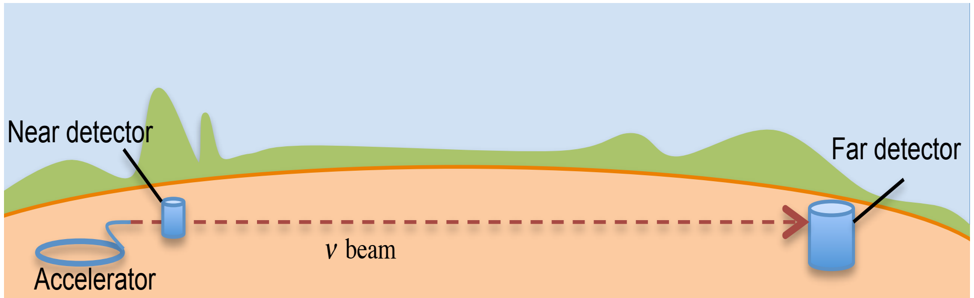
Validation of neutrino energy estimation using electron scattering data

Student
Mariana Khachatryan
Supervisor
Lawrence Weinstein

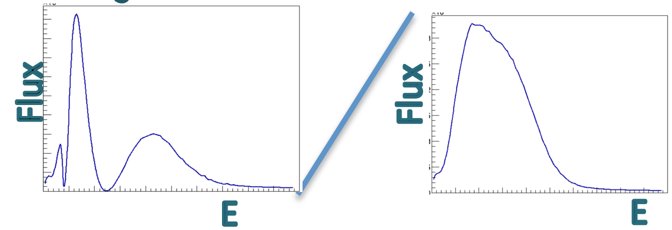
Outline

- 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



Oscillations are ratios of reconstructed ν energy spectra.
But: reconstructing neutrino energies requires understanding neutrino-nucleus interactions.

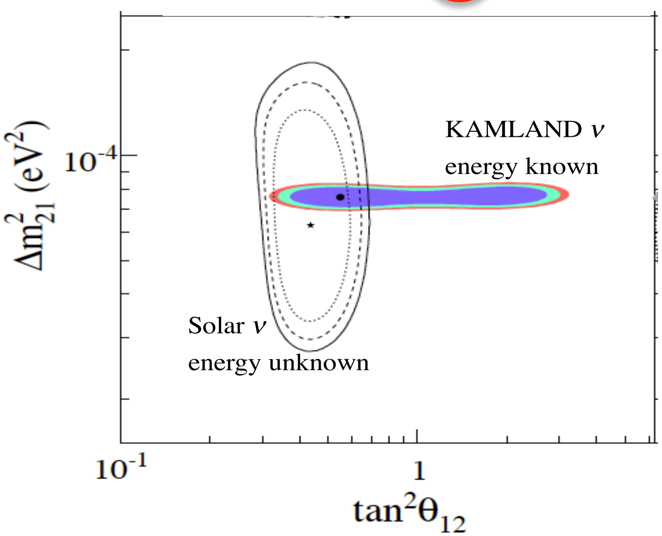


- Energy (x-axis): Reconstructed from the measured final state.
- Flux (y-axis): Corrected using reaction model

ν-Beam → Low energy: reactors / High energy: accelerators → mixed beams of all energies

$$P(\nu_\mu \rightarrow \nu_x) = \sin^2(2\theta) \times \sin^2\left(\frac{\Delta m^2 L}{4E_\nu}\right)$$

→ **Real E**



Error in Reconstructed E → Error in extracted oscillation parameters

What can we learn from e- scattering studies?

- Similar e^- and neutrino interactions with nuclei (FSI, when knock-out nucleon rescatters of other nucleons before coming out of nuclei , Resonance production, Multinucleon effects, etc.)
- e- beam energy is known ⟶can test energy reconstruction in selective kinematics
- compare to GENIE neutrino event generator results running in e- scattering mode

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

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

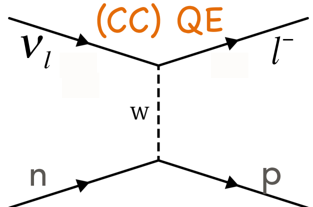
$F(Z,k')$ – Fermi function v-known factors

G- $\mathrm{G}_F \cos\theta_C (CC)$, $\mathrm{G}_F (NC)$ R-nuclear response

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

$\nu - N$ and $\mathrm{e}^- - N$ Quasi-Elastic (QE) scattering

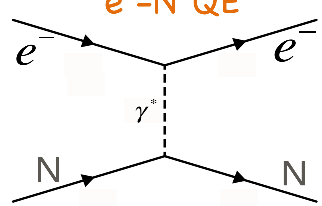
Charged Current (CC) QE



$\nu_l + n \rightarrow l + p$

$\bar{\nu}_l + p \rightarrow l^+ + n$

e⁻-N QE



$e^- + N \rightarrow e^- + N$

Testing energy reconstruction methods in neutrnio experiments with e- scattering data

E_ν Reconstruction from lepton kinematics [(e,e') or (ν, l)] (assumes QE)

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

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

M -nucleon mass

m_1 outgoing lepton mass

k_1 – lepton three momentum

θ – lepton scattering angle

E_ν Reconstruction from 'full' final state [$(e, e'pX)$ or (ν, 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

Look at A(e,e') and A(e,e'p) no pion spectra (Standard QE selection) to test E reconstruction techniques.

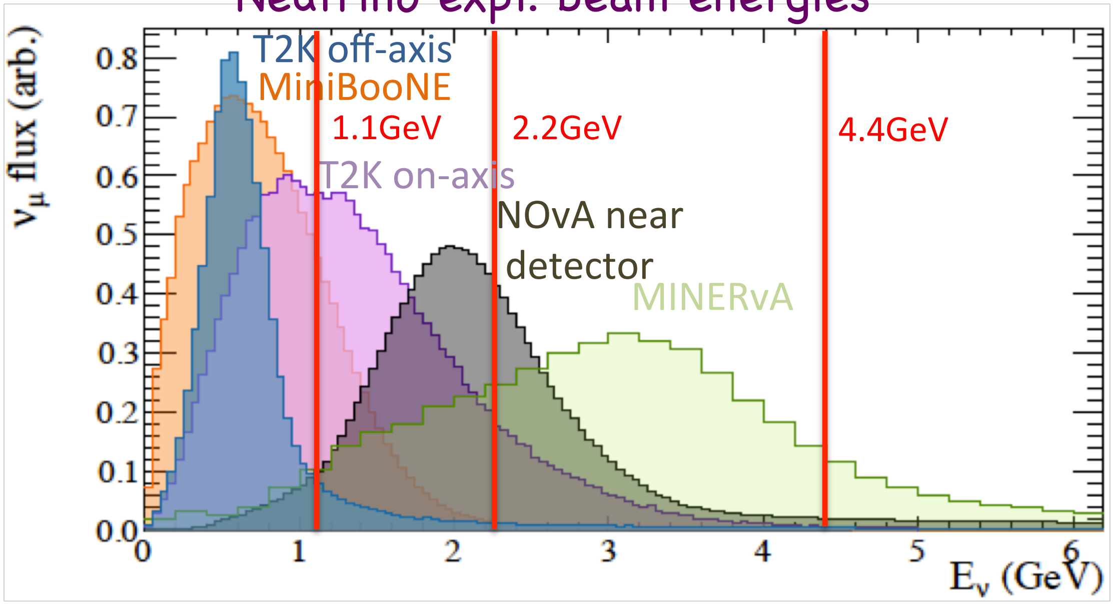
Scale the e^- scattering data with $1/\sigma_{\text{Mott}}$ to have 'neutrino like' data!

E2a experiment

^3He , ^4He, ^{12}C, ^{56}Fe 4.461,
2.261 GeV e2a experiment data

Other data available ^3He, ^4He, C, Fe 1.1 GeV

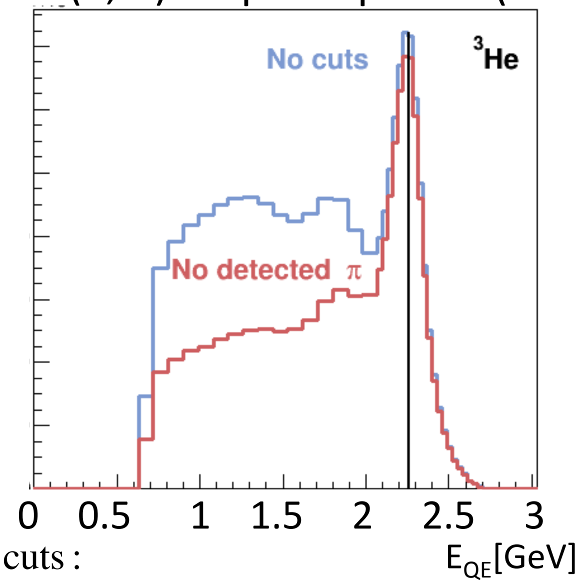
Neutrino expt. beam energies

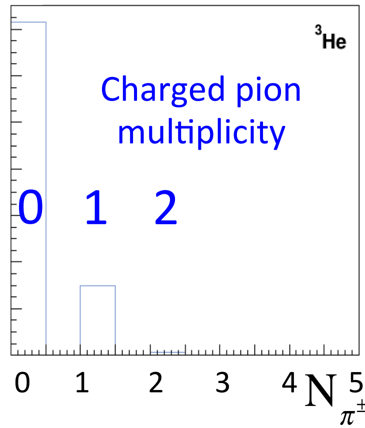


Pion subtraction

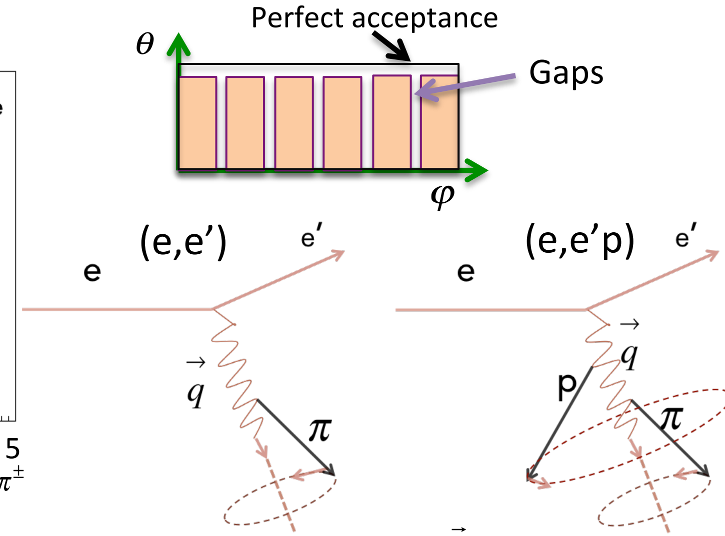
E2a ^{3}He 2.26 GeV

Look at A(e,e') no pion spectra (Standard QE selection)





Subtracting undetected pions to get 0pi sample

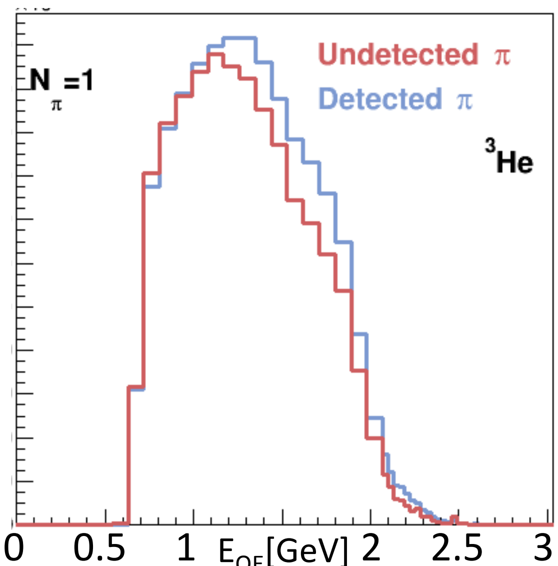


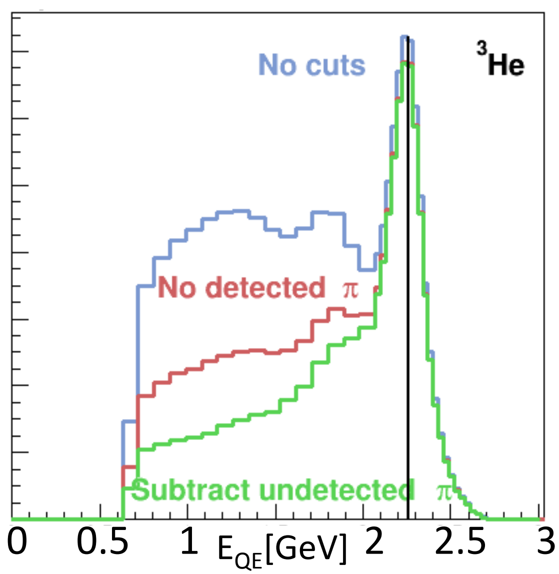
Rotate π around $\vec{q}$ to determine detection acceptance

The π cuts :

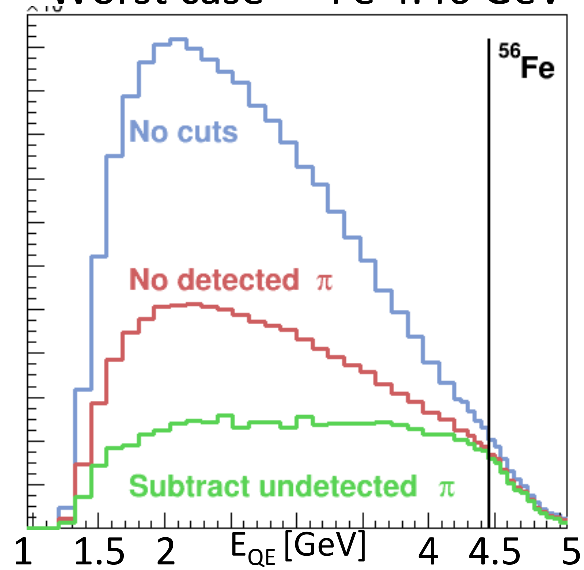
$\Delta t = t_{TOF} - d_{TOF} / v_{DC} - t_{Start}$, Fiducial, $e^{-} - \pi^{\pm}$ vertex diff.

No photons from π_0 decay





Worst case ^{56}Fe 4.46 GeV



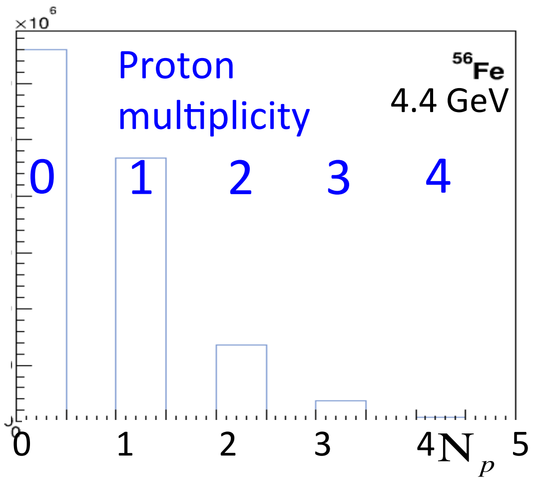
Subtracting protons

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

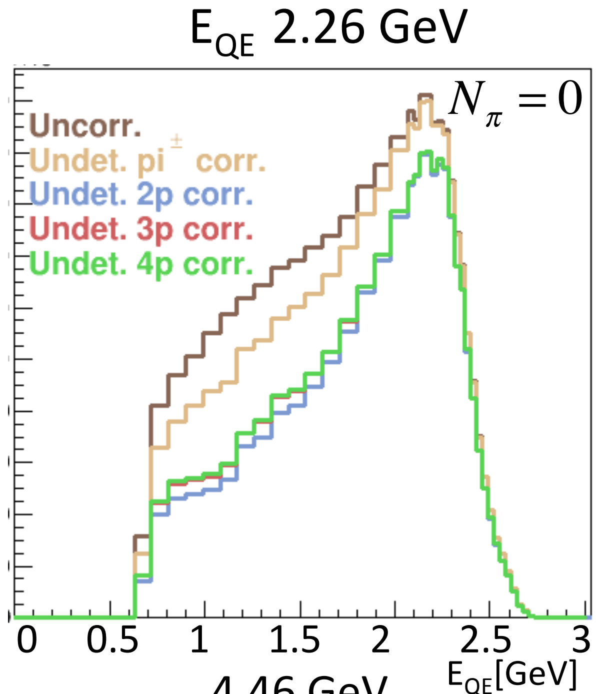
Goal: Two spectra

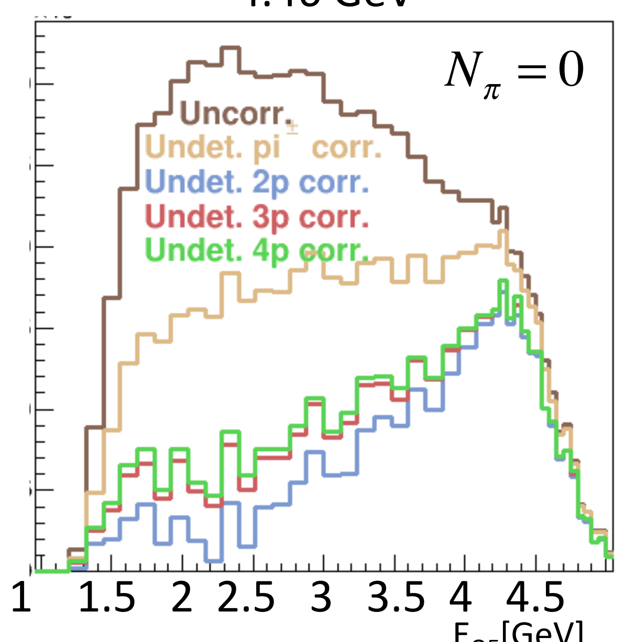
(e,e'p) true → Requires subtracting undetected p

(e,e'p)X measured

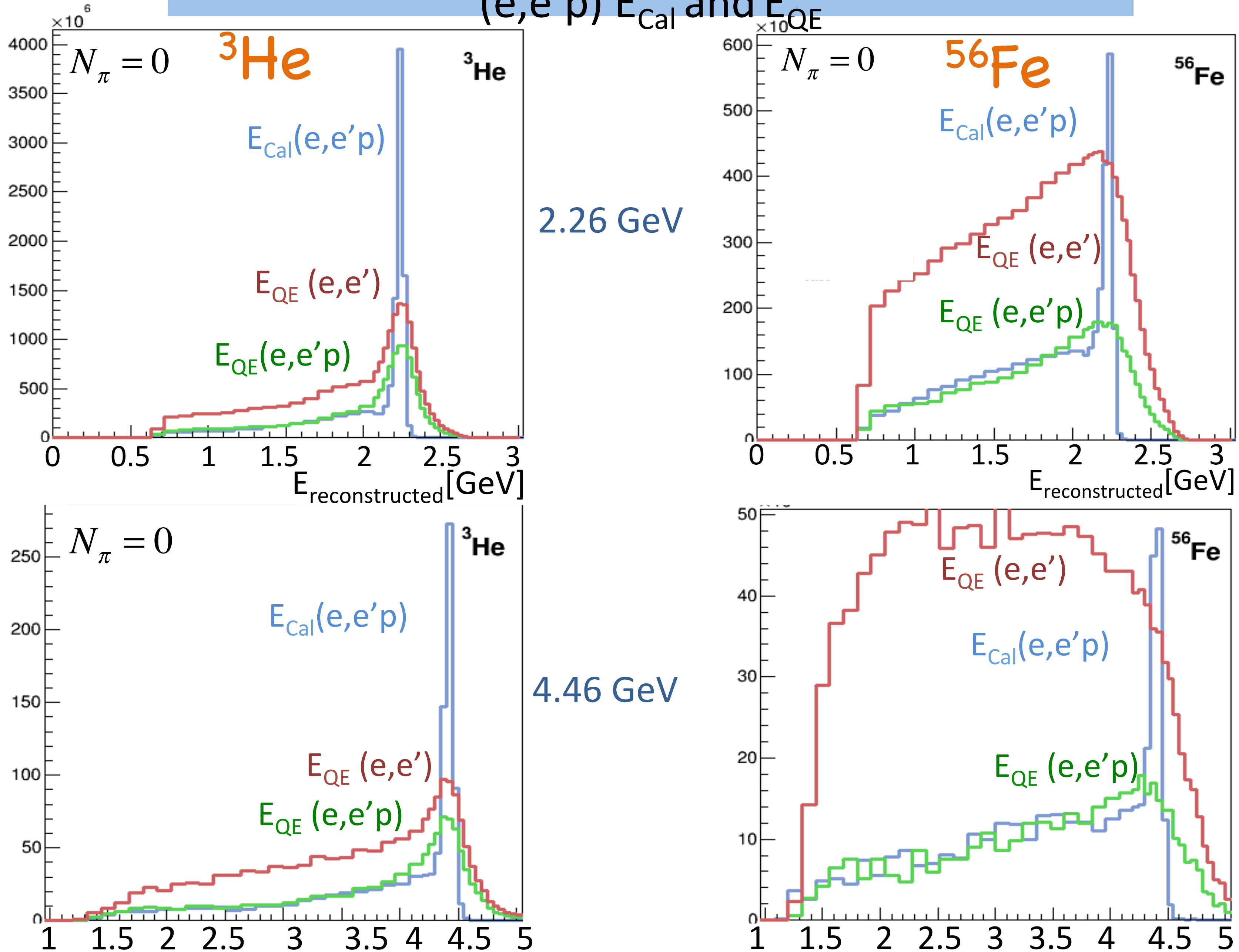


Need to consider 3p and 4p
But it converges





(e,e'p) E_{Cal} and E_{QE}



E_{QE} has Worse peak resolution than E_{Cal}
Same tail for E_{QE}+E_{Cal},

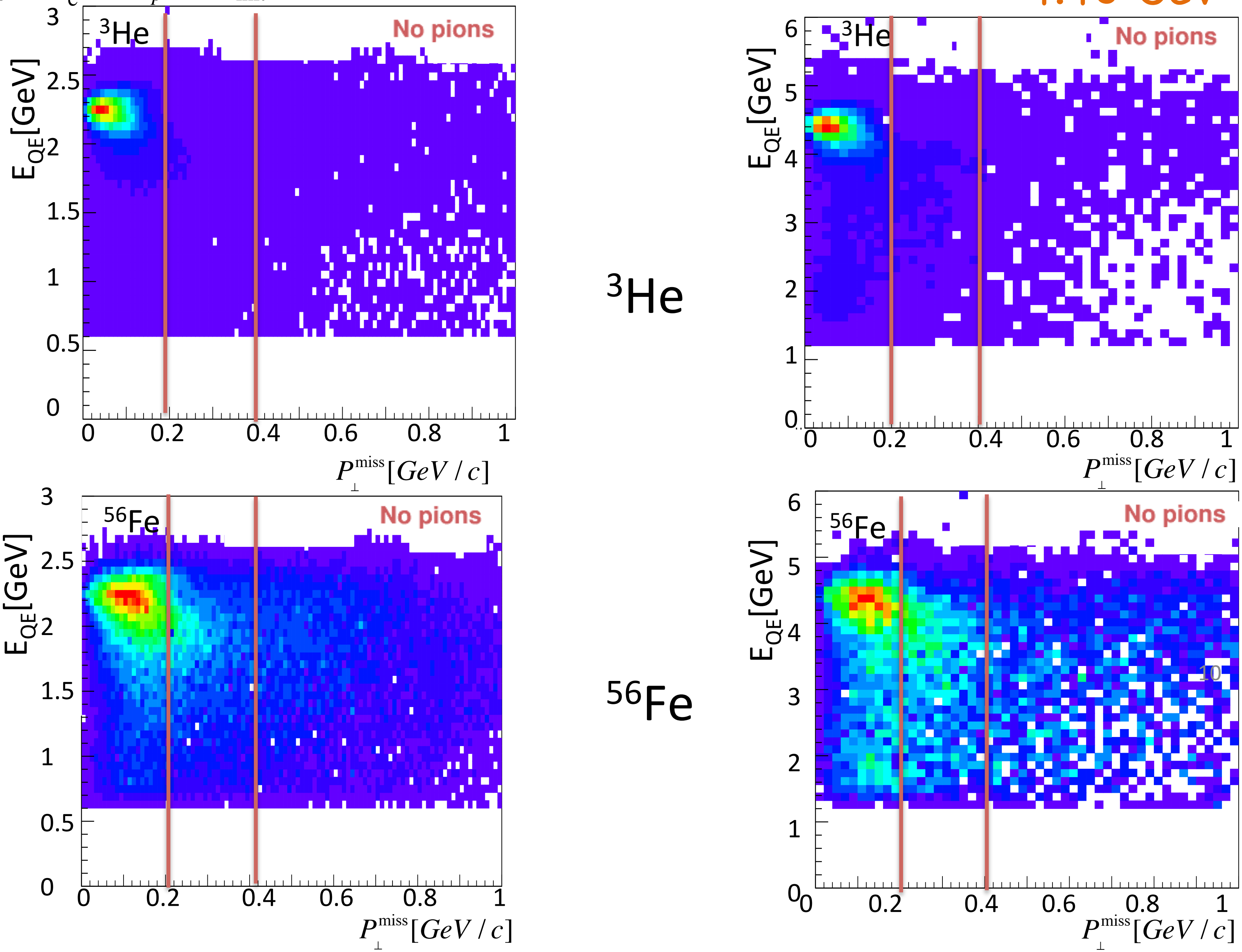
^{56}Fe is much worse than ^{3}He
^{56}Fe predominantly tail

Reconstructed (e,e’) energy

$P^{\perp}_{\text{miss}} = P^{\perp}_{e^-} + P^{\perp}_{p} = P^{\perp}_{\text{init}}$

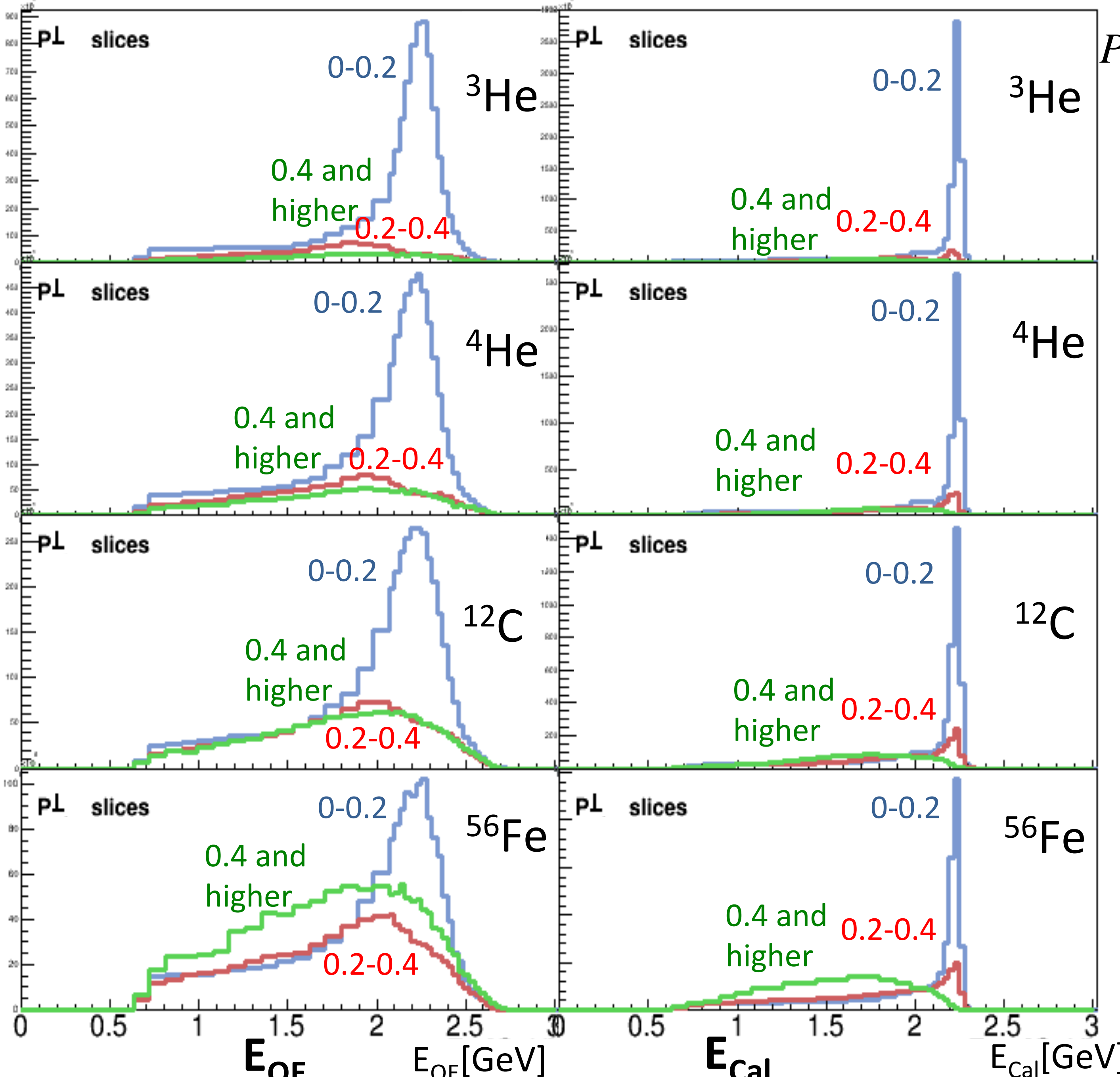
2.26 GeV

4.46 GeV



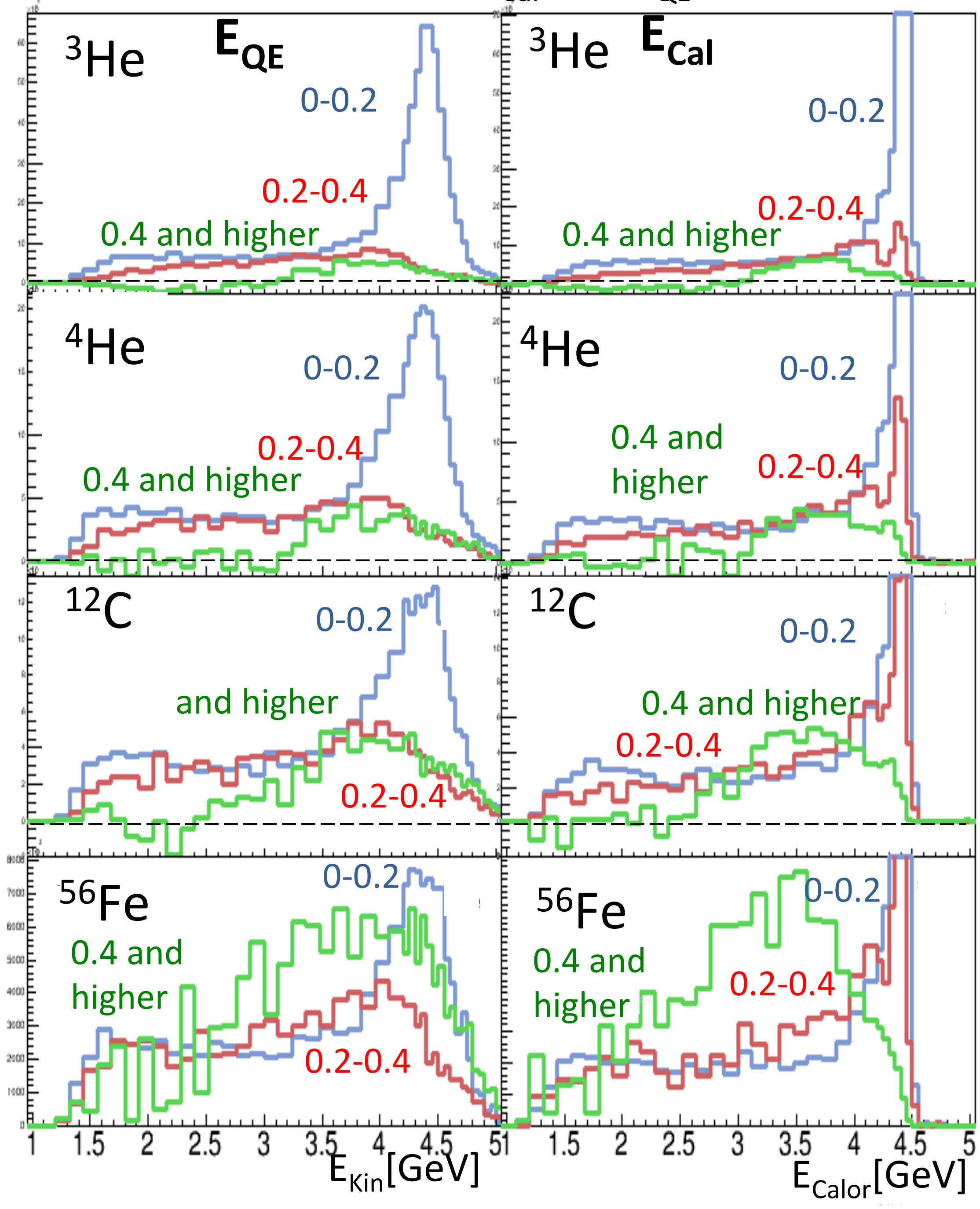
E_{Cal} and E_{QE} for all targets at 2.261 GeV in $P^{\perp}_{miss}$ slices

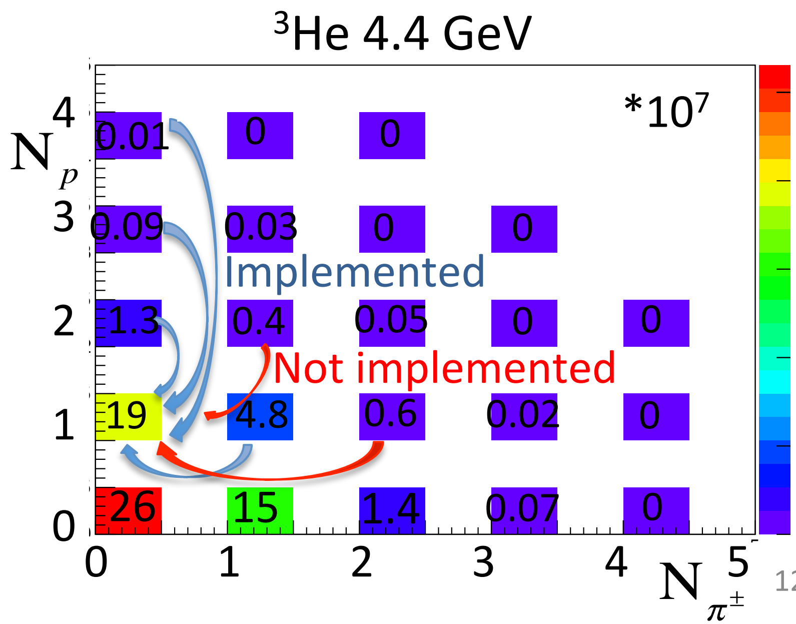
$$P^{\perp}_{miss} = P^{\perp}_{e^-} + P^{\perp}_{p} = P^{\perp}_{init}$$



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

E_{Cal} and E_{QE} for all targets at 4.461 GeV in $P_{miss}^{\perp}$ slices





Need to consider effect of $(e,e'pp\pi^{\pm})$

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

(e,e'p) E_{Cal} , (e,e') E_{QE} and (e,e'p) E_{QE}

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

	2.2 GeV		4.4GeV	
	E_{QE} 1e	E_{Cal} 1e1p	E_{QE} 1e	E_{Cal} 1e1p
^{3}He	33	56	26	47
^{4}He	25	47	20	39
^{12}C	22	40	15	35
^{56}Fe	17	26	10	23

From 0.1 to 0.56 fraction of events reconstruct to within 5% of beam energy.

Fraction of events reconstructed in different energy bins with $p_{\perp} > 0.2$ GeV

2 GeV

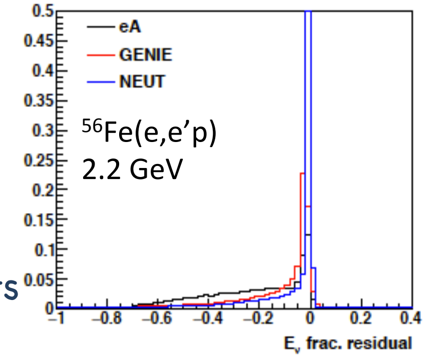
E_{Cal}	^{12}C	^{56}Fe
1.75-2	0.117 ± 0.001	0.136 ± 0.001
1.5-1.75	0.096 ± 0.001	0.127 ± 0.001
1.25-1.5	0.067 ± 0.001	0.109 ± 0.002
1-1.25	0.042 ± 0.001	0.082 ± 0.002
0.75-1	0.023 ± 0.001	0.048 ± 0.002

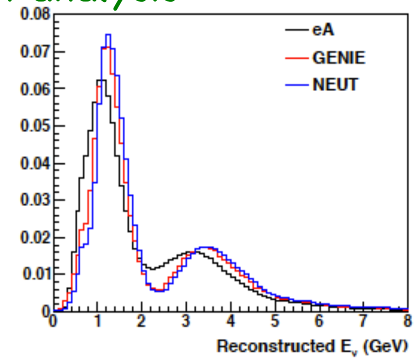
4 GeV

E_{Call}	^{12}C	^{56}Fe
3.5-4	0.129 ±0.005	0.141 ± 0.005
3-3.5	0.106 ±0.006	0.041 ± 0.007
2.5-3	0.057 ±0.007	0.104 ± 0.007
2-2.5	0.032 ±0.007	0.077 ± 0.009
1.5-2	0.022 ±0.007	0.05 ±0.01

Summary

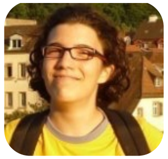
1. The first use of electron data to test neutrino energy reconstruction algorithms
   - select zero-pion events to enhance quasi-elastic signal
     - Subtract for undetected few protons
     - Subtract for undetected 1 pion events
   - just using scattered lepton (E_{QE})
     - used in Cherenkov-type neutrino detectors
   - total energy of electron plus proton (E_{Cal})
     - used in calorimetric neutrino detectors
2. Only 0.1-0.56 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 presented by L. Weinstein (previous talk).
4. Comparison to models to be presented by Afroditi (next talk).
5. Work to be done before submitting the analysis note
   - Need to subtract for undetected few pion events
   - Finalize error calculations
6. Work in progress
   - extend analysis to other types of events
   - more targets and energies
   - Proposal "Electrons for Neutrinos" conditionally approve by PAC 45.





Fractional Energy feed down spectra

Chris Marshal
(LBL)



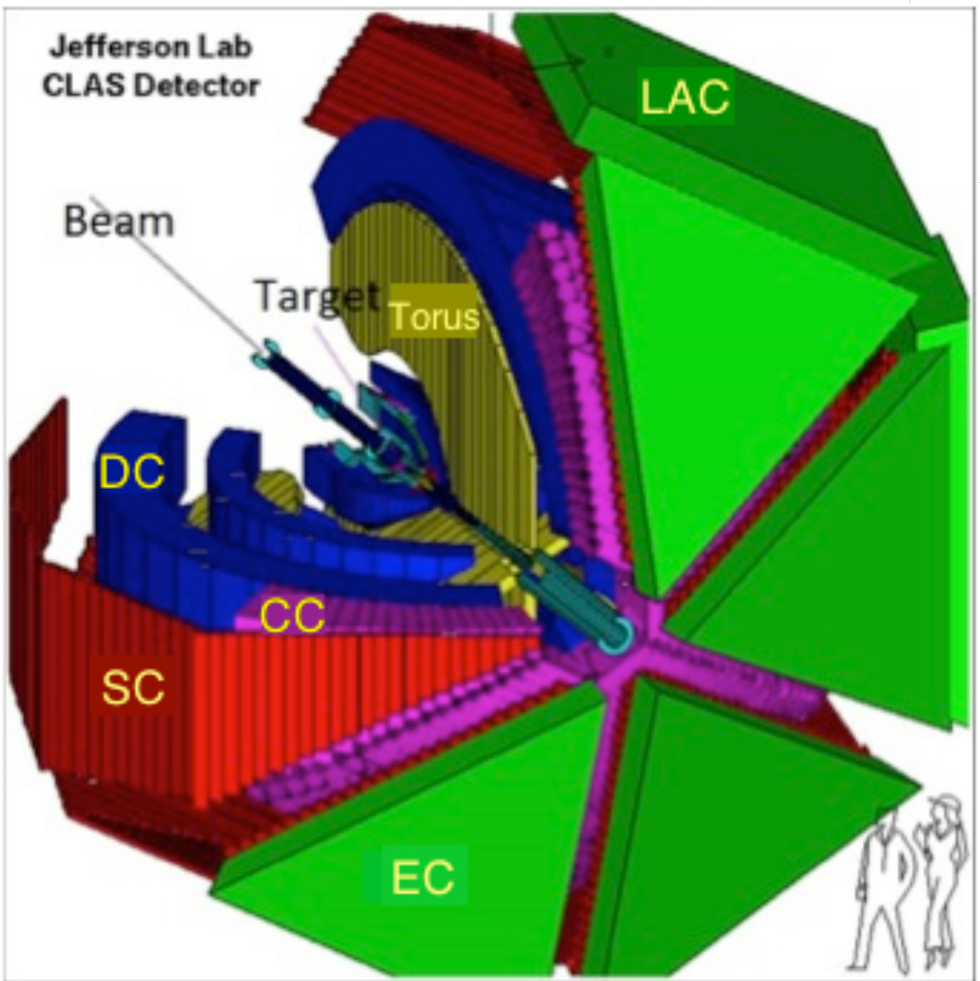
Afroditi
Papadopoulou
(MIT@FNAL)

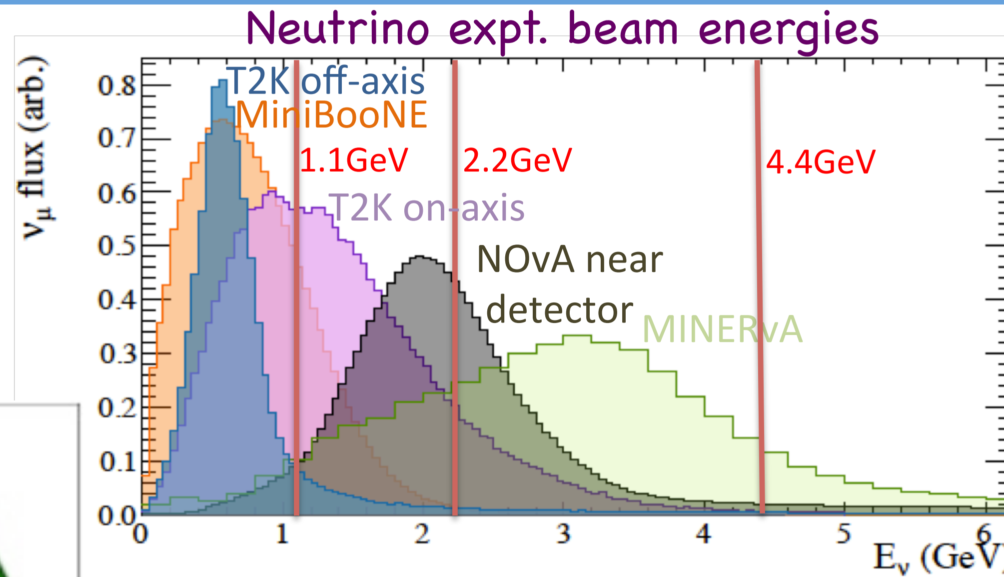
Adi Ashkenazi
(MIT@FNAL)

CLAS detector

^3He , ^4He, ^{12}C, ^{56}Fe 4.461,
2.261 GeV e2a experiment data
Other data available ^3He, ^4He, C, Fe 1.1 GeV

3D view



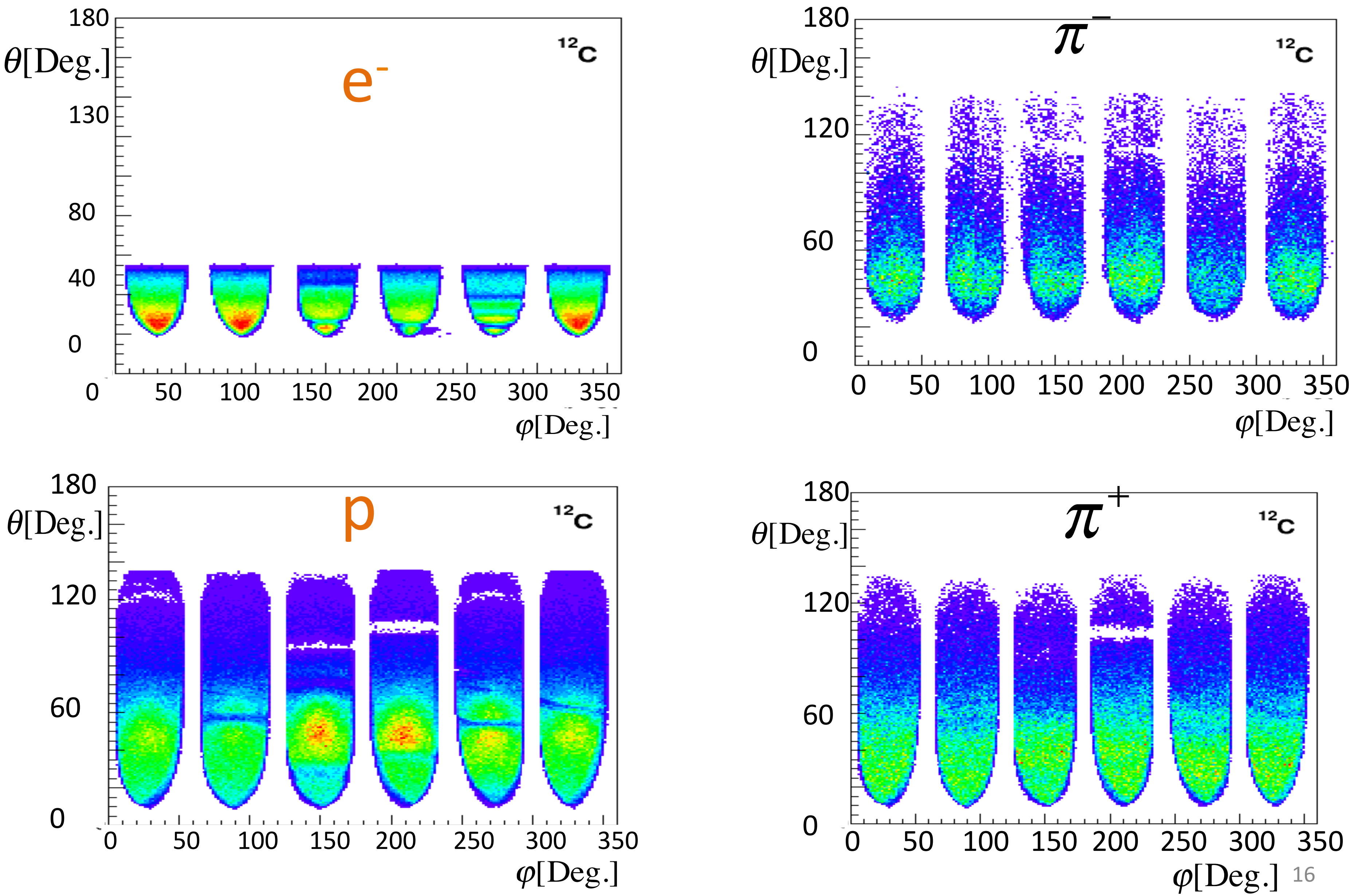


E2a target properties

Target	Length [cm]	Density [g/cm³]	Length*density [g/cm²]
^3He	4.13	0.067	0.277
^4He	3.72- 4.99	0.125	0.624
^{12}C	0.1	1.786	0.179
^{56}Fe	0.015	7.872	0.118
CH_2	0.07 (2*0.035)	1.392	0.097

θ and φ distributions

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



Fraction of events reconstructed in different energy bins with $p_\perp > 0.2$ GeV

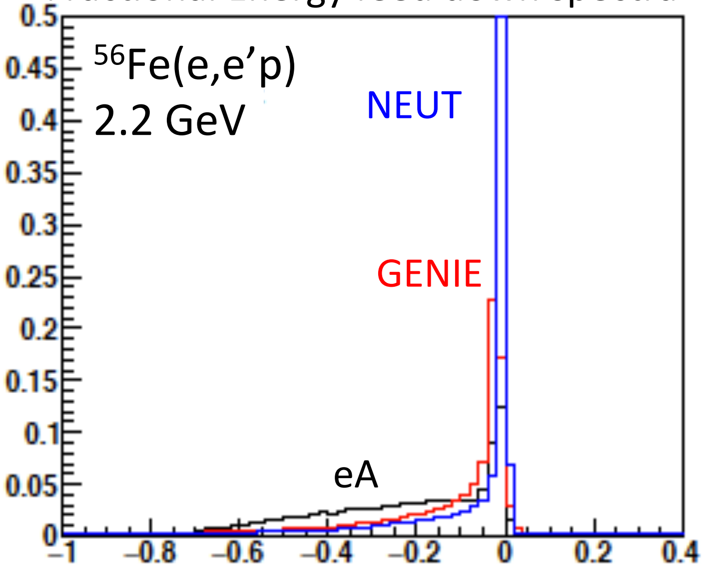
2 GeV

E_{Cal}	^{12}C	^{56}Fe
1.75-2	0.117 ± 0.001	0.136 ± 0.001
1.5-1.75	0.096 ± 0.001	0.127 ± 0.001
1.25-1.5	0.067 ± 0.001	0.109 ± 0.002
1-1.25	0.042 ± 0.001	0.082 ± 0.002
0.75-1	0.023 ± 0.001	0.048 ± 0.002

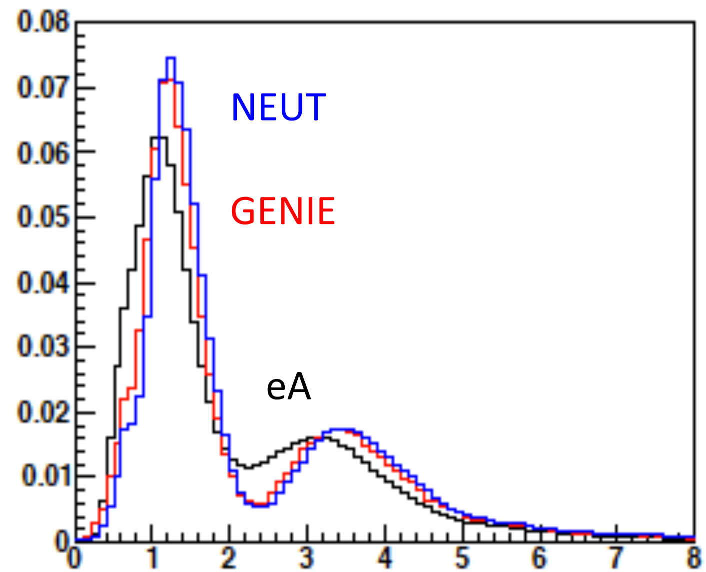
4 GeV

E_{Call}	^{12}C	^{56}Fe
3.5-4	0.129 ± 0.005	0.141 ± 0.005
3-3.5	0.106 ± 0.006	0.041 ± 0.007
2.5-3	0.057 ± 0.007	0.104 ± 0.007
2-2.5	0.032 ± 0.007	0.077 ± 0.009
1.5-2	0.022 ± 0.007	0.05 ± 0.01

Fractional Energy feed down spectra



2.26 GeV E_{rec} fractional error



Reconstructed E_ν [GeV]

-> Very different oscillation parameters!

- 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

Error sources

- ✧ Statistical error due to the amount of the analyzed data
- ✧ Systematic error due to imperfect geometrical acceptance (to be studdied)
- ✧ Errors of the weights for subtraction of undetected pions and protons

-Statistical error due to the number of rotations is kept less than 1% with sufficient number of rotation (is not included in error calculation)
-Systematic error due to the dependence of the cross section on the angle between $(\vec{p}_e, \vec{p}_{e'})$ and $(\vec{q}, \vec{p}_\pi)$ or $(\vec{q}, \vec{p}_{\text{prot}})$ planes (is small and is being studded)