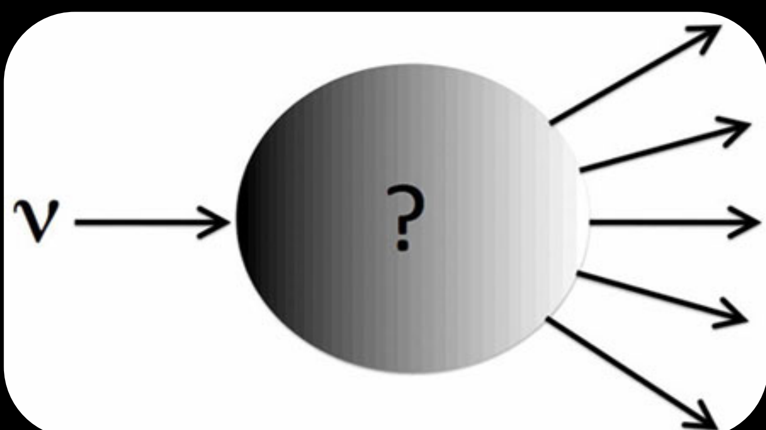
Jefferson Lab
Thomas Jefferson National Accelerator Facility
MIT
Old Dominion University
Michigan State University
Tel Aviv University

Electrons for Neutrinos: Addressing Critical Neutrino-Nucleus Issue

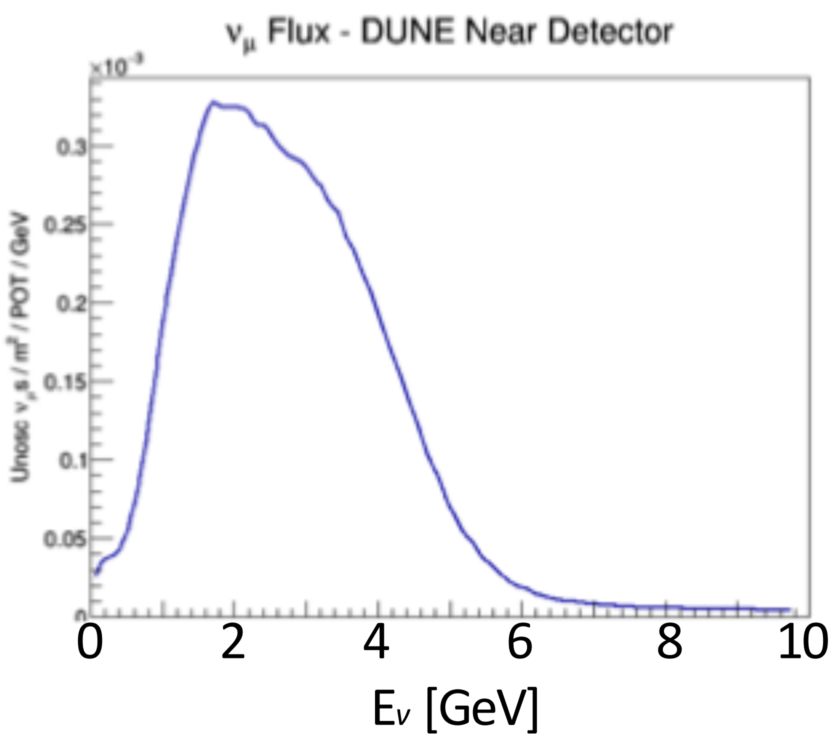
Proposal C12-17-006

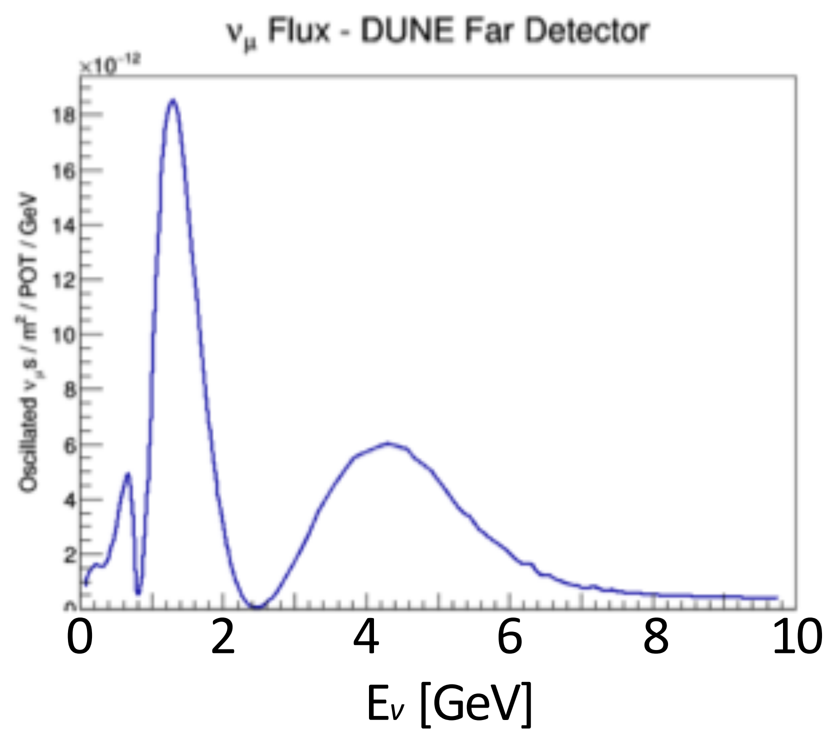
Spokespersons:
O. Hen (MIT), K. Mahn (MSU),
E. Piasetzky (TAU), S. Stepanyan (JLab)
and L.B. Weinstein (ODU).



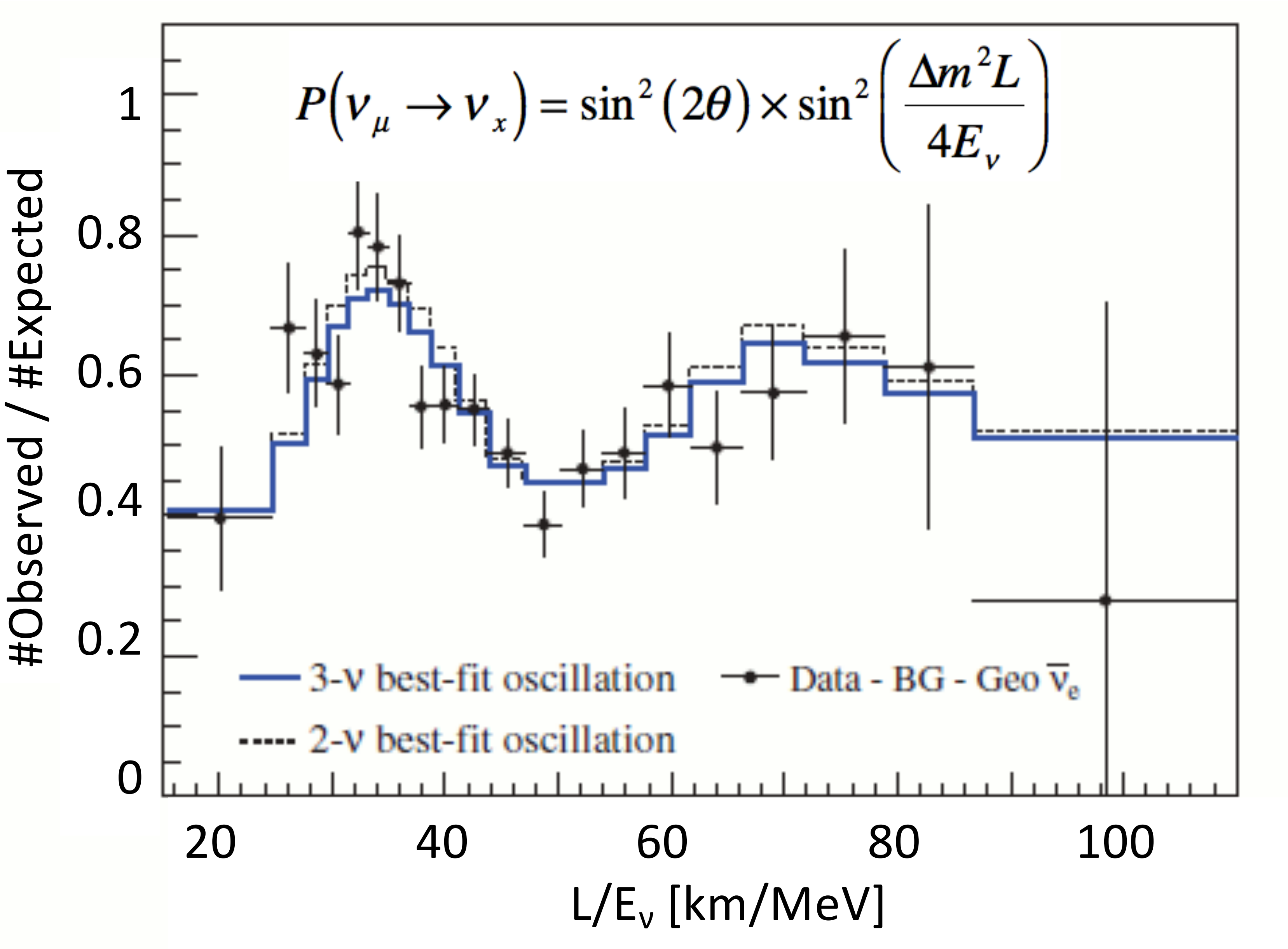
Jefferson Lab PAC-46, July 17th, 2018

Long Baseline Oscillations



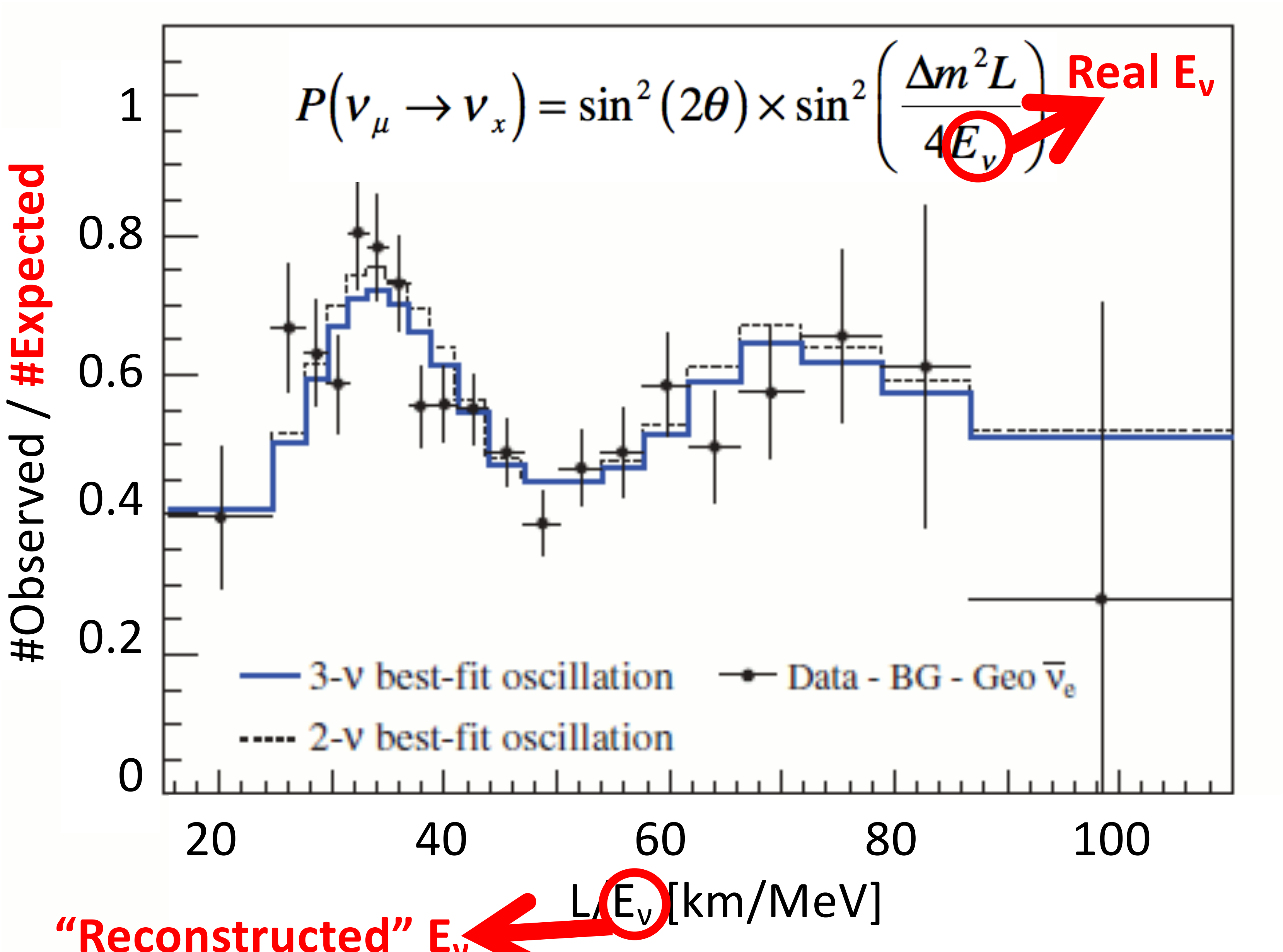


Neutrino Oscillations



KamLAND, PRL 100, 221803 (2008)

Neutrino Oscillations



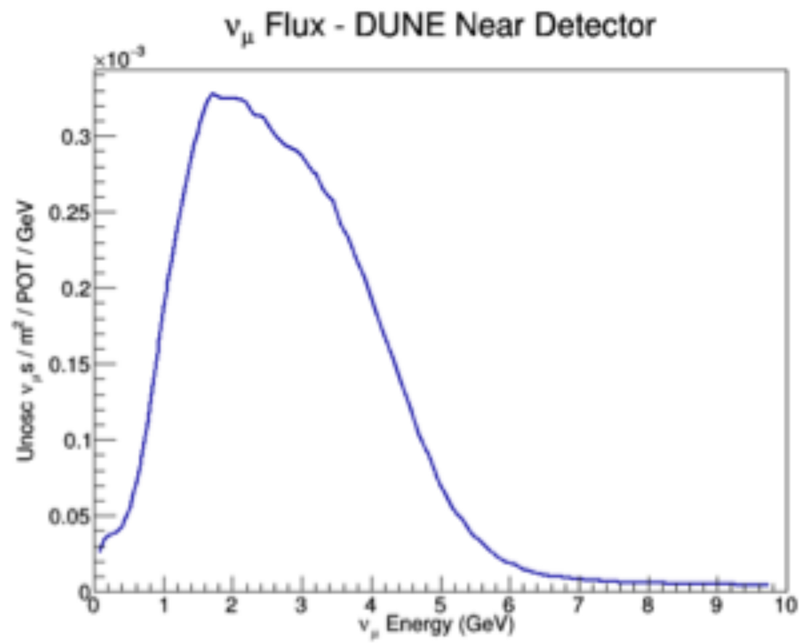
KamLAND, PRL 100, 221803 (2008)

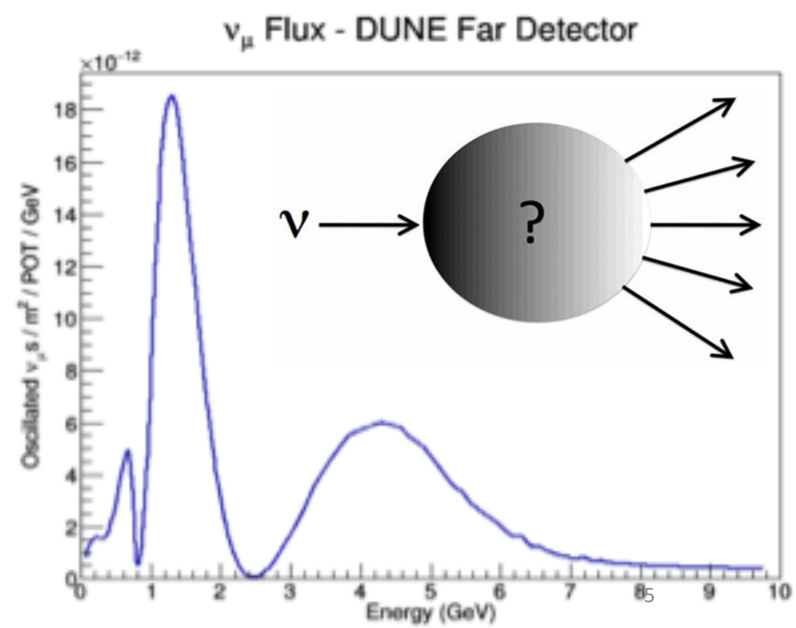
(Long Baseline) Oscillation Challenge

Oscillations are ratios of reconstructed ν energy spectra:

- Energy (x-axis): Reconstructed from the measured final state.
- Flux (y-axis): Reconstructed using reaction model (cross-section + FSI + …)

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





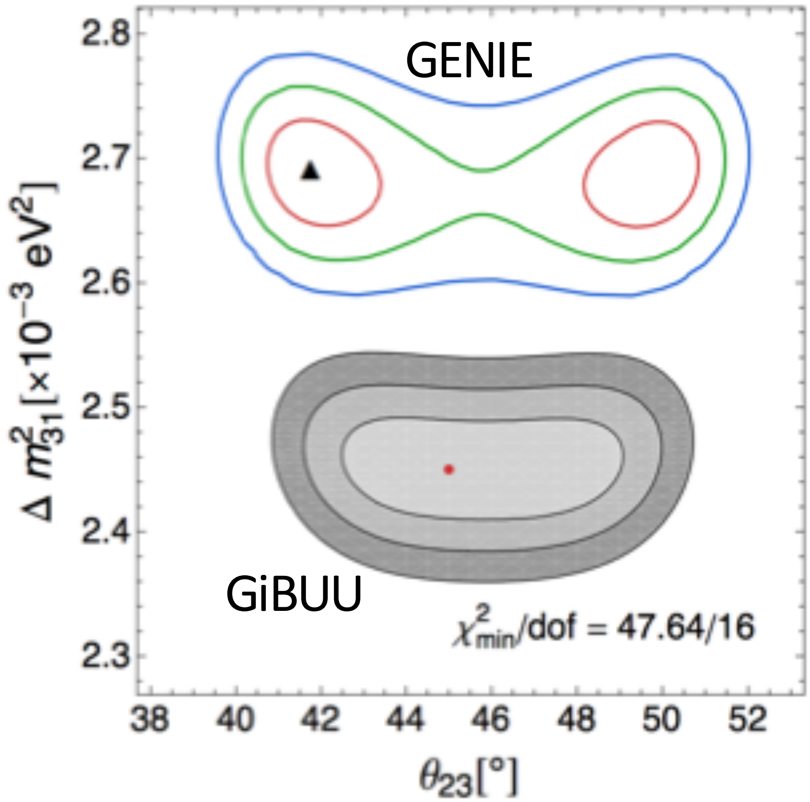
(Long Baseline) Oscillation Challenge

Oscillations are ratios of reconstructed ν energy spectra:

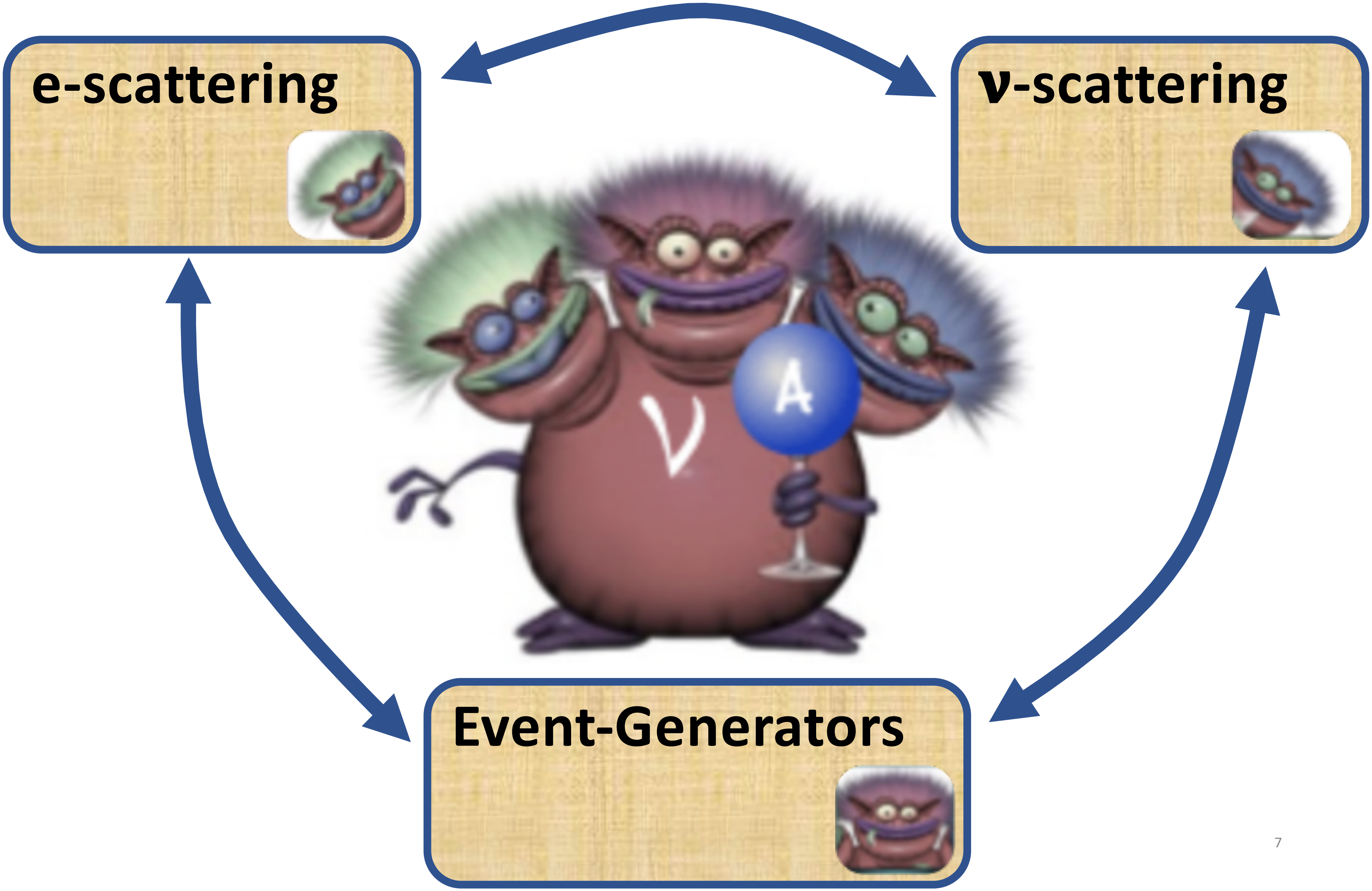
- Energy (x-axis): Reconstructed from the measured final state.
- Flux (y-axis): Reconstructed using reaction model (cross-section + FSI + …)

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

Phys.Rev. D89 (2014), 073015



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.

Existing e-scattering data

"We've been throwing electrons at nuclei for over 40 years – why new data?"

Lots of data, usually not in useful phase-space for ν expts:

- W-boson mass makes the ν 'Mott' cross-section flat. Electron cross section very forward peaked.
- Electron expts focus on nuclear structure, minimize reaction mechanism complications. ν expts cannot avoid these.
  - **A(e,e'):** well described using various scaling approaches.
  - **A(e,e'p):** measured primarily in selective kinematics (around the QE peak).
  - **A(e,e'n), A(e,e'NN):** Sparse data, especially at GeV energies.
  - **Resonance production**: lacking systematic data on nuclei and at large multiplicities.

Existing e-scattering data

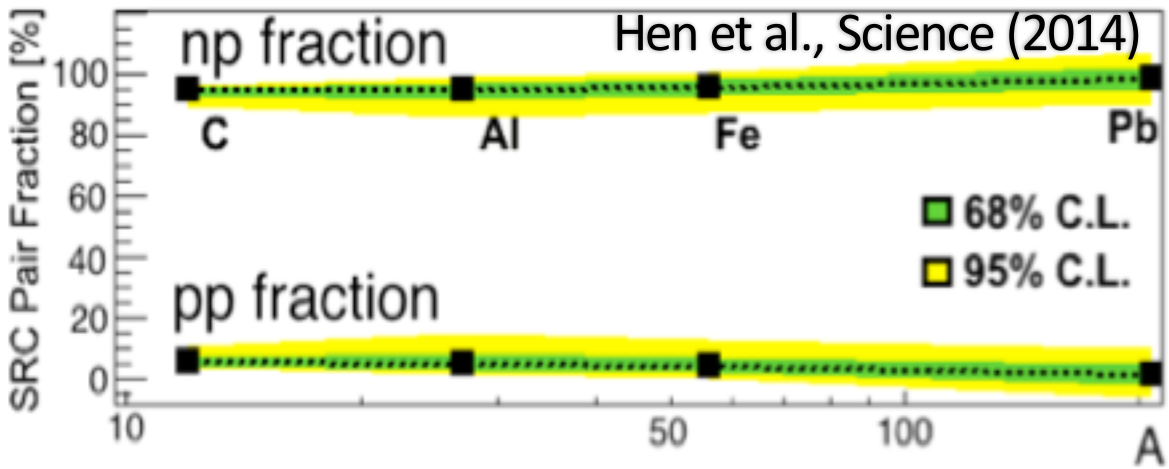
“We’ve been throwing electrons at nuclei for over 40 years – why new data?”

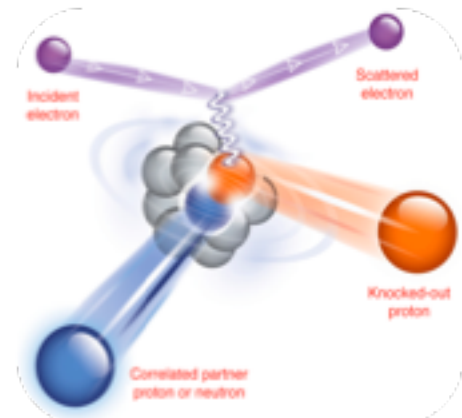
Lots of data, usually not in useful phase-space for ν expts:

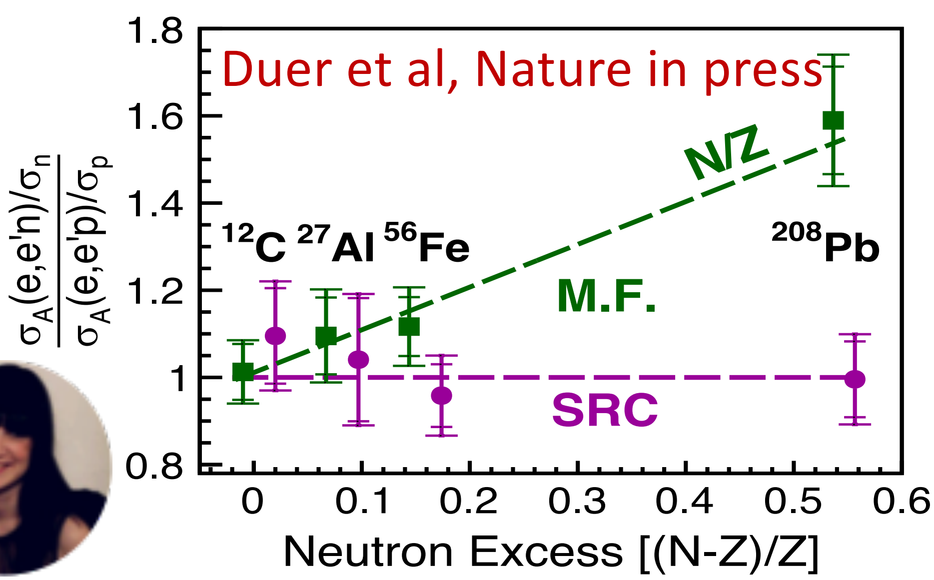
- W-boson mass makes the ν ‘Mott’ cross-section flat. Electron cross section very forward peaked.
- Electron expts focus on nuclear structure, minimize reaction mechanism complications. ν expts cannot avoid these.
  - **A(e,e’):** well described using various scaling approaches.
  - **A(e,e’p):** measured primarily in selective kinematics (around the QE peak).
  - **A(e,e’n), A(e,e’NN):** Sparse data, especially at GeV energies.
  - **Resonance production**: lacking systematic data on nuclei and at large multiplicities.

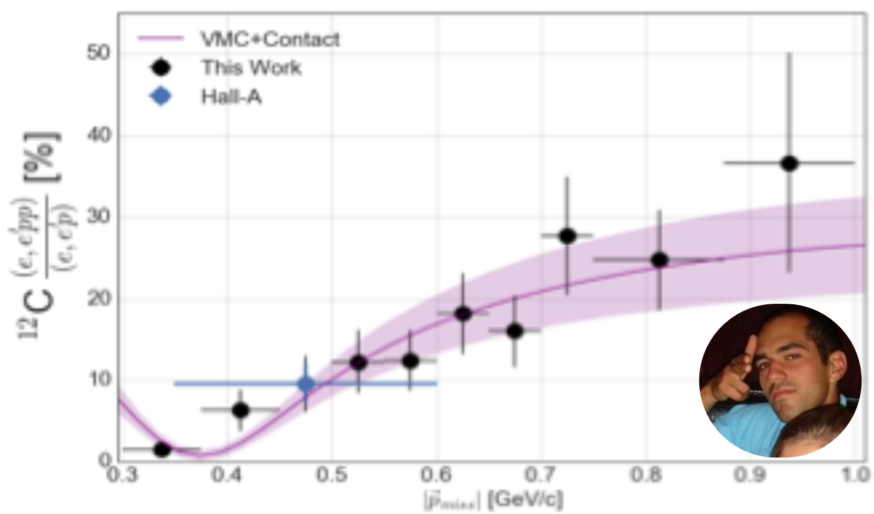
JLab Data-Mining

Utilizing existing CLAS data to extract physics from different parts of the phase-space not considered in the original proposal.









Mining For Neutrinos

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

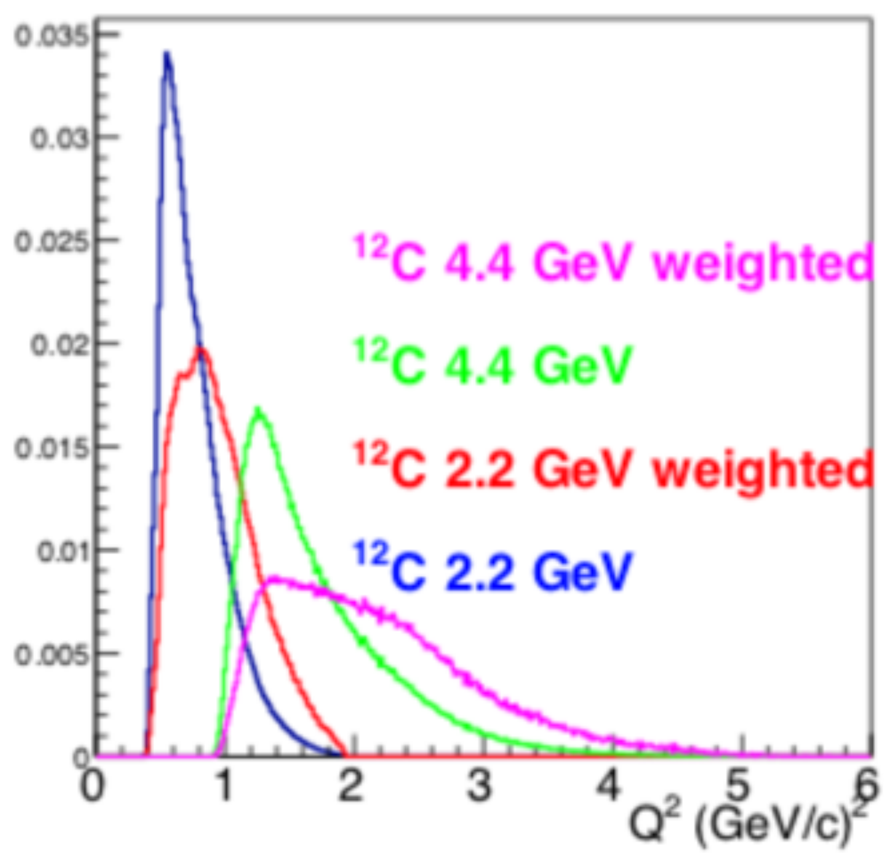
Means (for QE study):

- 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 GENIE predictions,
- Identify phase-space regions of data/GENIE agreement and disagreement

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



+ EG2 (~ x10 less stat): 5 GeV on d, ^{12}C, ^{27}Al, ^{56}Fe, ^{208}Pb ($Q^2 > 1.5$)

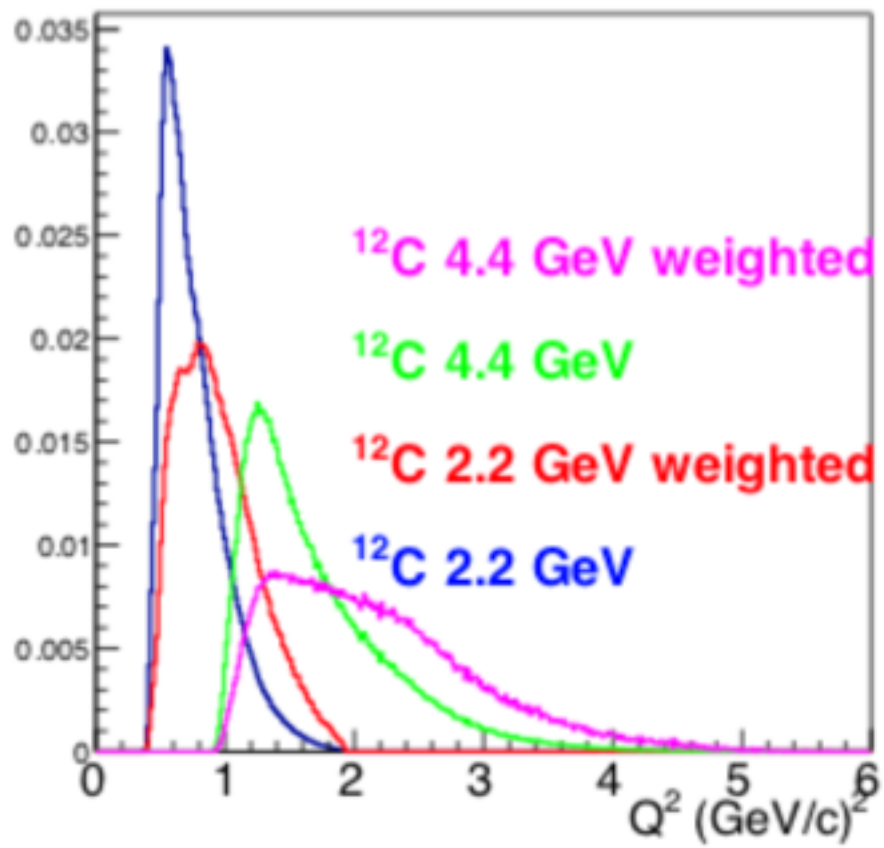
Existing CLAS6 Data (e2a)

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

⇒ **Very limited medium / heavy nuclei data.**

⇒ **Limited low-Q^2 reach.**

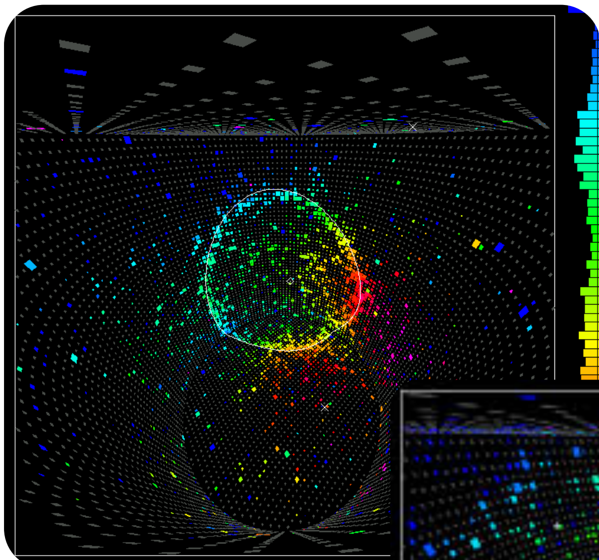


+ EG2 (~ x10 less stat): 5 GeV on d, ^{12}C, ^{27}Al, ^{56}Fe, ^{208}Pb (Q^2 > 1.5)

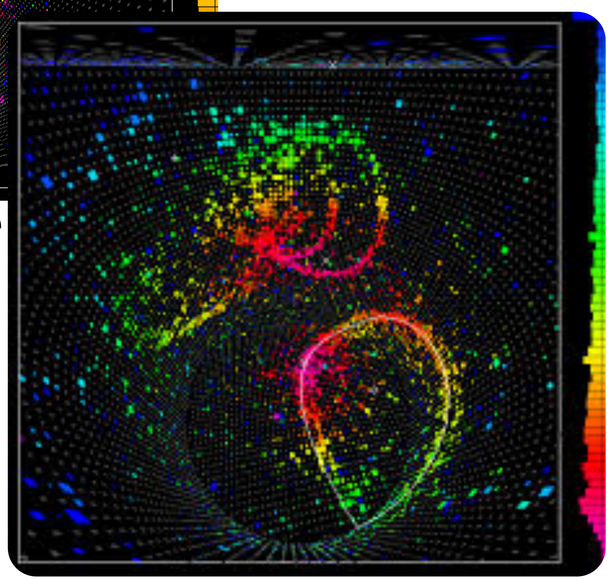
Final state detection approaches

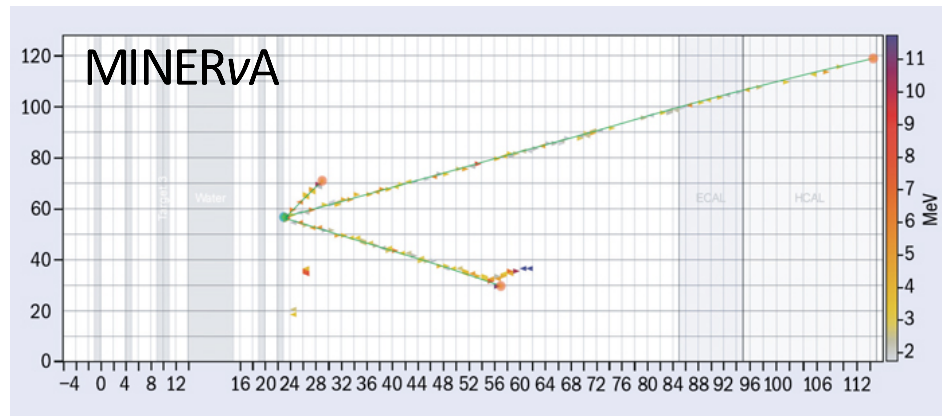
Cherenkov detectors:
- Electrons & Pions
- No protons / neutrons

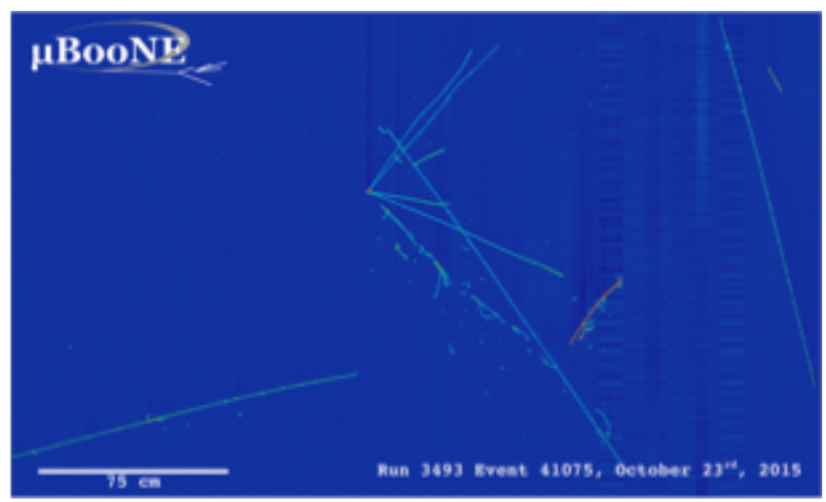
Tracking detectors:
- Charged particles $+\pi^0$
- [Progress towards neutrons]



Super-Kamiokande







Final state detection approaches

Cherenkov detectors:

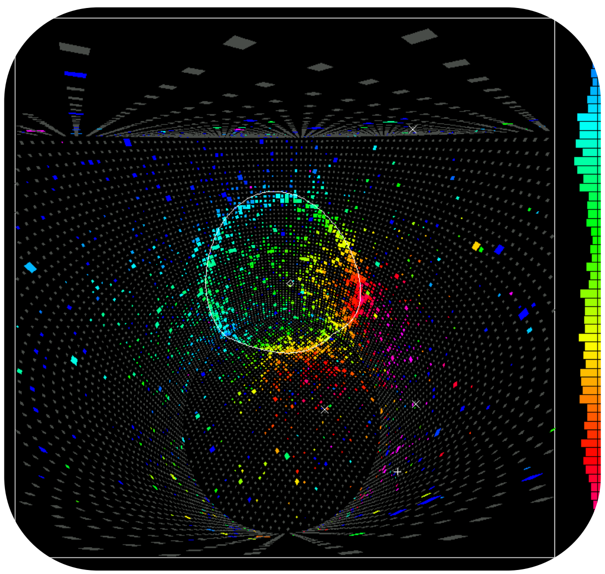
- Electrons & Pions
- No protons / neutrons

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

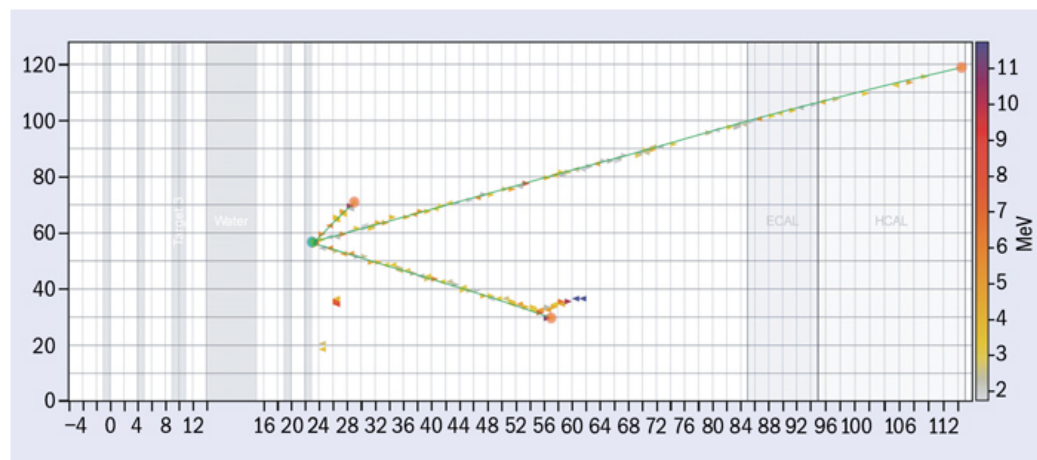
Tracking detectors:

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

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



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

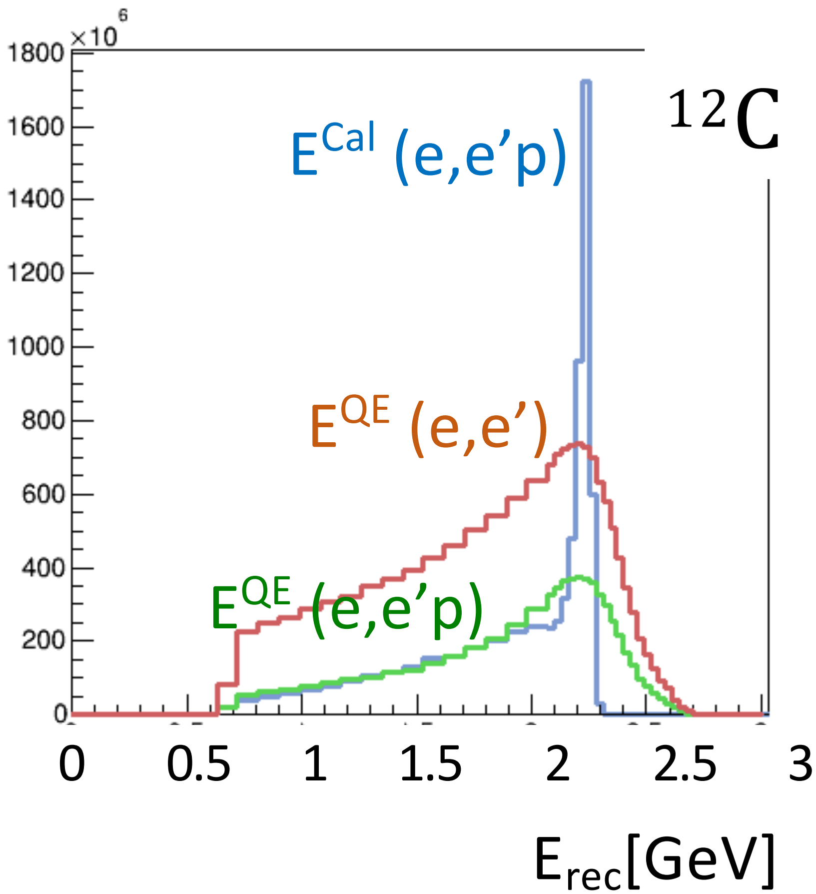


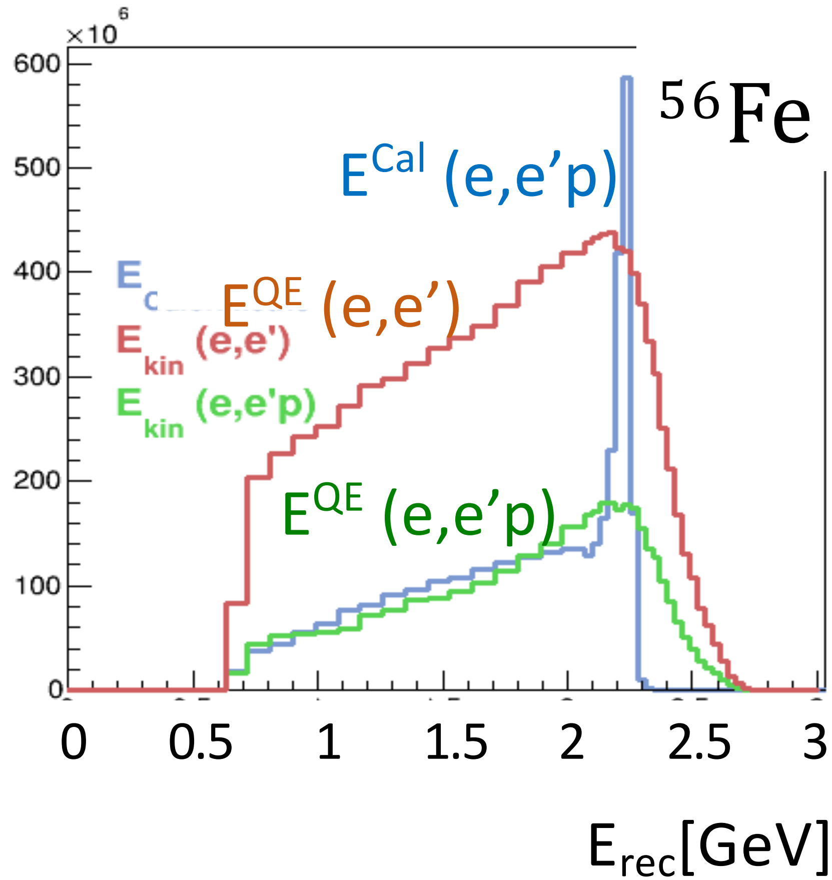
$E_{cal} = E_l + E_p^{kin} + \varepsilon_B$ for (e,e'p)

$\varepsilon, \varepsilon_B$ are effective binding energies

Energy Reconstruction Example

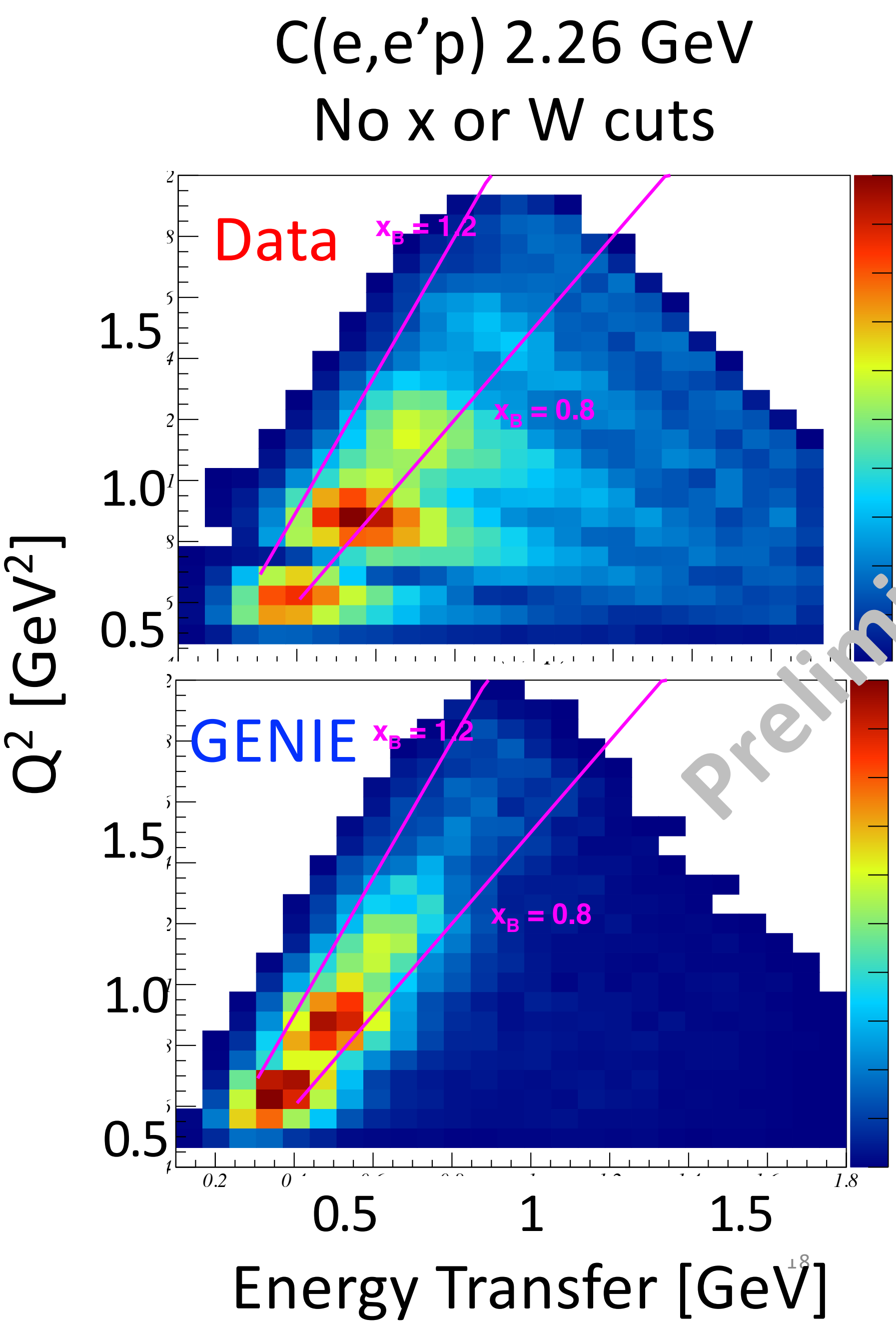
2.26 GeV beam   Zero pion events

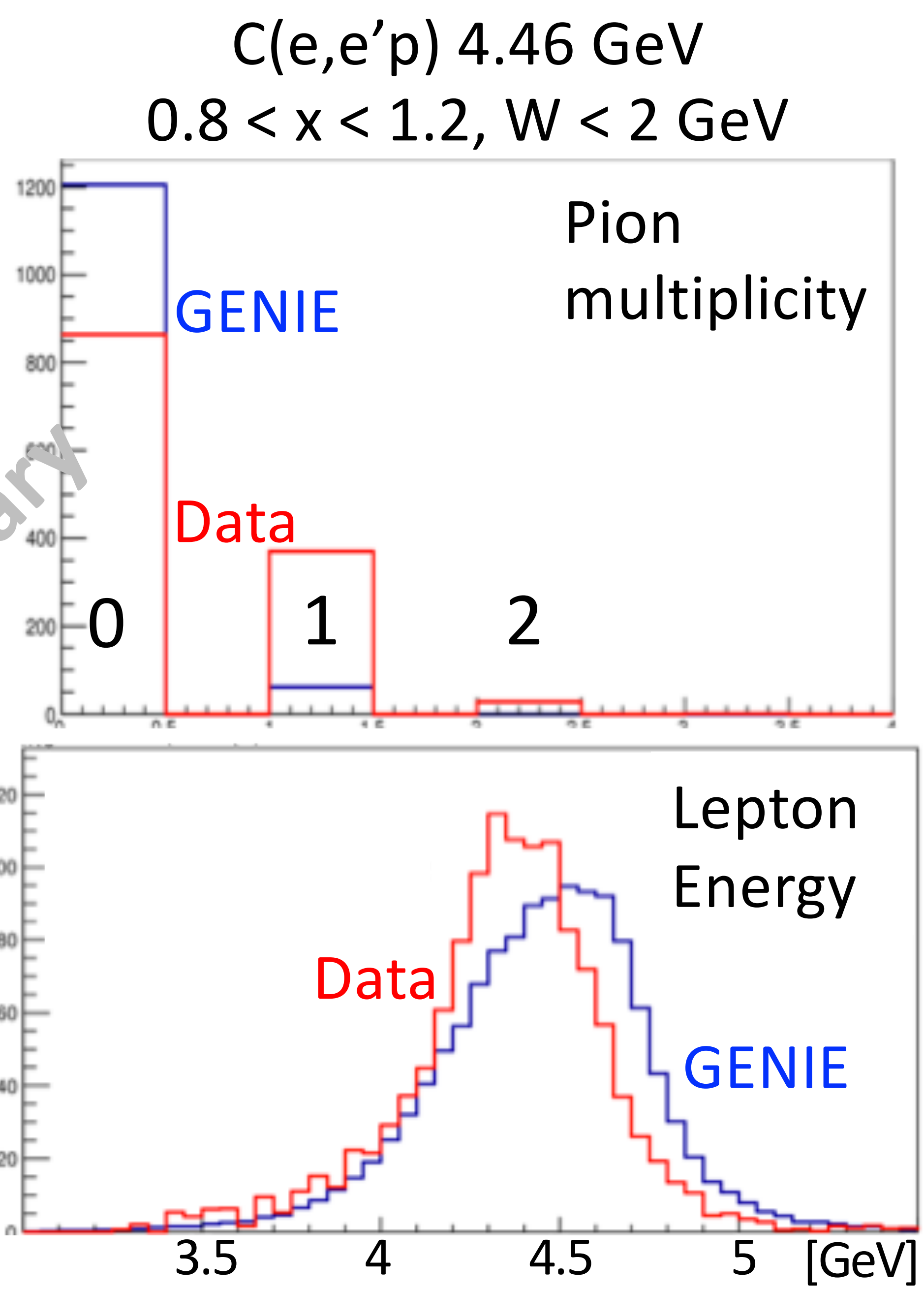




Even 0pi events have a LOT of non-QE events

Data-Generator Comparisons

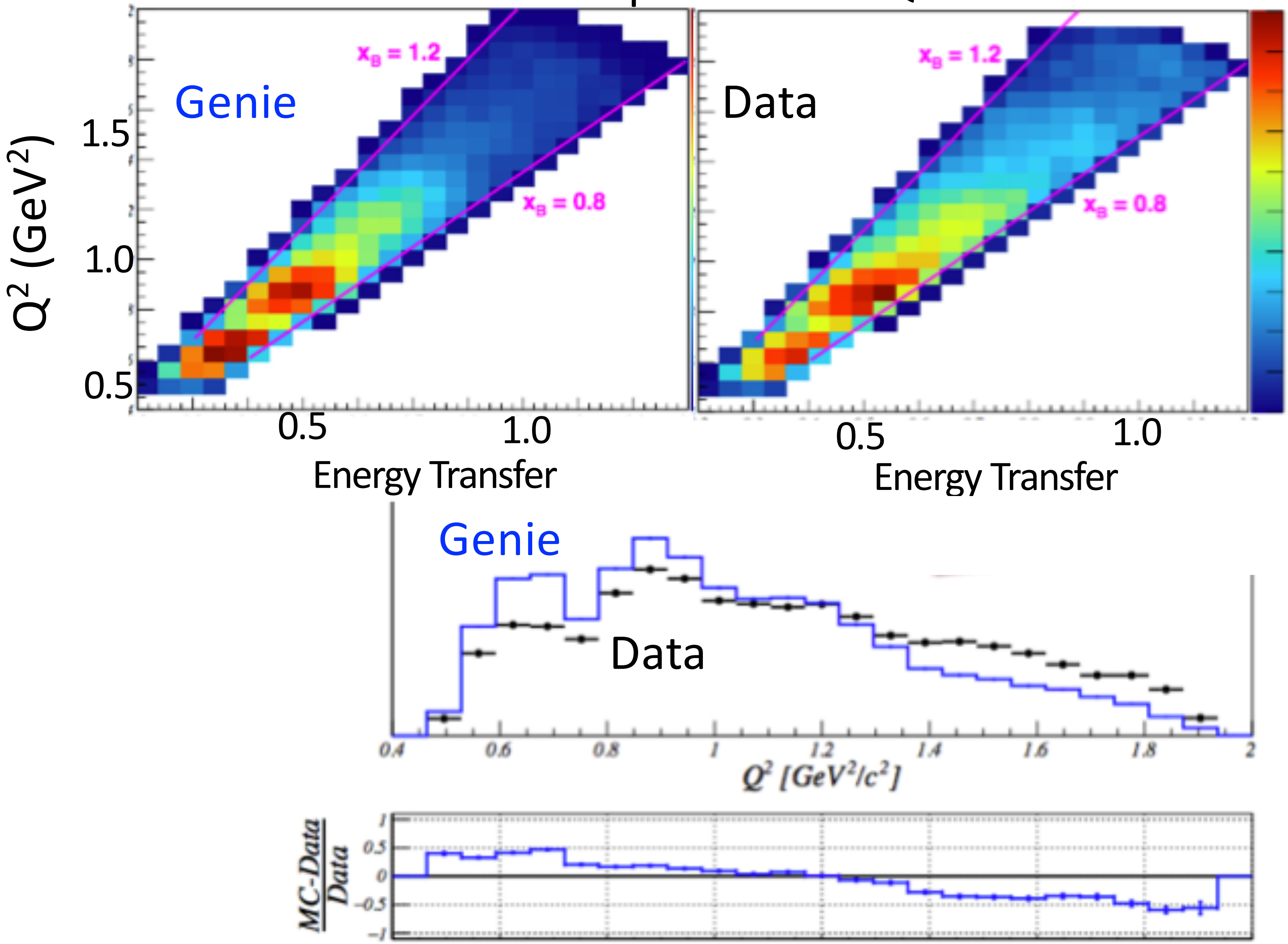




Data/Generator Comparisons

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

On the peak of the QE



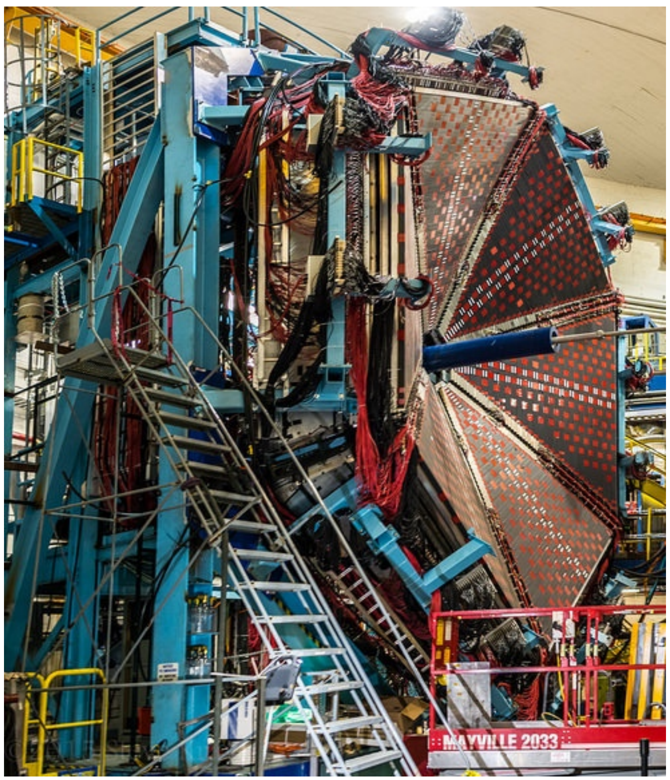
New Proposal: Systematic study!

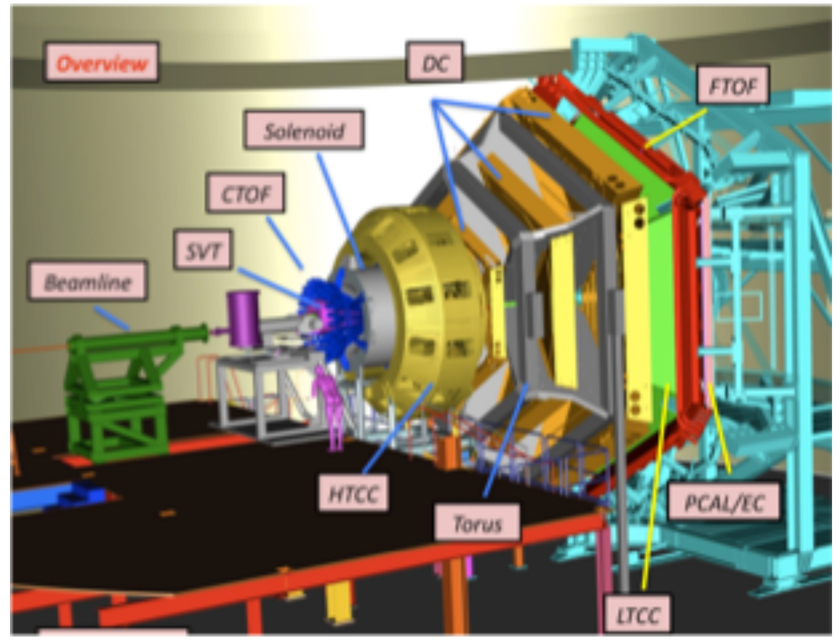
Targets:

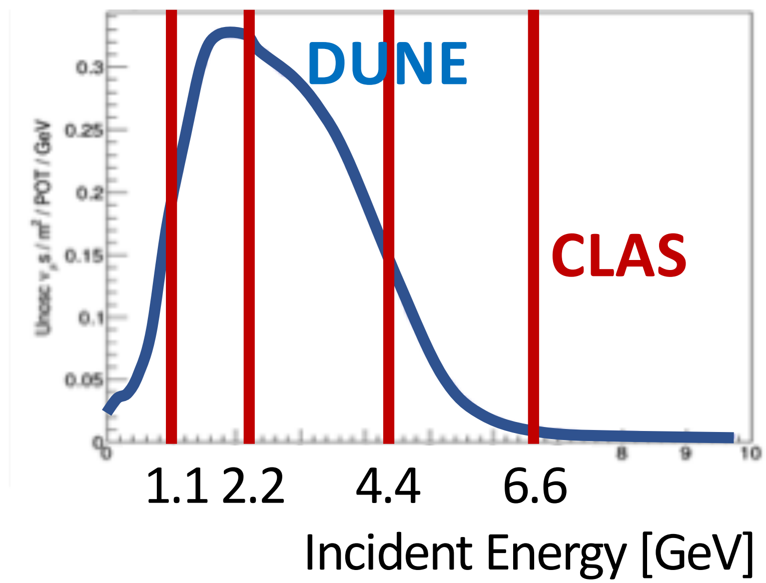
^{4}He, ^{12}C, ^{16}O, $\mathbf{^{40}Ar}$, ^{120}Sn

Beam Energies:

1.1, 2.2, 4.4, 6.6 GeV







New Proposal: Systematic study!

Targets:

^{4}He, ^{12}C, ^{16}O, **^{40}Ar**, ^{120}Sn

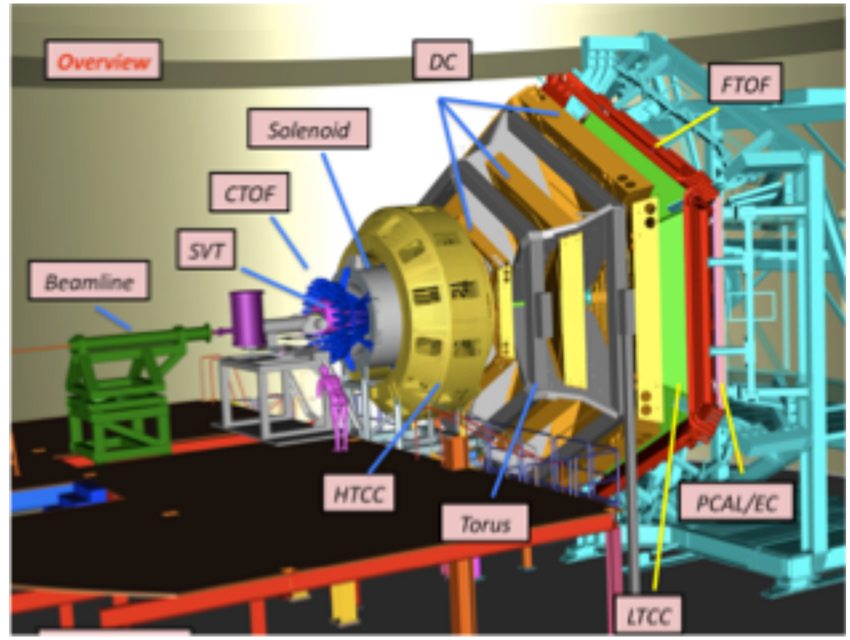
Beam Energies:

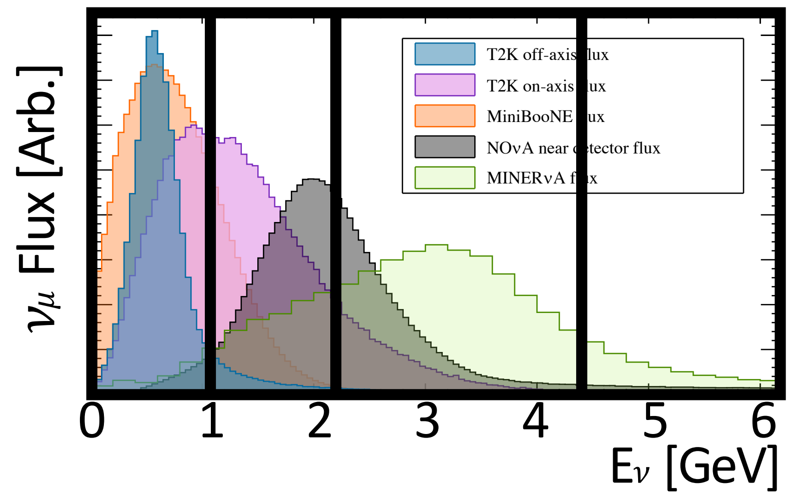
1.1, 2.2, 4.4, 6.6 GeV

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!

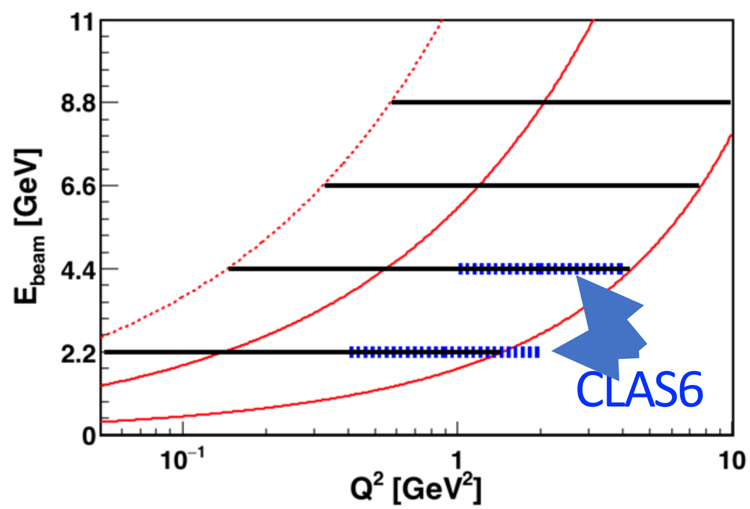
CLAS12: Neutrons + Lower Q^2!

Neutron efficiency

- 40% for high momentum ($p > 1$ GeV/c) forward neutrons ($5 < \theta < 40^o$)
- 10% for $40 < \theta < 120^o$

Lower Q^2 coverage!

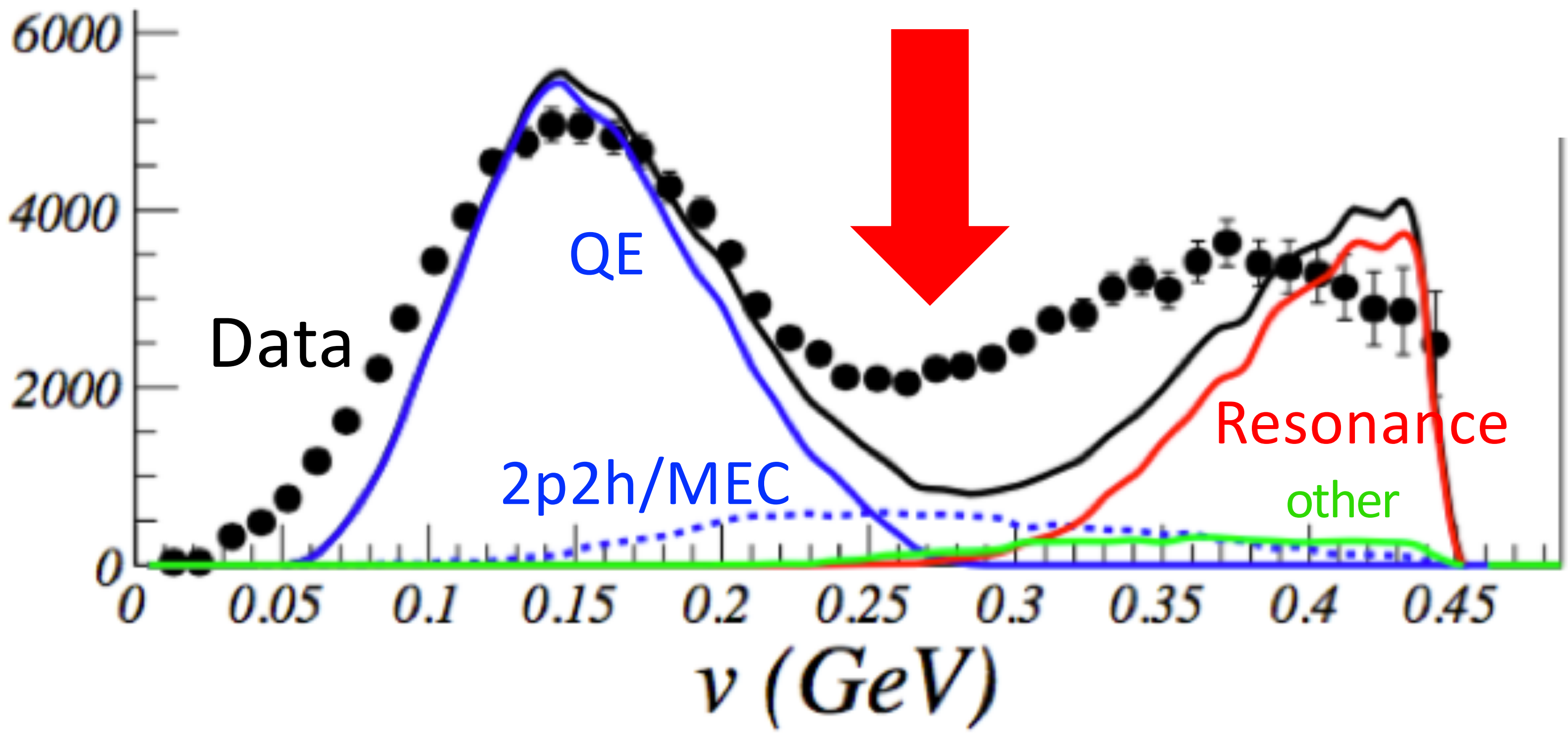
E_{Beam}	Q^2_{QE} (GeV^2)		
	15°	10°	5°
1.1	0.08	0.04	0.01
2.2	0.30	0.15	0.04
4.4	1.14	0.55	0.15
6.6	2.40	1.20	0.30
11	5.90	3.10	0.90
	CLAS6	CLAS12 In-Bend	CLAS12 Out-Bend



Example I: 2p2h Effects

2p2h is a phenomenological model intended to include Meson Exchange Currents, short range correlations, pion production and reabsorption, and any other process (except rescattering) leading to two nucleons in the final state

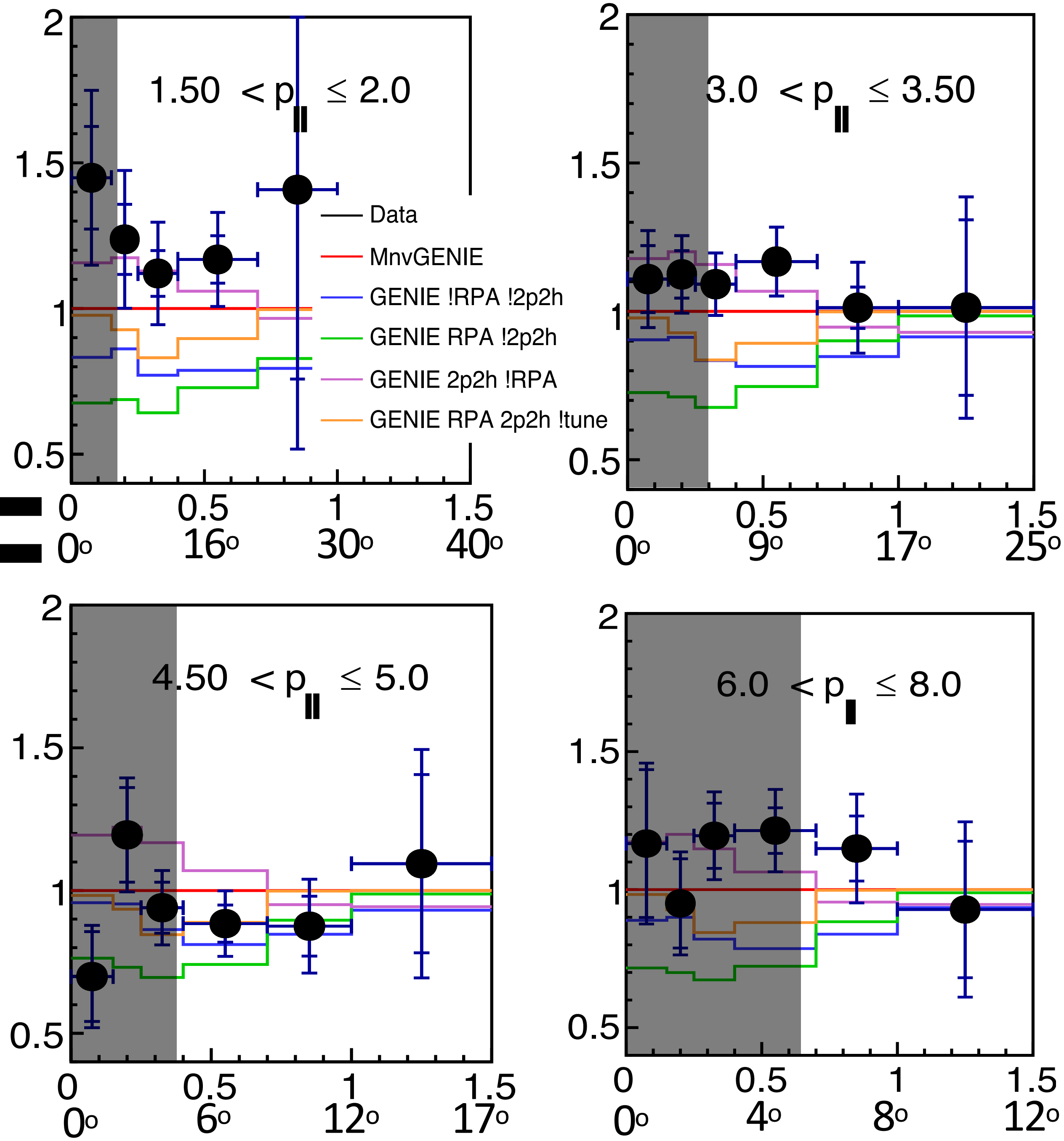
$$\text{C(e,e')}\ 560\ \text{MeV}\ \theta = 60^o$$



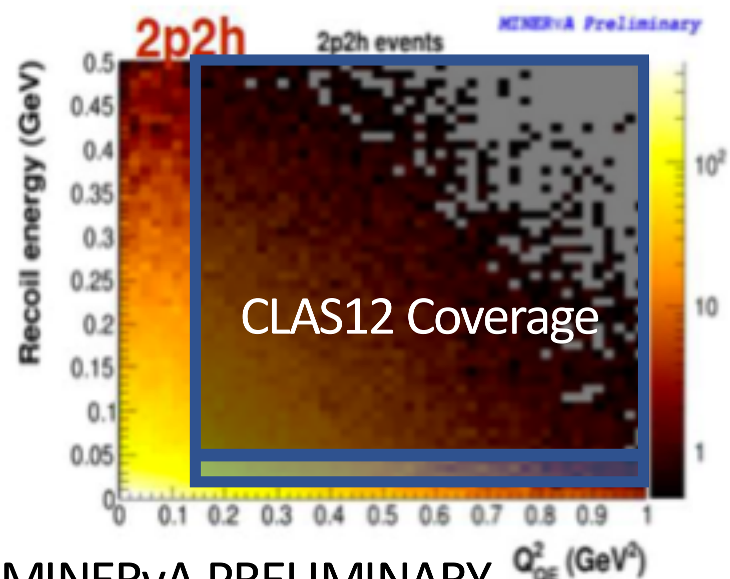
Still large issues with Genie, even in inclusive (e,e')

Example I: 2p2h / RPA Effects

X2 effects in regions accessible by CLAS12

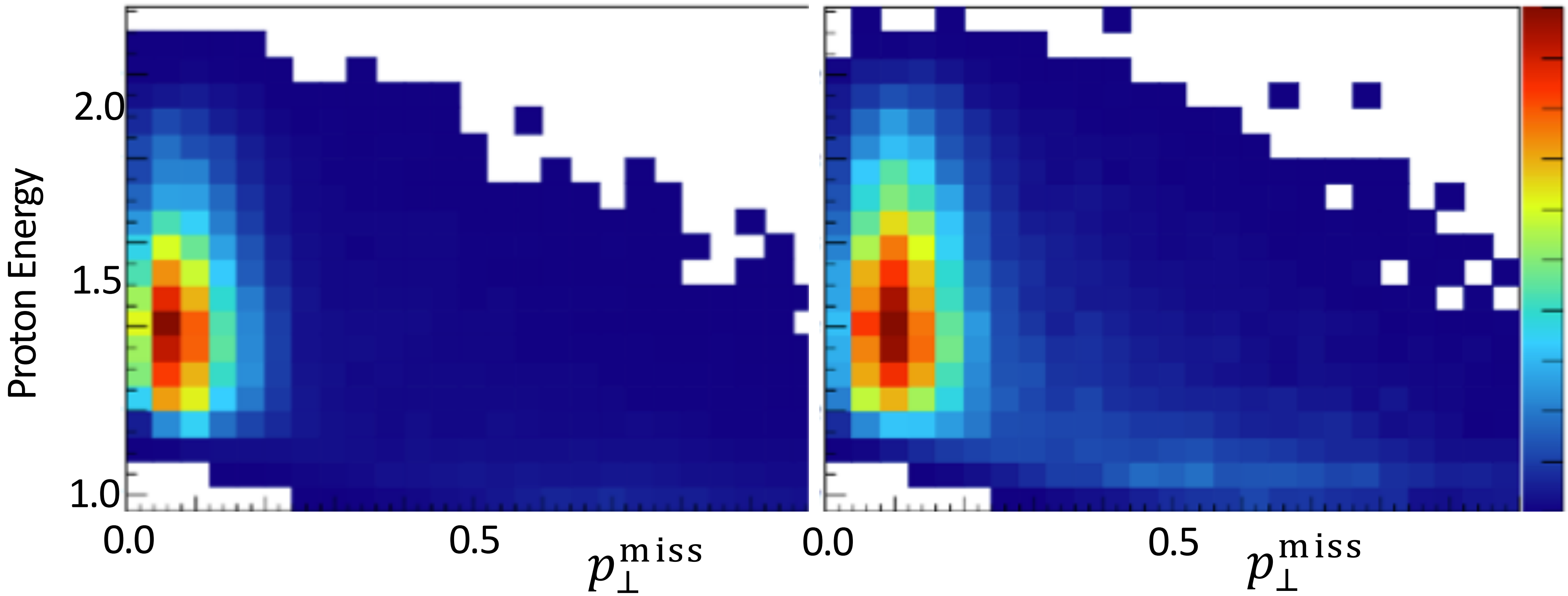


Scattered muon P_T
Scattered muon angle

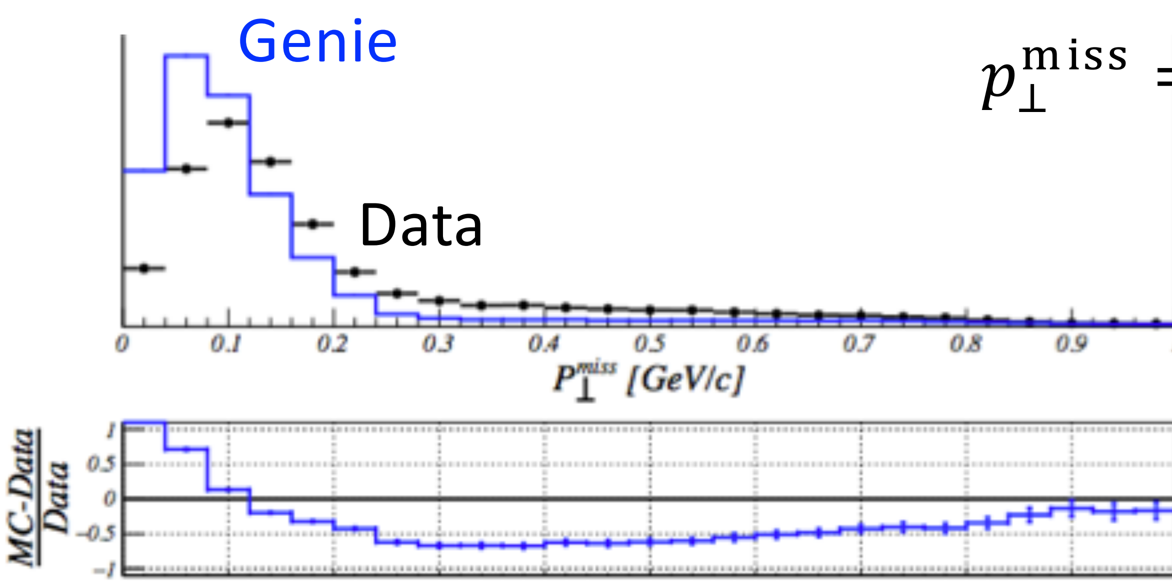


MINERvA PRELIMINARY

Example I: 2p2h / RPA Effects

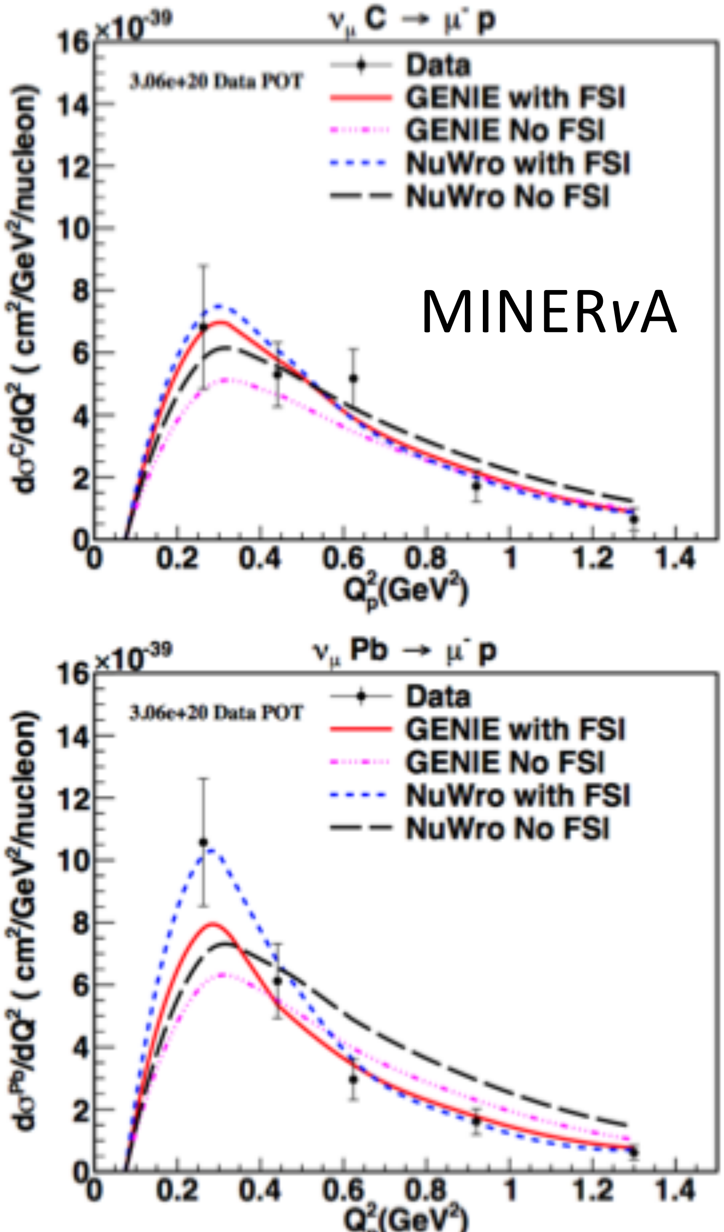


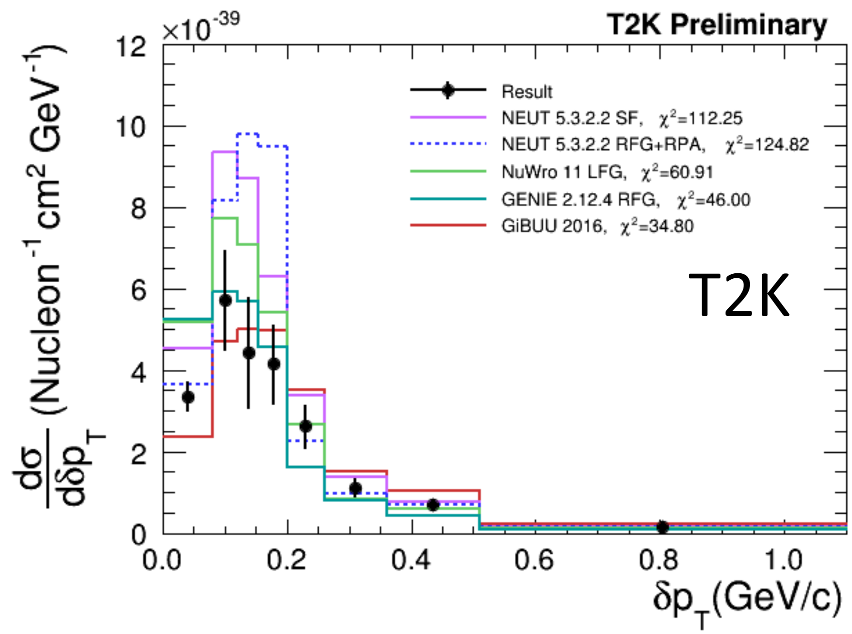
C(e,e’p)
2.26 GeV,
0.8 < x < 1.2



$$p_\perp^{\mathrm{miss}} = p_\perp^{e'} + p_\perp^{p}$$

Example II: FSI Effects

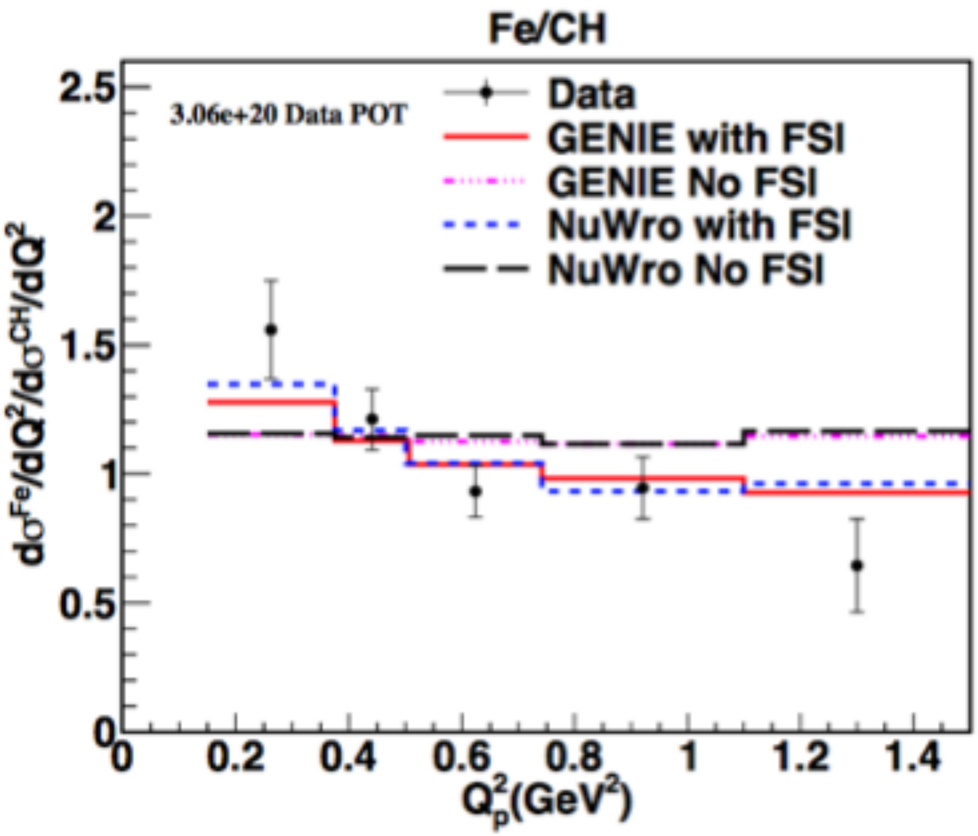




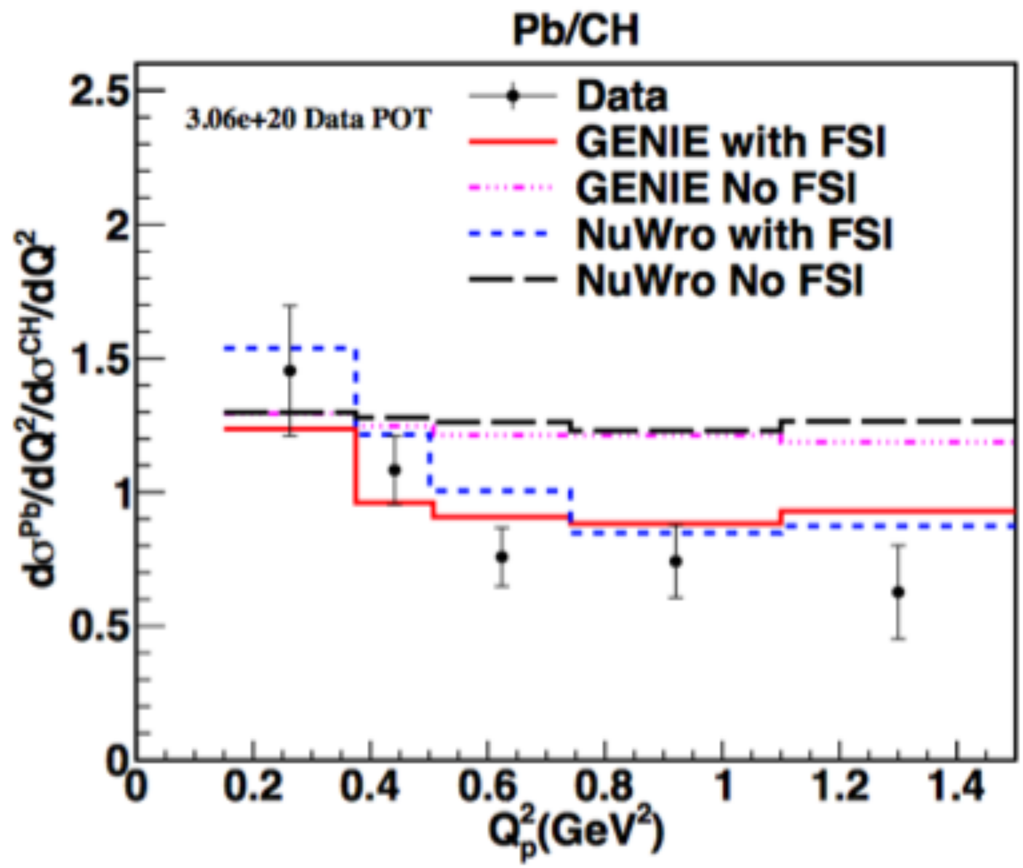
20 - 50% differences
@ Q^2 ~ 0.3 GeV^2

M. Betancourt et al. (MINERvA Collaboration), PRL **119**, 082001 (2018)

Example II: FSI Effects



30-40% FSI effects
@ Q^2 ~ 1.0 GeV^2



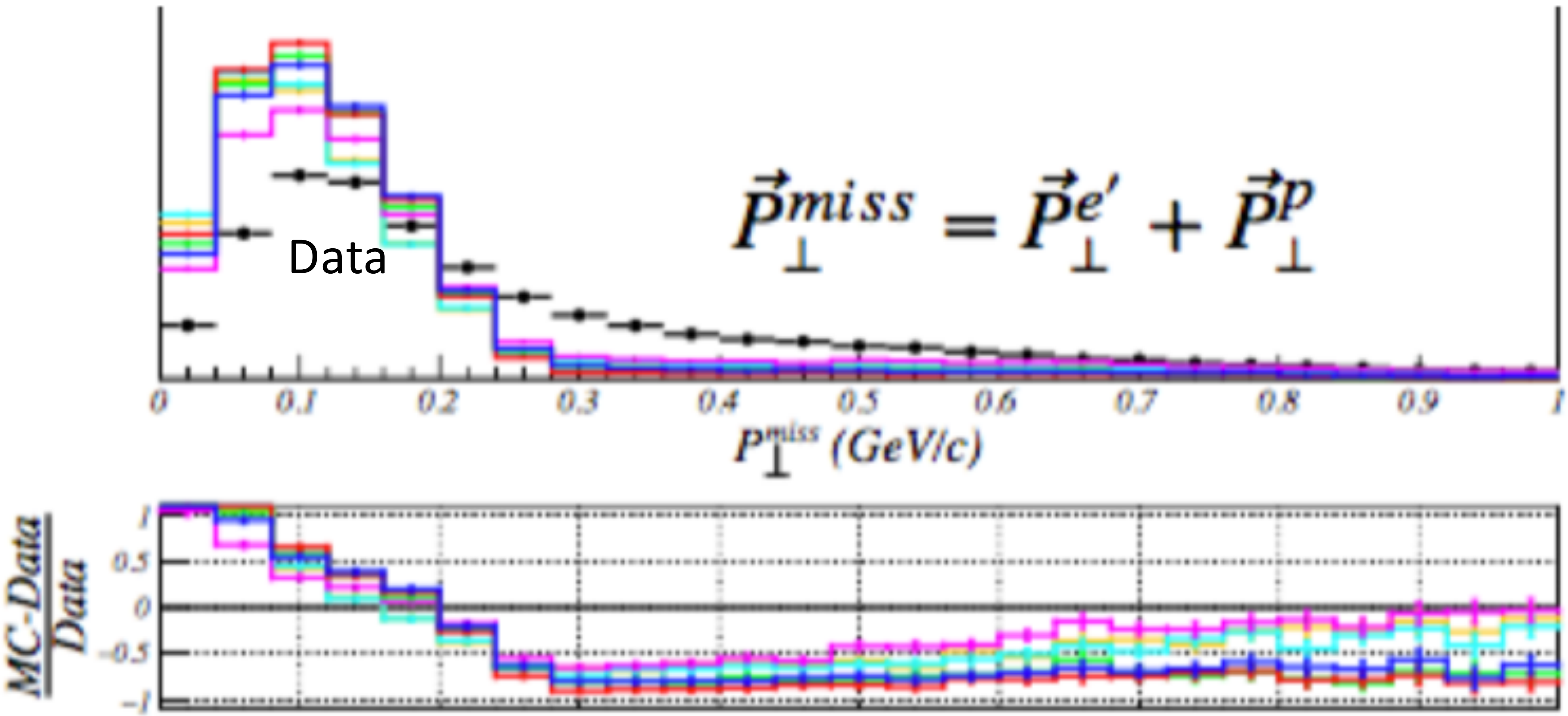
Note A/CH ratio.
Effect for individual nuclei is larger!

M. Betancourt et al. (MINERvA Collaboration), PRL **119**, 082001 (2018)

Example II: FSI Effects

C(e,e'p) 2.26 GeV, $Q^2 > 0.5\ GeV^2$ and W < 2 GeV

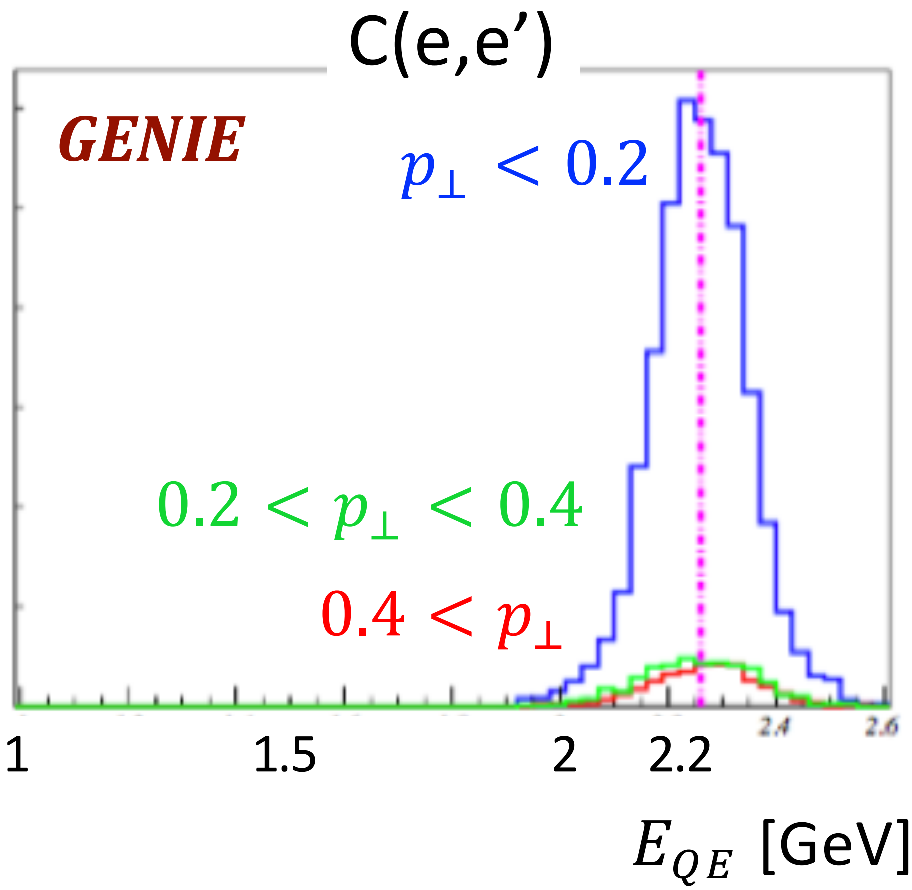
Histograms: various GENIE models (hA, hA2014, hA2015, hN, hN2014, hN2015)

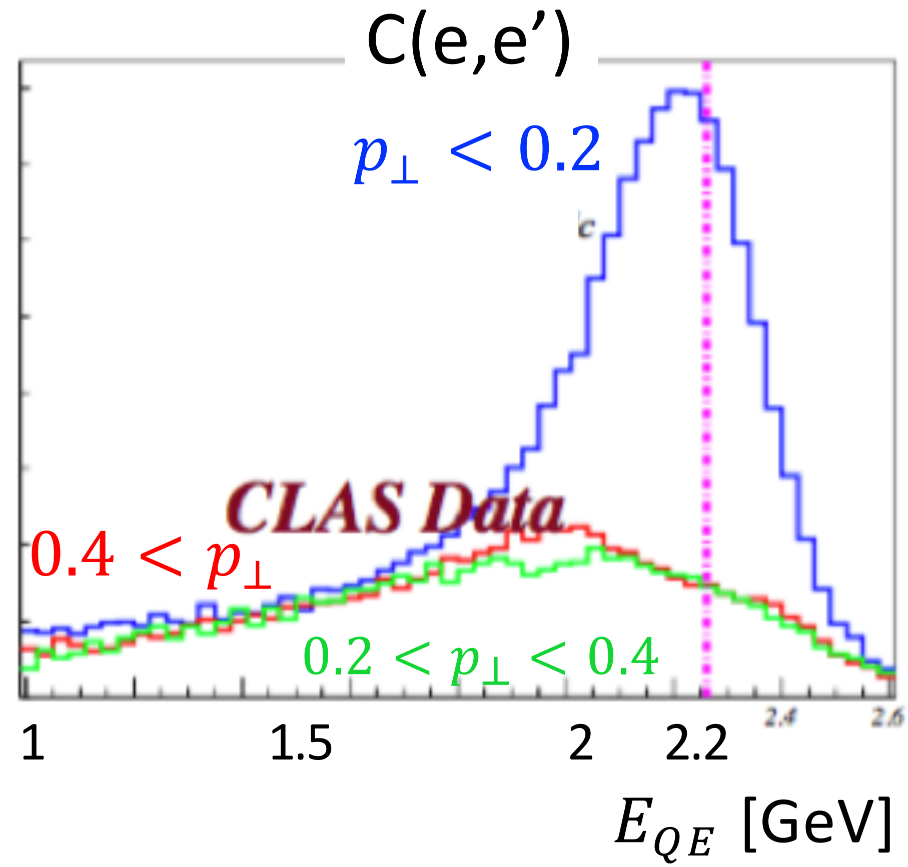


Significant differences at large $p_{\perp}$, none describe the data well

Example III: E_ν Reconstruction

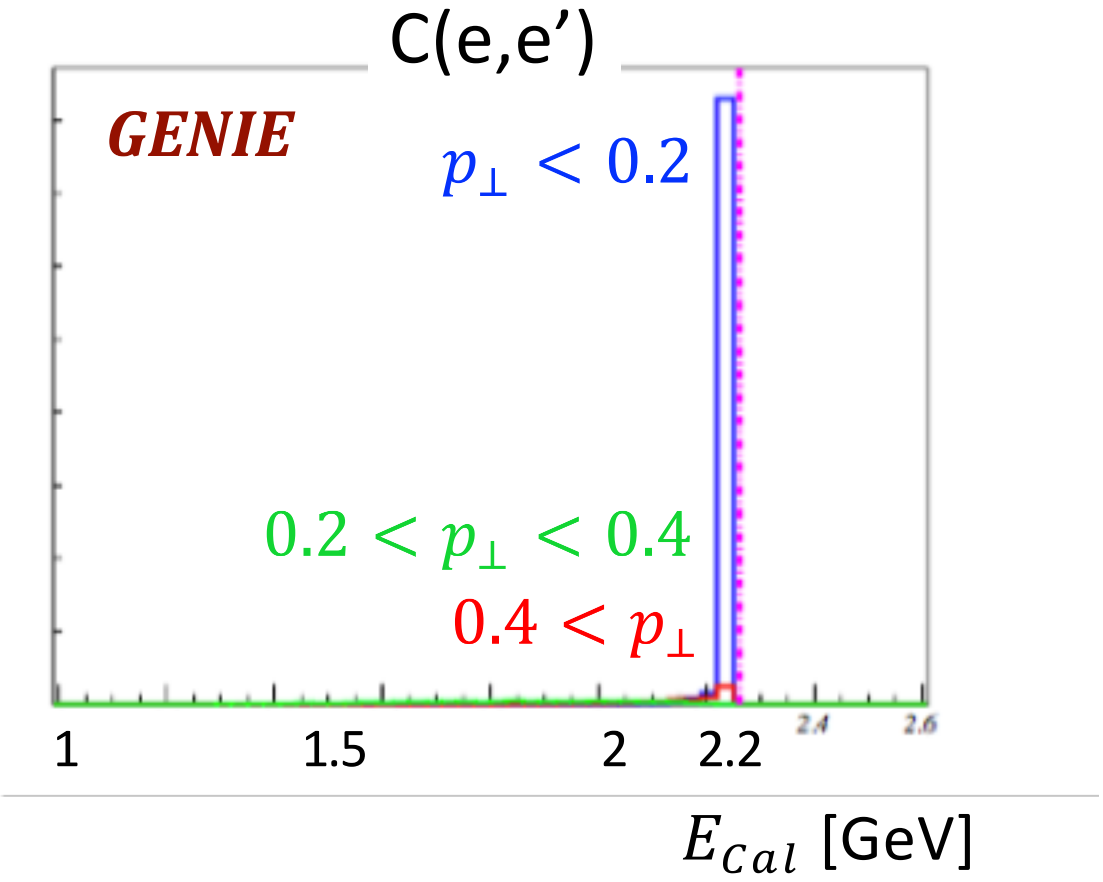
$$E_{QE} = \frac{2M\epsilon + 2ME_l - m_l^2}{2(M - E_l + |k_l|cos\theta)}$$

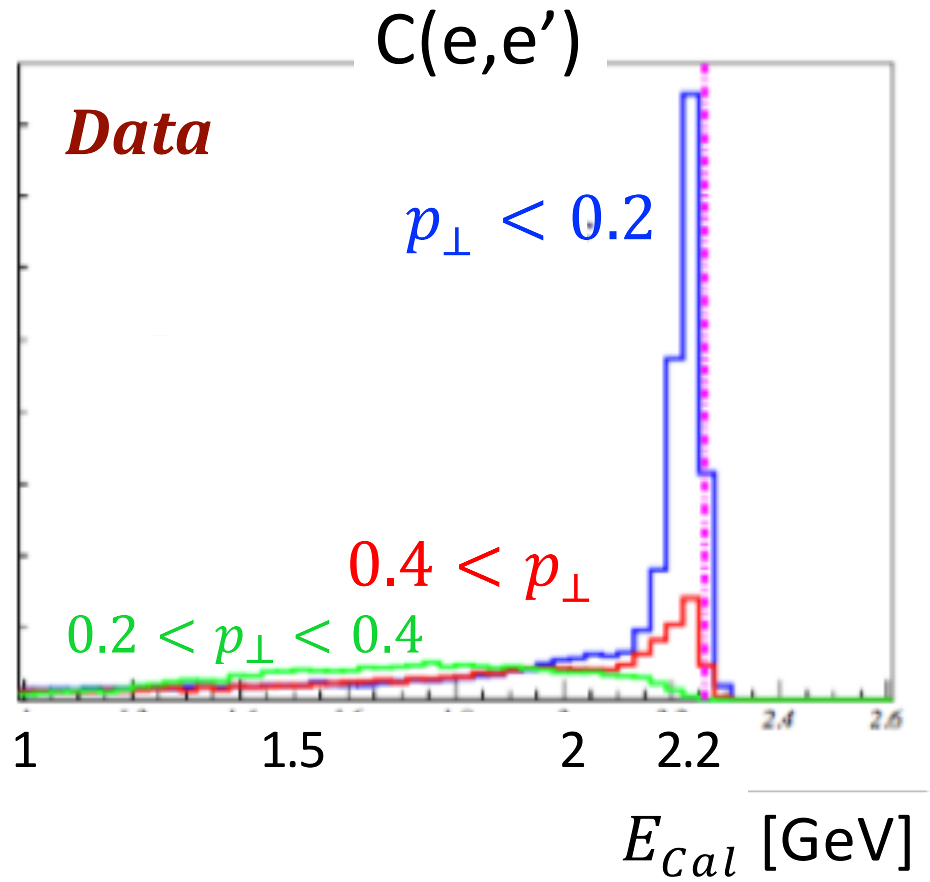




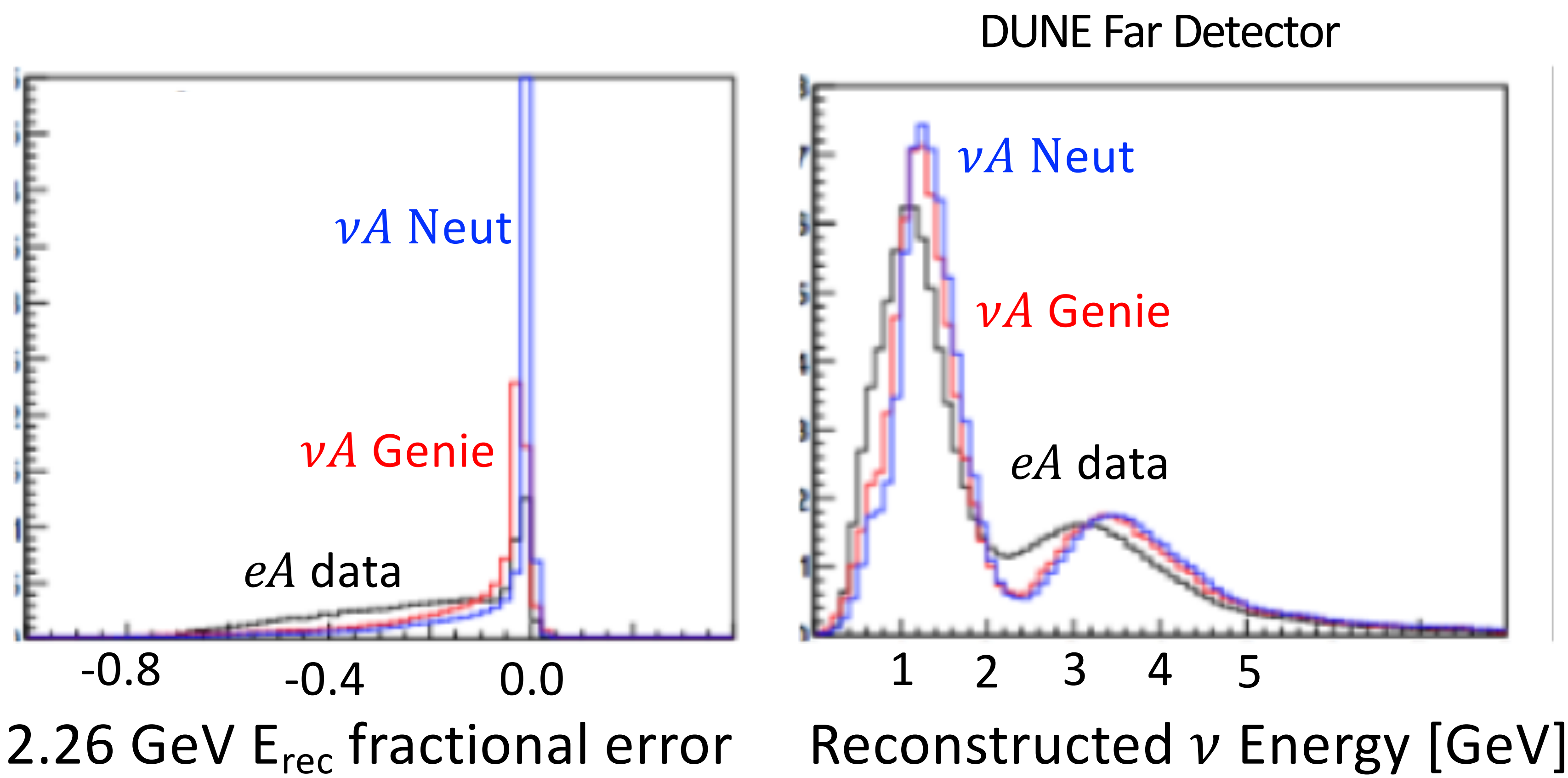
Example III: E_ν Reconstruction

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





Example IV: Energy Feeddown and Oscillation analyses



→ Very different oscillation parameters!

Details:

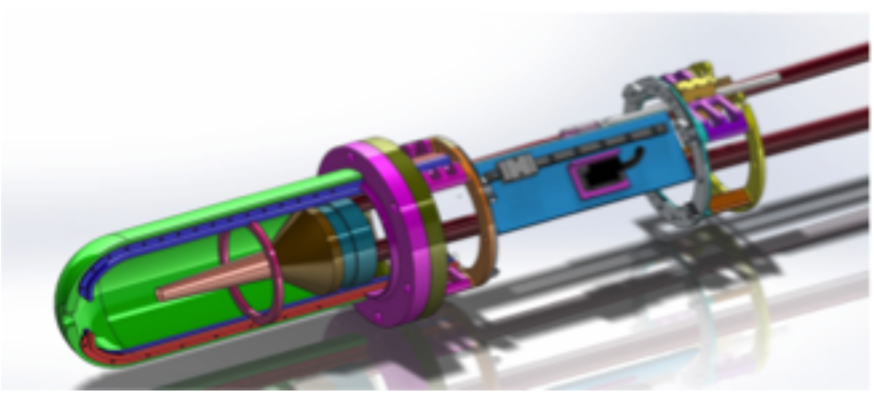
- Compared E_{rec} for eA to E_{rec} for νA
- Used 2.26 GeV eA E_{rec} for all incident energies
- Threw events with νA Genie
    - Reconstructed with νA Neut or eA data

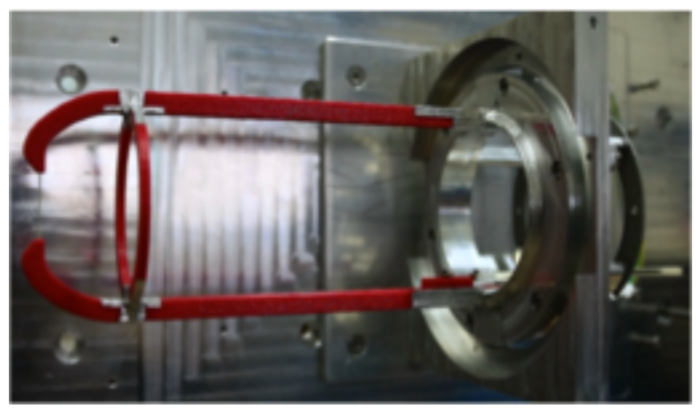
Electrons 4 Neutrinos

Energy [GeV]	H	^{4}He	^{12}C	^{16}O	^{40}Ar	^{120}Sn	Total
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





Beam Time Rationale

CLAS6

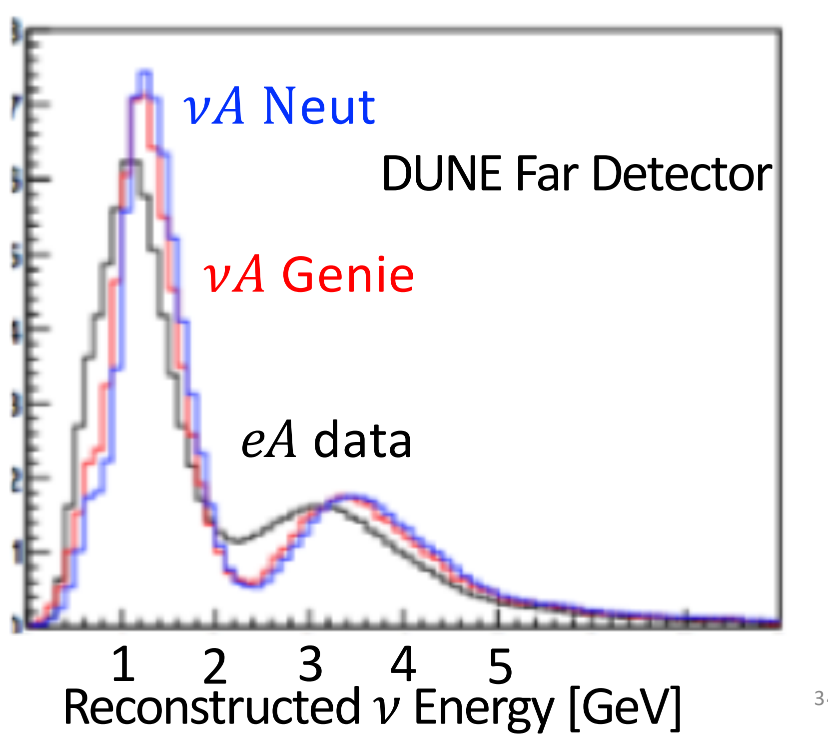
E_{rec}(%)	^{56}Fe 4.46 GeV	
	Fraction	Error
80—90	0.18	0.01
70—80	0.16	0.01
60—70	0.08	0.01
50—60	0.01	0.01

$p_\perp > 0.2$ GeV/c

4—6% error per 10% bin in reconstructed energy

Error feeds directly into energy reconstruction plot and oscillation parameters

Ten times more statistics
→1.5% error per 10% E bin
<or>
→5% error per 3% E bin



Electrons 4 Neutrinos

Changes to conditionally approved proposal:

- Beam time request reduced almost 50%
  - Focused on low and intermediate Q^2
    - 8.8 GeV beam time removed
    - 1.1 and 2.2 GeV running at reversed field
- Applied CLAS6 data to Dune energy reconstruction
- Coordinated with SRC proposal

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.
- **The 'Vector Currents' partner of the short-baseline (near-detector) neutrino program.**
- Impact on electron-scattering event generators
- Impact on high-luminosity accelerators R&D (RadCon interest to improve Geant4, Fluka etc.).

"benchmarking of the simulation packages such as Geant4 and FLUKA … is a long-standing important problem for the radiological evaluations at JLab and other high energy electron facilities" (RadCon)

Electrons 4 Neutrinos Team

Mariana Khachatryan (ODU@JLab)

Afroditi Papadopoulou (MIT@FNAL)

Adi Ashkenazi (MIT@FNAL)

+ L.B. Weinstein, F. Hauenstein (ODU), S. Stepanyan (JLab)
O. Hen, A. Schmidt, A. Silva (MIT), E. Piasetzky, E. Cohen (TAU)
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

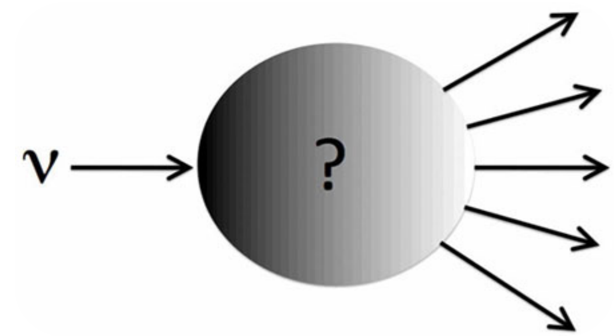
ANNIE
Accelerator Neutrino Neutron Interaction Experiment

μBooNE

GiBUU
The Giessen Boltzmann-Uehling-Uhlenbeck Project

JLab Argon - Titanium Experiment

Determining the Spectral Function from DATA



- In the absence of FSI

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

- Källën-Lehman representation

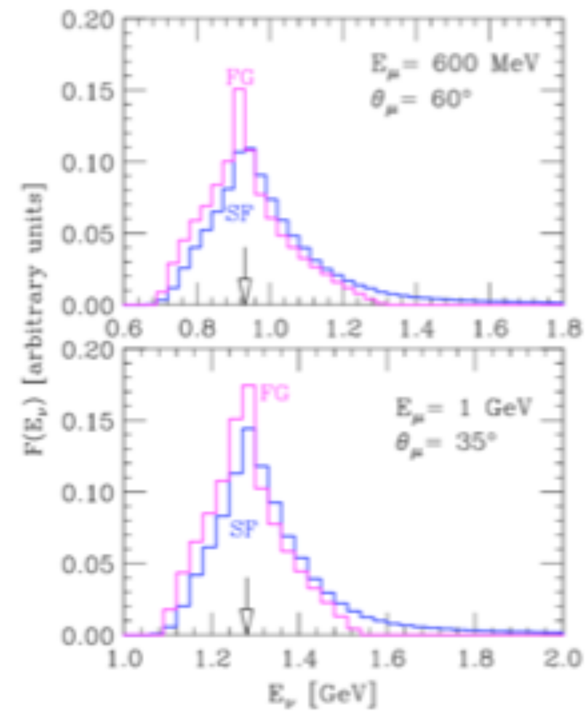
$$P(\mathbf{p}_m, E_m) = P_{\rm MF}(\mathbf{p}_m, E_m) + P_{\rm corr}(\mathbf{p}_m, E_m)$$

- 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: $Z_\alpha \to 1$, $F_\alpha(E_m - \epsilon_\alpha) \to \delta(E_m - \epsilon_\alpha)$

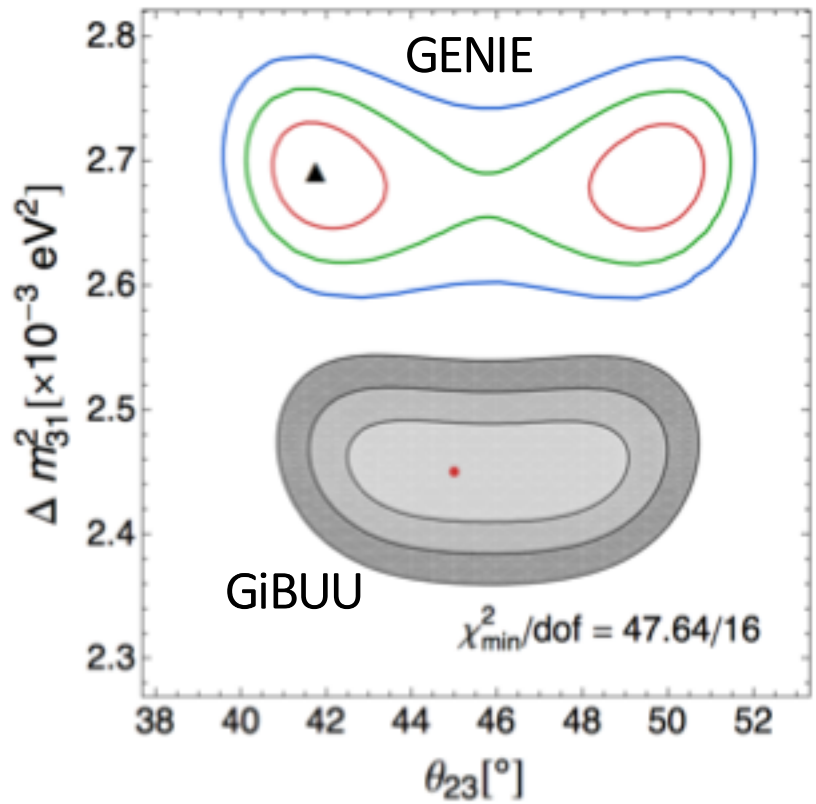
- $P_{\rm corr}(\mathbf{p}_m, E_m)$ from theoretical calculations of uniform nuclear matter and Local Density Approximation (LDA)



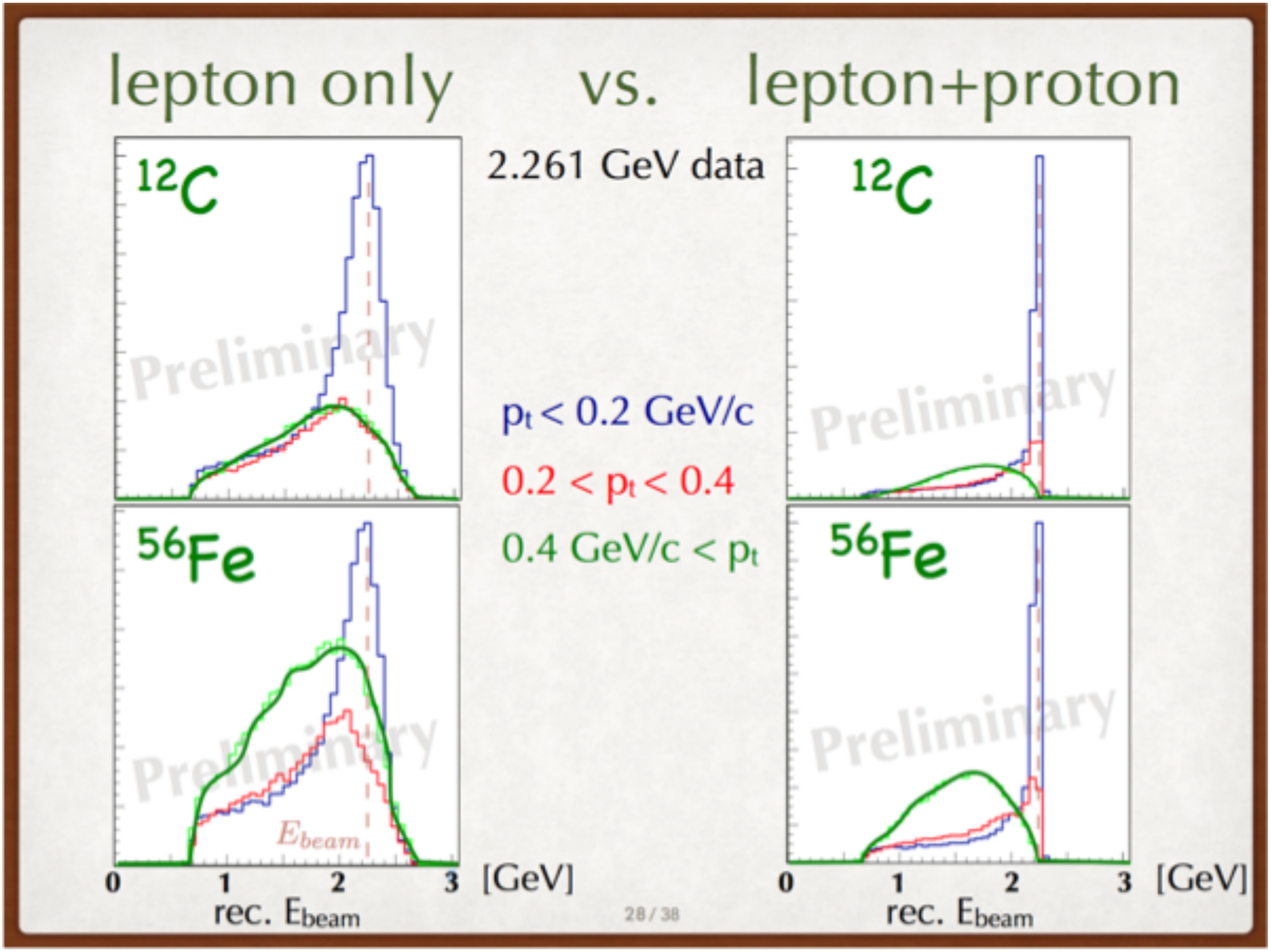
$$E_\nu = \frac{m_p^2 - m_\mu^2 - {E_n}^2 + 2E_\mu E_n - 2\mathbf{k}_\mu \cdot \mathbf{p}_n + |{\mathbf{p}_n}^2|}{2(E_n - E_\mu + |\mathbf{k}_\mu|\cos\theta_\mu - |\mathbf{p}_n|\cos\theta_n)}$$

Adapted from P. Pandey talk (July 2017)

Phys.Rev. D89 (2014), 073015



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



Generic oscillation analysis: **improving robustness**

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

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)

This proposal provides data to test:

- Cross section proces models as implemented in generators
- Efficiency of detector to hadronic system, which in practice relies on generator to calculate
- Relationship to true neutrino energy, true Q^2 (R) assumed in generator

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)

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

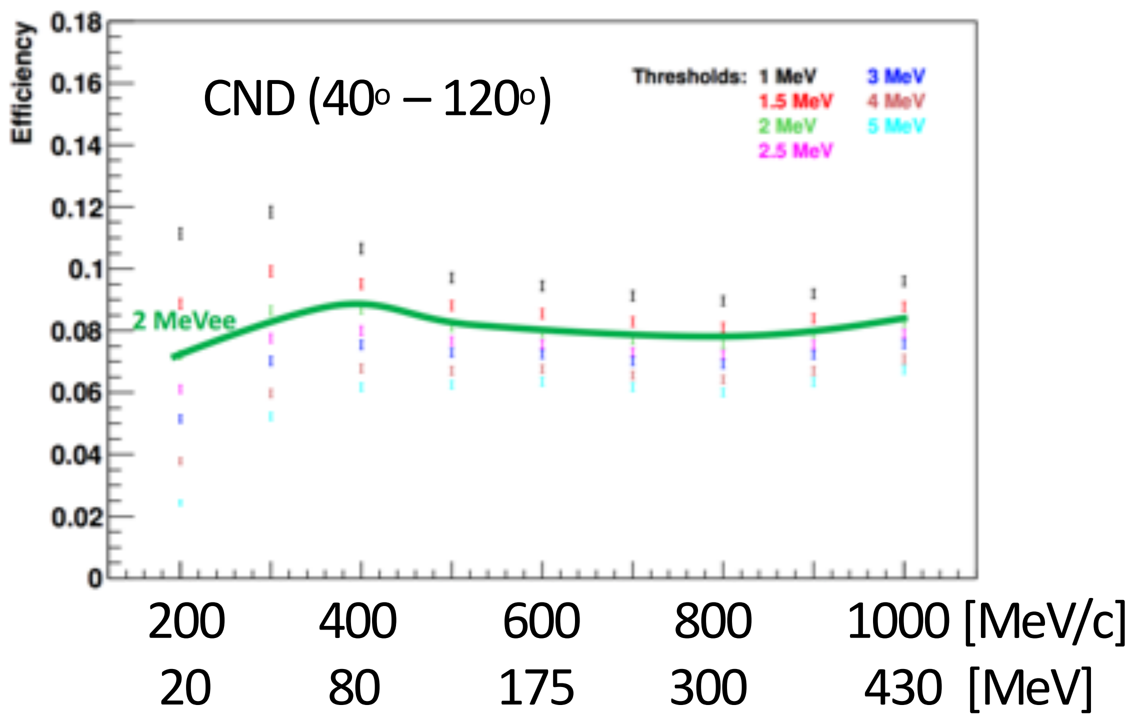
Near detector provides partial cancellation of all uncertainties through rate with a different flux:

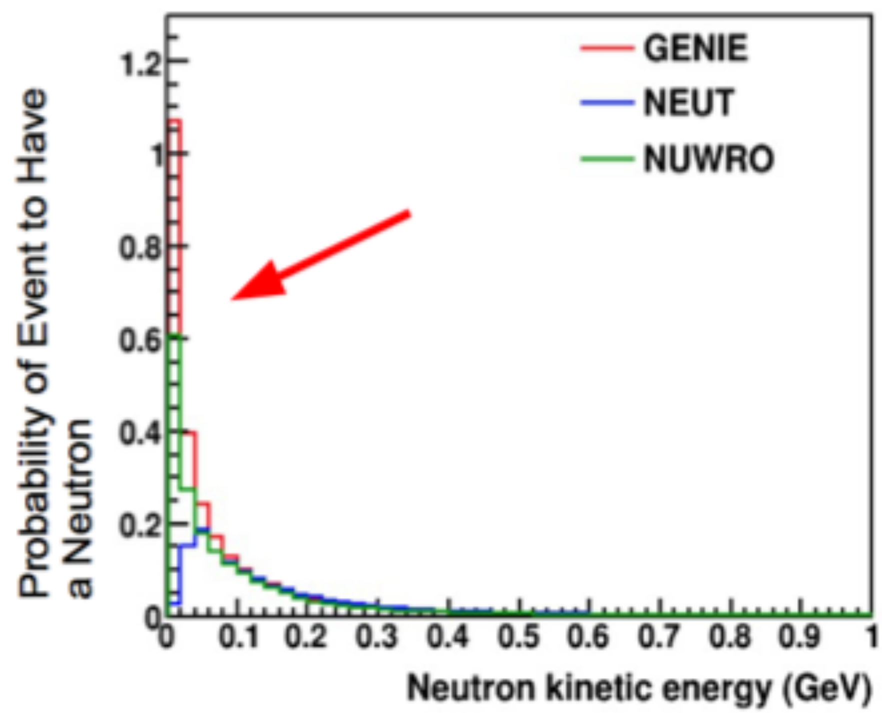
- T2K: ~5% total uncertainty, starting from ~10% flux uncertainties and 10-30% cross sections. Relies on correct models and ingredients.

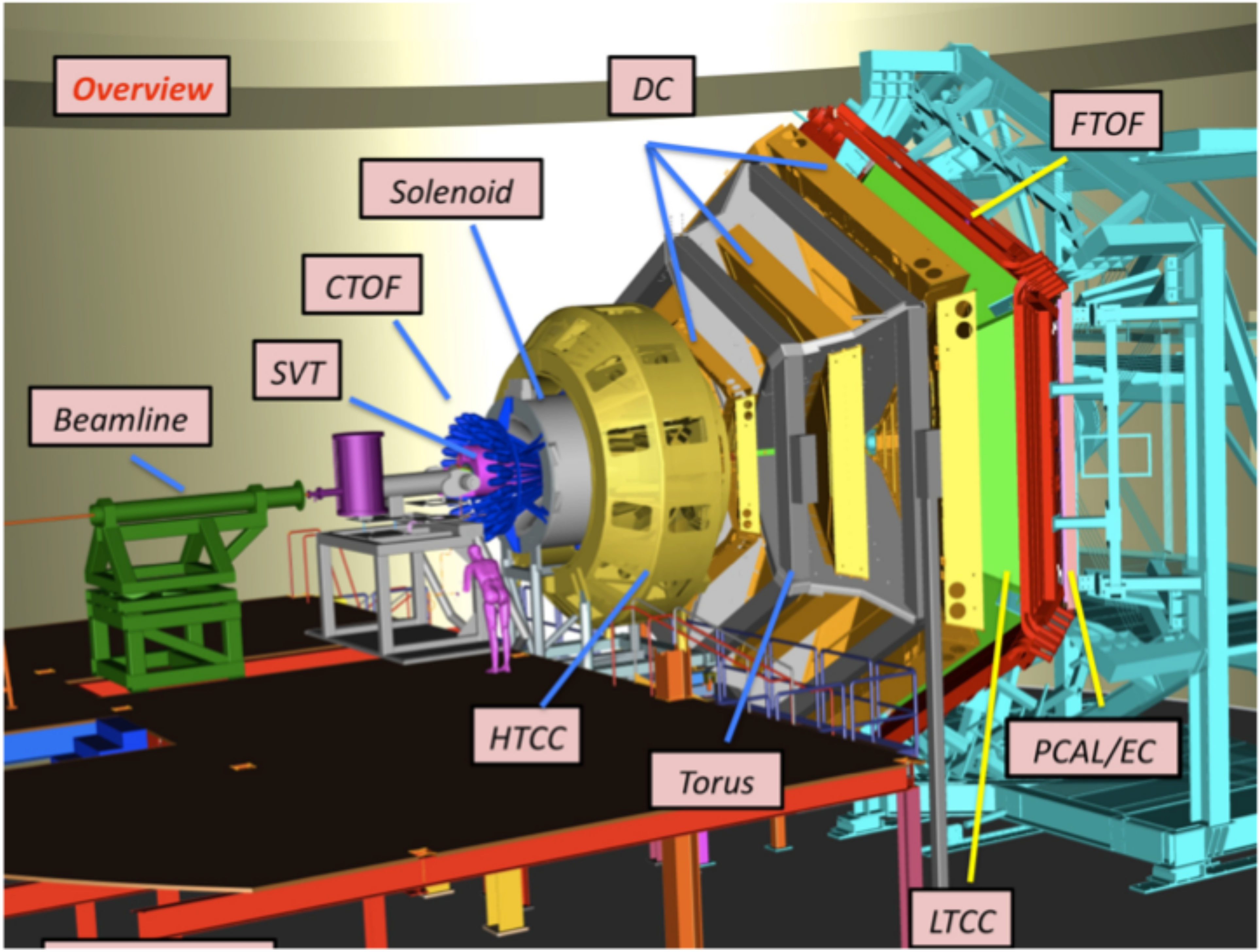
This proposal is like another near detector. Provide third rate, with unique handles of vector coupling, known beam energy and ability to separate processes.

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

Neutron Multiplicity

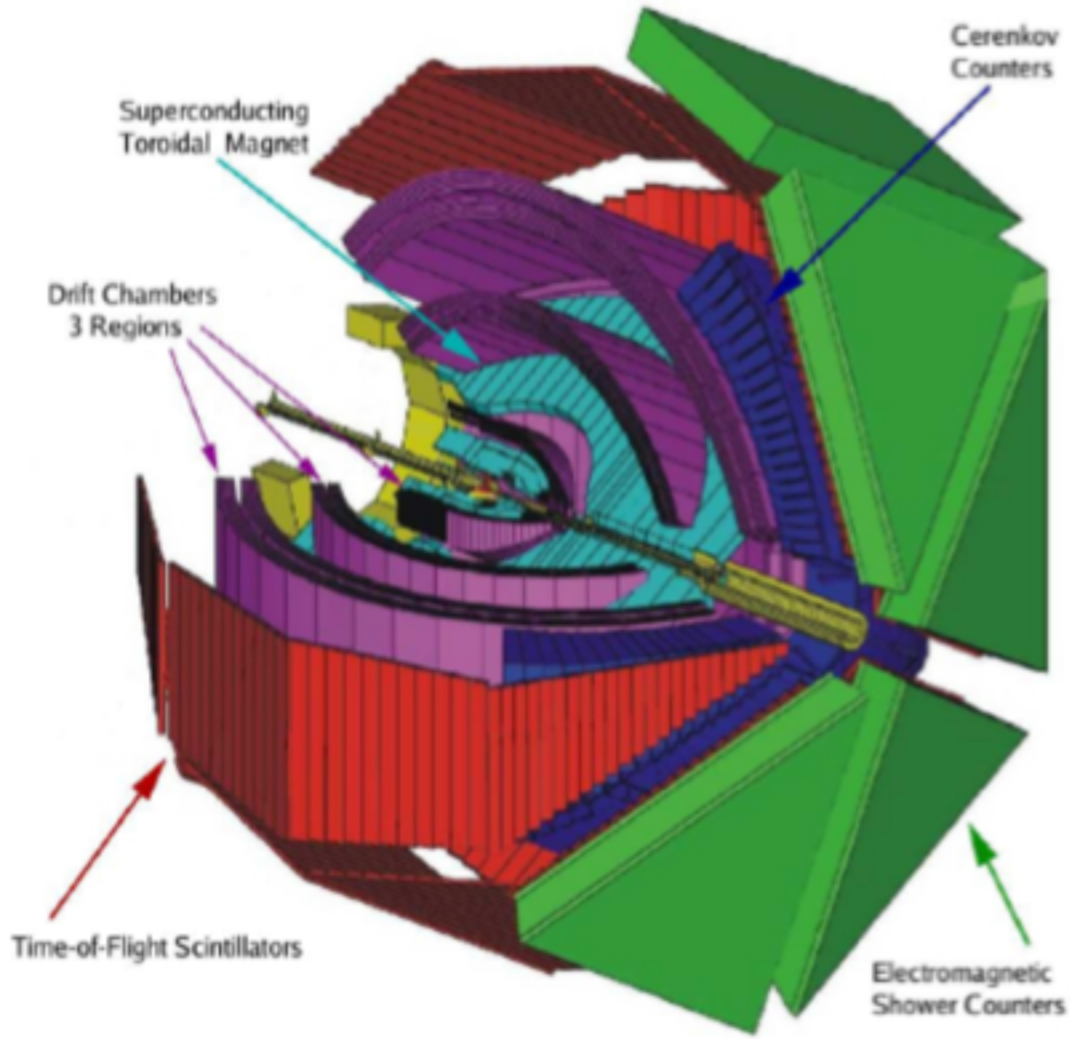





Overview
DC
FTOF
Solenoid
CTOF
SVT
Beamline
HTCC
Torus
PCAL/EC
LTCC

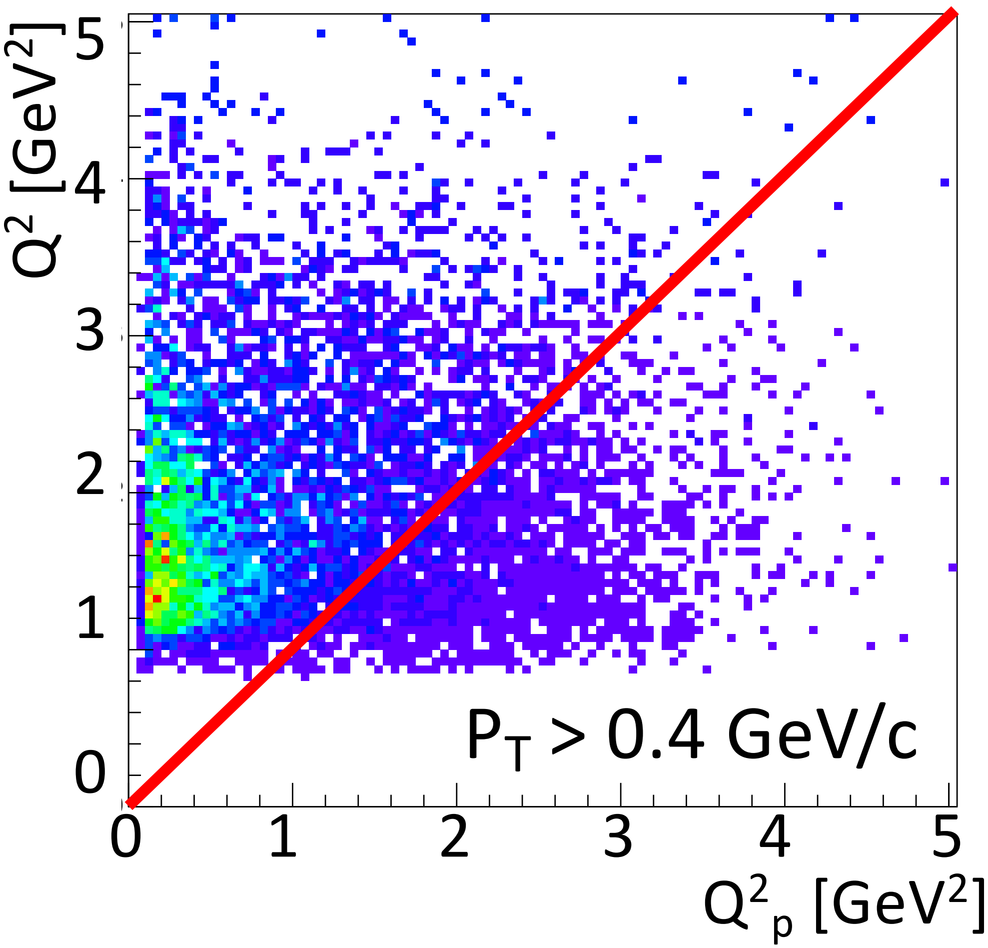
CLAS6 Spectrometer

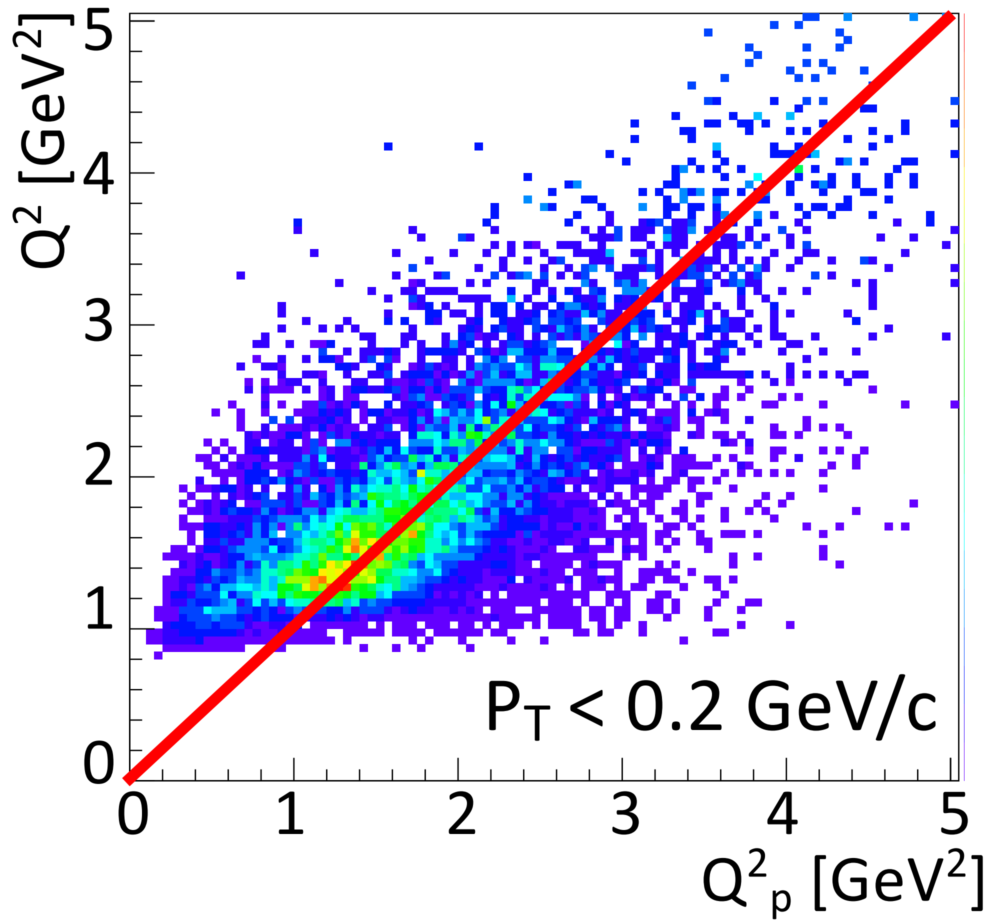
- 1 - 5 GeV electron beam,
- (almost) 4π acceptance,
- Charged particles (8^{o}-143^{o}): Toroidal field + tracking, TOF, Cerenkov, and EM Calorimeter,
- Neutral particles: EM Calorimeter (8^{o}-75^{o}) and TOF (8^{o}-143^{o}).
- Low detection threshold (~300MeV/c),
- <u>OPEN TRIGGER !</u>



Example IV: E_ν & Q^2 Reconstruction

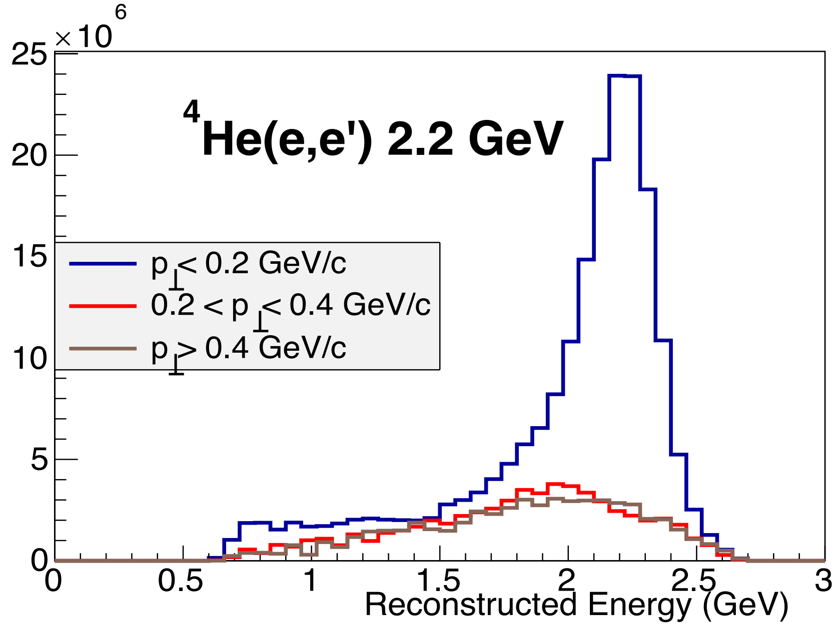
High Q^2 events reconstructed as low Q^2_p due to nuclear effects

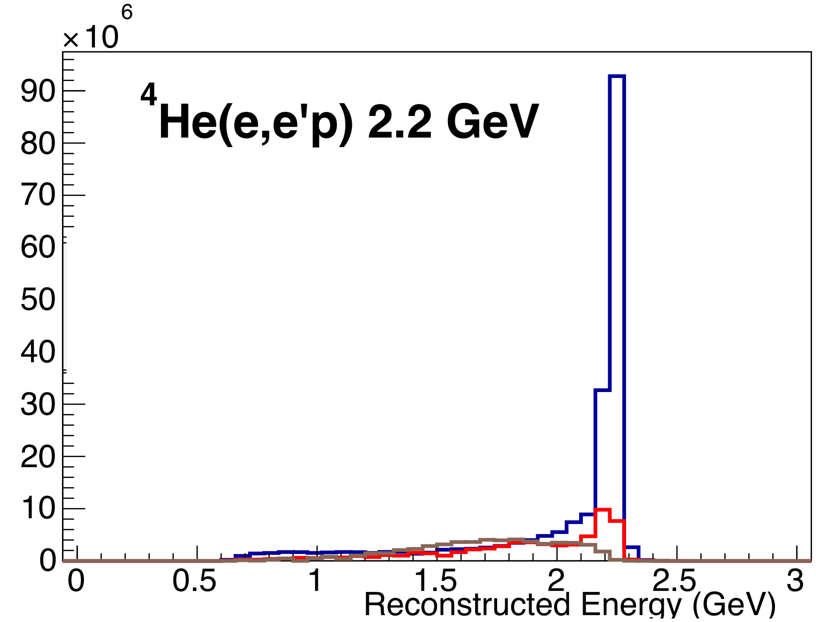


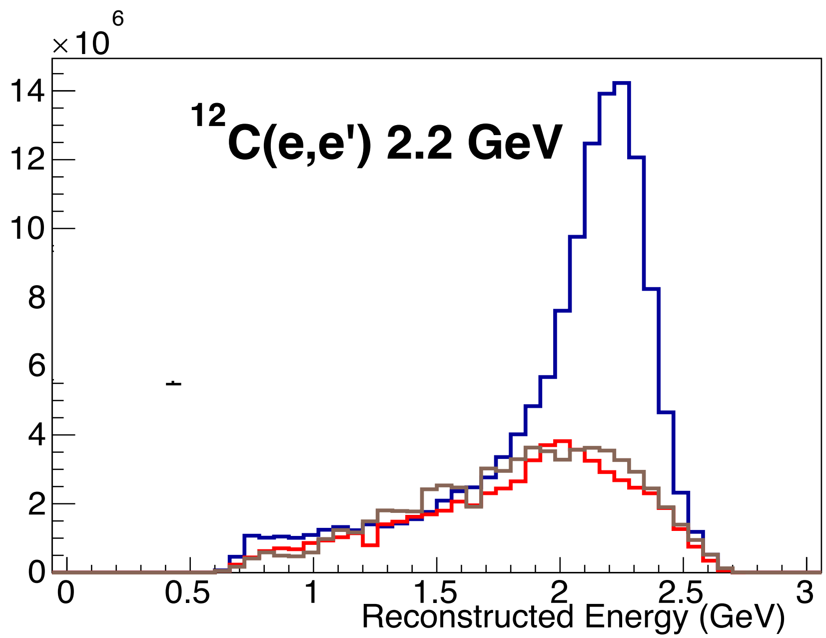


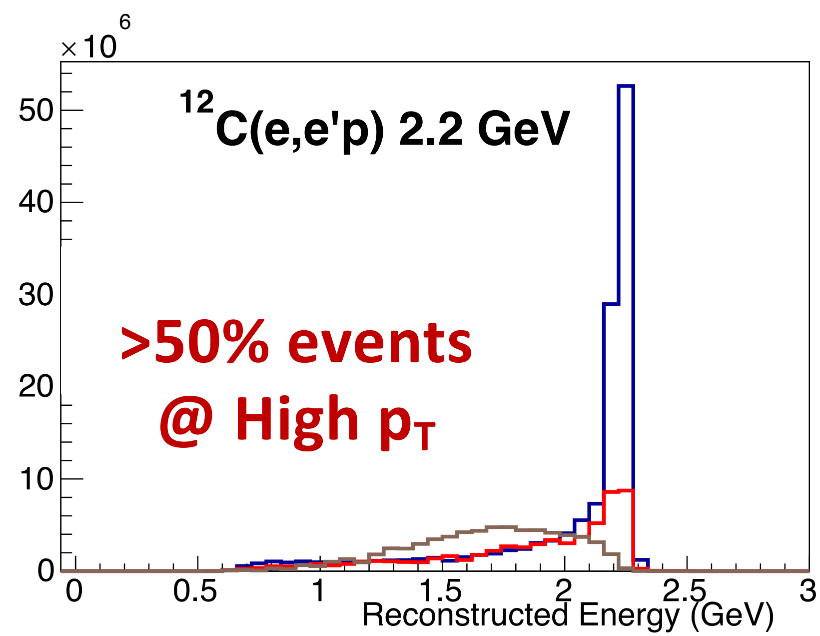
CLAS6 Data,
4.4 GeV Incoming beam.
$^{12}C(e,e'p)$ no pion events.

Energy Reconstruction Example





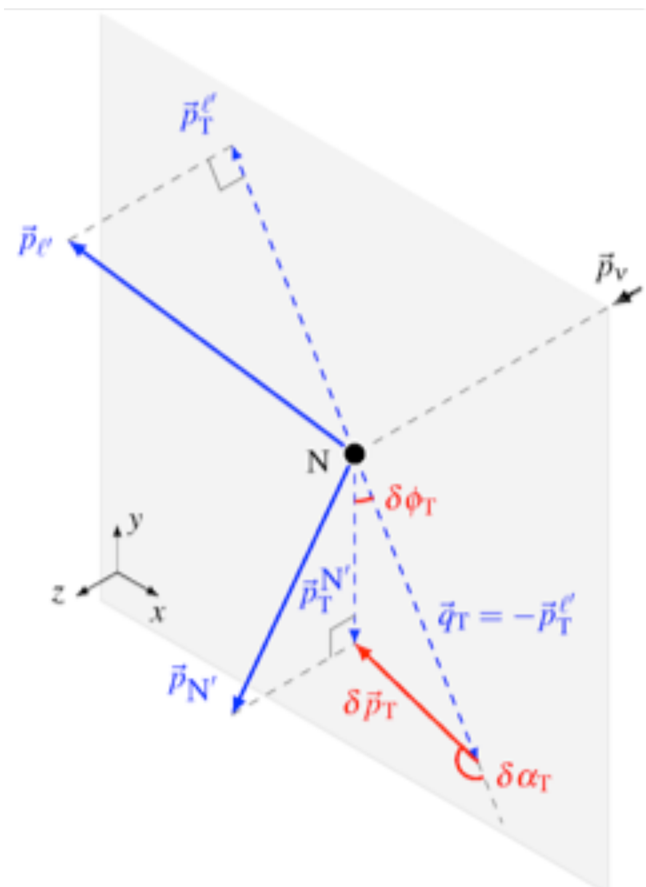


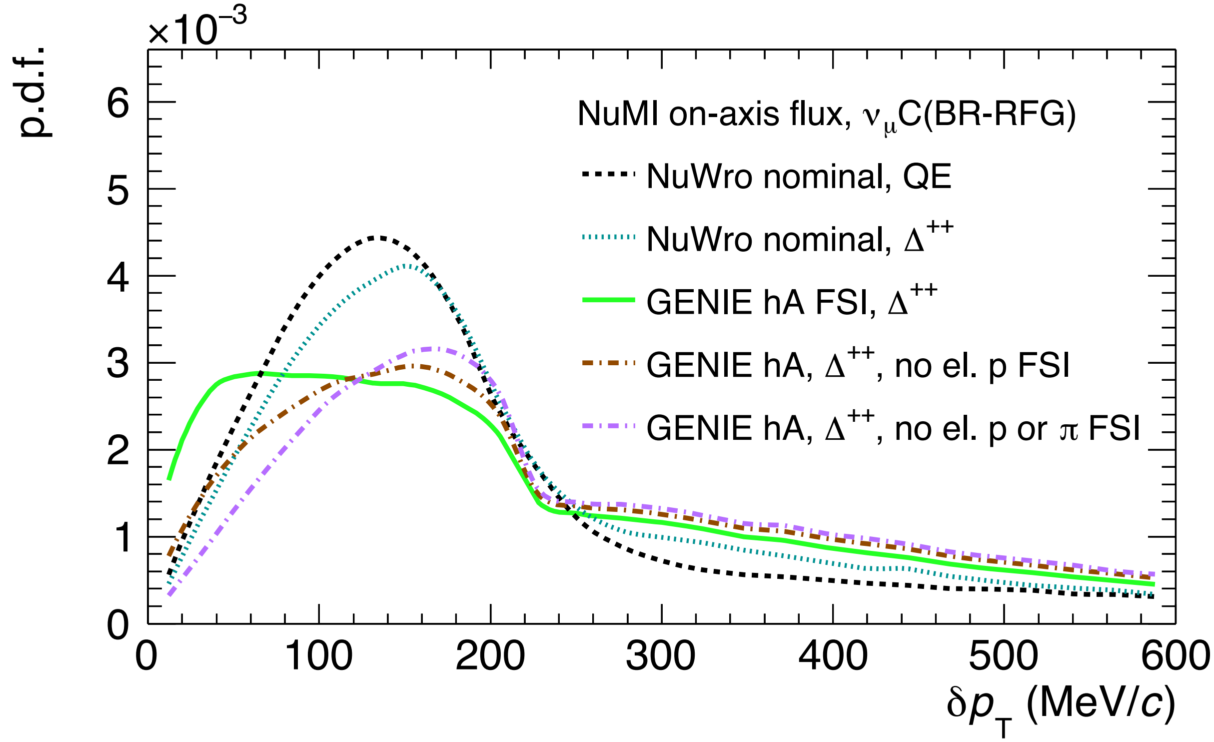


$$P_T^{miss} = P_T^{lepton} + P_T^{Proton}$$

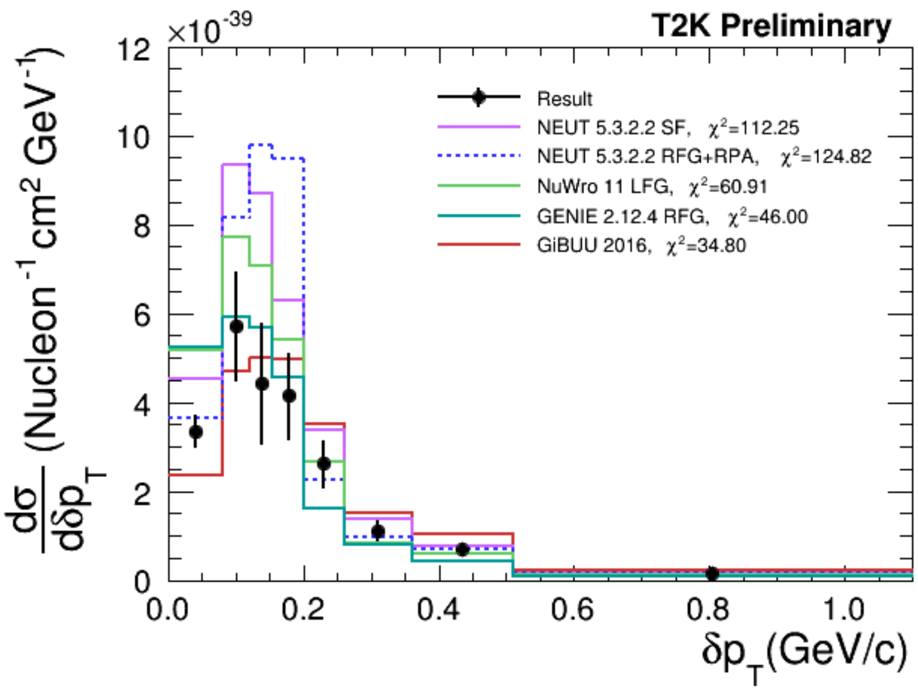
“Transverse variables”

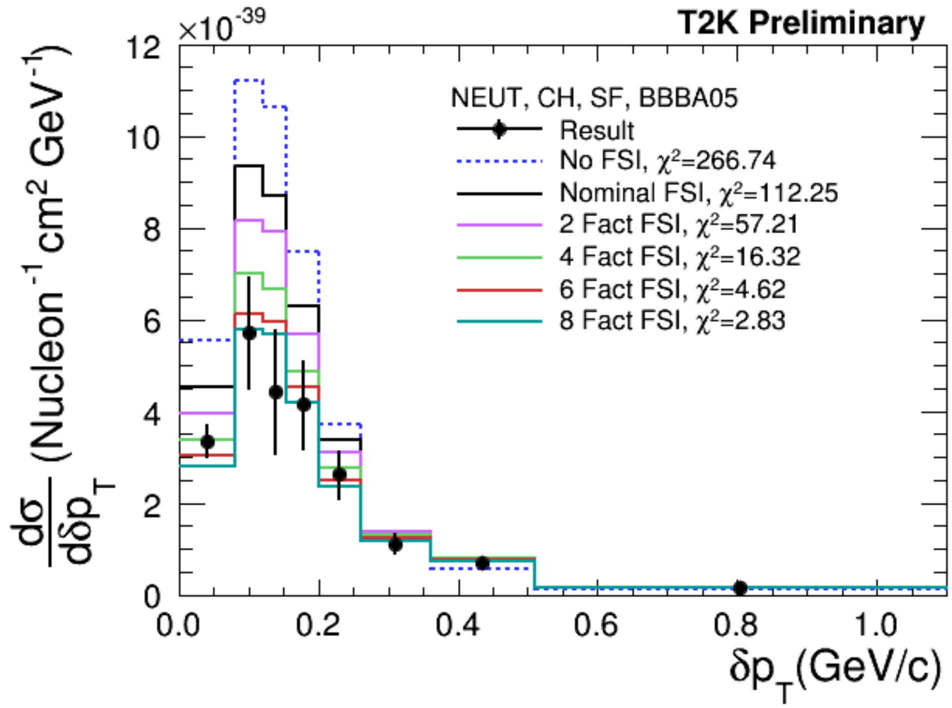
Relative momentum or angle between proton and muon from semi-inclusive scattering





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

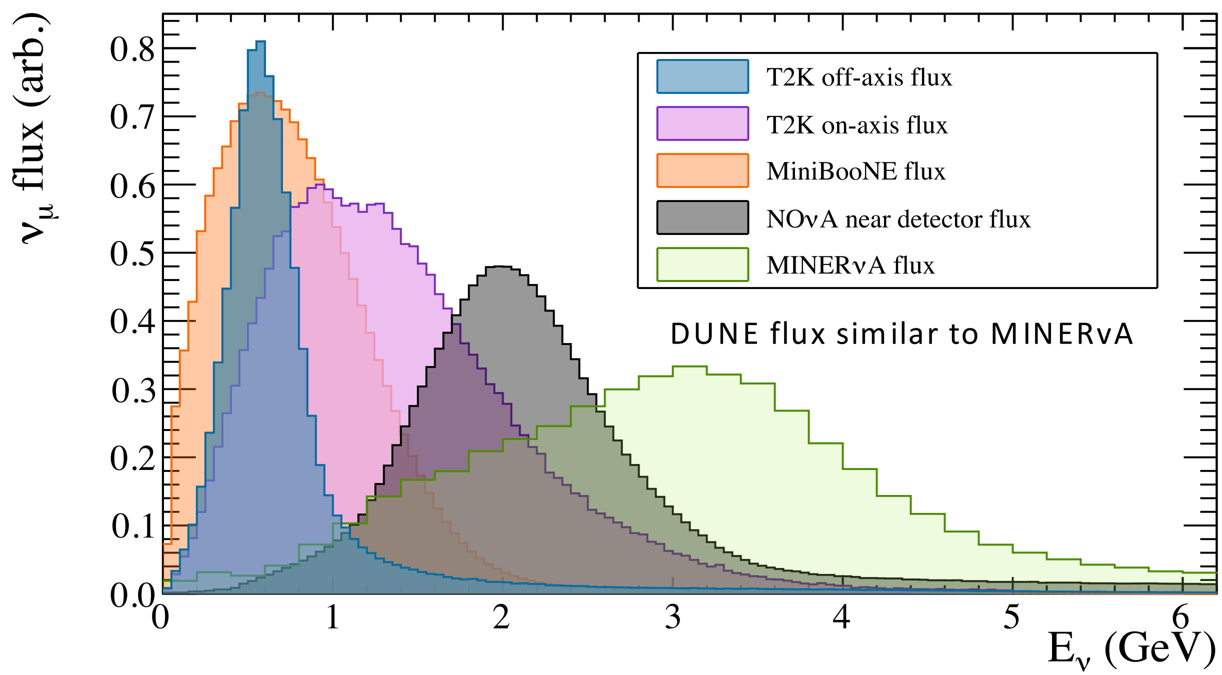
Models in NEUT, GENIE are insufficient to describe this data

Artificial, extreme change to FSI to "match" data in NEUT

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

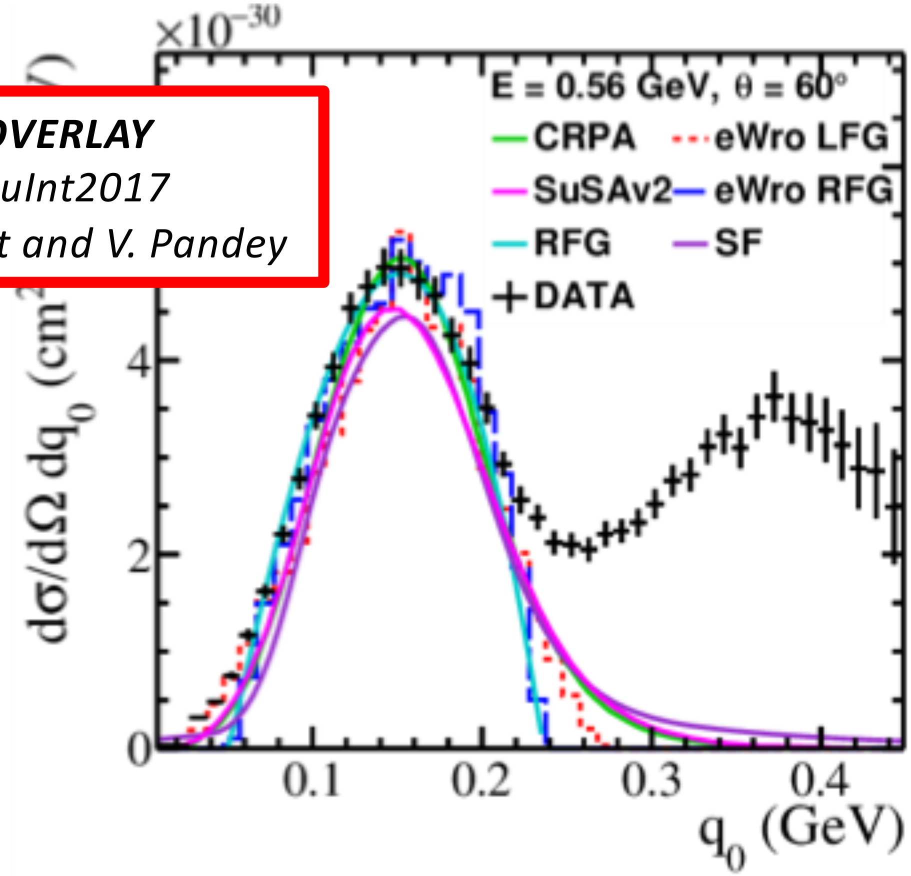
NuSTEC white paper (arxiv.org/1706.03621)
NOvA far detector event rate:

	% 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