Impact of systematics on neutrino oscillation experiments

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NuSTEC school

Fermilab, Oct 29th, 2014

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

Impact of normalization uncertainties

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

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

We need:

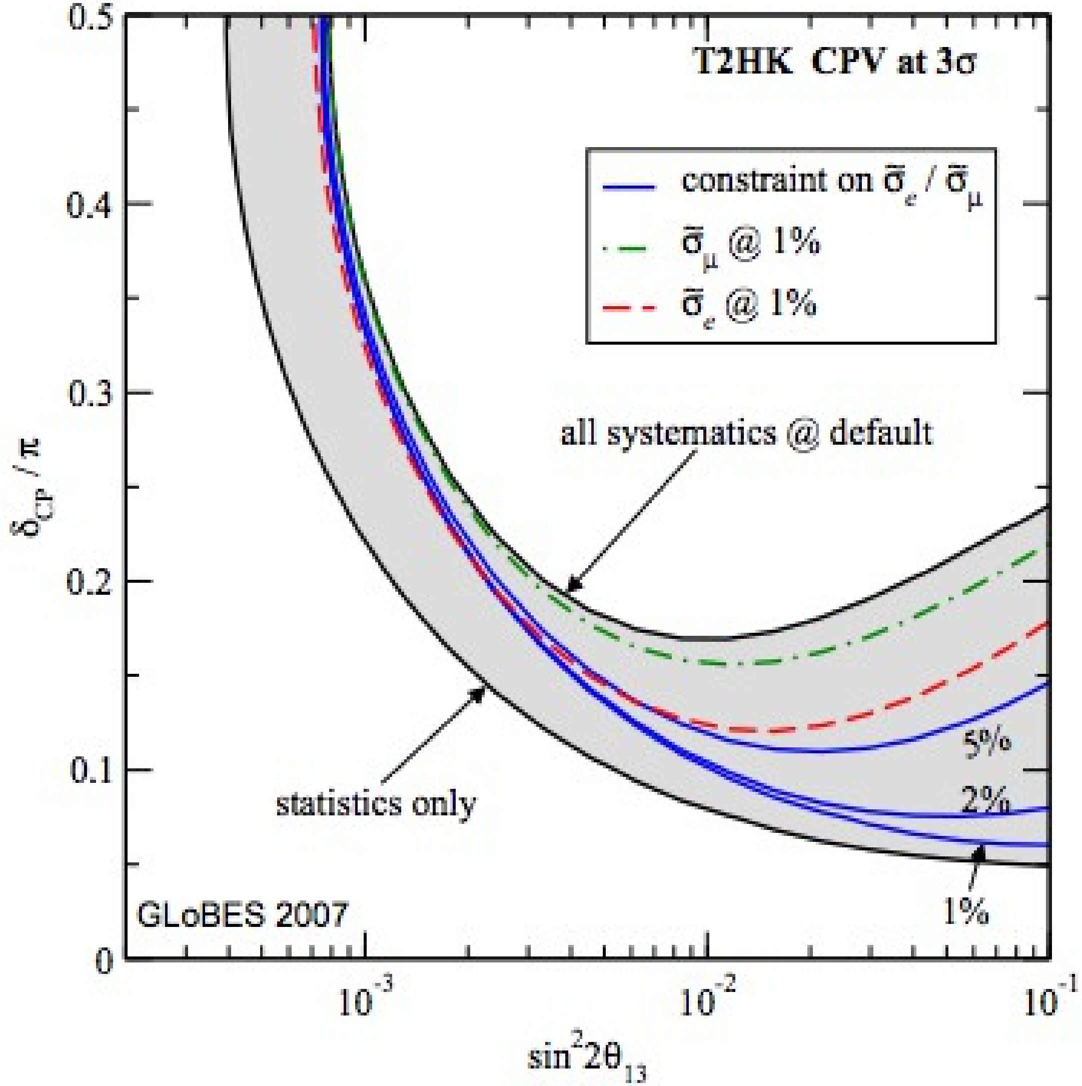
$$\frac{\tilde{\sigma}_{\nu_e}}{\tilde{\sigma}_{\nu_\mu}} \text{ and } \frac{\tilde{\sigma}_{\bar{\nu}_e}}{\tilde{\sigma}_{\bar{\nu}_\mu}} \qquad \text{OR} \qquad \frac{\tilde{\sigma}_{\nu_e}}{\tilde{\sigma}_{\bar{\nu}_e}} \text{ and } \frac{\tilde{\sigma}_{\nu_\mu}}{\tilde{\sigma}_{\bar{\nu}_\mu}}$$

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

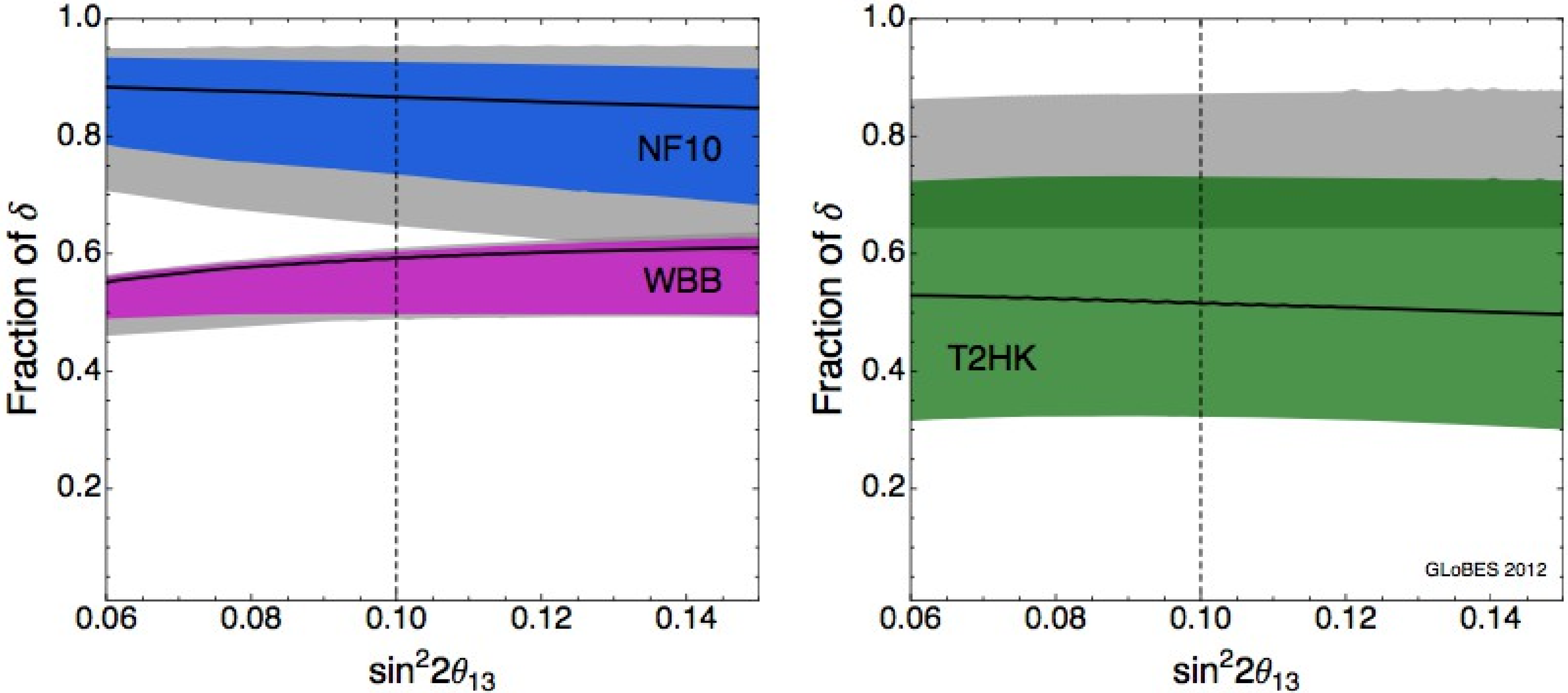
Huber, Mezzetto and Schwetz, 0711.2950 [hep-ph]

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

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

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

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

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

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

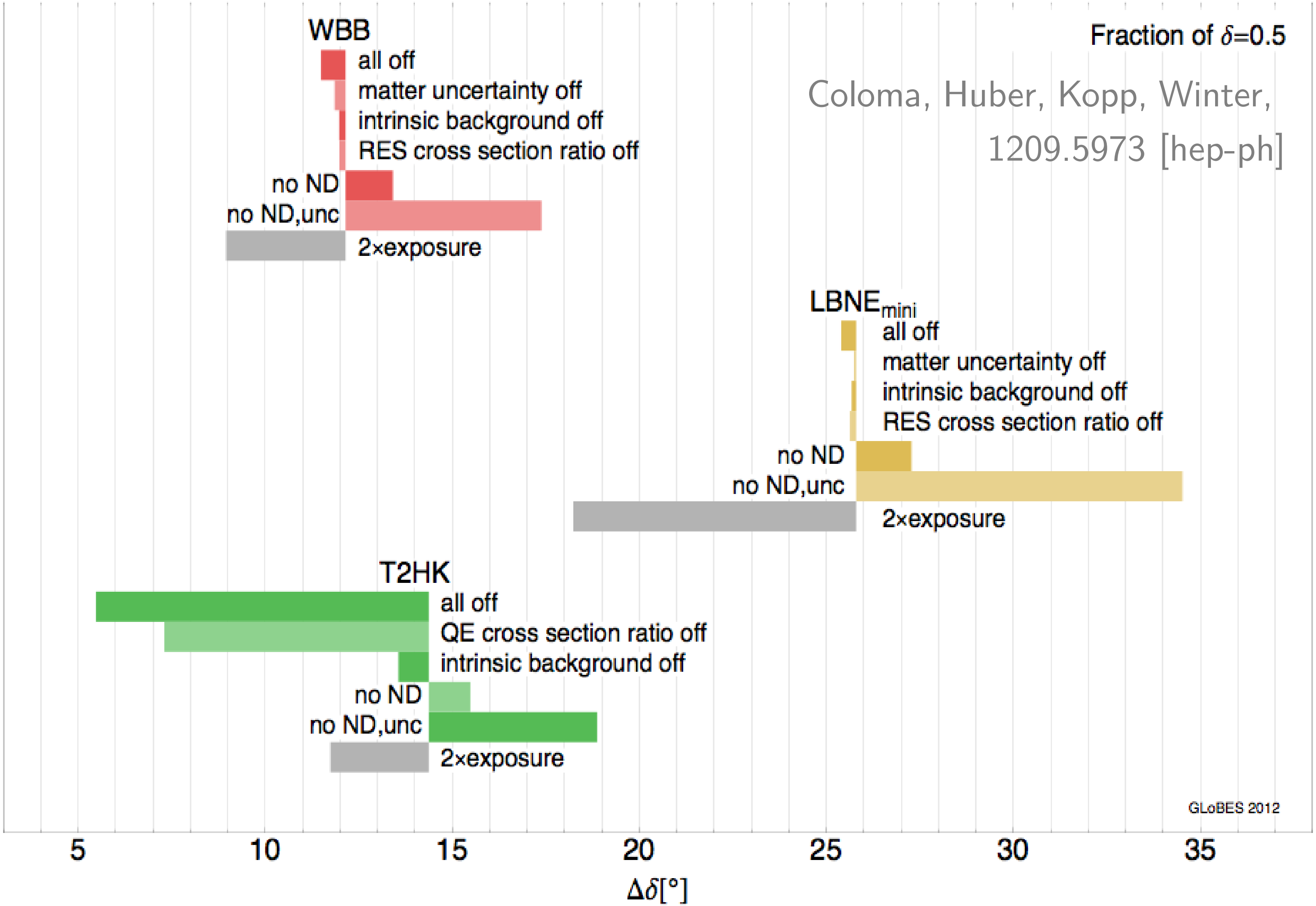
Either 1 (corr.) or 0 (unc.)

	SB			BB			NF		
Systematics	Opt.	Def.	Cons.	Opt.	Def.	Cons.	Opt.	Def.	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 $\times$ eff. QE†	10%	15%	20%	10%	15%	20%	10%	15%	20%
Cross secs $\times$ eff. RES†	10%	15%	20%	10%	15%	20%	10%	15%	20%
Cross secs $\times$ 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]

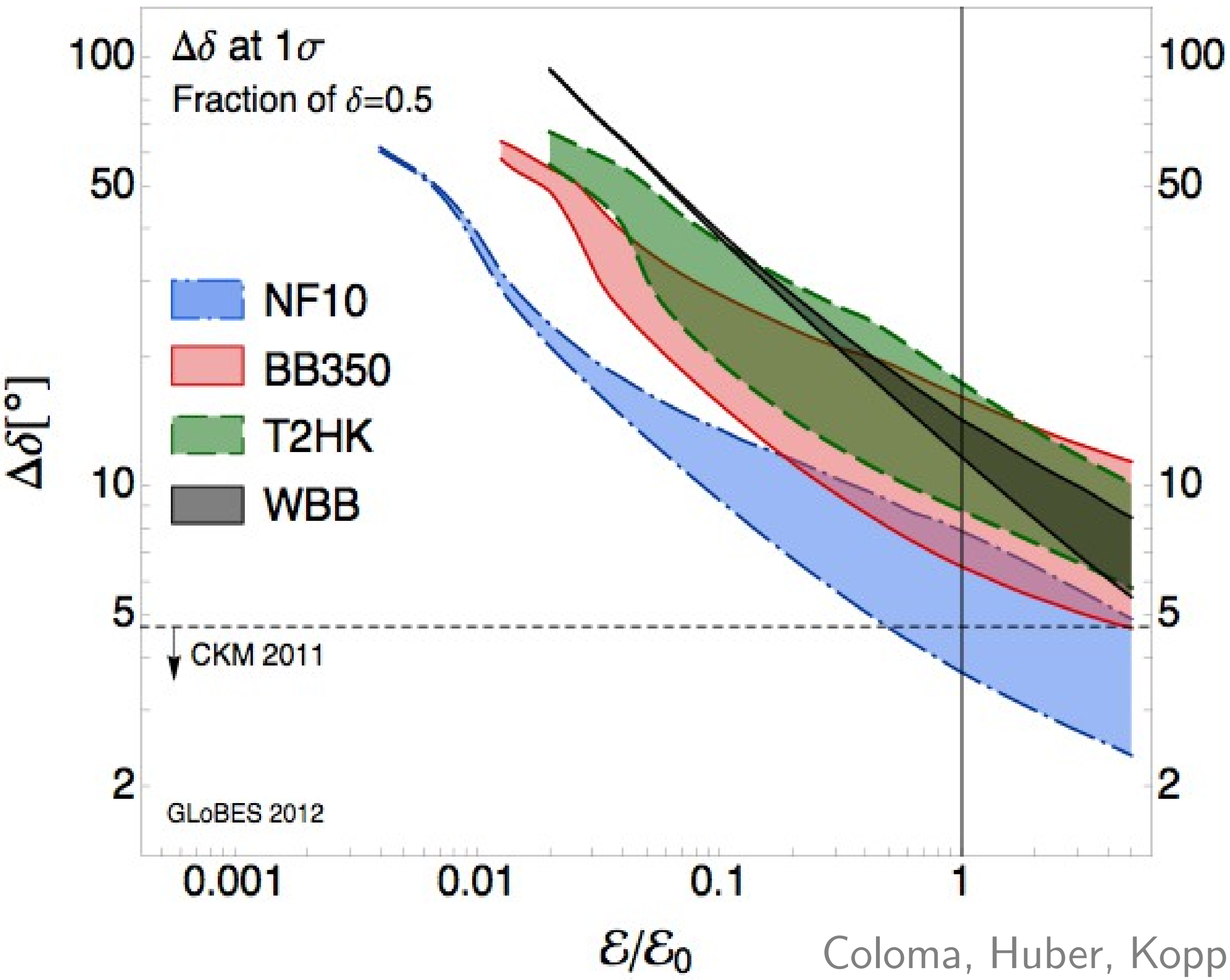
(Theoretical constraint)

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

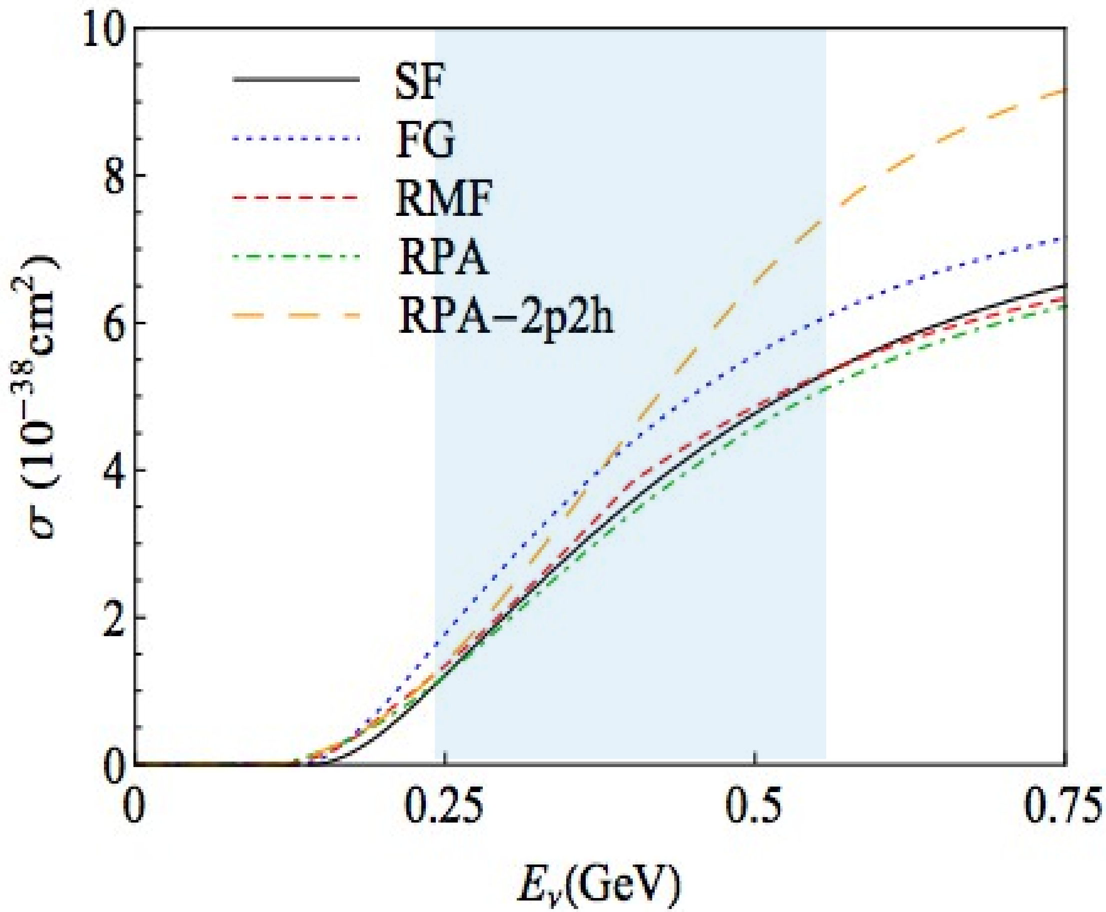
- Near and far detector fluxes can be very different:
  - Geometrical acceptance
  - If you don't know your flux nor your cross section, how can you constrain both?
- Near and far detector efficiencies will unfortunately be not so identical:
  - Different capabilities to contain events
  - Different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

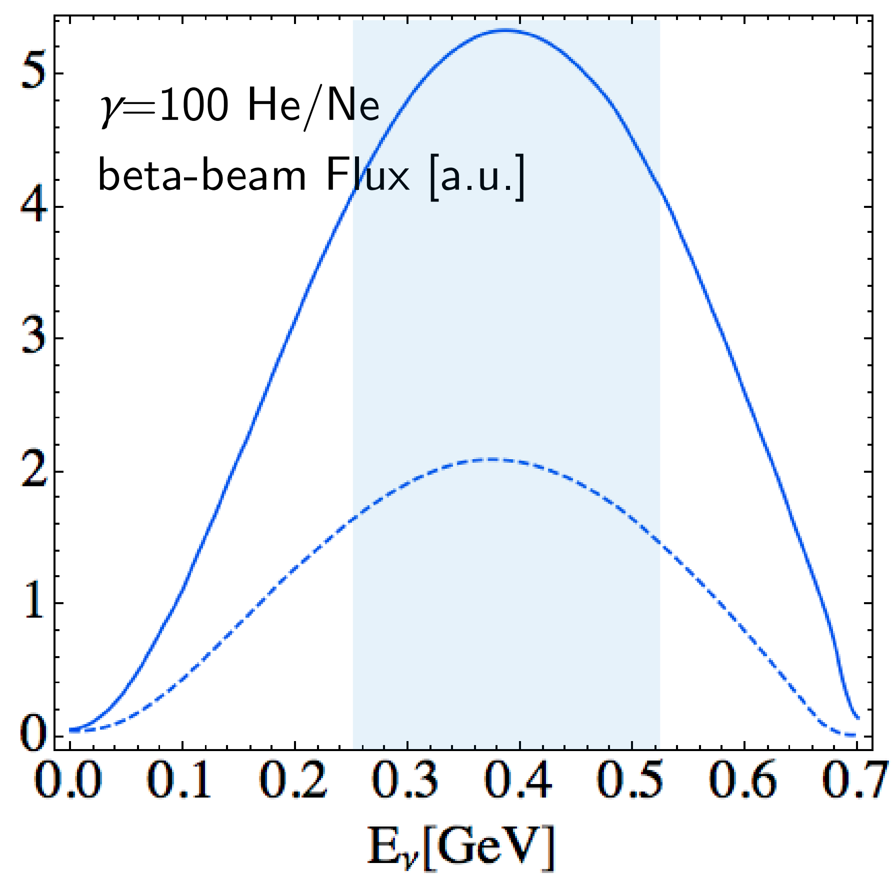
Shape uncertainties

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

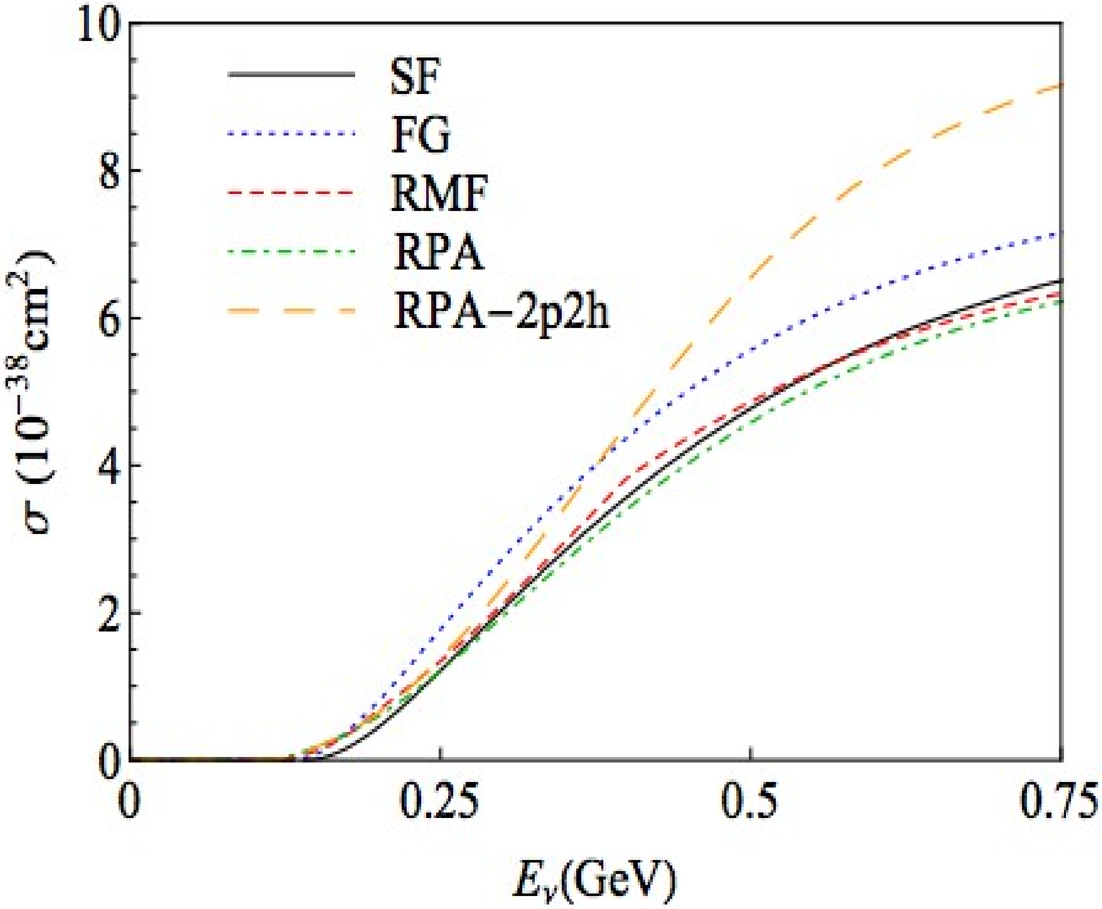


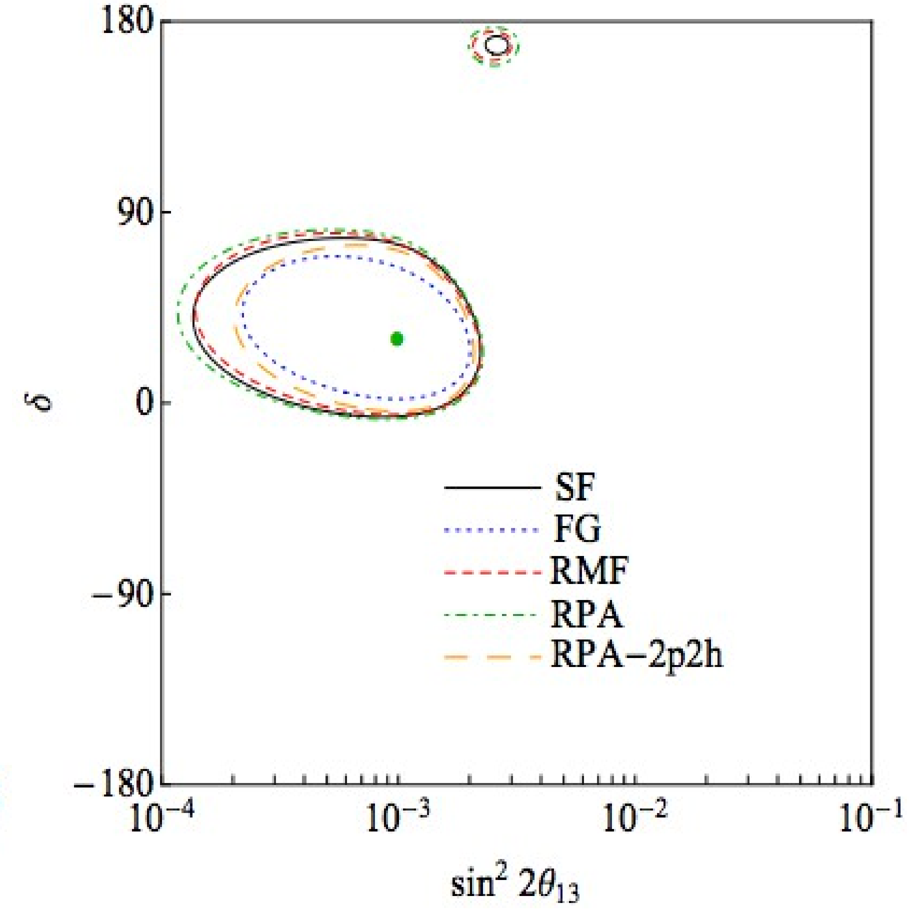


SF = Spectral Function; RMF = Relativistic mean field
FG = Fermi Gas; RPA = Random Phase Approximation

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

Cross section models



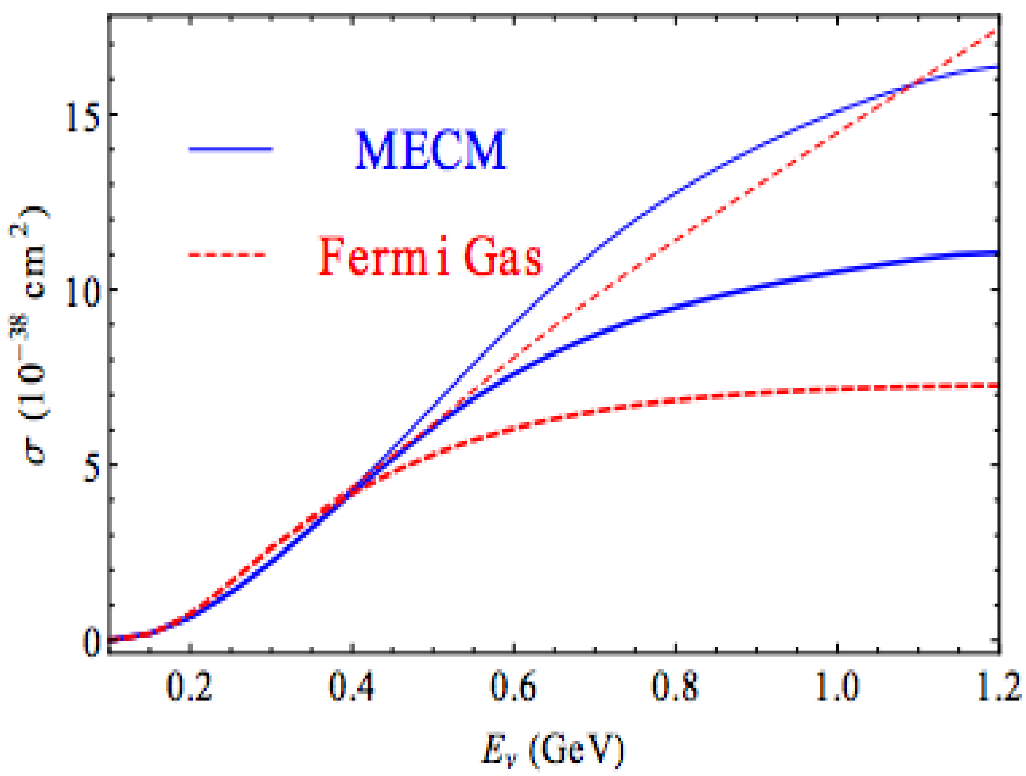


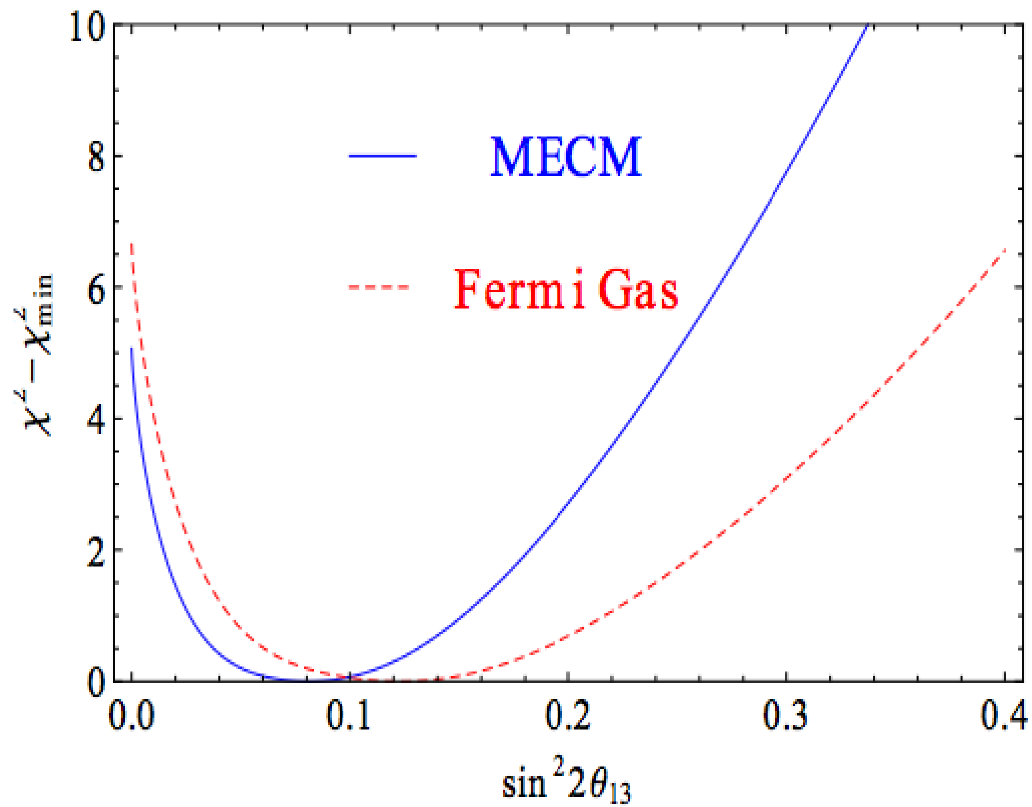
SF = Spectral Function; RMF = Relativistic mean field
FG = Fermi Gas; RPA = Random Phase Approximation

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

Cross section models

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



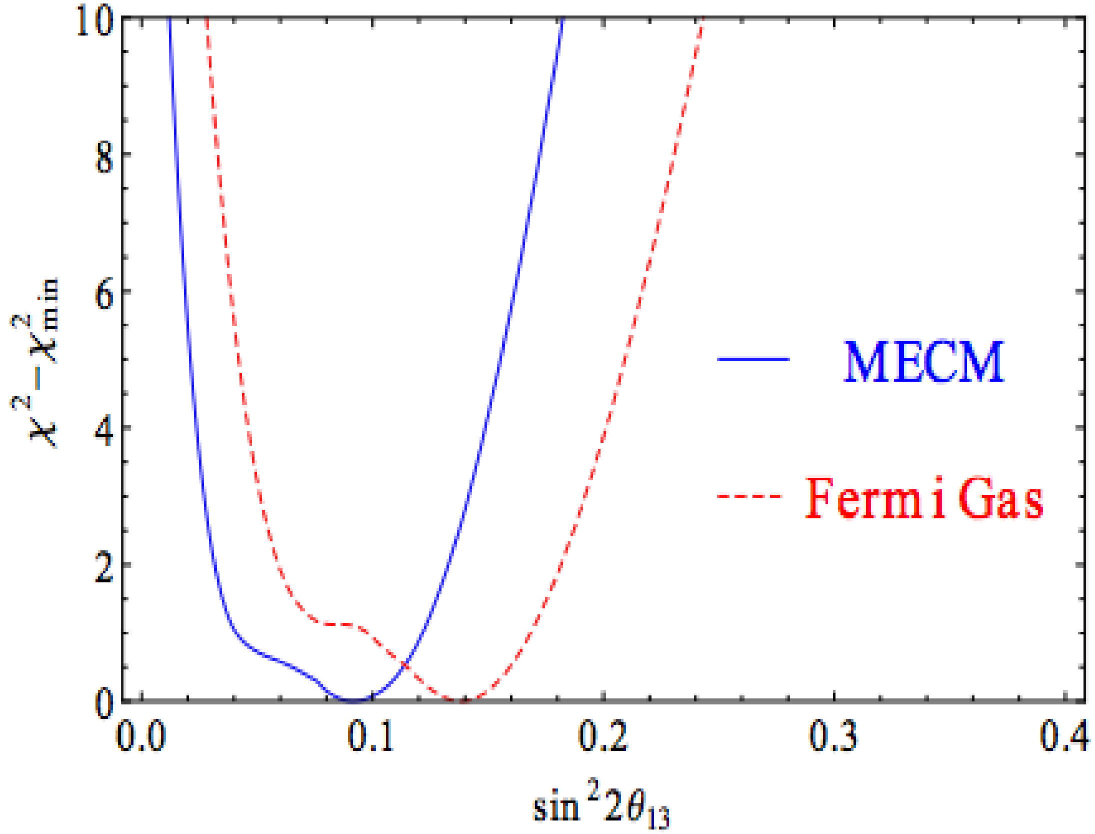


Martini, Meloni, 1203.3335 [hep-ph]

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]

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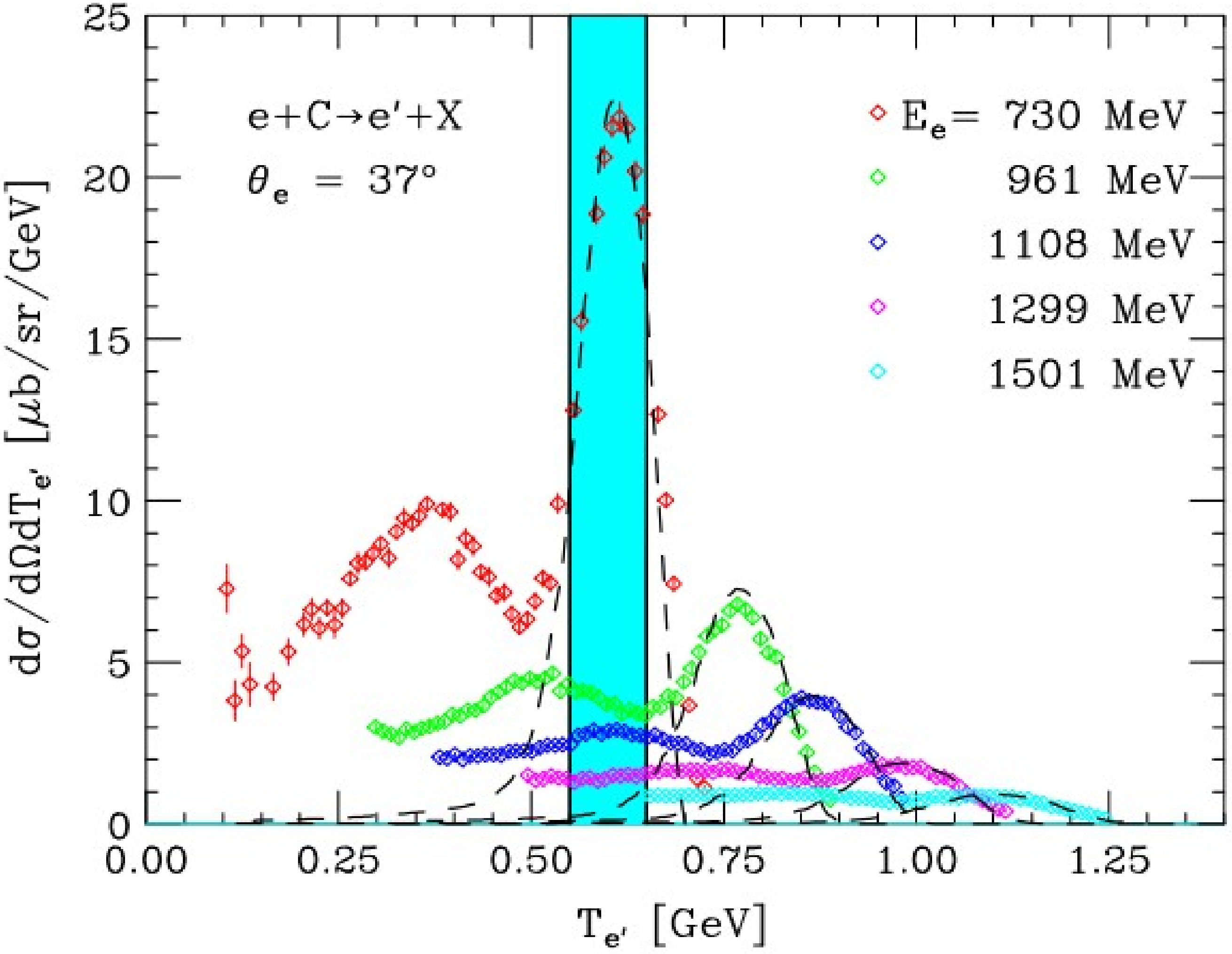
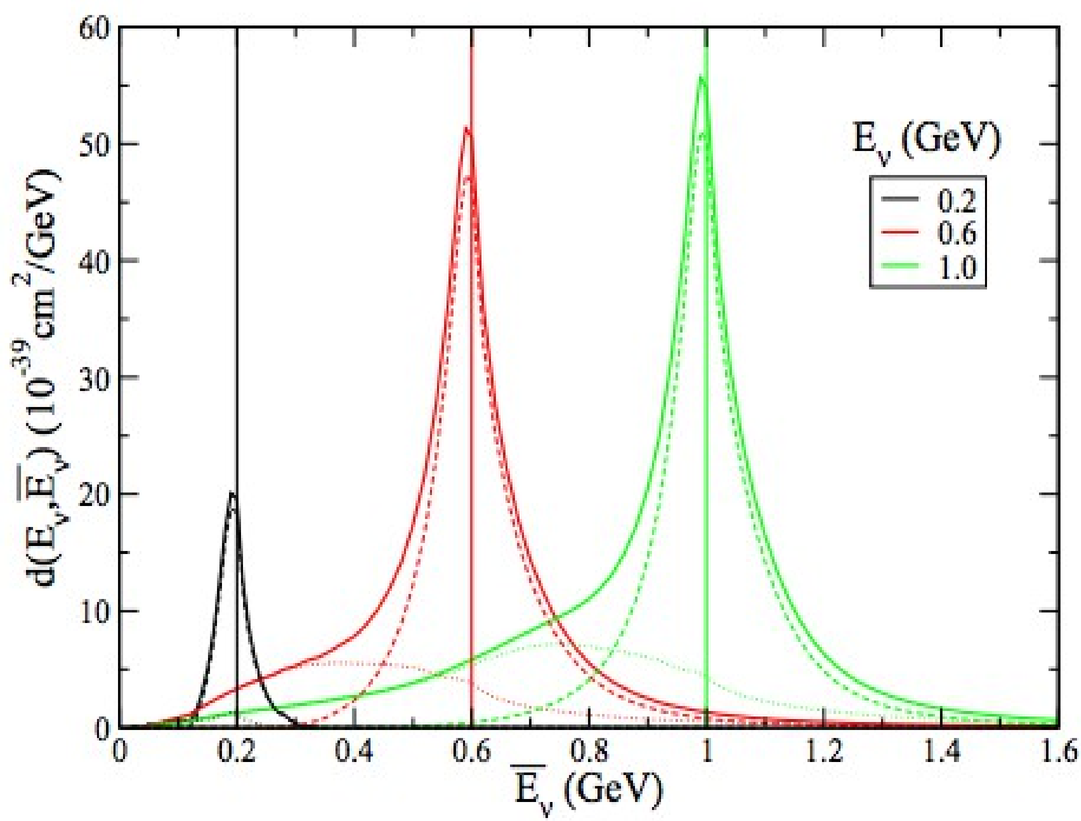
Energy reconstruction issues



Benhar, 1110.1835 [hep-ph]

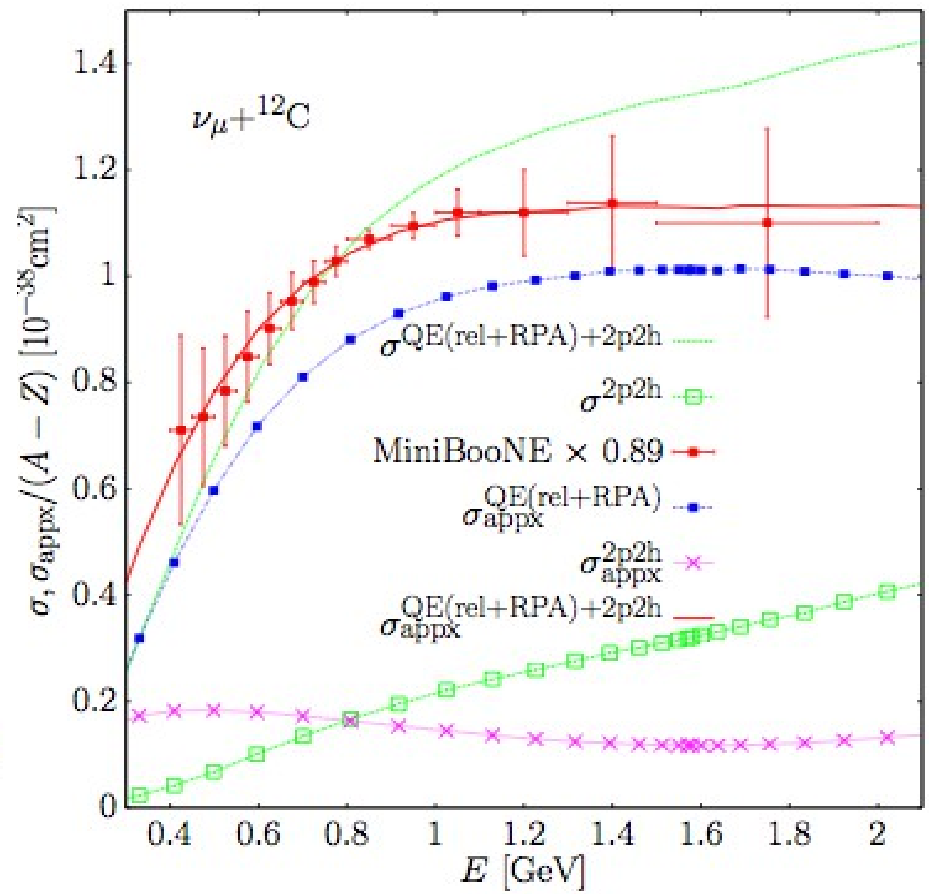
Energy reconstruction issues

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



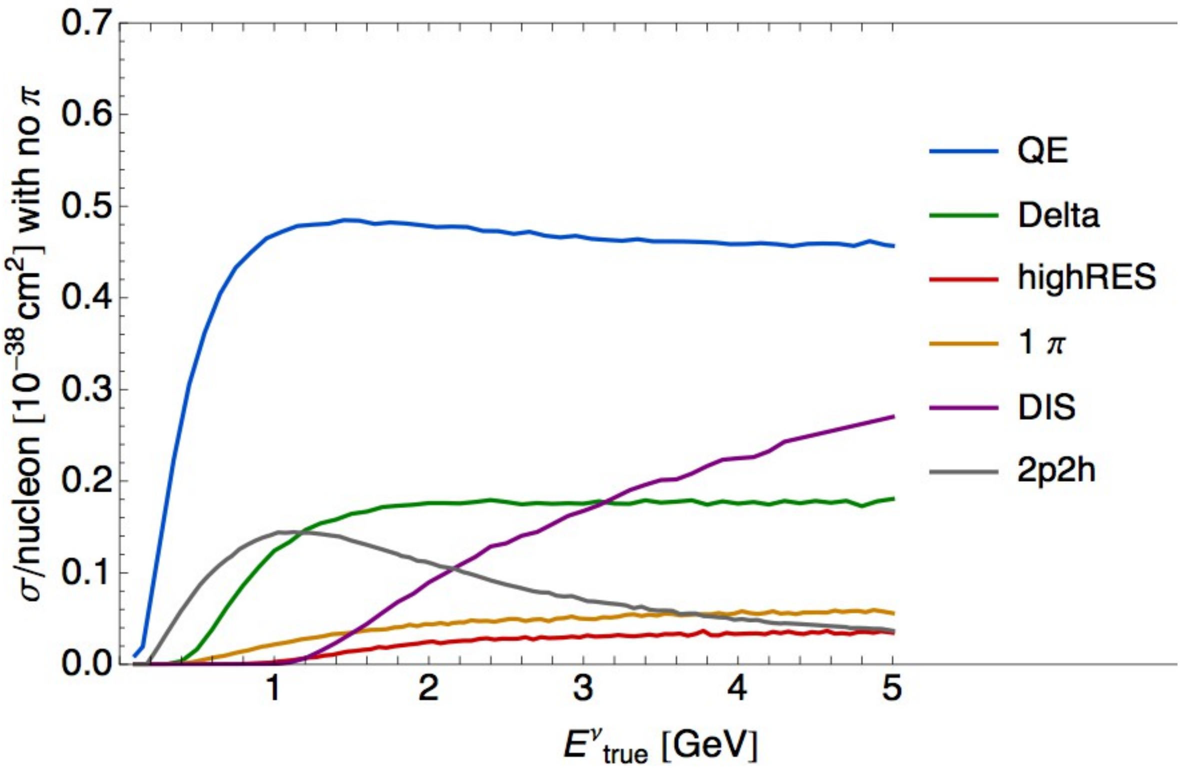
Martini, Ericson, Chanfray, 1211.1523 [hep-ph]

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

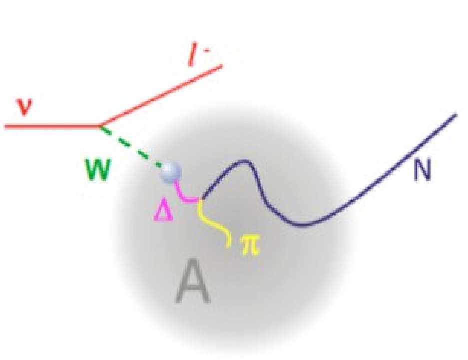


Final State Interactions

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:

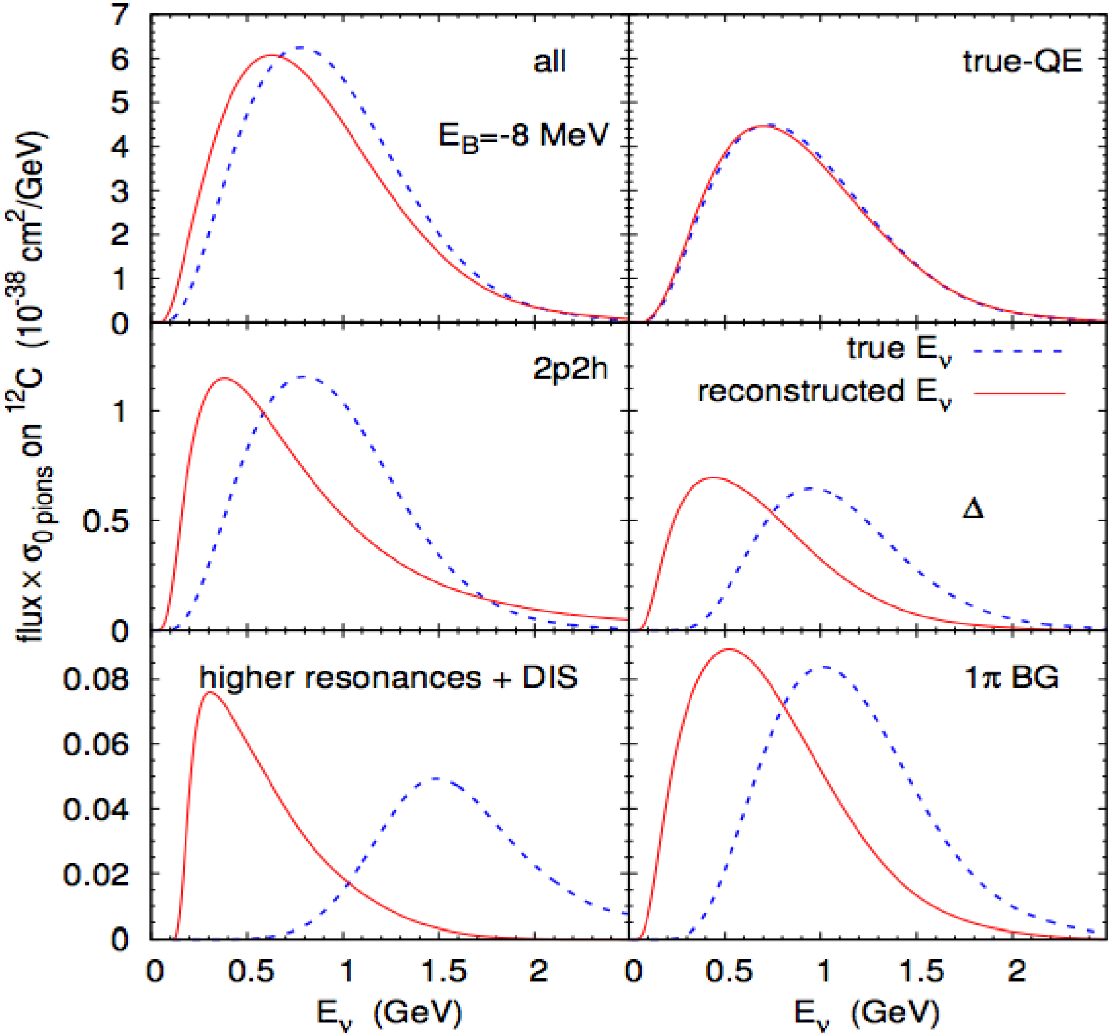


Lalakulich, Mosel, Gallmeister, 1208.3678 [nucl-th]
Coloma, Huber, 1307.1243 [hep-ph]



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

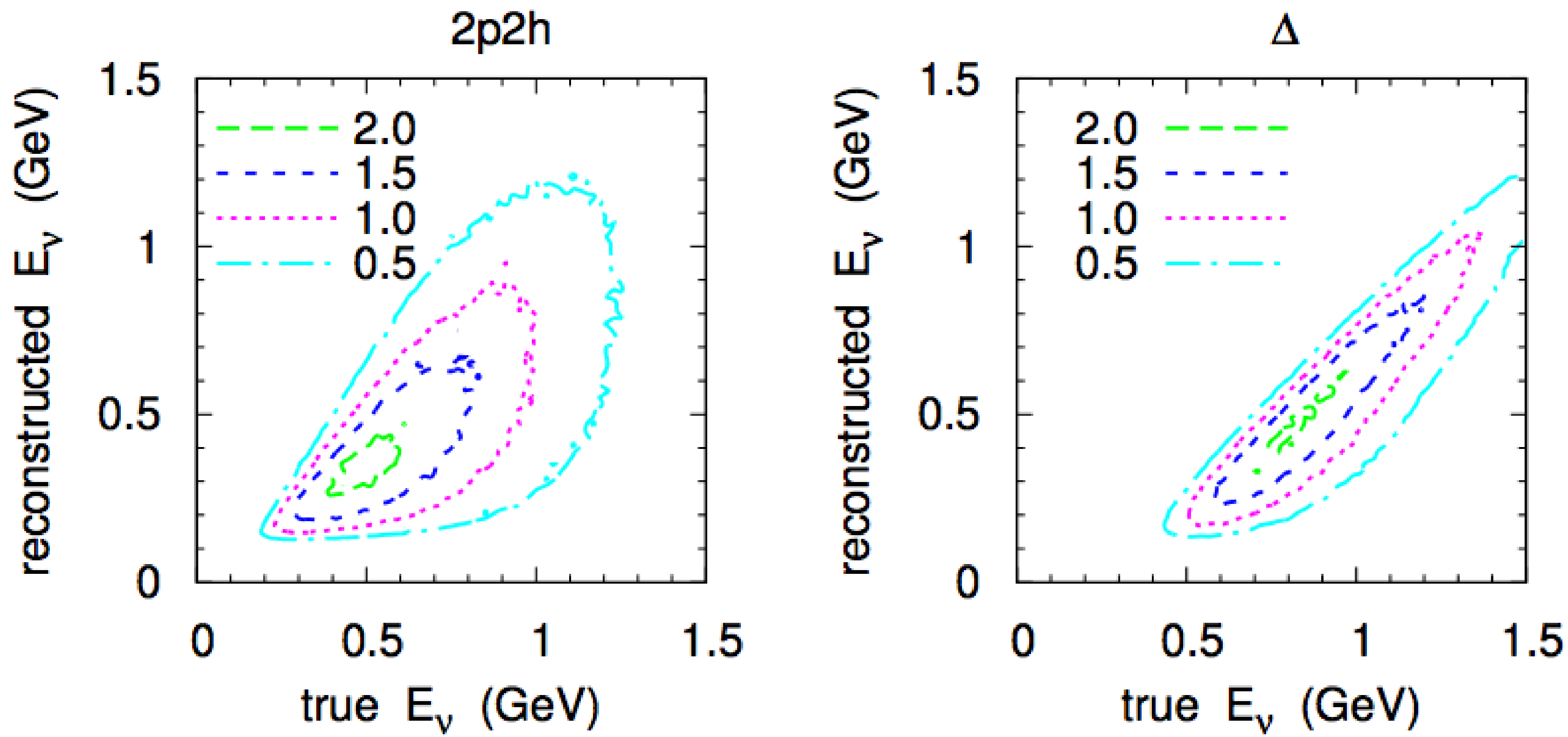
Energy reconstruction and FSI



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

Energy reconstruction effects

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

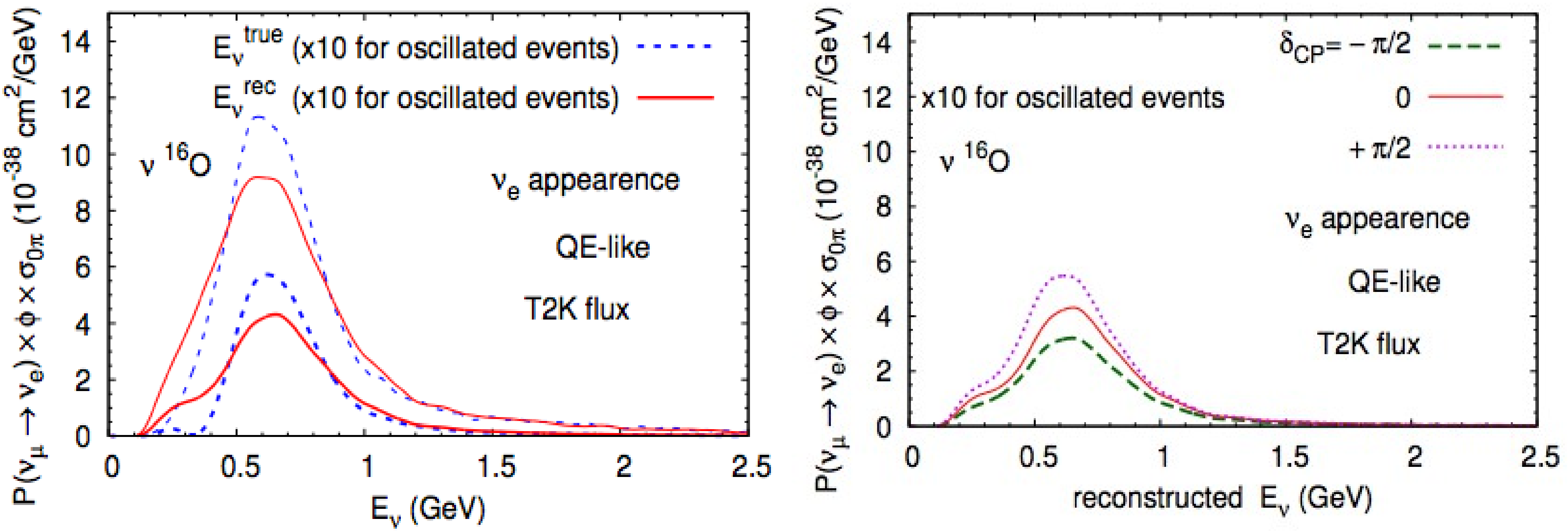


Lalakulich, Mosel and Gallmeister, 1208.3678 [nucl-th]

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 $\rightarrow$ 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 $\rightarrow$ 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:

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

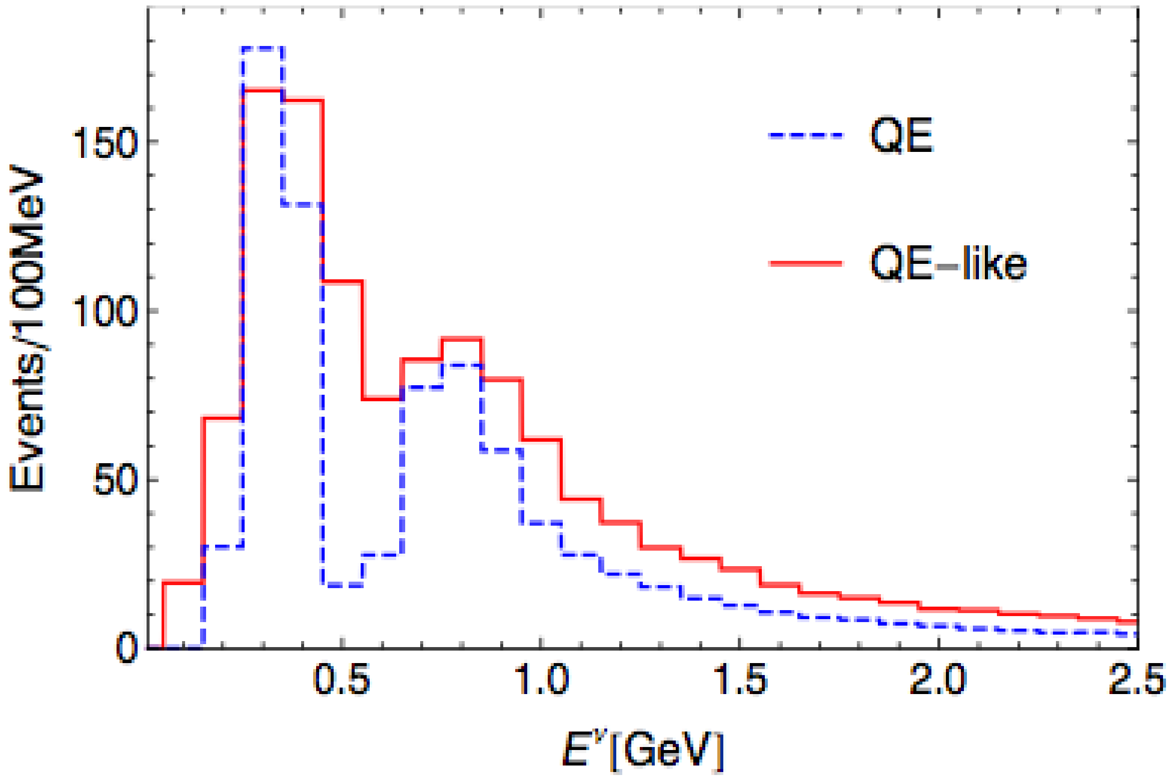
- An intermediate situation would most likely take place:

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

Coloma and Huber, 1307.1243 [hep-ph]

Toy model

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



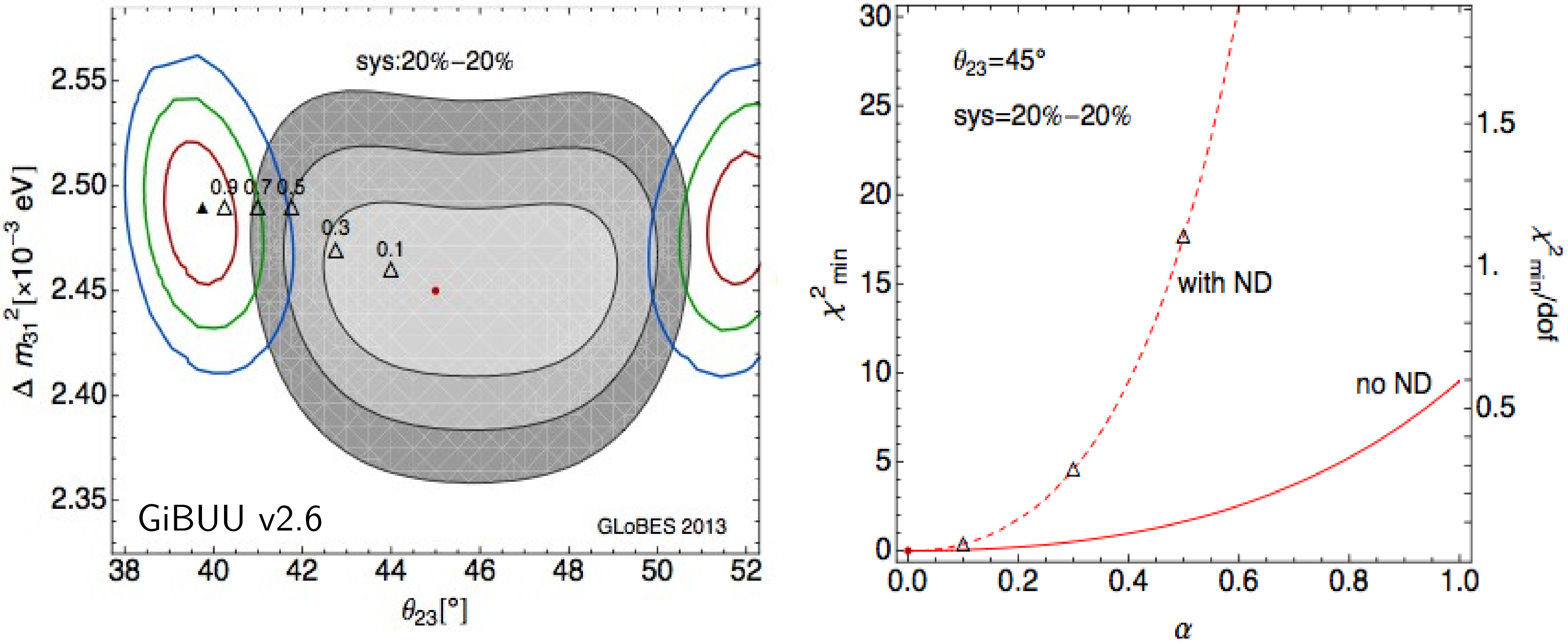
<u>Events</u>

QE	QE-like
870	1270

Coloma and Huber, 1307.1243 [hep-ph]

Toy model

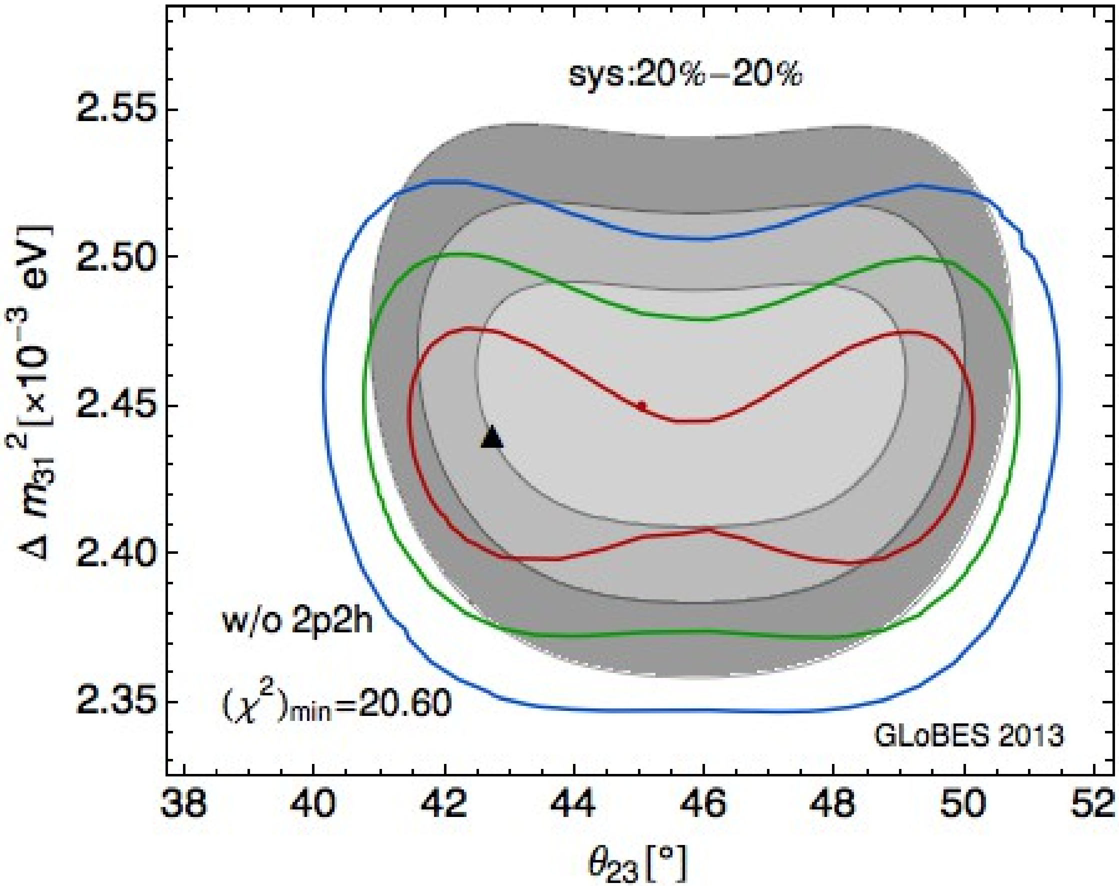
$$N_i^{\text{test}}(\alpha) = \alpha \times N_i^{QE} + (1-\alpha) \times N_i^{QE-like}$$



Coloma and Huber, 1307.1243 [hep-ph]

Impact of 2p2h

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



<u>Events</u>

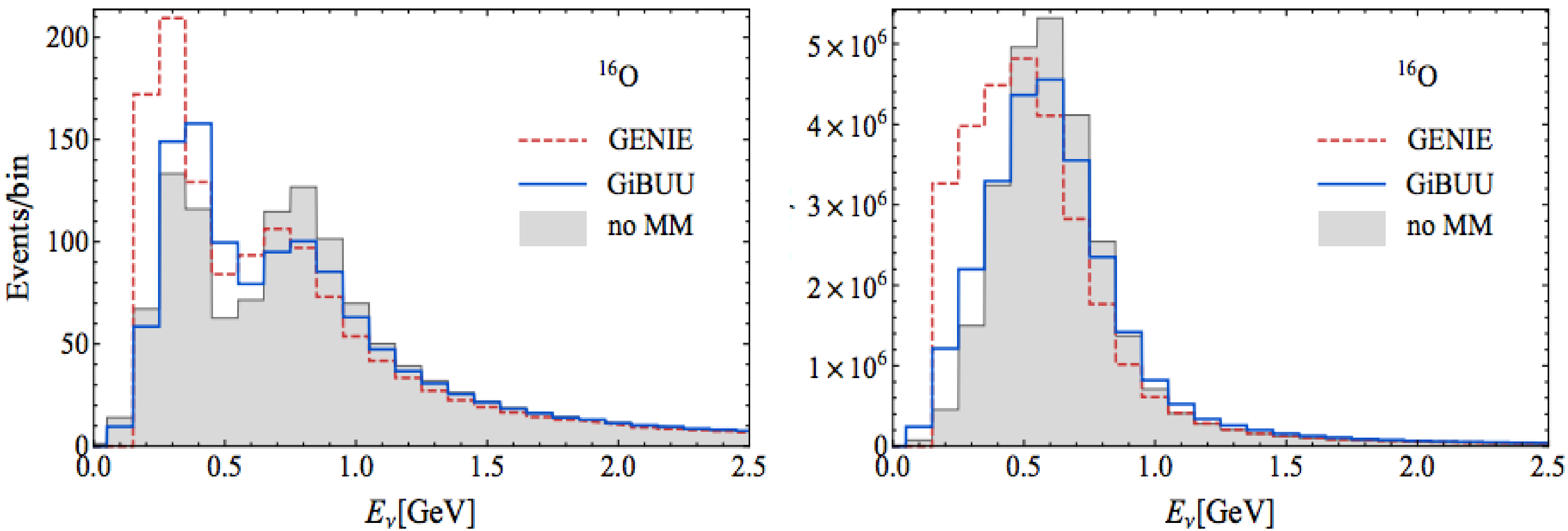
QE	2p2h	QE-like
∼870	∼215	∼1270

GiBUU v2.6

Coloma and Huber, 1307.1243 [hep-ph]

Impact of target nucleus

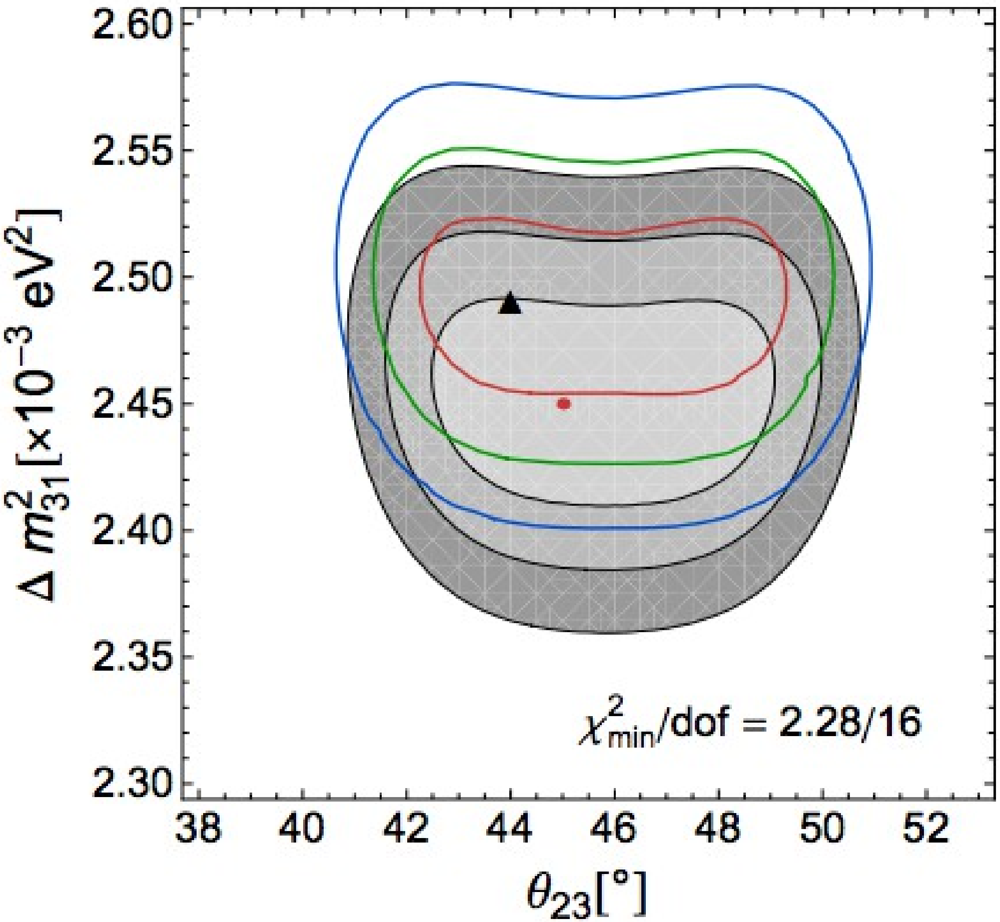
Oxygen vs Carbon:



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

Impact of target nucleus

Oxygen vs Carbon:

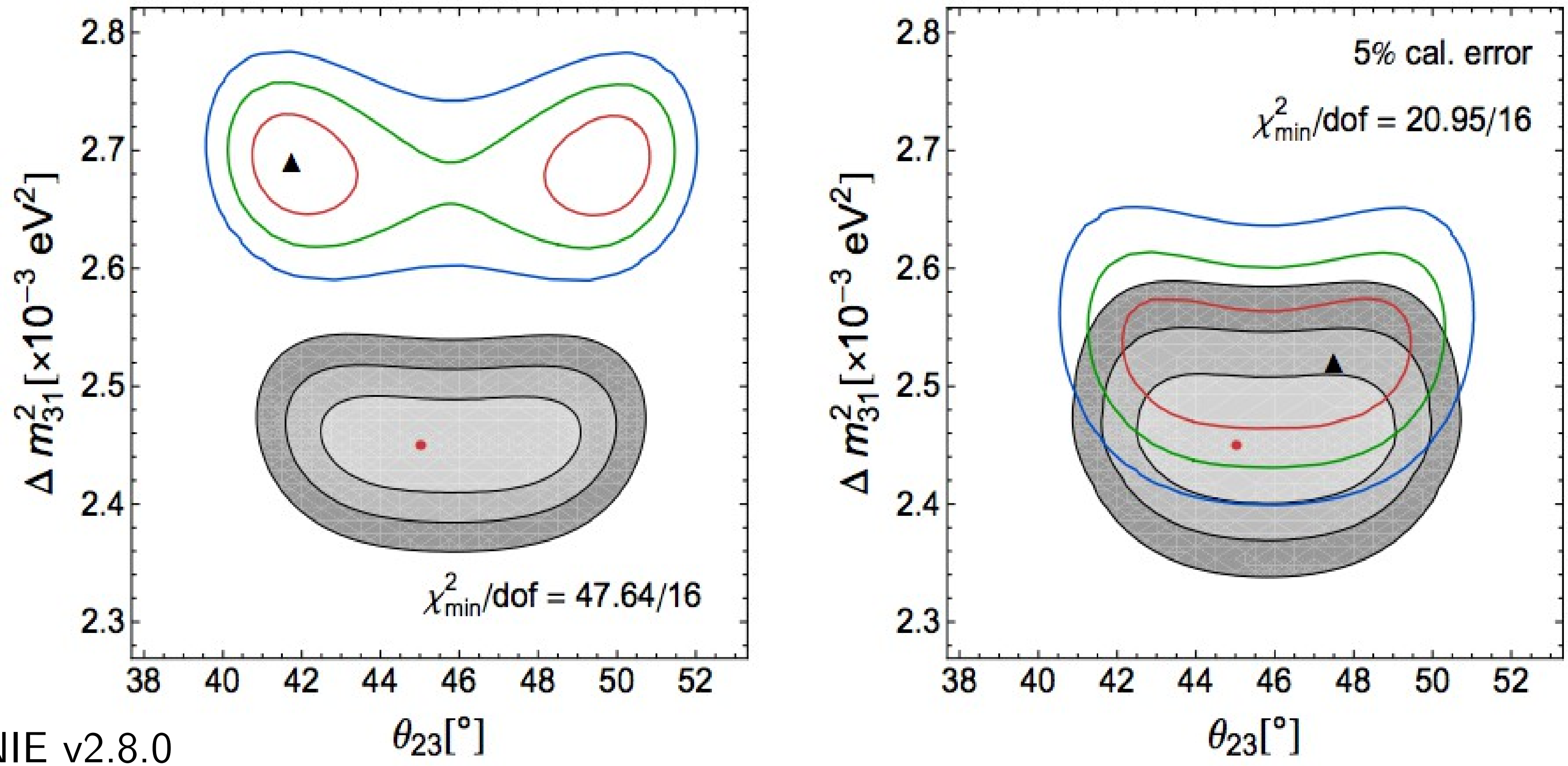


GENIE v2.8.0

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

Impact of nuclear model

How large can these effects be?



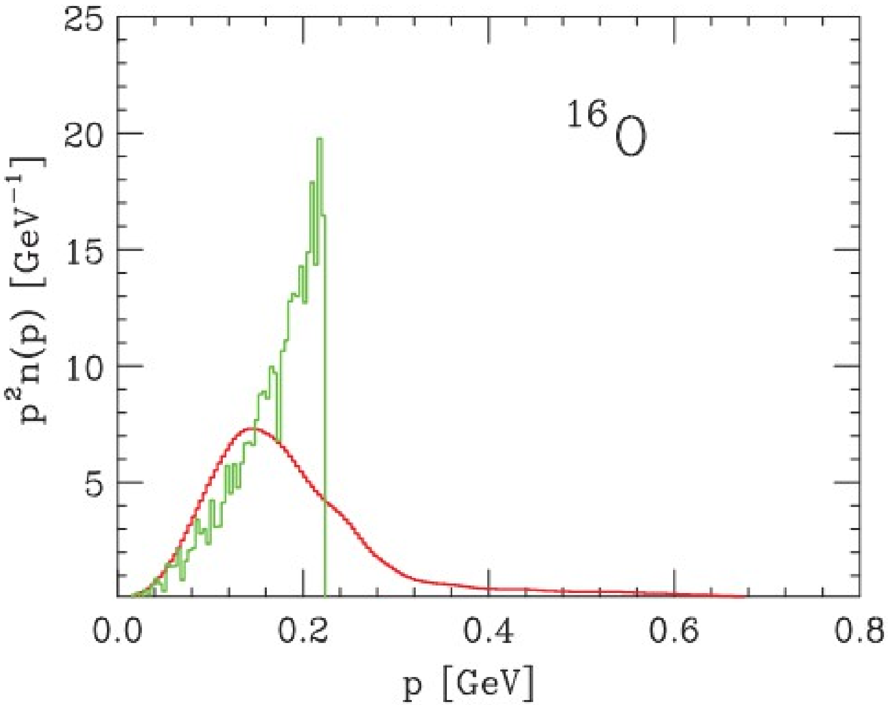
GENIE v2.8.0

GiBUU v2.6

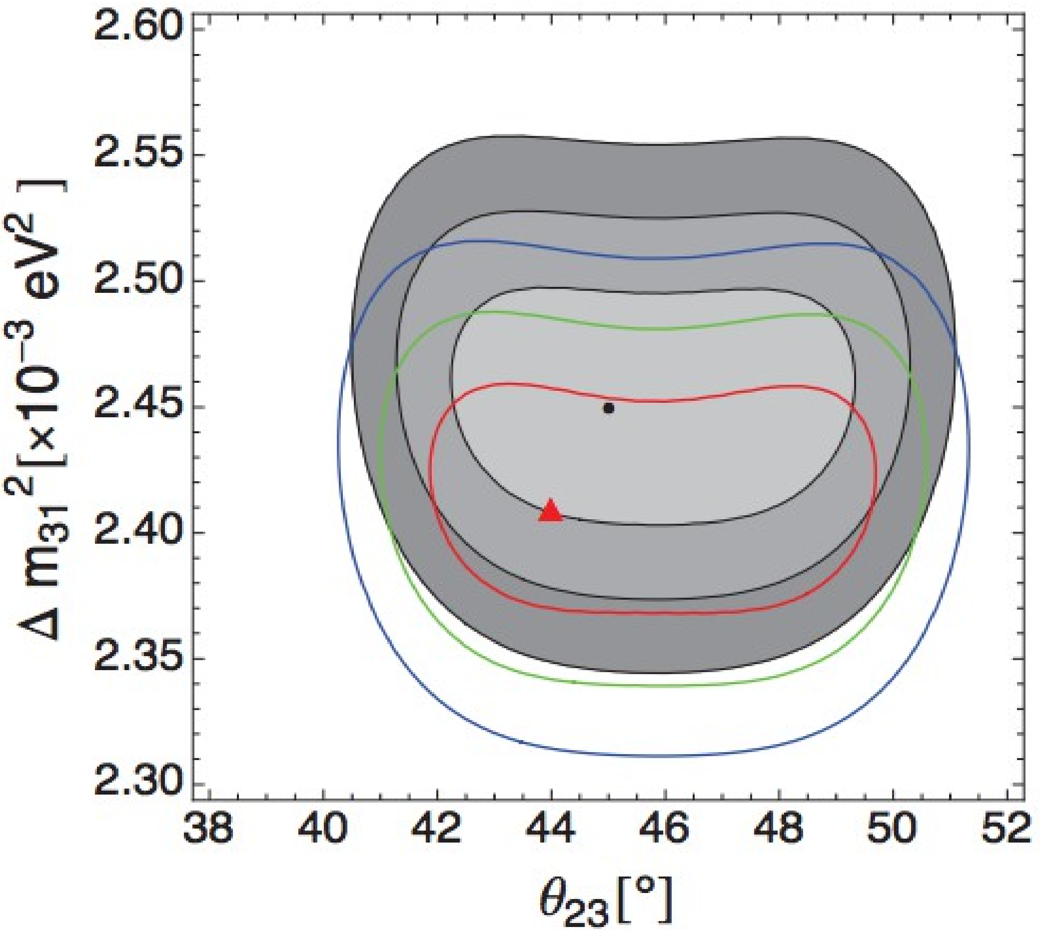
Coloma, Huber, Mariani and Jen, 1311.4506 [hep-ph]

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:

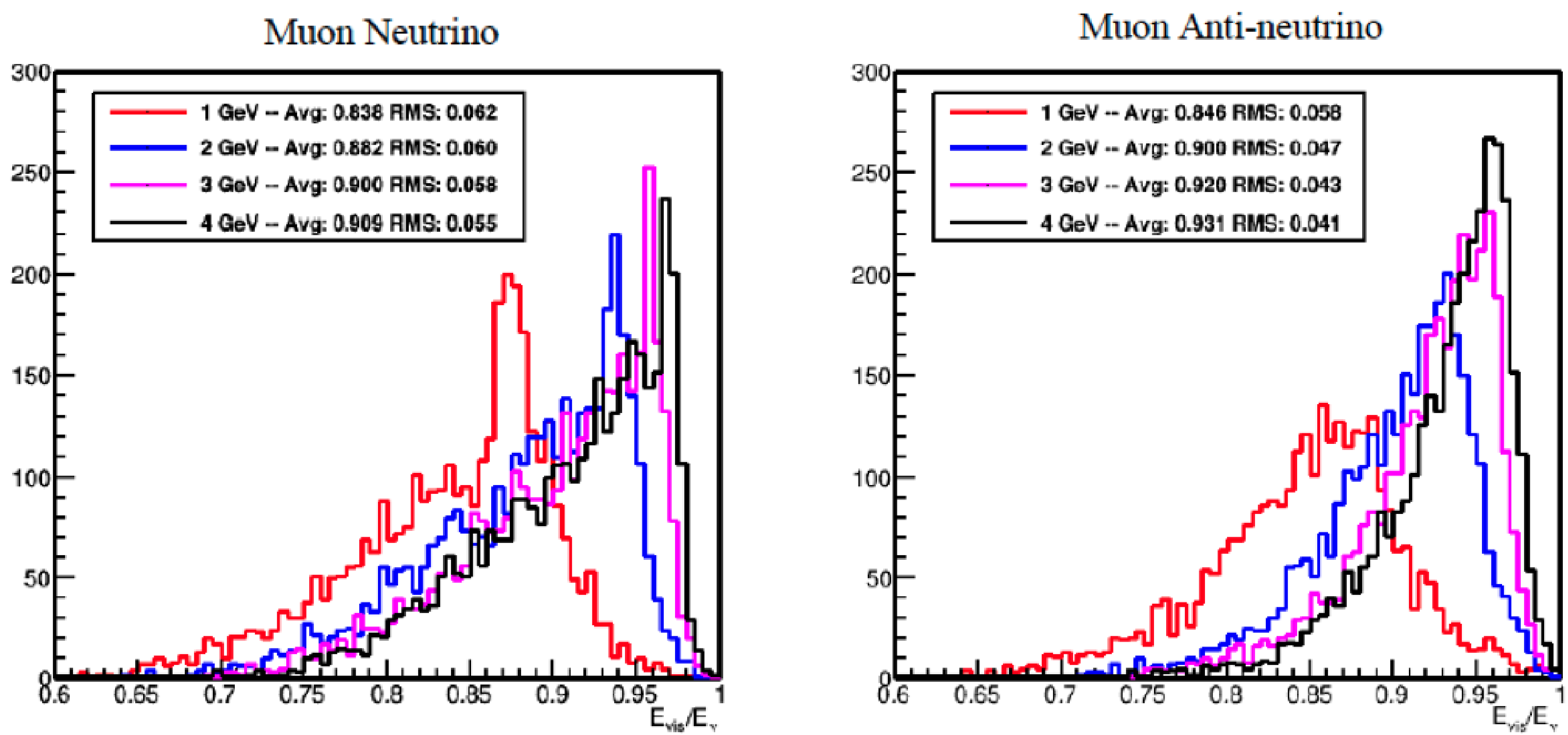
$$E_{\nu,\mathrm{rec}} = E_{\mathrm{had}} + E_{\mathrm{lep}} + E_{\mathrm{inv}}$$

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!

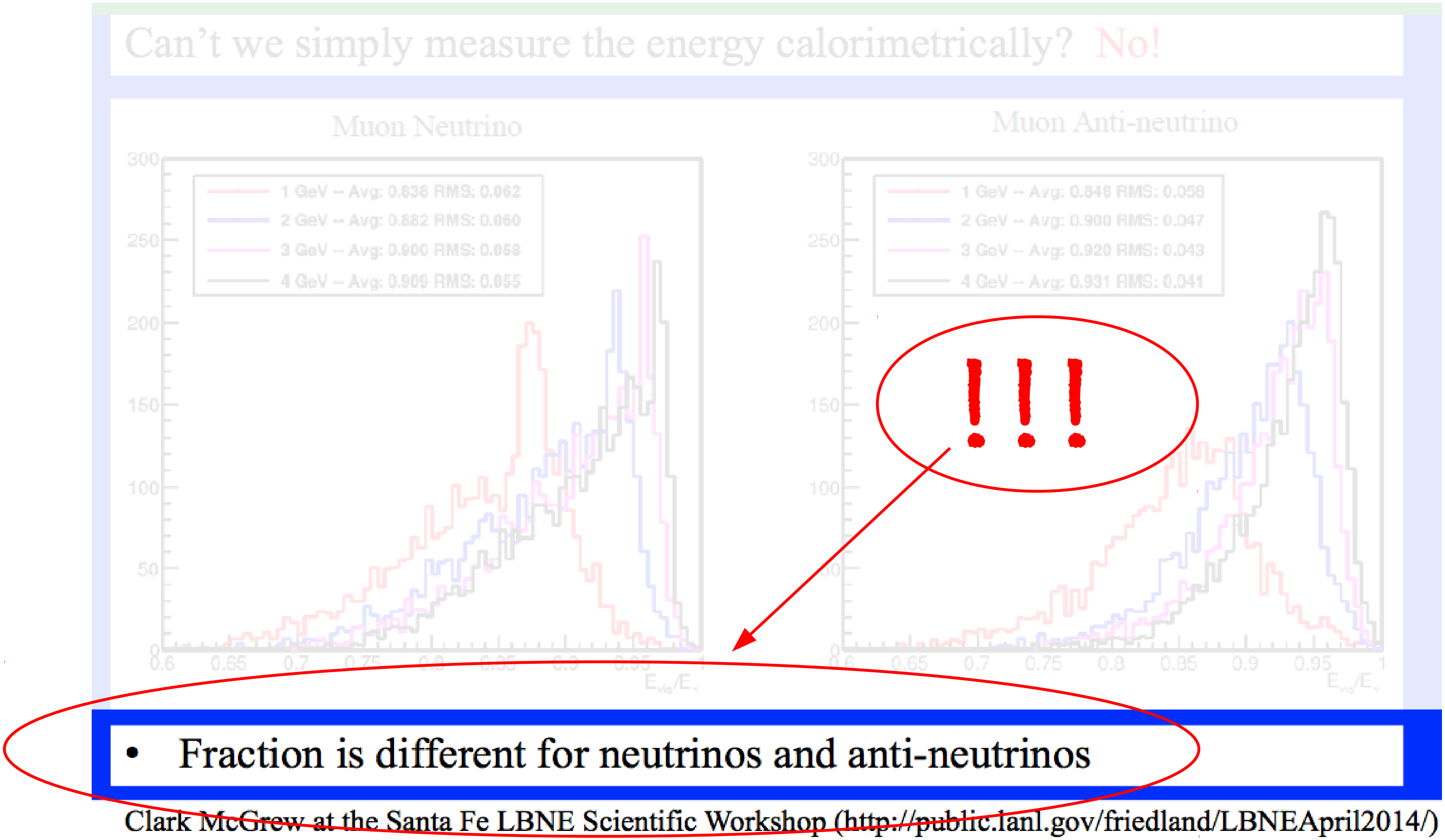


- Fraction is different for neutrinos and anti-neutrinos

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

Does this improve with calorimetry?

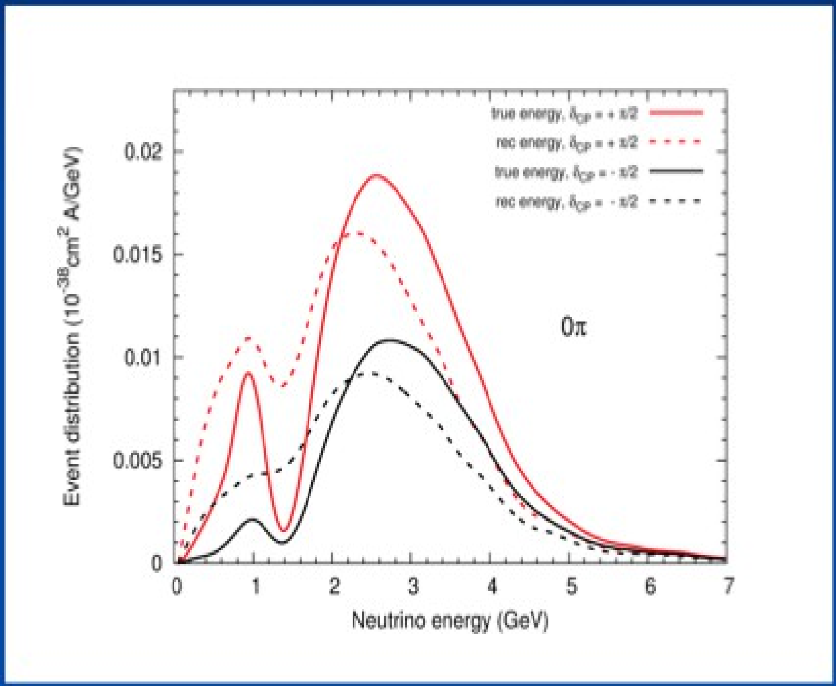
See talk by Christopher Mauger here at nuSTEC

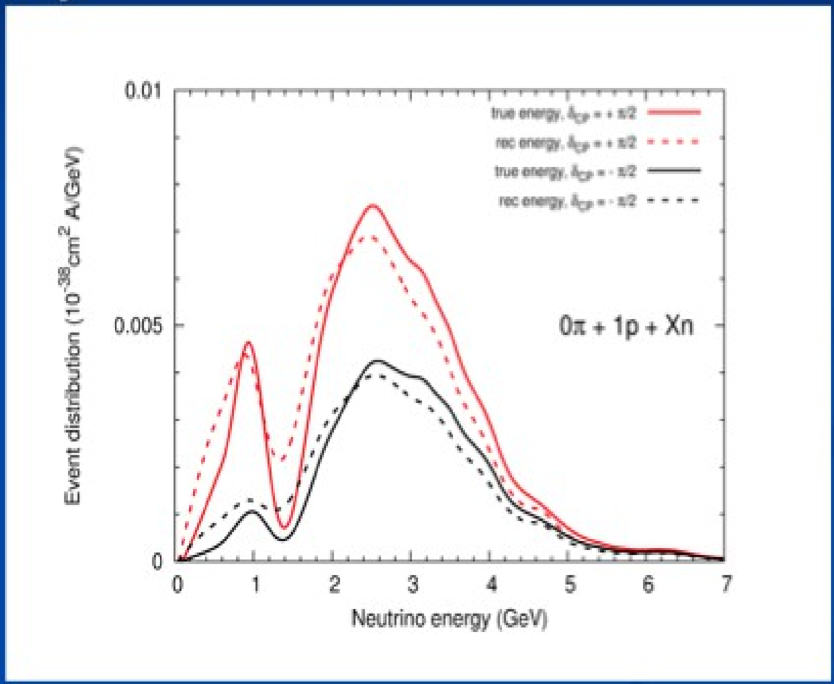


Clark McGrew at the Santa Fe LBNE Scientific Workshop (http://public.lanl.gov/friedland/LBNEApril2014/)

LBNE e-appearance

Sensitivity to δ_{CP}





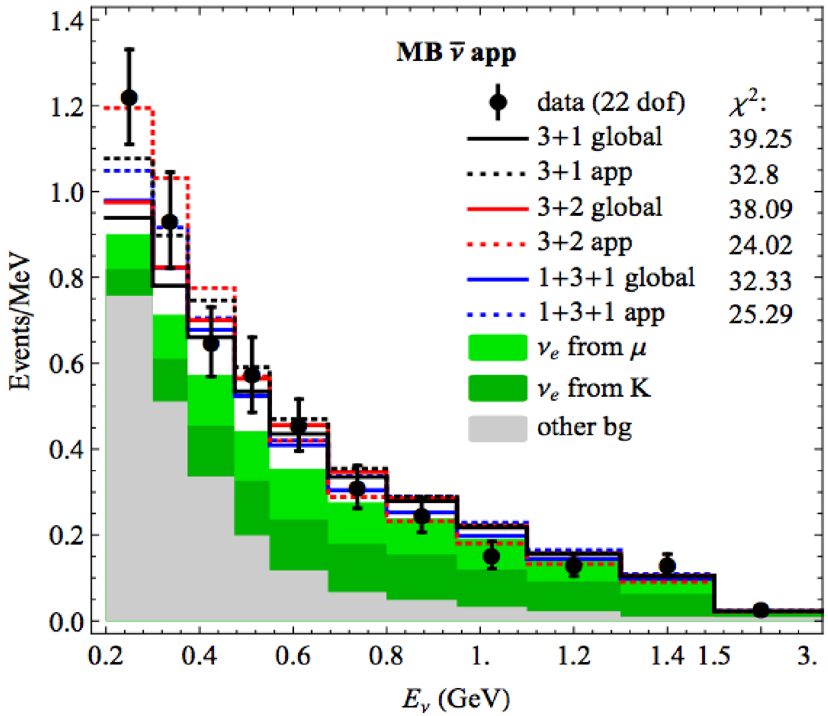
Dramatic improvement in 0 pi, 1p, Xn sample, down by only factor 3

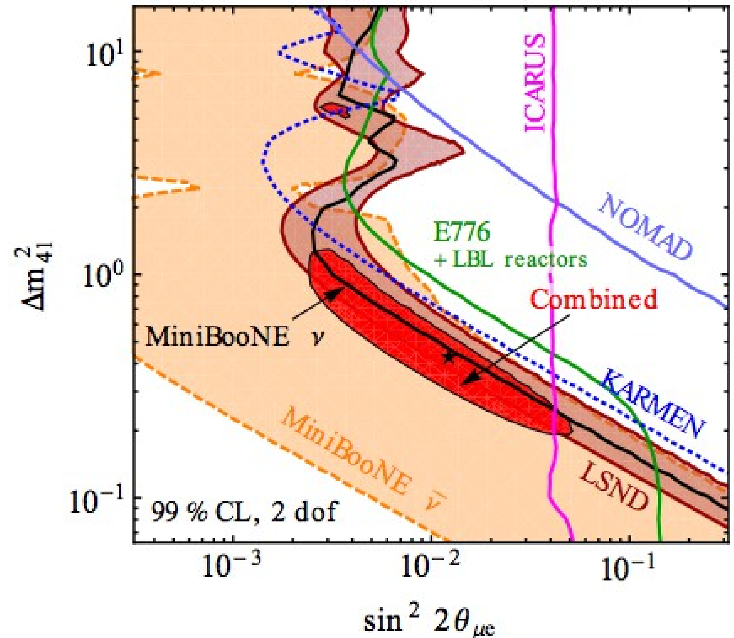
Mosel, Lalakulich, Gallmeister, 1311.7288 [nucl-th]

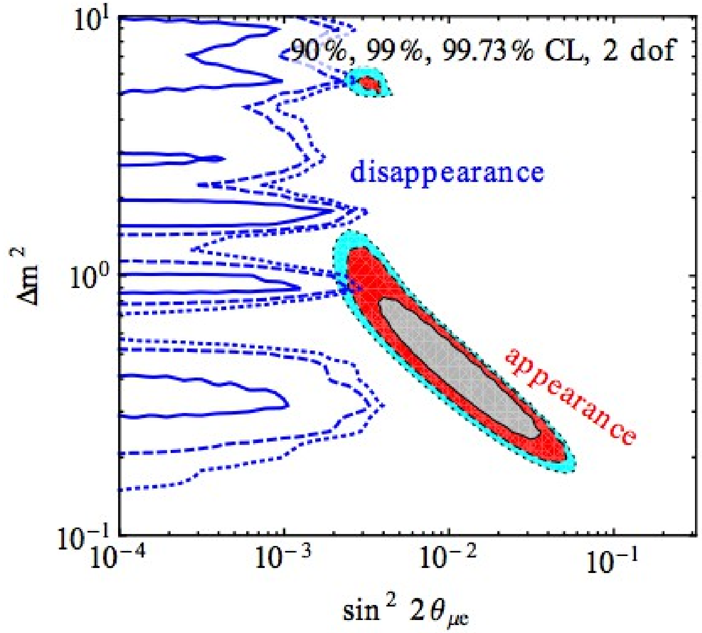
See also U. Mosel's talk at KITP workshop (Present and future neutrino physics), Oct 2014

Curious things/random thoughts

Curious things

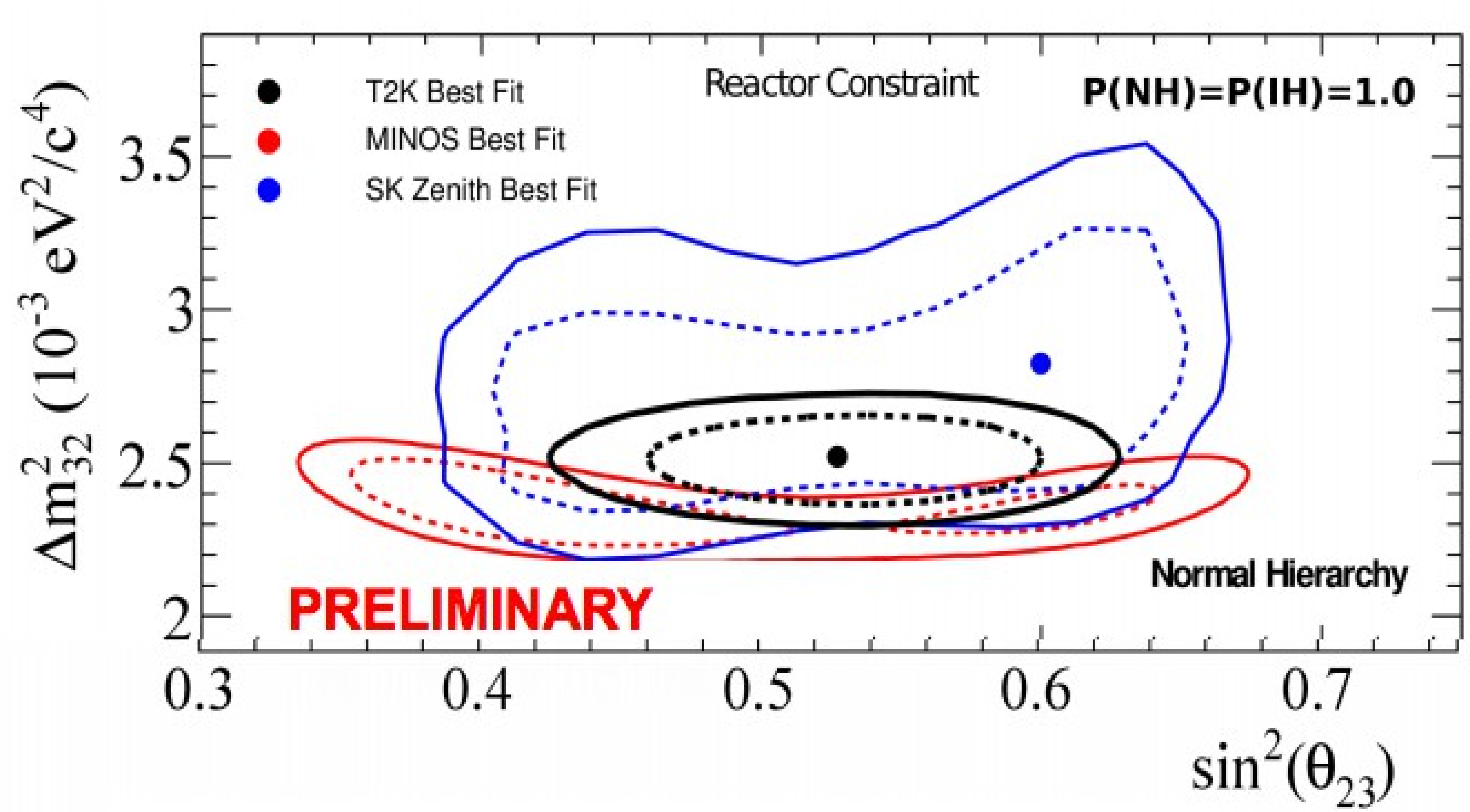






Machado, Kopp, Maltoni, Schwetz, 1303.3011 [hep-ph]

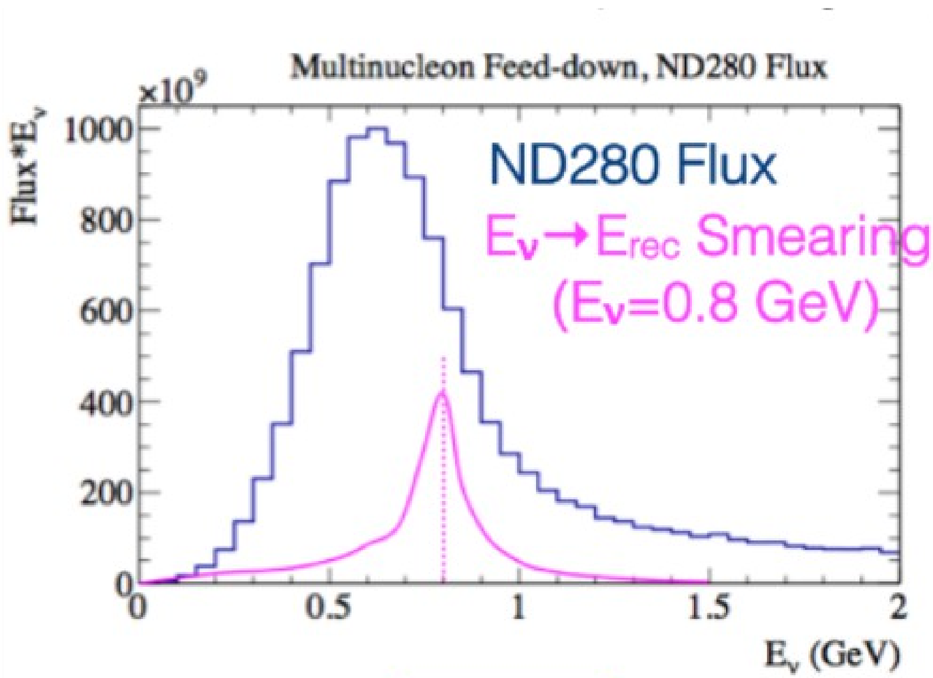
Curious things

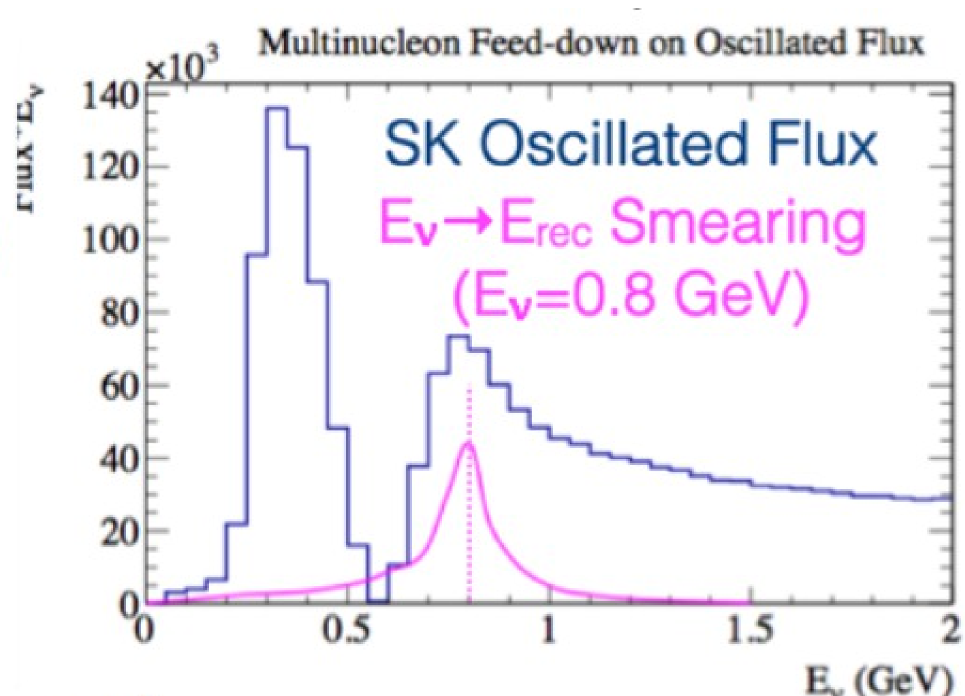


Slide stolen from K. Mahn's talk

Curious things

What will happen when we add antineutrino data?



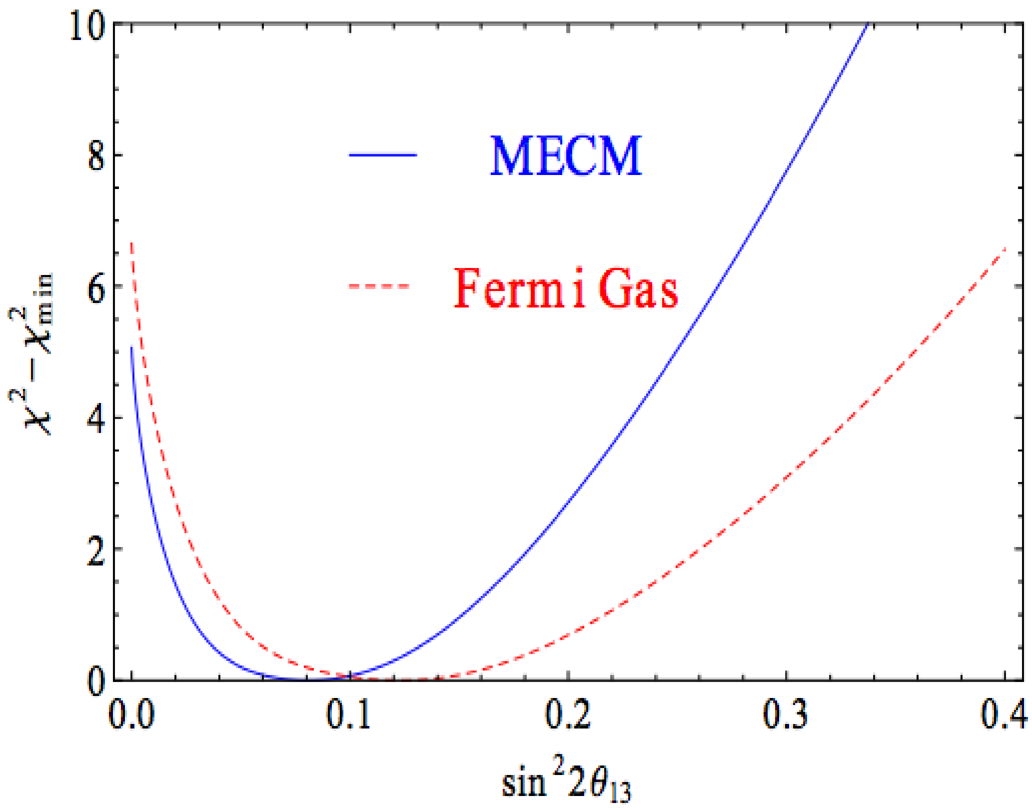


$$FD(\nu_e) = \boxed{\Phi \times \sigma} \times \epsilon \times P(\nu_\mu \to \nu_e)$$
$$ND(\nu_\mu) = \boxed{\Phi \times \sigma} \times \epsilon_{ND}$$

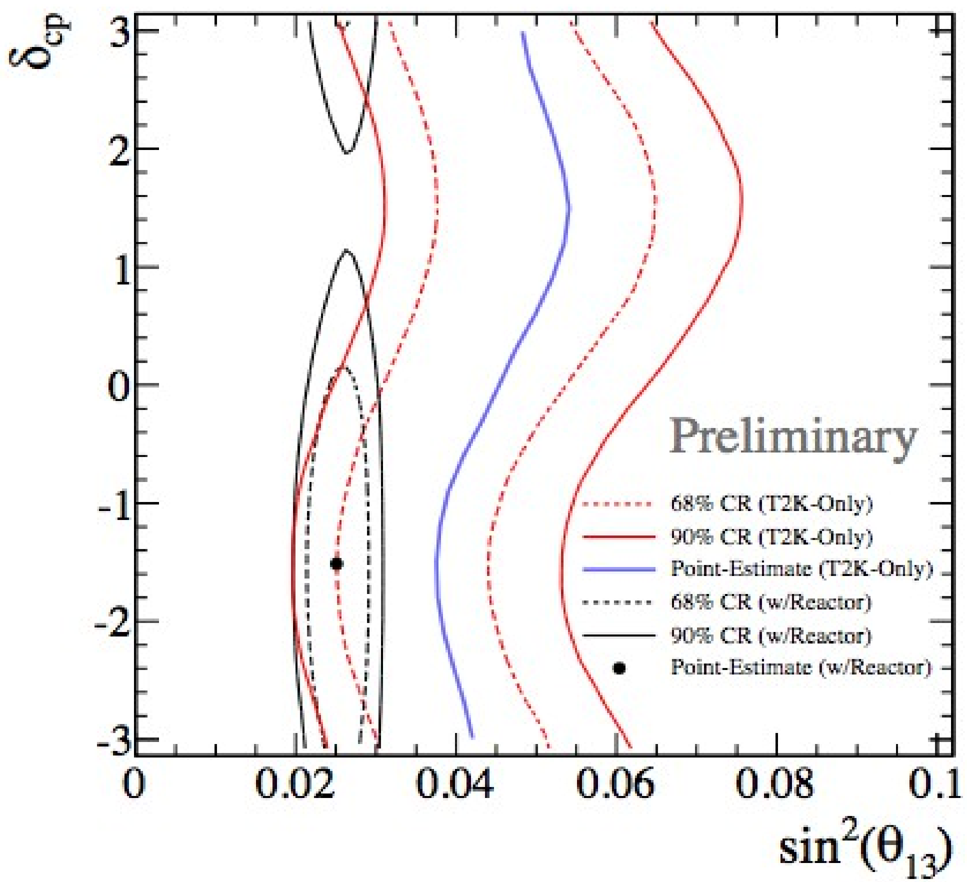
$$E_\nu^{QE} = \frac{m_p^2 - m'^2_n - m_\mu^2 + 2m'_n E_\mu}{2(m'_n - E_\mu + p_\mu \cos\theta_\mu)}$$

Slide stolen from K. Mahn's talk

Curious things



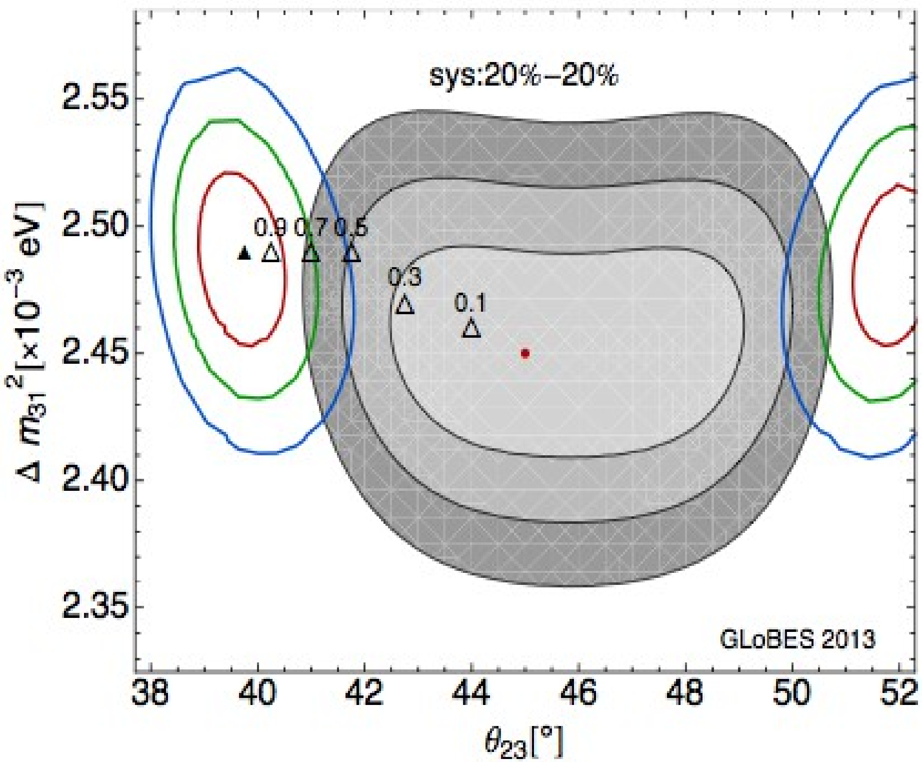
Martini, Meloni, 1203.3335 [hep-ph]



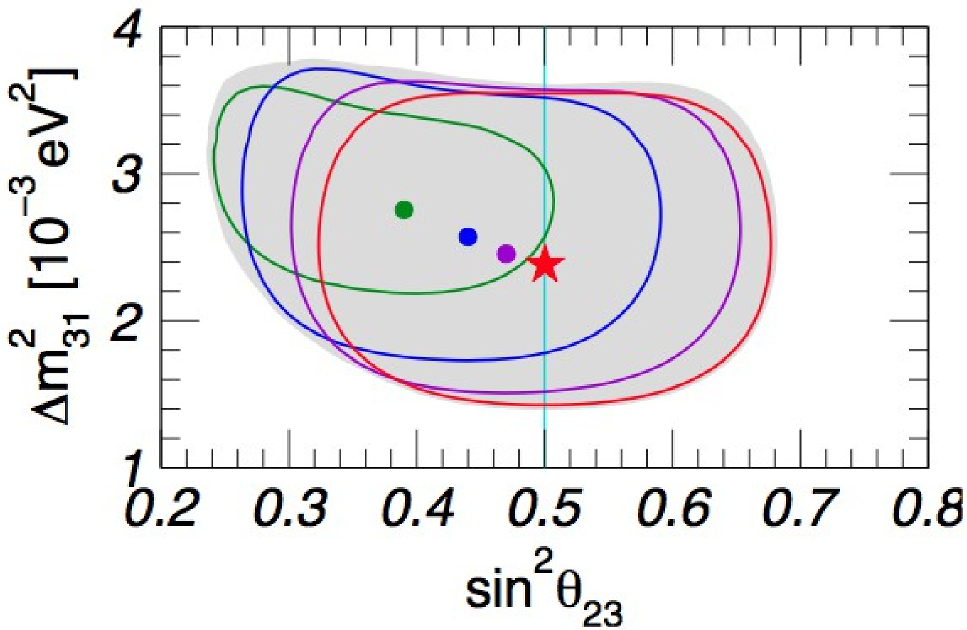
The T2K collab., 1405.3871 [hep-ex]

Curious things

Coloma, Huber, 1307.1243 [hep-ph]

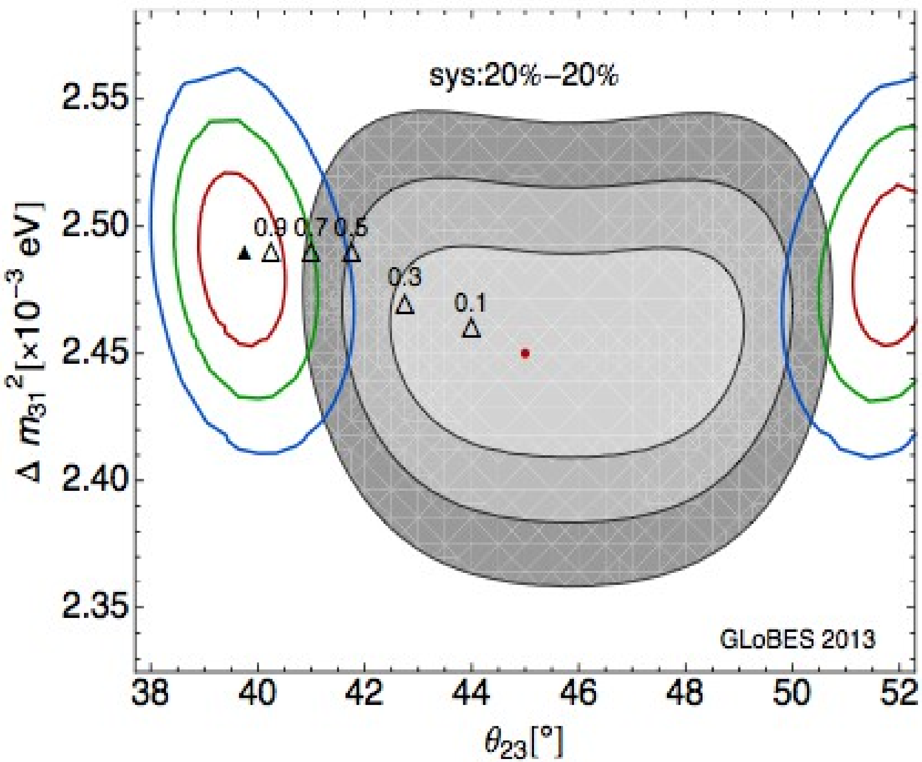


Friedland, Lunardini, Maltoni, hep-ph/0408264



Curious things

Coloma and Huber, 1307.1243 [hep-ph]



Friedland, Lunardini, Maltoni, hep-ph/0408264

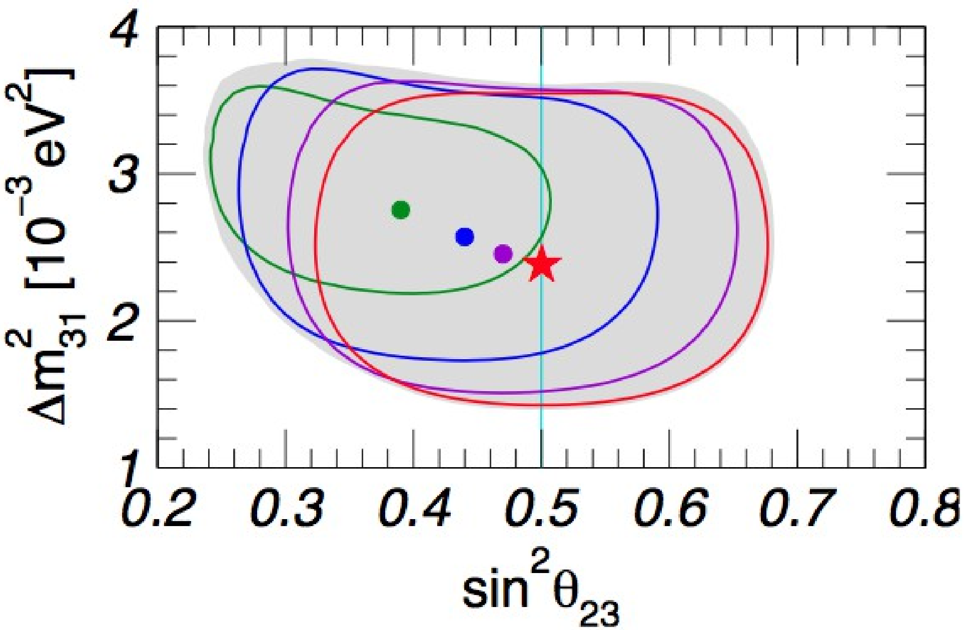


FIG. 2: The effect of the NSI on the allowed region and best-fit values of the oscillation parameters; see text for details.

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!

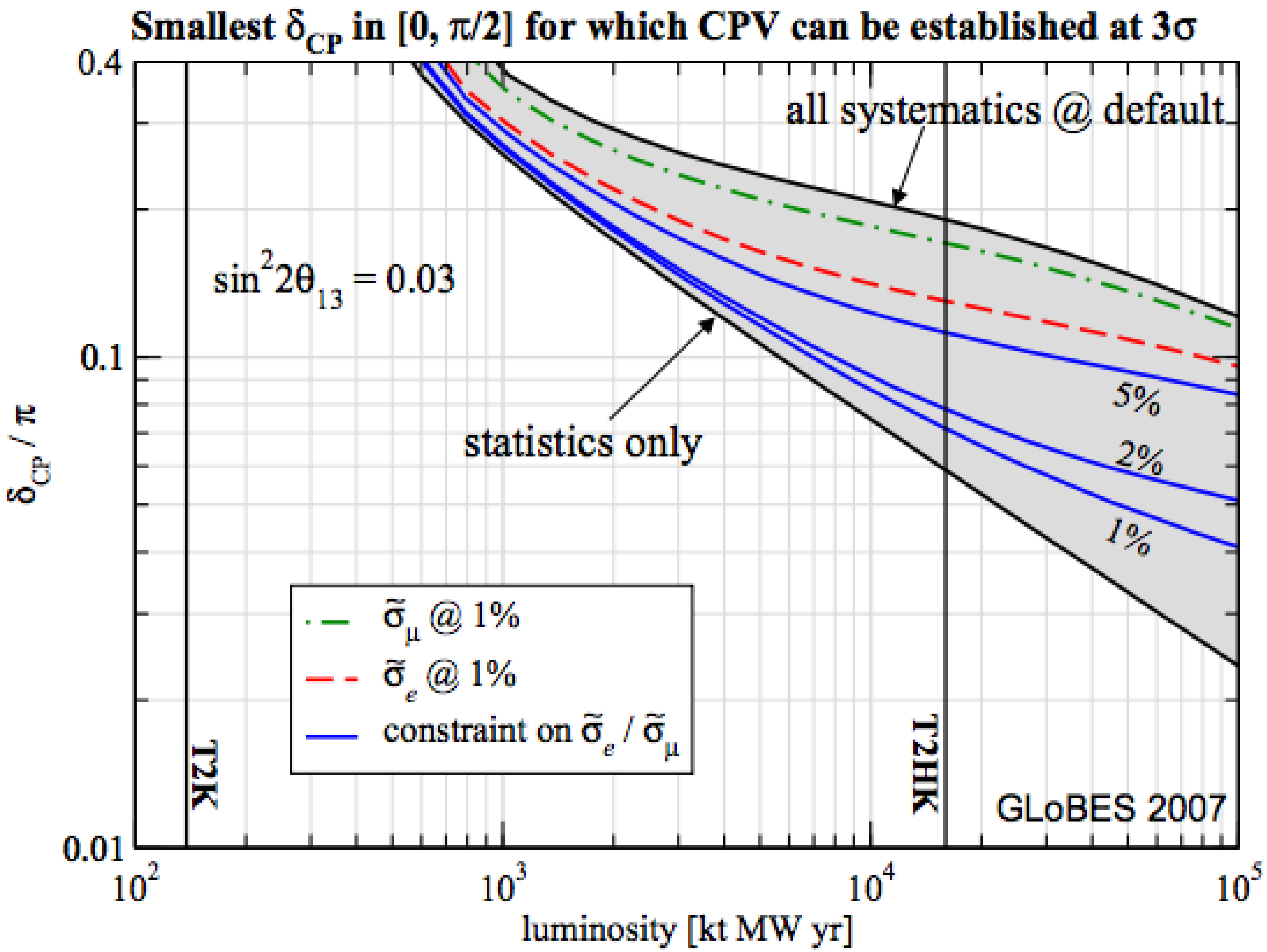
BACKUP SLIDES

Setups

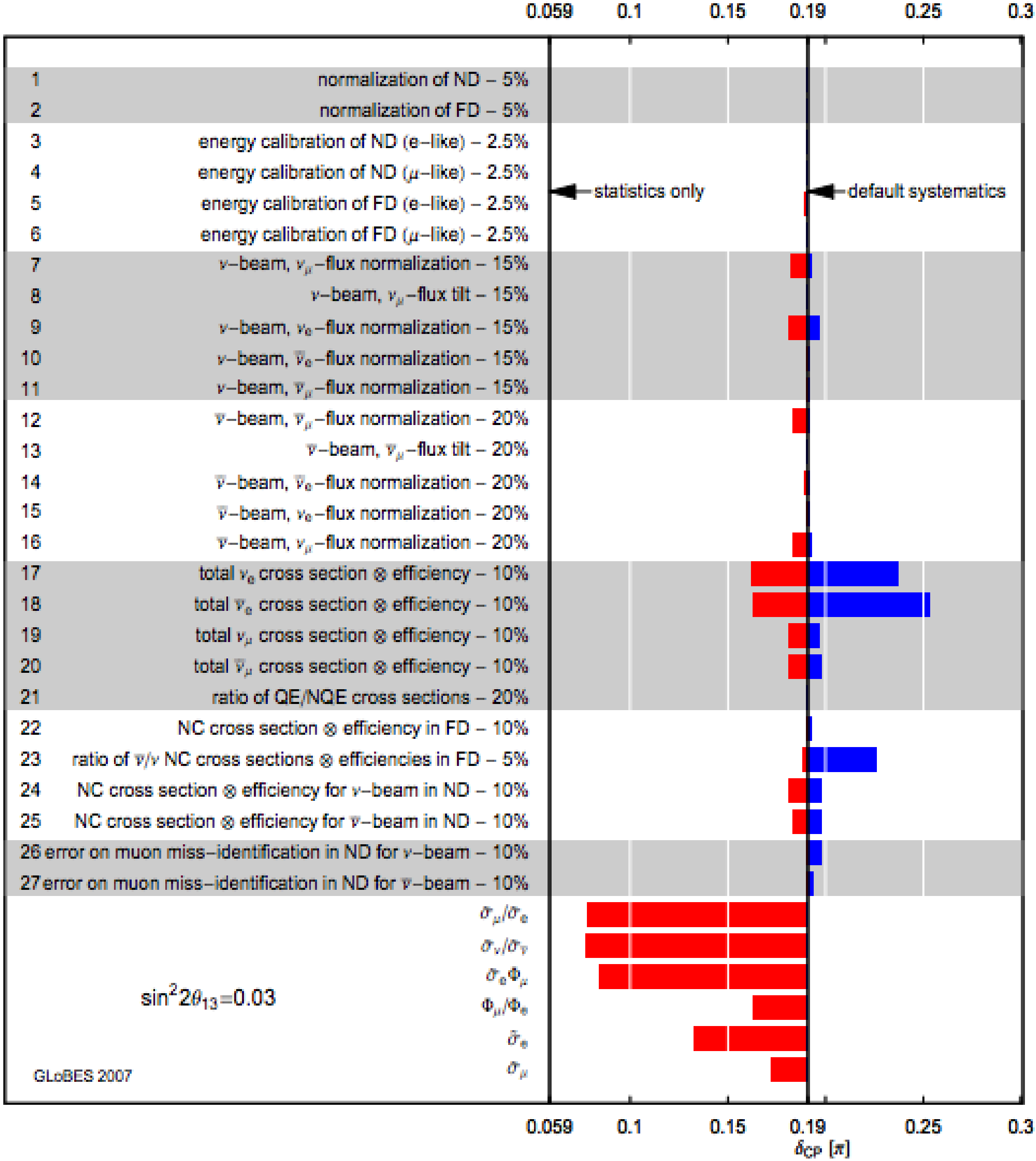
	Setup	E_ν^{peak}	L	OA	Detector	kt	MW	Decays/yr	$(t_\nu, t_{\bar\nu})$
Benchmark	BB350	1.2	650	–	WC	500	–	$1.1(2.8)\times10^{18}$	(5,5)
	NF10	5.0	2 000	–	MIND	100	–	7×10^{20}	(10,10)
	WBB	4.5	2 300	–	LAr	100	0.8	–	(5,5)
	T2HK	0.6	295	2.5°	WC	560	1.66	–	(1.5,3.5)
Alternative	BB100	0.3	130	–	WC	500	–	$1.1(2.8)\times10^{18}$	(5,5)
	+ SPL			–			4	–	(2,8)
	NF5	2.5	1 290	–	MIND	100	–	7×10^{20}	(10,10)
	$\mathrm{LBNE_{mini}}$	4.0	1 290	–	LAr	10	0.7	–	(5,5)
	$\mathrm{NO}\nu\mathrm{A}^+$	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)
	$\mathrm{NO}\nu\mathrm{A}$	2.0	810	0.8°	TASD	15	0.7	–	(4,4)

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

Impact of normalization uncertainties

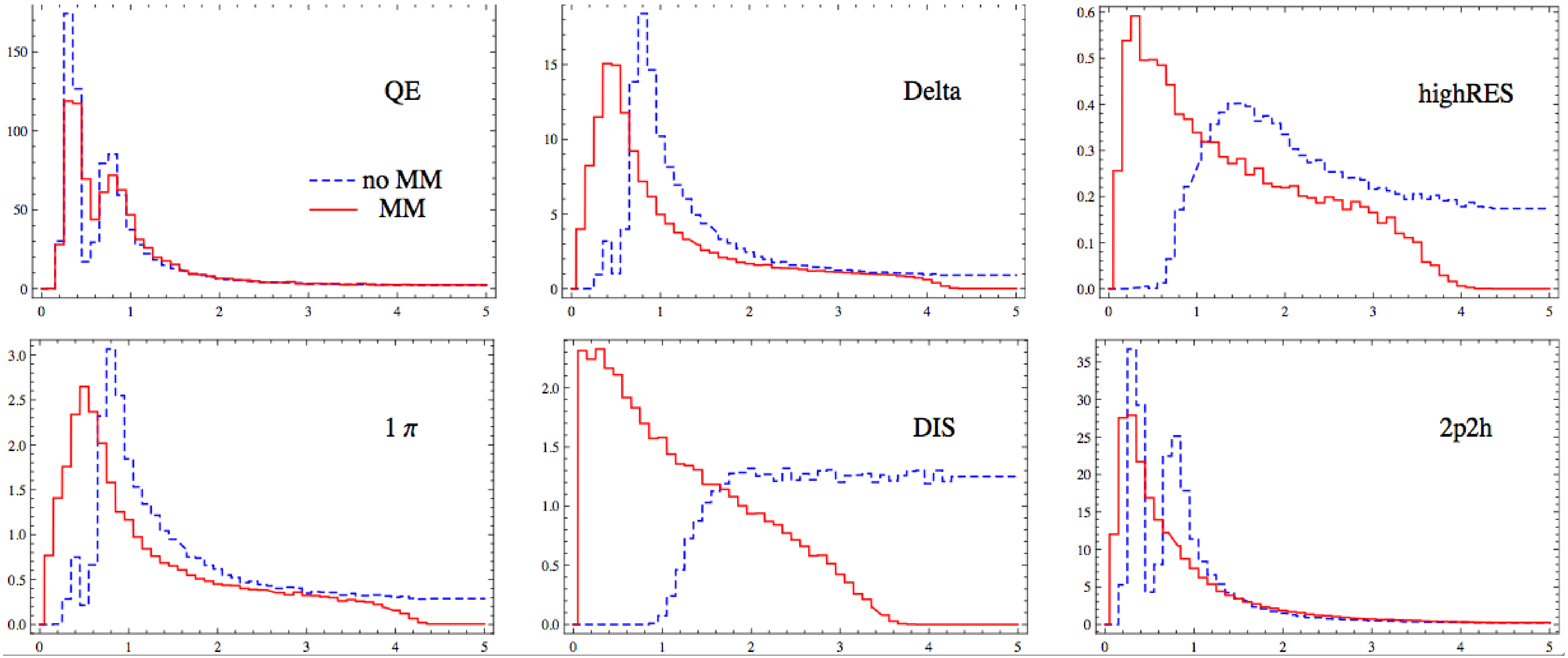


Huber, Mezzetto and Schwetz, 0711.2950 [hep-ph]

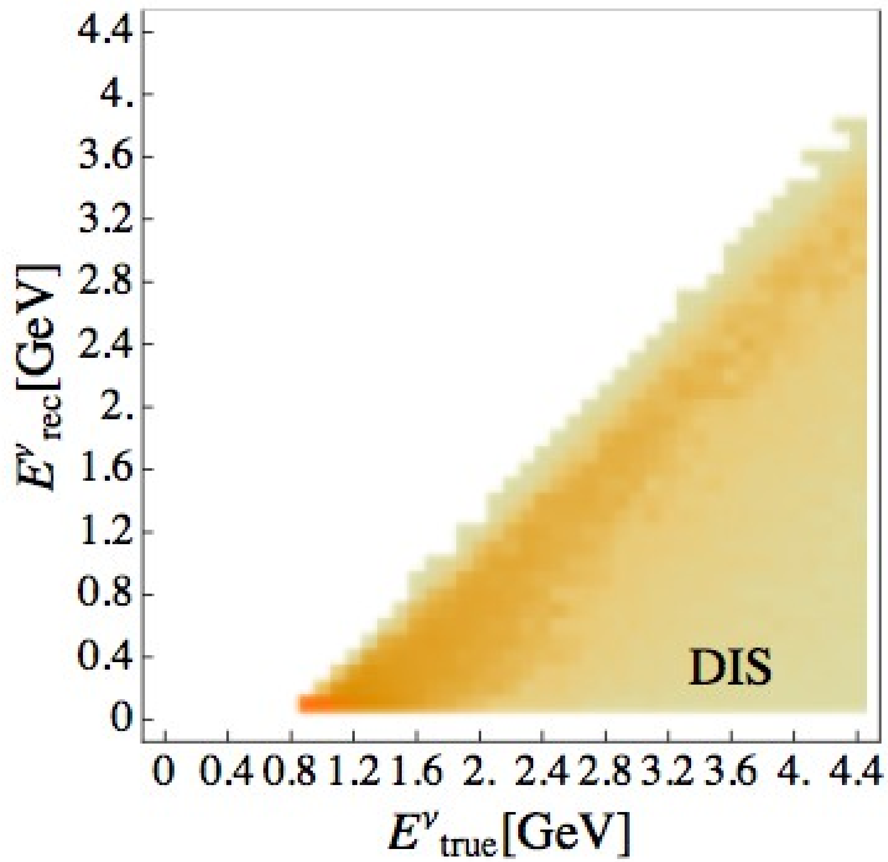


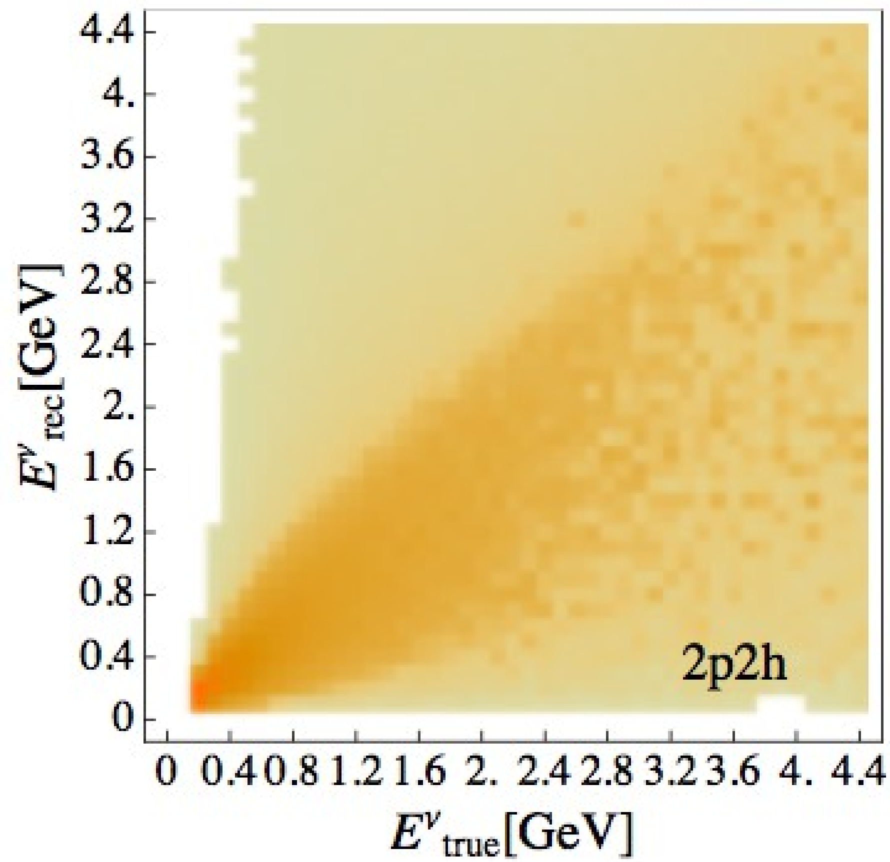
Huber, Mezzetto and Schwetz, 0711.2950 [hep-ph]

Event distributions

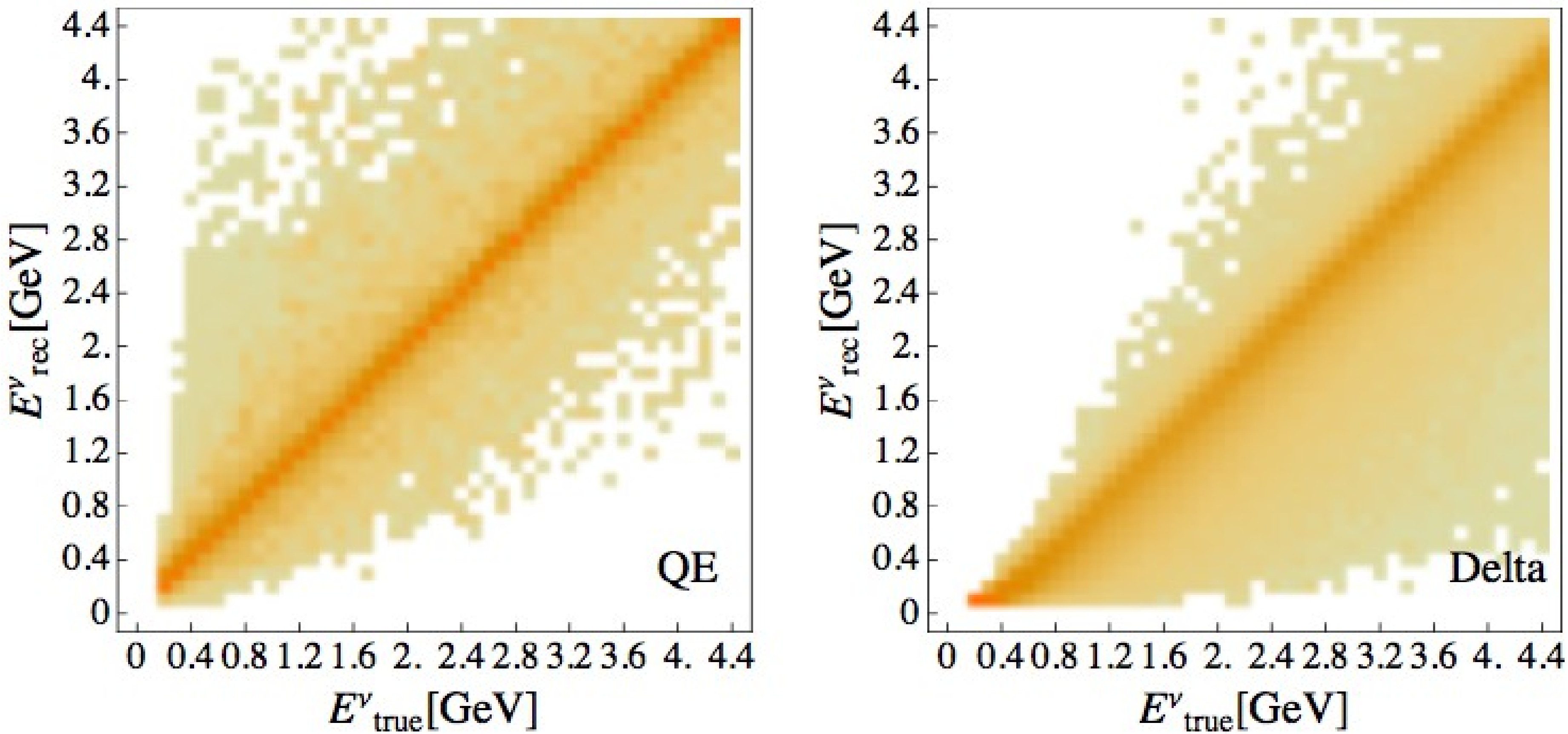


Migration matrices

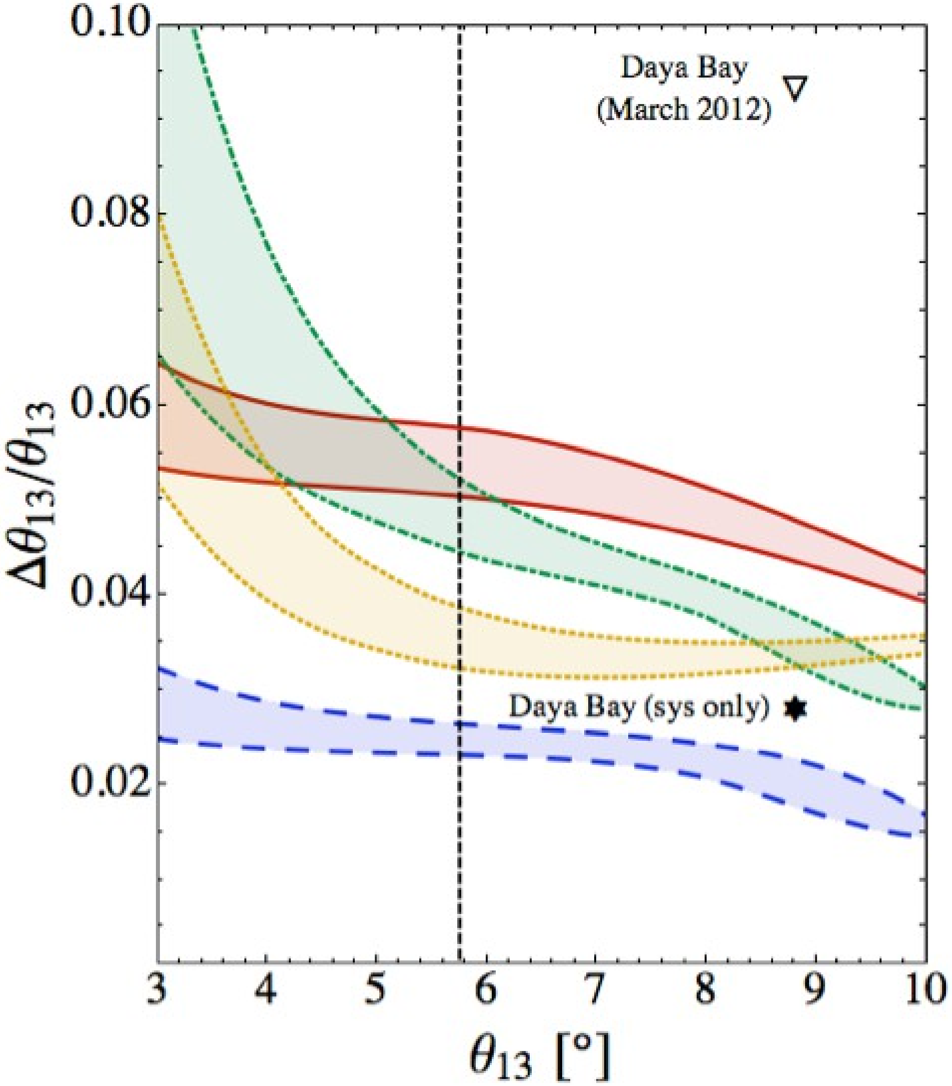


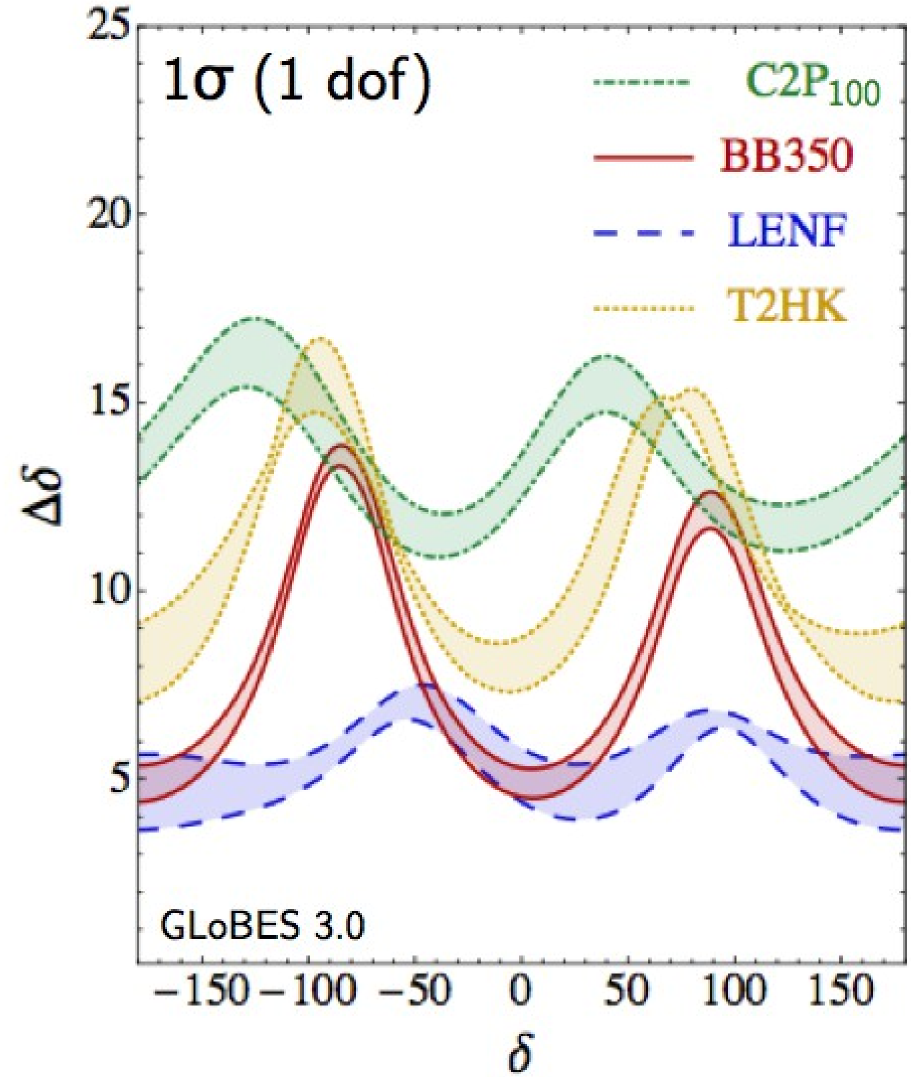


Migration matrices

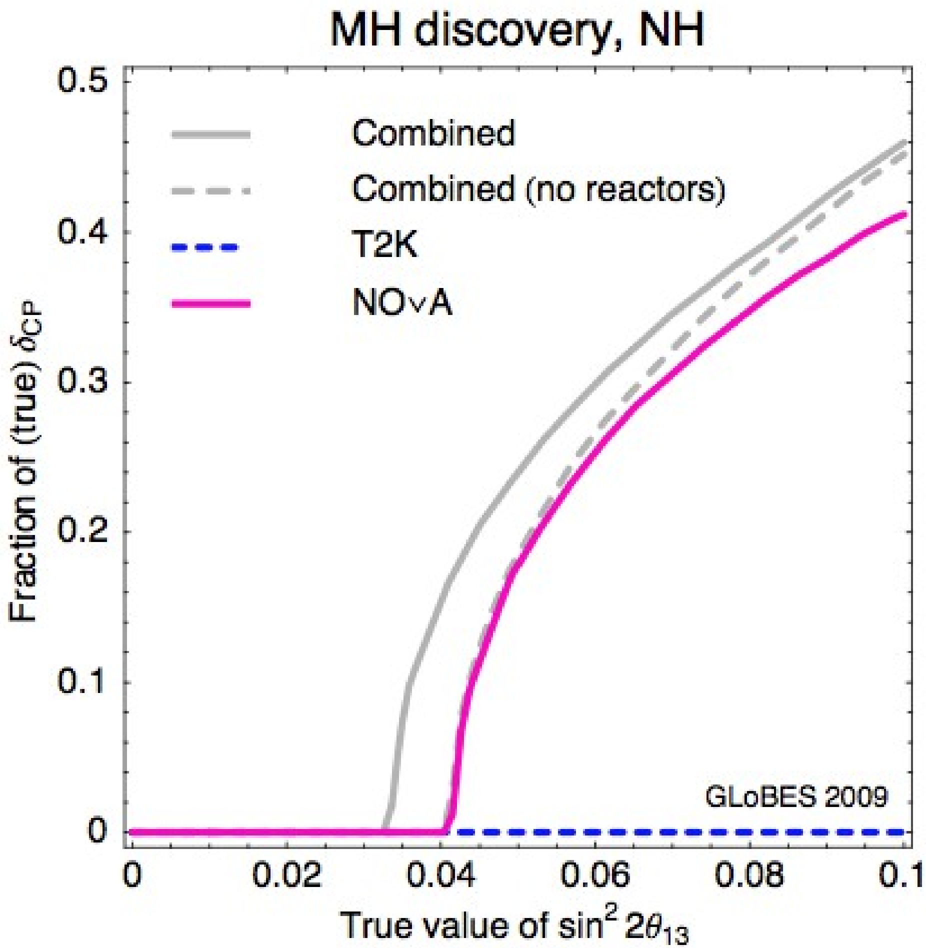


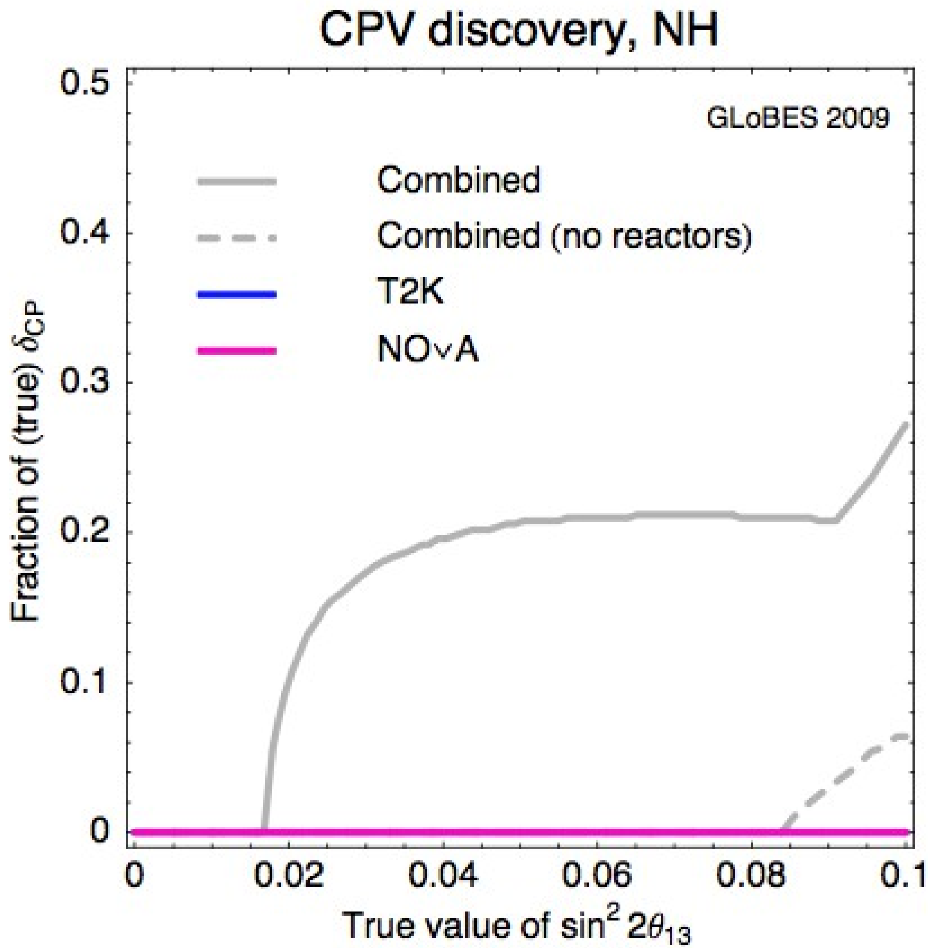
Future prospects



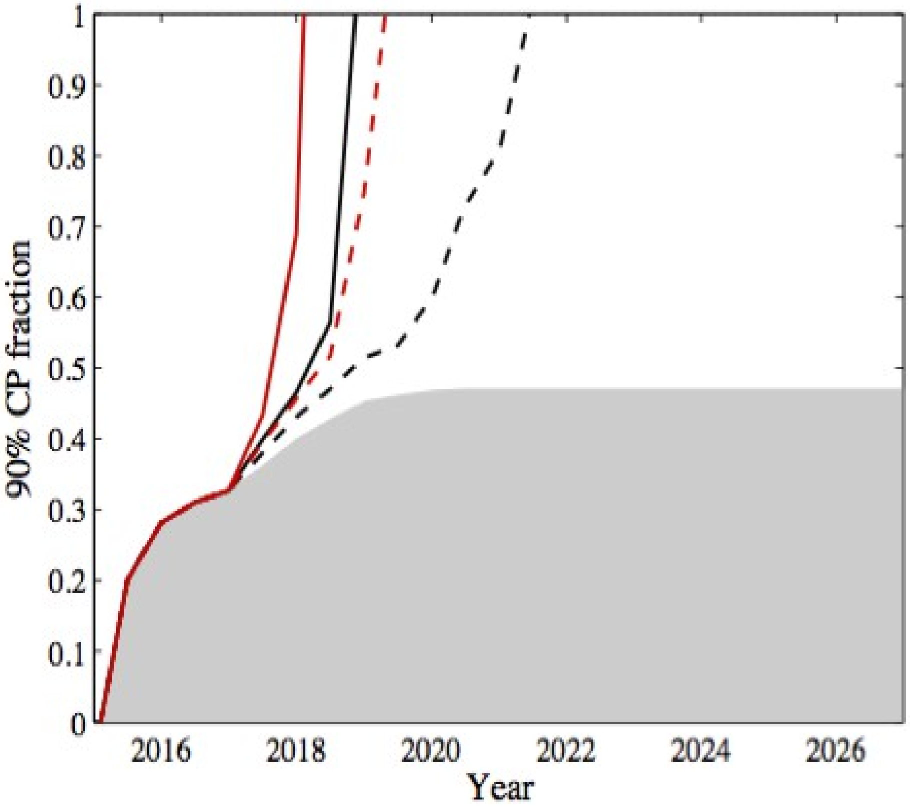


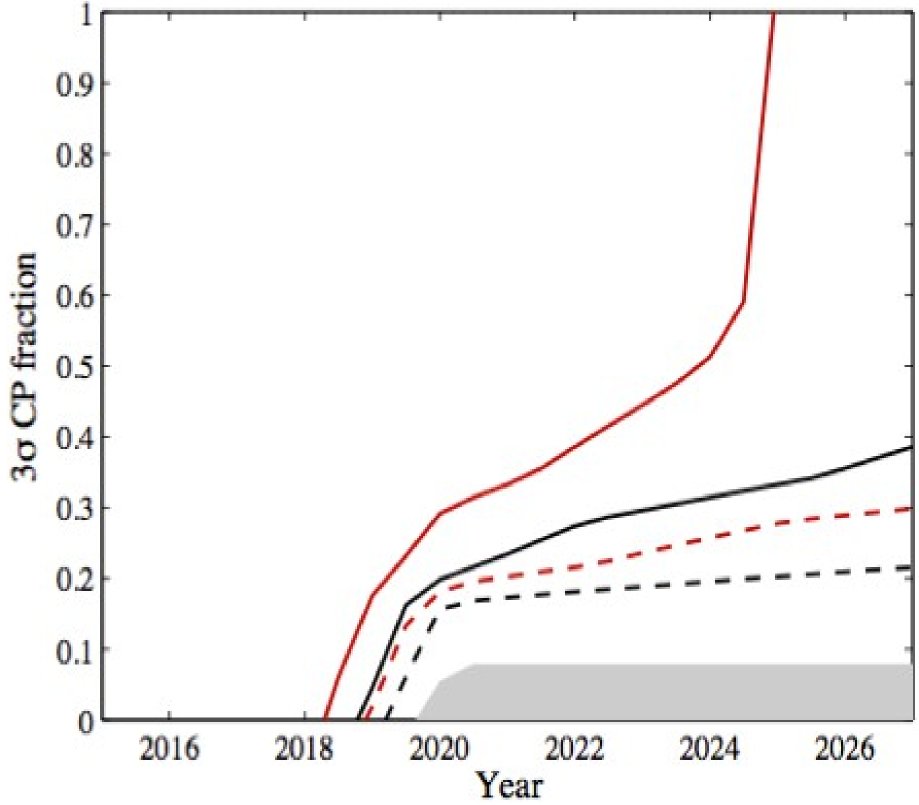
Current generation





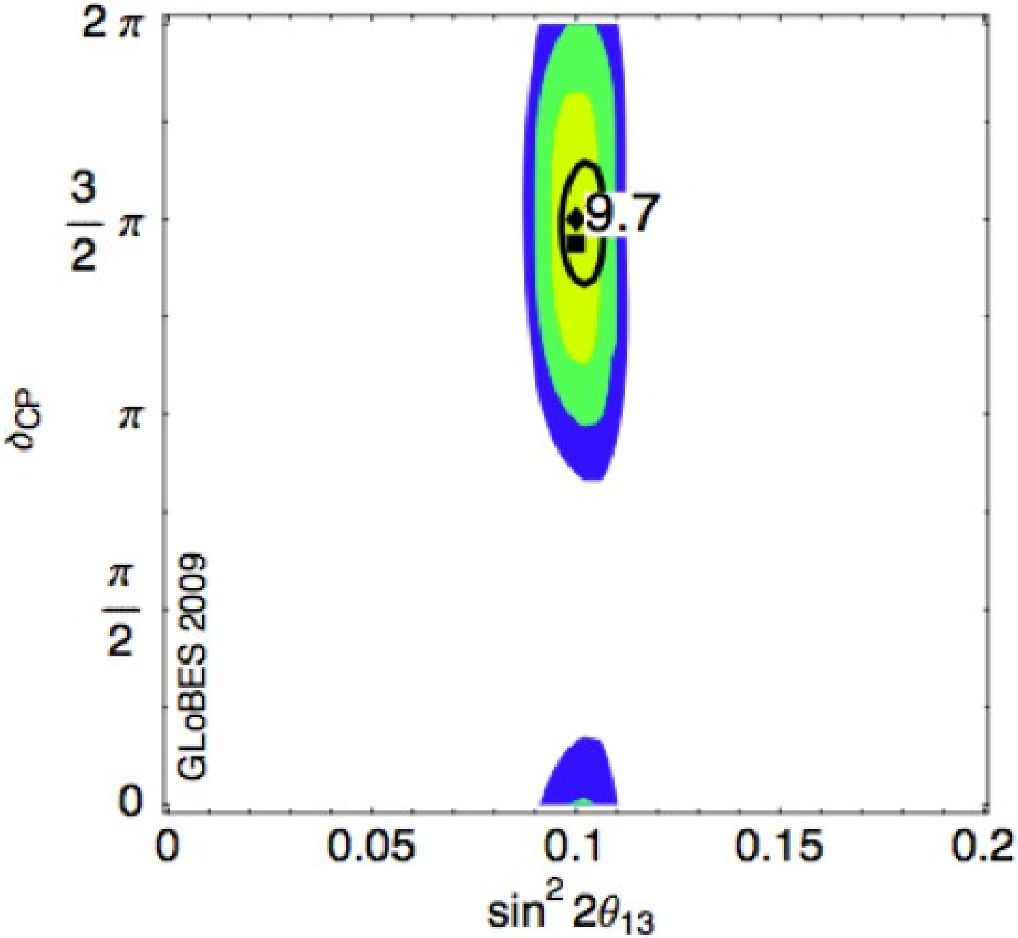
Current generation





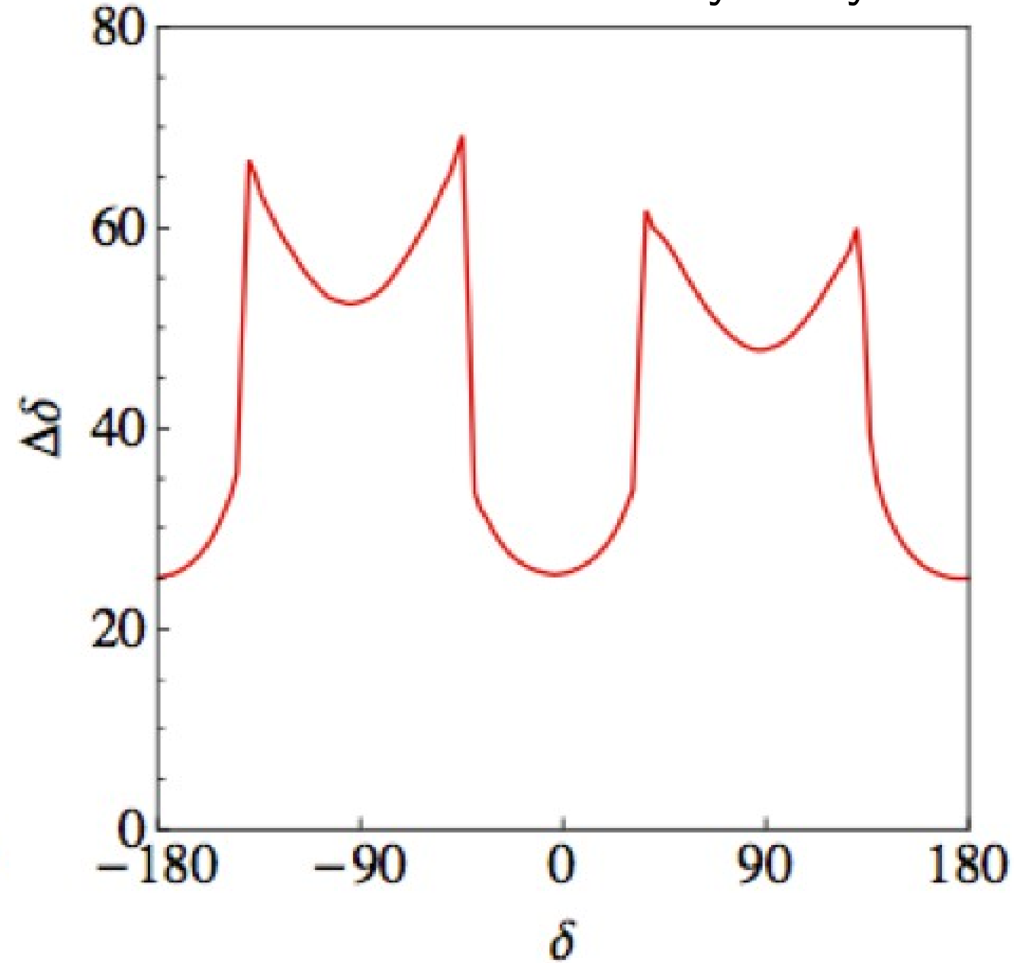
Degeneracies

T2K + NOvA + Daya Bay



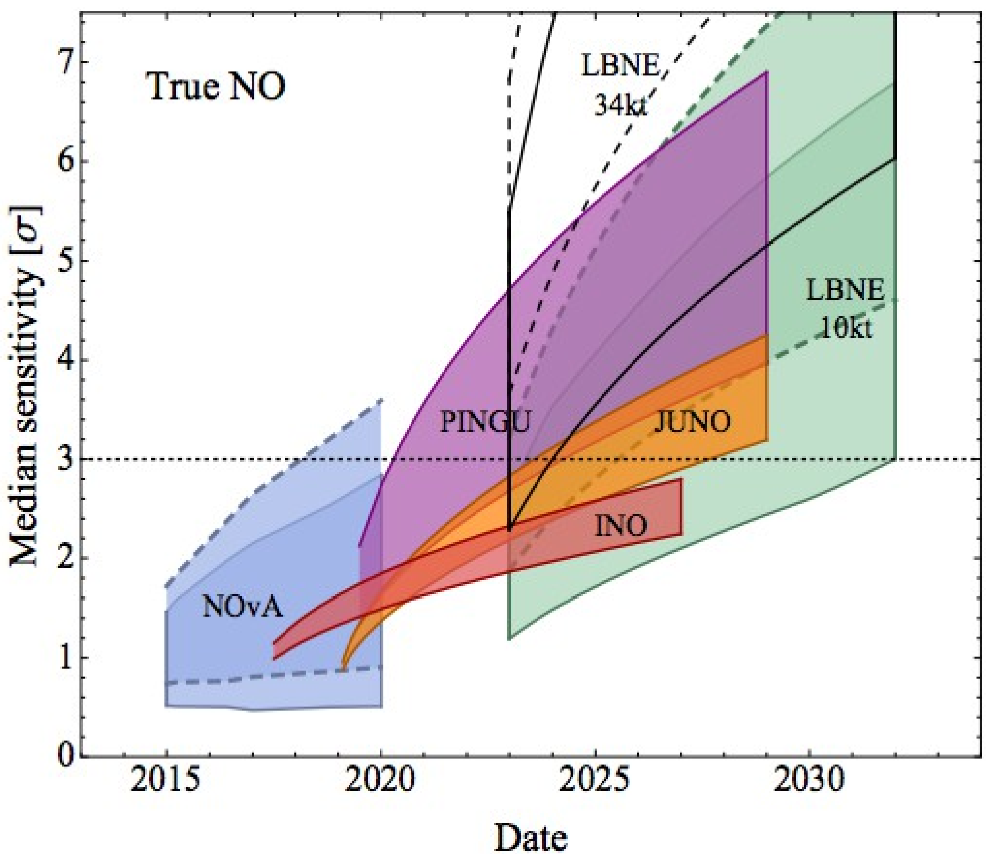
Huber et al, 0907.1896 [hep-ph]

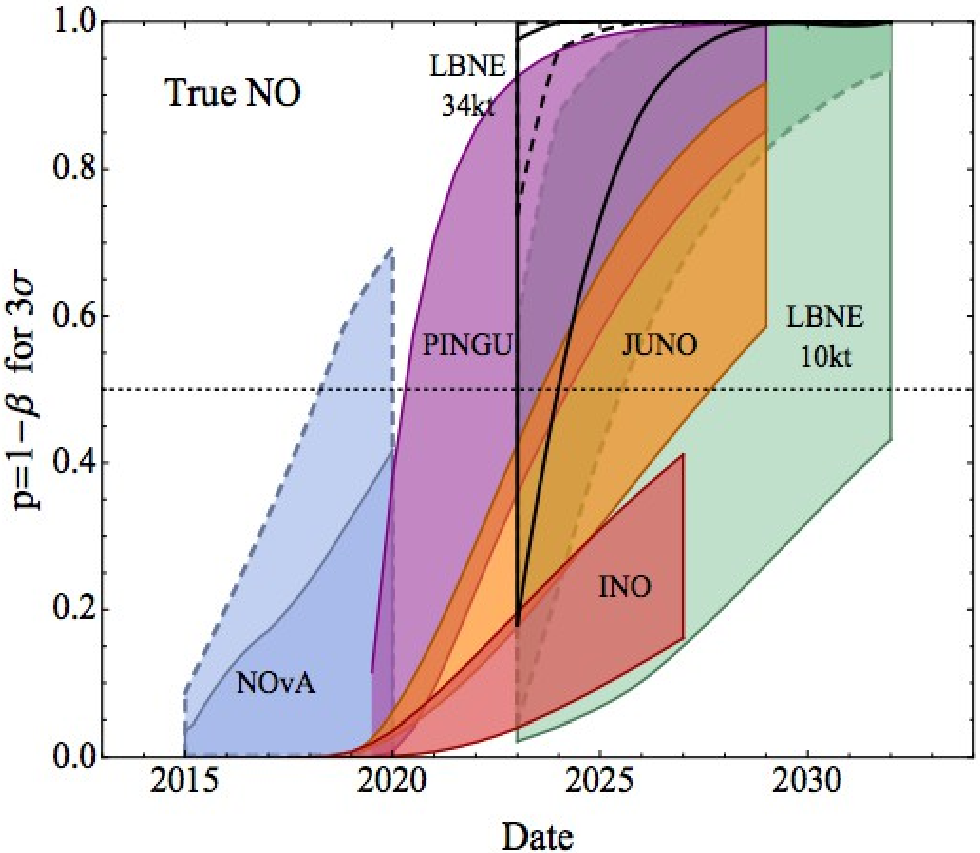
T2K + NOvA + Daya Bay



Coloma et al, 1203.5651 [hep-ph]

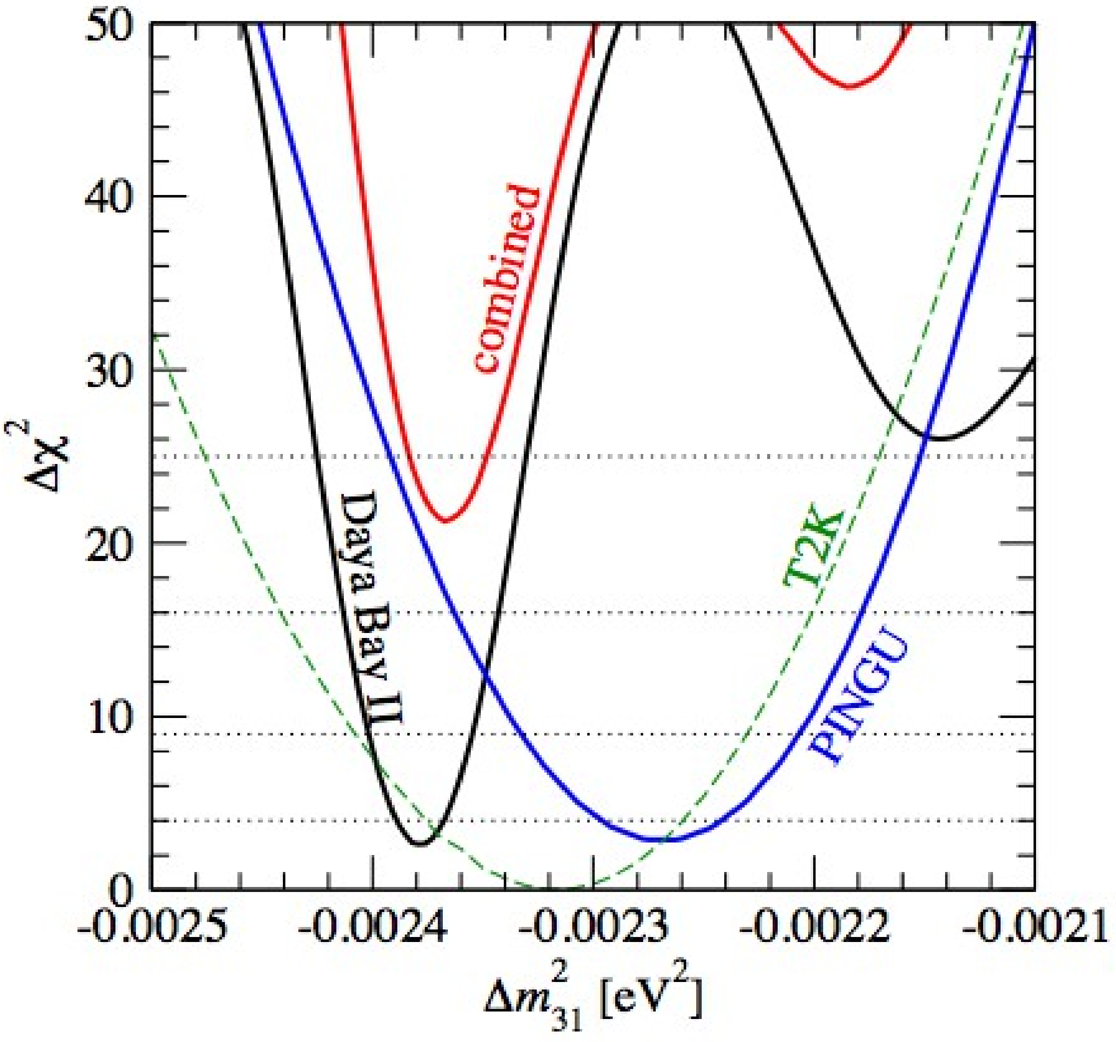
Prospects for mass hierarchy





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

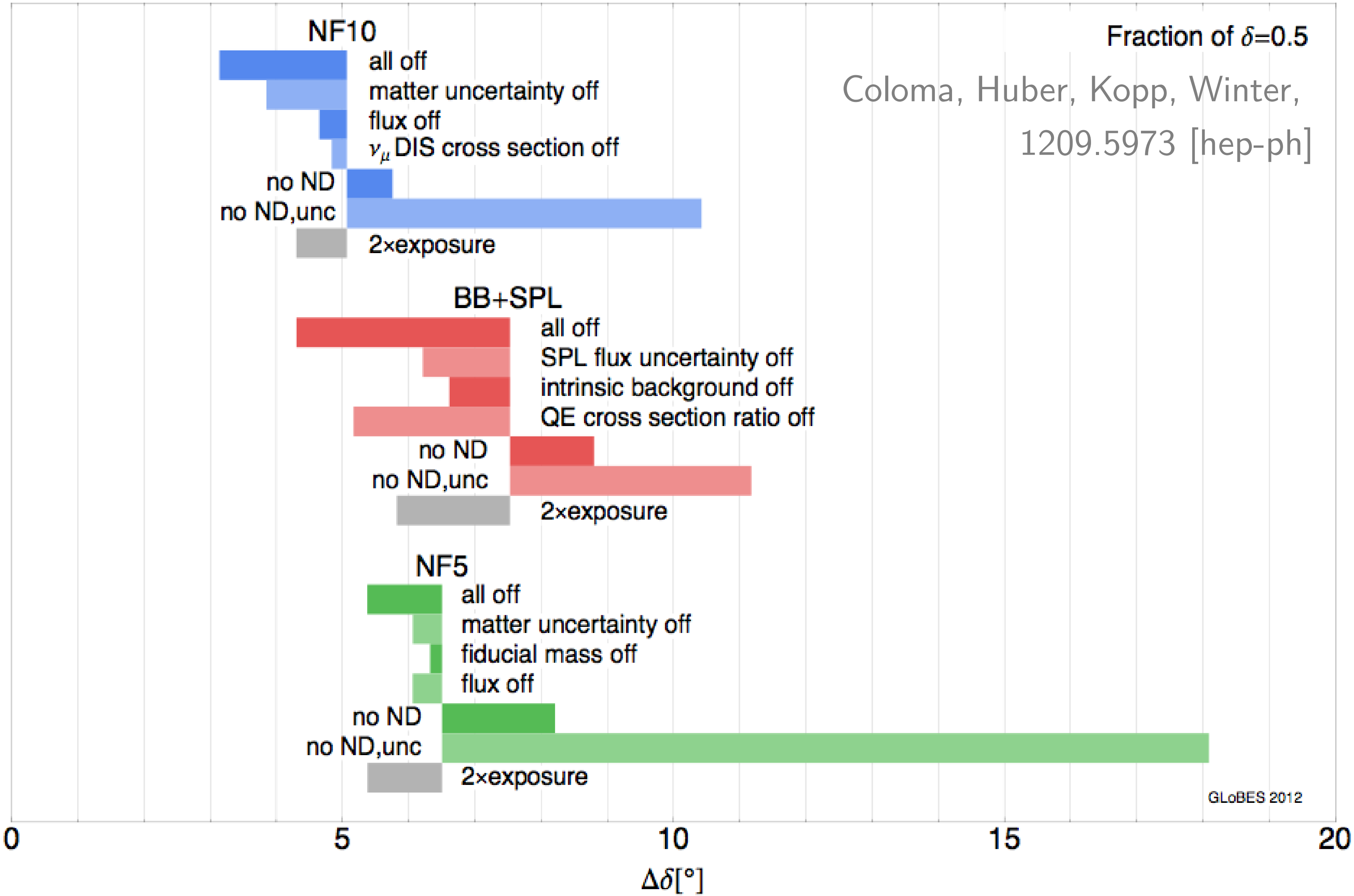
Mass hierarchy determination



Blennow, Schwetz, 1306.3988 [hep-ph]

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

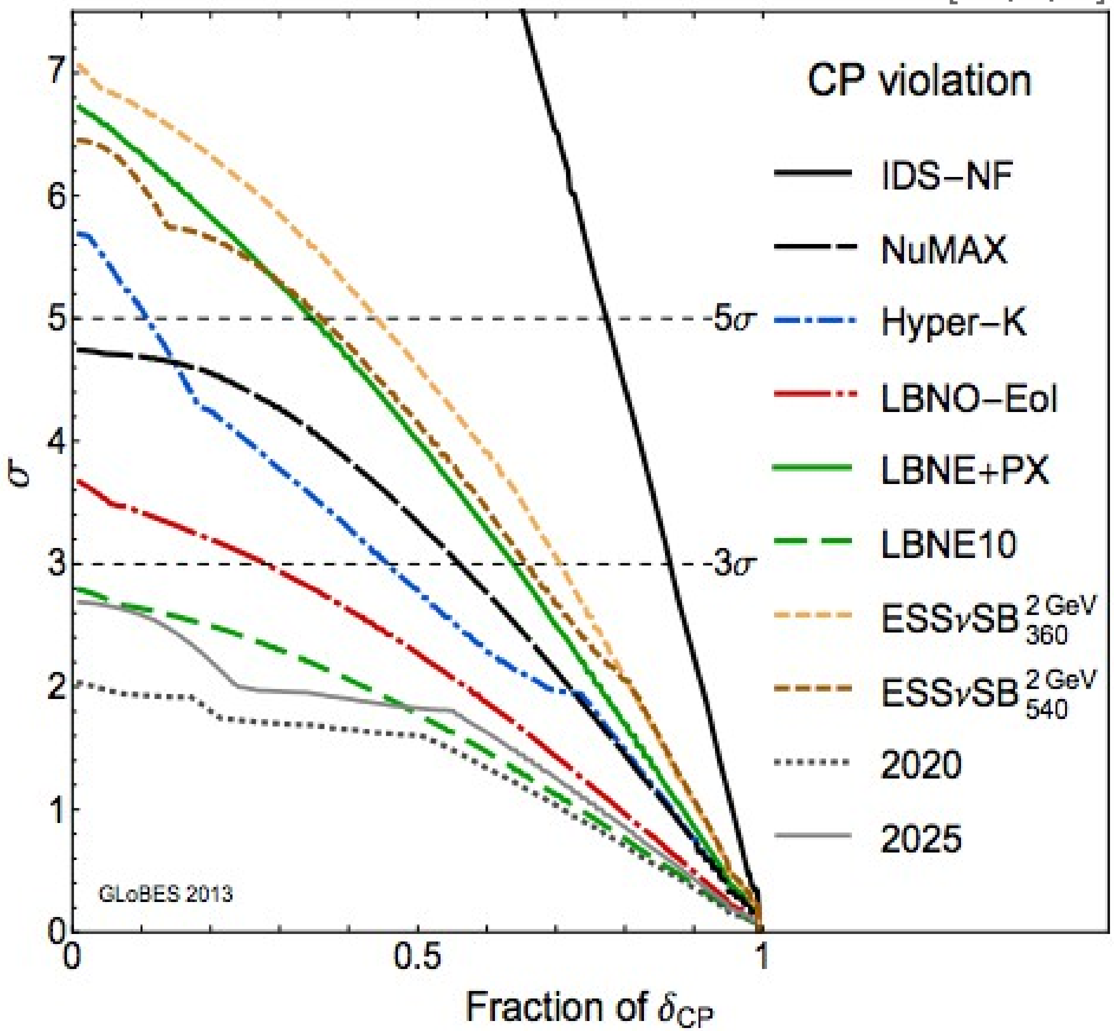
Impact on precision



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

Experimental overview: CP violation

Baussan et al., 1309.7022 [hep-ph]



Experimental overview: precision

Snowmass process, 1310.4340 [hep-ph]