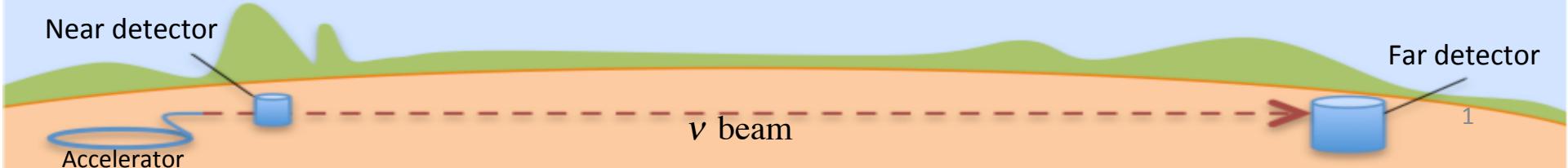


Study of neutrino energy reconstruction using electron scattering data

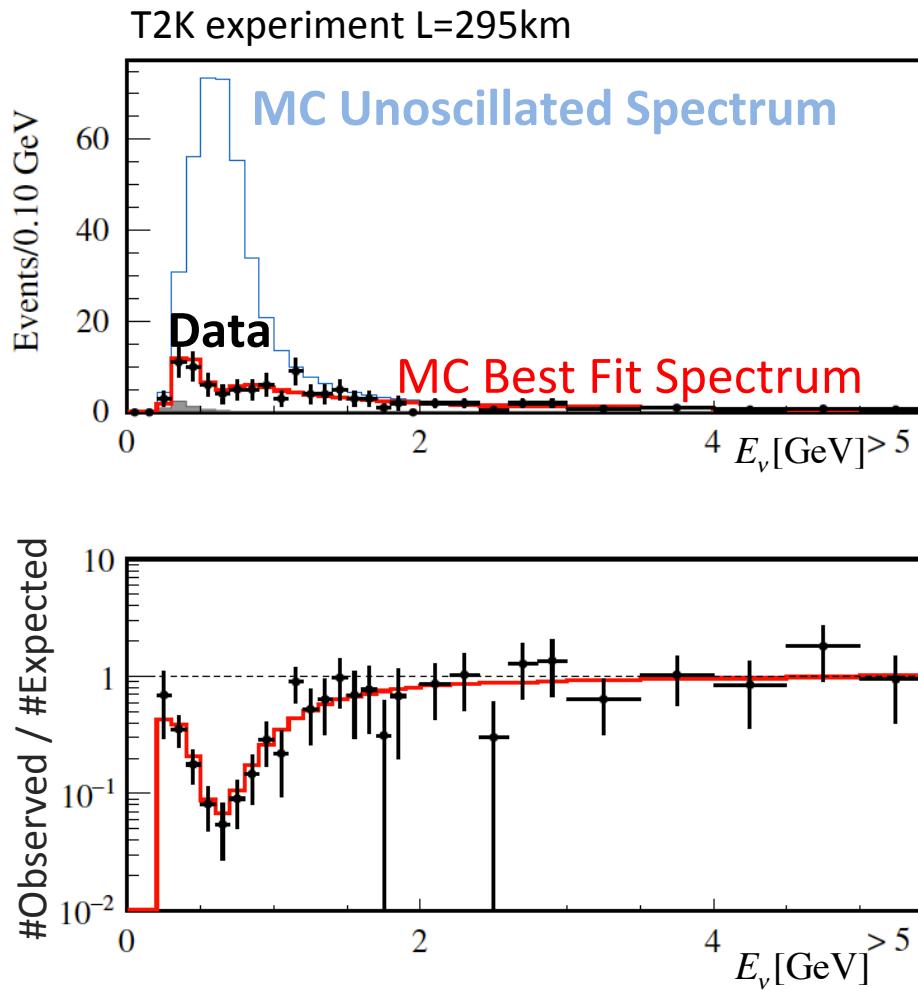
Mariana Khachatryan - ODU



Outline

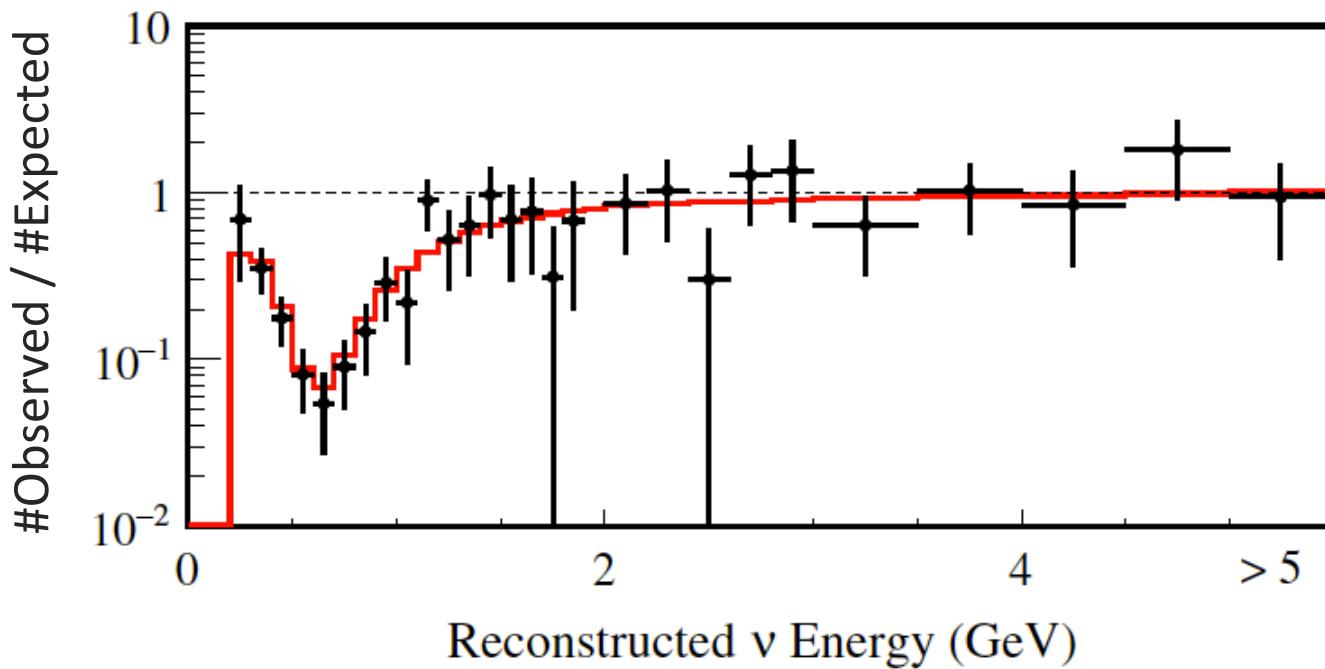
- Energy reconstruction in neutrino oscillation experiments.
- Why e- scattering?
- Testing neutrino energy reconstruction using electron scattering data.

(Long Baseline) Oscillation Challenge



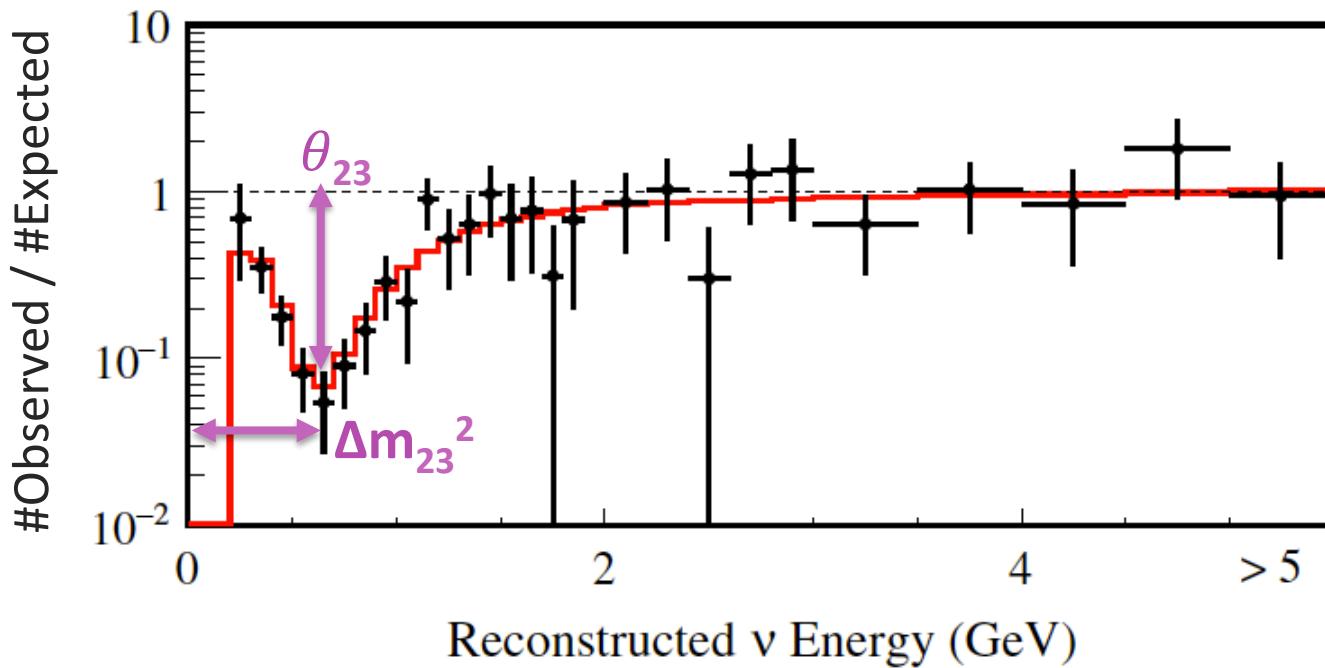
(Long Baseline) Oscillation Challenge

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



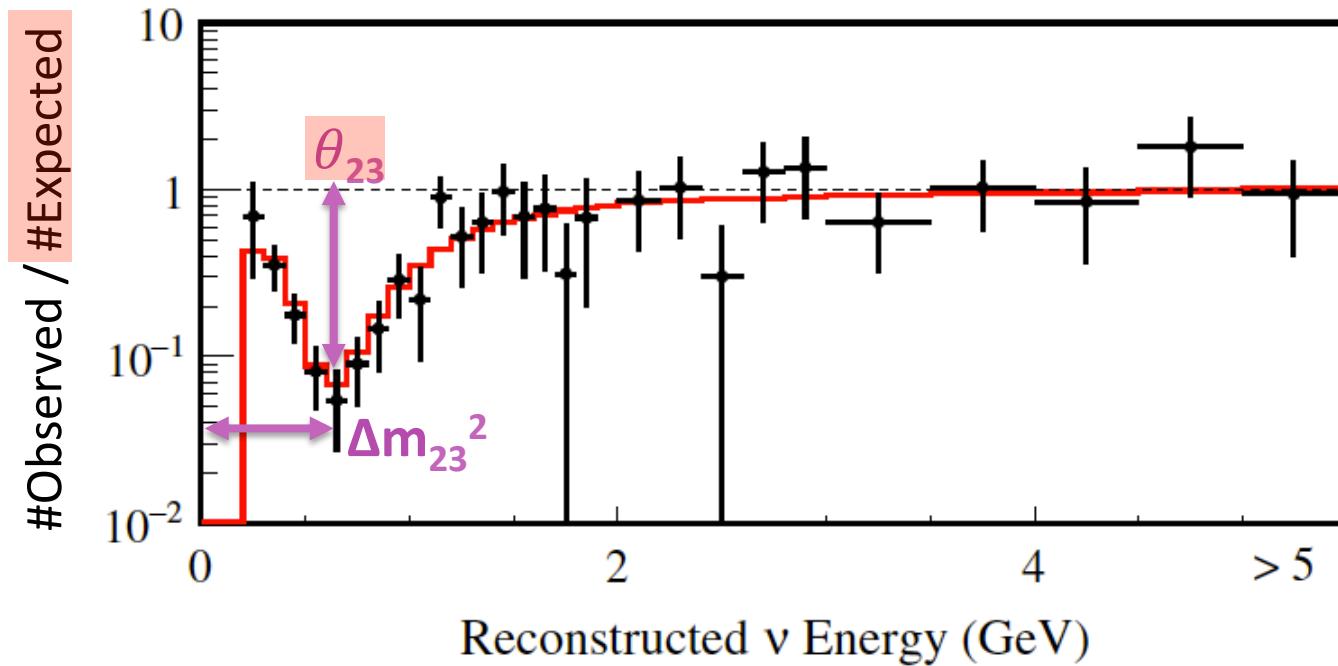
(Long Baseline) Oscillation Challenge

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

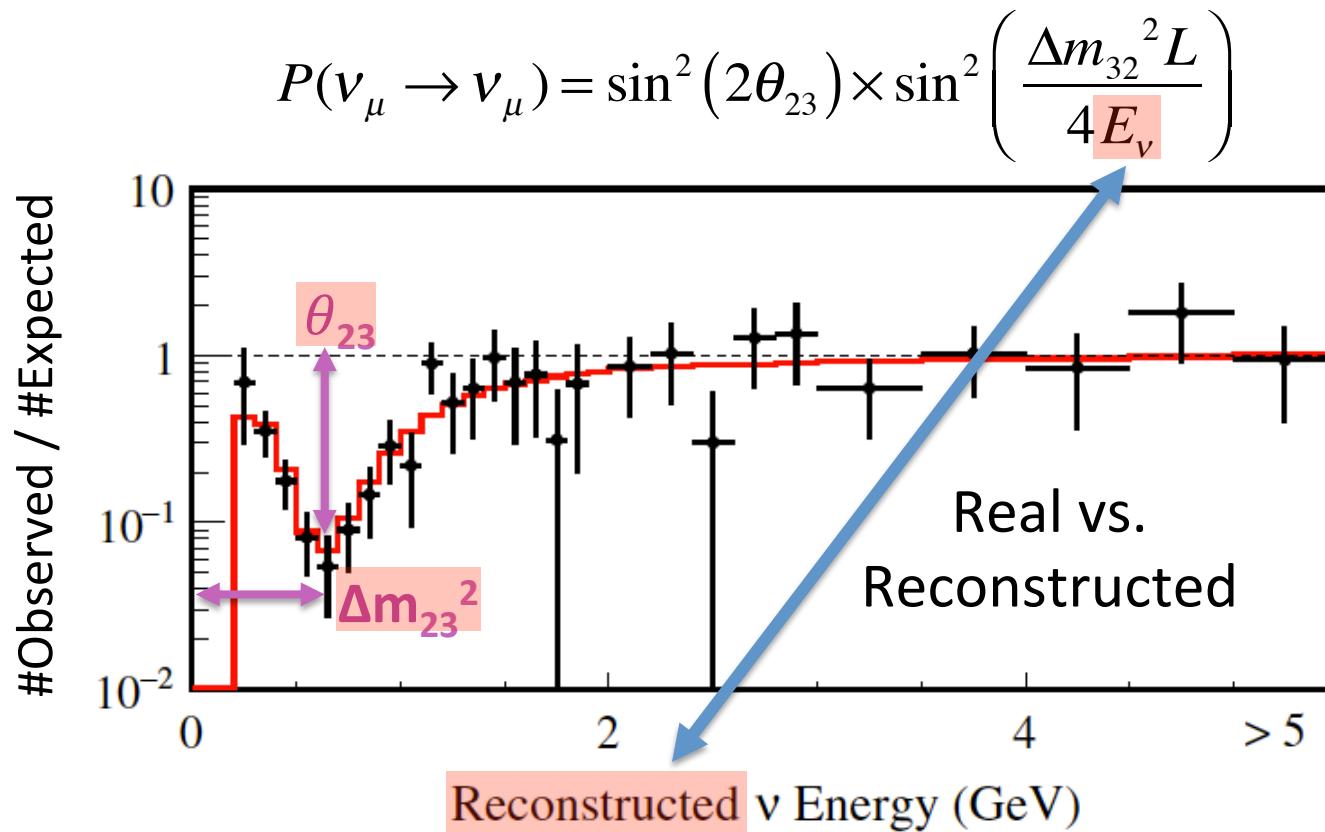


(Long Baseline) Oscillation Challenge

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

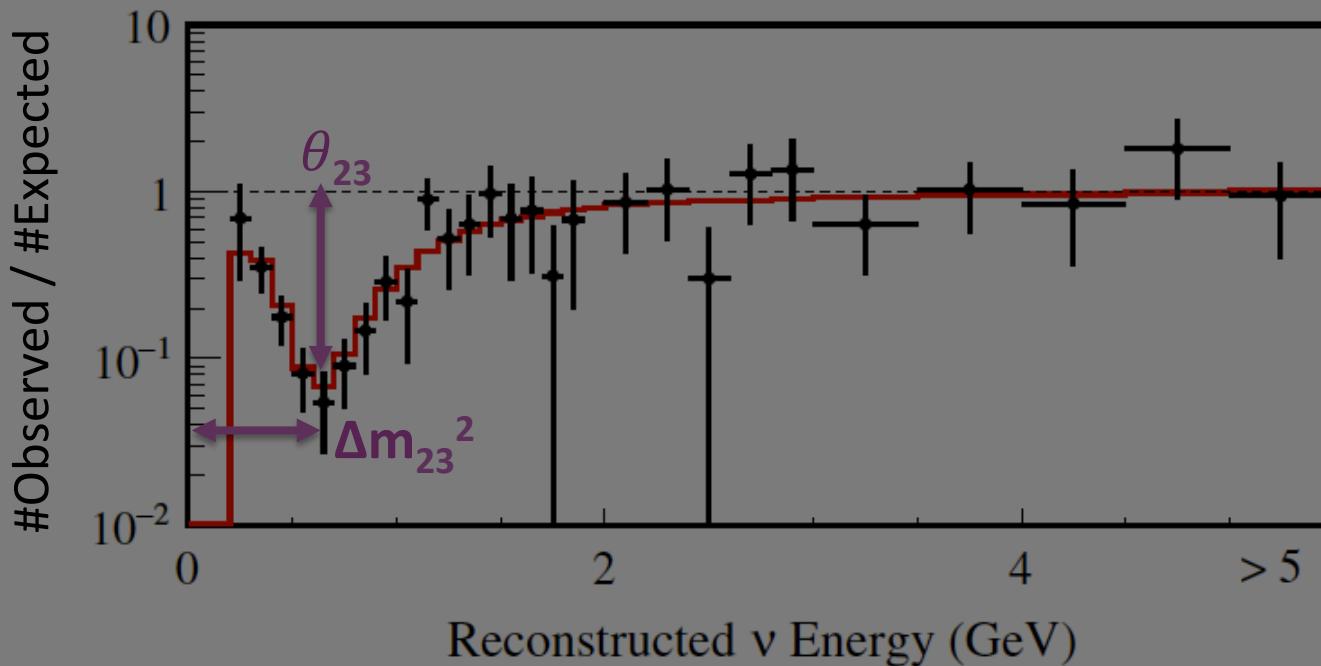


(Long Baseline) Oscillation Challenge



(Long Baseline) Oscillation Challenge

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



Error in Reconstructed E \rightarrow Error in extracted oscillation parameters

Neutrino Energy Reconstruction for QE reactions

Cherenkov detectors:

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

Tracking detectors:

- Detect: Charged particles + π^0 .
- Miss: Neutrons and charge particles below threshold.

Lepton kinematics:

$[(e, e') \text{ or } (\nu, l)]$

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

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

M -nucleon mass

m_l outgoing lepton mass

k_l – lepton three momentum

θ – lepton scattering angle

Final state Calorimetry

$[(e, e' pX) \text{ or } (\nu, lX)]$

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

E_{Binding} – Binding energy

T_p – kinetic energy of knock out proton

E_e' – energy of scattered electron

E_π – energy of produced meson

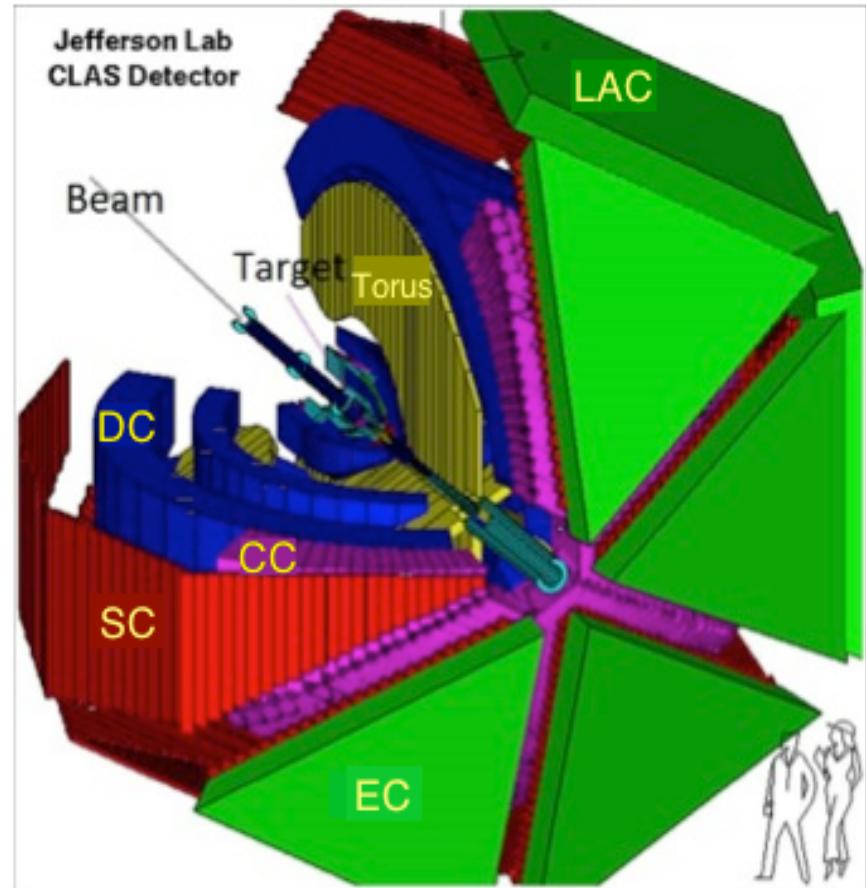
Testing with e^- scattering?

- ◆ e^- and neutrino interactions are similar.
- ◆ Various nuclear effects are practically identical (FSI rescattering of the knock-out nucleon on other nucleons, multi-nucleon effects, etc).
- ◆ e^- beam energy is known → can test energy reconstruction in selective kinematics.
- ◆ Test neutrino interaction event generator by running in electron-mode (turning off the axial response etc).

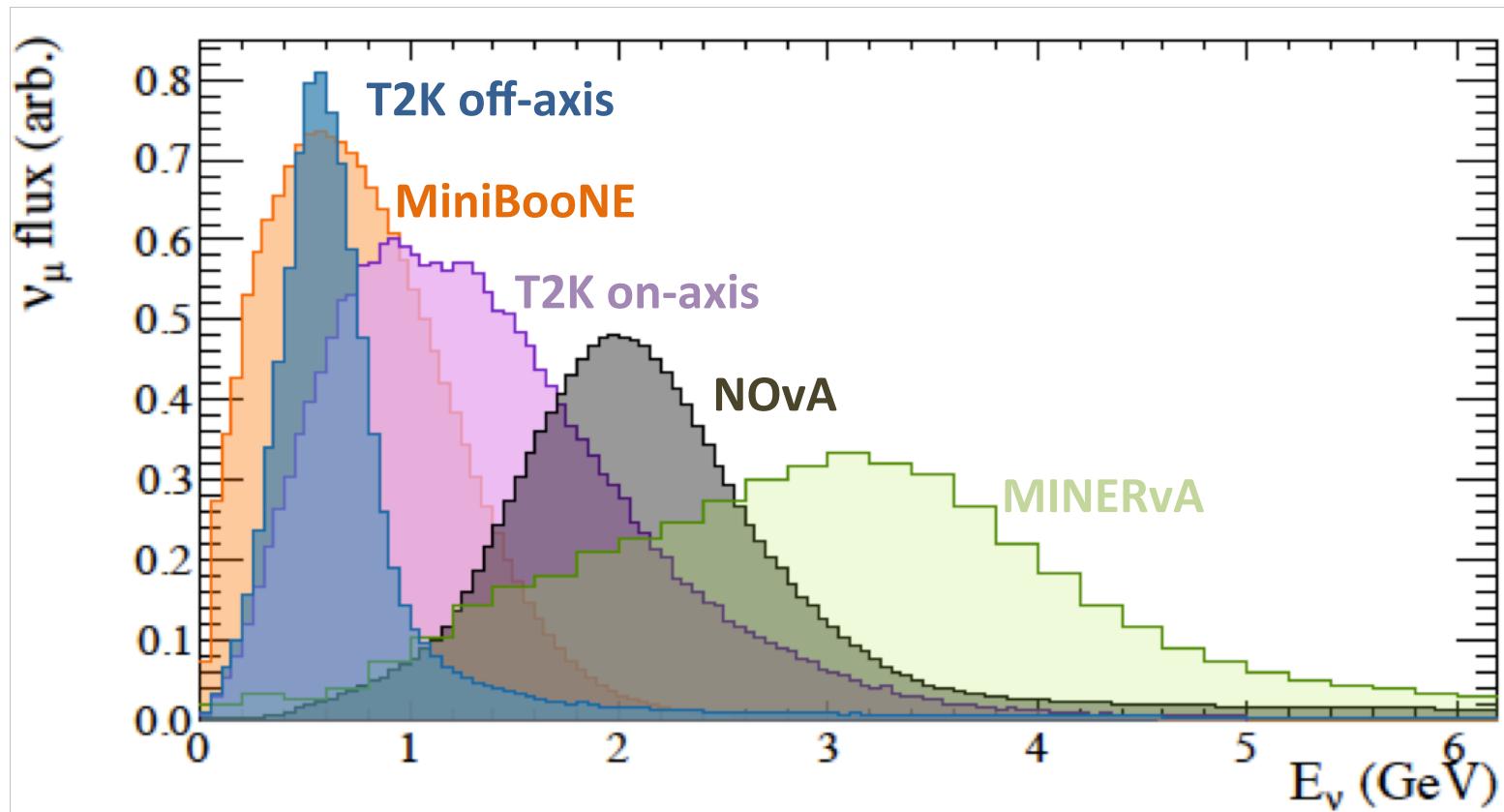
CLAS detector

Targets: ${}^3, {}^4\text{He}$, ${}^{12}\text{C}$, and ${}^{56}\text{Fe}$.
Energies: 4.4, 2.2 and 1.1.

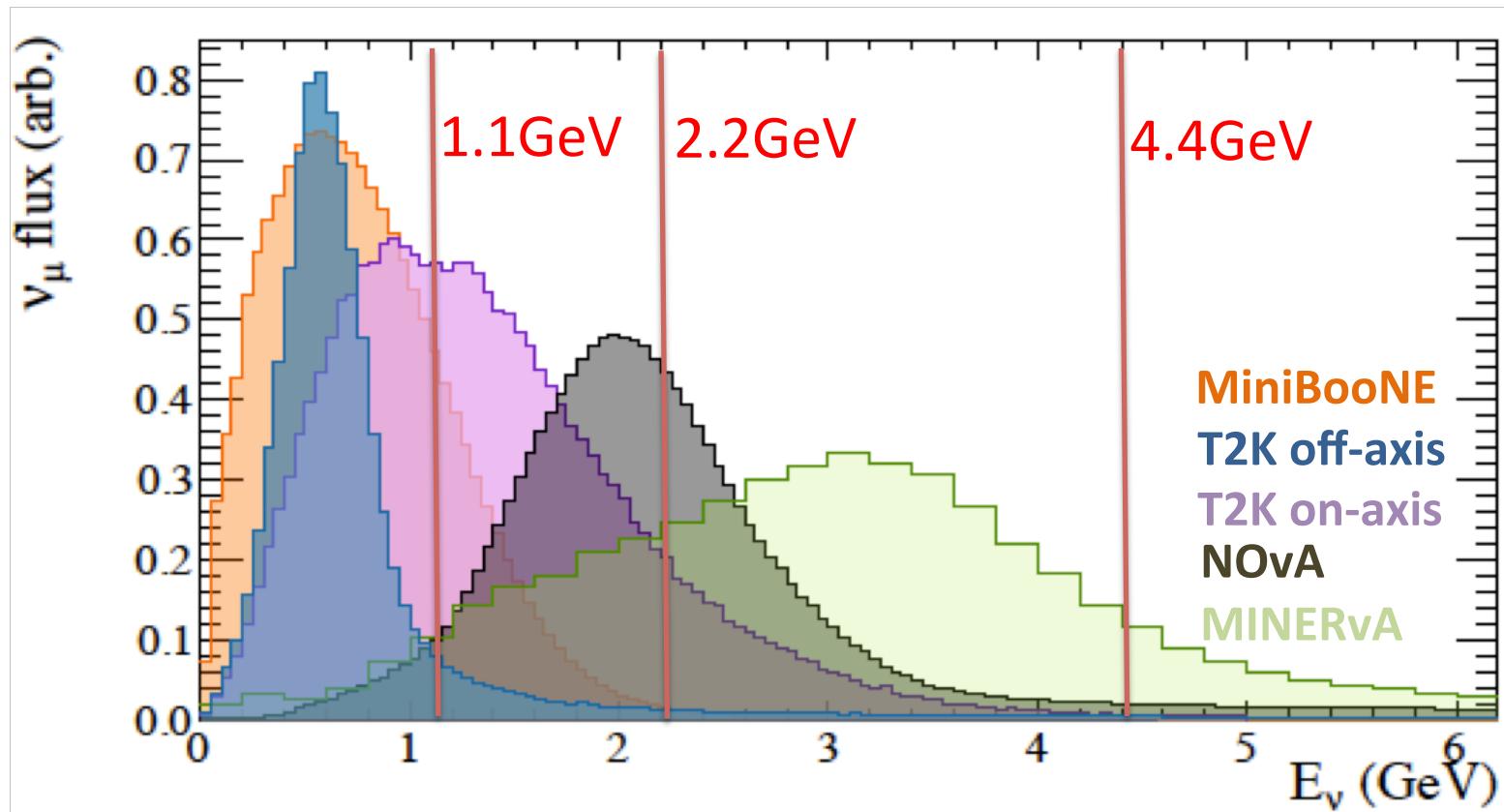
- ✧ 4π acceptance (almost).
- ✧ Charged particles ($8-143^\circ$):
 - $P_p > 300 \text{ MeV}/c$
 - $P_\pi > 150 \text{ MeV}/c$
- ✧ Neutral particles:
 - EM calorimeter ($8-75^\circ$) and
 - TOF ($8-143^\circ$)



Neutrino Energies



Neutrino Energies



QE Event Selection

As close to QE as one can get:

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

QE Event Selection

As close to QE as one can get:

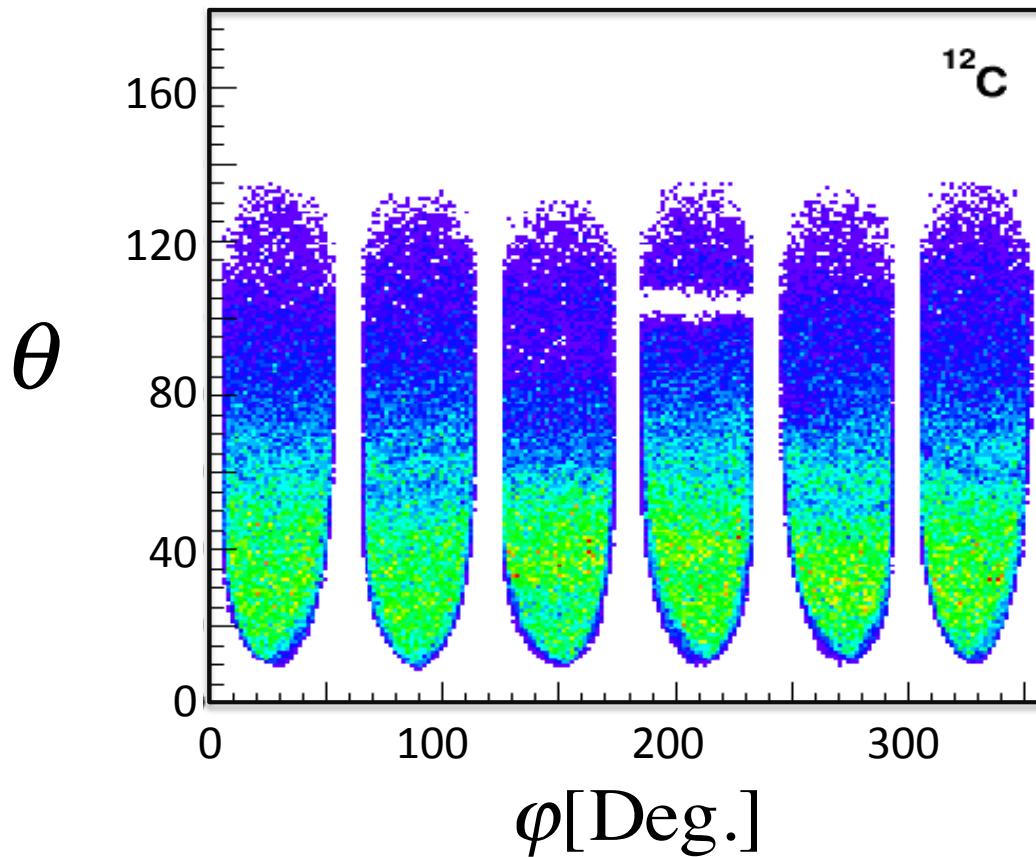
- Scattered electron,
- Knockout proton,
- Zero pion,
- Zero gammas in the EC or LAC.

Scale the e^- scattering data with $1/\sigma_{\text{Mott}}$ 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.



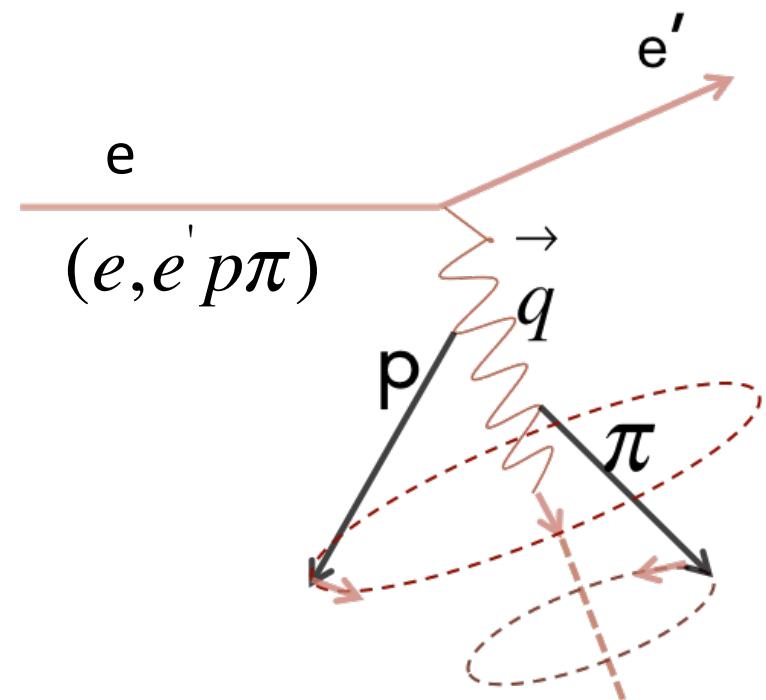
Background Subtraction

Non-QE interactions lead to multi hadron final states.

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

Data Driven Correction:

1. Use measured $(e, e' p\pi)$ events,
2. Rotate π around q to determine its acceptance,
3. Subtract $(e, e' p\pi)$ contributions



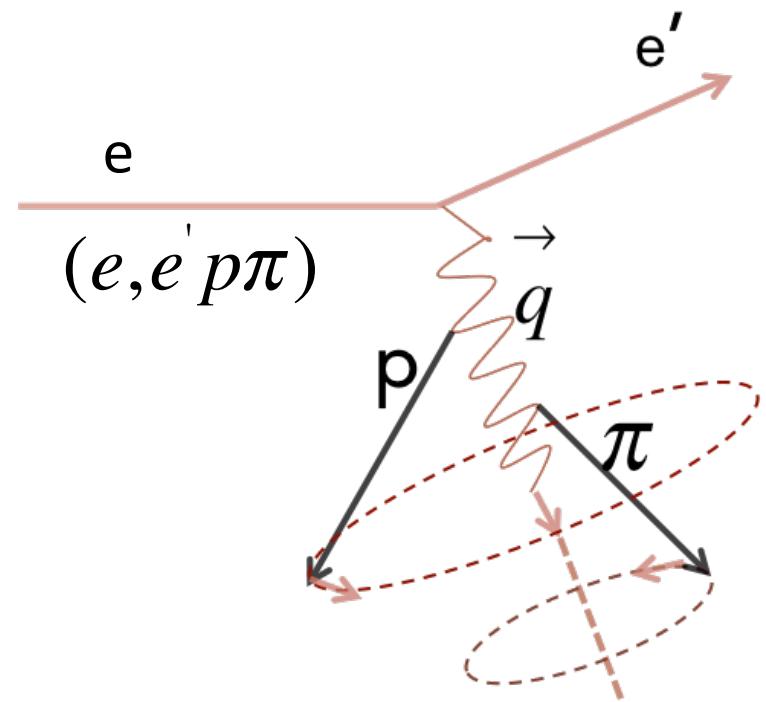
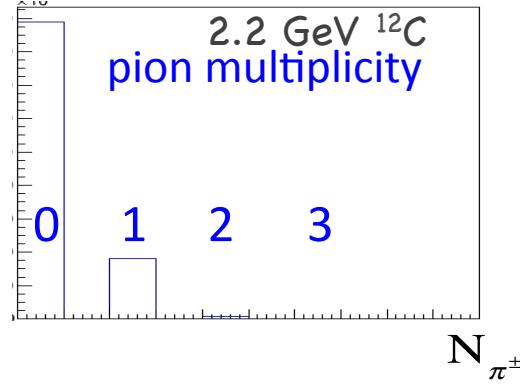
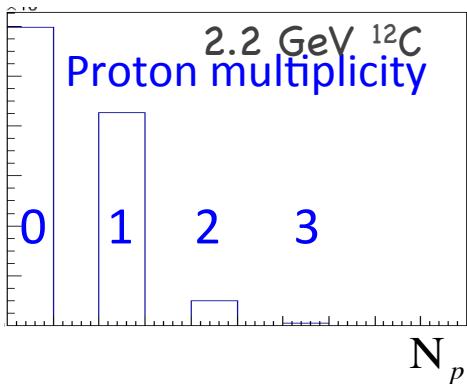
Background Subtraction

Non-QE interactions lead to multi hadron final states

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

Data Driven Correction:

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



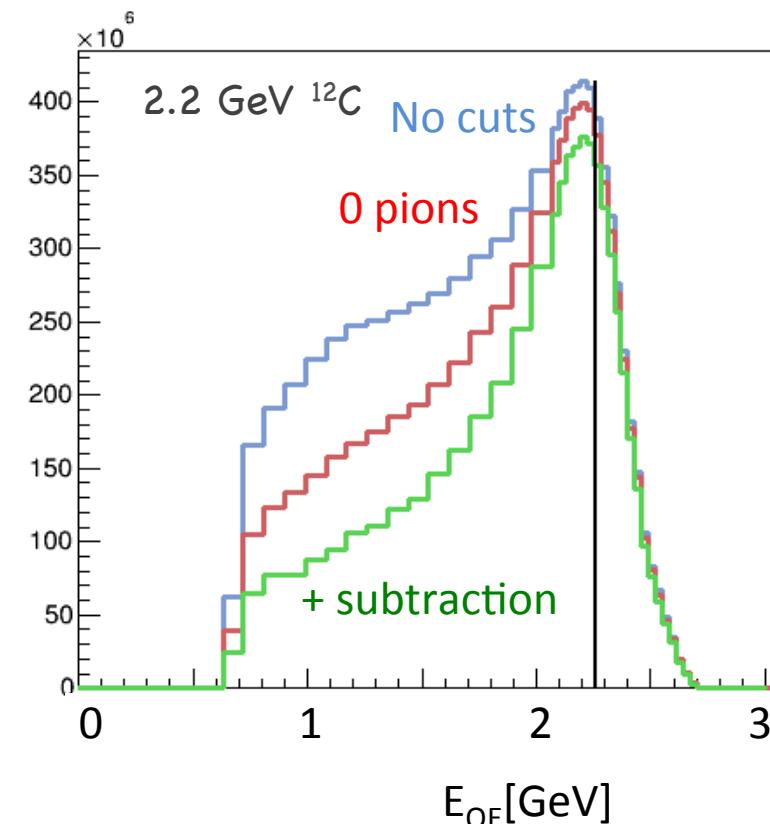
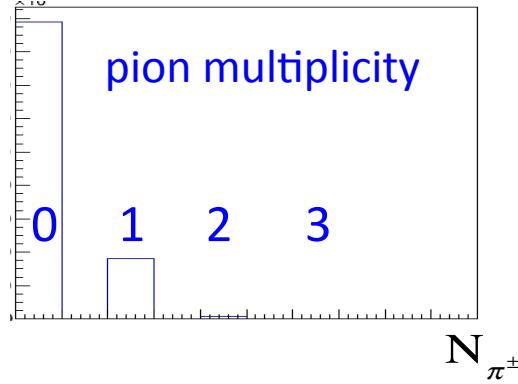
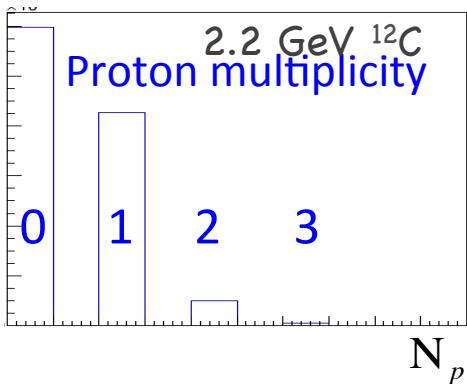
Background Subtraction

Non-QE interactions lead to multi hadron final states

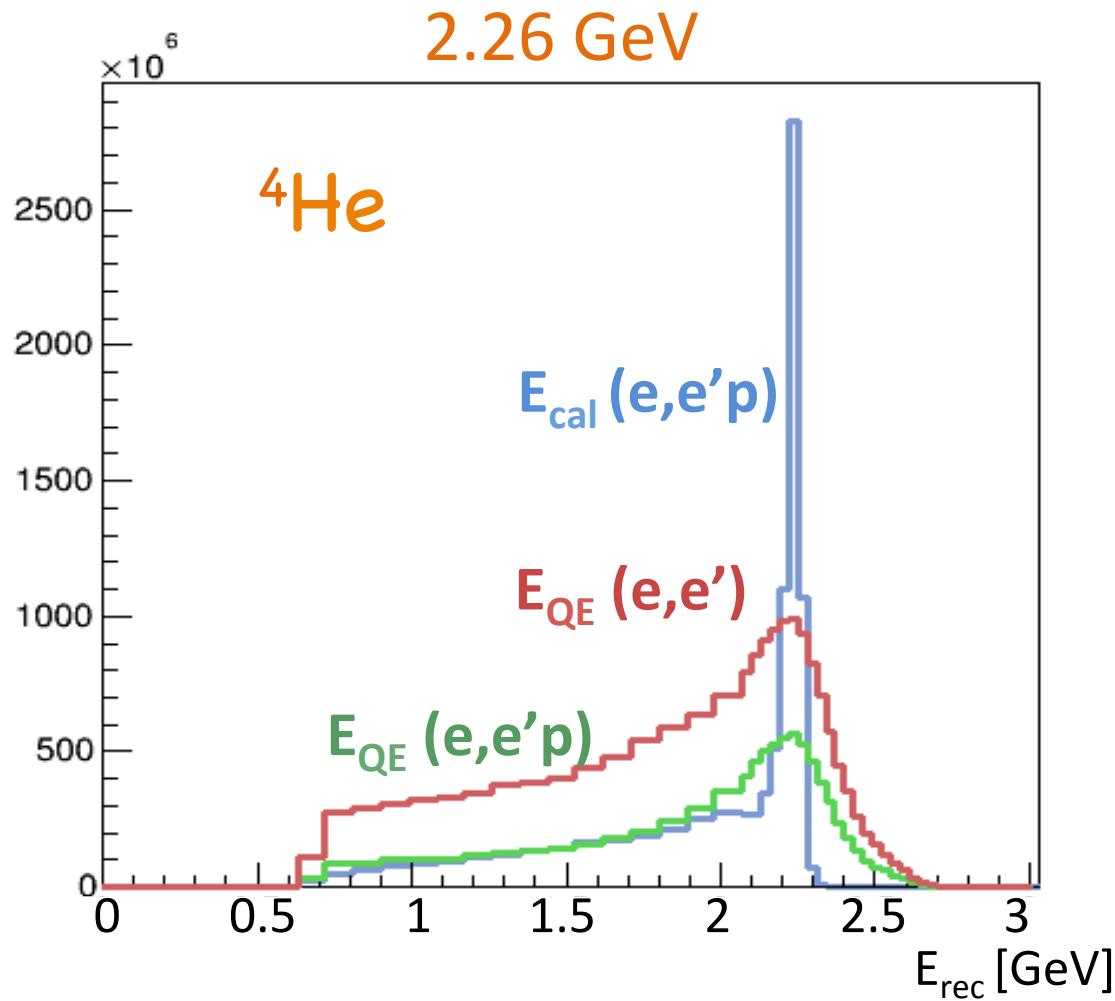
Gaps in CLAS acceptance will make them look like $(e, e' p)$ events

Data Driven Correction:

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



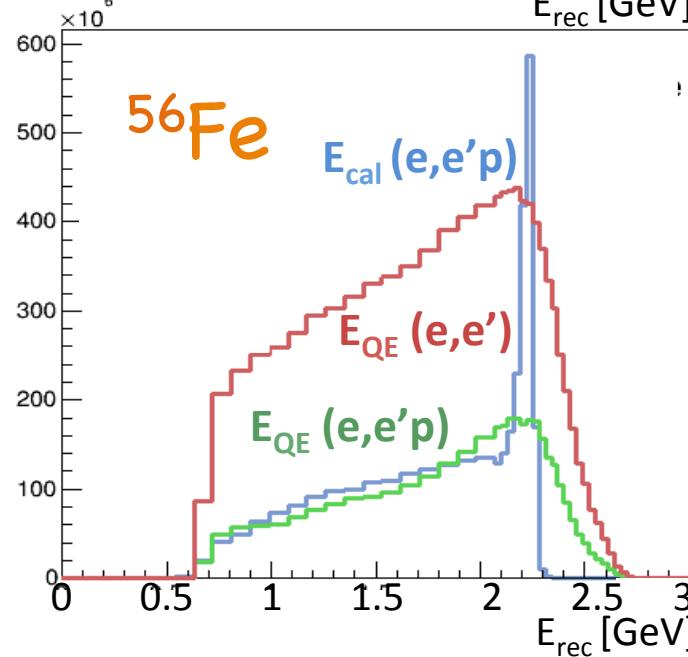
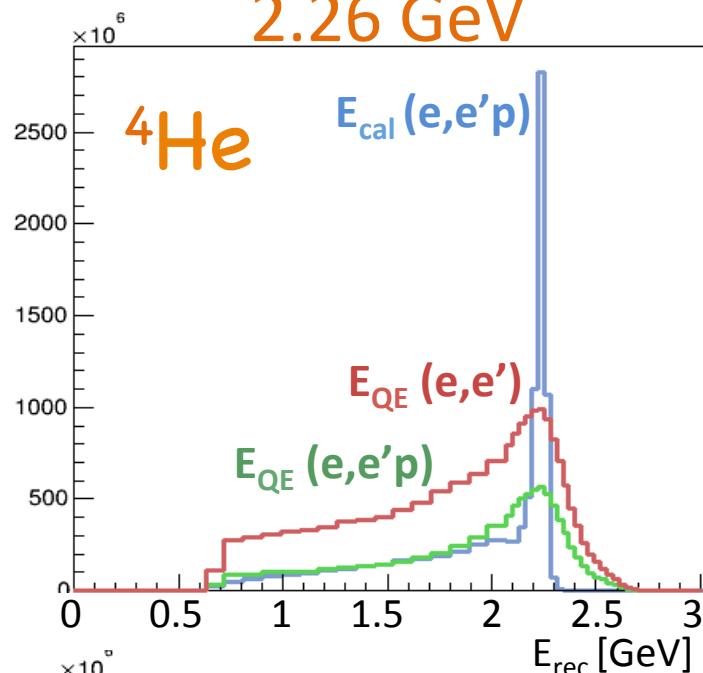
Energy Reconstruction



1. E_{QE} has worse peak resolution than $E_{\text{Cal.}}$.
2. Same tail for $E_{\text{QE}} + E_{\text{Cal.}}$.

Large A dependence

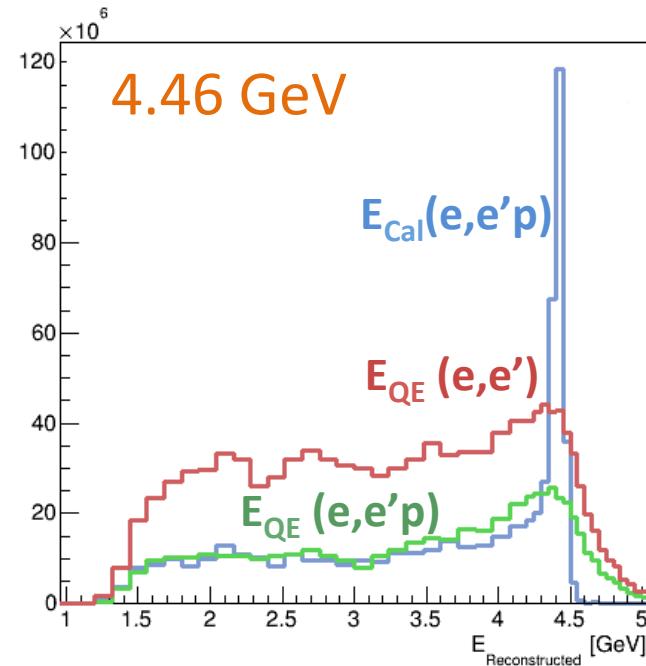
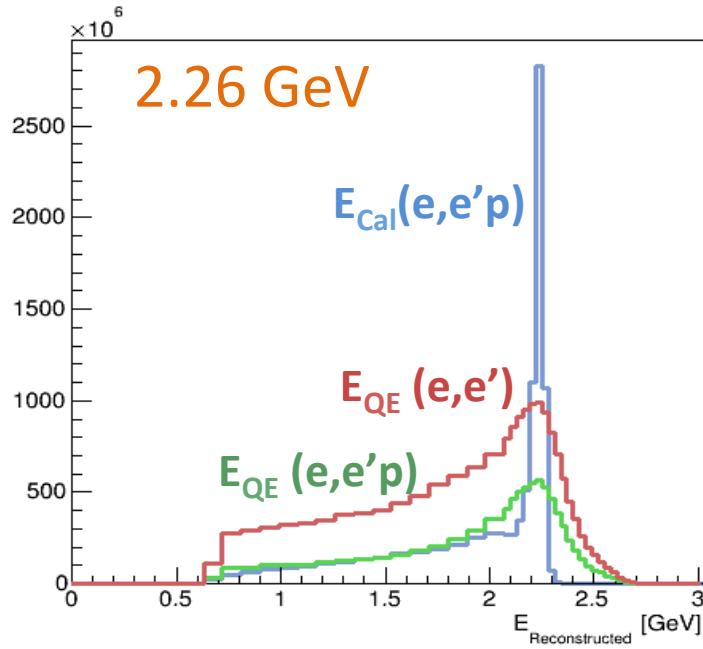
2.26 GeV



1. ${}^{56}\text{Fe}$ is predominantly tail.
2. ${}^{56}\text{Fe}$ is much worse than ${}^4\text{He}$.

Large E dependence

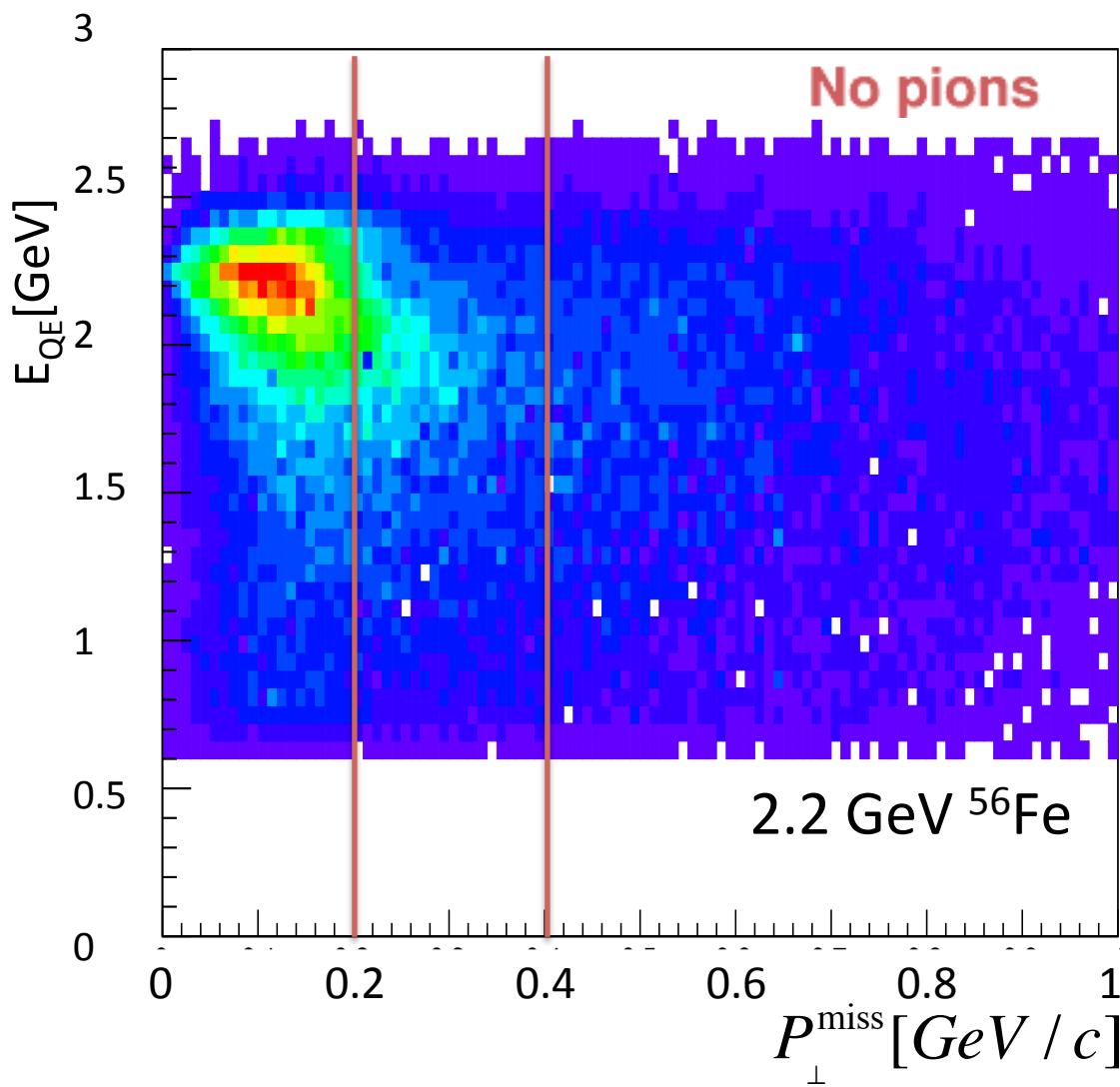
${}^4\text{He}$



Better reconstruction at lower energies.

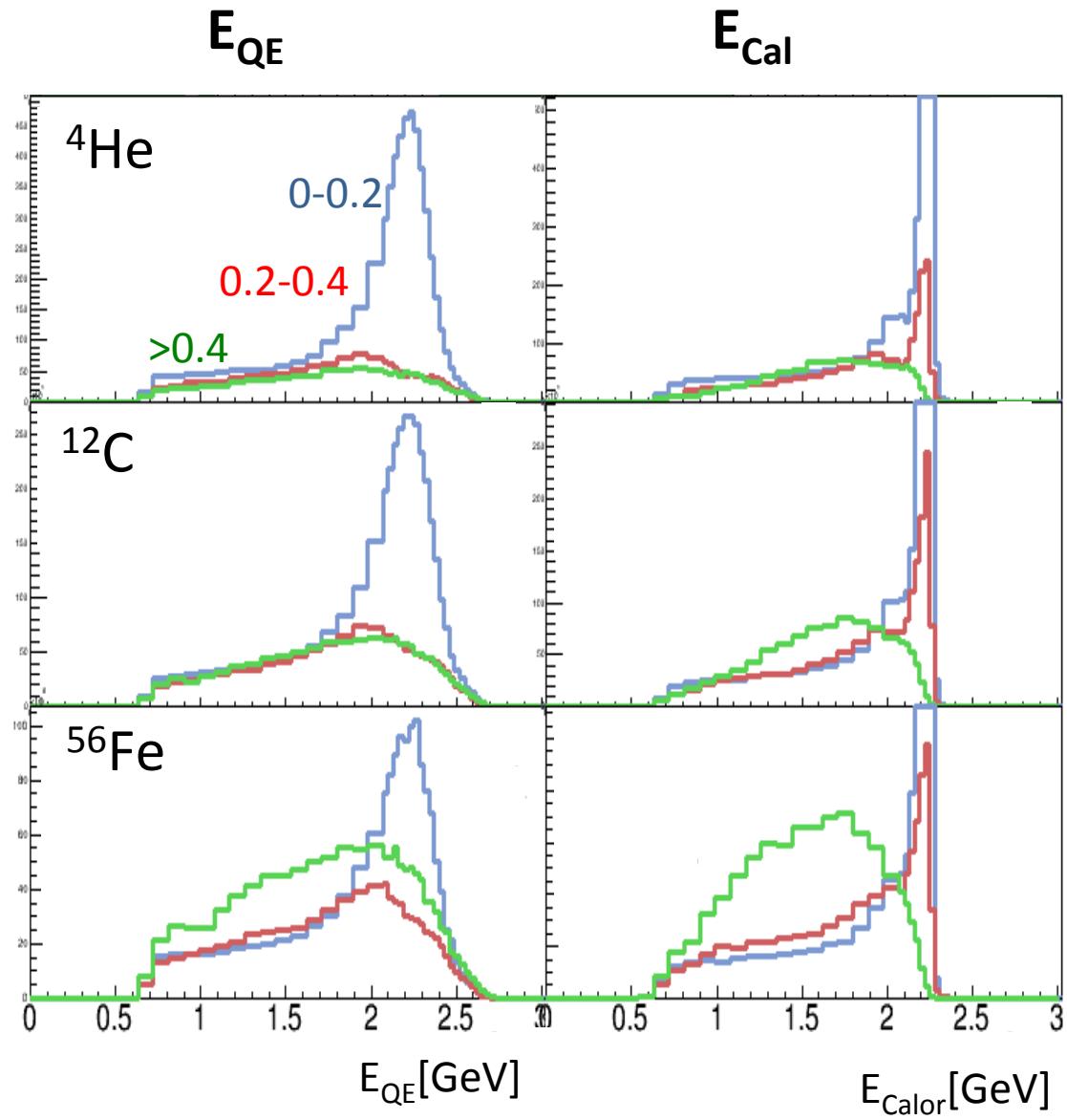
E_{QE} vs P_{\perp}^{miss}

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



P_{miss}^{\perp} slices

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

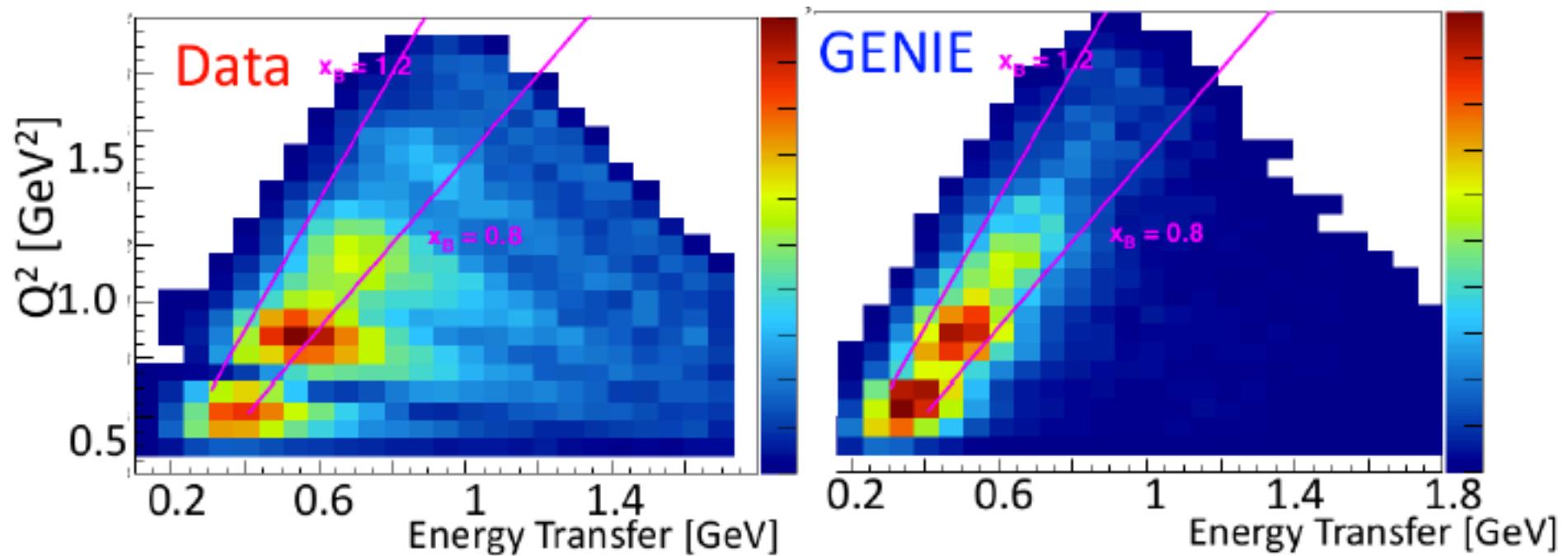


Percent of events reconstructed to within 5% of the beam energy

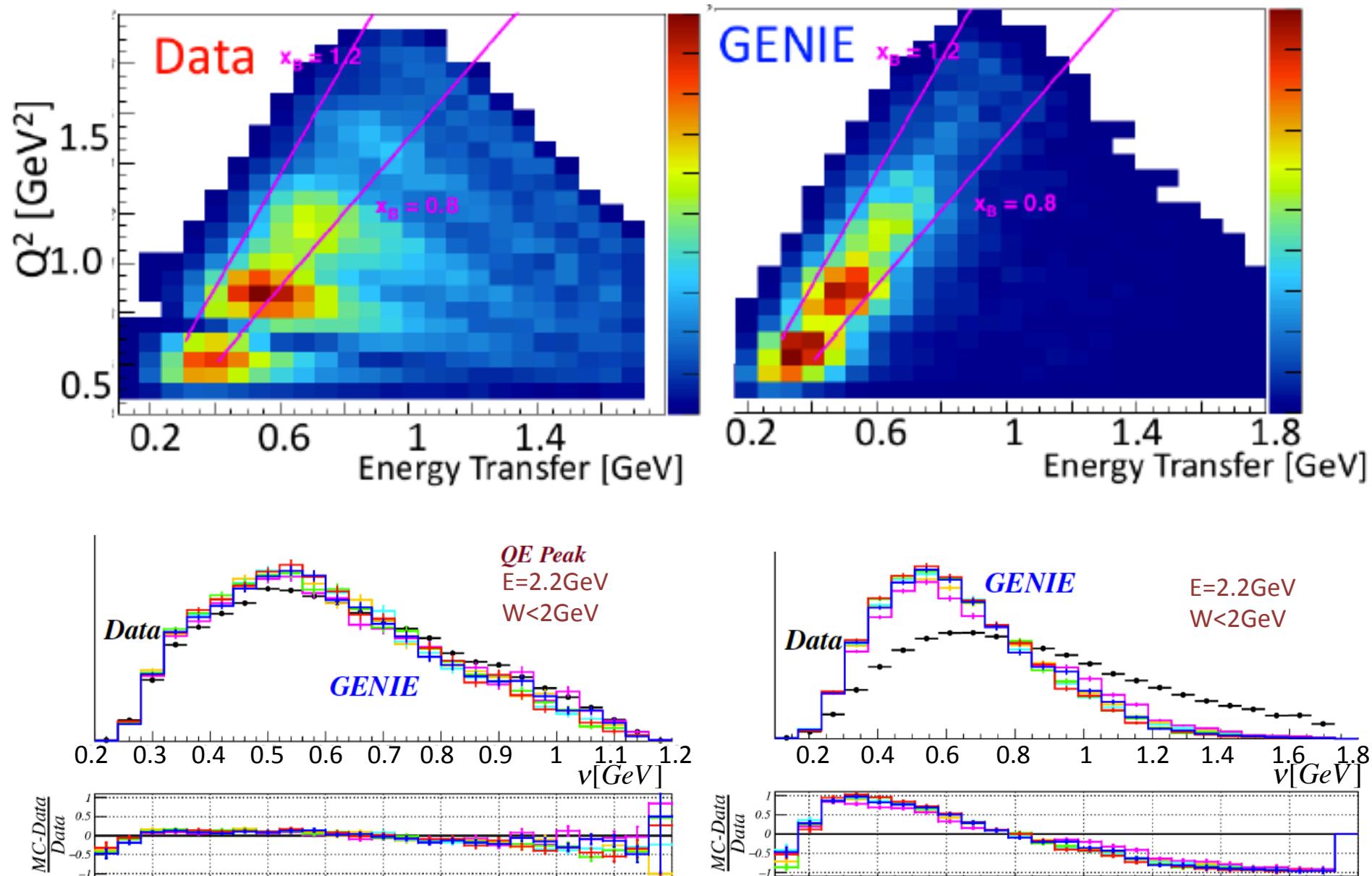
	2.2 GeV		4.4 GeV	
	E_{QE} 1e	E_{Cal} 1e1p	E_{QE} 1e	E_{Cal} 1e1p
^4He	25	46	16	32
^{12}C	22	39	13	27
^{56}Fe	17	25	10	16

From 10 to 46% of events reconstruct to within
5% of beam energy.

Data-Generator Comparisions

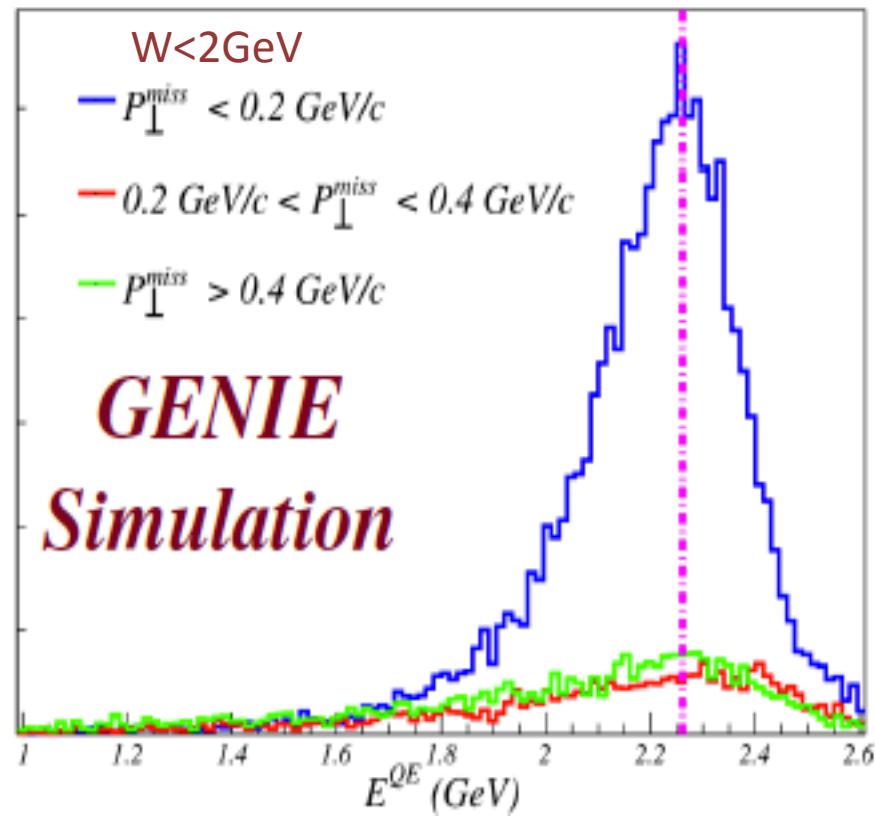


Data-Generator Comparisons

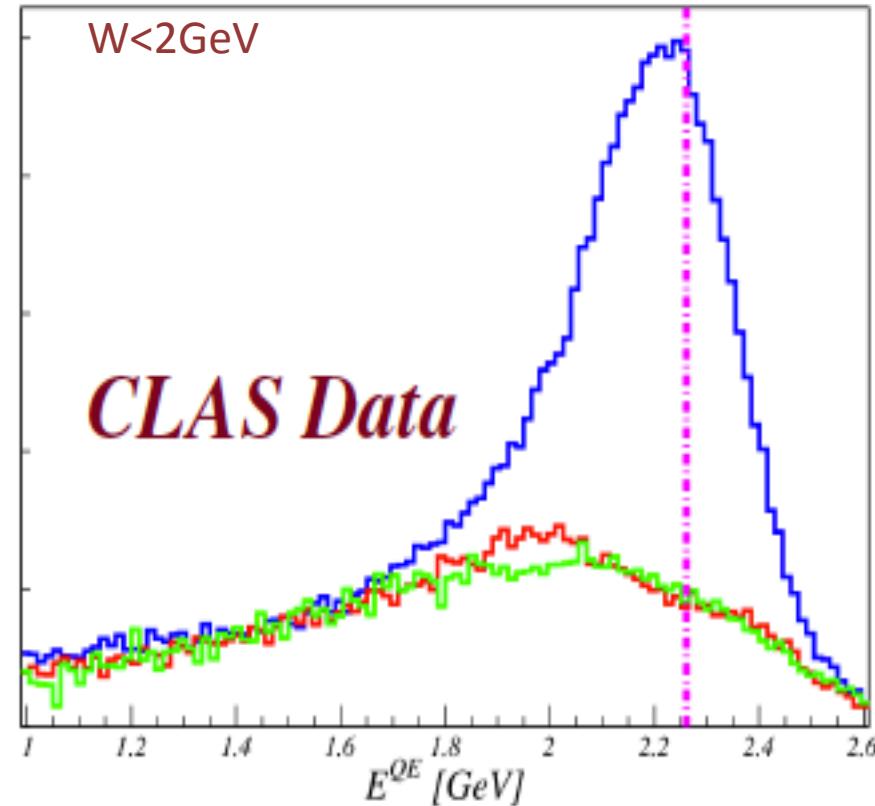


Data-Generator Comparisons

^{12}C



^{12}C



Data-Generator Comparisons

Fe	e ⁻ Data	GENIE
2.2 GeV	26%	62%
4.4 GeV	14%	62%

Fraction of events with E_{cal} within 5% of E_{beam}

Summary

1. First use of e data to test neutrino energy reconstruction.
2. Small fraction of events reconstruct to within 5% of the beam energy.
3. Data - MC comparisons will constrain the nuclear models.
4. Significant disagreement between data-generator results.
5. Relatively good data-generator agreement in QE region.
6. Further GENIE event generator development and and benchmarking against electron scattering data.



Afroditi Papadopoulou
(MIT)

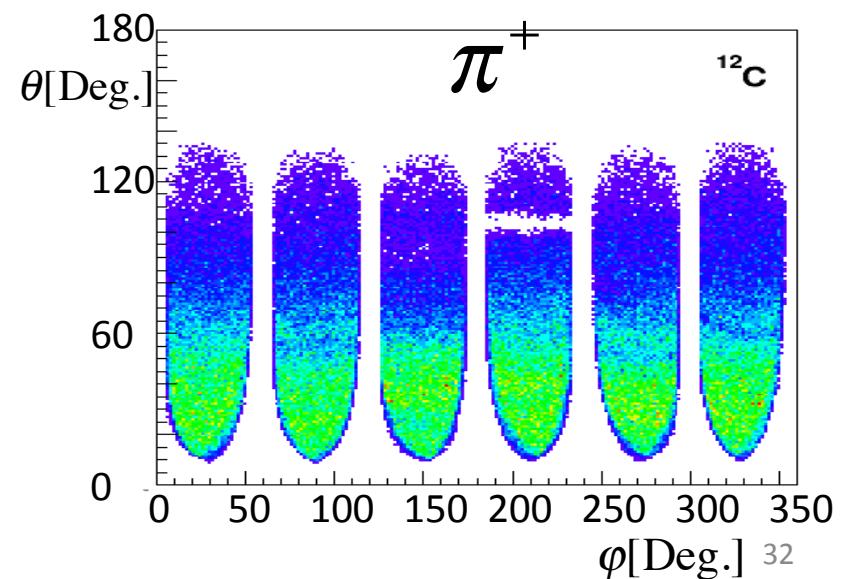
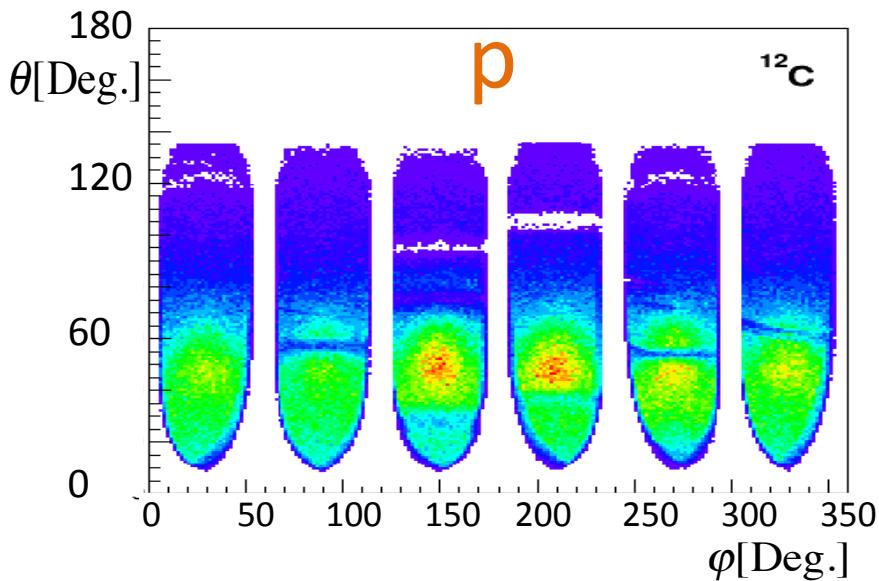
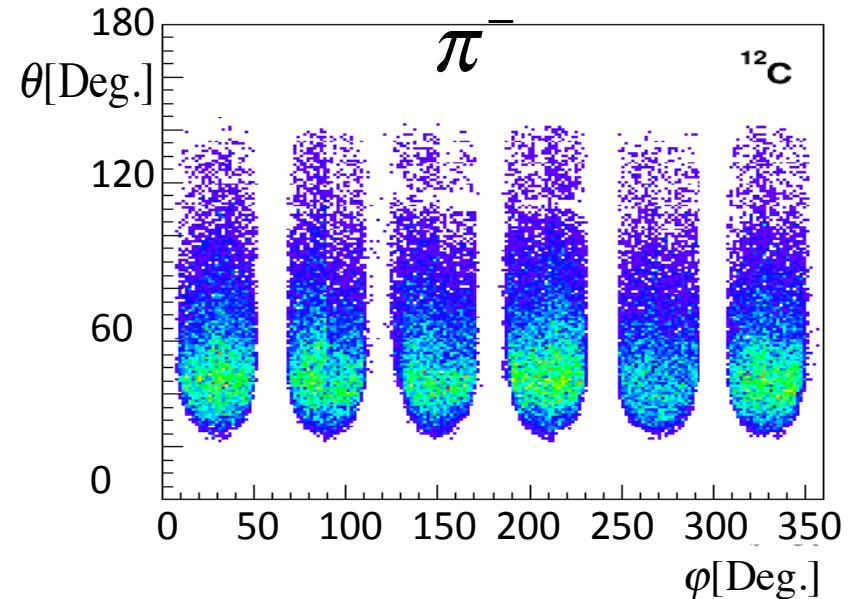
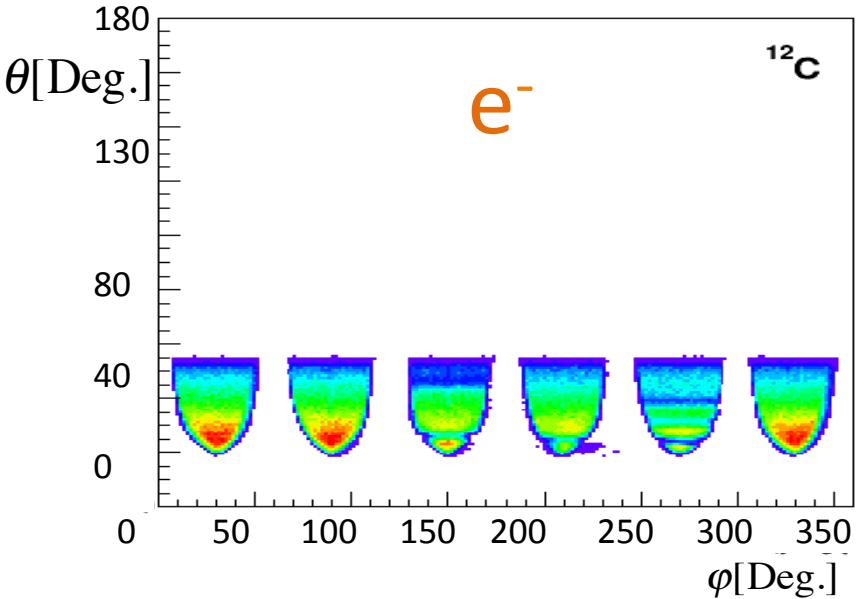


Adi Ashkenazi
(MIT)

Backup

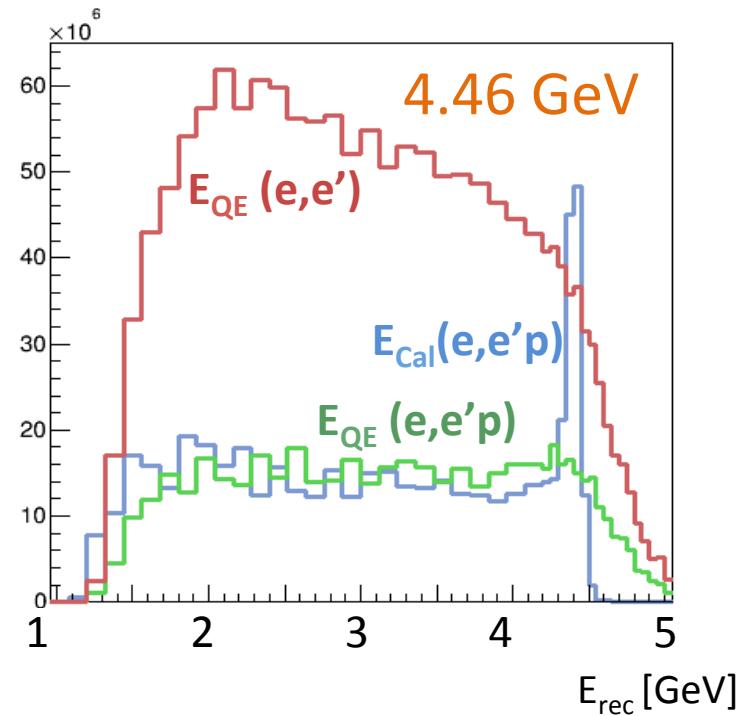
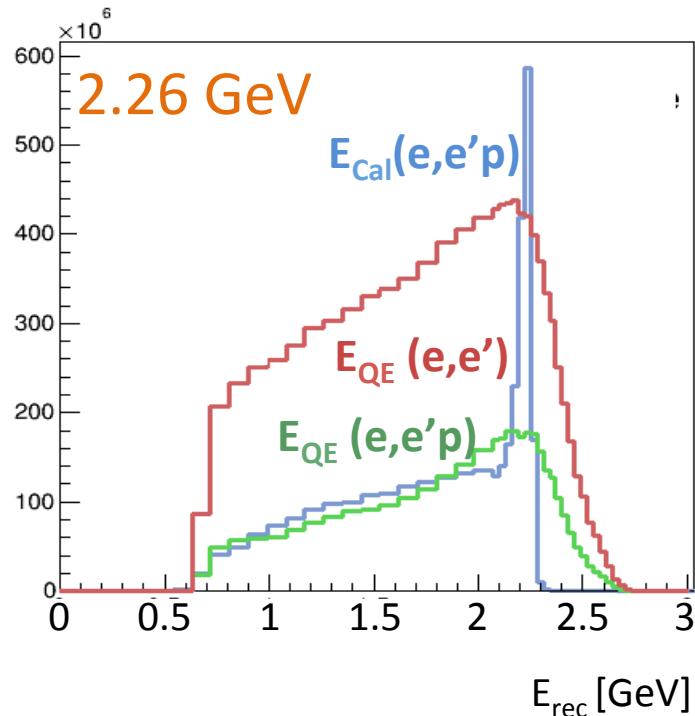
θ and φ distributions

E2a ^{12}C (e, e') and ($e, e' p$) 2.261 GeV



Large E dependence

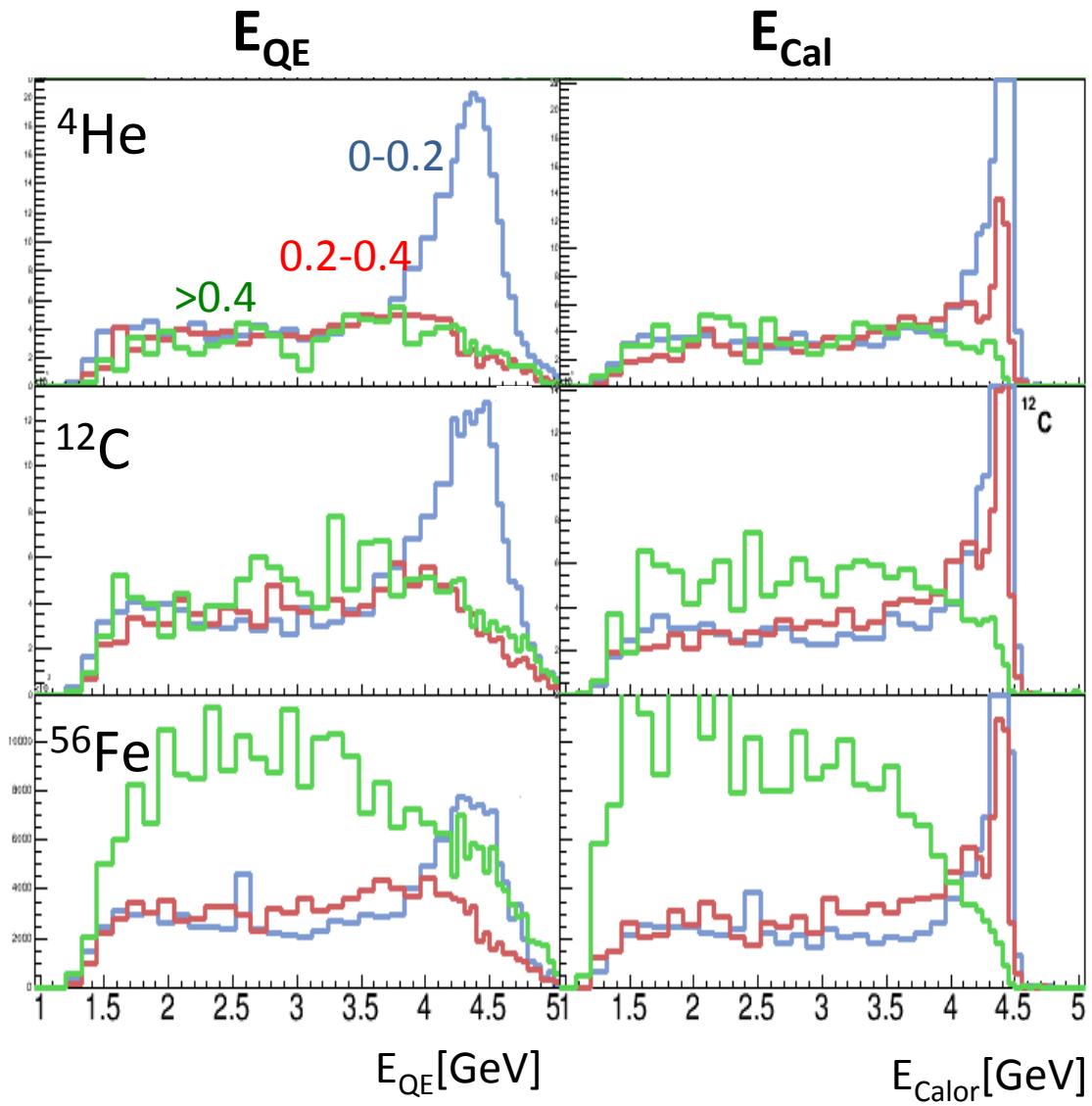
^{56}Fe



Better reconstruction at lower energies.

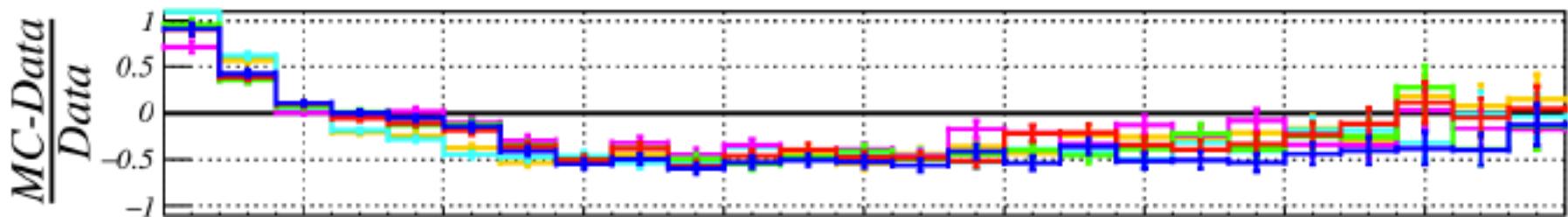
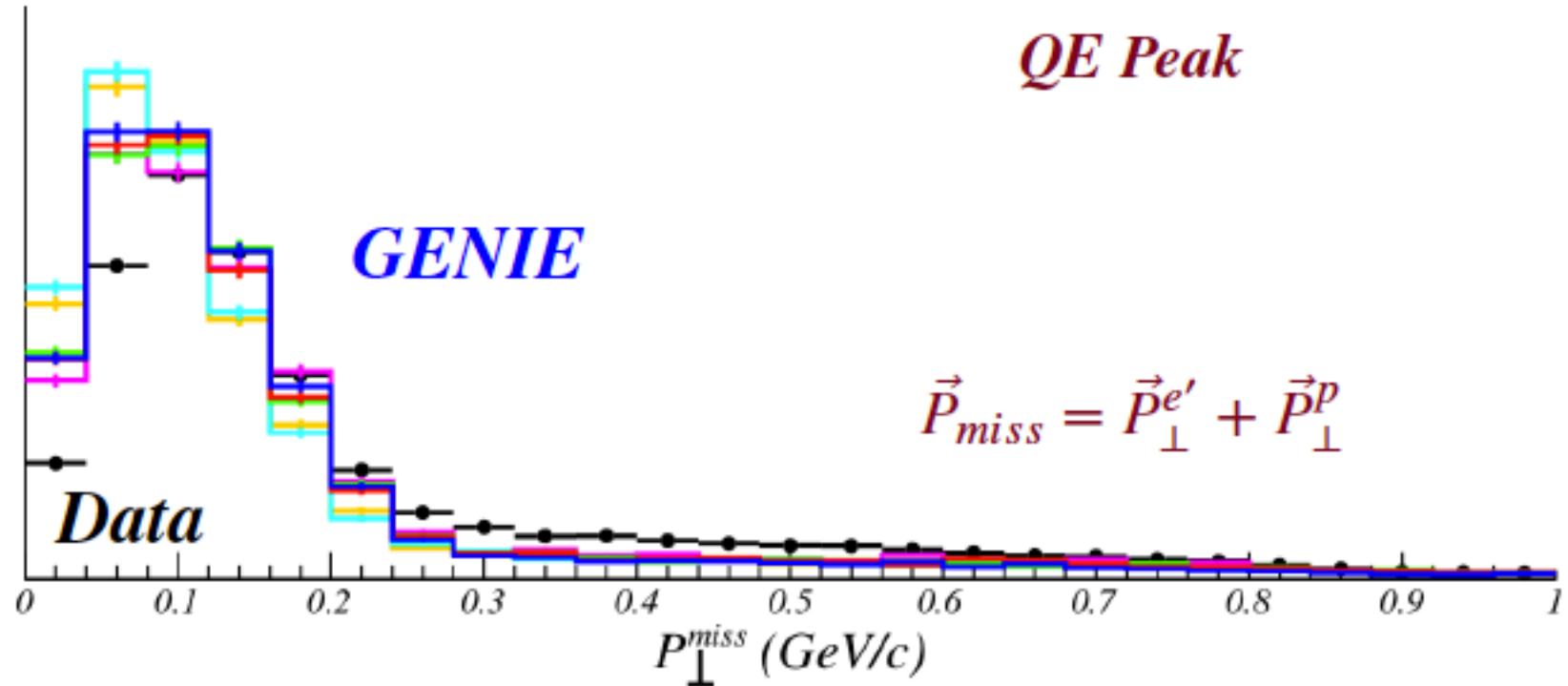
P_{miss}^{\perp} slices

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



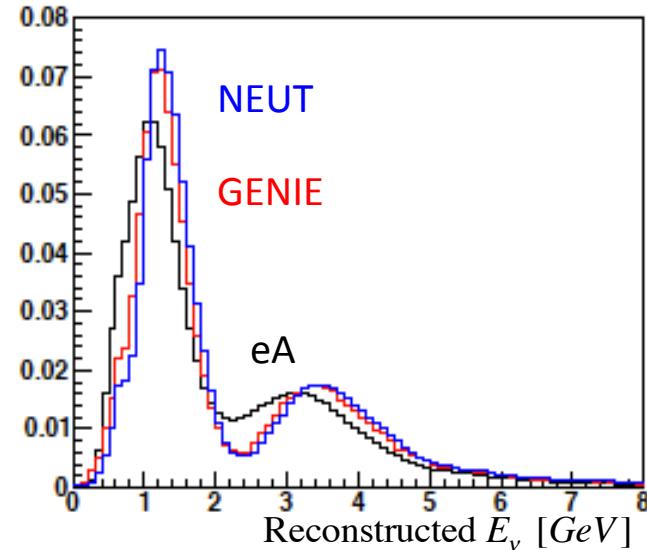
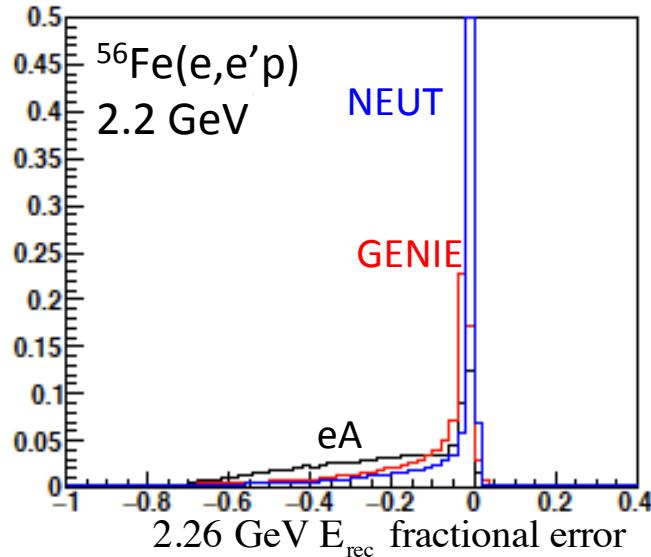
Data-Generator Comparisons

$C(e,e'p) @ E = 2.261 \text{ GeV}$



Possible Implication on DUNE analysis

The expected energy at DUNE far detector as reconstructed using the energy feed down from $A(e,e'p)$ data at one beam energy and simulation.



- 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!

Mott Difference

e^-, ν (NC, CC) – nucleus inclusive scattering cross sections

$$\left(\frac{d^2\sigma}{d\varepsilon' d\Omega} \right)_{e^-} = \left(\frac{d\sigma}{d\Omega} \right)_M [v_L R_L + v_T R_T] \quad \left(\frac{d^2\sigma}{d\varepsilon' d\Omega} \right)_{\nu/\bar{\nu}} = \frac{G^2}{2\pi^2} k' \varepsilon' F(Z, k') \cos^2 \frac{\theta}{2} [v_L R_L + v_T R_T + v_{zz} R_{zz} - v_{0z} R_{0z} \mp v_{xy} R_{xy}]$$

$F(Z, k')$ – Fermi function

v-known factors

z - is along three momentum transfer \vec{q}

$G_F \cos \theta_C$ (CC), G_F (NC)

R-nuclear response

$x \perp z$ – lies on (\vec{k}, \vec{k}') plane

$k^\mu = (\varepsilon, \vec{k}), k'^\mu = (\varepsilon', \vec{k}')$ – initial and final lepton four momenta

$y \perp z$ – is perpendicular to (\vec{k}, \vec{k}') plane

Cross-section Systematics

- Even with a near detector, cross-section systematics are a significant source of uncertainty in long-baseline experiments.
- Right now, nuclear effects (MEC/2p2h, Charge Screening/RPA) are among largest pieces of that uncertainty.

