Impact of systematics on neutrino oscillation experiments

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NuSTEC school
Fermilab, Oct 29th, 2014

Outline

1) Introduction/Motivation
    a) Oscillation probabilities
    b) Energy info versus rate info
    c) Second oscillation maximum
2) Types of neutrino oscillation experiments
3) Impact of systematics on CP violation and mass ordering

Outline (II)

4) Impact of systematic uncertainties on future oscillation experiments

   a) Normalization uncertainties:

      - Near detectors
      - Correlations

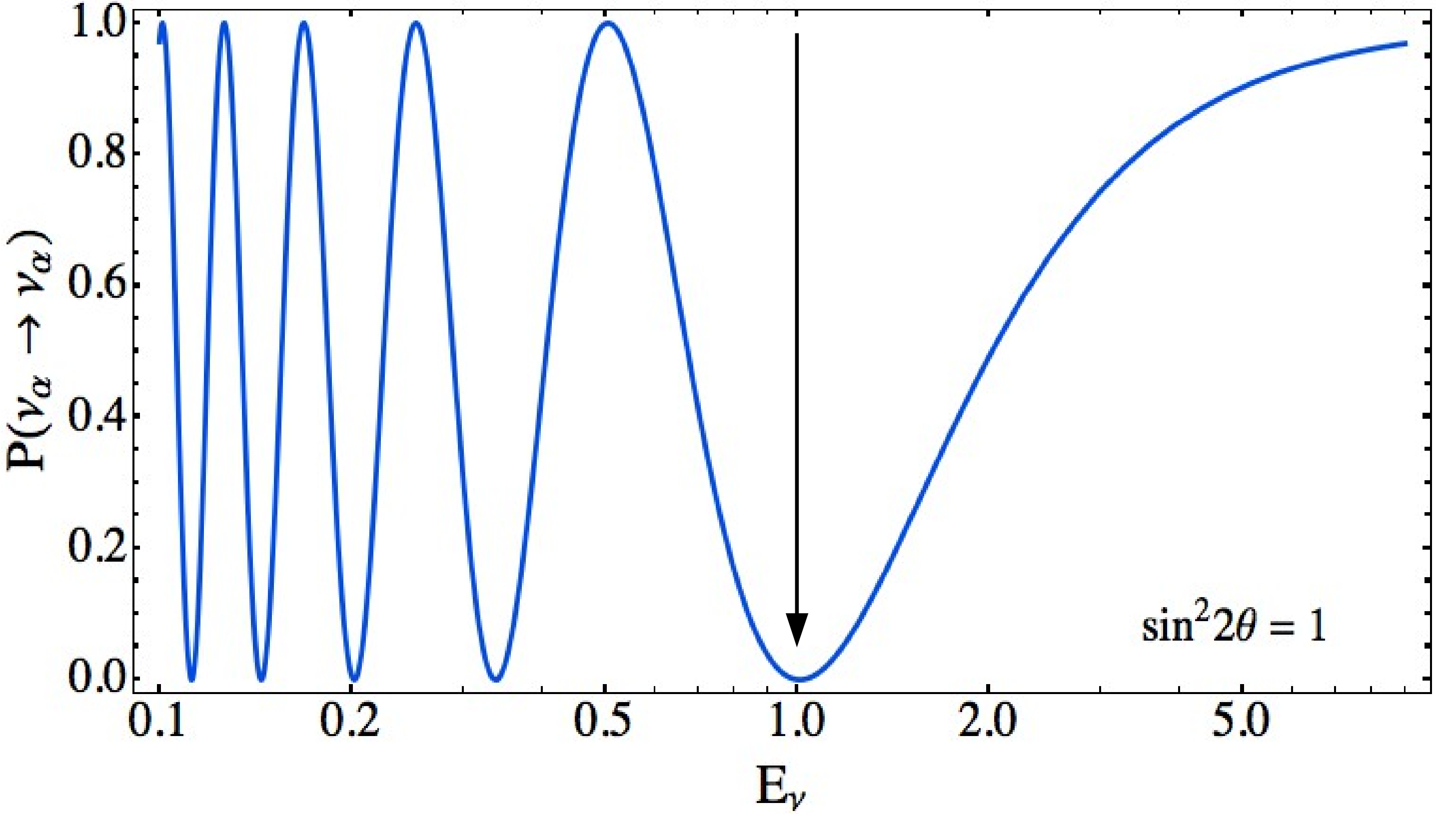
   b) Shape uncertainties

      - Different cross section models
      - Energy reconstruction issues

5) Curiousities/random thoughts

The two-family approximation

$$P_{\alpha\alpha} = 1 - \sin^2 2\theta \sin^2 \frac{\Delta m^2 L}{4E}$$



The two-family approximation

$$P(\bar{\nu}_e \to \bar{\nu}_e) \simeq 1 - \sin^2 2\theta_{12} \sin^2\left(\frac{\Delta m^2_{21} L}{4E}\right)$$

(KamLAND)

$$\sim 33^\circ$$

$$\sim 7.5 \times 10^{-5}\mathrm{eV}^2$$

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$$P(\bar{\nu}_e \to \bar{\nu}_e) \simeq 1 - \sin^2 2\theta_{13} \sin^2\left(\frac{\Delta m^2_{31} L}{4E}\right)$$

(Daya Bay,
RENO,
D-CHOOZ)

$\sim 9^\circ$

$\sim 2.5 \times 10^{-3} \mathrm{eV}^2$

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(Daya Bay,
RENO,
D-CHOOZ)

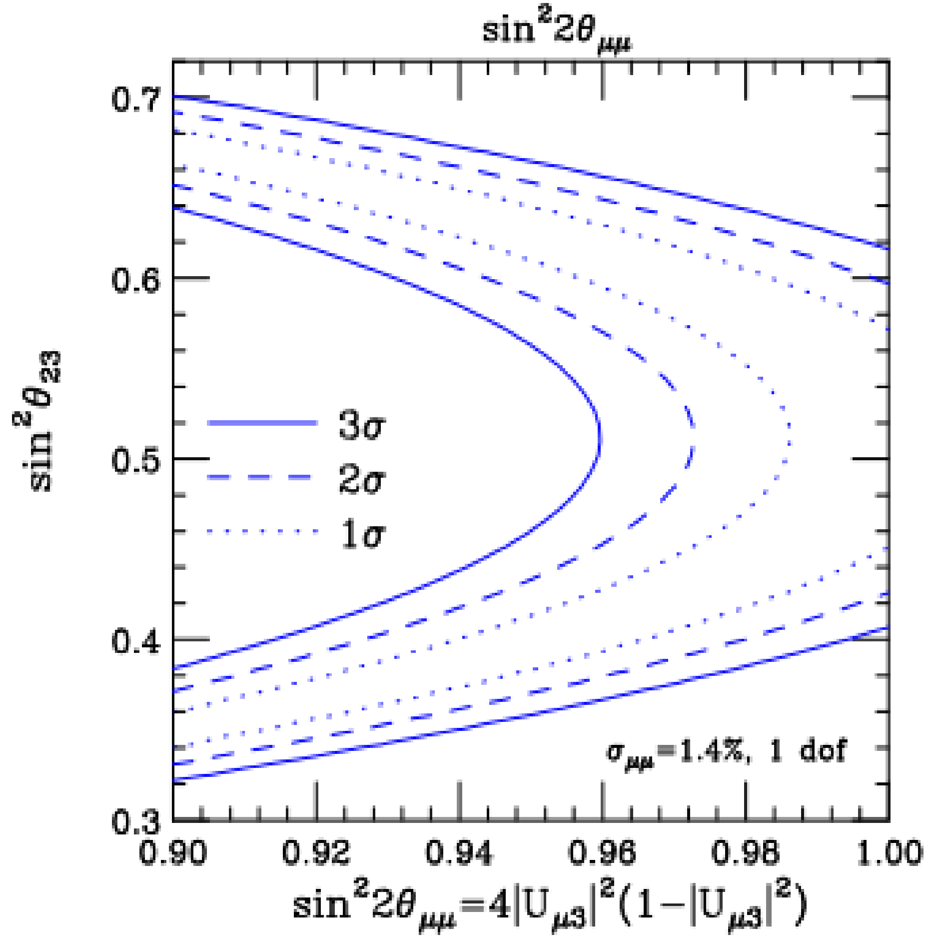
$$P(\nu_\mu \to \nu_\mu) \simeq 1 - \sin^2 2\theta_{23} \sin^2\left(\frac{\Delta m^2_{32} L}{4E}\right)$$

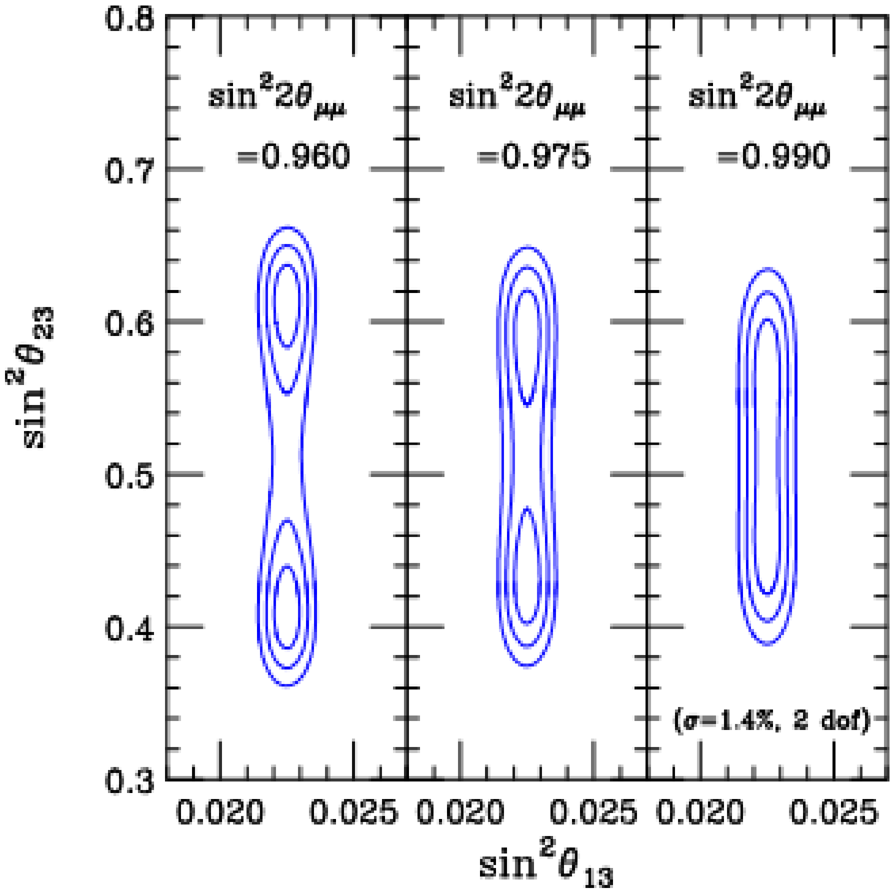
(K2K, MINOS,
T2K)

$$\sim 40^\circ - 50^\circ$$

$$\sim 2.5 \times 10^{-3} \mathrm{eV}^2$$

The two-family approximation





Coloma, Minakata, Parke, 1406.2551 [hep-ph]

Current status in neutrino oscillations

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

Atmospheric Reactor/Interference Solar

$$\begin{aligned} \theta_{12} &= 31.29^\circ \to 35.91^\circ \\ \theta_{23} &= 38.3^\circ \to 53.3^\circ \\ \theta_{13} &= 7.87^\circ \to 9.11^\circ \\ \Delta m^2_{21} &= (7.02 \to 8.09) \times 10^{-5}\mathrm{eV}^2 \\ \Delta m^2_{31} &= (-2.590 \to -2.307) \times 10^{-3}\mathrm{eV}^2 \\ &= (2.325 \to 2.599) \times 10^{-3}\mathrm{eV}^2 \end{aligned}$$

Unknown

$$\delta \neq 0, \pi?$$

$$m_3 \gtrless m_2?$$

$$\theta_{23} \gtreqless 45^\circ?$$

Gonzalez-Garcia, Maltoni, Schwetz, 1409.5439 [hep-ph]
(see also arXiv: 1405.7540[hep-ph] and 1312.2878 [hep-ph])

Why precision?

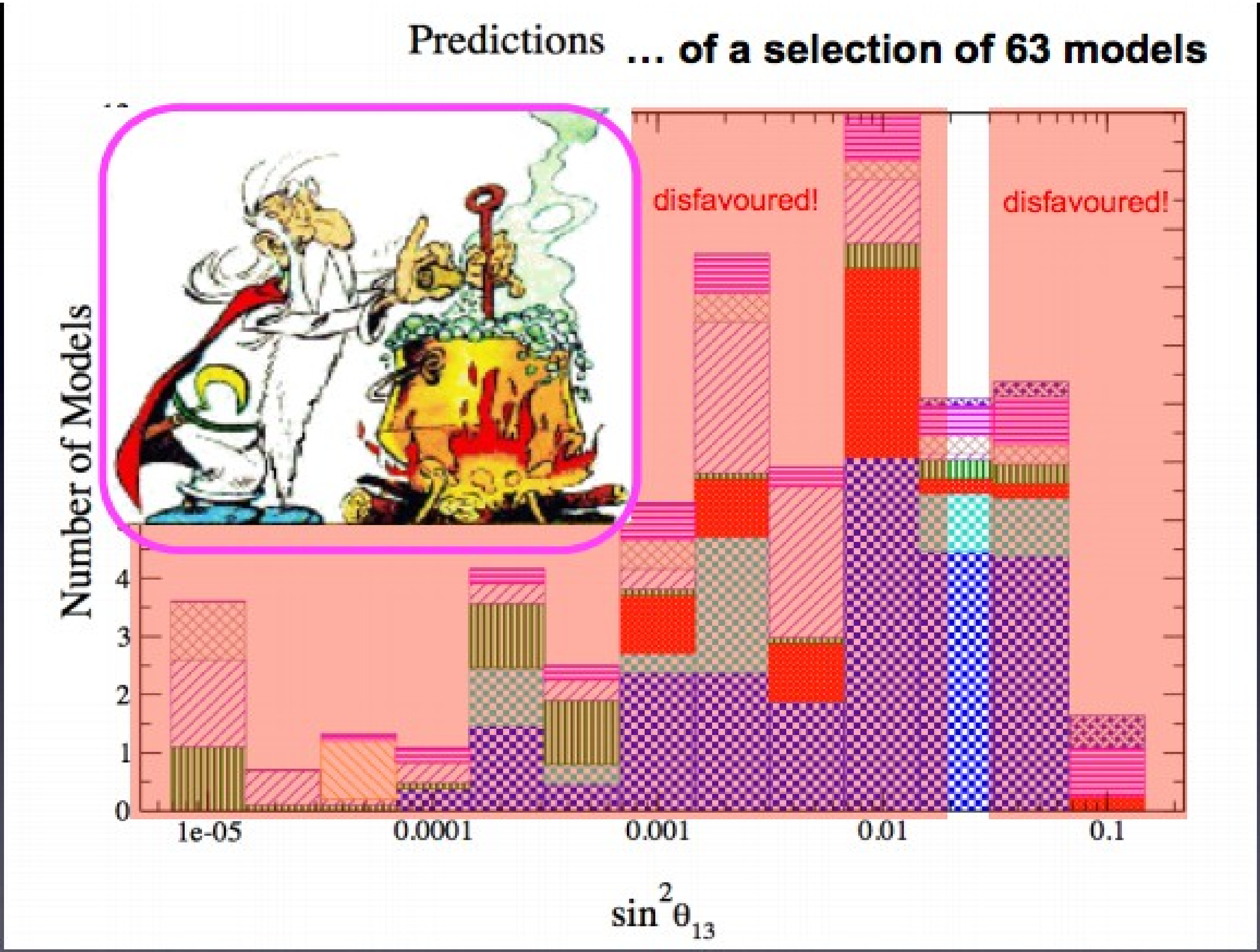
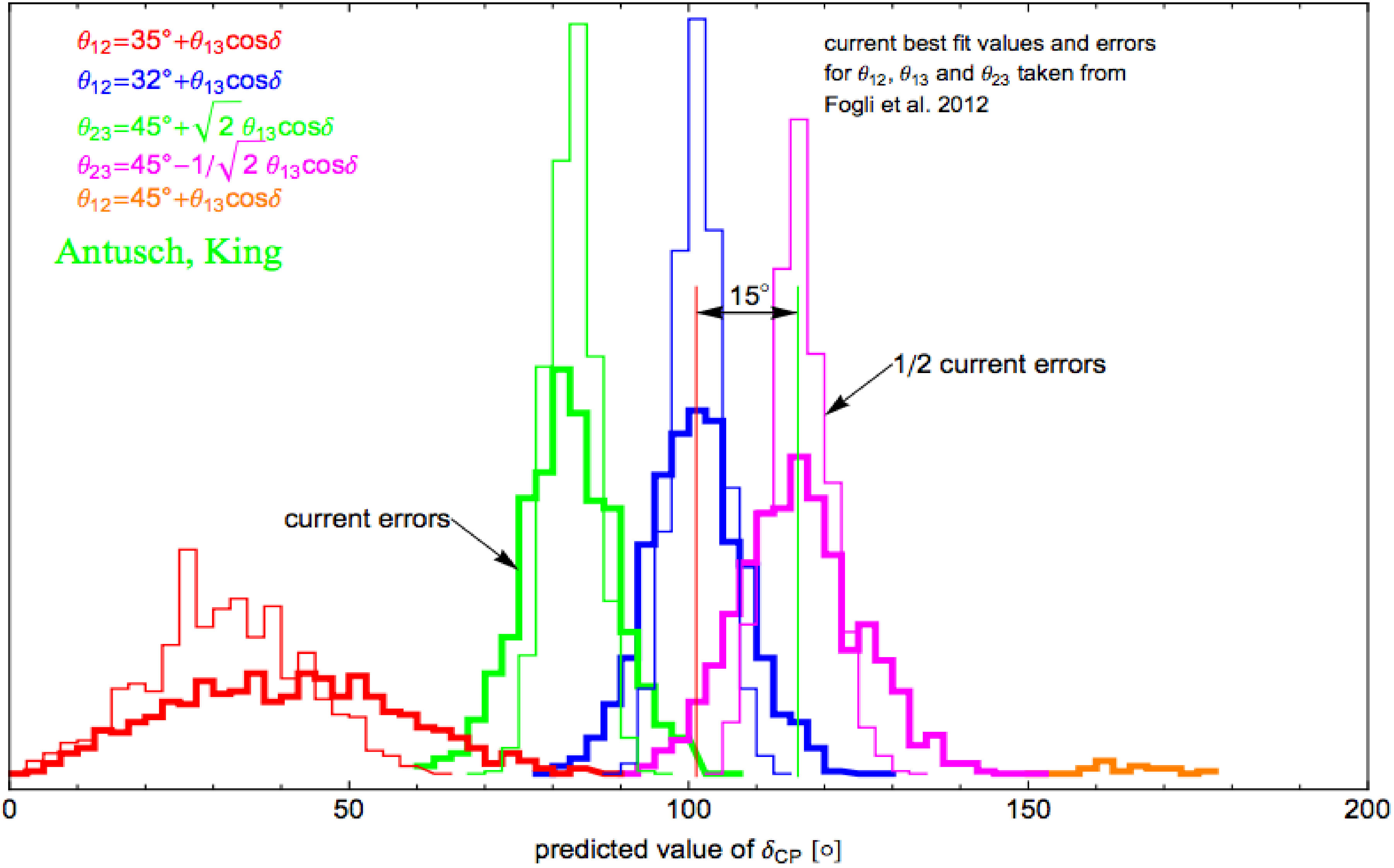


Figure shows only a small subset of the existing models ... !

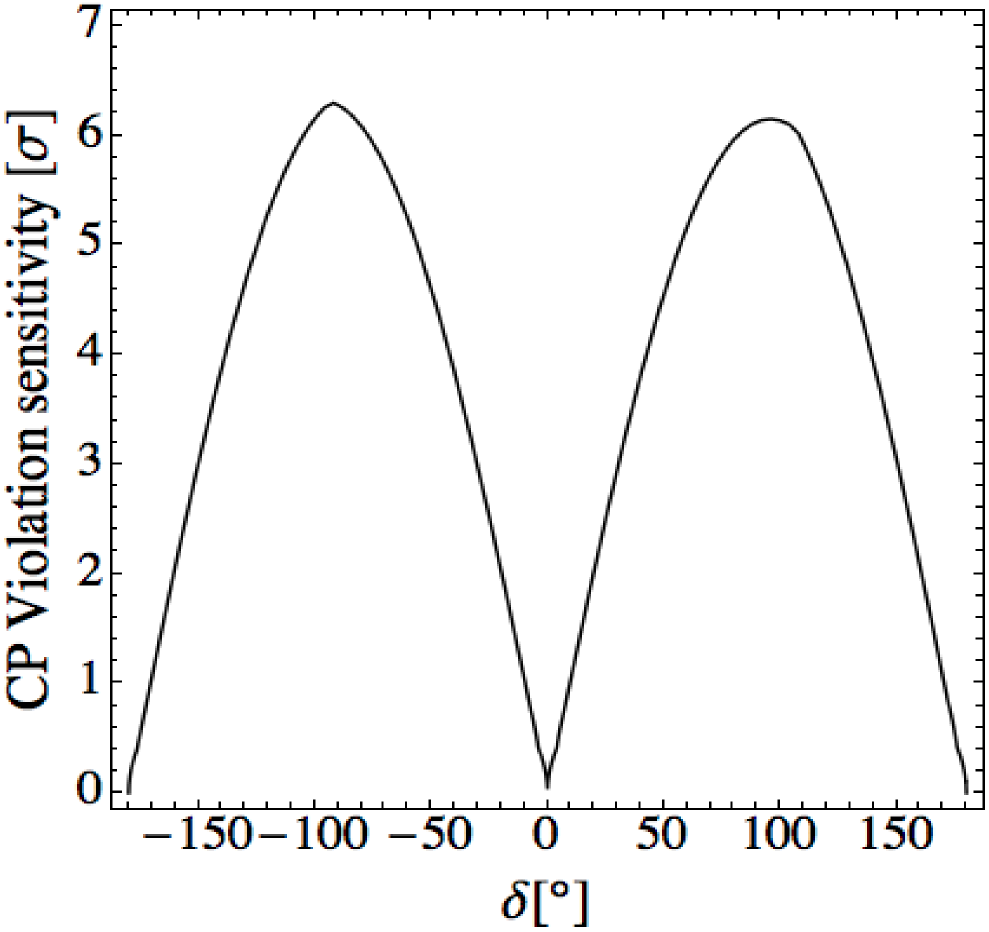
based on figure from Albright, Mu-Chun Chen ('06)

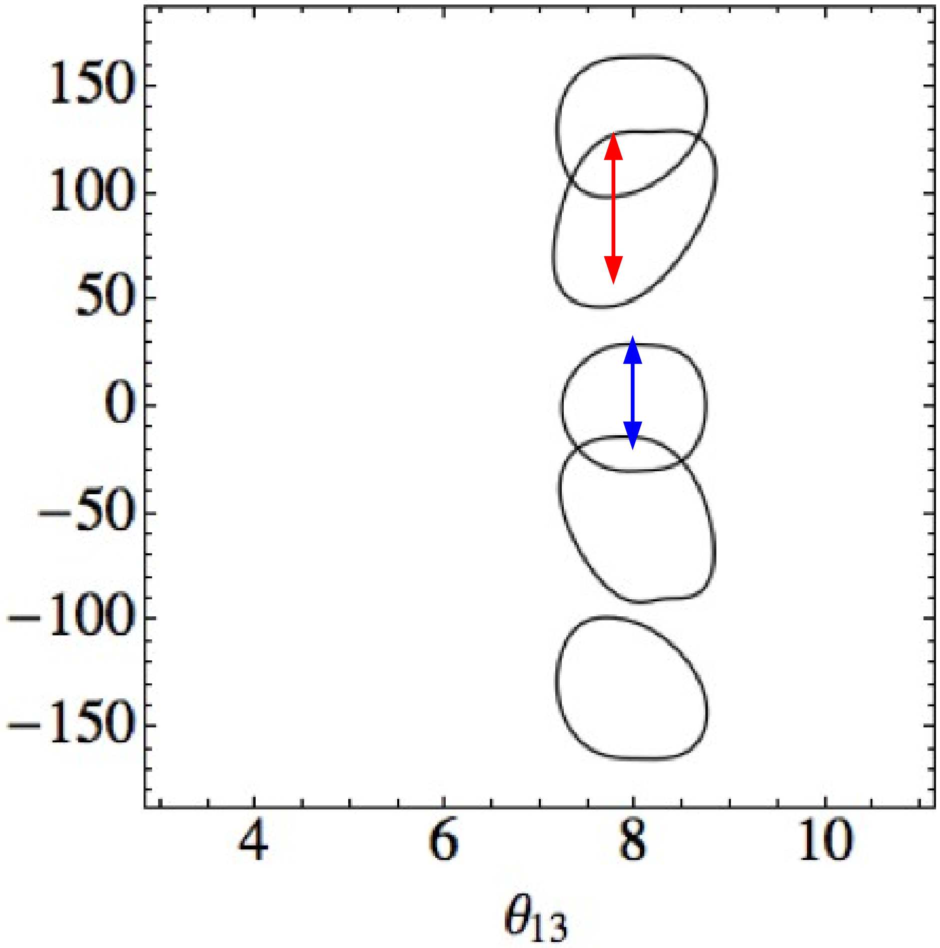
Why precision?



Plot courtesy of Patrick Huber

Why precision?





Are ν masses different?

When the SM was formulated, neutrino masses had not been observed yet. The simplest way to give them a mass is:

$$Y \overline{L}_L \widetilde{\phi} \nu_R + h.c. \xrightarrow{\text{EWSB}} m_{dirac} \propto Y v$$

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Right-handed neutrinos are SM singlets, though...

$$Y\overline{L}_L\widetilde{\phi}\nu_R + \frac{1}{2}M\overline{\nu}^c_R\nu_R + h.c. \qquad\qquad (\not{L})$$

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Small M implies extra sterile neutrino species

SBL anomalies?

Large M could explain the smallness of neutrino masses
→ window to scale of NP at high energies

leptogenesis?

Yanagida, 1979; Ramond, Gell-Mann, Slansky, 1979
Fukugita, Yanagida, 1986

Are ν masses different?

$$\mathcal{L}^{eff} = \mathcal{L}_{SM} + \frac{1}{\Lambda}\,\delta\mathcal{L}^{d=5} + \frac{1}{\Lambda^2}\,\delta\mathcal{L}^{d=6} + \ldots$$

The only d=5 operator which can be built within the SM particle content is

$$\mathcal{L}^{(5)} = \frac{c_5}{\Lambda_{NP}}(\overline{L}_L\widetilde{\phi})(\widetilde{\phi}^t L_L^c) \quad \longrightarrow \quad m_\nu \propto c_5\frac{v^2}{\Lambda}$$

Weinberg, 1979

If neutrino masses are generated through this operator, we should expect additional effects coming from higher dimension operators too…

Think outside of the box!

- New physics needed to give neutrinos a mass
- Neutrino oscillation experiments can be a good probe for physics beyond the Standard Model
  - Sterile neutrino searches
  - Extra dimensions
  - Non-Standard ν Interactions
  - Lorentz/CPT violation

All these need low systematics as well as a good and reliable energy reconstruction!

CP violation

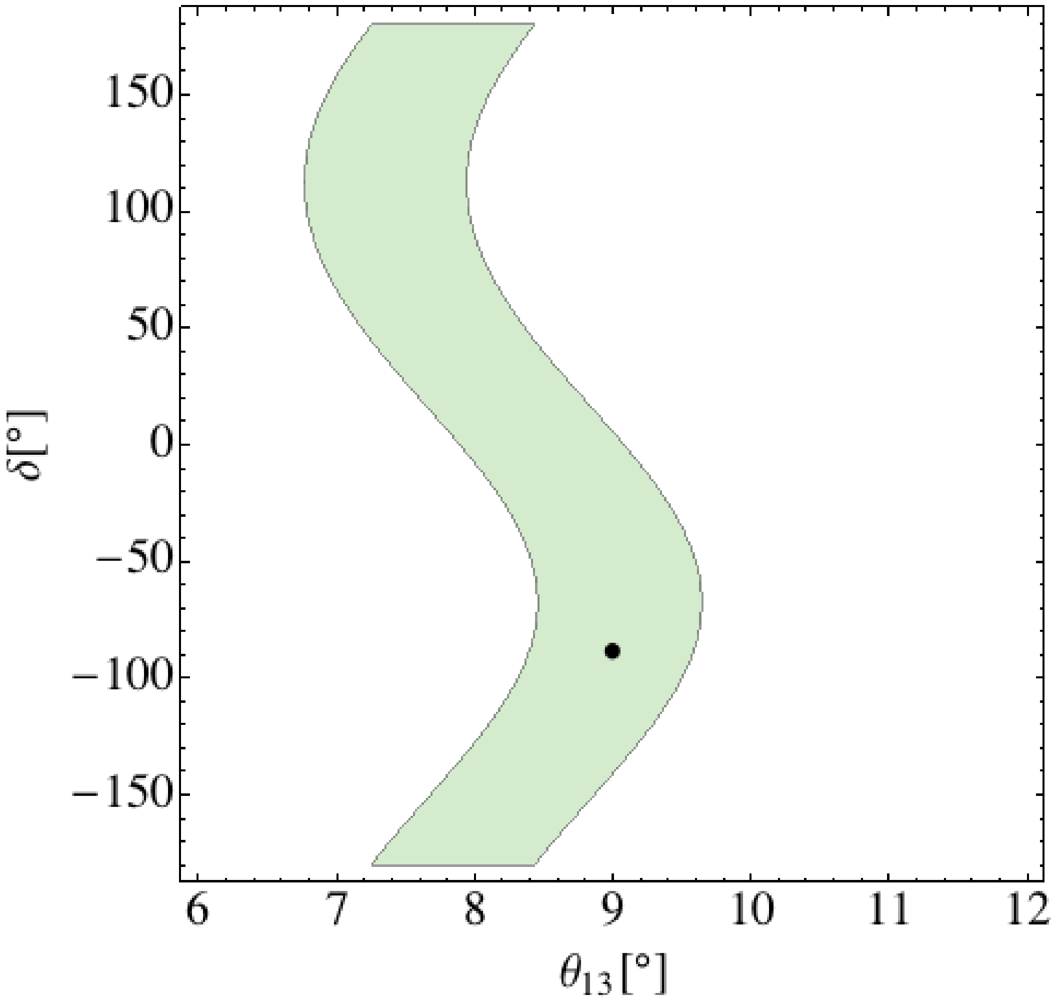
The golden channel in neutrino oscillations is:

$$P_{e\mu} = 4\left| \mathcal{W}_2 \sin\Delta_{21} + \mathcal{W}_3 \sin\Delta_{31} e^{i\Delta_{32}} \right|^2$$

$$\begin{aligned} P^{\pm}_{e\mu} &= \boxed{X_{\pm} \sin^2 2\theta_{13} \sin^2\left(\frac{\Delta m^2_{31} L}{4E}\right)} \\ &+ \boxed{Y_{\pm} \sin 2\theta_{13} \cos\left(\delta - \frac{\Delta m^2_{31} L}{4E}\right)} \\ &+ \boxed{Z} \end{aligned}$$

Cervera et al., hep-ph/0002108

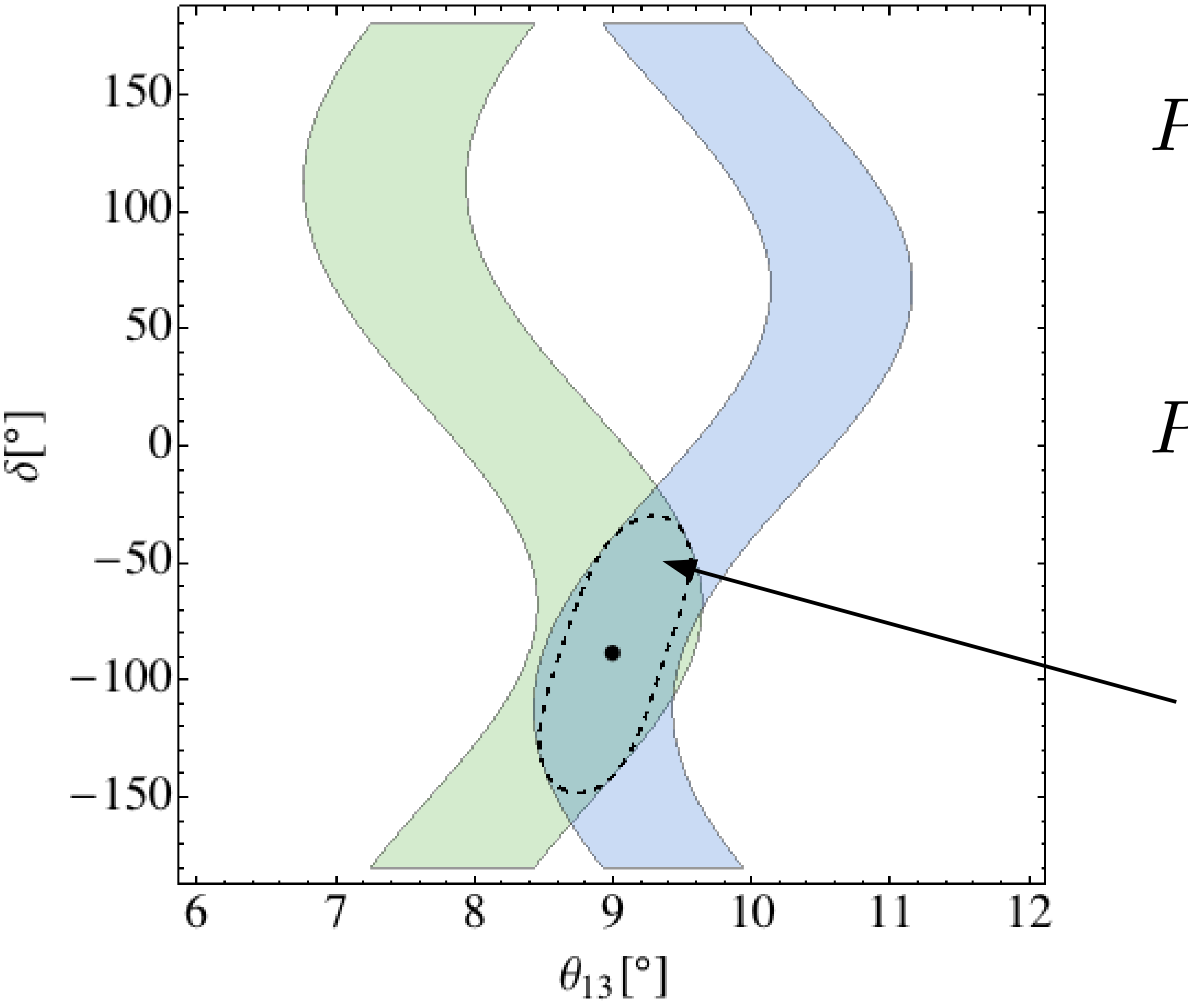
Rate info vs energy info



$$P_{\nu_e\nu_\mu}(\theta_{13},\delta) = \overline{P_\nu}$$

$$E_\nu = E_{peak}$$

Rate info vs energy info



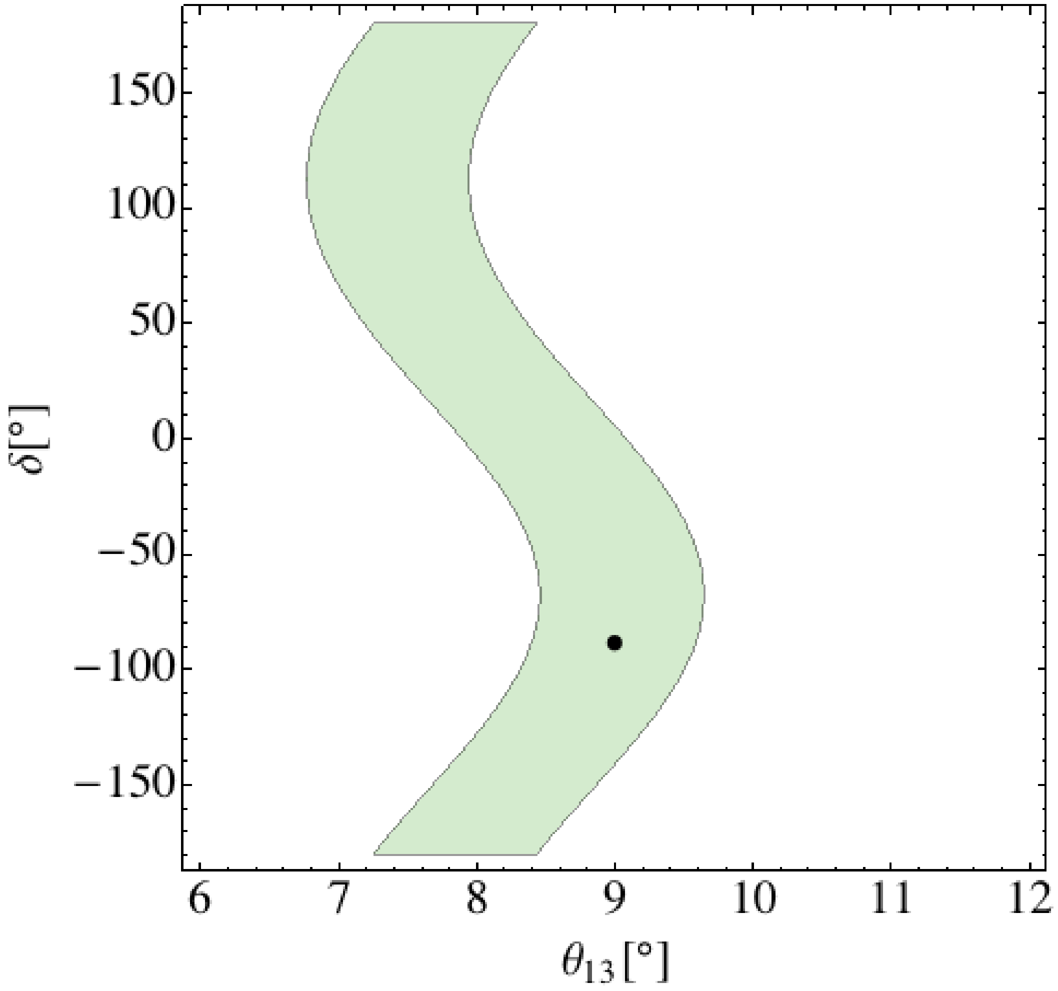
$$P_{\nu_e\nu_\mu}(\theta_{13},\delta) = \overline{P_\nu}$$

$$E_\nu = E_{peak}$$

$$P_{\bar{\nu}_e\bar{\nu}_\mu}(\theta_{13},\delta) = \overline{P_{\bar{\nu}}}$$

Notice the different shape

Rate info vs energy info



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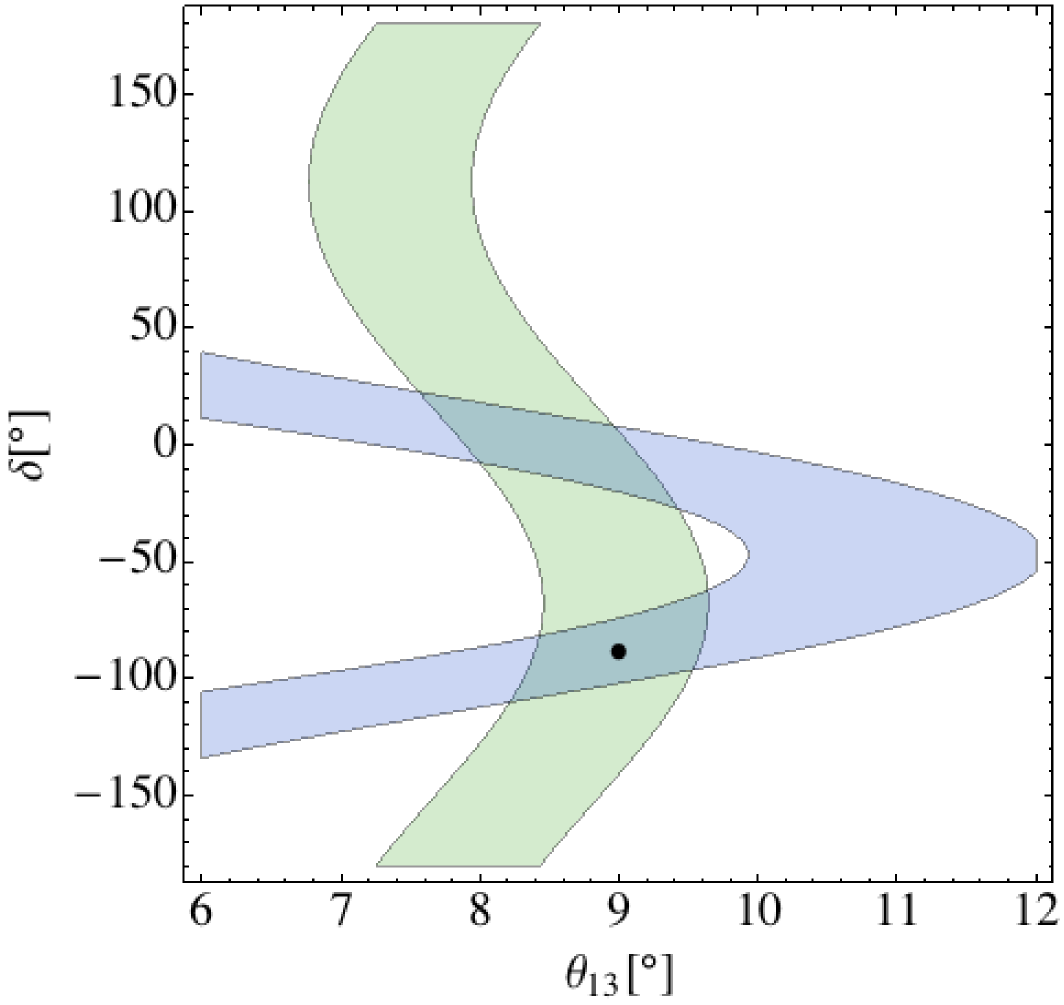
Rate info vs energy info

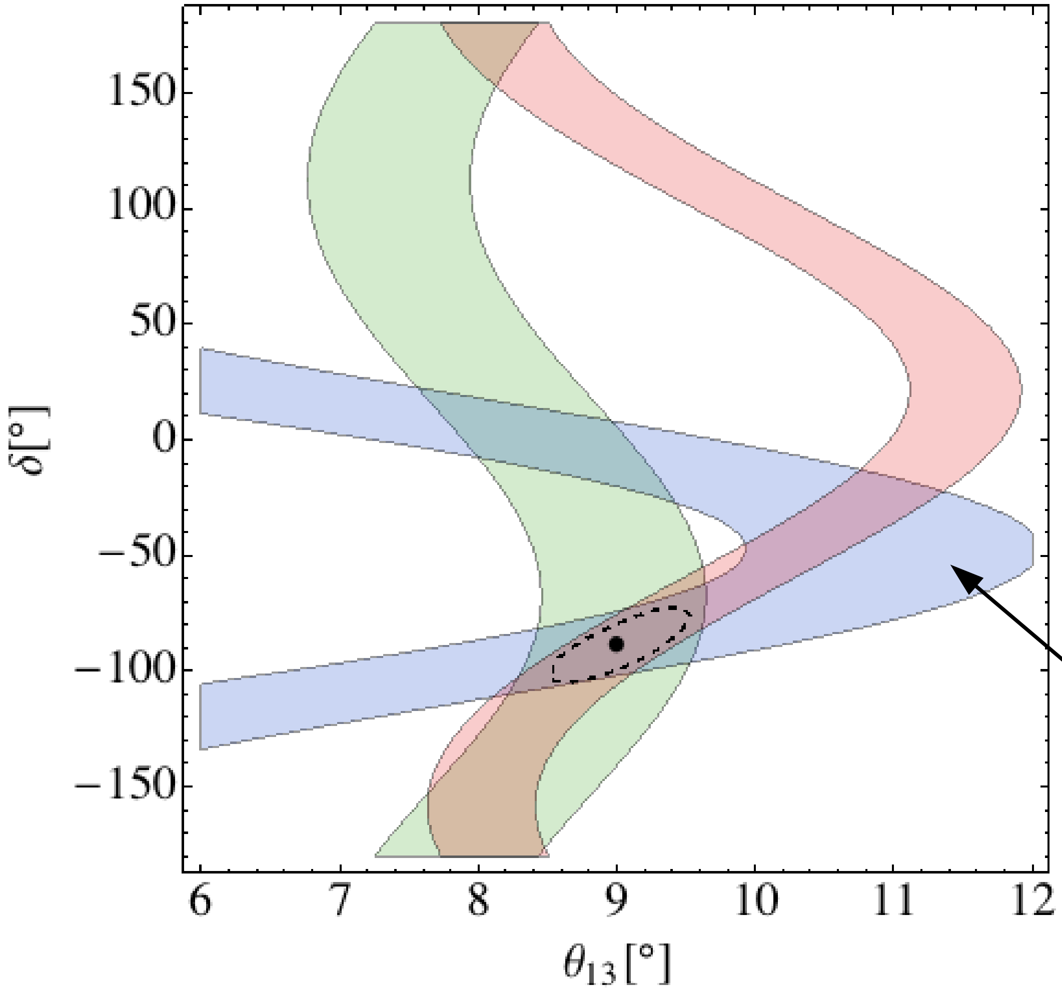


$$P_{\nu_e\nu_\mu}(\theta_{13},\delta) = \overline{P_\nu}$$

$$E_\nu = E_{peak}$$

$$E_\nu = 0.2E_{peak}$$

Rate info vs energy info



$$P_{\nu_e\nu_\mu}(\theta_{13},\delta) = \overline{P_\nu}$$

$$E_\nu = E_{peak}$$

$$E_\nu = 0.2E_{peak}$$

$$E_\nu = 0.1E_{peak}$$

As E decreases, the dependence with delta changes!

Mass ordering determination

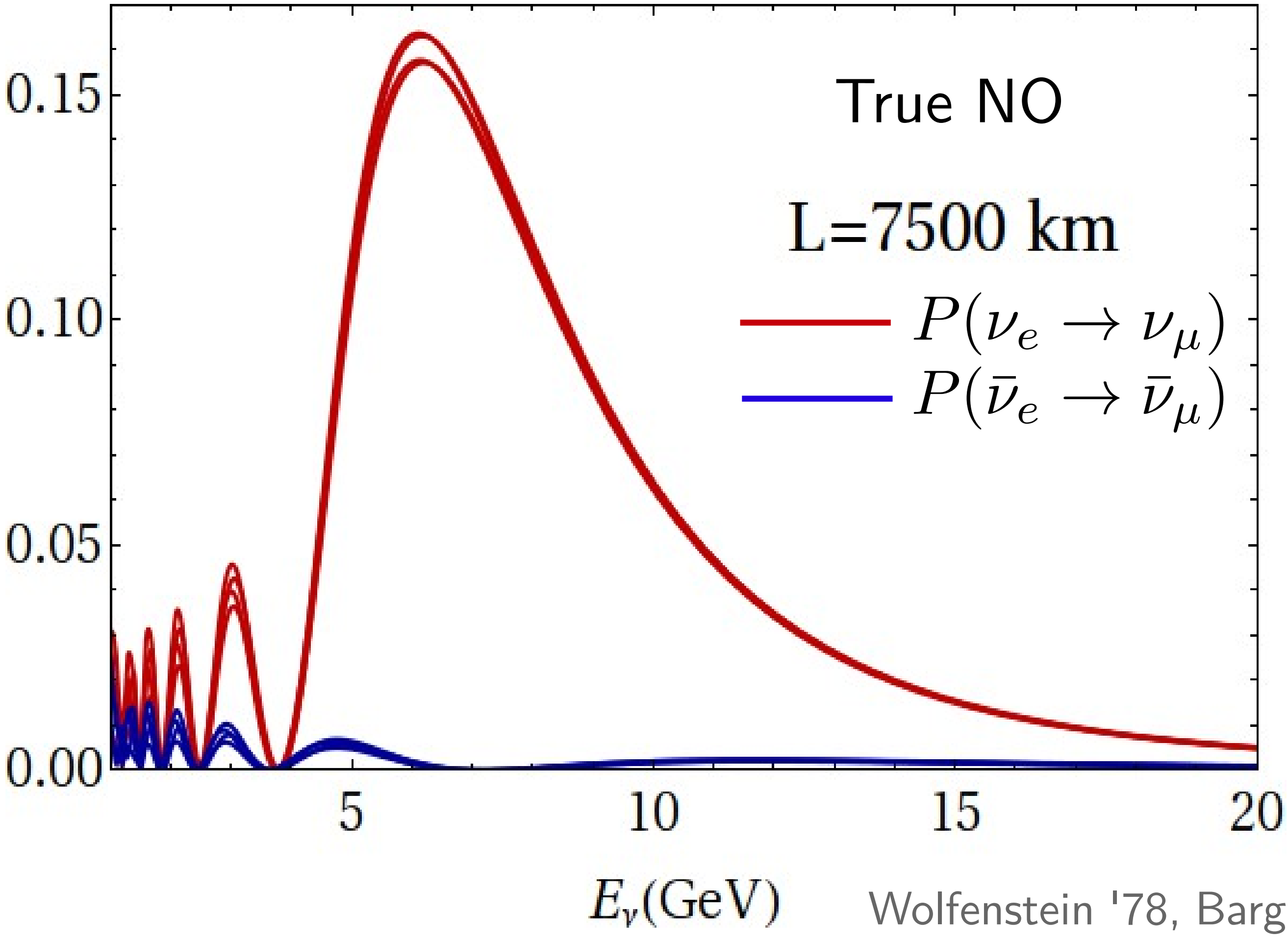
Freund, hep-ph/0103300

$$\begin{aligned} P_{e\mu} \simeq\ & \sin^2\theta_{23}\sin^2 2\theta_{13}\frac{\sin^2[(1-\hat{A})\Delta]}{(1-\hat{A})^2} \\ & \pm\ \alpha\sin 2\theta_{13}\sin 2\theta_{12}\sin 2\theta_{23}\sin\delta_{\mathrm{CP}}\sin(\Delta)\frac{\sin(\hat{A}\Delta)}{\hat{A}}\frac{\sin[(1-\hat{A})\Delta]}{(1-\hat{A})} \\ & +\ \alpha\sin 2\theta_{13}\sin 2\theta_{12}\sin 2\theta_{23}\cos\delta_{\mathrm{CP}}\cos(\Delta)\frac{\sin(\hat{A}\Delta)}{\hat{A}}\frac{\sin[(1-\hat{A})\Delta]}{(1-\hat{A})} \\ & +\ \alpha^2\cos^2\theta_{23}\sin^2 2\theta_{12}\frac{\sin^2(\hat{A}\Delta)}{\hat{A}^2}, \end{aligned}$$

$$\Delta \equiv \frac{\Delta m^2_{31}L}{4E_\nu}, \quad \hat{A} \equiv \frac{A}{\Delta m^2_{31}}, \quad A = \pm 2\sqrt{2}G_F N_e E_\nu$$

Effect is directly proportional to the baseline

Long-baseline experiments and MO



Wolfenstein '78, Barger et al '80
Mikheev and Smirnov '85

Other ways to determine the MO

1) Reactor experiments at medium baselines (JUNO, RENO50)

2) Matter effects in atmospheric neutrino experiments (PINGU, ORCA, INO)

3) Precise determination of mass splittings

Experimental landscape,
and introduction to systematics

Types of neutrino beams

- Based on pion-decay (NOνA, T2K, LBNE, LBNO, ESSnuSB, DAEδALUS*)

$$\pi^+ \to \mu^+ \nu_\mu \qquad\qquad \nu_\mu \longrightarrow \nu_e$$

  Technology well-known; but intrinsic backgrounds and typically large systematics

- Based on muon decay (IDS-NF, NuMAX,DAEδALUS*)

$$\mu^+ \to e^+ \bar{\nu}_\mu \nu_e \qquad\qquad \begin{matrix} (\nu_\mu \longrightarrow \nu_e(\nu_\tau)) \\ \nu_e \longrightarrow \nu_\mu(\nu_\tau) \end{matrix}$$

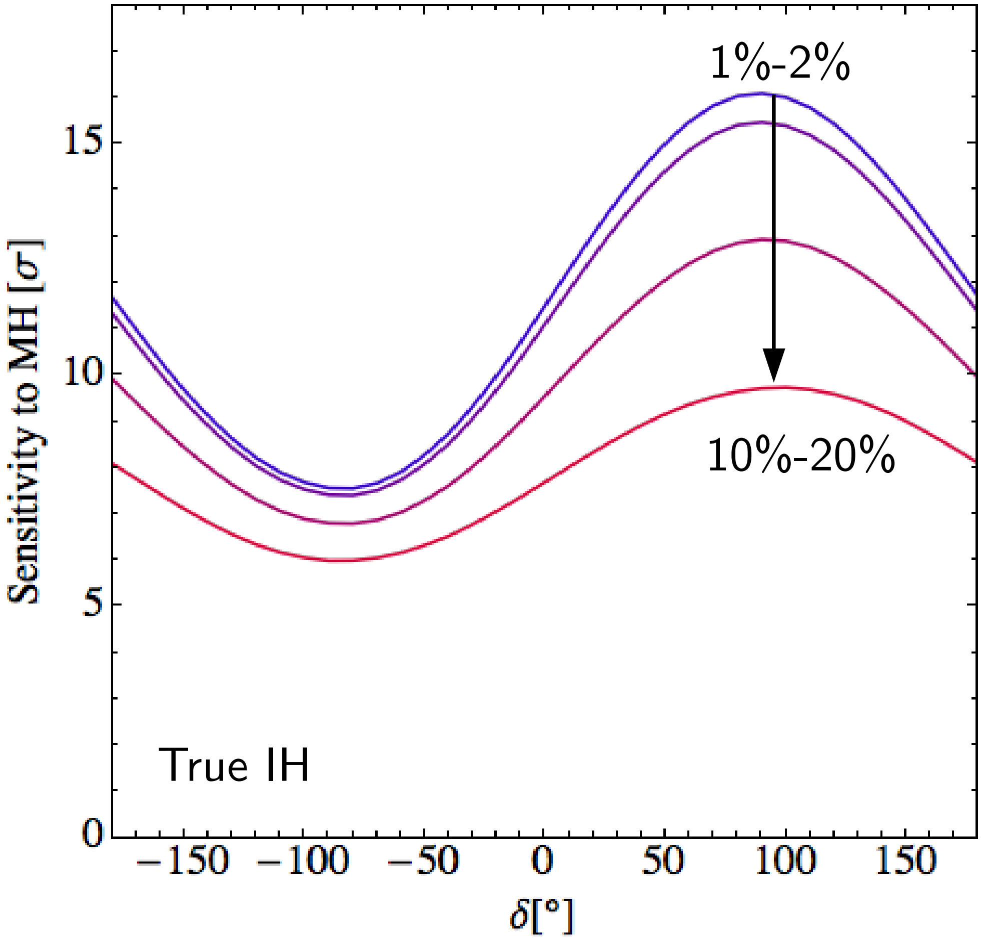
  Very clean, low systematics, flavor rich; but technically challenging and typically requires charge discrimination at detector

- Beta-Beams (gamma = 100, 350, …)
  - Ions used: He/Ne, or Li/B

Systematics and mass ordering

- The resonance is a leading order term, and the effect is proportional to the baseline
- Statistics helps
- Matter uncertainty is a dangerous systematics
- Normalization uncertainties affect the sensitivity, but motsly for some values of δ

LBNF: 1.2MW, 34 kt



Impact of systematics on CPV

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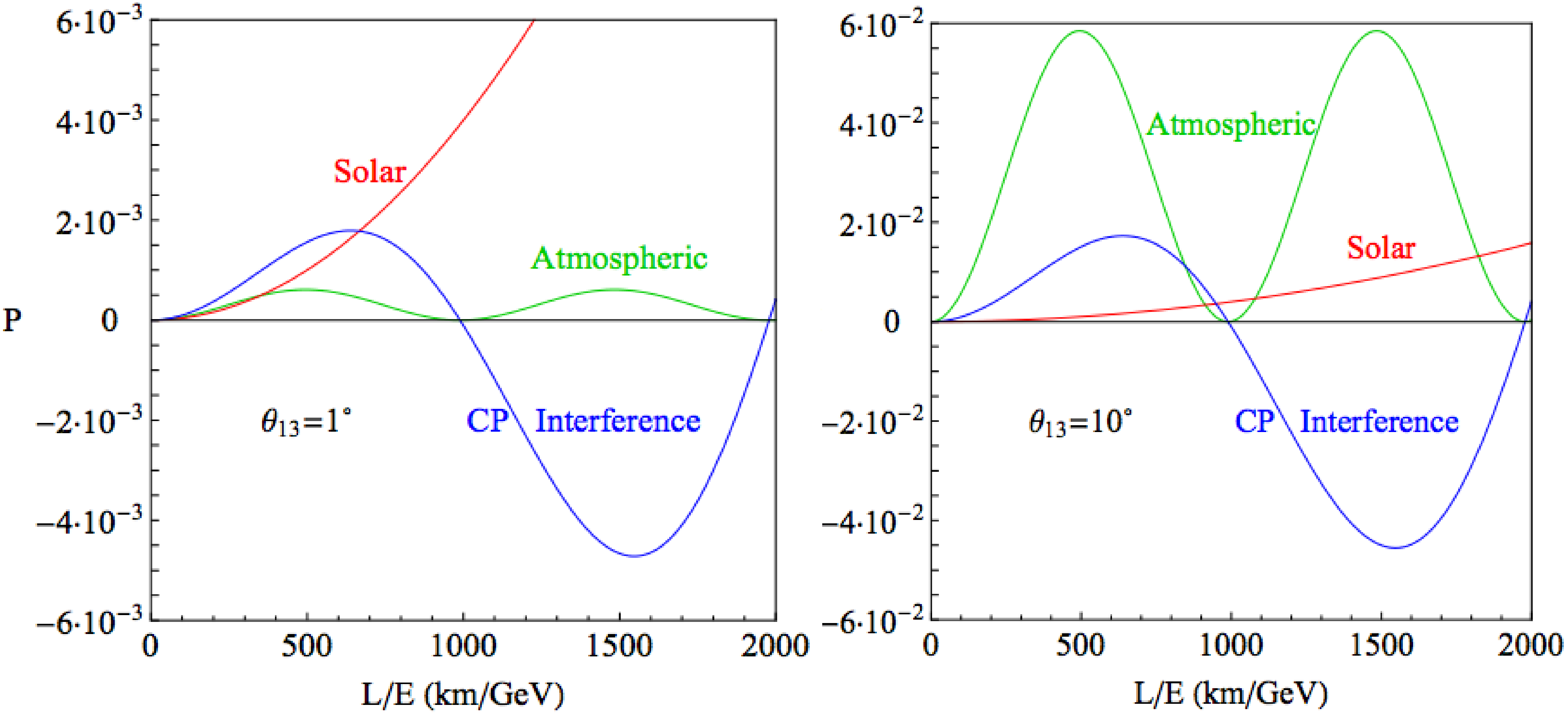

Coloma and Fernandez-Martinez, 1110.4583 [hep-ph]

Impact of normalization uncertainties

- Traditional approach:
  - Add a normalization uncertainty as a nuisance parameter in your χ^2

$$\chi^2 = min_\xi \left\{ \frac{(\overline{N} - N(1+\xi))^2}{\overline{N}} + \left(\frac{\xi}{\sigma_\xi} \right)^2 \right\}$$

  - One needs to determine what is the correct value for σ beforehand: may be difficult
  - Near detector: what is the impact?
  - Correlations not implemented in a physics-wise manner
  - No shape uncertainties here!

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Shopping list:

- One needs to determine what is the correct value for σ beforehand: may be difficult
- Near detector: what is the impact?
- Correlations not implemented in a physics-wise manner
- No shape uncertainties here!

Normalization uncertainties
And Near detectors

Near/Far cancellation?

$$n_{\alpha\to\beta}(L,E) \sim \frac{1}{L^2}\epsilon_\beta(E)\times\sigma_\beta(E)\times\phi_\alpha(E)\times P_{\alpha\beta}(L,E)$$

At reactor experiments, the cancellation of systematics between near/far detectors is very effective:

$$\frac{n_{ee}^{FD}}{n_{ee}^{ND}} \sim \frac{L_{ND}^2}{L_{FD}^2}\cancel{\frac{\epsilon_e\sigma_e\phi_e}{\epsilon_e\sigma_e\phi_e}}P_{ee}$$

- Daya Bay has measured

$$\sin^2 2\theta_{13} = 0.084^{+0.005}_{-0.005}$$

(Results presented at Neutrino2014, see talk by Chao Zhang)

Near/Far cancellation?

- For CP violation searches, we need an apperance experiment
- An ideal near detector can be used to predict some backgrounds:

$$n_{\nu_e}^{FD,bg} \sim n_{\nu_e}^{ND,bg} \frac{L_{ND}^2}{L_{FD}^2} \frac{V_{FD}}{V_{ND}}$$

  - How well can the extrapolation be done?
  - How large is the nue sample at the ND?
  - Mis-identification backgrounds coming from CC numu interactions will be different (oscillations)

Huber, Mezzetto and Schwetz, 0711.2950 [hep-ph]

Impact of normalization uncertainties

- However, a similar extrapolation for the signal will not work that well:

$$n_{\nu_e}^{FD,sig} \sim n_{\nu_\mu}^{ND,sig} \frac{L_{ND}^2}{L_{FD}^2} \frac{V_{FD}}{V_{ND}} \boxed{\frac{\tilde{\sigma}_{\nu_e}}{\tilde{\sigma}_{\nu_\mu}}} \times P(\nu_\mu \to \nu_e)$$

!!!!

$(\tilde{\sigma} \equiv \sigma\epsilon)$

Huber, Mezzetto and Schwetz, 0711.2950 [hep-ph]

Impact of normalization uncertainties

- CP violation is observed comparing ν and anti-ν rates:

$$\frac{n_{\nu_e}^{FD,sig}}{n_{\bar{\nu}_e}^{FD,sig}} \sim \frac{n_{\nu_\mu}^{ND,sig}}{n_{\bar{\nu}_\mu}^{ND,sig}} \boxed{\frac{\tilde{\sigma}_{\nu_e}}{\tilde{\sigma}_{\nu_\mu}} \frac{\tilde{\sigma}_{\bar{\nu}_\mu}}{\tilde{\sigma}_{\bar{\nu}_e}}} \times \frac{P(\nu_\mu \to \nu_e)}{P(\bar{\nu}_\mu \to \bar{\nu}_e)}$$

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Huber, Mezzetto and Schwetz, 0711.2950 [hep-ph]

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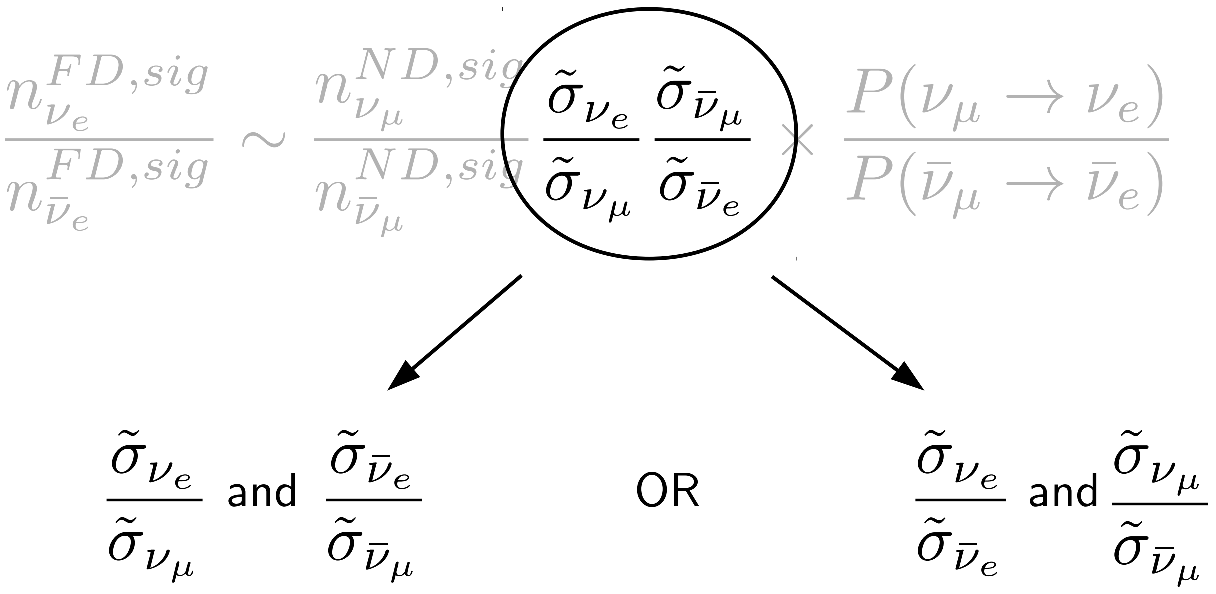

$$\frac{n^{FD,sig}_{\nu_e}}{n^{FD,sig}_{\bar{\nu}_e}} \sim \frac{n^{ND,sig}_{\nu_\mu}}{n^{ND,sig}_{\bar{\nu}_\mu}} \boxed{\frac{\tilde{\sigma}_{\nu_e}}{\tilde{\sigma}_{\nu_\mu}} \frac{\tilde{\sigma}_{\bar{\nu}_\mu}}{\tilde{\sigma}_{\bar{\nu}_e}}} \times \frac{P(\nu_\mu \to \nu_e)}{P(\bar{\nu}_\mu \to \bar{\nu}_e)}$$

We need:

$\frac{\tilde{\sigma}_{\nu_e}}{\tilde{\sigma}_{\nu_\mu}}$ and $\frac{\tilde{\sigma}_{\bar{\nu}_e}}{\tilde{\sigma}_{\bar{\nu}_\mu}}$ OR $\frac{\tilde{\sigma}_{\nu_e}}{\tilde{\sigma}_{\bar{\nu}_e}}$ and $\frac{\tilde{\sigma}_{\nu_\mu}}{\tilde{\sigma}_{\bar{\nu}_\mu}}$

$(\tilde{\sigma} \equiv \sigma\epsilon)$

Huber, Mezzetto and Schwetz, 0711.2950 [hep-ph]

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We need:

$$\frac{\tilde{\sigma}_{\nu_e}}{\tilde{\sigma}_{\nu_\mu}} \text{ and } \frac{\tilde{\sigma}_{\bar{\nu}_e}}{\tilde{\sigma}_{\bar{\nu}_\mu}} \longleftarrow$$

I will focus on this choice

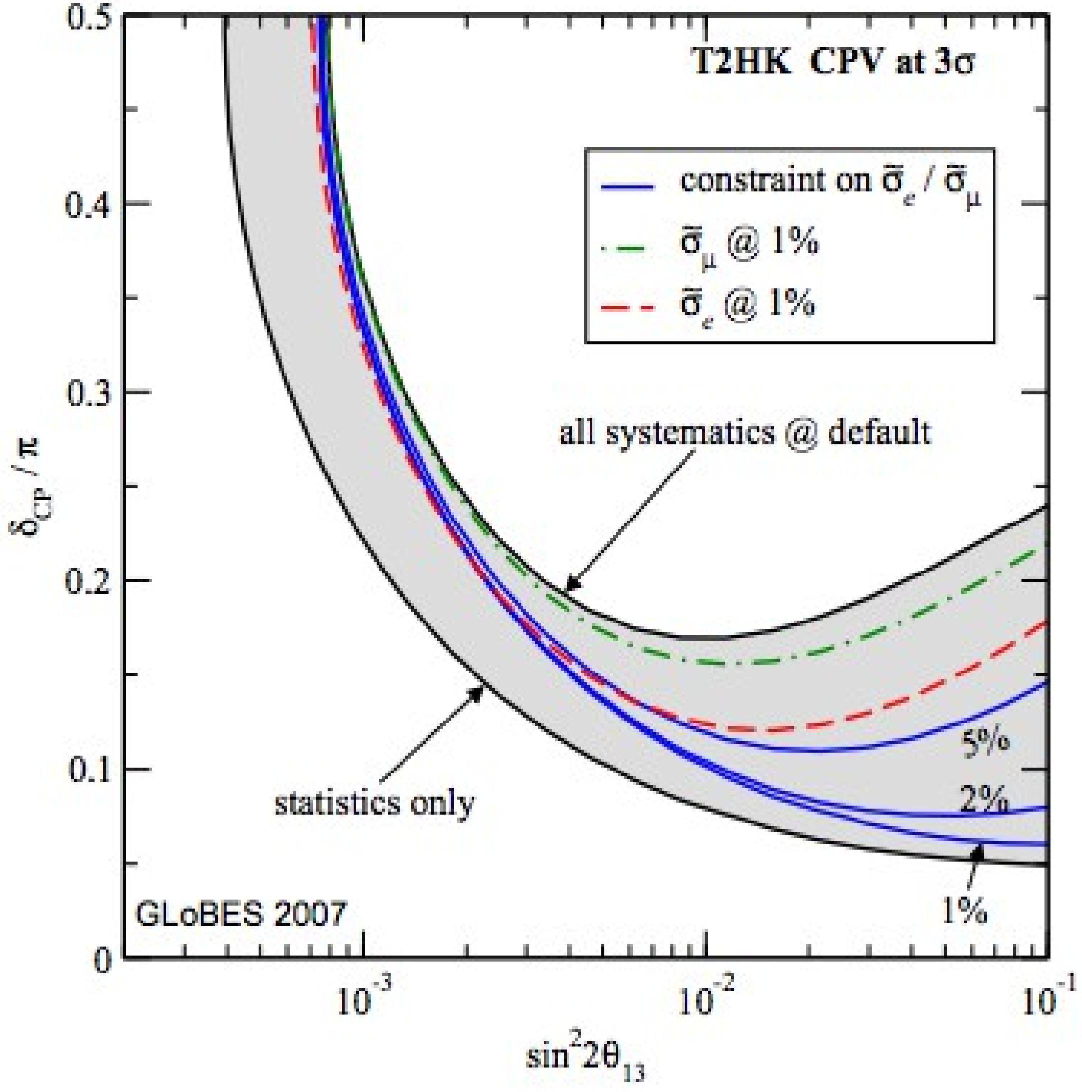
(see Day, McFarland,
1206.6745 [hep-ph])

$$(\tilde{\sigma} \equiv \sigma\epsilon)$$

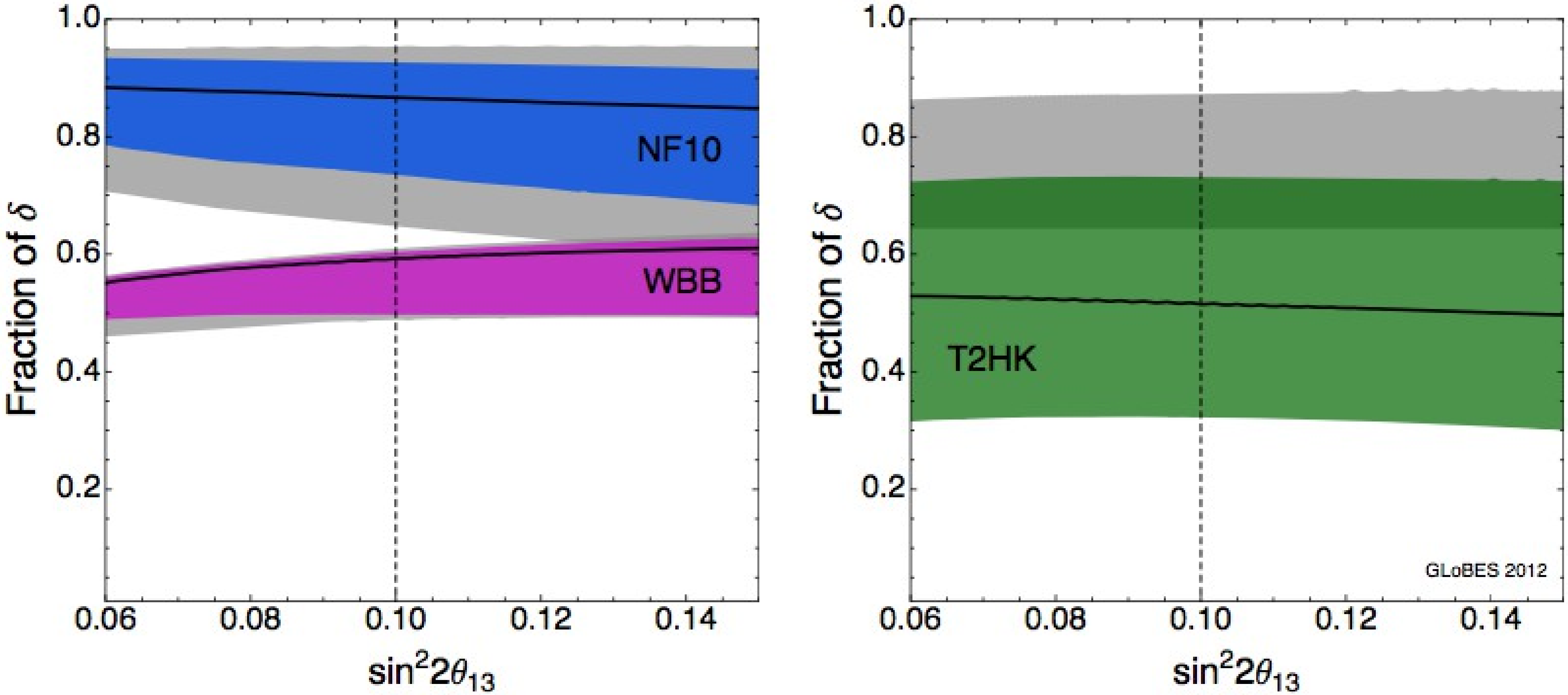
Huber, Mezzetto and Schwetz, 0711.2950 [hep-ph]

Impact of normalization uncertainties

Huber, Mezzetto and Schwetz, 0711.2950 [hep-ph]



Large theta13 scenario



Coloma, Huber, Kopp, Winter,
1209.5973 [hep-ph]

Normalization uncertainties
And Correlations

Correlations

- Correlations can help to reduce impact of systematics:
    - If the flux has been underestimated, I should expect the same effect for appearance and disappearance channels $\rightarrow$ the far detector can act as a "near detector"
    - The effect is rather large

Correlations

$$\chi_r^2 = \sum_i 2\left(T_{r,i}(\vec{\Theta},\vec{\xi}) - O_{r,i} + O_{r,i}\ln\frac{O_{r,i}}{T_{r,i}(\vec{\Theta},\vec{\xi})}\right)$$

$$\chi^2 = \sum_r \chi_r^2 + \sum_k \left(\frac{\xi_k}{\sigma_k}\right)^2 .$$

observed

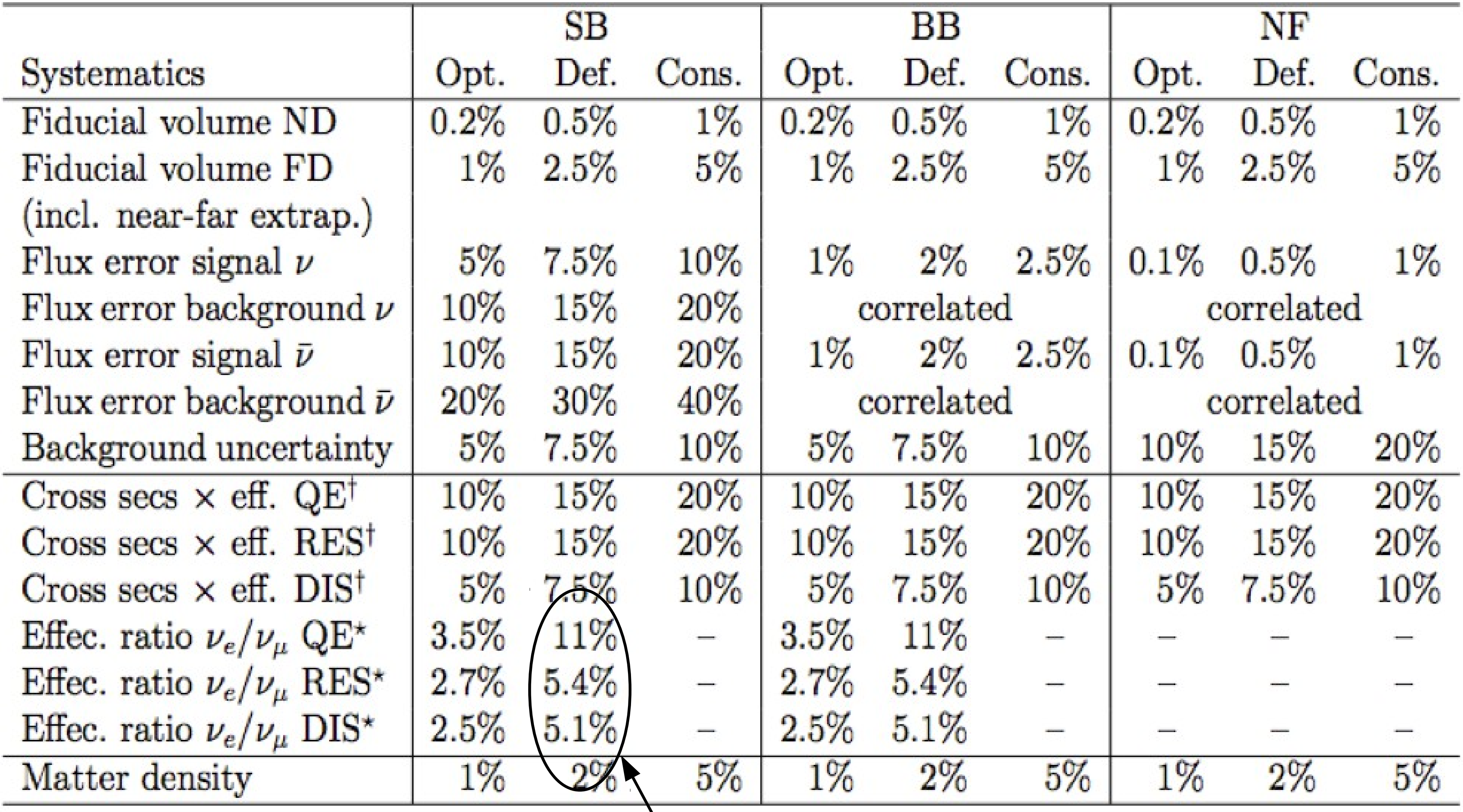
predicted

Precited event rates may include correlations between different channels and/or detectors:

$$T_{r,i}(\vec{\Theta},\vec{\xi}) = \sum_c \left(1 + a_{r,c}(\vec{\xi})\right) S_{r,c,i}(\vec{\Theta})$$

$$a_{r,c} \equiv \sum_k w_{r,c,k}\,\xi_k$$

Either 1 (corr.) or 0 (unc.)

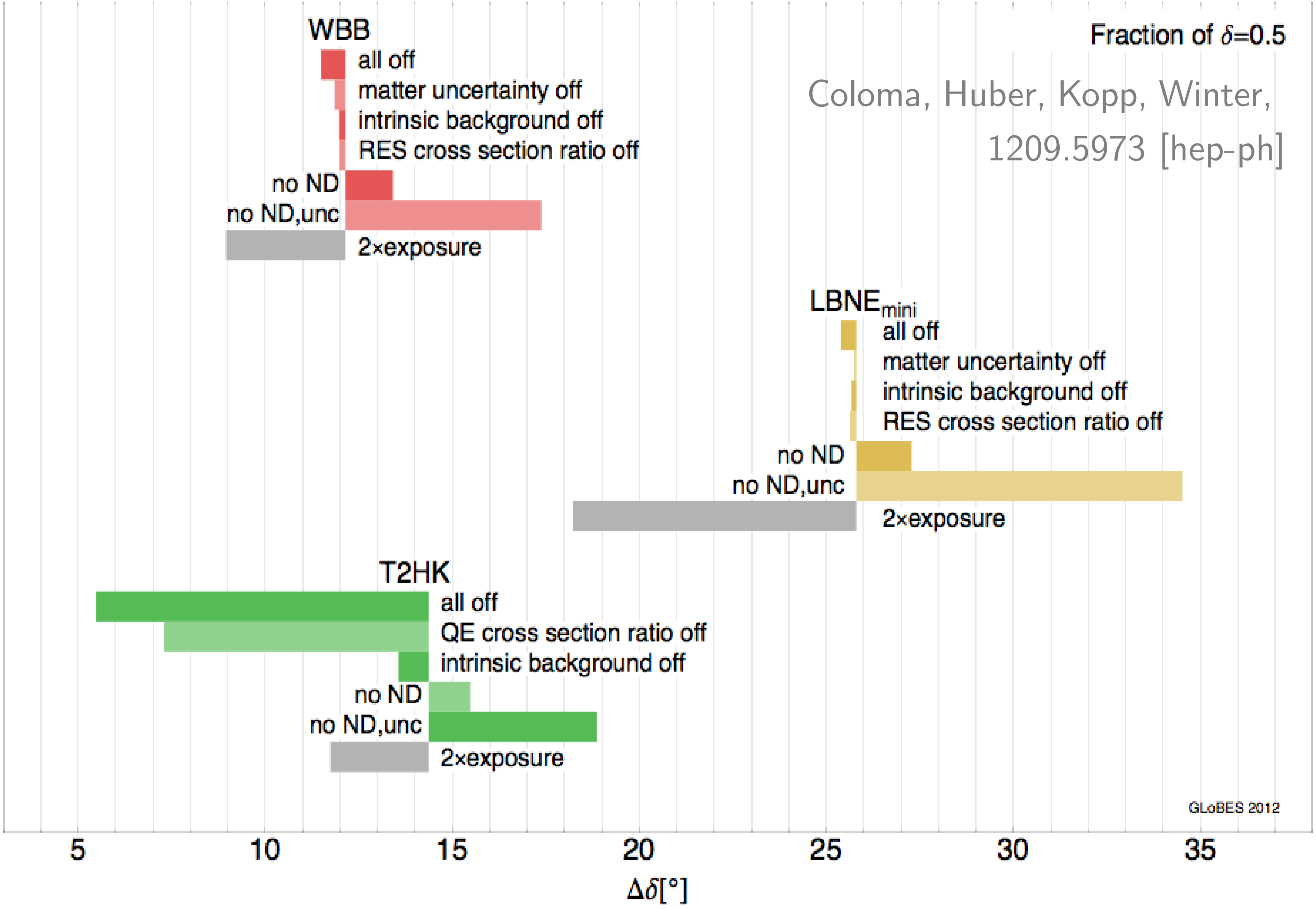


Systematics	SB Opt.	SB Def.	SB Cons.	BB Opt.	BB Def.	BB Cons.	NF Opt.	NF Def.	NF Cons.
Fiducial volume ND	0.2%	0.5%	1%	0.2%	0.5%	1%	0.2%	0.5%	1%
Fiducial volume FD (incl. near-far extrap.)	1%	2.5%	5%	1%	2.5%	5%	1%	2.5%	5%
Flux error signal ν	5%	7.5%	10%	1%	2%	2.5%	0.1%	0.5%	1%
Flux error background ν	10%	15%	20%	correlated			correlated		
Flux error signal $\bar{\nu}$	10%	15%	20%	1%	2%	2.5%	0.1%	0.5%	1%
Flux error background $\bar{\nu}$	20%	30%	40%	correlated			correlated		
Background uncertainty	5%	7.5%	10%	5%	7.5%	10%	10%	15%	20%
Cross secs × eff. QE†	10%	15%	20%	10%	15%	20%	10%	15%	20%
Cross secs × eff. RES†	10%	15%	20%	10%	15%	20%	10%	15%	20%
Cross secs × eff. DIS†	5%	7.5%	10%	5%	7.5%	10%	5%	7.5%	10%
Effec. ratio ν_e/ν_μ QE*	3.5%	11%	–	3.5%	11%	–	–	–	–
Effec. ratio ν_e/ν_μ RES*	2.7%	5.4%	–	2.7%	5.4%	–	–	–	–
Effec. ratio ν_e/ν_μ DIS*	2.5%	5.1%	–	2.5%	5.1%	–	–	–	–
Matter density	1%	2%	5%	1%	2%	5%	1%	2%	5%

Coloma, Huber, Kopp, Winter, 1209.5973 [hep-ph]

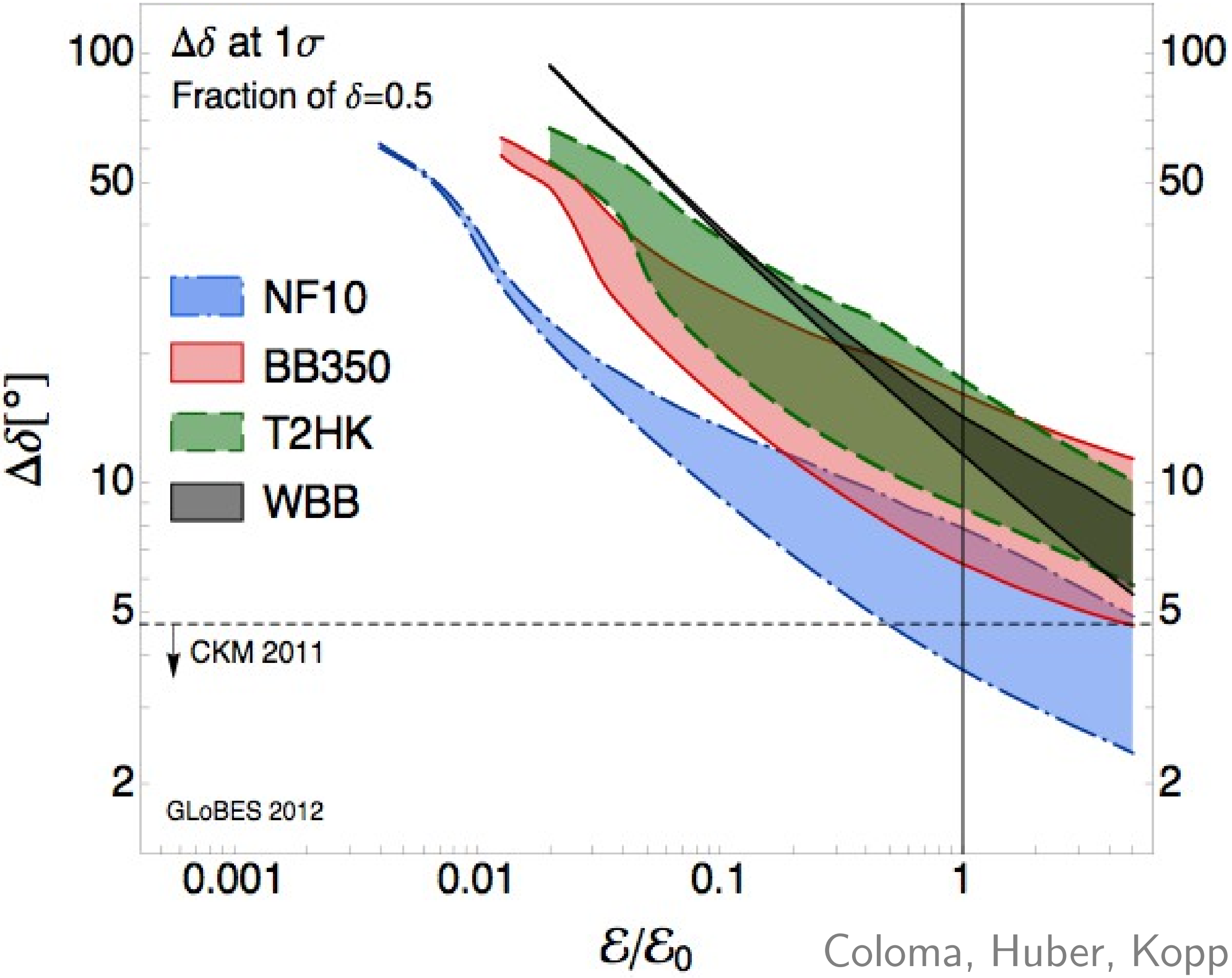
(Theoretical constraint)

Impact on precision



Coloma, Huber, Kopp, Winter, 1209.5973 [hep-ph]

Impact on precision



Coloma, Huber, Kopp, Winter, 1209.5973 [hep-ph]

Some things to take home...

Possible ways to reduce the effect of <u>normalization uncertainties</u>:

1. measure final flavor cross sections at a near detector. If this cannot be done, put constraints on ratios between cross sections for different flavors
2. measure intrinsic background at near detector
3. use data from disappearance channels at the far detector

Caveats

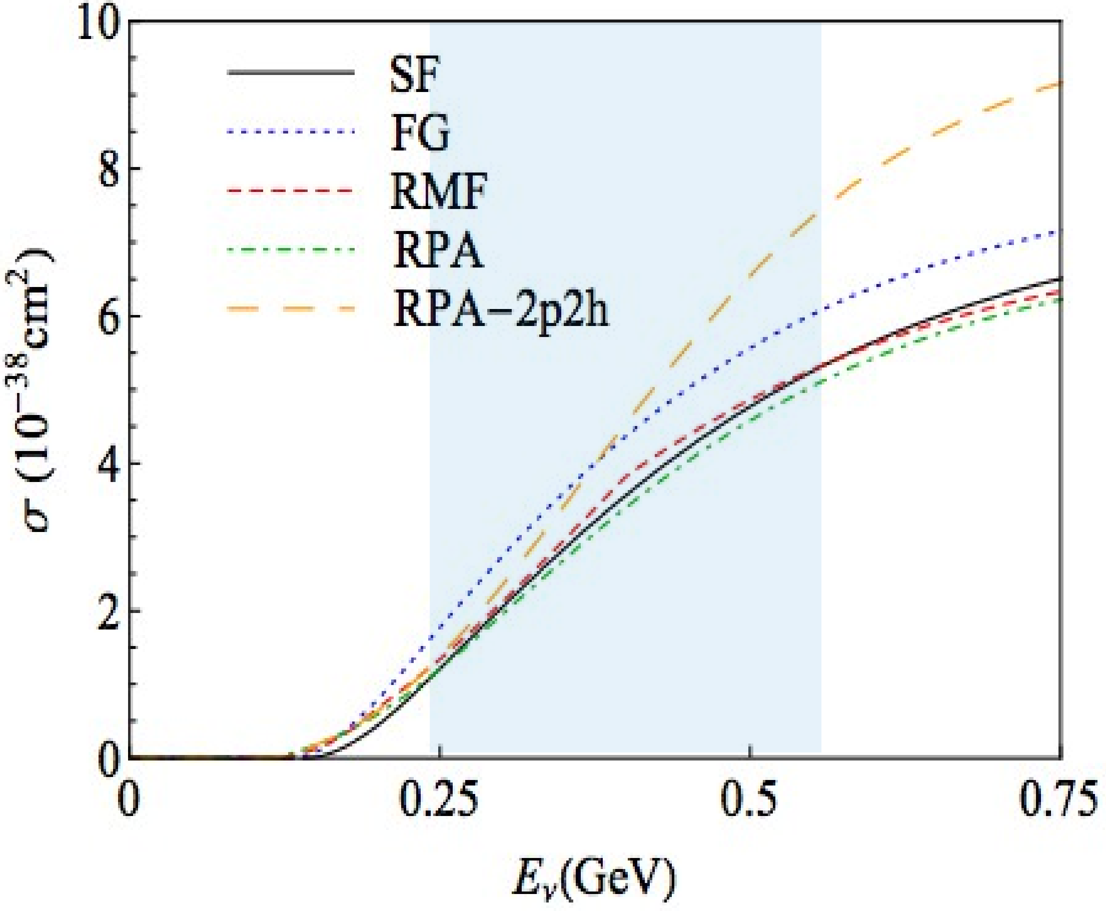
- Near and far detector fluxes can be very different:
  - Geometrical acceptance
  - If you don't know your flux nor your cross section, how can you constrain both?
- Near and far detector efficiencies will unfortunately be not so identical:
  - Different capabilities to contain events
  - Different background rejection capabilities

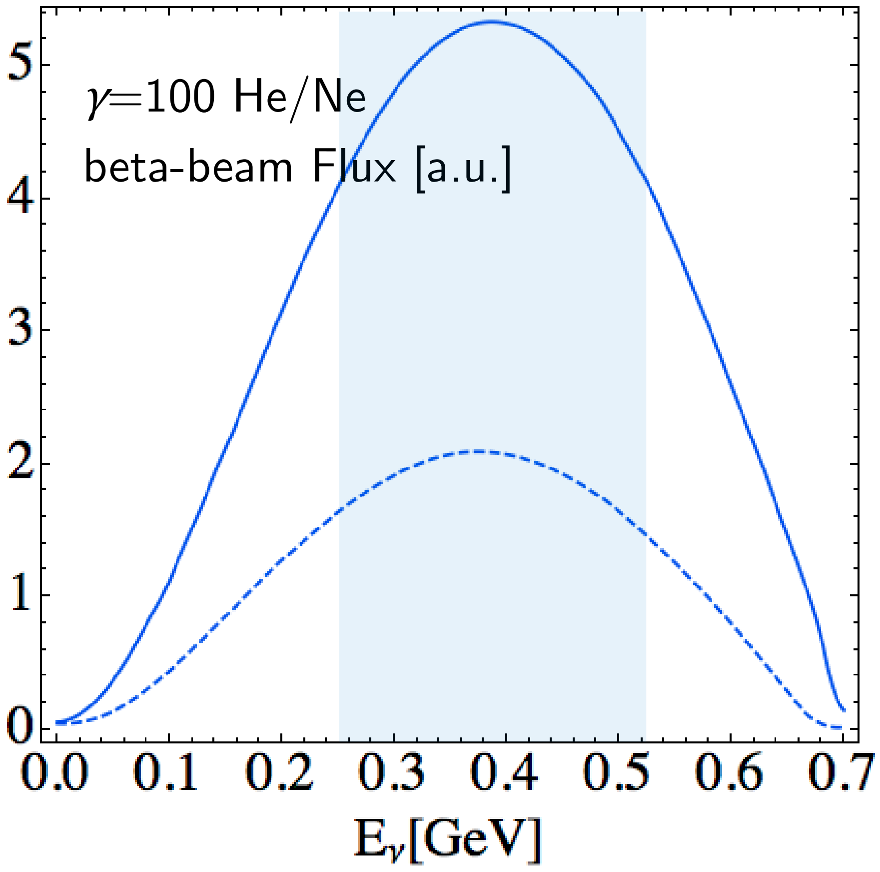
Shape uncertainties

Cross section models

- In Fernandez-Martinez & Meloni, arXiv: 1010.2329 [hep-ph], the performance of a beta-beam setup (QE regime) was studied using different cross sections:
  - Fermi Gas model, with p_F and E_B from electron scattering data
  - SF: Spectral function computed within the local density approximation, see talks by O. Benhar
    (Benhar et al, Nucl.Phys. A579 (1994) 493-517)
  - Relativistic Mean Field (Udias et al, nucl-th/0101038)
  - RPA (long range correlations, see J. Nieves talks), with and without 2p2h (Martini et al, 0910.2622 [nucl-th]])

Cross section models

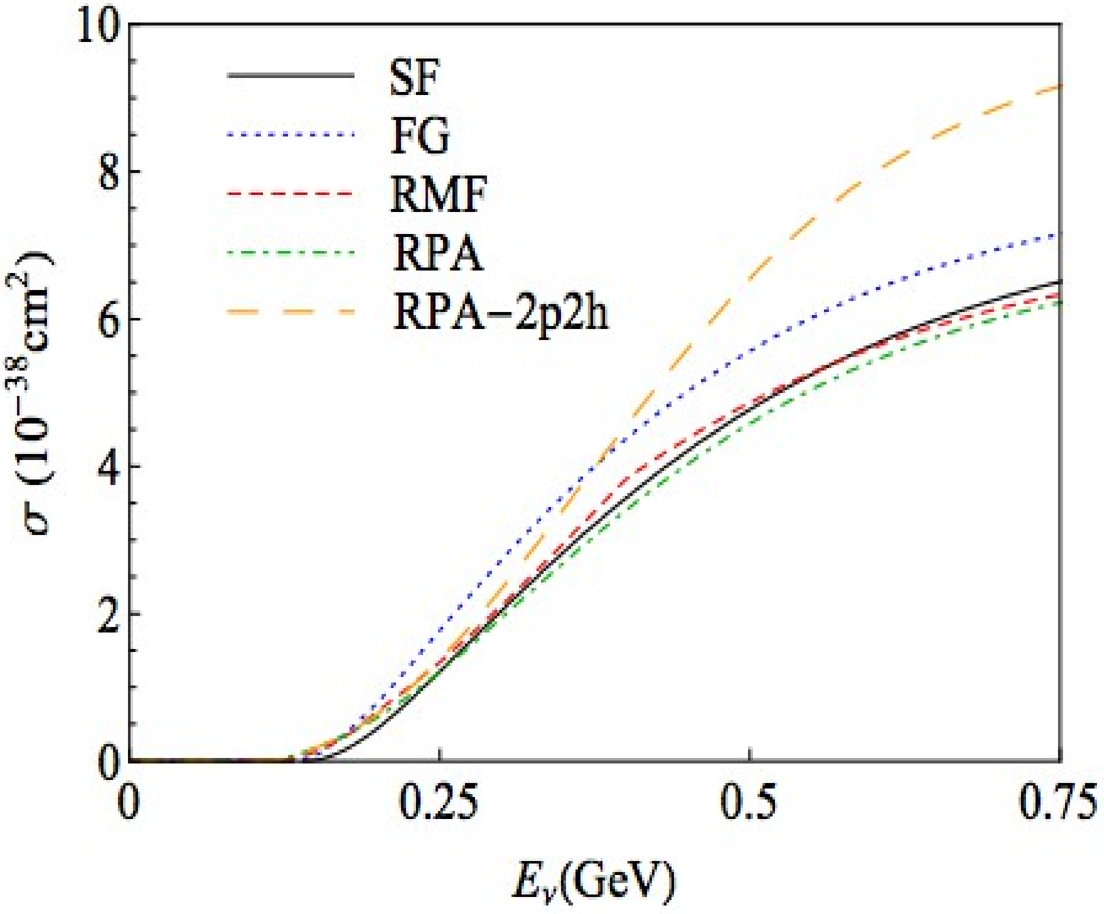


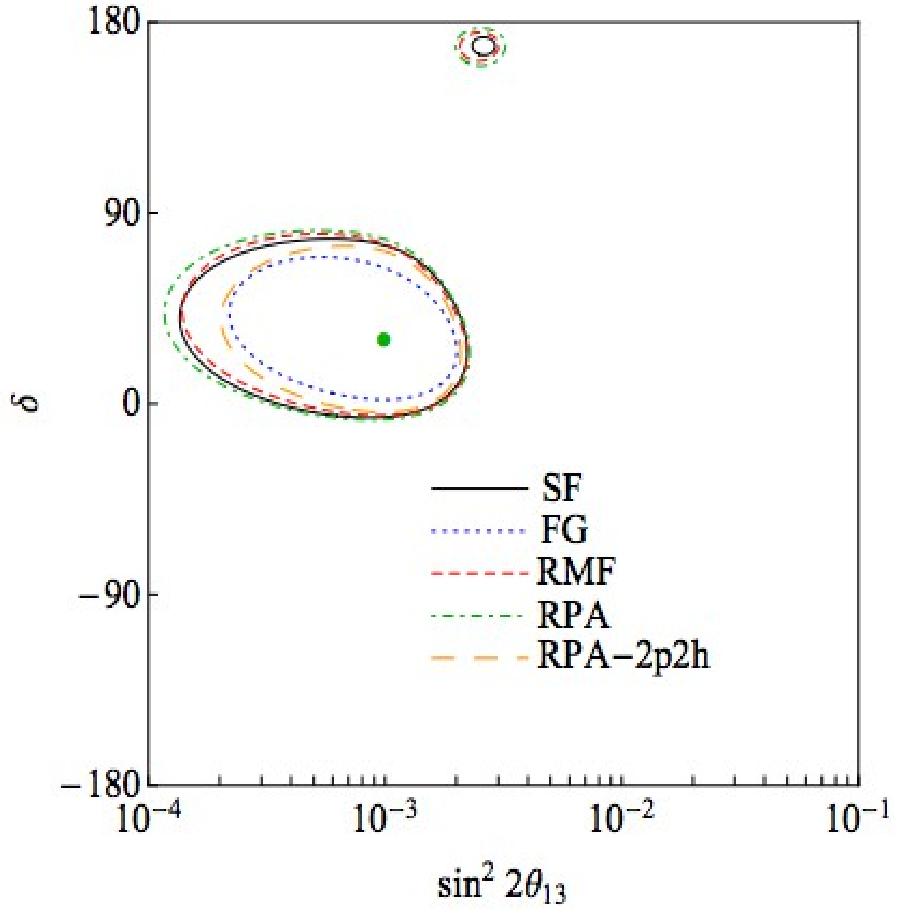


SF = Spectral Function; RMF = Relativistic mean field
FG = Fermi Gas; RPA = Random Phase Approximation

Fernandez-Martinez, Meloni,
1010.2329 [hep-ph]

Cross section models





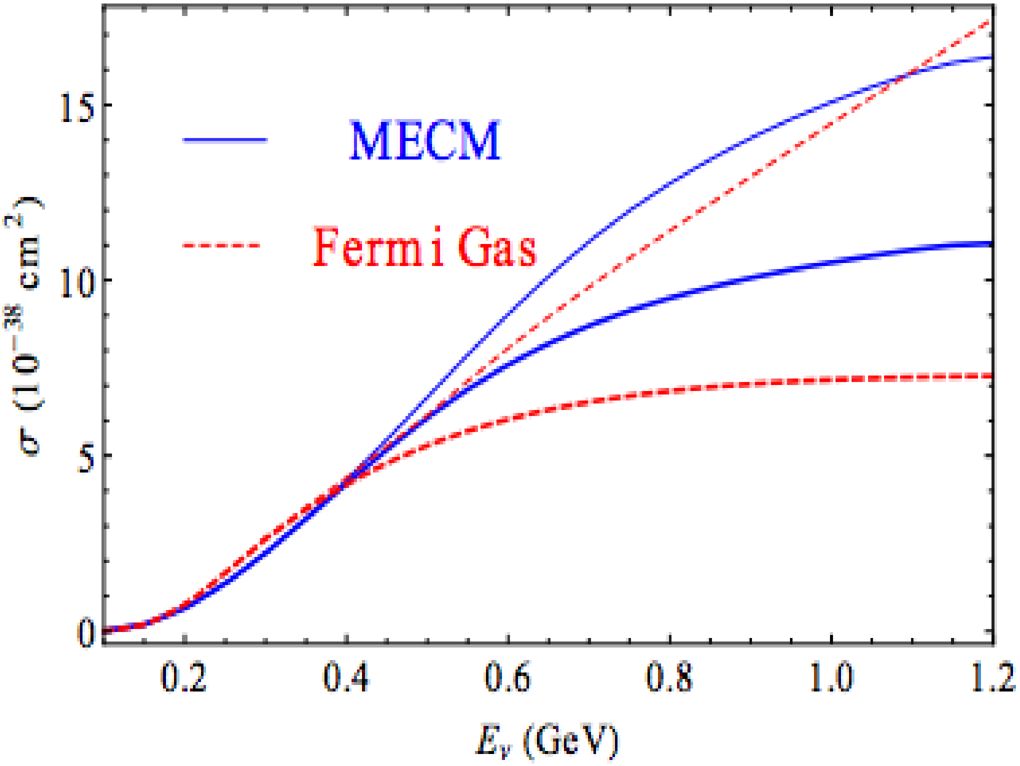
SF = Spectral Function; RMF = Relativistic mean field

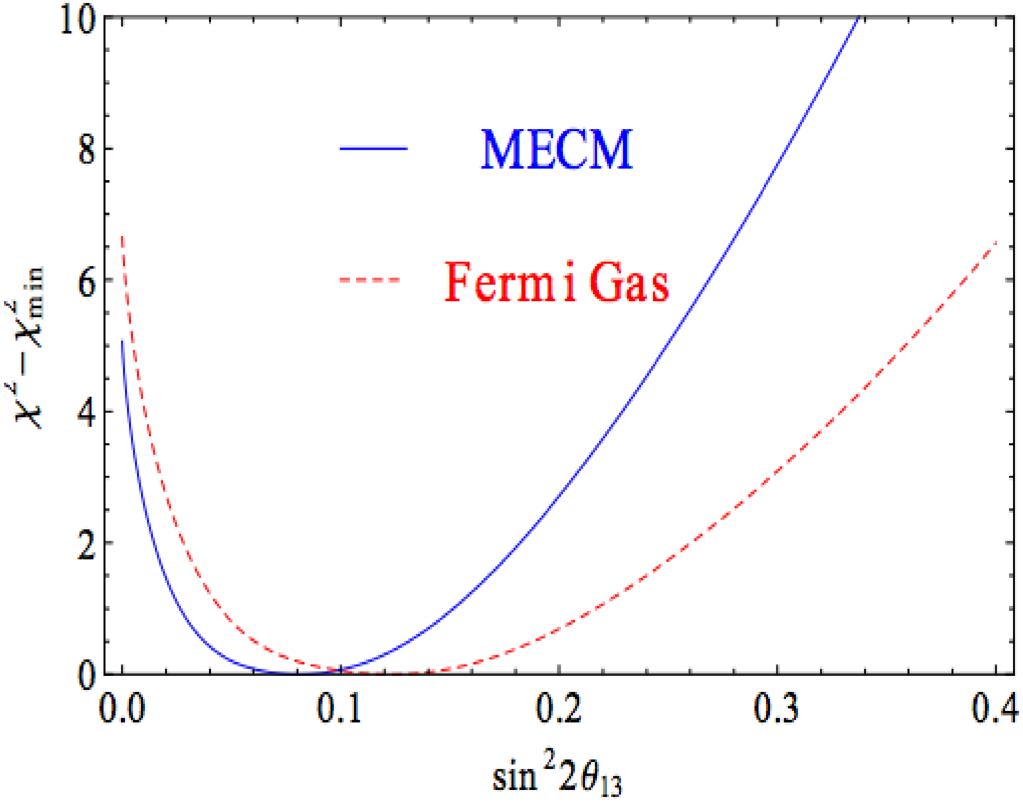
FG = Fermi Gas; RPA = Random Phase Approximation

Fernandez-Martinez, Meloni, 1010.2329 [hep-ph]

Cross section models

Impact on an analysis which reproduces T2K results in 1106.2822 [hep-ex]



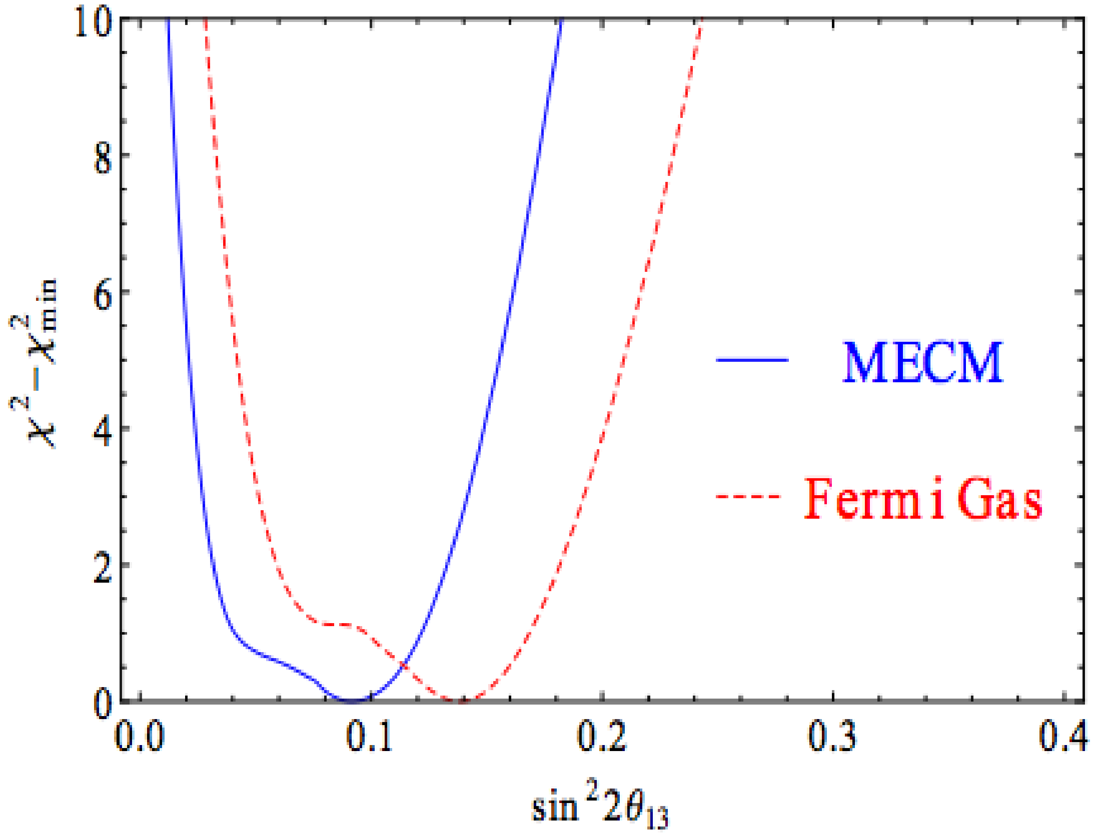


Martini, Meloni, 1203.3335 [hep-ph]

MECM = model from Martini, Ericson, Chanfray, Marteau, 0910.2622 [nucl-th]

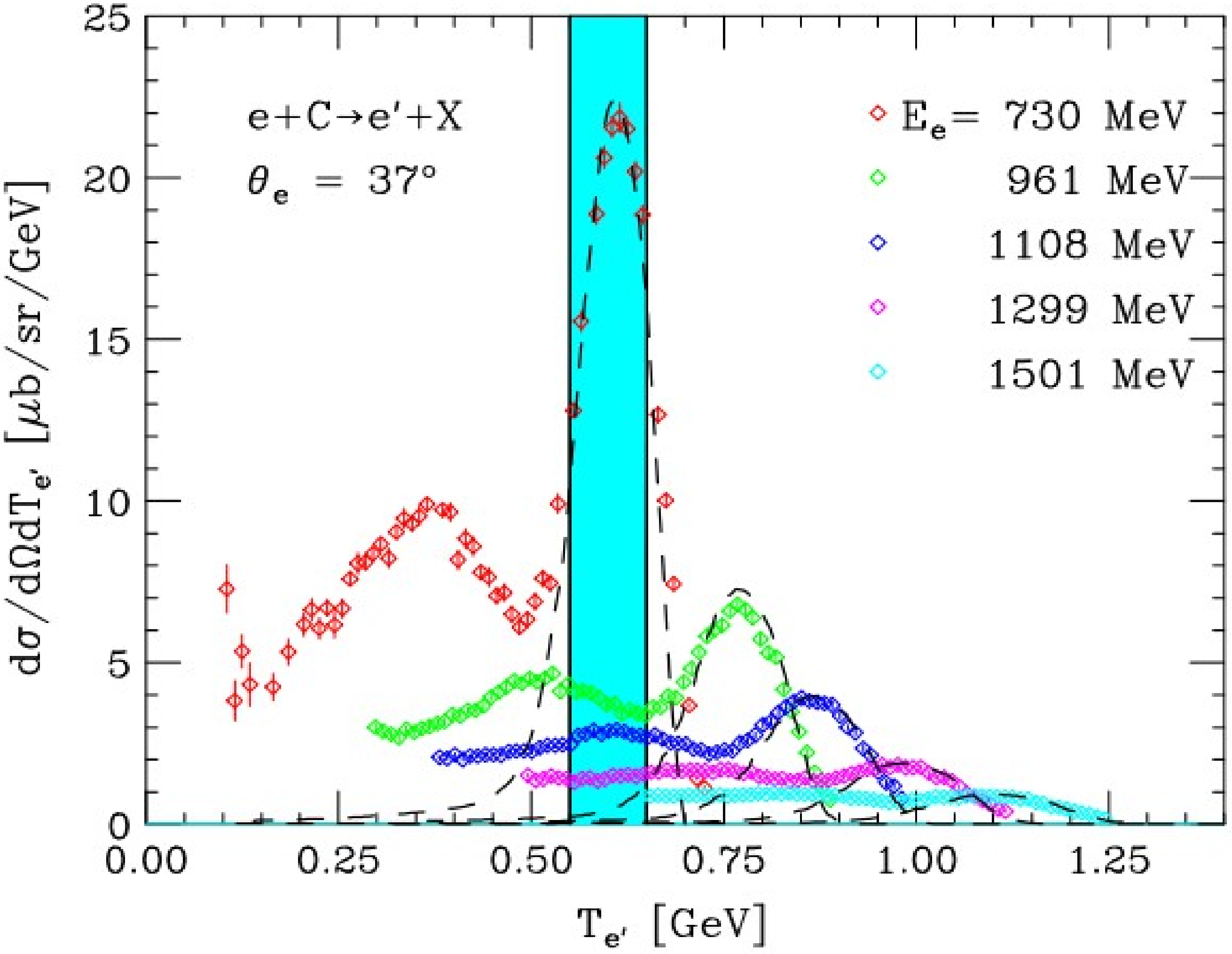
Cross section models

Effect is there, but not so large.
What would happen if the
statistics is increased?



Martini, Meloni, 1203.3335 [hep-ph]
MECM = model from Martini, Ericson, Chanfray, Marteau, 0910.2622 [nucl-th]

Energy reconstruction issues

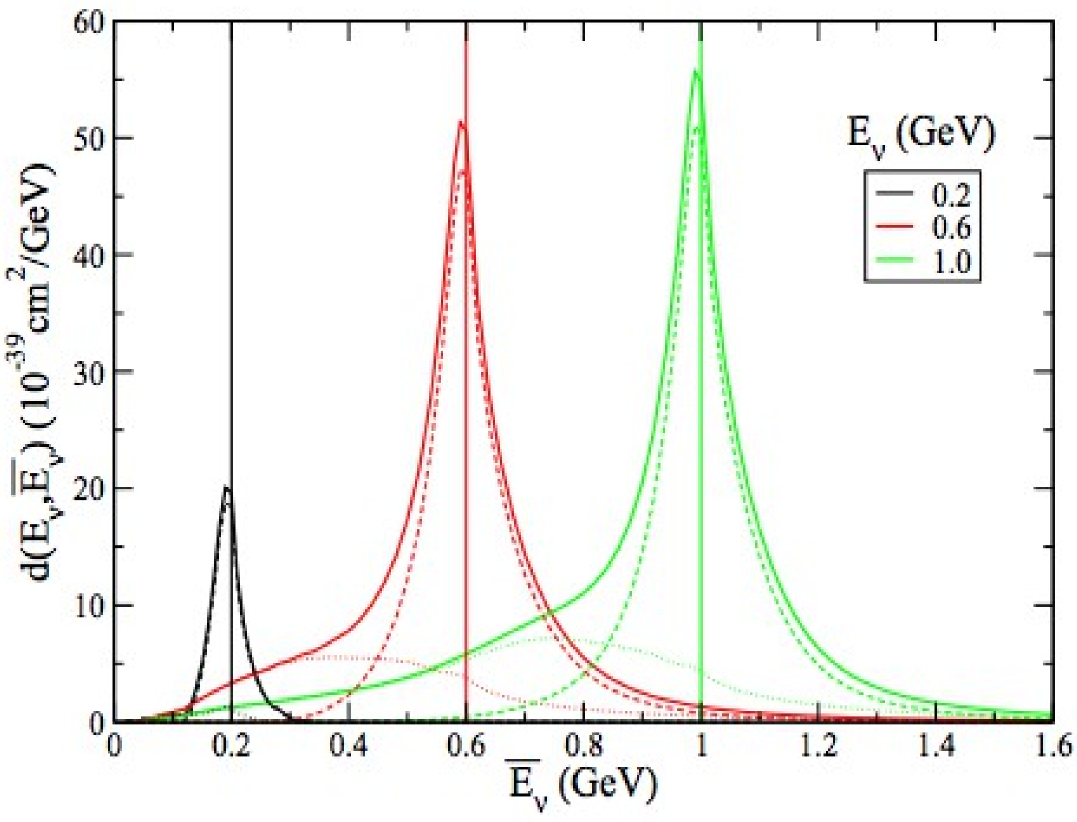


Benhar, 1110.1835 [hep-ph]

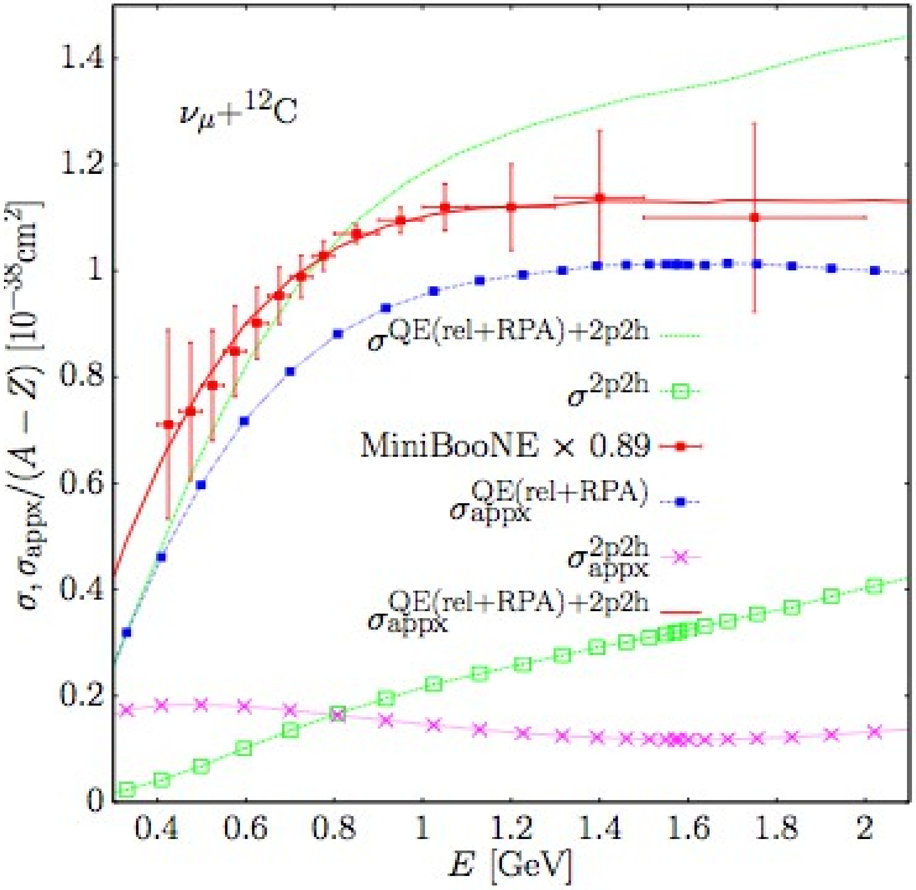
Energy reconstruction issues

$$E_{\text{rec}} = \frac{ME_\ell - m_\ell^2/2}{M - E_\ell + |\vec{p}_\ell|\cos\theta_\ell}$$

Nieves, Sanchez, Ruiz Simo, Vicente Vacas, 1204.5404 [hep-ph]

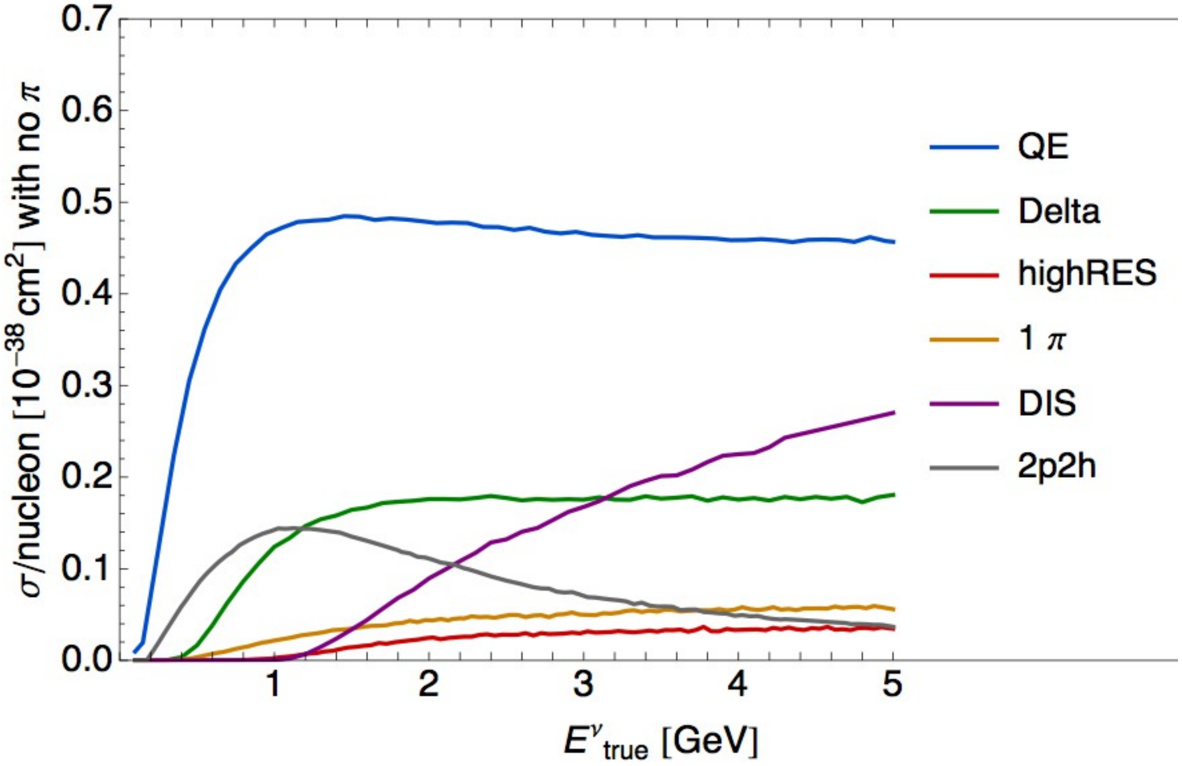


Martini, Ericson, Chanfray, 1211.1523 [hep-ph]



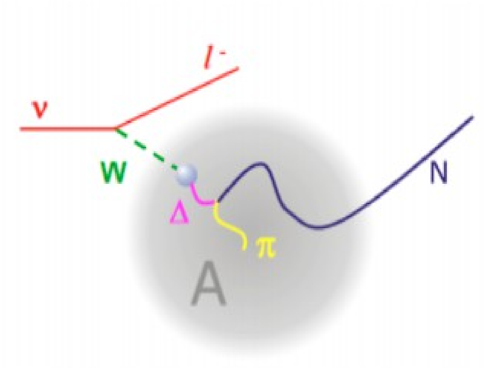
Final State Interactions

If the QE sample is defined as an event with only a charged lepton in the final state, many processes contribute to the event sample:



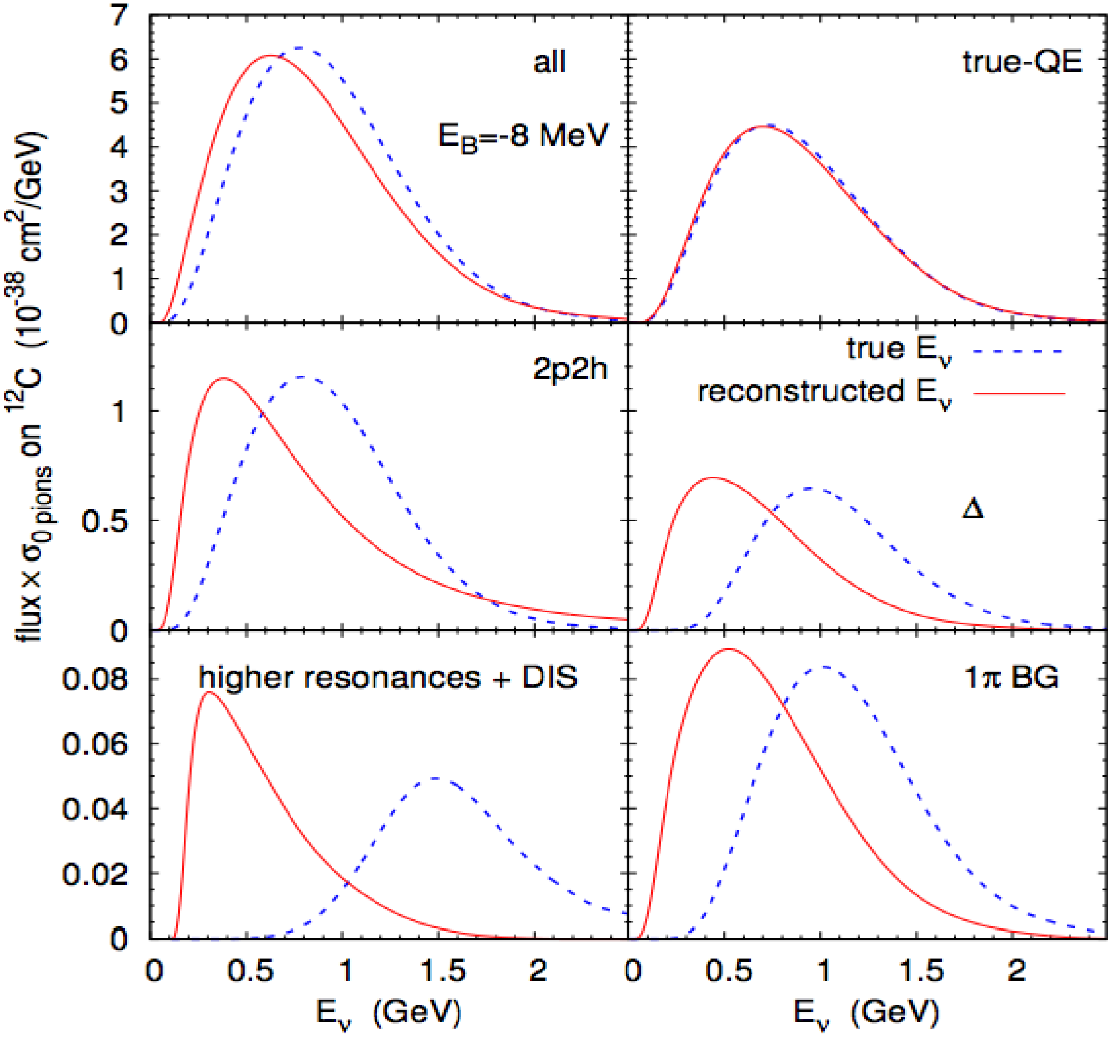
Lalakulich, Mosel, Gallmeister, 1208.3678 [nucl-th]

Coloma, Huber, 1307.1243 [hep-ph]



NOTE: the 2p2h here does not come from a microscopic model

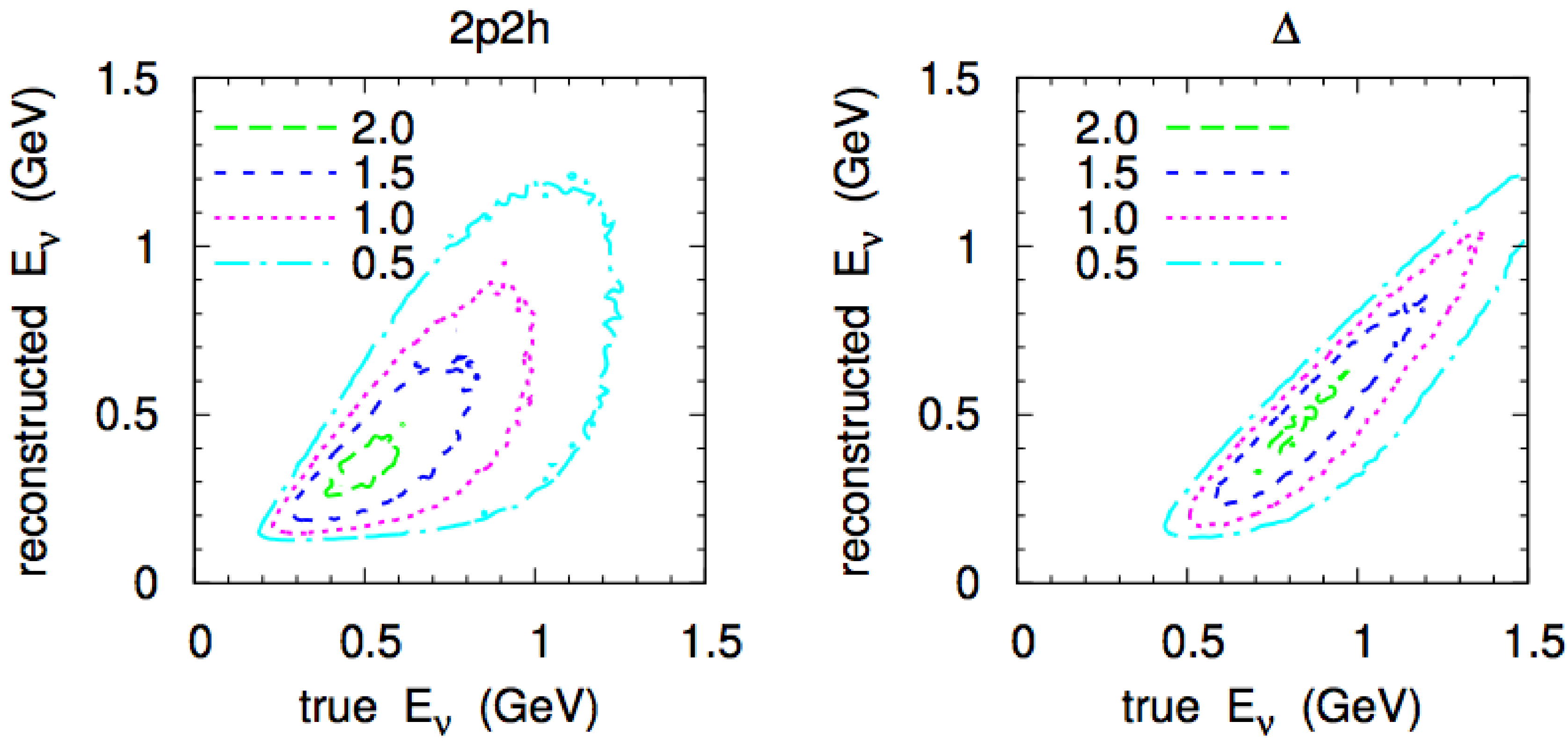
Energy reconstruction and FSI



Lalakulich, Mosel and Gallmeister, 1208.3678 [nucl-th]

Energy reconstruction effects

These effects can be parametrized as migration matrices from true to reconstructed energy:

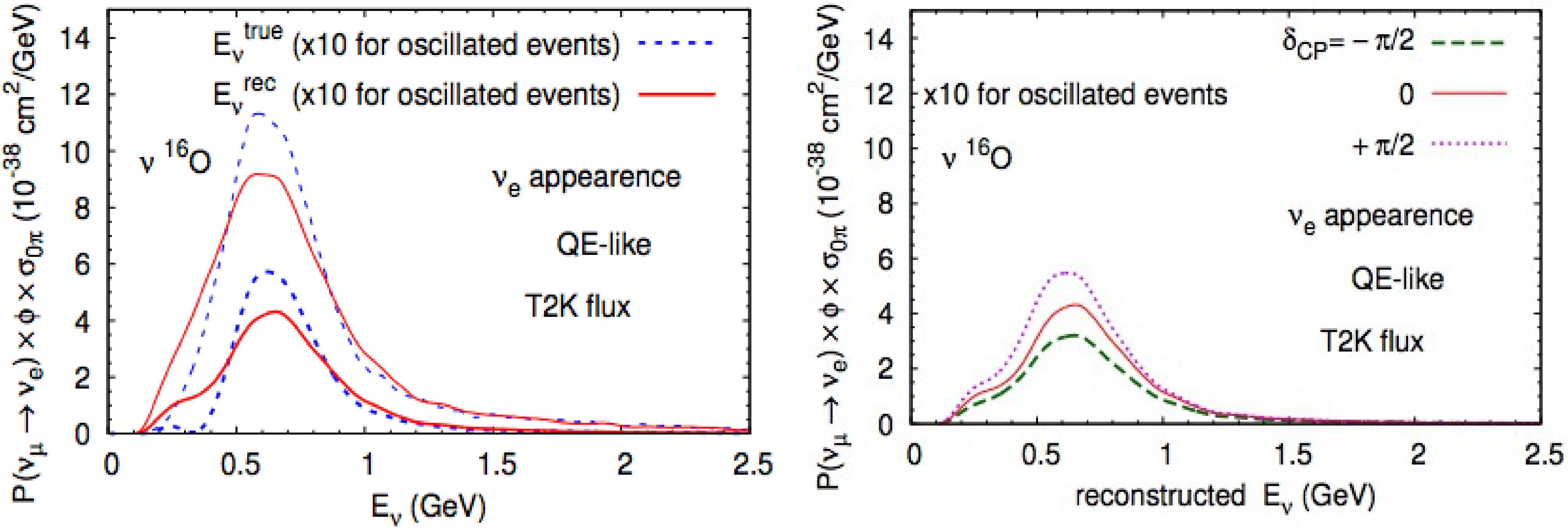


Lalakulich, Mosel and Gallmeister, 1208.3678 [nucl-th]

What would happen if we don't include these effects in the MC?

(…or, if we don't do it properly)

Nuclear effects and FSI



Lalakulich, Mosel and Gallmeister, 1208.3678 [nucl-th]

Toy model

- Super-Beam with peak energy around 0.6 MeV, L=295 km
  22.5 kton WC detector → QE events only (1-ring)

- Use migration matrix for ^{16}O produced with GiBUU or with GENIE

Buss et al., 1106.1344 [hep-ph]

Andreopoulos et al., 0905.2517 [hep-ph]

- Muon neutrino disappearance only → fit to atmospheric parameters
- Inclusion of bin-to-bin uncorrelated systematics (20%) to try to accomodate shape differences
- Ideal near detector assumed

Toy model

- 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:

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

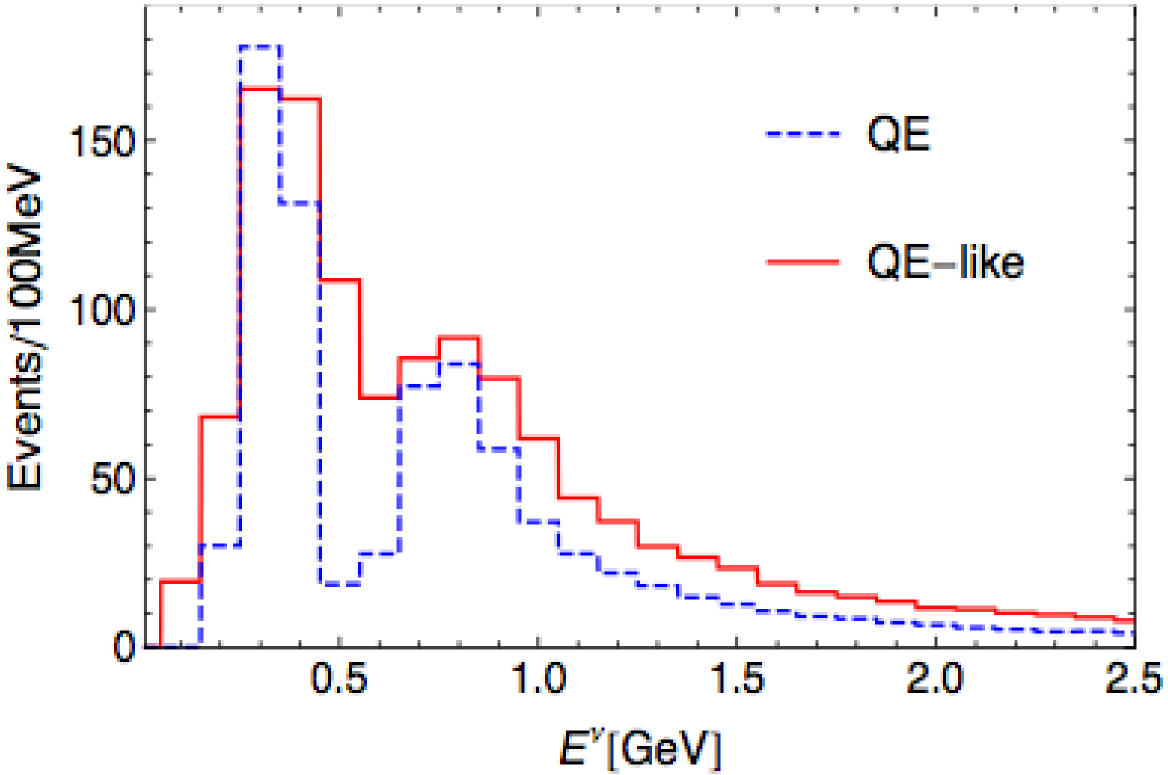
- An intermediate situation would most likely take place:

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

Coloma and Huber, 1307.1243 [hep-ph]

Toy model

$$P_{\mu\mu} \sim 1 - \sin^2 2\theta \sin^2 \frac{\Delta m^2 L}{4E}$$



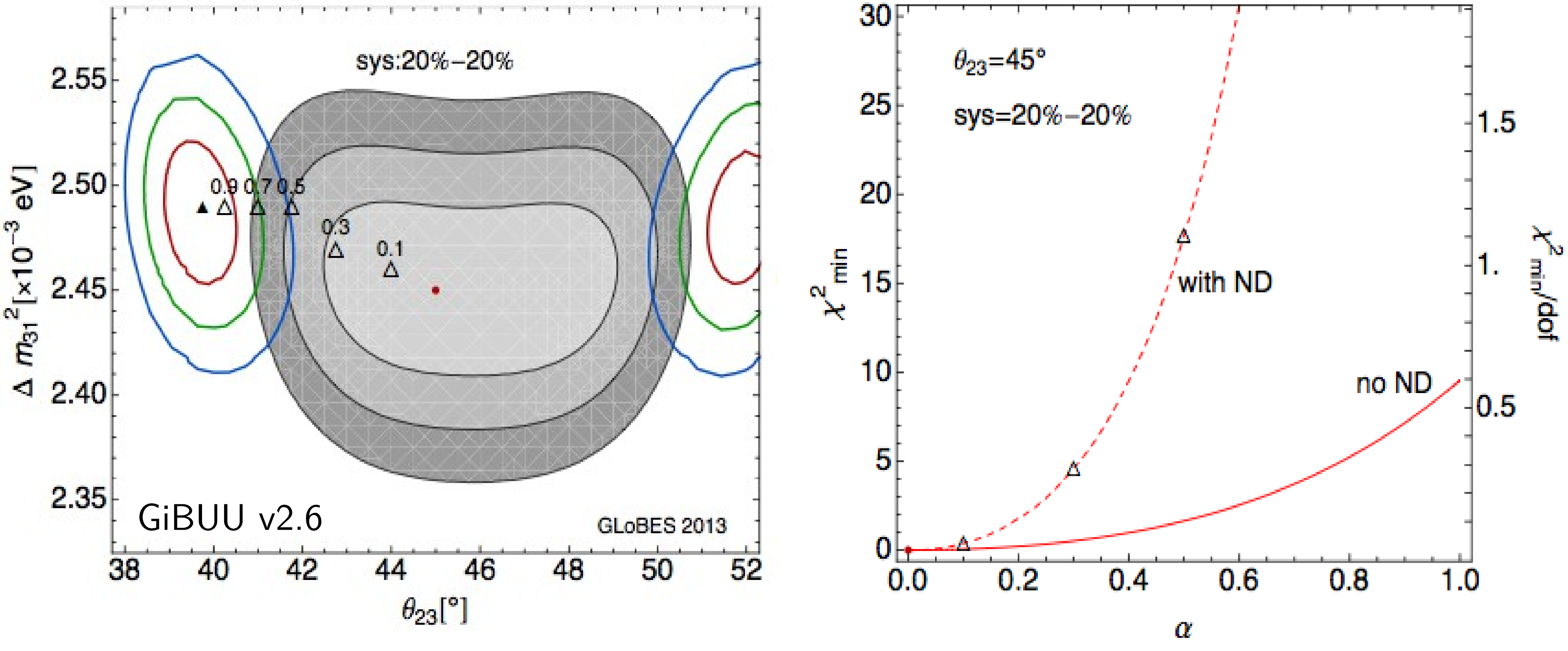
<u>Events</u>

QE	QE-like
870	1270

Coloma and Huber, 1307.1243 [hep-ph]

Toy model

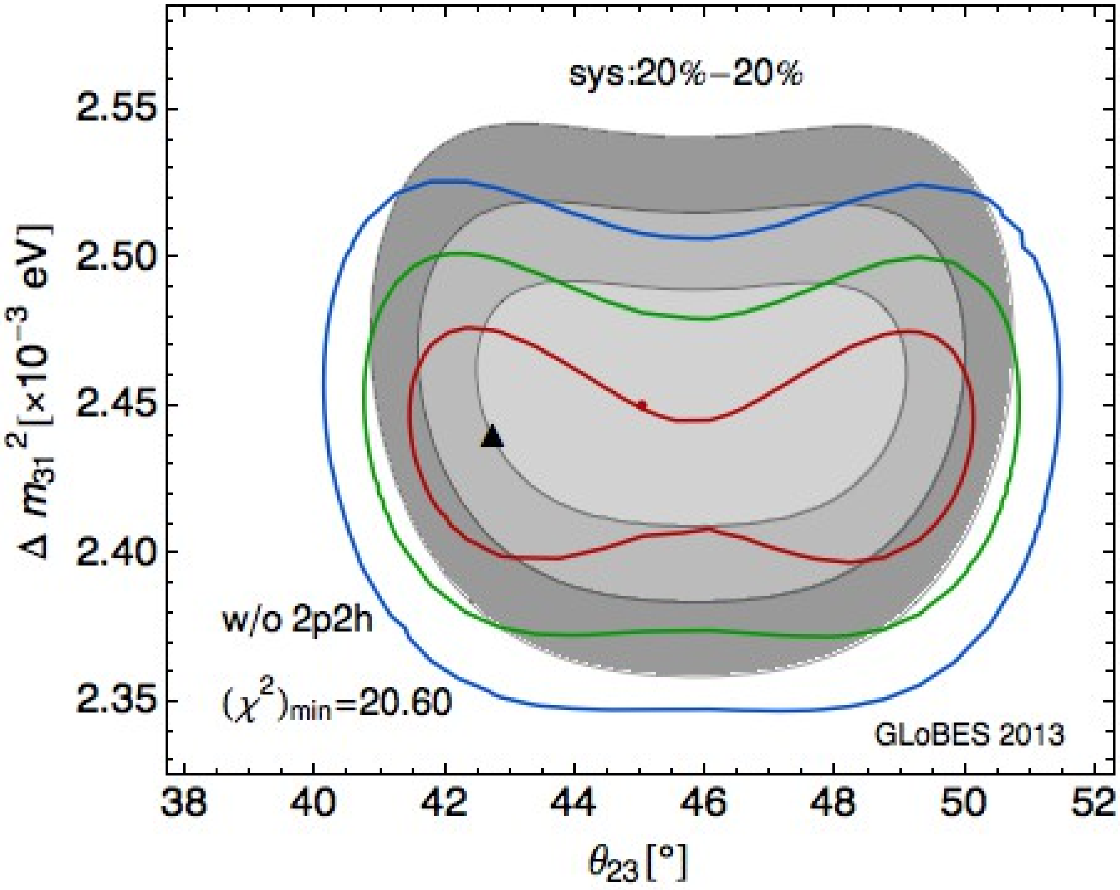
$$N_i^{\rm test}(\alpha) = \alpha \times N_i^{QE} + (1-\alpha) \times N_i^{QE-like}$$



Coloma and Huber, 1307.1243 [hep-ph]

Impact of 2p2h

Even if we get all contributions right except 2p2h...



<u>Events</u>

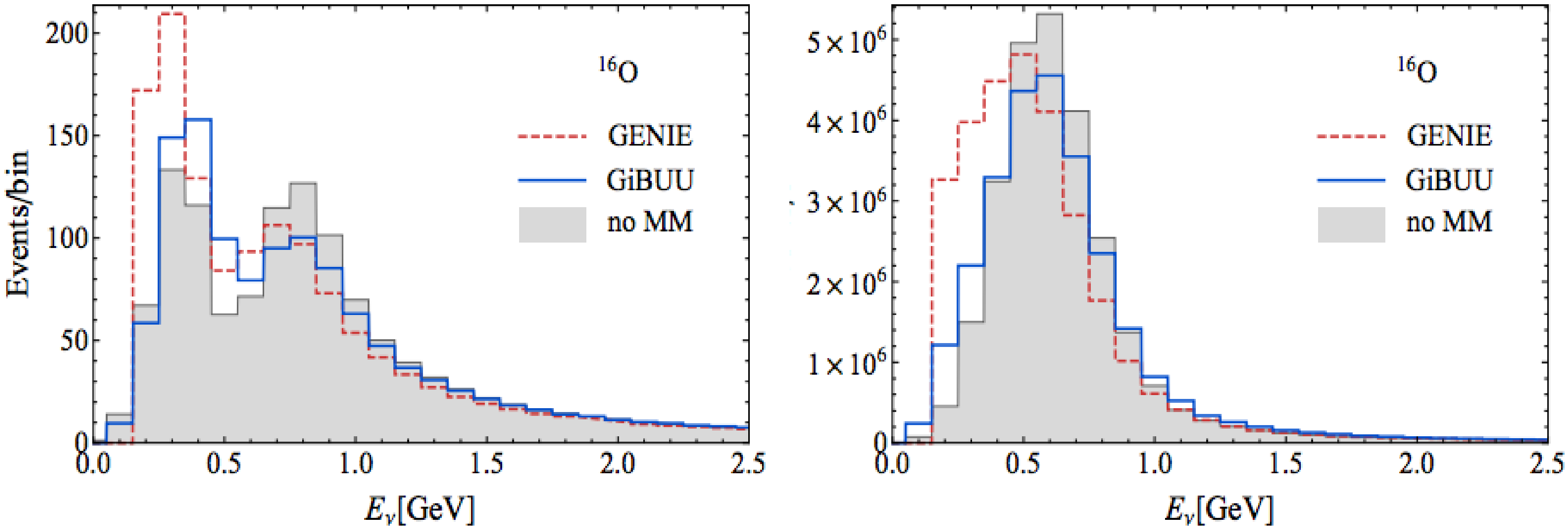
QE	2p2h	QE-like
∼870	∼215	∼1270

GiBUU v2.6

Coloma and Huber, 1307.1243 [hep-ph]

Impact of target nucleus

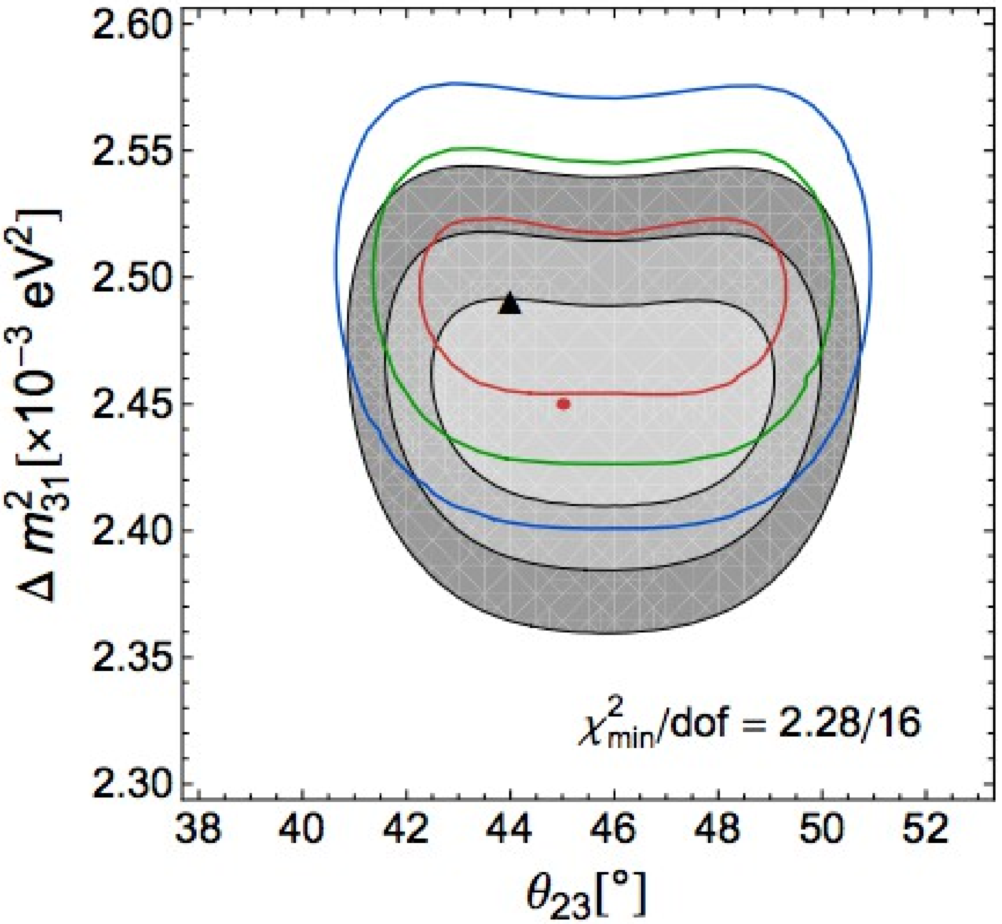
Oxygen vs Carbon:



Coloma, Huber, Mariani and Jen, 1311.4506 [hep-ph]

Impact of target nucleus

Oxygen vs Carbon:

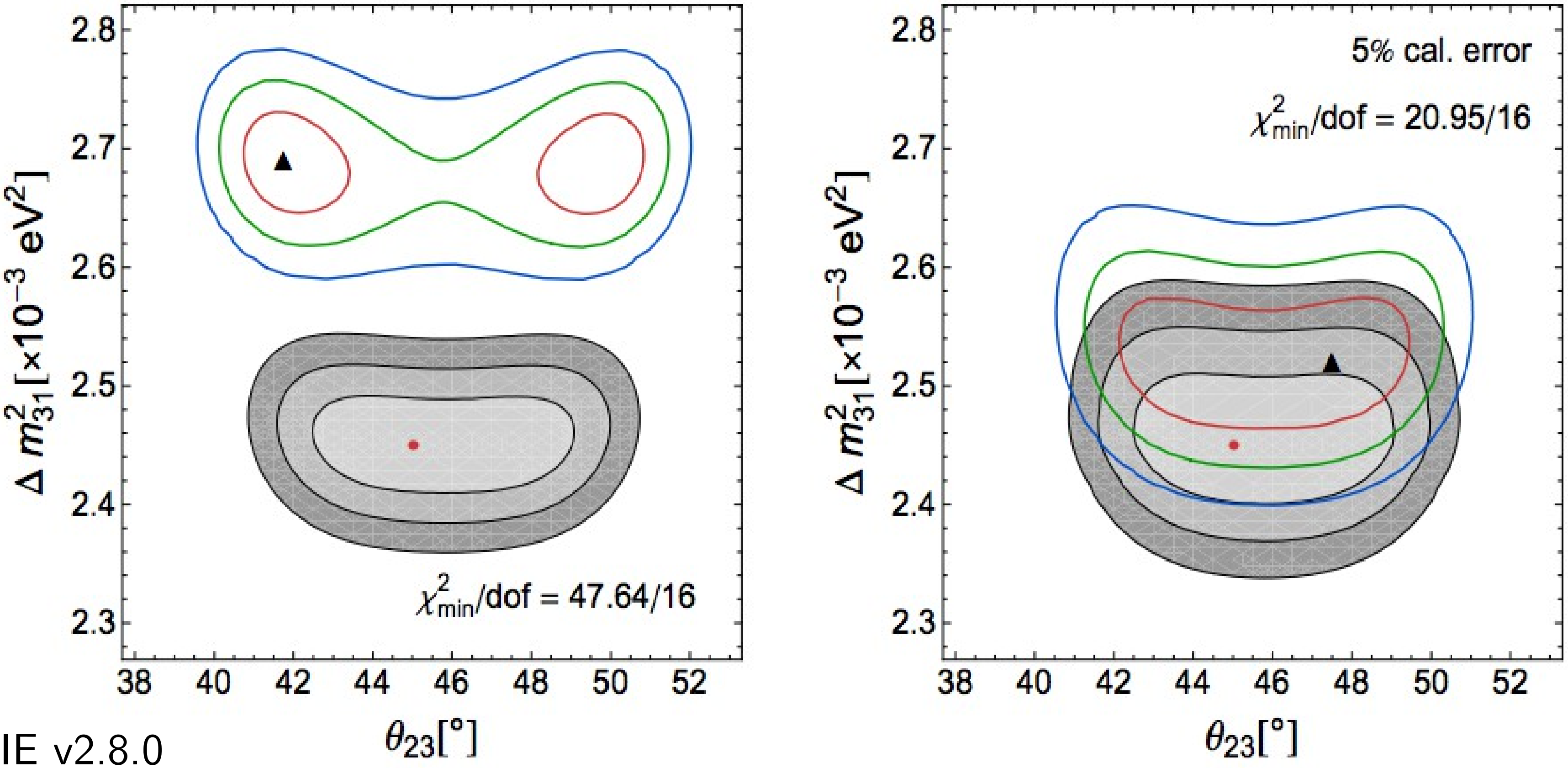


GENIE v2.8.0

Coloma, Huber, Mariani and Jen, 1311.4506 [hep-ph]

Impact of nuclear model

How large can these effects be?



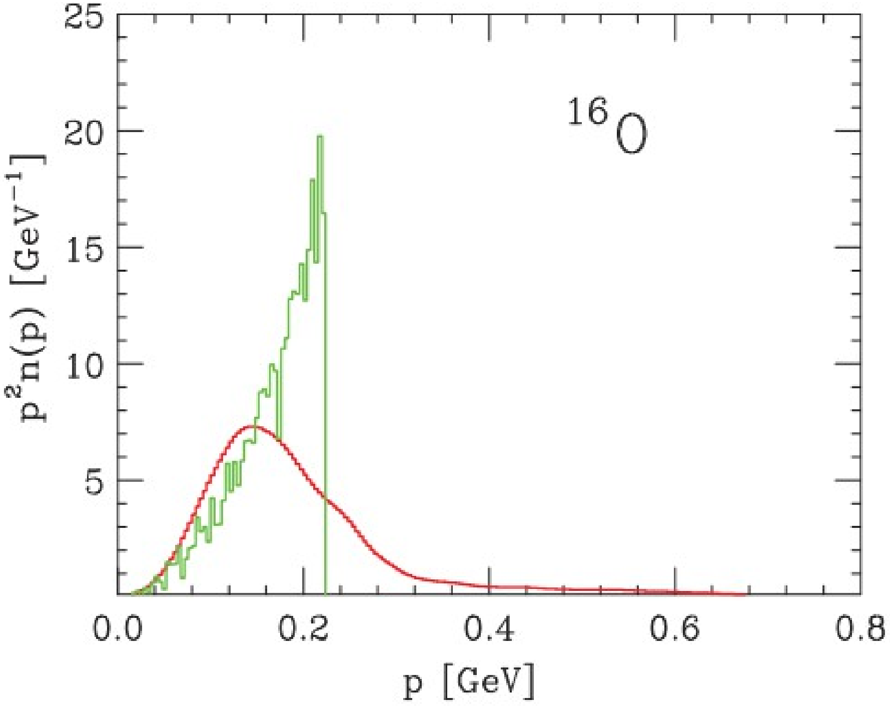
GENIE v2.8.0

GiBUU v2.6

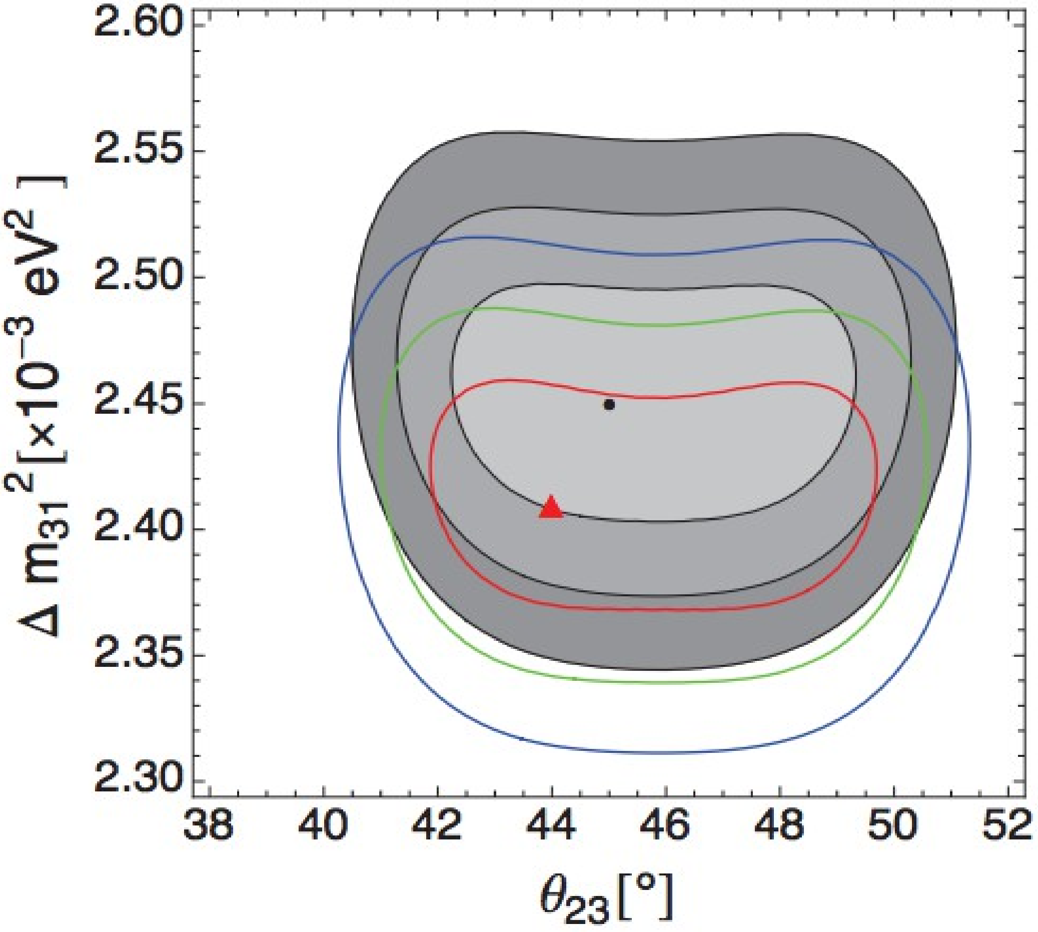
Coloma, Huber, Mariani and Jen, 1311.4506 [hep-ph]

Other factors: RFGM vs SF

Nucleon momentum distribution:



Jen et al, 1402.6651 [hep-ex]



GENIE v2.8.0 - modified

Does this improve with calorimetry?

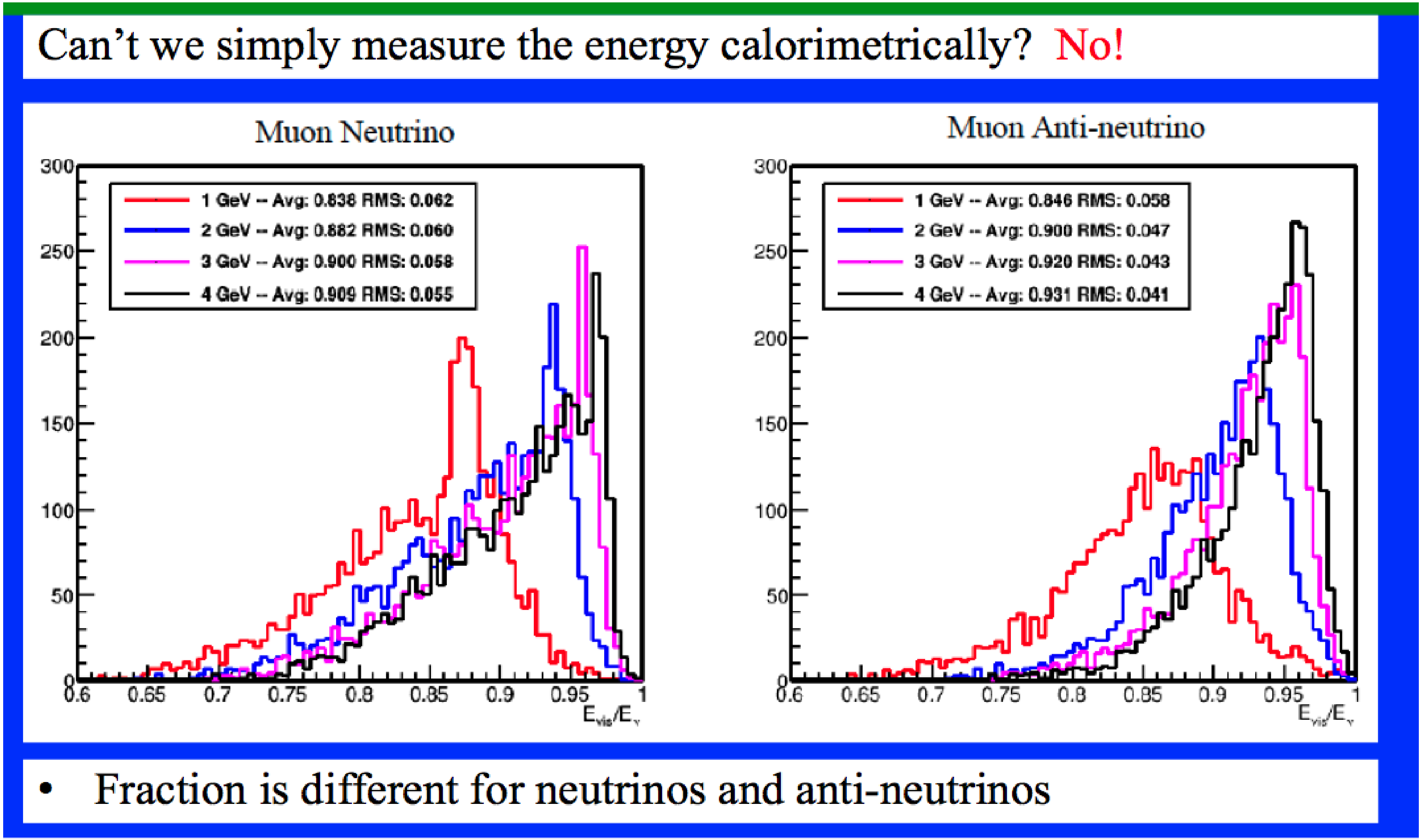
- At a WC, we are only sensitive to the info carried by the lepton
- At a calorimetric detector:

$$E_{\nu,\mathrm{rec}} = E_{\mathrm{had}} + E_{\mathrm{lep}} + E_{\mathrm{inv}}$$

Can this help?
Of course!

Does this improve with calorimetry?

See talk by Christopher Mauger here at nuSTEC



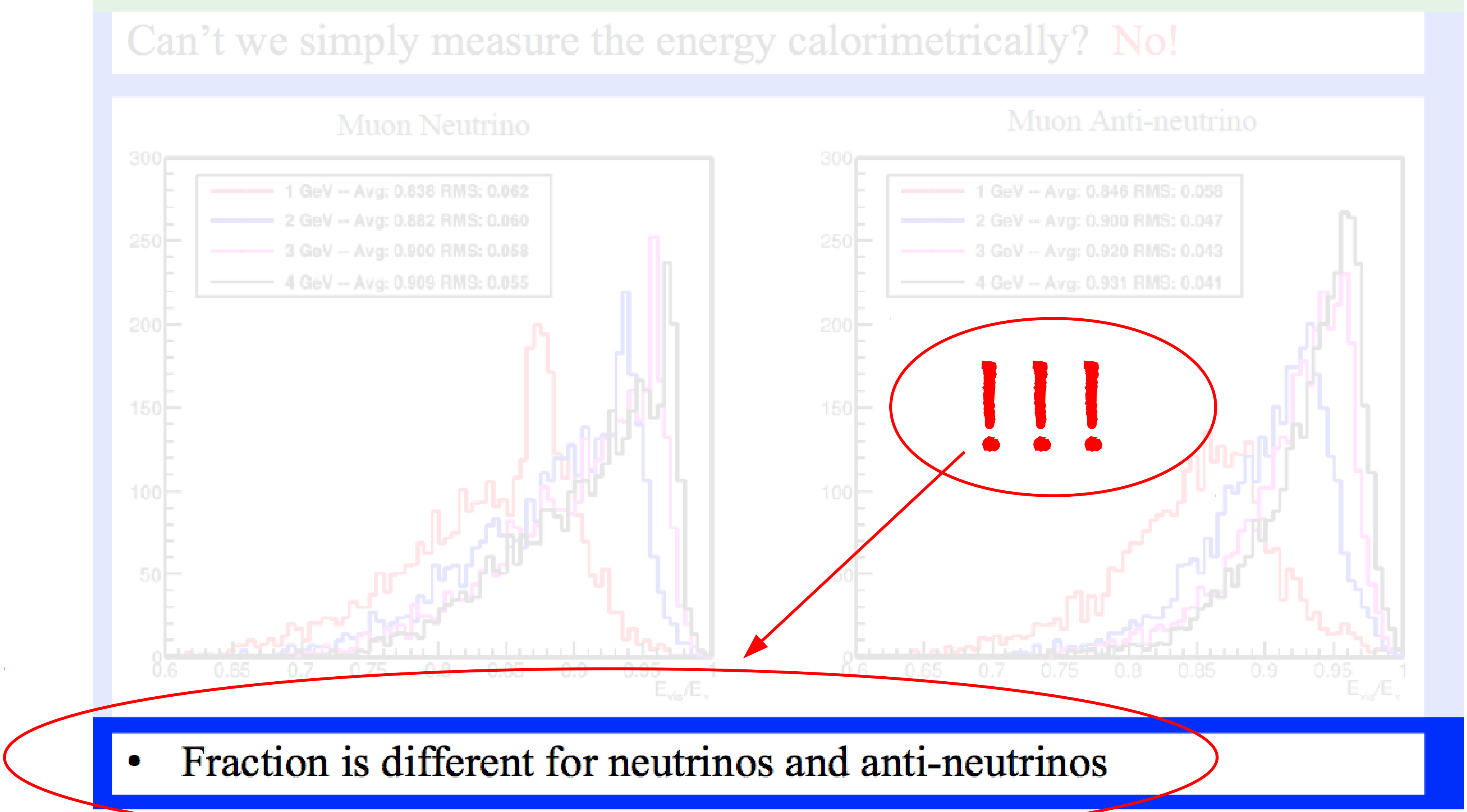
Can't we simply measure the energy calorimetrically? No!

- Fraction is different for neutrinos and anti-neutrinos

Clark McGrew at the Santa Fe LBNE Scientific Workshop (http://public.lanl.gov/friedland/LBNEApril2014/)

Does this improve with calorimetry?

See talk by Christopher Mauger here at nuSTEC



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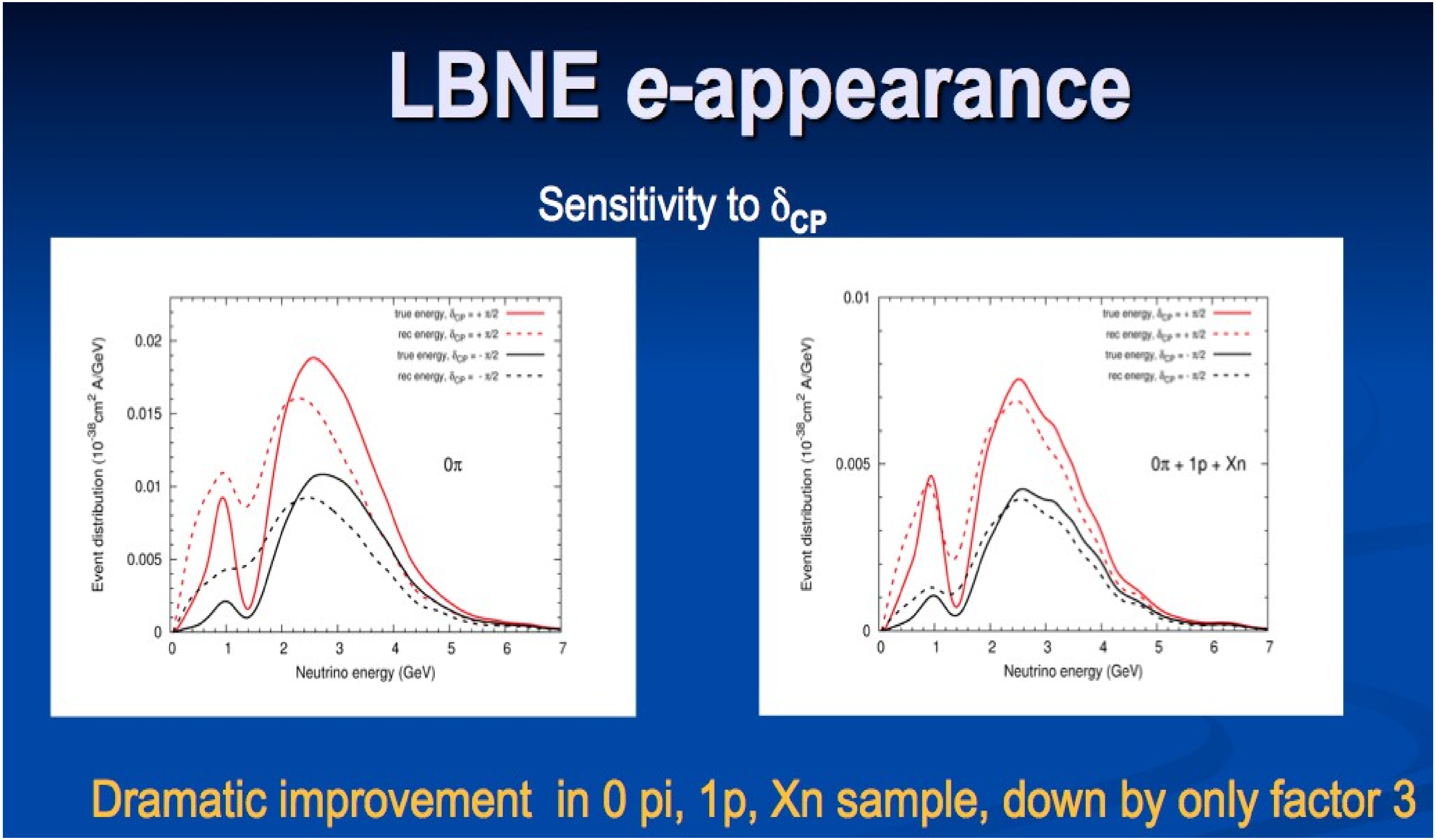
Clark McGrew at the Santa Fe LBNE Scientific Workshop (http://public.lanl.gov/friedland/LBNEApril2014/)



LBNE e-appearance

Sensitivity to δ_{CP}

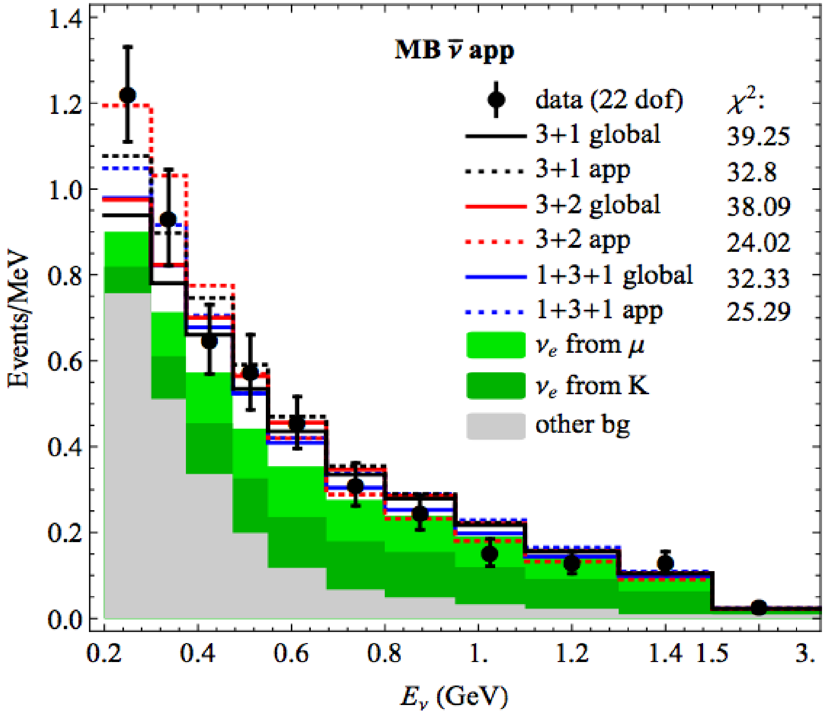
Dramatic improvement in 0 pi, 1p, Xn sample, down by only factor 3

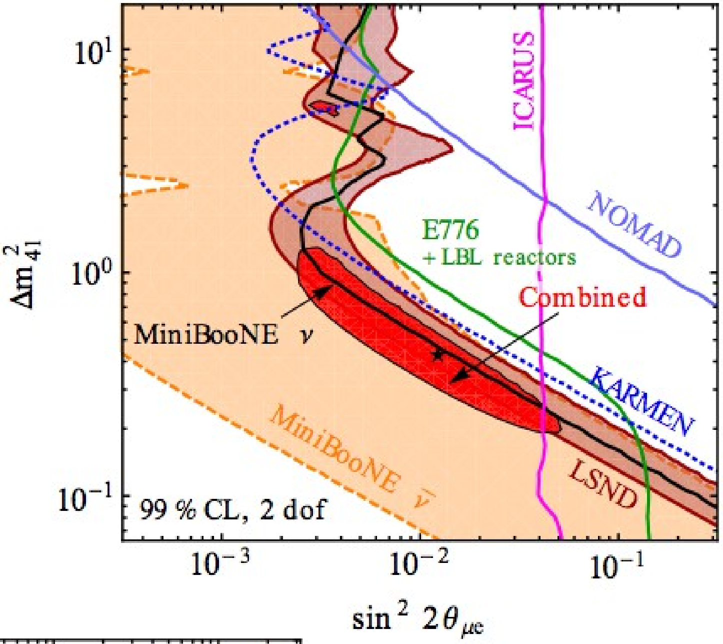
Mosel, Lalakulich, Gallmeister, 1311.7288 [nucl-th]

See also U. Mosel's talk at KITP workshop (Present and future neutrino physics), Oct 2014

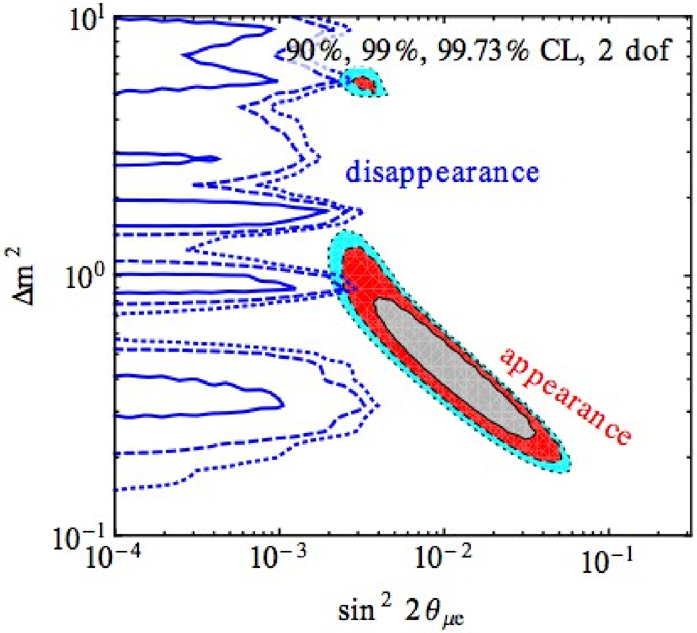
Curious things/random thoughts

Curious things

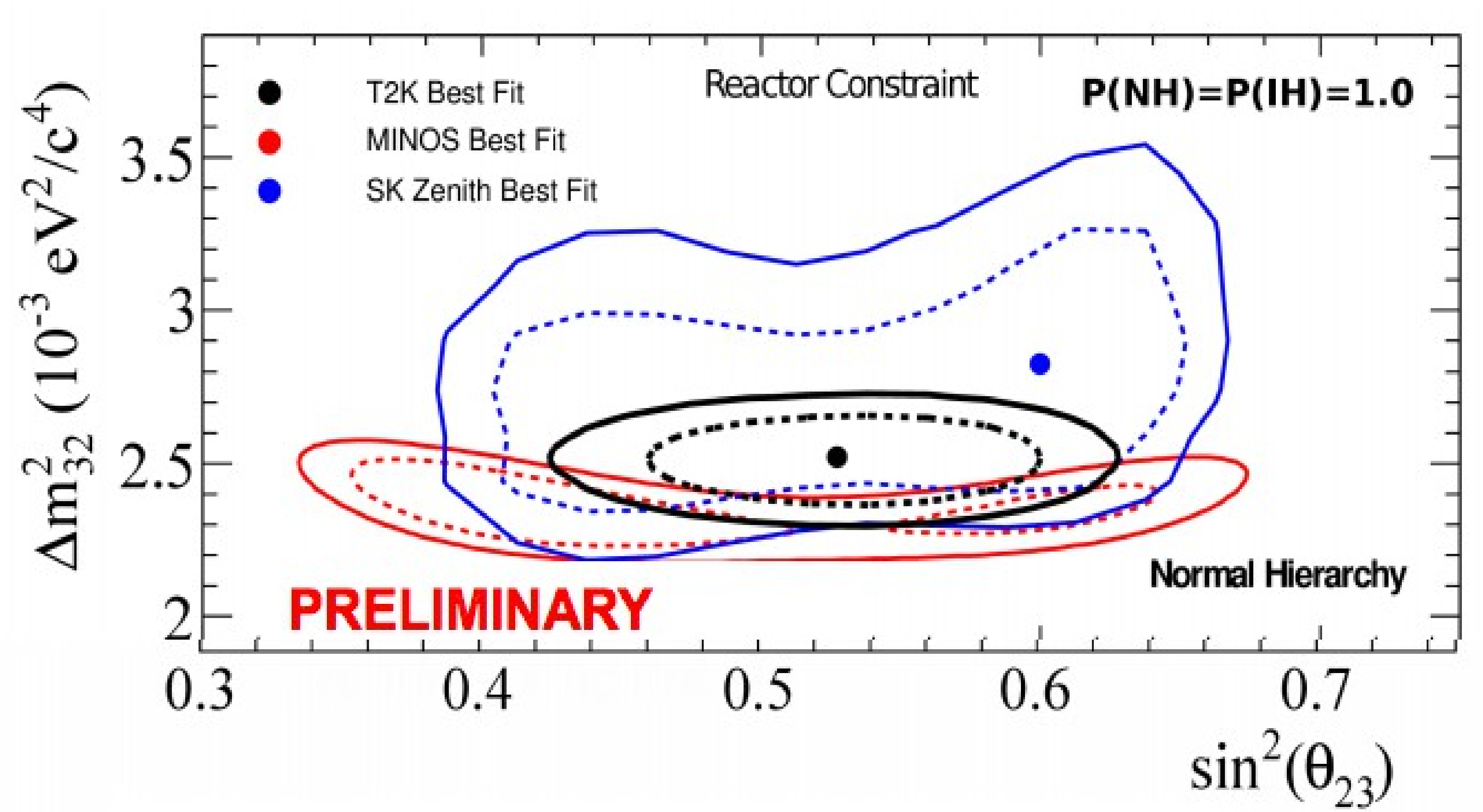




Machado, Kopp, Maltoni, Schwetz, 1303.3011 [hep-ph]



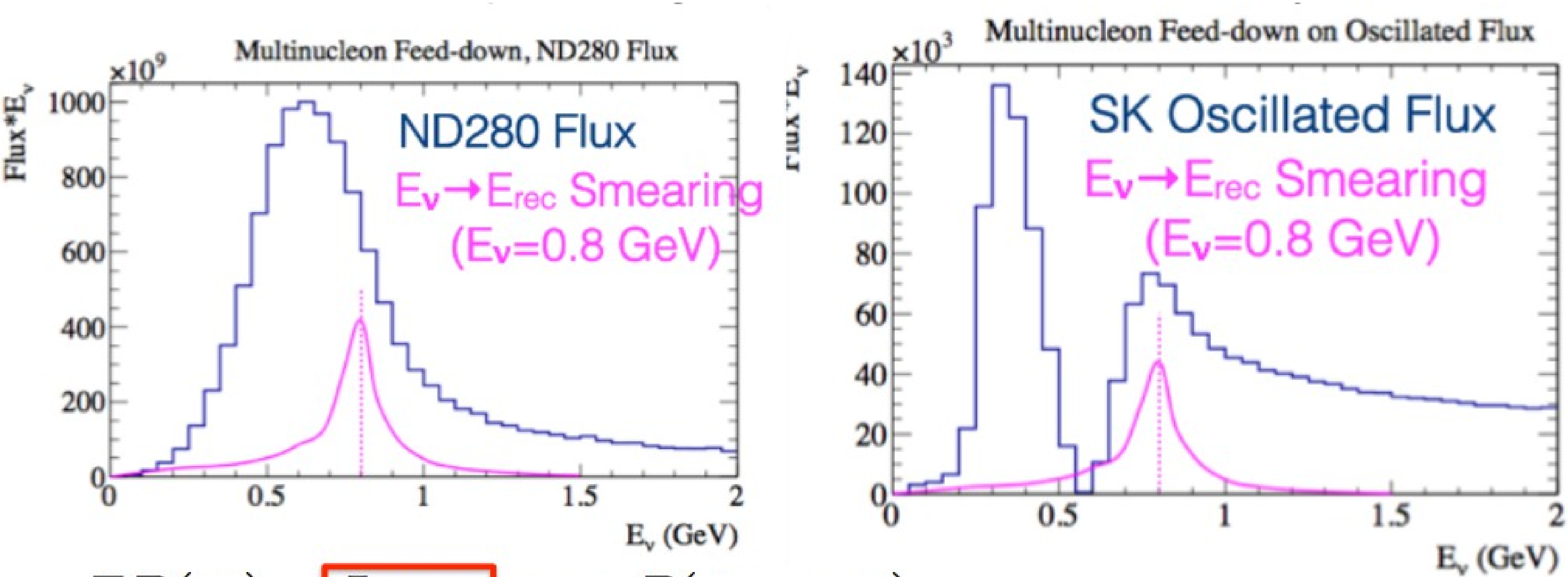
Curious things



Slide stolen from K. Mahn's talk

Curious things

What will happen when we add antineutrino data?



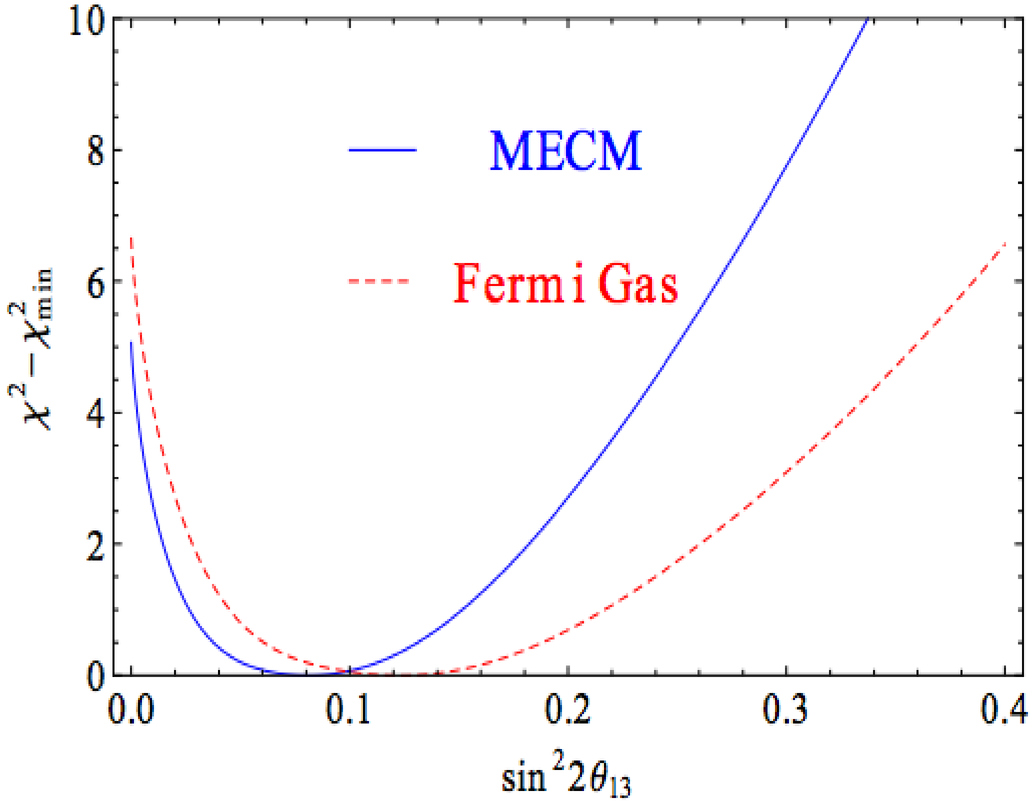
$$FD(\nu_e) = \boxed{\Phi \times \sigma} \times \epsilon \times P(\nu_\mu \rightarrow \nu_e)$$

$$ND(\nu_\mu) = \boxed{\Phi \times \sigma} \times \epsilon_{ND}$$

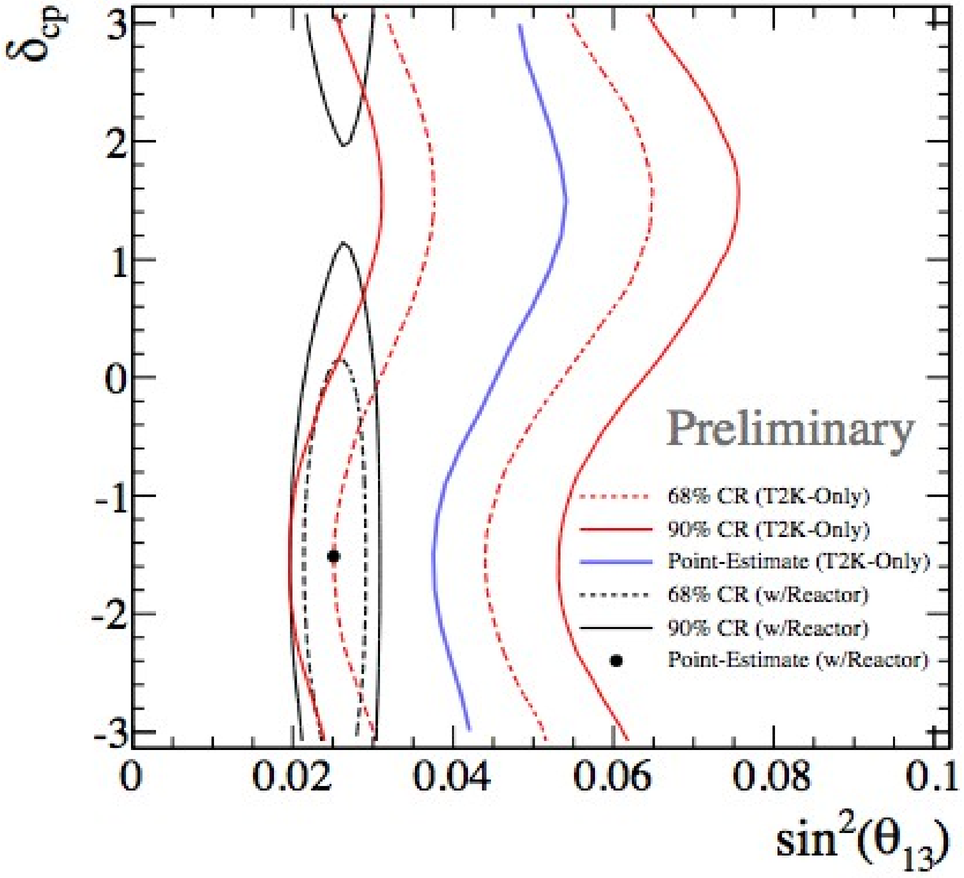
$$E_\nu^{QE} = \frac{m_p^2 - m'^2_n - m_\mu^2 + 2m'_n E_\mu}{2(m'_n - E_\mu + p_\mu \cos\theta_\mu)}$$

Slide stolen from K. Mahn's talk

Curious things



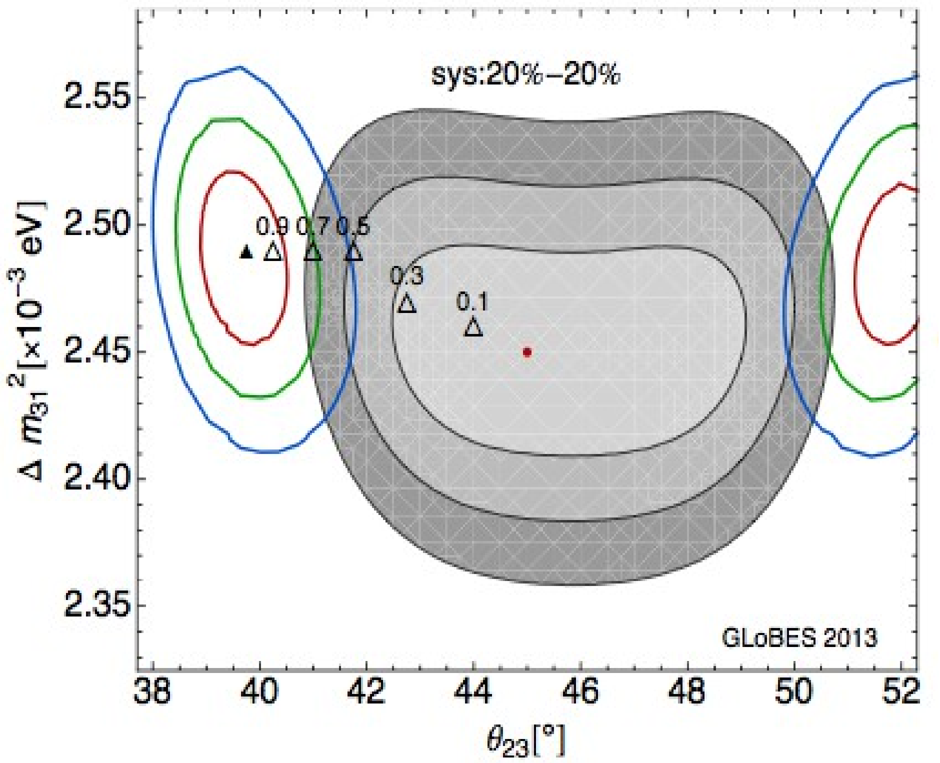
Martini, Meloni, 1203.3335 [hep-ph]



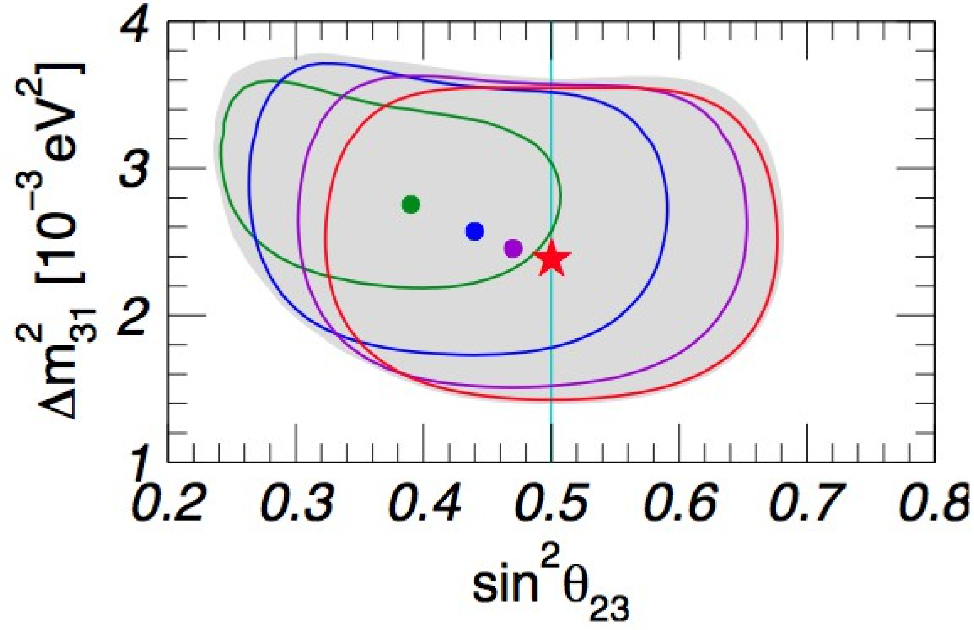
The T2K collab., 1405.3871 [hep-ex]

Curious things

Coloma, Huber, 1307.1243 [hep-ph]

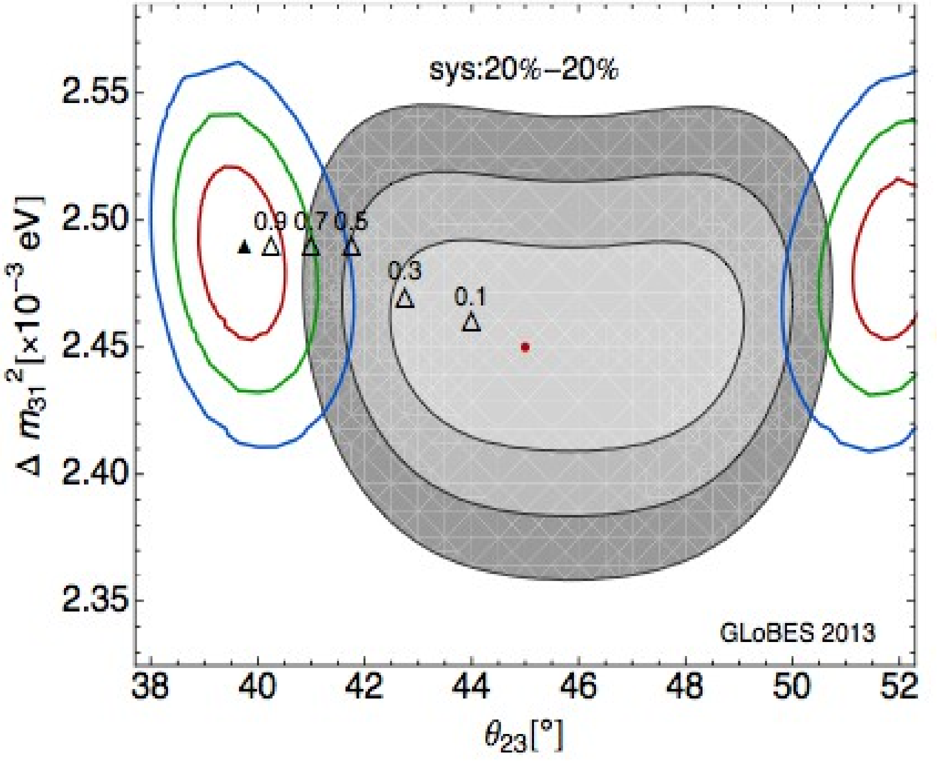


Friedland, Lunardini, Maltoni,
hep-ph/0408264



Curious things

Coloma and Huber, 1307.1243 [hep-ph]



Friedland, Lunardini, Maltoni,
hep-ph/0408264

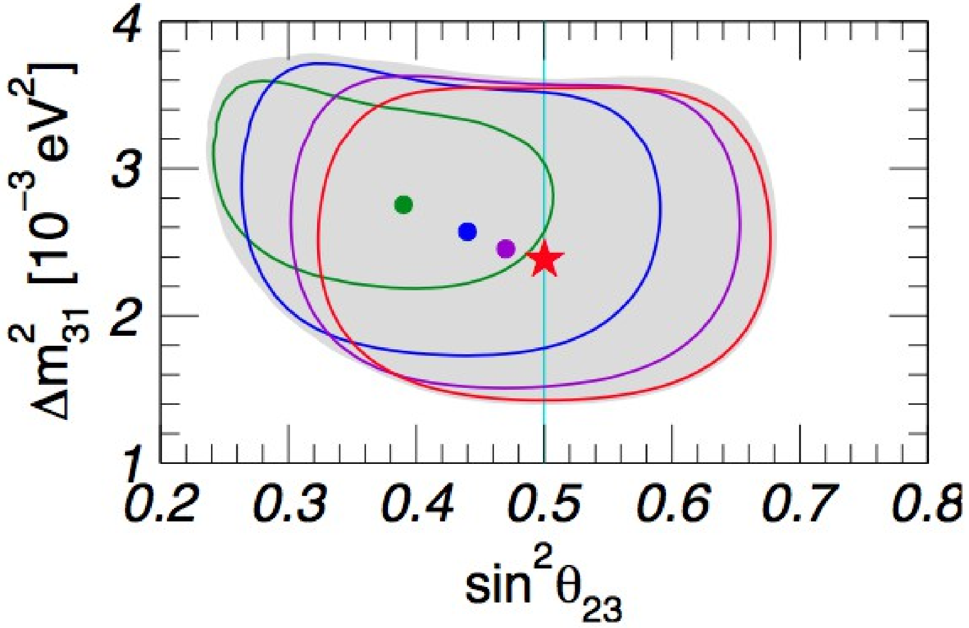


FIG. 2: The effect of the NSI on the allowed region and best-fit values of the oscillation parameters; see text for details.

Summary and Outlook

- If we want to measure things accurately, energy reconstruction is crucial
- If we want to determine θ_{23}, careful with unexpected effects!
- Cross check between different experiments/detectors/channels will give us the key (Crosscheck-crosscheck-crosscheck!!)
- Near detectors are not the tooth fairy: careful!

Summary and Outlook

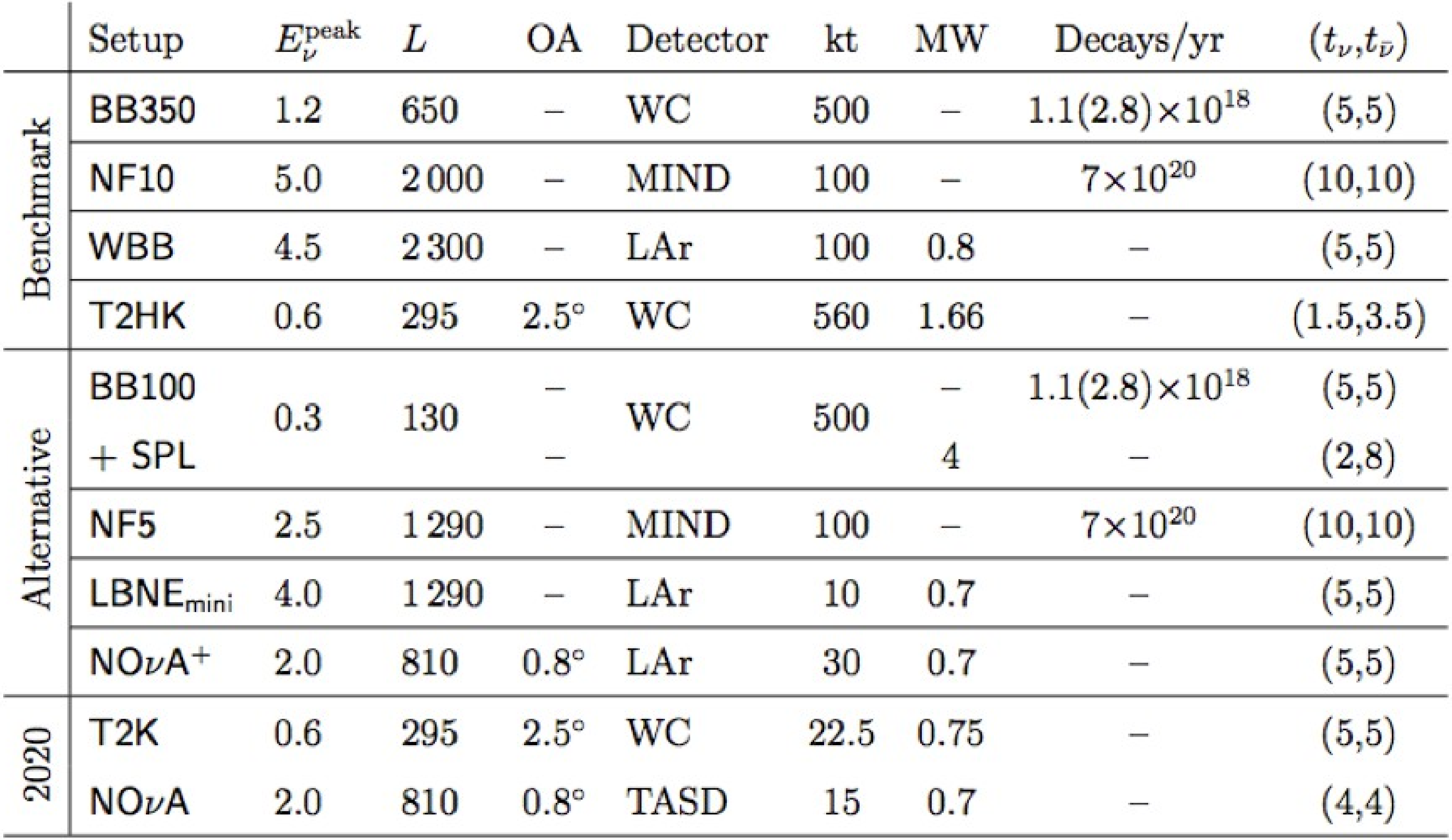
- Calorimetric detectors will likely help with these issues. However:
  - Have Cross sections been measured in Ar? (large differences between C and O)
  - Neutrons will most likely still be an issue no matter what we do
  - How much energy can an Ar nuclei absorb from a given event?

Keep all of these in mind, but above all…

…be ready for the unexpected!

BACKUP SLIDES

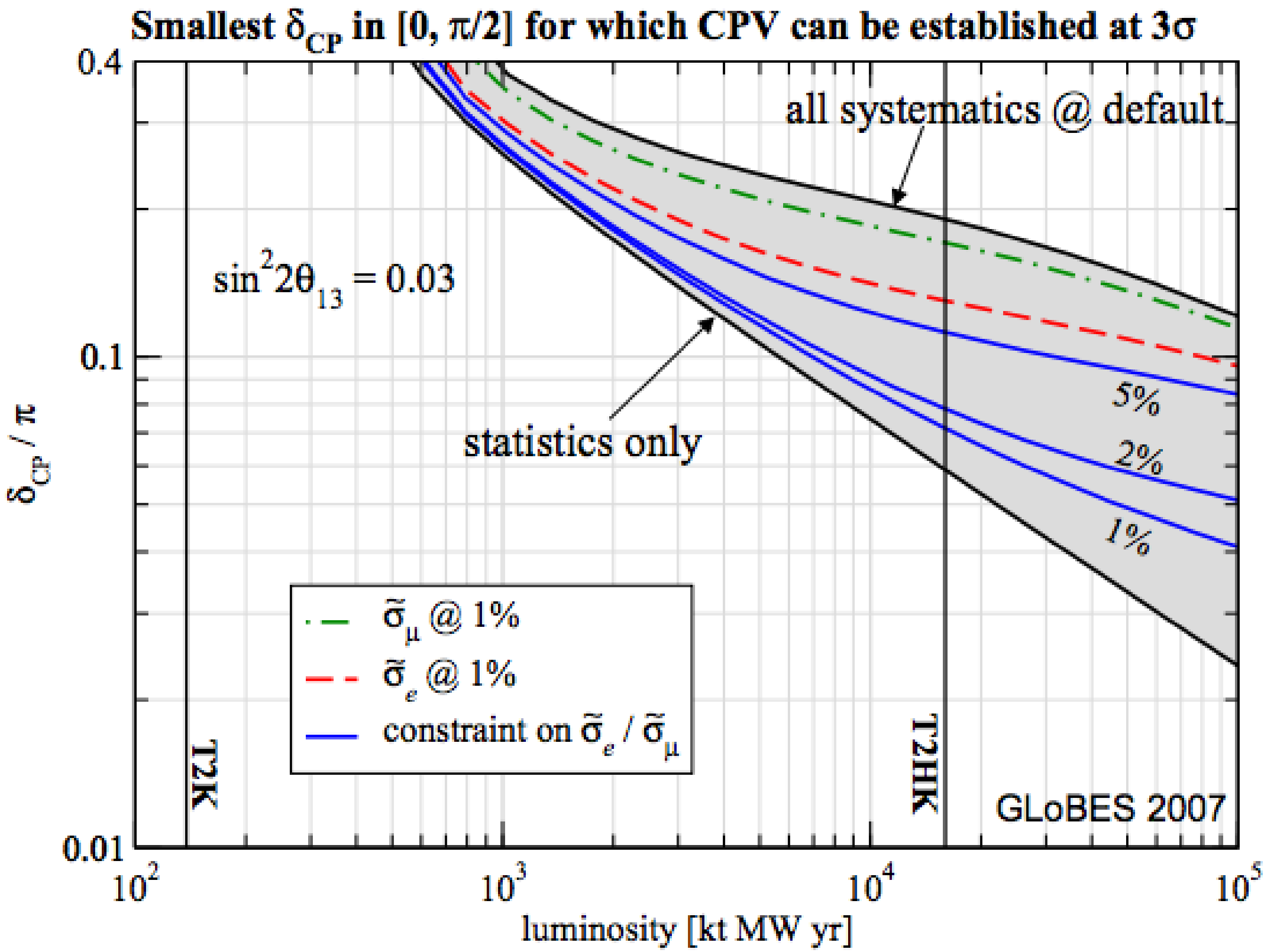
Setups



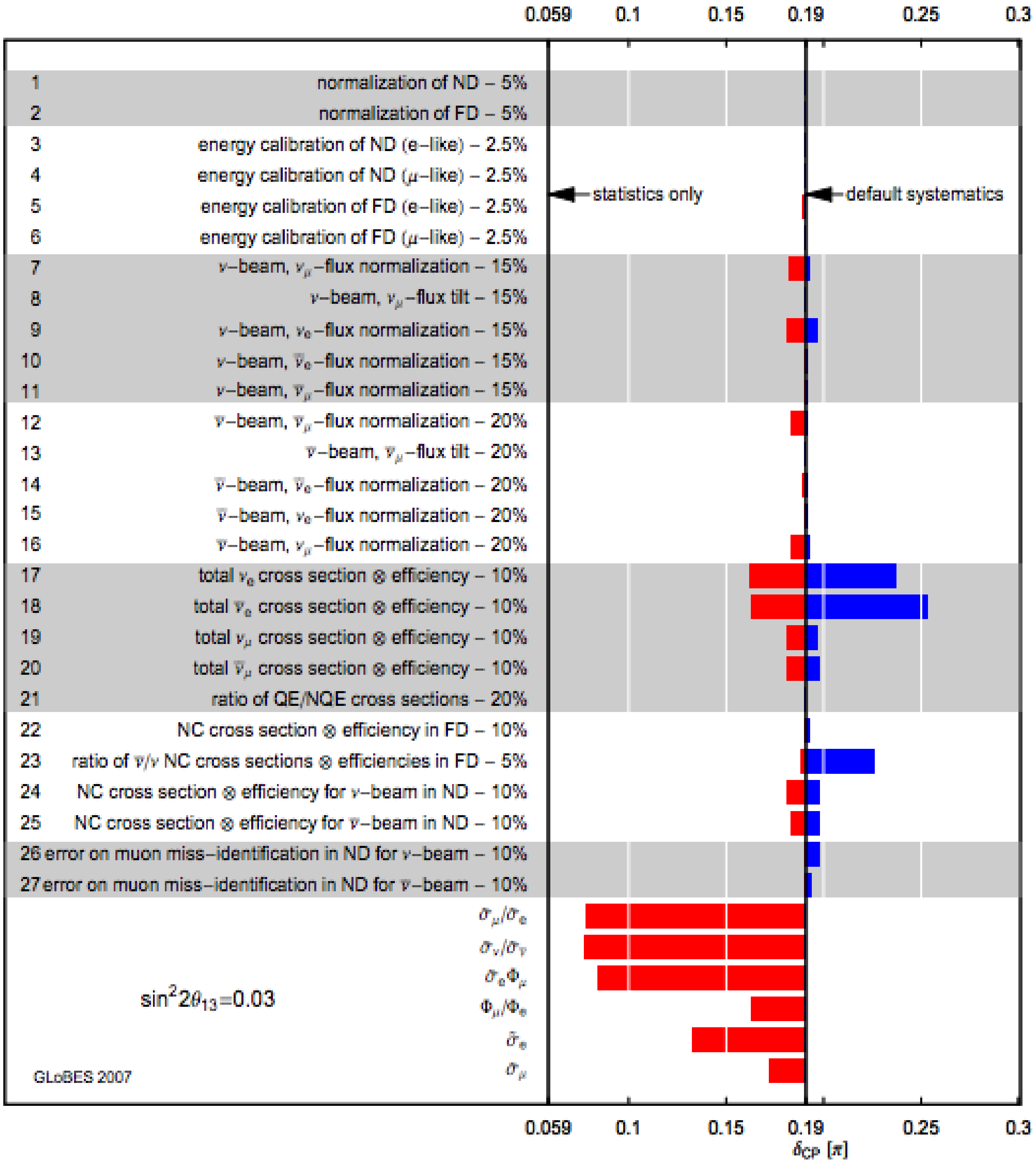
	Setup	E_ν^{peak}	L	OA	Detector	kt	MW	Decays/yr	$(t_\nu,t_{\bar\nu})$
Benchmark	BB350	1.2	650	–	WC	500	–	$1.1(2.8)\times10^{18}$	(5,5)
	NF10	5.0	2 000	–	MIND	100	–	7×10^{20}	(10,10)
	WBB	4.5	2 300	–	LAr	100	0.8	–	(5,5)
	T2HK	0.6	295	2.5°	WC	560	1.66	–	(1.5,3.5)
Alternative	BB100	0.3	130	–	WC	500	–	$1.1(2.8)\times10^{18}$	(5,5)
	+ SPL			–			4	–	(2,8)
	NF5	2.5	1 290	–	MIND	100	–	7×10^{20}	(10,10)
	LBNE$_{\text{mini}}$	4.0	1 290	–	LAr	10	0.7	–	(5,5)
	NOνA$^+$	2.0	810	0.8°	LAr	30	0.7	–	(5,5)
2020	T2K	0.6	295	2.5°	WC	22.5	0.75	–	(5,5)
	NOνA	2.0	810	0.8°	TASD	15	0.7	–	(4,4)

Coloma, Huber, Kopp, Winter, 1209.5973 [hep-ph]

Impact of normalization uncertainties

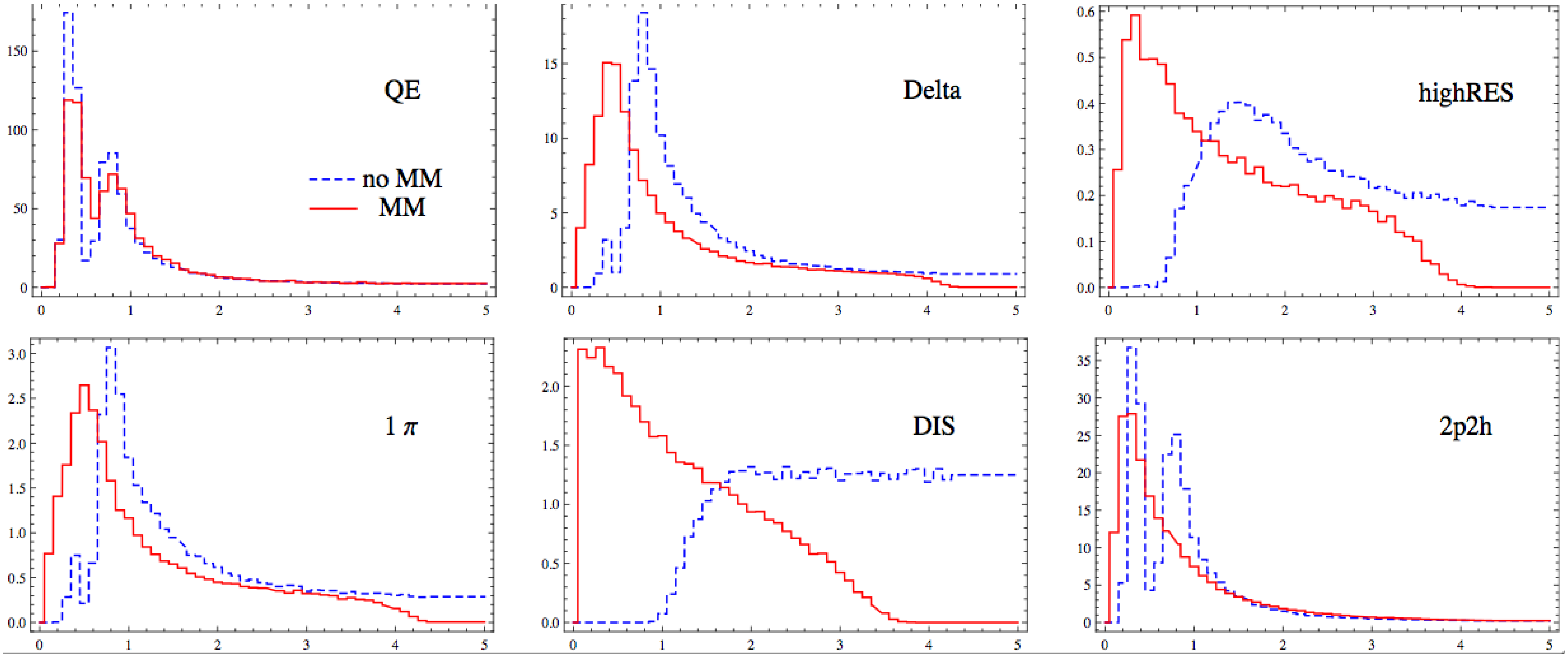


Huber, Mezzetto and Schwetz, 0711.2950 [hep-ph]

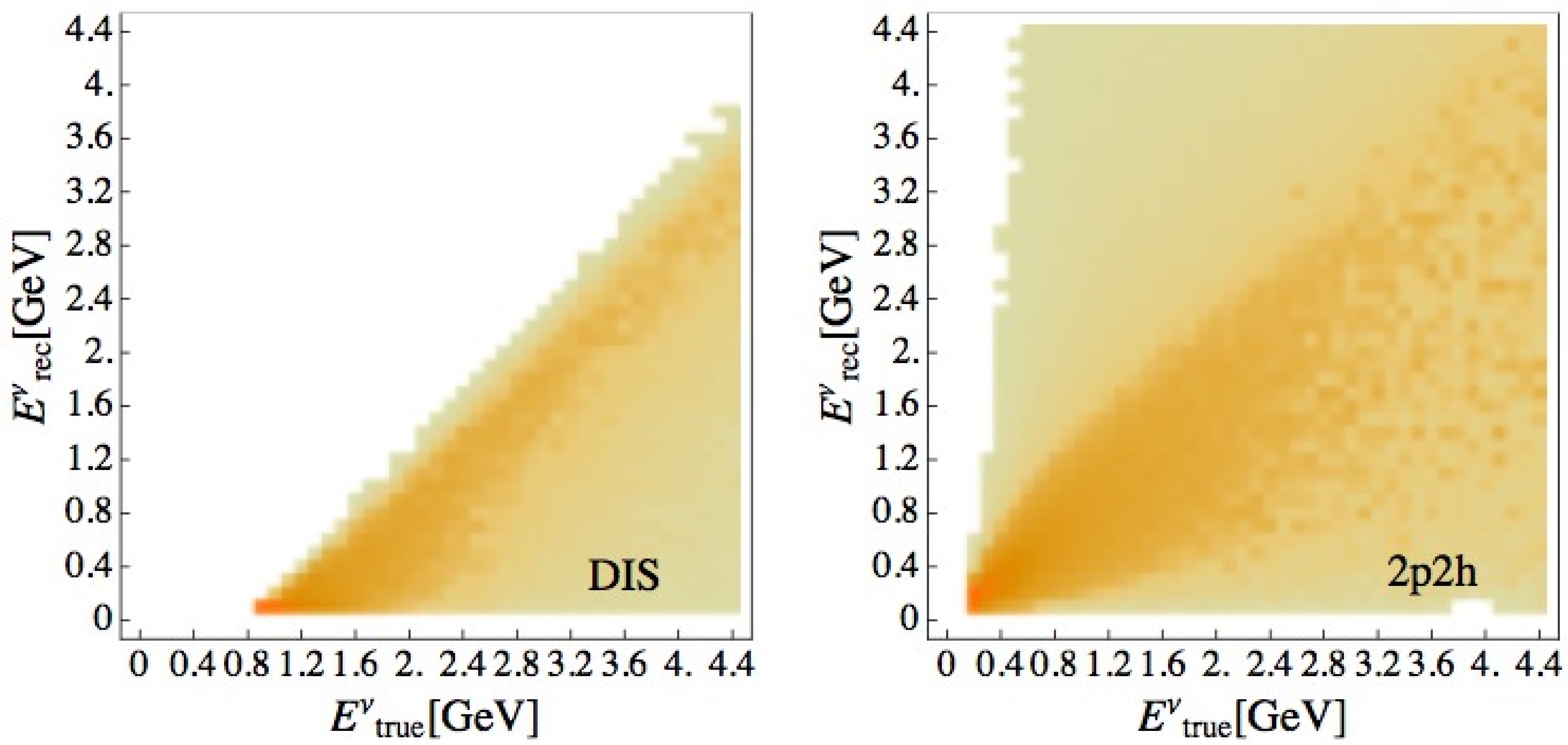


Huber, Mezzetto
and Schwetz,
0711.2950 [hep-ph]

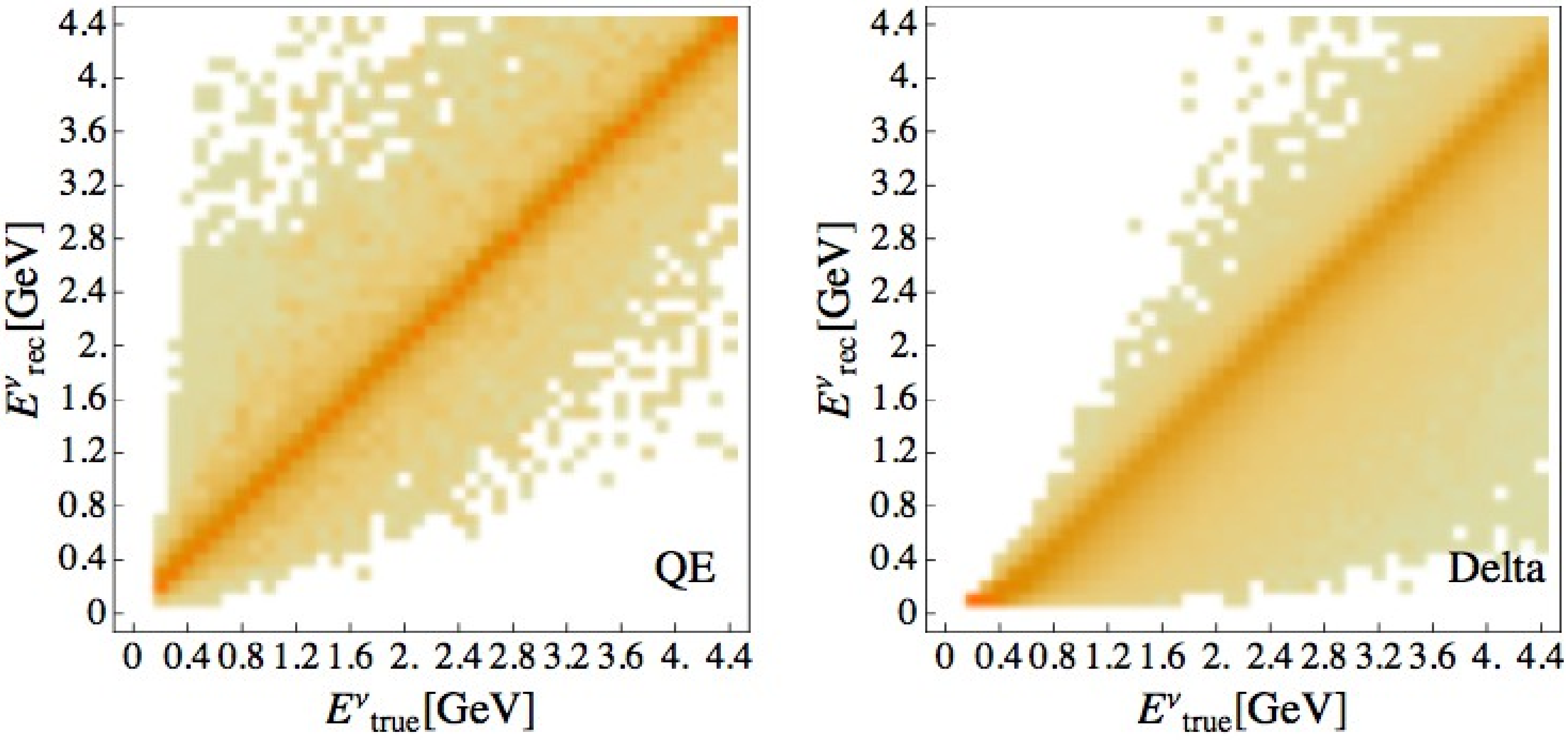
Event distributions



Migration matrices

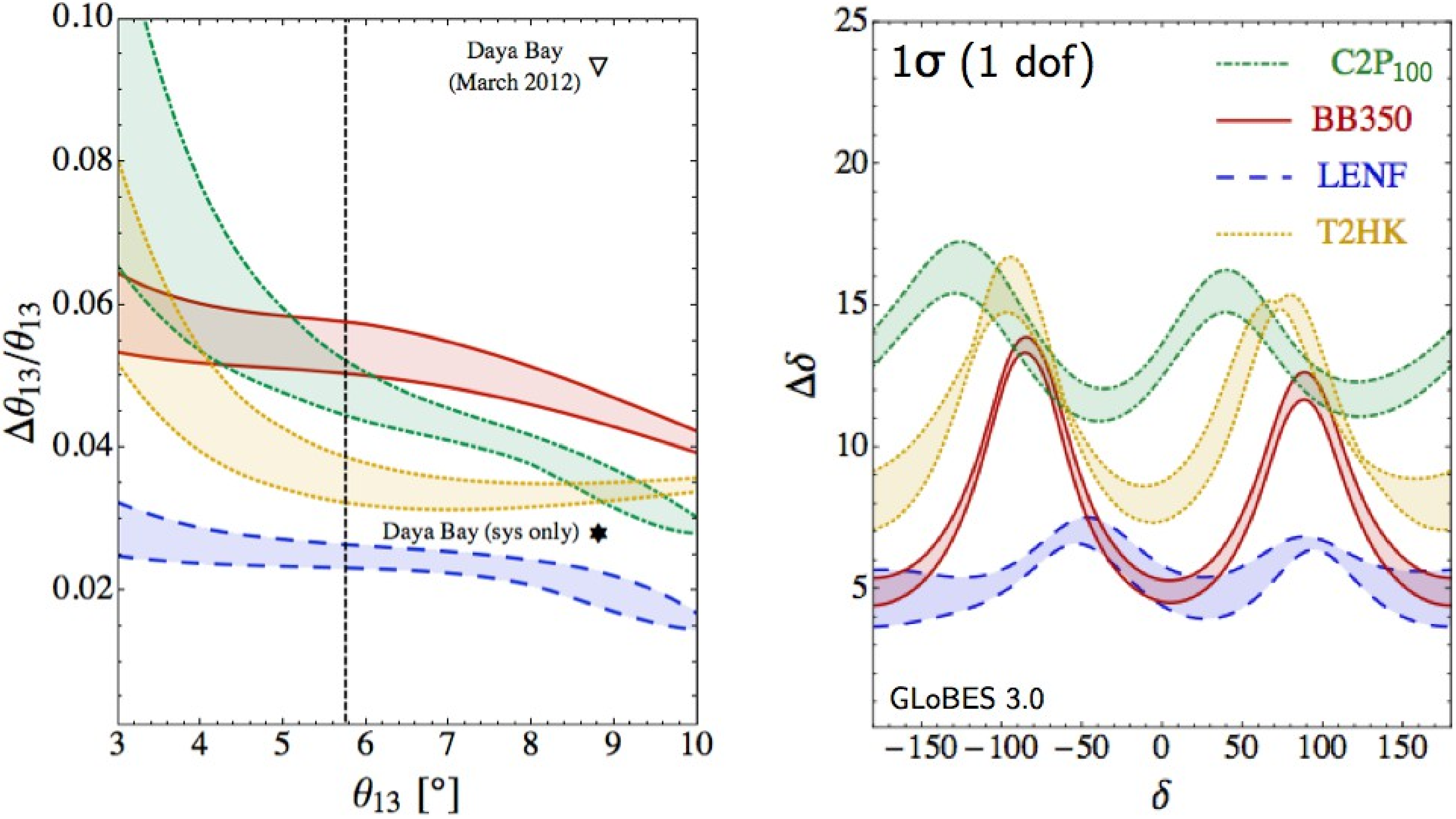


Migration matrices

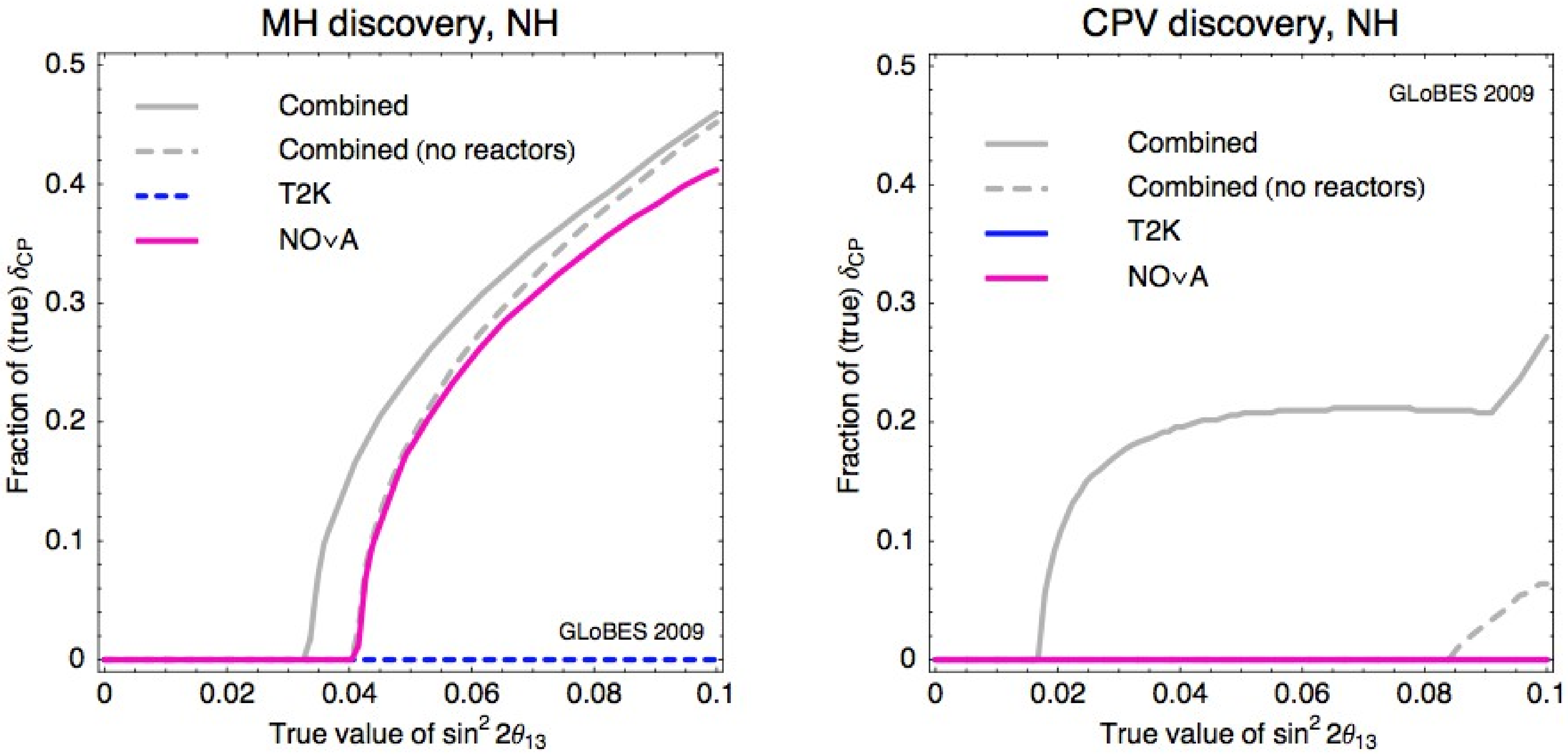


Backup

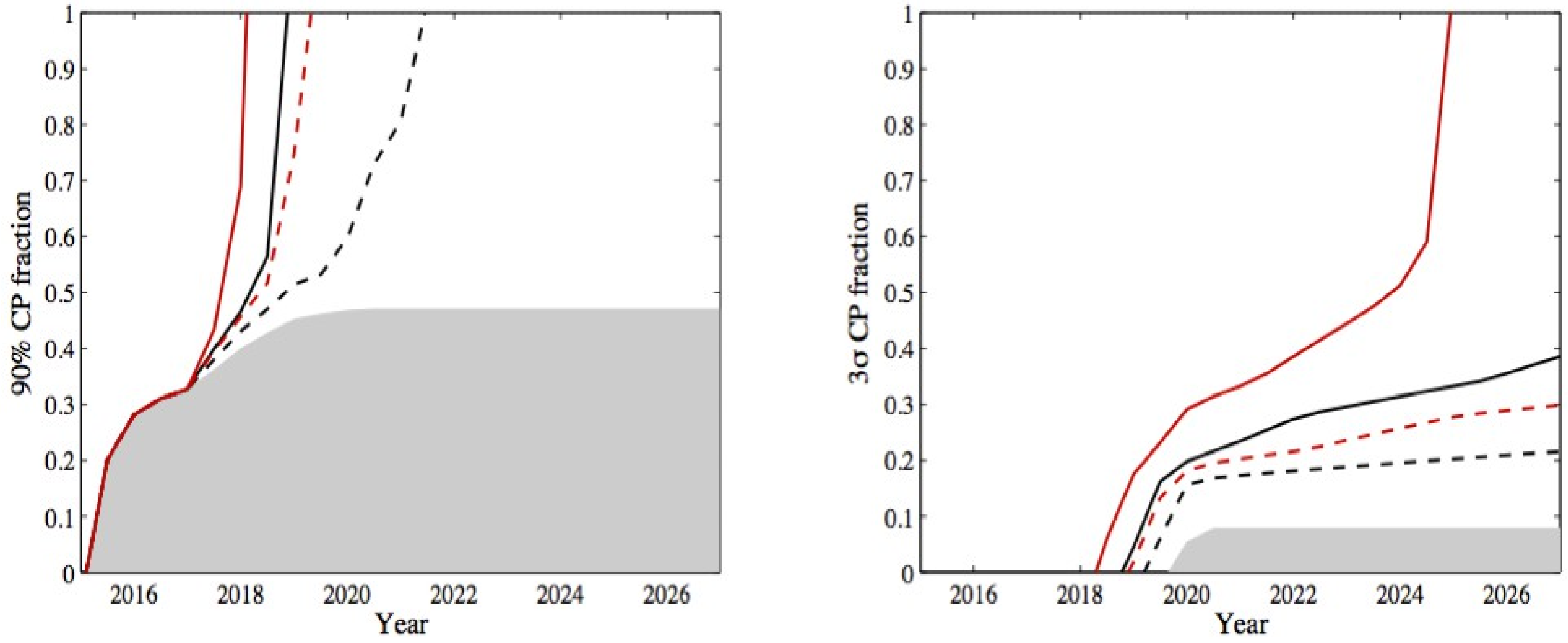
Future prospects



Current generation

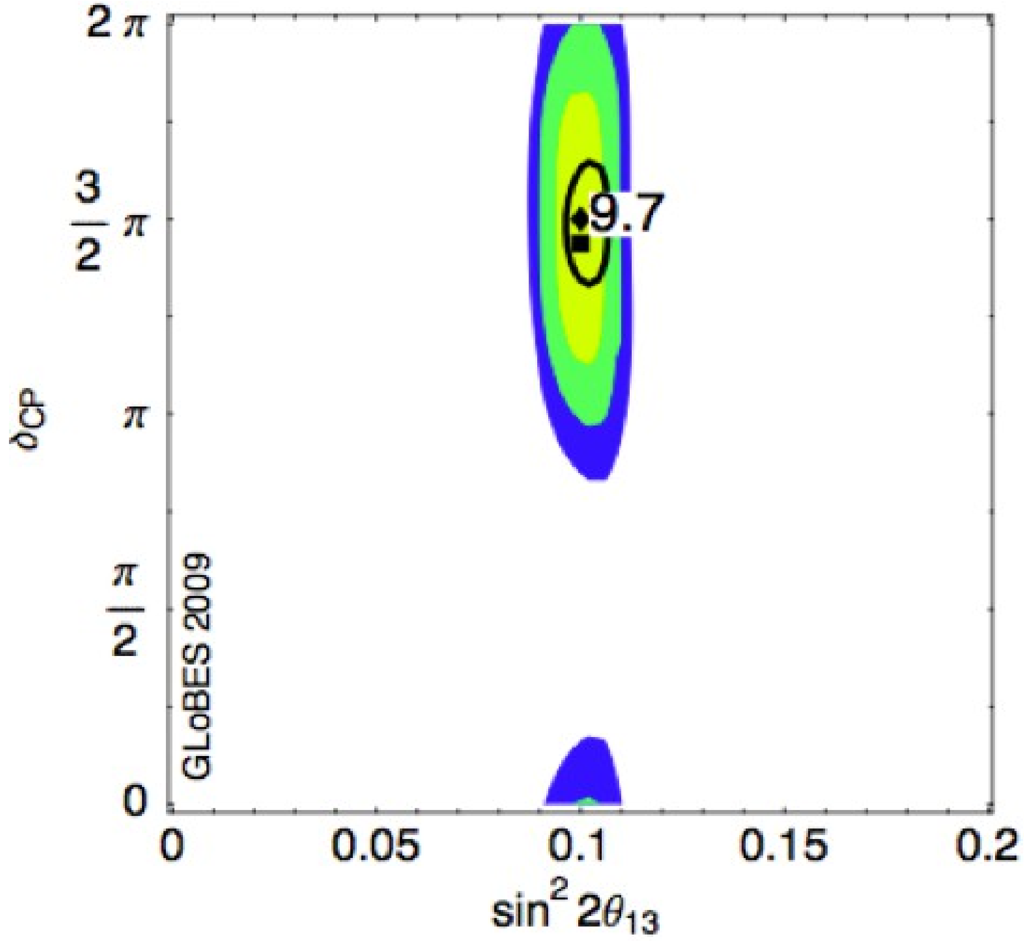


Current generation



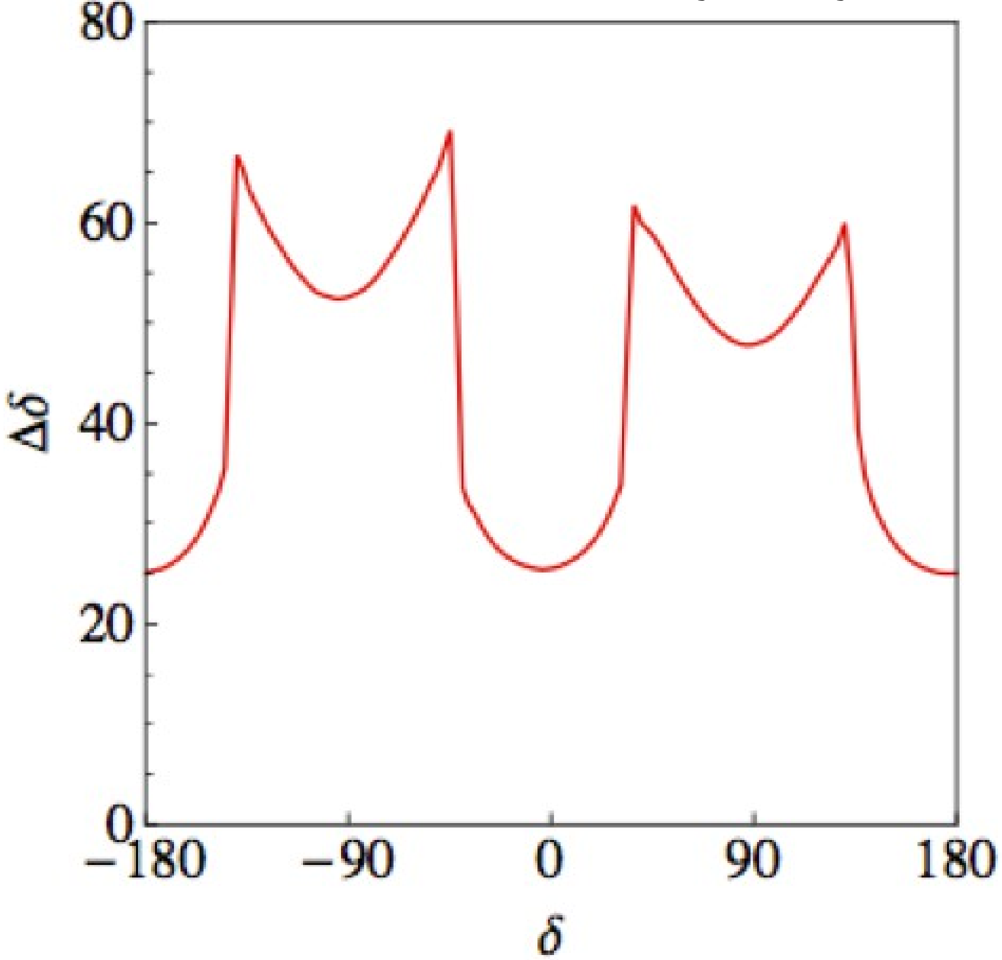
Degeneracies

T2K + NOvA + Daya Bay



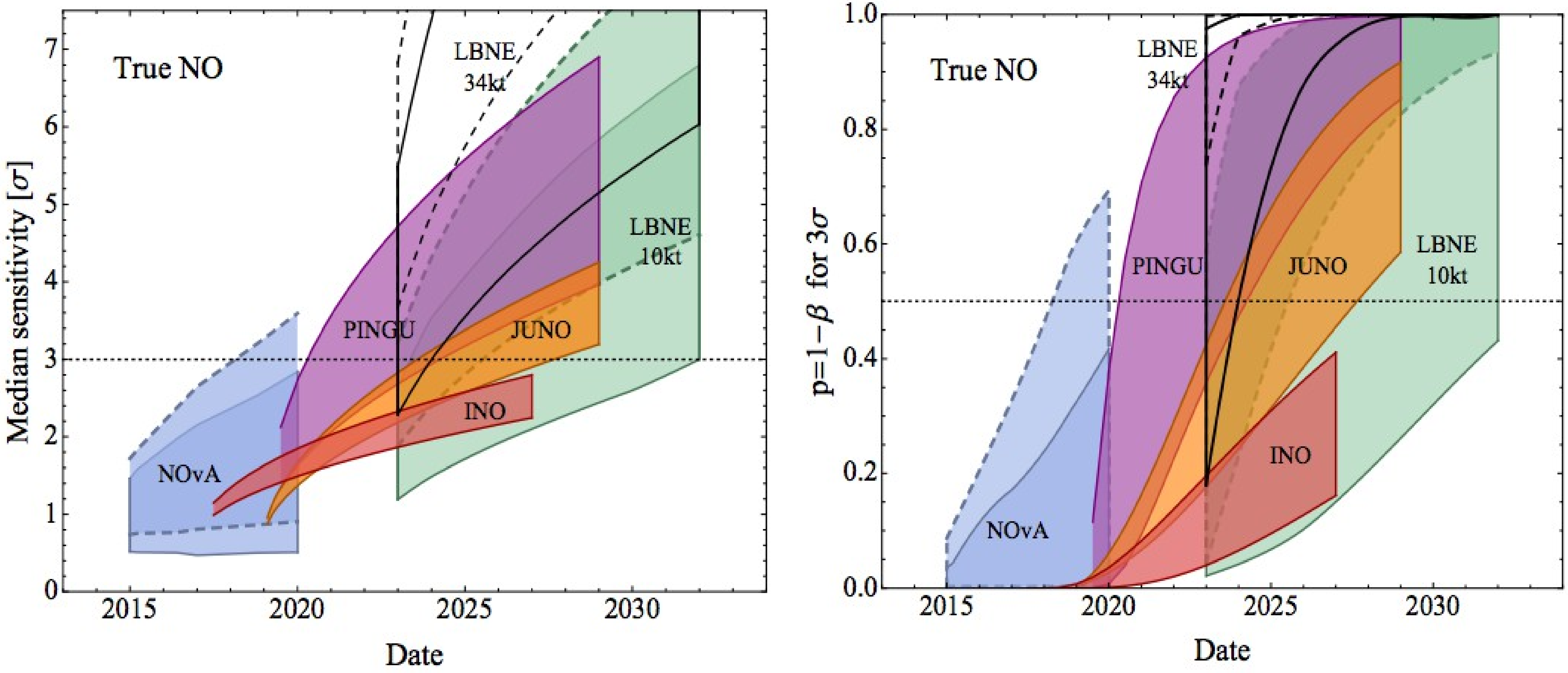
Huber et al, 0907.1896 [hep-ph]

T2K + NOvA + Daya Bay



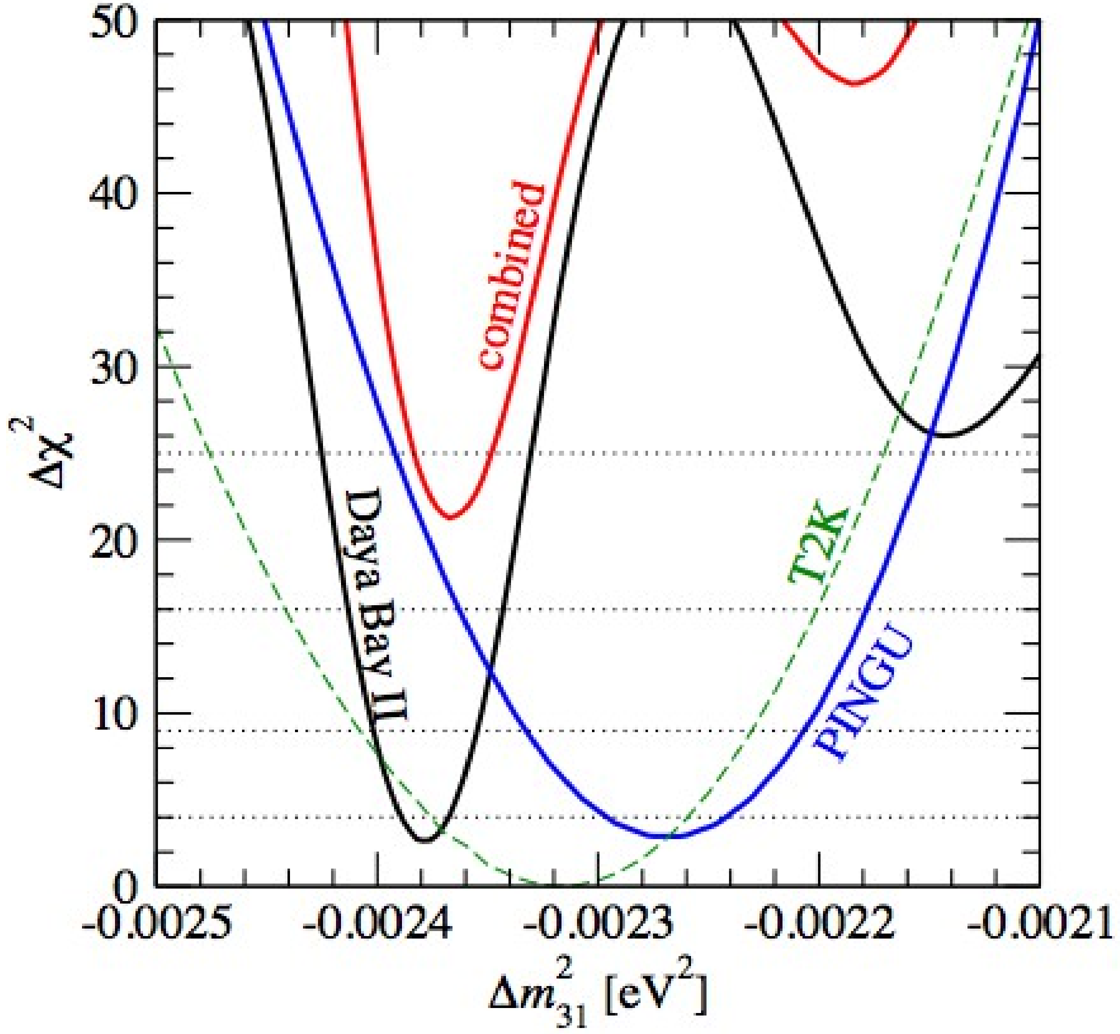
Coloma et al, 1203.5651 [hep-ph]

Prospects for mass hierarchy



Blennow, Coloma, Huber and Schwetz, 1311.1822 [hep-ph]

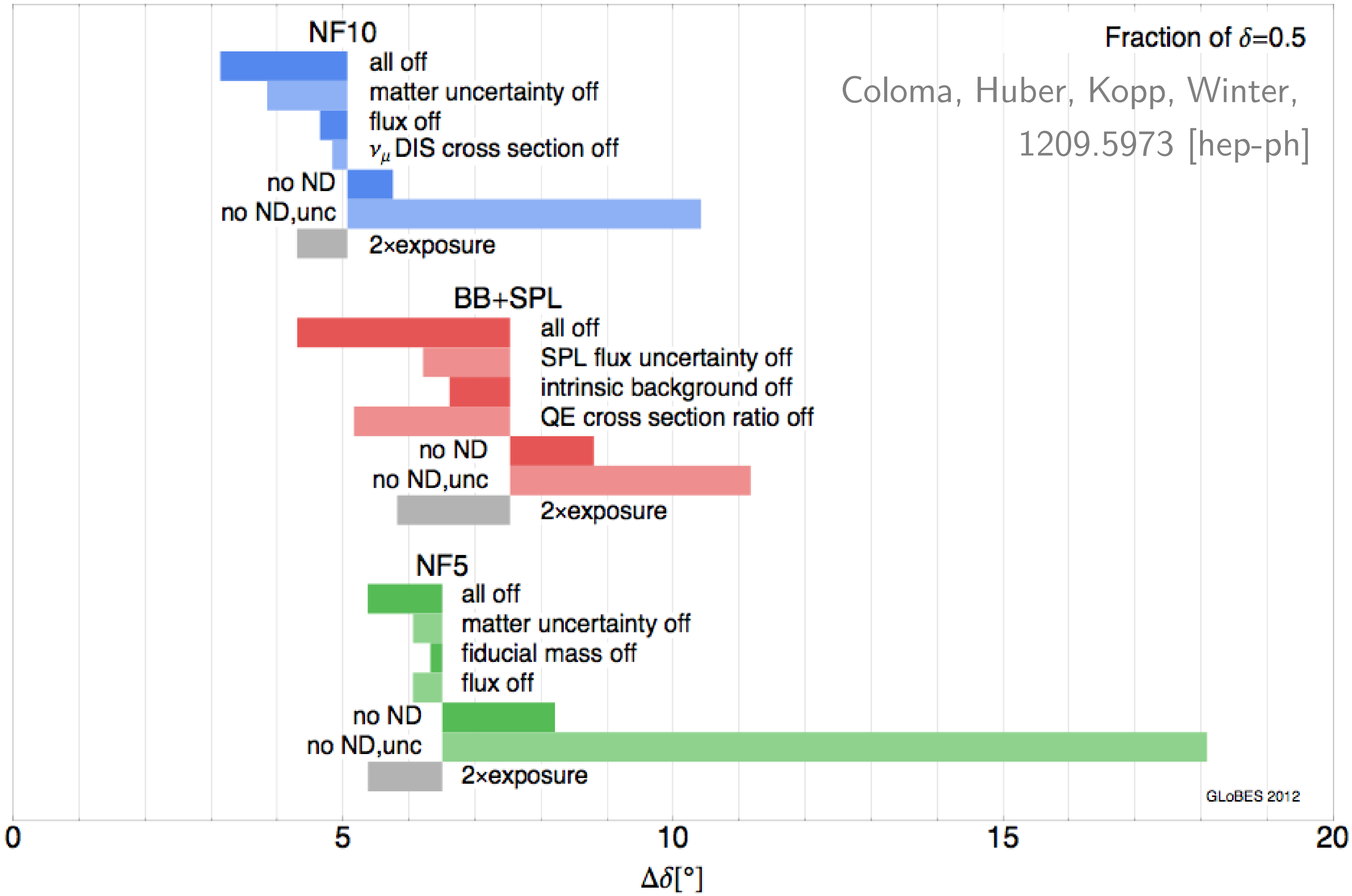
Mass hierarchy determination



Blennow, Schwetz, 1306.3988 [hep-ph]

(see also Li *et al*, 1303.6733 [hep-ph], for instance)

Impact on precision



Coloma, Huber, Kopp, Winter, 1209.5973 [hep-ph]

Experimental overview: mass ordering

NuMAX 1290 km

~300/60 events/ch

LBNE 10kt 1290 km

~200/60 events

NOvA 810 km

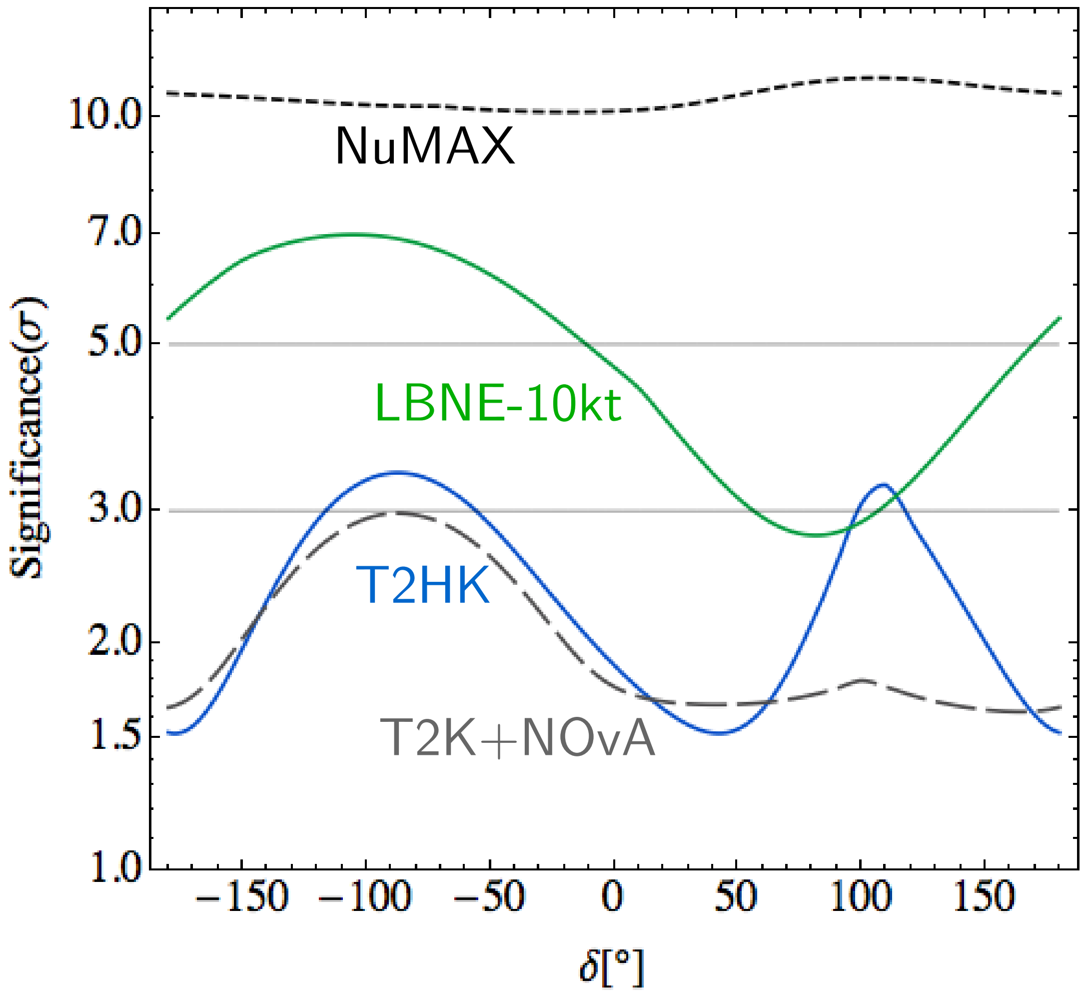
~80/23 events

T2(H)K 295 km

~4000/2200 events

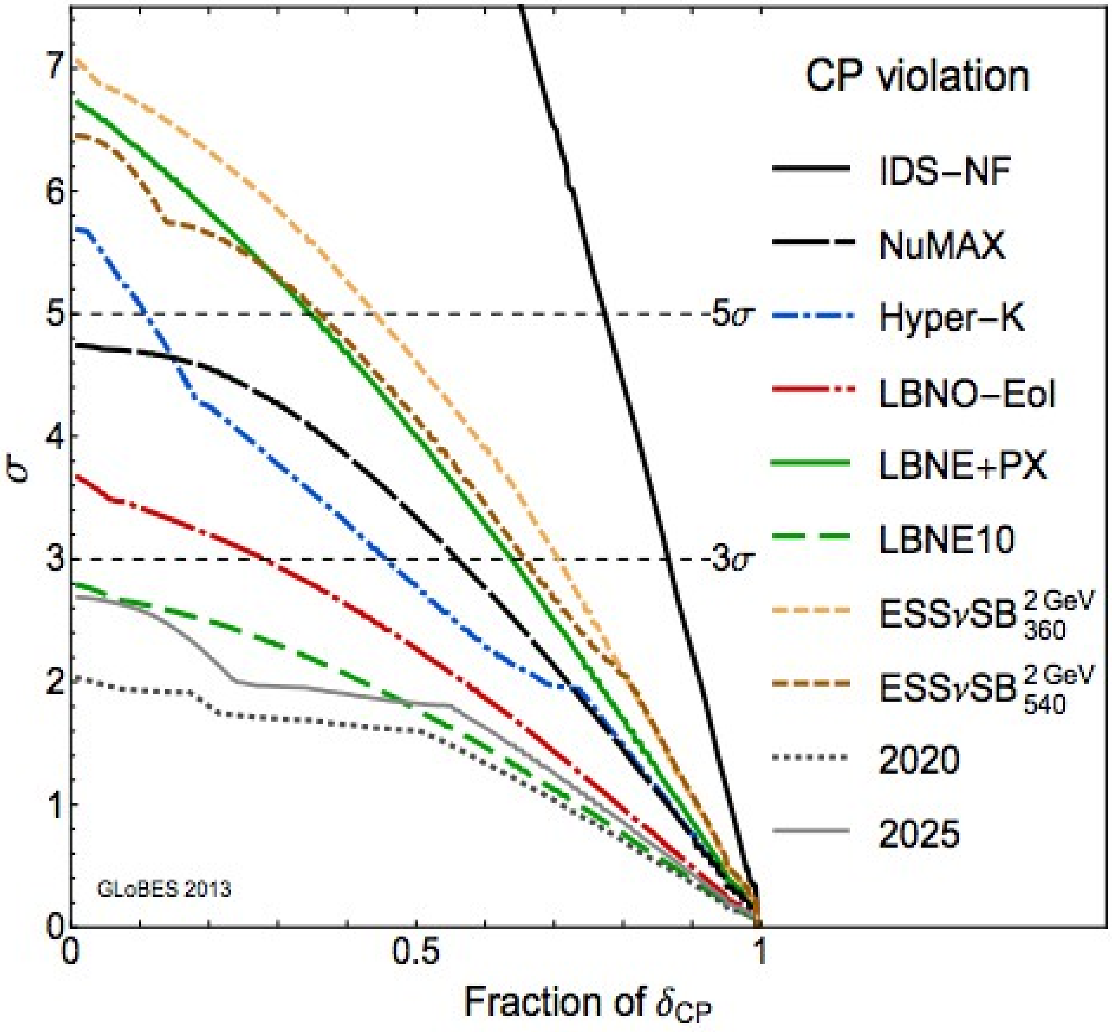
baseline

Mass ordering



Experimental overview: CP violation

Baussan et al., 1309.7022 [hep-ph]



P. Coloma - NuSTEC school

Experimental overview: precision

Snowmass process, 1310.4340 [hep-ph]