Electrons for Neutrinos: Addressing Critical Neutrino-Nucleus Issue

Proposal C12-17-006

$e4\nu$ Spokespersons:

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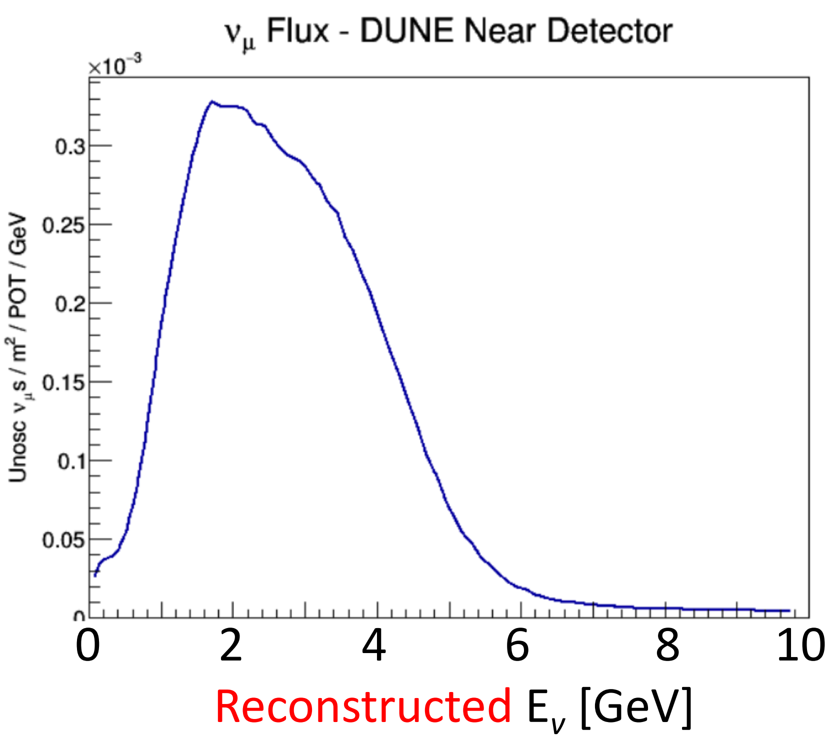
Jefferson Lab PAC-46, July 17th, 2018

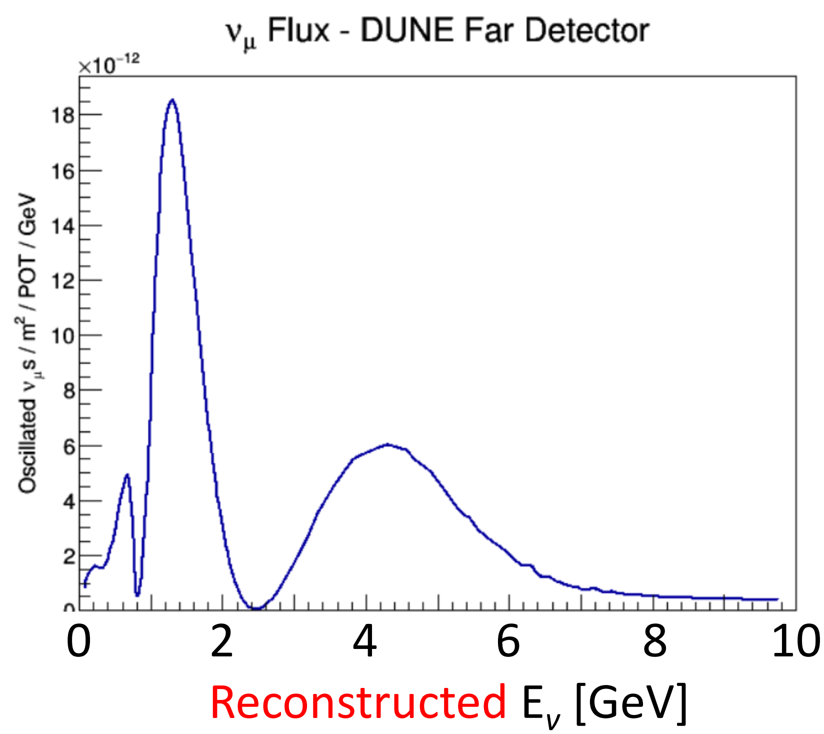
Outline

- Physics motivation and proposal
- PAC45 comments and response
  - Comparisons of electron data and event generators
  - Improvements to event generators
  - Impact on DUNE energy reconstruction
  - Updated beam time request

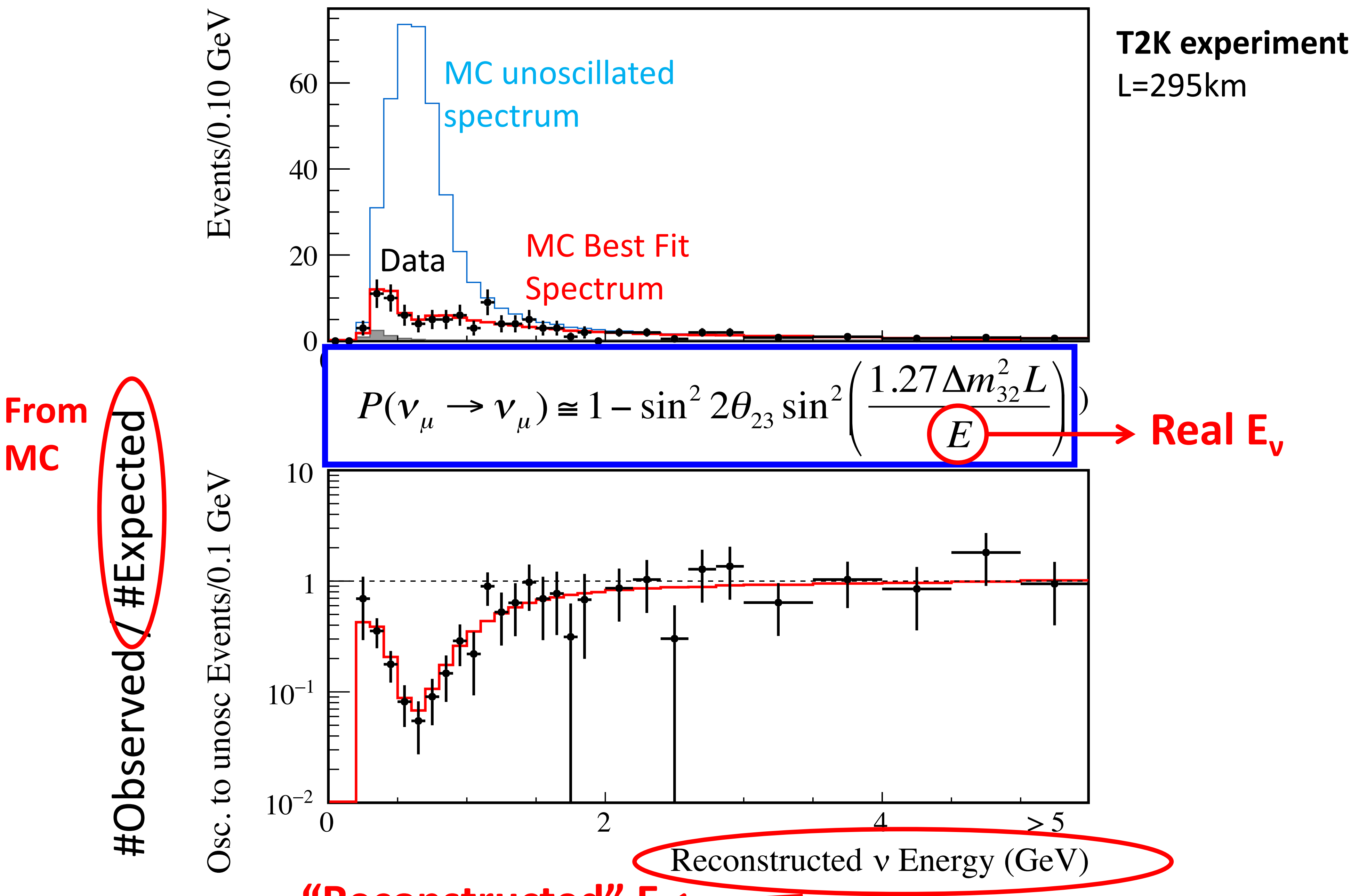
Note: all CLAS data preliminary and not approved for publication.

Long Baseline Oscillations



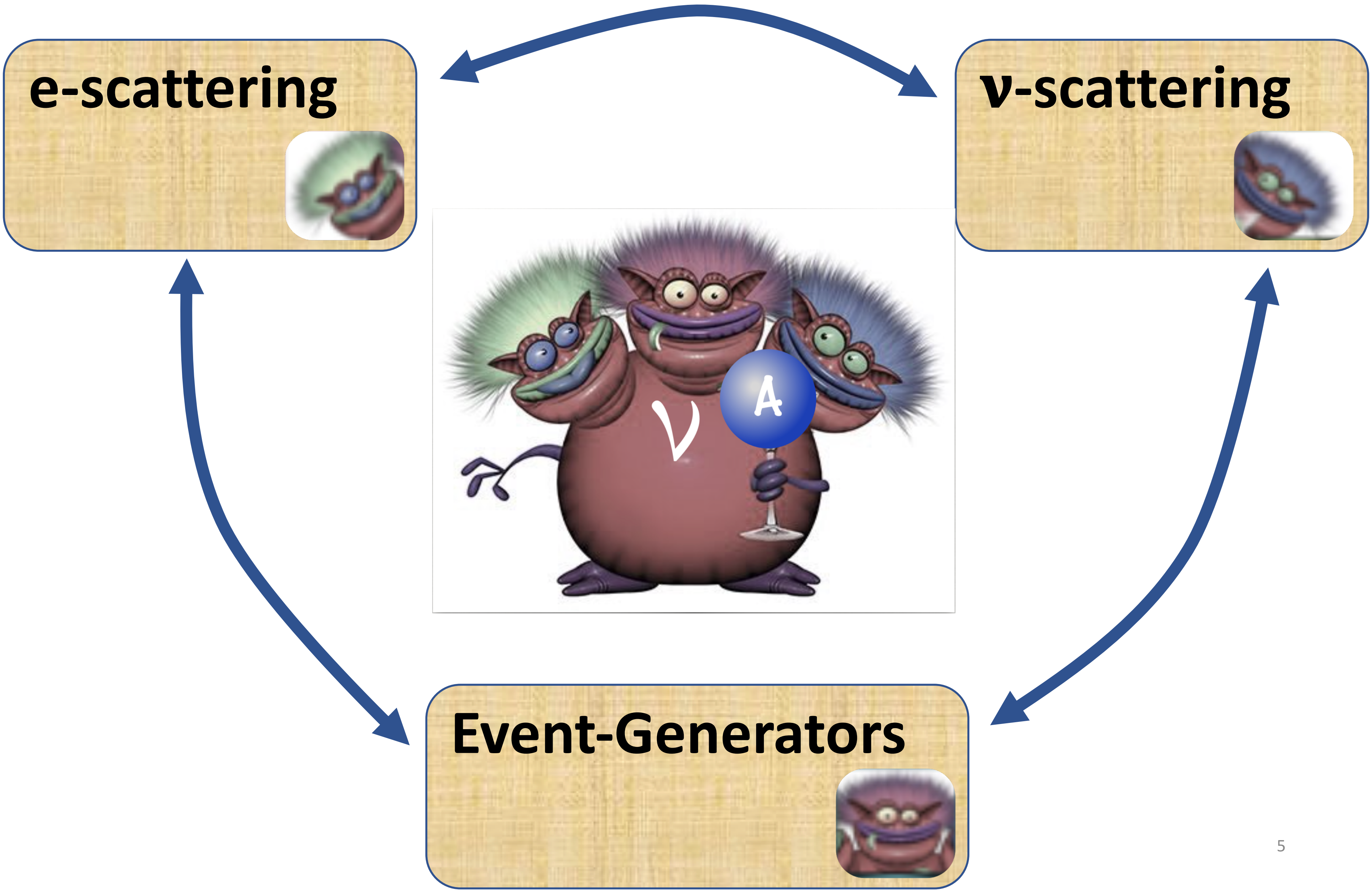


Neutrino Oscillations (disappearance)



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

Attacking the Monster From All Sides

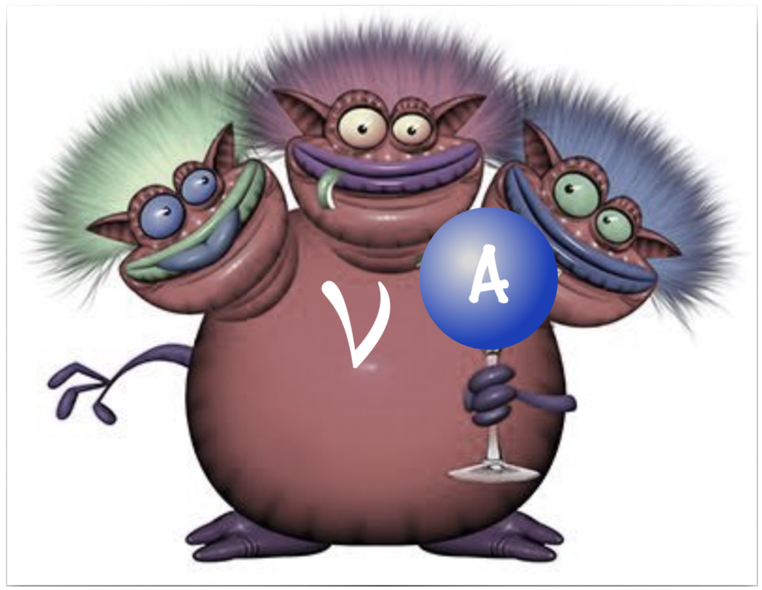


Attacking the Monster From All Sides

e-scattering

(1) Monochromatic e-beam constrains:

- **Vector currents**
- **Nuclear model**
- **Reaction effects**
- **…**



ν-scattering

(2) ν ‘near-detector’ data constrains:

- Axial / Vector-Axial currents
- Ultra-low Q^2
- …

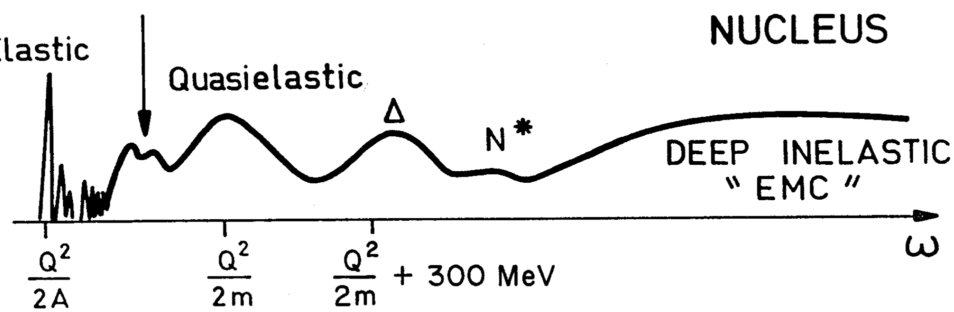
Event-Generators

(3) Must reproduce e-data and ν ‘near-detector’ data before reliably used to extract oscillation parameters.

“We’ve been throwing electrons at nuclei for over 40 years – why new data?”

Not enough data in useful phase-space for ν expts:

- Electron expts focus on nuclear structure, minimize reaction mechanism complications. ν expts cannot avoid these.
- Need many reaction channels (event topologies): (e,e’), (e,e’p), (e,e’p pi), etc over a wide kinematic range
  - Quasielastic (QE)
  - Dip (MEC/2p2h)
  - Resonance region
    - Very little data to date
    - Especially important for DUNE



Existing Data: Mining For Neutrinos

Goal: Use CLAS data to study E_{beam} reconstruction and vector-current cross-sections for different energies / nuclei.

Means (for QE study):

- Select clean (e,e'p) events (no pions, 2nd protons, ...),
- Reweight by *e-N* / *ν-N* "Mott" cross-section ratio.
- Analyze as 'neutrino data' (assume unknown beam energy),
- Study beam energy reconstruction methods,
- Compare to neutrino event generator predictions

Data almost final. Analysis note in preparation for CLAS approval.

Existing CLAS6 Data (e2a)

Target	2.2 GeV		4.4 GeV	
	(e,e’)	(e,e’p)	(e,e’)	(e,e’p)
^{3}He	24.5	9.3	4.1	1.5
^{4}He	46.3	17.3	8.0	2.8
^{12}C	30.0	11.0	4.8	1.5
^{56}Fe	1.4	0.5	0.4	0.1

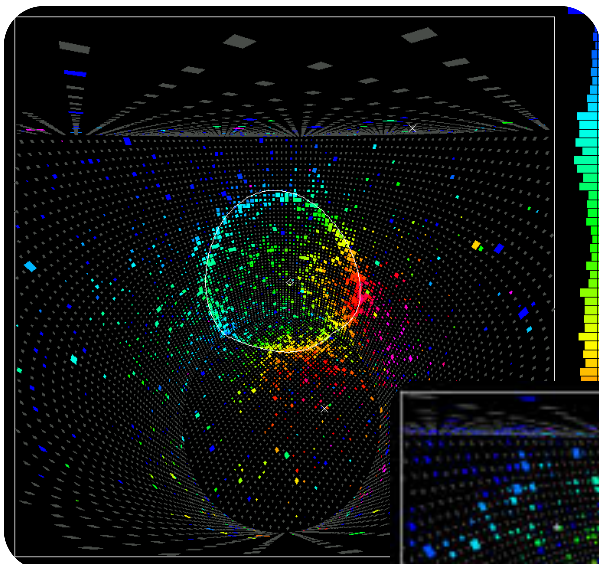
Million events

$\Rightarrow$ Limited nuclei
$\Rightarrow$ Limited Q^2 range
$\Rightarrow$ Limited statistics

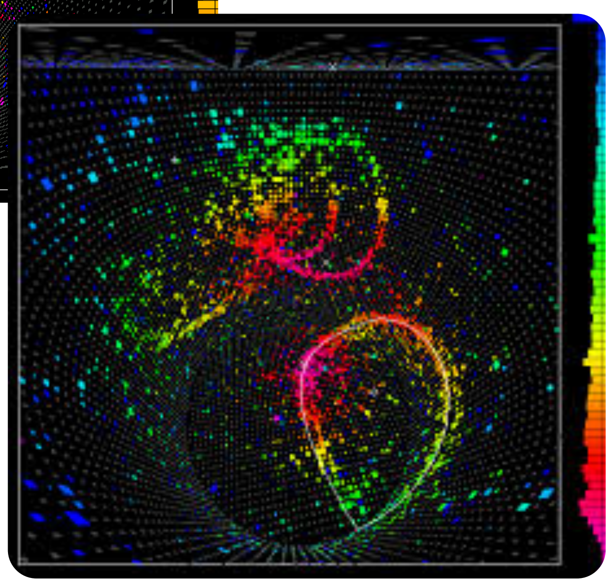
Final state detection approaches

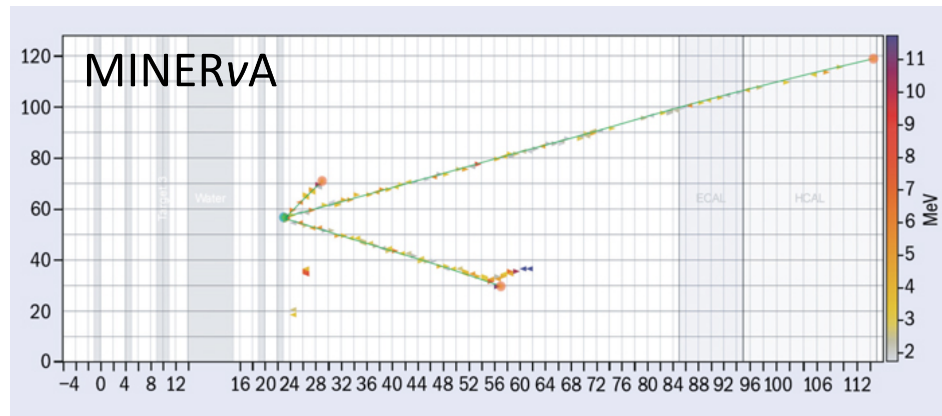
Cherenkov detectors:
- Electrons & Pions
- No protons / neutrons

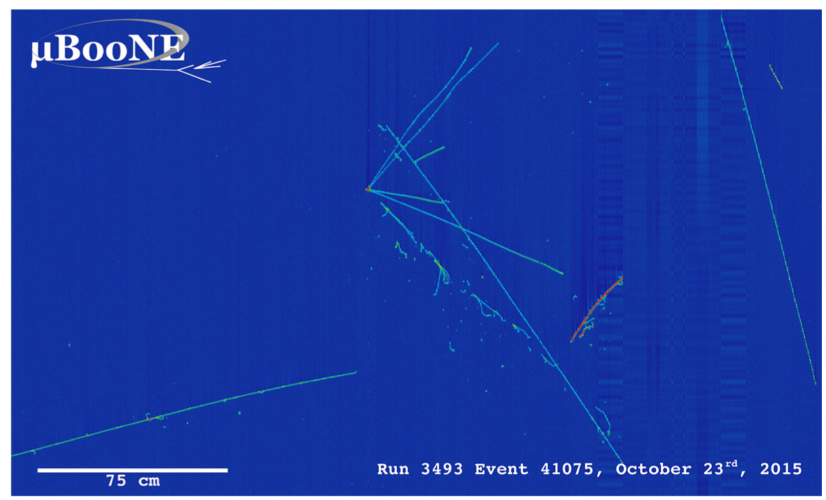
Tracking detectors:
- Charged particles +π^0
- [Progress towards neutrons]



Super-Kamiokande







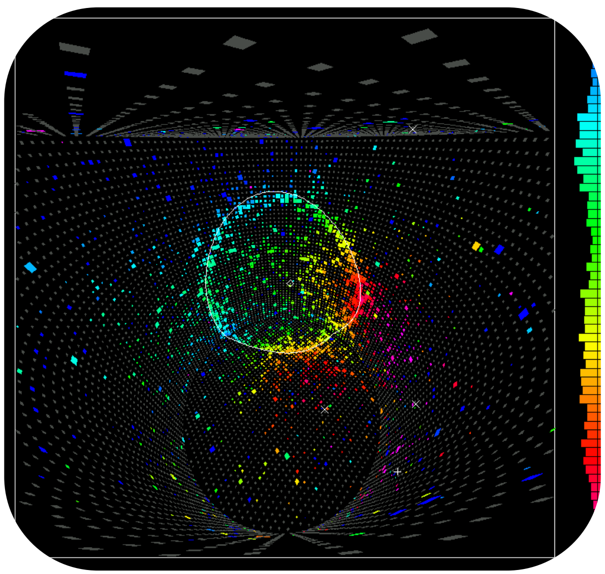
Final state detection approaches

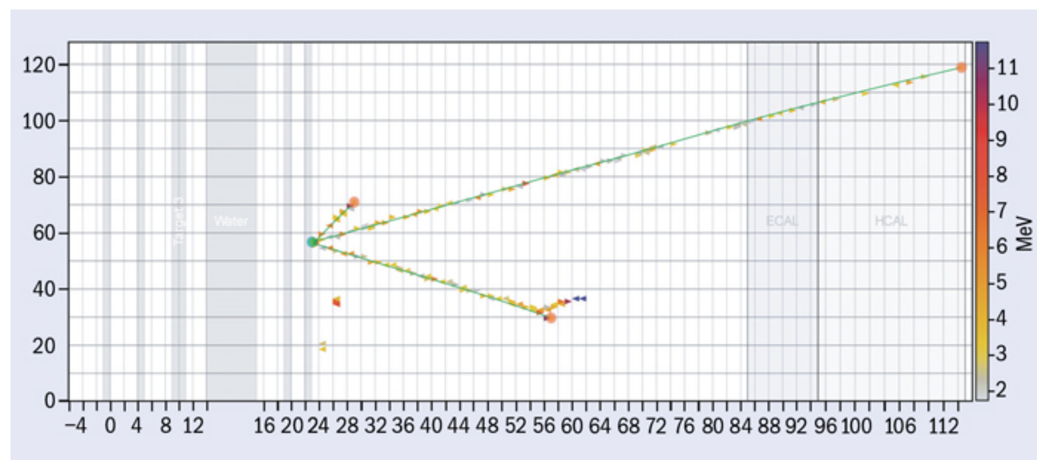
Cherenkov detectors:
- Electrons & Pions
- No protons / neutrons

$\Rightarrow$ E_ν Reconstruction from "QE" lepton kinematics.

Tracking detectors:
- Charged particles $+\pi^0$
- [Progress towards neutrons]

$\Rightarrow$ E_ν Reconstruction from 'full' final state.





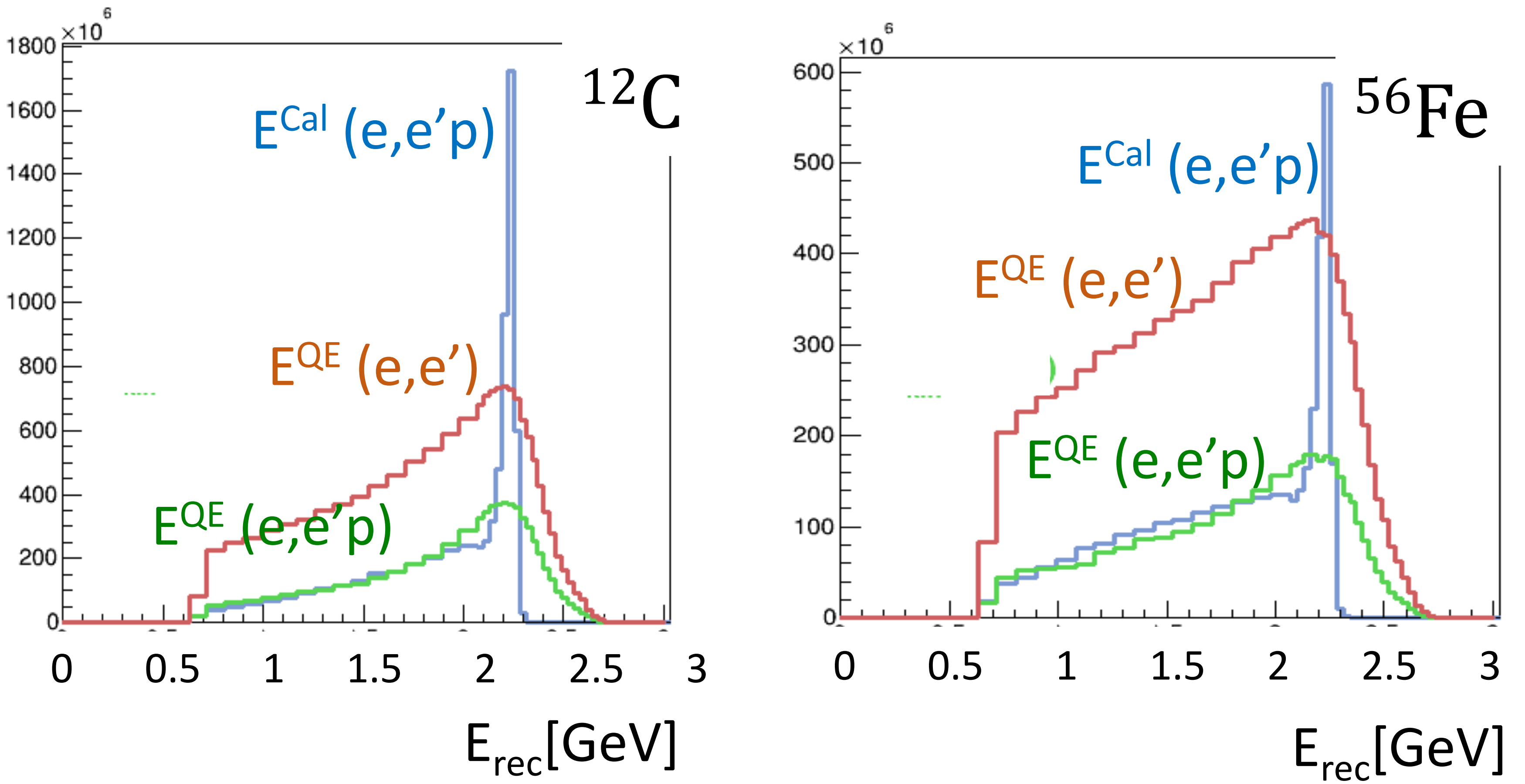
$$E_{QE} = \frac{2ME_l + 2M\varepsilon - m_l^2}{2(M - E_l + |k_l|\cos\theta)}$$

$$E_{cal} = E_l + E_p^{kin} + \varepsilon_B \text{ for (e,e'p)}$$

$\varepsilon, \varepsilon_B$ are effective binding energies

Energy Reconstruction Example

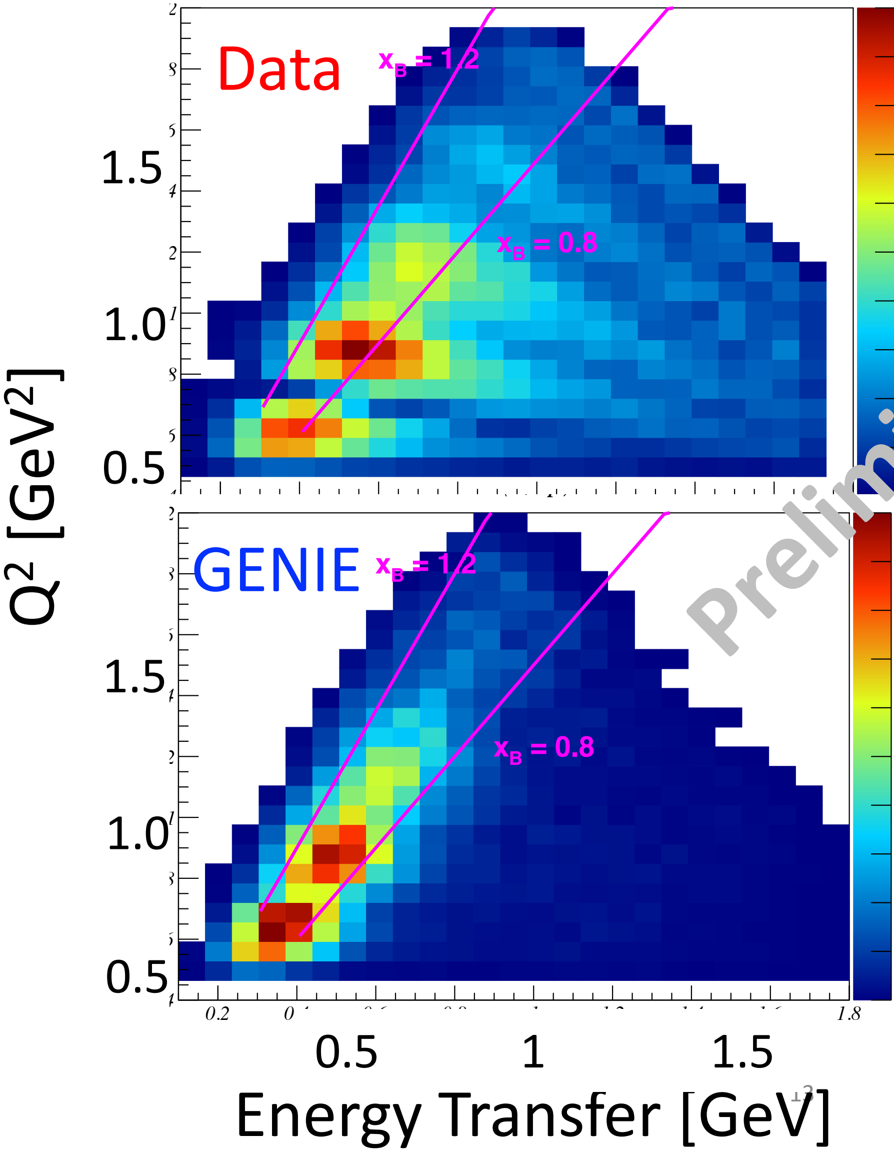
2.26 GeV beam   Zero pion events



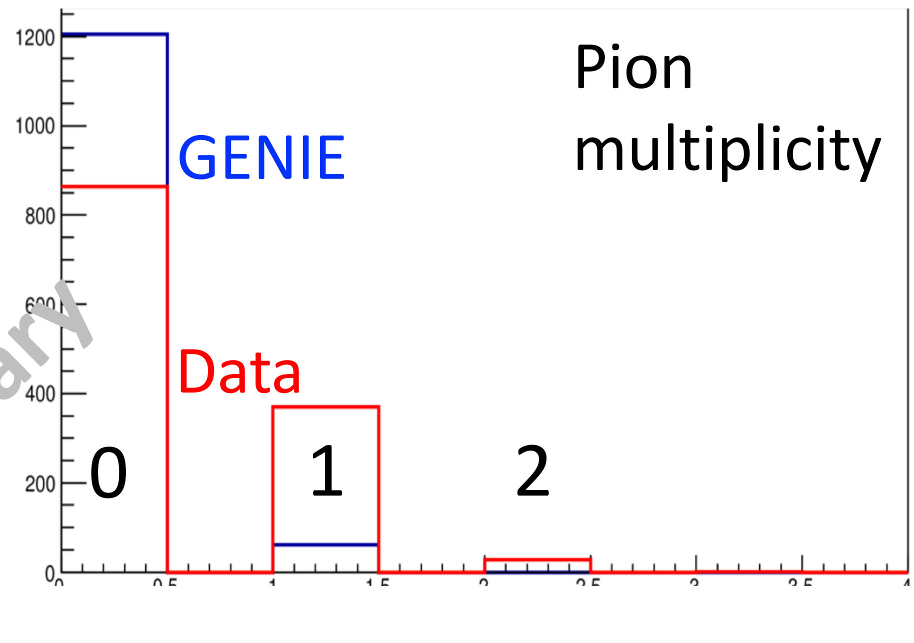
Even 0pi events have a LOT of non-QE events

Data-Generator Comparisons

C(e,e'p) 2.26 GeV
No x or W cuts



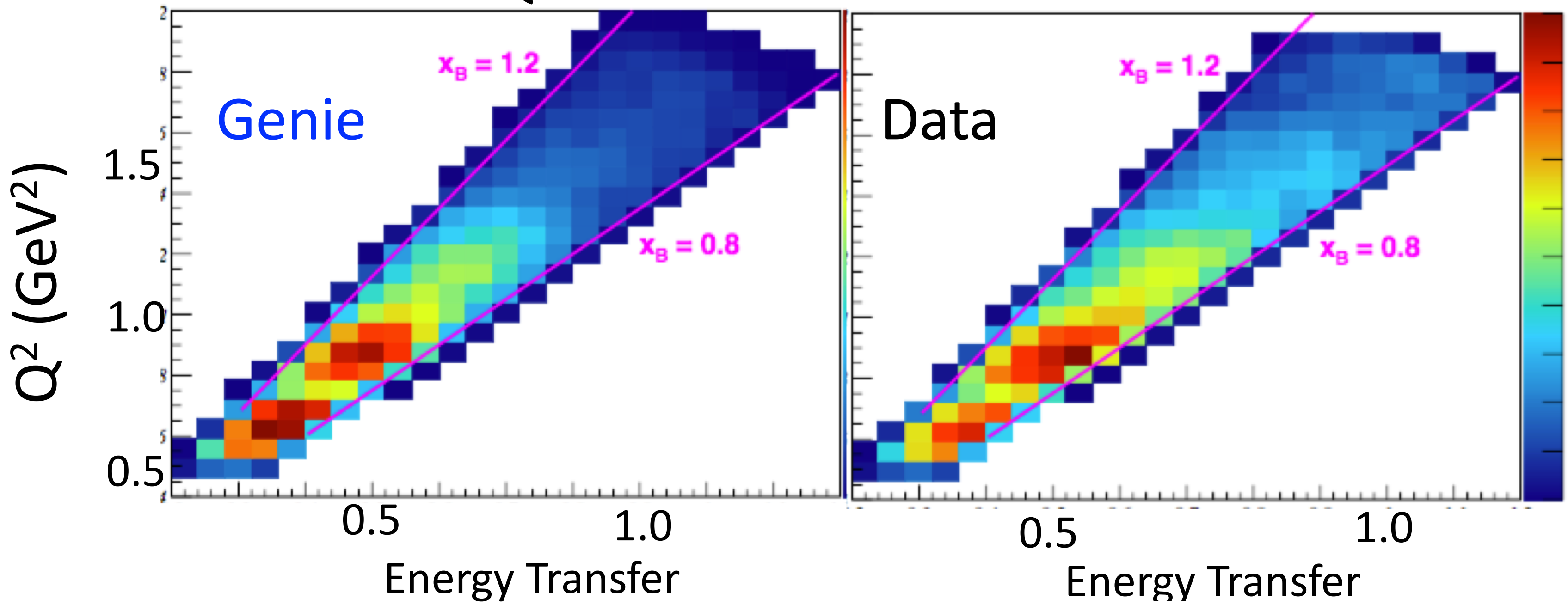
C(e,e'p) 4.46 GeV
0.8 < x < 1.2, W < 2 GeV

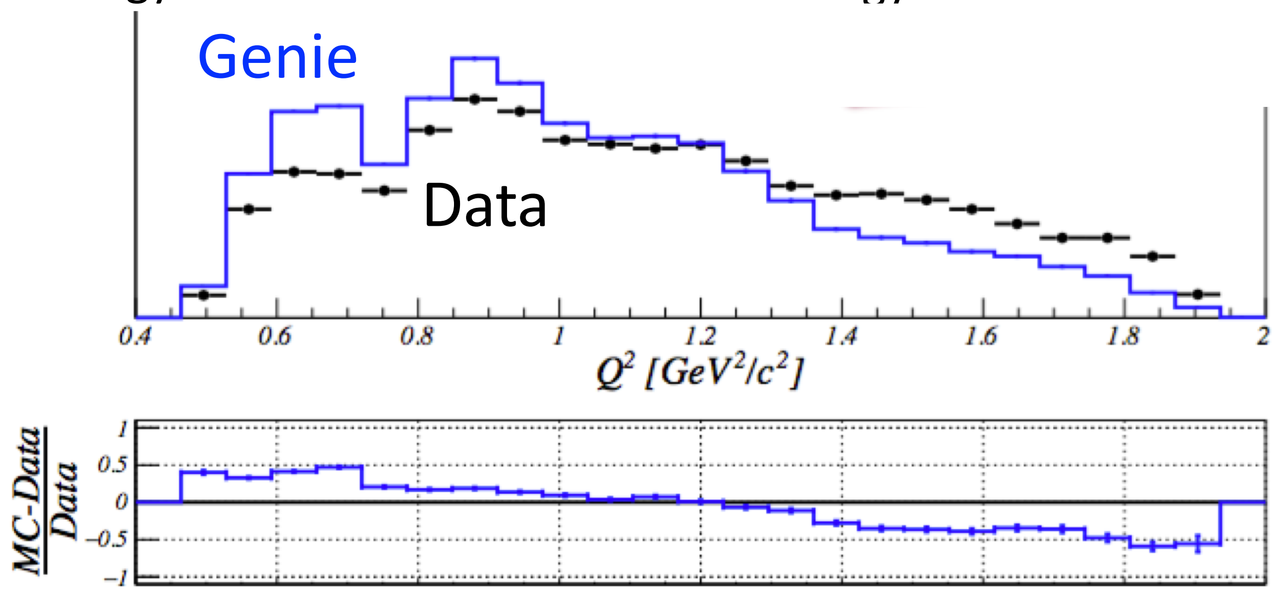


Data/Generator Comparisons

C(e,e'p) 2.26 GeV, 0.8 < x < 1.2

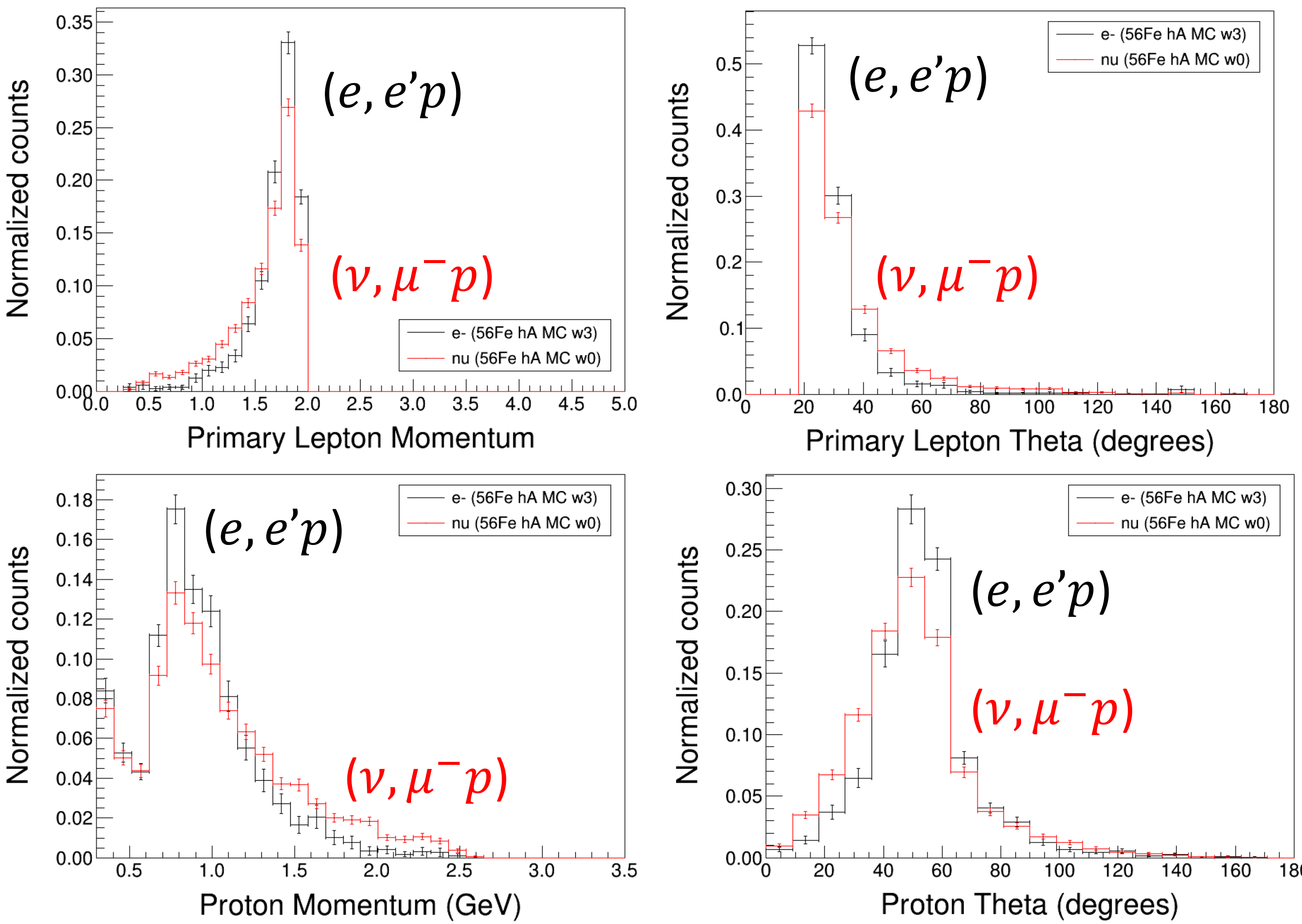
QE Peak: where Genie is best





Similarity of electron and neutrino GENIE

2.2 GeV Fe, zero-pion. QE



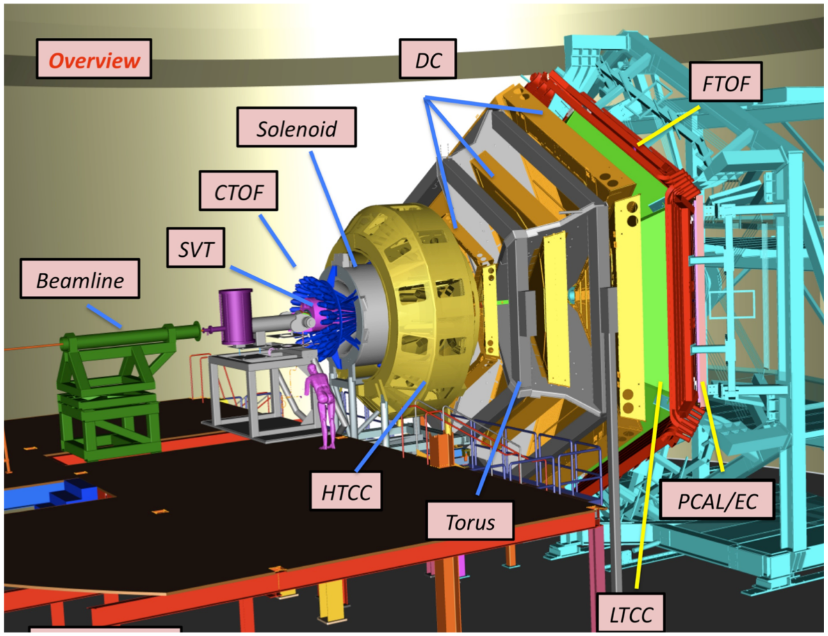
New Proposal: Systematic study!

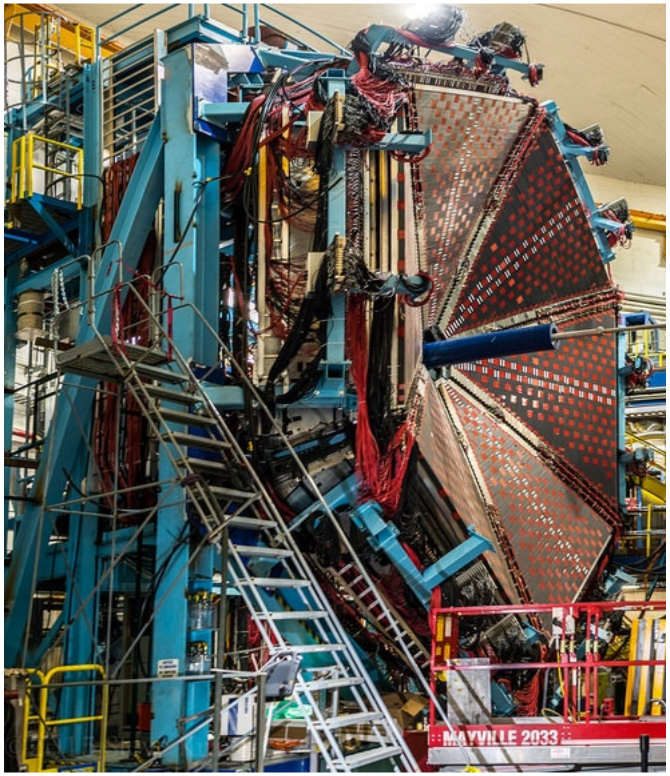
Targets:

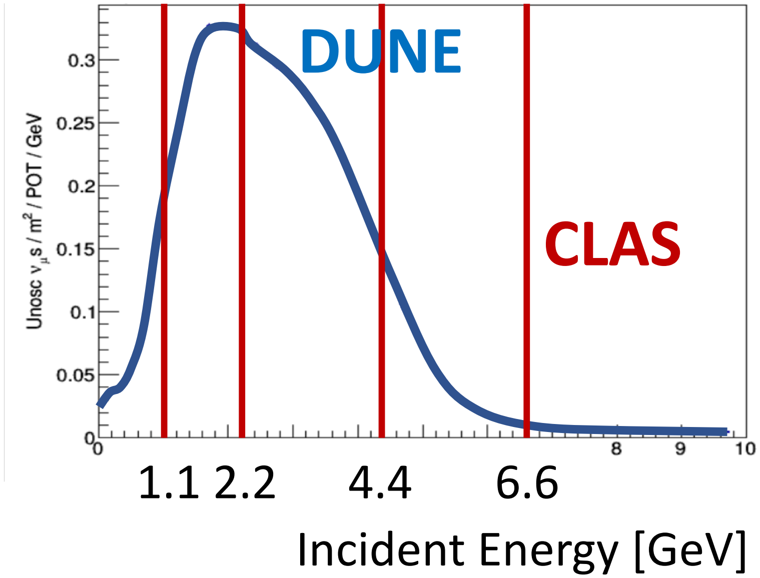
^{4}He, ^{12}C, ^{16}O, $\mathbf{^{40}Ar}$, ^{120}Sn

Beam Energies:

1.1, 2.2, 4.4, 6.6 GeV







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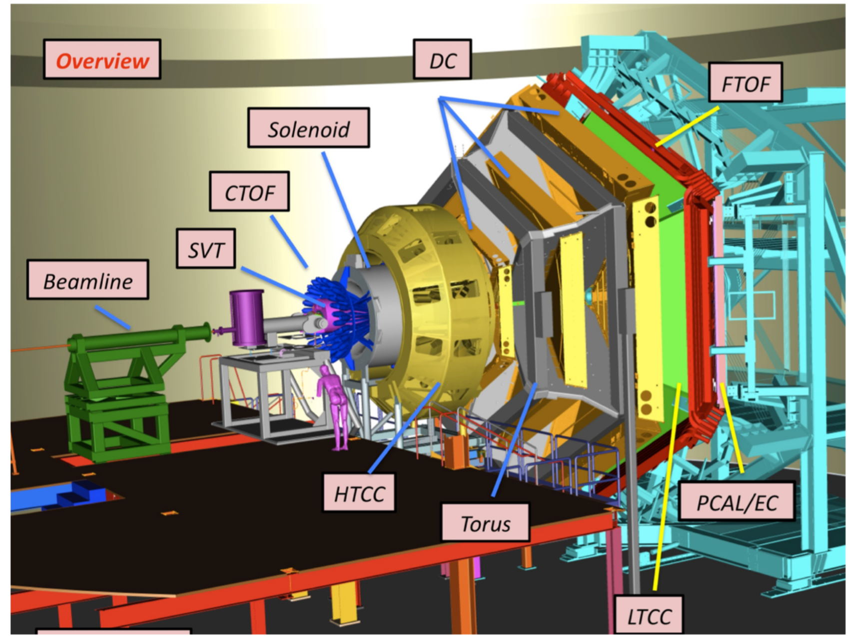
Beam Energies:

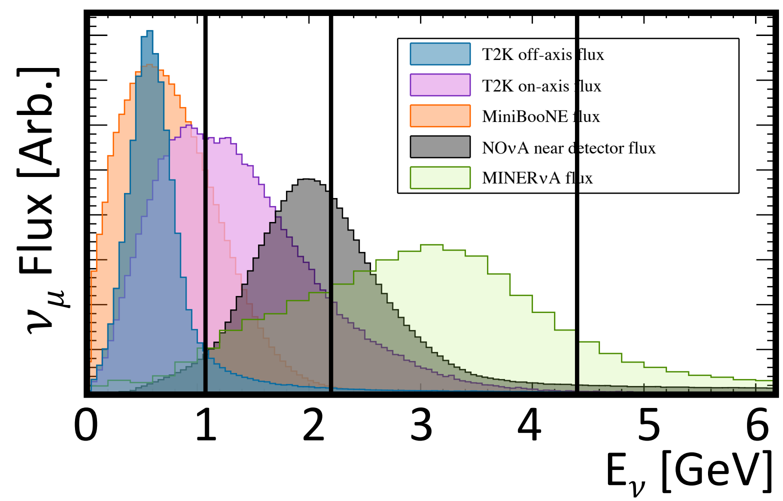
1.1, 2.2, 4.4, 6.6 GeV

CLAS12 Spectrometer:

- Luminosity: x10 higher than CLAS6 !
- Charged Particles: 5° – 120°
- Neutrons: 5° – 120° + 160° – 170°
- Threshold: ~300 MeV/c

=> High stat. semi-inclusive and exclusive data sets on multiple targets at multiple energies.





Unique hadronic models test!

Conditionally Approved by PAC45

Summary: The committee overall finds the proposed physics is well motivated, but (1) the actual measurements are in need of significant optimization. We are glad to see that neutrino and electron scattering physicists are working together on this proposal, which should lead to a better joint interpretation and use of the data. The committee was also impressed with the preliminary work done with CLAS6 data and with the plan discussed in the open session for evaluating neutrino simulation models using the proposed running. (2) We would like to see a preliminary application of the CLAS6 data (and possibly projected CLAS12 data) to neutrino models and (3) comparison of the improved models with one of the existing neutrino data samples (such as T2K, MINERvA, NOvA, or MiniBooNE). We believe the collaboration is more than capable of doing this before the next PAC meeting and that this would lead to a better optimized run plan. We therefore recommend C2 conditional approval.

“More traditional nuclear physics considerations may offer a stronger motivation for this [higher energy] beam setting.” – see SRC proposal next.

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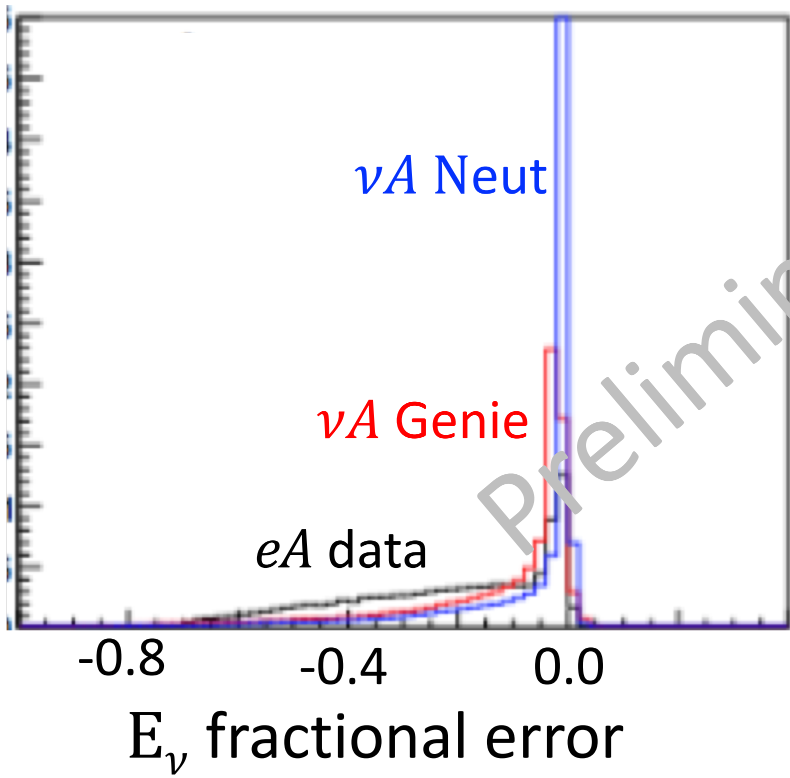
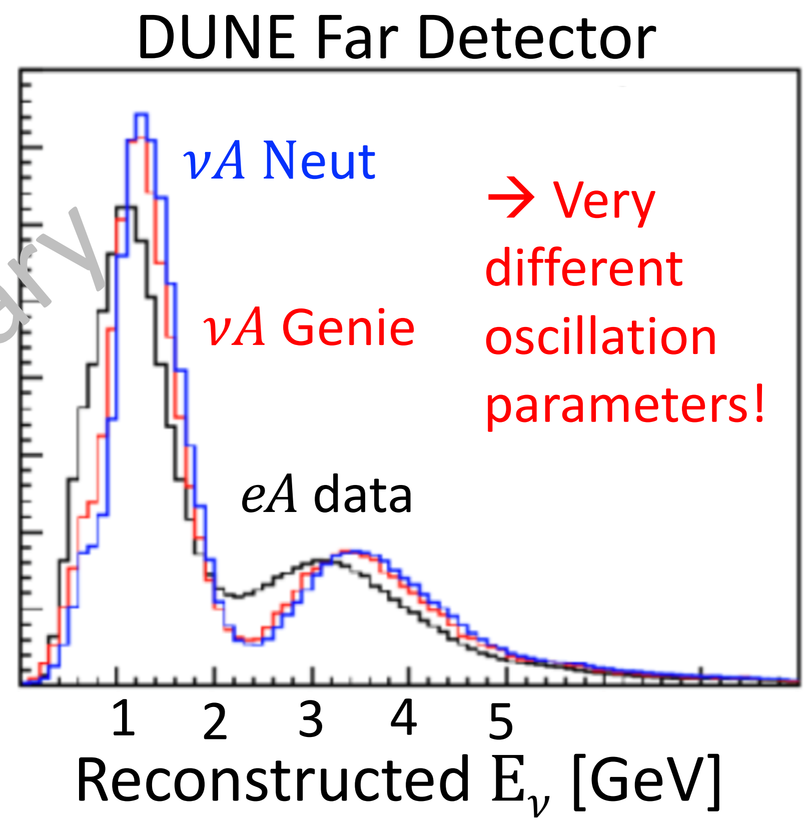
Changes to proposal

1. CLAS6 data applied to Dune oscillation analysis
2. Improvements to Genie
3. Compared data to Genie models
4. Optimized beam time request
5. Coordinated with SRC proposal

1. Apply CLAS data to DUNE Oscillation





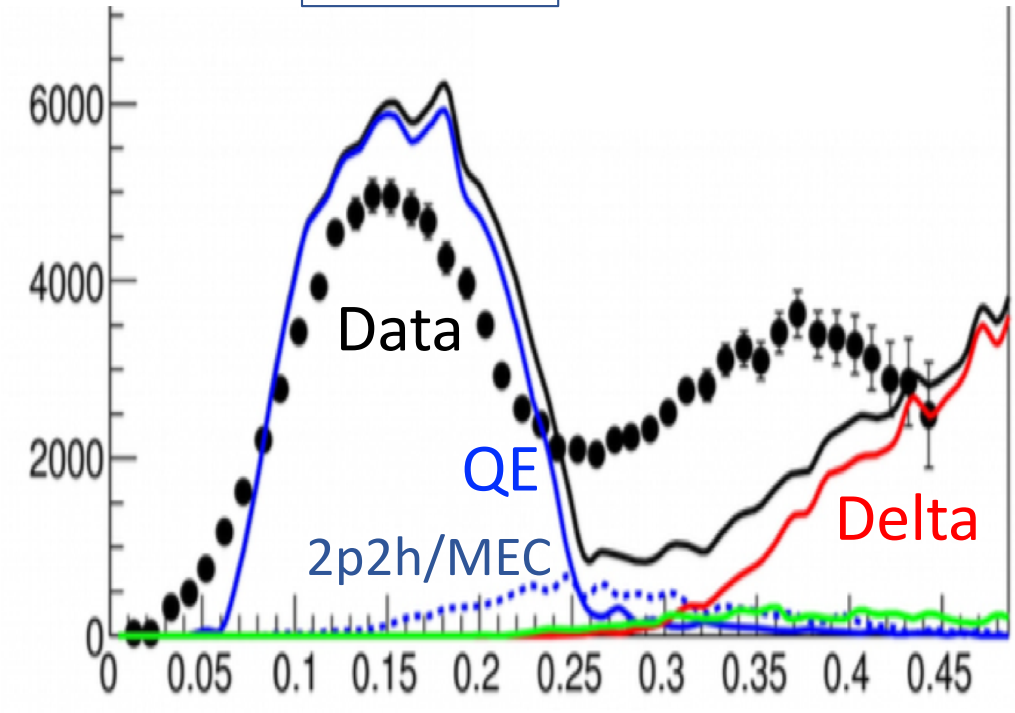
(Chris Marshall, LBNL)

- Proof of principle to show potential impact
- Threw events with νA Genie
  - Reconstructed with νA Neut or eA data
- Compared E_{rec} for eA to E_{rec} for νA
- Used 2.26 GeV eA E_{rec} for all incident energies

2: Improving Genie

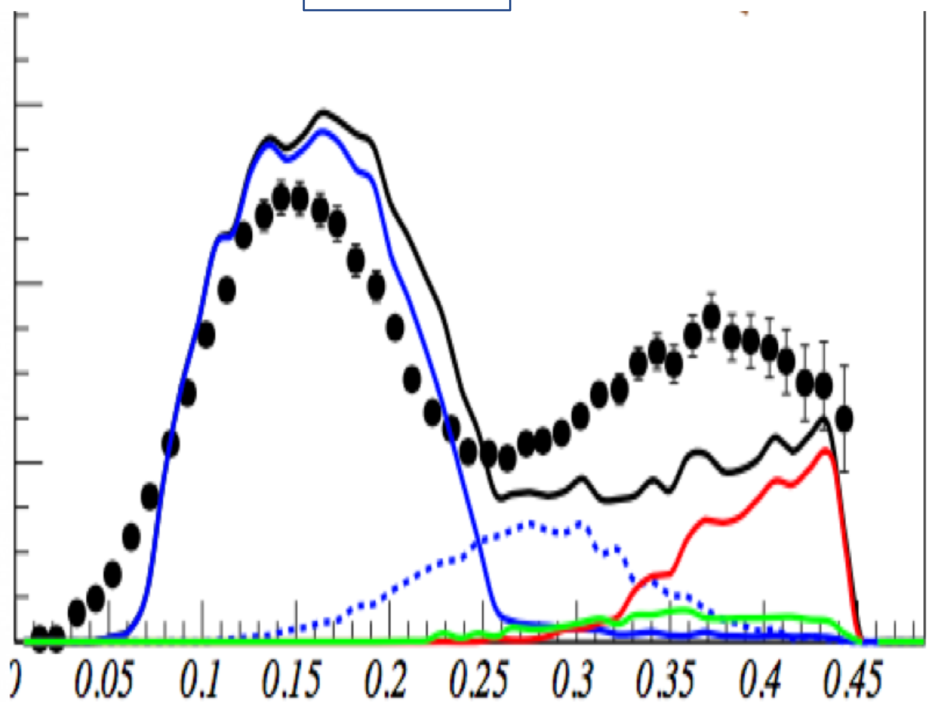
$$C(e,e') \text{ } 560 \text{ MeV } \theta = 60^{o}$$

Before



Energy Transfer [GeV]

After



Energy Transfer [GeV]

2: Improving Genie

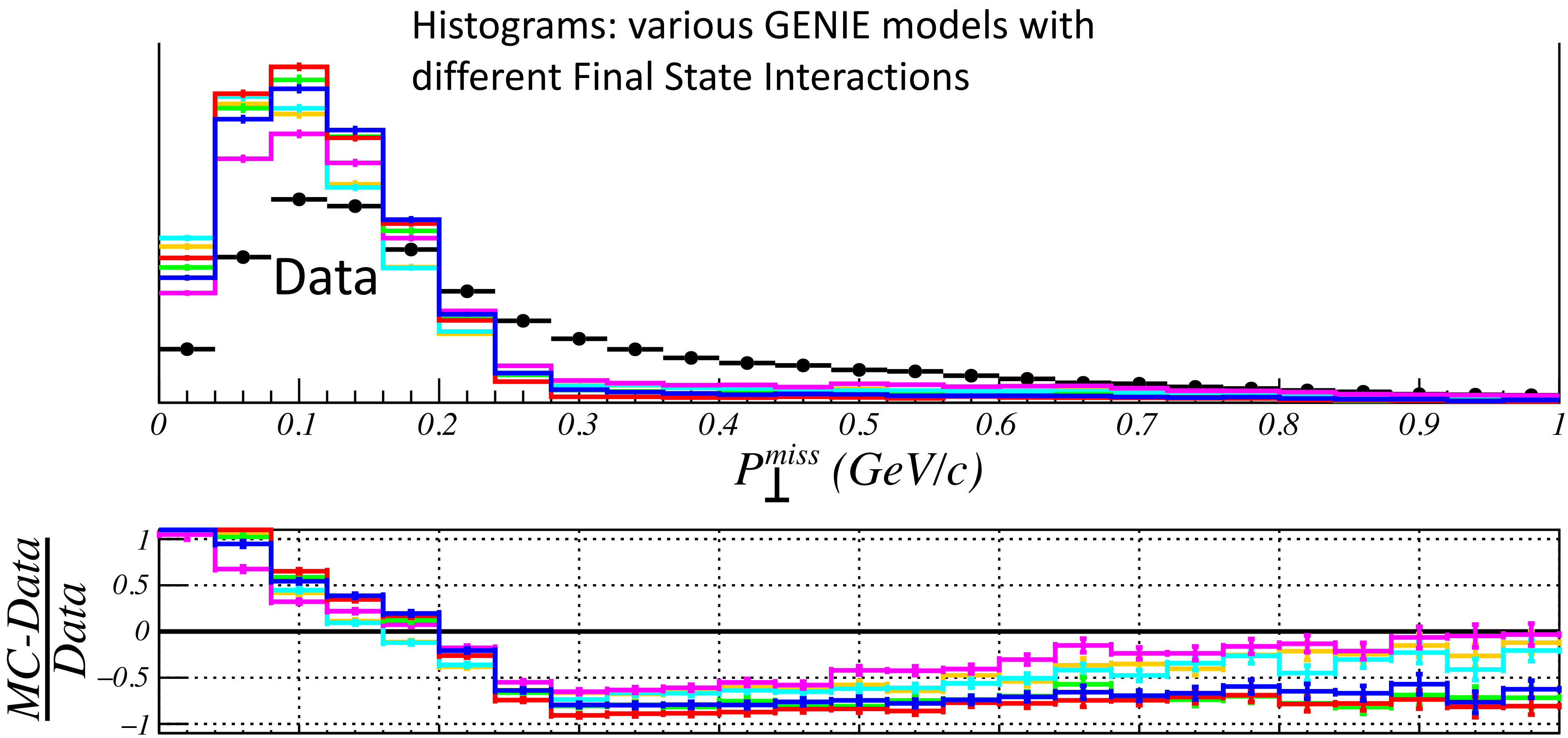
1. Corrected expression for Mott cross section in QE
2. MEC/2p2h
   1. Added boost back to lab frame
   2. Corrected mass for cluster of particles
   3. Corrected Form Factors
3. Resonance
   1. Replaced old calculation with GSL Minimizer (now gives correct peak location)
   2. Switched to Berger-Seghal model
   3. Used corrected coupling constant for EM interactions
4. Nucleon momentum distributions
   1. Switched to Local Fermi Gas Model

Beginning work on NuWro and GiBUU.
Consulting with the relevant experts on each code.

3. Comparing Data to Genie

C(e,e'p) 2.26 GeV,

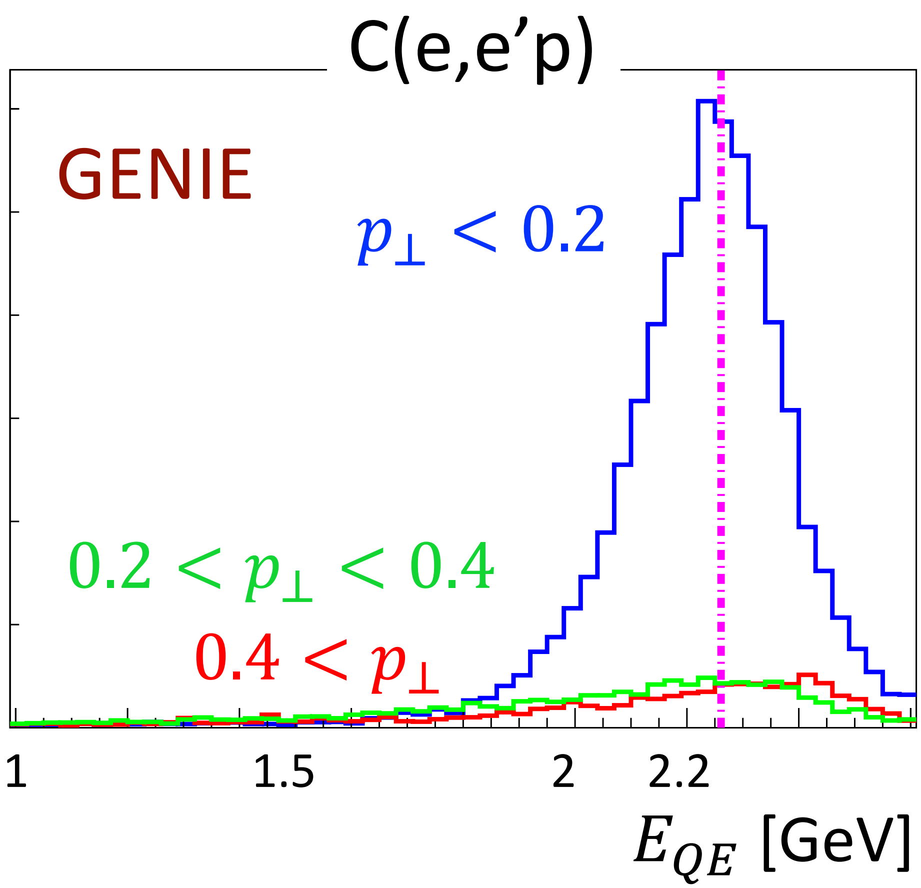
$Q^2 > 0.5$ GeV^2, W < 2 GeV

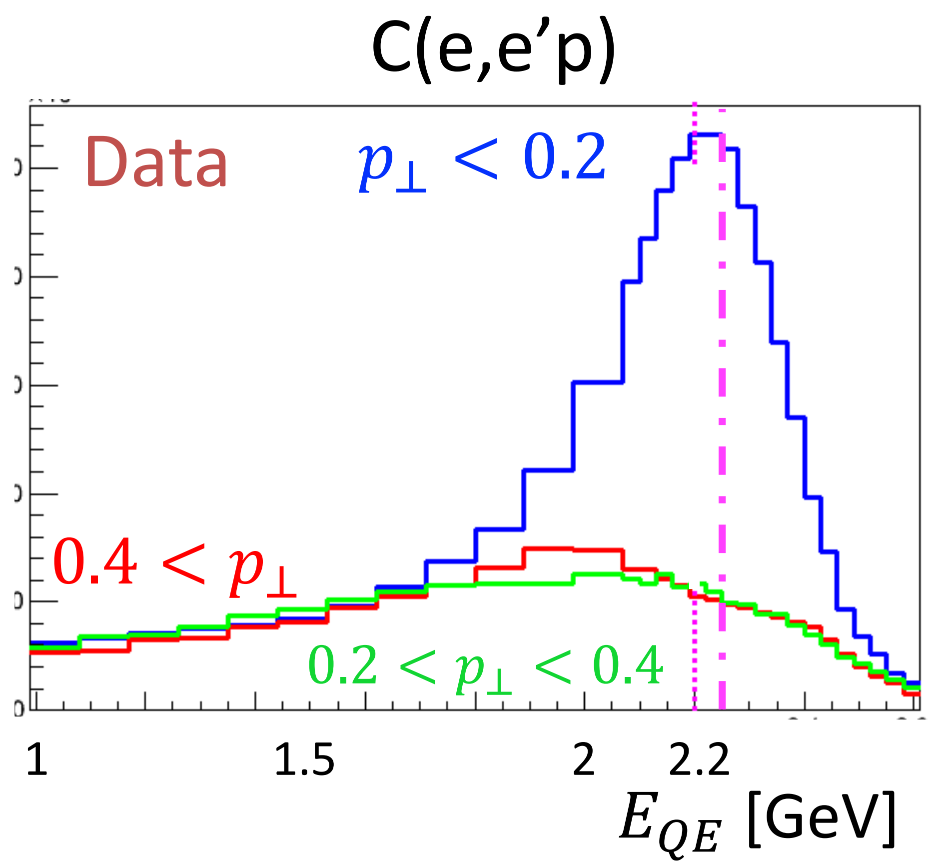


Significant differences at large $p_{\perp}$, none describe the data well

3. Comparing Data to GENIE: E_{beam} Reconstruction

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



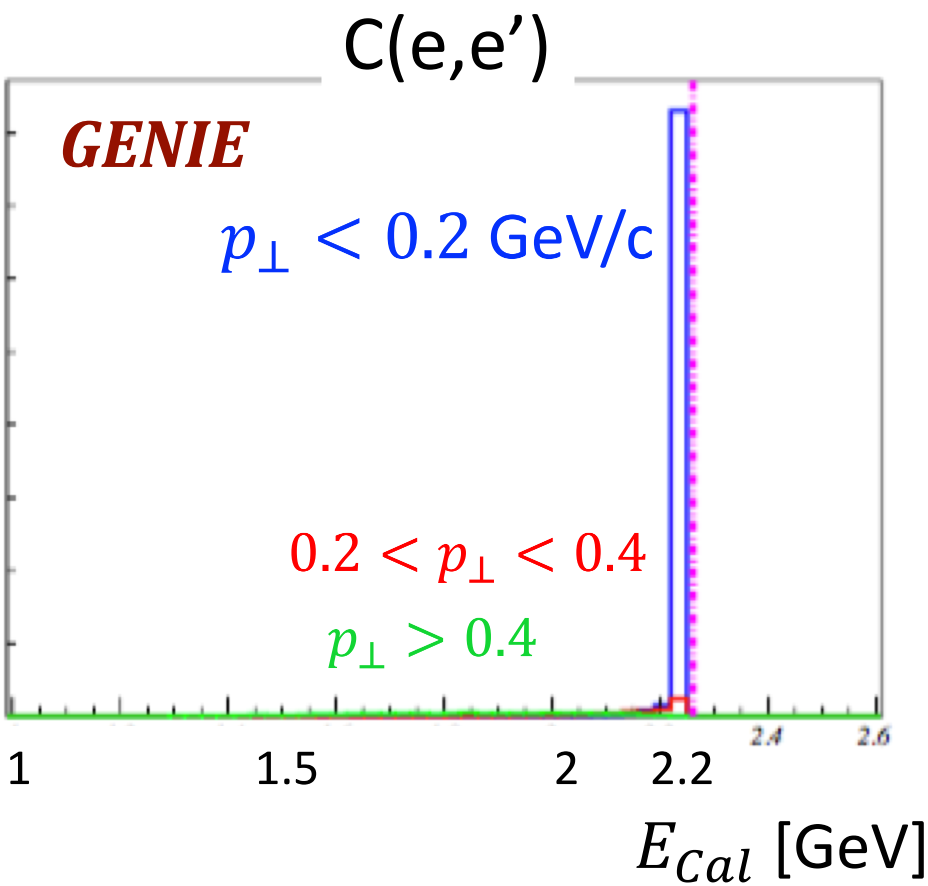


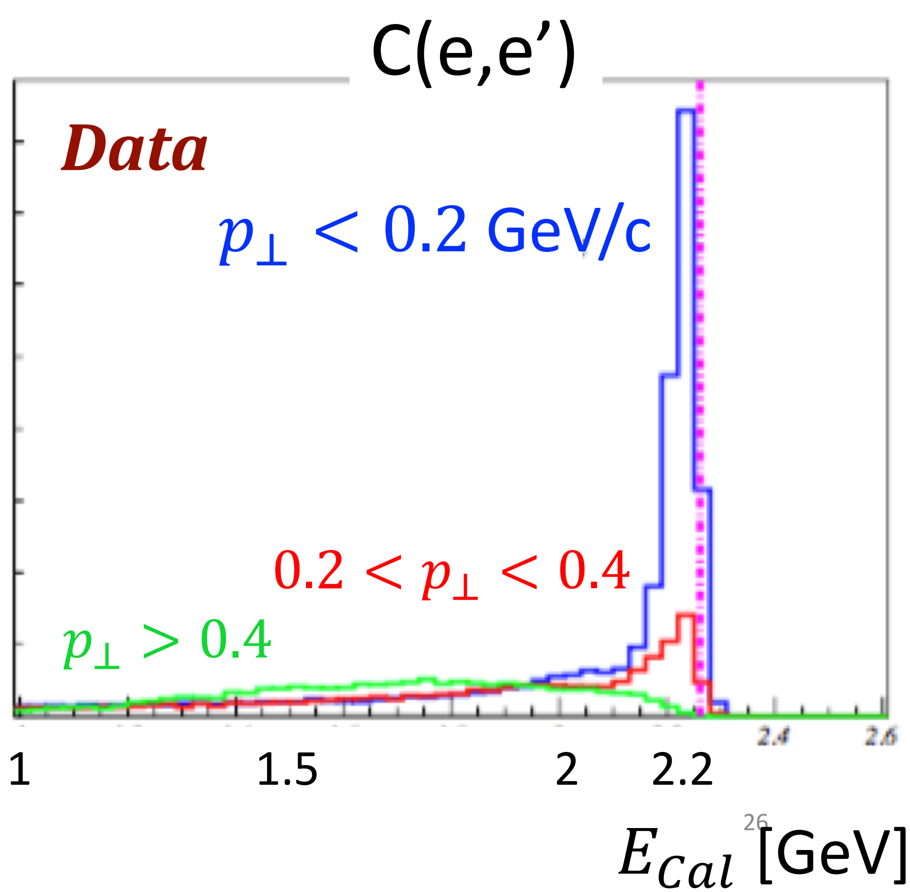
Peaks in same location

3. Comparing Data to Genie:

E_{beam} Reconstruction

$$E_{cal} = E_l + \Sigma E_p + \epsilon + \Sigma E_\pi$$





3. Comparing Data to Genie: E_{beam} Reconstruction

Fe	e^- Data	ν GENIE
2.2 GeV	26%	62%
4.4 GeV	14%	62%

Fraction of Fe$(e, e'p)$ and Fe$(\nu, \mu^- p)$ events with E_{Cal} within 5% of E_{beam}

4. Optimize Beam Time Request

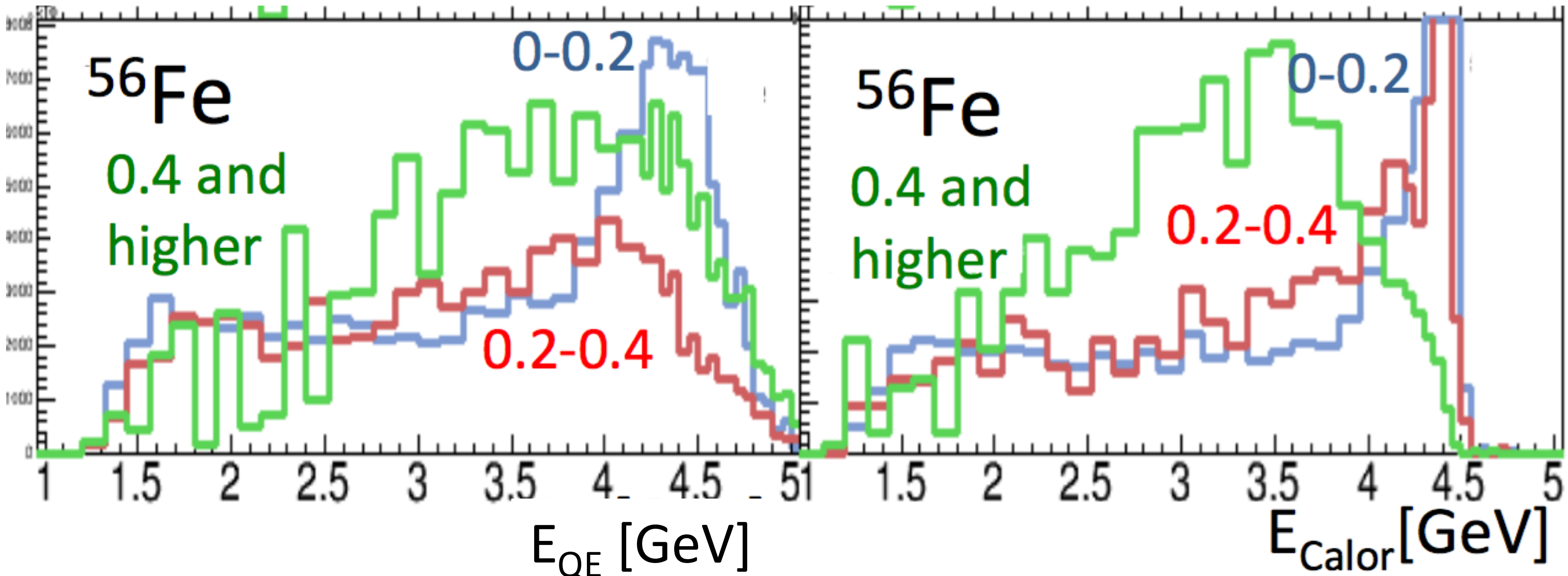
Energy [GeV]	H	^{4}He	^{12}C	^{16}O	^{40}Ar	^{120}Sn	Total
1.1	0.2	0.5	0.5	0.5	0.5	0.5	**2.7**
2.2	0.2	1	1	1	1	1	**5.2**
4.4	0.2	1	1	x	1	1	**4.2**
6.6	0.2	2	2	x	2	2	**8.2**
Total (days)	**1**	**4.5**	**4.5**	**1.5**	**4.5**	**4.5**	**20.5**

1.1 and 2.2 GeV: out-bending, Lower min Q^2

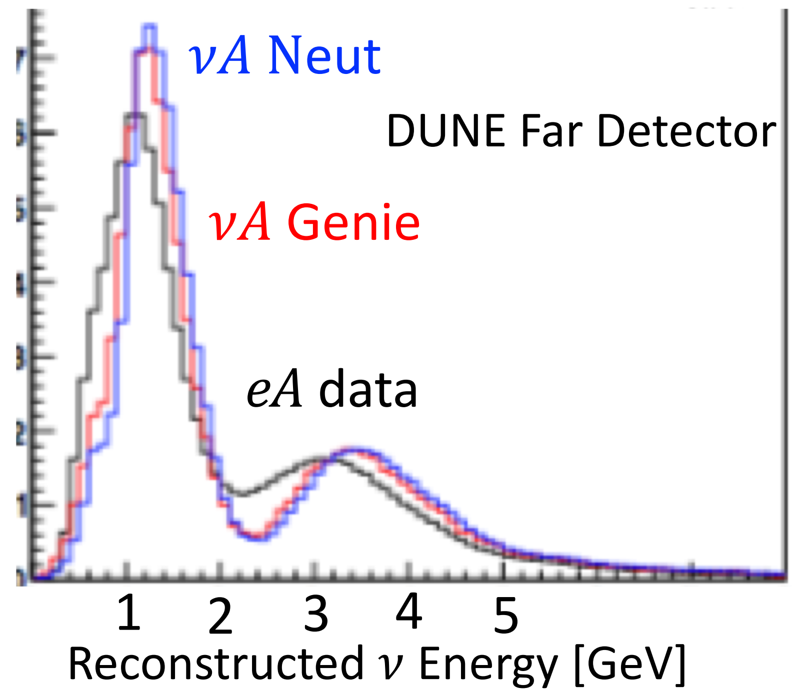
4.4 and 6.6 GeV: in-bending

- Reduced beam time request from 37.5 days to 20.5 days
- Focused on low and intermediate Q^2
  - Removed 8.8 GeV beam time
  - 1.1 and 2.2 GeV running now at reversed field

4. Optimize Beam Time Request



Error feeds directly into energy reconstruction plot and oscillation parameters



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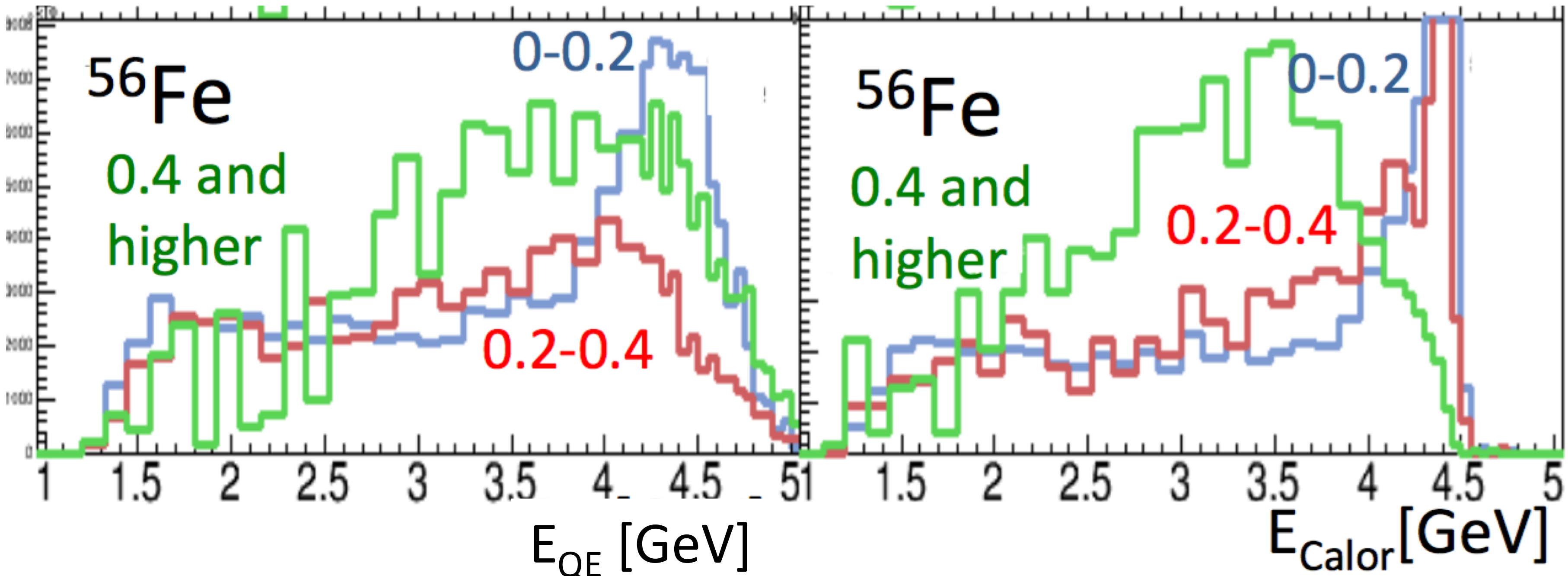
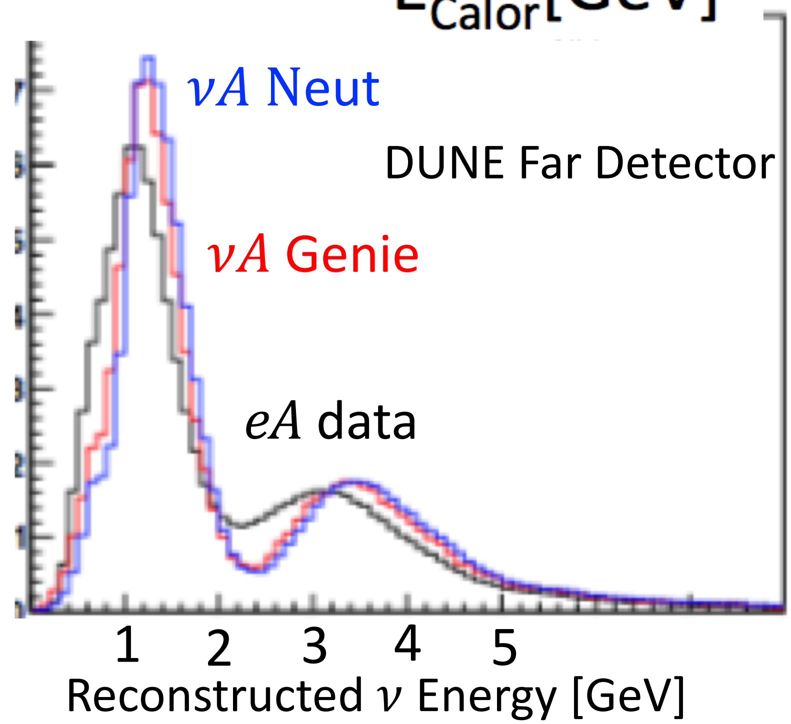


The requested beam time will double the CLAS6 statistics analyzed for $e4\nu$ (x20 for Fe). This will allow:

- Multiple Q2 bins to interpolate between beam energies to create continuous beam energy feed down plots.
- Multiple reaction channels (e,e'), (e,e'p), (e,e'n), (e,e'p pi), (e,e'pn), etc



5. Coordinate with SRC Proposal

This experiment: (C12-17-006) 20.5 PAC days + 3.5 days overhead

Energy (GeV)	4He	12C	16O	40Ar	Sn	Total
1.1	0.5	0.5	0.5	0.5	0.5	2.5
2.2	1	1	1	1	1	5
4.4	1	1	0	1	1	4
6.6	2	2	0	2	2	8
Total (days)	4.5	4.5	1.5	4.5	4.5	20.5+3.5

SRC program (PR12-18-003): 37 PAC days

Combined experiments: 43.5 PAC days + 6 days overhead

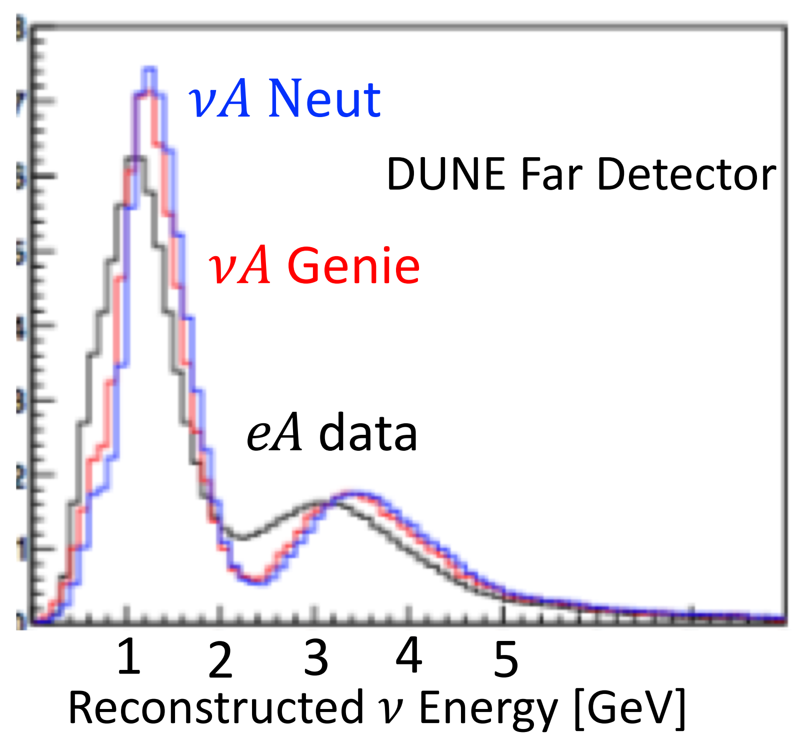
Energy	d	4He	C	O	28Si	40Ar	40Ca	48Ca	120Sn	208Pb	Total
1.1	X	0.5	0.5	0.5	X	0.5	X	X	0.5	X	2.5
2.2	X	1	1	1	X	1	X	X	1	X	5
4.4	2	1	1	X	X	1	X	X	1	1	7
6.6	5	3	2	X	2	2	3	3	4	5	29
Total (days)	7	5.5	4.5	1.5	2	4.5	3	3	6.5	6	43.5 +6*

Electrons 4 Neutrinos

High impact study of bias in neutrino oscillation analyses:

- Identify and correct biases due to incident energy reconstruction,
- Identify and correct biases due to neutrino event generators
  - Final State Interactions,
  - Resonance production,
  - Multinucleon effects (2p2h/MEC/SRC)

Summary of July Trento workshop: “MIT/ODU group’s comparisons to electrons is shining a harsh light on this model and motivating efforts to improve the situation.”



$e4\nu$ Team

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K. Mahn (MSU), L. Pickering (MSU), C. Marshall (LBNL)
M. Betancourt (FNAL)

Overwhelming Support

Fermilab

Hyper-Kamiokande

DUNE

IceCube
SOUTH POLE NEUTRINO OBSERVATORY

NOvA

MINERvA

T2K

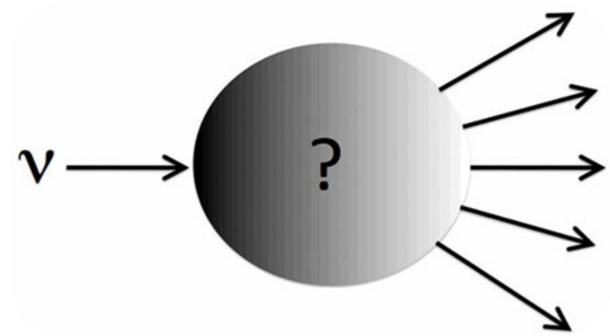
ANNIE
Accelerator Neutrino Neutron Interaction Experiment

µBooNE

GiBUU
The Giessen Boltzmann-Uehling-Uhlenbeck Project

JLab Argon - Titanium Experiment

Determining the Spectral Function from DATA



- In the absence of FSI

$$\frac{d\sigma_A}{dE_{e'}d\Omega_{e'}dE_p d\Omega_p} \propto \sigma_{ep} P(p_m, E_m)$$

- Kállën-Lehman representation

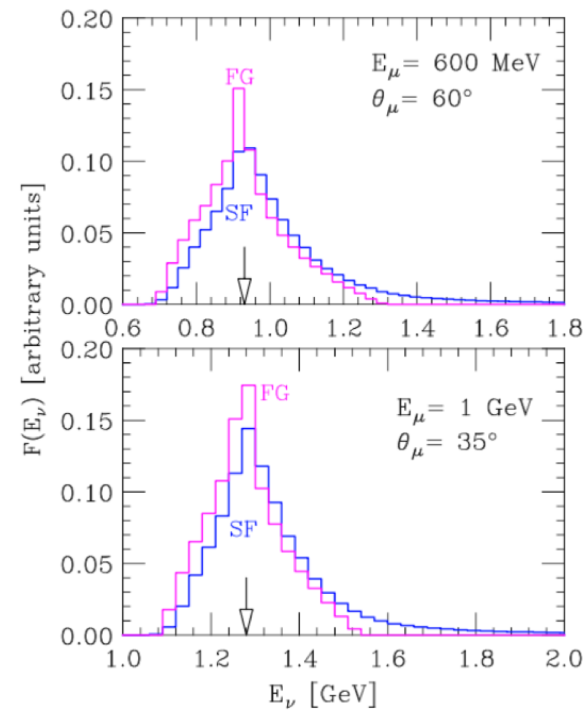
$$P(\mathbf{p}_m, E_m) = P_{\rm MF}(\mathbf{p}_m, E_m) + P_{\rm corr}(\mathbf{p}_m, E_m)$$

- In the kinematical region corresponding to knock-out from the shell-model states ($6 \lesssim E_m \lesssim 60$ MeV and $|\mathbf{p}_m| \lesssim 350$ MeV for Argon)

$$P_{\rm MF}(\mathbf{p}_m, E_m) = \sum_{\alpha \in \{F\}} Z_\alpha \, |\phi_\alpha(\mathbf{p}_m)|^2 \, F_\alpha(E_m - \epsilon_\alpha)$$

  Z_α and width of F_α obtained from the measured cross section.
  Neglecting correlations: $Z_\alpha \to 1$, $F_\alpha(E_m - \epsilon_\alpha) \to \delta(E_m - \epsilon_\alpha)$

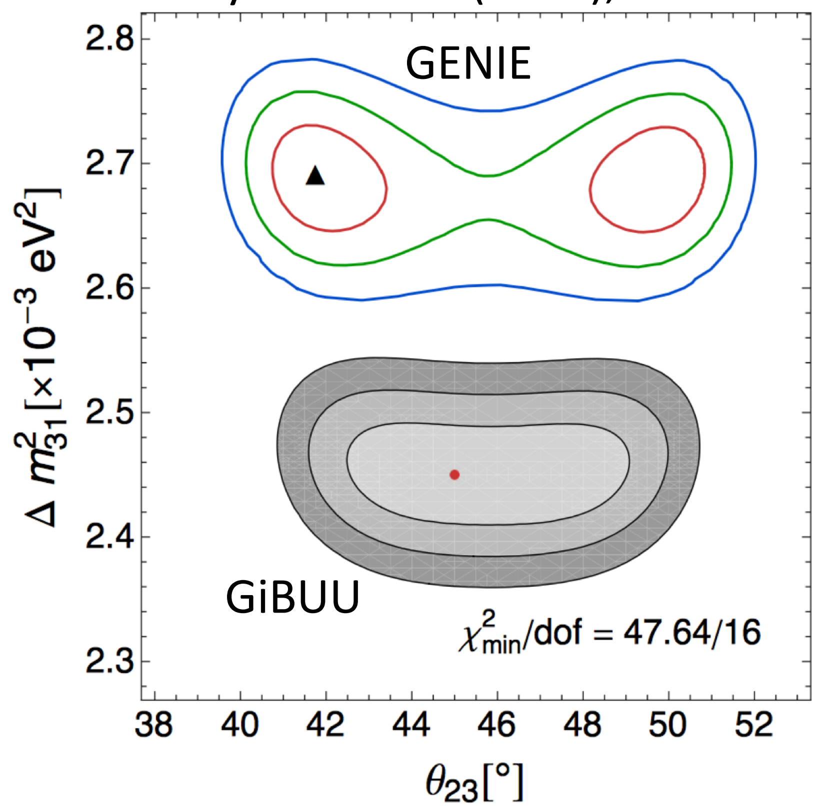
- $P_{\rm corr}(\mathbf{p}_m, E_m)$ from theoretical calculations of uniform nuclear matter and Local Density Approximation (LDA)



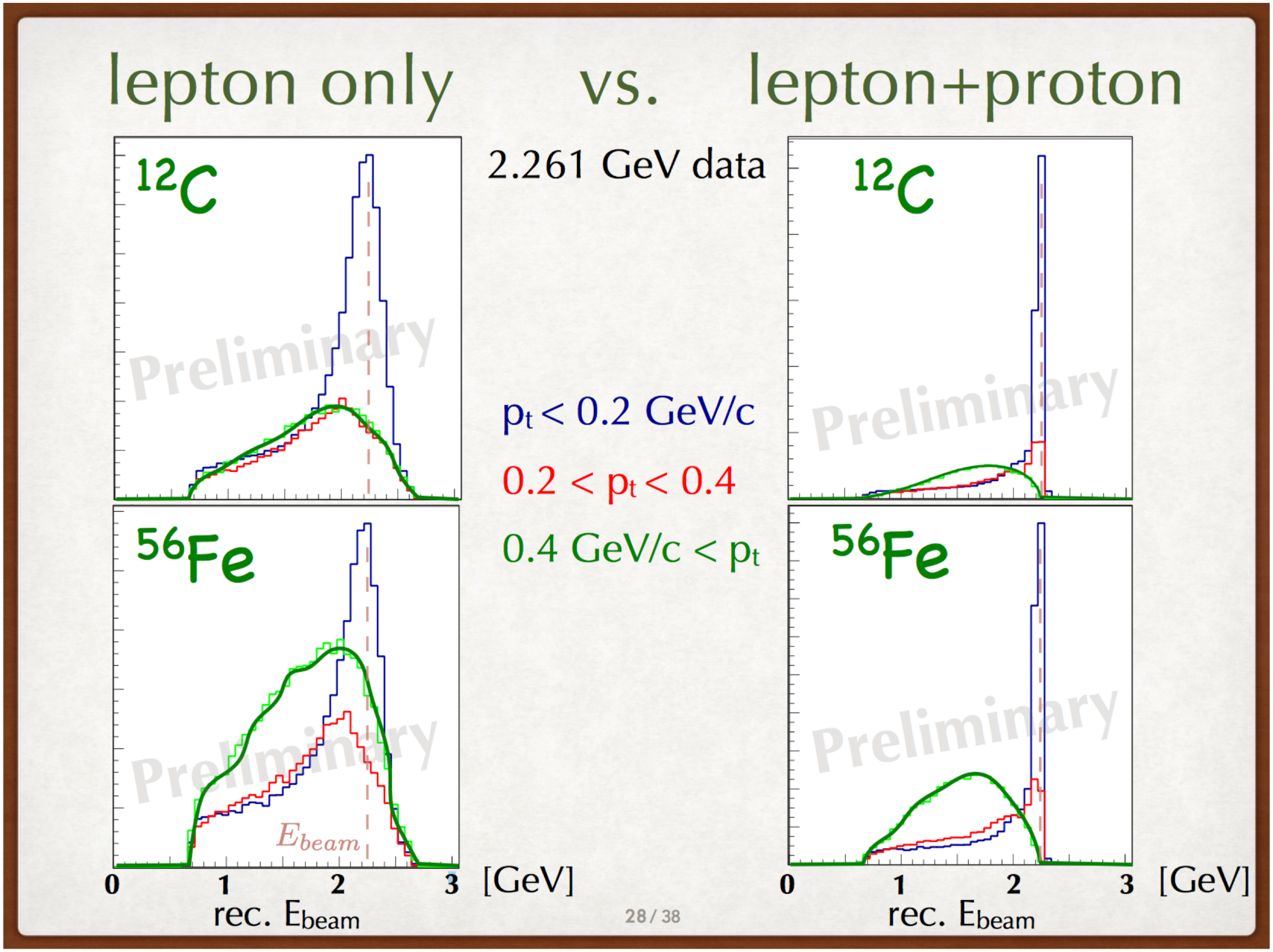
$$E_\nu = \frac{m_p^2 - m_\mu^2 - {E_n}^2 + 2E_\mu E_n - 2\mathbf{k}_\mu \cdot \mathbf{p}_n + |{\mathbf{p}_n}^2|}{2(E_n - E_\mu + |\mathbf{k}_\mu| \cos\theta_\mu - |\mathbf{p}_n| \cos\theta_n)}$$

Adapted from P. Pandey talk (July 2017)

Phys.Rev. D89 (2014), 073015



$$N_{FD}^{\alpha\to\beta}(\mathbf{p}_{reco}) = \sum_i \phi_\alpha(E_{true}) \times \sigma_\beta^i(\mathbf{p}_{true}) \times P_{\alpha\beta}(E_{true}) \times \epsilon_\beta(\mathbf{p}_{true}) \times R_i(\mathbf{p}_{true};\mathbf{p}_{reco})$$



How relative errors matter in a generic oscillation analysis

$$N_{FD}^{\alpha\to\beta}(\mathbf{p}_{reco}) = \sum_i \phi_\alpha(E_{true}) \times \sigma_\beta^i(\mathbf{p}_{true}) \times P_{\alpha\beta}(E_{true}) \times \epsilon_\beta(\mathbf{p}_{true}) \times R_i(\mathbf{p}_{true};\mathbf{p}_{reco})$$

Far detector rate used to determine oscillation (P)

- Flux (Φ), cross section processes (σ), efficiency (ϵ)
- Correct association of reconstructed objects to true kinematics of an event (R)

$$N_{ND}^{\alpha}(\mathbf{p}_{reco}) = \sum_i \phi_\alpha(E_{true}) \times \sigma_\alpha^i(\mathbf{p}_{true}) \times \epsilon_\alpha(\mathbf{p}_{true}) \times R_i(\mathbf{p}_{true};\mathbf{p}_{reco})],$$

This proposal provides an important **test of the response function:**

- Current experiments attempt to validate the data with neutrino measurements at different energies; indirect and limited by model assumptions
- Near detectors are important, but do not test this directly.

How relative errors matter in a generic oscillation analysis

$$N_{FD}^{\alpha\to\beta}(\mathbf{p}_{reco}) = \sum_i \phi_\alpha(E_{true}) \times \sigma_\beta^i(\mathbf{p}_{true}) \times P_{\alpha\beta}(E_{true}) \times \epsilon_\beta(\mathbf{p}_{true}) \times R_i(\mathbf{p}_{true};\mathbf{p}_{reco})$$

Far detector rate used to determine oscillation (P)

- Flux (Φ), cross section processes (σ), efficiency (ϵ)
- Correct association of reconstructed objects to true kinematics of an event (R)

$$N_{ND}^{\alpha}(\mathbf{p}_{reco}) = \sum_i \phi_\alpha(E_{true}) \times \sigma_\alpha^i(\mathbf{p}_{true}) \times \epsilon_\alpha(\mathbf{p}_{true}) \times R_i(\mathbf{p}_{true};\mathbf{p}_{reco})|,$$

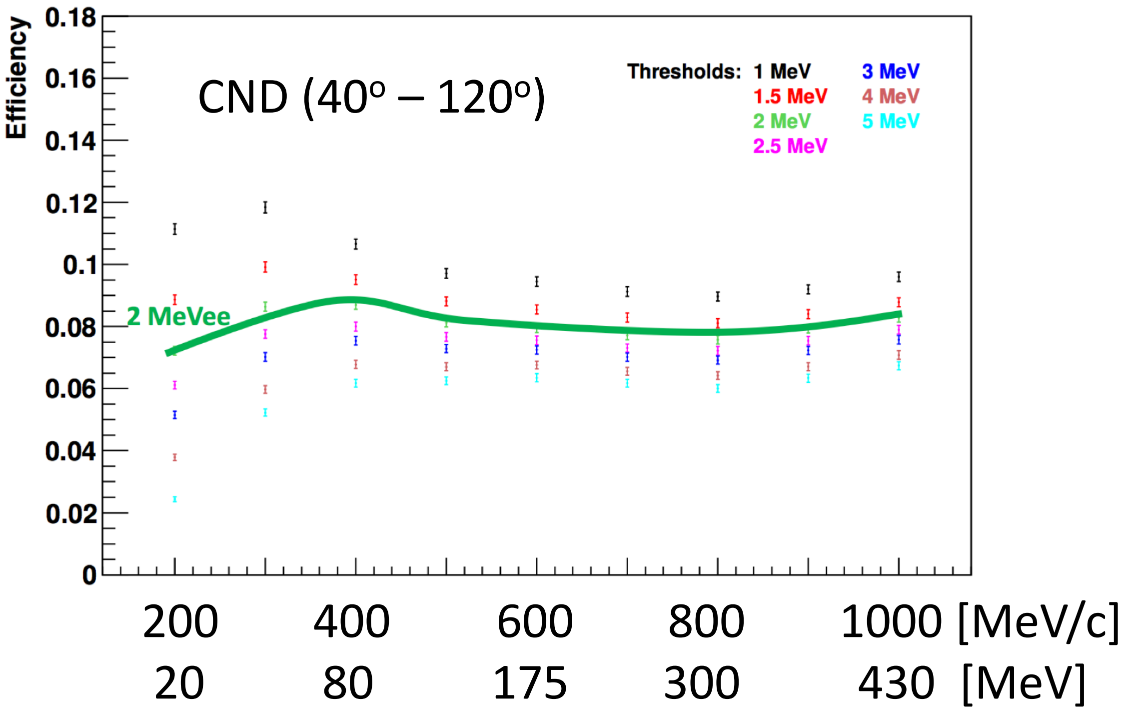
Near detector provides partial cancellation of all uncertainties through rate with a different flux:

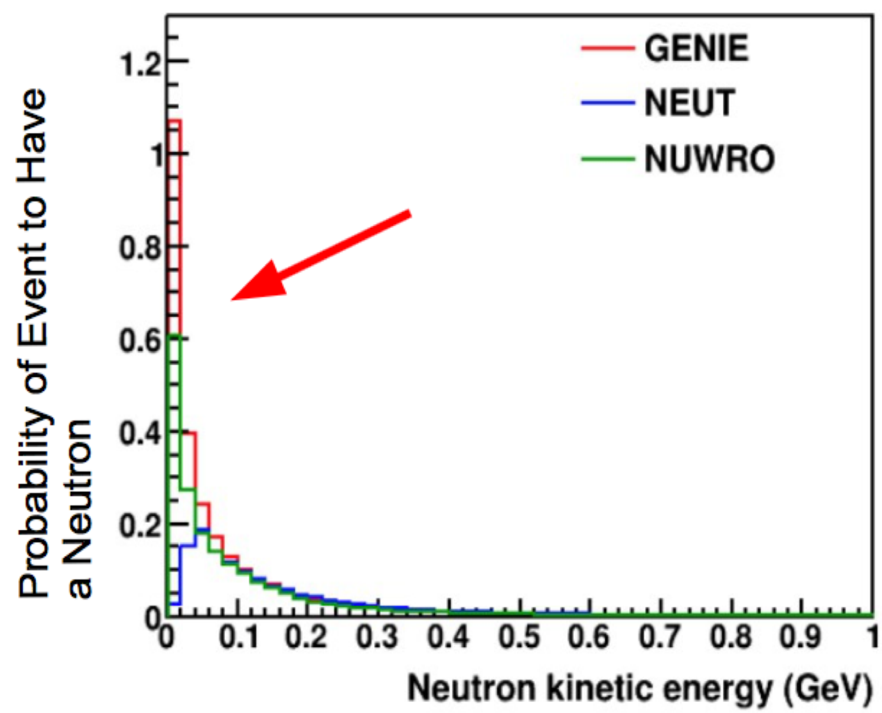
- T2K: ~5% total uncertainty, starting from ~10% flux uncertainties and 10-30% cross sections. Relies on correct models and ingredients.

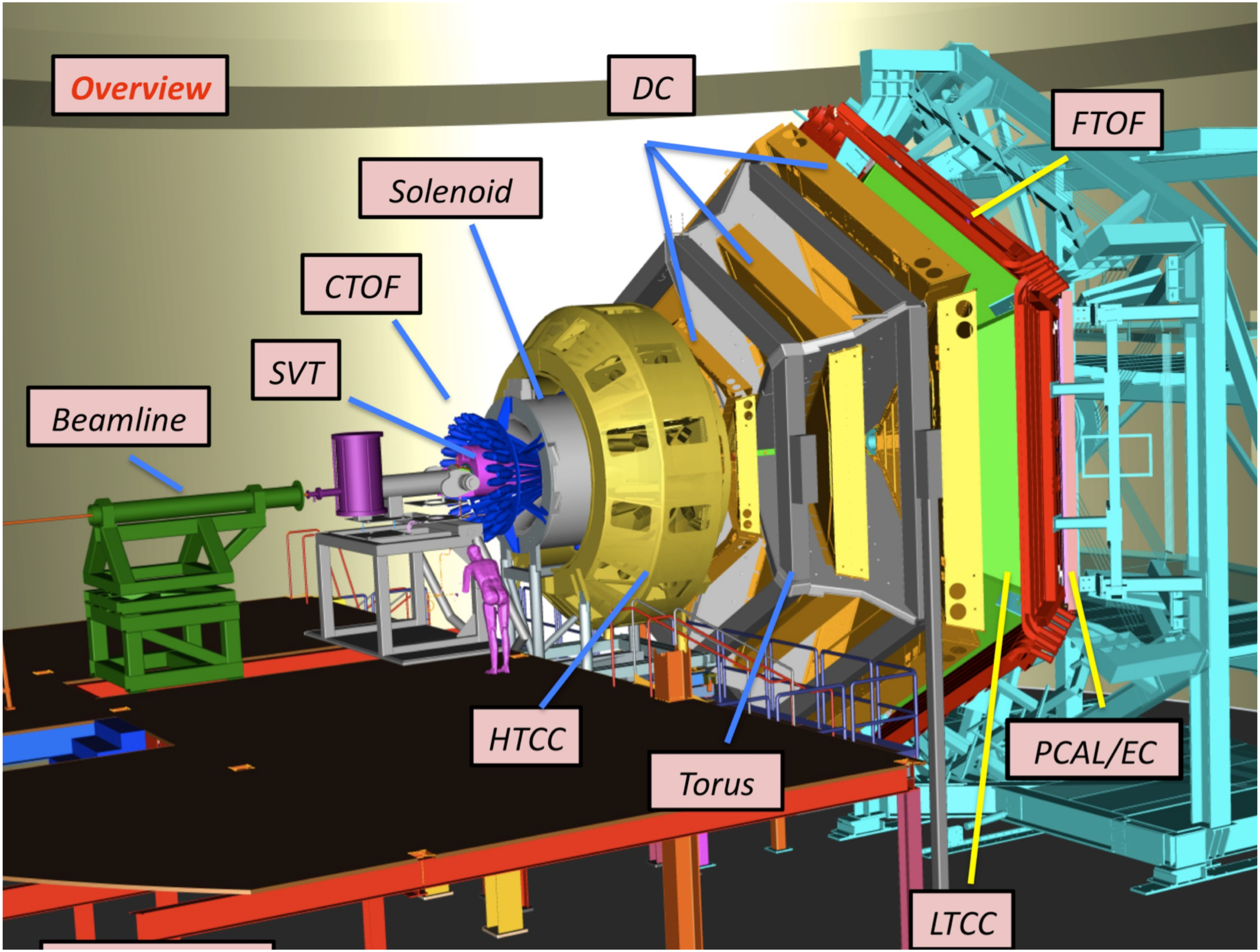
This proposal is like another near detector. Provide third rate, with unique handles of vector coupling, known beam energy and ability to separate processes.

- Relies on relative errors between beam configurations, targets
- Controllable thorough identical detector and well characterized beam

Neutron Multiplicity



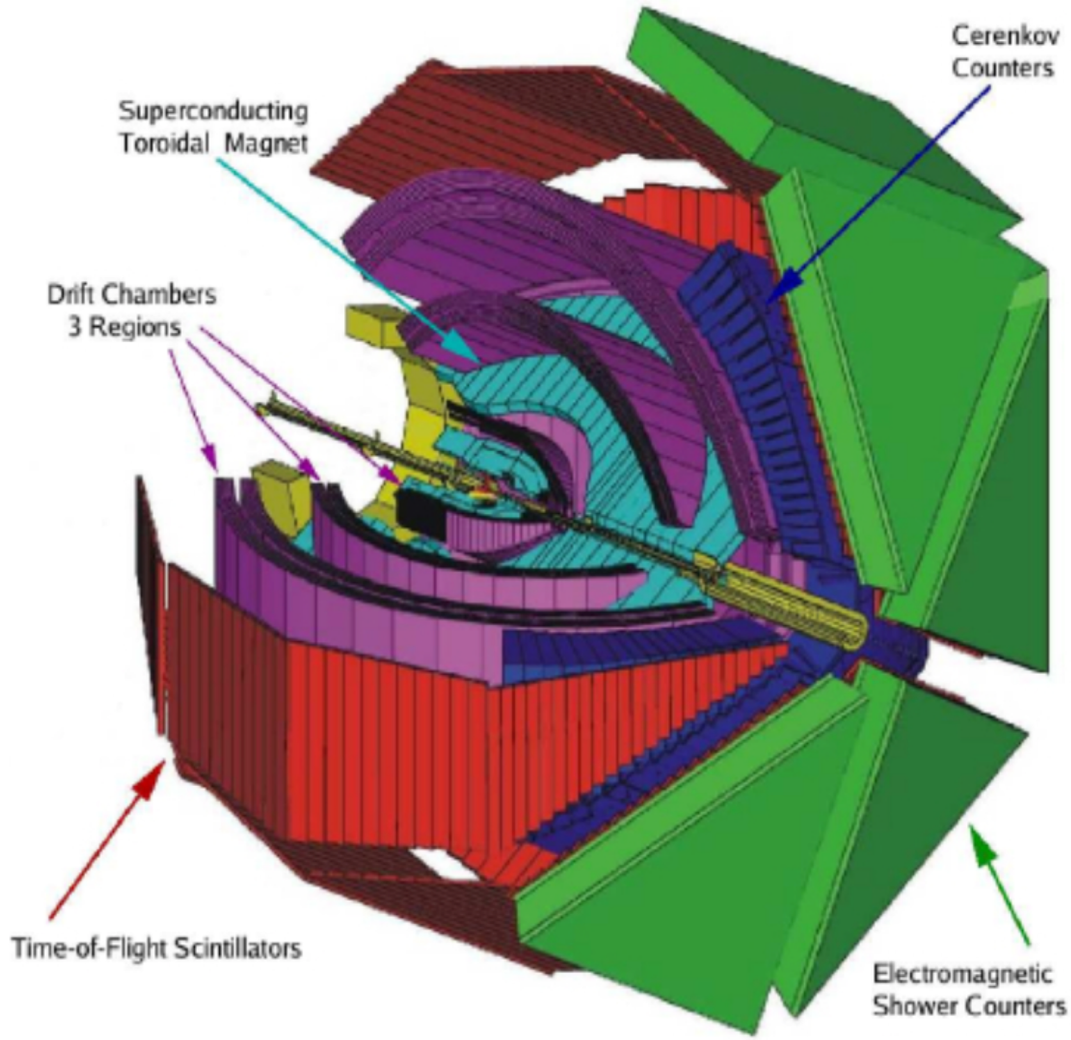




Overview
DC
FTOF
Solenoid
CTOF
SVT
Beamline
HTCC
Torus
PCAL/EC
LTCC

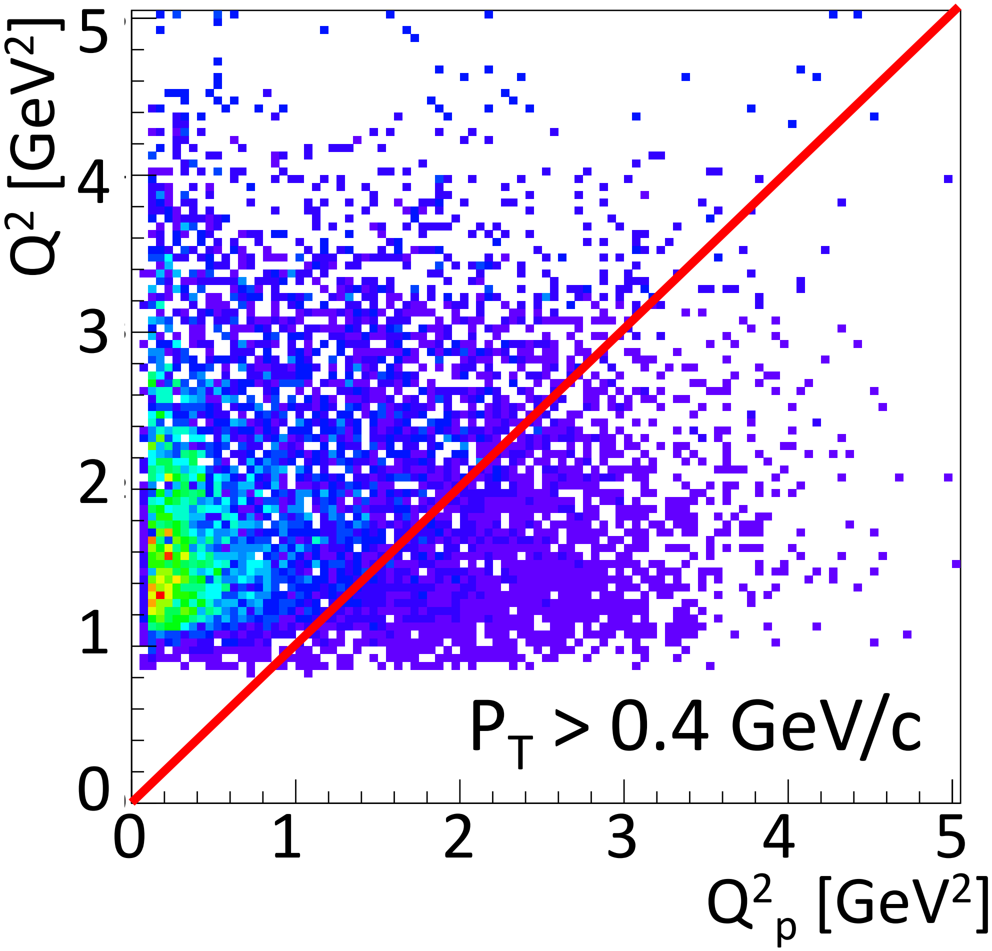
CLAS6 Spectrometer

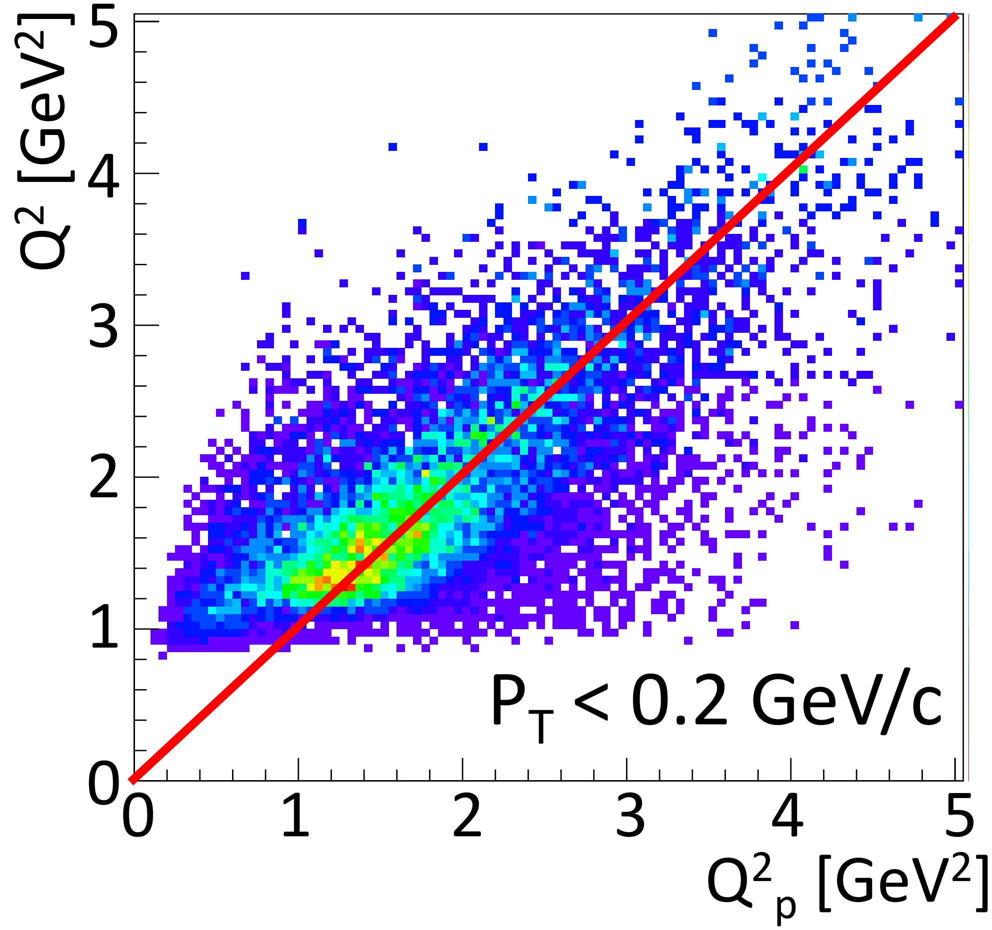
- 1 - 5 GeV electron beam,
- (almost) 4π acceptance,
- Charged particles (8^o-143^o): Toroidal field + tracking, TOF, Cerenkov, and EM Calorimeter,
- Neutral particles: EM Calorimeter (8^o-75^o) and TOF (8^o-143^o).
- Low detection threshold (~300MeV/c),
- <u>OPEN TRIGGER !</u>



Example IV: E_ν & Q^2 Reconstruction

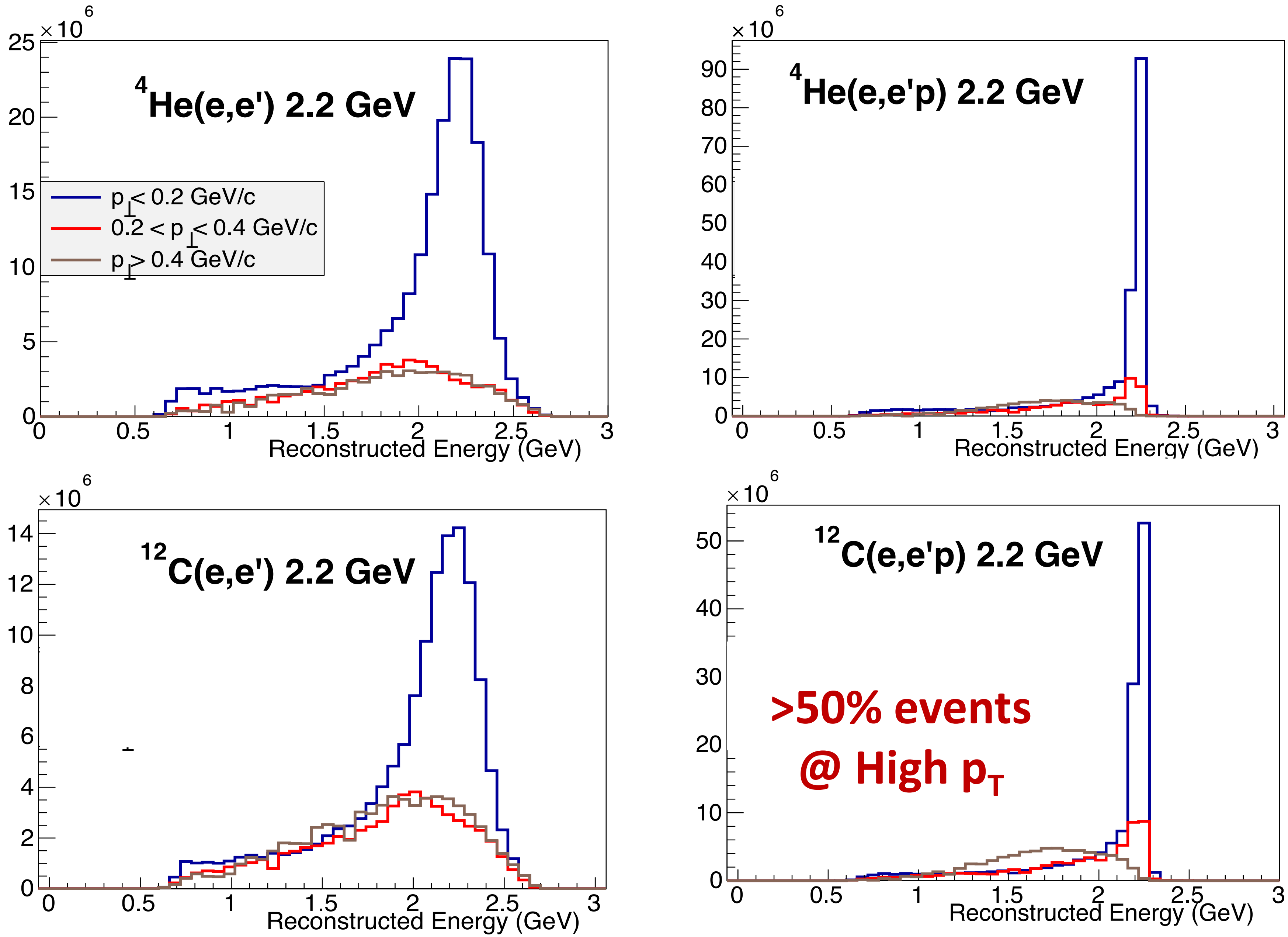
High Q^2 events reconstructed as low Q^2_p due to nuclear effects





CLAS6 Data,
4.4 GeV Incoming beam.
$^{12}C(e,e'p)$ no pion events.

Energy Reconstruction Example

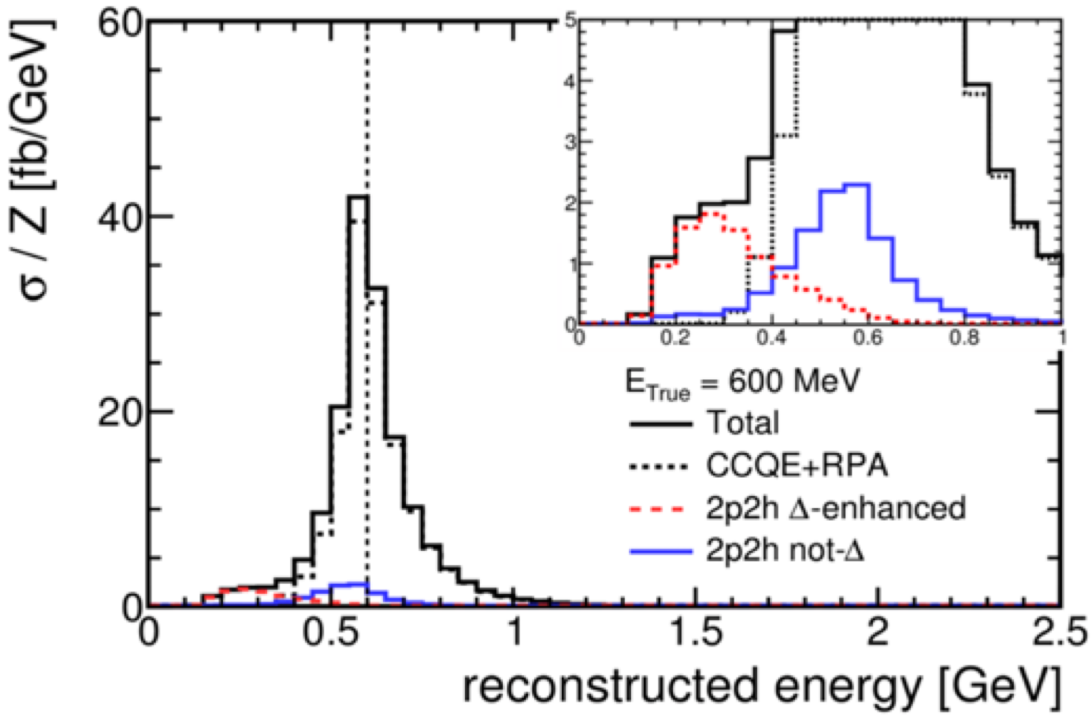


$$P_T^{miss} = P_T^{lepton} + P_T^{Proton}$$

T2K 2p2h uncertainties:

- Overall strength for neutrinos and antineutrinos
- Freedom to change strength from 2p2h to maximal energy estimator bias (terms which couple to Δ) and minimal bias (other terms non-Δ, NN etc)

Phys. Rev. D 96, 092006 (2017)

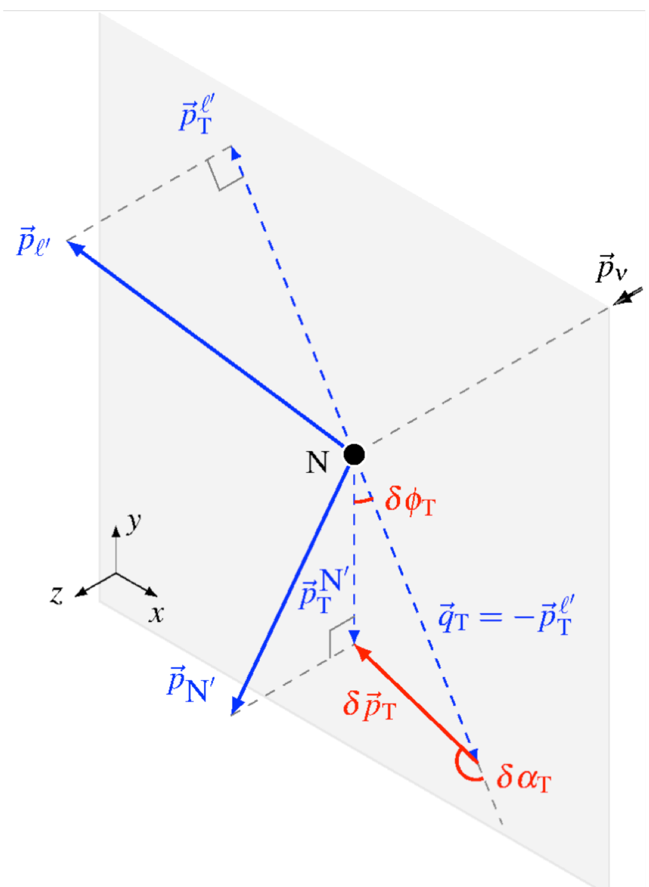


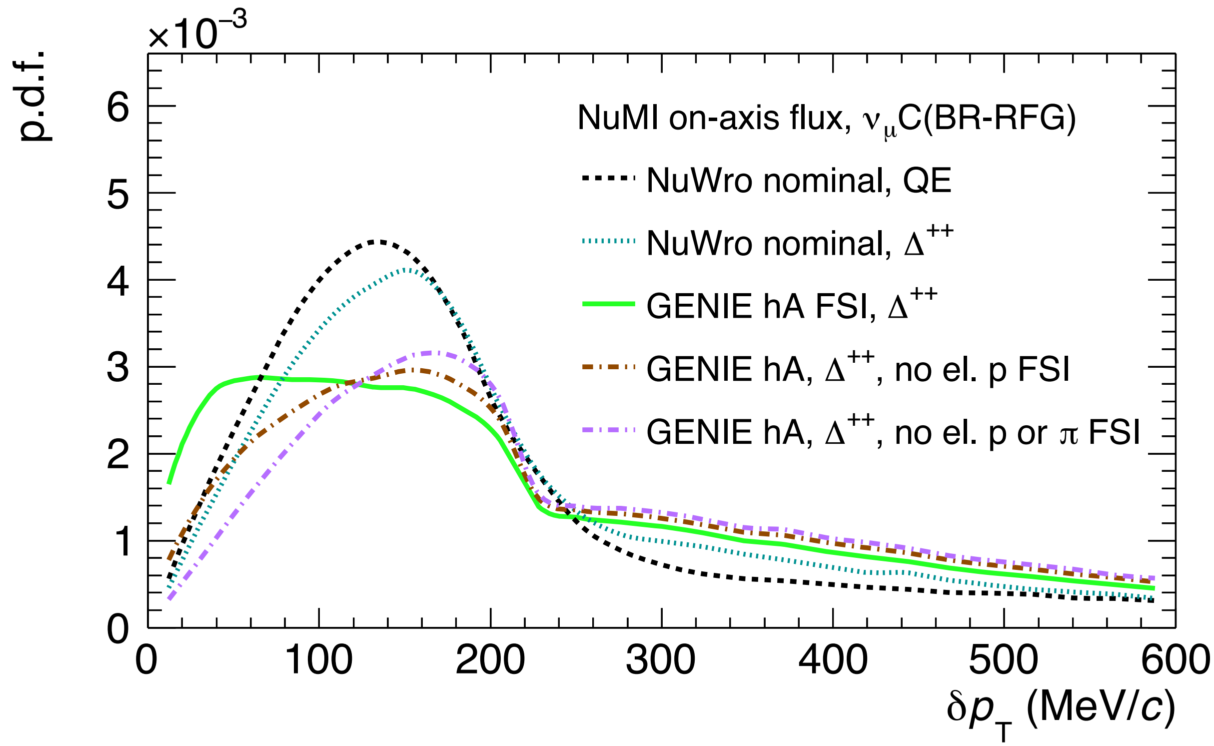
CLAS data allows a direct test of this relationship for T2K uncertainties

- For QE, resonance and 2p2h components

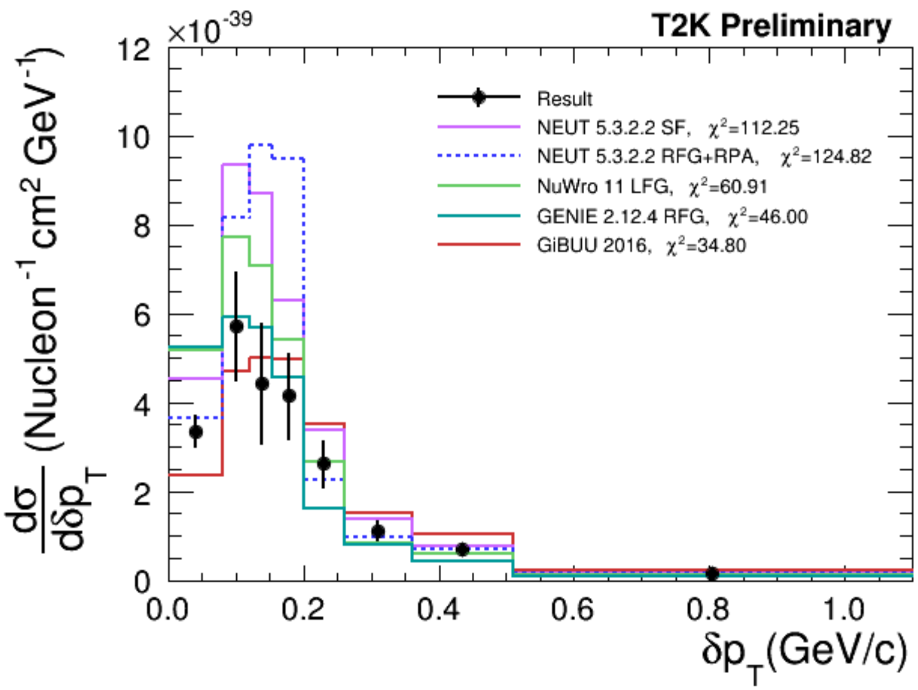
“Transverse variables”

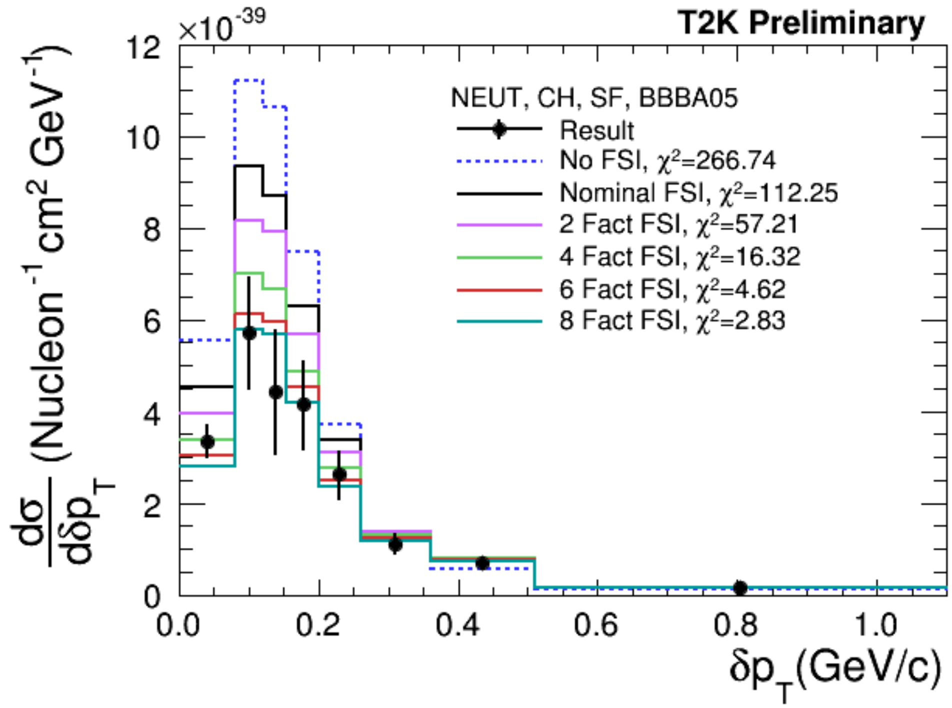
Relative momentum or angle between proton and muon from semi-inclusive scattering





Reference: X. Lu et al, Phys.Rev. C94 (2016) no.1, 015503, arxiv.org/pdf/1512.05748.pdf





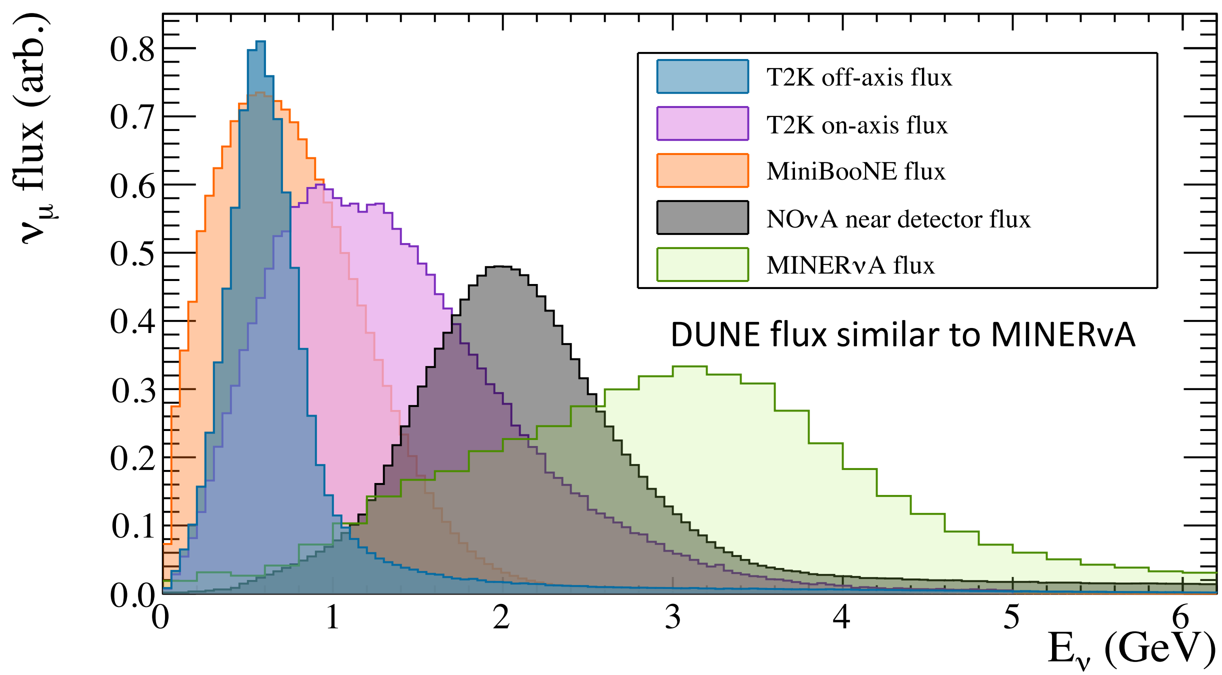
CC0pi+1p measurement from T2K
Includes CCQE, 2p2h/MEC, resonance processes

Models in NEUT, GENIE are insufficient to describe this data
Artificial, extreme change to FSI to "match" data in NEUT

Experiments have significant contributions from QE, resonance, and SIS/DIS kinematic regions.

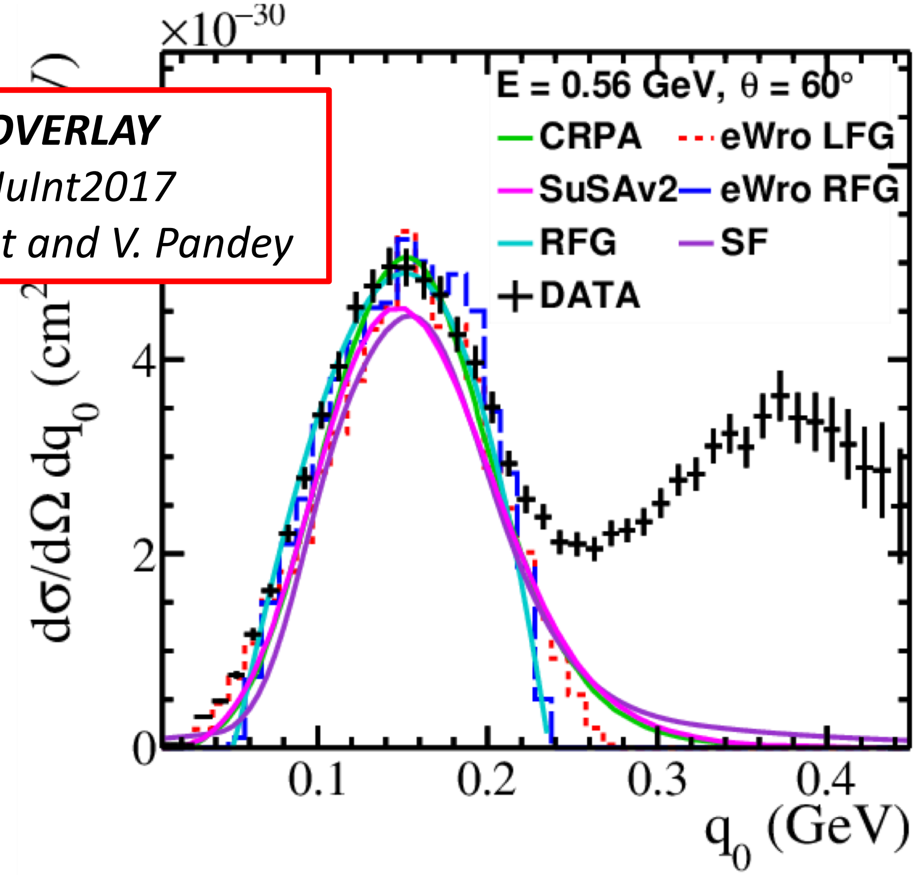
NuSTEC white paper (arxiv.org/1706.03621)
NOvA far detector event rate:

	% of MC Events
QE	28.2%
2p2h	11.0%
RES	39.2%
COH	1.6%
DIS	19.8%



Comparisons to electron scattering data, various generators through **NUISANCE:** *general purpose cross section comparison framework*

EXAMPLE OVERLAY
Shown at NuInt2017
from C.Wret and V. Pandey



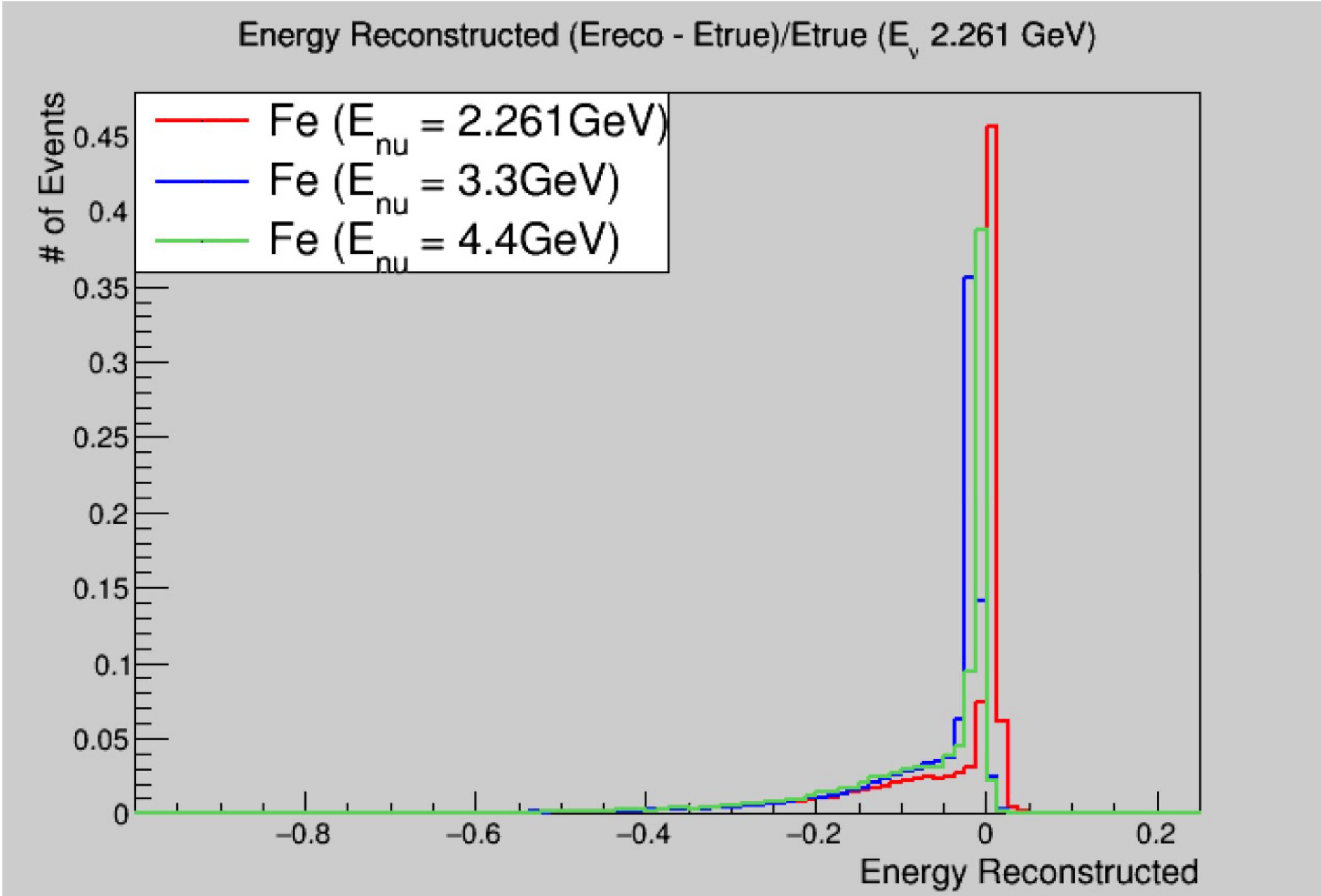
Used on T2K, DUNE for:

- How well models agree with our data, others data
- Determination of suitable set of uncertainties on cross section model
- Provide pseudo-data to test impact of cross section mis-modelling on oscillation analysis

Question: What level of uncertainties are needed for the future experiments and how does this proposal meet that need?

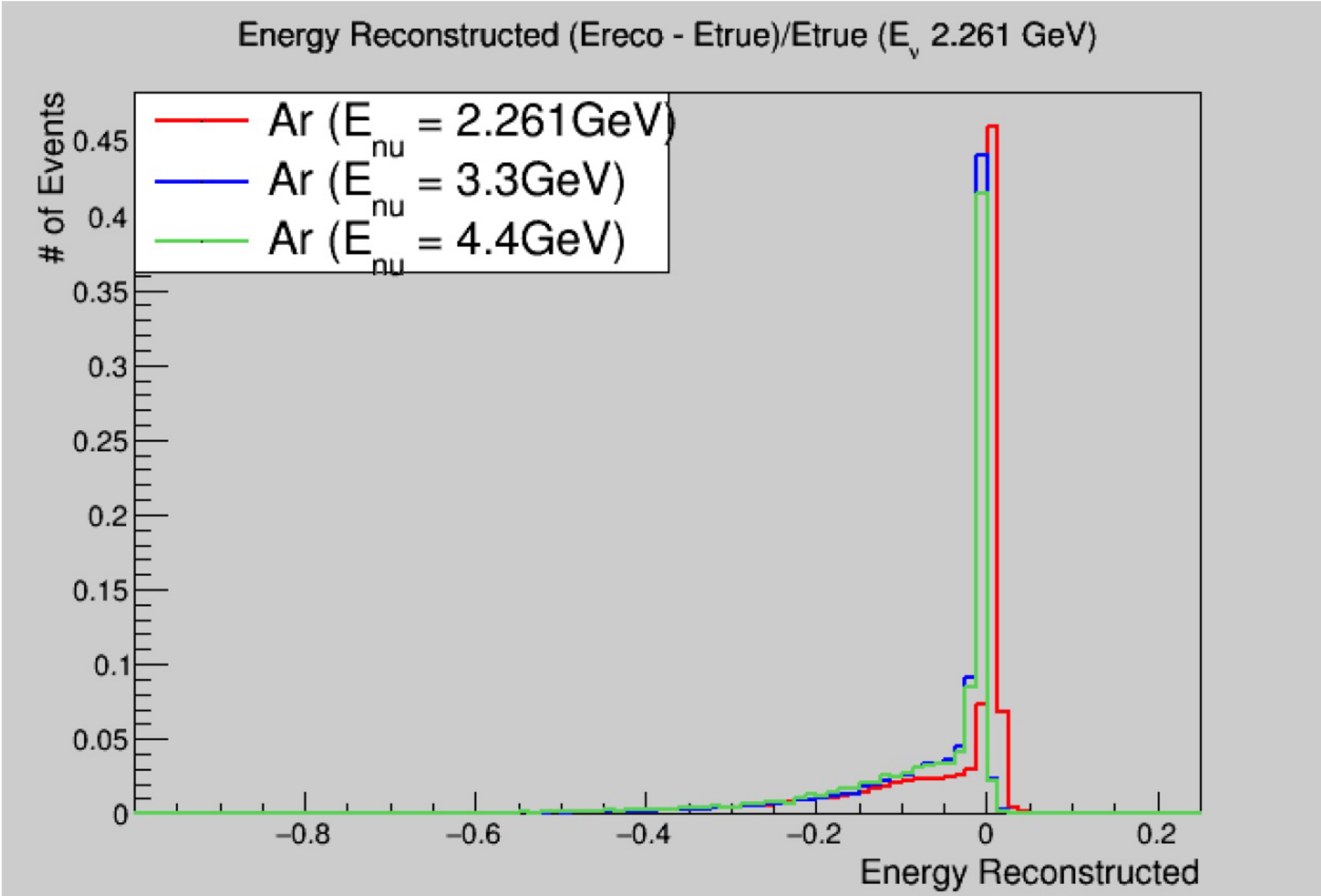
Answer:

- This program will *reduce sources of bias for neutrino experiments* through generator validation, development enabled from data
- Relative uncertainties are most relevant for oscillation physics



Details of application of eA feeddown to neutrino simulation

- Consistent CLAS acceptance applied to eA and nuA
- Feeddown from 2.2 – 4.4. GeV is similar - Scale fractional feeddown at 2.2 GeV to other energies - *assumption to be further tested*



Details of application of eA feeddown to neutrino simulation

- Consistent CLAS acceptance applied to eA and nuA
- Feeddown from 2.2 – 4.4. GeV is similar
- Differences between Fe and Ar (in nuA) are small relative to difference between data and generators – *this can also be quantified*

	2.2 GeV		4.4 GeV	
Target	E_{kin}	E_{cal}	E_{kin}	E_{cal}
^{4}He	0.23	0.46	0.21	0.34
C	0.20	0.39	0.16	0.27
Fe	0.16	0.26	0.11	0.14

Table: Fraction of events reconstructed to within 5 percent of the beam energy at 2.26 and 4.46 GeV for the lepton-only method (E_{kin}) and for the electron energy plus proton energy method (E_{cal}).

Replicated Table with GENIE

	2.2 GeV		3.3 GeV		4.4 GeV	
Target		E_{cal}		E_{cal}		E_{cal}
Fe		0.622		0.660		0.622
Ar		0.633		0.674		0.633

Fraction of events within the 5% of the beam energy is strikingly different between neutrino simulation and electron scattering

4. Optimize Beam Time Request

Energy [GeV]	H	^{4}He	^{12}C	^{16}O	^{40}Ar	^{120}Sn	Total
1.1	0.2	0.5	0.5	0.5	0.5	0.5	**2.5**
2.2	0.2	1	1	1	1	1	**5**
4.4	0.2	1	1	x	1	1	**4**
6.6	0.2	2	2	x	2	2	**8**
Total (days)	**1**	**4.5**	**4.5**	**1.5**	**4.5**	**4.5**	**19.5**

out-bending
Lower min Q^2

in-bending

Reduced from 37.5 days

E_{Beam}	Q^2_{QE} (GeV^2)		
	15°	10°	5°
1.1	0.08	0.04	0.01
2.2	0.30	0.15	0.04
4.4	1.14	0.55	0.15
6.6	2.40	1.20	0.30
11	5.90	3.10	0.90

1. Reduced almost 50%
2. Focused on low and intermediate Q^2
   1. 8.8 GeV beam time removed
   2. 1.1 and 2.2 GeV running at reversed field

out-bending
Lower min Q^2

in-bending