# Update: Validation of neutrino energy estimation using electron scattering data

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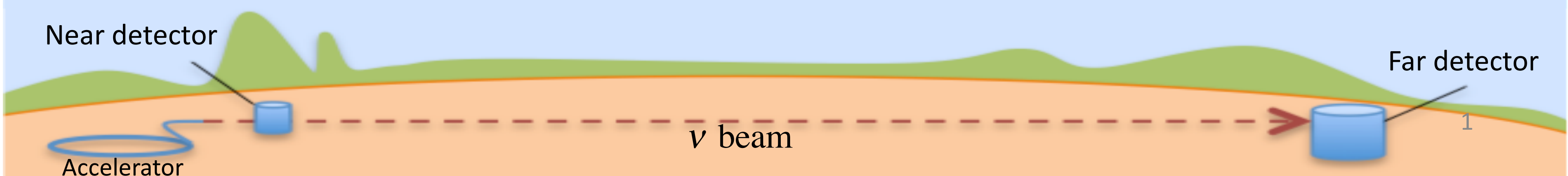


# Outline

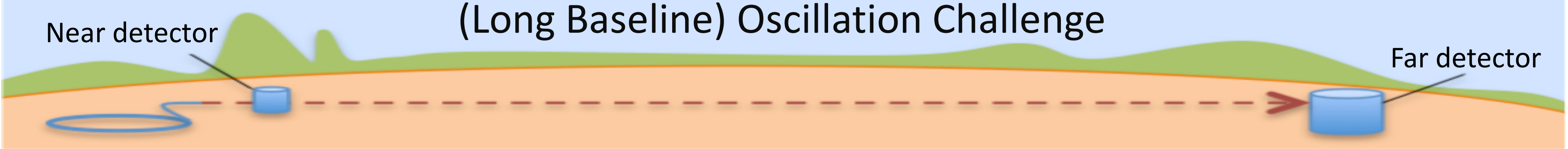
1. Introduction.
2. June 2019 status:

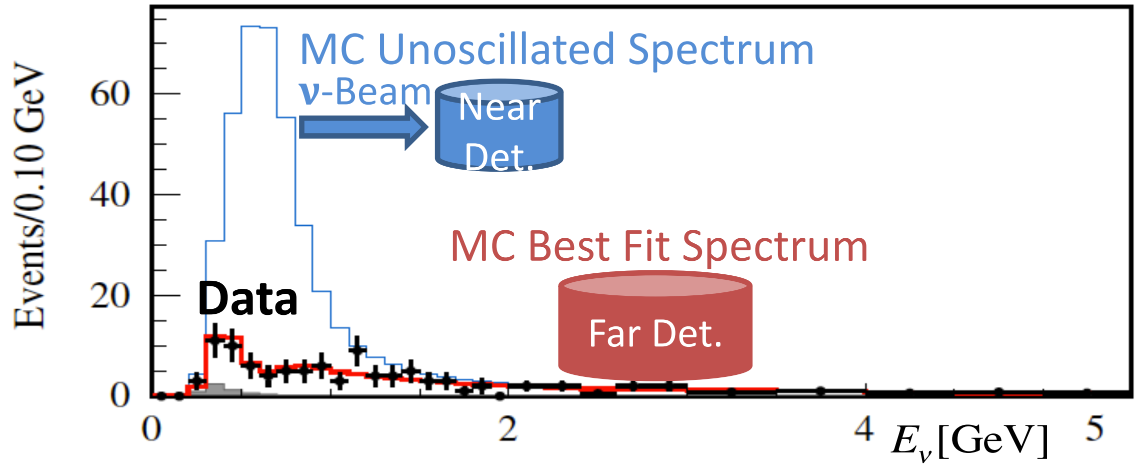
   - Looked at (e,e’), (e,e’p) events with zero detected pions and photons.
   - Reconstructed energies $E_{Cal}$, $E_{QE.}$
   - Completed subtraction for undetected $\pi^+, \pi^-, \gamma$ and extra p.
   - Modified $e^-$ momentum correction.
   - Analyzed the 1.1 GeV e2a data.
   - Determined binding energy values for $E_{Rec}$ calculations.
   - Analysis review ongoing.

3. Status today:

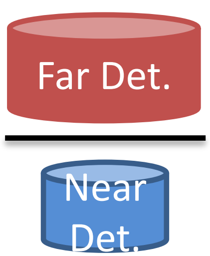
   - Obtained final results on energy reconstruction.
   - Completed estimation of uncertainties from different sources.
   - Compared to $\nu$ event generator results running in $e^-$ mode.
   - Show potential impact on DUNE oscillation analysis.
   - Completed analysis review.

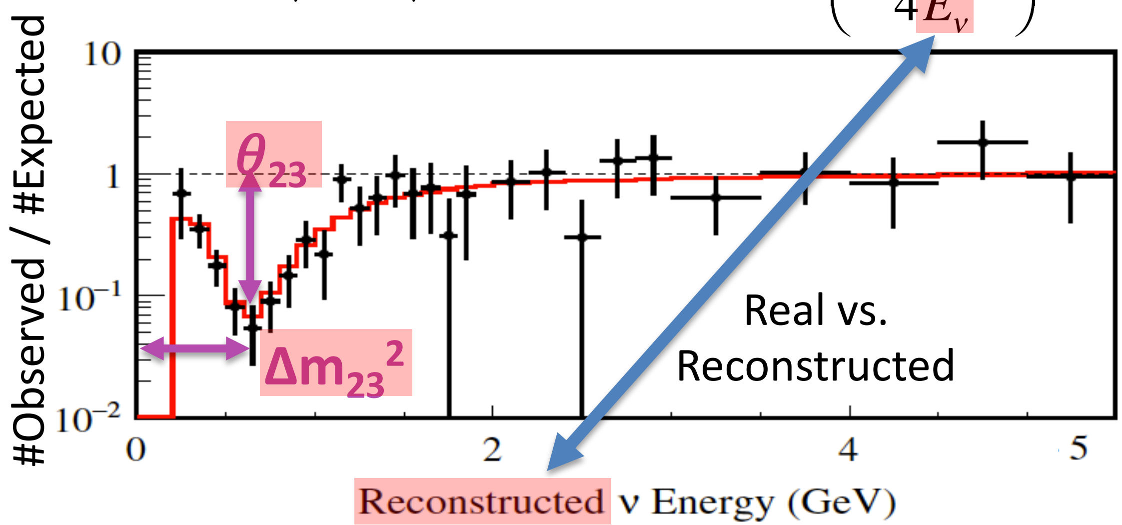
# (Long Baseline) Oscillation Challenge




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




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

# Energy Reconstruction for QE reactions

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

**(2) Tracking detectors:**
- Detect: Charged particles + $\pi^0$
- Miss: Neutrons and charged particles below threshold

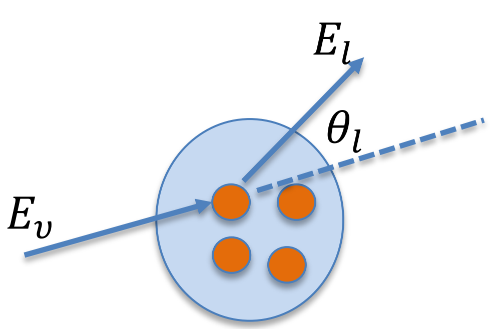
Use lepton kinematics assuming QE interaction

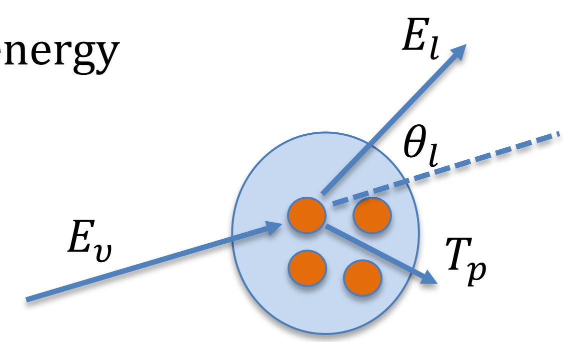
$$E_{QE} = \frac{2M\varepsilon + 2ME_l - m_l^2}{2\left(M - E_l + |k_l| cos(\theta_l)\right)}$$

Use final-state calorimetry assuming low residual excitations

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

$$\varepsilon = E_{\text{bind}} = \text{Binding energy}$$



# Targets and beam energies

## Targets in E2a:

- $^{3}He$
- $^{4}He$
- $^{12}C$
- $^{56}Fe$

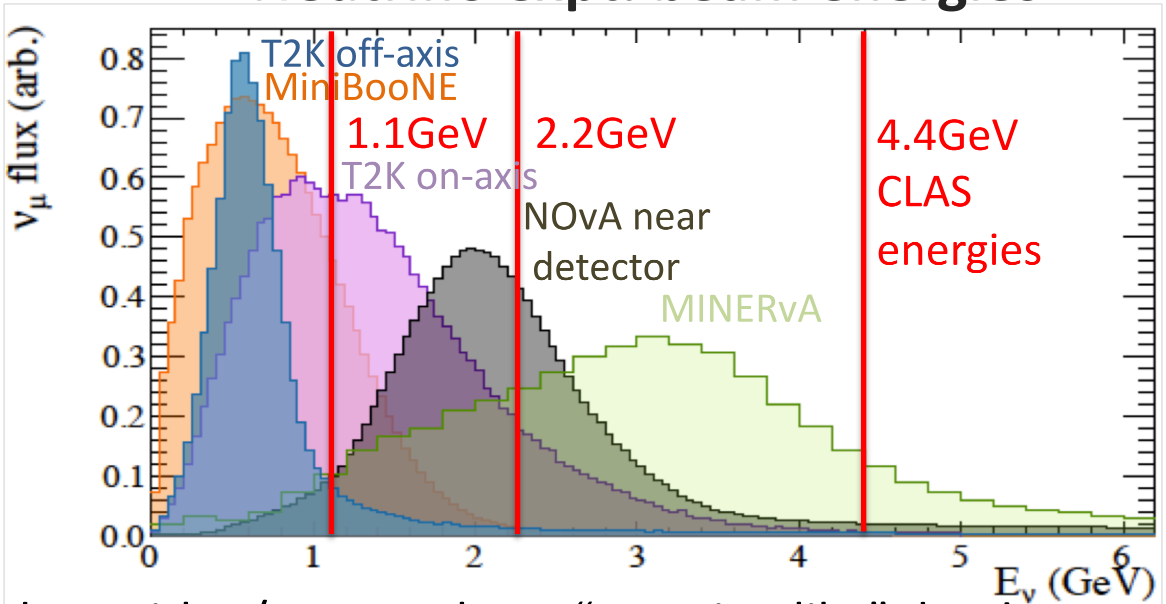
## Targets in neutrino experiments:

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

## Beam energies E2a:

- 1.161 GeV
- 2.261 GeV
- 4.461 GeV

## Neutrino expt. beam energies

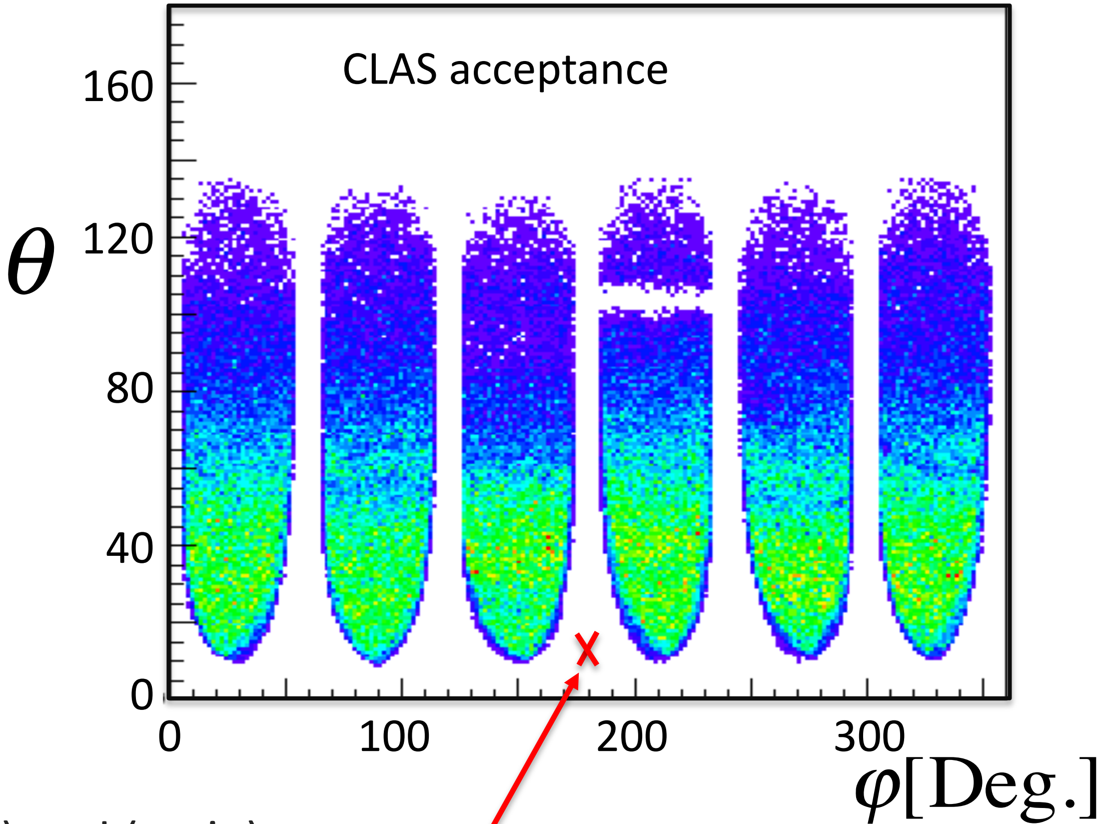



Scale the electron scattering data with $1/\sigma_{\text{Mott}}$ to have "neutrino like" data!

# Background Subtraction

As close to QE as one can get:

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




Want $0\pi$ (e,e') and (e,e'p) events.

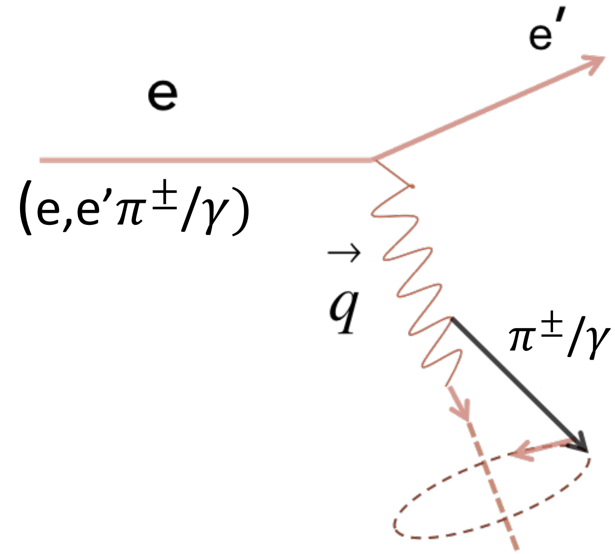
Need to account for undetected $\pi, \gamma$ and extra protons.

# Background Subtraction in (e,e') analysis

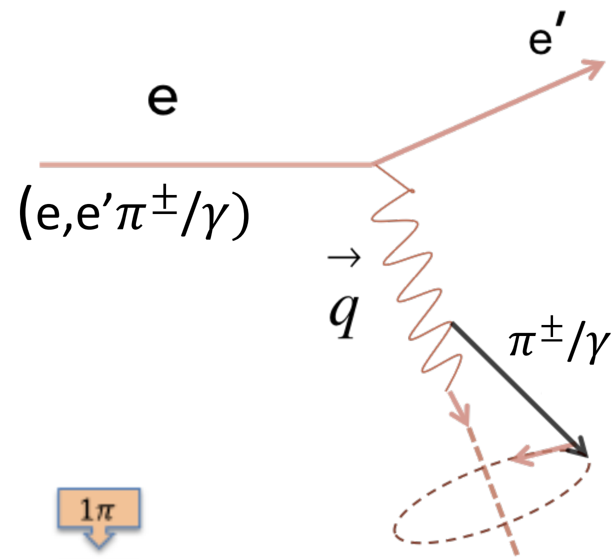
Subtract for undetected $\pi^{\pm}$ and $\gamma$:

Data Driven Correction (example $1\pi$):

1. Use measured (e,e'$\pi$) events,
2. Rotate $\pi$ around $\vec{q}$ to determine its acceptance A,
3. Determine (e,e')$\pi$ contributions using A,
4. Subtract (e,e')$\pi$ contributions,

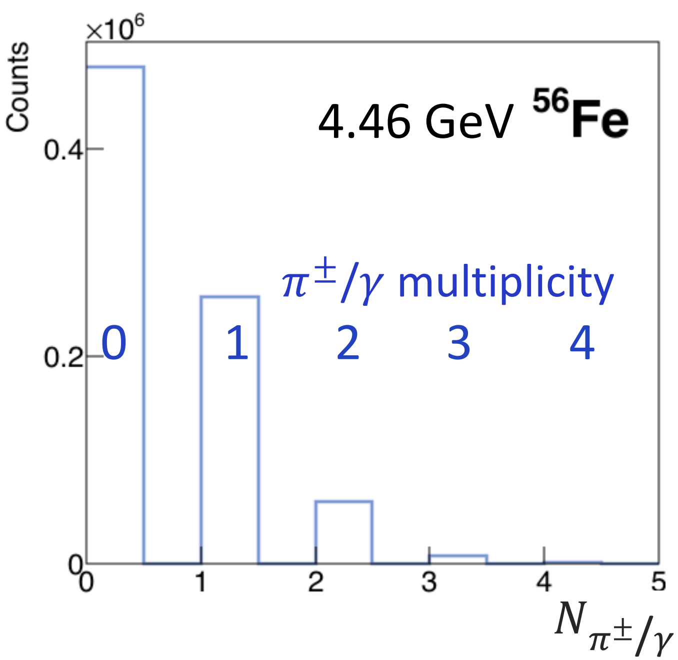


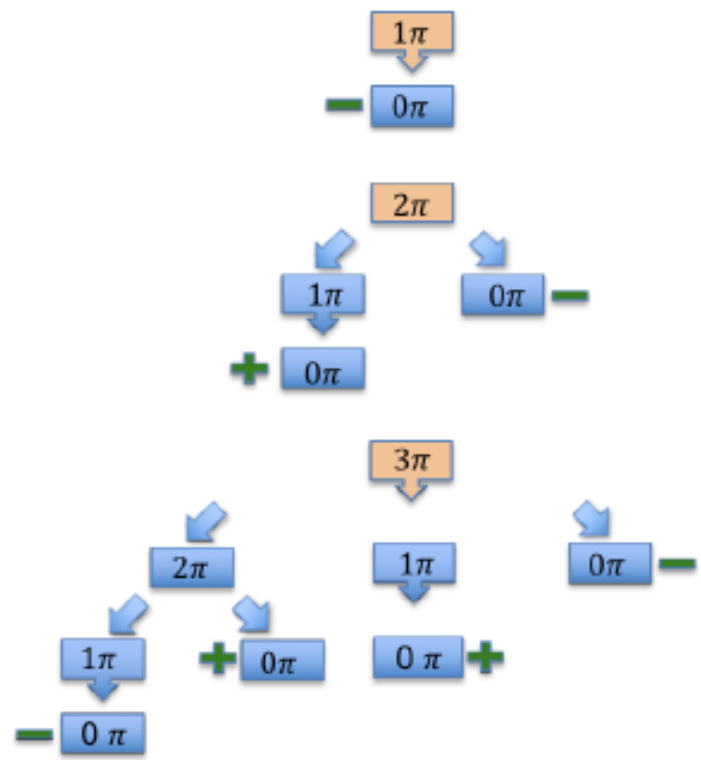
Subtract for undetected $\pi^{\pm}$ and $\gamma$:




Data Driven Correction (example $1\pi$):

1. Use measured (e,e'$\pi$) events,
2. Rotate $\pi$ around $\vec{q}$ to determine its acceptance A,
3. Determine (e,e')$\pi$ contributions using A,
4. Subtract (e,e')$\pi$ contributions,
5. Repeat for $2\pi$, $3\pi$, $4\pi$.

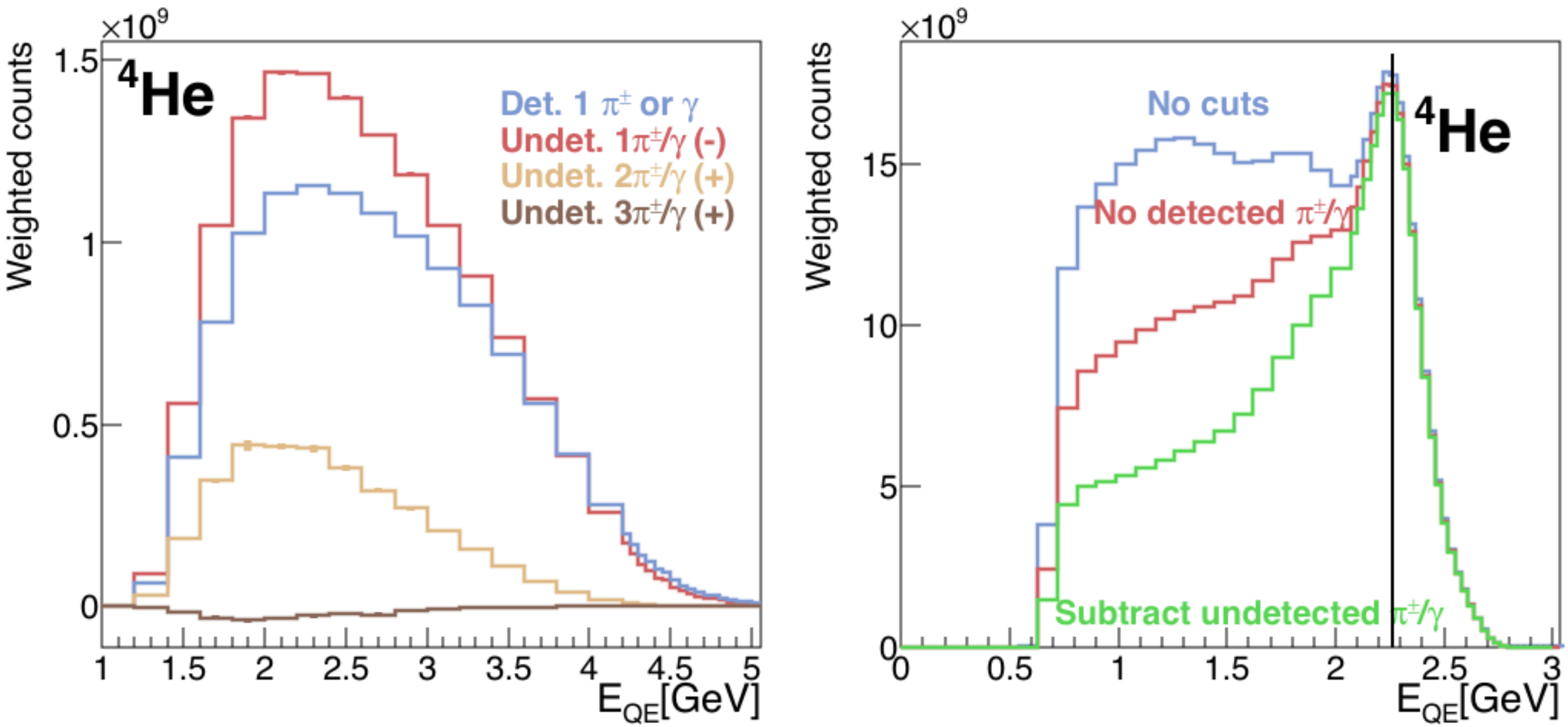


# (e,e') $\pi^{\pm}/\gamma$ subtraction

2.26 GeV

$\pi^{\pm}/\gamma$ subtraction

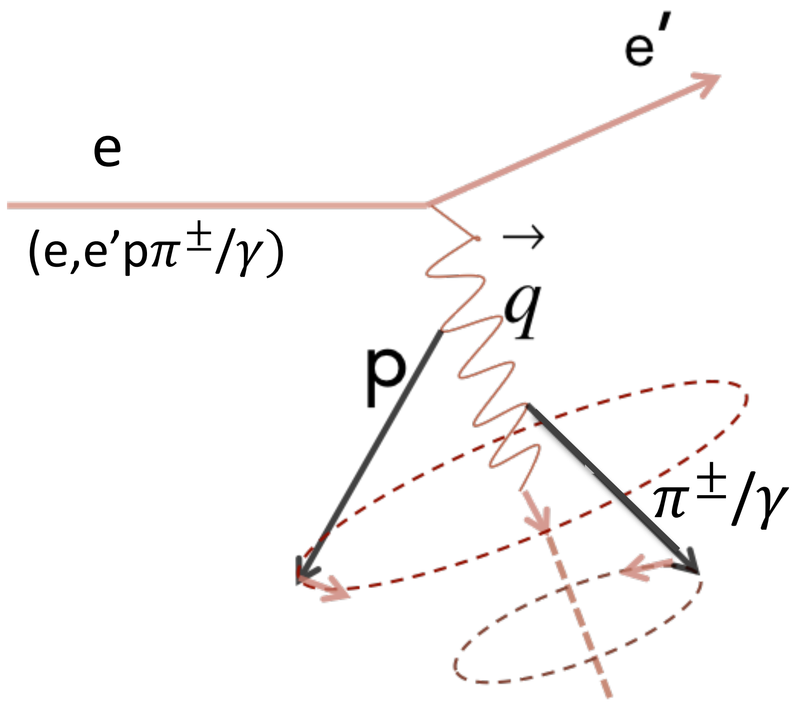



$\pi$ detected in TOF+DC

$\gamma$ detected in EC

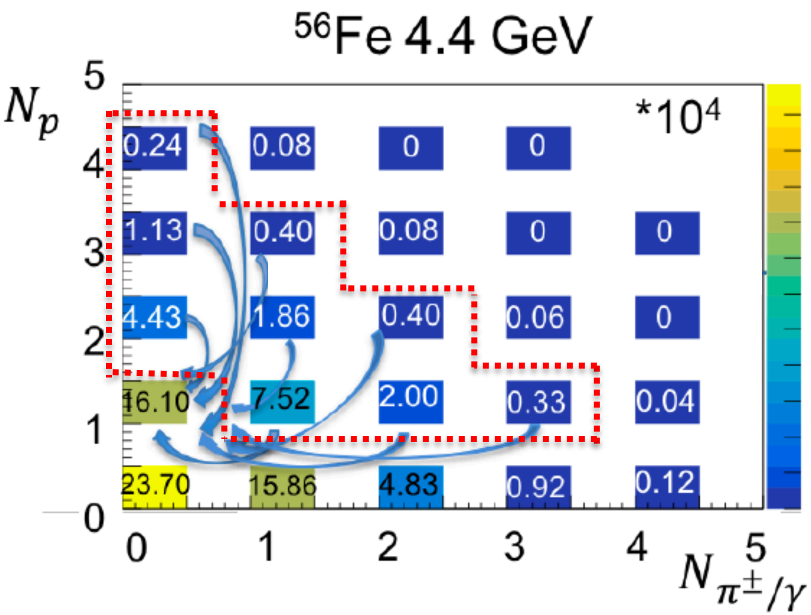
# Background Subtraction in (e,e'p) analysis

Want A(e,e'p) events.
Subtract for undetected $\pi$, $\gamma$ and multiple p.

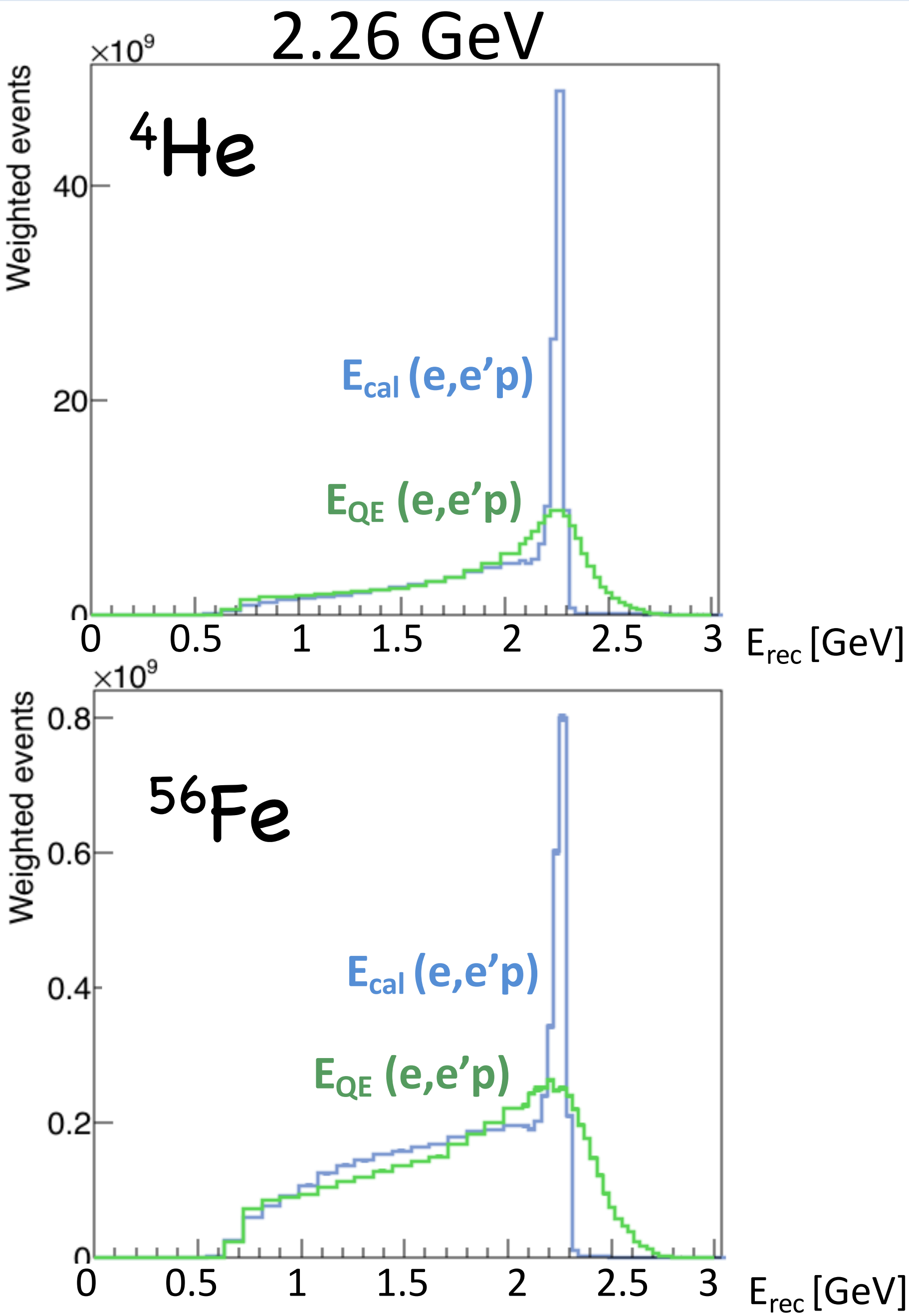



Data Driven Correction (example *1p+1π*):

1. Use measured (e,e'p$\pi$) events,
2. Rotate $\pi$ and p around $\vec{q}$ to determine their acceptance A,
3. Determine (e,e'p)$\pi$ contributions using A,
4. Subtract (e,e'p)$\pi$ contributions,
5. Do the same for 2p, 3p, 2p+ $\pi$ etc



# Energy reconstruction: A dependence




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

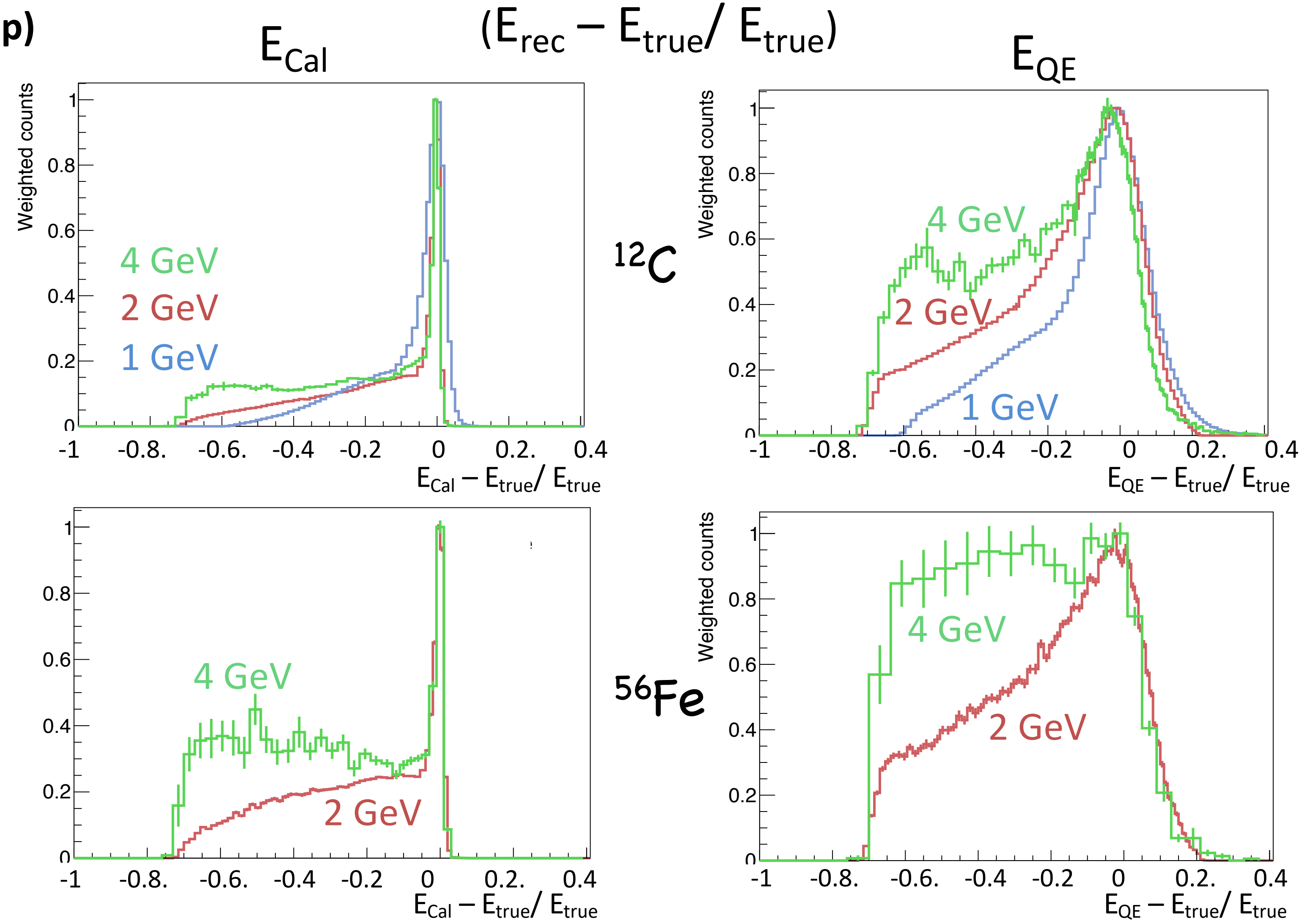
$$E_{Cal} = E_l + T_p + \varepsilon$$

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

# Energy reconstruction: E Dependence
# Fractional energy feed down

**(e,e'p)**

$(E_{rec} - E_{true}/E_{true})$

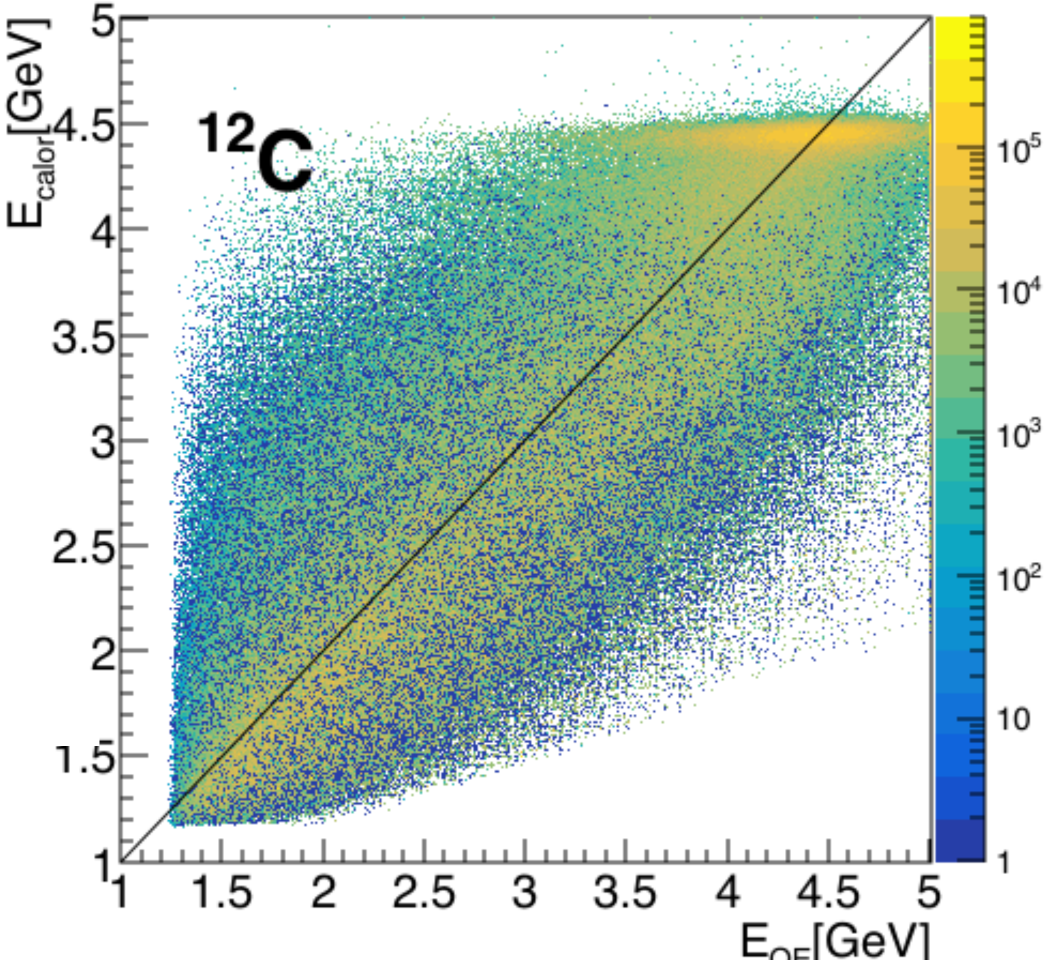



Better reconstruction at lower energies.

# Energy reconstruction: method dependence

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

4.46 GeV



# Reconstruction accuracy

| | 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 | 47 | 72 | 32 | 54 | **25** | **44** |
| $^{4}$He | | | 24 | 47 | **18** | **36** |
| $^{12}$C | 33 | 55 | 20 | 39 | **21** | **28** |
| $^{56}$Fe | | | 16 | 26 | **16** | **16** |

% of events reconstructed to within 5% of $E_{beam}$

$E_{rec}$ conclusions:

1) $E_{cal}$ better than $E_{QE}$

# Reconstruction accuracy

| | 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 | 47 | 72 | 32 | 54 | 25 | 44 |
| $^4$He | | | 24 | 47 | 18 | 36 |
| **$^{12}$C** | **33** | **55** | **20** | **39** | **21** | **28** |
| $^{56}$Fe | | | 16 | 26 | 16 | 16 |

% of events reconstructed to within 5% of $E_{beam}$

$E_{rec}$ conclusions:

1) $E_{cal}$ better than $E_{QE}$
2) Degrades with E

# Reconstruction accuracy

| | 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 | 47 | 72 | 32 | 54 | 25 | **44** |
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% of events reconstructed to within 5% of $E_{beam}$

$E_{rec}$ conclusions:

1) $E_{cal}$ better than $E_{QE}$
2) Degrades with E
3) Degrades with A

# Reconstruction accuracy

| | 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 | 47 | 72 | 32 | 54 | 25 | 44 |
| $^{4}$He | | | 24 | 47 | 18 | 36 |
| $^{12}$C | **33** | **55** | **20** | **39** | **21** | **28** |
| $^{56}$Fe | | | **16** | **26** | **16** | **16** |

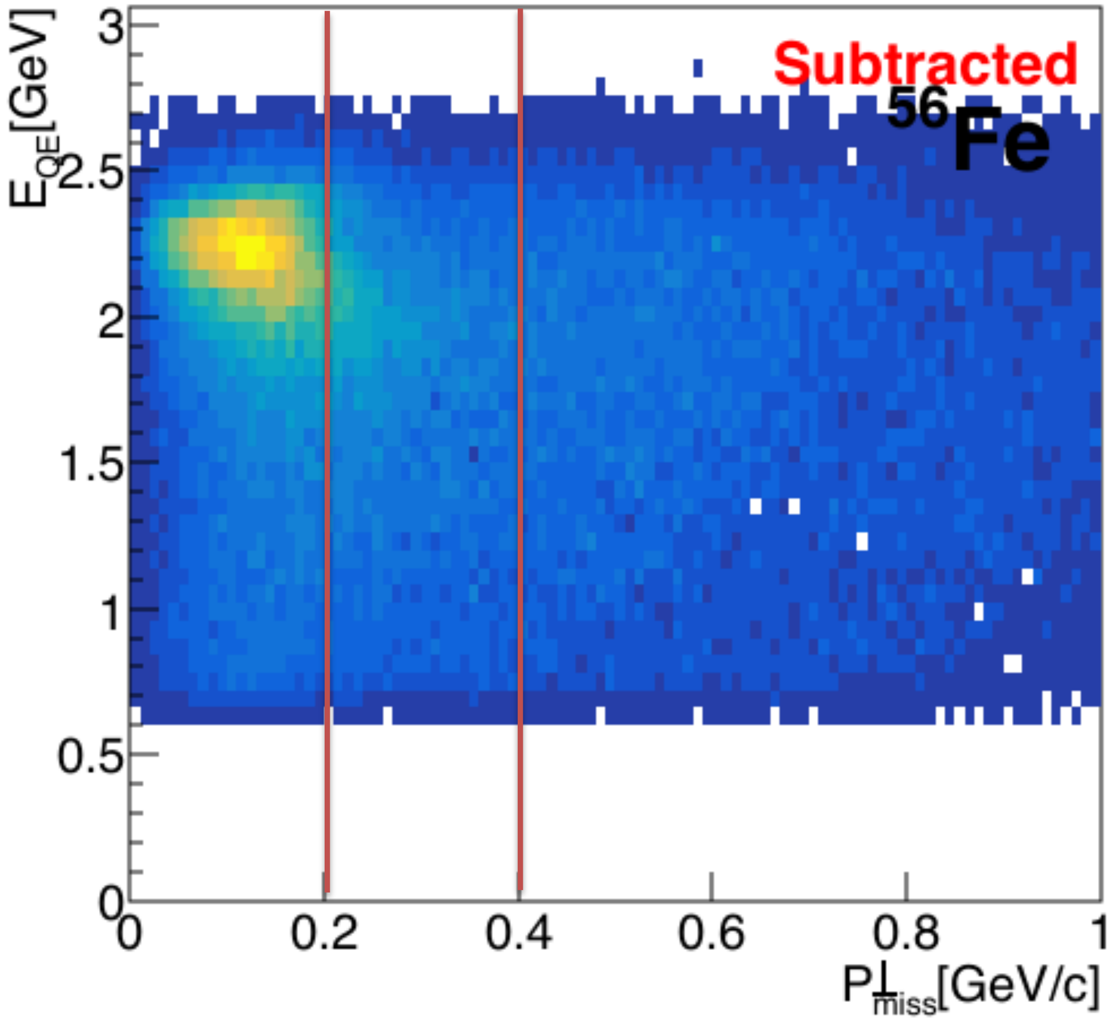
$E_{rec}$ conclusions:

1) $E_{cal}$ better than $E_{QE}$
2) Degrades with E
3) Degrades with A
4) Never very good

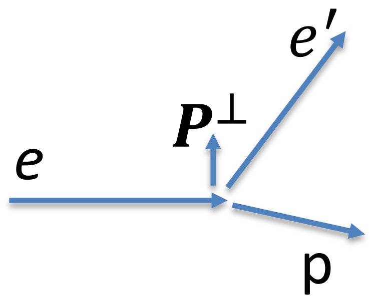
Only 16 to 55% of events reconstruct to within 5% of beam energy (for nuclei similar to those used in neutrino detectors).

# How do we do better?

2.2 GeV $^{56}$Fe

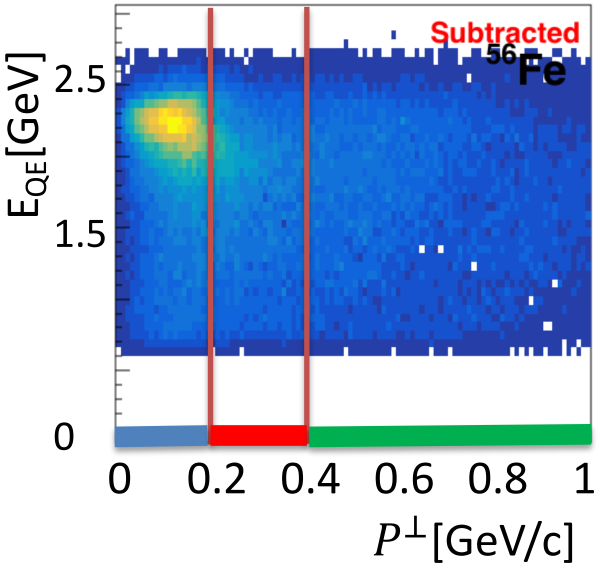


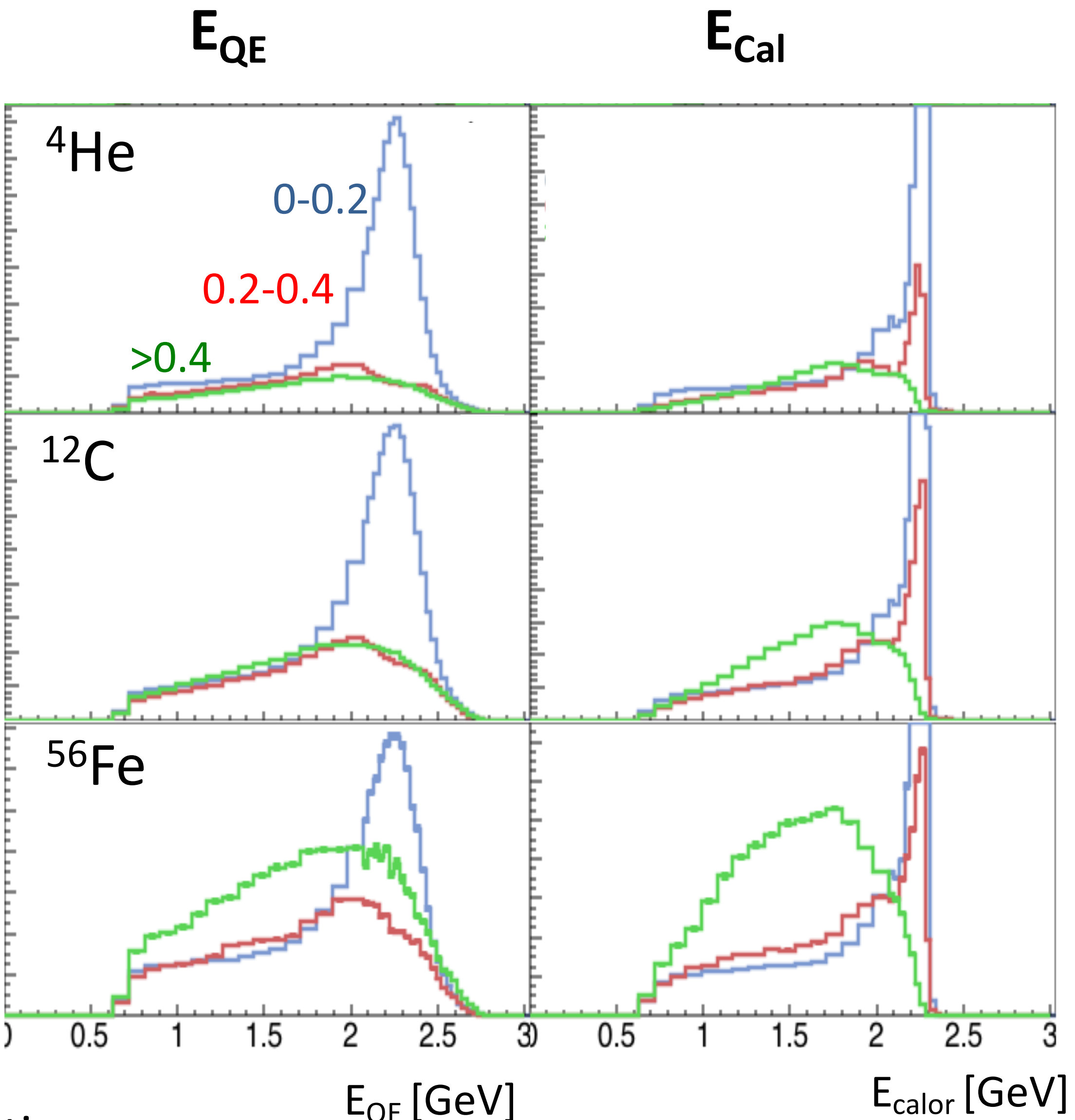

$$P^{\perp} = P^{\perp}_{e^-} + P^{\perp}_{p} = P^{\perp}_{\text{init}}$$



# $P_{\mathrm{miss}}^{\perp}$ slices

2.2 GeV




Large $P_{miss}^{\perp}$ → bad reconstruction.

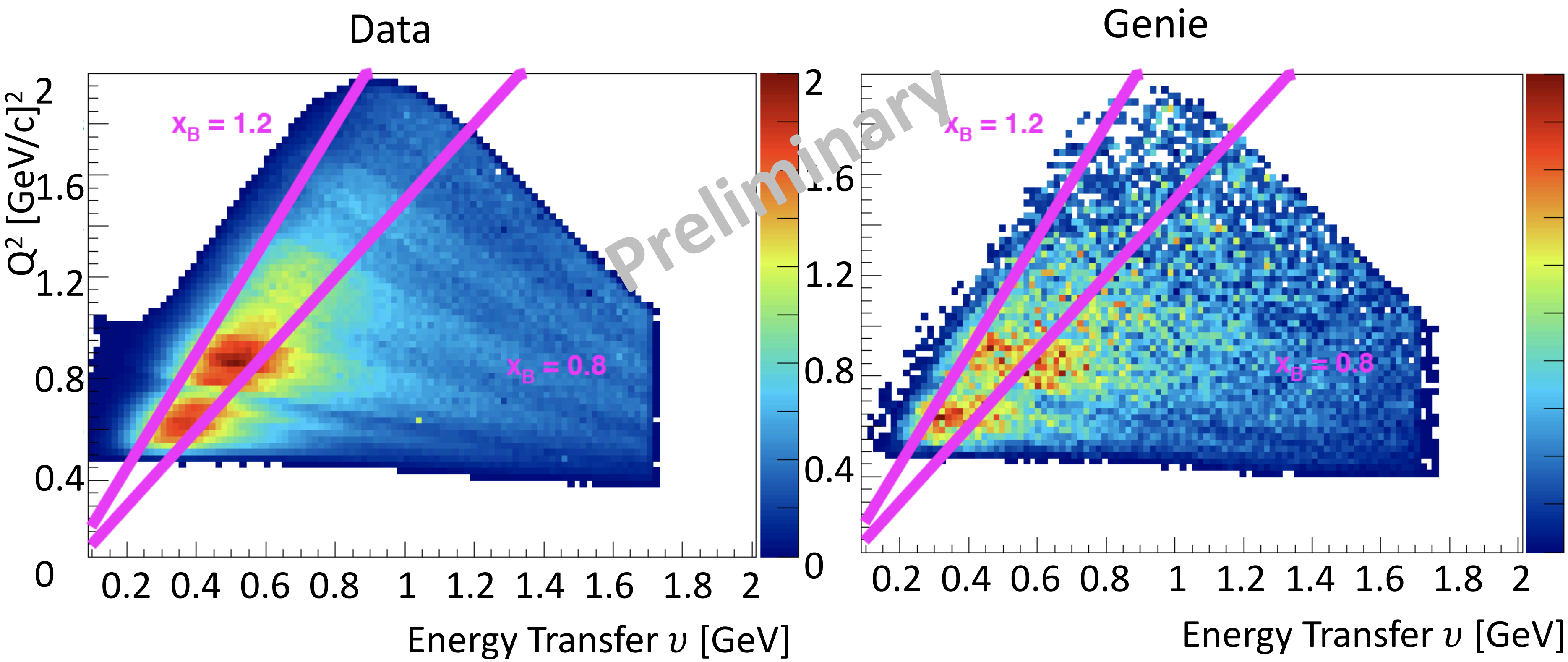
# Sources of uncertainty

- Statistical uncertainty is shown by error bars.
- Uncertainties of the weights for subtraction of undetected $\pi$ and protons.
  - ✧ Systematic uncertainty due to the $\phi$-dependence of the pion cross section modeled and found to be negligible (less than 1%).
  - ✧ Rotate (e,e'$\pi$) events enough times to reduce statistical uncertainty below 1%.
  - ✧ Systematic uncertainty due to imperfect description of the geometrical acceptance.
  - ✧ Systematic uncertainty due to $\gamma$ ID (missing $\gamma s$ and n contamination).

| E [GeV] | Uncertainty due to | | | |
|---|---|---|---|---|
| | $\varphi$ dep. | #(e,e'$\pi$) rot. | Imperf. accept. | $\gamma$ ID cut |
| 1.1 | 1% | 1% | 0.8% | 0.1% |
| 2.2 | 1% | 1% | 1.2% | 0.5% |
| 4.4 | 1% | 1% | 4% | 2% |

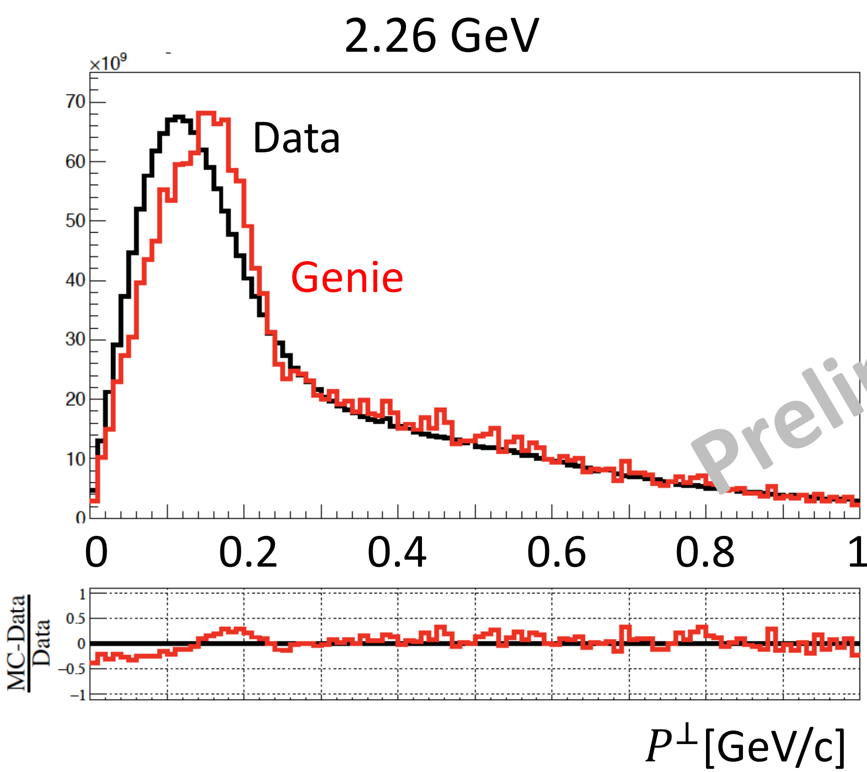
# $0\pi$ Data – Generator Comparisons

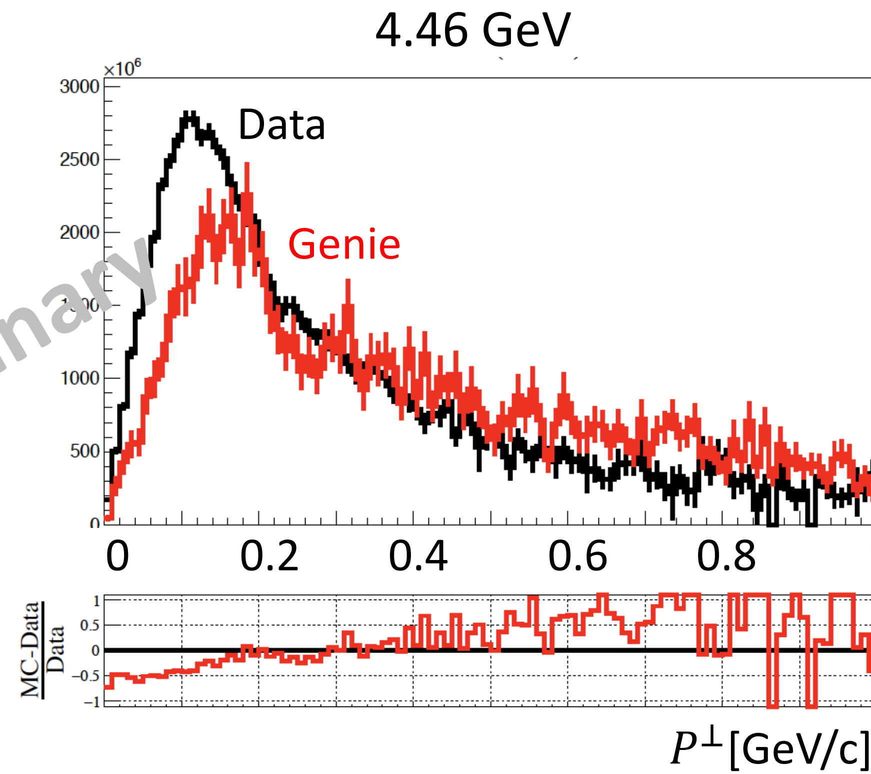
C(e,e’p) 2.26 GeV



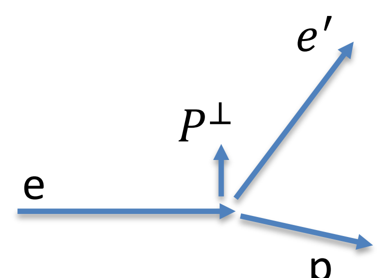
# $0\pi$ Data vs Genie

## C(e,e'p)

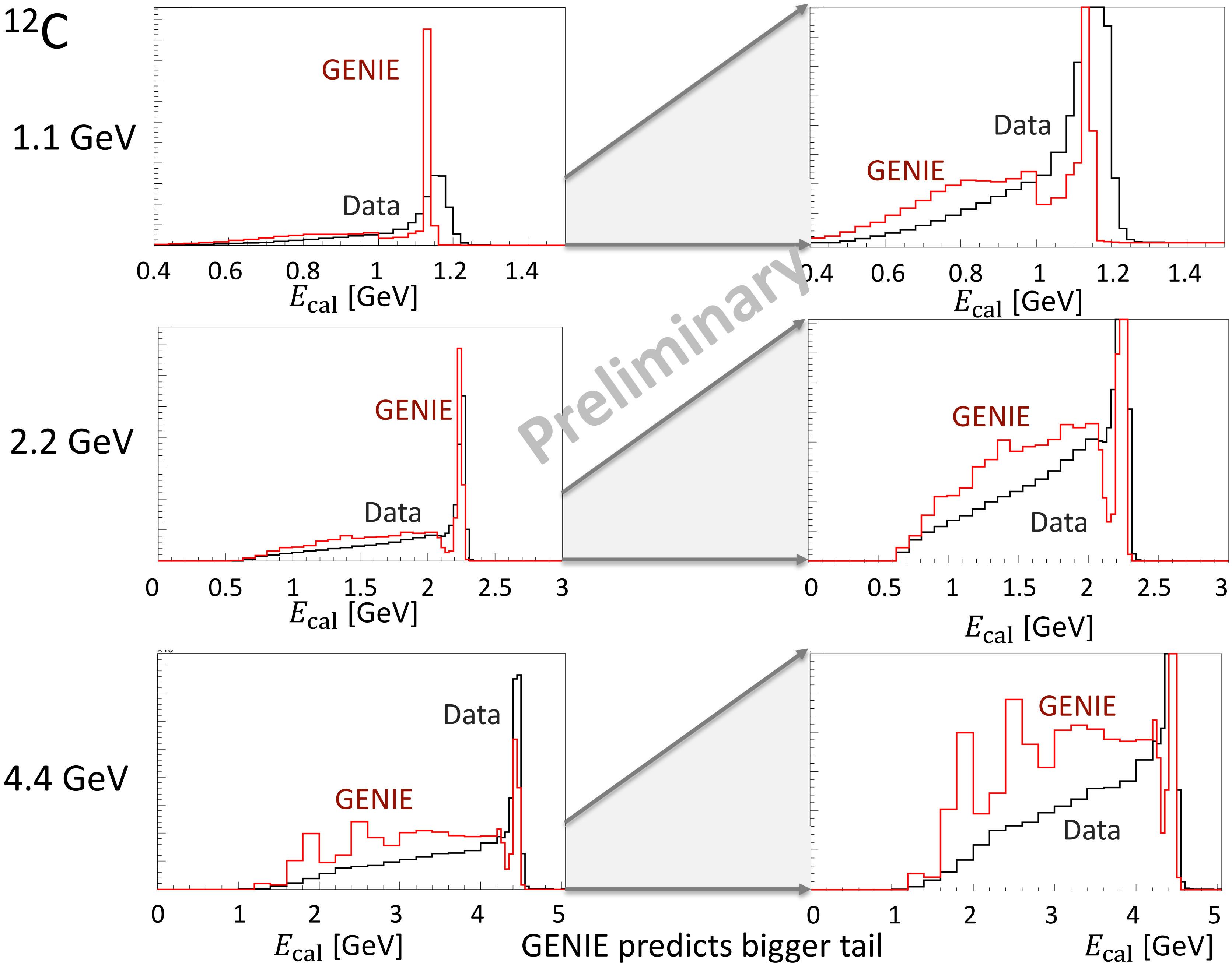



$$P^{\perp} = P_{e^-}^{\perp} + P_{p}^{\perp} = P_{\text{init}}^{\perp}$$

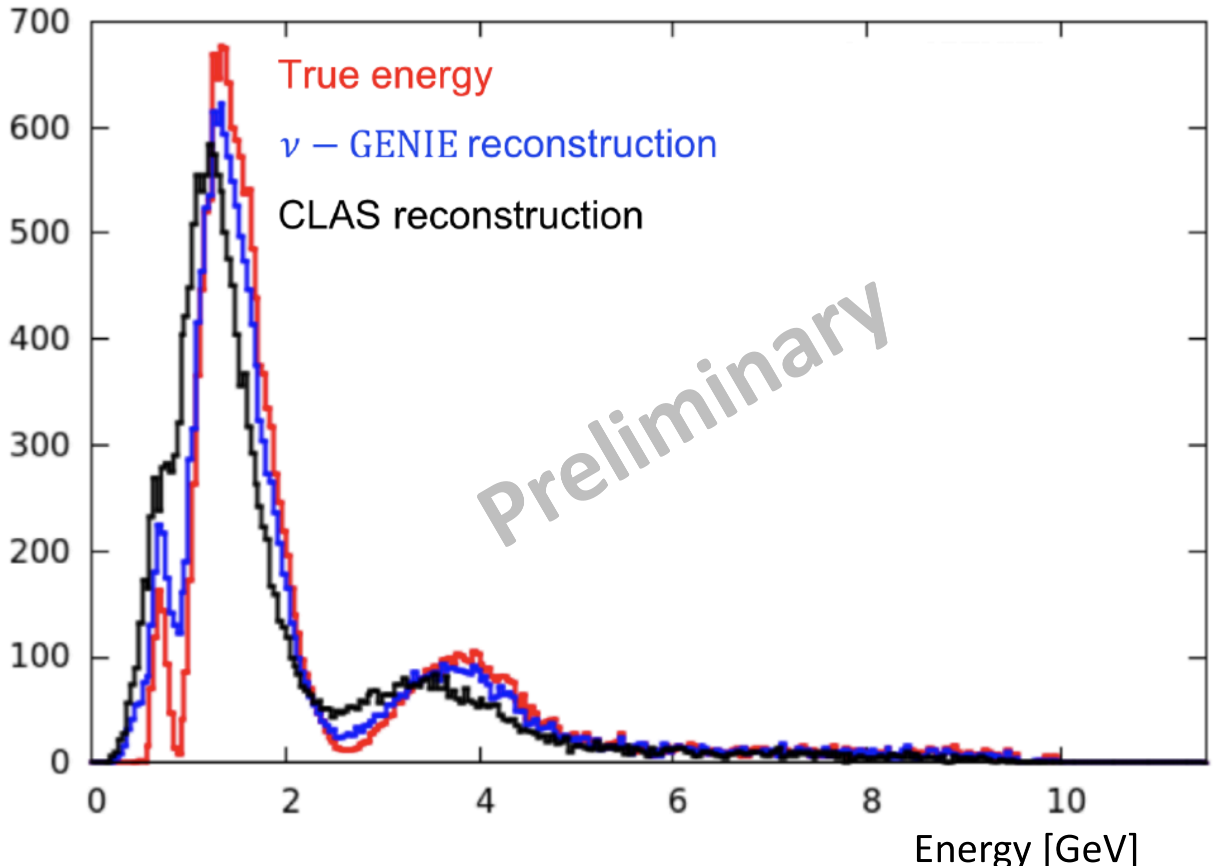


# Data vs Genie: $E_{beam}$ Reconstruction




GENIE predicts bigger tail

# Potential impact on DUNE oscillation analysis

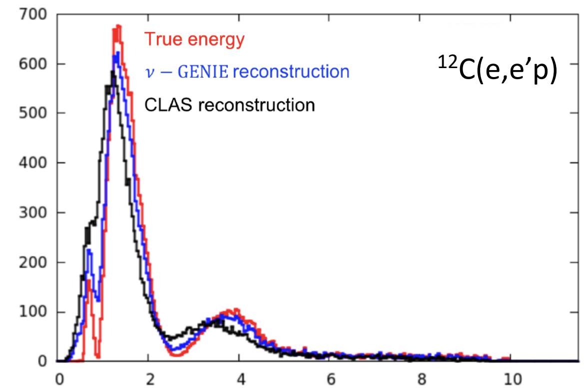


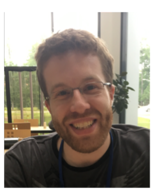

- Compare $E_{rec}$ for e$^{12}$C to $E_{rec}$ for $\upsilon^{12}$C
- Used 1.1, 2.2 and 4.4 GeV e$^{12}$C $E_{rec}$ and interpolated linearly between the energies to get $E_{rec}$ at all incident energies
- Threw events with $\nu^{12}$C Genie
- Reconstruct with $\nu^{12}$C Genie or e$^{12}$C data

-> Very different oscillation parameters!

# 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 $\pi$ 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 0.16-0.55 of events reconstruct to within 5% of the beam energy:
   - better for lighter nuclei and lower energies
   - improved by a transverse momentum cut
   - agreement between two methods does not imply accurate energy reconstruction.
3. There is a discrepancy between energy reconstruction from e-Genie and data.
4. Probable significant impact on oscillation analysis of proposed $1.5B DUNE experiment.
5. Inspired upcoming "Electrons for Neutrinos" experiment .
6. CLAS analysis review complete.
7. Paper submission soon.



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# Phi dependence

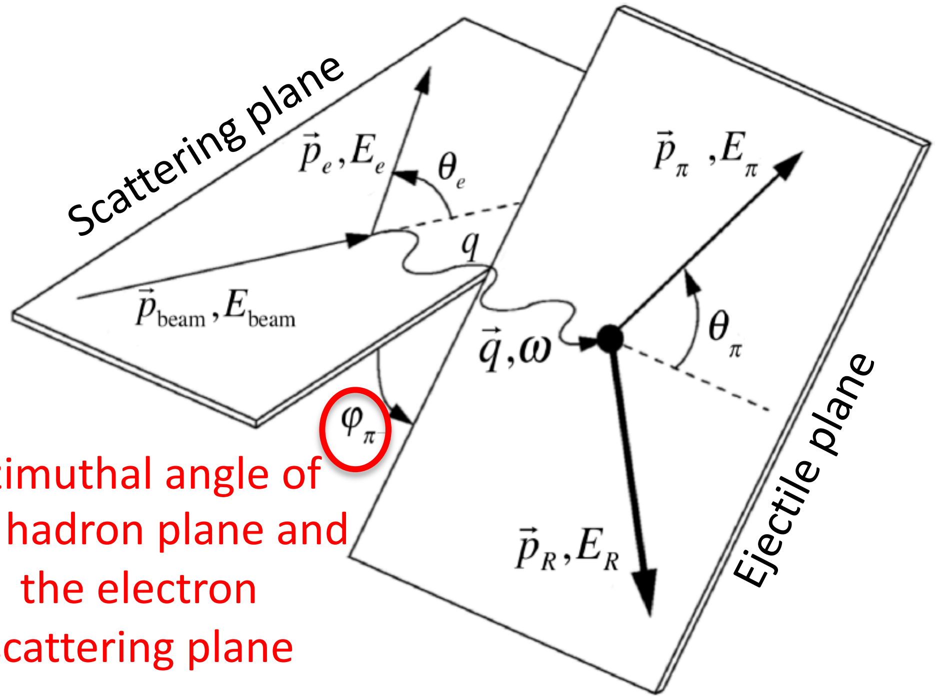
Cross section for unpolarized pion electroproduction on a single nucleon:

$$\frac{d^4\sigma}{dW dQ^2 d\Omega_\pi^*} = J\Gamma_\upsilon(A + B\cos\varphi_\pi + C\cos 2\varphi_\pi)$$

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

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

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




Azimuthal angle of the hadron plane and the electron scattering plane

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

Where $p_\pi^*, \theta_\pi$ and $\varphi_\pi$ are the momentum, scattering and azimuthal angles of the $\pi^0$ in the CM frame. Jacobian $J=\partial(Q^2, W)/\partial(E', cos\theta_e, \theta_e)$, $\Gamma_\upsilon$ is virtual photon flux.

N. Markov et al. arXiv:1907.11974

# Phi dependence

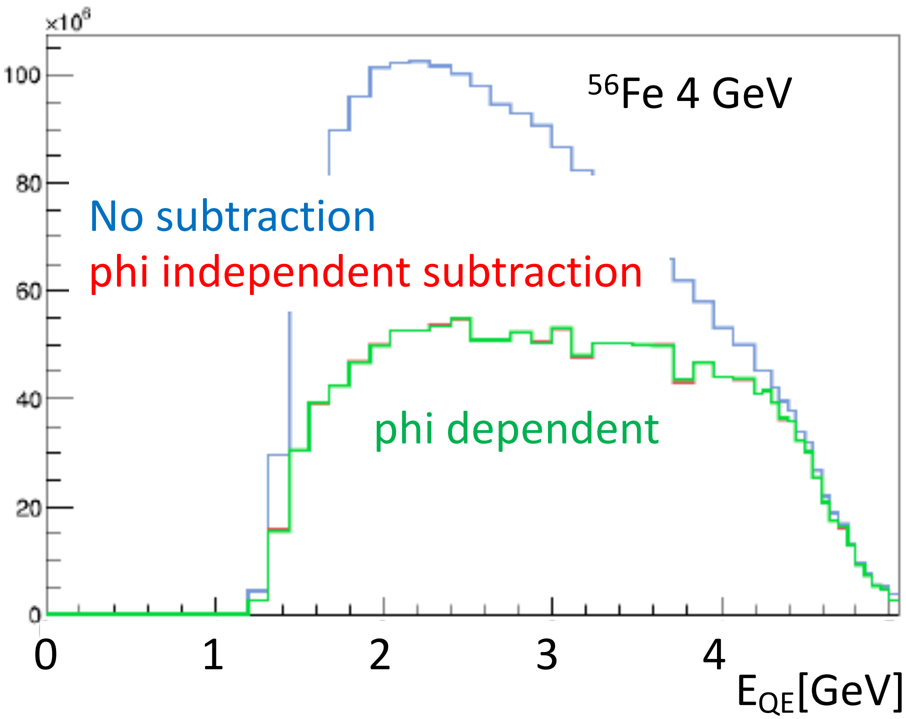
Weight without $\varphi_\pi$ dependence

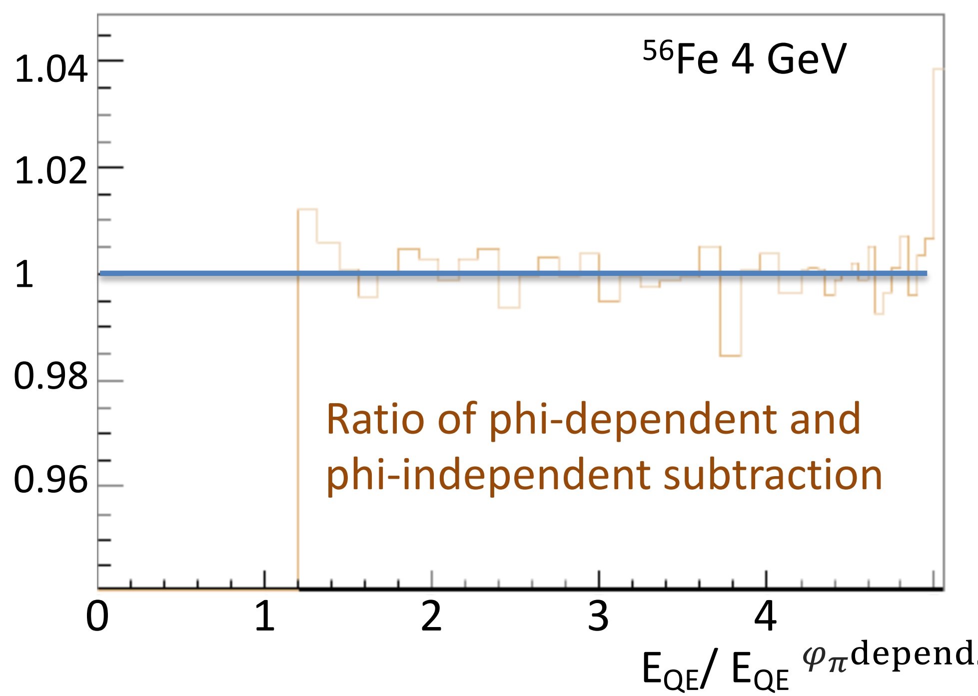
$$W = \frac{\sum_{i=1}^{N_{Undet}} 1}{\sum_{i=1}^{N_{Det}} 1}$$

Weight with $\varphi_\pi$ dependence

$$W = \frac{\sum_{i=1}^{N_{Undet}} 1 + \frac{B}{A} cos\varphi_\pi + \frac{C}{A} cos2\varphi_\pi}{\sum_{i=1}^{N_{Det}} 1 + \frac{B}{A} cos\varphi_\pi + \frac{C}{A} cos2\varphi_\pi}$$

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




Negligible phi dependence!