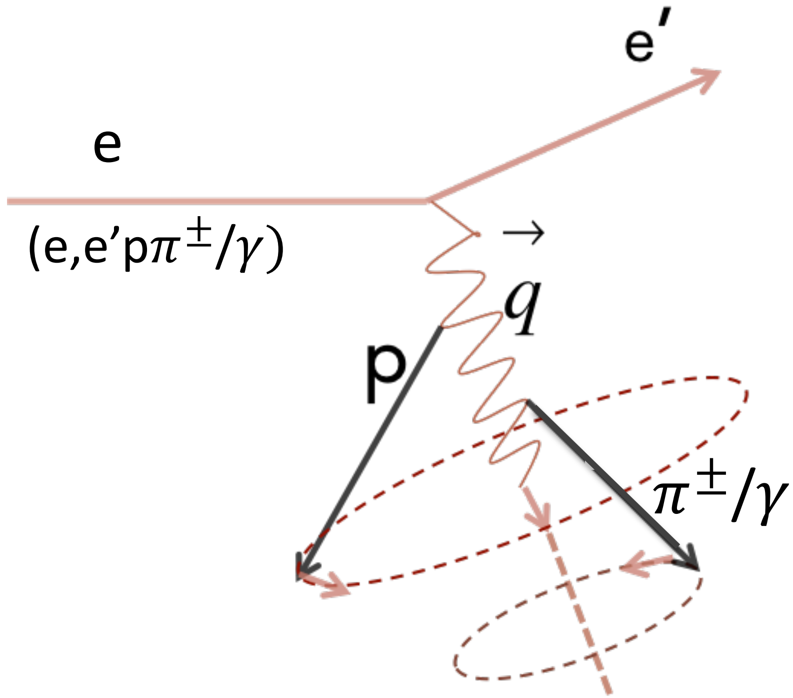
Background Subtraction in (e,e'p) analysis

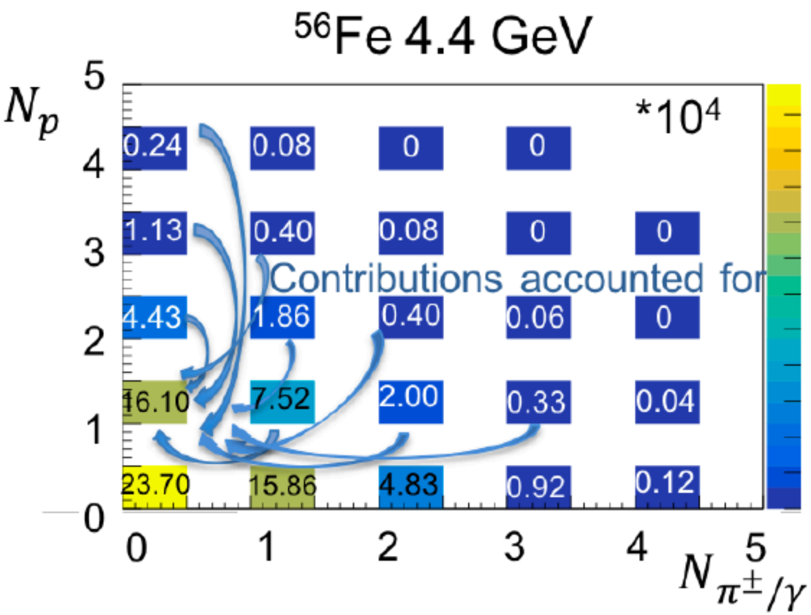
Want A(e,e'p) events.

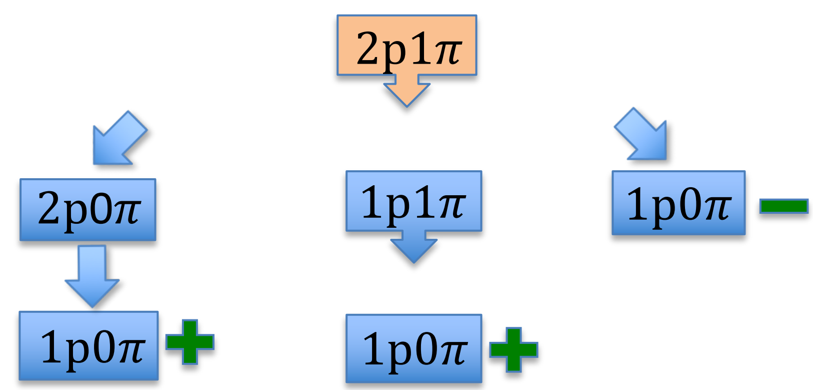
Subtract for undetected π, γ and multiple p.

Data Driven Correction:

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





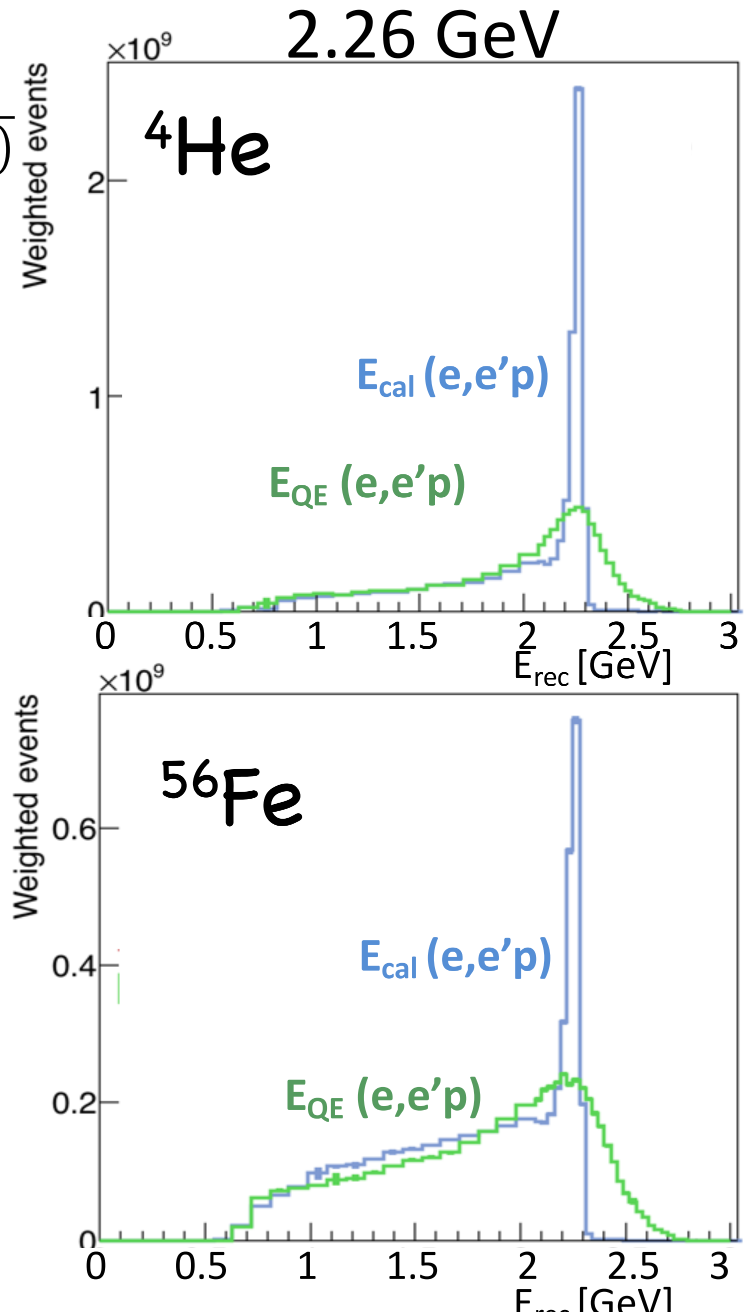


Results

Large A dependence

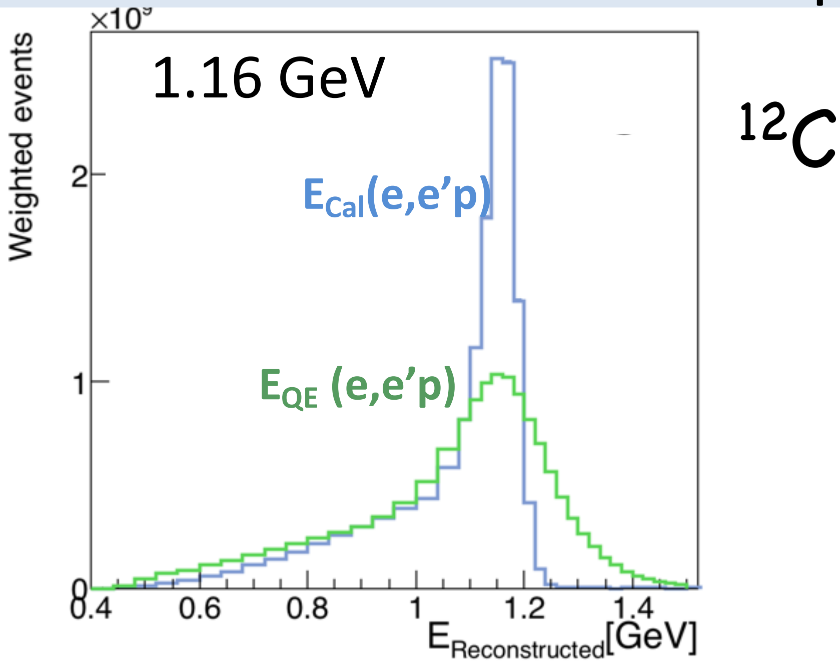
$$E_{QE} = \frac{2M\varepsilon + 2ME_l - m_l^2}{2\left(M - E_l + |k_l|cos(\theta_l)\right)}$$

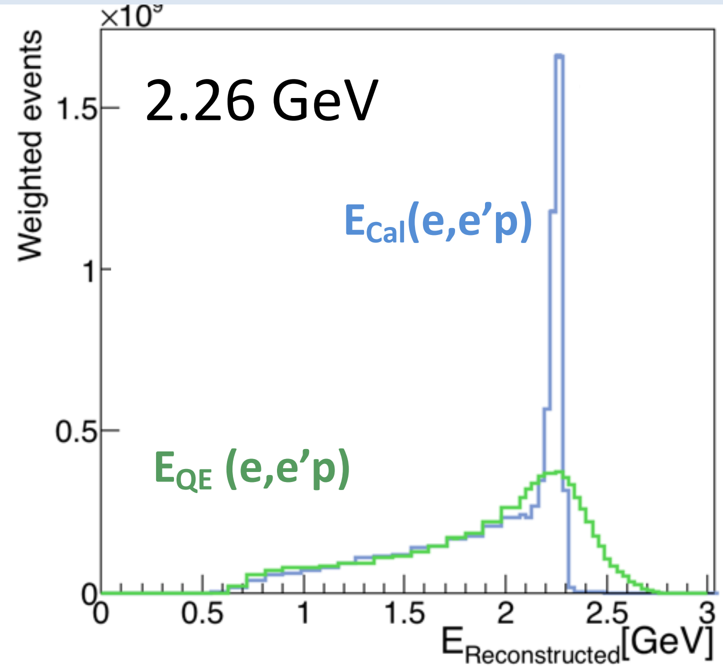
$$E_{Cal} = E_l + T_p + \varepsilon$$

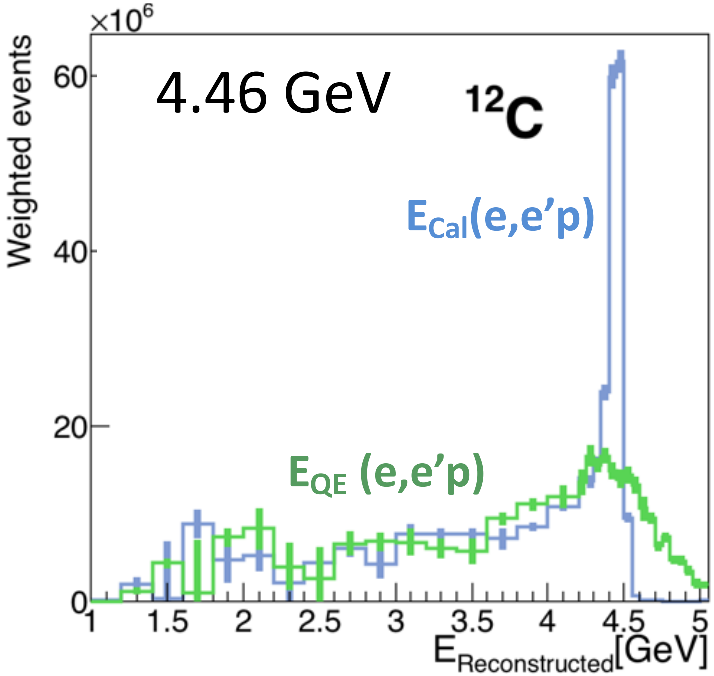


1. E_{QE} has worse peak resolution than E_{Cal}.
2. Same tail for E_{QE}+E_{Cal}.
3. ^{56}Fe is predominantly tail.
4. ^{56}Fe is much worse than ^{4}He.

E dependence





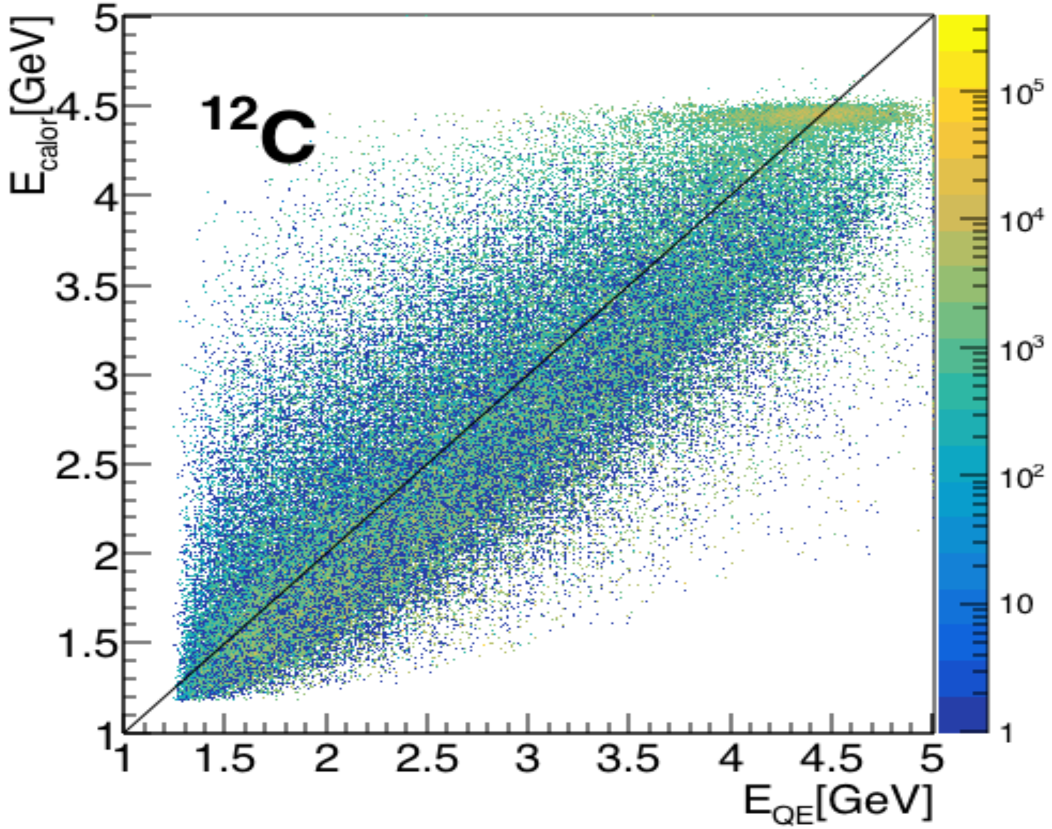


Better reconstruction at lower energies.

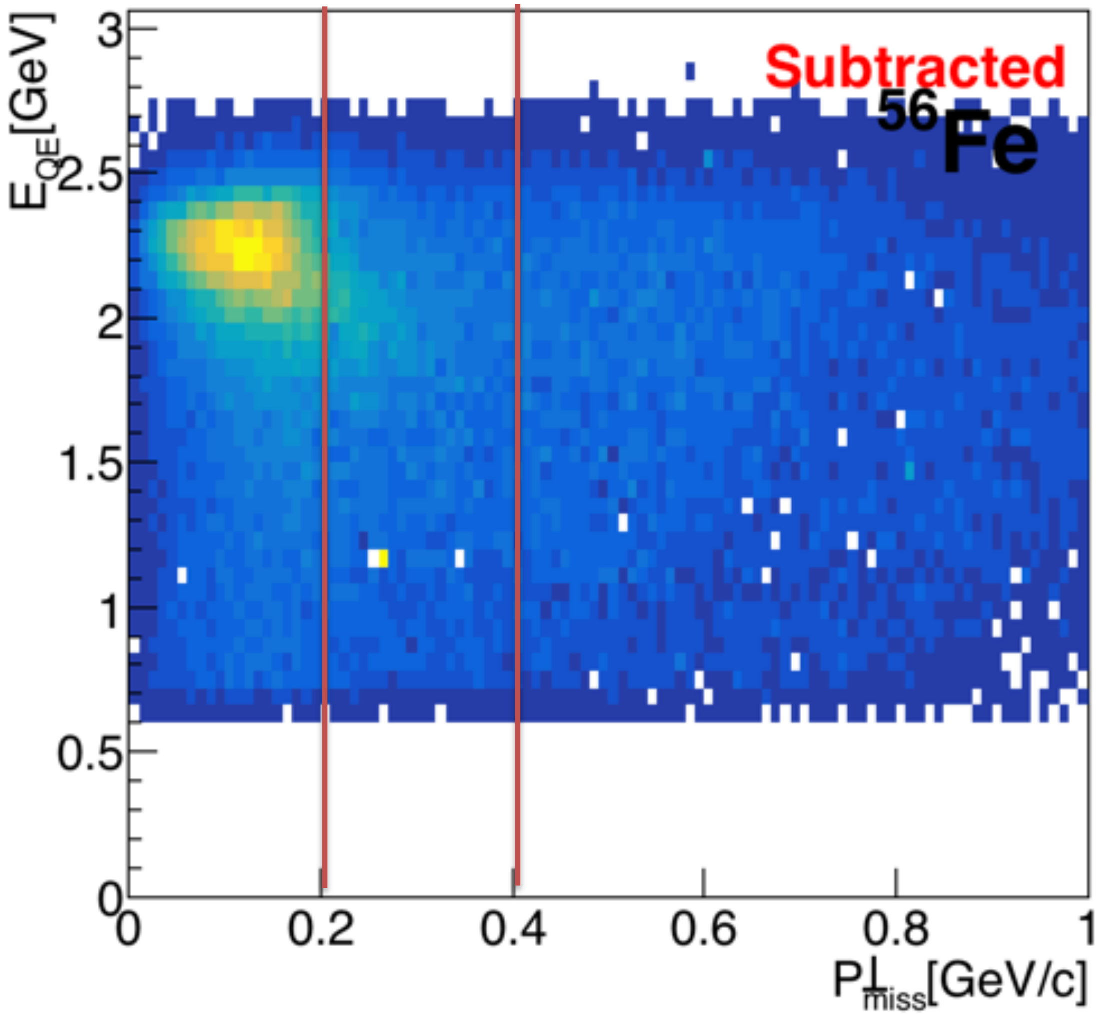
E_{QE} vs E_{Cal}

Agreement between to methods doesn't imply correct energy reconstruction.

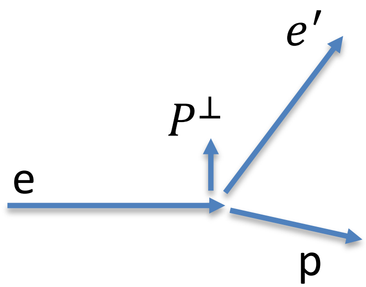
4.46 GeV



2.2 GeV ^{56}Fe

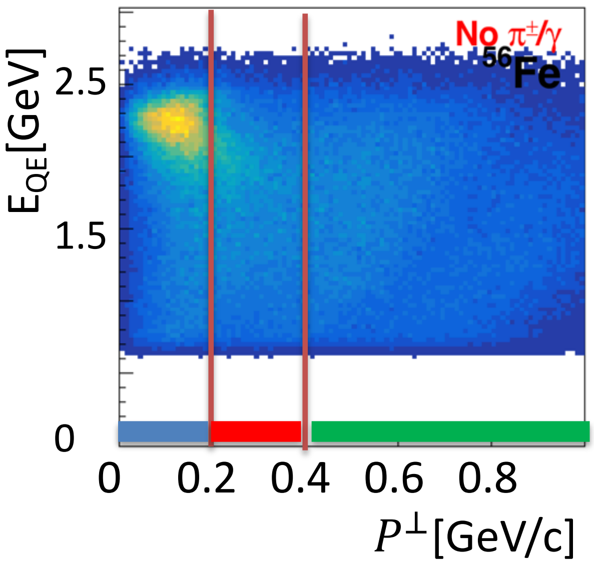


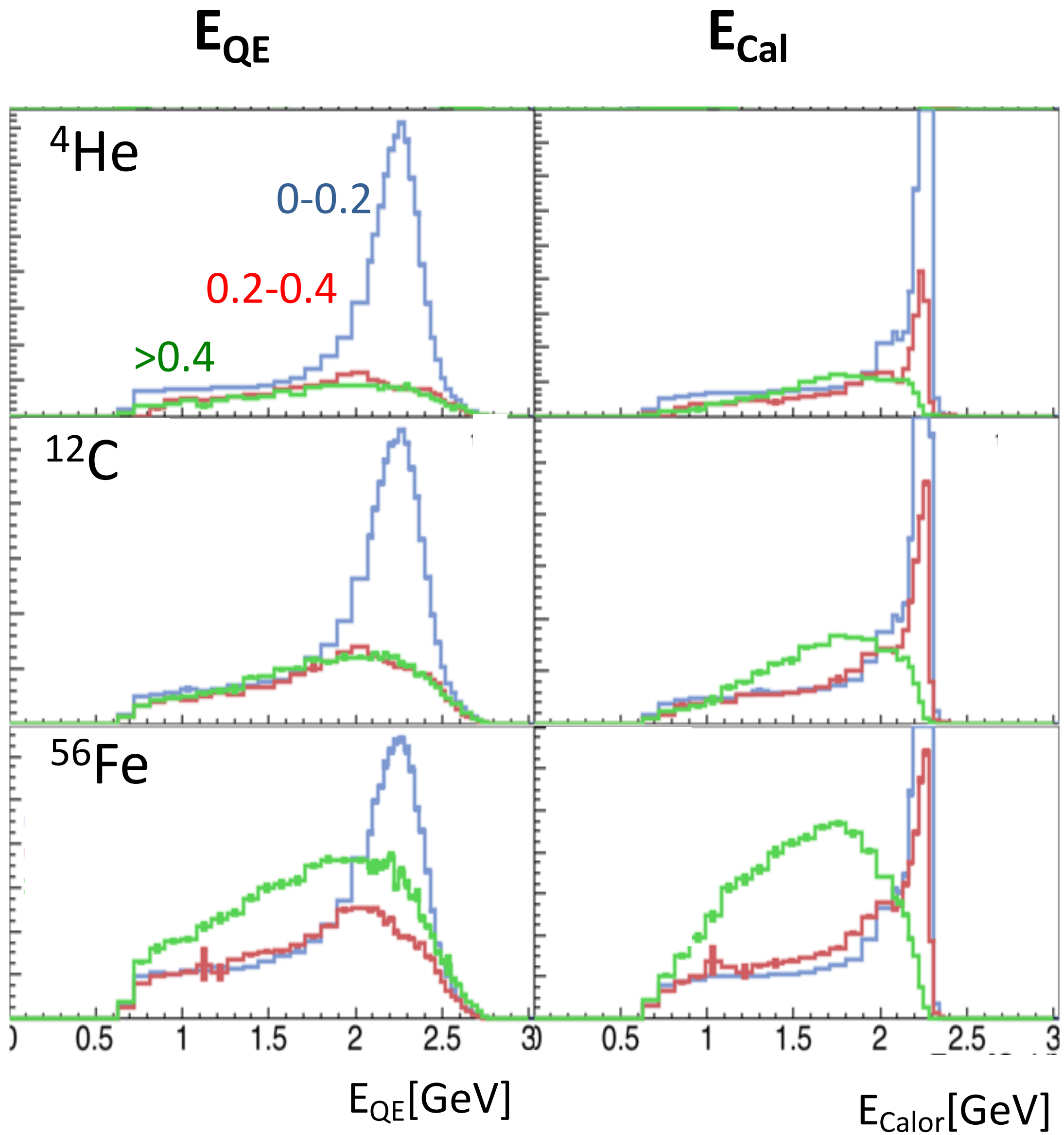
$P^{\perp} = P_{e'}^{\perp} + P_{p}^{\perp} = P_{\text{init}}^{\perp}$



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

2.2 GeV

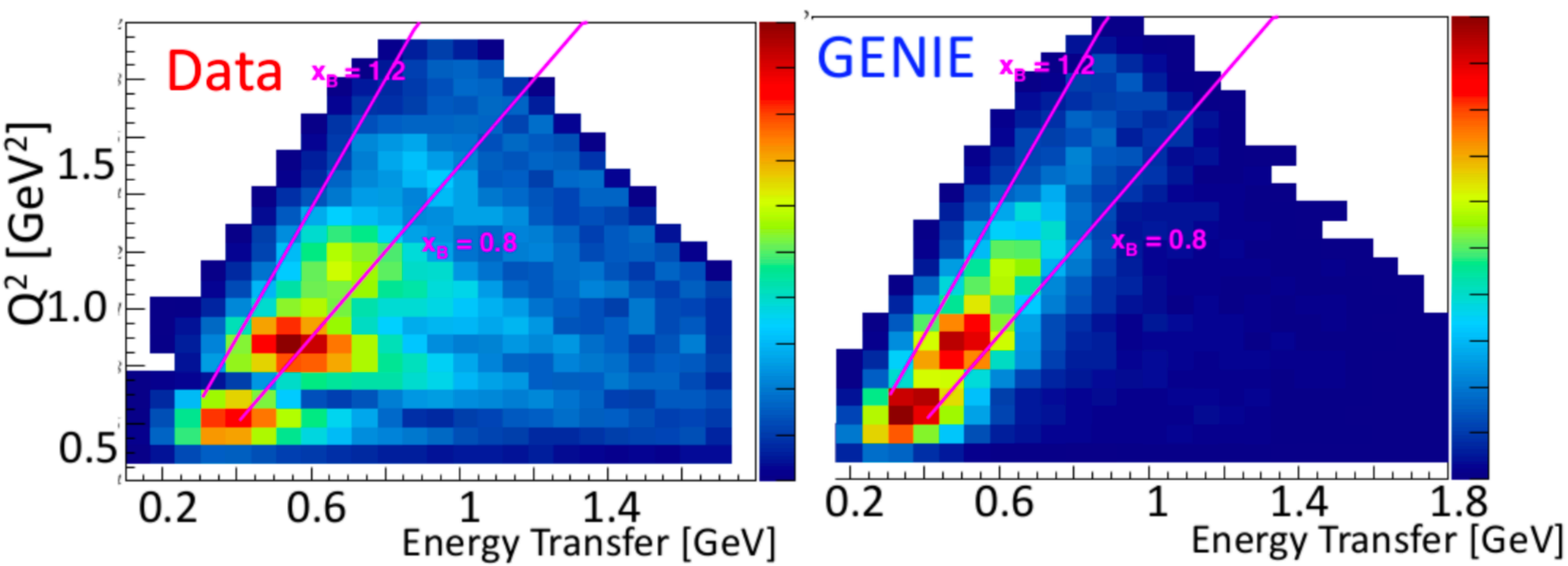




1. Large $P_{miss}^{\perp}$ ->bad reconstruction.

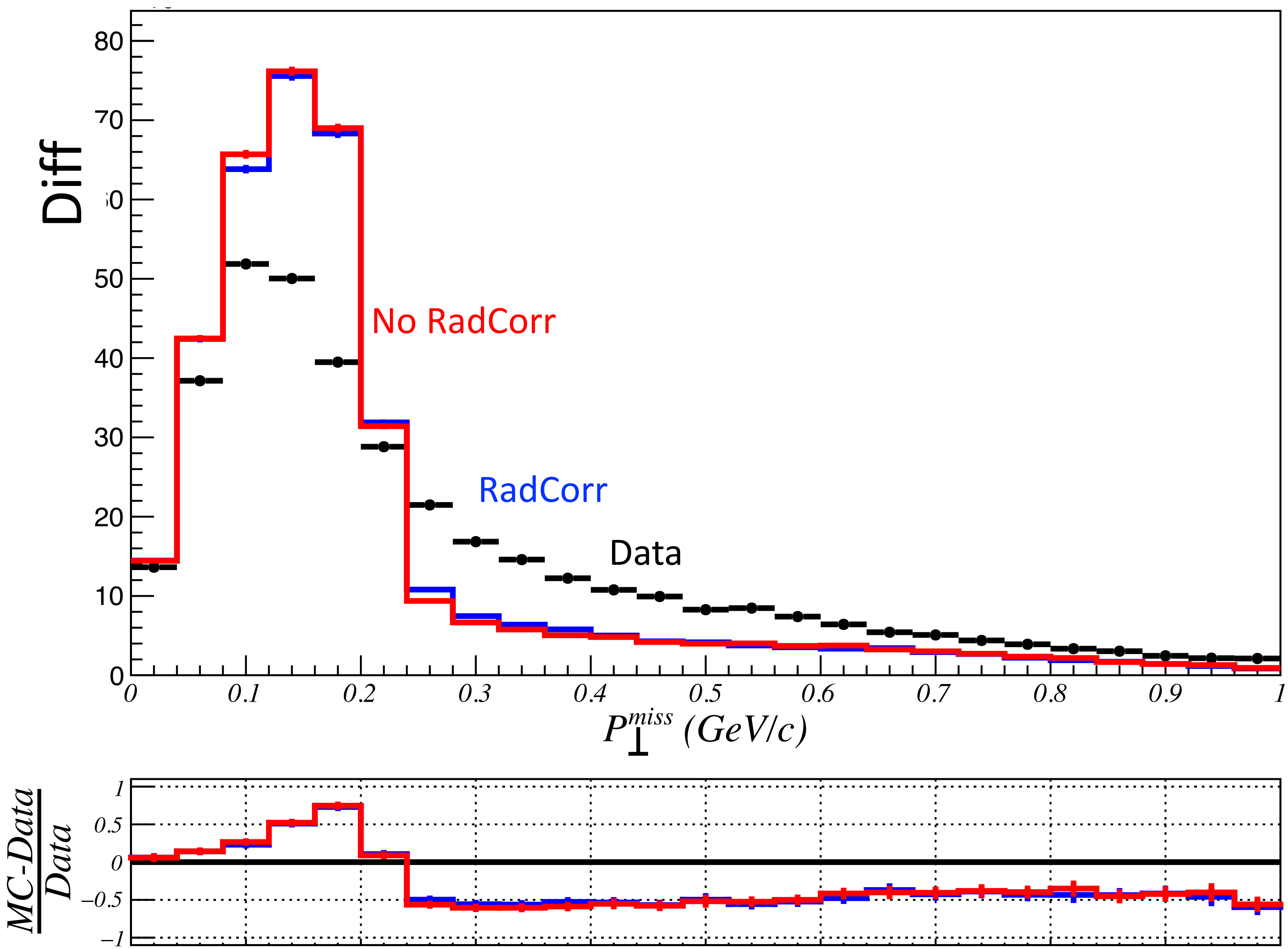
Data – Generator Comparisons

C(e,e'p) 2.26 GeV



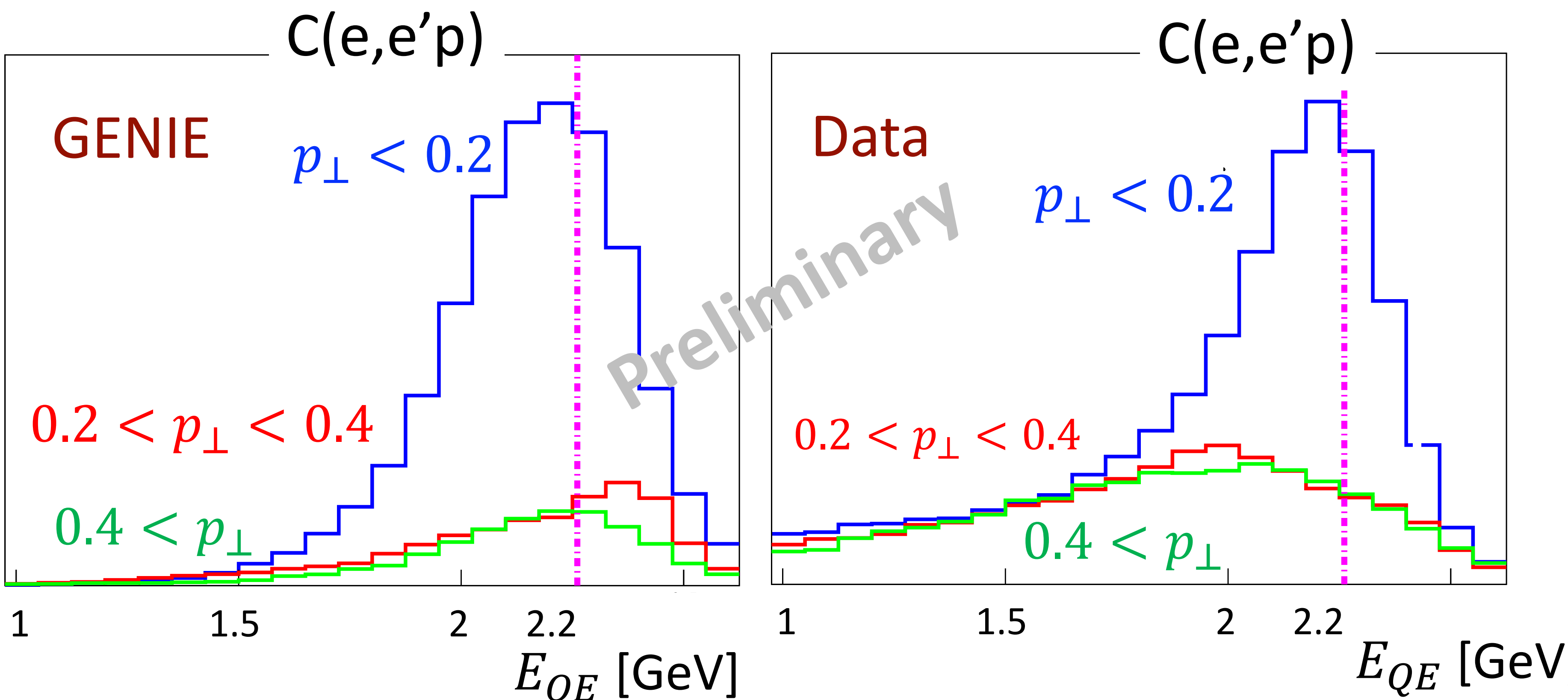
0π Data vs Genie: everywhere

C(e,e'p) 2.26 GeV



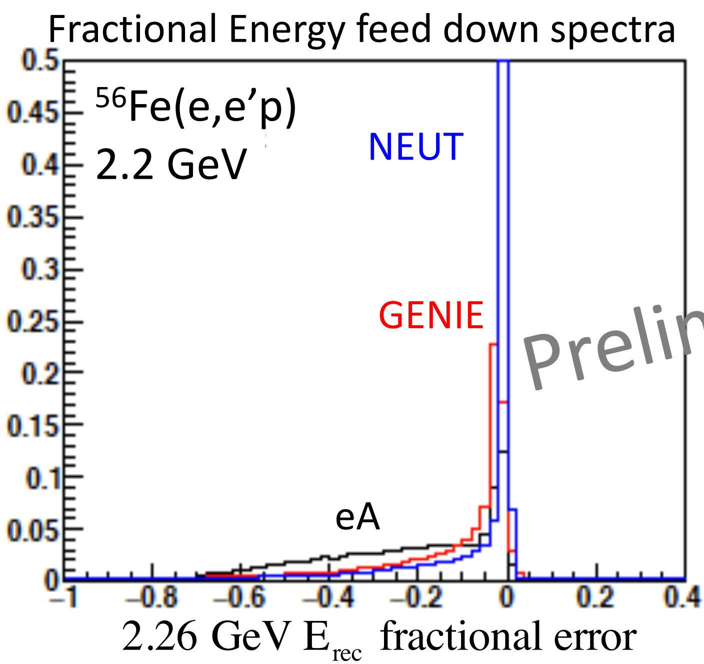
Data vs Genie: E_{beam} Reconstruction

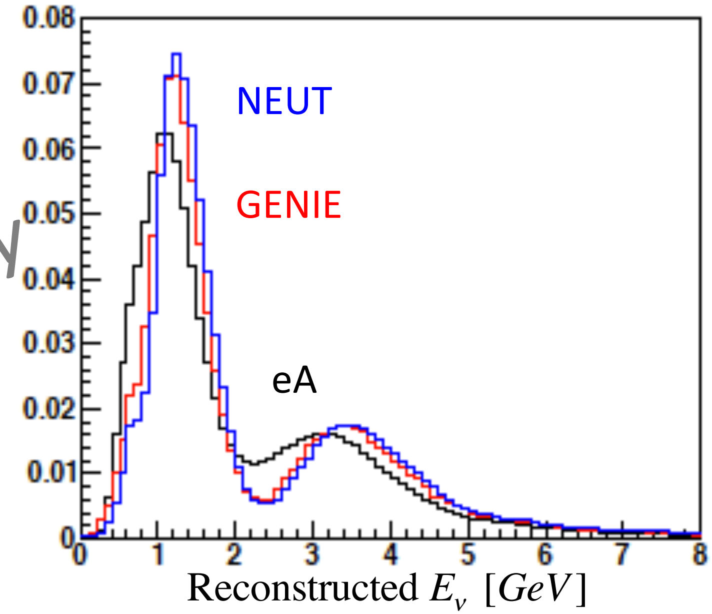
$$E_{QE} = \frac{2M\varepsilon + 2ME_l - m_l^2}{2\left(M - E_l + |k_l|cos(\theta_l)\right)}$$



Peaks in same location

Potential impact on DUNE oscillation analysis





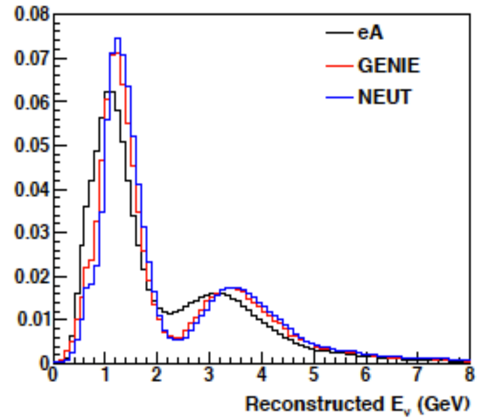
- Compare E_{rec} for eA to E_{rec} for νA
- Used 2.26 GeV eA E_{rec} for all incident energies
- Threw events with νA Genie
- Reconstruct with νA Neut or eA data

-> Very different oscillation parameters!

Will do with latest data.

Summary

1. The first use of electron data to test neutrino energy reconstruction algorithms
   - select zero-pion events to enhance quasi-elastic signal
     - ✧ Subtract for undetected π, γ and extra p.
   - just using scattered lepton (E_{QE})
     - ✧ used in Cherenkov-type neutrino detectors
   - total energy of electron plus proton (E_{Cal})
     - ✧ used in calorimetric neutrino detectors
2. Only 0.1-0.66 of events reconstruct to within 5% of the beam energy
   - better for lighter nuclei
   - improved by a transverse momentum cut
3. First preliminary attempt to quantify the impact of this work on oscillation analysis.



4. Under CLAS analysis review.
5. Anticipate paper submission soon.

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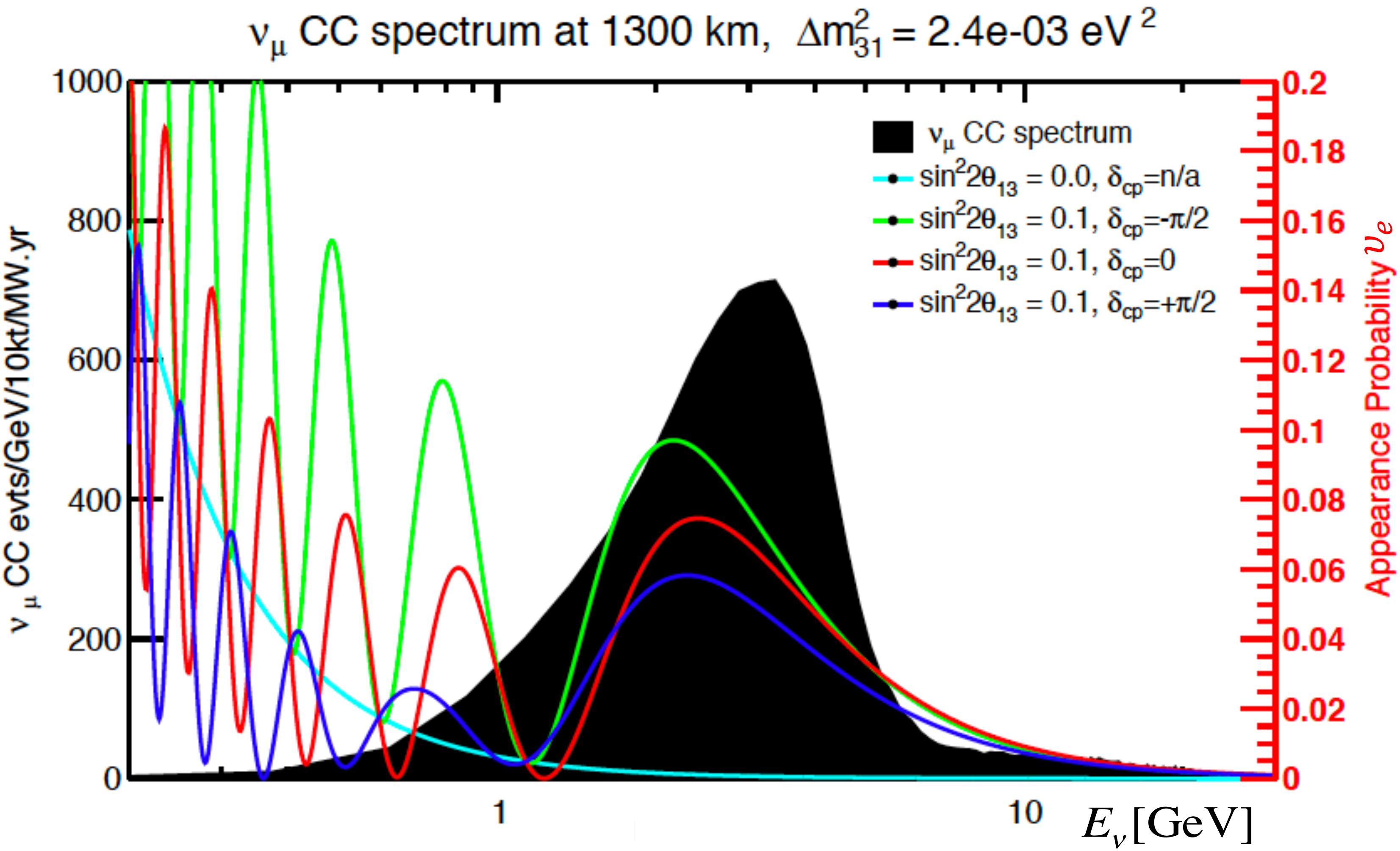
Appearance probability expected in DUNE for three different sets of values of δ_{CP} and θ_{13}



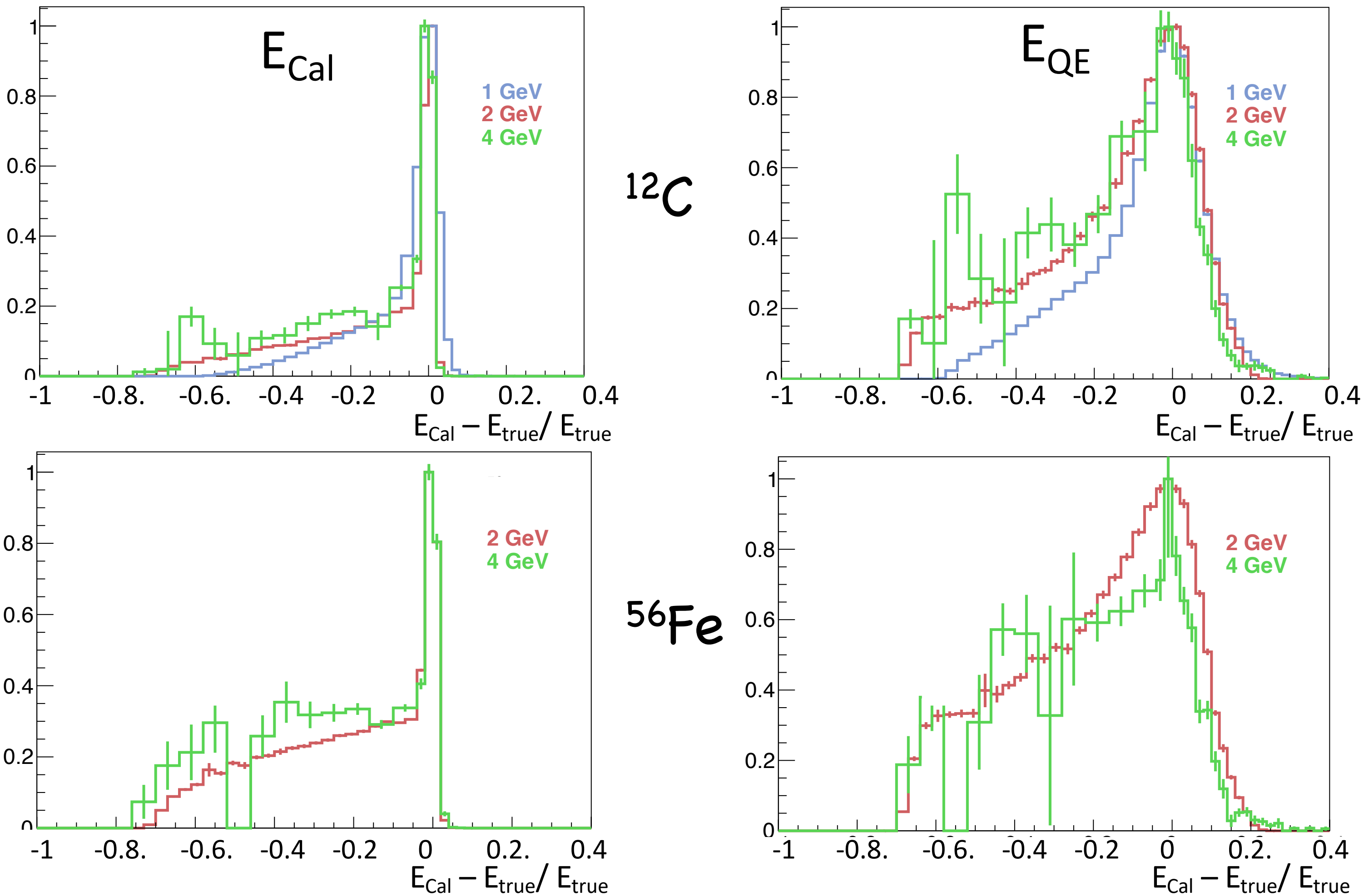
Need $\Delta E_\upsilon < 0.1$ GeV.

arXiv:1307.7335 LBNE Collaboration

Fractional energy feed down ($E_{rec.} - E_{true} / E_{true}$)

(e,e'p)

The fractional energy feed down is bigger at higher energies.



Percent of events reconstructed to within 5% of the beam energy

	1.1 GeV		2.2 GeV		4.4GeV	
	E_{QE} 1e	E_{Cal} 1e1p	E_{QE} 1e	E_{Cal} 1e1p	E_{QE} 1e	E_{Cal} 1e1p
^{3}He	44	66	32	54	21	41
^{4}He			25	46	16	32
^{12}C	28	47	22	39	13	27
^{56}Fe			17	25	10	16

From 10 to 66% of events reconstruct to within 5% of beam energy.

Error sources (new)

- Statistical error.
- Errors of the weights for subtraction of undetected pions and protons.
  - ✧ Statistical error due to number of (e,e'π) events used to determine undetected pion contribution
  - ✧ Rotate (e,e'π) events enough times to reduce statistical error below 1%.
- Systematic error due to the ϕ-dependence of the pion cross section modeled and found to be negligible (less than 1%).

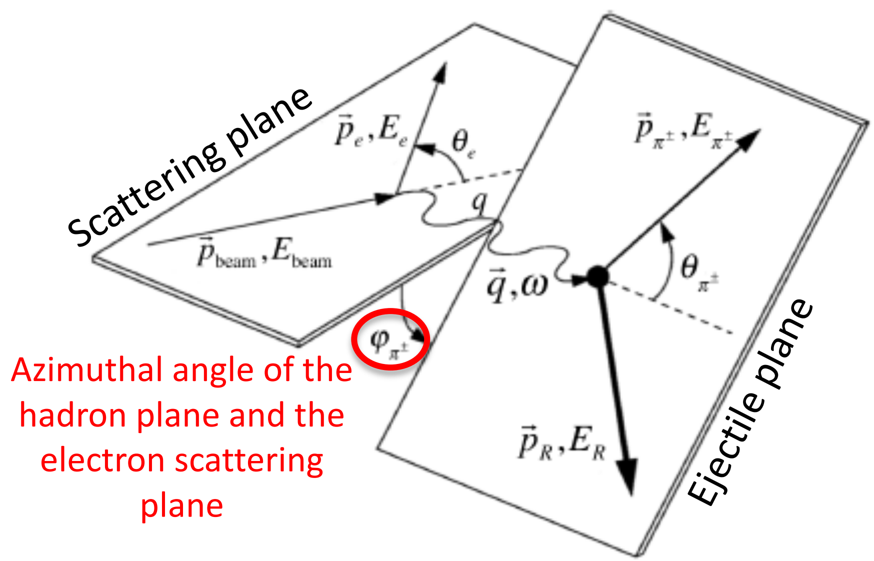
Error sources

-Systematic error due to the ϕ-dependence of the cross section.

$$\frac{d^6\sigma}{d\Omega_e d\Omega_p dE_{\text{miss}} d\omega} = K\sigma_{\text{Mott}}\left[v_L R_L + v_T R_T + v_{LT} R_{LT}\cos(\varphi) + v_{TT} R_{TT}\cos(2\varphi)\right]$$

$K = \text{(phase space)}$

$v = v(q,\omega)$ electron kinematics



Phi dependence

Cross section for unpolarized pion electroproduction on a single nucleon:

$$\frac{d\sigma}{d\Omega_\pi^*}(W, Q^2, \theta_\pi, \phi_\pi) = A + B\cos\phi + C\cos 2\phi$$

$$A = (\sigma_{\mathrm{T}} + \epsilon\sigma_{\mathrm{L}})\frac{p_\pi^*}{k_\gamma^*}$$

$$B = \sigma_{\mathrm{LT}}\frac{p_\pi^*}{k_\gamma^*}\sin\theta_\pi\sqrt{2\epsilon(\epsilon+1)}$$

$$C = \sigma_{\mathrm{TT}}\frac{p_\pi^*}{k_\gamma^*}\sin^2\theta_\pi\epsilon$$

$$k_\gamma = \frac{W^2 - M^2}{2M} \qquad k_\gamma^* = k_\gamma M/W \qquad \epsilon = \frac{1}{1 + 2(1 + \frac{\nu^2}{Q^2}\tan^2\frac{\theta_e}{2})}$$

Where p_π^*, θ_π and ϕ_π are the momentum, scattering and azimuthal angles of the π^0 in the CM frame.

Weight without φ *dependence*

$$W = \frac{\sum_{i=1}^{N_{\mathrm{Undet}}} 1}{\sum_{i=1}^{N_{\mathrm{Det}}} 1}$$

Weight with φ *dependence*

$$W = \frac{\sum_{i=1}^{N_{\mathrm{Undet}}} 1 + B/A\cos\phi_\pi + C/A\cos 2\phi_\pi}{\sum_{i=1}^{N_{\mathrm{Det}}} 1 + B/A\cos\phi_\pi + C/A\cos 2\phi_\pi}$$

Phi dependence

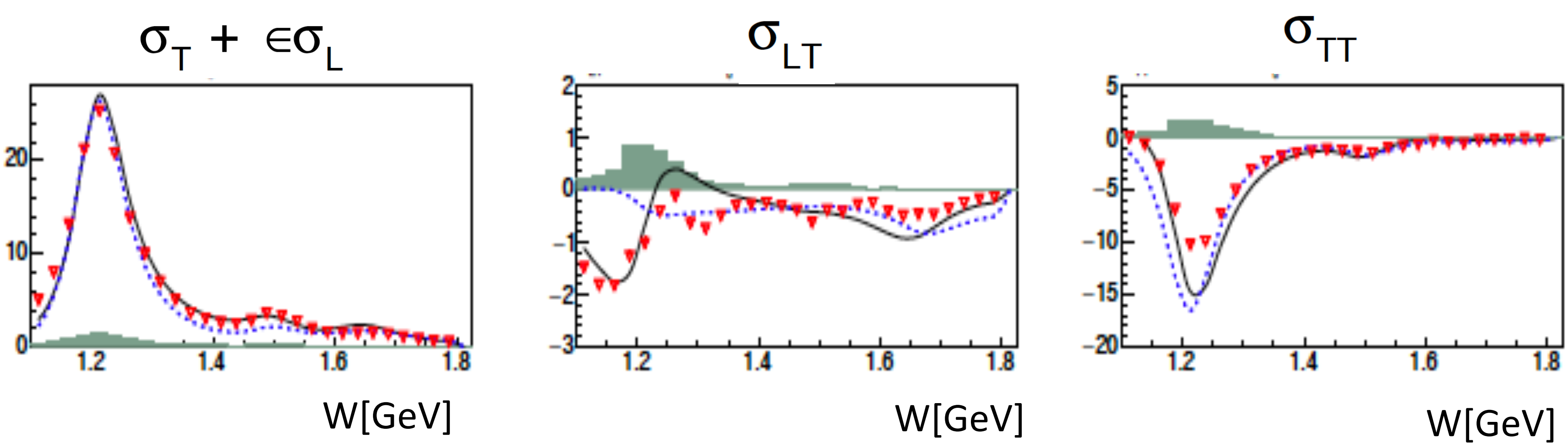
Use maximum of structure functions from Markov et al. paper [ref] for $cos\theta_\pi = 0.1$ and $0.4 \leq Q^2 \leq 1GeV^2$.
The absolute values are the biggest for Q^2=0.45GeV^2.
$\sigma_T + \epsilon\sigma_L = 30\mu b$, $\sigma_{TT} = -10\mu b$ and $\sigma_{LT} = -2\mu b$.

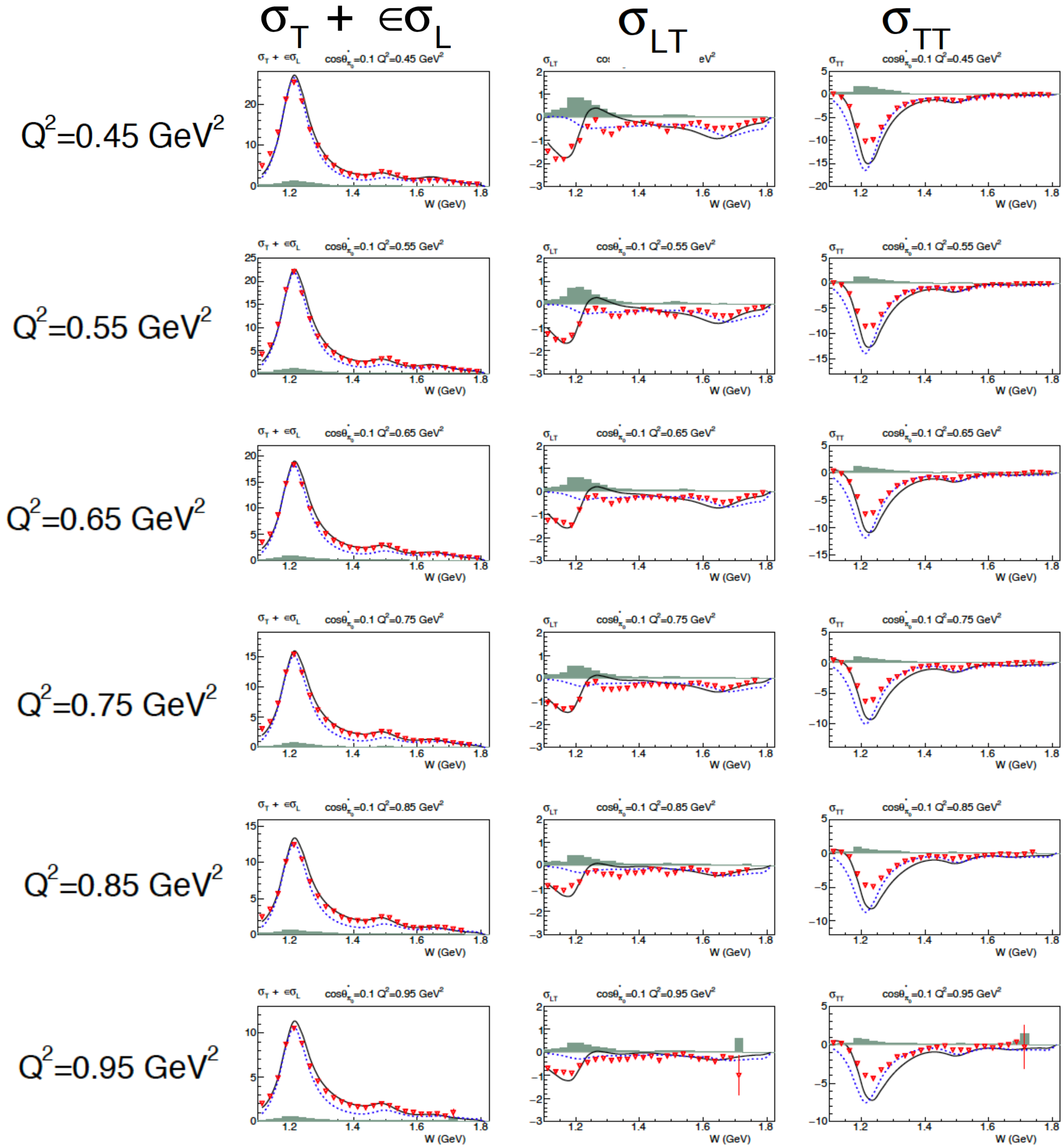
$$A = (\sigma_T + \epsilon\sigma_L)\frac{p_\pi^*}{k_\gamma^*}$$

$$B = \sigma_{LT}\frac{p_\pi^*}{k_\gamma^*}\sin\theta_\pi\sqrt{2\epsilon(\epsilon+1)}$$

$$C = \sigma_{TT}\frac{p_\pi^*}{k_\gamma^*}\sin^2\theta_\pi\epsilon$$

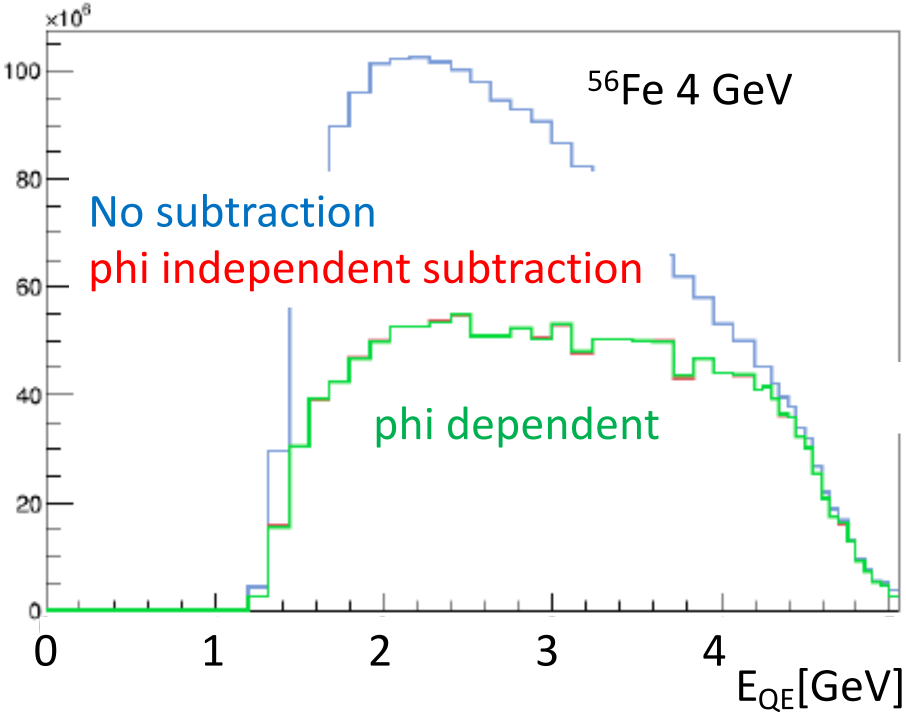
$\cos\theta^*_{\pi_0}$=0.1 Q^2=0.45 GeV^2

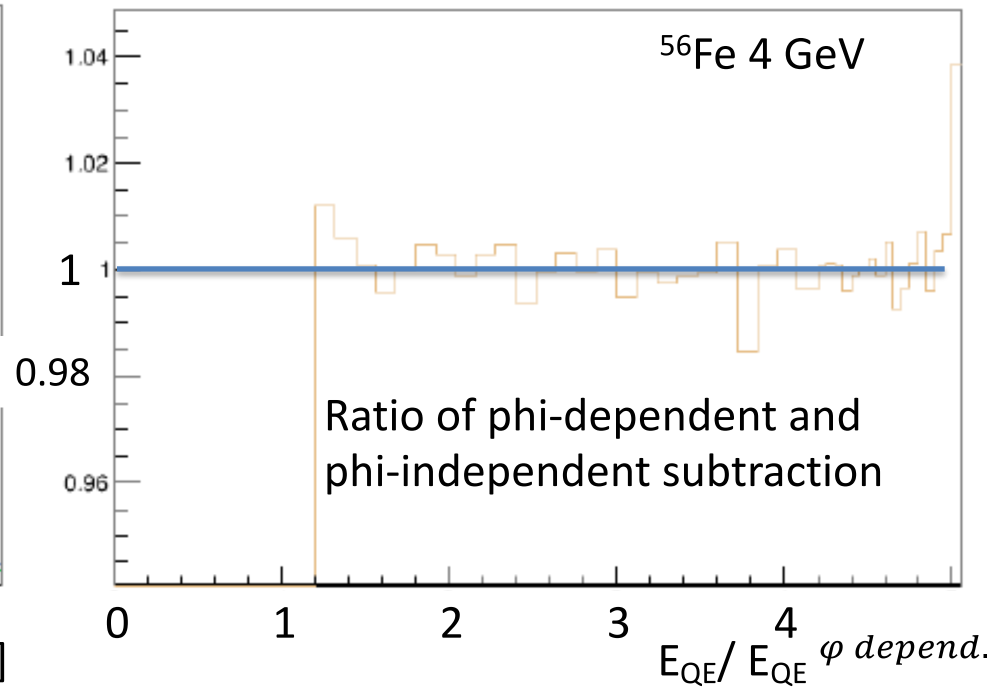



σT + ∈σL
σLT
σTT
Q2=0.45 GeV2
Q2=0.55 GeV2
Q2=0.65 GeV2
Q2=0.75 GeV2
Q2=0.85 GeV2
Q2=0.95 GeV2
W (GeV)

Error sources: Phi dependence

Subtracting for undetected one π events in $^{56}Fe(e,e')$ 4 GeV analysis





Negligible phi dependence!