Impact of systematic uncertainties on long baseline neutrino oscillations

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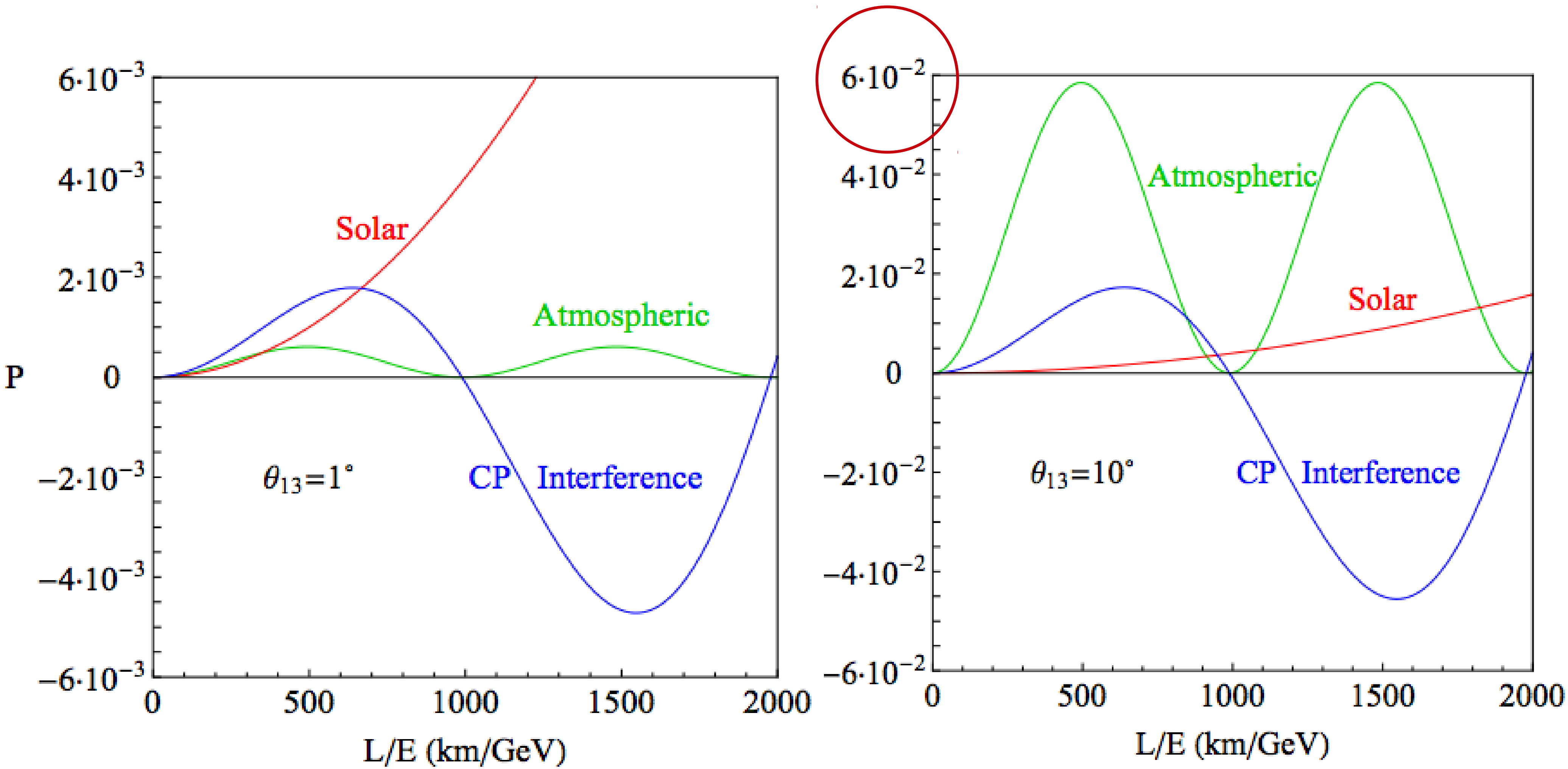
Based on the work by P. Coloma, P. Huber, J. Kopp and W. Winter,
Phys. Rev. D 87, 033004 (2013)
(arXiv: 1209.5973 [hep-ph])

3rd open meeting for the Hyper-Kamiokande project
Tokyo, June 21-22, 2013

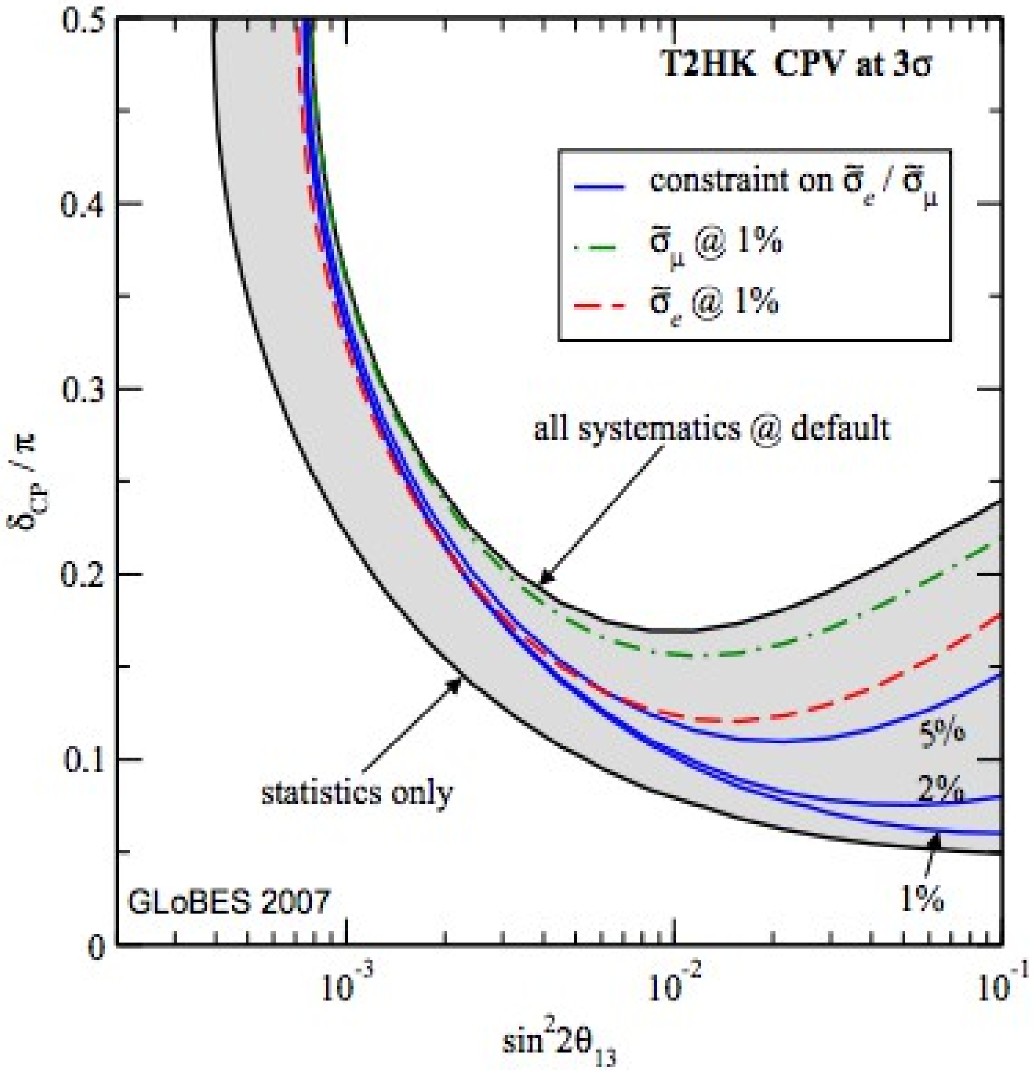
CP interference is subleading



Neutrino beams

- Pion-decay $\pi^+ \to \mu^+ \nu_\mu$
  - Intrinsic bg, large flux and cross section uncertainties
  - Technology already well-known
  - No charge ID required $\to$ allows for the use of Mton WC detectors $\to$ large statistics + rich physics program
- Muon-decay $\mu^+ \to e^+ \nu_e \bar{\nu}_\mu$
  - No intrinsic bg, small flux uncertainties
  - Final flavor cross sections can be measured at near detector
  - Flavor rich
  - Charge ID is required

Systematics and CPV



Huber et al, 0711.2950 [hep-ph]

Appearance experiments are not able to measure final flavor xsecs at the near detector (exception: NuFact)

Systematics

Possible ways to reduce impact of systematics:

1) Measure final flavor cross sections at the near detector. If not possible, put constraints on the ratios between different flavors

Day, McFarland, 1206.6745

2) Measure intrinsic backgrounds at the near detector

3) Use data from disappearance at the far detector to reduce impact of systematics in appearance

Some technical details...

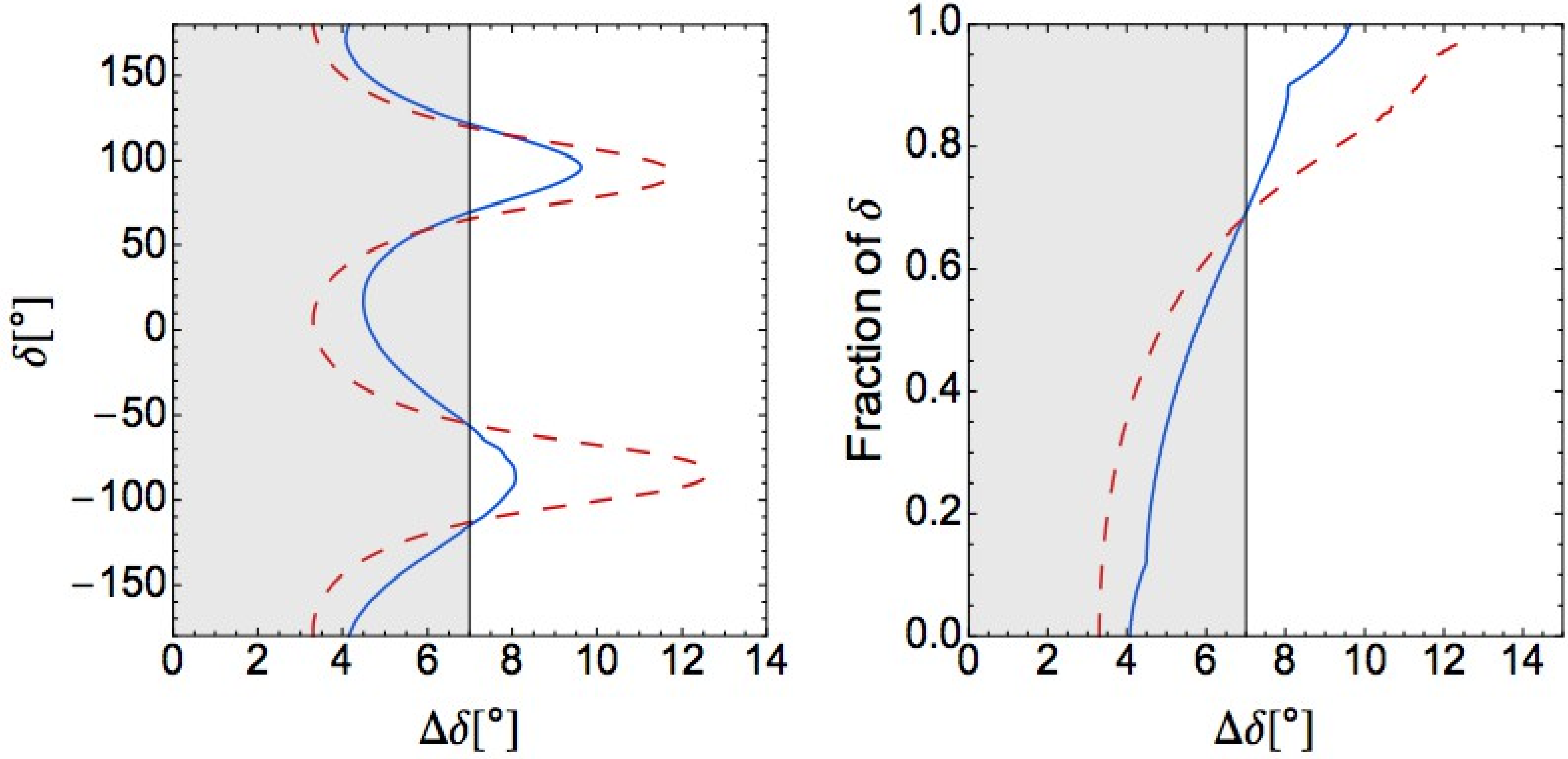
- A modification of GLoBES software used hep-ph/0407333, 0701187
- Marginalization over 1σ allowed ranges for the oscillation parameters around their best fits 1108.1376[hep-ph], 1205.5254[hep-ph]
- Atmospheric angle set to maximal (no octant degeneracy)
- Poissonian χ^2 used, with 100 MeV bins. Ideal near detector considered
- Systematics introduced as independent normalization uncertainties for cross section, fluxes, fiducial mass, backgrounds, etc
- Correlations between channels and detectors fully taken into account

Systematics

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%

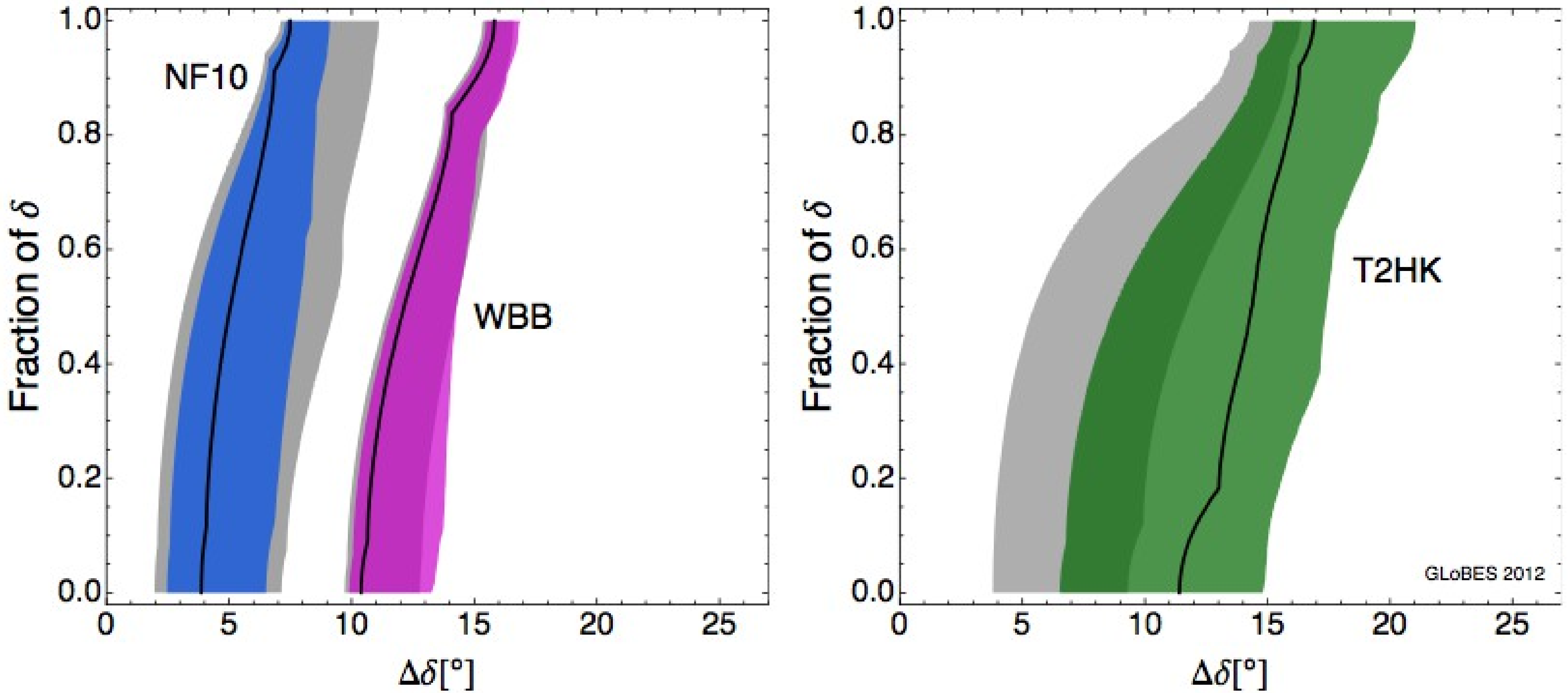
Coloma, Huber, Kopp and Winter, 1209.5973 [hep-ph]

Systematics and precision on δ



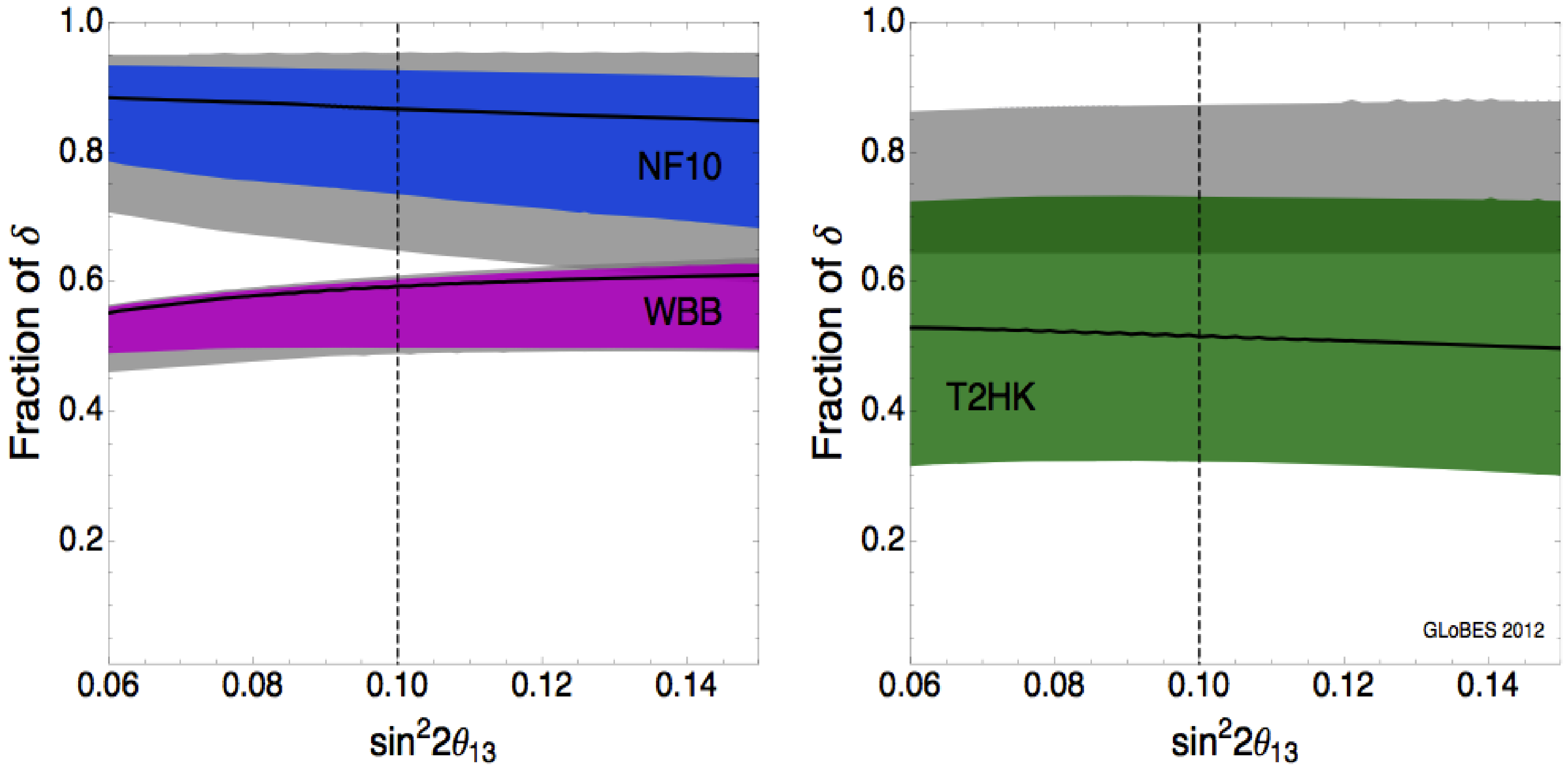
Coloma, Huber, Kopp and Winter, 1209.5973 [hep-ph]

Systematics and precision on δ



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

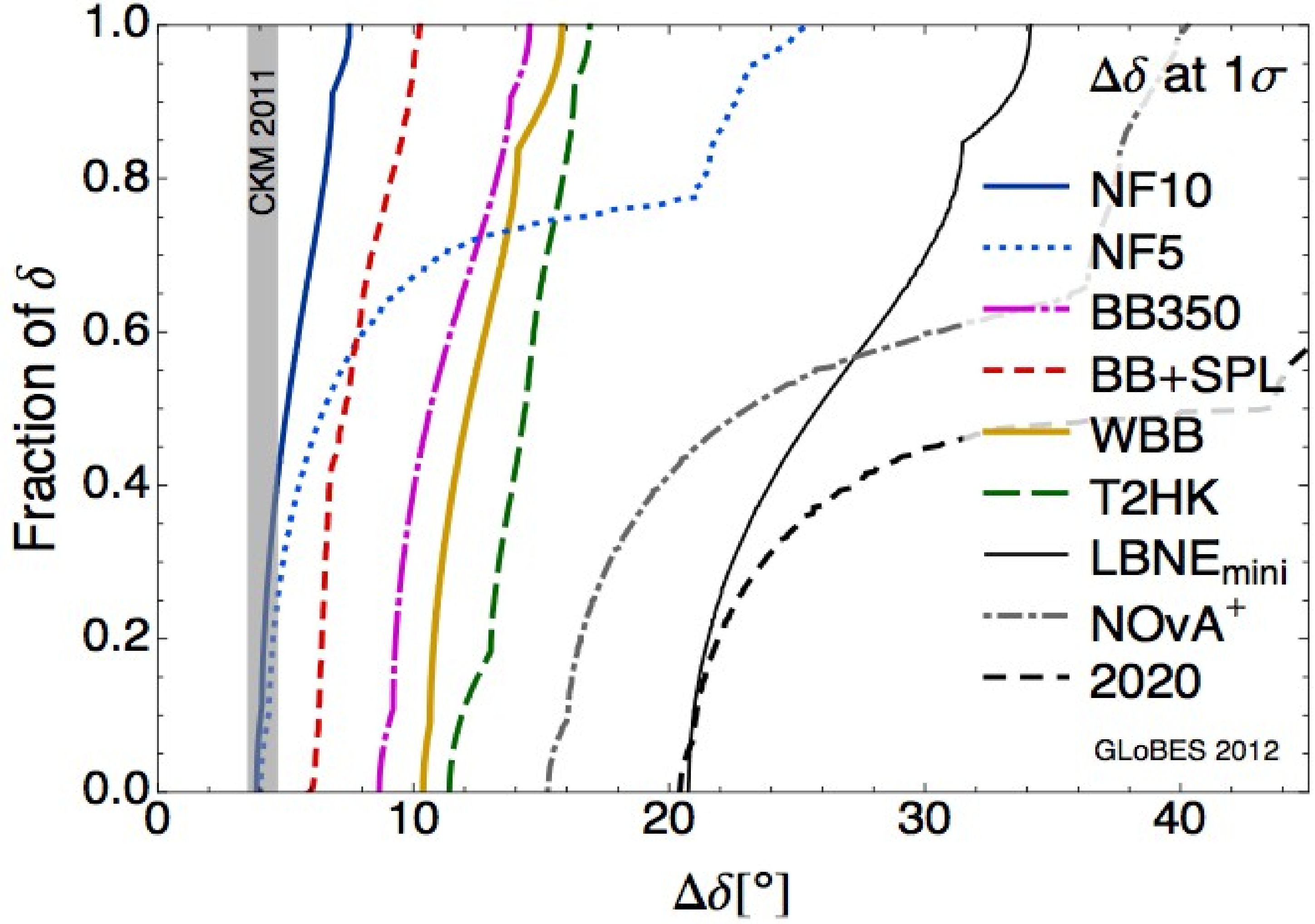
Systematics and CPV



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

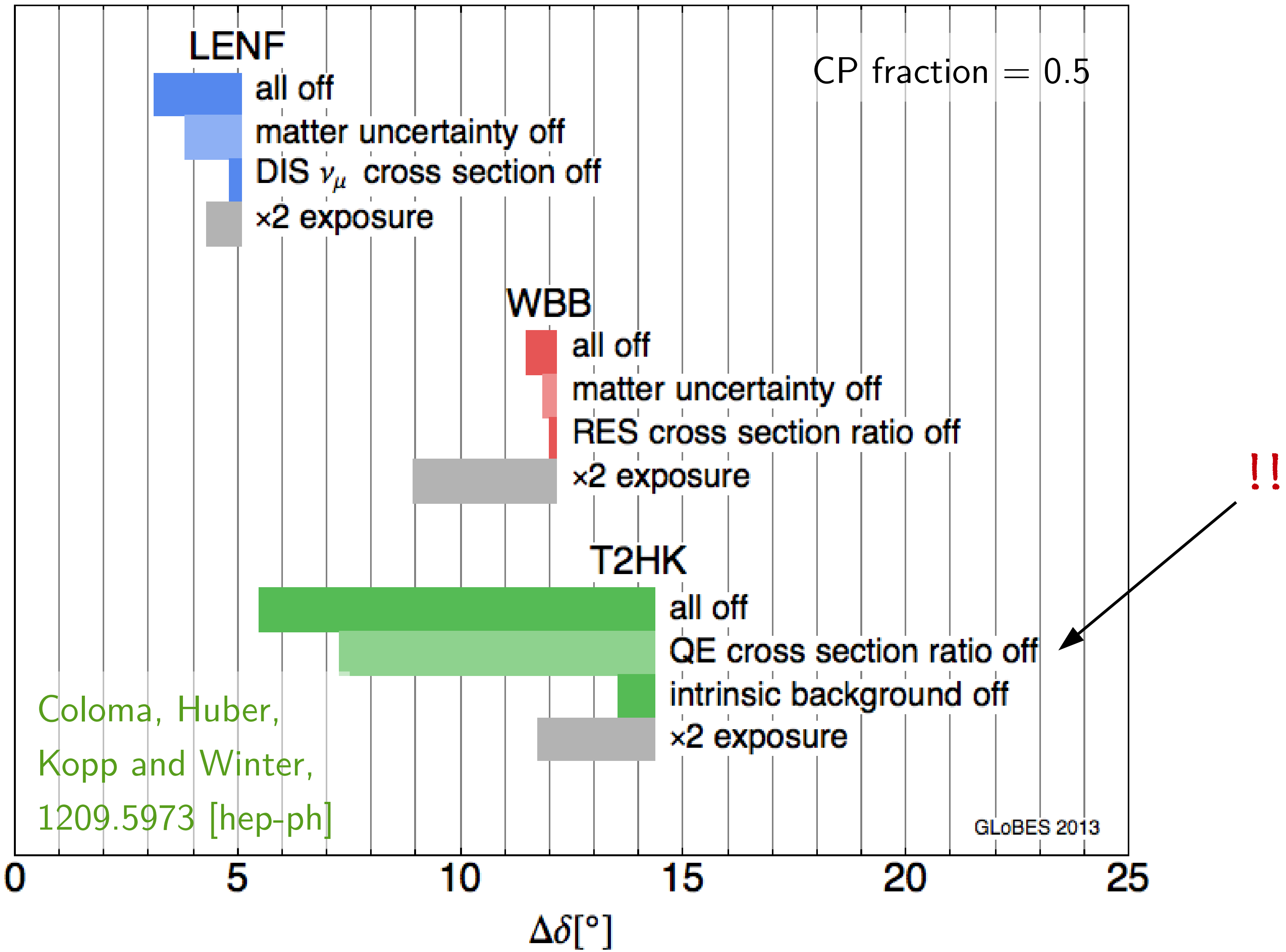
General comparison

How far do we want to get?

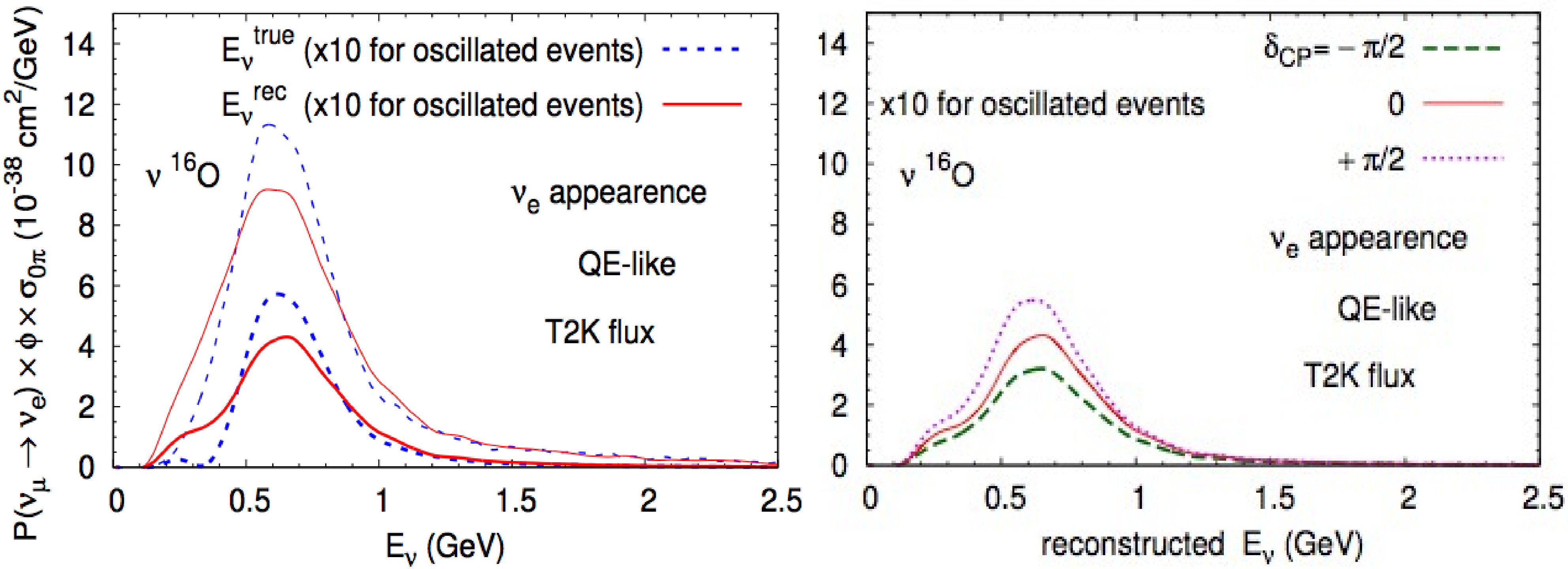


Coloma, Huber, Kopp and Winter, 1209.5973 [hep-ph]

Sytematics and precision



Nuclear effects and FSI



If ignored, this could lead to a wrong fit for the oscillation parameters!!!

Lalakulich, Mosel and Gallmeister, 1208.3678 [nucl-th]
(see also 1202.4745 [hep-ph], 1204.5404 [hep-ph], 1302.0703 [hep-ph] and
Annu. Rev. Nucl. Part. Sci. 2011.61:355-378)

Conclusions

Addressing the impact of systematics on the physics reach of long baseline experiments is highly relevant:

- Systematics have a huge impact on CPV searches due to the large value of θ_{13}
    - an analysis using normalization errors already shows large impact on the results.
- Cross section uncertainties are particularly relevant for appearance experiments since the final flavor is not initially present in the beam

Conclusions

Now that θ_{13} is measured, long baseline experiments will focus on δ and the mass hierarchy

- T2HK has great potential for CPV from long baseline data
- Aditionally, the large value of θ_{13} will make it extremely likely to have a measurement of the hierarchy from atmospheric data as well!

Addressing the robustness of T2HK sensitivities under the impact of systematic uncertainties is highly relevant. A detailed study including both shape and normalization uncertainties is needed

Thank you!

Backup

Setups

	Setup	$E_\nu^{\rm peak}$	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)
	$\text{LBNE}_{\text{mini}}$	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)

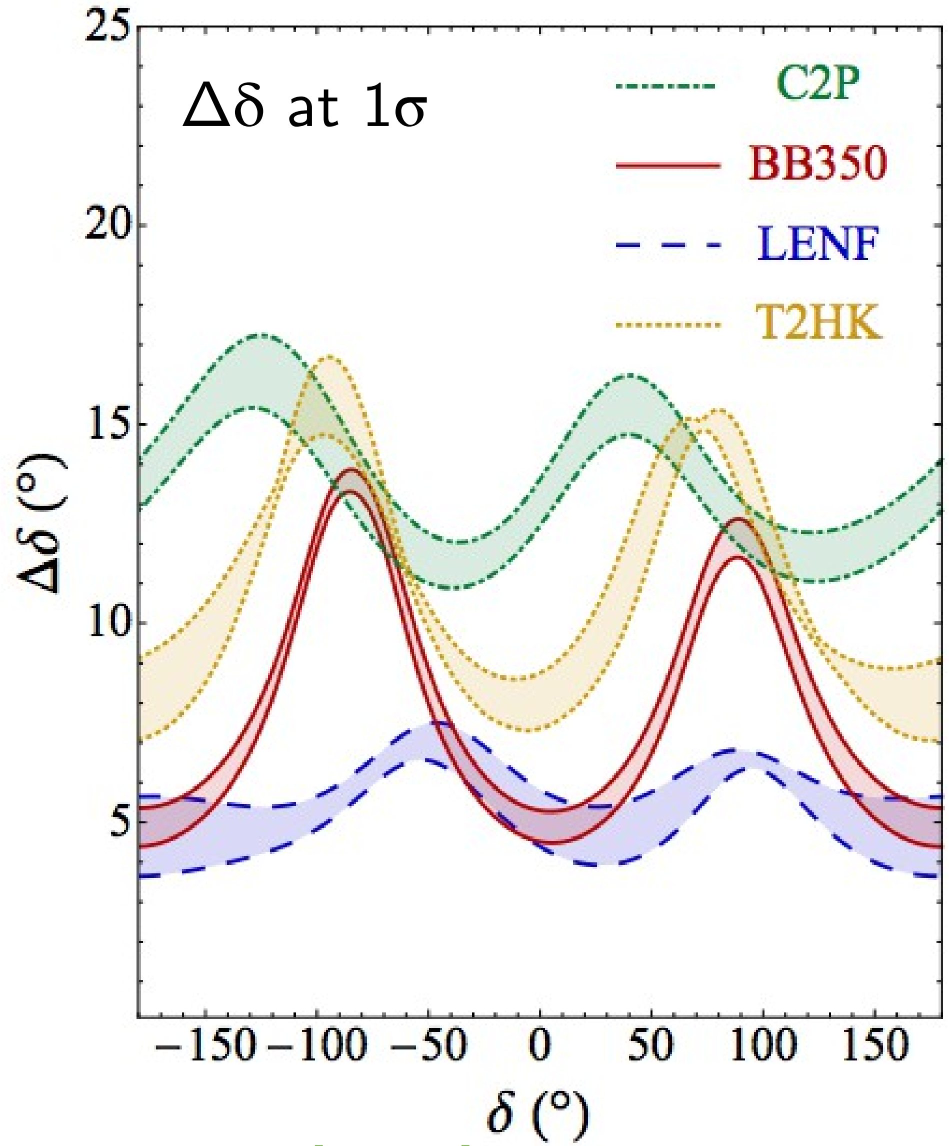
Precision on δ

C2P: Wide Band Beam, long baseline and high energy

BB350: Beta Beam at high gamma

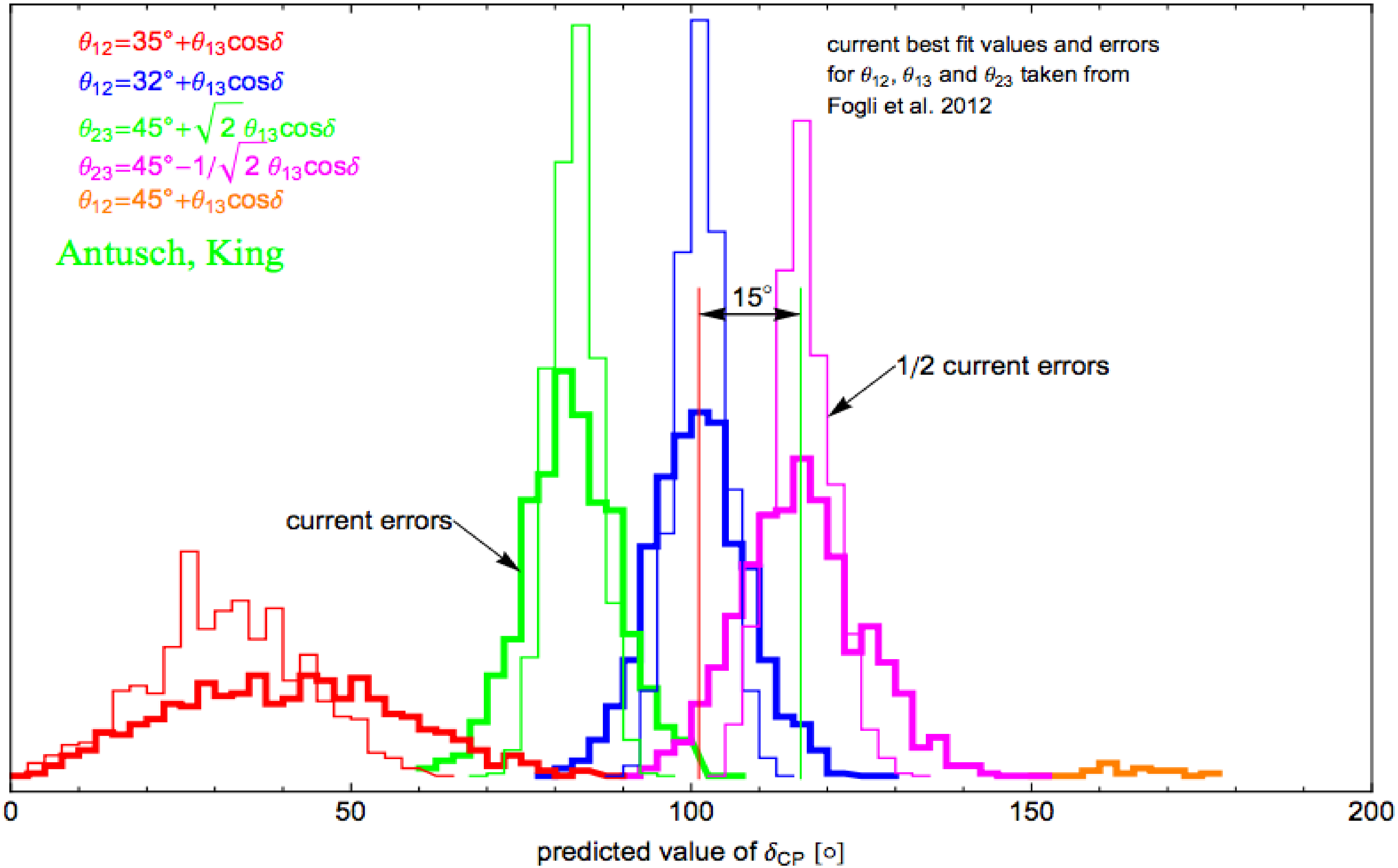
LENF: Neutrino Factory, high energy

T2HK: off-axis beam, “short” baseline, low energy



Coloma, Donini, Fernandez-Martinez, Hernandez, 1203.5651 [hep-ph]

Why precision?



Plot courtesy of Patrick Huber

The golden and platinum channels

Our golden observable at long baseline experiments is:

$$P^{\pm}_{e\mu}(\theta_{13},\delta) = X_{\pm}\sin^2 2\theta_{13}$$

$$+ Y_{\pm}\cos\theta_{13}\sin 2\theta_{13}\cos\left(\pm\delta - \frac{\Delta m^2_{31}L}{4E}\right)$$

$$+ Z$$

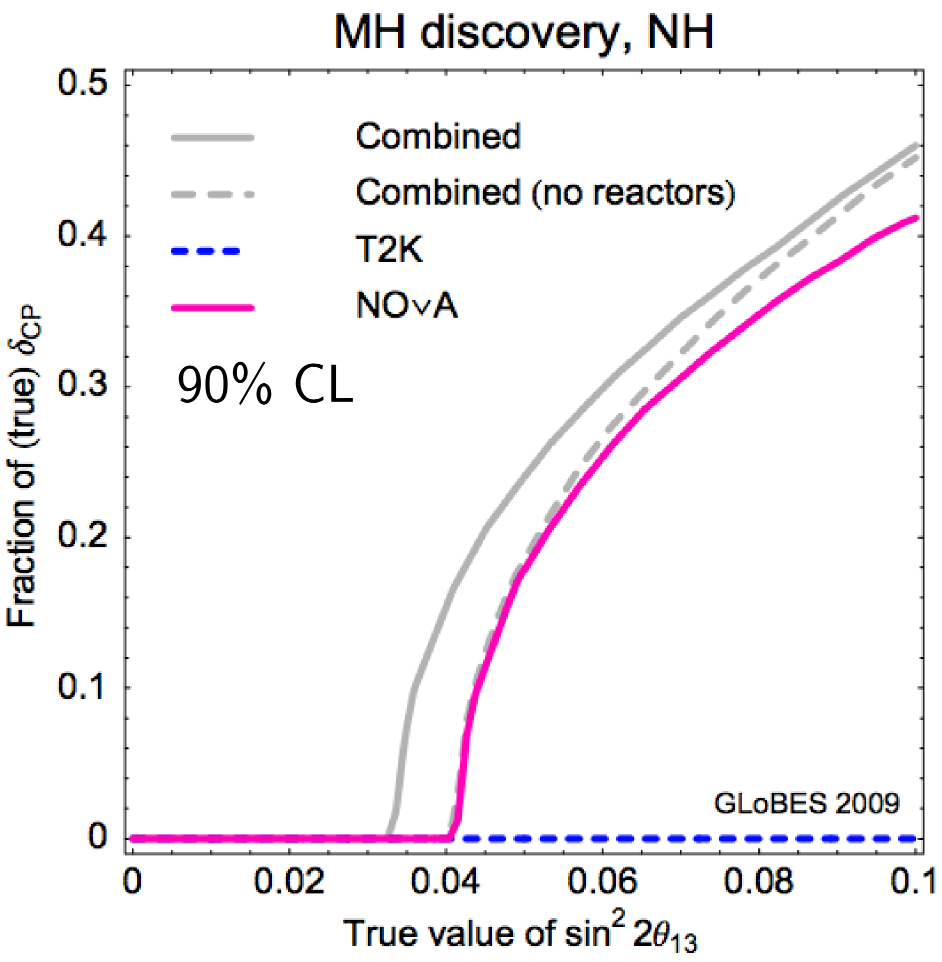
A. Cervera *et al.* hep-ph/0002108

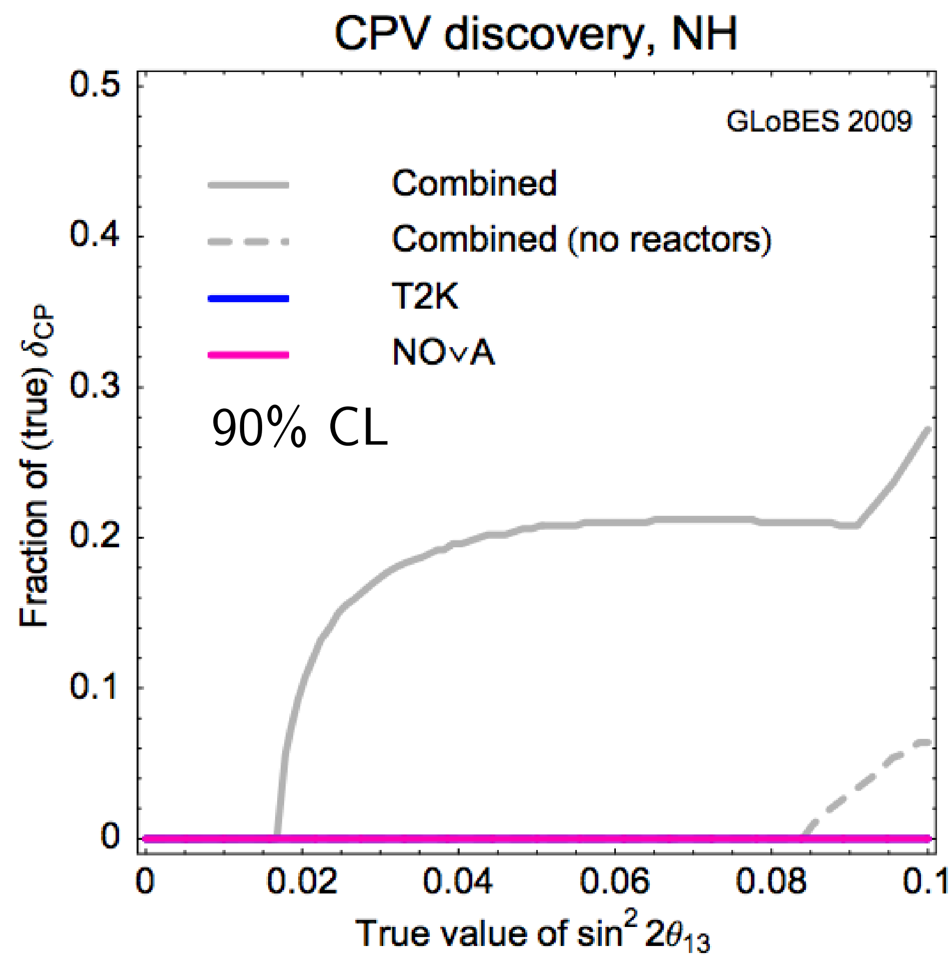
$$X_{vac} \propto \sin^2\left(\frac{\Delta m^2_{31}L}{4E}\right)$$

$$Y_{vac} \propto \sin\left(\frac{\Delta m^2_{31}L}{4E}\right)\sin\left(\frac{\Delta m^2_{21}L}{4E}\right)$$

$$Z \propto \sin^2\left(\frac{\Delta m^2_{21}L}{4E}\right)$$

Pion-based ν beams: present

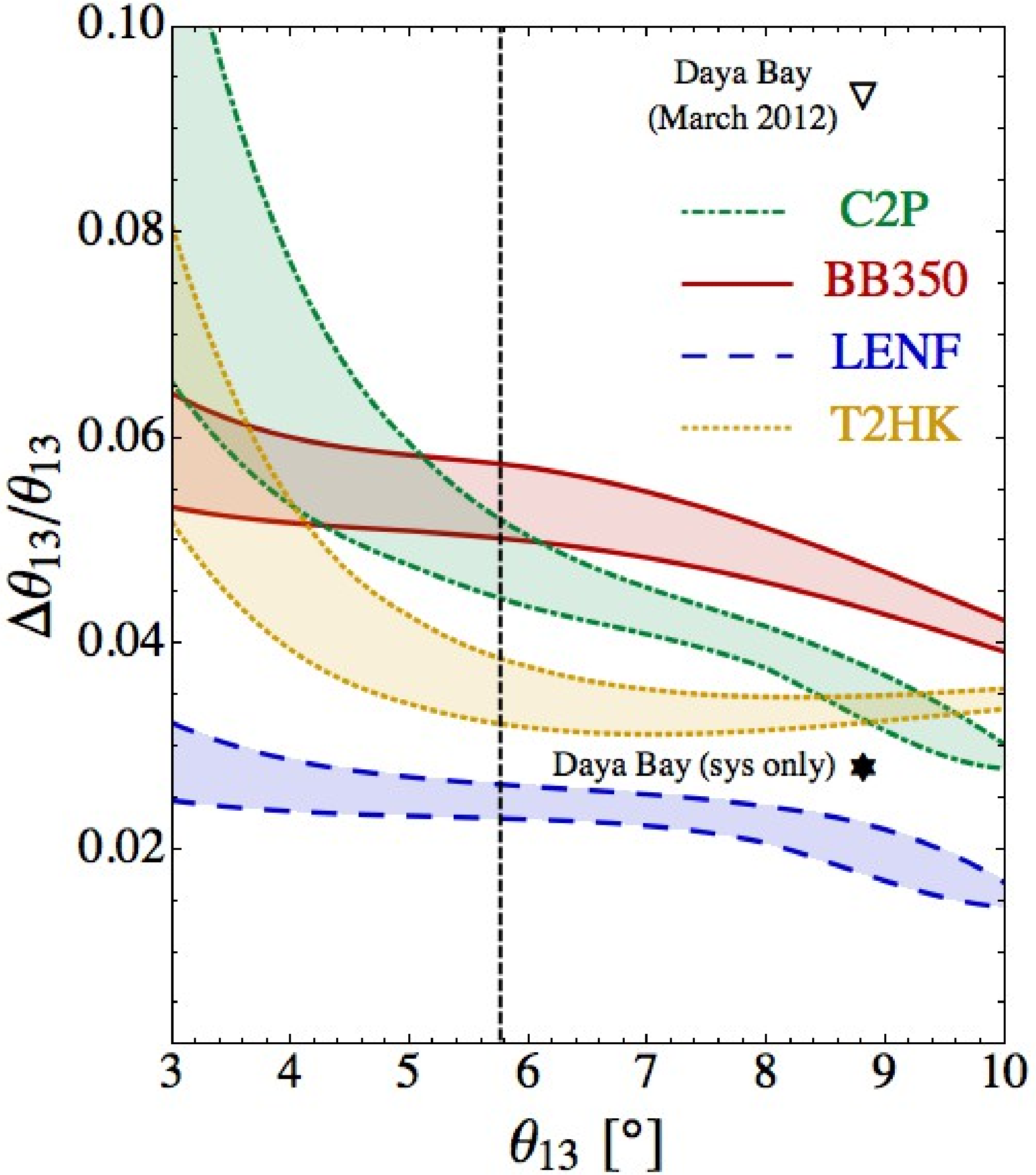




Both beams are off-axis!

Huber et al, 0907.1896 [hep-ph]

Precision on θ_{13}



The precision on θ_{13} obtained at Daya Bay will hardly be beaten by any beam experiment!!

Coloma, Donini, Fernandez-Martinez and Hernandez, 1203.5651 [hep-ph]