Neutrino Interactions with Nucleons and Nuclei

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Motivation and Contents

- Determination of neutrino oscillation parameters requires knowledge of neutrino energy

- Modern experiments use complicated nuclear targets: from Carbon to Argon

- Nuclear effects affect everything:
  - event cross section measurements
  - event identification
  - final state particles
  - neutrino energy reconstruction
  - determination of oscillation parameters

Neutrino Oscillations

- 2-Flavor Oscillation:

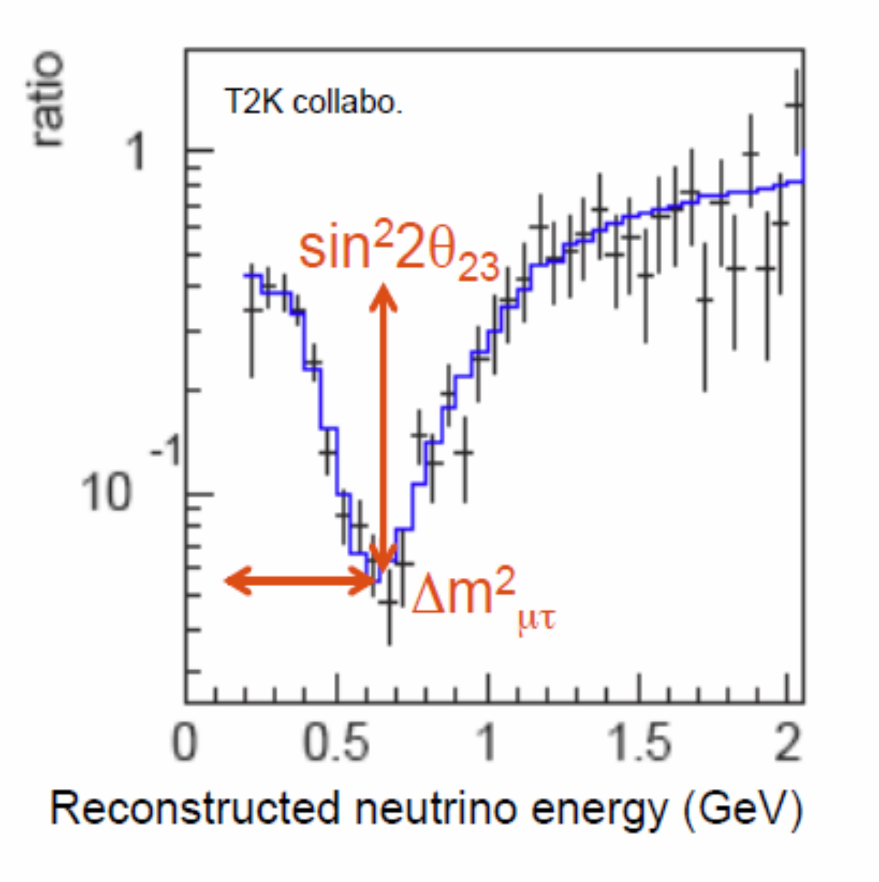
$$P(\nu_\mu \rightarrow \nu_e) = \sin^2 2\theta \sin^2\left(\frac{\Delta m^2 L}{4E_\nu}\right)$$

Know: L, need E_ν to determine Δm^2, θ

- 3-Flavor Oscillation: allows for CP violation

Observable Oscillation Parameters

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



Oscillation probability

Long-Baseline Accelerator Appearance Experiments

- Oscillation probability complicated and dependent not only on θ_{13} but also:
  1. CP violation parameter (δ)
  2. Mass hierarchy (sign of Δm_{31}^2)
  3. Size of $\sin^2\theta_{23}$

$$
\begin{aligned}
P(\nu_\mu \rightarrow \nu_e) = {} & 4C_{13}^2 S_{13}^2 S_{23}^2 \sin^2\frac{\Delta m_{31}^2 L}{4E} \times \left(1 + \frac{2a}{\Delta m_{31}^2}\left(1 - 2S_{13}^2\right)\right) \\
& + 8C_{13}^2 S_{12} S_{13} S_{23} (C_{12} C_{23} \cos\delta - S_{12} S_{13} S_{23}) \cos\frac{\Delta m_{32}^2 L}{4E} \sin\frac{\Delta m_{31}^2 L}{4E} \sin\frac{\Delta m_{21}^2 L}{4E} \\
& - 8C_{13}^2 C_{12} C_{23} S_{12} S_{13} S_{23} \sin\delta \sin\frac{\Delta m_{32}^2 L}{4E} \sin\frac{\Delta m_{31}^2 L}{4E} \sin\frac{\Delta m_{21}^2 L}{4E} \\
& + 4S_{12}^2 C_{13}^2 \left\{C_{12}^2 C_{23}^2 + S_{12}^2 S_{23}^2 S_{13}^2 - 2C_{12} C_{23} S_{12} S_{23} S_{13} \cos\delta\right\} \sin^2\frac{\Delta m_{21}^2 L}{4E} \\
& - 8C_{13}^2 S_{13}^2 S_{23}^2 \cos\frac{\Delta m_{32}^2 L}{4E} \sin\frac{\Delta m_{31}^2 L}{4E} \frac{aL}{4E} \left(1 - 2S_{13}^2\right)
\end{aligned}
$$

⇒ These extra dependencies are both a "curse" and a "blessing"

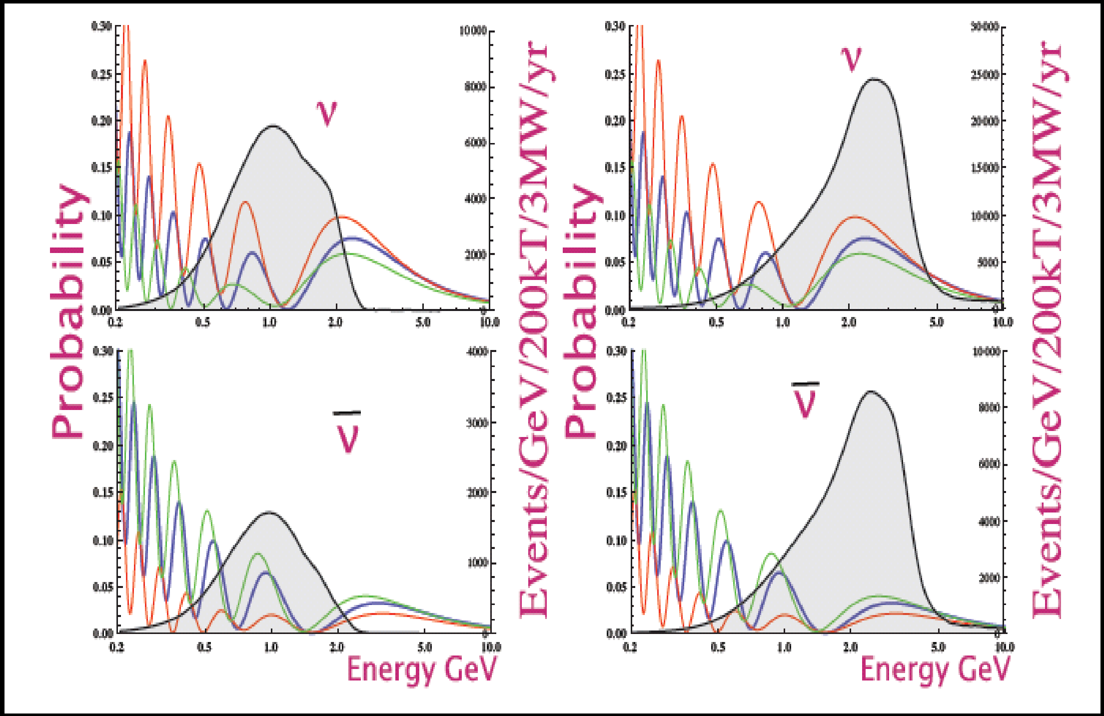
Reactor Disappearance Experiments

- Reactor disappearance measurements provide a straight forward method to measure θ_{13} with no dependence on matter effects and CP violation

$$P(\bar{\nu}_e \rightarrow \bar{\nu}_e) = 1 - \sin^2 2\theta_{13} \sin^2\frac{\Delta m_{13}^2 L}{4E} + \textit{small terms}$$

LBNE, δ_{CP} Sensitivity

From: Bishai et al., hep-ex 12034090



8 GeV

60 GeV

proton energy

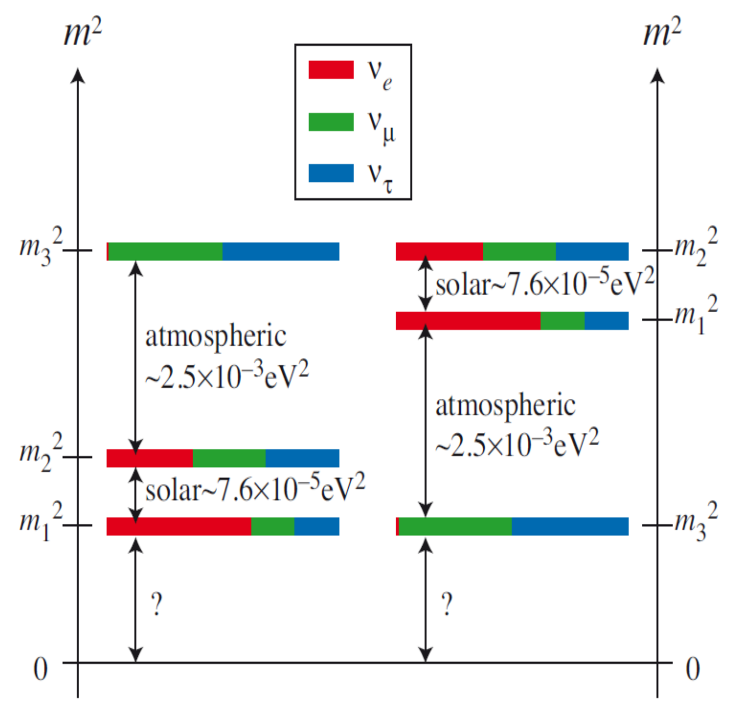
From:
Bishai et al
arXiv:1203.409

$\delta_{CP} = 0$
$\delta_{CP} = \pi/2$
$\delta_{CP} = -\pi/2$

Need energy to distinguish between different δ_{CP}

Oscillation Signal

Dependence on Hierarchy and Mixing Angle



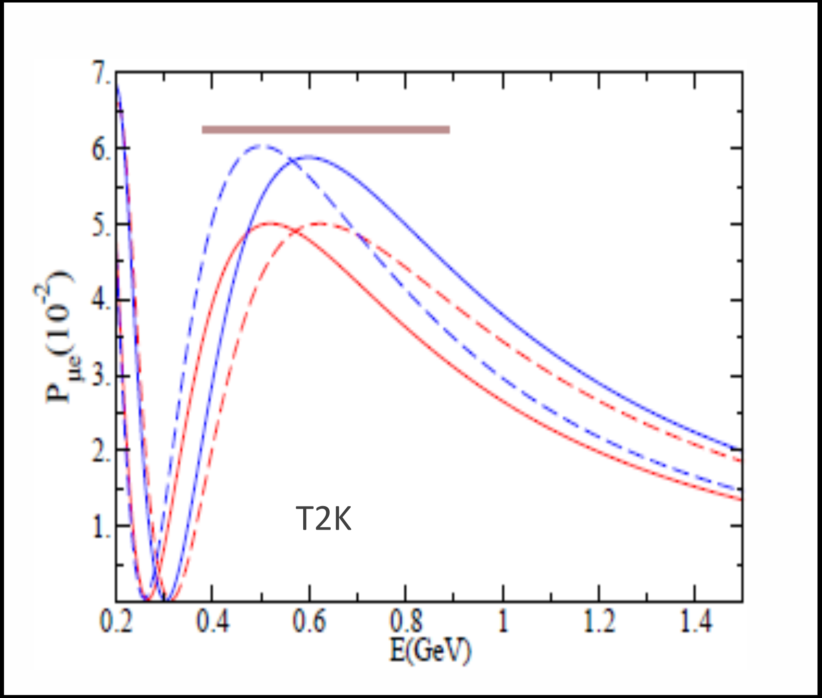


Fig. 2. $\mathcal{P}_{\mu e}$ in matter versus neutrino energy for the T2K experiment. The blue curves depict the normal hierarchy, red the inverse hierarchy. Solid curves depict positive θ_{13}, dashed curves negative θ_{13}

D.J. Ernst et al., arXiv:1303.4790 [nucl-th]

Energy has to be known better than 50 MeV

Shape sensitive to hierarchy and sign of mixing angle

Appearance experiment

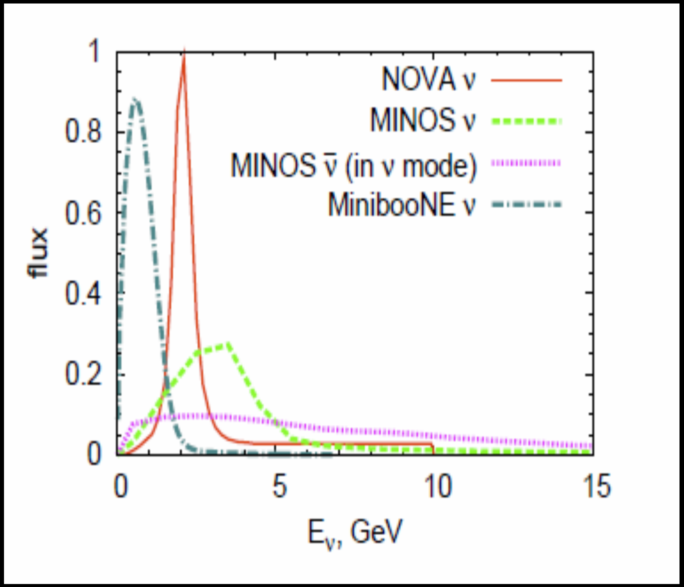
- Near detector:
  - Neutrino Flux
  - Background
  - Intrinsic ν_e
  - Neutrino energy

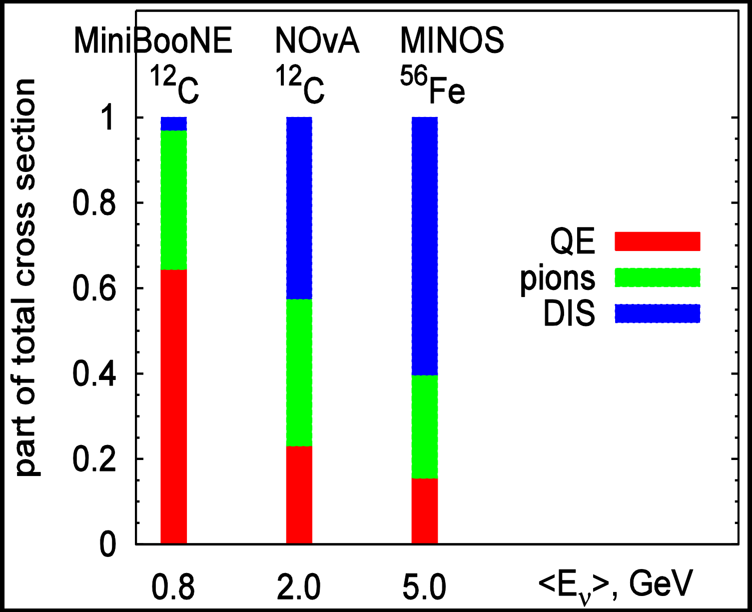
- Far detector:
  - Extrapolate Flux
  - Background
  - Neutrino energy

$$P\left(\nu_\mu \rightarrow \nu_e\right) = 1 - \sin^2 2\theta\ \sin^2\left(\frac{1.27\Delta m^2 L}{\boxed{E_\nu}}\right) + other$$

Neutrino Beams

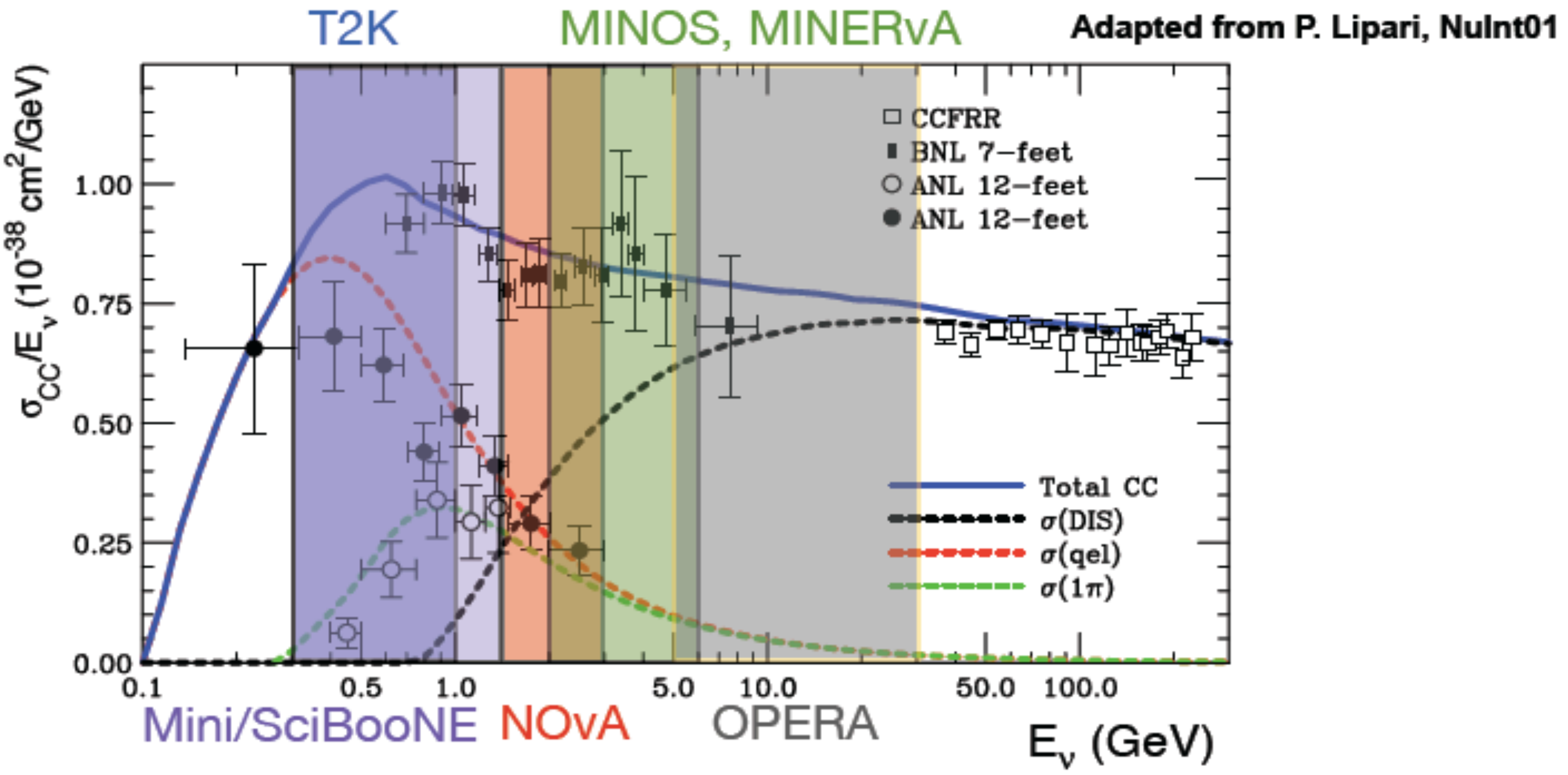
- Neutrinos do not have fixed energy nor just one reaction mechanism





Have to reconstruct energy from final state of reaction
Different processes are entangled

Neutrino Cross-Sections



Upcoming experiments will continue to work in an "interesting" region:

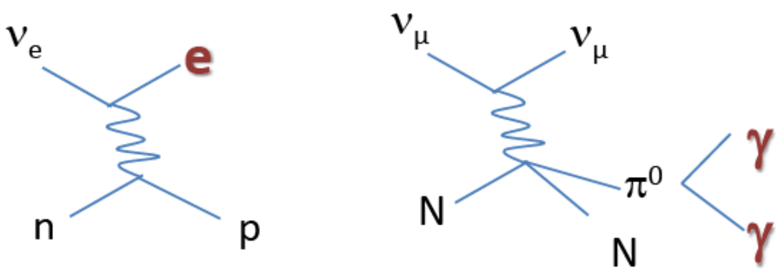
- Large contributions from QE, Resonances and DIS regions
- Are these categories even sufficient ?

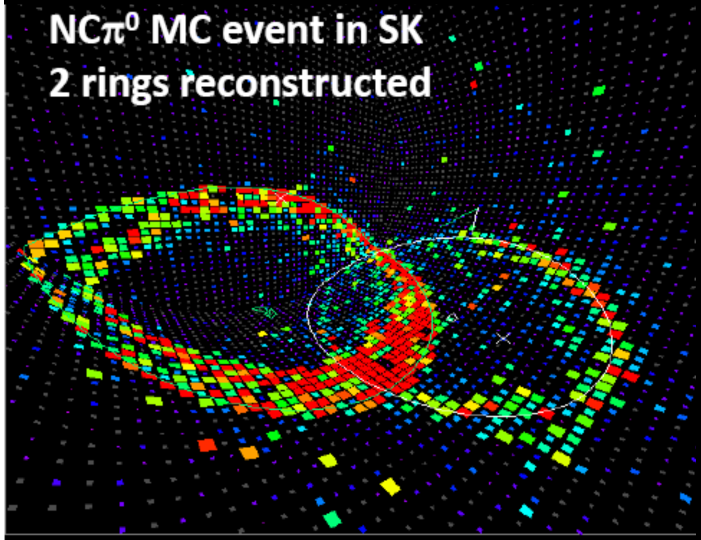
Neutrino Interactions

•for ν_e appearance

-beam ν_e

-NCπ^0 events

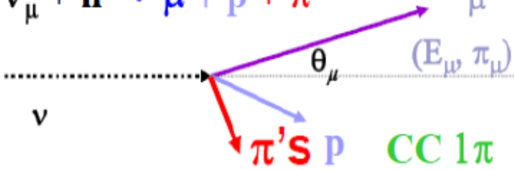



NCπ^0 MC event in SK
2 rings reconstructed

•for ν_μ disappearance (muon energy measurement)

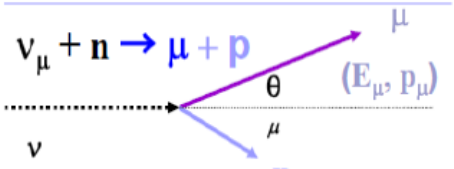
-inelastic processes

$\nu_\mu + n \rightarrow \mu + p + \pi$



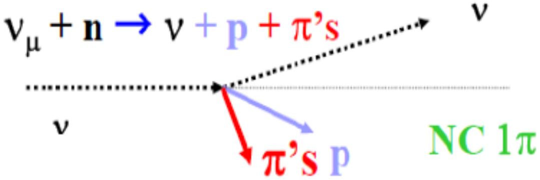
CC 1π

$\nu_\mu + n \rightarrow \mu + p$



Quasi-Elastic process

$\nu_\mu + n \rightarrow \nu + p + \pi\text{'s}$



NC 1π

Energy reconstruction

$$\nu_\mu + n \rightarrow \mu^- + p$$

$$E_\nu = E_\nu(E_\mu, \theta_\mu)$$

Kinematic:

  - Rely on underlying interaction to use relate outgoing lepton kinematics to neutrino energy
- Advantage:
  - don't need hadron reconstruction
- Disadvantages
  - energy is wrong if underlying interaction is wrong (i.e. not CCQE)
  - Nuclear effects smear resolution

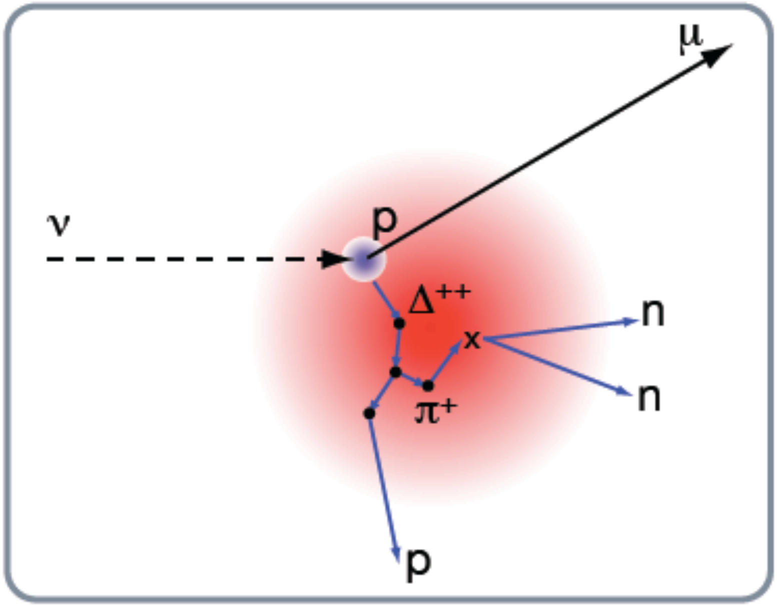
$$\nu_\mu + N \rightarrow \mu^- + X$$

$$E_\nu = E_\mu + E_X$$

Calorimetric

  - Add up the energy from the leptonic and hadronic components
- Advantages
  - No *a priori* assumption about underlying interaction
- Disadvantages
  - Relies on hadron reconstruction

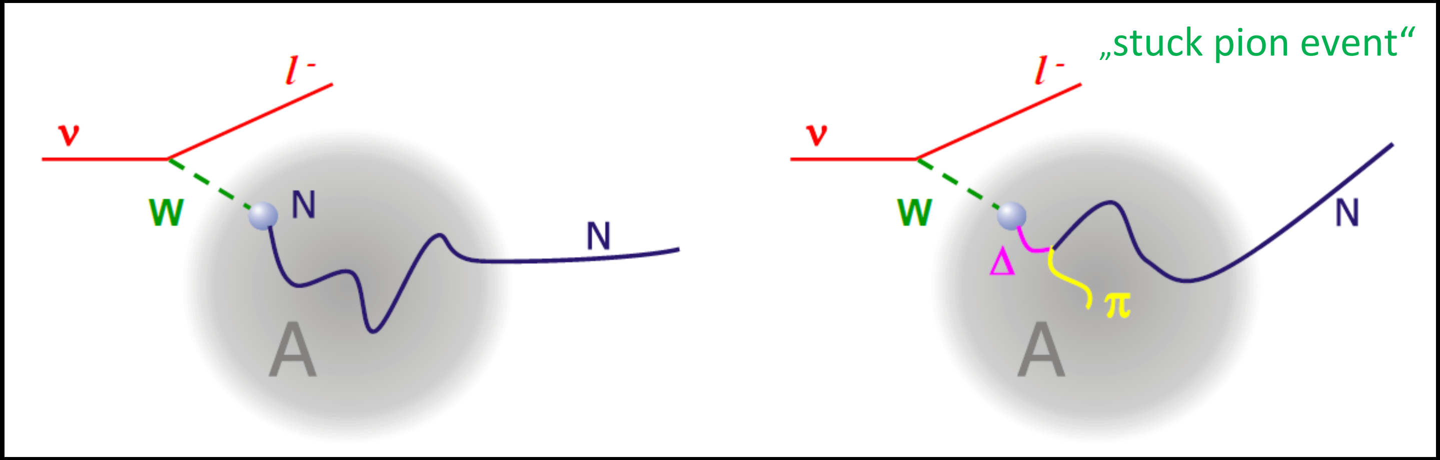
Background: Nuclear re-interactions



- Lepton kinematics shifted/smeared
- Outgoing hadronic final state ("topology") may differ from expectation from "underlying" ν-nucleon interaction
- FSI effects may appear degenerate with hadronic interactions outside of the target nucleus.

Modeling ν interactions in nucleus

- Underlying ν-nucleon/quark interaction
  - Mode (CCQE, resonance, etc.)
  - Determine "final" state of interaction
- Initial state nucleon/quark
  - Fermi motion, binding energy
- Final state effects
  - Pauli blocking
  - Propagate hadrons within nucleus
    - Absorption, scattering, CEX, etc.

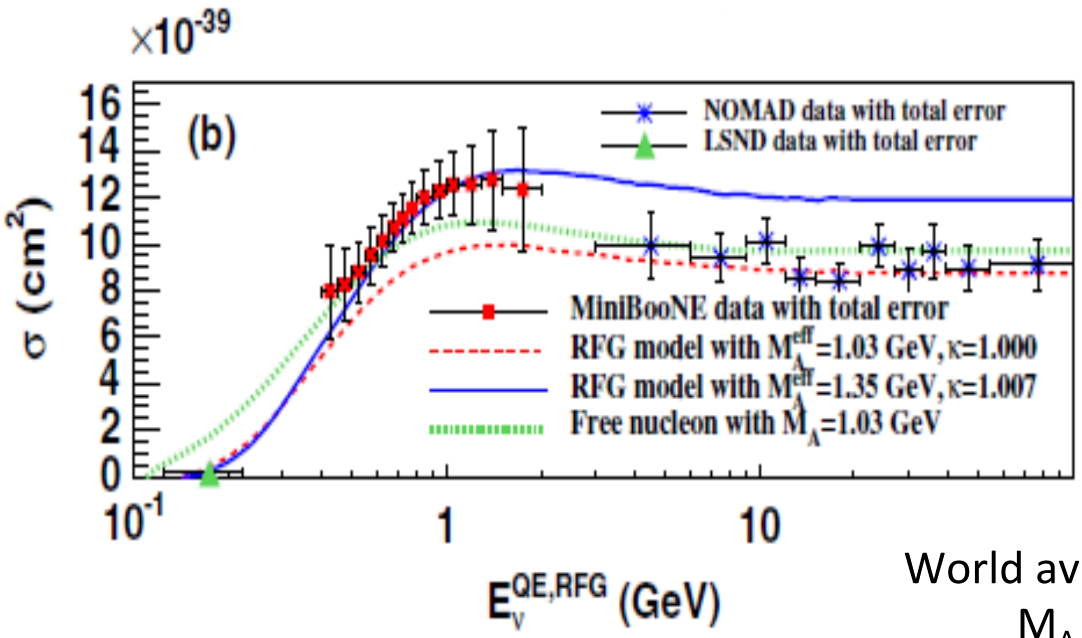


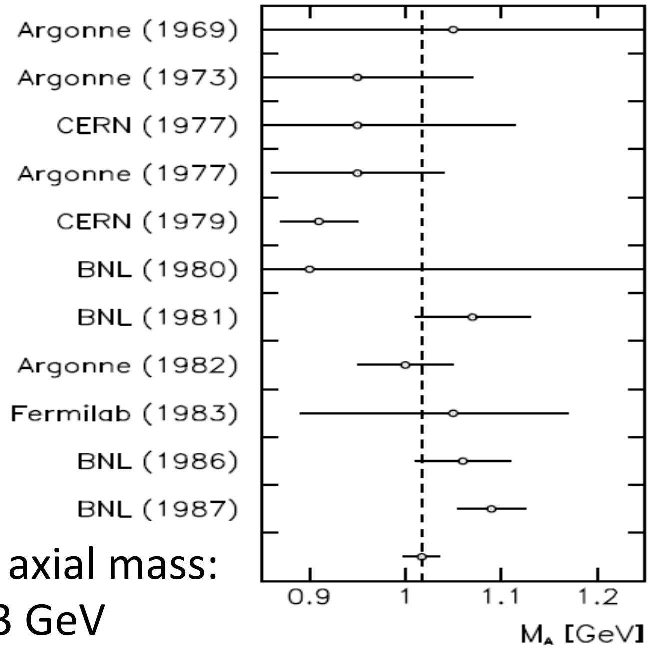
„stuck pion event“

Complication to identify QE, entangled with π production

Nuclear Targets (K2K, MiniBooNE, T2K, MINOS, Minerva, ….)

MiniBooNE QE puzzle





World average axial mass:
M_A = 1.03 GeV

MiniBooNE use mineral oil (Cerenkov rings): identifies QE by muon and zero pion, corrects for ‚stuck pions'

Can the nuclear effects be responsible for a higher axial mass value ?

Consider only events with no pion in final state: Cerenkov Experiments

- Experimental oscillation analyses requires QE identification (QE-like) with no pions in final state. This is why we care about QE.
- 0-pion events can involve pion production with subsequent pion absorption → ‚stuck pion events‘
- Experiments remove the contribution of pionless events due to absorption according to MC models
- Definition of QE cannot distinguish between true QE (1p-1h), N* and 2p-2h interactions

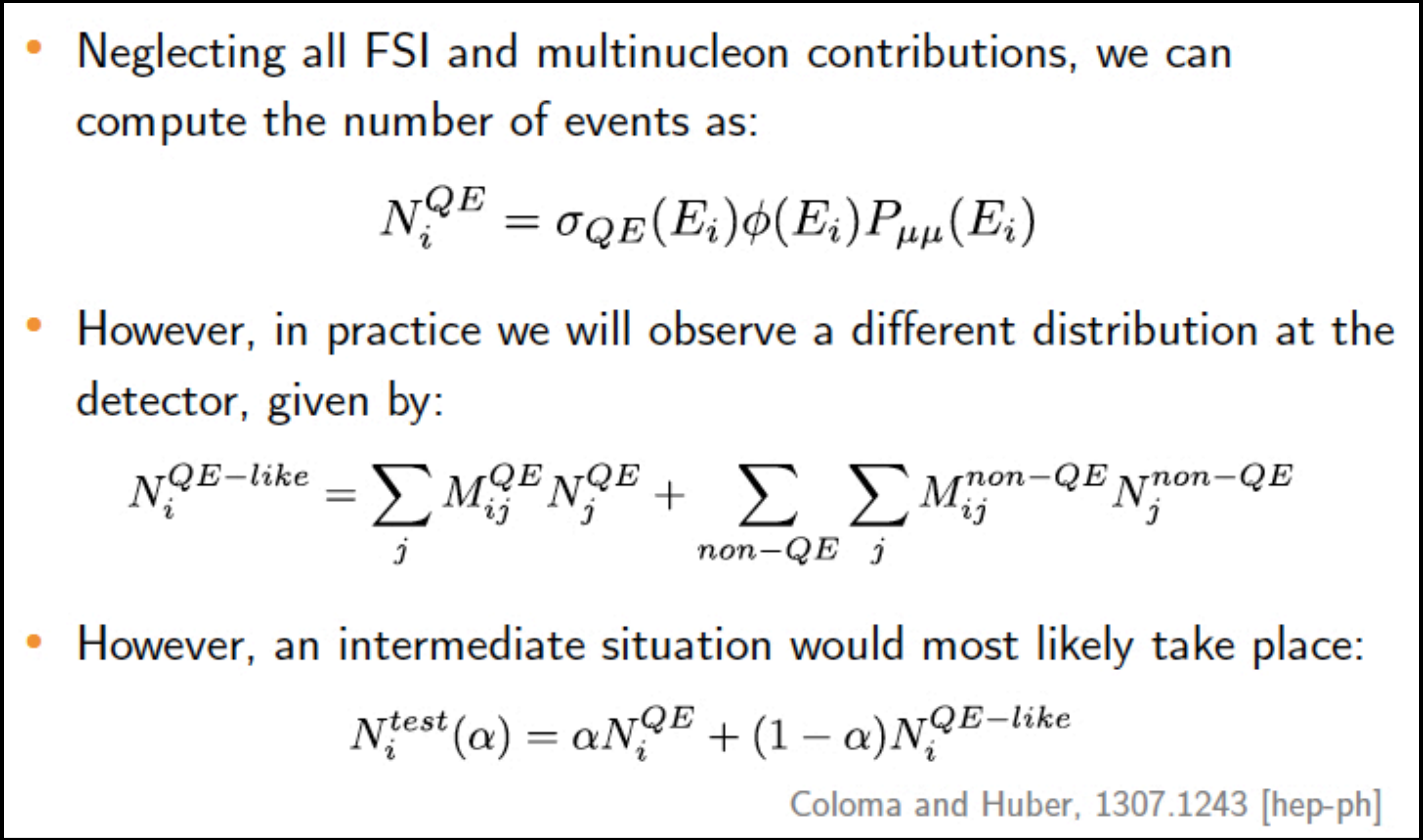
Oscillation analysis
and
Energy Reconstruction
in an ideal Long Baseline Experiment

Experimental Setup

- Ideal and perfect near detector (^{12}C or ^{16}O), 1 km, 1kton
- Far detector at 295 km, 22.5 kton
  - Oxigen
  - Carbon
- Use T2K flux, peak at 0.6 GeV, 750kW, 5 years running
- Use SK reconstruction efficiency as function of energy
- Use migration matrices produced by GiBUU(1.6) and GENIE(2.8.0)
- Muon neutrino disappearance only -> fit to atmospheric parameters

Go beyond simple case (arxiv:1311.4506)

- Use one neutrino generator (GiBUU) to simulate the nuclear effects and use another neutrino generator (GENIE) to extract the oscillation parameters
- In a real experiment the “real” effects from data will be used in the oscillation analysis together with “some” simulation of nuclear effects
- Neutrino generators are “enough” different to help understanding what will be the effect of different nuclear models on neutrino oscillation analyses



- Neglecting all FSI and multinucleon contributions, we can compute the number of events as:

$$N_i^{QE} = \sigma_{QE}(E_i)\phi(E_i)P_{\mu\mu}(E_i)$$

- However, in practice we will observe a different distribution at the detector, given by:

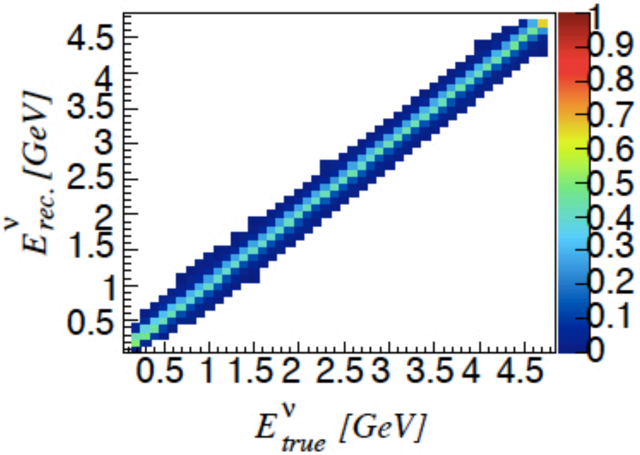
$$N_i^{QE-like} = \sum_j M_{ij}^{QE} N_j^{QE} + \sum_{non-QE} \sum_j M_{ij}^{non-QE} N_j^{non-QE}$$

- However, an intermediate situation would most likely take place:

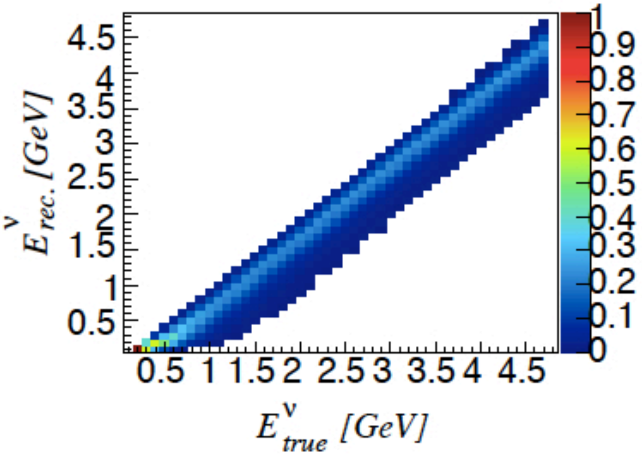
$$N_i^{test}(\alpha) = \alpha N_i^{QE} + (1-\alpha) N_i^{QE-like}$$

Coloma and Huber, 1307.1243 [hep-ph]

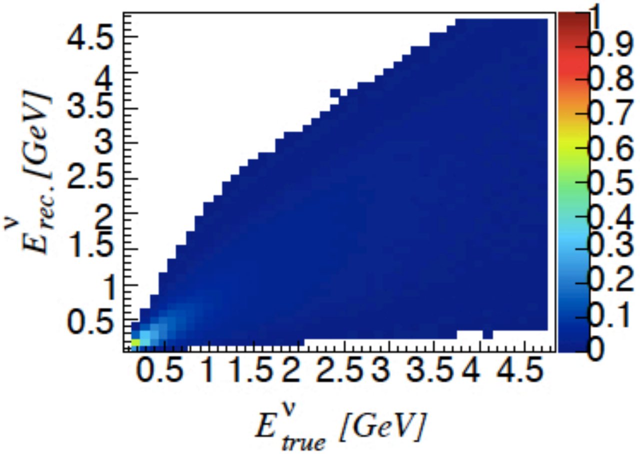
Migration matrices: GiBUU (^{16}O)



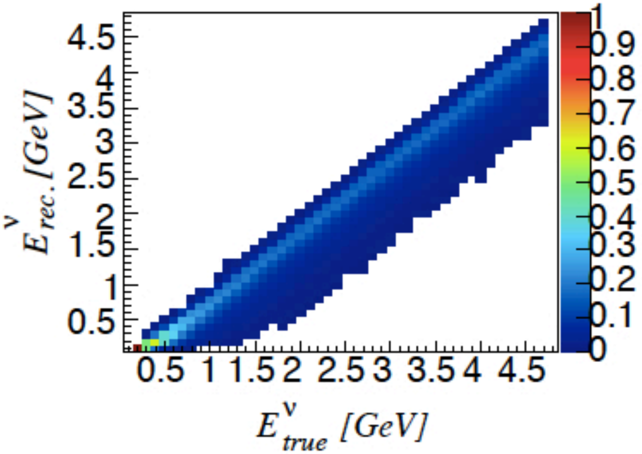
(a) Matrix for QE events



(b) Matrix for RES events

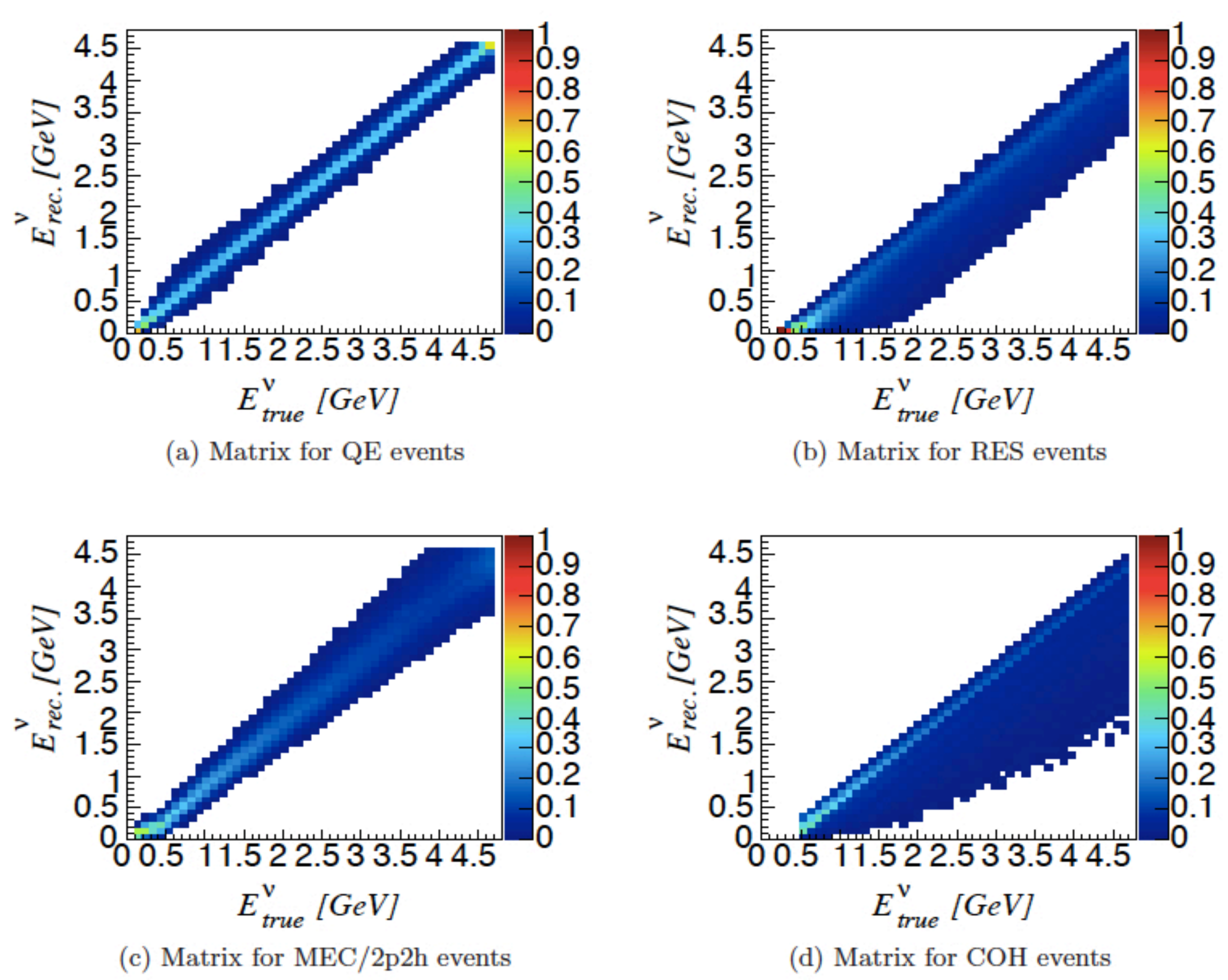


(c) Matrix for MEC/2p2h events



(d) Matrix for COH events

Migration matrices: GENIE (^{16}O)



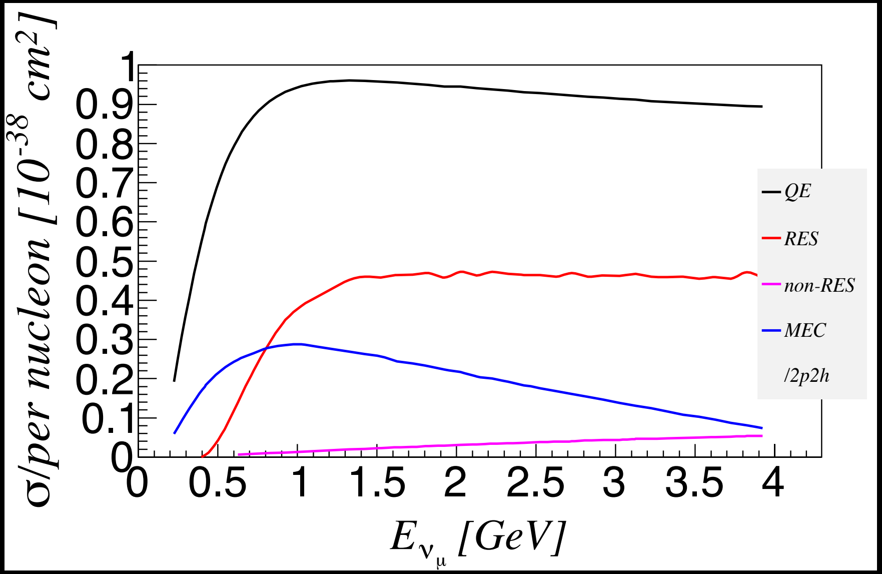
(a) Matrix for QE events

(b) Matrix for RES events

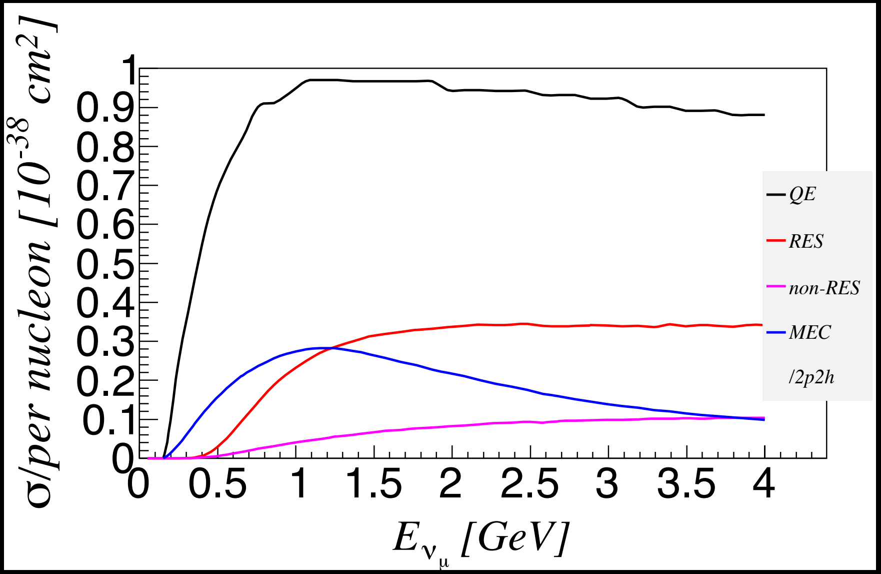
(c) Matrix for MEC/2p2h events

(d) Matrix for COH events

Cross-sections

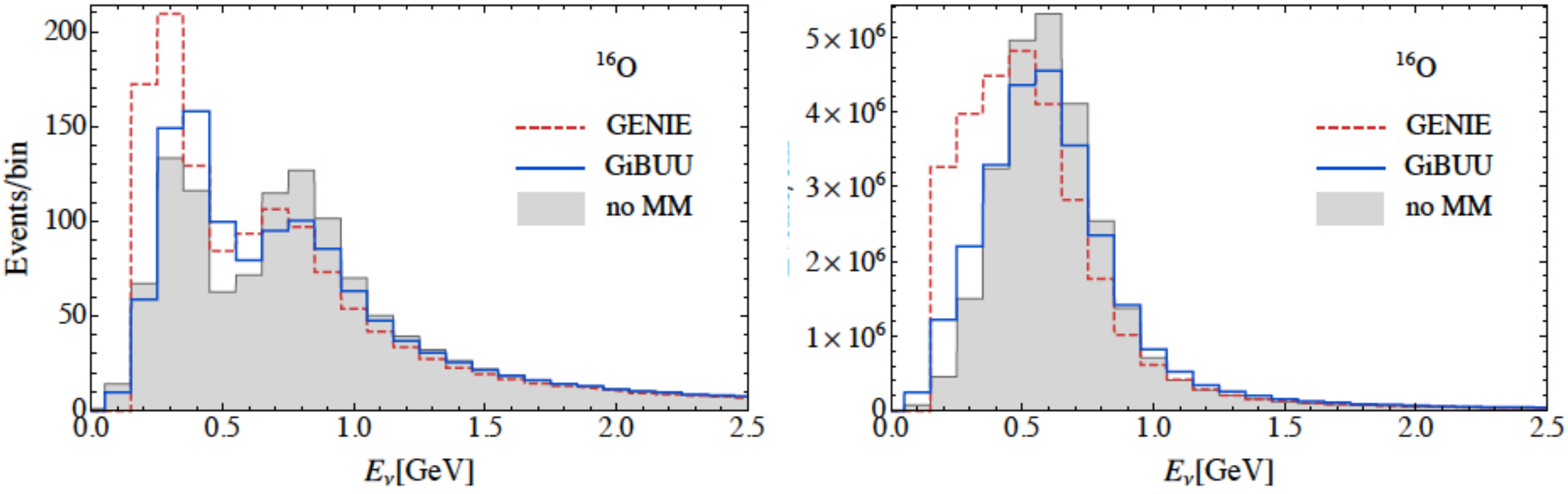


Genie 2.8.0



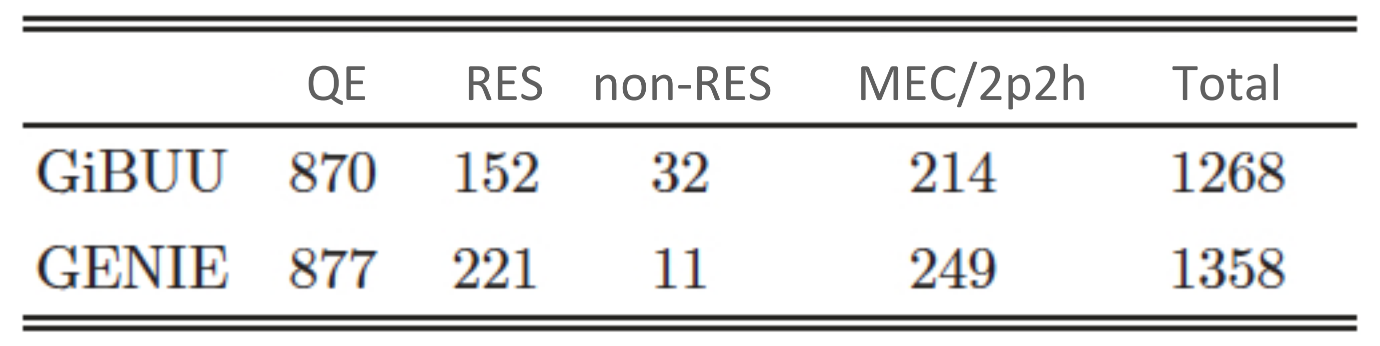
GiBUU 1.6

Event distributions

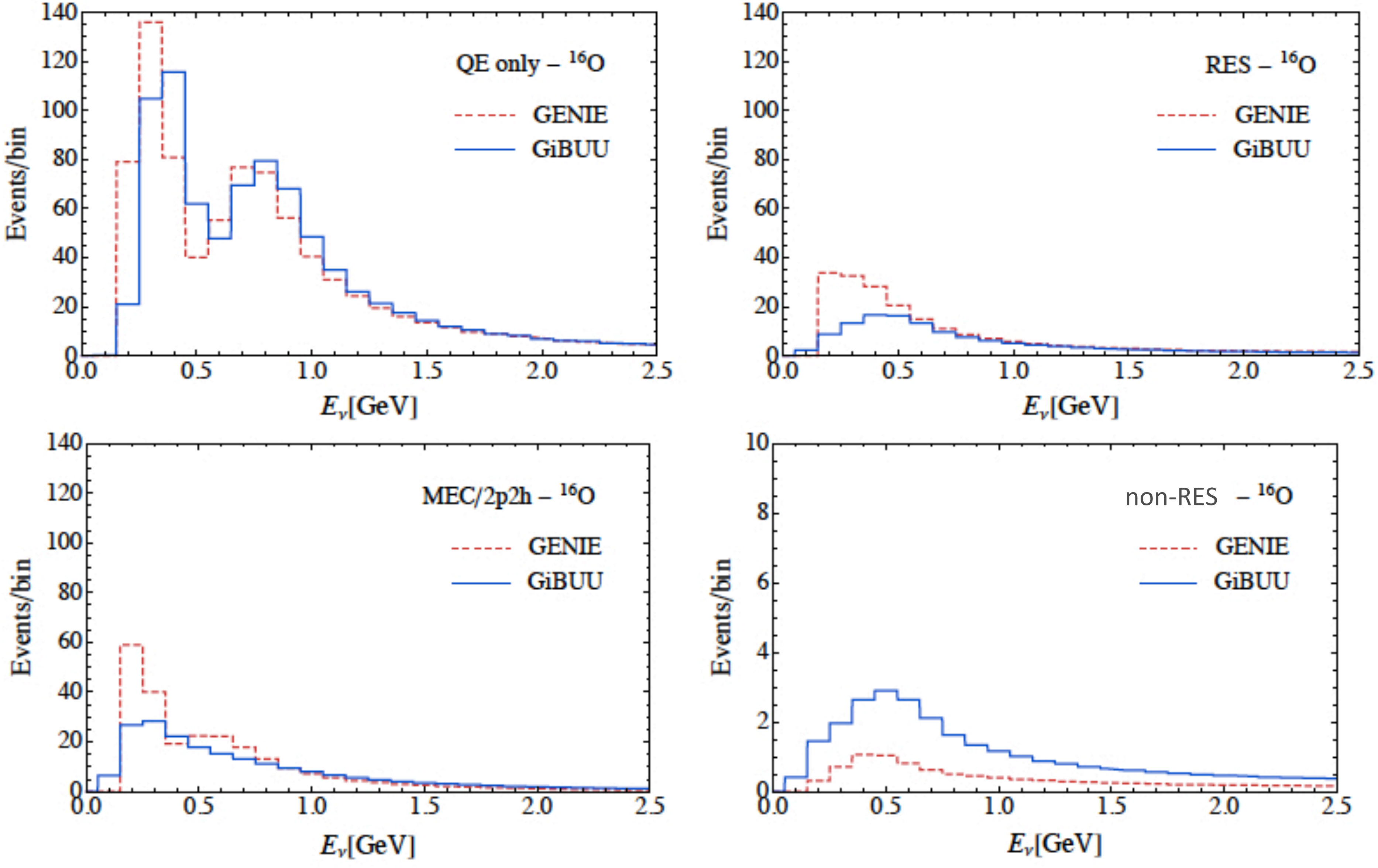


(a) Expected events at the far detector

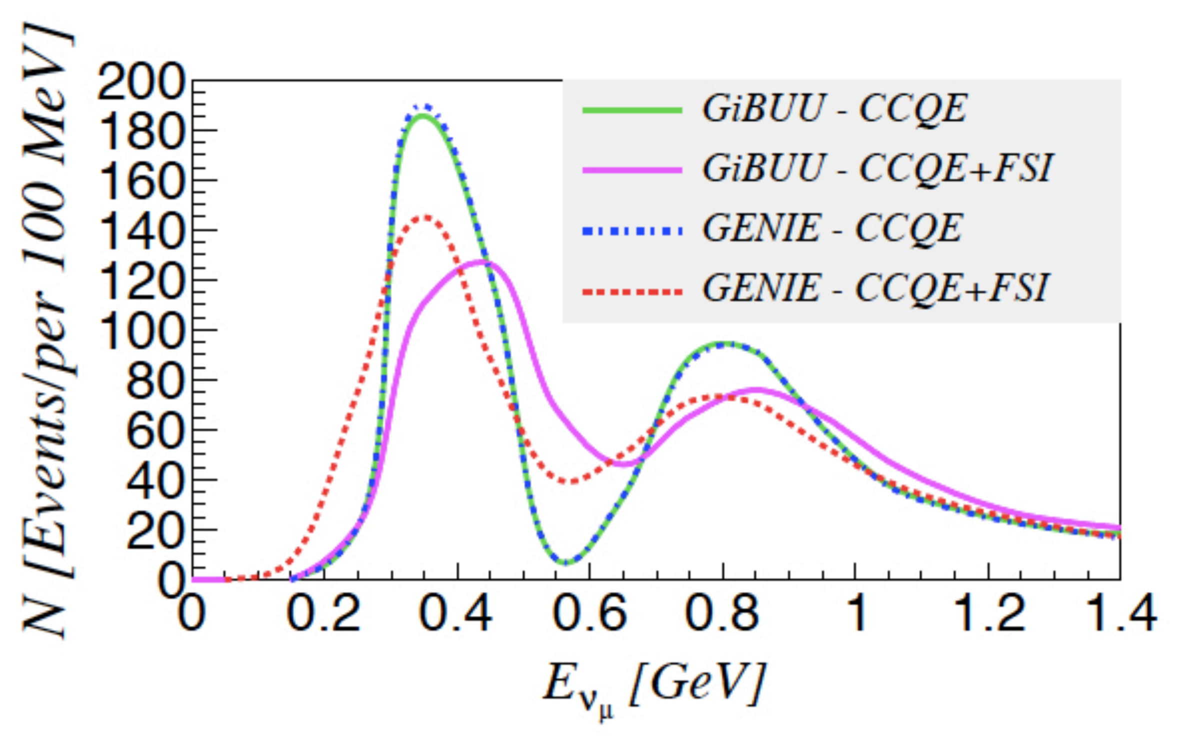
(b) Expected events at the near detector



	QE	RES	non-RES	MEC/2p2h	Total
GiBUU	870	152	32	214	1268
GENIE	877	221	11	249	1358


QE only – ^{16}O
GENIE
GiBUU
Events/bin
0
20
40
60
80
100
120
140
0.0
0.5
1.0
1.5
2.0
2.5
E_ν[GeV]
RES – ^{16}O
GENIE
GiBUU
Events/bin
E_ν[GeV]
MEC/2p2h – ^{16}O
GENIE
GiBUU
Events/bin
E_ν[GeV]
non-RES – ^{16}O
GENIE
GiBUU
Events/bin
0
2
4
6
8
10
E_ν[GeV]

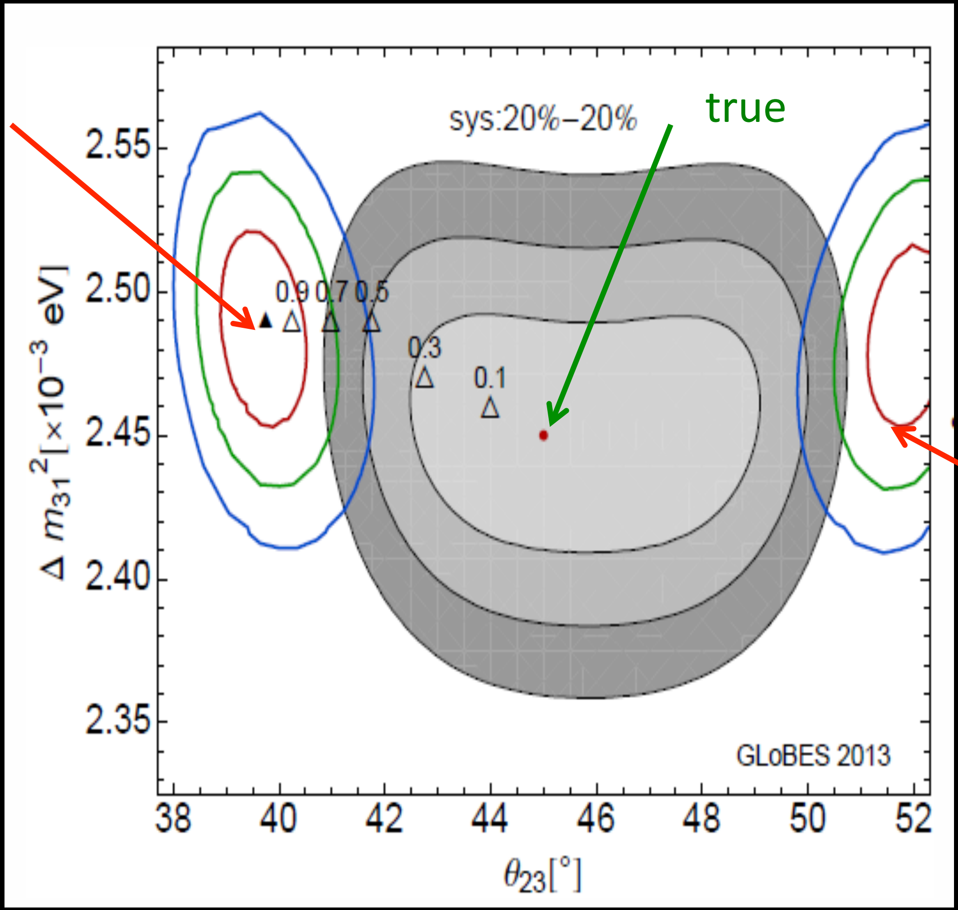
A surprise …



Number of events predicted as function of neutrino energy shifted by 10% for pure QE and 17% for all the QE-like events

- Due to FSI – difference is in the migration matrices
- Intrinsic model differences between GENIE and GiBUU
- Intrinsic differences in the model implementations

How to read the plots



reconstructed from naive QE dynamics

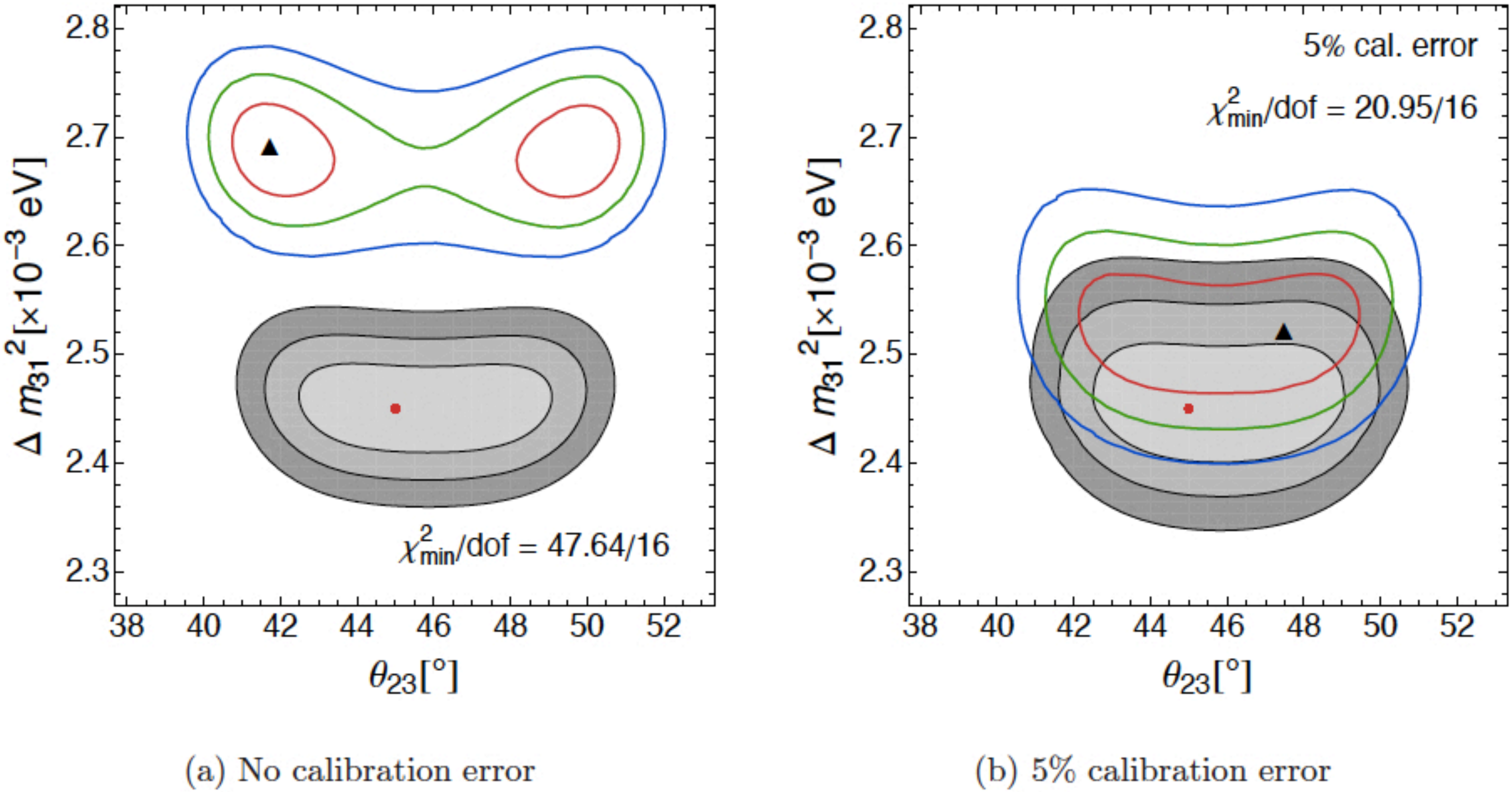
true

P. Coloma, P. Huber,
arXiv:1307.1243, July 2013

Analysis based on GiBUU

1, 2 and 3σ allowed regions

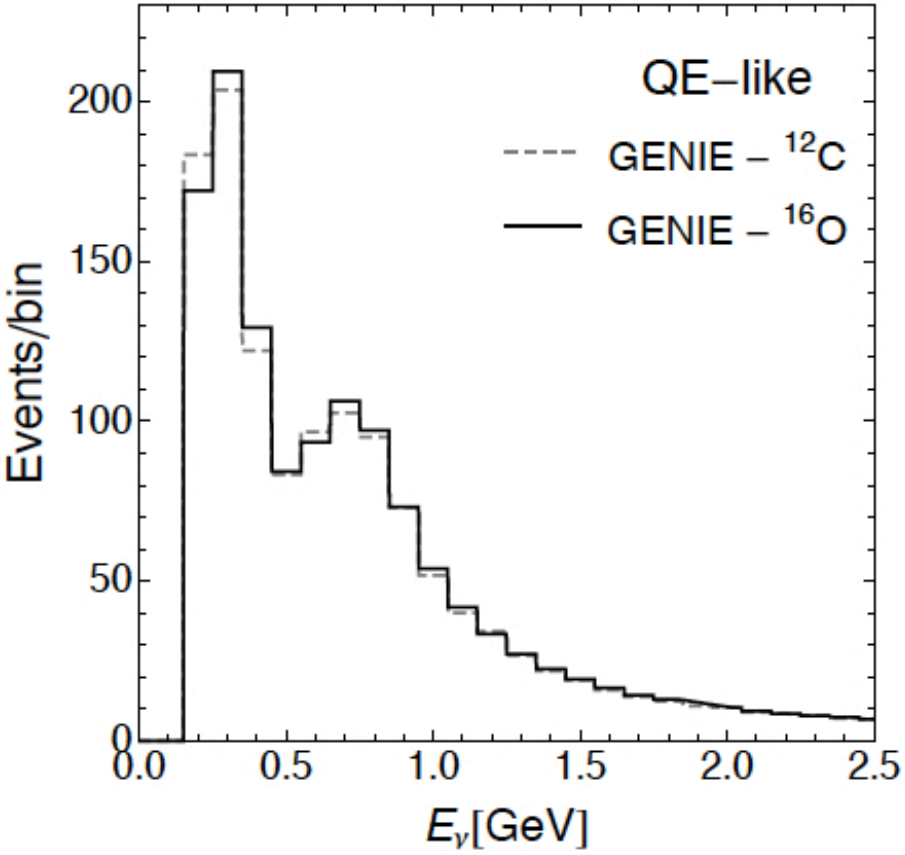
Simulating with GiBUU and extracting oscillations with GENIE: with and without calibration error



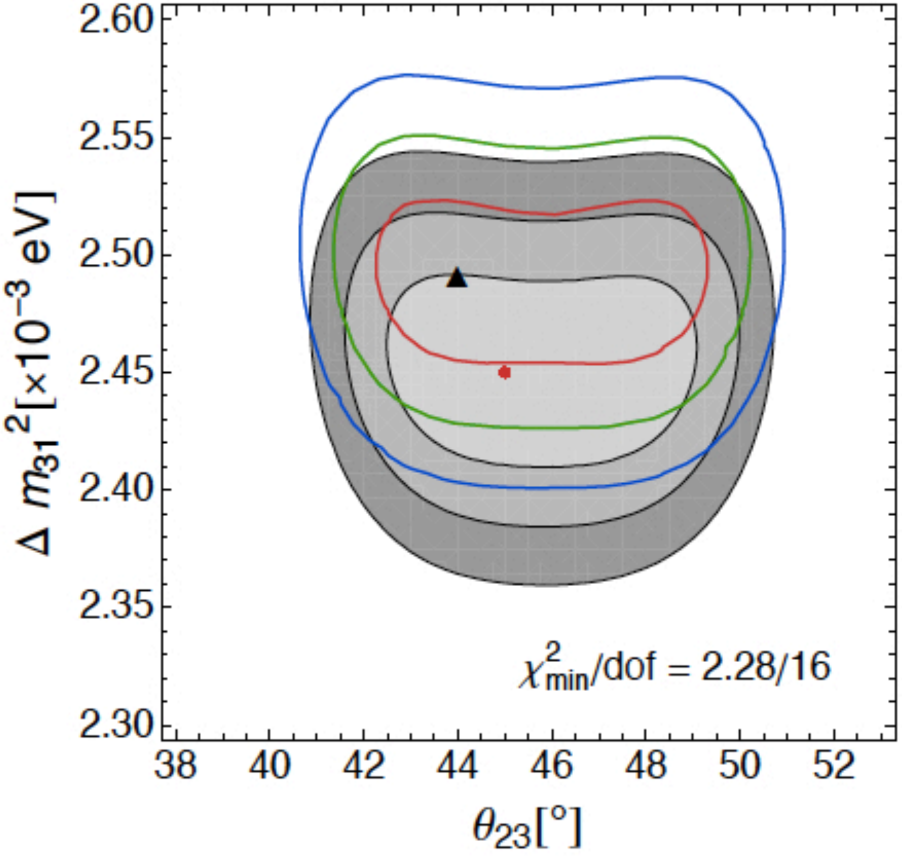
(a) No calibration error

(b) 5% calibration error

Carbon vs Oxygen

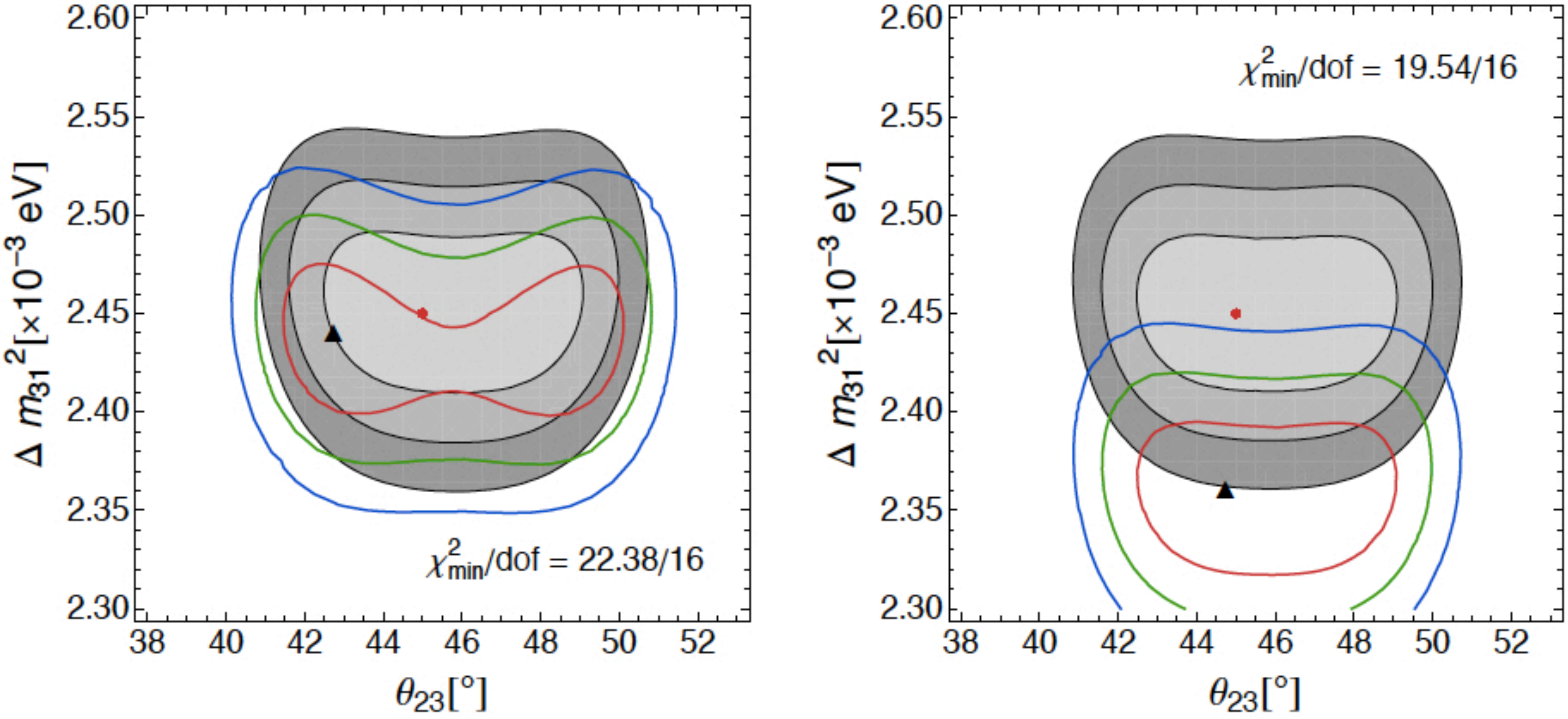


(a) QE-like event distributions



(b) Confidence regions

With and without MEC/2p2h

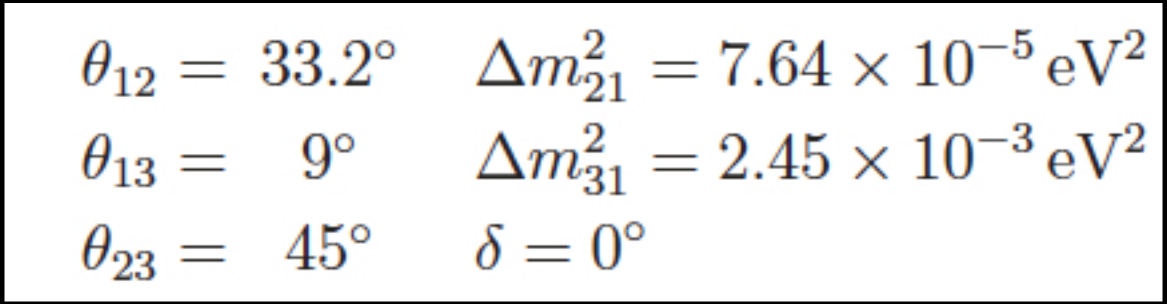


(a) Results using GiBUU matrices

(b) Results using GENIE matrices

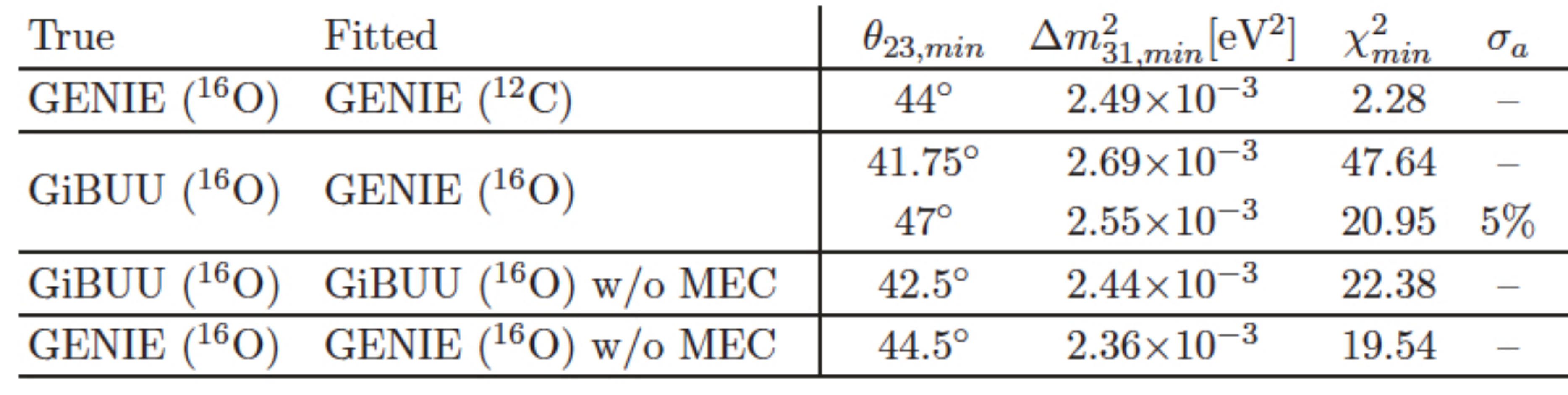
Summary of results

Input “true” Values



$$\begin{array}{llll} \theta_{12} = & 33.2^\circ & \Delta m^2_{21} = 7.64\times10^{-5}\,\mathrm{eV}^2 \\ \theta_{13} = & 9^\circ & \Delta m^2_{31} = 2.45\times10^{-3}\,\mathrm{eV}^2 \\ \theta_{23} = & 45^\circ & \delta = 0^\circ \end{array}$$

Fitted Values



True	Fitted	$\theta_{23,min}$	$\Delta m^2_{31,min}[\mathrm{eV}^2]$	χ^2_{min}	σ_a
GENIE (^{16}O)	GENIE (^{12}C)	44°	2.49×10^{-3}	2.28	–
GiBUU (^{16}O)	GENIE (^{16}O)	41.75°	2.69×10^{-3}	47.64	–
		47°	2.55×10^{-3}	20.95	5%
GiBUU (^{16}O)	GiBUU (^{16}O) w/o MEC	42.5°	2.44×10^{-3}	22.38	–
GENIE (^{16}O)	GENIE (^{16}O) w/o MEC	44.5°	2.36×10^{-3}	19.54	–

Conclusions

- Energy reconstruction essential for precision determination of neutrino oscillation parameters and neutrino-hadron cross sections

- Impact on neutrino oscilaltion experiments due to nuclear models, what they are and how they are implemented is not negligible (order 10%)
  - comparing systematically generators is important
  - neutrino event generators use almost same data set so there are correlations that are non-negligible
  - using wrong models affect neutrino oscillation parameters determination

- In future extend the case to CP violation:
  - neutrino vs anti-neutrino cross-section,: do we have reliable event generators for anti-neutrino ?

- MEC/2p2h: heavily tuned to MiniBooNE data in both GiBUU and GENIE.
  - the contribution of MEC/2p2h is the same between Carbon and Oxygen, should it be ?

- Energy reconstruction requires reliable event generators,
  of same quality as experimental equipment

- Precision era of neutrino physics requires much more sophisticated generators and a dedicated effort in theory

- Theorists-phenomenologists and experimentalists need to work together: NuSTEC

Generators are a crucial part of any experiment!

Must be of same quality as the experimental equipment itself!

Needed resources are relatively small, but still not available

"What we especially like about these theoretical types is that they don't tie up thousands of dollars worth of equipment."

millions

Thanks

- Omar: for everything (where should I start ?)
- Ulrich and Olga:
  - very interesting discussion
  - GiBUU support
- Patrick and Pilar:
  - GlOBES
  - oscillation analysis
  - great discussions

Neutrino generators and oscillation analyses: discussion and questions

- Systematic errors
  - Uncertainties in input cross sections
  - Mis-identification of reaction mechanisms
  - Generator-specific numerical implementation

- What to do next

- Systematical comparison of generators

- Could and should we extend these studies and the nuclear theories to heavier targets (Ar) ?

Backup

Energy shift

$$N[E] \rightarrow N[(1+a)\,E]$$

Modify the number of events as function of energy introducing a calibration error “a” and additional pull tem is added to the chi^2 of the fit.