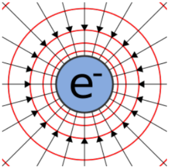
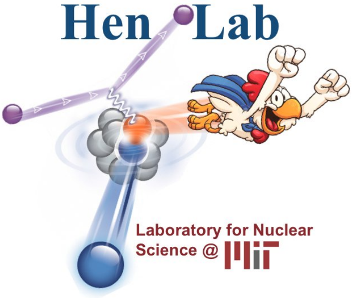
Electrons for Neutrinos





A. Papadopoulou

EINN2019, Paphos, Cyprus
October 31, 2019

Future ν Experiments

• Extraction of oscillation parameters

by making high precision measuments

• Demand for good understanding of

cross–sections & energy reconstruction

Key role

Availability of e–scattering data

e4ν Objective

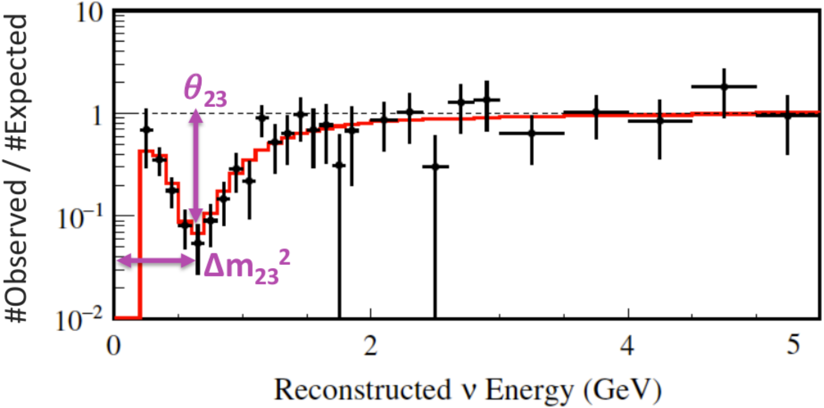
- Accuracy of ν energy reconstruction methods using e-scattering data

- Benchmarking of ν event generator models against e-scattering data

Energy Reconstruction Significance

Neutrino Oscillations

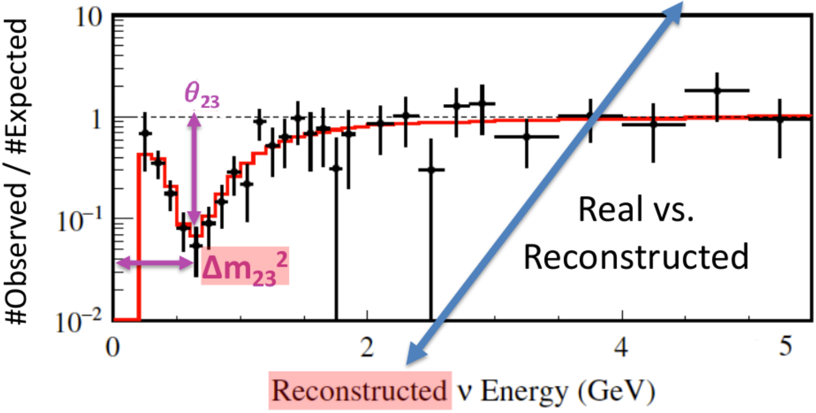
$$P(\nu_\mu \rightarrow \nu_\mu) = \sin^2(2\theta_{23}) \times \sin^2\left(\frac{\Delta m_{32}{}^2 L}{4E_\nu}\right)$$



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

Neutrino Oscillations

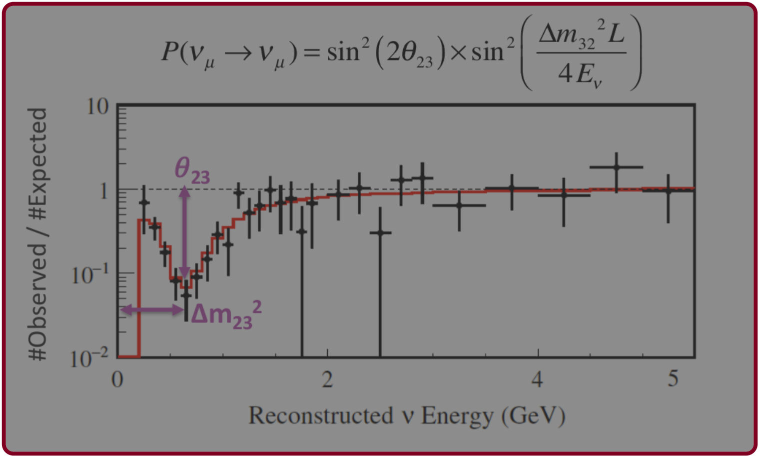
$$P(\nu_\mu \rightarrow \nu_\mu) = \sin^2(2\theta_{23}) \times \sin^2\left(\frac{\Delta m_{32}{}^2 L}{4E_\nu}\right)$$



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

Neutrino Oscillations

Error in E_{reco} $\Rightarrow$ **Error in extracted oscillation parameters**



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

Energy Reconstruction

Cherekov Detectors

- Leptons & Pions
- No Protons or Neutrons

Use lepton kinematics assuming QE interaction

$$E_{QE} = \frac{m_n^2 - (m_p - \epsilon)^2 - m_l^2 + 2(m_p - \epsilon)E_l}{2(m_p - \epsilon - E_l + p_l cos(\theta_l))}$$

Tracking Detectors

- Charged particles & π^0
- Progress Towards Neutrons

Use final–state calorimetry assuming low energy excitations

$$E_{cal} = E_l + T_p + \epsilon$$

Accurate only if PWIA is applicable!

Energy Reconstruction

Cherekov Detectors

- Leptons & Pions
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Tracking Detectors

- Charged particles & π^0
- Progress Towards Neutrons

Use final–state calorimetry assuming low energy excitations

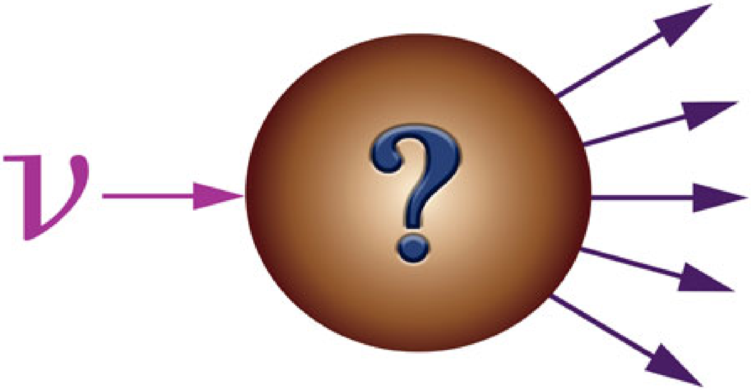
$$E_{cal} = E_l + T_p + \epsilon$$

Accurate only if PWIA is applicable!

Which is not always the case...

Generator Modeling

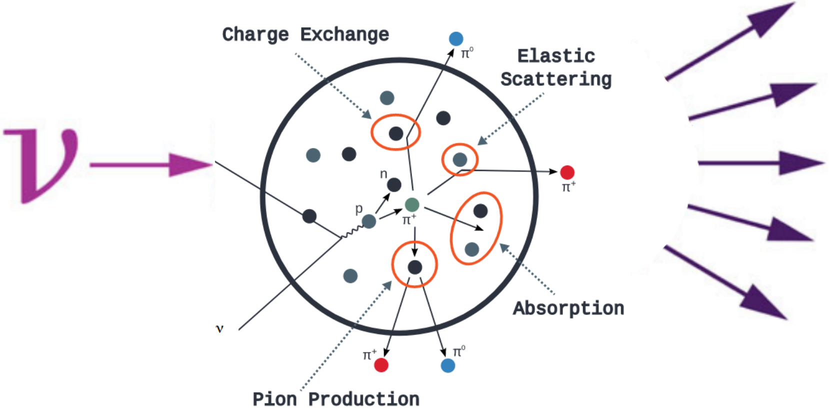
Use final state particles to reconstruct ν energy & direction



Generator Modeling

Models: Effective. Often Empirical. Semi–classical (no interference terms)

⇒ **MUST tune to data!**



Attacking from all sides

e–scattering

ν–scattering

Event Generators

Attacking from all sides

e–scattering

ν–scattering

- Monoenergetic beam
  - Vector currents

Event Generators

Attacking from all sides

e–scattering

ν–scattering

- Axial / Vector–axial currents
- Ultra–low Q^2

Event Generators

Attacking from all sides

e–scattering

ν–scattering

Event Generators

Must reproduce e & ν

data to extract

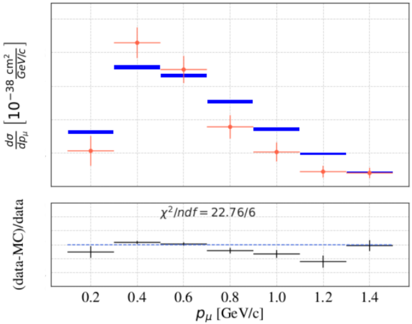
oscillation parameters

Attacking from all sides

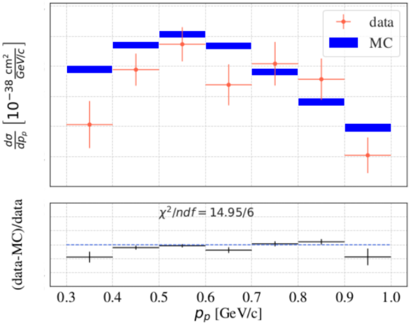
MicroBooNE LArTPC
Extraction of
exclusive 1μ1p cross–sections

ν–scattering

Work in progress



Work in progress



Attacking from all sides

e–scattering

ν–scattering

Today

Event Generators

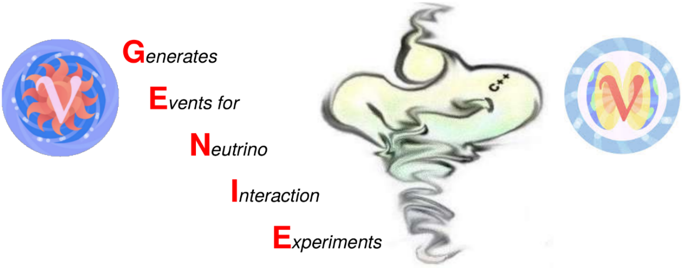
Why e4ν?

Why e4ν?

- Very similar interactions (vector part)
- Nuclear effects practically identical
- Known beam energy
- Benchmark ν event generators by running in e–mode

Generator vs (e,e') data

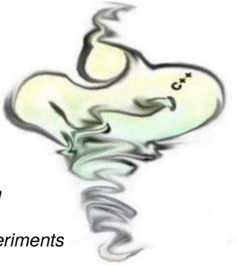
Genie Event Generator



- Used by many neutrino experiments in the US
  - Can simulate both e– and ν–events

Genie Event Generator

Generates
Events for
Neutrino
Interaction
Experiments

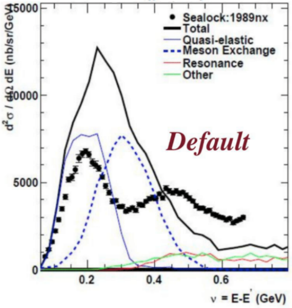


Lots of issues discovered for e–scattering

Tried to identify and fix them

Generator vs (e,e') data

When we started

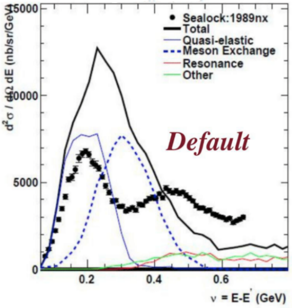


^{12}C @ 0.961 GeV & $\theta = 37.5^o$

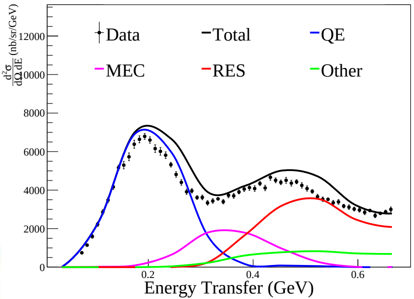
R. Sealock et al. Phys. Rev. Lett., 62, 1350 (1989) (C12,Fe56 Sealock:1989nx)

Generator vs (e,e') data

When we started



Today

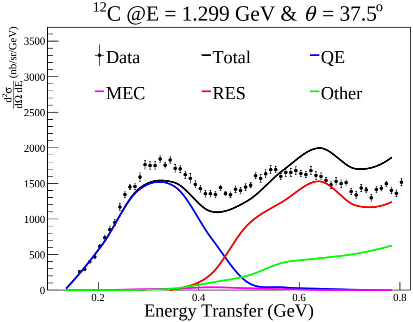


^{12}C @ 0.961 GeV & θ = 37.5^o

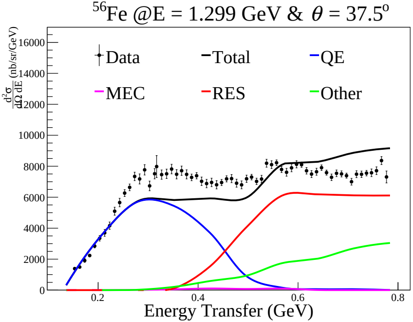
R. Sealock et al. Phys. Rev. Lett., 62, 1350 (1989) (C12,Fe56 Sealock:1989nx)

Generator vs (e,e') data

Higher energies



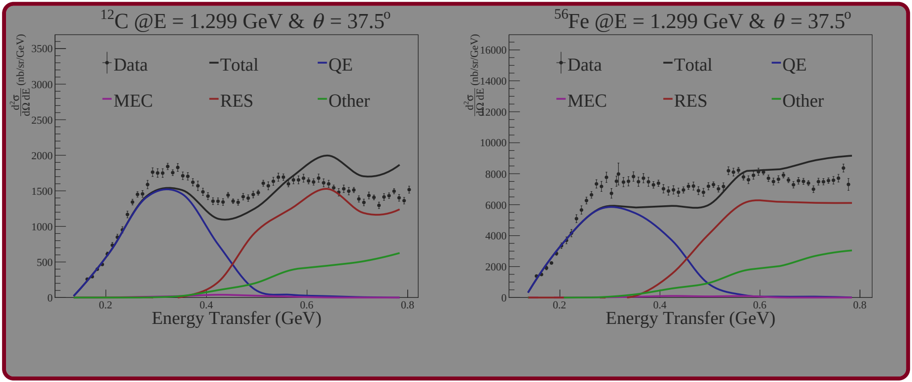
Heavier nuclei



R. Sealock et al. Phys. Rev. Lett., 62, 1350 (1989) (C12,Fe56 Sealock:1989nx)

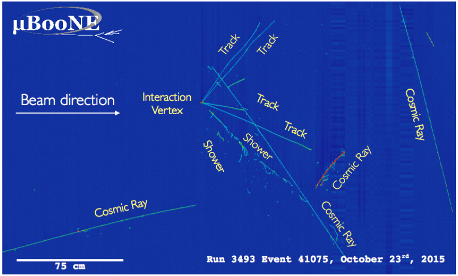
Generator vs (e,e') data

Inclusive channel ~ ok. What about exclusive channels?



R. Sealock et al. Phys. Rev. Lett., 62, 1350 (1989) (C12,Fe56 Sealock:1989nx)

Exclusive Channels



Tracking Detectors

- Charged particles & π^0
- Progress Towards Neutrons

Use final–state calorimetry assuming low energy excitations

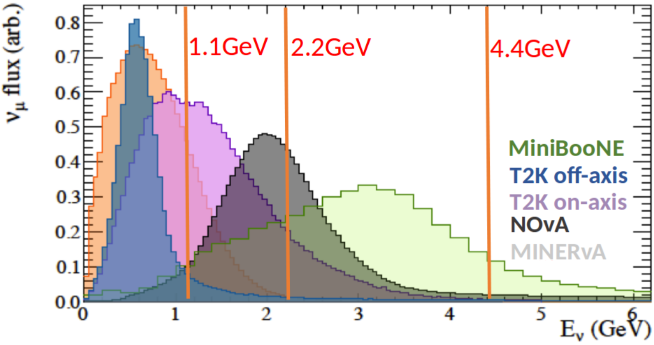
$$E_{cal} = E_l + T_p + \epsilon$$

CLAS@JLab

CLAS@JLab

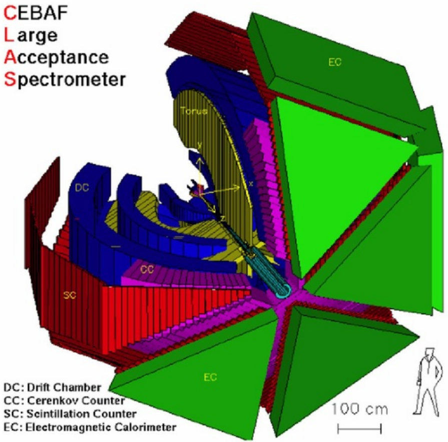
Targets: ^{4}He, ^{12}C, ^{56}Fe

Energies: 1.1, 2.2 and 4.4 GeV



CLAS Detector

- Almost 4π acceptance
- Charged particles (8-143^o):
  P_p > 300 MeV/c
  P_π > 150 MeV/c
- Neutral particles:
  EM calorimeter (8-75^o)
  and TOF (8-143^o)



Neutrino Game

Neutrino Game

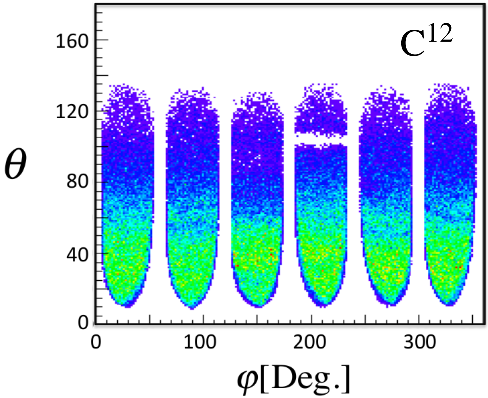
As close to Quasi-Elastic kinematics as one can get

- Select "clean" (e,e'p) events
- Scale electron data with 1 / σ_{Mott}
- Study energy reconstruction
- Compare to event generators

Background Subtraction

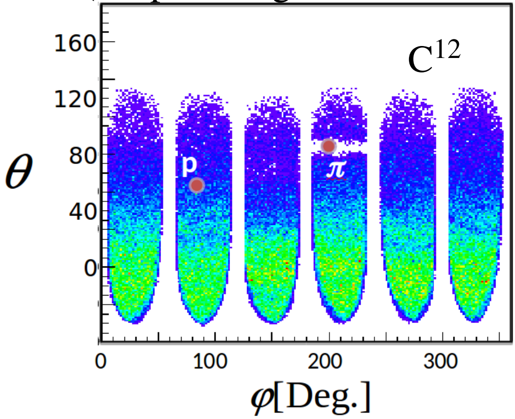
Background Subtraction

Non-QE interactions lead to multi-hadron final states



Background Subtraction

Non-QE interactions lead to multi-hadron final states
Gaps make them look like (e,e'p) events
(e,e'pπ background dominates)

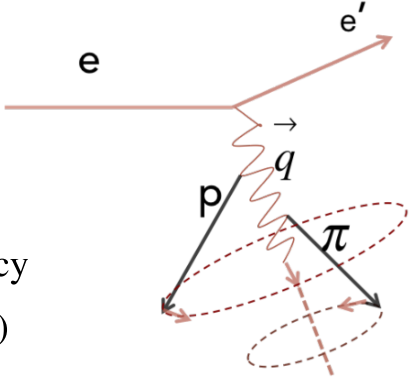


Background Subtraction

Non-QE interactions lead to multi-hadron final states
Gaps make them look like (e,e'p) events

<u>Driven Correction</u>

- Measured (e,e'pπ) events
- Rotate p, π around $\vec{q}$ to determine π detection efficiency
- Subtract undetected (e,e'pπ)



Background Subtraction

Non-QE interactions lead to multi-hadron final states

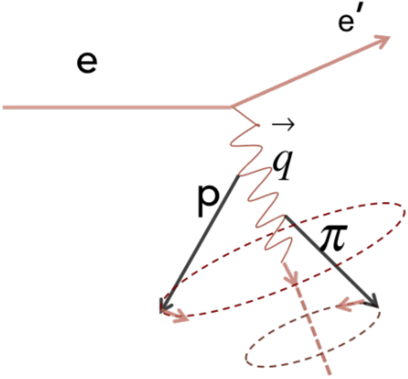
Gaps make them look like (e,e'p) events

<u>Driven Correction</u>

Repeat the process

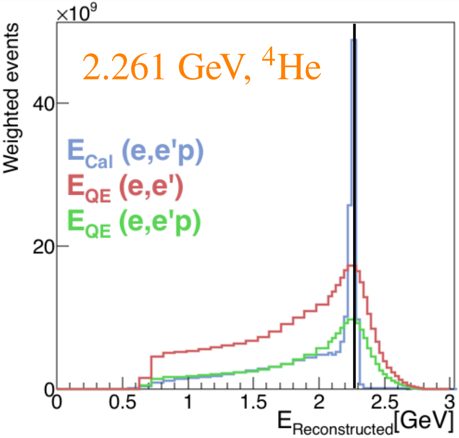
for higher multiplicities

(2p, 3p, 2p + π etc)



Energy Reconstruction

Energy Reconstruction Methods



Calorimetric Approach

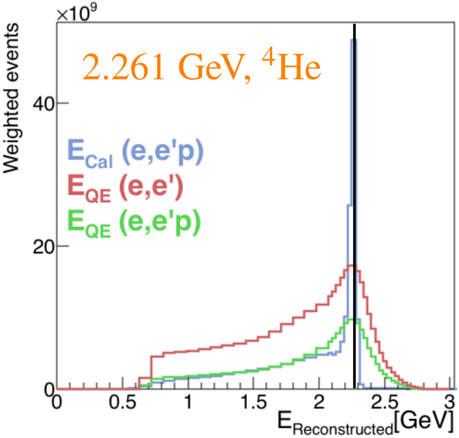
(lepton & proton info)

vs

QE Approach

(only lepton kinematics)

Energy Reconstruction Methods



Calorimetric Approach

(lepton & proton info)

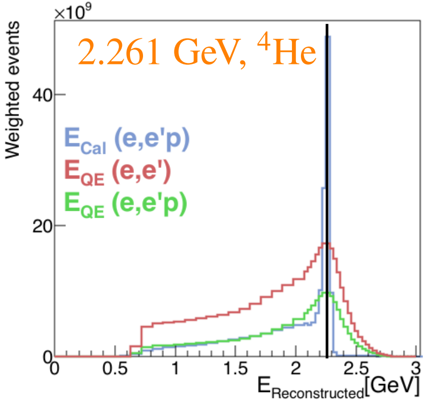
vs

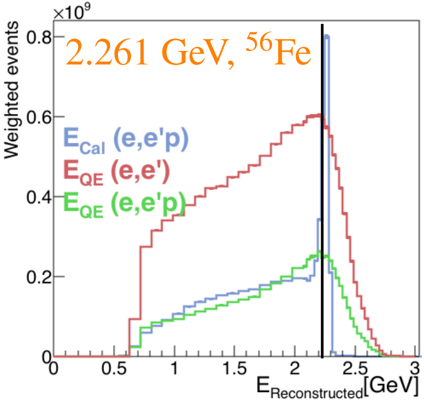
QE Approach

(only lepton kinematics)

- E_{QE} has worse peak resolution than E_{cal}
- Long tail for both E_{QE} and E_{cal}

Large A dependence

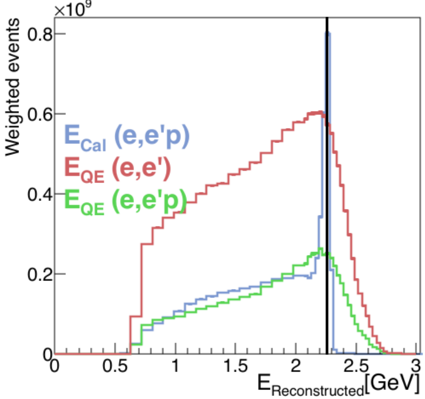




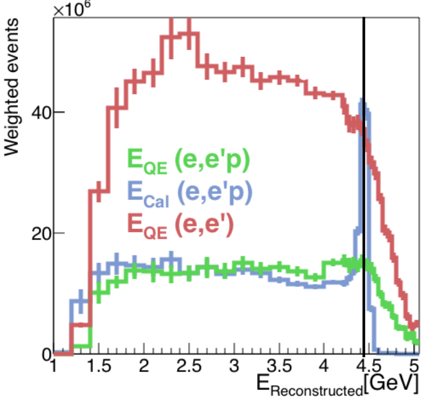
- ^{56}Fe is predominantly tail
- ^{56}Fe is worse than ^{4}He

Large E dependence

2.261 GeV, ^{56}Fe



4.461 GeV, ^{56}Fe



Better reconstruction at lower energies

Event fraction within 5% of E_{beam}

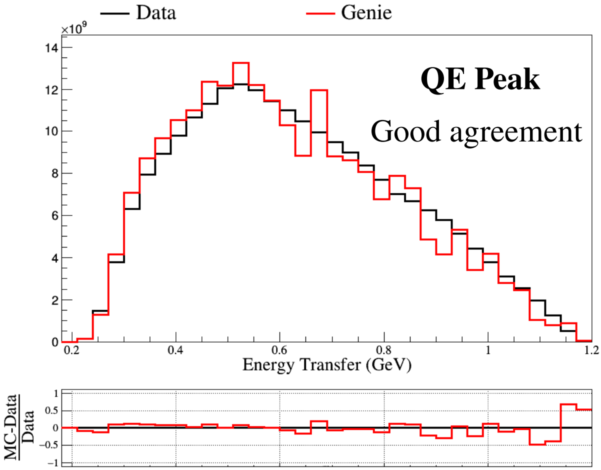
	2.2 GeV		4.4GeV	
	E_{QE} 1e	E_{Cal} 1e1p	E_{QE} 1e	E_{Cal} 1e1p
^{4}He	25%	$\boxed{46\%}$	16%	32%
^{12}C	22%	39%	13%	27%
^{56}Fe	17%	25%	$\boxed{10\%}$	16%

Not necessarily bad if our generators can reproduce the energy spectrum

Generator vs (e,e'p) data

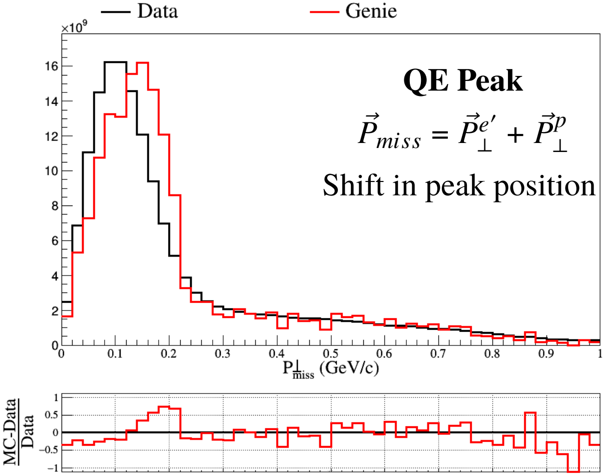
Generator vs (e,e'p) data

$^{12}C(e,e'p)$ @ E = 2.261 GeV

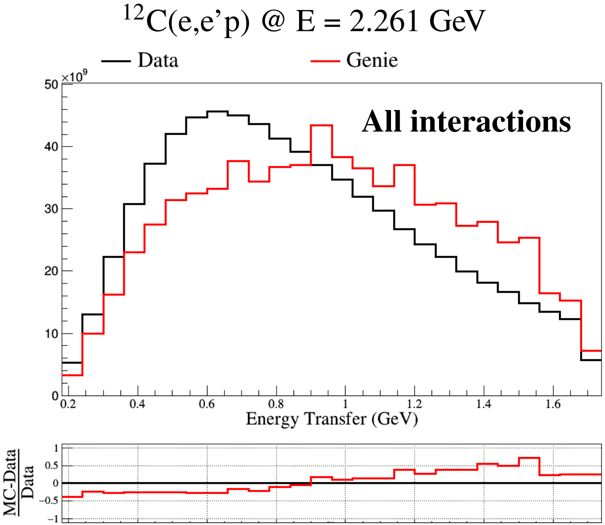


Missing Momentum

^{12}C(e,e'p) @ E = 2.261 GeV



Generator vs (e,e'p) data

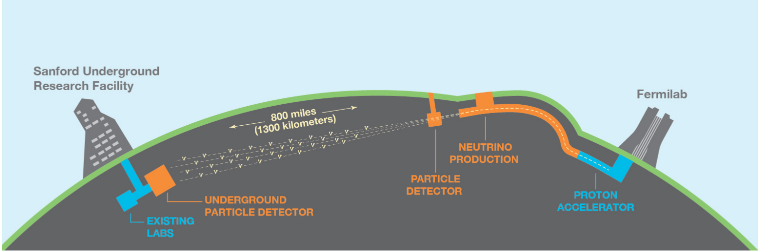


Implications to

DUNE

DEEP UNDERGROUND NEUTRINO EXPERIMENT

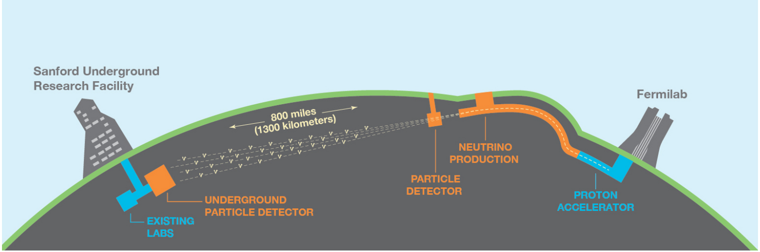
DUNE Goals



Extraction of oscillation parameters

with an accuracy of ~ 5 %

DUNE Goals



Extraction of oscillation parameters

with an accuracy of ~ 5 %

But energy reconstruction deviations & data–MC disagreement

Is

DUNE

DOOMED?

Attacking from all sides

Not yet!

e–scattering

ν–scattering

Event Generators

Attacking from all sides

Not yet,

but need for ...

e–scattering

ν–scattering

More data

More data

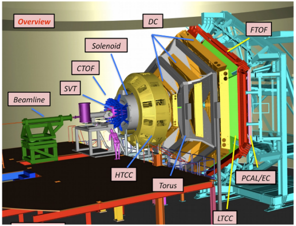
Event Generators

More theory input

New Proposal

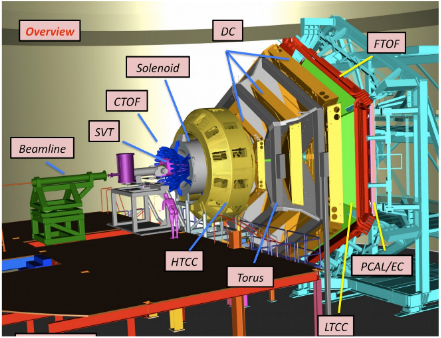
CLAS12 Spectrometer @ JLab

- Luminosity: x10 higher than CLAS6!
- Charged particles: 5^o – 120^o
- Neutrons: 5^o – 120^o & 160^o – 170^o
- Threshold: $\sim$ 300 MeV/c



New Proposal

High statistics for semi–inclusive and exlusive data sets on multiple targets at multiple energies



New Proposal

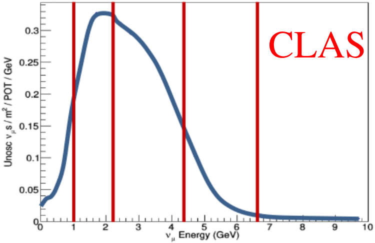
Targets

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

Beam Energies

1.1, 2.2, 4.4, 6.6 GeV

DUNE Spectrum



Wrap Up

Wrap Up

Used e-scattering events to test accuracy of E_{reco} and to benchmark event generators

Wrap Up

Used e-scattering events to test accuracy of E_{reco}
and to benchmark event generators

- E_{reco} shows significant deviations from E_{true}
- Good data-generator agreement in inclusive channel
- Significant disagreement in exclusive channels

Next Steps

- Further event generator development & benchmarking against electron scattering data

- New data for exclusive analyses & study of energy reconstruction accuracy

Thank you!

e4ν Team

Mariana Khachatryan [ODU]

Afroditi Papadopoulou [MIT]

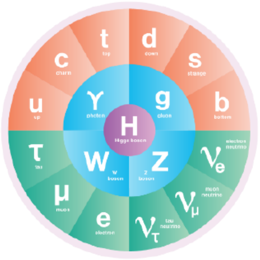
Dr. Adi Ashkenazi [MIT]

Backup Slides

Oscillation Parameters PDG 2018

Parameter	best-fit	3σ
Δm^2_{21} $[10^{-5}$ eV $^2]$	7.37	6.93 – 7.96
$\Delta m^2_{31(23)}$ $[10^{-3}$ eV $^2]$	2.56 (2.54)	2.45 – 2.69 (2.42 – 2.66)
$\sin^2\theta_{12}$	0.297	0.250 – 0.354
$\sin^2\theta_{23}$, $\Delta m^2_{31(32)} > 0$	0.425	0.381 – 0.615
$\sin^2\theta_{23}$, $\Delta m^2_{32(31)} < 0$	0.589	0.384 – 0.636
$\sin^2\theta_{13}$, $\Delta m^2_{31(32)} > 0$	0.0215	0.0190 – 0.0240
$\sin^2\theta_{13}$, $\Delta m^2_{32(31)} < 0$	0.0216	0.0190 – 0.0242
δ/π	1.38 (1.31)	2σ: (1.0 - 1.9) (2σ: (0.92-1.88))

Neutrino Physics



In the Standard Model

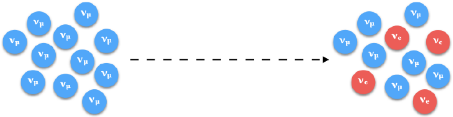
• 3 neutrinos of 3 different flavors (and 3 anti-neutrinos)

• massless neutrinos

• neutrinos only interact weakly (W and Z bosons mediate the interactions)

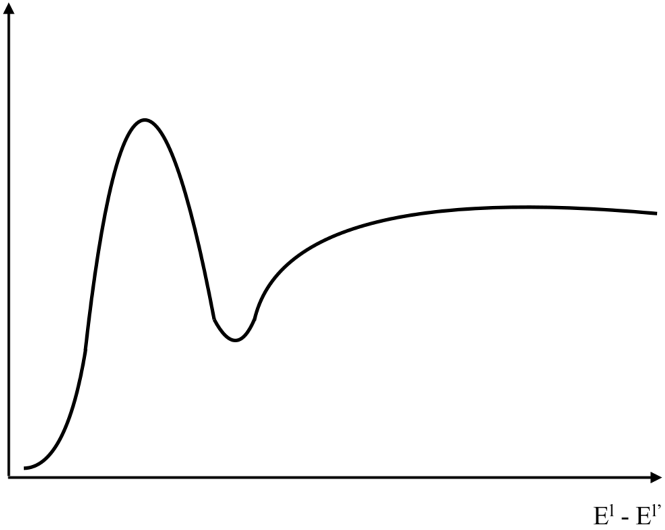
Beyond the Standard Model

Neutrino Oscillations: New Physics → neutrinos have mass

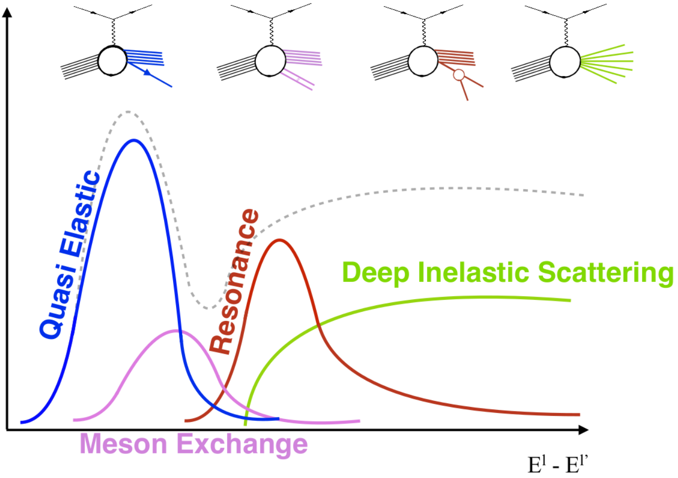


However, neutrinos are still the least understood particles ...

No Interference Terms



No Interference Terms



Identified Genie Issues

- Quasi–Elastic Channel
  - Rosenbluth cross–section

    (Mott cross–section, Jacobean)
- MEC Channel
  - Empirical model

    (missing boost from center–of–mass frame

    to lab frame)

Identified Genie Issues

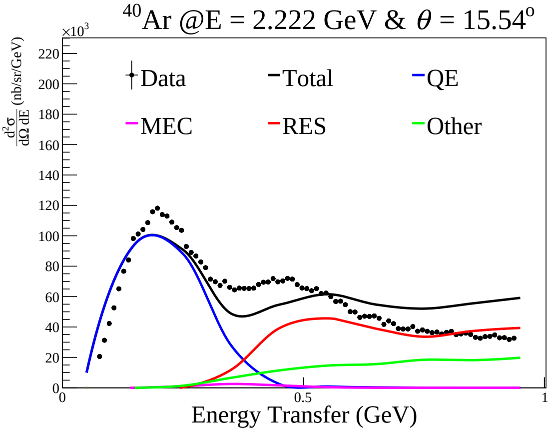
- Resonant Channel
  - Berger–Sehgal cross–section

    (used correct couplings for EM interactions,

    missing multiplication by Jacobean)

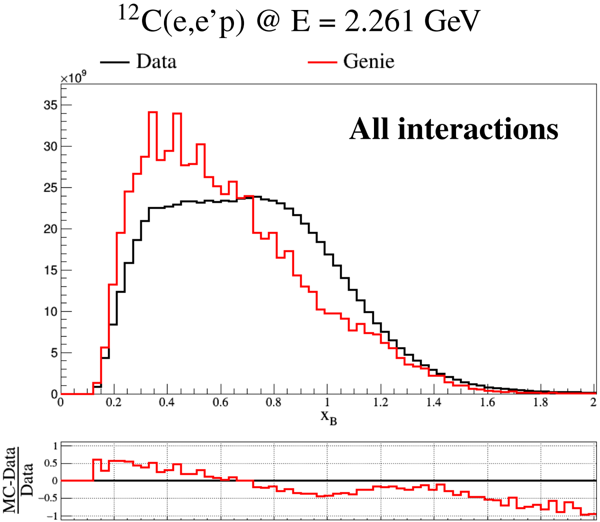
and this is the change with the greatest impact.

First Results on ^{40}Ar



arXiv:1803.01910

QE Peak Selection

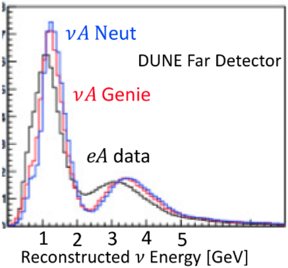


e4ν Impact

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)

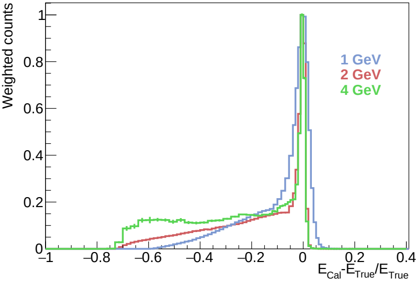
Summary of July Trento workshop: "MIT/ODU group's comparisons to electrons is shining a harsh light on this model and motivating efforts to improve the situation."



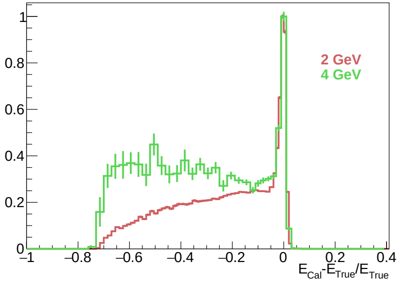
Fractional Feed Down

CLAS Data

^{12}C



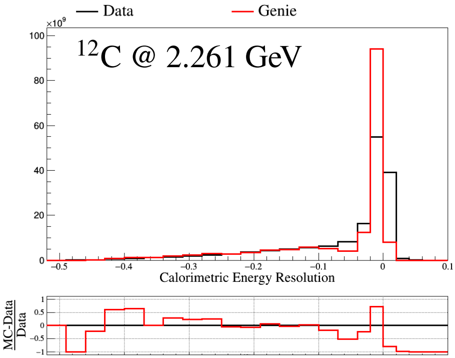
^{56}Fe

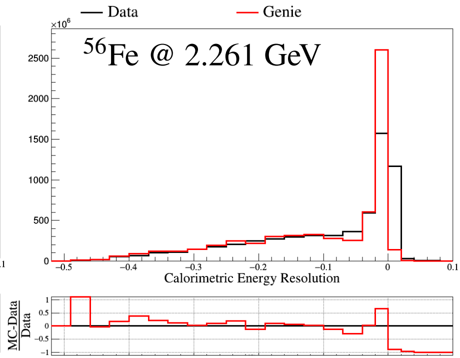


Energy resolution worsens at higher energies

Energy Resolution

QE Peak





Sanity check

Overwhelming Support

Fermilab

Hyper-Kamiokande

DUNE

ICECUBE
SOUTH POLE NEUTRINO OBSERVATORY

NOvA

MINERvA

T2K

ANNIE
Accelerator Neutrino Neutron Interaction Experiment

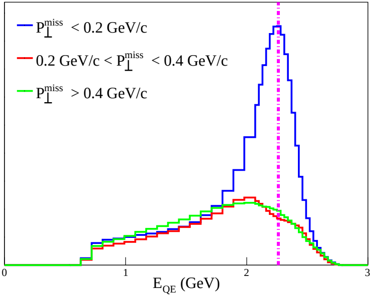
μBooNE

GiBUU
The Giessen Boltzmann-Uehling-Uhlenbeck Project

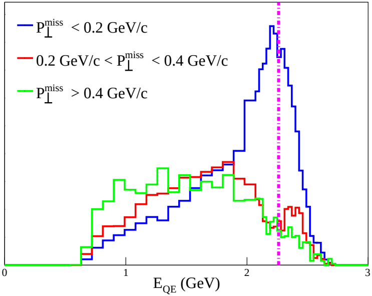
Missing Momentum Slices

All interaction channels

CLAS Data



Genie Simulation



Non-negligible differencies
for higher $P_\perp^{miss}$ slices