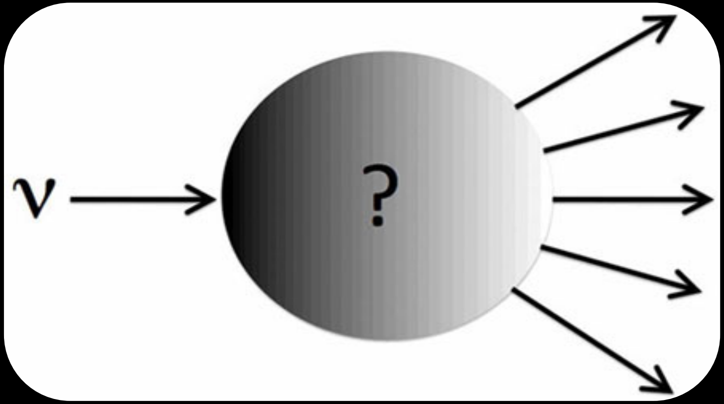
Electrons for Neutrinos: Addressing Critical Neutrino-Nucleus Issue

Proposal PR12-17-006

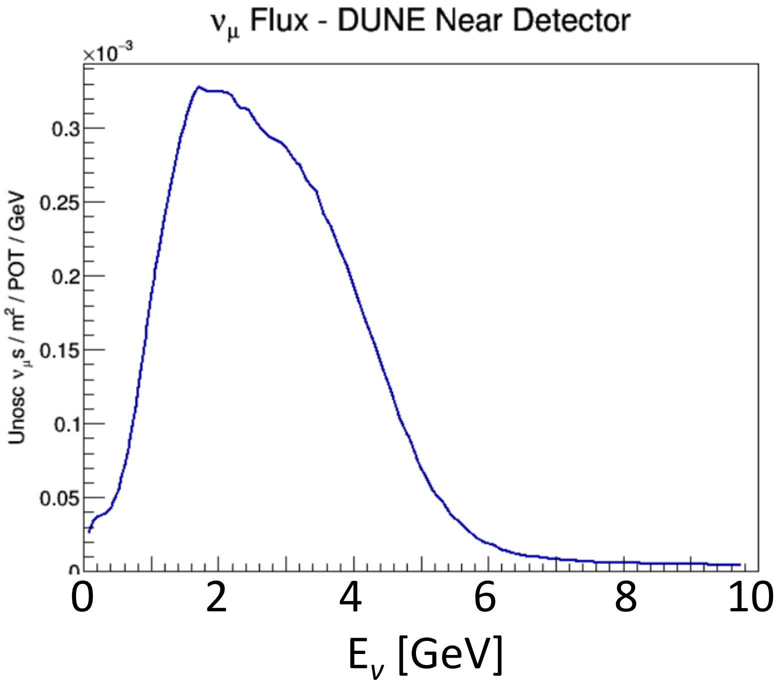
Spokespersons:

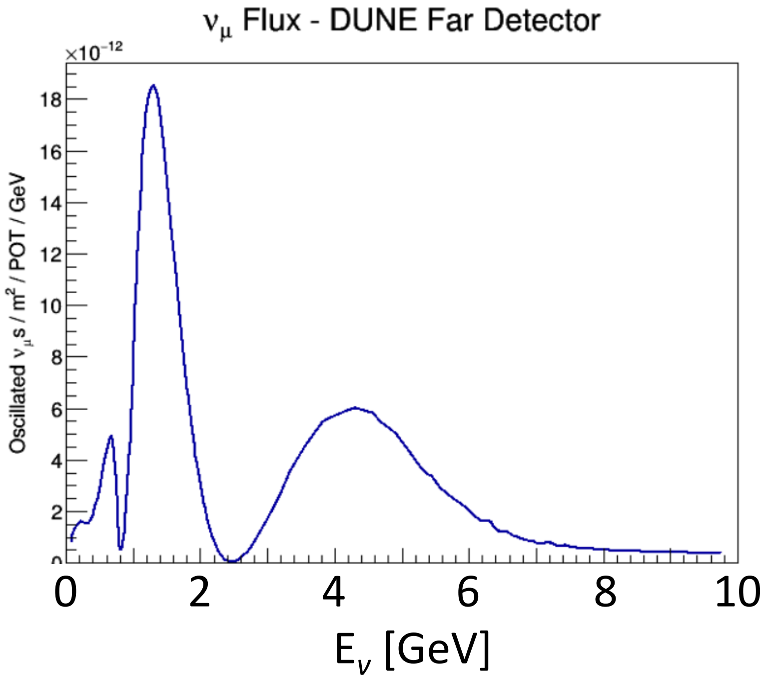
O. Hen (MIT), K. Mahn (MSU),
E. Piasetzky (TAU), S. Stepanyan (JLab)
and L.B. Weinstein (ODU).



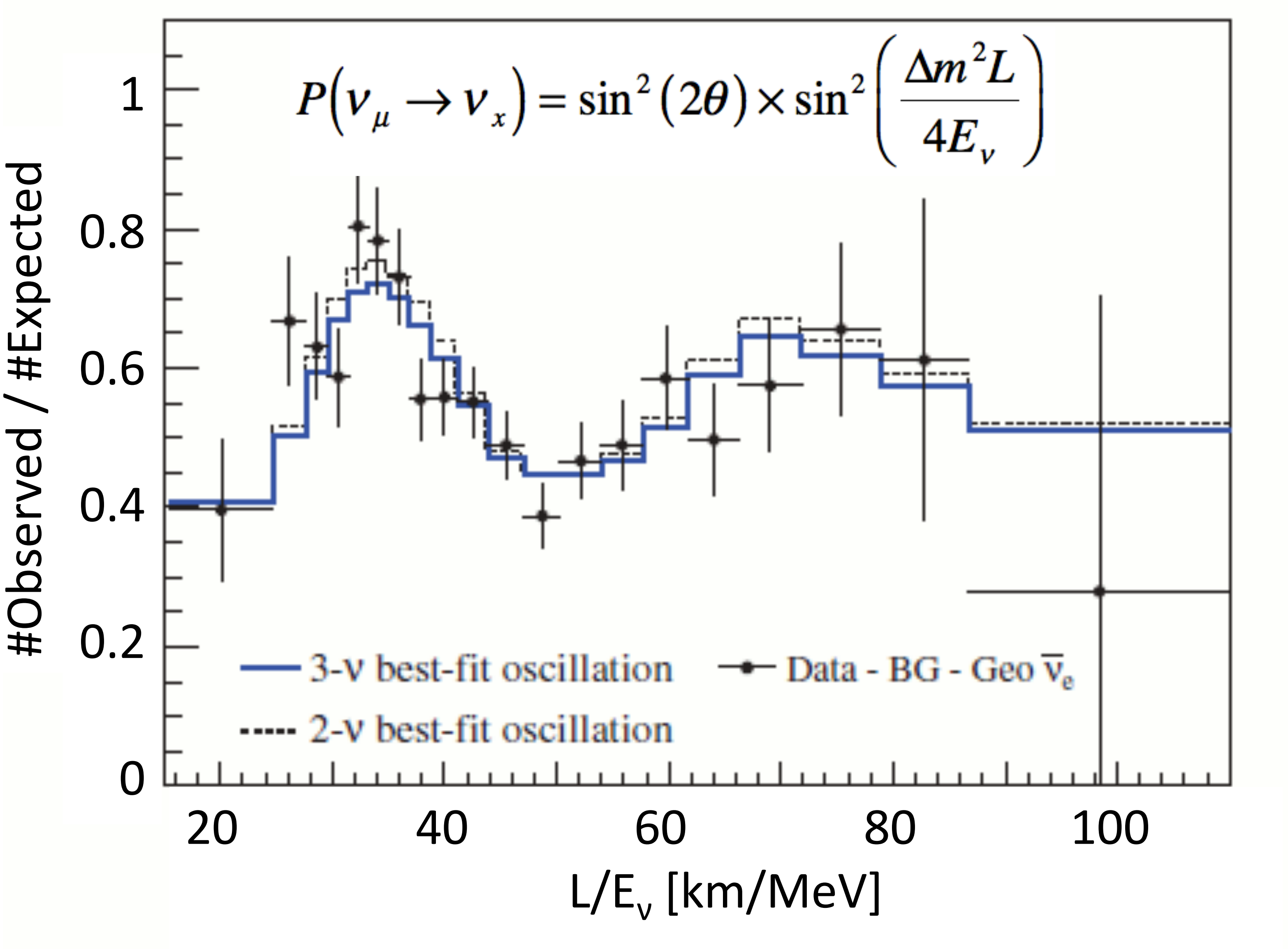
Jefferson Lab PAC-45, July 11th, 2017

Long Baseline Oscillations


ν_μ Flux - DUNE Near Detector


ν_μ Flux - DUNE Far Detector

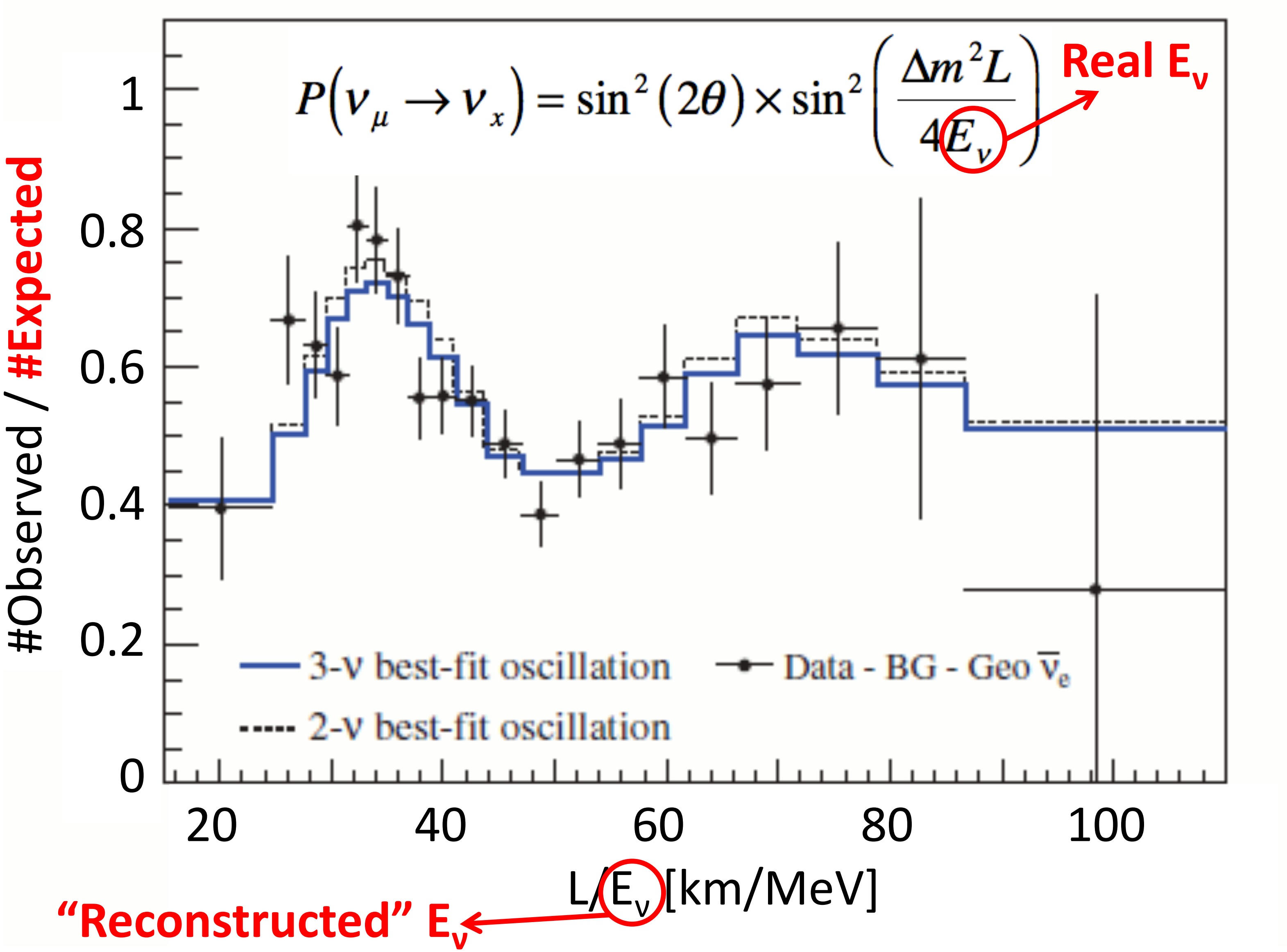
Neutrino Oscillations



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

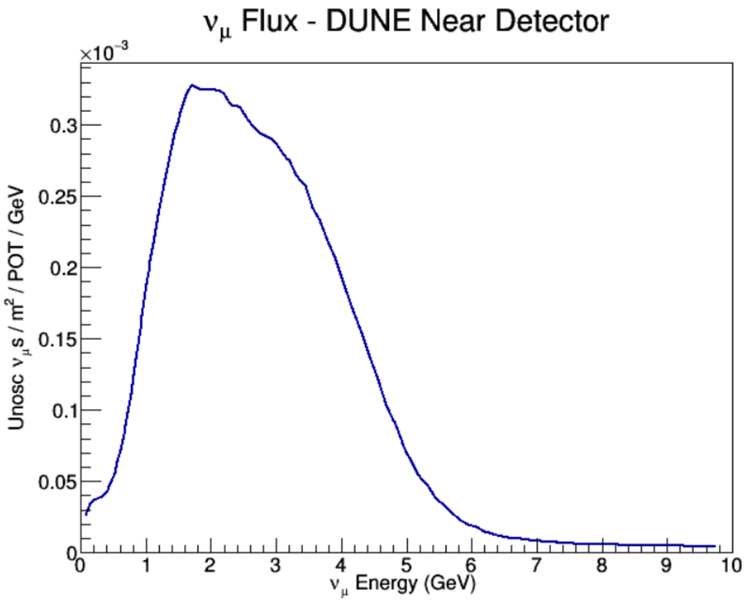
KamLAND, PRL 100, 221803 (2008)

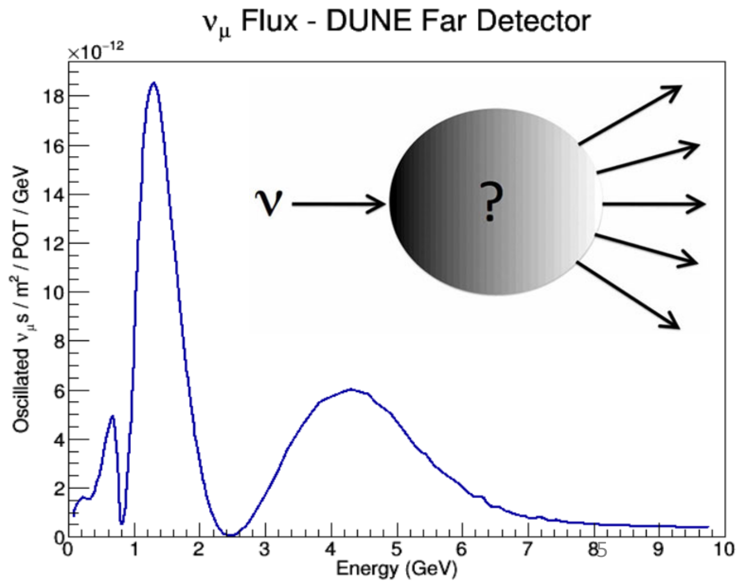
Neutrino Oscillations



KamLAND, PRL 100, 221803 (2008)

(Long Baseline) Oscillation Challenge





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

- 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

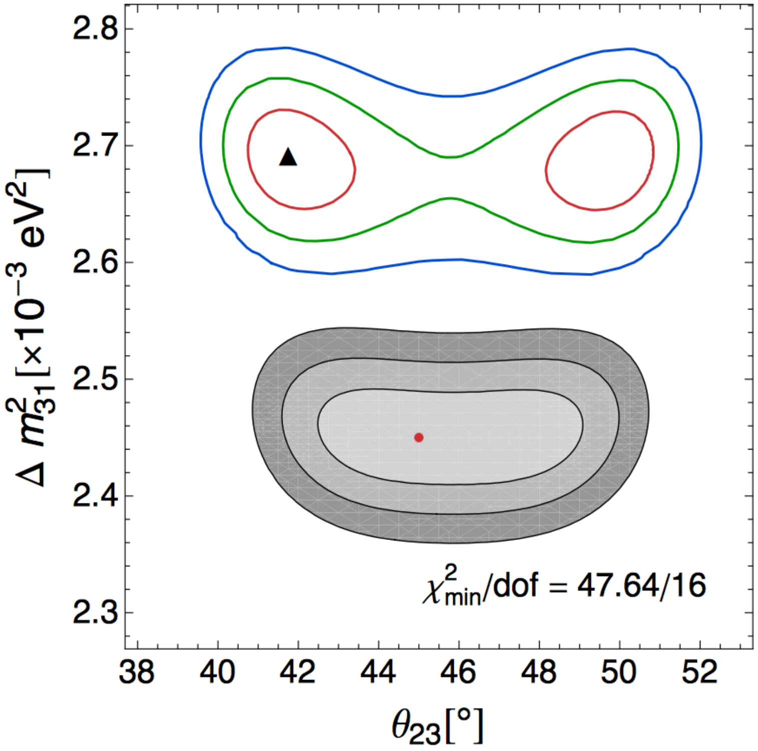
(Long Baseline) Oscillation Challenge

Oscillations are basically ratios of reconstructed ν energy spectra:

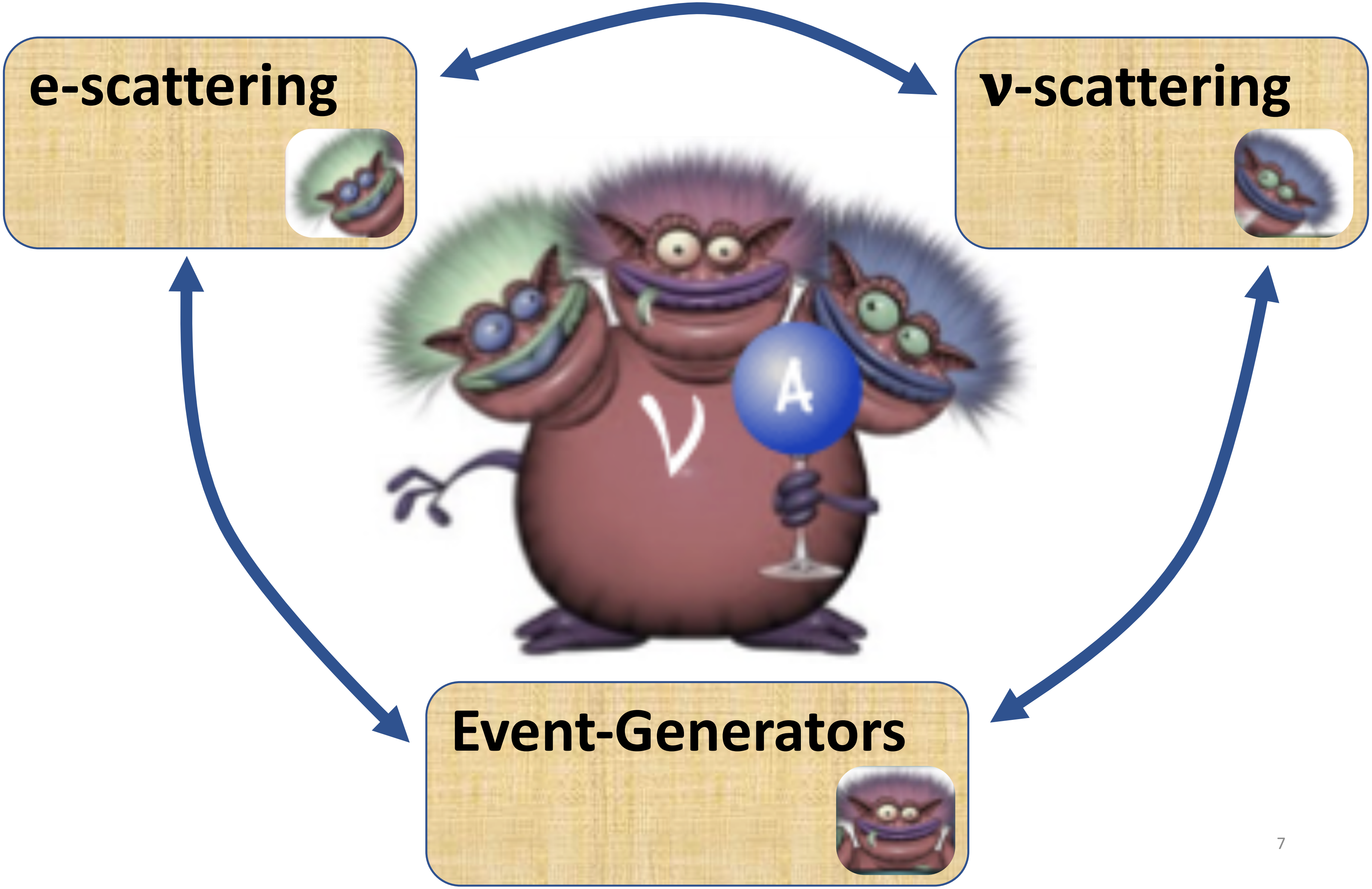
- Energy (x-axis): Reconstructed from the measured final state.
- Flux (y-axis): Reconstructed using reaction model (cross-section + FSI + …)

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

Phys.Rev. D89 (2014), 073015



Attacking the Monster From All Sides



e-scattering

ν-scattering

Event-Generators

Attacking the Monster From All Sides

e-scattering

(1) Monochromatic e-beam constrains:
- **Vector currents**
- **Nuclear FSI**
- **…**

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?”

General situation – lots of data, usually not in the relevant phase-space for neutrino experiments:

- W-boson mass makes the neutrino ‘Mott’ cross-section flat. In contrast to the forward peaked electron case.
- A(e,e’): measured extensively; well described using various scaling approaches.
- A(e,e’p): measured primarily in selective kinematics (around the QE peak). Usually reported as ratio to theory.
- 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?”

General situation – lots of data, usually not in the relevant phase-space for neutrino experiments:

- W-boson mass makes the neutrino ‘Mott’ cross-section flat. In contrast to the forward peaked electron case.
- <u>A(e,e’):</u> measured extensively; well described using various scaling approaches.
- <u>A(e,e’p):</u> measured primarily in selective kinematics (around the QE peak). Usually reported as ratio to theory.
- <u>A(e,e’n), A(e,e’NN):</u> 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?”

General situation – lots of data, usually not in the relevant phase-space for neutrino experiments:

- W-boson mass makes the neutrino ‘Mott’ cross-section flat. In contrast to the forward peaked electron case.
- A(e,e’): measured extensively; well described using various scaling approaches.
- A(e,e’p): measured primarily in selective kinematics (around the QE peak). Usually reported as ratio to theory.
- 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?”

General situation – lots of data, usually not in the relevant phase-space for neutrino experiments:

- W-boson mass makes the neutrino ‘Mott’ cross-section flat. In contrast to the forward peaked electron case.
- A(e,e’): measured extensively; well described using various scaling approaches.
- A(e,e’p): measured primarily in selective kinematics (around the QE peak). Usually reported as ratio to theory.
- 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

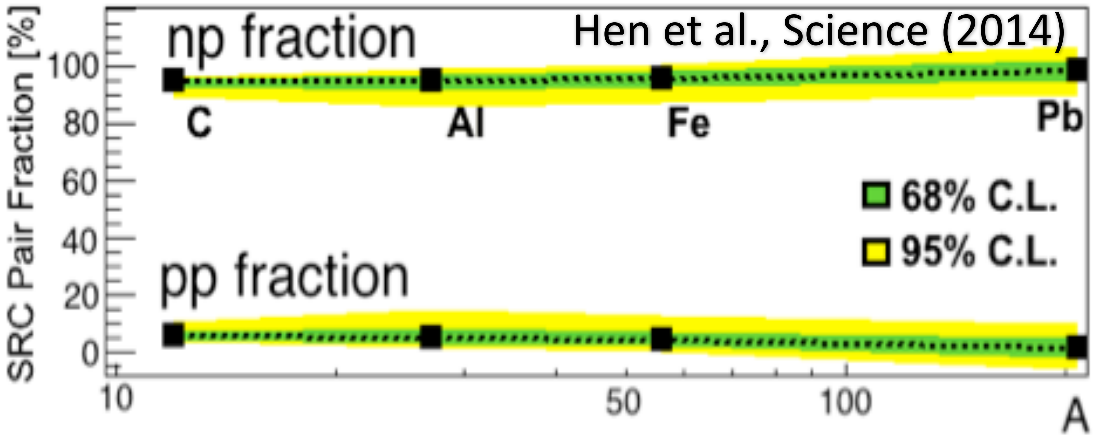
“We’ve been throwing electrons at nuclei for over 40 years – why new data?”

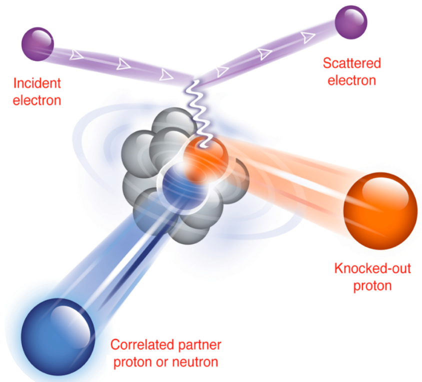
General situation – lots of data, usually not in the relevant phase-space for neutrino experiments:

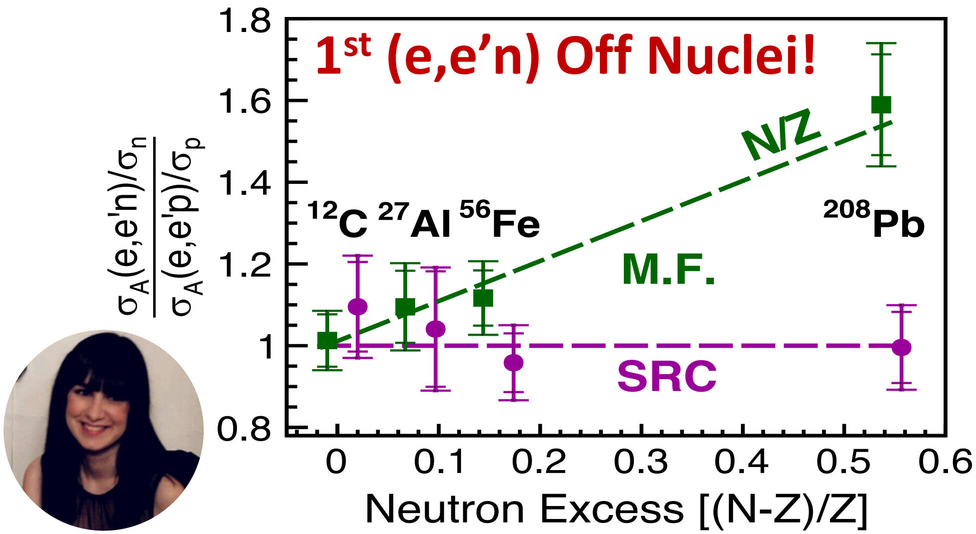
- W-boson mass makes the neutrino ‘Mott’ cross-section flat. In contrast to the forward peaked electron case.
- <u>A(e,e’):</u> measured extensively; well described using various scaling approaches.
- <u>A(e,e’p):</u> measured primarily in selective kinematics (around the QE peak). Usually reported as ratio to theory.
- <u>A(e,e’n), A(e,e’NN):</u> Sparse data, especially at GeV energies.
- Resonance production: lacking systematic data on nuclei and at large multiplicities.

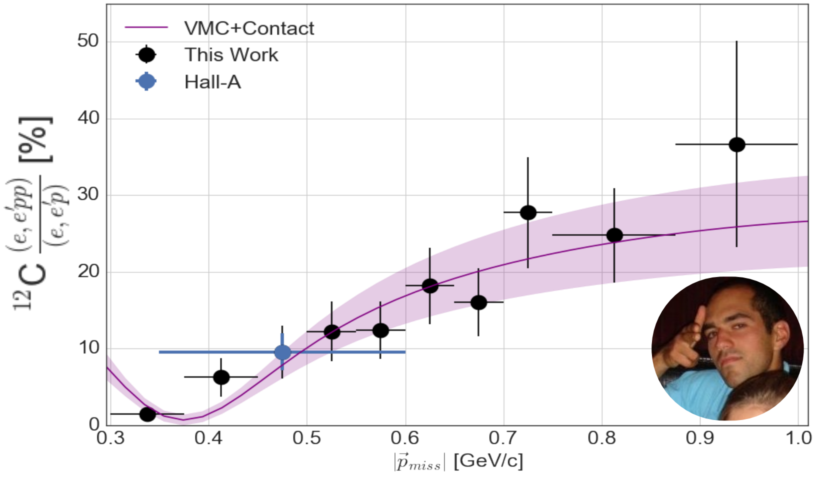
JLab Data-Mining

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



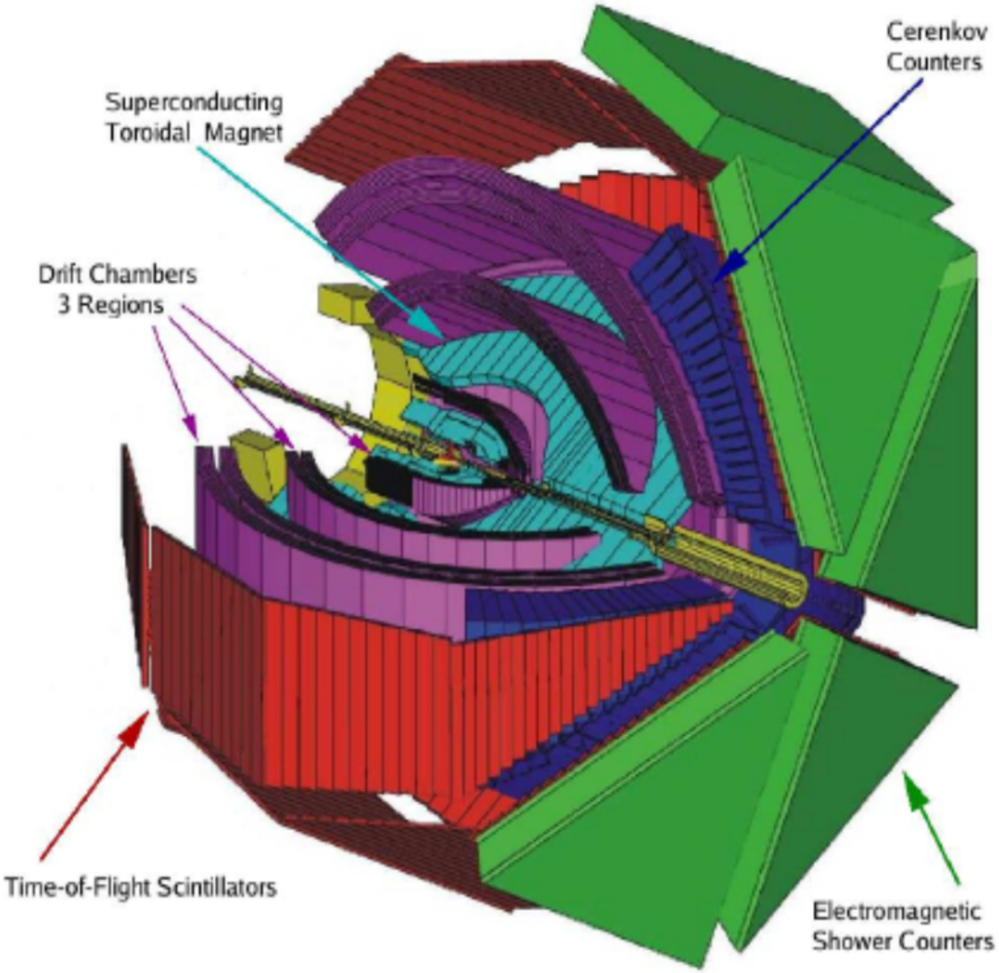






CLAS6 Spectrometer

- 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>



Mining For Neutrinos

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

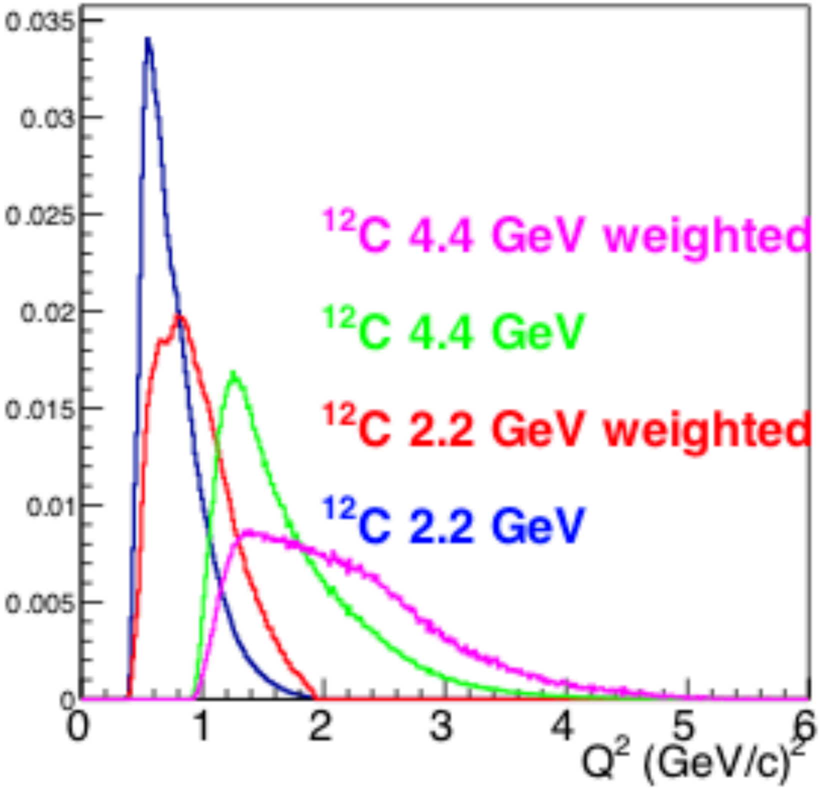
Means (for QE study):

- Select clean (e,e'p) events (no pions, 2nd protons, ...),
- Reweight by *e-N* / $\boldsymbol{\nu}$*-N* cross-section ratio.
- Analyze as ‘neutrino data’ (assume unknown beam energy),
- Study beam energy reconstruction methods,
- Compare to GENIE predictions,
- Identify regions in phase-space where energy reconstruction and GENIE predictions agree well.

Existing CLAS6 Data

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

* #Triggers x 10$^{\text{allot!}}$



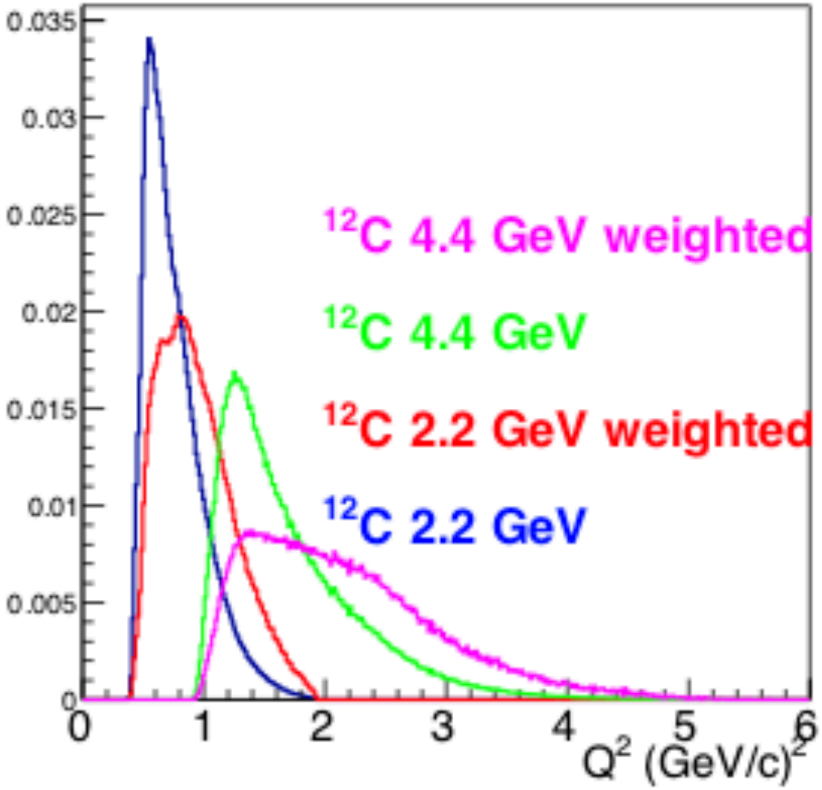
\+ EG2 (~ x10 less stat): 5 GeV on d, ^{12}C, ^{27}Al, ^{56}Fe, ^{208}Pb ($Q^2 > 1.5$)

Existing CLAS6 Data

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

* #Triggers x $10^{\text{allot!}}$

- ⇒ **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 ($Q^2 > 1.5$)

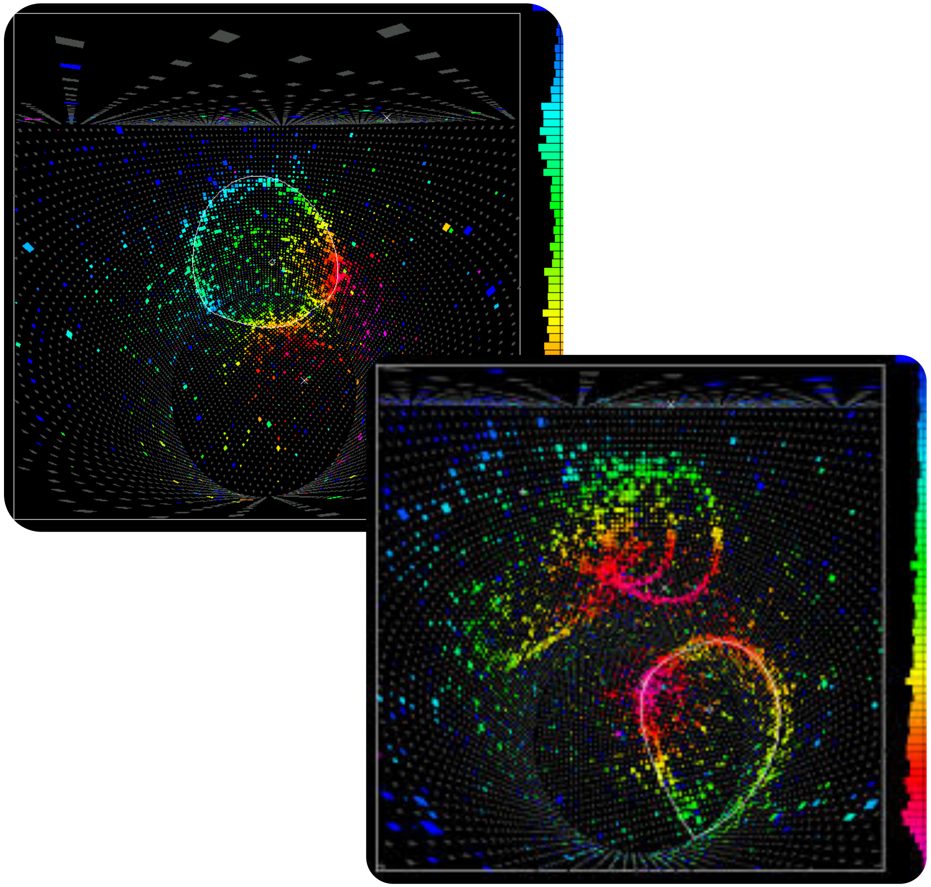
Final state detection approaches

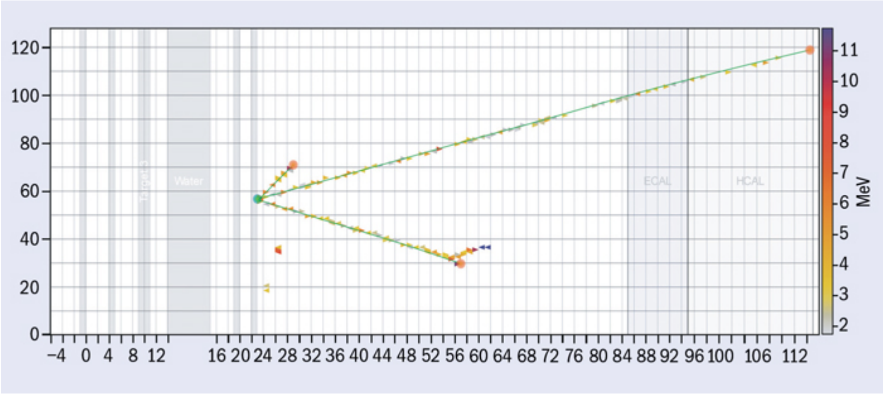
Cherenkov detectors:

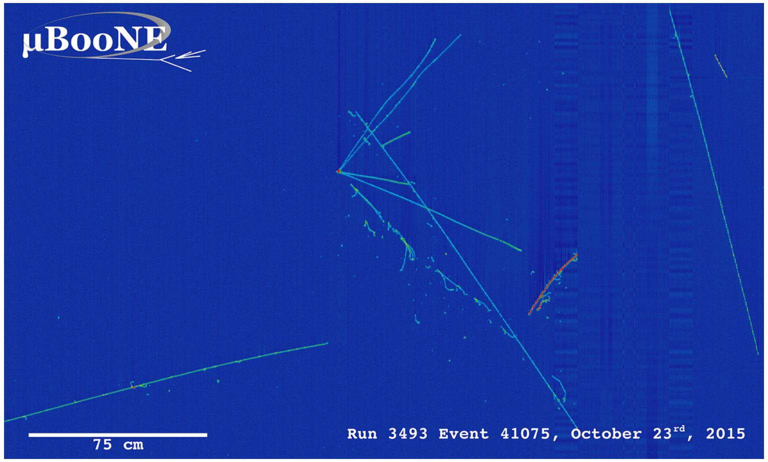
- Electrons & Pions
- No protons / neutrons

Tracking detectors:

- All charged particles + π
  [Progress towards neutrons]







Final state detection approaches

Cherenkov detectors:

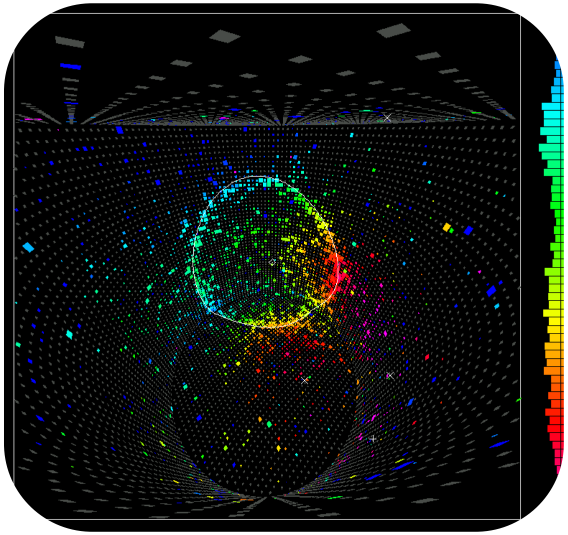
- Electrons & Pions
- No protons / neutrons

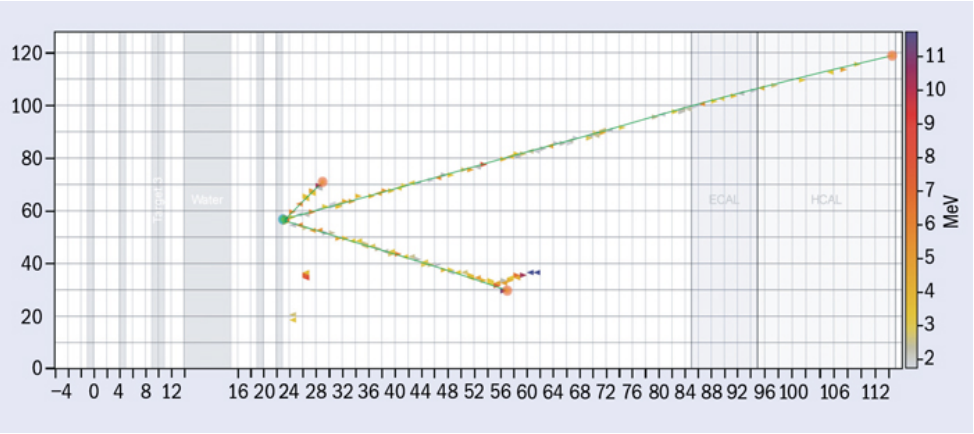
$\Rightarrow$ E_ν Reconstruction from lepton kinematics.

Tracking detectors:

- All charged particles + $\boldsymbol{\pi}$ [Progress towards neutrons]

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

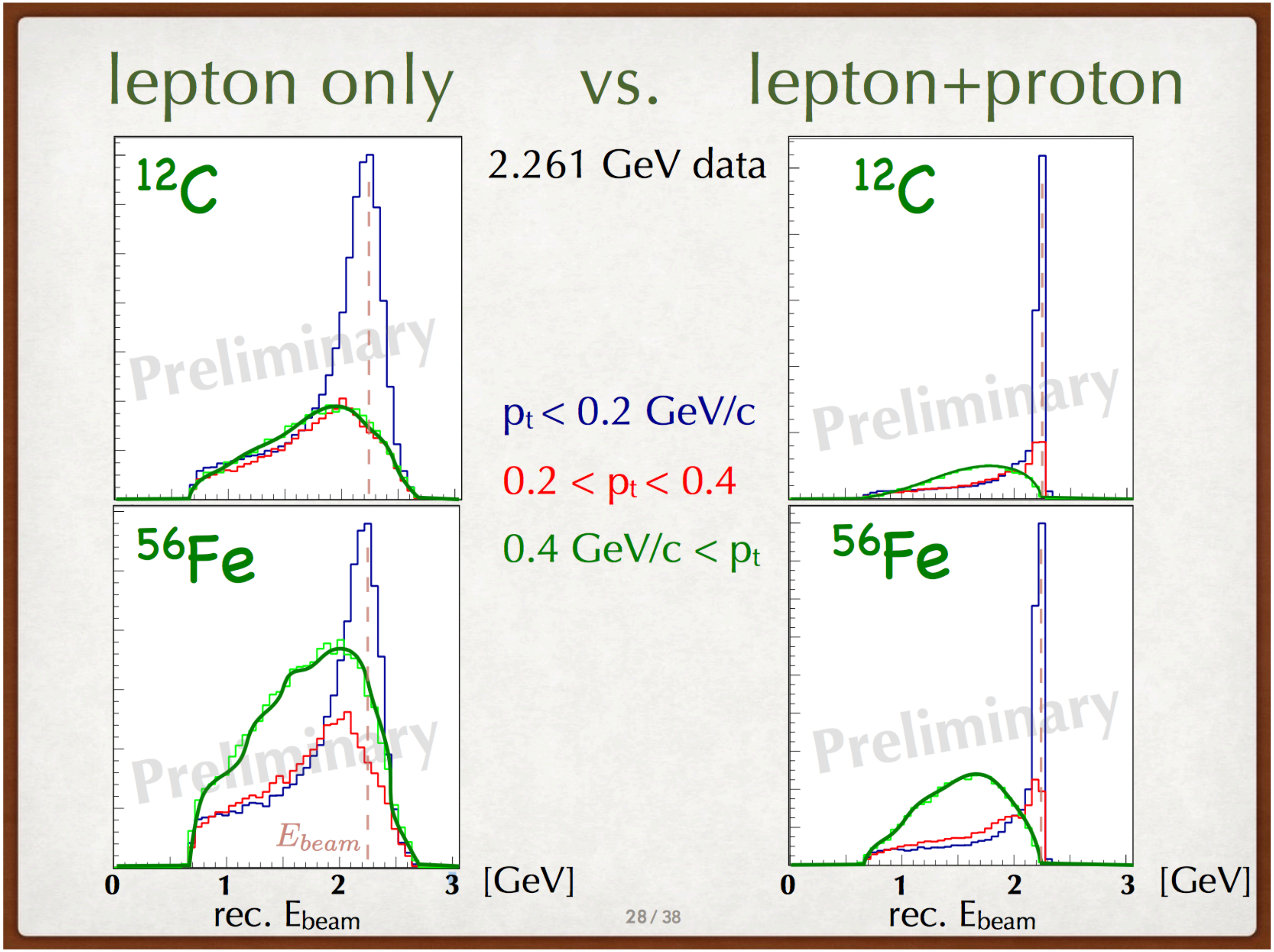




$$E_\nu = E_l + E_p^{kin} + E_b$$

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

Energy Reconstruction Example



lepton only vs. lepton+proton

2.261 GeV data

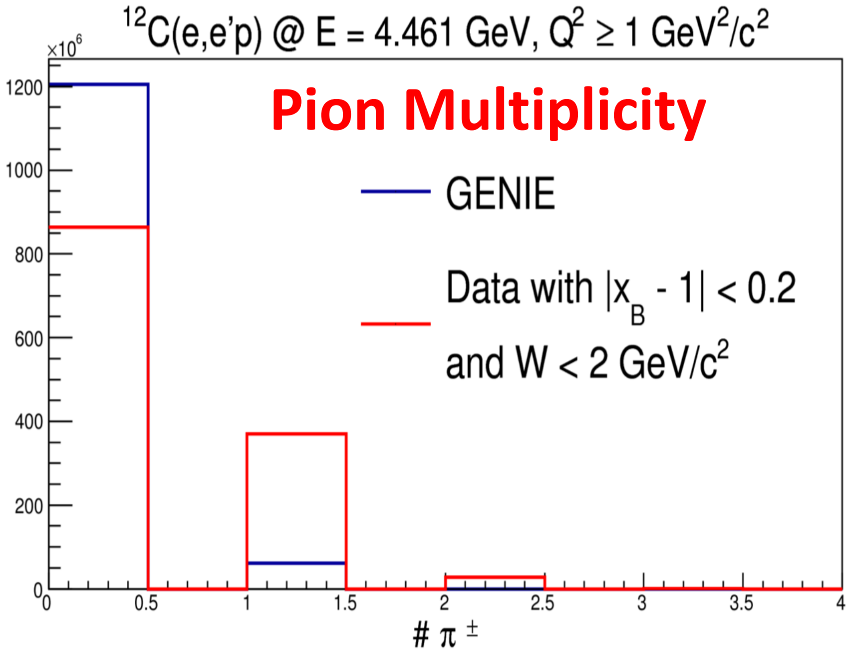
$p_t < 0.2$ GeV/c

$0.2 < p_t < 0.4$

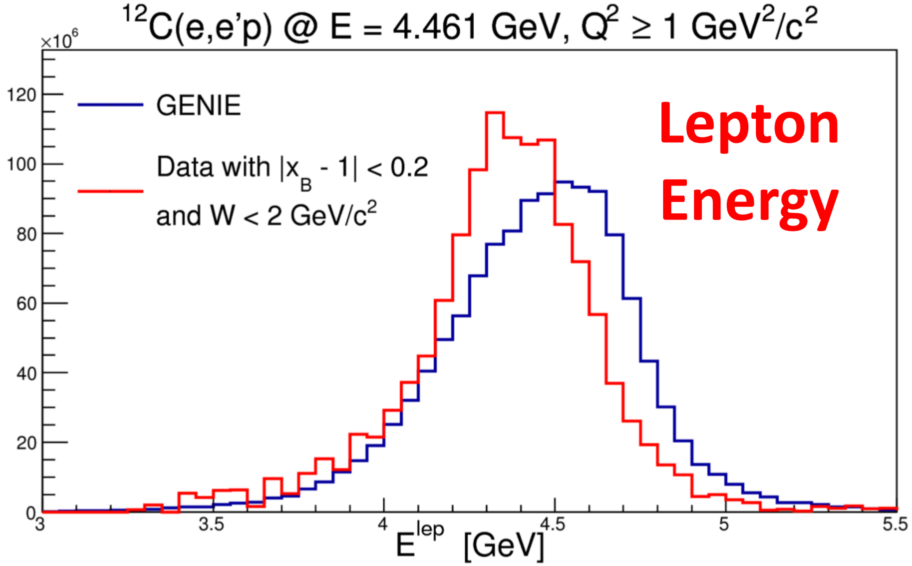
0.4 GeV/c $< p_t$

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

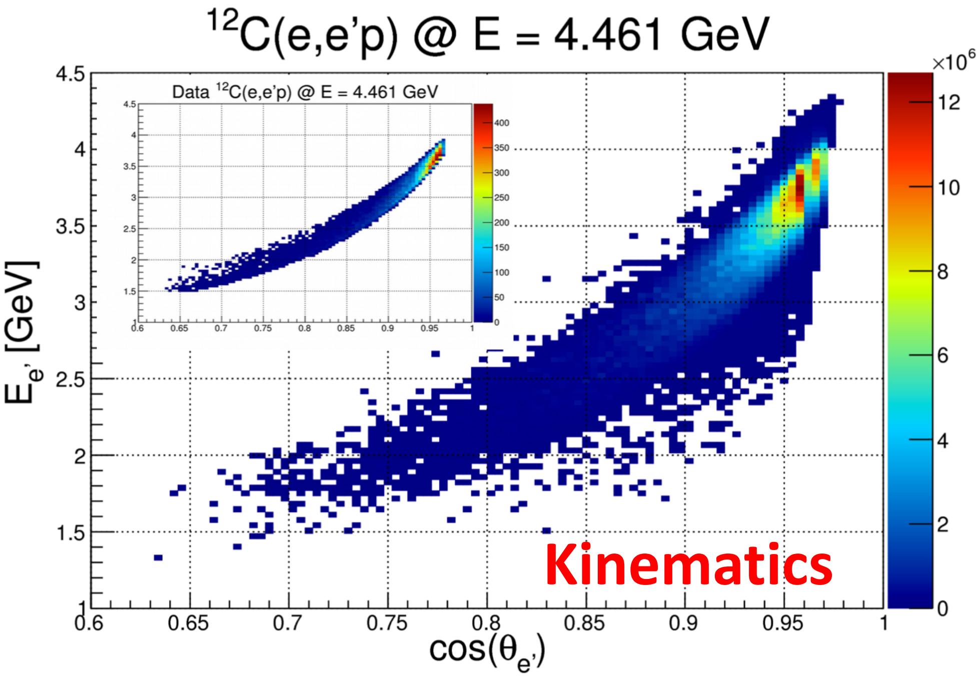
Data-Generator Comparisons



Pion Multiplicity



Lepton Energy



Kinematics

Preliminary

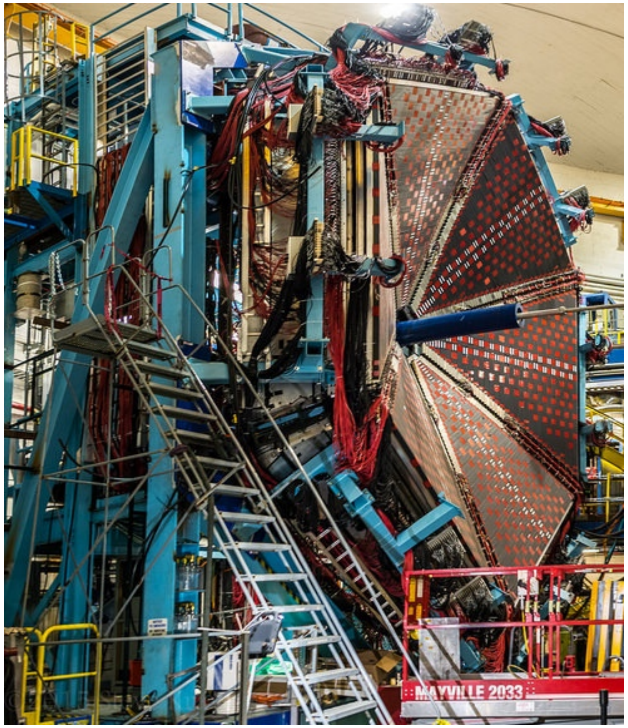
New Proposal: Systematic study!

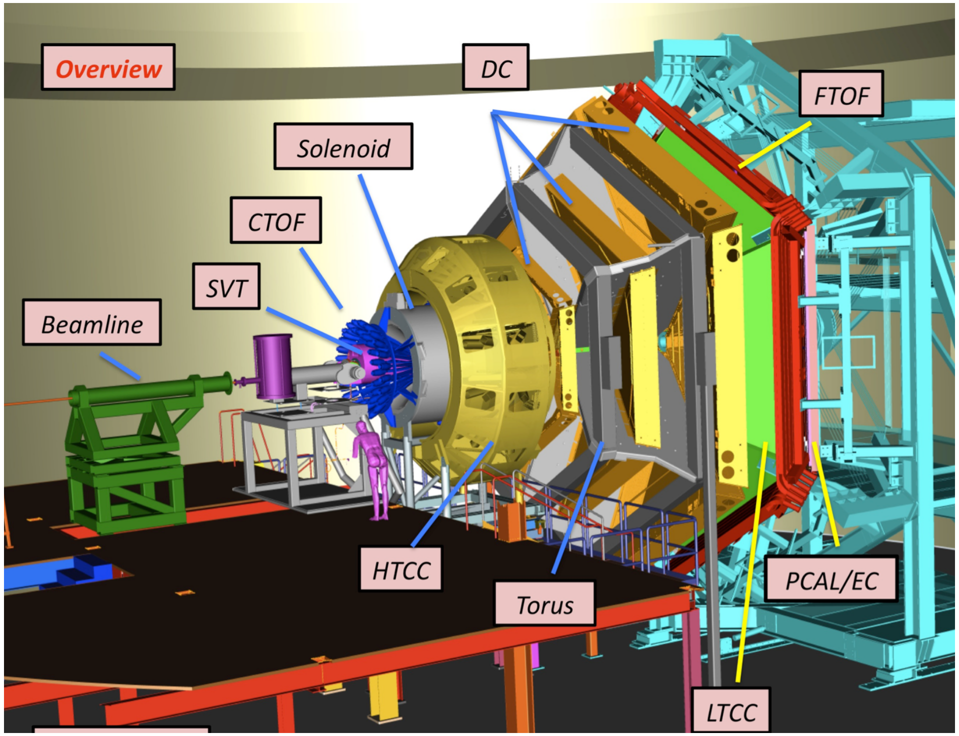
Targets:

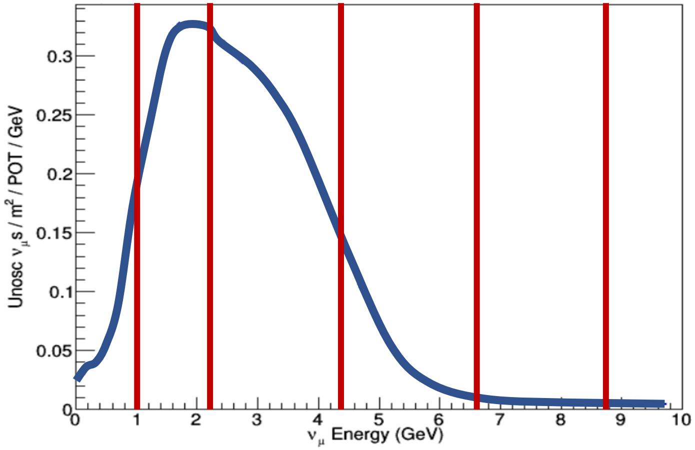
^{4}He, ^{12}C, ^{16}O, ^{40}Ar, ^{120}Sn

Beam Energies:

1.1, 2.2, 4.4, 6.6, 8.8 GeV







New Proposal: Systematic study!

Targets:

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

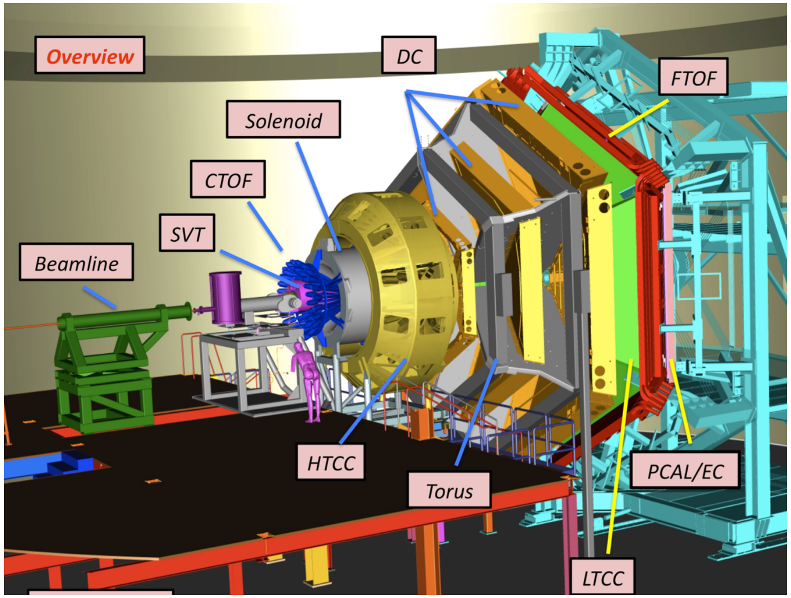
Beam Energies:

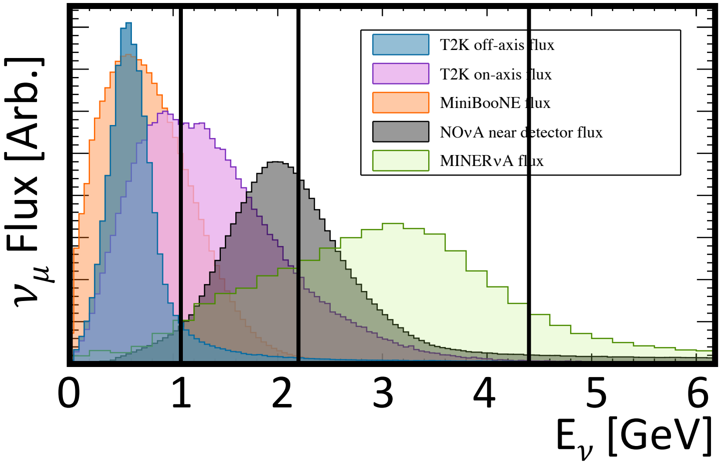
1.1, 2.2, 4.4, 6.6, 8.8 GeV

CLAS12 Spectrometer:

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

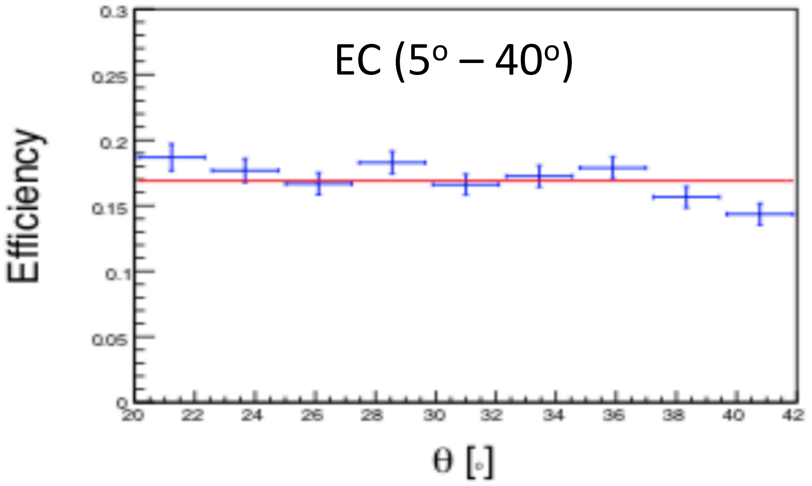
=> High stat. semi-inclusive and exclusive data sets on multiple targets at multiple energies.

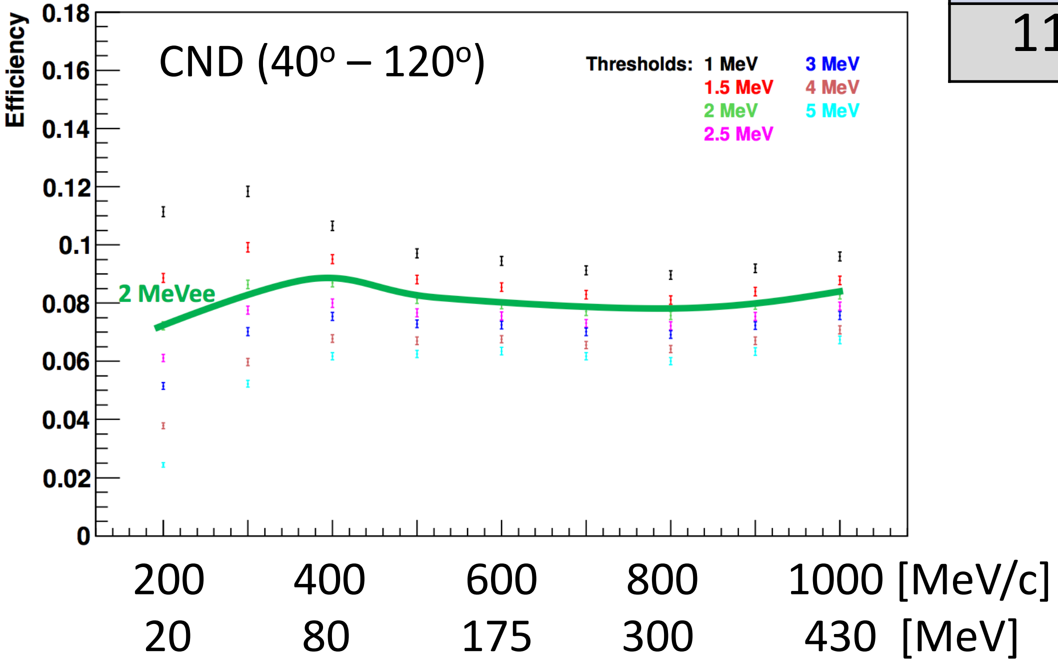




Unique hadronic models test!

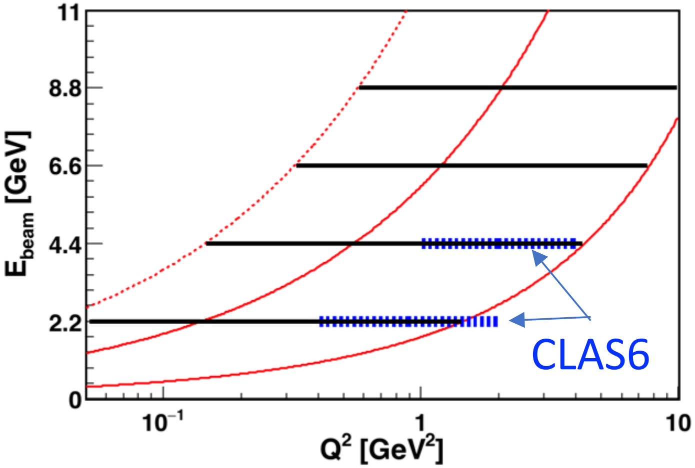
CLAS12: Neutrons + Lower Q^2!





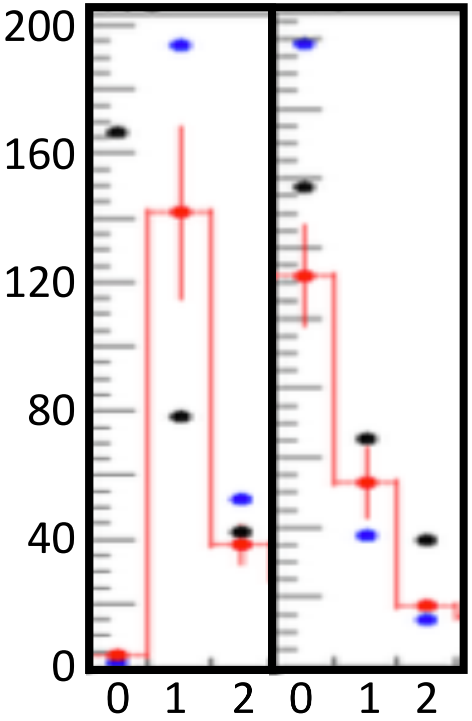
Lower Q^2 coverage!

E_{Beam}	Q^2_{QE}		
	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

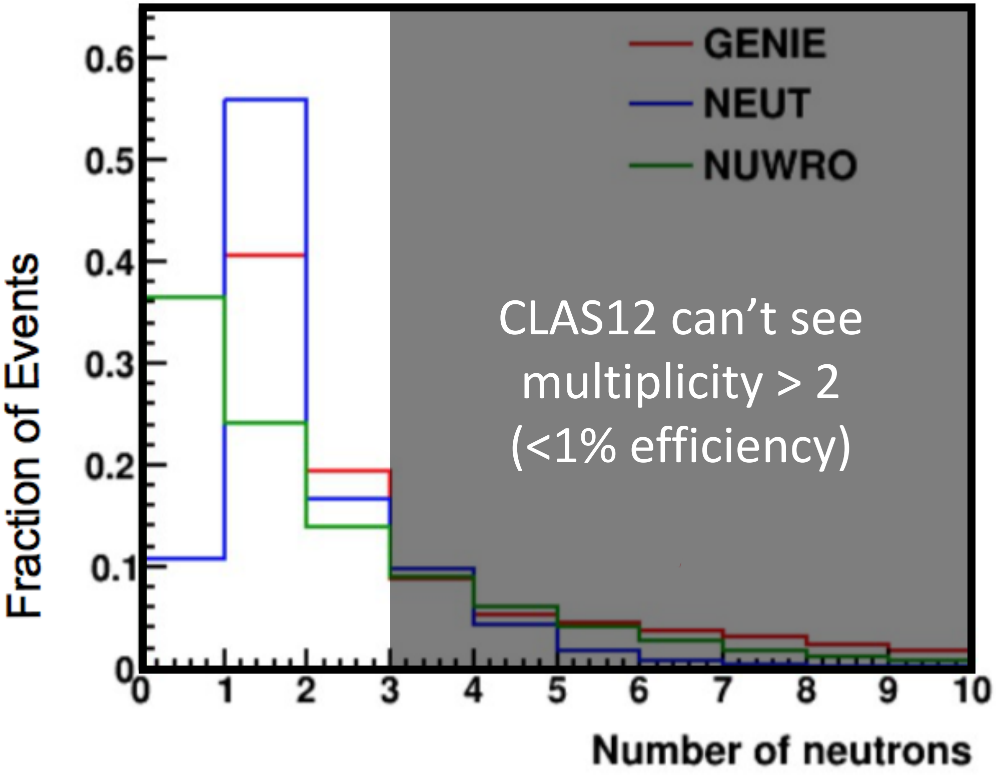


Example I: Neutron Multiplicity (0 – x2)

DUNE neutron multiplicity predictions



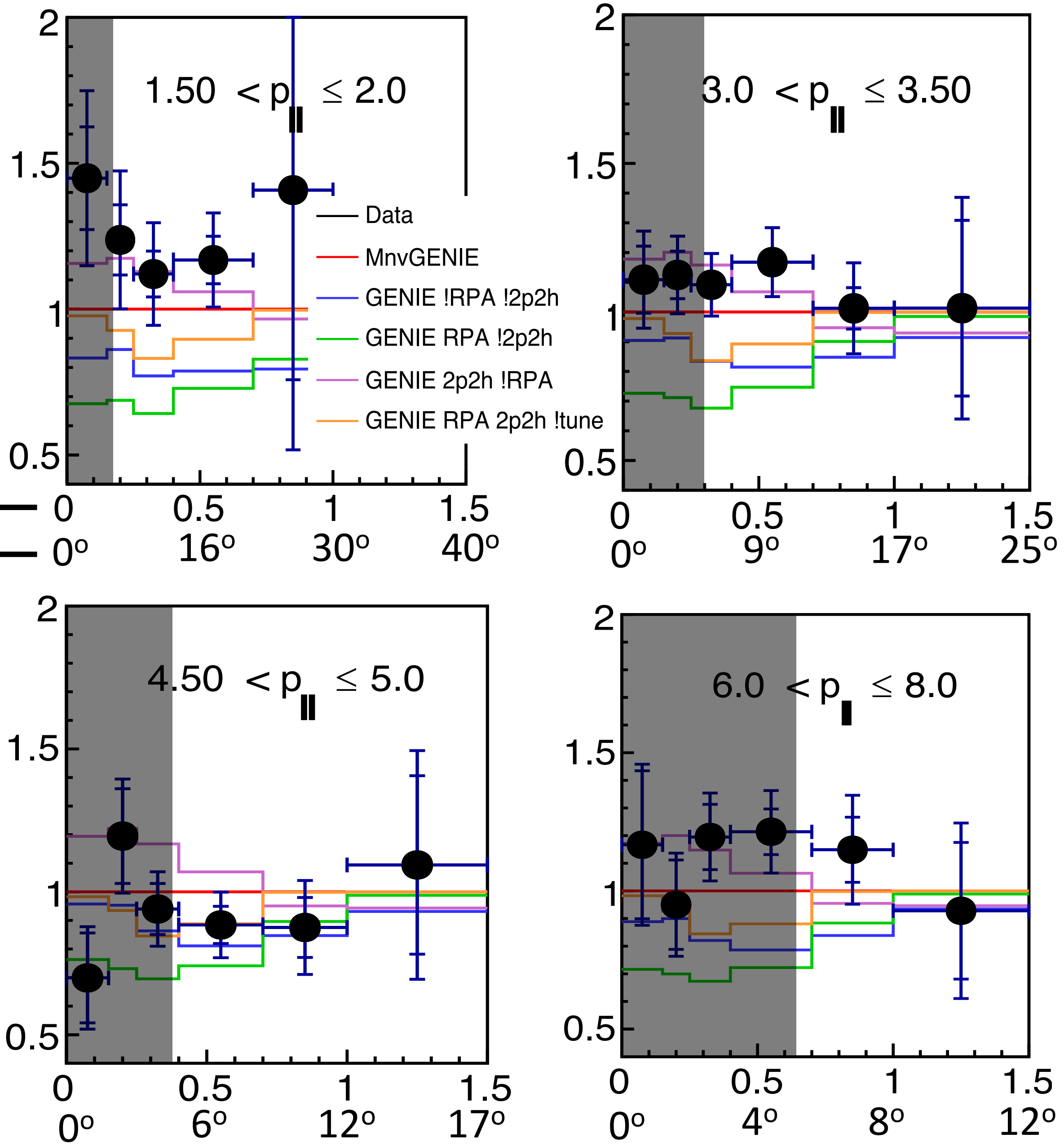
Preliminary MINERvA neutron multiplicity



CLAS12 can't see multiplicity > 2 (<1% efficiency)

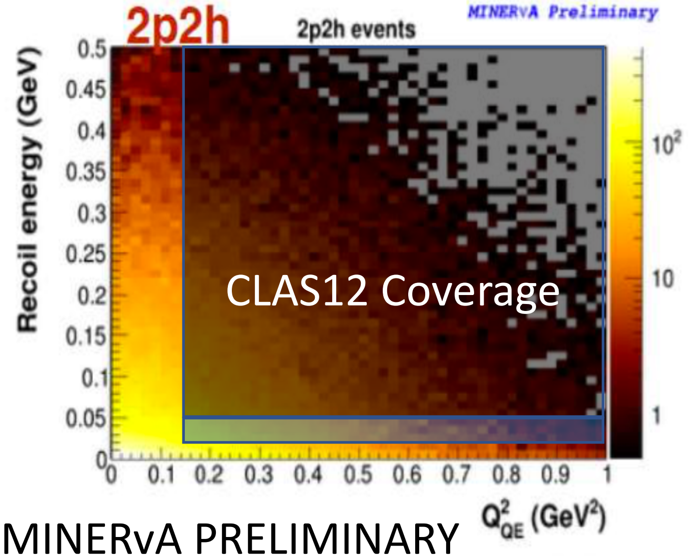
Example II: 2p2h / RPA Effects

X2 effects in regions accessible by CLAS12



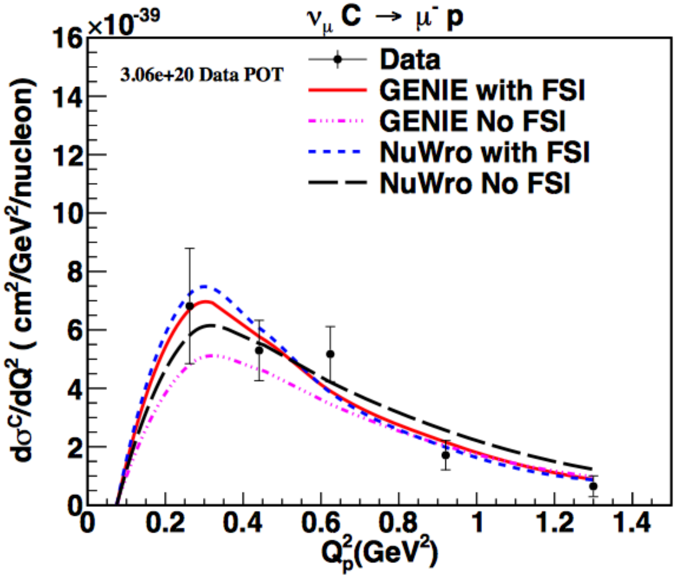
Scattered muon P_T ←

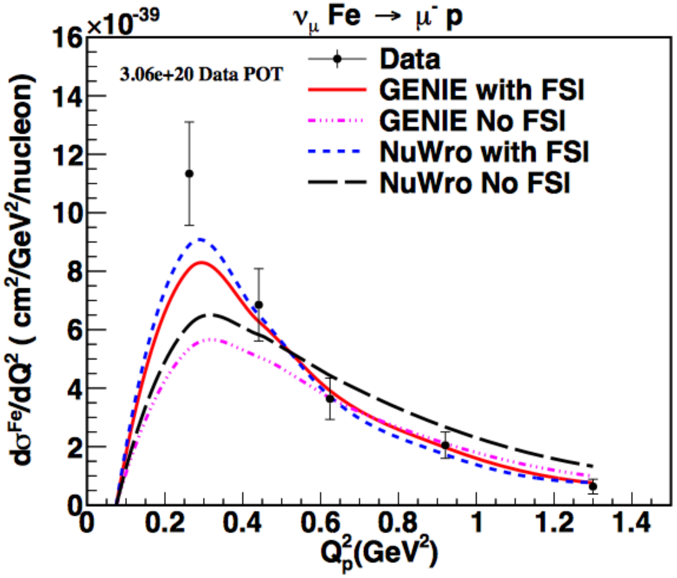
Scattered muon angle ←

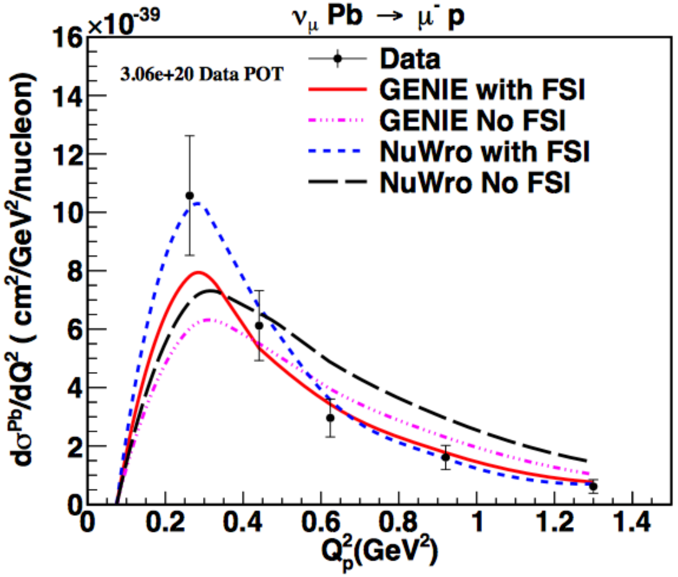


MINERvA PRELIMINARY

Example III: FSI Effects



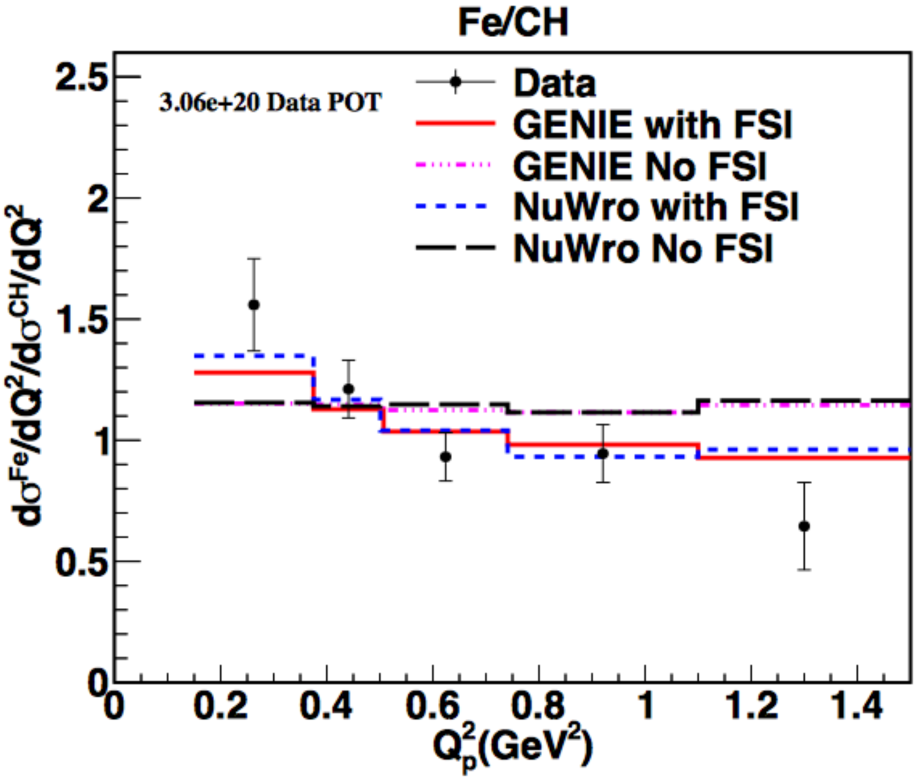




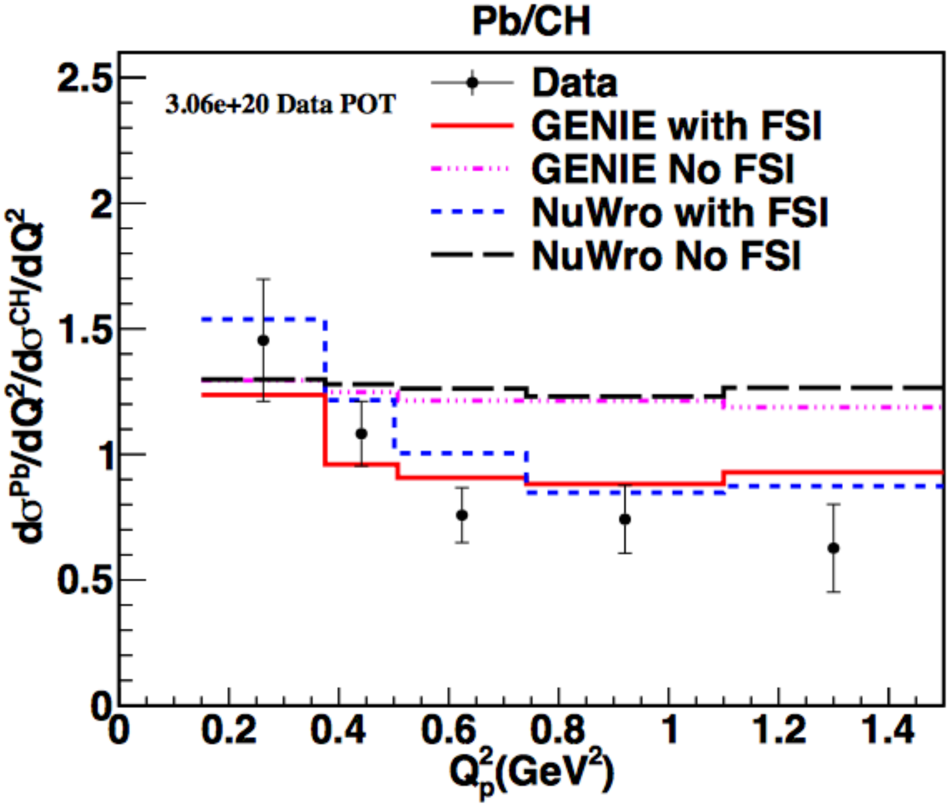
20 - 50% differences @ Q^2 ~ 0.3 GeV^2

M. Betancourt et al. (MINERvA Collaboration), arXiv: 1705.03791 (2017)

Example III: FSI Effects



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

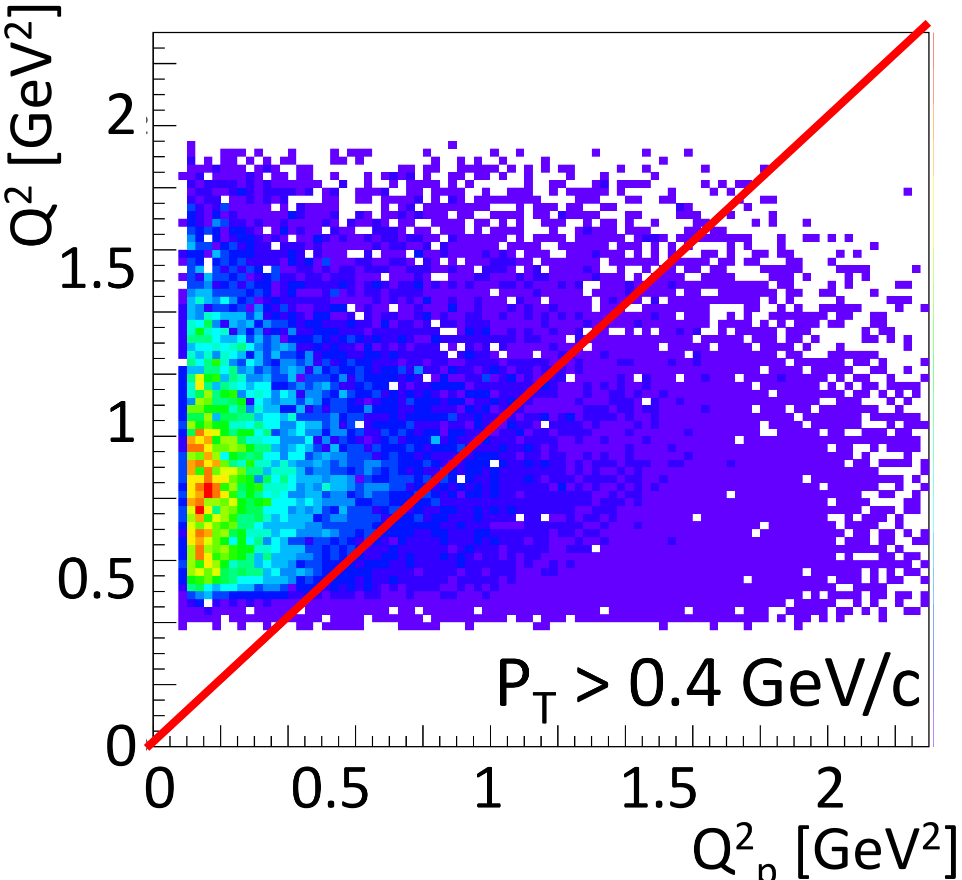


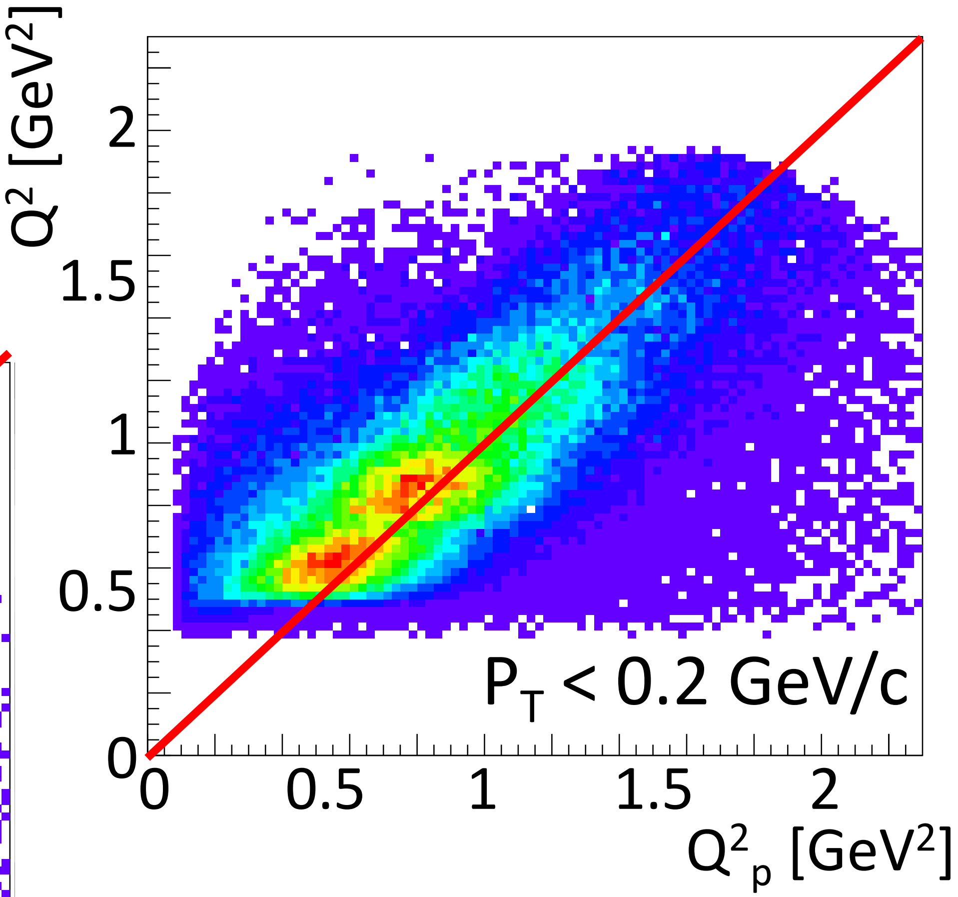
Note A/CH ratio.
Effect for individual nuclei is larger!

M. Betancourt et al. (MINERvA Collaboration), arXiv: 1705.03791 (2017)

Example IV: E_ν & Q^2 Reconstruction

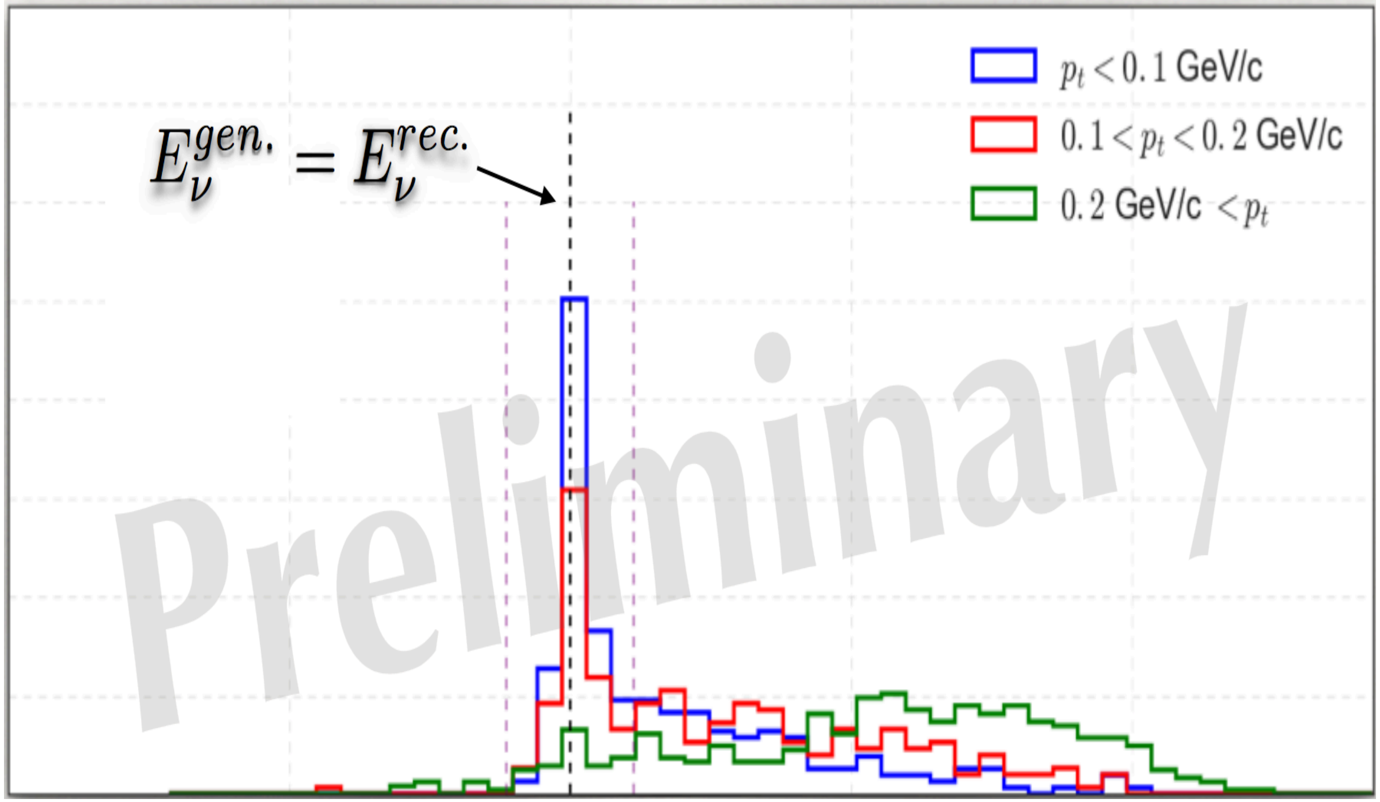
High Q^2 events reconstructed as low Q^2_p due to nuclear effects





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

Example IV: E_ν & Q^2 Reconstruction



$(E_{gen} - E_{rec}) \,/\, E_{gen}$

MicroBooNE Preliminary (MIT-TAU Analysis)

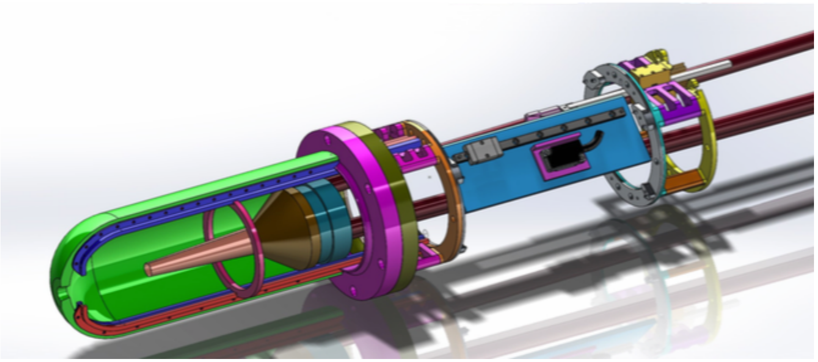
Electrons 4 Neutrinos

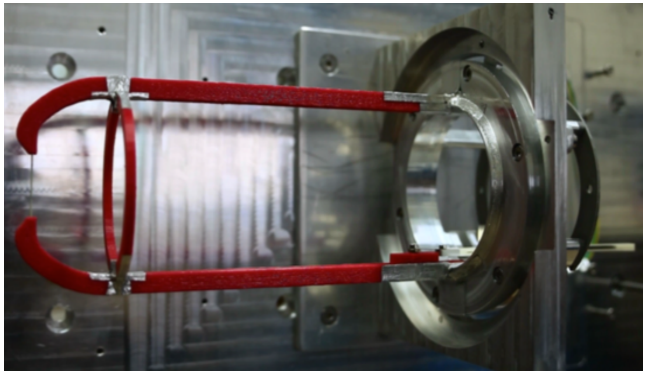
Energy [GeV]	H	^{4}He	^{12}C	^{16}O	^{40}Ar	^{120}Sn	Total
1	0.2	0.5	0.5	0.5	0.5	0.5	**2.5**
2.2	0.2	1	1	1	1	1	**5**
4.4	0.2	1	1	1	1	1	**5**
6.6	0.2	2	2	X	2	2	**8**
8.8	0.2	4	4	X	4	4	**16**
Total (days)	**1**	**8.5**	**8.5**	**2.5**	**8.5**	**8.5**	**37.5**

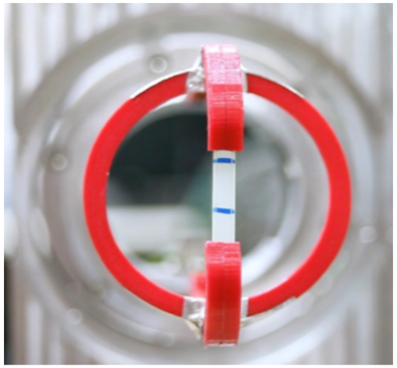
4 days out-bending

[added low-Q^2 running @ 4.4,6.6 and 8.8 GeV]

1 day in-bending







Electrons 4 Neutrinos

- **High impact study of bias in neutrino oscillation analyses:**
  - Incident energy reconstruction,
  - Final State Interactions,
  - Resonance production,
  - Multinucleon effects.
- **The 'Vector Currents' partner of the short-baseline (near-detector) neutrino program.**
- **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 (ODU),
O. Hen, A. Schmidt, A. Silva (MIT),
K. Mahn (MSU),
E. Piasetzky, E. Cohen (TAU)
S. Dytman (Pittsburgh),
M. Betancourt (FNAL)

Overwhelming Support

Fermilab

Hyper-Kamiokande

DUNE

ICECUBE
SOUTH POLE NEUTRINO OBSERVATORY

NOvA

MINERvA

T2K

ANNIE
Accelerator Neutrino Neutron Interaction Experiment

μBooNE
LArTPC

GiBUU
The Giessen Boltzmann-Uehling-Uhlenbeck Project