Impact of nuclear effect and interaction models on neutrino oscillation analysis

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Motivation and Contents

- Neutrino oscillation: state of the art
- CP violation – require precision, systematic error ~1% level
  - new detector technology
  - high intensity beam makes a lot of neutrinos
  - new problems to tackle - cross section and nuclear model uncertainties
- Accelerator Experiments:
  - Method
  - Event rates
  - Non-simple target material (carbon, argon) -> nuclear effects & ν-N cross sections
  - Neutrino energy reconstruction: a known problem
- Summary and future prospects

ν_e, ν_μ, and ν_τ ***are not the neutrino mass eigenstates*** but ***superpositions*** of the mass eigenstates:

$$|\nu_\alpha\rangle = \sum_i U^*_{\alpha i}\,|\nu_i\rangle \quad .$$

Neutrino of flavor α = e, μ, or τ

Unitary Leptonic Mixing Matrix

Neutrino of definite mass m_i

neutrino flavors

The leptonic mixing matrix

$$U = \begin{array}{c} \\ \nu_e \\ \nu_\mu \\ \nu_\tau \end{array} \begin{array}{c} \begin{array}{ccc} \nu_1 & \nu_2 & \nu_3 \end{array} \\ \begin{bmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{bmatrix} \end{array}$$

neutrino masses

The Lepton Mixing Matrix U

$$U = \begin{bmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{bmatrix} \times \begin{bmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{bmatrix} \times \begin{bmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

$$\underbrace{\times \begin{bmatrix} e^{i\alpha_1/2} & 0 & 0 \\ 0 & e^{i\alpha_2/2} & 0 \\ 0 & 0 & 1 \end{bmatrix}}_{\text{Does not affect oscillation}}$$

$c_{ij} \equiv \cos\theta_{ij}$
$s_{ij} \equiv \sin\theta_{ij}$

Note big mixing!

$\underbrace{\theta_{12} \approx 33°, \theta_{23} \approx 40\text{-}52°,}_{\text{Note big mixing!}}$ $\theta_{13} \approx 8\text{-}9° \leftarrow$ *Not very small!*

The phases violate CP. δ would lead to $P(\bar{\nu}_\alpha \rightarrow \bar{\nu}_\beta) \neq P(\nu_\alpha \rightarrow \nu_\beta)$.

$\cancel{CP}$

But note the crucial role of $s_{13} \equiv \sin\theta_{13}$.

We know essentially nothing about the phases. Only hints.

- we have a very success full parameterization of the neutrino sector, we have identified what we know and what we don't know
- we can explore neutrino properties in
  - laboratory experiment,
  - cosmology
  - astrophysics
- neutrino masses are very small – we do not know why but we think that means something important
- lepton mixing is very different from quark mixing, we do not know why but we think that means something important
- the fact that neutrinos have mass may be intimately connected to the fact that there are more baryons than antibaryons in the universe – can we test it ?
- we need to understand the fate of the lepton number: is it conserved or not ? Do neutrino violate CP ?

Charge-Parity (CP) violation

There are only very few parameters in the standard model which can violate CP:

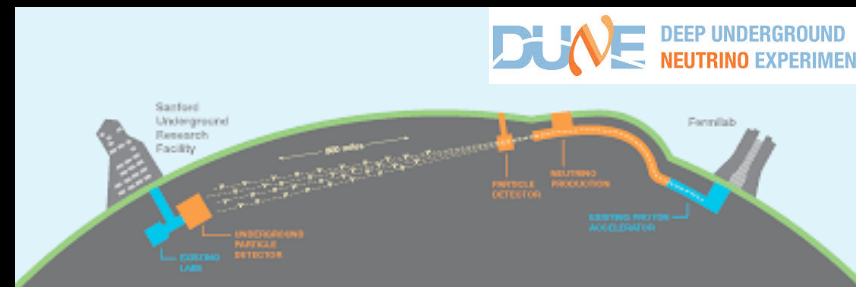
- CKM phase in the quark mixing – measured to be about 70 deg
- θ of the QCD vacuum – measured to be $< 10^{-10}$
- Dirac phase (δ) of the neutrino mixing
- Possibly if neutrino is a Majorana particle: 2 Majorana phases of neutrinos

At the same time we know that the quark-sector CP violation is ~10 orders of magnitude too small for the Baryon Asymmetry of the Universe

Long baseline neutrino experiments: a way to measure CP violation

Long-Baseline Accelerator Experiments (also called appearance experiment)

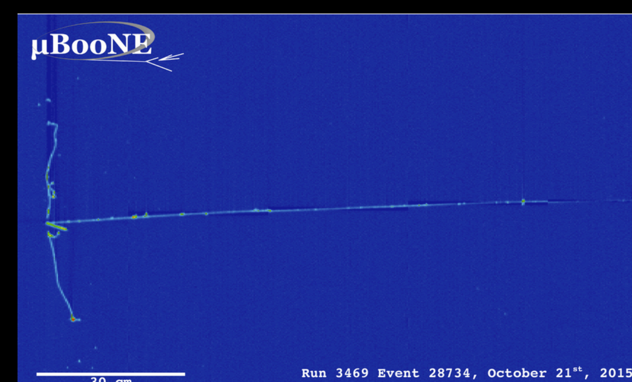
- Oscillation probability complicated:
1. Dependent on θ_{13}
2. CP violation parameter (δ)
3. Mass hierarchy (sign of Δm_{31}^2)
4. Size of $\sin^2\theta_{23}$



Next generation experiments are now being planned.

What do we need:
- ***more neutrinos***
- ***bigger detectors***
- ***better detectors***
- ***precision***

New facilities: more powerful beams and new detector technology - liquid argon



Tough one, I will try to explain a way of reaching it in the rest of the talk

DUNE: Deep Underground Neutrino Experiment

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

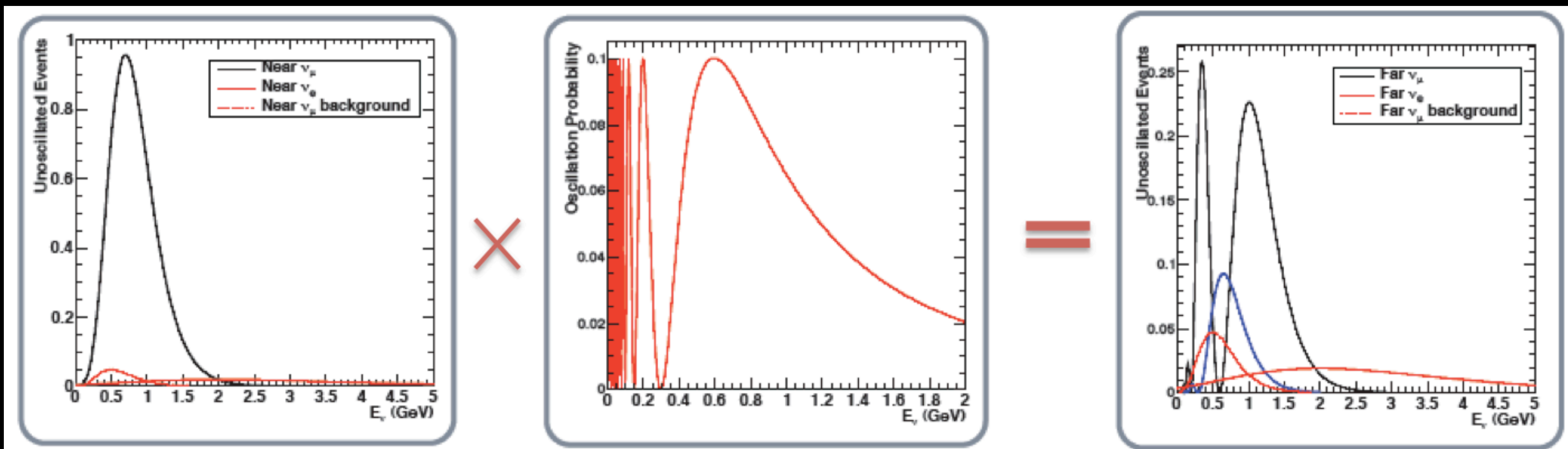
- Far detector:
  - Extrapolate Flux
  - Background
  - Neutrino energy

Additional problem:
we do not measure probabilities, but we measure event rates

Near detector

Oscillation probability

Far detector



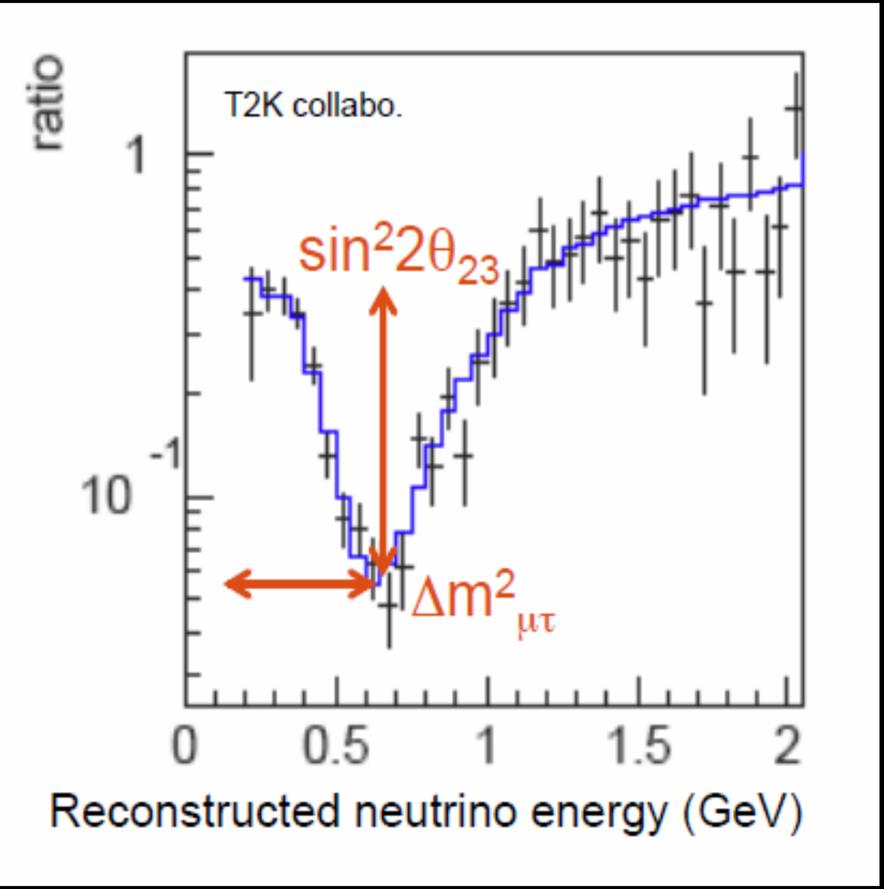
measure # events = flux x cross section

Black curve: ν_μ disappearance
Blue curve: ν_e appearance
Red curve: intrinsic ν_e/ν_μ bkg

Beam between Near and Far detector is not the same: divergence

Observable Oscillation Parameters

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



Neutrino energy >1 GeV

Oscillation parameter determination depends on the reconstructed neutrino energy.

2 methods currently used:

- kinematic
- calorimetric

Neutrino 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 kinematic to neutrino energy
- Advantages:
    - don't need hadron reconstruction
- Disadvantages
    - energy is wrong if underlying interaction is misidentified (i.e. not quasi-elastic)
    - Nuclear effects smear energy resolution

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

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

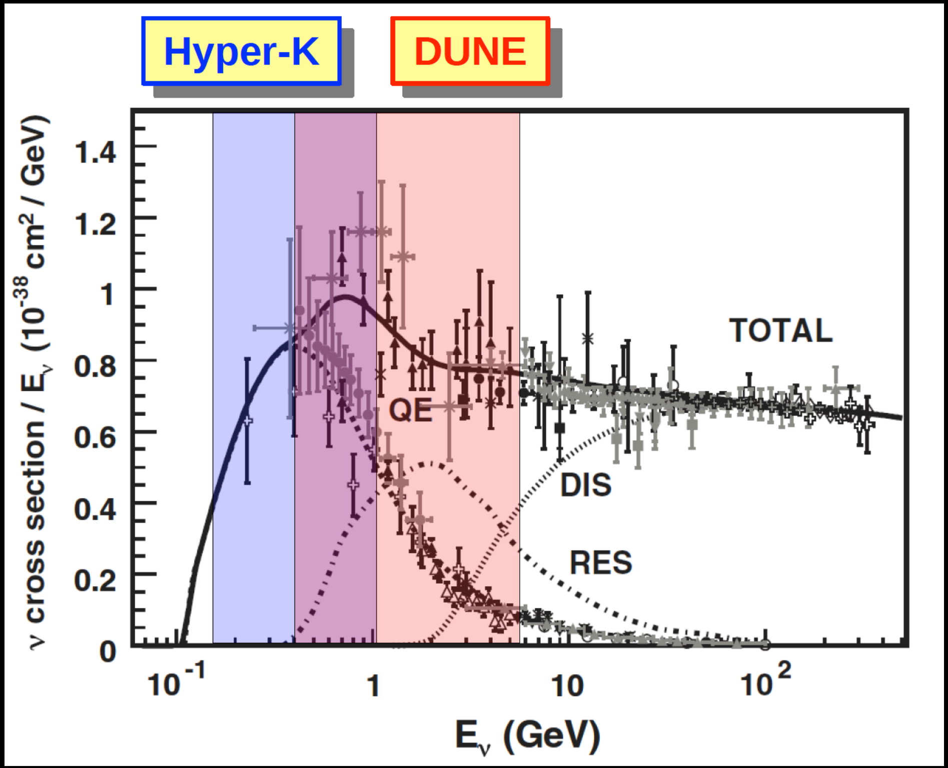
Calorimetric

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

Neutrino Cross-Sections

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

- Large contributions from QE, Resonances and DIS regions
- Reaction products have to leave the nucleus (final state interactions)
- More complex interactions (2p2h) are important



As function of Q^2 these effects are not depending on flavor they could NOT be the same for neutrino and anti-neutrino

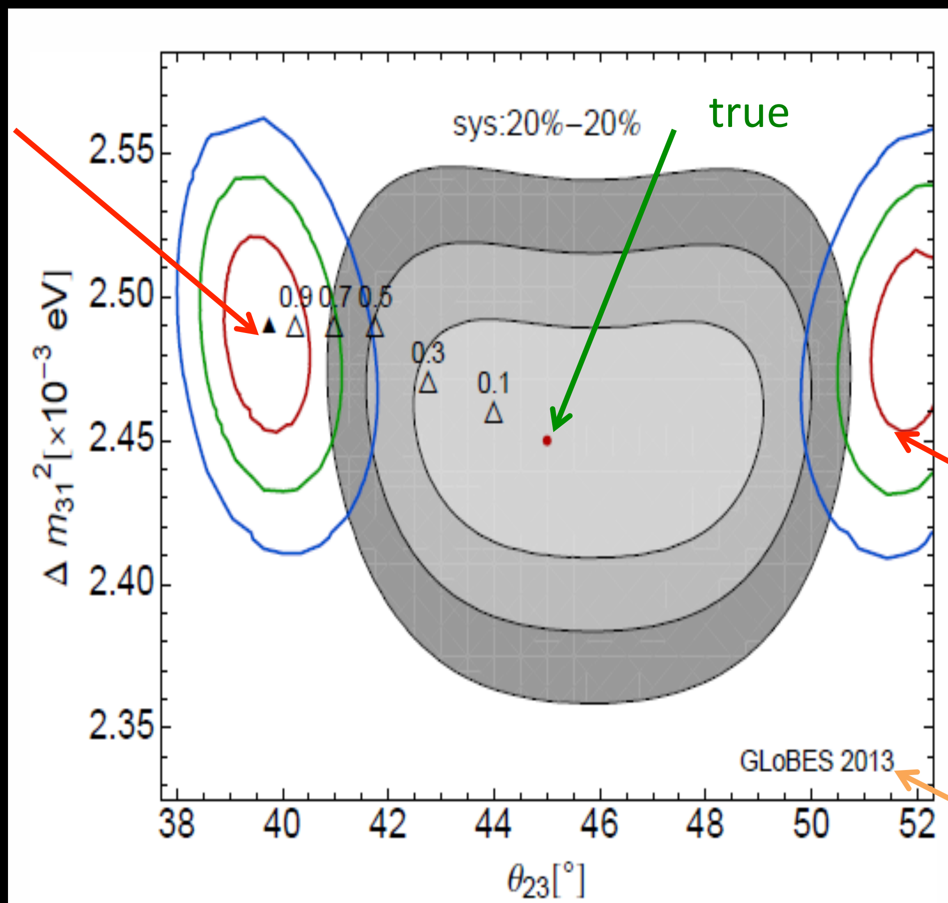
Oscillation analysis
and
Energy Reconstruction
in
an ideal
Long Baseline Experiment

Experimental Setup

- Ideal, perfect near detector (^{12}C), 1 km, 1kton
- Far detector at 295 km, 22.5 kton, Carbon (SF)
- Use flux that peak at 0.6 GeV, 750kW, 5 years running
- Use a second flux that peaks at 1.5 GeV, 750kW, 5 years running
- Use Super Kamiokande (water cherenkov detector) reconstruction efficiency as function of energy
- Use migration matrices to take into account how neutrino energy reconstruction is affected by the what kind of interaction the neutrino undergo in the detector and how well we can identify them
- Muon neutrino disappearance only -> fit to atmospheric parameters

How to read the plots in the following slides

reconstructed from naive QE dynamics



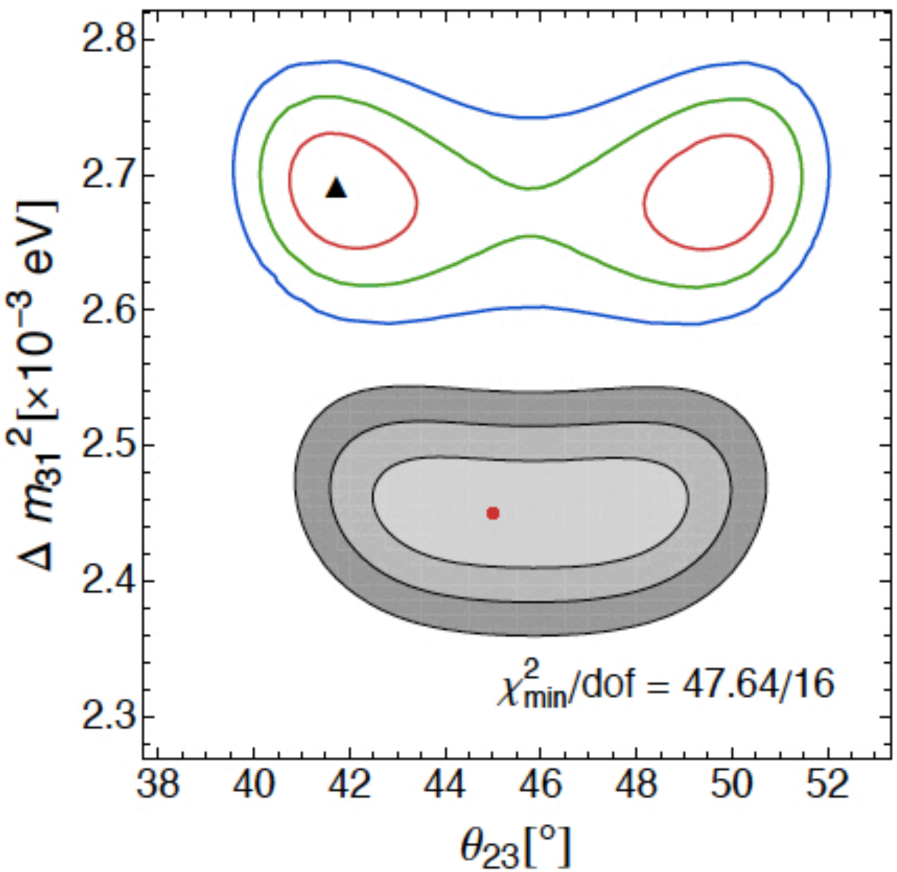
1, 2 and 3σ allowed regions

Simulation of long baseline neutrino oscillation

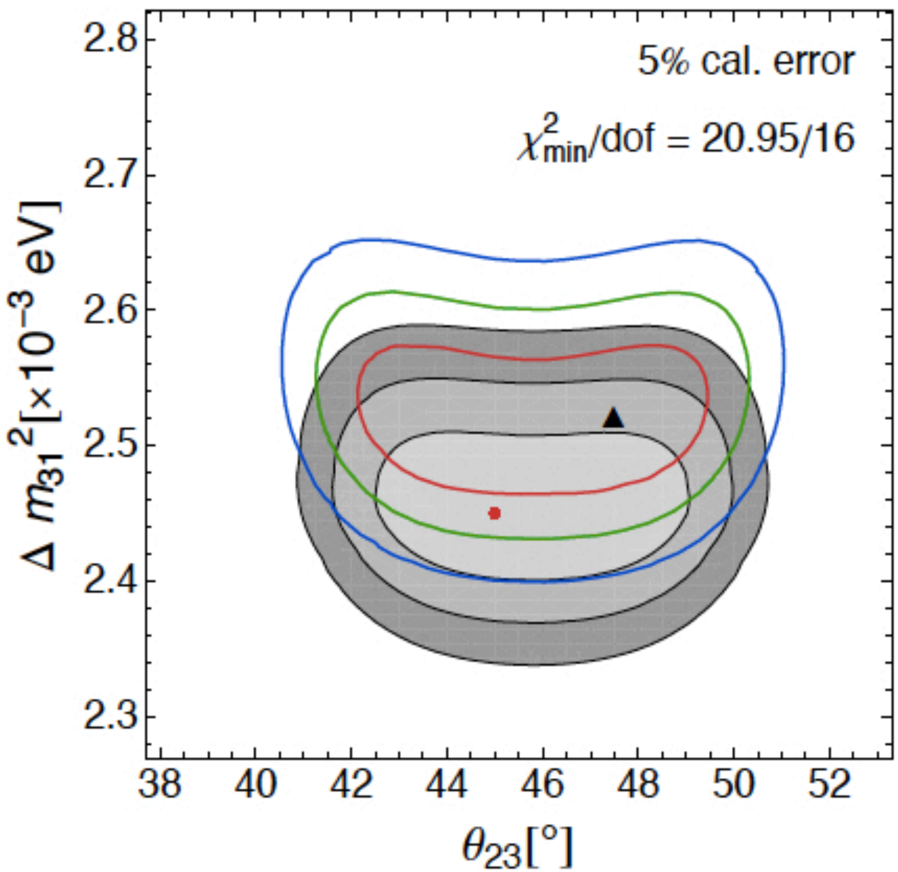
Impact on oscillation

(simulate with one neutrino interaction generator (GENIE) and fit with another generator (GiBUU))

Phys. Rev. D 89, 073015 (2014)
Coloma, Huber, Jen and CM



(a) No calibration error



(b) 5% calibration error

With and without nucleon-nucleon correlation

Phys. Rev. D 89, 073015 (2014)
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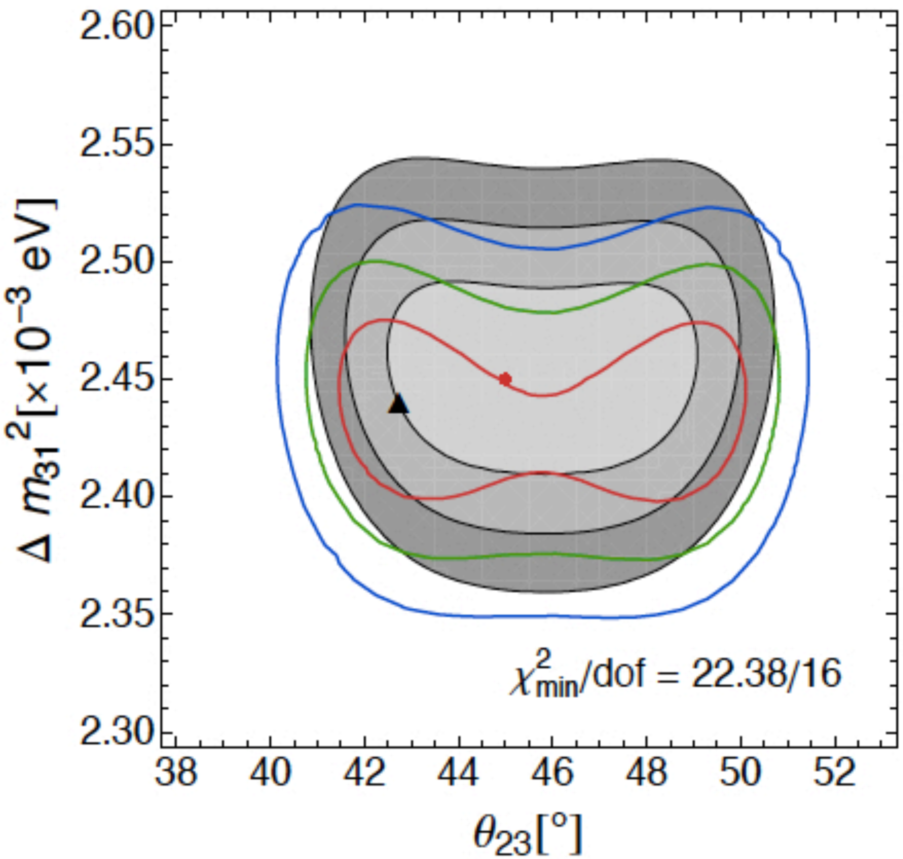
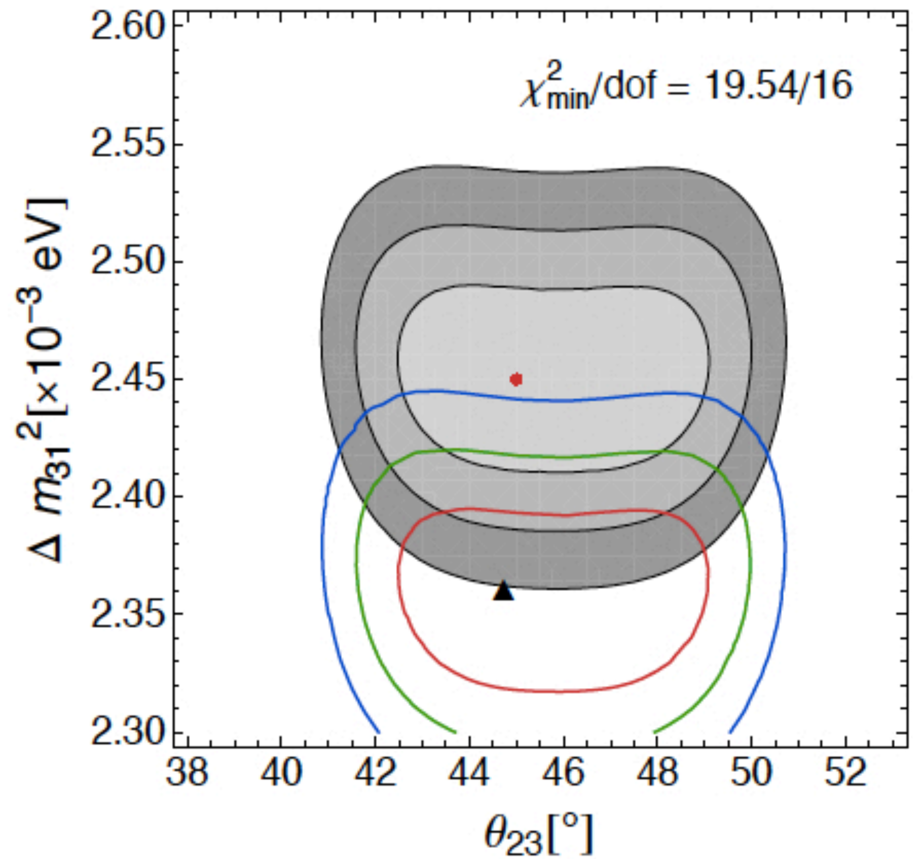


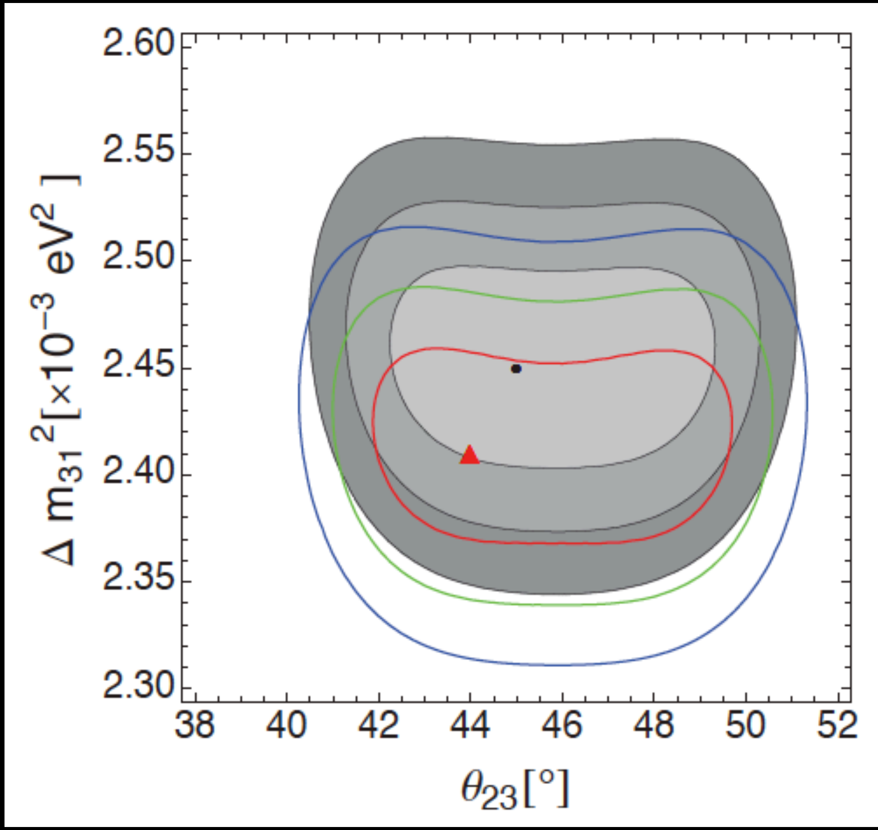
(a) Results using GiBUU matrices

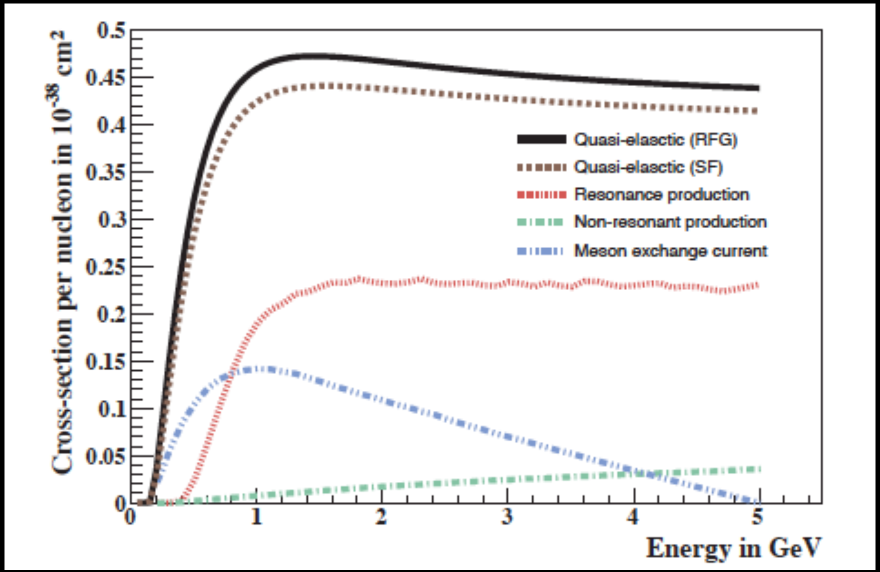


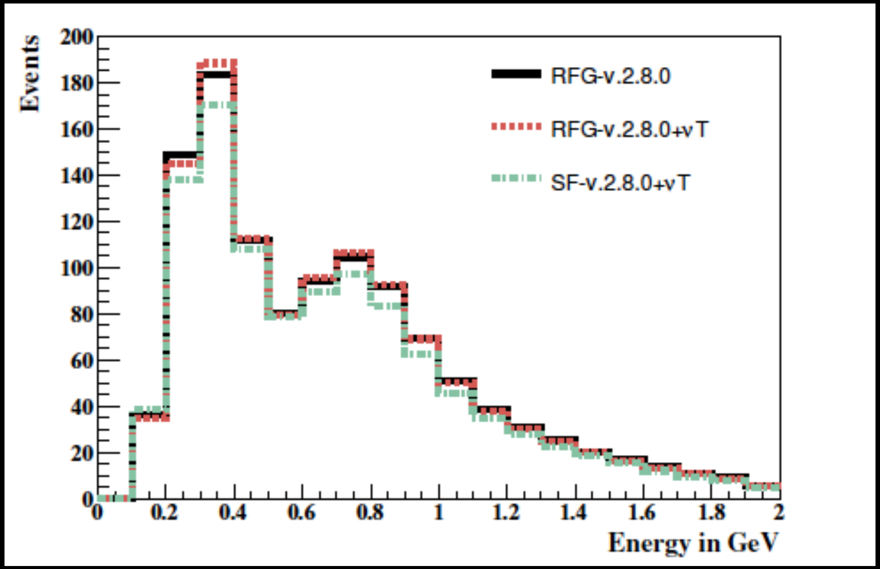
(b) Results using GENIE matrices

Different nuclear model effects

Jen et al. 2014





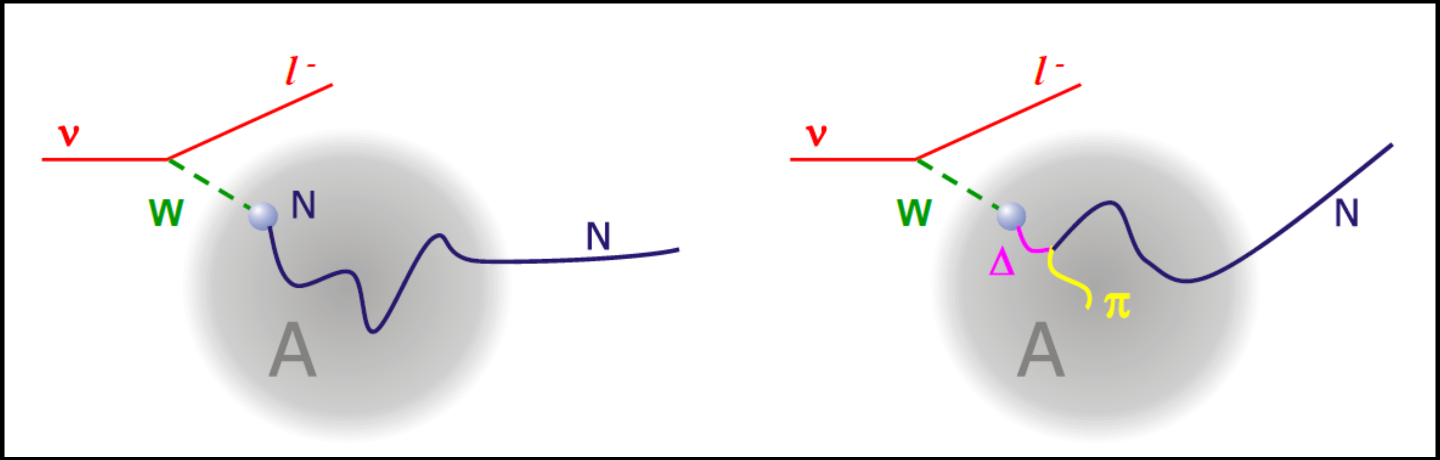


Phys. Rev. D 90, 093004 (2014)
Jen,Ankowski,Benhar,Kalousis,CM,Furmanski

First conclusion

- We need a reliable neutrino interaction generator
- Effect on oscillation parameters due to nuclear models is big - > we need work

Two ways to reconstruct the neutrino energy



- Kinematic: use only info on the outgoing lepton kinematic

- Calorimetric: sum all energy in final state

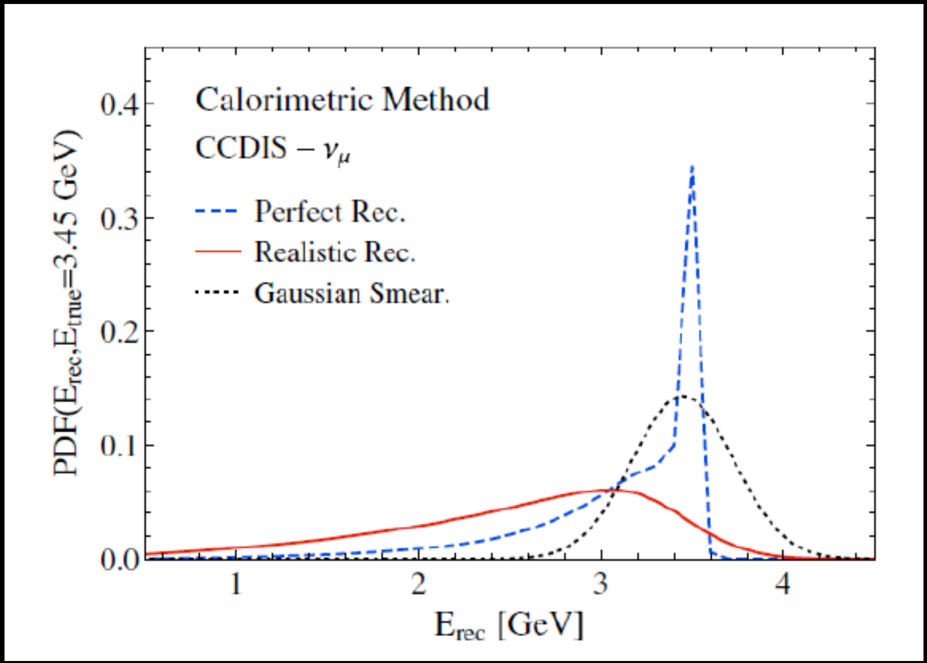
Simulating a non perfect detector

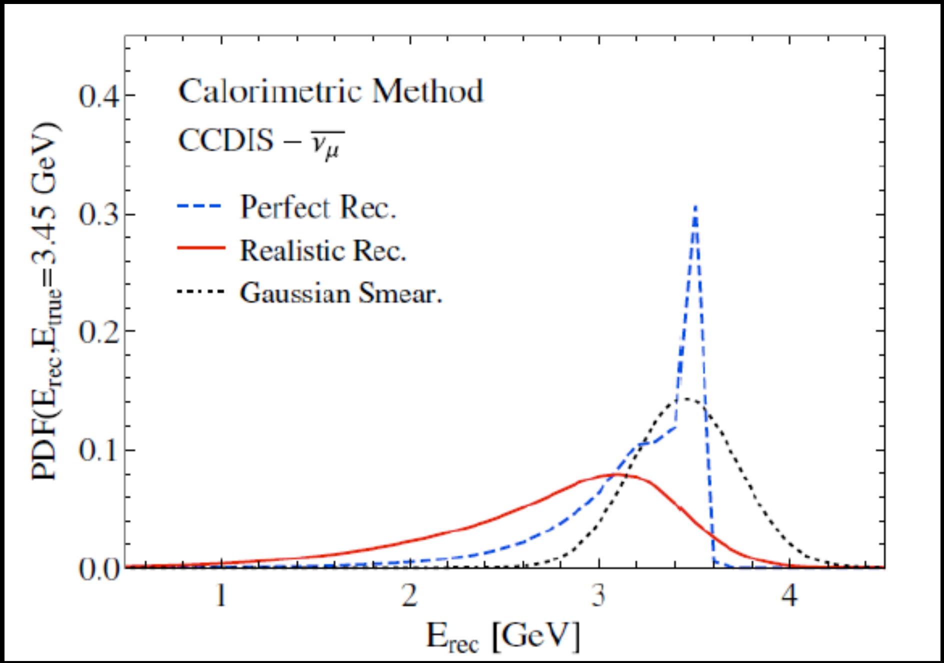
- Detection thresholds
  - 20 MeV for mesons,
  - 40 MeV for protons

- Efficiencies
  - 60% for π^0,
  - 80% for other mesons,
  - 50% for protons,
  - *neutrons undetected*

Reconstructed-energy distributions

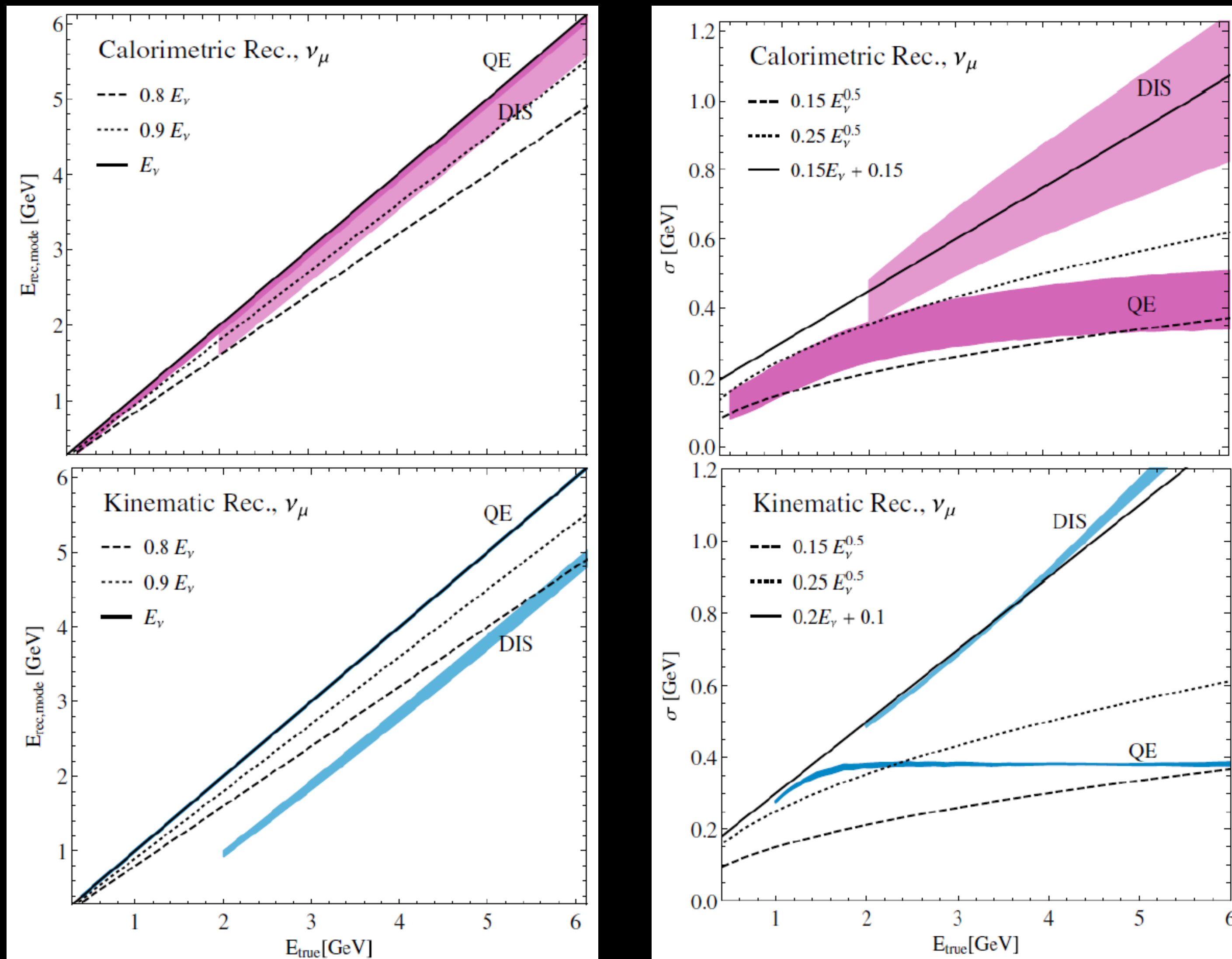
DIS at E=3.5 GeV





Phys. Rev. D 92, 073014 (2015)
Ankowski,Benhar,Coloma,Huber,Jen,CM, Vagnoni,Meloni

Effective energy resolution as a f(E_ν)



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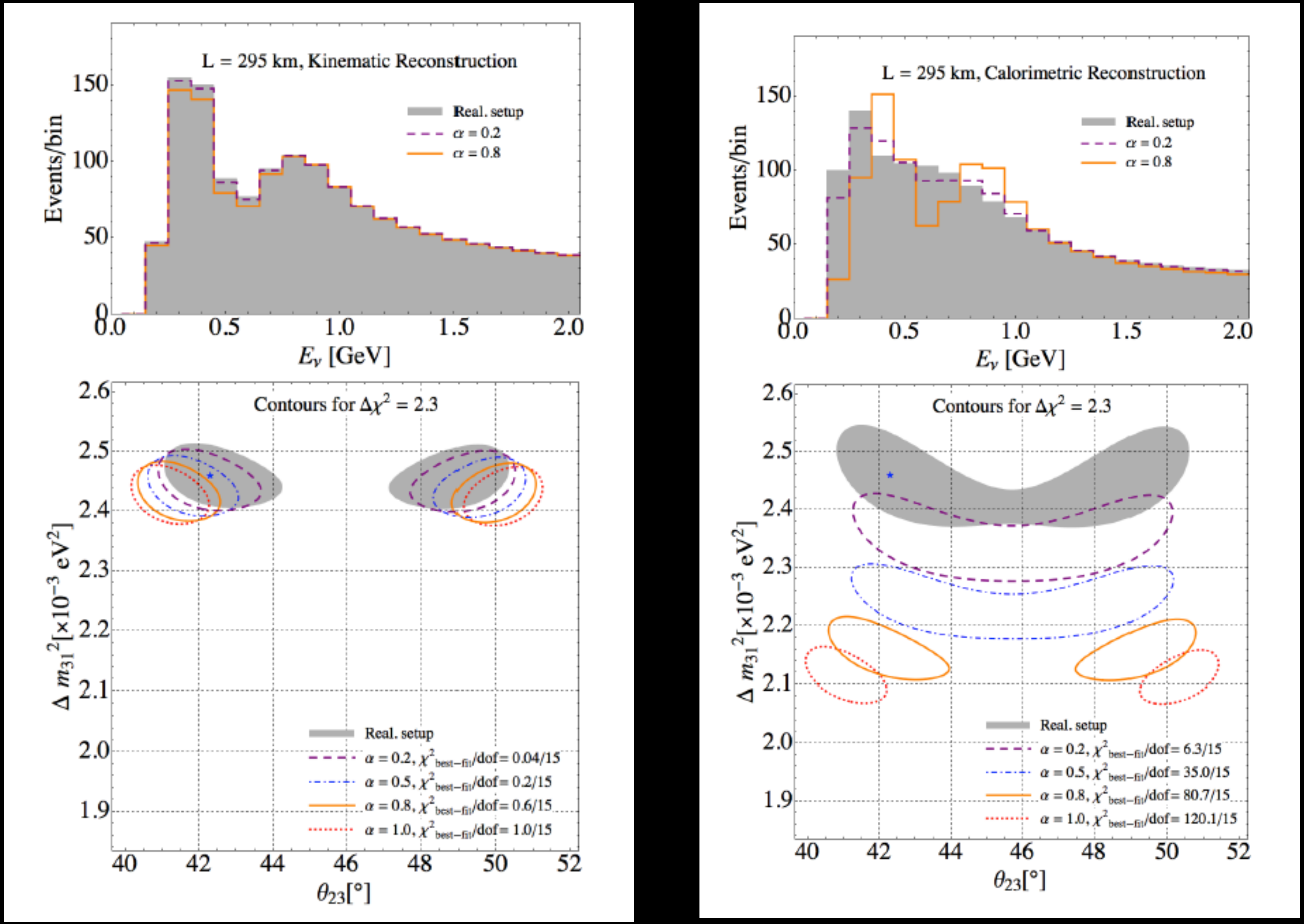

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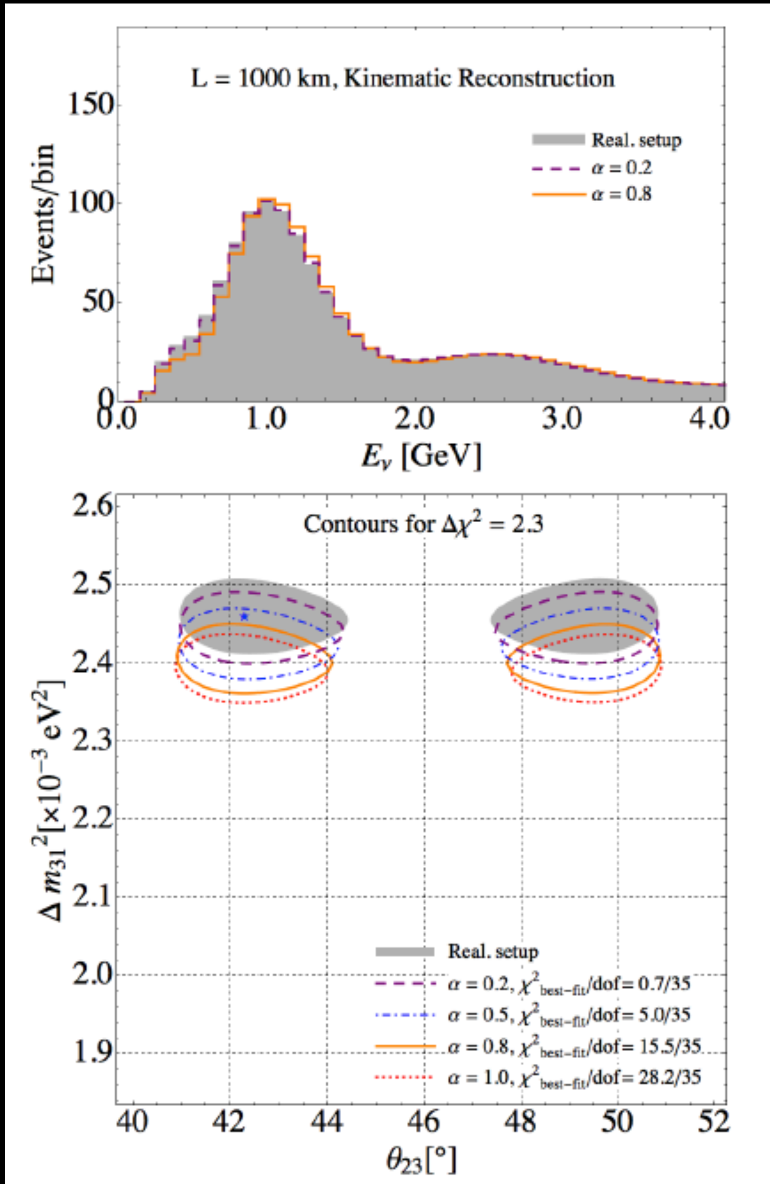
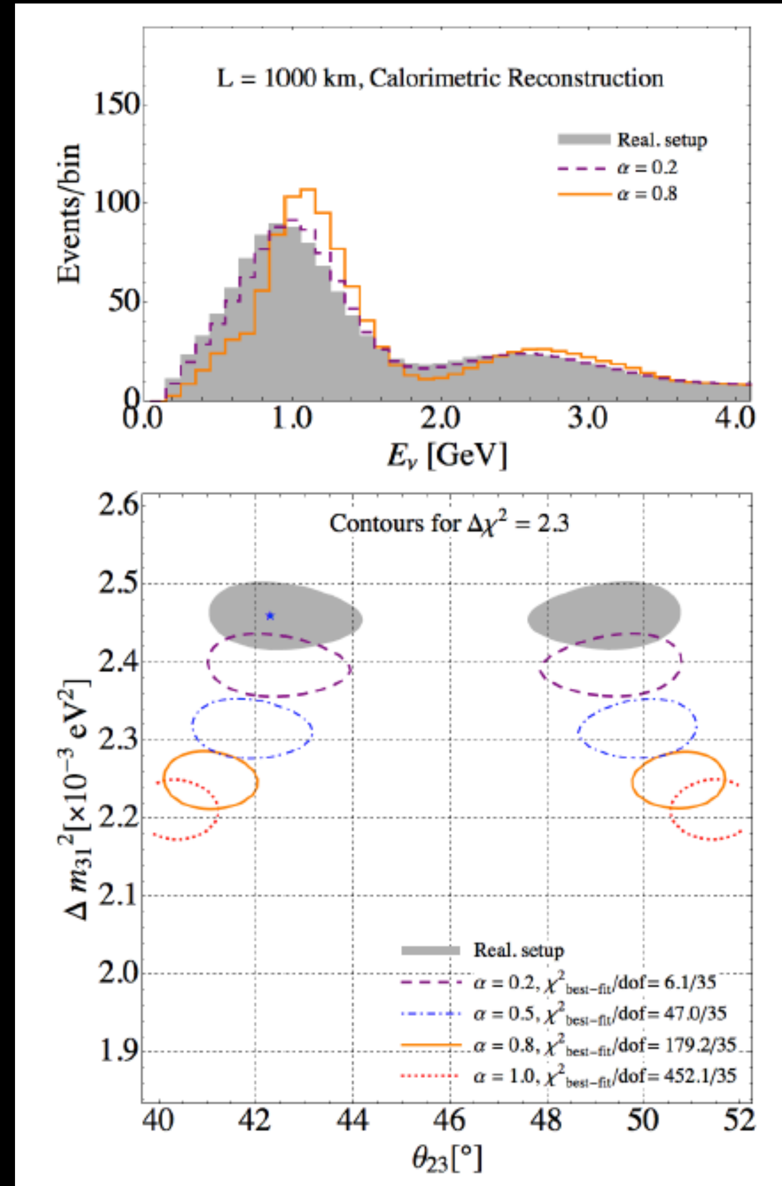
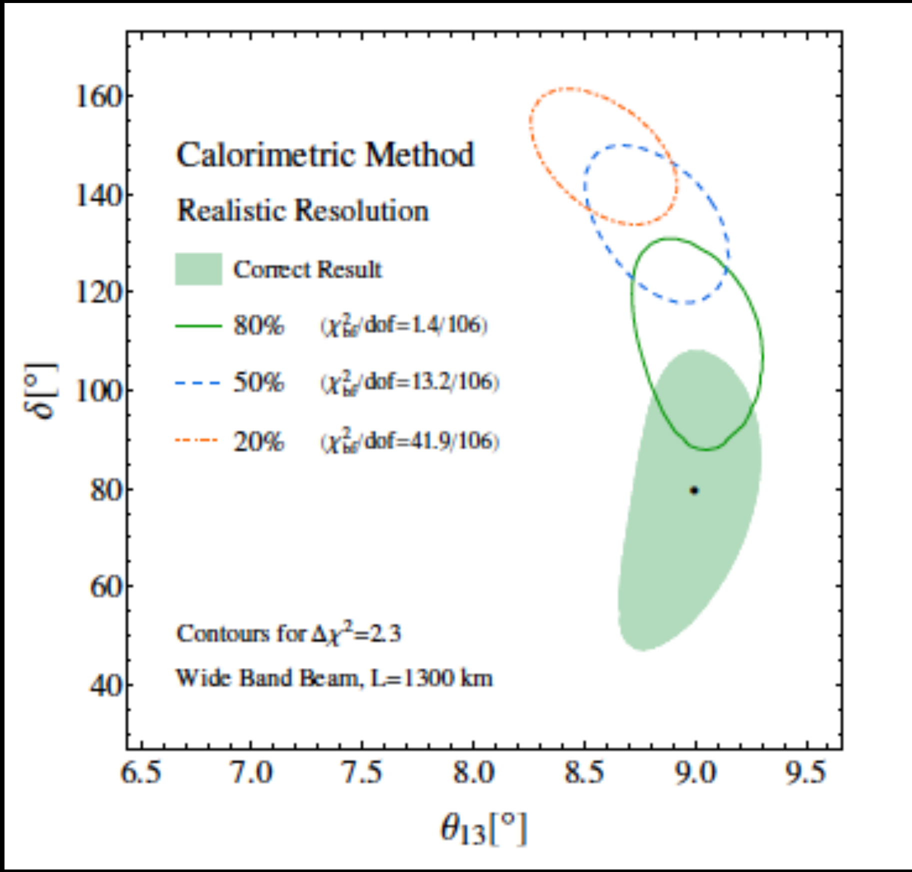
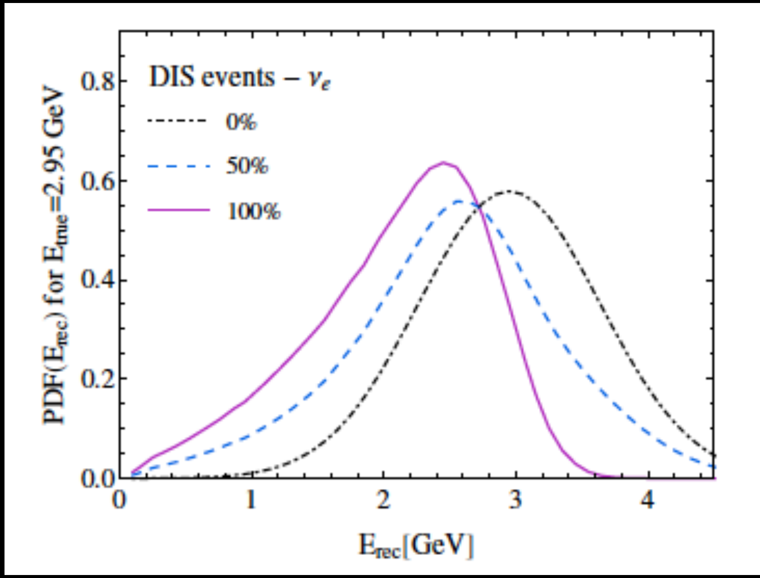




Phys. Rev. D 92, 073014 (2015)
Ankowski,Benhar,Coloma,Huber,Jen,CM, Vagnoni,Meloni

Effect on CP violation





Missing energy coming from undetected neutrons

In print PRD Rapid Communication
Ankowski,Coloma,Huber,CM,Vagnoni

We should find a way to identify and measure energy from neutrons

Summary

- Systematics at the 1% level is necessary to ensure the success of the future US neutrino program in measuring the CP violating phase
- Liquid Argon technology is the choosen one, need development
- Precise (exclusive) neutrino-nucleus cross sections are essential for reliable energy reconstruction and accurate determination of oscillation parameters
- Need electron scattering data on Argon – there is an experiment approved that will collect Argon data
- High resolution near detector – very important but not sufficient: we need precise knowledge of neutrino cross-sections
- Electron scattering offers a way to deal with nuclear models, models can then be validated on electron scattering and used to describe neutrino interactions

Thank you

ELBNF

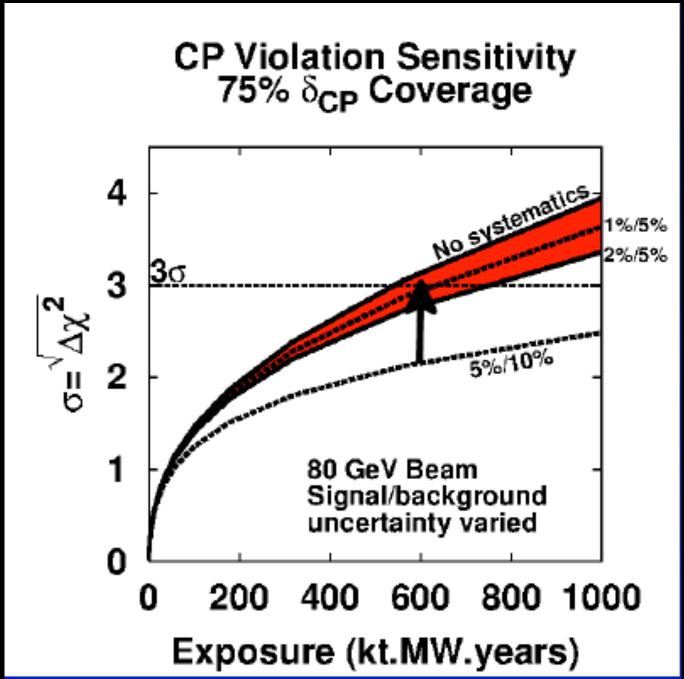
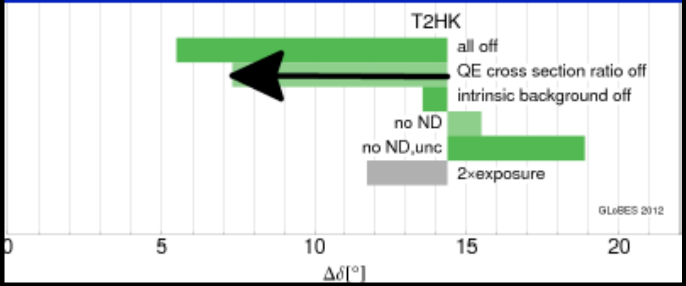
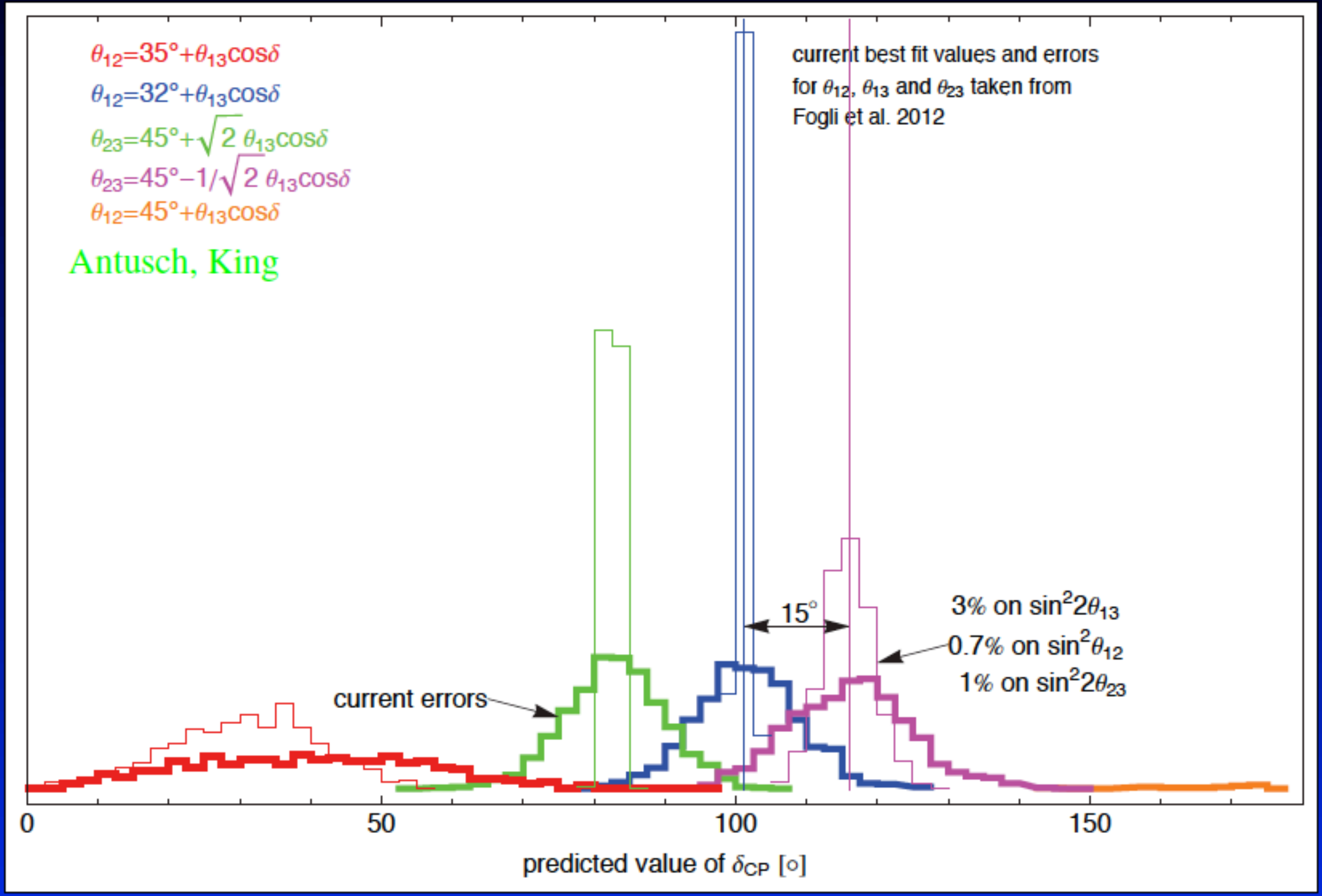


figure courtesy M. Bass, 2014



A precision game ….

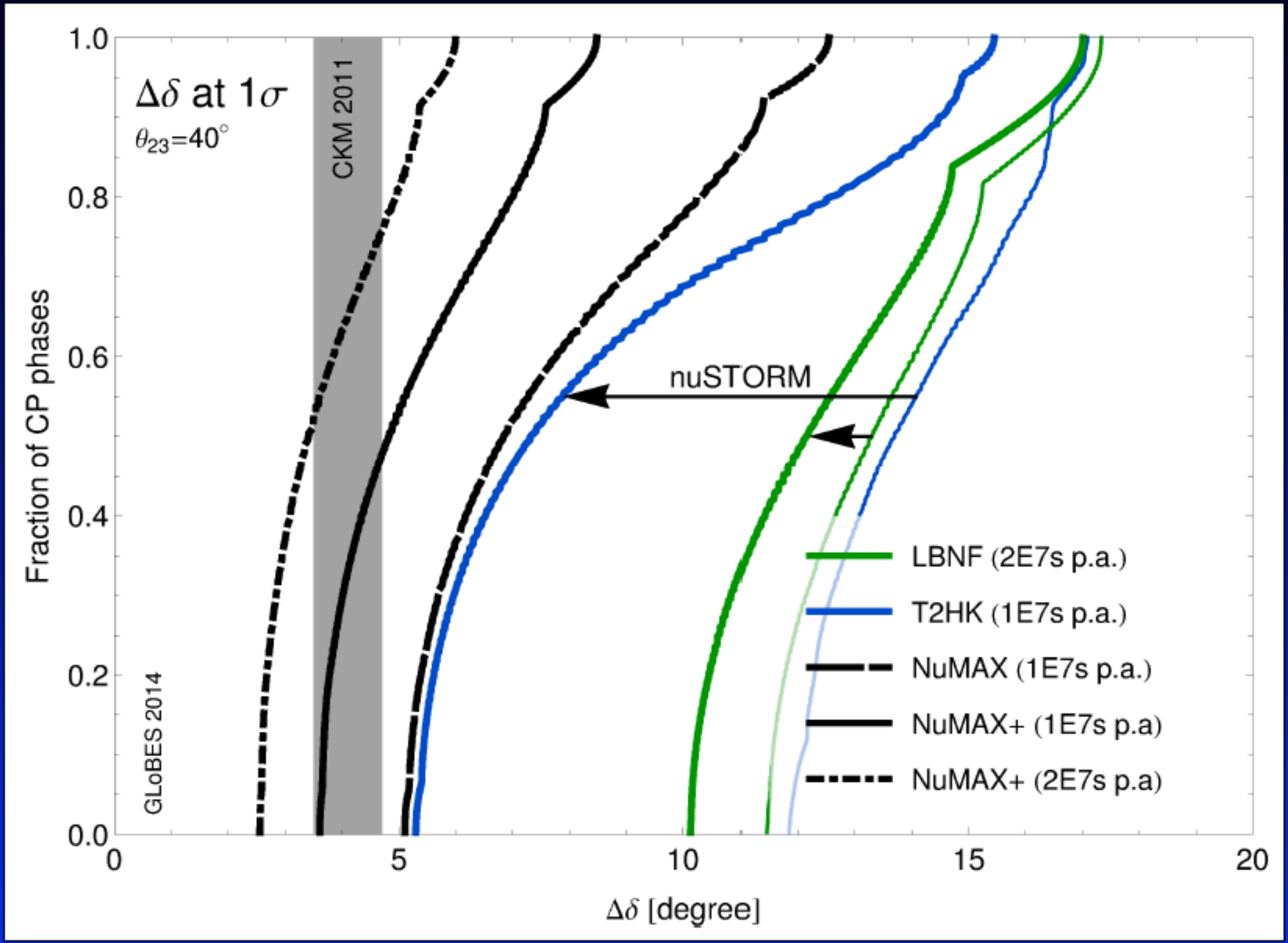
Sum rules



$3\,\sigma$ resolution of 15° distance requires 5° error. NB – smaller error on θ_{12} requires dedicated experiment like JUNO

P. Huber -

Is 5° feasible?



PH, Bross, Palmer, arXiv:1411.0629

P. Huber -

- kinematic

$$E_\nu^{kin} = \frac{2(nM - \varepsilon_n)E_l + W^2 - (nM - \varepsilon_n^2) - m_l^2}{2(M - \varepsilon - E_l + |k_l|\cos\theta)}$$

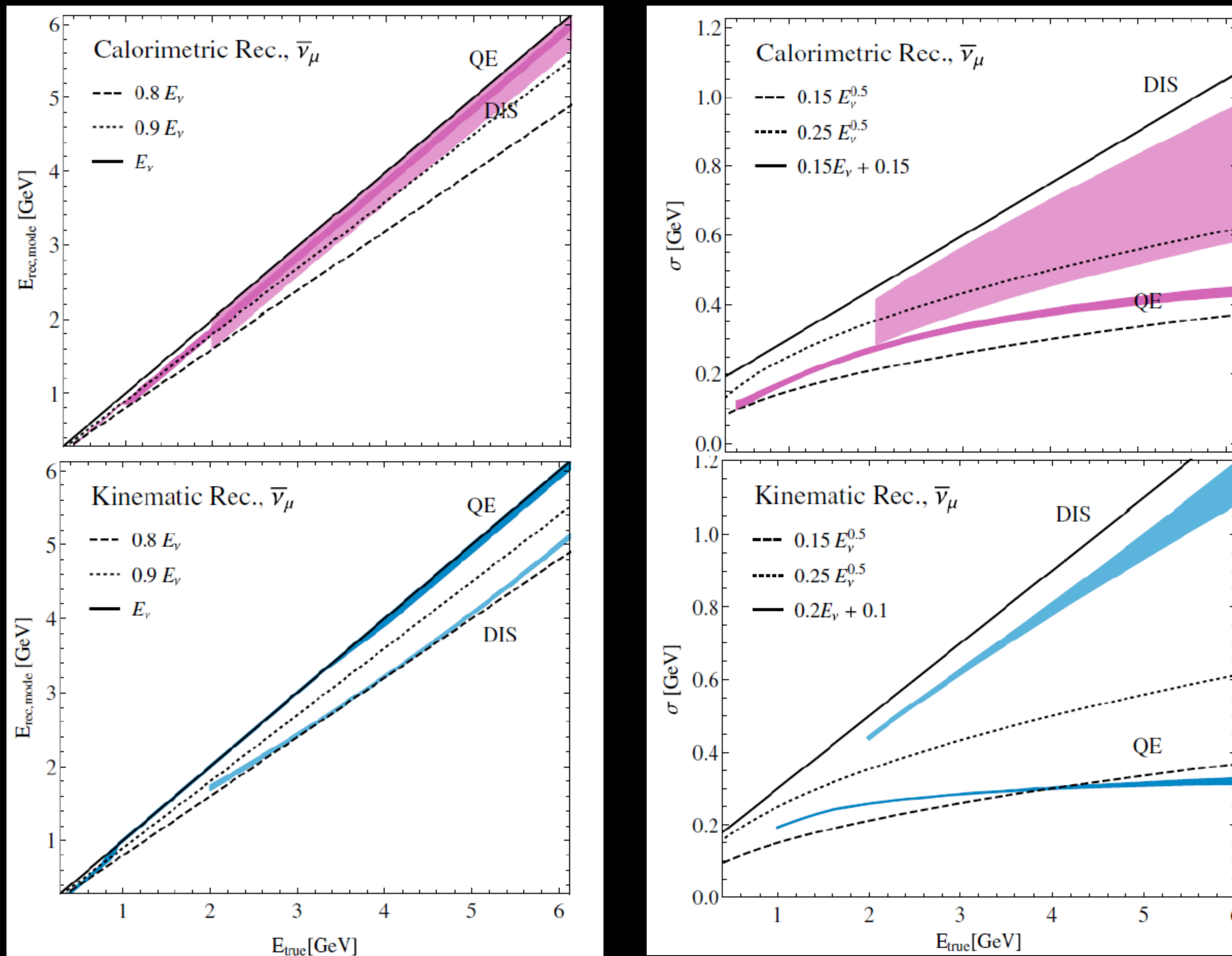
- calorimetric

$$E_\nu^{cal} = \varepsilon_n + E_l + \sum_i (E_{p_i^{'}} - M) + \sum_j E_{h_j^{'}}$$

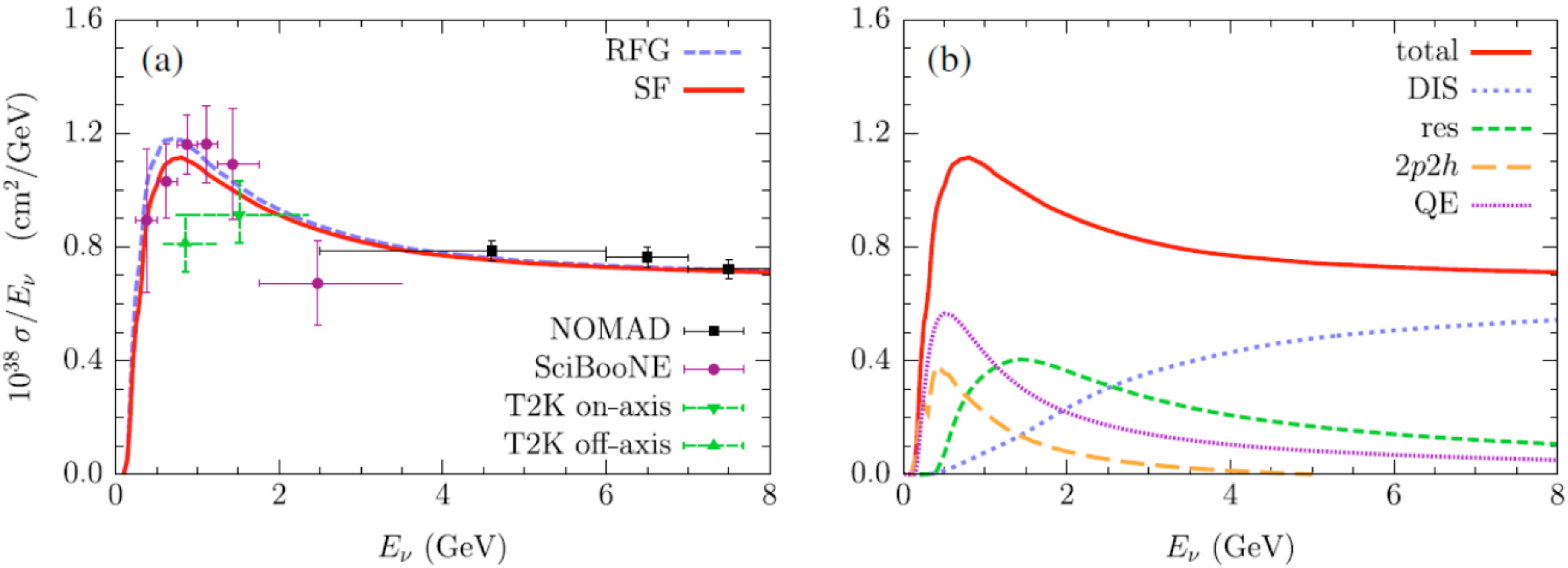
- matrix and fit:

$$N_i^{fit} = \sum_X \sum_j \{(1-\alpha)M_{ij}^{X,real} + \alpha M_{ij}^{X,perfect}\} N_i^X$$

Effective energy resolution as a f(E_ν)



Event Generator



Phys. Rev. D 90, 093004 (2014)
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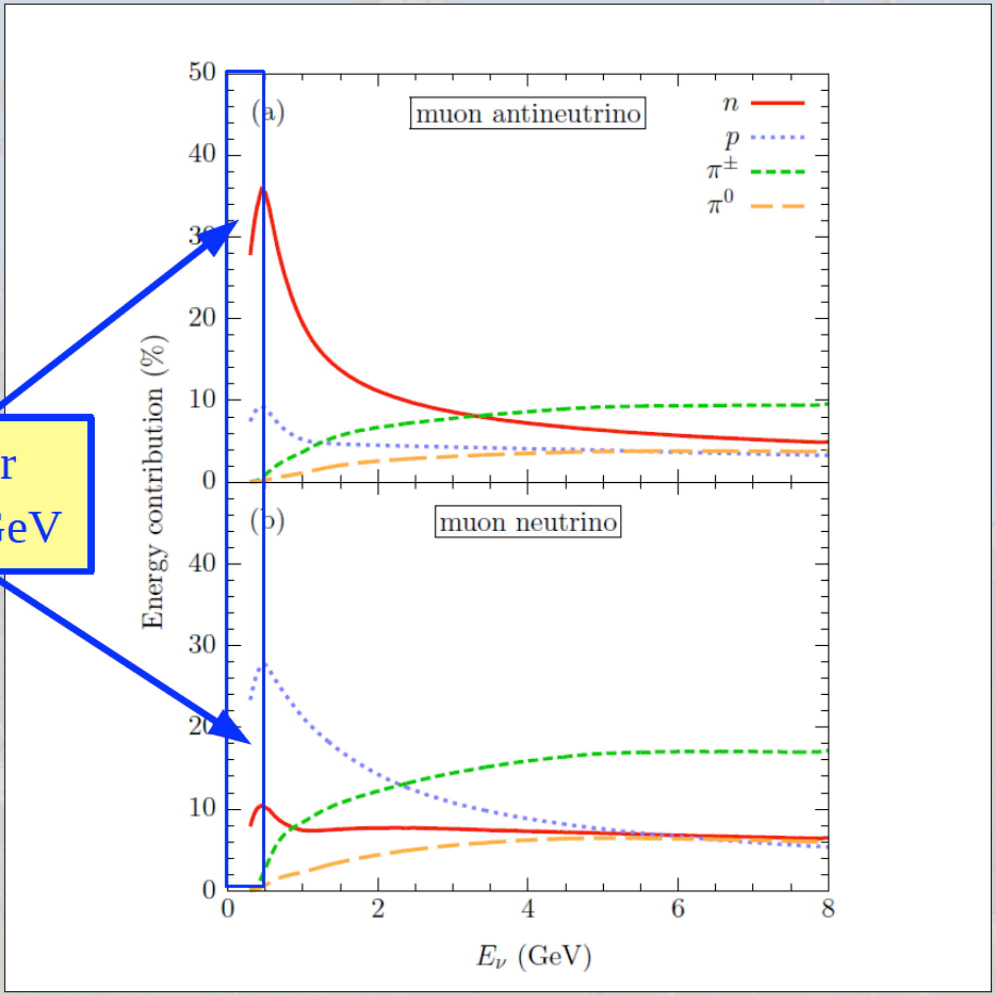
Missing energy contributions for a DIS event at E=3 GeV

neutrino (average):	antineutrino (average):
n's 100%*0.34 GeV	n's 100%*0.27 GeV
p's 50%*0.31 GeV	p's 50%*0.23 GeV
π^0's 40%*0.30 GeV	π^0's 40%*0.23 GeV
$\pi^\pm$'s 20%*0.73 GeV	$\pi^\pm$'s 20%*0.53 GeV
total: ~0.76 GeV	total: ~0.58 GeV

Final-state energy contributions



ν_e and ν_μ differ only at $E < 0.5$ GeV