Validation of neutrino energy estimation using electron scattering data

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Outline

- The importance of energy reconstruction in neutrino oscillation experiments
- Neutrino-nucleon Charged Current interactions
- Testing neutrino beam energy reconstruction methods with electron scattering CLAS e2a experiment data

Long Baseline Oscillations

ν-Beam
- Low energy: reactors
- High energy: accelerators

→ mixed beams of all energies

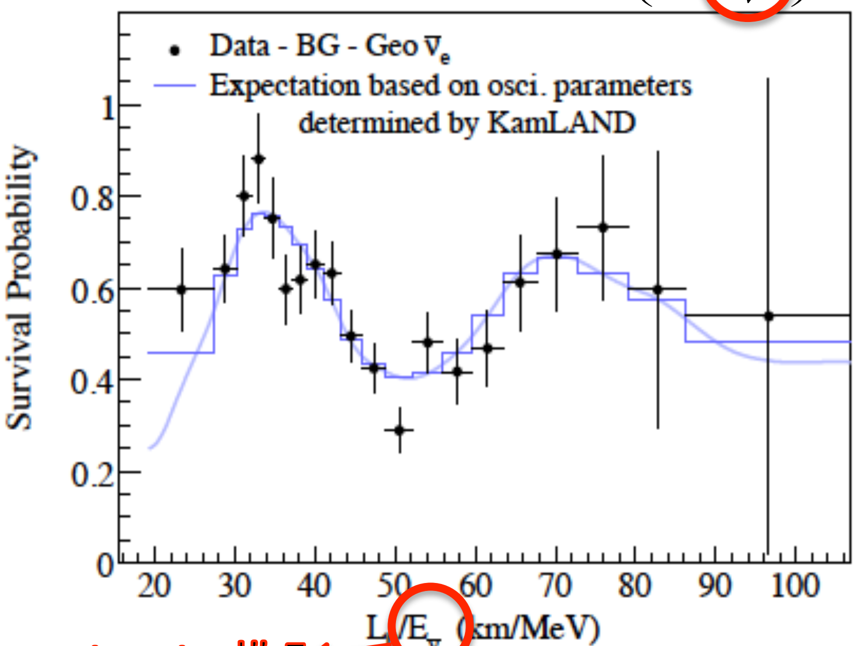
Types

1.Appearance experiments: Use neutrino beam of type A and search for neutrinos of type B after distance L

2.Disappearance experiments: Compare the fluxes of neutrinos of given type before and after oscillations

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

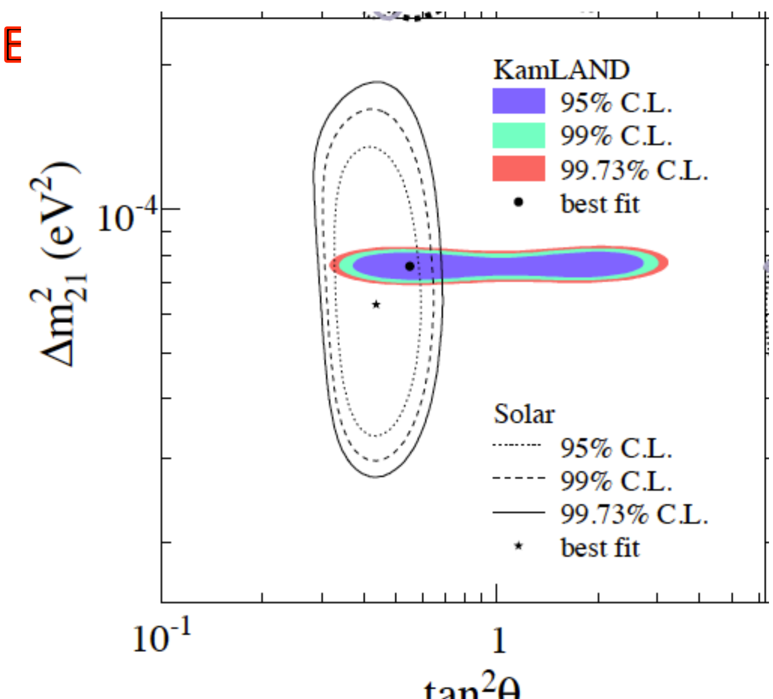
→ Real E



"Reconstructed" E

KamLAND, PRL 100, 221803 (2008)

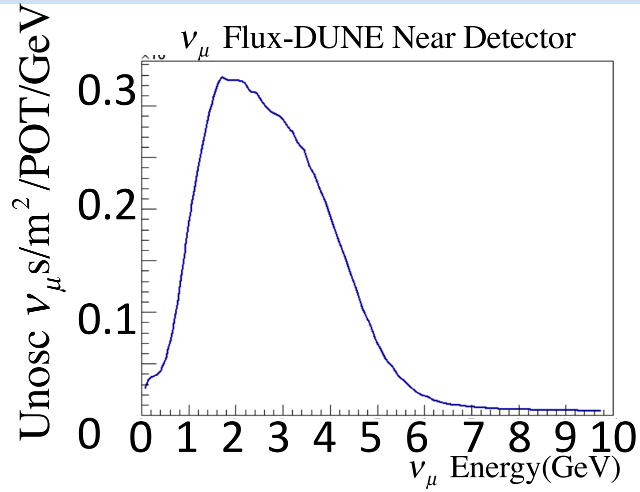
(Reactor beam)

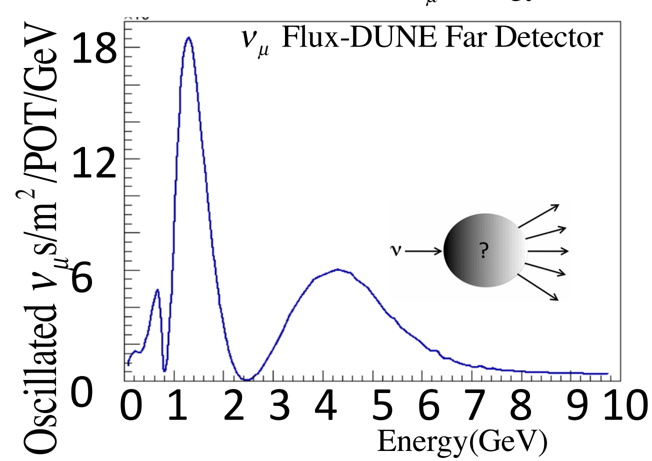


Allowed region for neutrino oscillation parameters from KamLAND and solar neutrino experiments

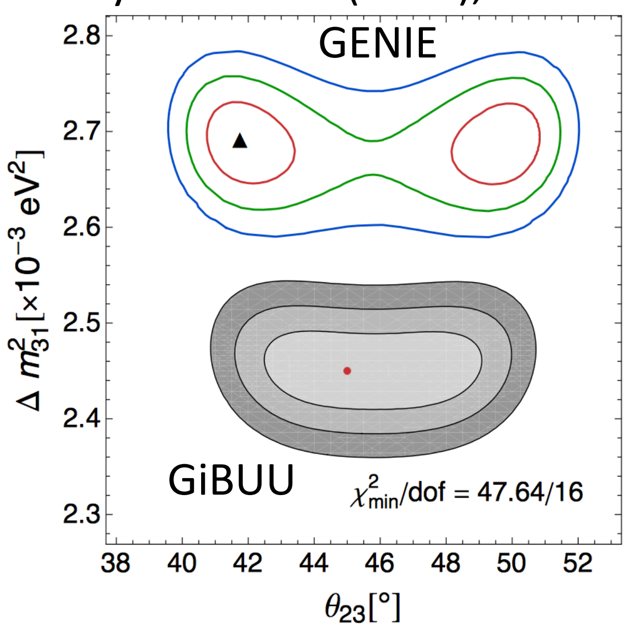
<u>Oscillations are basically ratios of reconstructed ν energy spectra:</u>

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





Phys.Rev. D89 (2014), 073015



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

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

$\nu - N$ and $e^- - N$ scattering

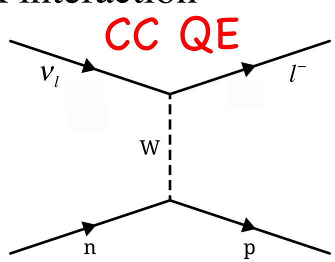
Weak Interactions | **Electromagnetic Interaction**

CC Weak Interactions | **NC Weak Interactions**

Charged Current (CC) Weak interaction mediated by $W^{\pm}$ bosons

$$j_\mu^{\pm} = \bar{u}\frac{-ig_W}{2\sqrt{2}}(\gamma^\mu - \gamma^\mu\gamma^5)u$$

g_W – coupling strength

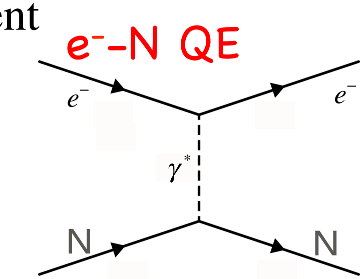


$$\nu_l + n \rightarrow l^- + p$$

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

Electromagnetic current

$$j_\mu^{em} = \bar{u}\gamma_\mu u$$



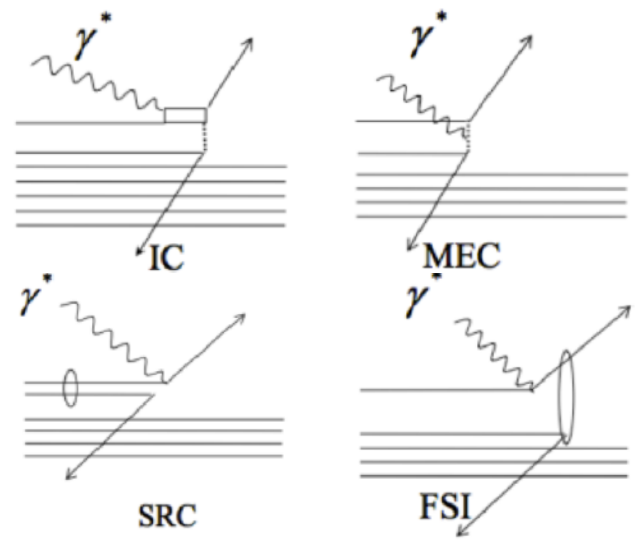
$$e^- + N \rightarrow e^- + N$$

What can we learn from e- scattering studies?

e⁻ and neutrino interactions with matter have many similarities
e- beam energy is known → can test energy reconstruction in selective kinematics

Goal:

- Analyze electron scattering data to study neutrino beam energy reconstruction methods for different energies and nuclei.
- Study nuclear responses (FSI, Resonance production, Multinucleon effects, etc.)
- Compare to Genie results and identify regions of phase space where simulation and data agree well



e⁻nucleus two body diagrams that lead to the same final state as that of e⁻-N QE

Energy reconstruction methods in neutrino experiments

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

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

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

M-nucleon mass

m_1 outgoing lepton mass

k_1 – lepton three momentum

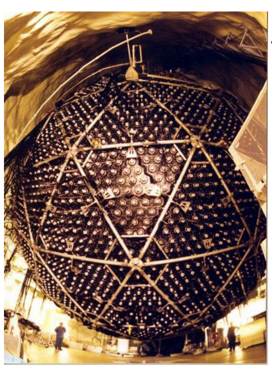
θ – lepton scattering angle

Problem: assumes QE

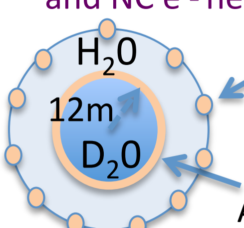
Cherenkov detectors:

- Electrons & Pions
- No protons / neutrons

SNO (Sudbury Neutrino Observatory, Canada, Ontario)



- 1000 ton heavy water $D_2 0$ and 3000 ton normal water
- Detect neutrinos via CCQE, NCQE and CC and NC e⁻- neutrino elastic scattering



Water Cherenkov detector

Study: Solar neutrino problem

Art McDonald was co-awarded Nobel prize in 2015

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

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

E_{Binding} – Binding energy

T_p – kinetic energy of knock out proton

$E_e^{'}$ – energy of scattered electron

E_π – energy of produced meson

We ignore the kinetic energy of A-1 system.

Tracking detectors:

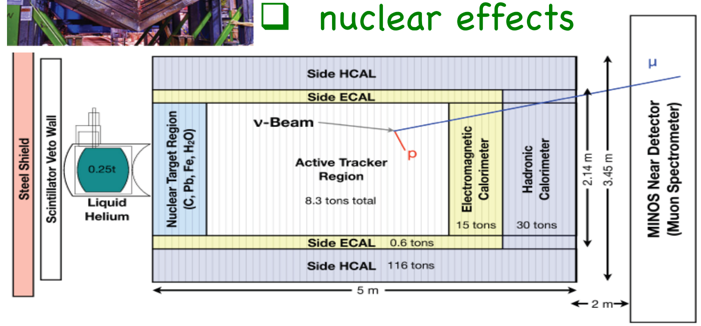
- Charged particles $+\pi^0$
- Neutron detection is challenging

MINERvA (Fermilab)

Scintillator based detector

Study:

- ❑ Neutrino interaction cross sections
- ❑ nuclear effects



Electron scattering data

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

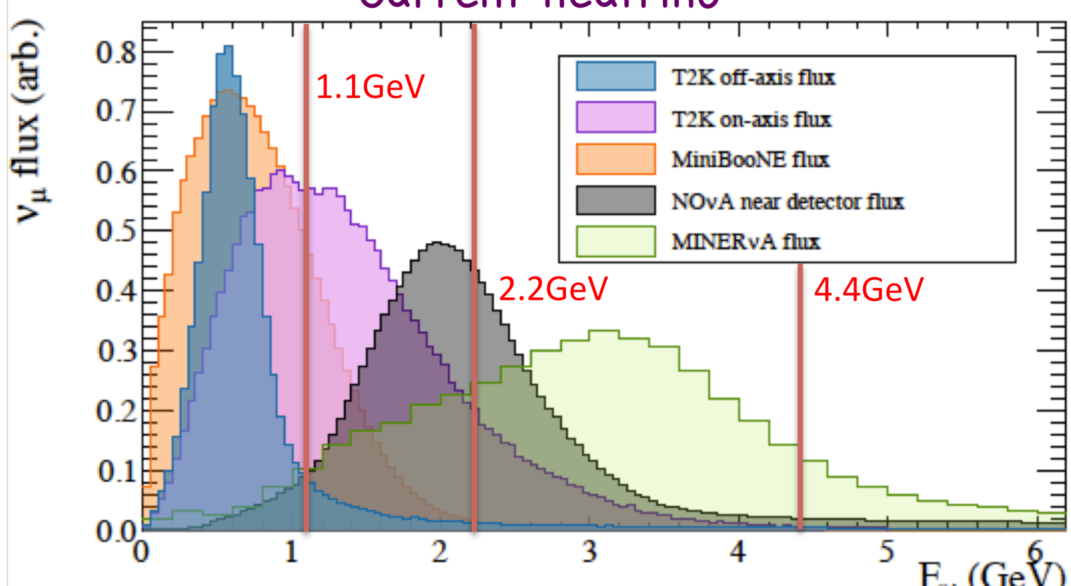
E2a target properties

Target	length [cm]	Density $*$ length [g/cm^2]
^{3}He	$4-5$	0.335
^{4}He	$4-5$	0.0625
^{12}C		0.221
^{56}Fe		0.118
CH_2		0.067

Good (e,e') and (e,e'p) events $*10^6$
with e and p PID, vertex and fiducial cuts and W<2

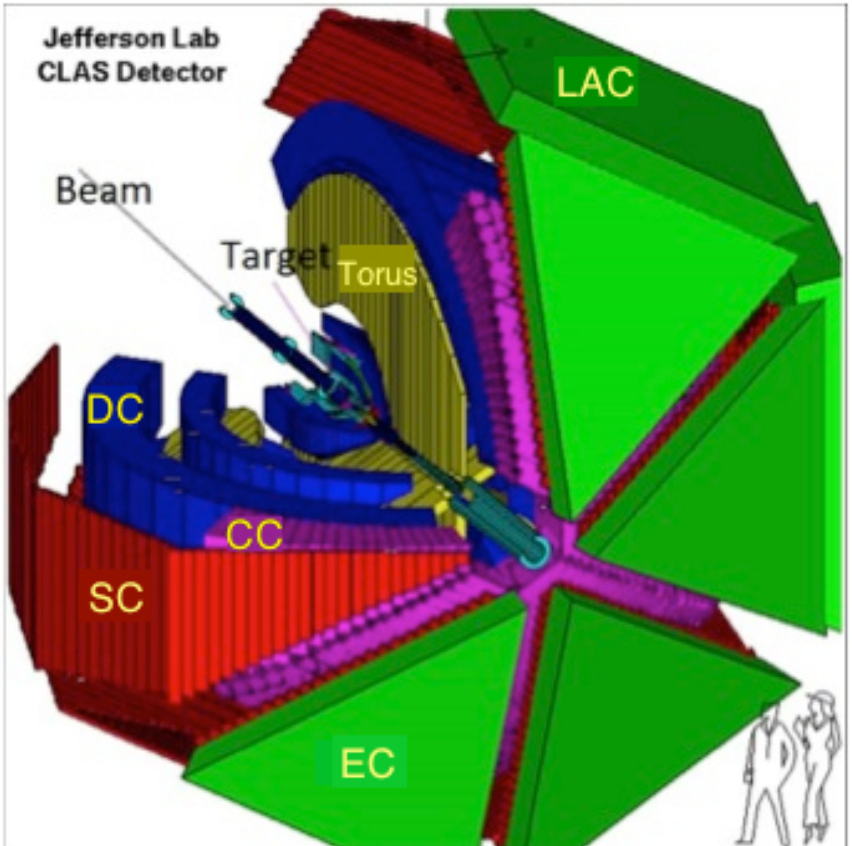
	2.2GeV (e,e')	2.2GeV (e,e'p)	4.4GeV (e,e')	4.4GeV (e,e'p)
3He	29	12	3.9	1.4
4He	46	17	8	2.6
12C	29	11	5	1.5
56Fe	1.5	0.5	0.4	0.1

Current neutrino

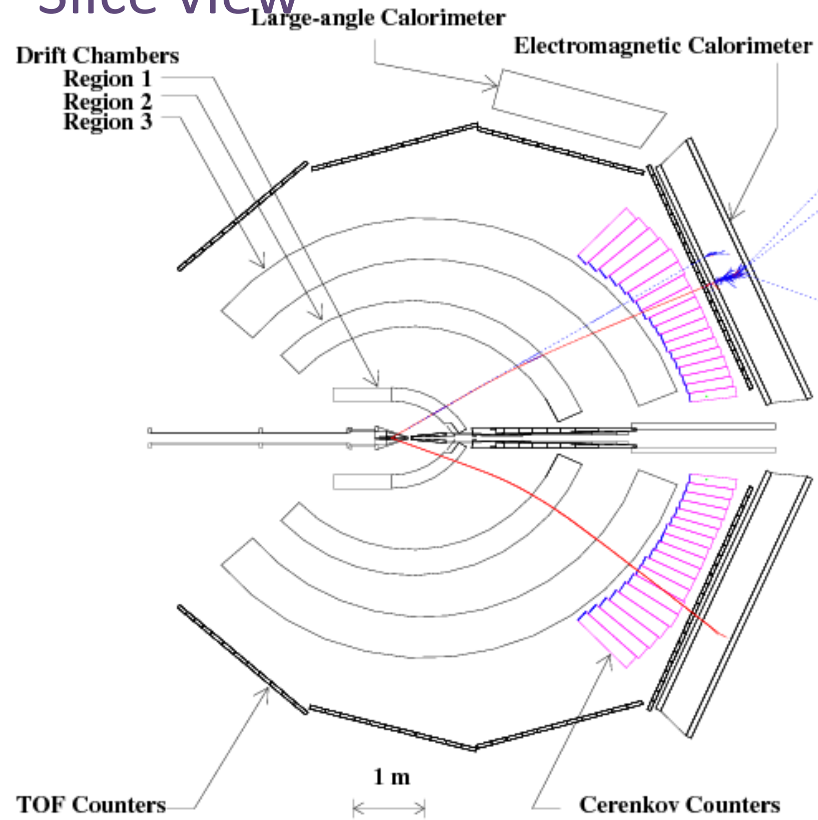


CLAS detector package

3D view



Slice view



$$\sigma \sim \left(\frac{1}{q^2 + M^2} \right)^2$$

$M = \mathrm{m}_{\mathrm{photon}}$ (for e^- scattering)

$M = \mathrm{m}_{W^\pm}$ (for CC weak interaction)

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

2.261 GeV analysis

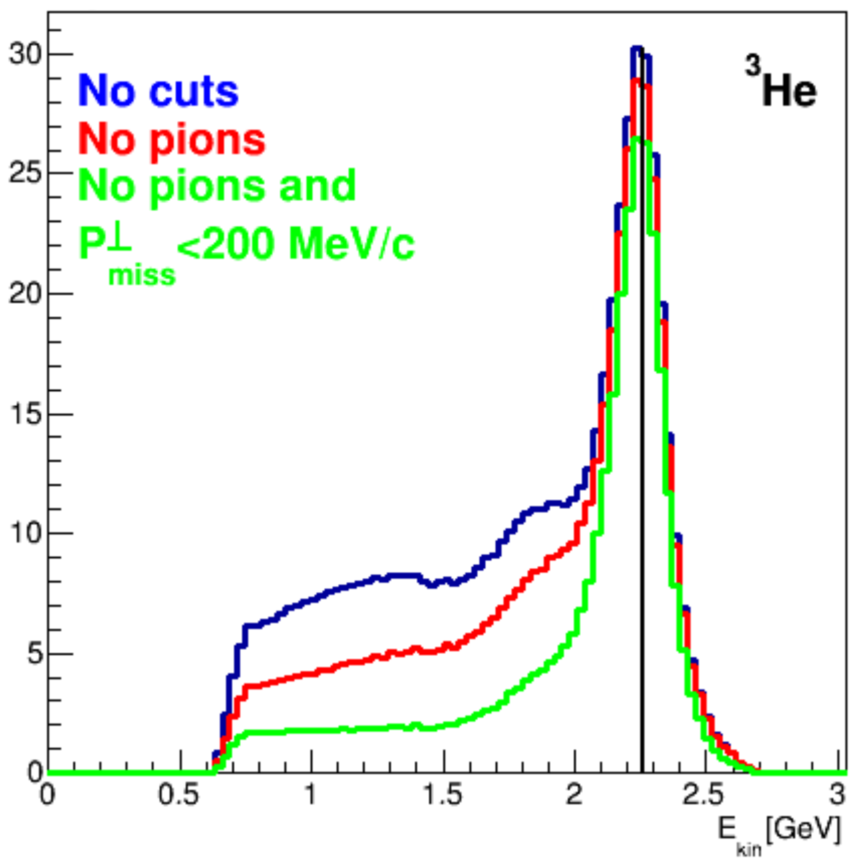
Reconstructed (e,e') energy

E2a ^{3}He 2.261 GeV

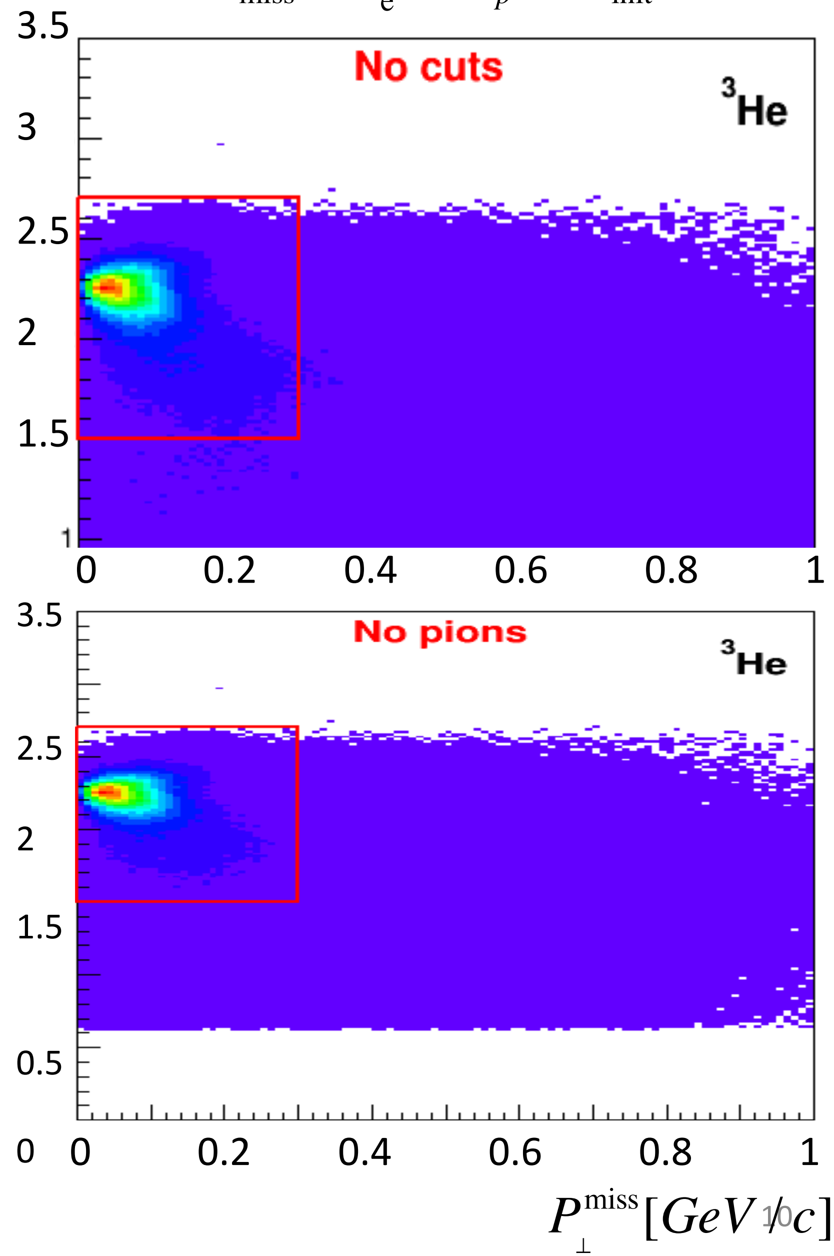
Standard CCQE event selection is 0 π

e⁻ only

E_{kin}[GeV]

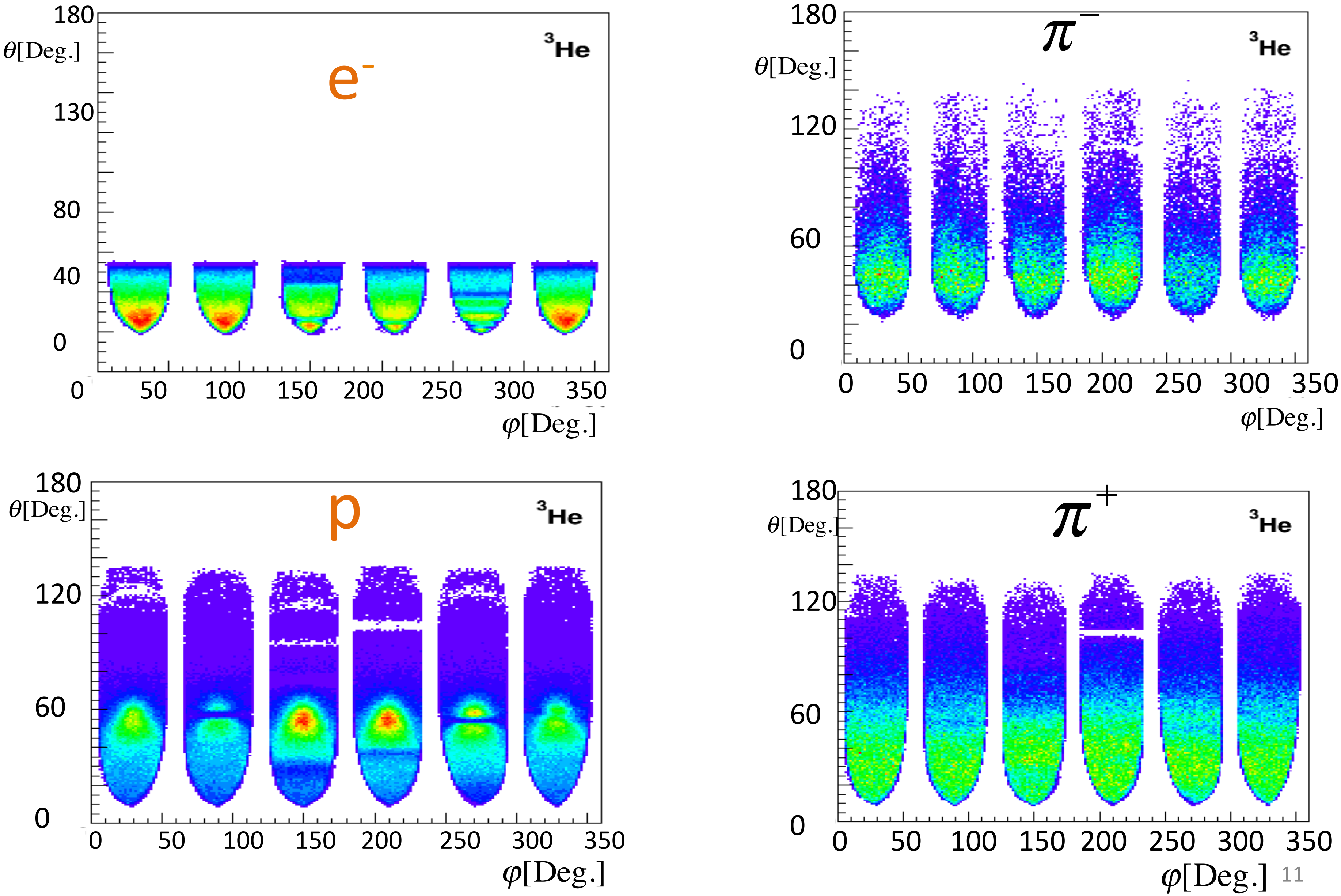


$$P^{\perp}_{\rm miss} = P^{\perp}_{e^-} + P^{\perp}_{p} = P^{\perp}_{\rm init}$$



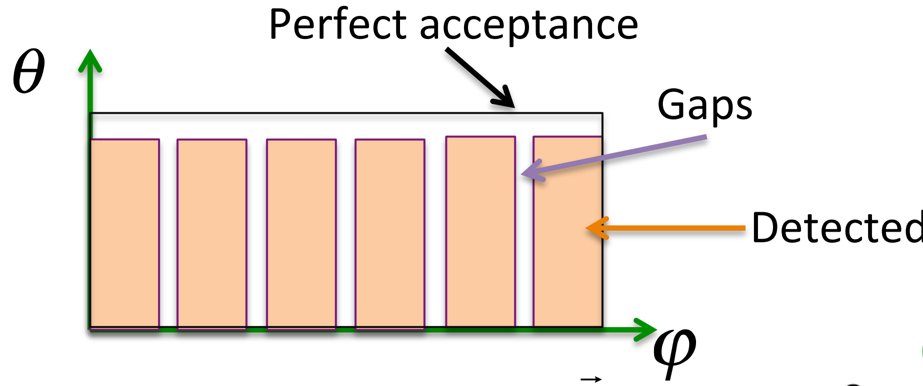
θ and φ distributions

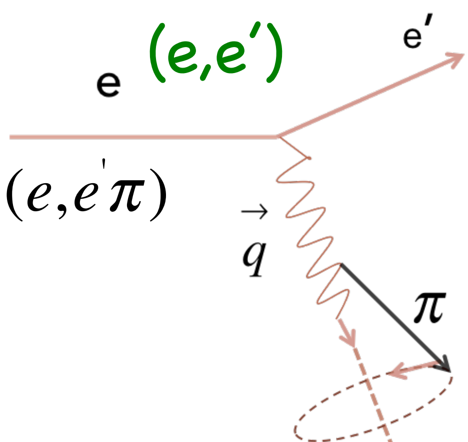
E2a ^{3}He 2.261 GeV



Subtracting undetected pions to get 0 pion sample

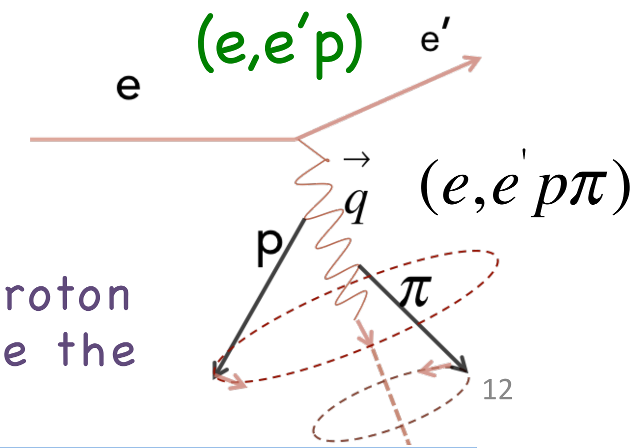
E2a ^{3}He 2.261 GeV



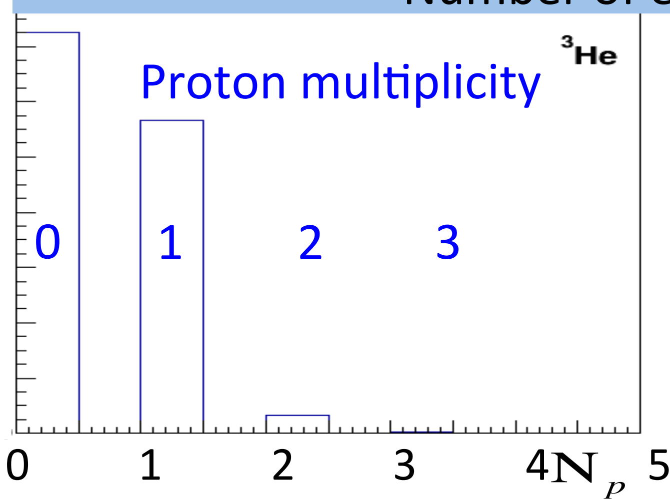


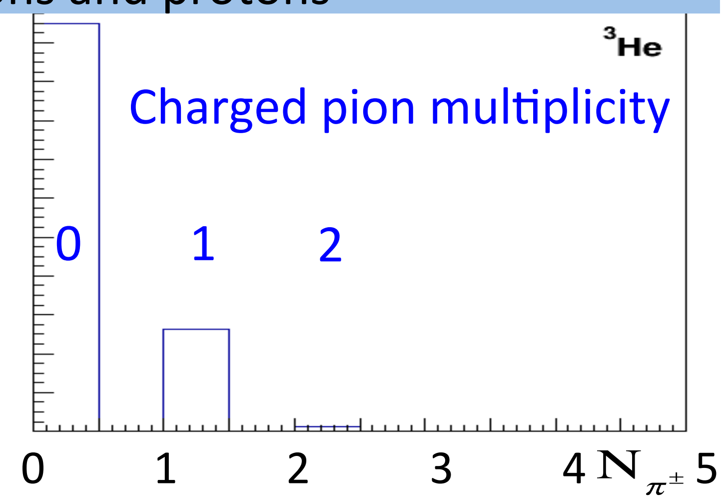
Rotate π around $\vec{q}$ to determine detection acceptance

Subtracting undetected 2 proton events to get 1proton sample the similar way



Number of events with pions and protons





Subtracting undetected pions

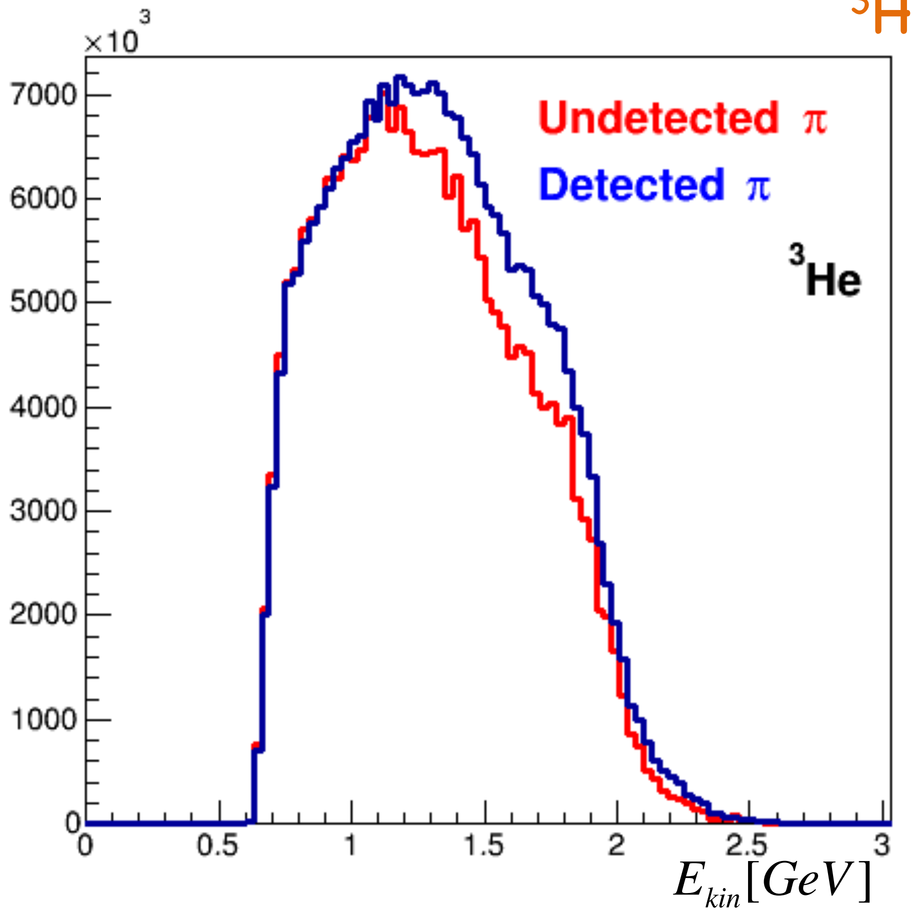
E2a ^3He 2.261 GeV

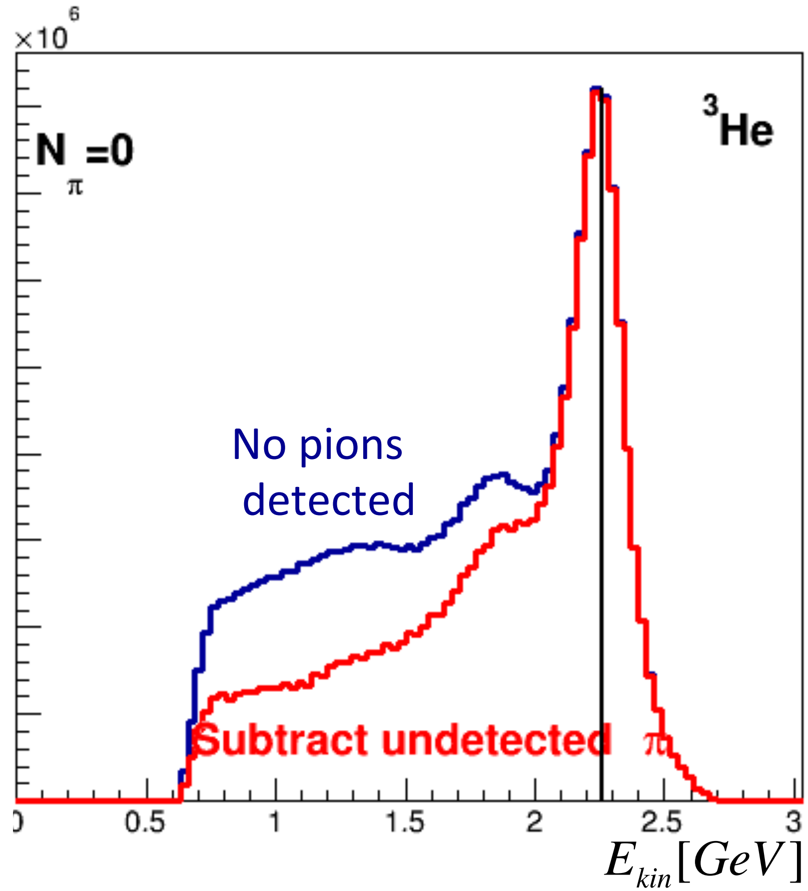
(e,e')

Cuts

No π_+ , π_- and no photons coming from π_0 decay

^3He





(e,e'p) $E_{Calorimetric}$

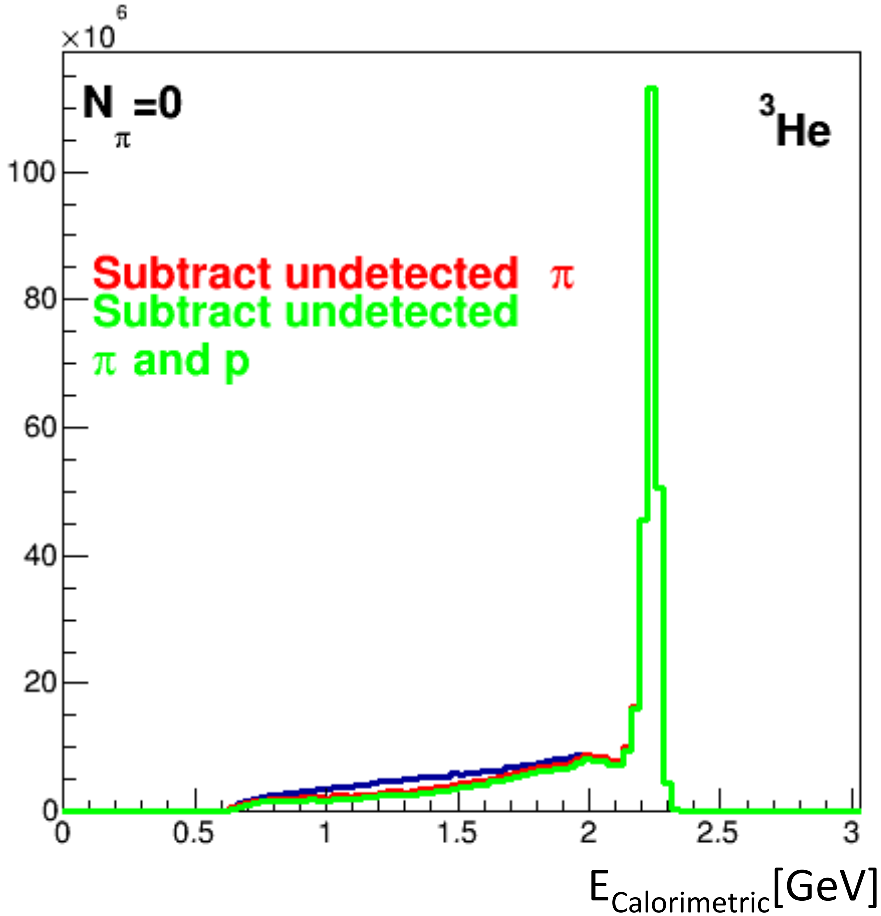
$E_{Calorimetric}=E_{e'}+T_p+E_{Binding}$

$E_{e'}$-energy of scattered electron

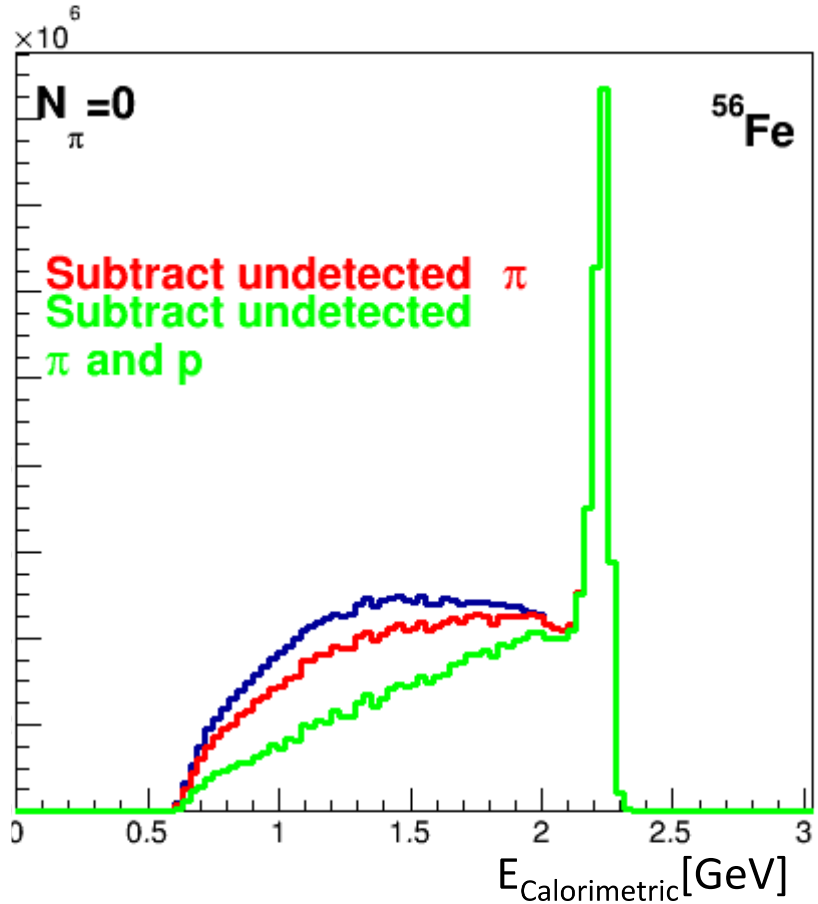
T_p-kinetic energy of knock-out proton

$E_{binding}$-Difference between binding energies of A and A-1 nuclei

^3He



^{56}Fe



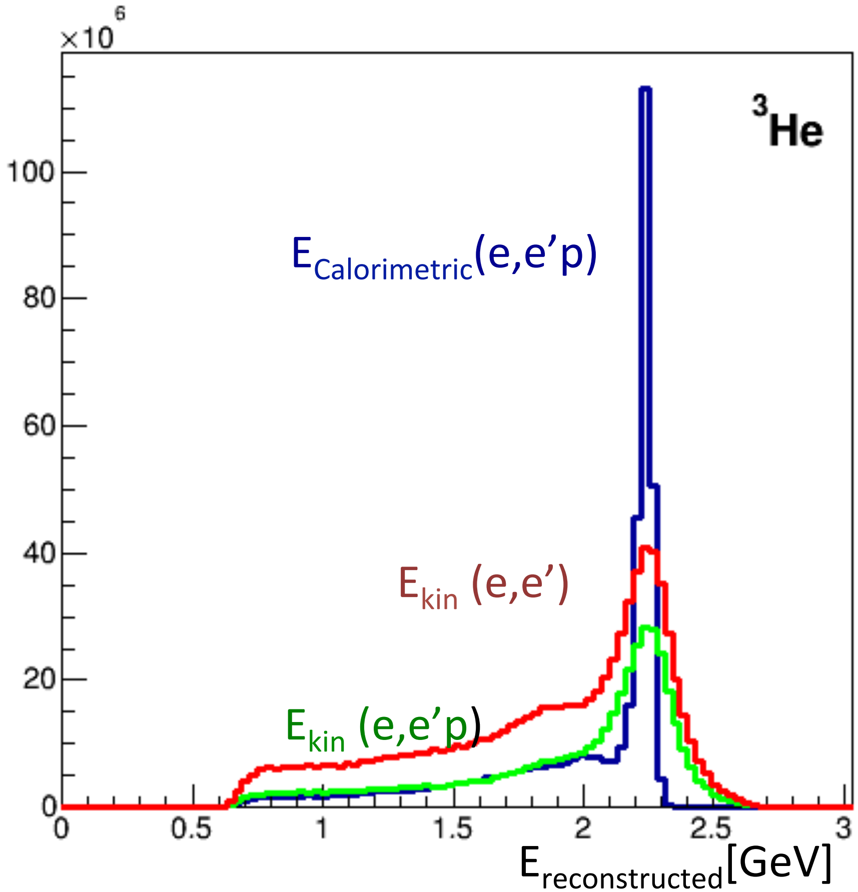
2.2GeV

(e,e'p) $E_{calorimetric}$, (e,e') E_{rec} and (e,e'p) E_{rec}

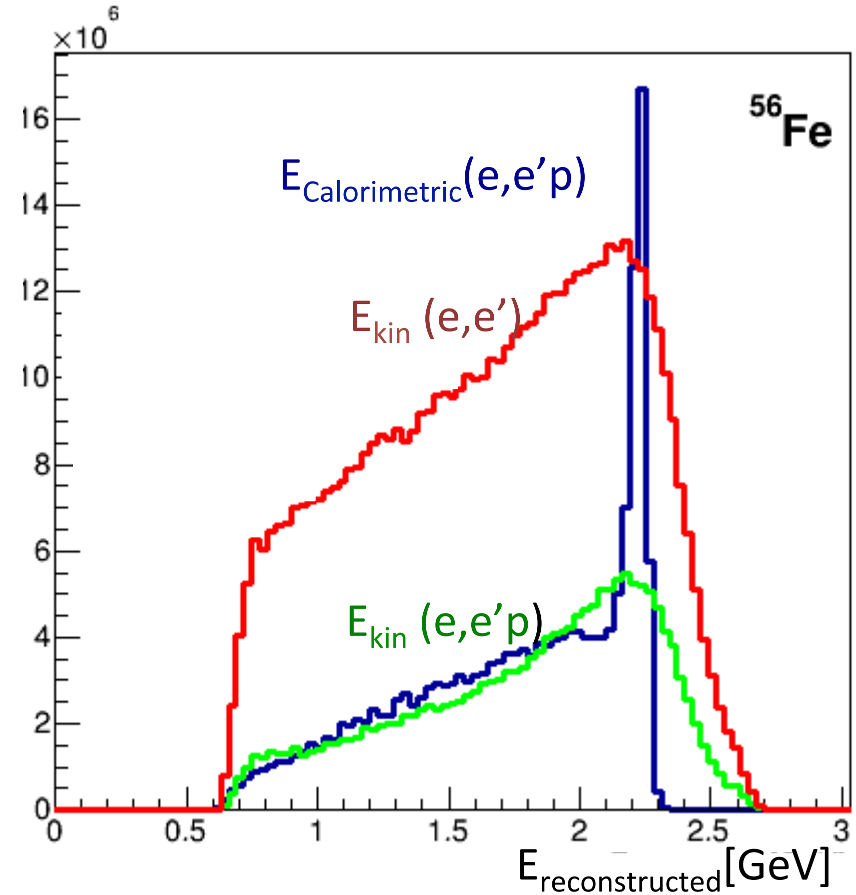
Cuts

No π^+, π^- and no photons coming from π^0 decay

^3He



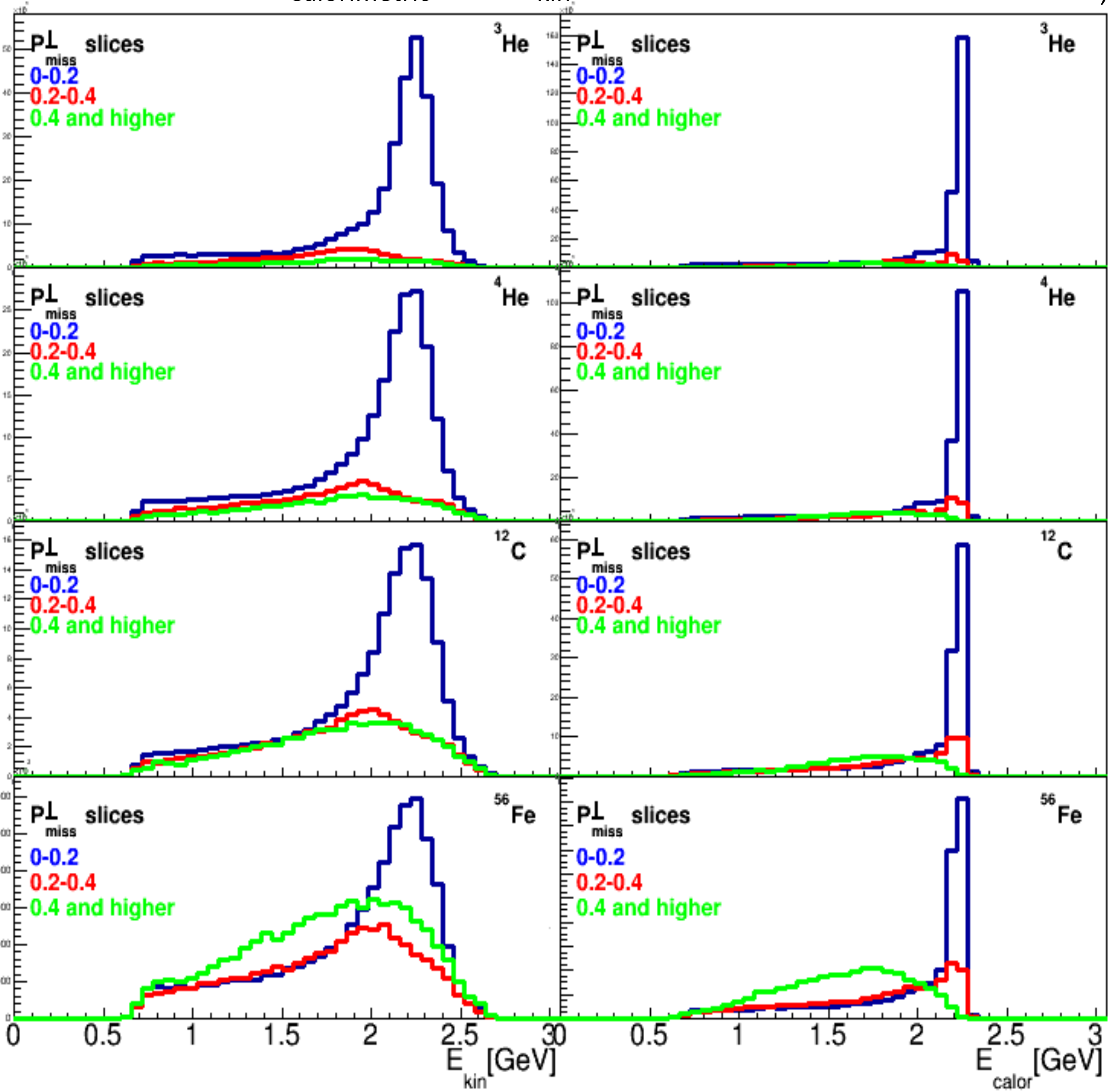
^{56}Fe



1. E_{kin} has Worse peak resolution than $E_{Calorimetric}$
2. ^{56}Fe is much worse than ^3He
3. Same tail for E_{kin}+$E_{calorimetric}$
4. ^{56}Fe predominantly tail

$E_{Calorimetric}$ and E_{kin} for all targets at 2.261 GeV in $P_{\perp}^{miss}$ slices

E_{kin}



$E_{Calorimetric}$

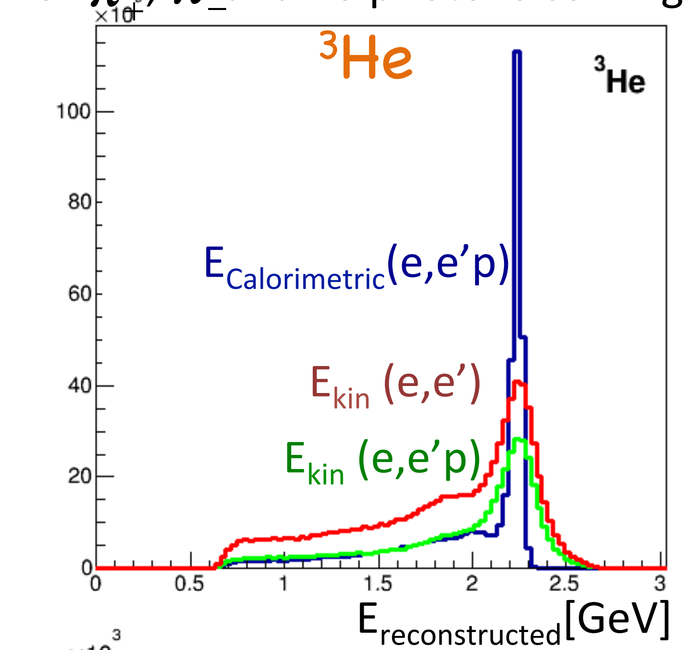
1. Increase in non-QE background with increasing $P_{miss}^{\perp}$
2. Radiative tail in $E_{calorimetric}$
3. Worse peak resolution for E_{kin}
4. Increase in non-QE background for heavier targets
5. $E_{Reconstructed}$ can be improved by cut

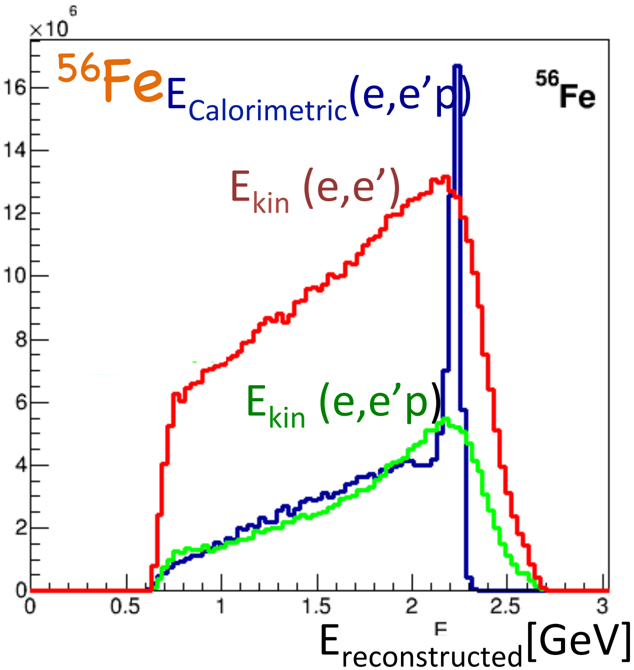
4.461 GeV analysis

Cuts

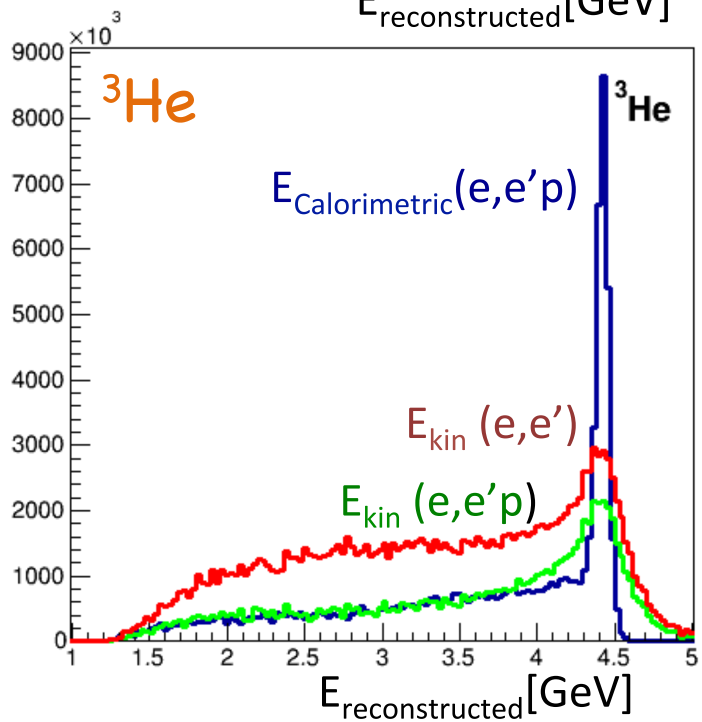
(e,e'p) $E_{calorimetric}$, (e,e') E_{kin} and (e,e'p) E_{kin}

No π_+, π_- and no photons coming from π_0 decay



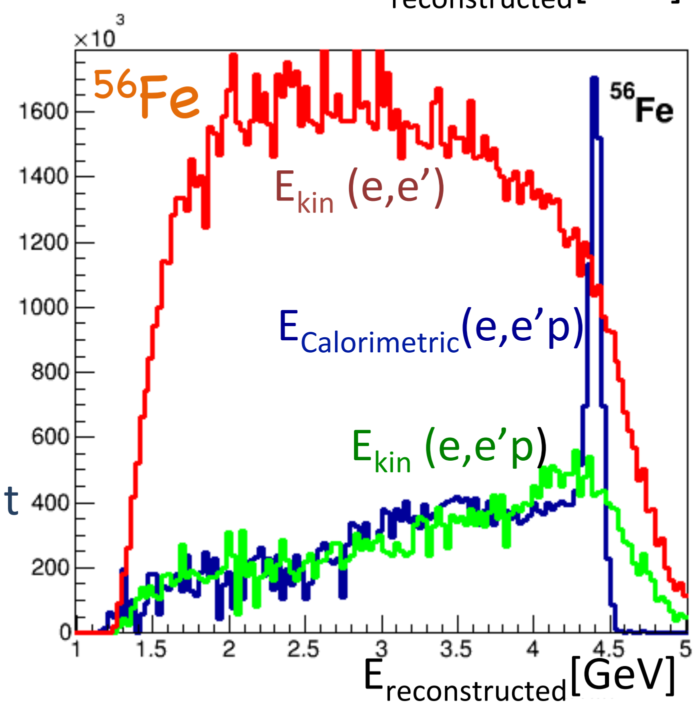


2.2 GeV



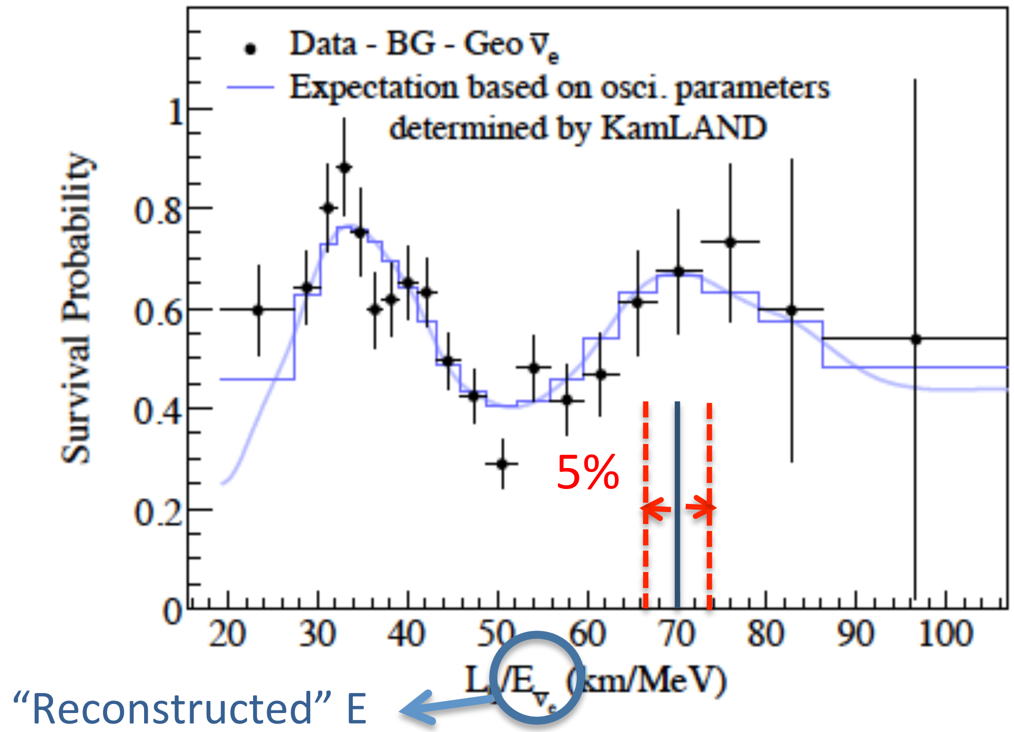
4.4 GeV

- No evident peak in E_{kin} of ^{56}Fe at 4GeV
- Work best for ^{3}He at 2GeV



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

	2.2 GeV		4.4GeV	
	E_{kin} (e,e')	$E_{calorimetric}$ (e,e'p)	E_{kin} (e,e')	$E_{calorimetric}$ (e,e'p)
^{3}He	0.32	0.55	0.21	0.40
^{4}He	0.23	0.46	0.15	0.31
^{12}C	0.2	0.39	0.12	0.29
^{56}Fe	0.16	0.26	0.09	0.22



KamLAND, PRL 100, 221803 (2008)

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)

Summary

1.First use of electron data to test neutrino energy reconstruction algorithms

- use zero-pion cuts to enhance quasi-elastic event selection
- just scattered lepton (E_{kin})
  - ✧ used in Cherenkov-type neutrino detectors
- total energy of electron plus proton ($E_{Calorimetric}$)
  - ✧ used in calorimetric neutrino detectors
- improved by a transverse momentum cut to better select QE events

2.Only 0.09-0.55 fraction of events reconstruct to within 5% of the beam energy at 2GeV

- better for lighter nuclei

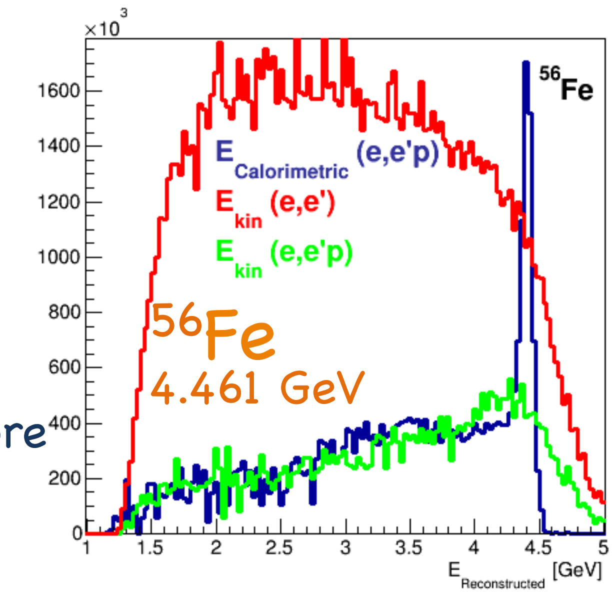
3. Serious implications for neutrino oscillation Measurements

4.Tremendous interest in the neutrino community

5.Analysis note in preparation, aiming for PRL

6.Future work

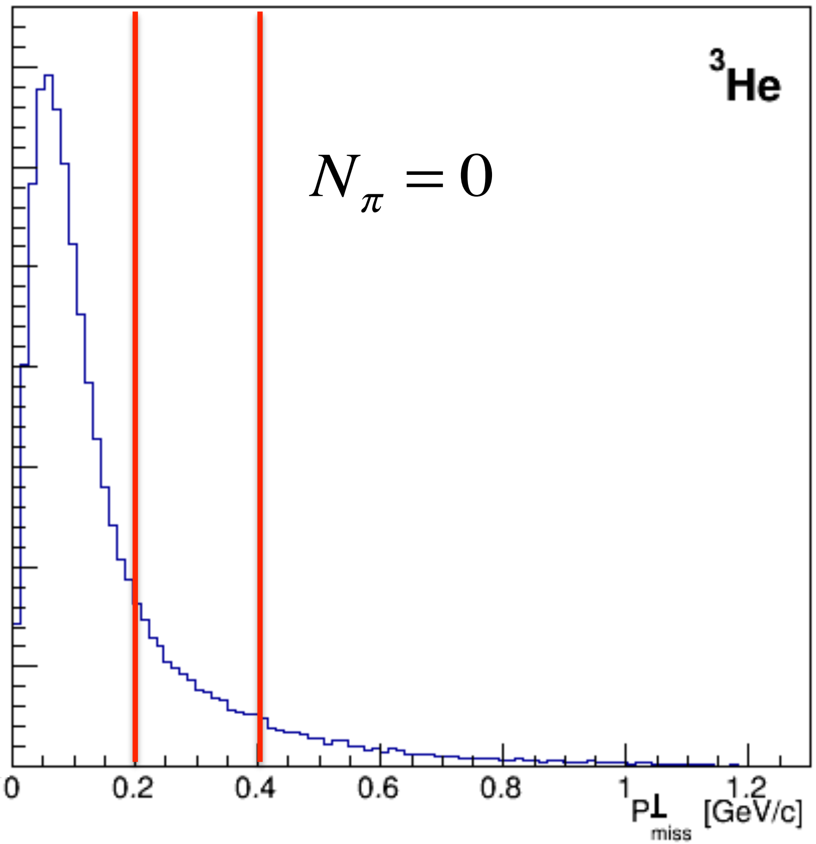
- extend analysis to other kinematic regions, more targets and energies
- Identify regions with good and bad energy reconstruction and GENIE modeling.
- Proposal "Electrons for Neutrinos" conditionally approved by PAC 45.



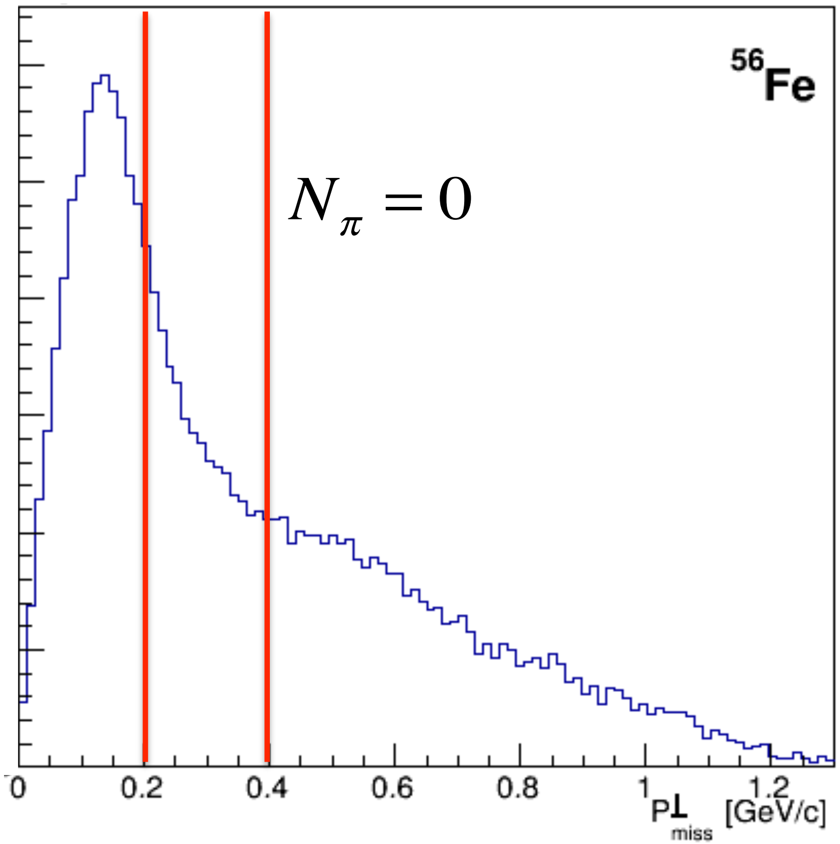
$P^{\perp}_{\text{miss}}$

2.2GeV $P^{\perp}_{\text{miss}} = P^{\perp}_{e^-} + P^{\perp}_{p} = P^{\perp}_{\text{init}}$

^{3}He

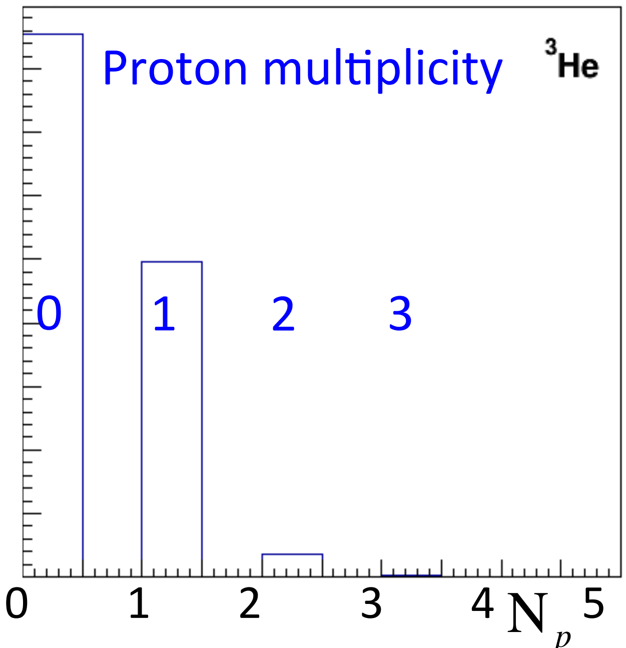


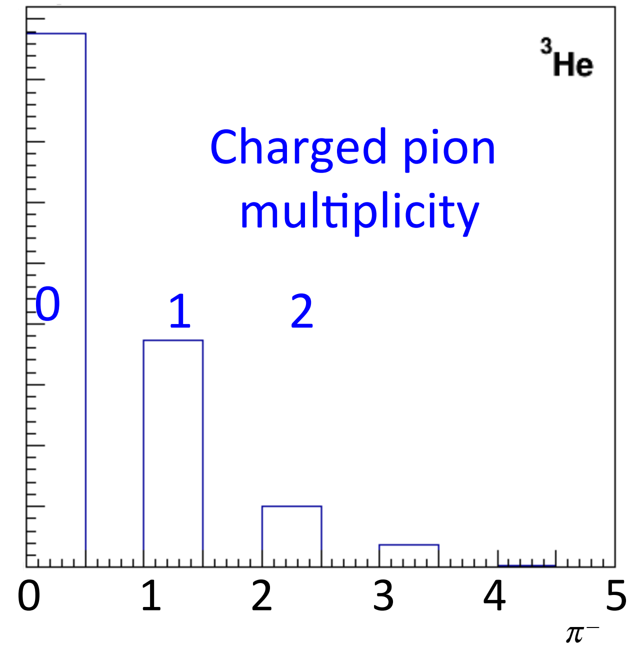
^{56}Fe



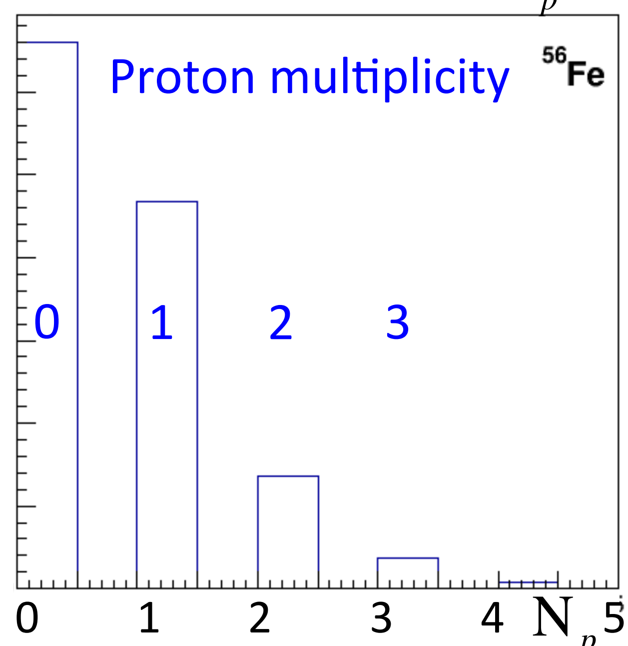
Number of events with pions and protons

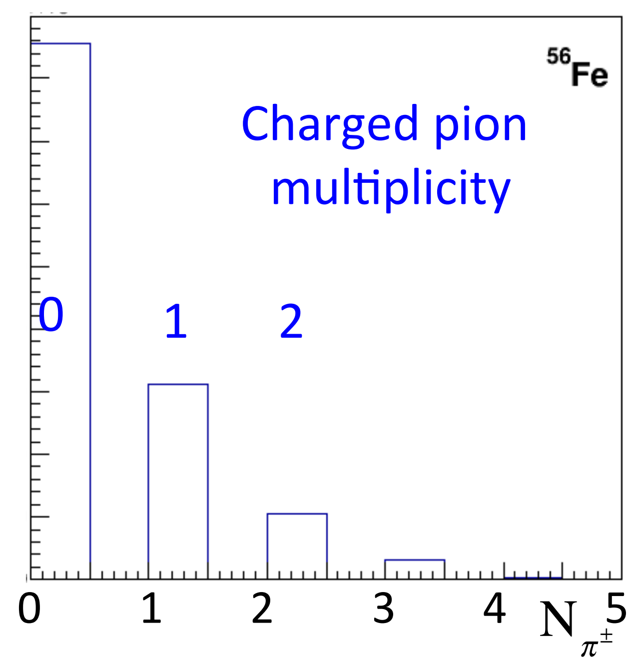
E2a 4.461 GeV





^{3}He





^{56}Fe

Subtracting undetected pions

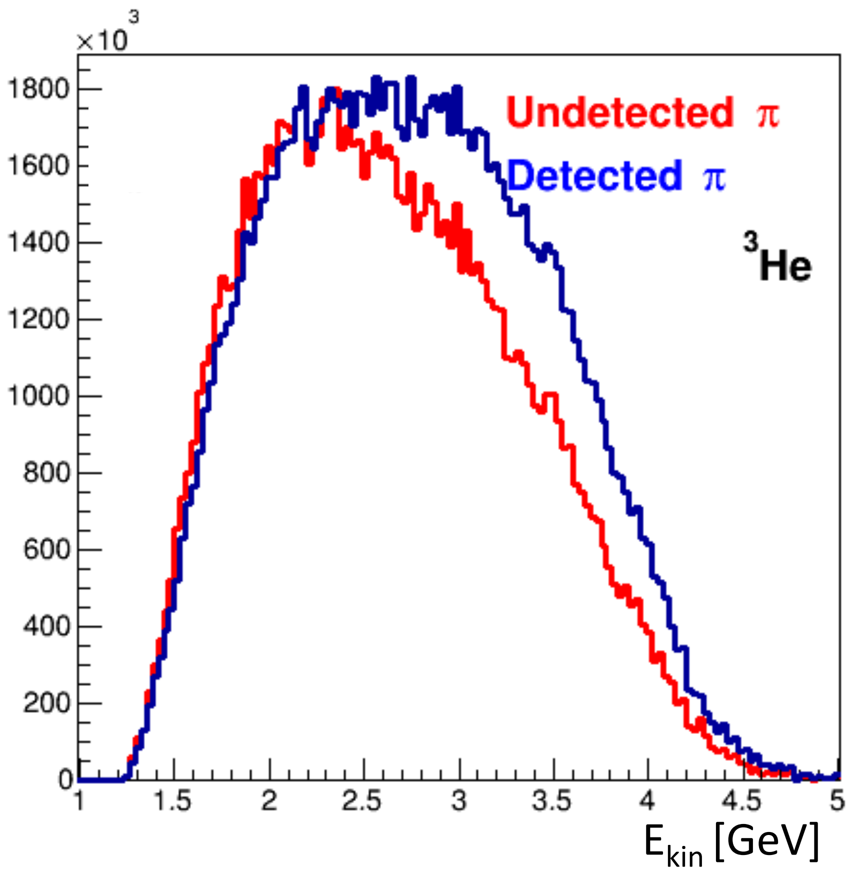
4.461 GeV

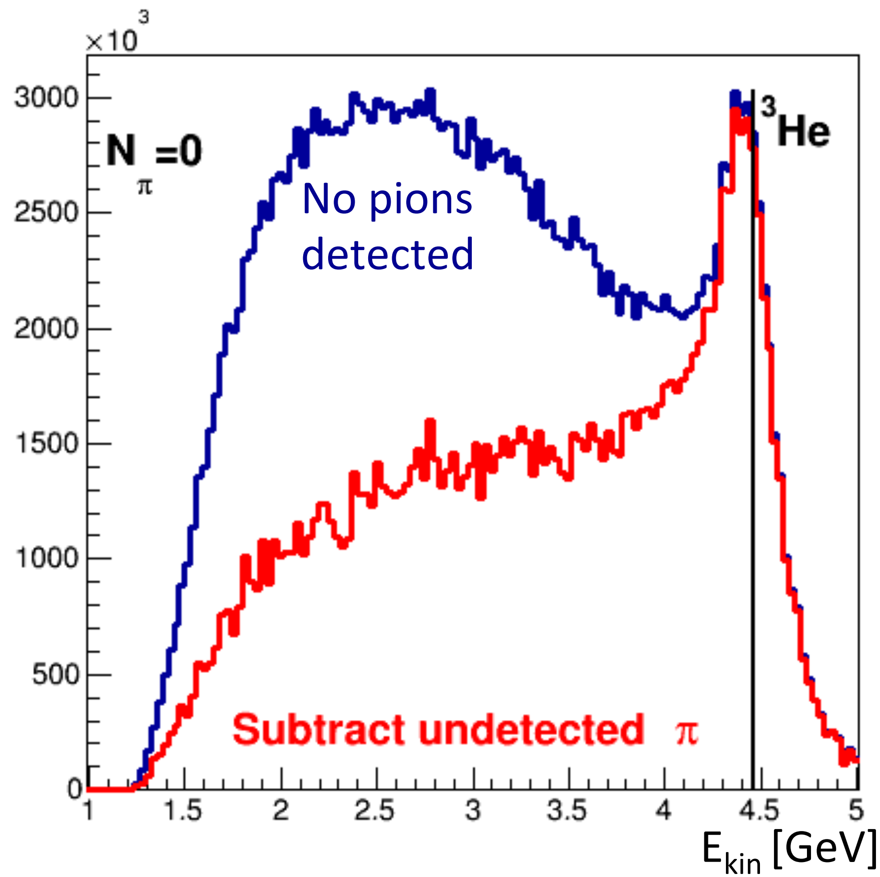
(e,e')

Cuts

No π_+ , π_- and no photons coming from π_0 decay

^{3}He





4.461 GeV

(e,e'p) $E_{Calorimetric}$

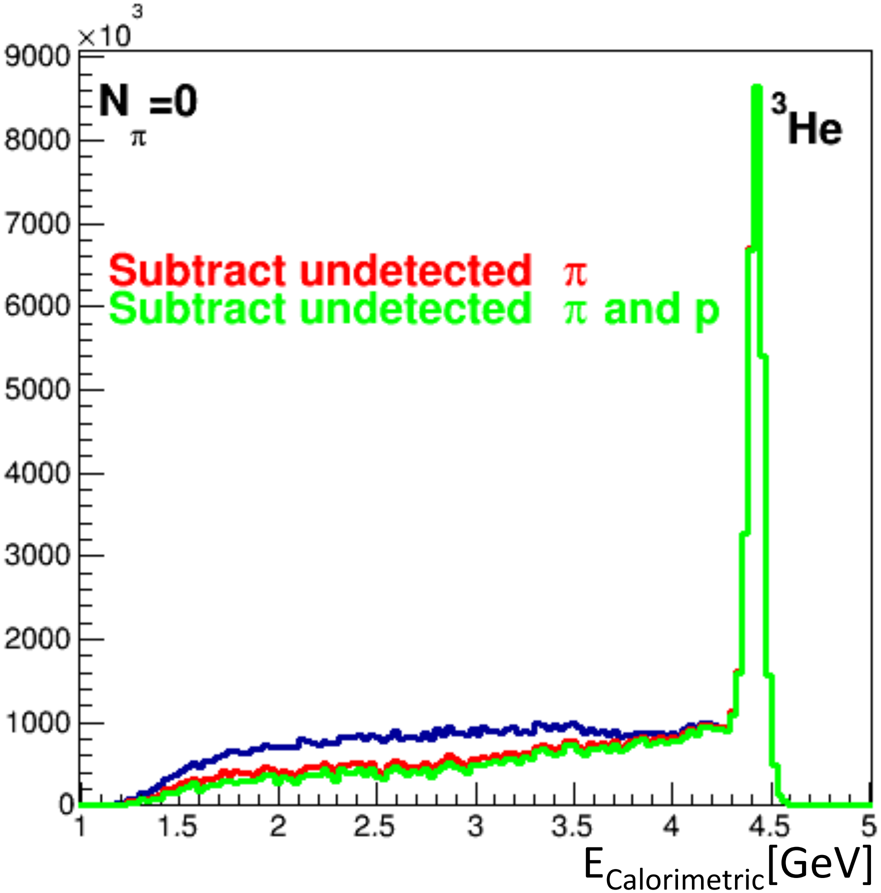
$E_{Calorimetric}=E_{e'}+T_p+E_{Binding}$

$E_{e'}$–energy of scattered electron

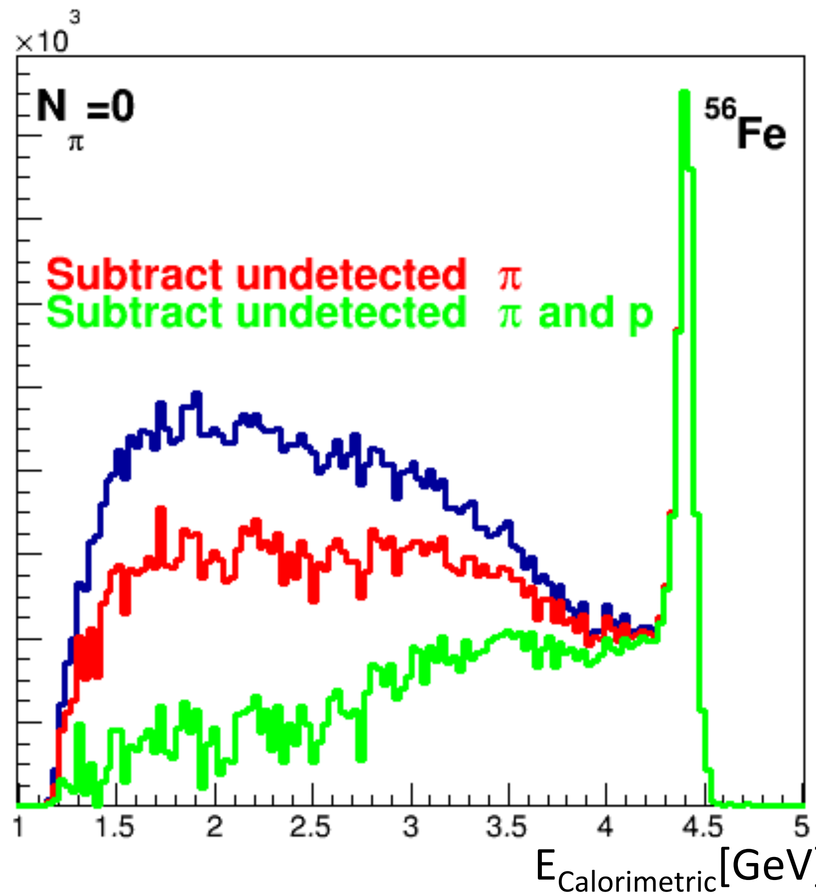
T_p–kinetic energy of knock-out proton

$E_{binding}$–Difference between binding energies of A and A-1 nuclei

^{3}He

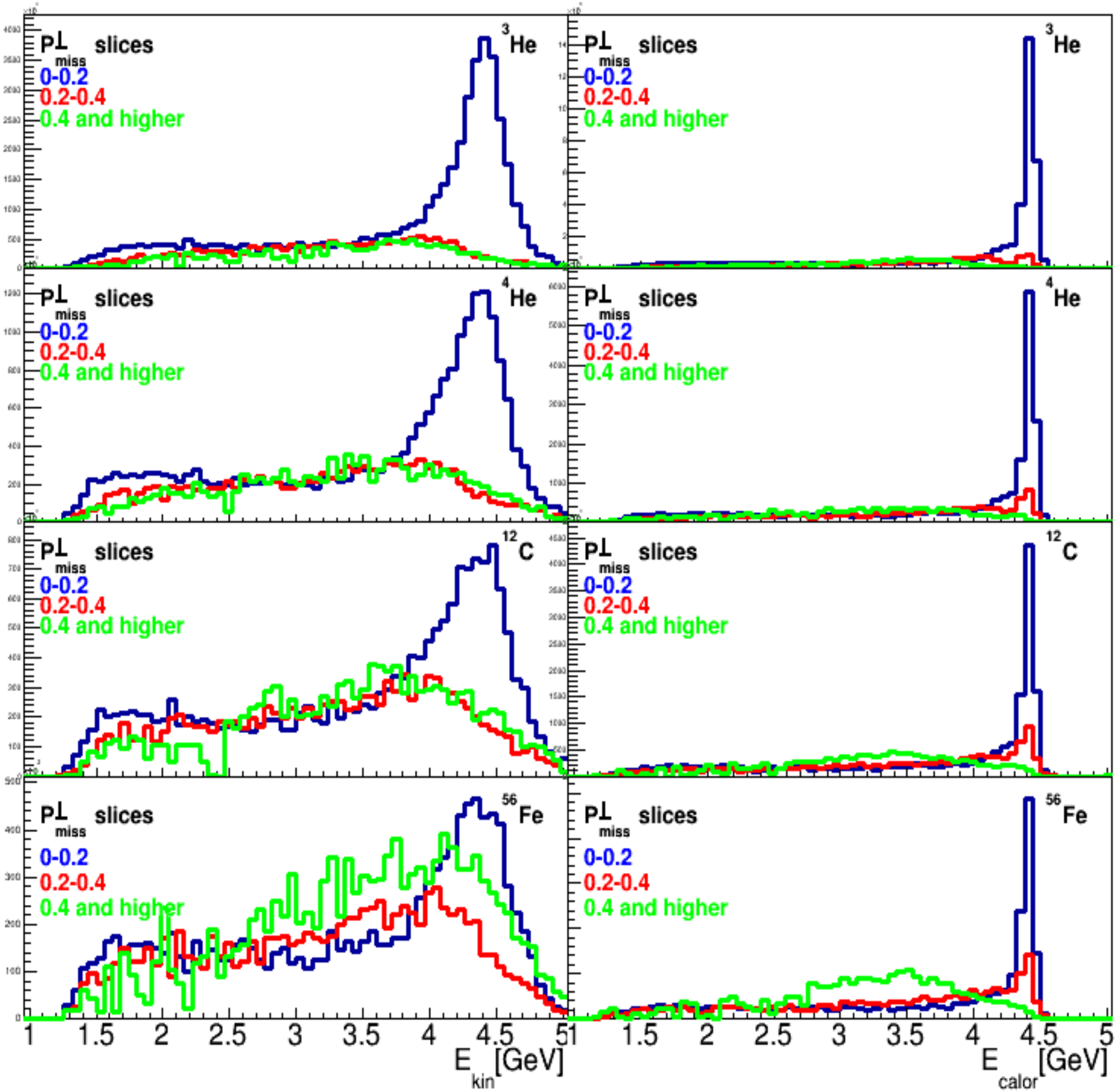


^{56}Fe



Energy reconstruction in $P_{\perp}^{miss}$ slices

E_{kin}



$E_{Calorimetric}$

1. The peak at beam energy broader than at 2GeV
2. Background tail is the smallest with respect to the peak for Ecalorimetric at 2 GeV and $P_{miss}^{\perp}$<200MeV/c
3. $E_{Reconstructed}$ can be improved by cut $P_{miss}^{\perp}$