Study of neutrino energy reconstruction using electron scattering data

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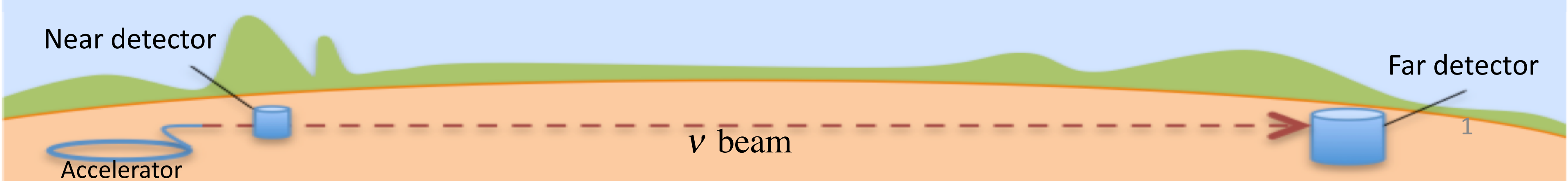


Outline

1. Why do this?

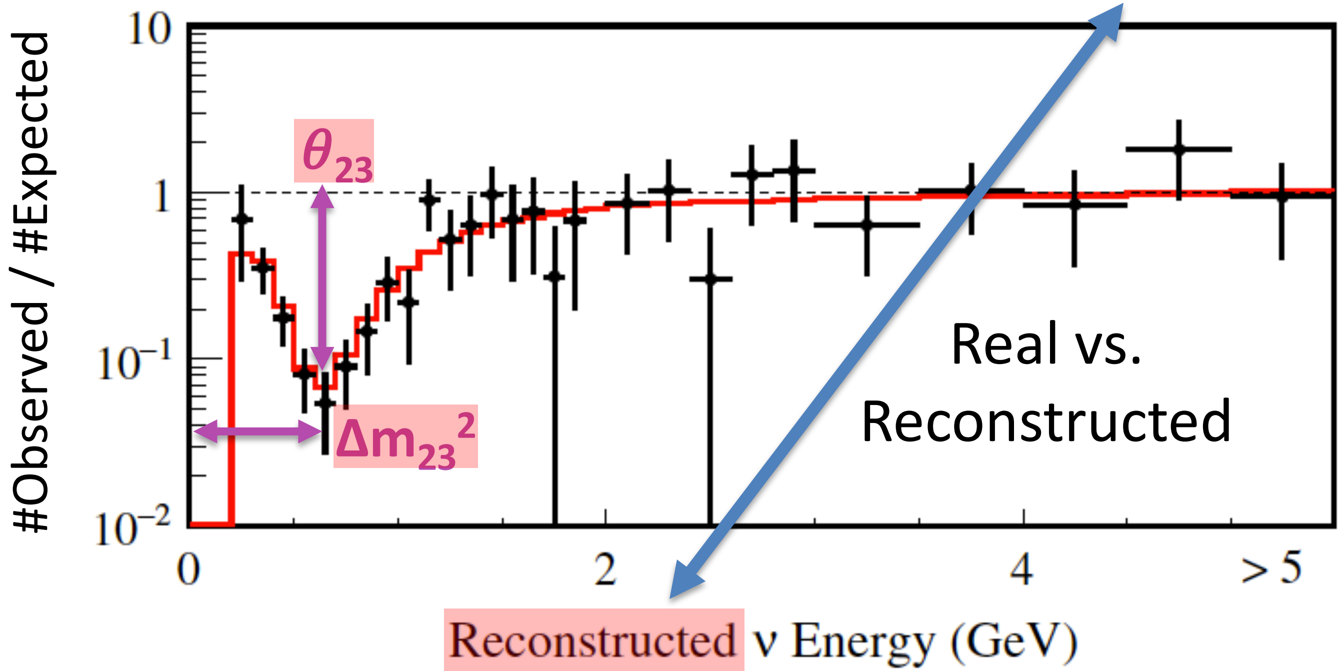
2. July 2018 status:
   - Channels (e,e’), (e,e’p) zero pions and photons.
   - E_{Cal}, E_{QE}.
   - Subtraction for undetected π^+, π^- and extra p incomplete.

3. Status today:
   - Completed subtraction for undetected π^+, π^- and extra p.
   - Under analysis review.
   - Started subtraction for undetected γ.
   - Fixed EC timing for γ PID.

4. To do:
   - Undetected photon subtraction.

(Long Baseline) Oscillation Challenge

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



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

Neutrino Energy Reconstruction for QE reactions

Cherenkov detectors:

- Detect: e-, muons & pions.
- Miss: protons and neutrons.

Tracking detectors:

- Detect: Charged particles $+\pi^0$.
- Miss: Neutrons and charge particles below threshold.

Lepton kinematics:
[(e,e') or (ν, l)]

$$E_{\text{QE}} = \frac{2M\varepsilon + 2ME_1 - m_l^2}{2(M - E_1 + |k_1|\cos\theta)}$$

$\varepsilon \approx 20$ MeV single nucleon separation energy

M -nucleon mass

m_1 outgoing lepton mass

k_1 – lepton three momentum

θ – lepton scattering angle

Final state Calorimetry
$[(e,e'pX)$ or $(\nu, lX)]$

$$E_{\text{Cal}} = E_e' + \sum T_p + E_{\text{Binding}} + \sum E_\pi$$

E_{Binding} – Binding energy

T_p – kinetic energy of knock out proton

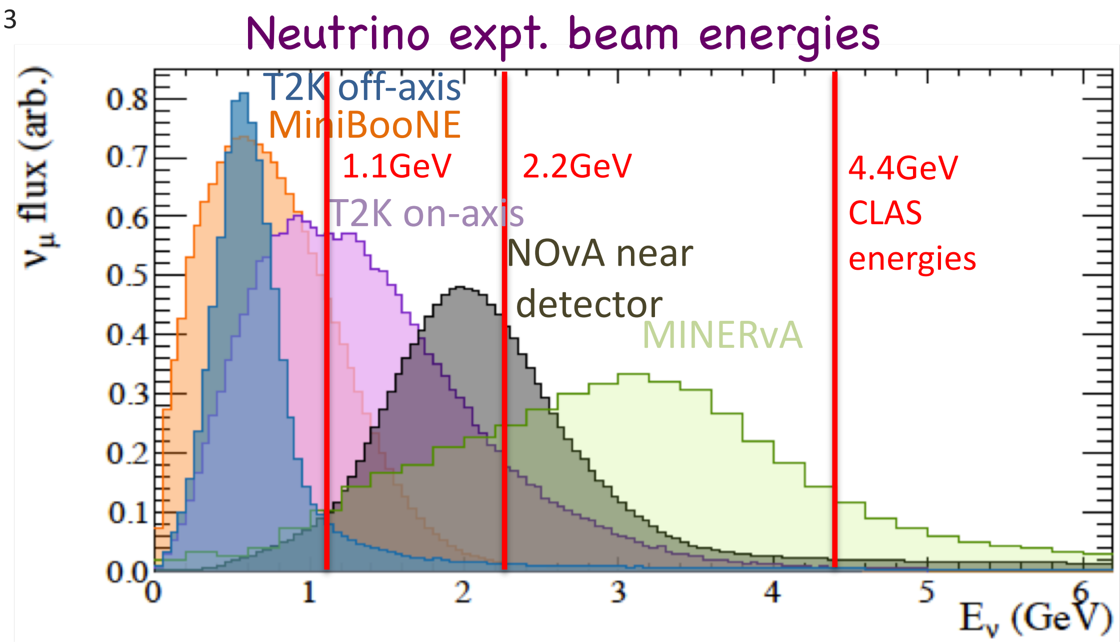
E_e' – energy of scattered electron

E_π – energy of produced meson

E2a experiment

Targets:

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



QE Event Selection

As close to QE as one can get:

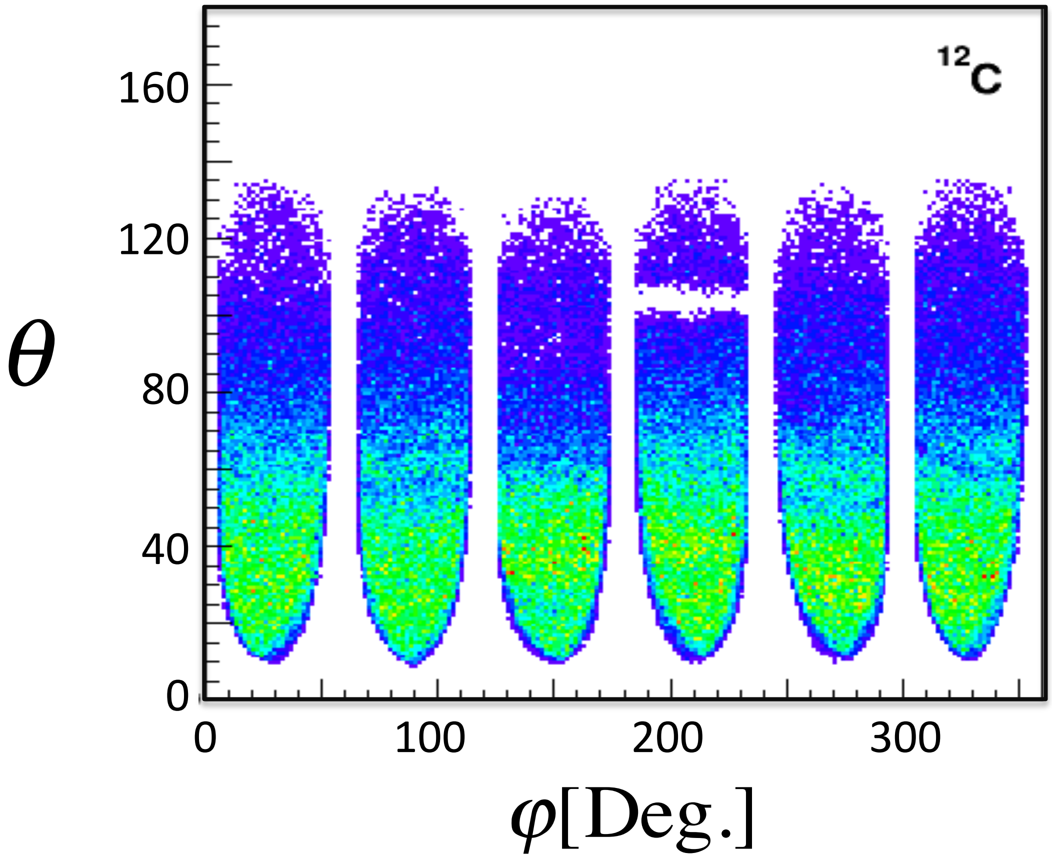
- Scattered electron,
- Knockout proton,
- Zero pion,
- Zero gammas in the EC or LAC.

Scale the e^- scattering data with $1/\sigma_{\mathrm{Mott}}$ to have 'neutrino like' data!

Background Subtraction

Non-QE interactions lead to multi hadron final states.

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

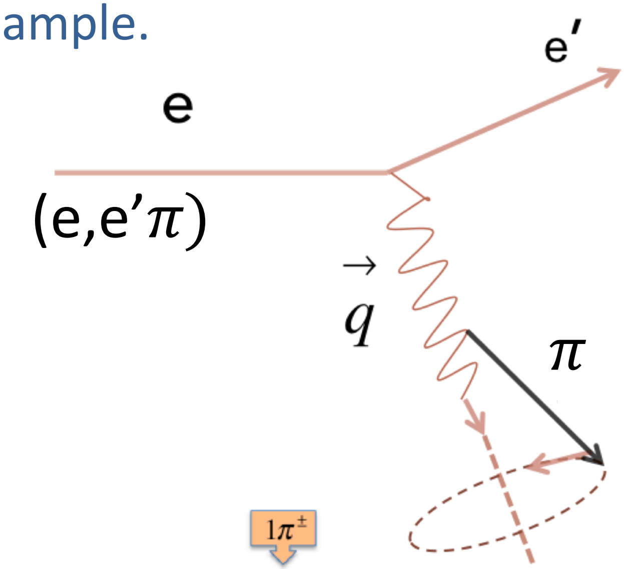


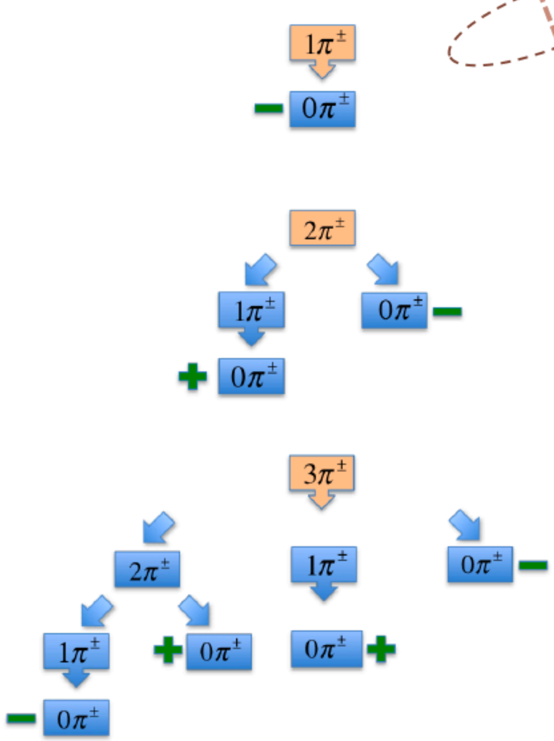
Background Subtraction in (e,e') analysis

Neutrino analysis select 0 π events to maximize QE sample.

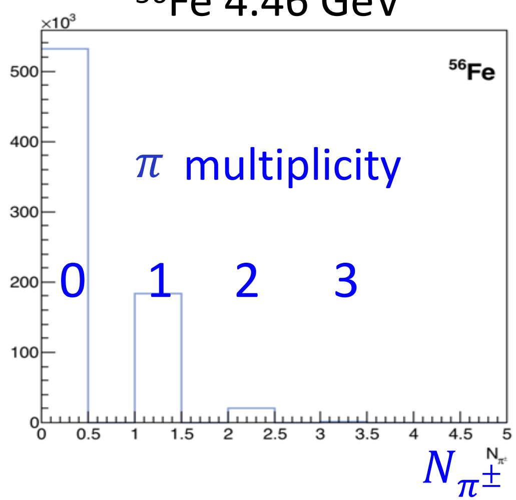
Data Driven Correction:

1. Use measured (e,e'π) events,
2. Rotate π around q to determine its acceptance,
3. Subtract undetected (e,e'π) contributions,
4. New: Do the same for 2π, 3π.

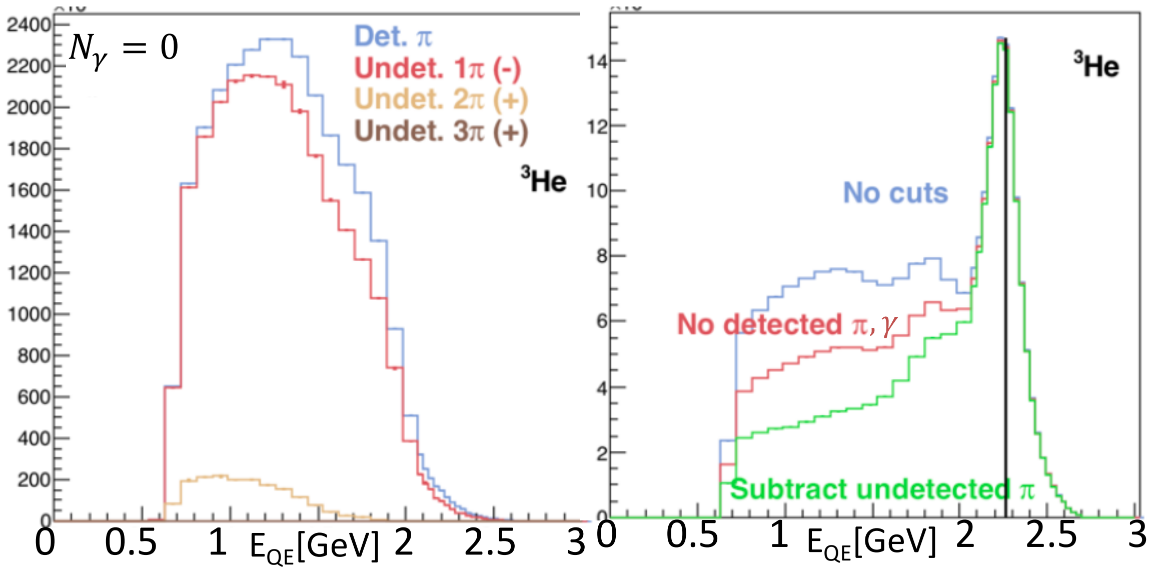




^{56}Fe 4.46 GeV



(e,e') $\pi^{\pm}$ subtraction



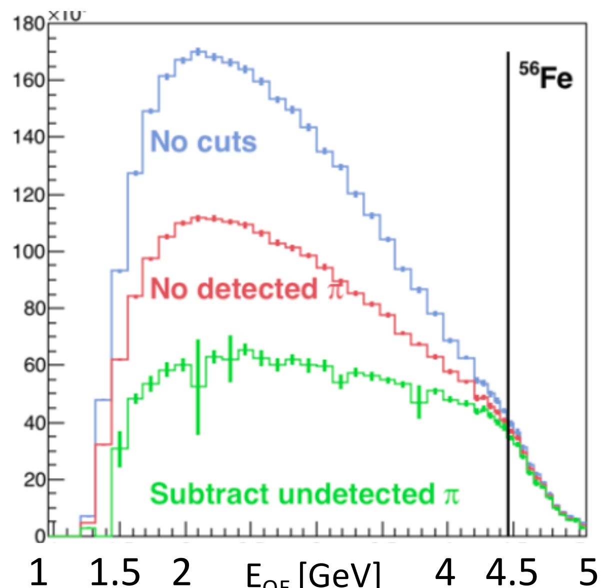
^{3}He 2.26 GeV

The π cuts :

- $\pm 3\sigma$ TOF timing cuts
- Fiducial cut
- $e^-, \pi^{\pm}$ vertex difference cut

The γ cuts :

- $\pm 2.5\sigma$ EC or LAC timing cut
- EC and LAC fiducial cut



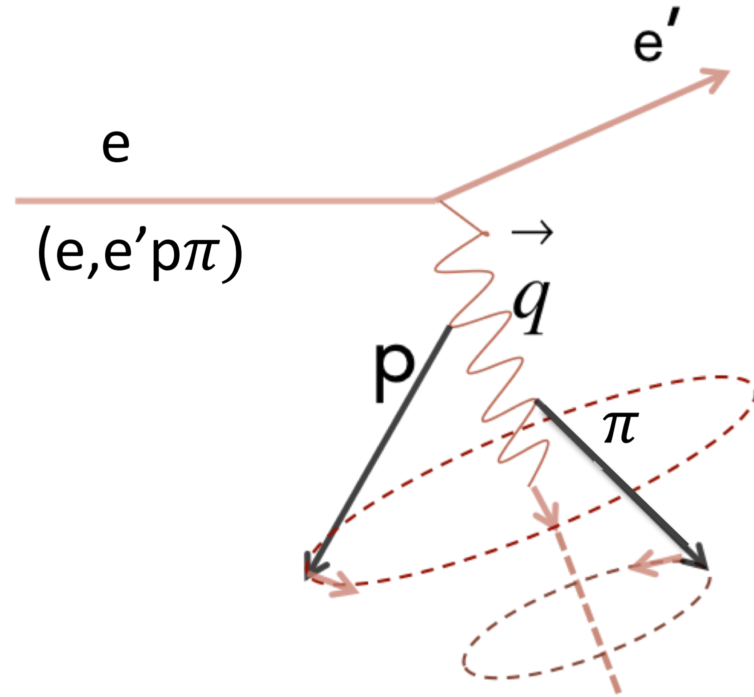
^{56}Fe 4.46 GeV

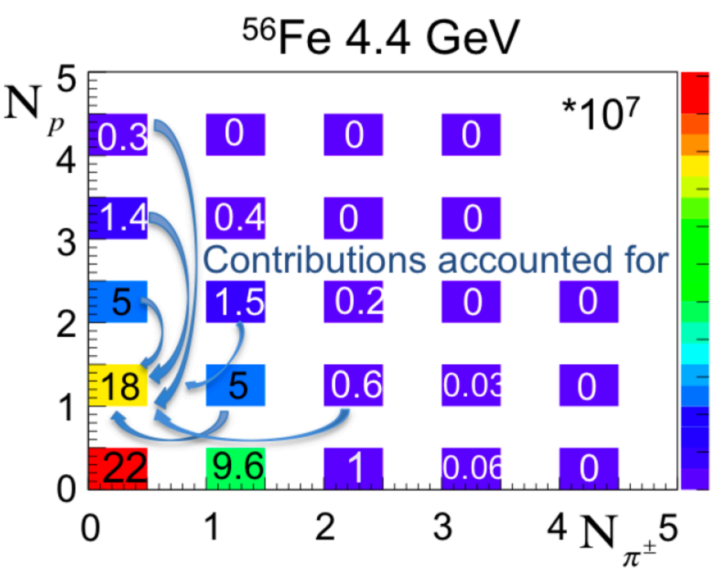
Background Subtraction in (e,e'p) analysis

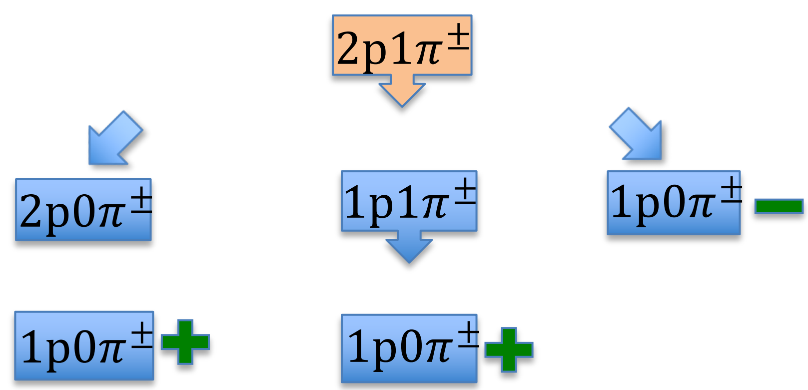
Subtract for undetected π and multiple p.

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. New: do the same for 2p, 3p 2p+ π etc



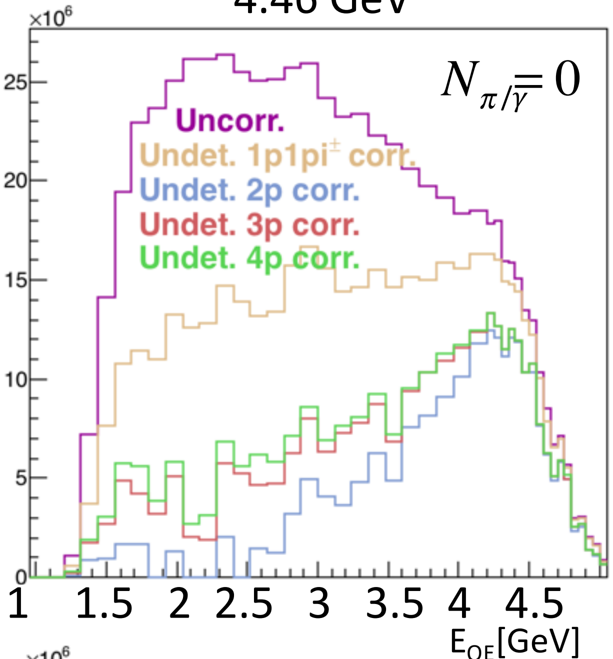


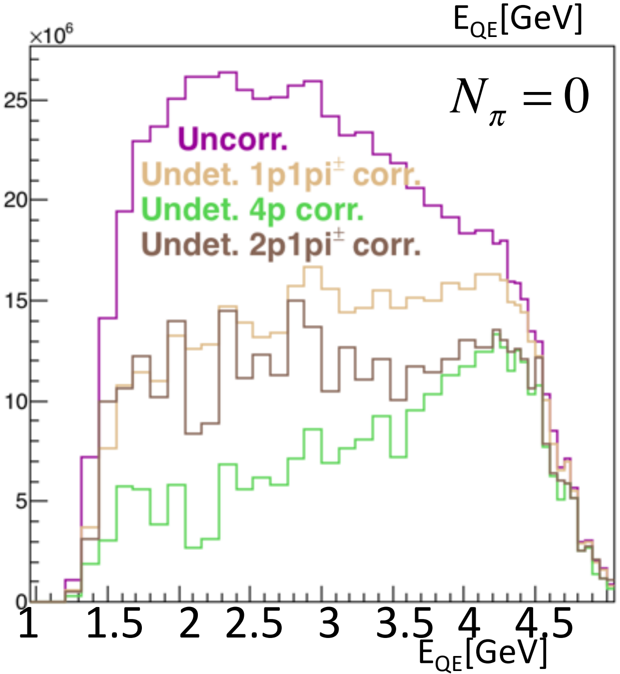


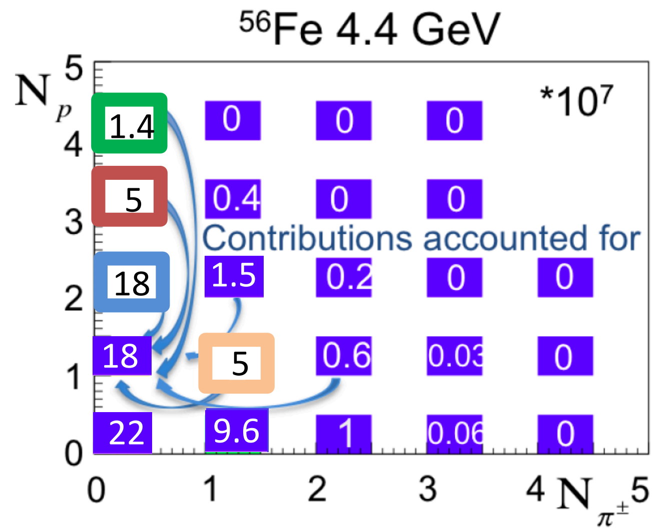
Proton subtarction

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

4.46 GeV



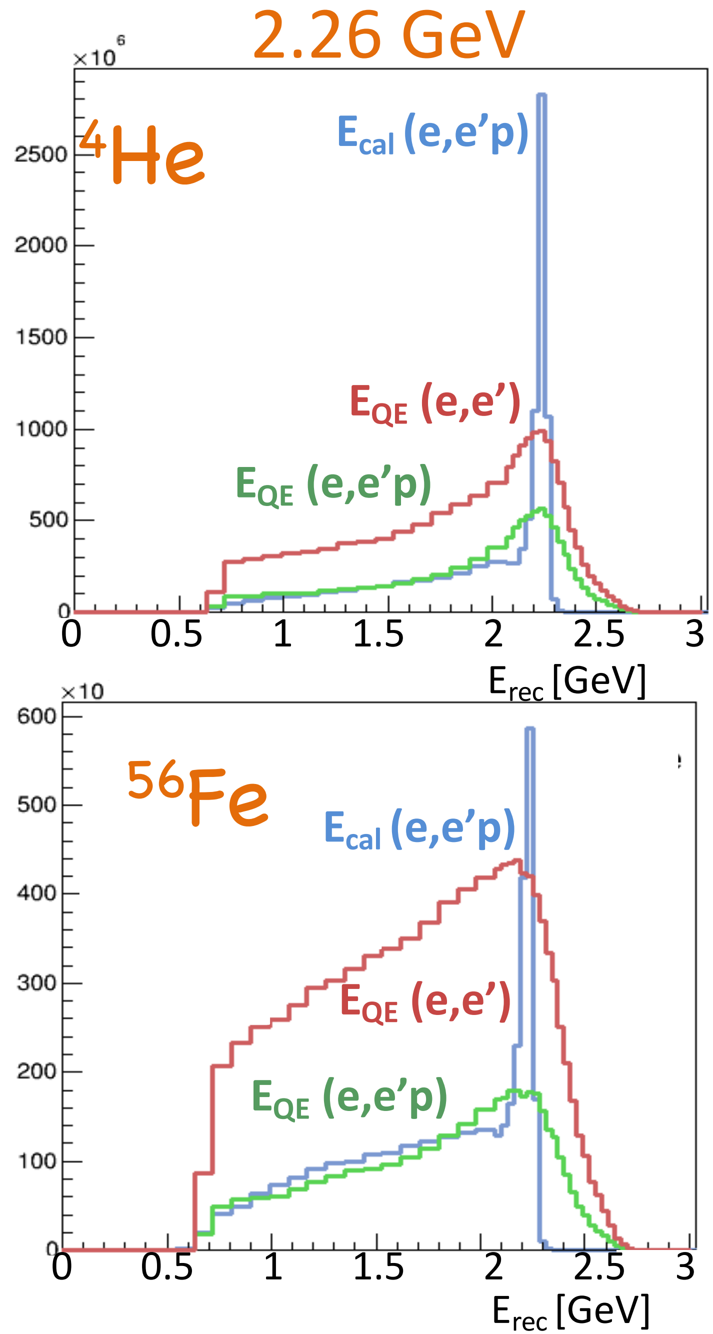




Large A dependence

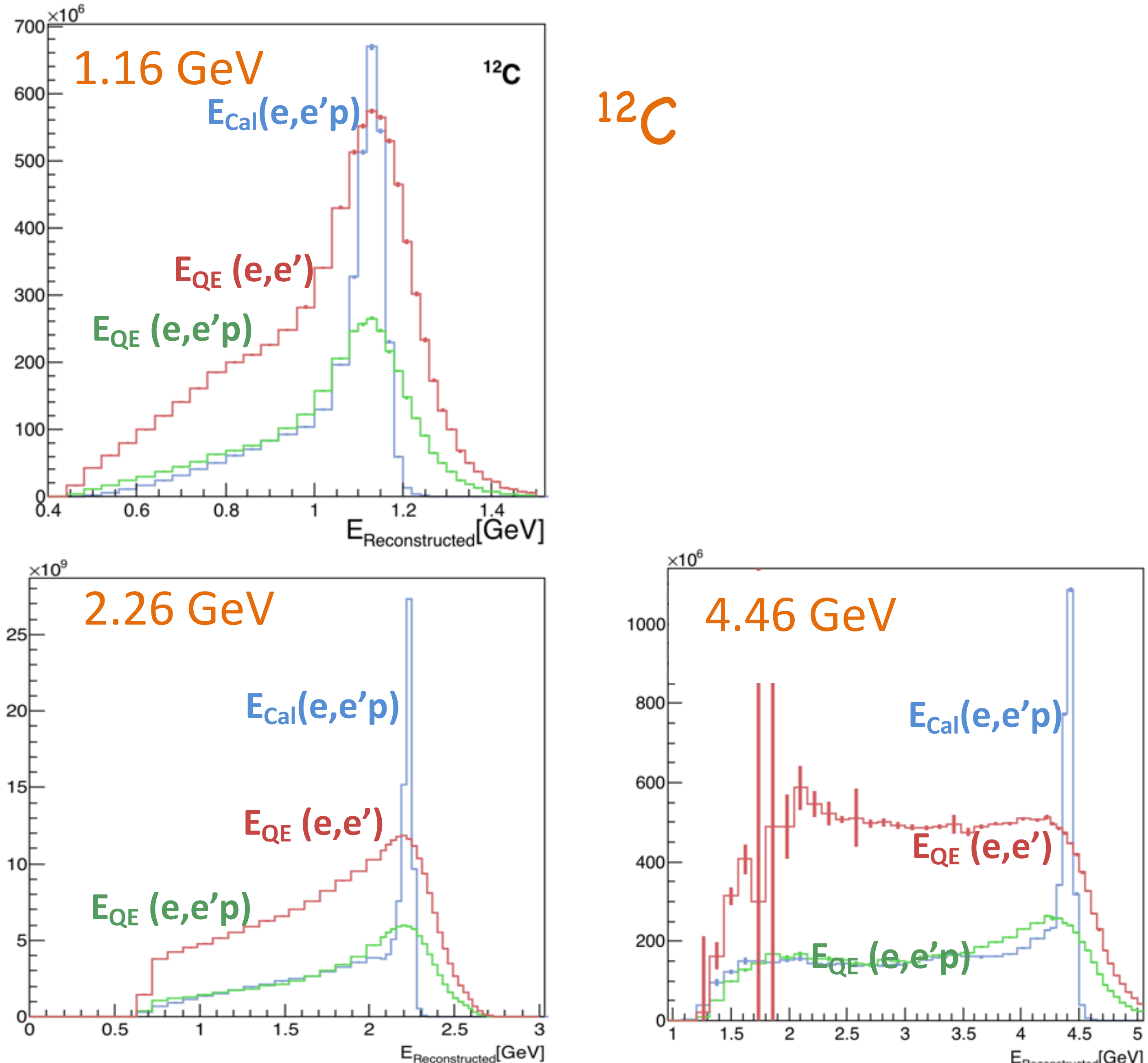
$$E_{\text{Cal}} = E'_e + T_p + E_{\text{Binding}}$$

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



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.

Large E dependence

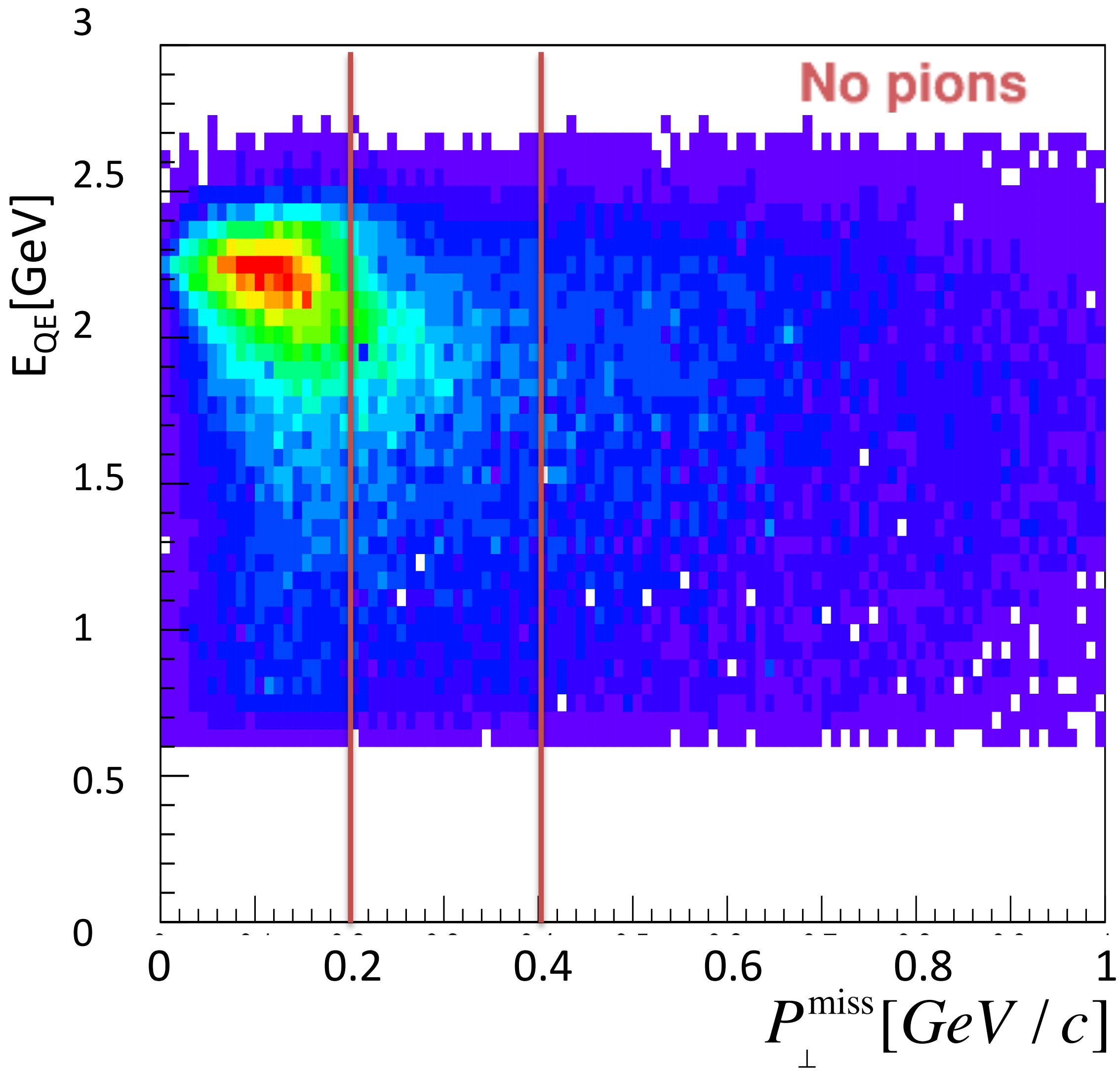


Better reconstruction at lower energies.

E_{QE} vs $P_{\perp}^{miss}$

2.2 GeV ^{56}Fe

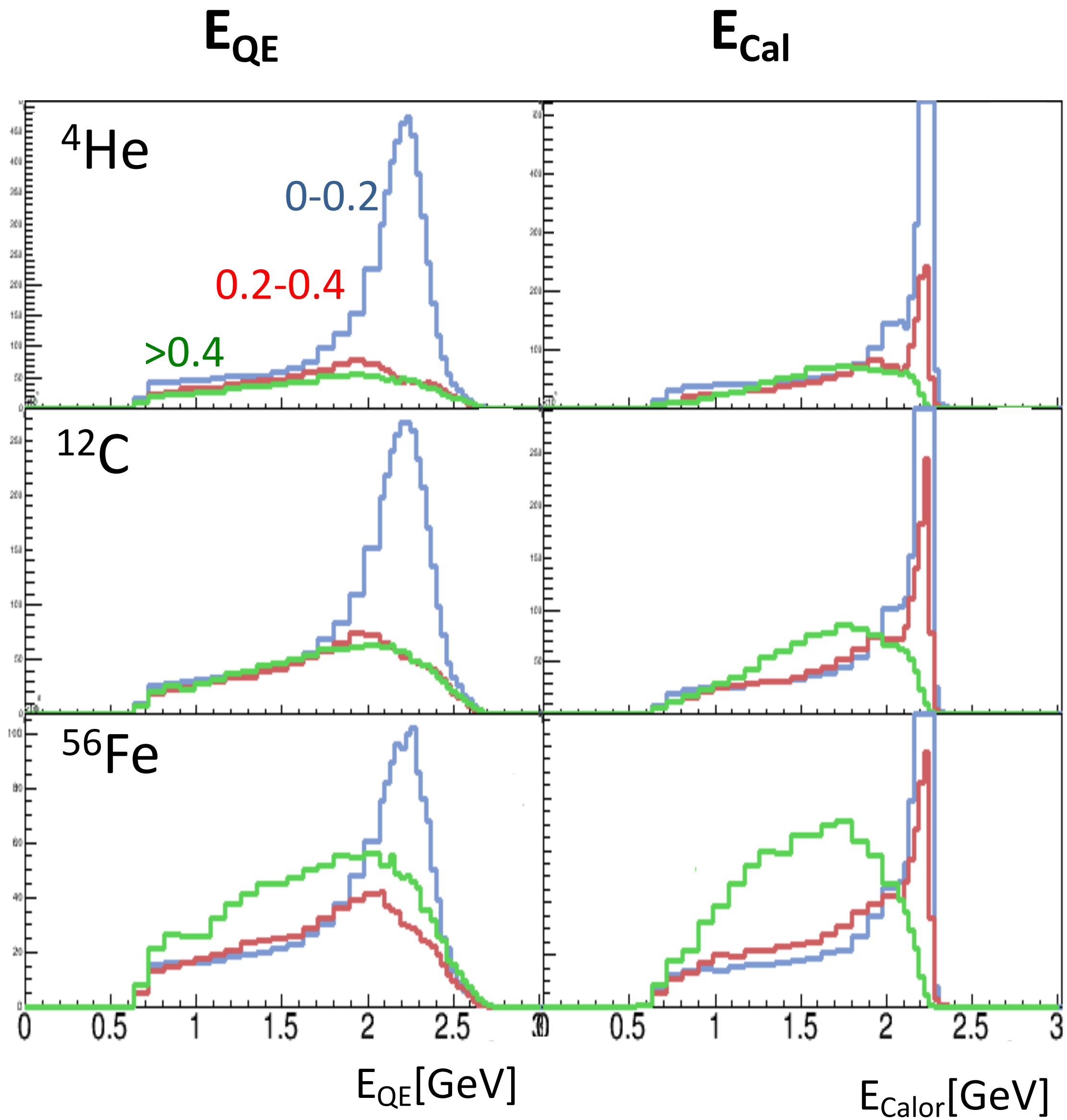
$$P_{miss}^{\perp} = P_{e^-}^{\perp} + P_{p}^{\perp} = P_{init}^{\perp}$$



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

2.2 GeV

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

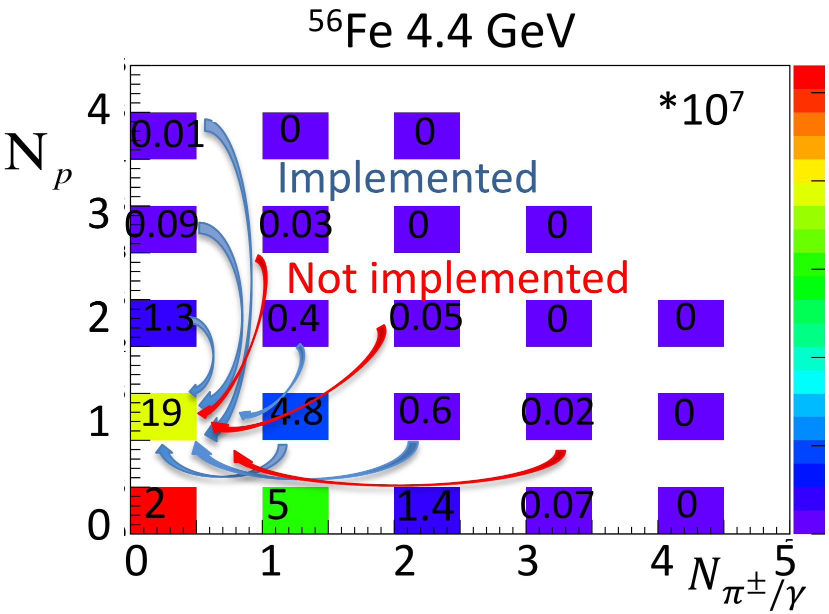


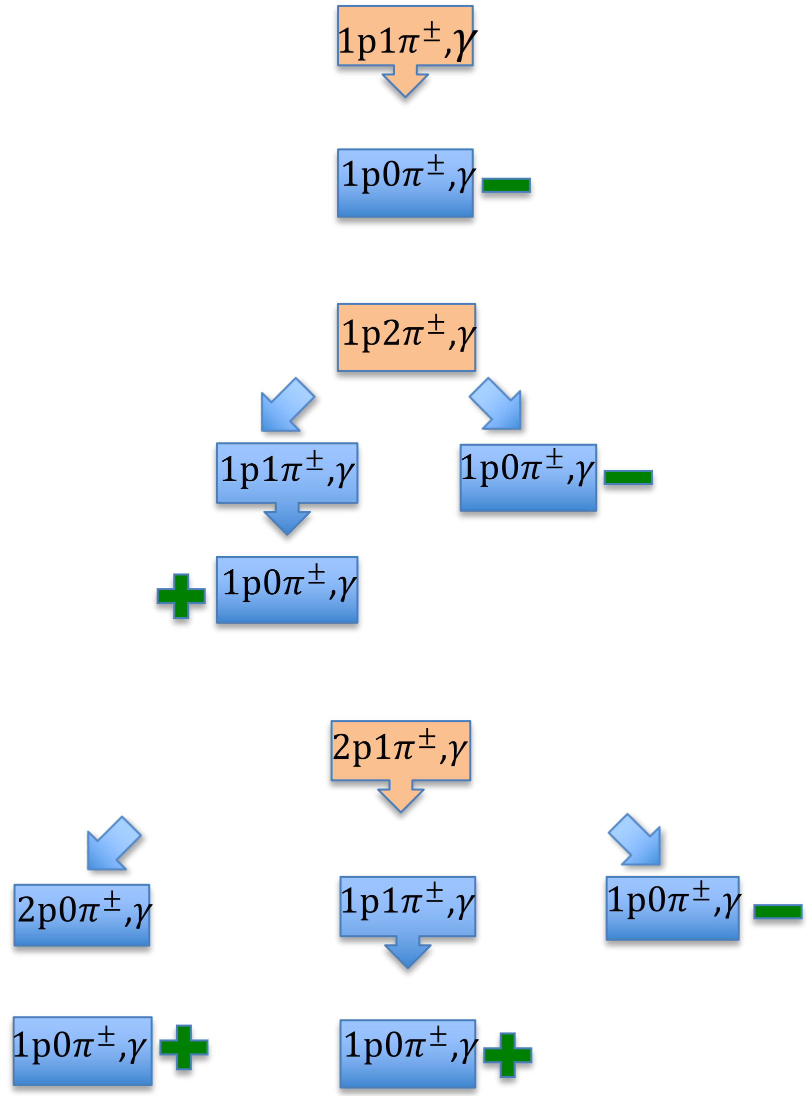
Percent of events reconstructed to within 5% of the beam energy

	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.

Subtracting for undetected γ similar way as for π





Need to consider effect of (e,e'ppp π/γ)
(e,e'pp π/γ π/γ)
(e,e'p π/γ π/γ π/γ)

Error sources

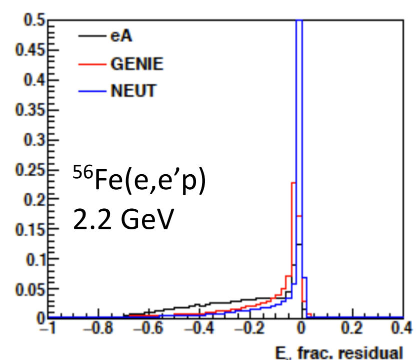
- Statistical error.

- 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%.

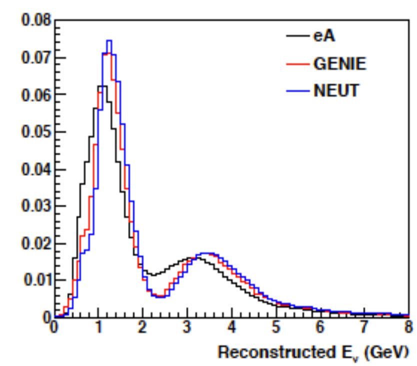
- Systematic error due to the ϕ-dependence of the pion cross section was modeled and found to be negligible (less than 1%).

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 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. Comparison to models to be presented by Adi (next talk).
5. Progress since 7/18 :
   - Completed subtraction for undetected π and extra p.
   - Started the analysis review.
   - Fixed EC timing for γ PID.
   - Analyzed the 1.1 GeV e2a data.
   - Adding the subtraction for undetected photons.
6. Anticipate paper submission soon.



Fractional Energy feed down spectra



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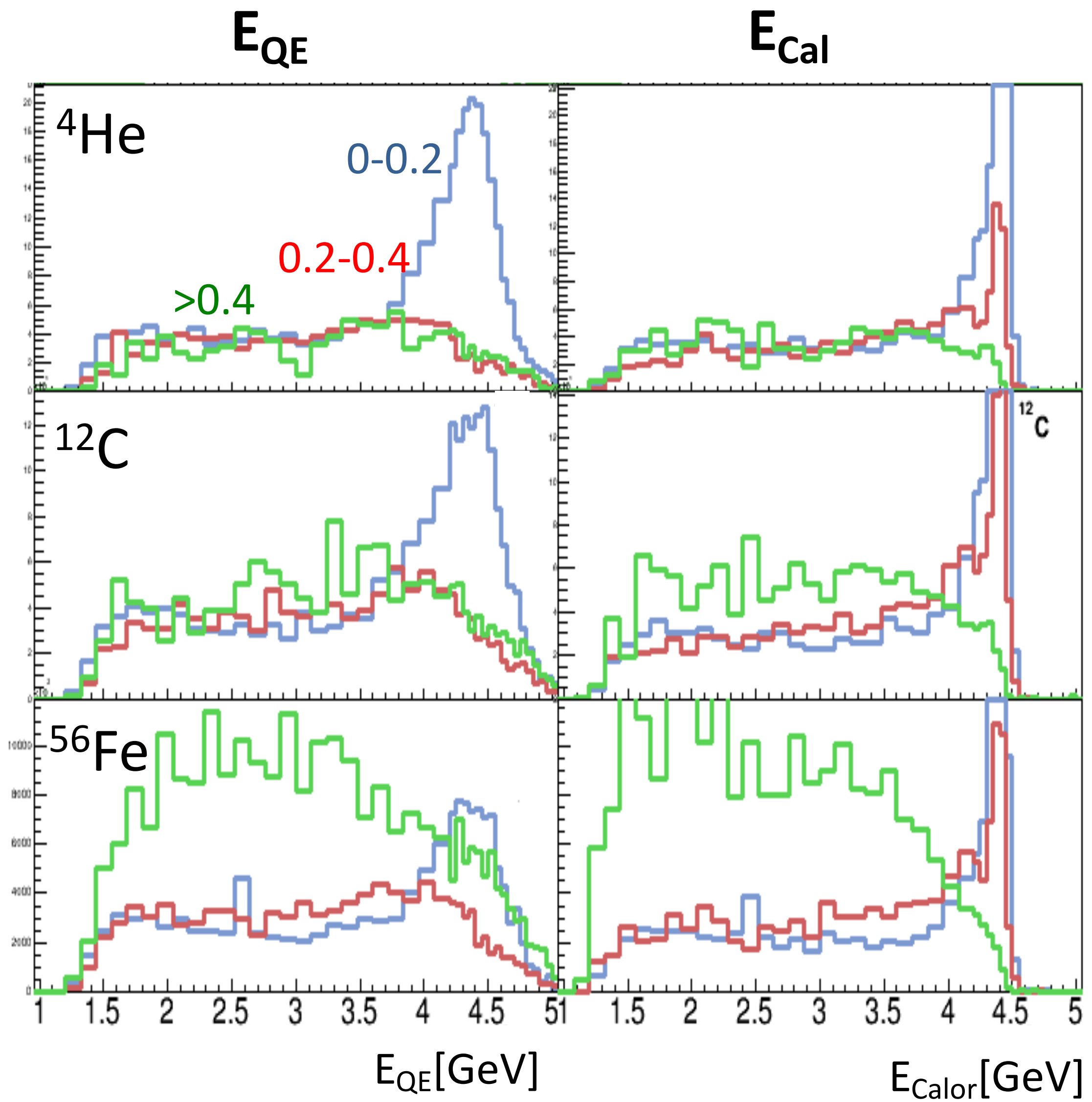
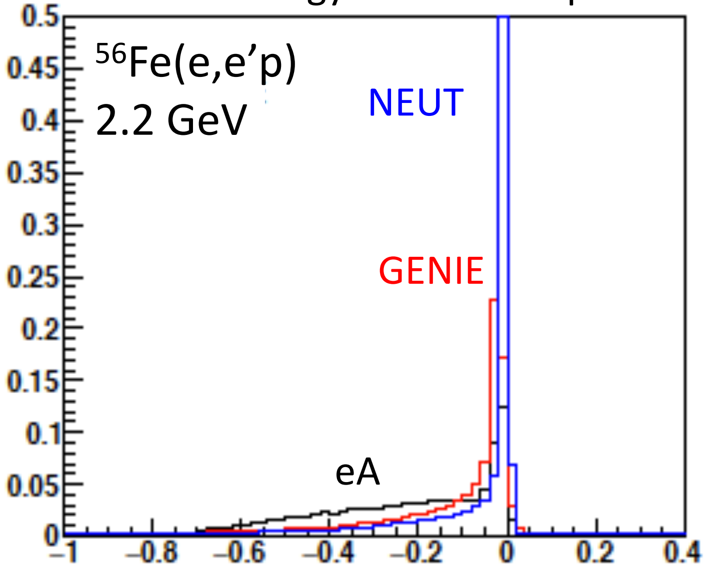
$P_{\rm miss}^{\perp}$ slices

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

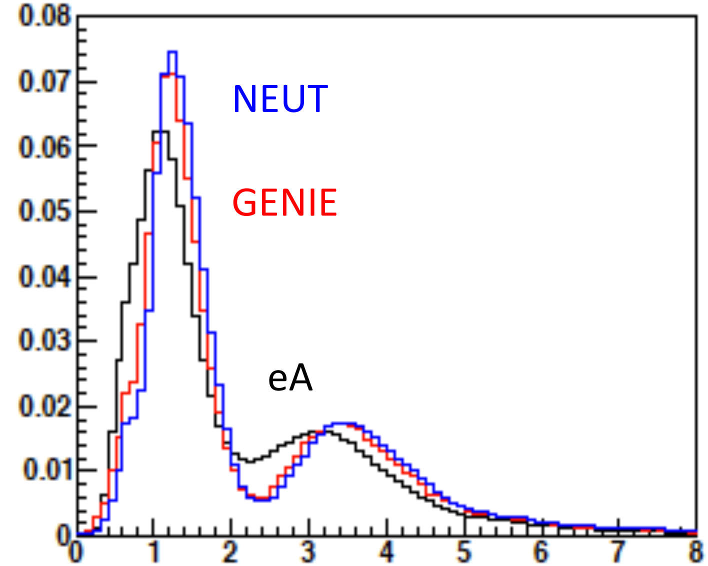


Potential impact on DUNE oscillation signal

Fractional Energy feed down spectra



2.26 GeV E_{rec} fractional error



Reconstructed E_ν $[GeV]$

- Compared 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

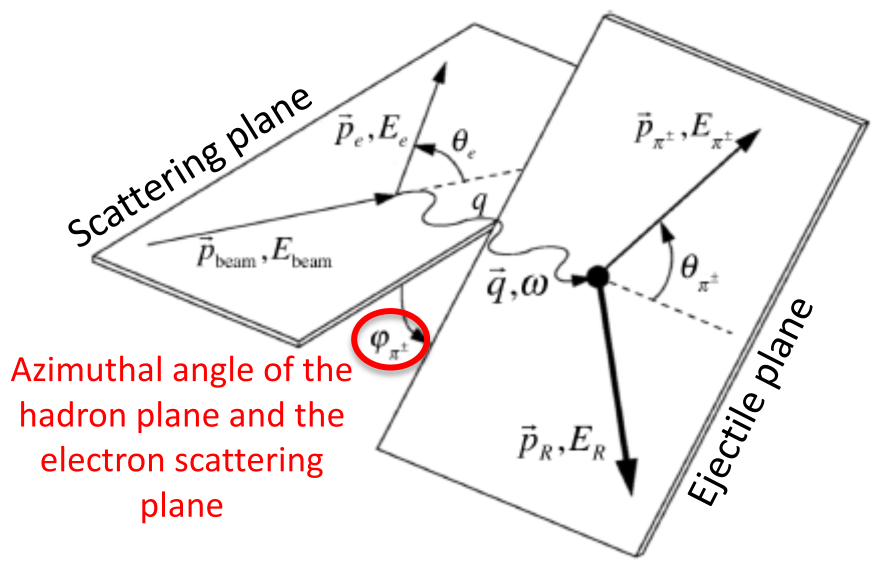
-> Very different oscillation parameters!

-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 = $ (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*

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

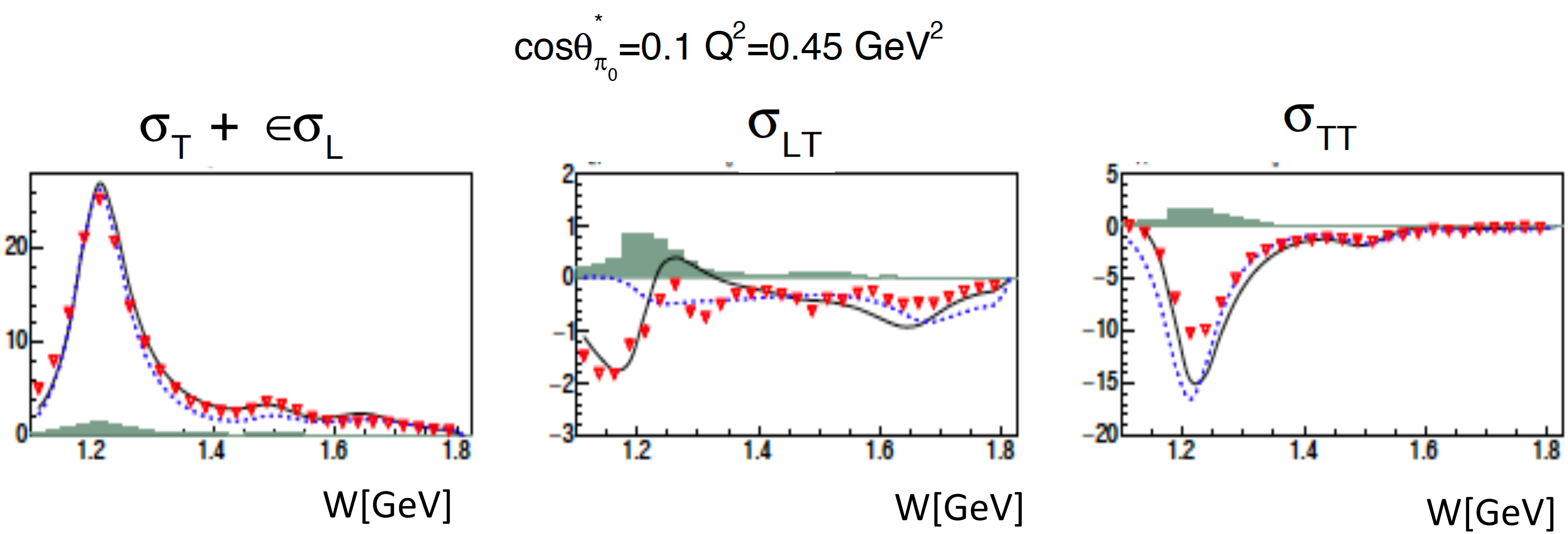
Phi dependence

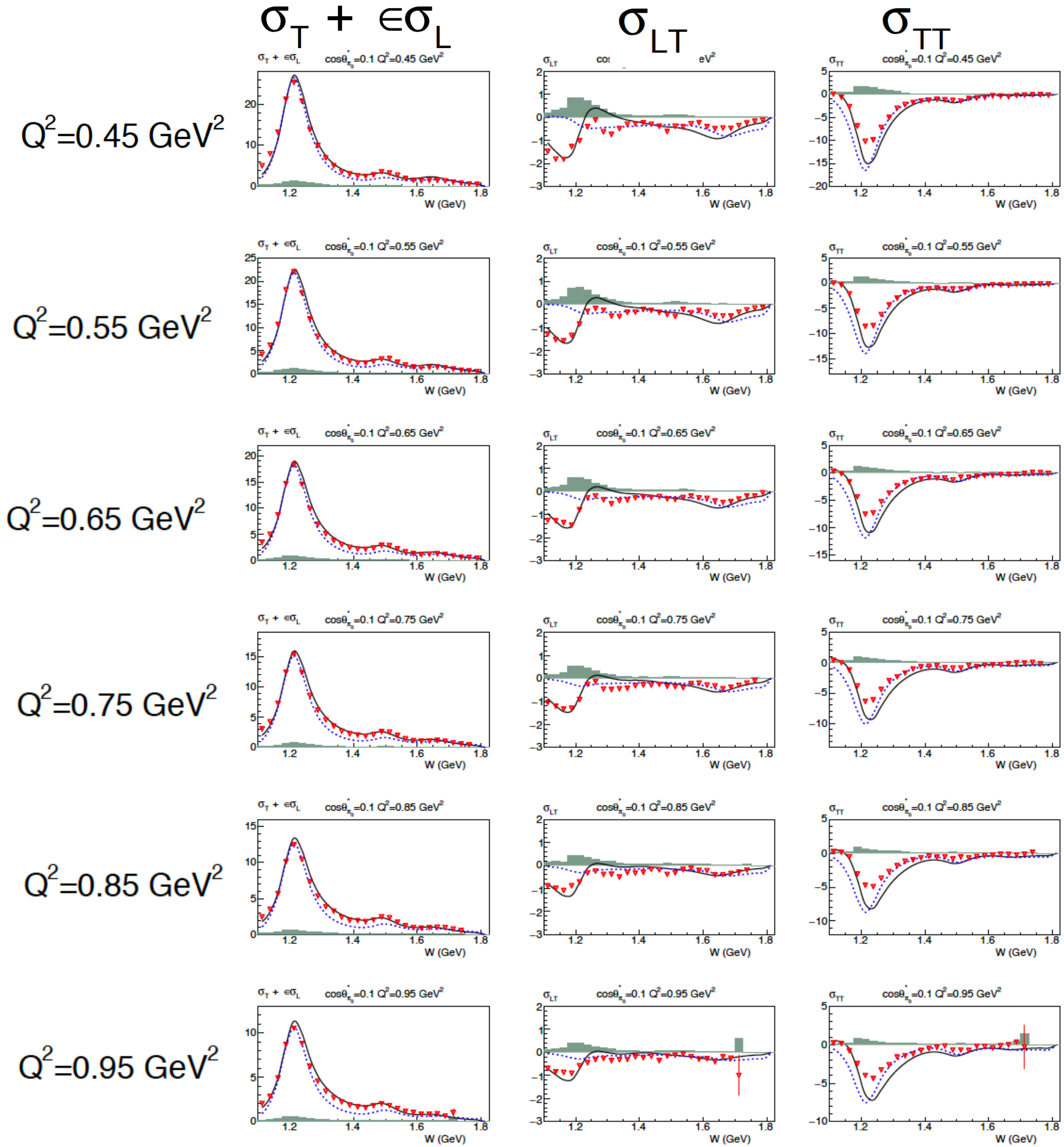
Use maximum of structure functions from Markov et al. paper [ref] for $cos\theta_\pi = 0.1$ and $0.4 \leq Q^2 \leq 1GeV^2$. The absolute values are the biggest for Q^2=0.45GeV^2. $\sigma_T + \epsilon\sigma_L = 30\mu b$, $\sigma_{TT} = -10\mu b$ and $\sigma_{LT} = -2\mu b$.

$$A = (\sigma_{\rm T} + \epsilon\sigma_{\rm L})\frac{p^*_\pi}{k^*_\gamma}$$

$$B = \sigma_{\rm LT}\frac{p^*_\pi}{k^*_\gamma}\sin\theta_\pi\sqrt{2\epsilon(\epsilon+1)}$$

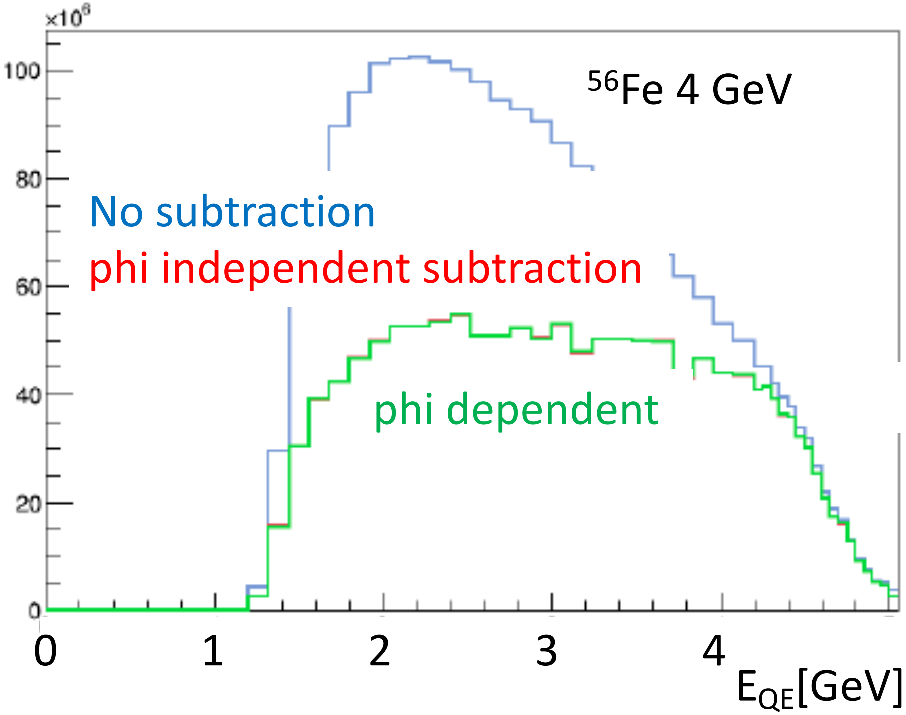
$$C = \sigma_{\rm TT}\frac{p^*_\pi}{k^*_\gamma}\sin^2\theta_\pi\epsilon$$

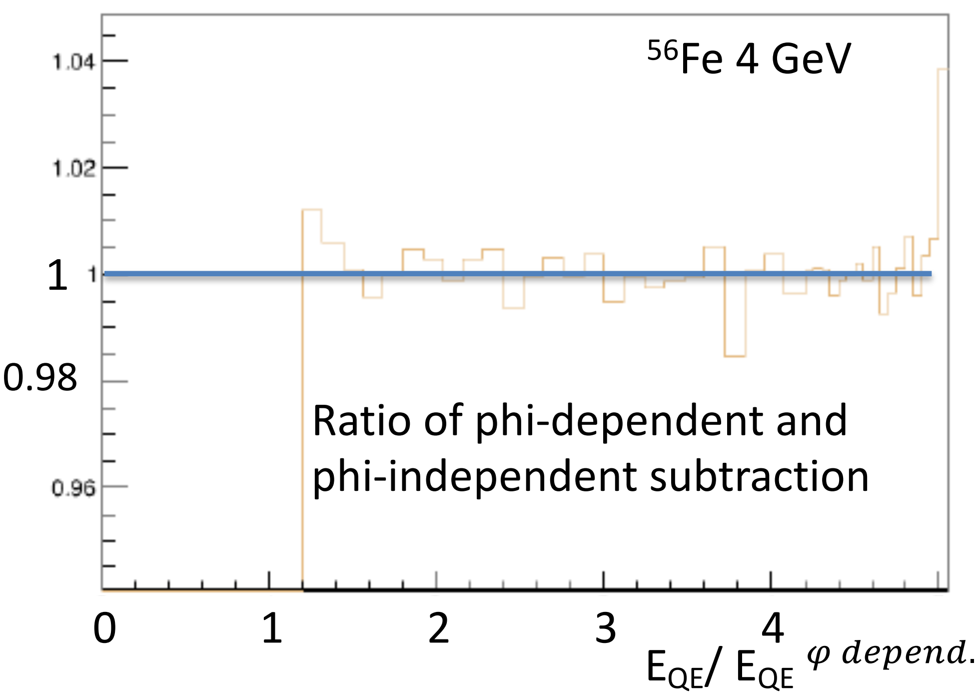



σ_T + ∈σ_L
σ_LT
σ_TT
Q²=0.45 GeV²
Q²=0.55 GeV²
Q²=0.65 GeV²
Q²=0.75 GeV²
Q²=0.85 GeV²
Q²=0.95 GeV²
W (GeV)

Error sources: Phi dependence

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





Negligible phi dependence!