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 identification
  - final state particles
  - reconstructed neutrino energy
  - event cross section measurements
  - neutrino oscillation parameters

Neutrino Oscillations

- 2-Flavor Oscillation:

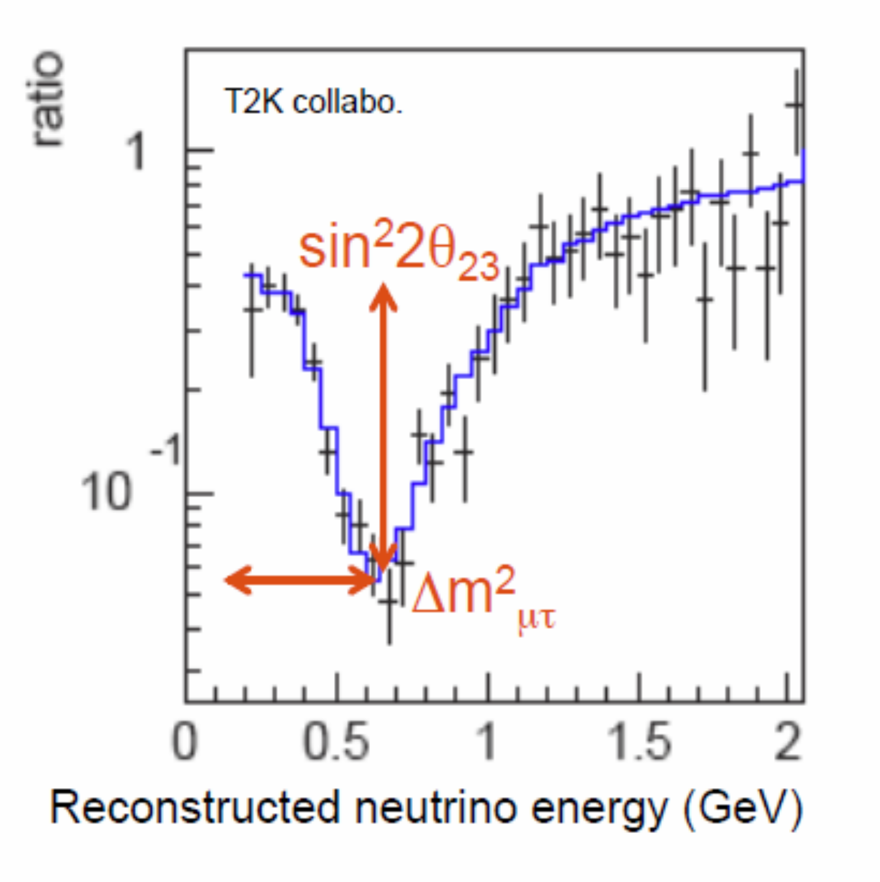
$$P(\nu_\mu \to \nu_e) = \sin^2 2\theta \sin^2\left(\frac{\Delta m^2 L}{4E_\nu}\right)$$

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

- 3-Flavor Oscillation: allows for CP violation

Observable Oscillation Parameters

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



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 $\sin^2\theta_{23}$

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

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

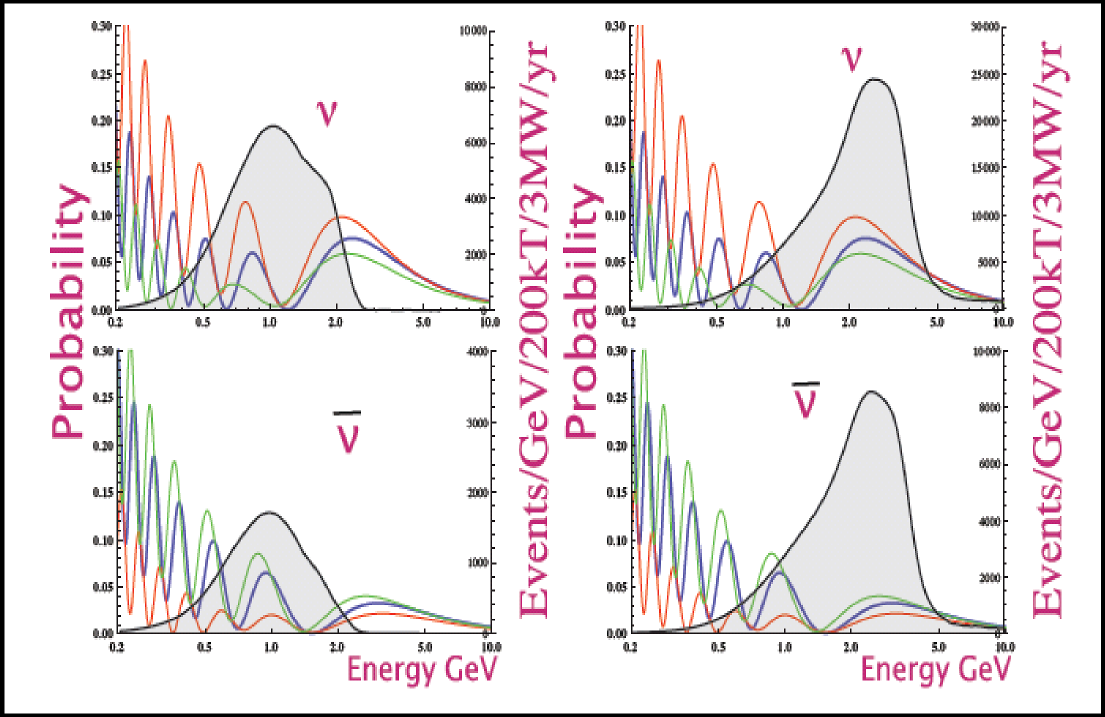
Reactor Disappearance Experiments

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

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

LBNE, δ_{CP} Sensitivity

From: Bishai et al., hep-ex 12034090



8 GeV

60 GeV

proton energy

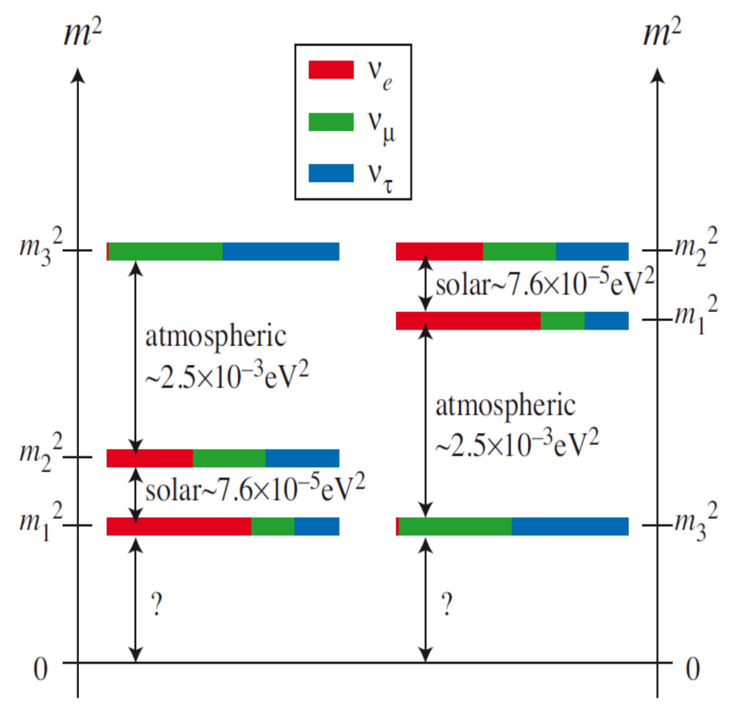
From:
Bishai et al
arXiv:1203.409

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

Need energy to distinguish between different δ_{CP}

Oscillation Signal

Dependence on Hierarchy and Mixing Angle



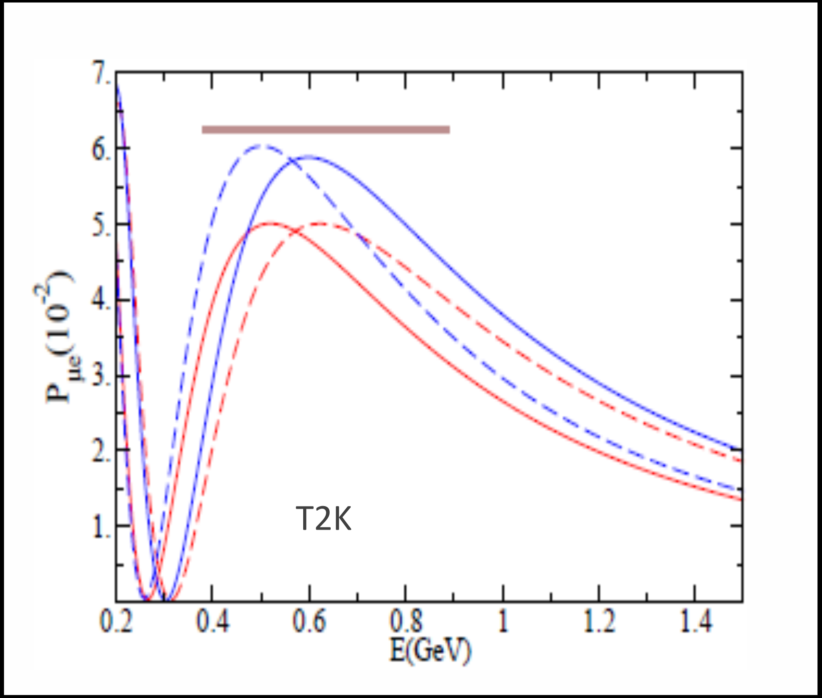


Fig. 2. $\mathcal{P}_{\mu e}$ in matter versus neutrino energy for the T2K experiment. The blue curves depict the normal hierarchy, red the inverse hierarchy. Solid curves depict positive θ_{13}, dashed curves negative θ_{13}

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

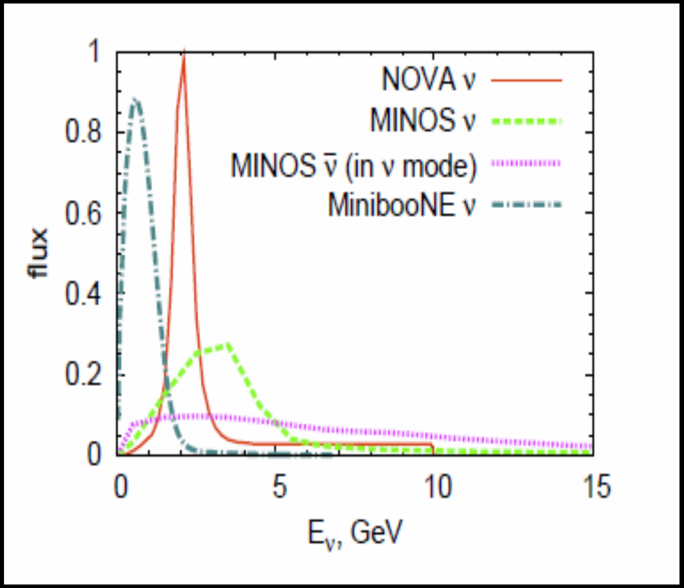
Appearance experiment

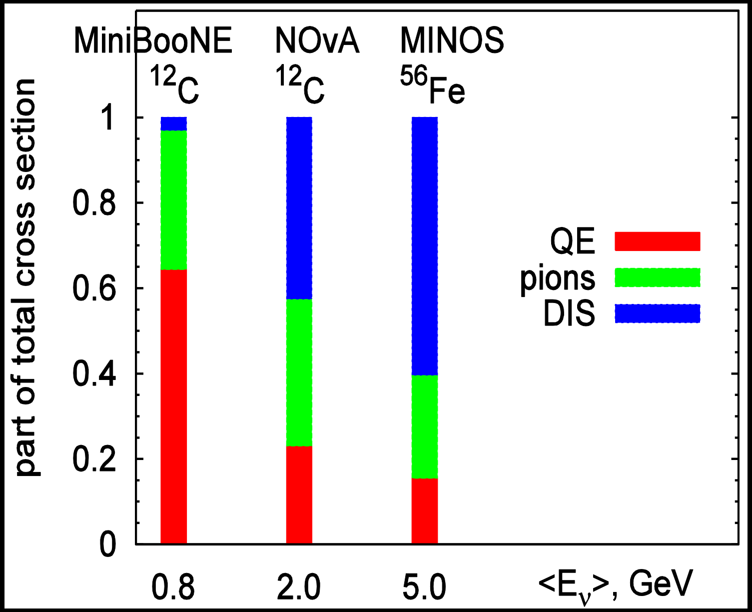
- Near detector:
  - Neutrino Flux
  - Background
  - Intrinsic ν_e
  - Neutrino energy
- Far detector:
  - Extrapolate Flux
  - Background
  - Neutrino energy

$$P\left(\nu_\mu \to \nu_e\right) = 1 - \sin^2 2\theta_{13} \sin^2\left(\frac{1.27\Delta m^2 L}{\boxed{E_\nu}}\right) + other$$

Neutrino Beams

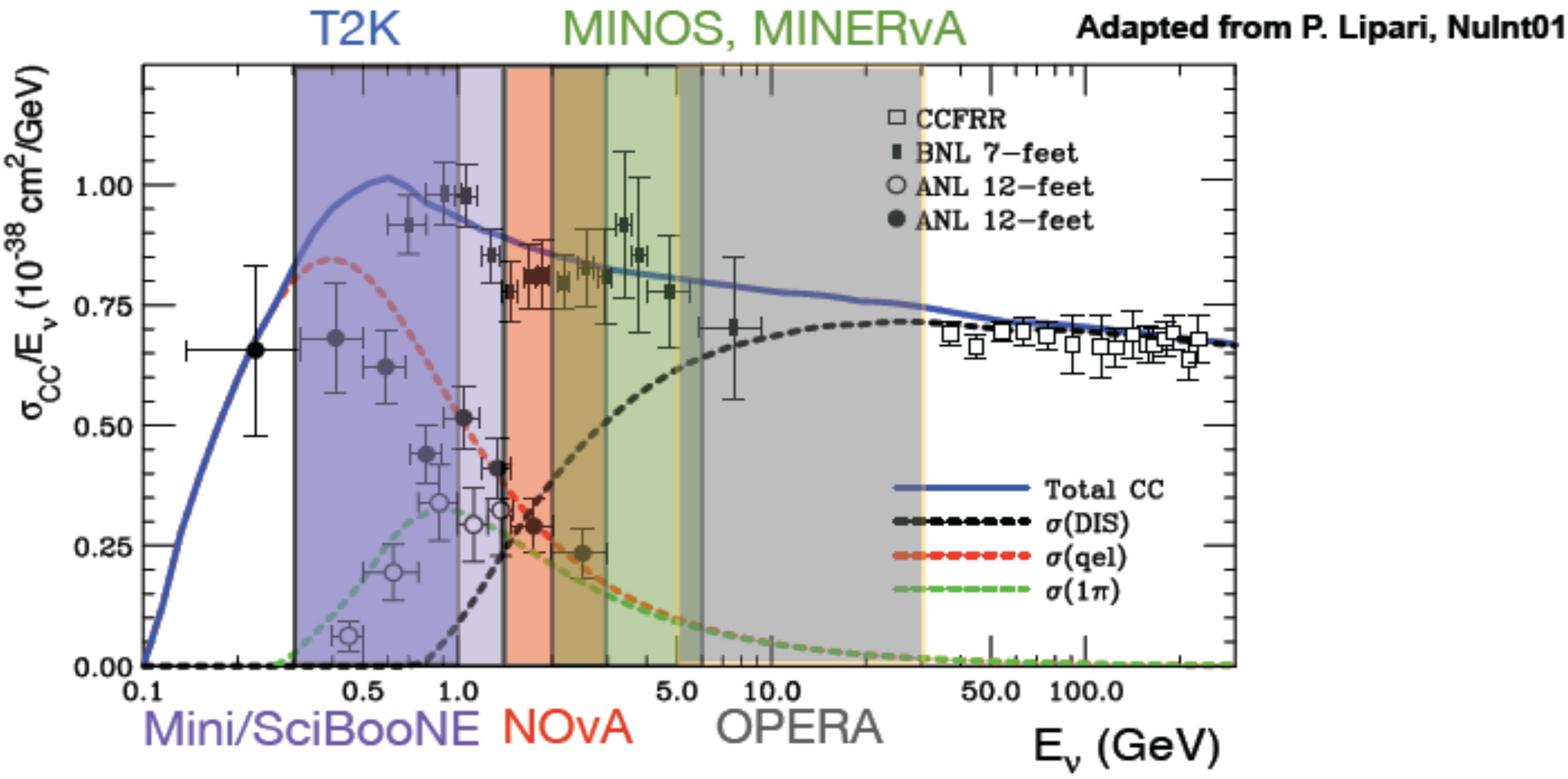
- Neutrinos do not have fixed energy nor just one reaction mechanism





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

Neutrino Cross-Sections

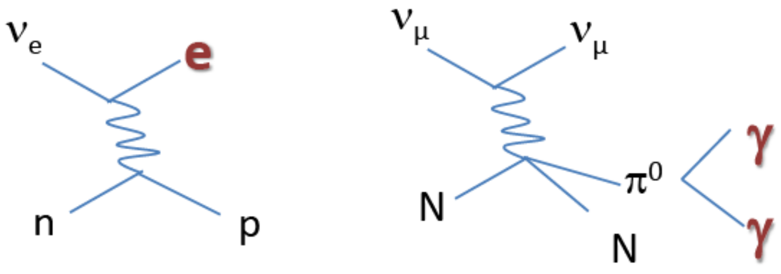


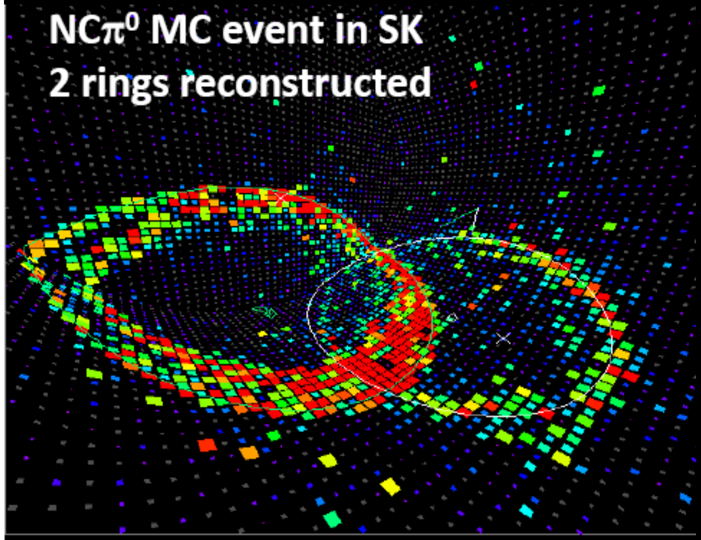
Upcoming experiments will continue to work in an “interesting” region:

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

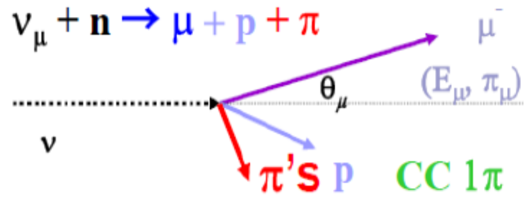
Neutrino Interactions

- for ν_e appearance
  - -beam ν_e
  - -NCπ^0 events

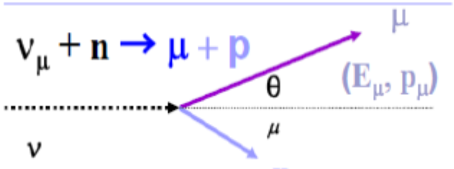



NCπ^0 MC event in SK
2 rings reconstructed

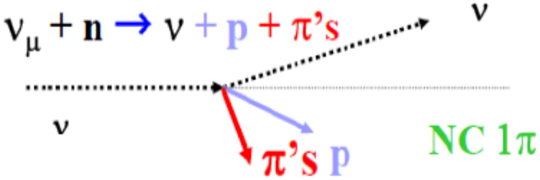
- for ν_μ disappearance (muon energy measurement)
  - -inelastic processes


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

CC 1π


$\nu_\mu + n \to \mu + p$

Quasi-Elastic process


$\nu_\mu + n \to \nu + p + \pi$'s

NC 1π

Energy reconstruction

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

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

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

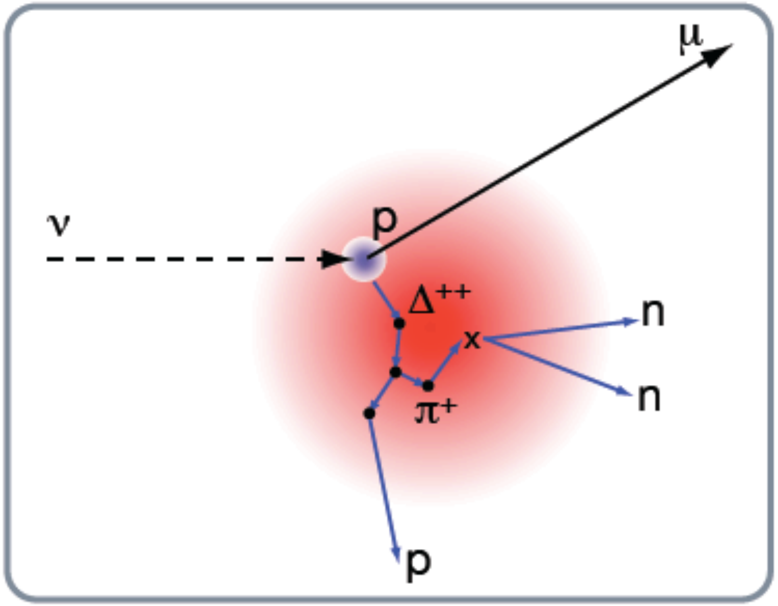
$$\nu_\mu + N \to \mu^- + X$$

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

Calorimetric

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

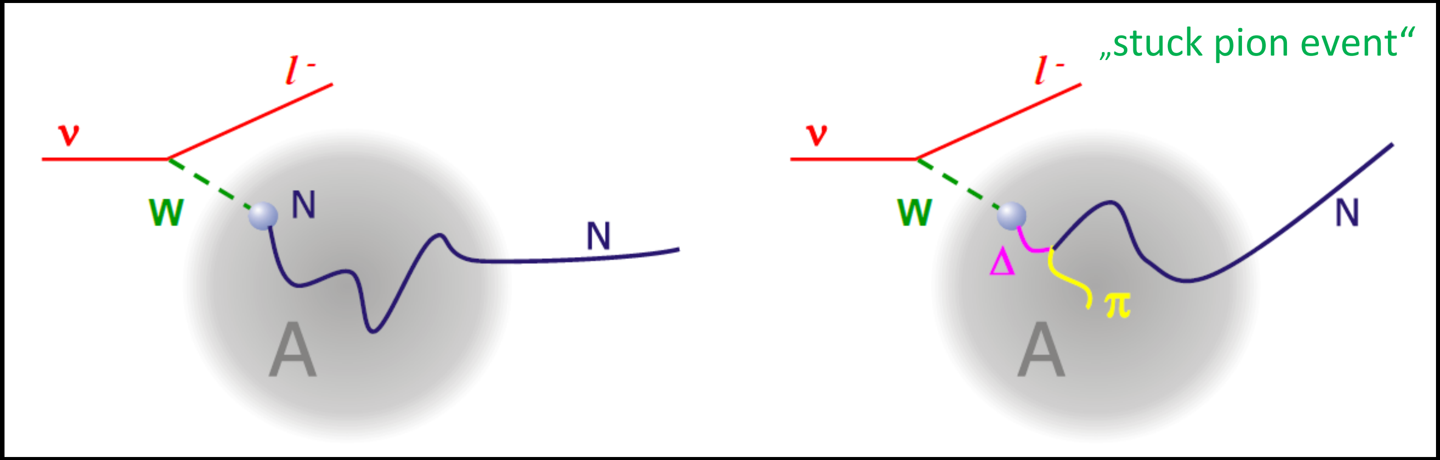
Background: Nuclear re-interactions



- 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

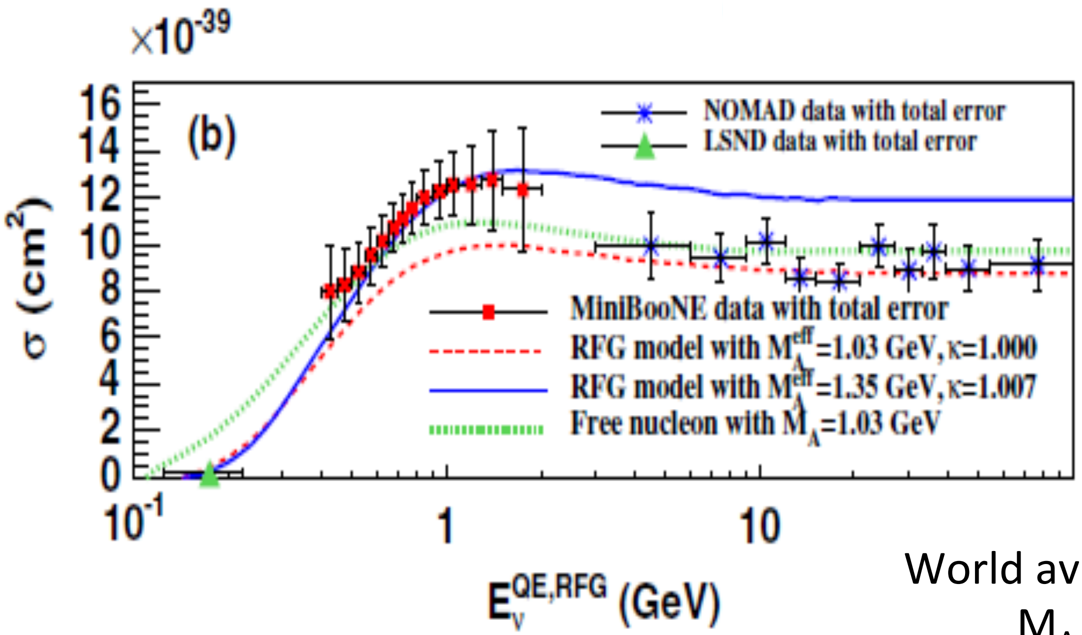
- Underlying ν-nucleon/quark interaction
  - Mode (CCQE, resonance, etc.)
  - Determine "final" state of interaction
- Initial state nucleon/quark
  - Fermi motion, binding energy
- Final state effects
  - Pauli blocking
  - Propagate hadrons within nucleus
    - Absorption, scattering, CEX, etc.

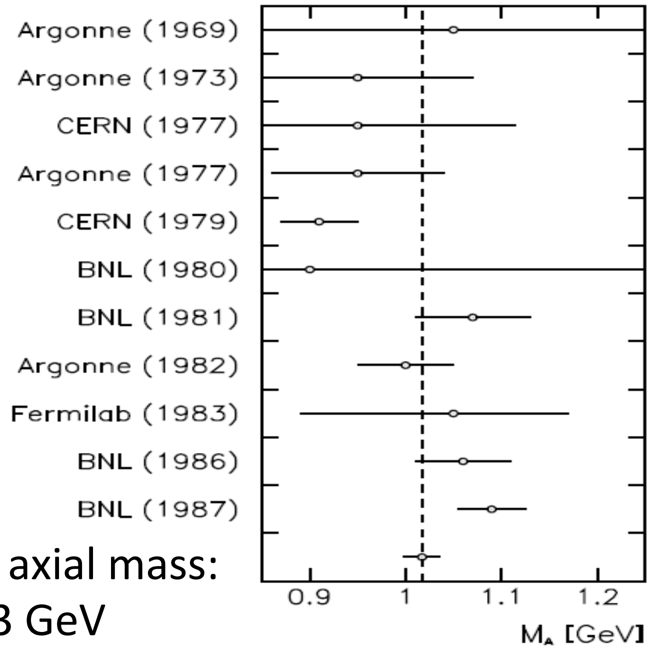


Complication to identify QE, entangled with π production

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 ?

New nuclear model in neutrino interaction generators

GENIE 2.8.0 + νT

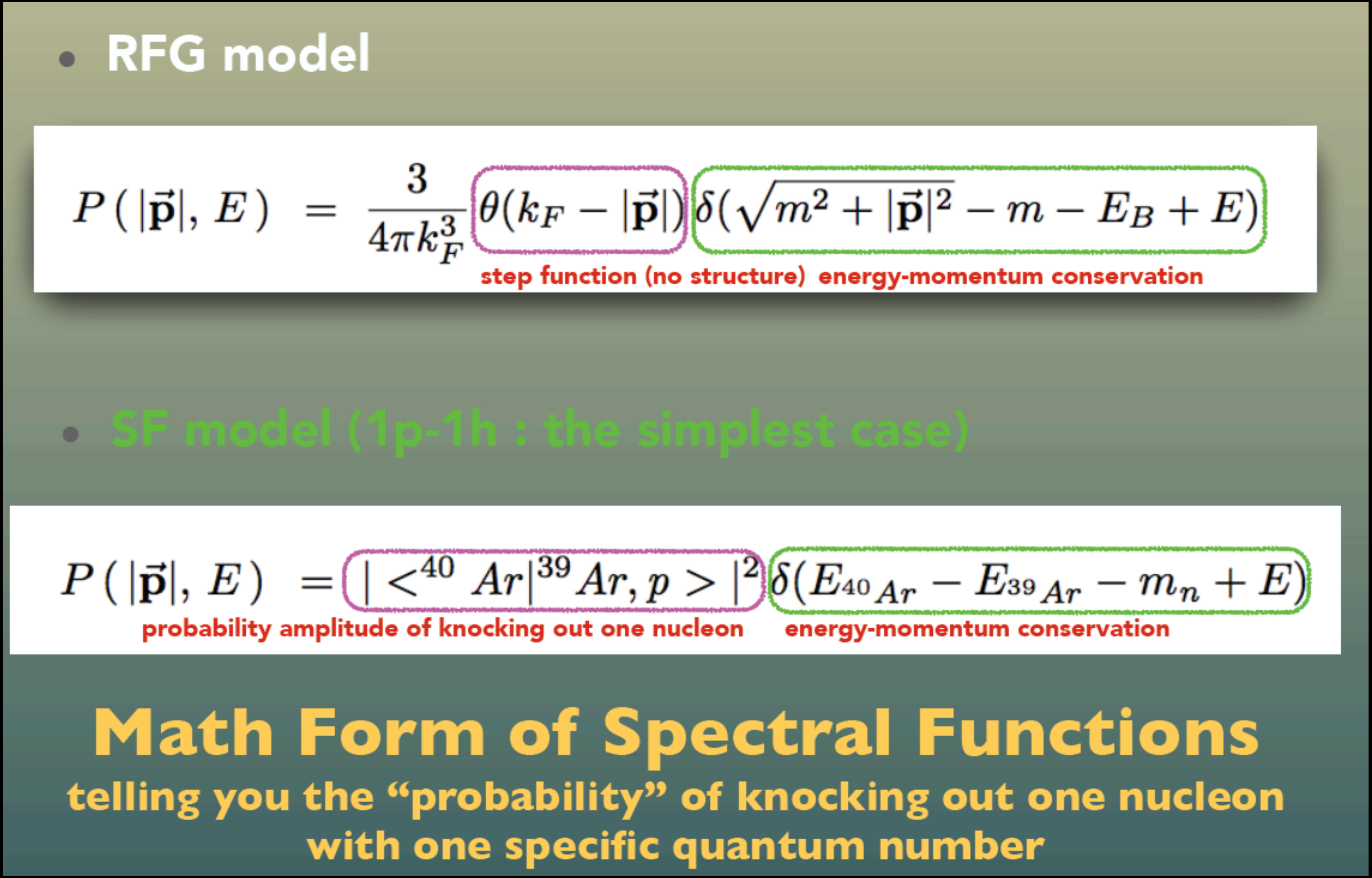
- Based on GENIE 2.8.0 plus few packages developed at VT with inputs from other experts: C. Jen, A. Ankowski, O.Benhar, L. Kalousis, CM

- Implementation of SF following nuclear theory recipe. Implemented for C, O, Ca and Ar.

- Very good comparison with electron scattering data, few examples in next slides.

- Corrected the Q^2 selection in GENIE 2.8.0, now the code conserve both energy and momentum.

Spectral function



- **RFG model**

$$P(|\vec{\mathbf{p}}|, E) = \frac{3}{4\pi k_F^3}\boxed{\theta(k_F - |\vec{\mathbf{p}}|)}\boxed{\delta(\sqrt{m^2 + |\vec{\mathbf{p}}|^2} - m - E_B + E)}$$

step function (no structure) **energy-momentum conservation**

- **SF model (1p-1h : the simplest case)**

$$P(|\vec{\mathbf{p}}|, E) = \boxed{|<^{40}Ar|^{39}Ar, p>|^2}\boxed{\delta(E_{^{40}Ar} - E_{^{39}Ar} - m_n + E)}$$

probability amplitude of knocking out one nucleon **energy-momentum conservation**

Math Form of Spectral Functions

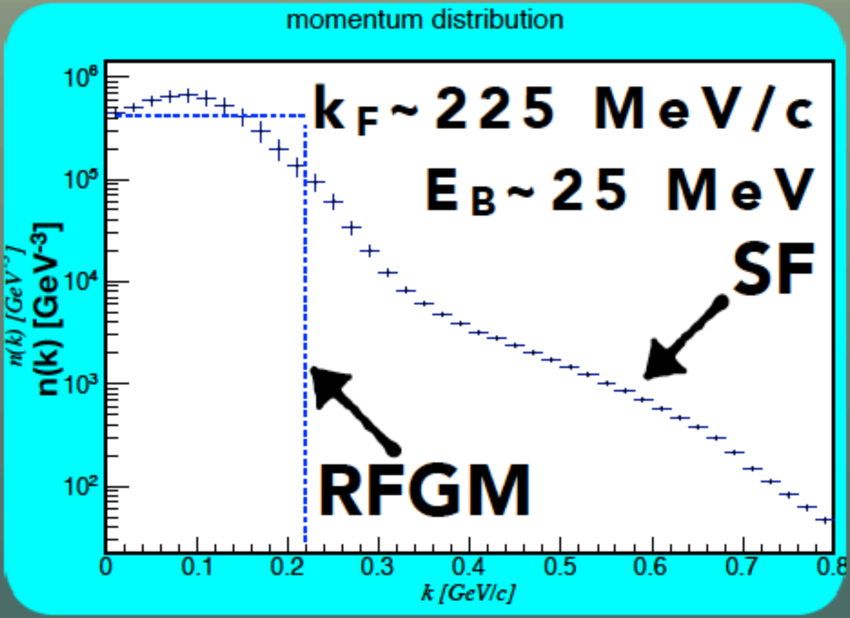
telling you the "probability" of knocking out one nucleon with one specific quantum number

Structure function from electron scattering data

- initial-state nucleon's momentum distribution, k_n, is assumed to be flat (no structure) for all shells below the Fermi sea (k_F)
- the spectral function theory considers the difference in the structure function for each shell and thus is capable of yielding a much better prediction while being compared to the measured electron cross-section than RFGM

$$n^D = \sigma_{(e,e'p)}/K\sigma_{cc1}$$

DWIA

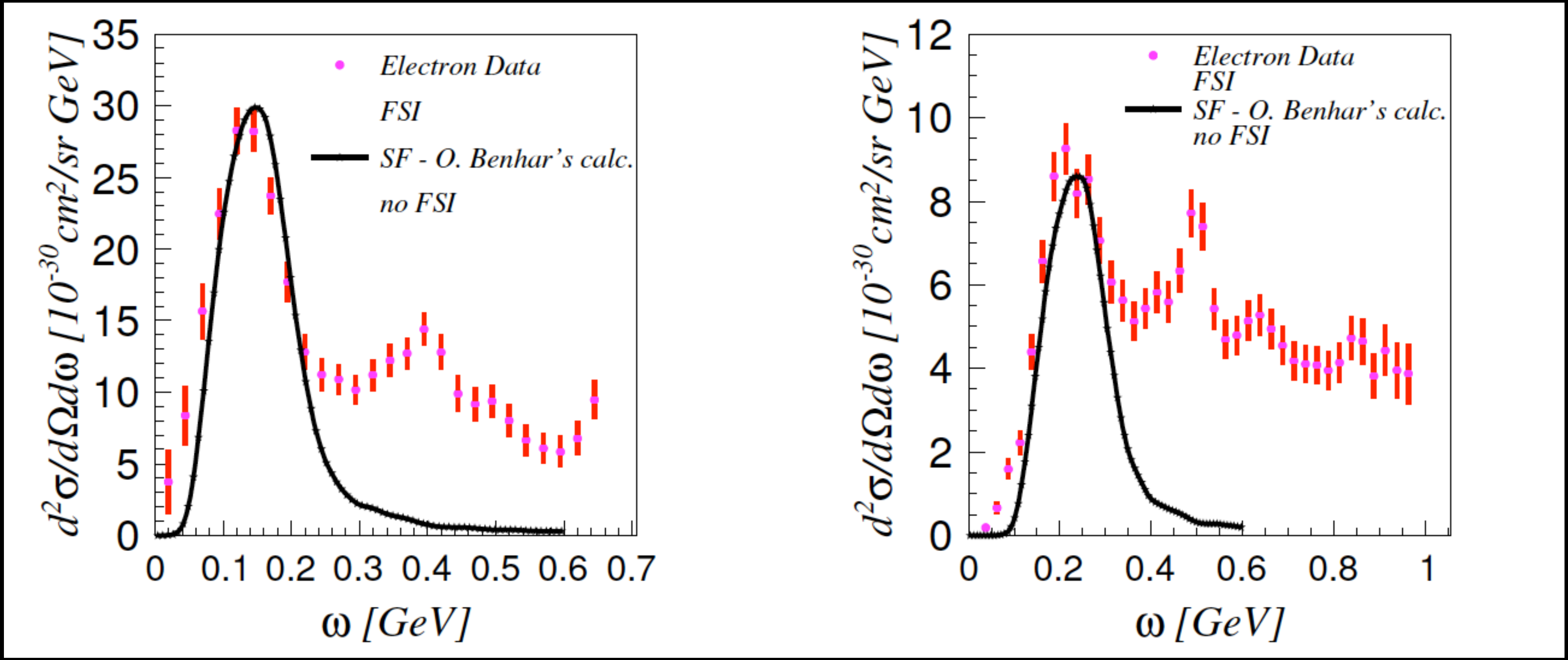


GENIE 2.8.0 + νT

$$e^- + {}^{16}_{8}O$$

E_e=0.88 GeV and θ_e=32 deg

E_e=1.2 GeV and θ_e=32 deg

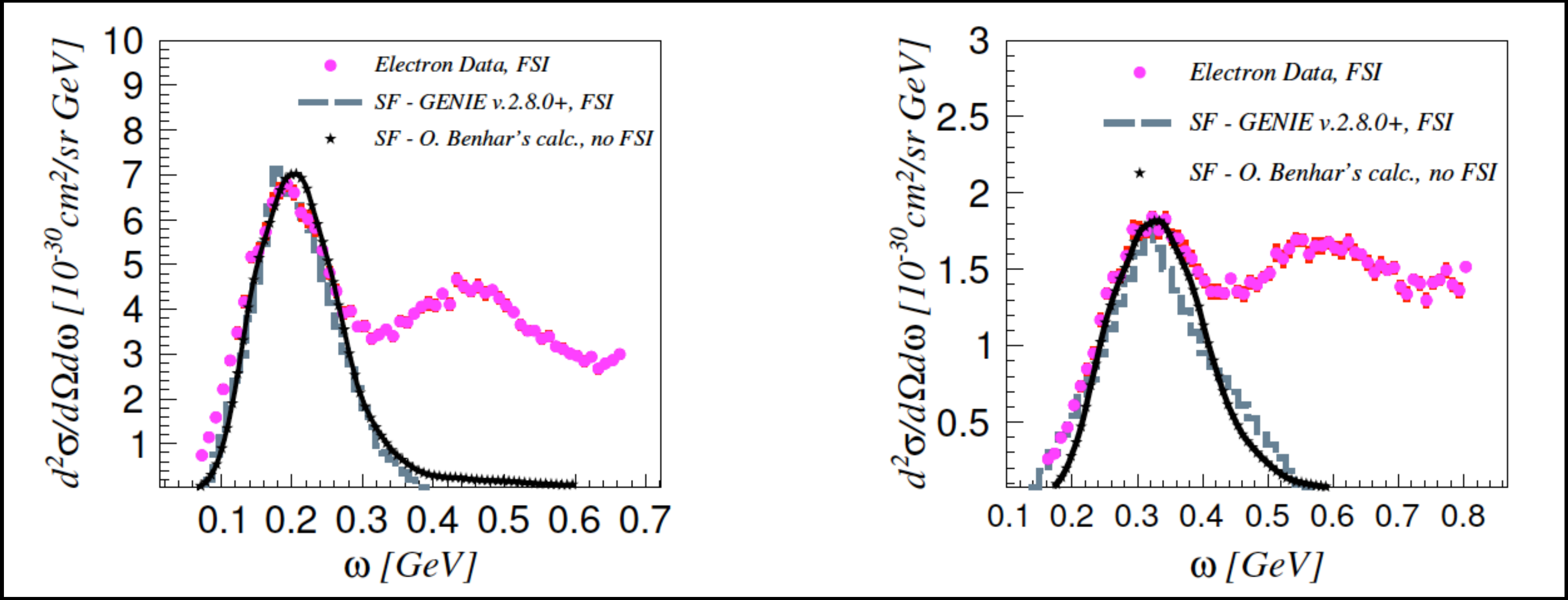


GENIE 2.8.0 + νT

$$e^- + {}^{12}_{6}C$$

E_e=0.961 GeV and θ_e=37.5 deg

E_e=1.299 GeV and θ_e=37.5 deg



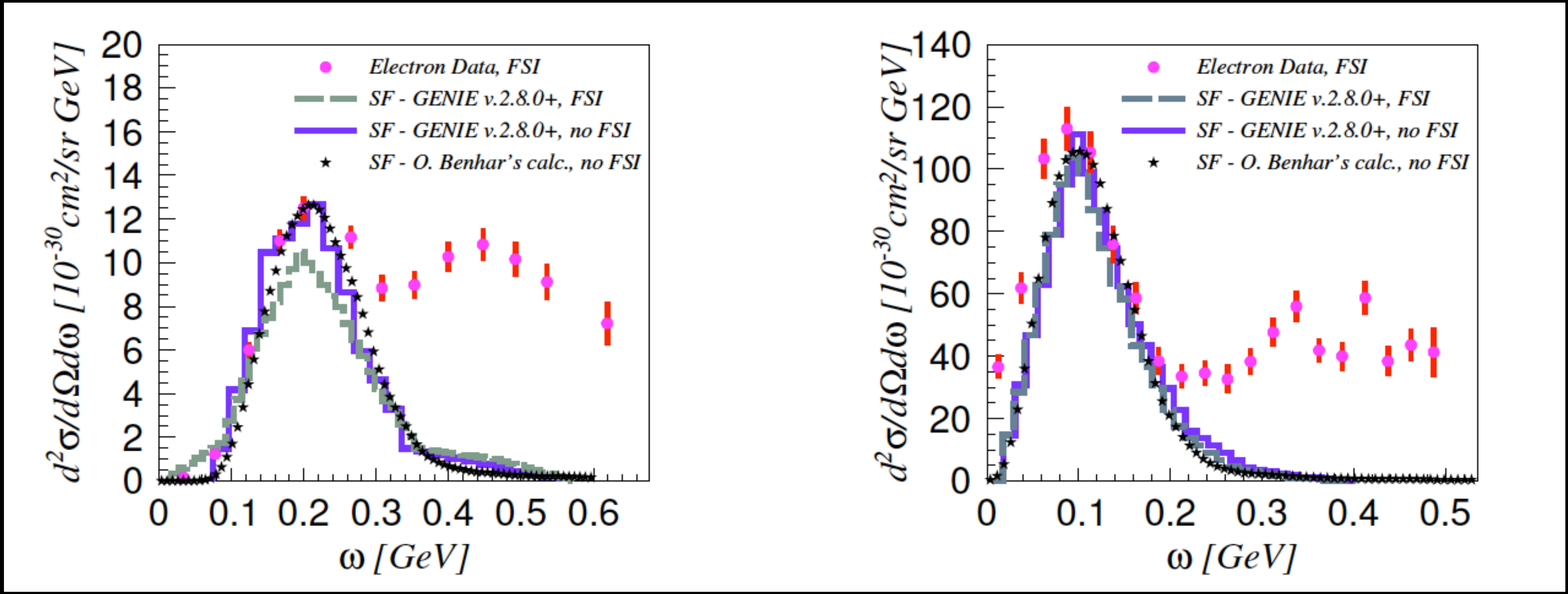
GENIE 2.8.0 + νT

$$e^- + {}^{40}_{20}Ca$$

E_e=0.841 GeV and θ_e=45.5 deg

$$e^- + {}^{40}_{22}Ar$$

E_e=0.7 GeV and θ_e=32 deg



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

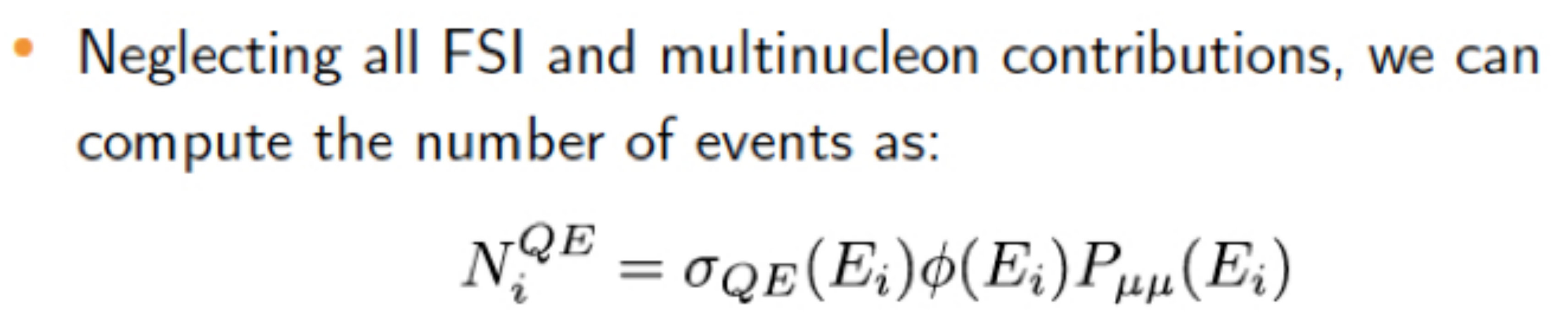
Oscillation analysis
and
Energy Reconstruction
in an ideal Long Baseline Experiment

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 (RFG and SF)
- 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), GENIE(2.8.0) and GENIE 2.8.0+νT
- Muon neutrino disappearance only -> fit to atmospheric parameters

Go beyond simple case (arxiv:1311.4506,1402.6651)

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



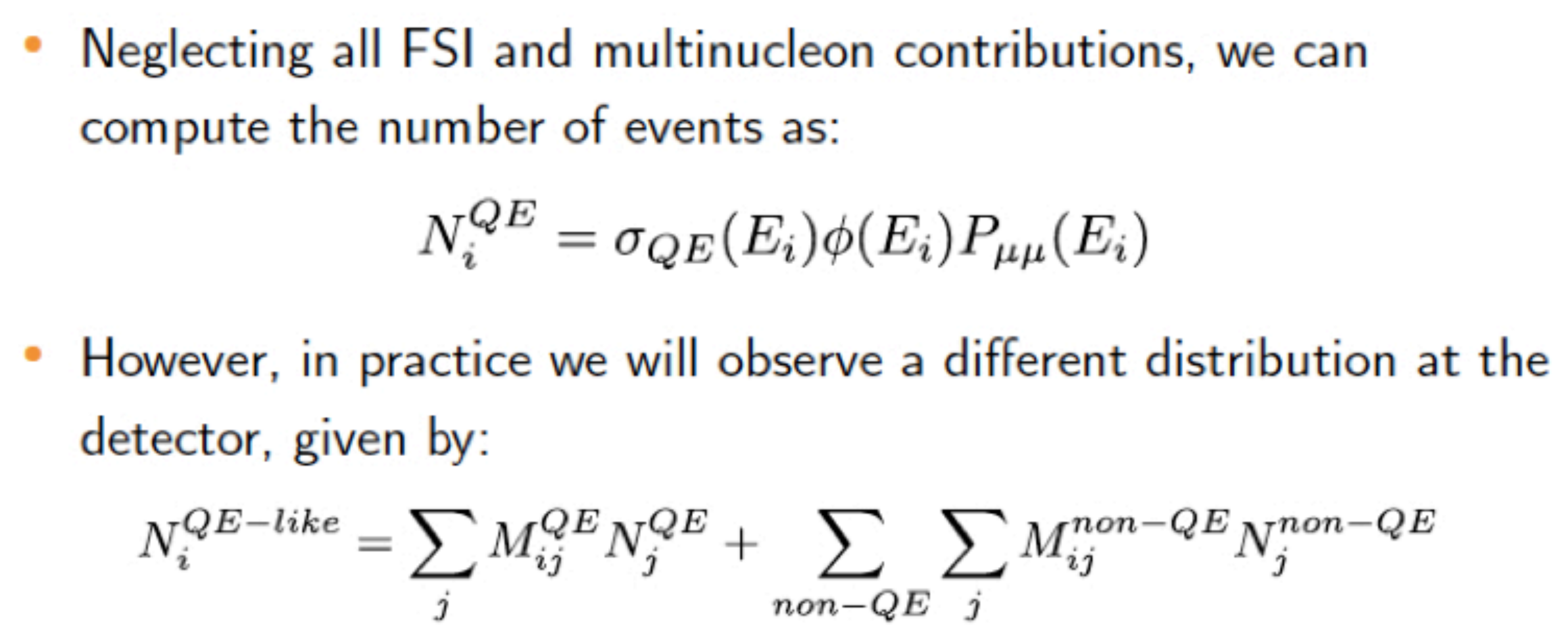
- Neglecting all FSI and multinucleon contributions, we can compute the number of events as:

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

$P_{\mu\mu}$ is the ν_μ oscillation probability - depends on neutrino energy (E_i)

ϕ is the neutrino flux - depends on neutrino energy (E_i)

σ is the cross section for QE event - depends on neutrino energy (E_i)



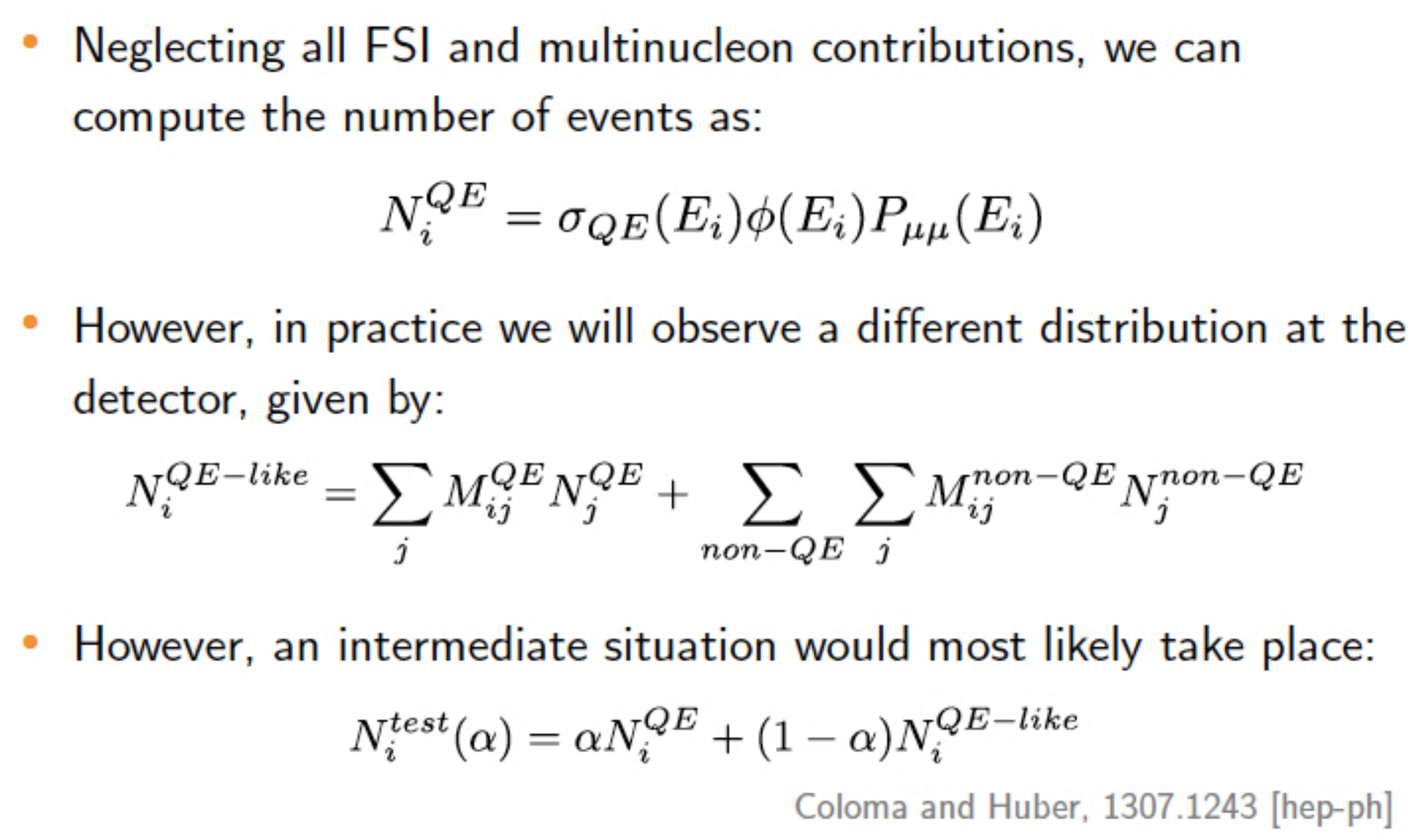
- Neglecting all FSI and multinucleon contributions, we can compute the number of events as:

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

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

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

Where M^{QE} is the migration matrix for the QE events. Matrix is mostly diagonal and therefore just adds some smearing over the event sample



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- 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]

Nuclear effect factor

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

α determine the amount of nuclear effect included:

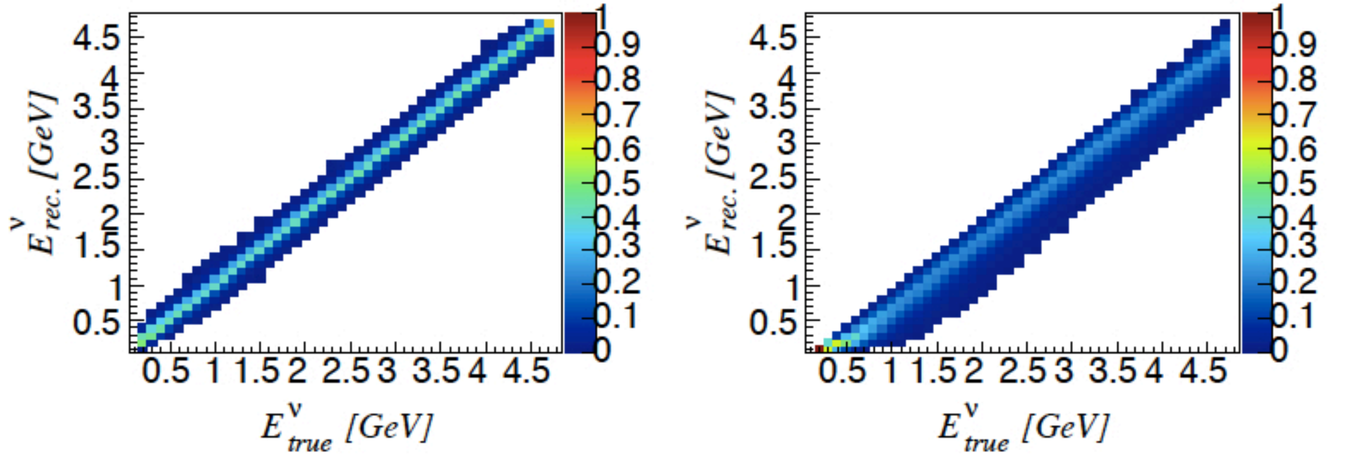
- α=0 no nuclear effect or nuclear effect perfectly known in the fit
- α=1 maximum nuclear effect or nuclear effect not known in the fit

Energy shift

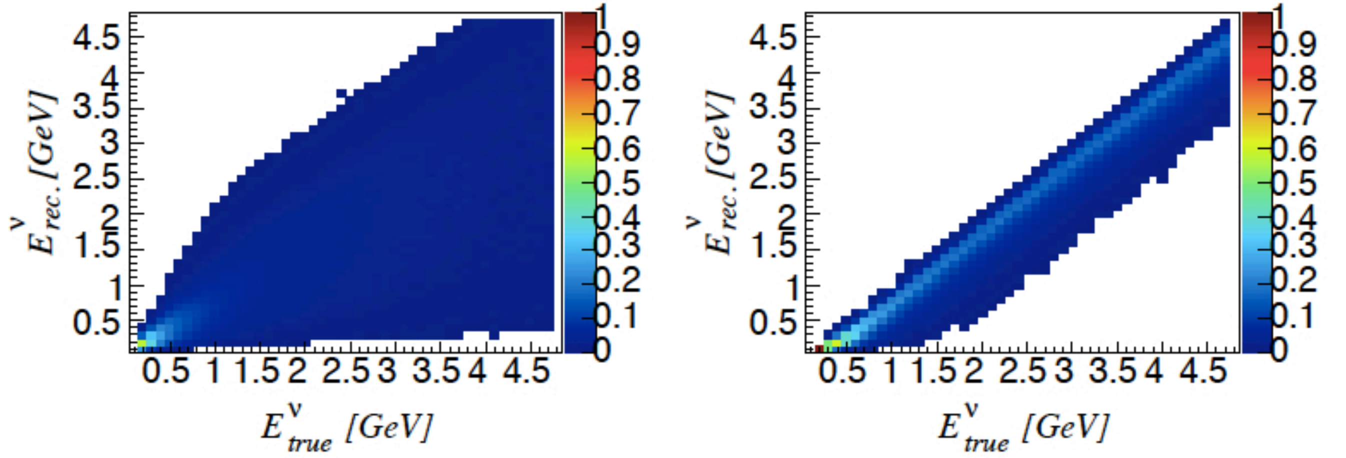
$$N[E] \rightarrow N[(1+a)\,E]$$

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.

Migration matrices: GiBUU (^{16}O)

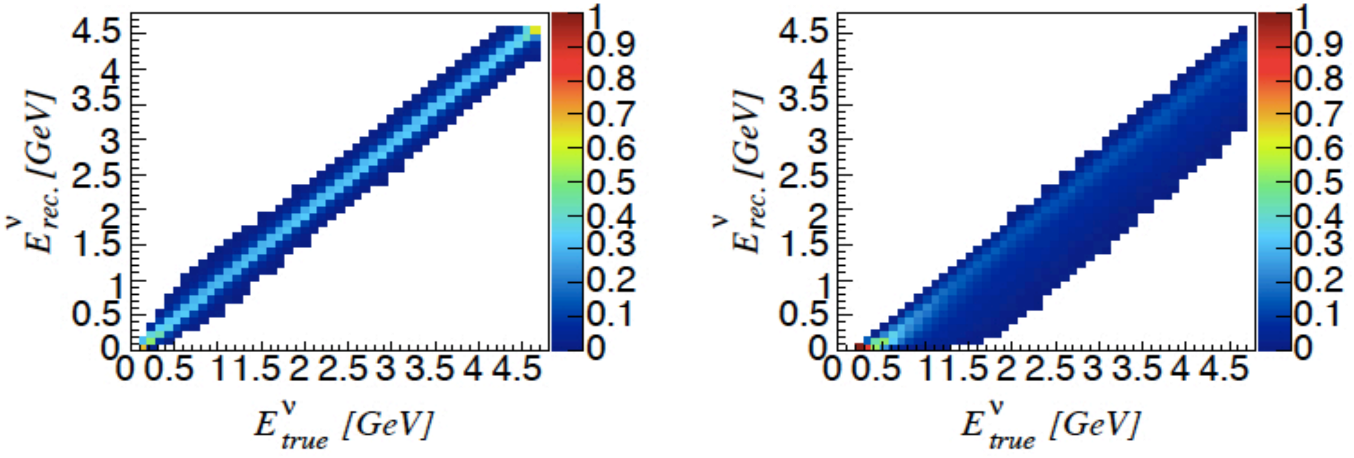


(a) Matrix for QE events (b) Matrix for RES events

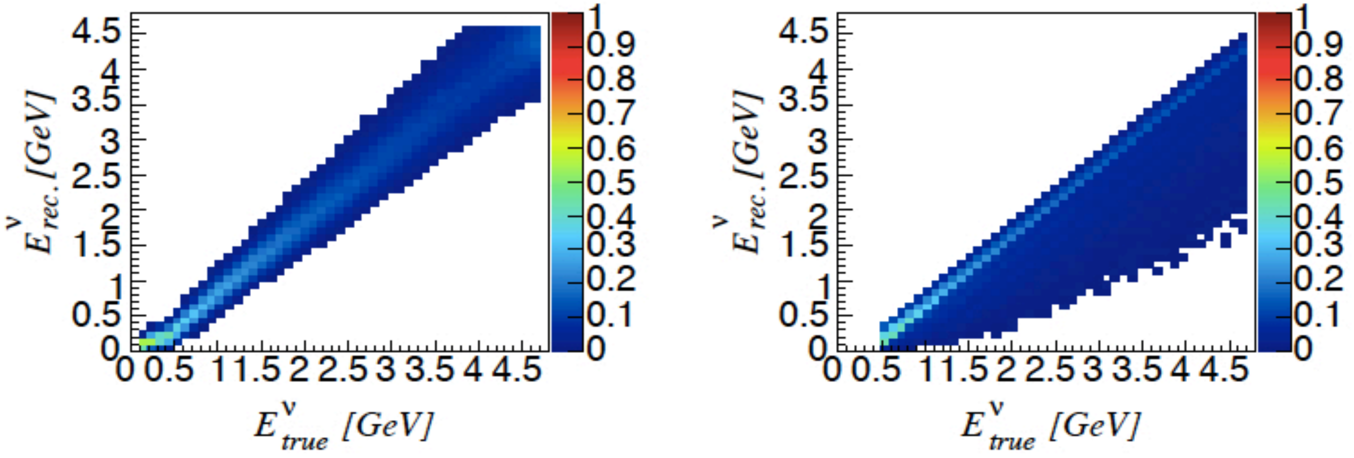


(c) Matrix for MEC/2p2h events (d) Matrix for COH events

Migration matrices: GENIE (^{16}O)

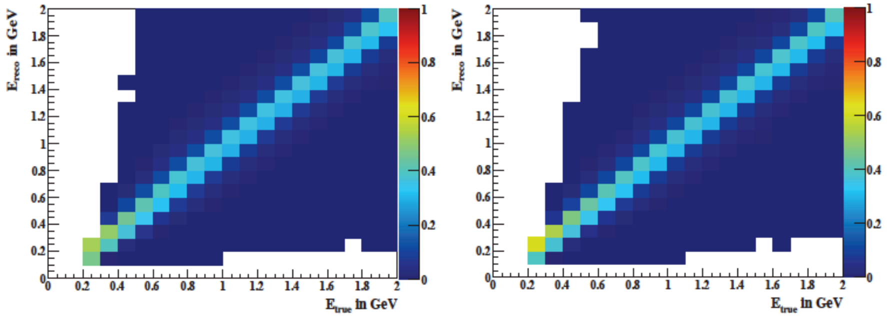


(a) Matrix for QE events (b) Matrix for RES events



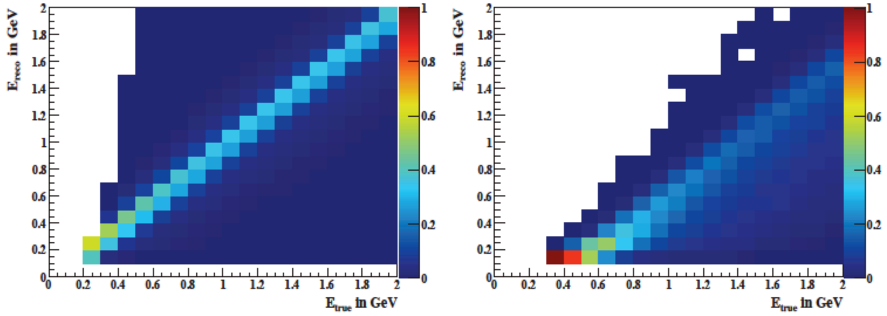
(c) Matrix for MEC/2p2h events (d) Matrix for COH events

Migration matrices: GENIE+νT (^{12}C)



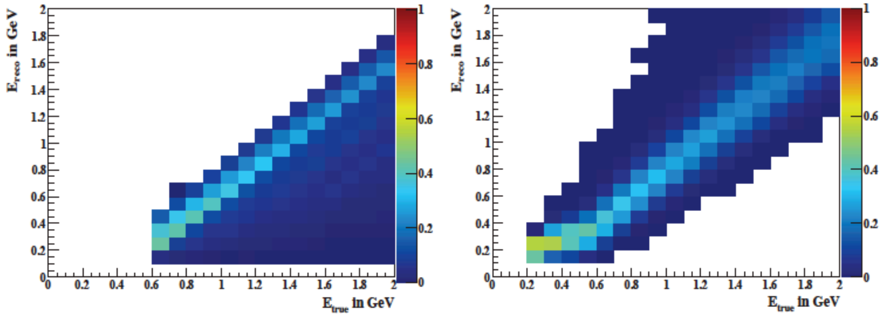
(a) QE-RFGM, GENIE 2.8.0

(b) QE-RFGM, GENIE 2.8.0+



(c) QE-SF model, GENIE 2.8.0+

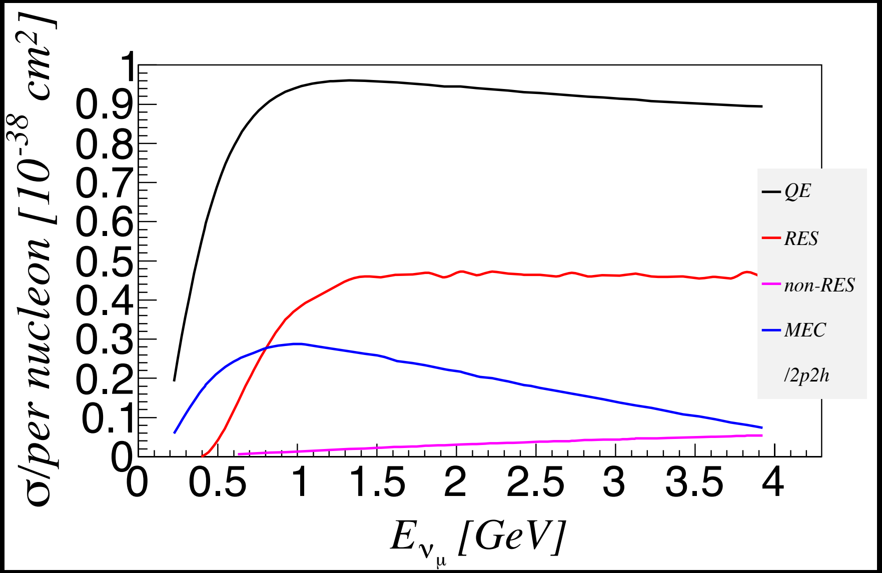
(d) Resonant production



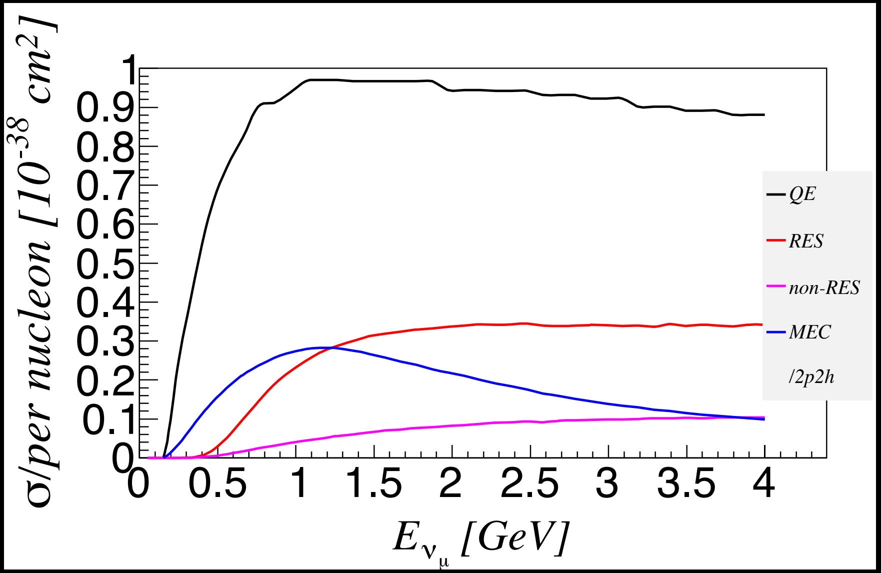
(e) Non-resonant production

(f) MEC/2p2h interactions

Cross-sections

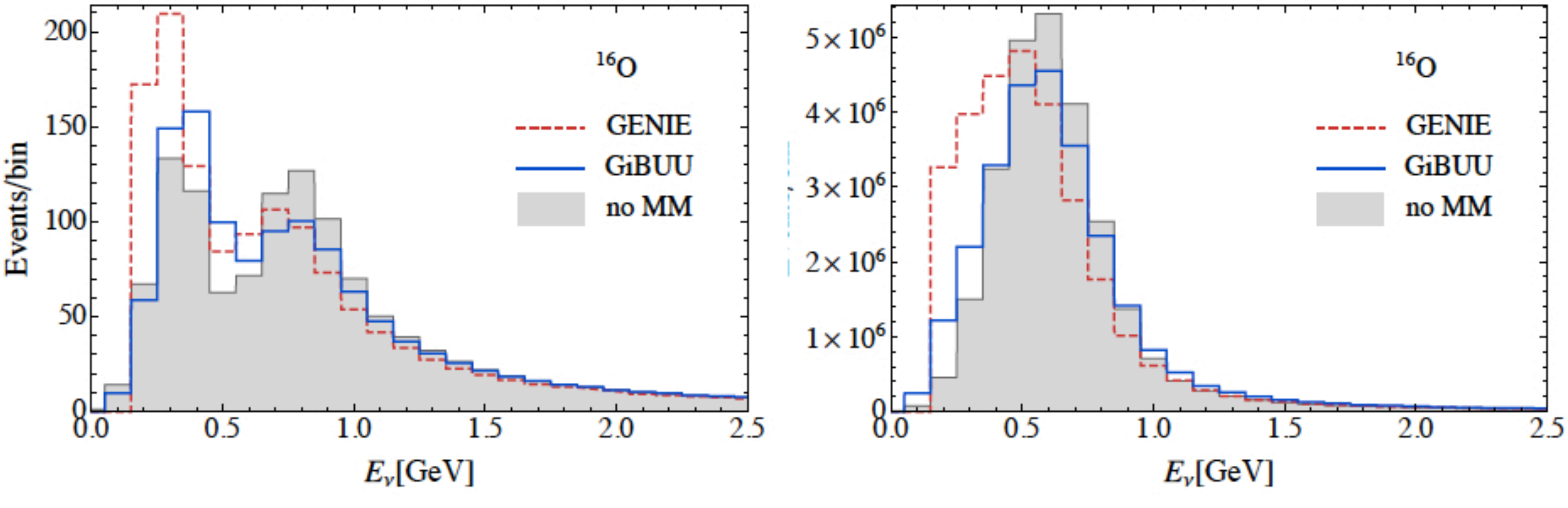


Genie 2.8.0



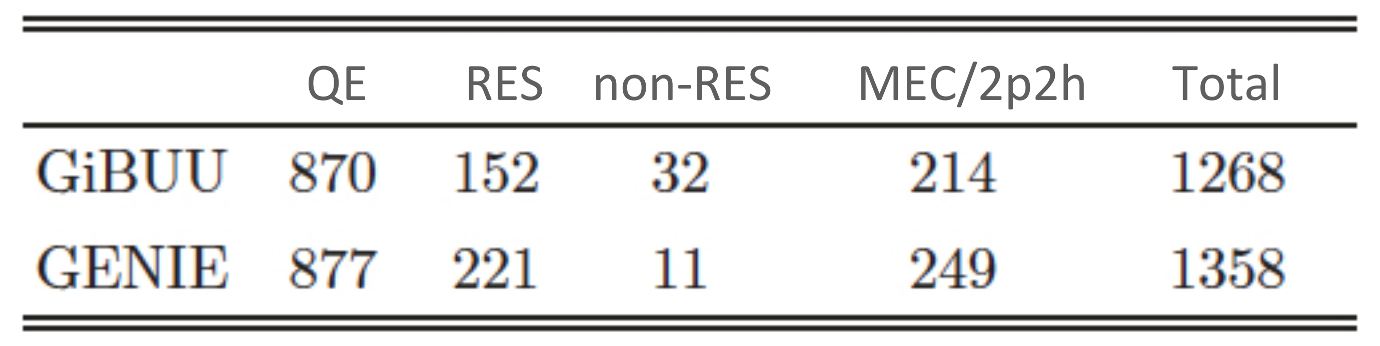
GiBUU 1.6

Event distributions

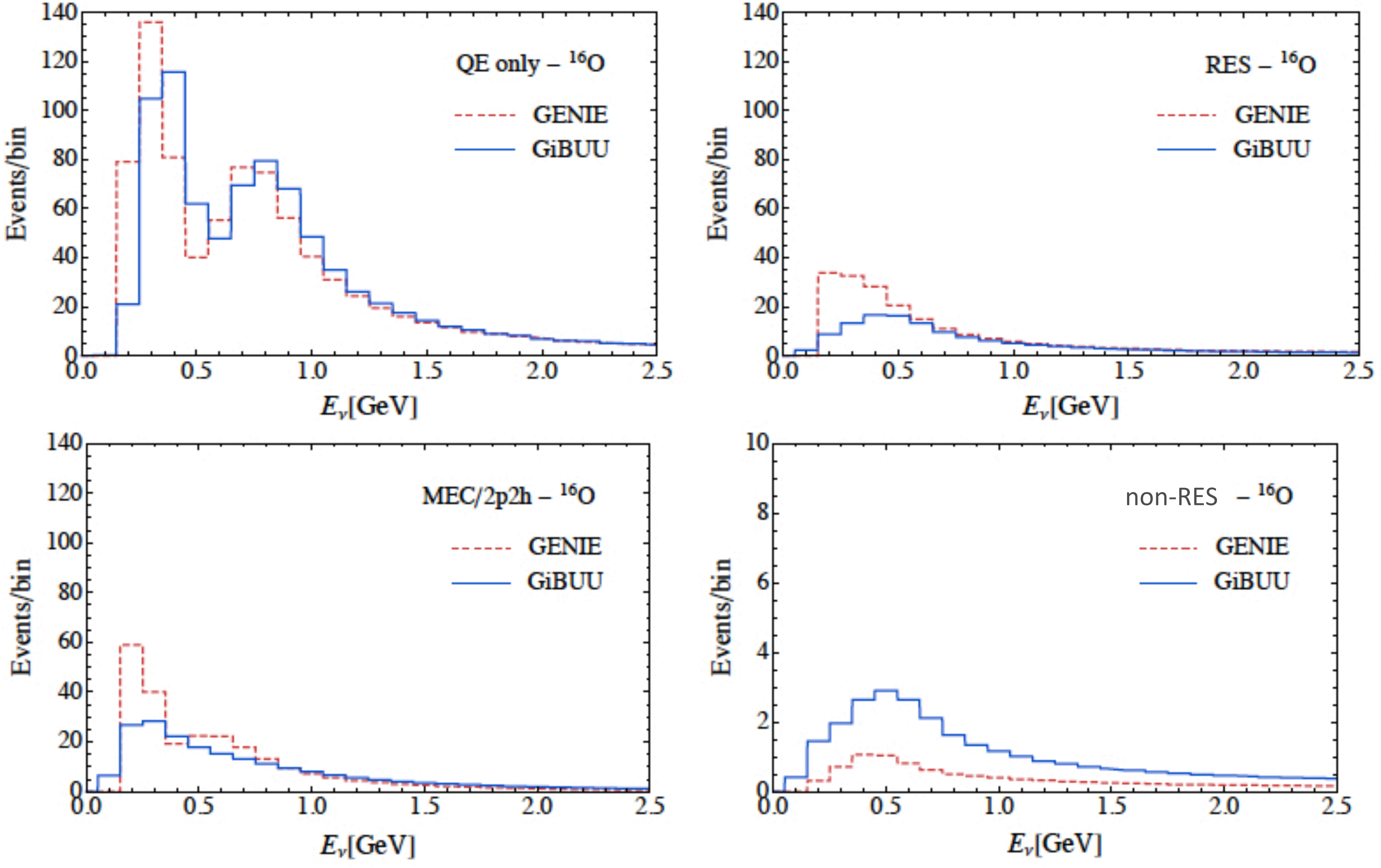


(a) Expected events at the far detector

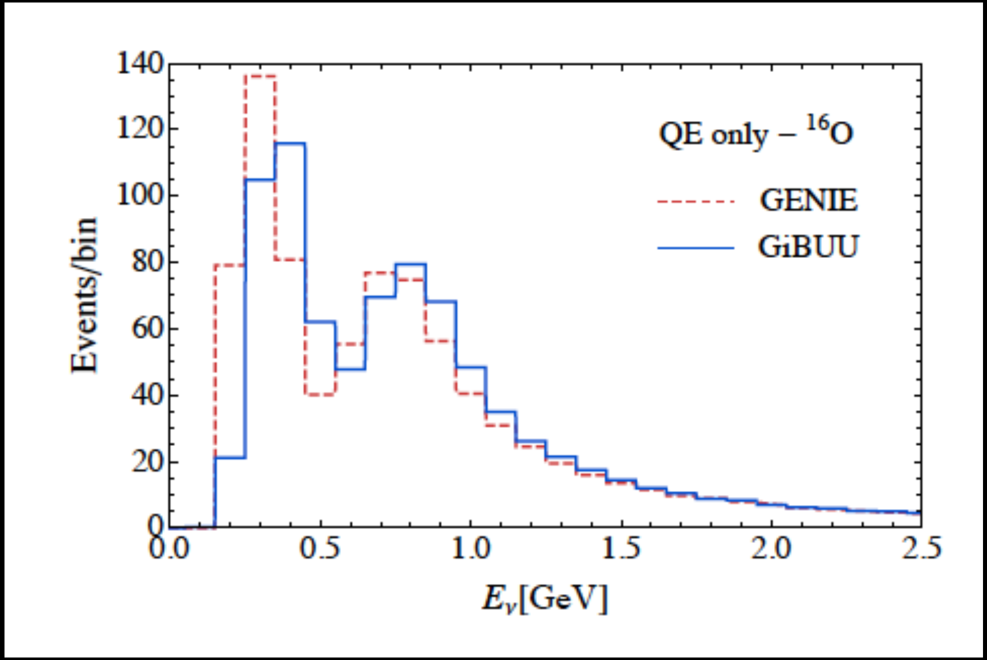
(b) Expected events at the near detector



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


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

A surprise …

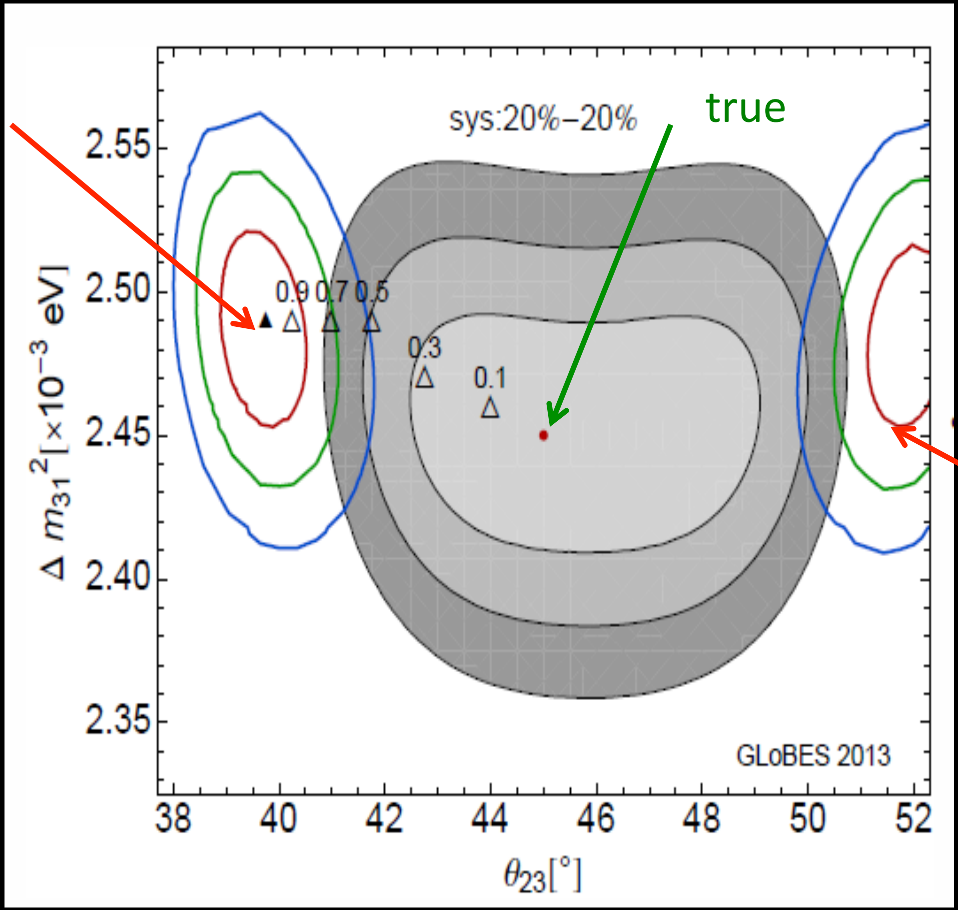


Number of events predicted as function of reconstructed neutrino energy shifted by 10% for pure QE and 17% for all the QE-like events

- 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

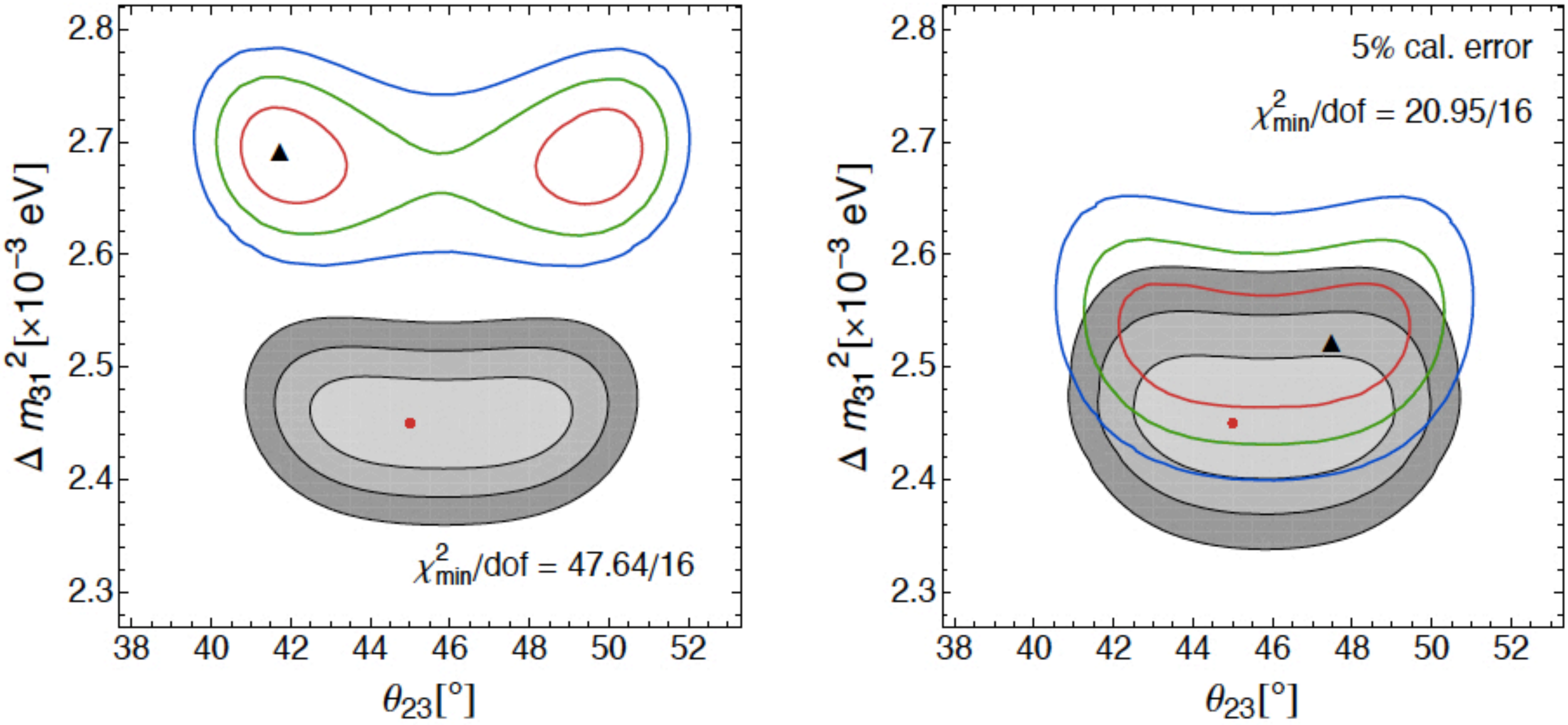


P. Coloma, P. Huber,
arXiv:1307.1243, July 2013

Analysis based on GiBUU

1, 2 and 3σ allowed regions

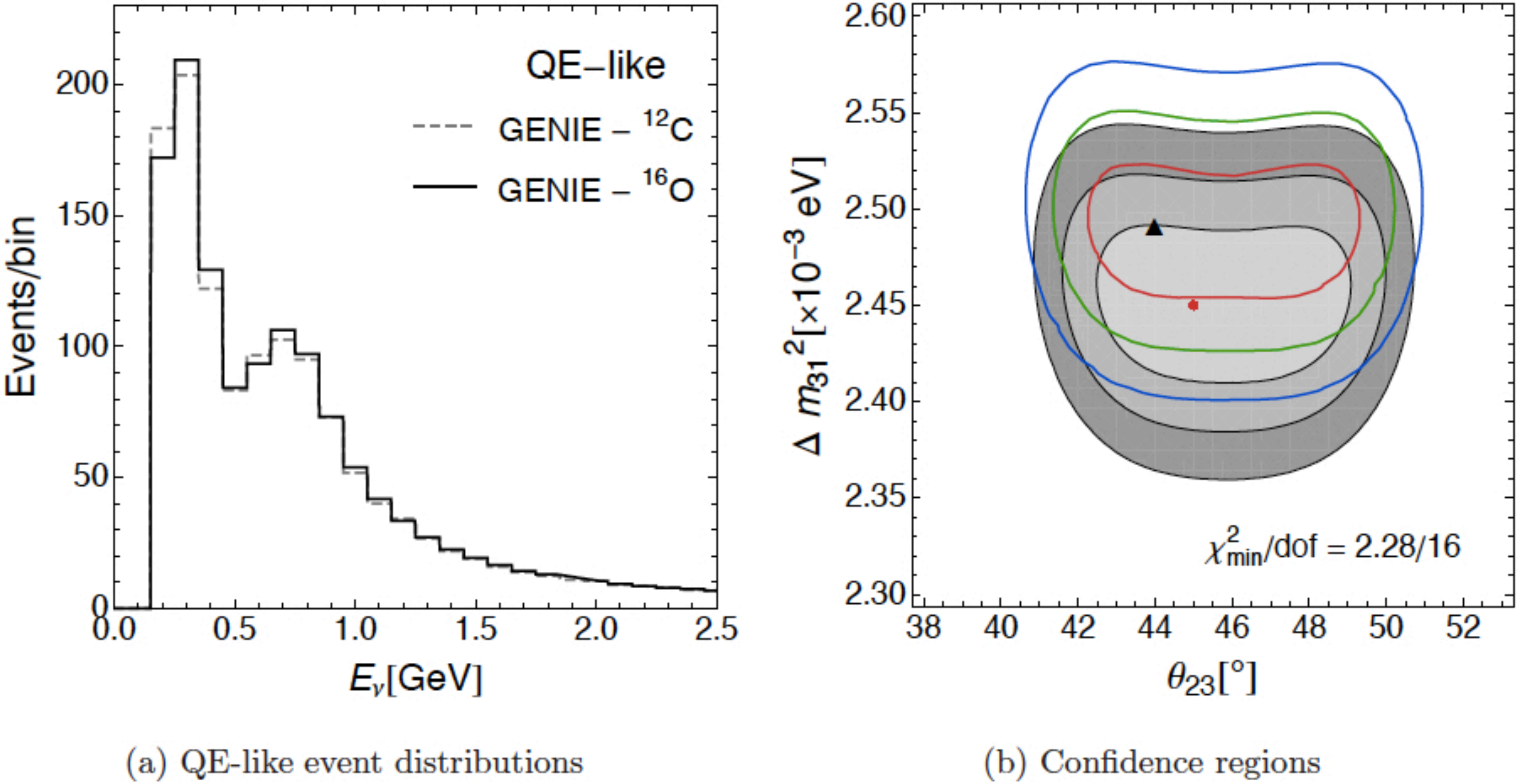
Simulating with GiBUU and extracting oscillations with GENIE 2.8.0: with and without calibration error



(a) No calibration error

(b) 5% calibration error

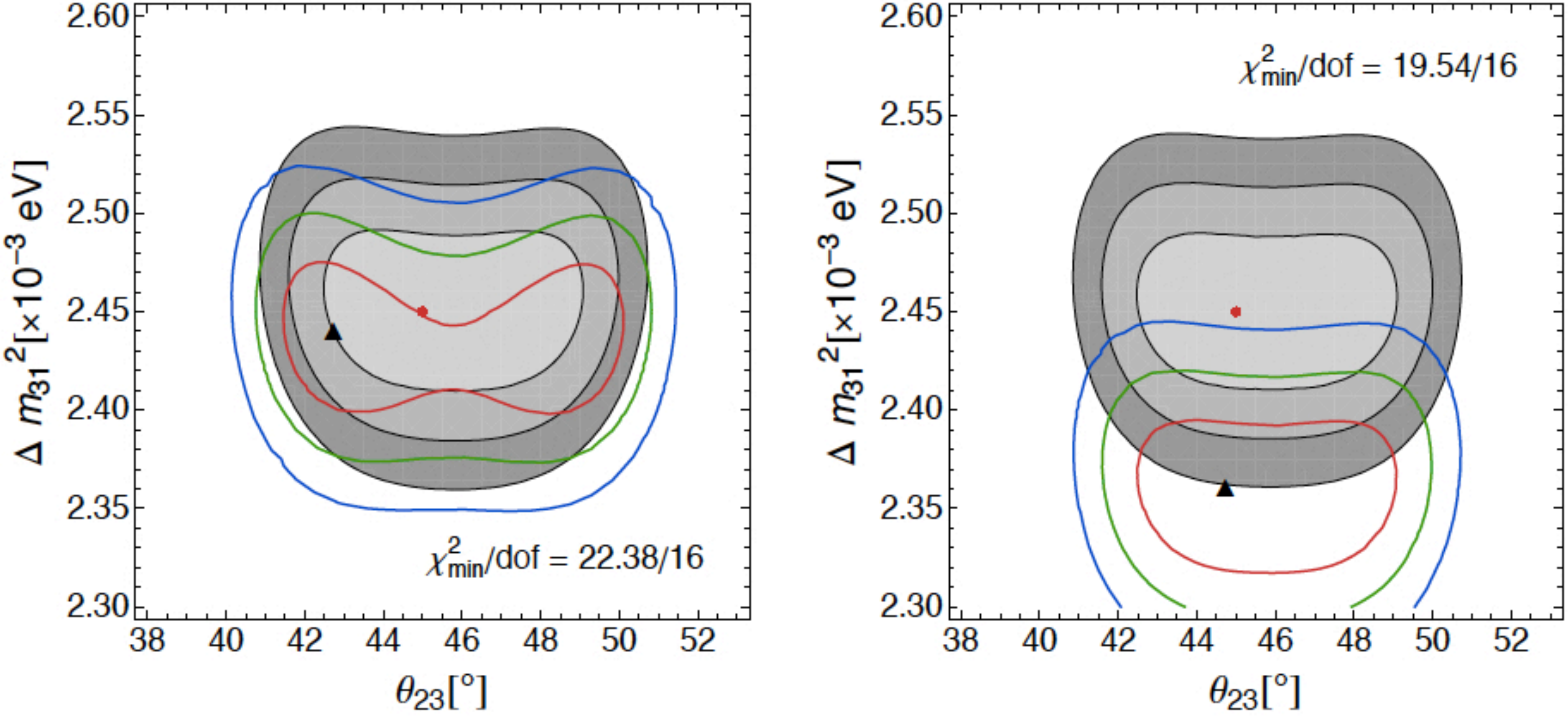
Carbon vs Oxygen



(a) QE-like event distributions

(b) Confidence regions

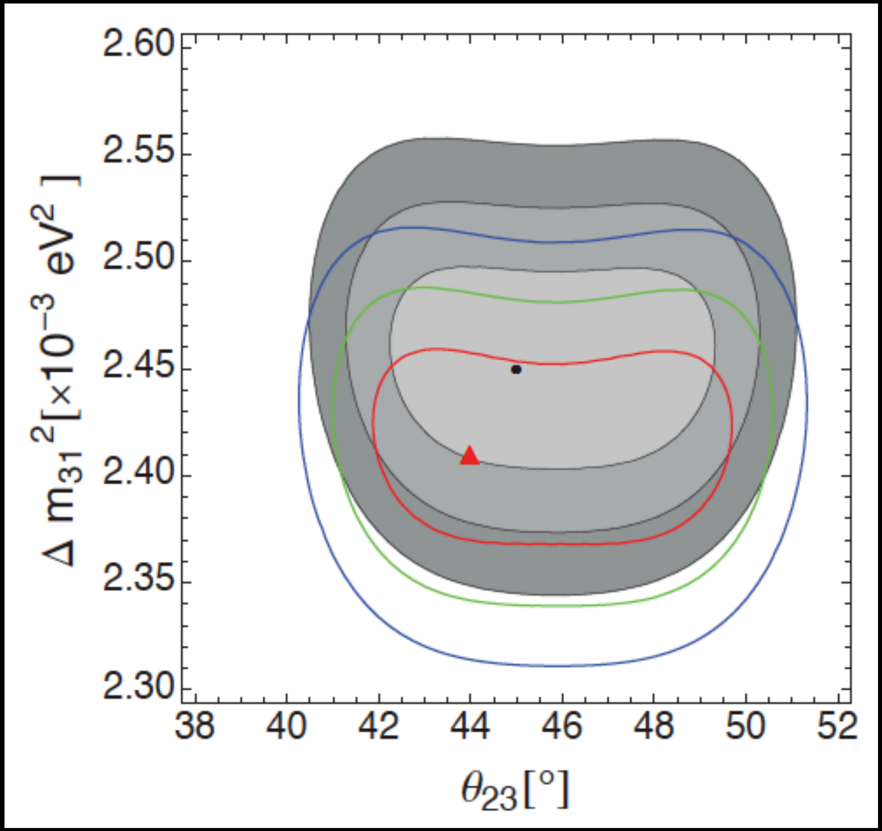
With and without MEC/2p2h

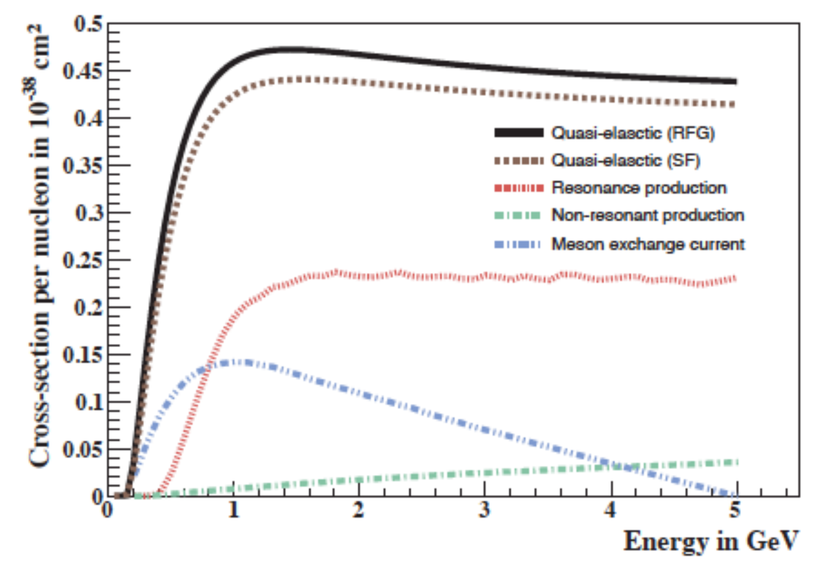


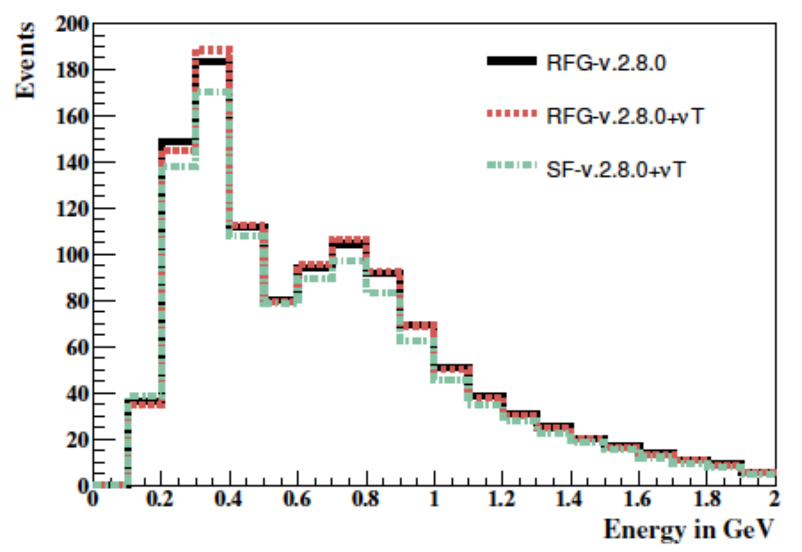
(a) Results using GiBUU matrices

(b) Results using GENIE matrices

RFG vs SF

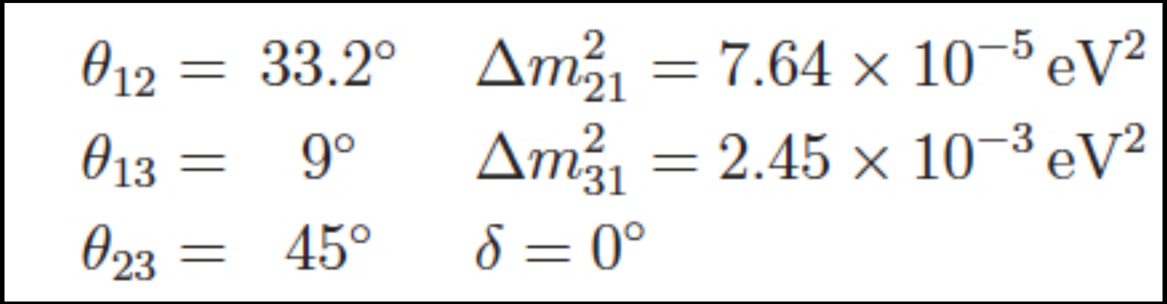

2.60
2.55
2.50
2.45
2.40
2.35
2.30
38
40
42
44
46
48
50
52
$\Delta m_{31}^2[\times10^{-3}\ \mathrm{eV}^2]$
$\theta_{23}[°]$


Cross-section per nucleon in 10^{-38} cm^2
0.5
0.45
0.4
0.35
0.3
0.25
0.2
0.15
0.1
0.05
0
1
2
3
4
5
Energy in GeV
Quasi-elasctic (RFG)
Quasi-elasctic (SF)
Resonance production
Non-resonant production
Meson exchange current


Events
200
180
160
140
120
100
80
60
40
20
0
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
1.8
2
Energy in GeV
RFG-v.2.8.0
RFG-v.2.8.0+νT
SF-v.2.8.0+νT

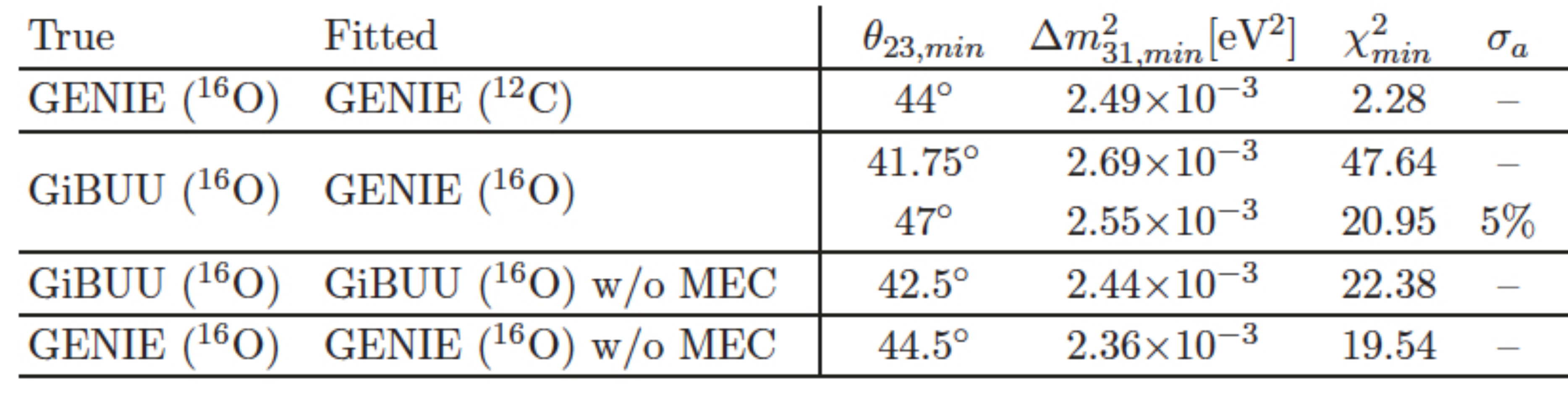
Summary of results

Input “true” Values



$$\theta_{12} = 33.2^\circ \quad \Delta m^2_{21} = 7.64 \times 10^{-5}\,\mathrm{eV}^2$$
$$\theta_{13} = 9^\circ \quad \Delta m^2_{31} = 2.45 \times 10^{-3}\,\mathrm{eV}^2$$
$$\theta_{23} = 45^\circ \quad \delta = 0^\circ$$

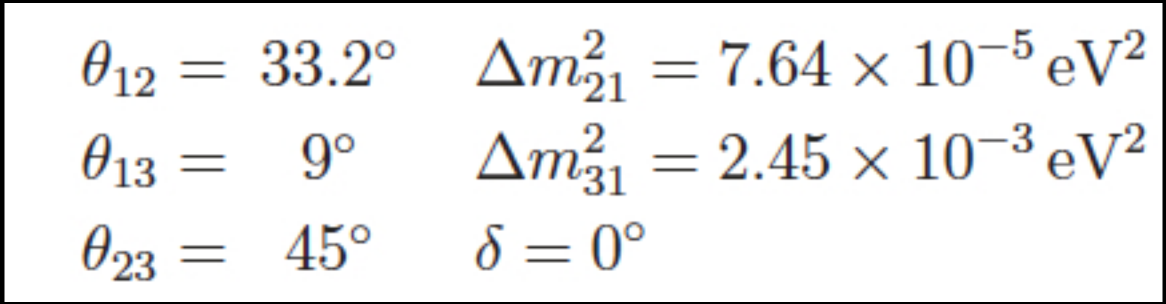
Fitted Values



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	–

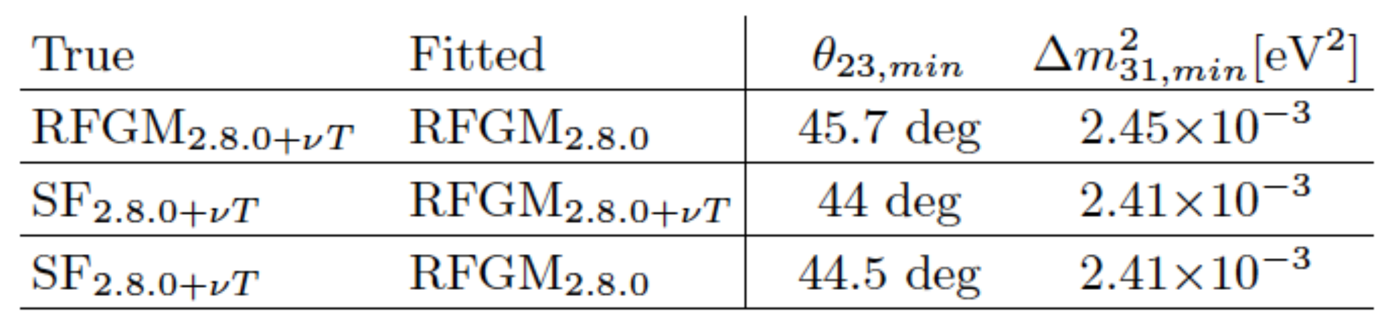
Summary of results cont'd

Input "true" Values



$$\theta_{12} = 33.2^\circ \quad \Delta m^2_{21} = 7.64 \times 10^{-5}\,\mathrm{eV}^2$$
$$\theta_{13} = 9^\circ \quad \Delta m^2_{31} = 2.45 \times 10^{-3}\,\mathrm{eV}^2$$
$$\theta_{23} = 45^\circ \quad \delta = 0^\circ$$

Fitted Values



True	Fitted	$\theta_{23,min}$	$\Delta m^2_{31,min}[\mathrm{eV}^2]$
$\mathrm{RFGM}_{2.8.0+\nu T}$	$\mathrm{RFGM}_{2.8.0}$	45.7 deg	2.45×10^{-3}
$\mathrm{SF}_{2.8.0+\nu T}$	$\mathrm{RFGM}_{2.8.0+\nu T}$	44 deg	2.41×10^{-3}
$\mathrm{SF}_{2.8.0+\nu T}$	$\mathrm{RFGM}_{2.8.0}$	44.5 deg	2.41×10^{-3}

Conclusions

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

- Impact on neutrino oscillation 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

Thank You !