Systematic uncertainties in long baseline neutrino oscillations for large θ_{13}

Pilar Coloma

Center for Neutrino Physics at Virginia Tech

Based on

P. Coloma, P. Huber, J. Kopp and W. Winter, 1209.5973 [hep-ph]

Flux Measurement and Determination in the Intensity Frontier Era Neutrino Beams

Pittsburgh PACC, Dec 8, 2012

Outline

- Introduction to precision in θ_{13} and δ
- Introduction to the problem of systematics for large θ_{13}
  - Possible ways to reduce their impact
- Simulation details
- Results
  - Comparison, key systematics, effect of luminosity

Precision in θ_{13}

$$(\Delta\theta_{13})_{\pm} \propto \left[\frac{(1 \mp \hat{A})^2}{\sin^2((1 \mp \hat{A})\Delta)}\right] \frac{1}{\theta_{13}} \Delta N_{\pm}$$

neutrino/antineutrino

Precision in θ_{13}

$$(\Delta\theta_{13})_\pm \propto \left[\frac{(1\mp\hat{A})^2}{\sin^2((1\mp\hat{A})\Delta)}\right]\frac{1}{\theta_{13}}\Delta N_\pm$$

Statistical limit:

$$\Delta N_\pm \propto \sqrt{N_\pm} \propto \theta_{13} \longrightarrow (\Delta\theta_{13})_\pm \propto const$$

Systematics on the signal:

$$\Delta N_\pm \propto N_\pm \propto \theta_{13}^2 \longrightarrow (\Delta\theta_{13})_\pm \propto \theta_{13}$$

Background error:

$$\Delta N_\pm \propto const \longrightarrow (\Delta\theta_{13})_\pm \propto 1/\theta_{13}$$

Precision in θ_{13}

Statistical limit:

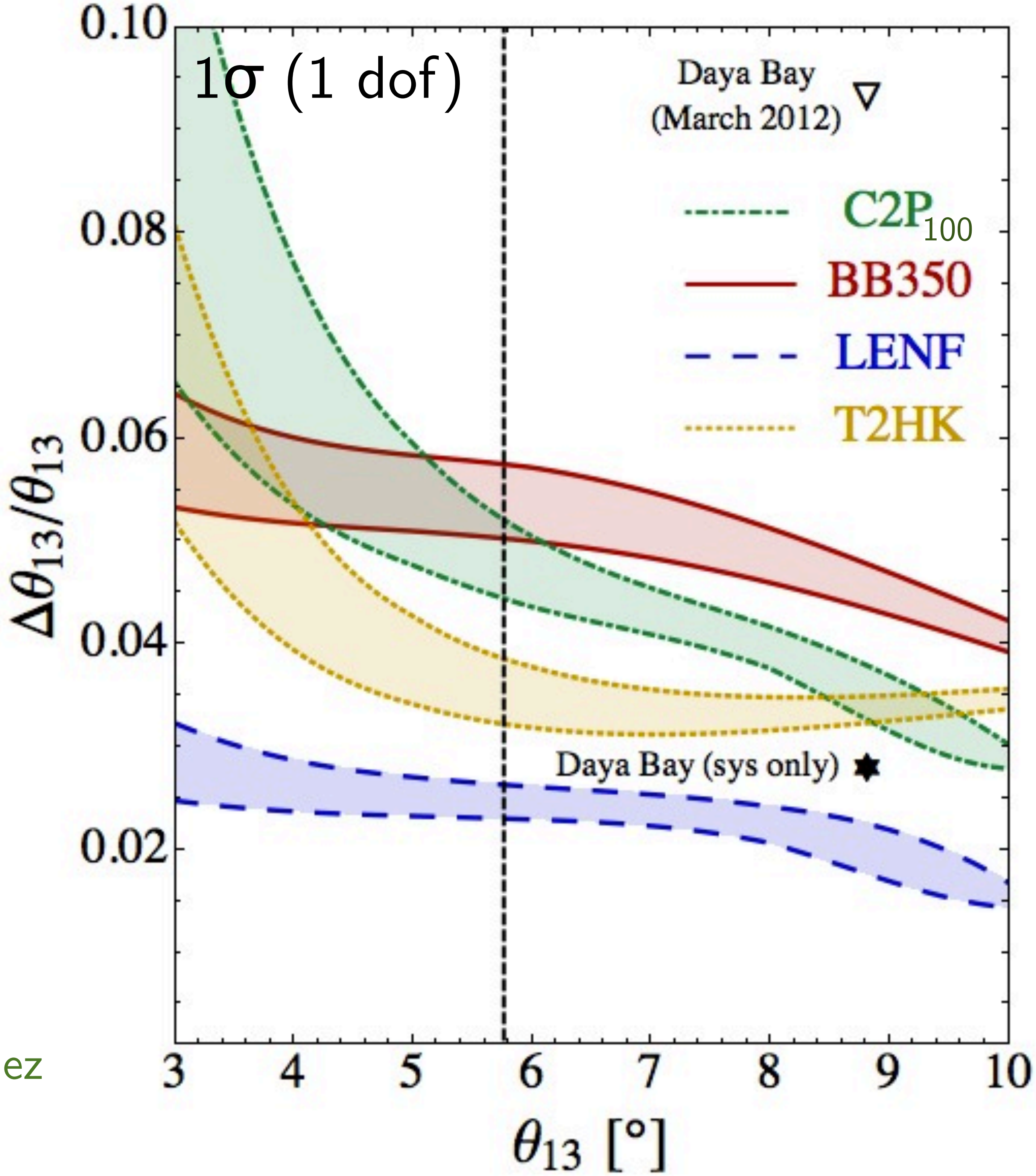
$$\frac{\Delta\theta_{13}}{\theta_{13}} \propto \frac{1}{\theta_{13}}$$

Systematics on the signal:

$$\frac{\Delta\theta_{13}}{\theta_{13}} \propto const$$

Background error:

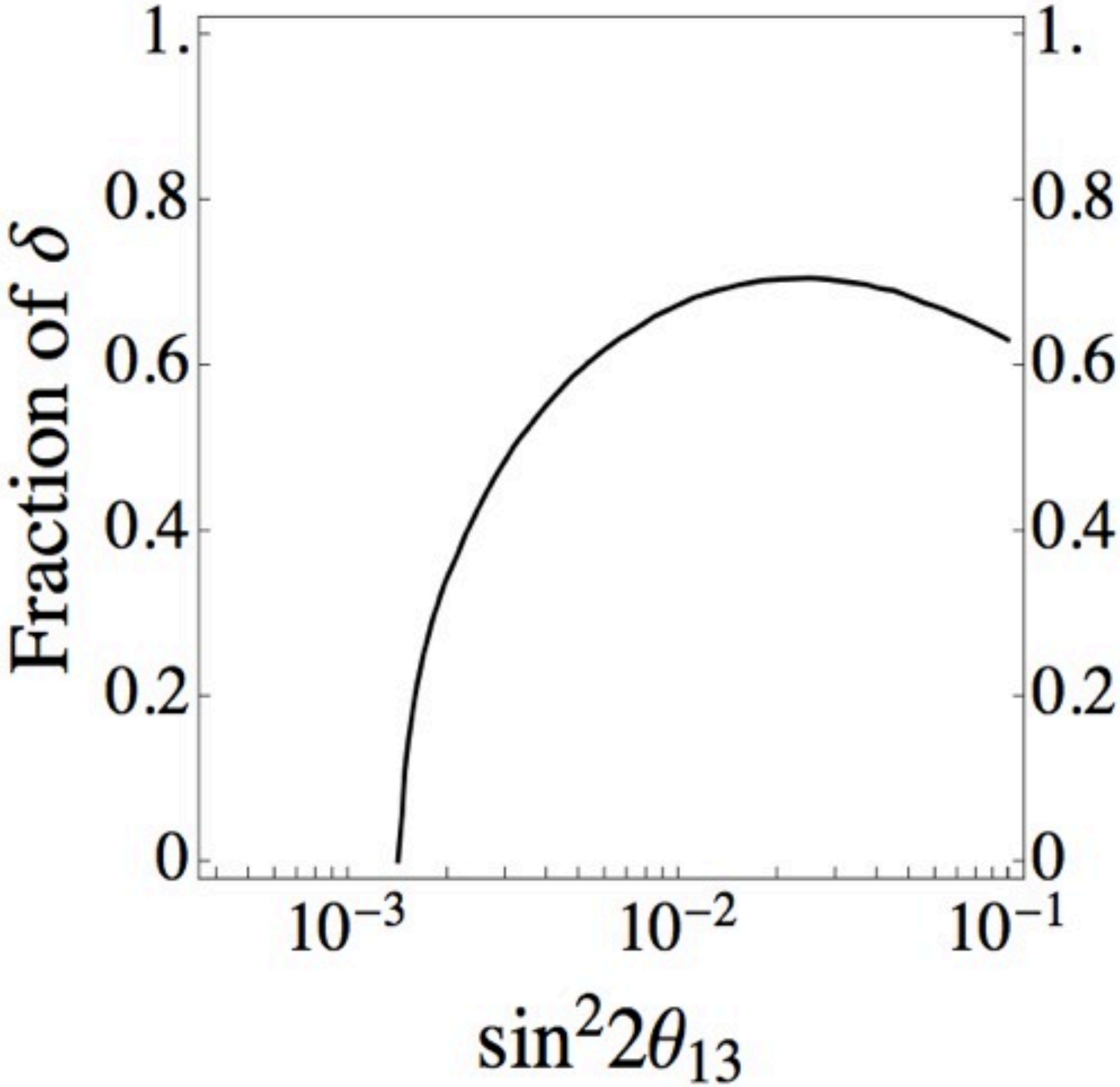
$$\frac{\Delta\theta_{13}}{\theta_{13}} \propto \frac{1}{\theta_{13}^2}$$

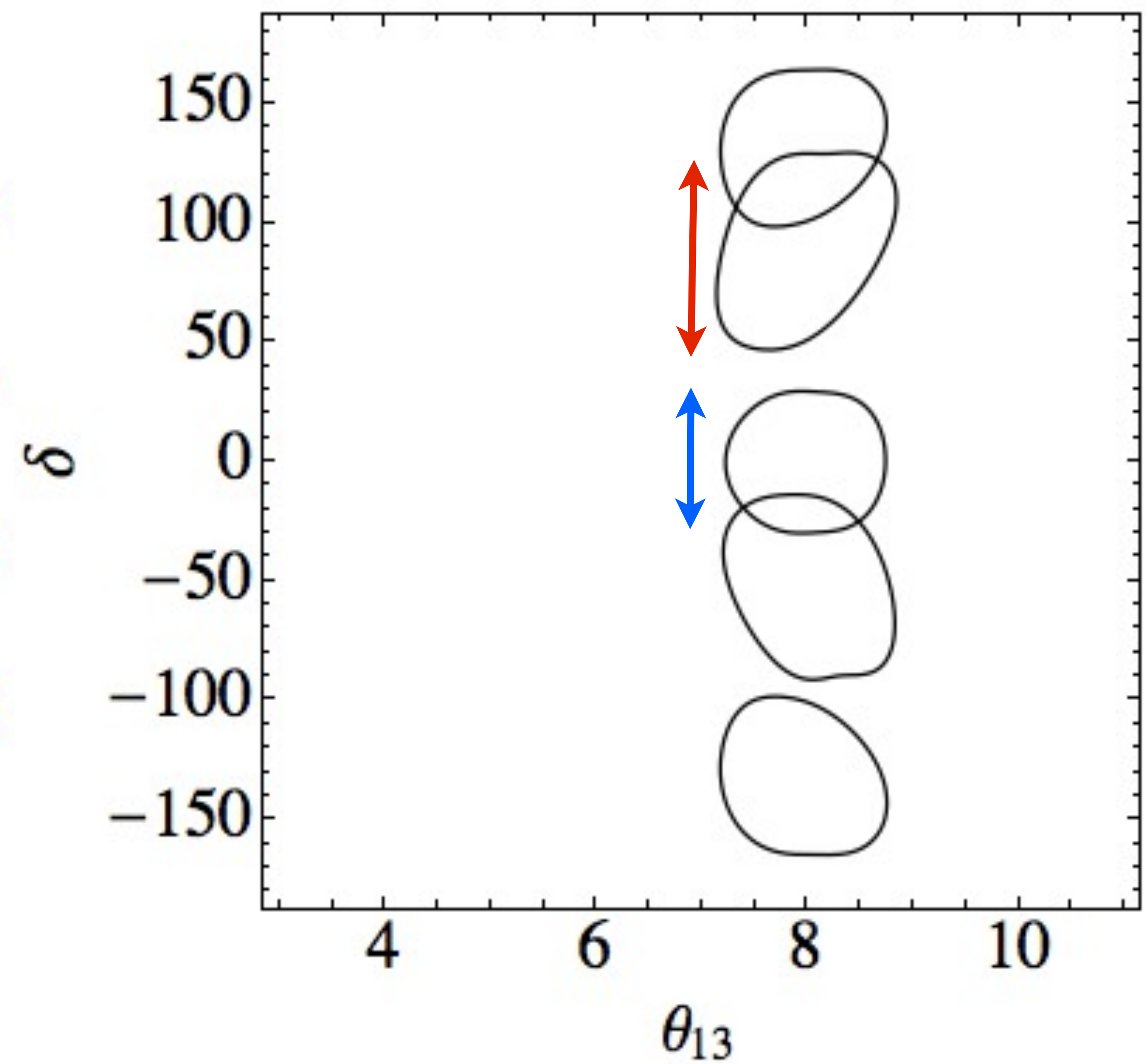


P. Coloma, A. Donini, E. Fernández-Martínez and P. Hernández, 1203.5651 [hep-ph]

Precision in δ

CPV discovery potential vs precision:



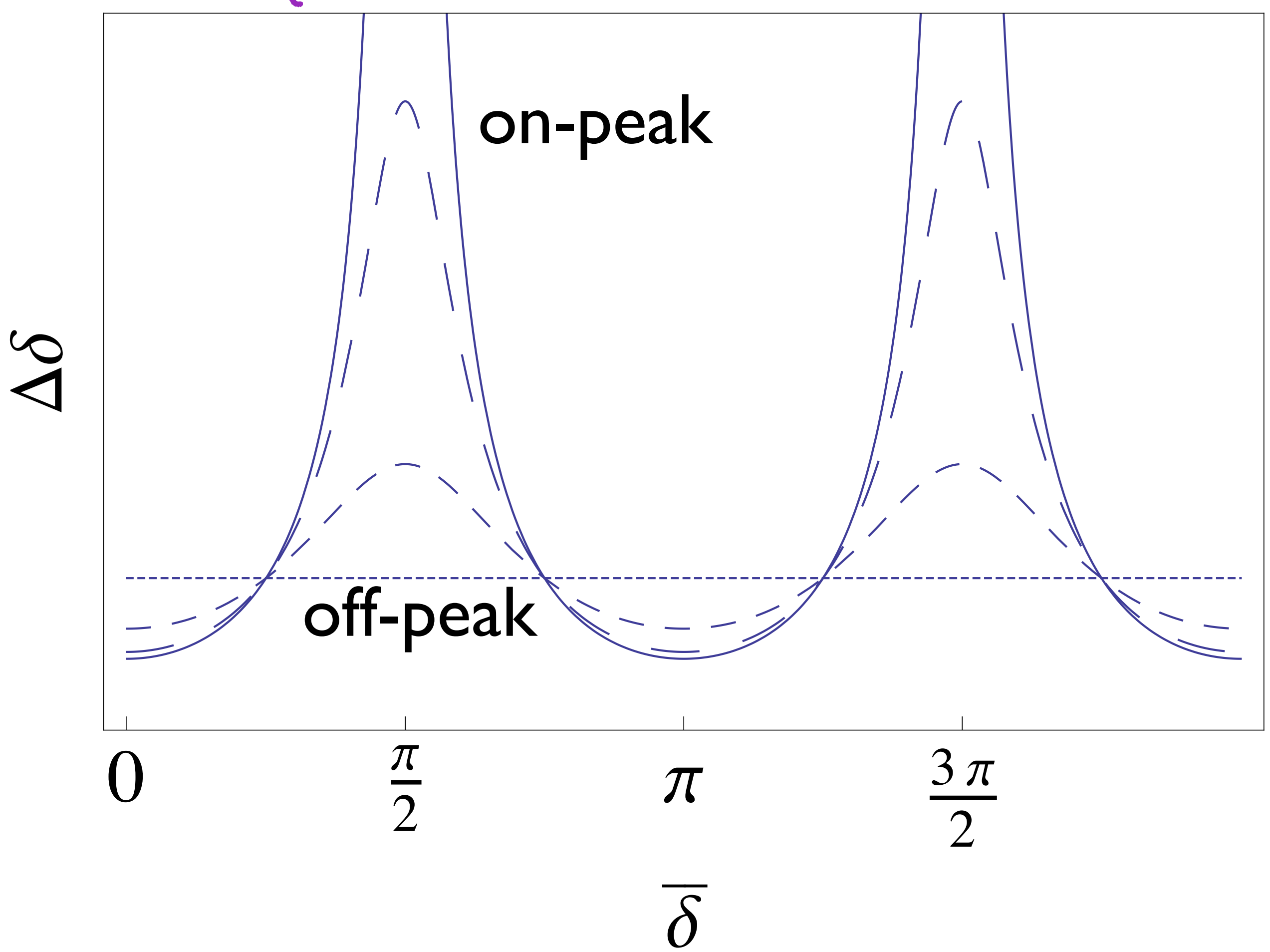


Precision in δ

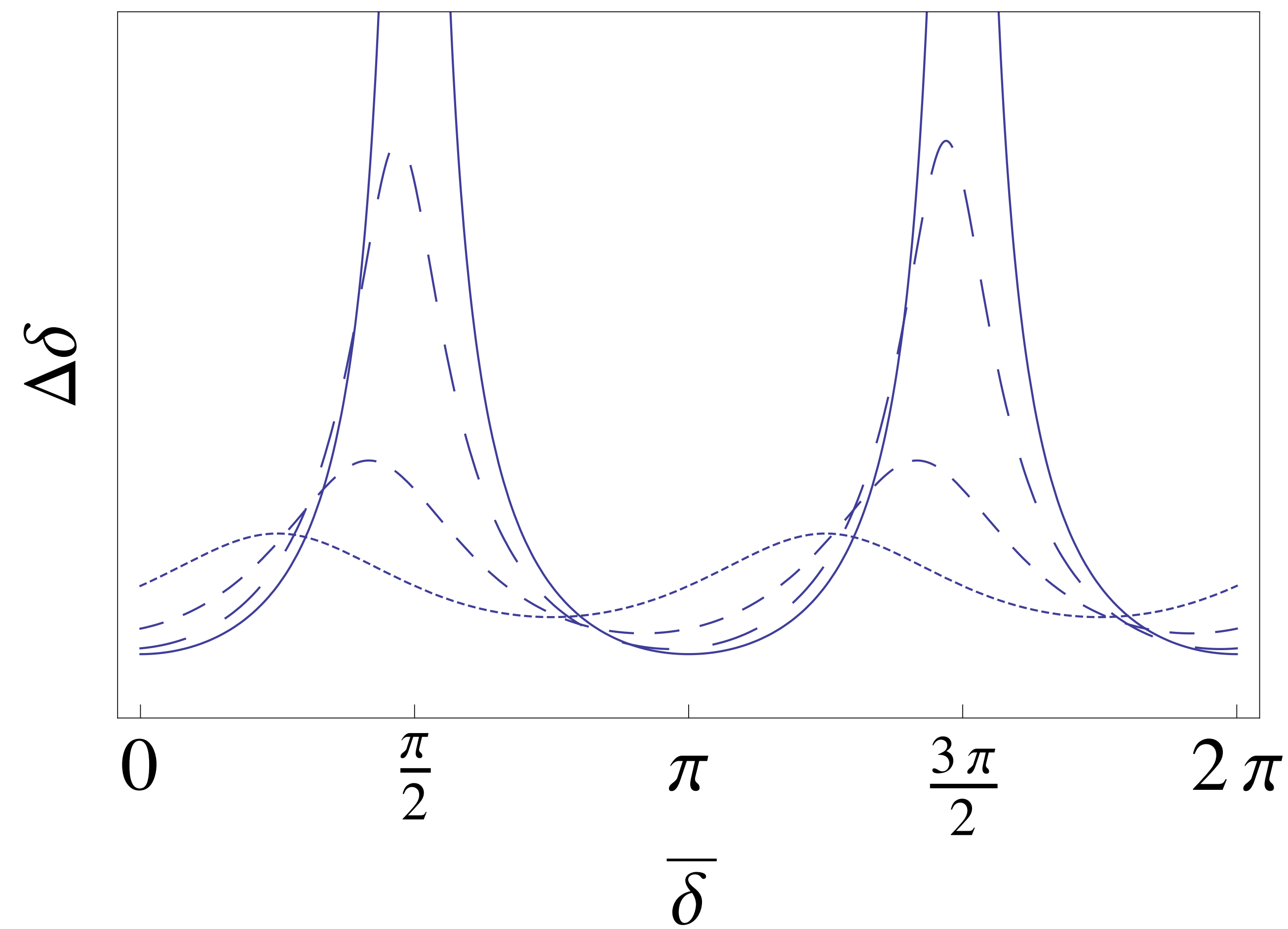
VACUUM

$$(\Delta\delta)_{\pm} \propto f\,[\Delta]\,\frac{1}{\sin(\Delta \mp \delta)}$$

equal nu and nubar events



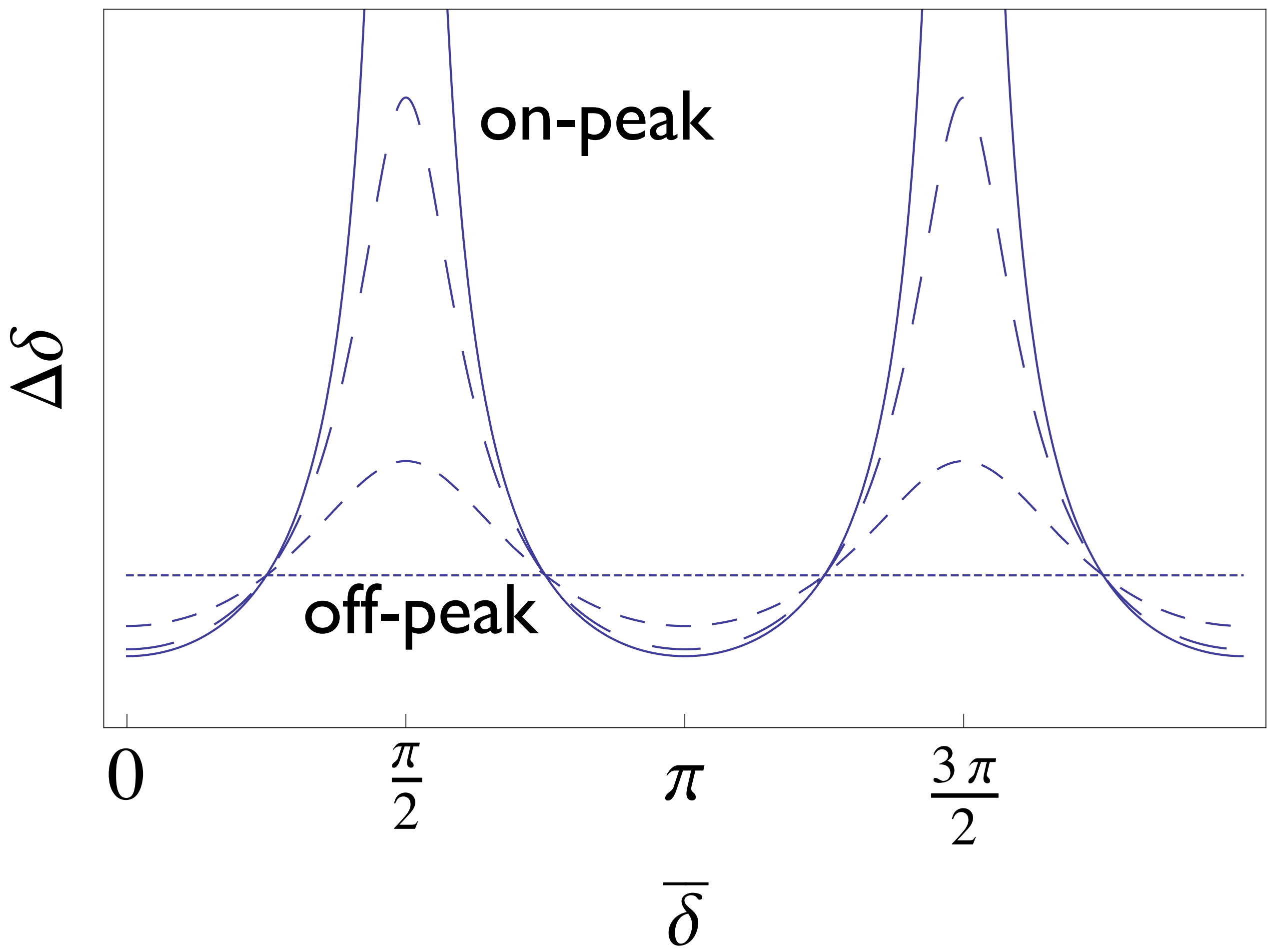
less nubar than nu events



Precision in δ

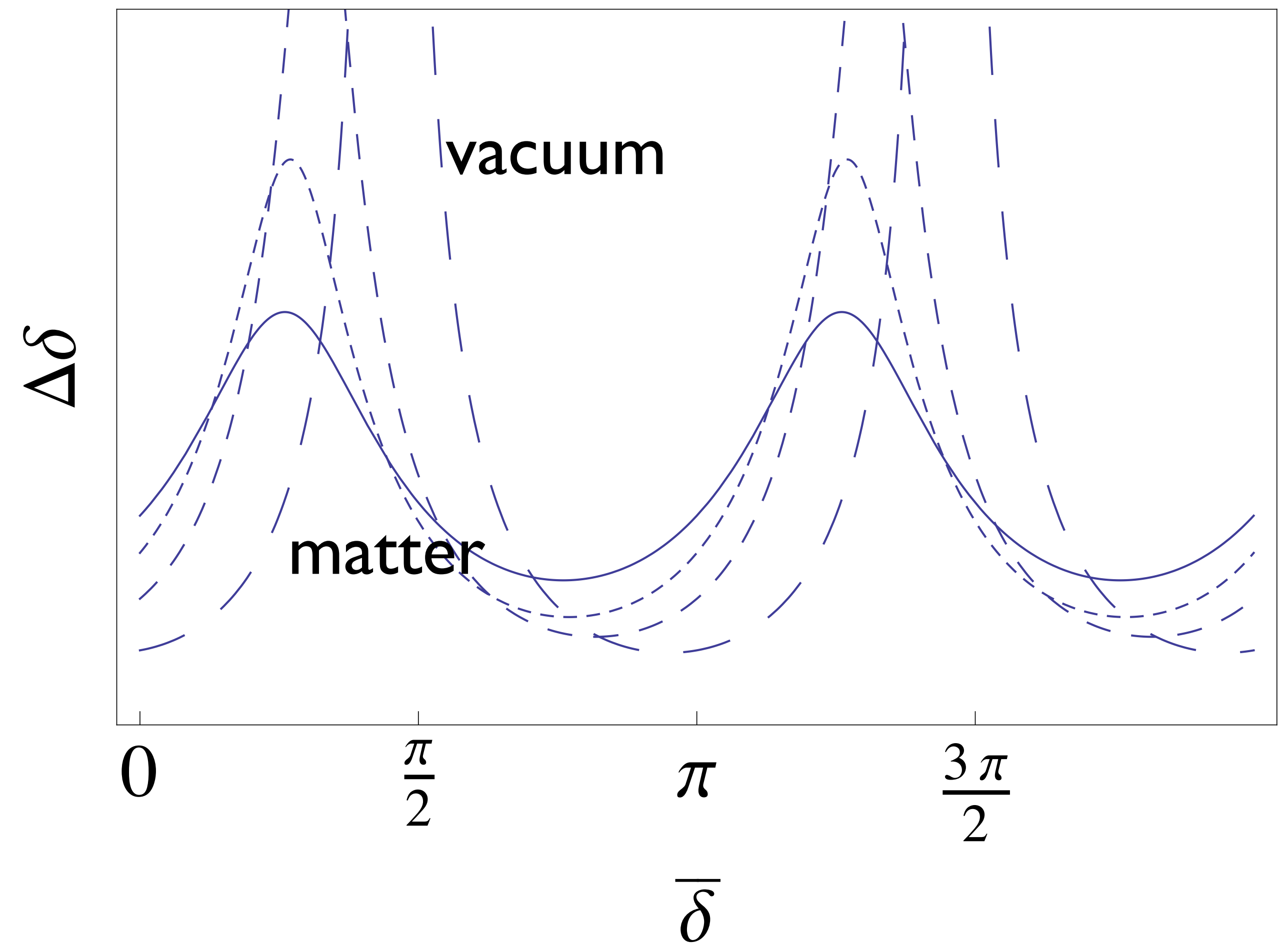
VACUUM

$$(\Delta\delta)_\pm \propto f\,[\Delta]\,\frac{1}{\sin(\Delta \mp \delta)}$$



MATTER

$$(\Delta\delta)_\pm \propto \tilde{f}[\hat{A},\Delta]\,\frac{1}{\sin\left(\Delta\frac{\hat{A}}{1\mp\hat{A}} \mp \delta\right)}$$

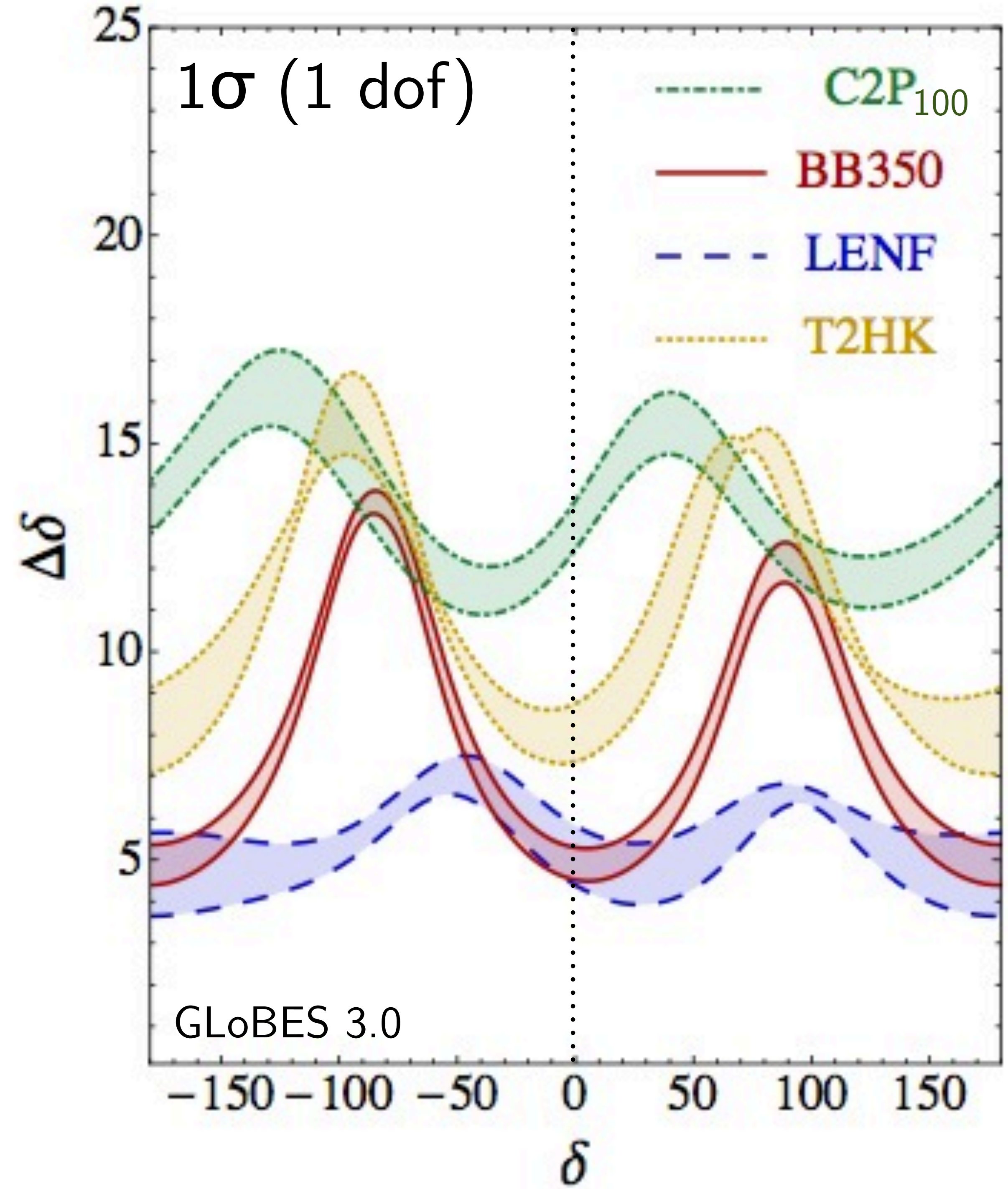


Precision in δ

1) Mild θ_{13} dependence

2) Strong δ dependence for BB350 due to no disappearance data

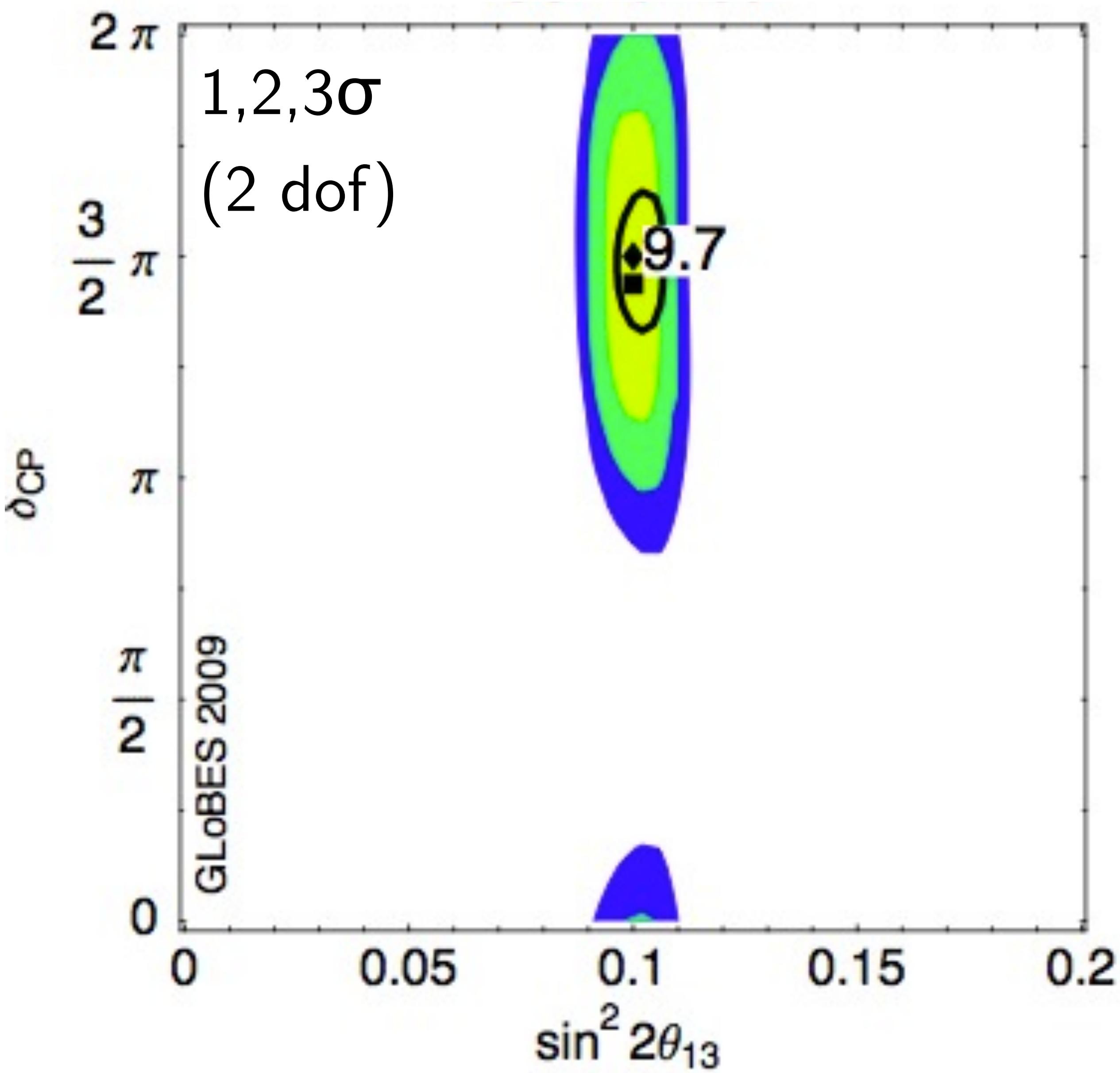
3) CPV discovery potential related to precision around 0,π: more favorable for setups in vacuum and with similar number of nu/nubar events

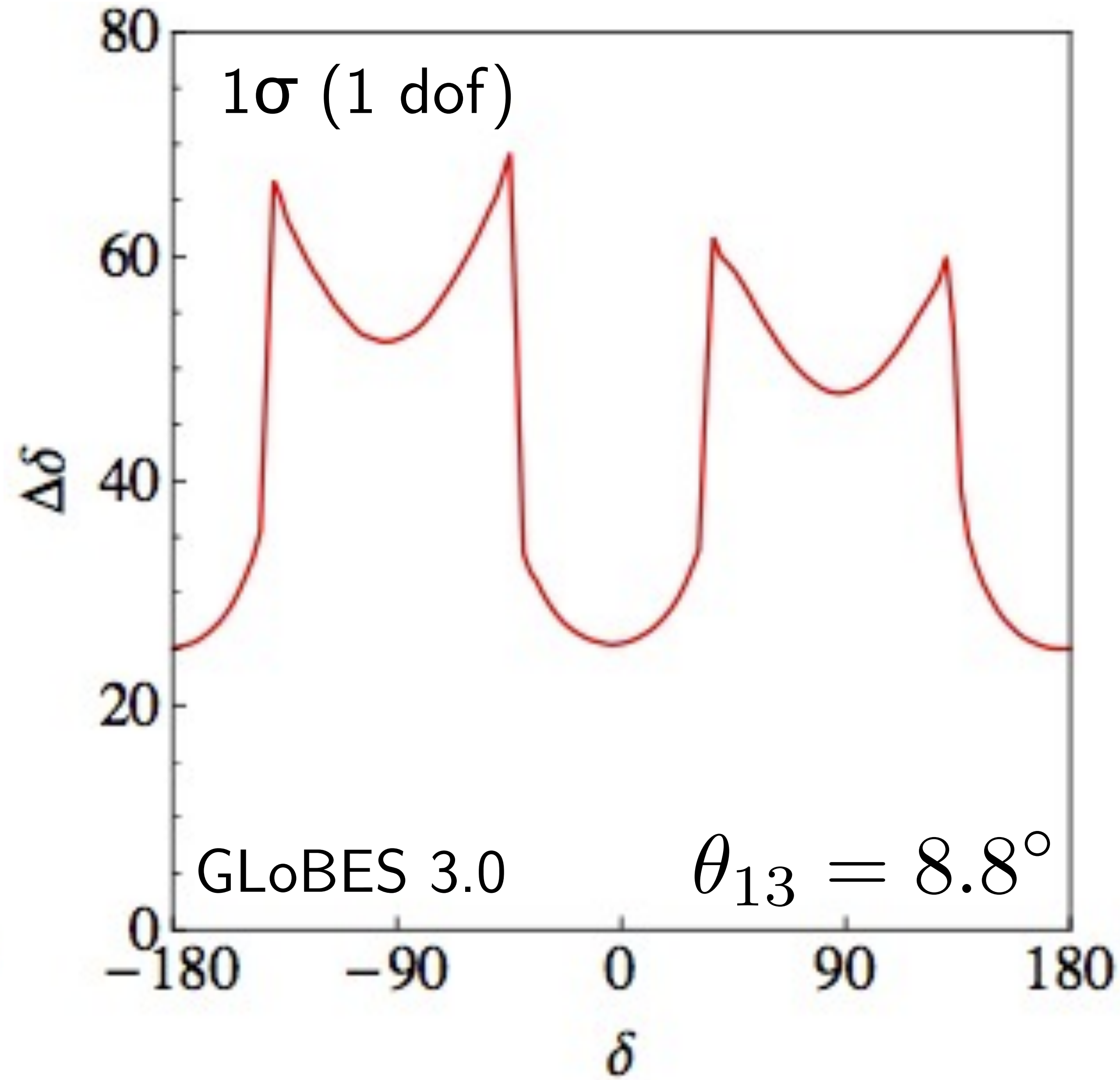


Coloma, Donini, Fernández-Martínez, Hernández, 1203.5651 [hep-ph]

The starting point

NOvA+T2K+Daya Bay

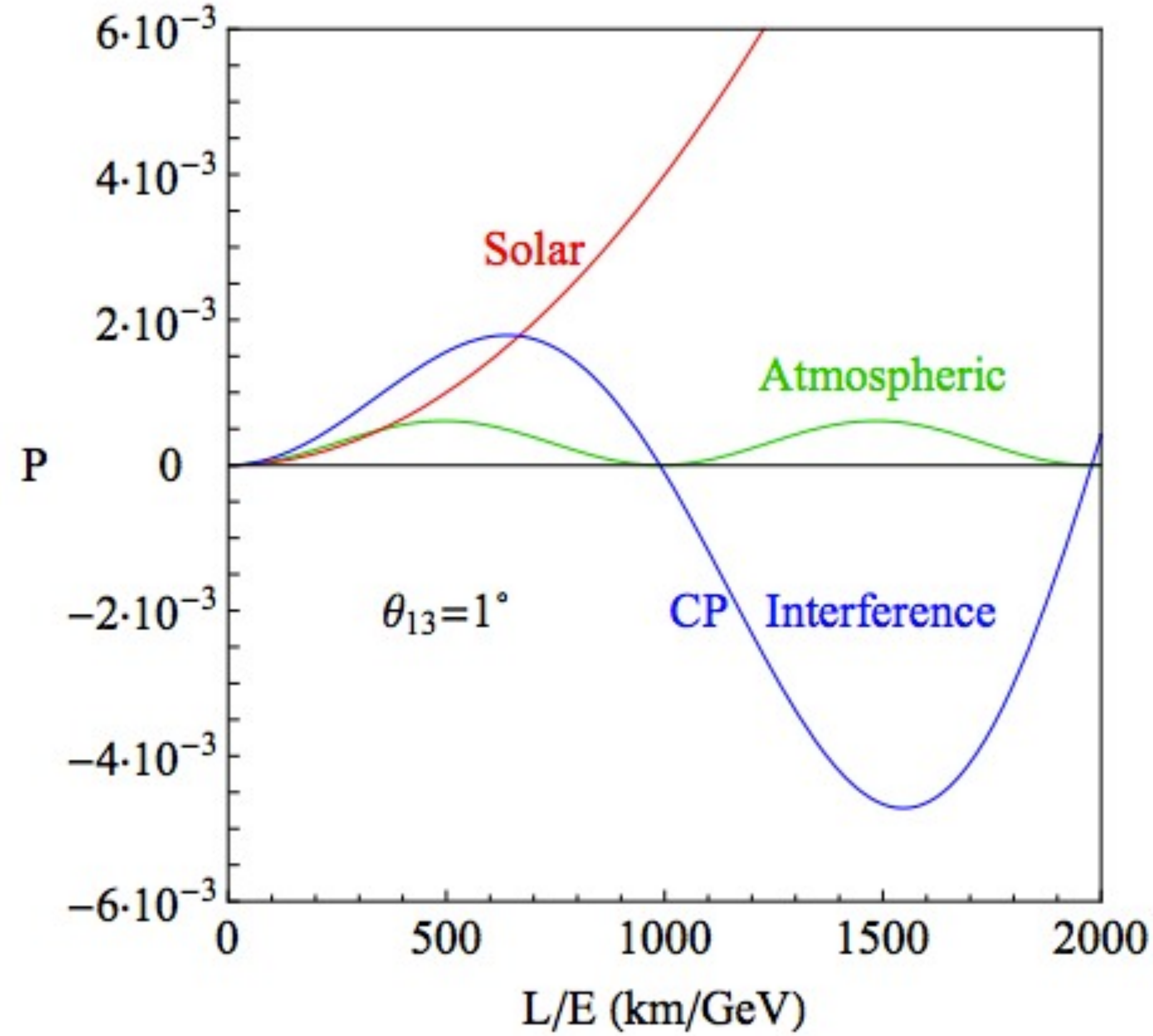




Huber, Lindner, Schwetz, Winter, 0907.1896 [hep-ph]

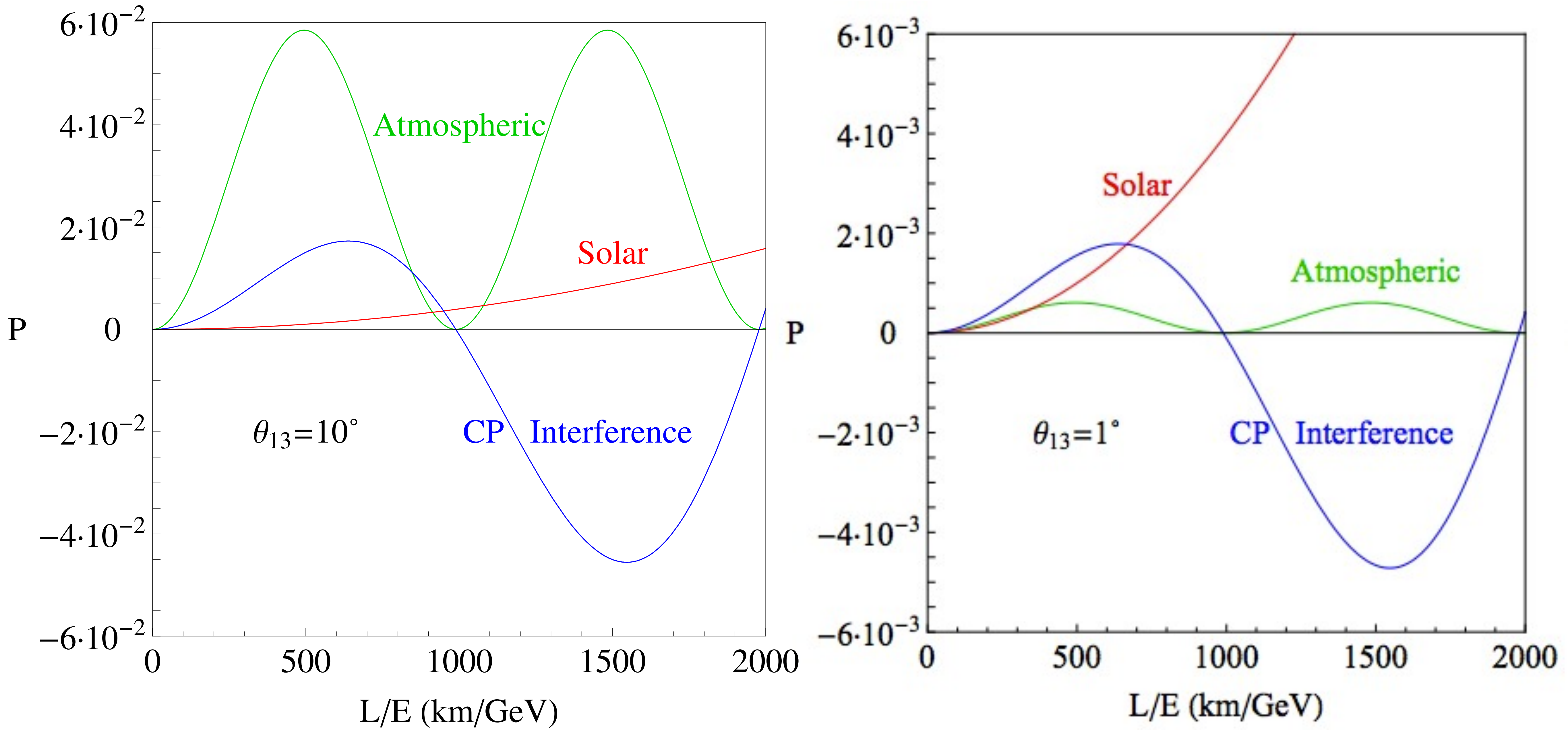
Coloma, Donini, Fernández-Martínez, Hernández, 1203.5651 [hep-ph]

Impact of systematics



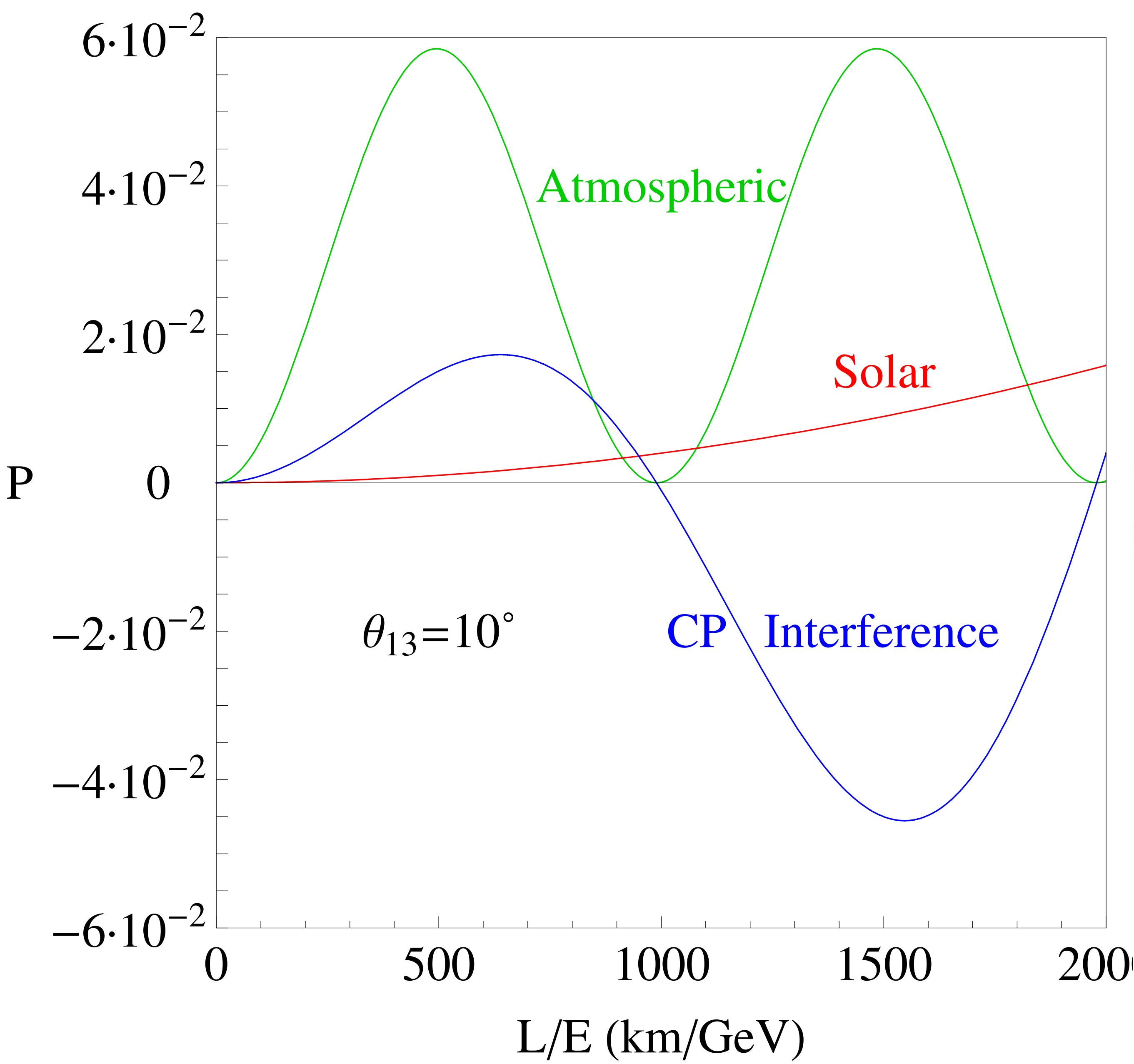
Coloma, Fernández-Martínez,
1110.4583 [hep-ph]

Impact of systematics

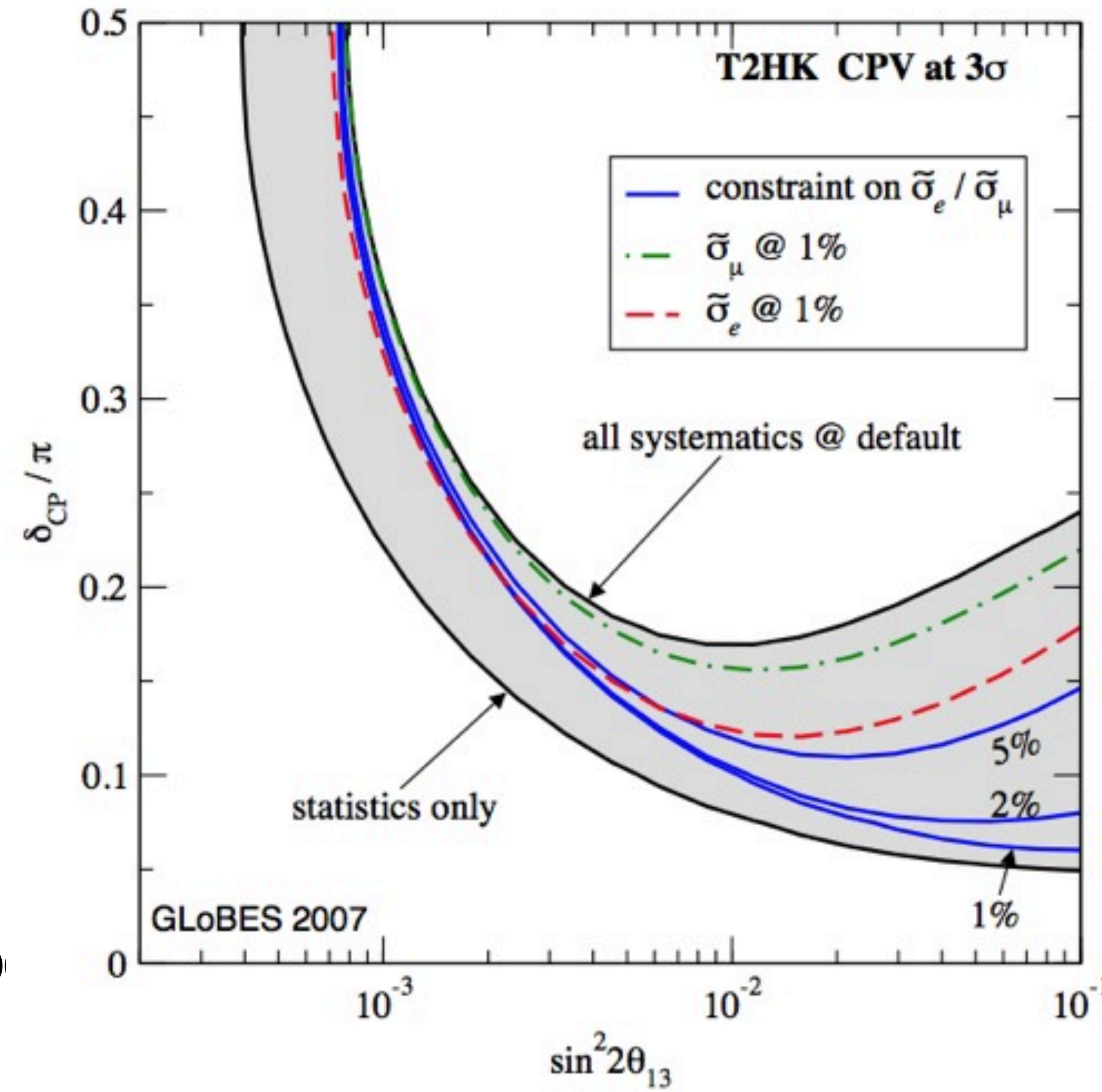


Coloma, Fernández-Martínez,
1110.4583 [hep-ph]

Impact of systematics



Coloma, Fernández-Martínez,
1110.4583 [hep-ph]



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

An example

Possible ways to reduce the effect of systematics:

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

Day, McFarland, 1206.6745 [hep-ph]
(see also Debbie's talk)

2) measure intrinsic background at near detector

3) use data from disappearance channels at the far detector

An example

$$\mu^- \to e^- \bar{\nu}_e \nu_\mu$$

FD: $\bar{\nu}_e \to \bar{\nu}_\mu$

An example

$$\mu^- \rightarrow e^- \bar{\nu}_e \nu_\mu$$

FD: $\bar{\nu}_e \rightarrow \bar{\nu}_\mu$	Mu-	V_{far}	Matter	Xsec

An example

$$\mu^- \to e^- \bar{\nu}_e \nu_\mu$$

		Mu-	ν_{far}	Matter	Xsec
FD:	$\bar{\nu}_e \to \bar{\nu}_\mu$				
ND:	$\nu_\mu \to \nu_\mu$				

An example

$$\mu^- \to e^- \bar{\nu}_e \nu_\mu$$

		Mu-	V_{far}	Matter	Xsec
FD:	$\bar{\nu}_e \to \bar{\nu}_\mu$	Mu-	V_{far}	Matter	Xsec
ND:	$\nu_\mu \to \nu_\mu$	Mu-	V_{near}	Vac	Xsec

An example

$$\mu^- \to e^- \bar{\nu}_e \nu_\mu$$

FD:	$\bar{\nu}_e \to \bar{\nu}_\mu$	Mu-	V_{far}	Matter	Xsec
ND:	$\nu_\mu \to \nu_\mu$	Mu-	V_{near}	Vac	Xsec
	$\bar{\nu}_\mu \to \bar{\nu}_\mu$	Mu+	V_{near}	Vac	Xsec

An example

$$\mu^- \to e^- \bar{\nu}_e \nu_\mu$$

FD:	$\bar{\nu}_e \to \bar{\nu}_\mu$	Mu-	V_{far}	Matter	Xsec
ND:	$\nu_\mu \to \nu_\mu$	Mu-	V_{near}	Vac	Xsec
	$\bar{\nu}_\mu \to \bar{\nu}_\mu$	Mu+	V_{near}	Vac	Xsec
FD:	$\nu_\mu \to \nu_\mu$				
	$\bar{\nu}_\mu \to \bar{\nu}_\mu$				

An example

$$\mu^- \to e^- \bar{\nu}_e \nu_\mu$$

FD:	$\bar{\nu}_e \to \bar{\nu}_\mu$	Mu-	V_{far}	Matter	Xsec
ND:	$\nu_\mu \to \nu_\mu$	Mu-	V_{near}	Vac	Xsec
	$\bar{\nu}_\mu \to \bar{\nu}_\mu$	Mu+	V_{near}	Vac	Xsec
FD:	$\nu_\mu \to \nu_\mu$	Mu-	V_{far}	Matter	Xsec
	$\bar{\nu}_\mu \to \bar{\nu}_\mu$	Mu+	V_{far}	Matter	Xsec

Simulation details

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%

(details in 1209.5973 [hep-ph])

Simulation details

Systematics	SB Opt.	SB Def.	SB Cons.	BB Opt.	BB Def.	BB Cons.	NF Opt.	NF Def.	NF Cons.
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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%

(details in 1209.5973 [hep-ph])

Simulation details

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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%

theoretical constraint

(details in 1209.5973 [hep-ph])

Simulation details

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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%
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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%
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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%

theoretical constraint

(details in 1209.5973 [hep-ph])

Simulation details

$$\chi^2 = \sum_{r,i} 2\left(T_{r,i}(\vec{\Theta},\vec{\xi}) - O_{r,i} + O_{r,i}\ln\frac{O_{r,i}}{T_{r,i}(\vec{\Theta},\vec{\xi})}\right) + \sum_k \left(\frac{\xi_k}{\sigma_k}\right)^2$$

- GLoBES software used hep-ph/0407333, hep-ph/0701187
- A near detector has been explicitly simulated for all experiments
- Correlations are fully taken into account between different channels (unless otherwise stated)
- Systematic uncertainties introduced as nuisance parameters
- Marginalization performed over all parameters
- No degeneracies considered. Normal hierarchy assumed.
- $\sin^2 2\theta_{13} = 0.1$

More simulation details

- No energy dependent effects included (nuclear effects, for instance)

  see Zeller's and Morfin's talks

  All errors included as norm errors.

  - However, different independent errors considered for the different cross section regimes: "effective" shape error
- Near detector is assumed to be sufficiently far away so that the spectrum is identical to the far detector (1-2 km)
- Near and far detector are assumed to be identical (except for the treatment of NC backgrounds)
- No tau backgrounds are included (very little impact for CPV, though)

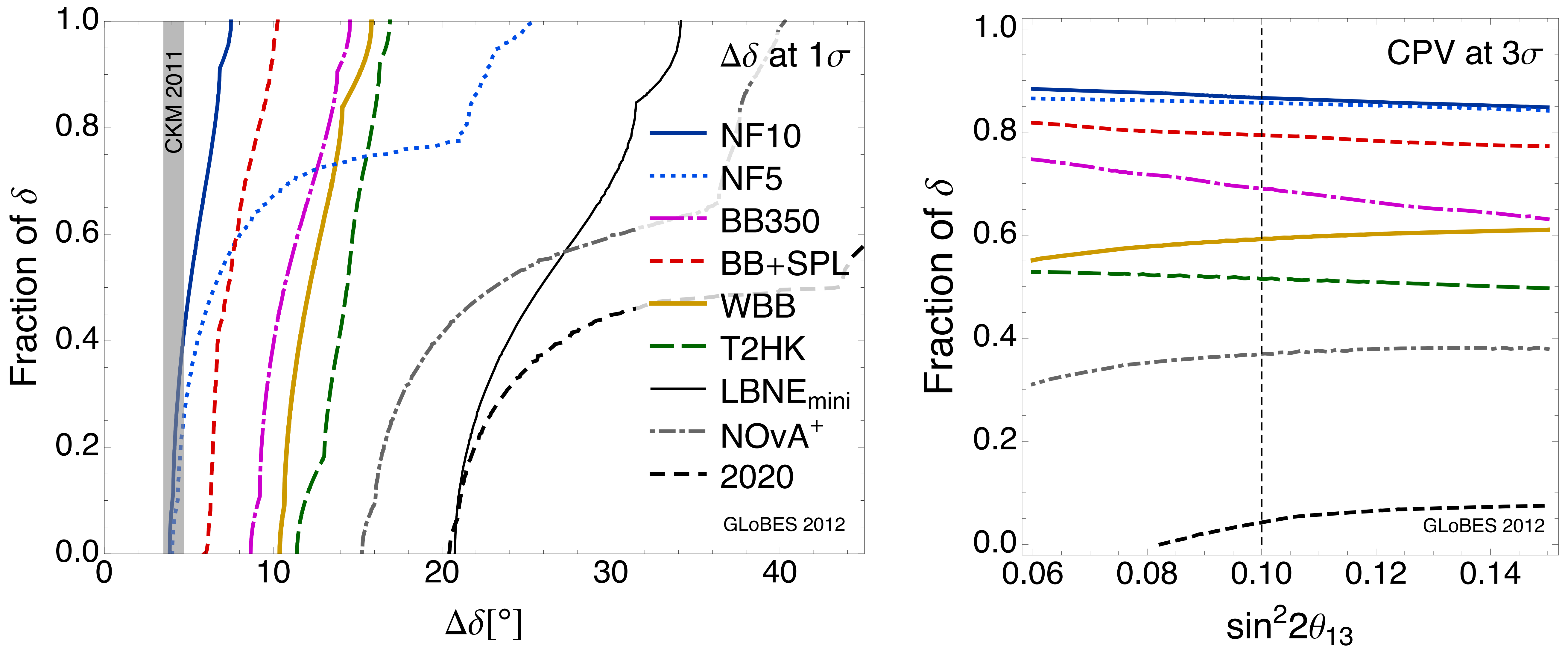
Donini, Gomez Cadenas, Meloni, 1005.2275 [hep-ph]

The 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)
	$\text{NO}\nu\text{A}^+$	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)
	$\text{NO}\nu\text{A}$	2.0	810	0.8°	TASD	15	0.7	–	(4,4)

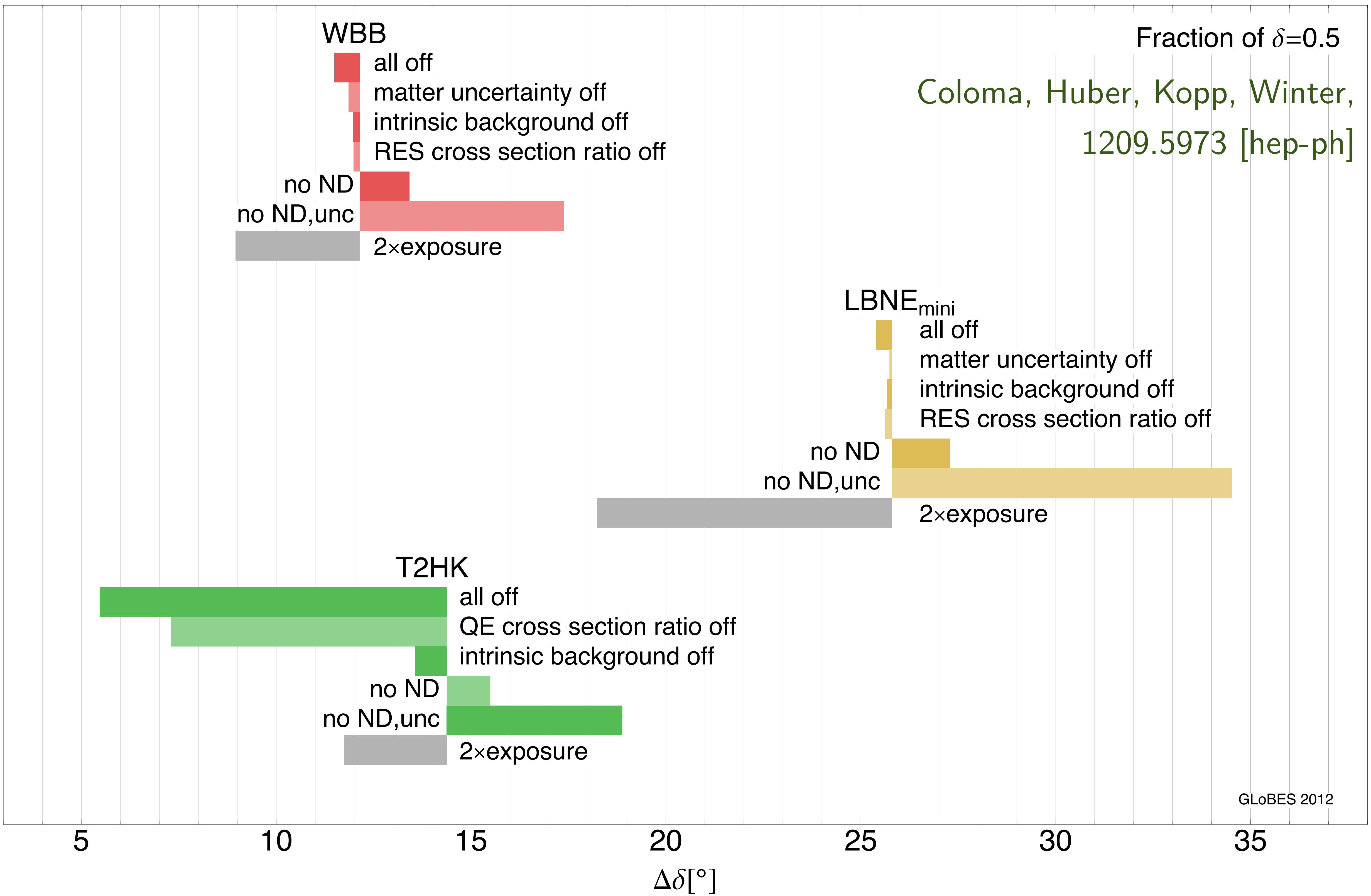
General comparison

How far do we want to get?

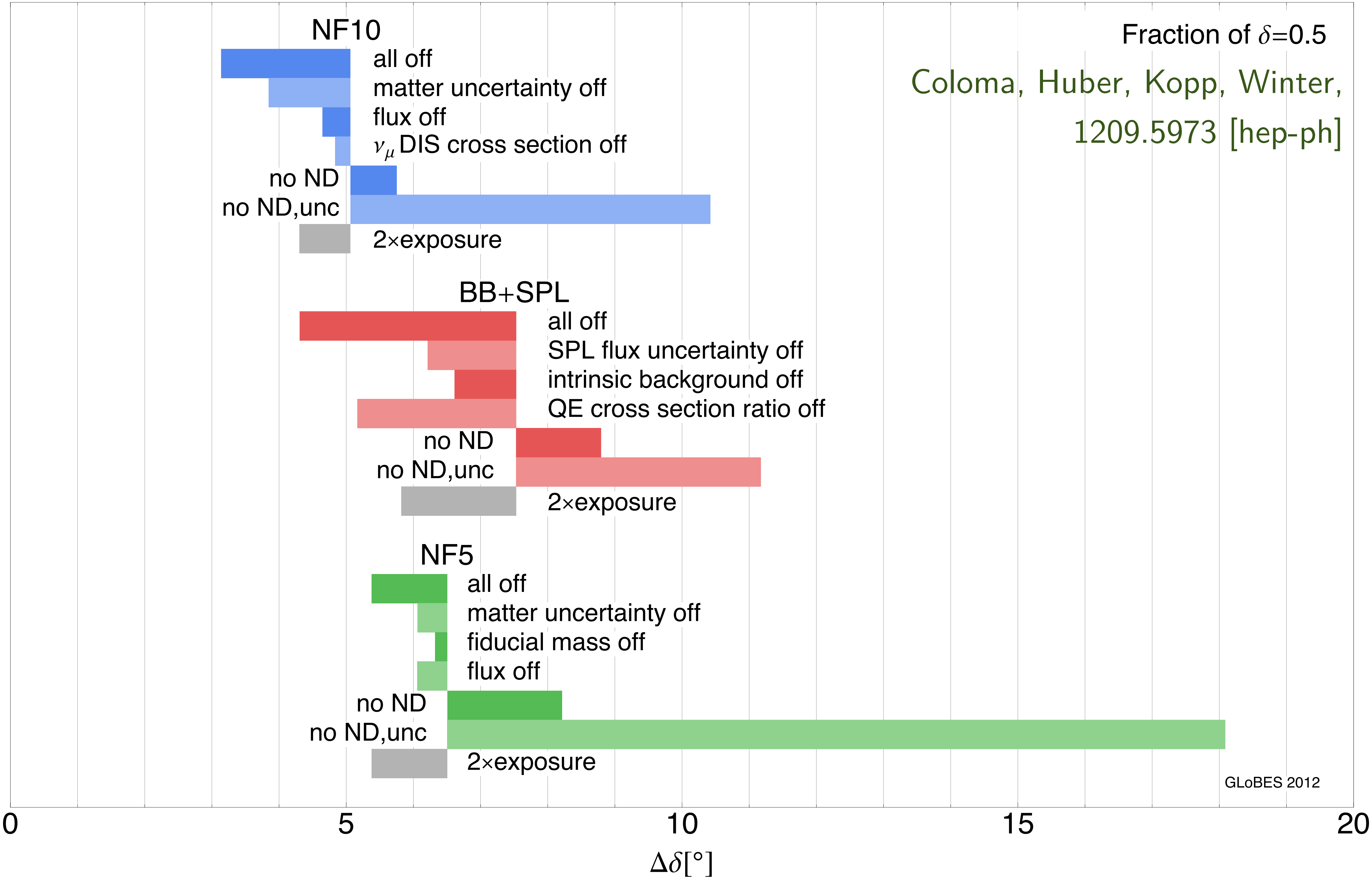


Coloma, Huber, Kopp, Winter, 1209.5973 [hep-ph]

Sys and near detectors

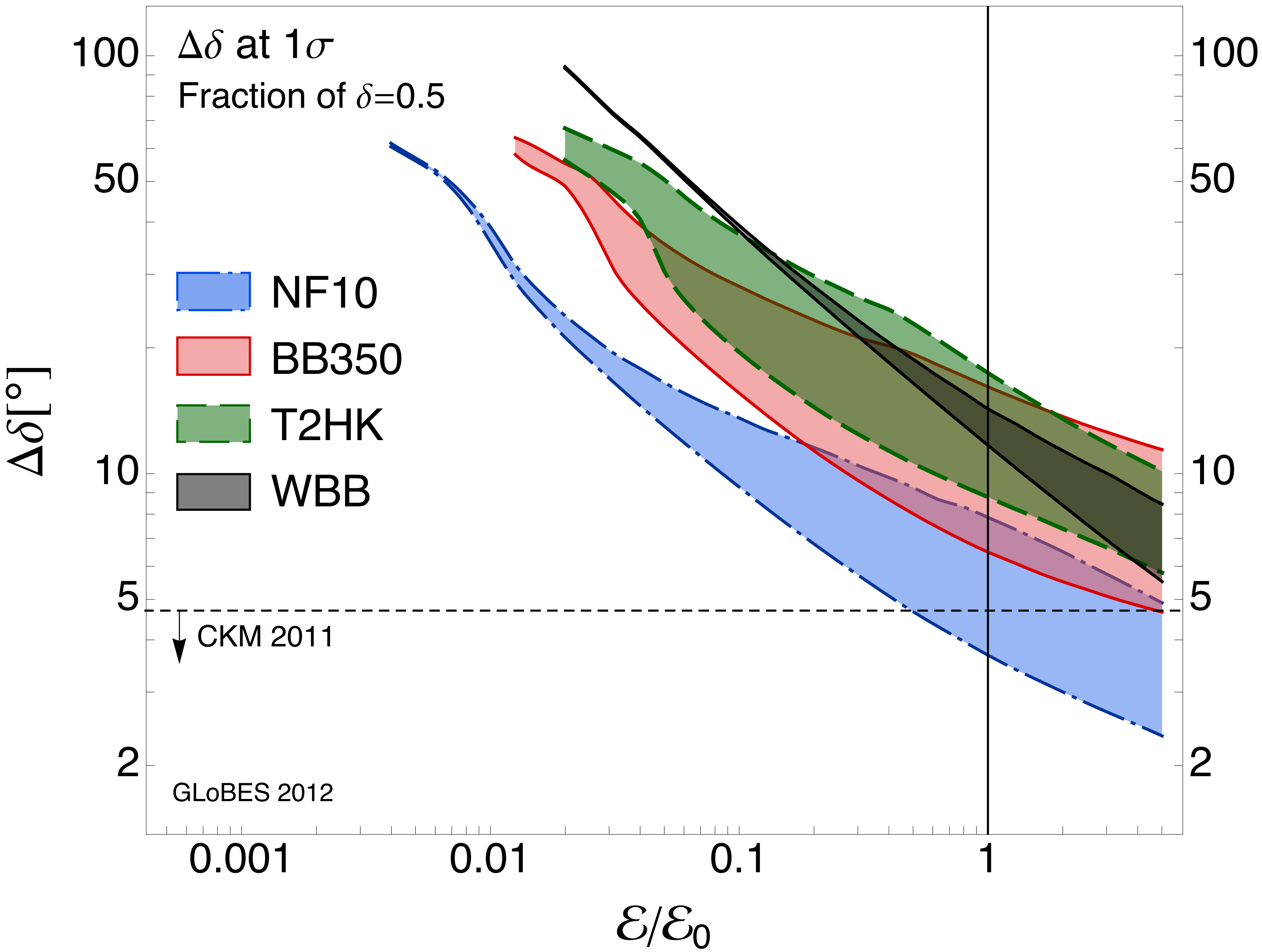


Sys and near detectors



Exposure vs systematics

Variation between optimistic and conservative assumptions:



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

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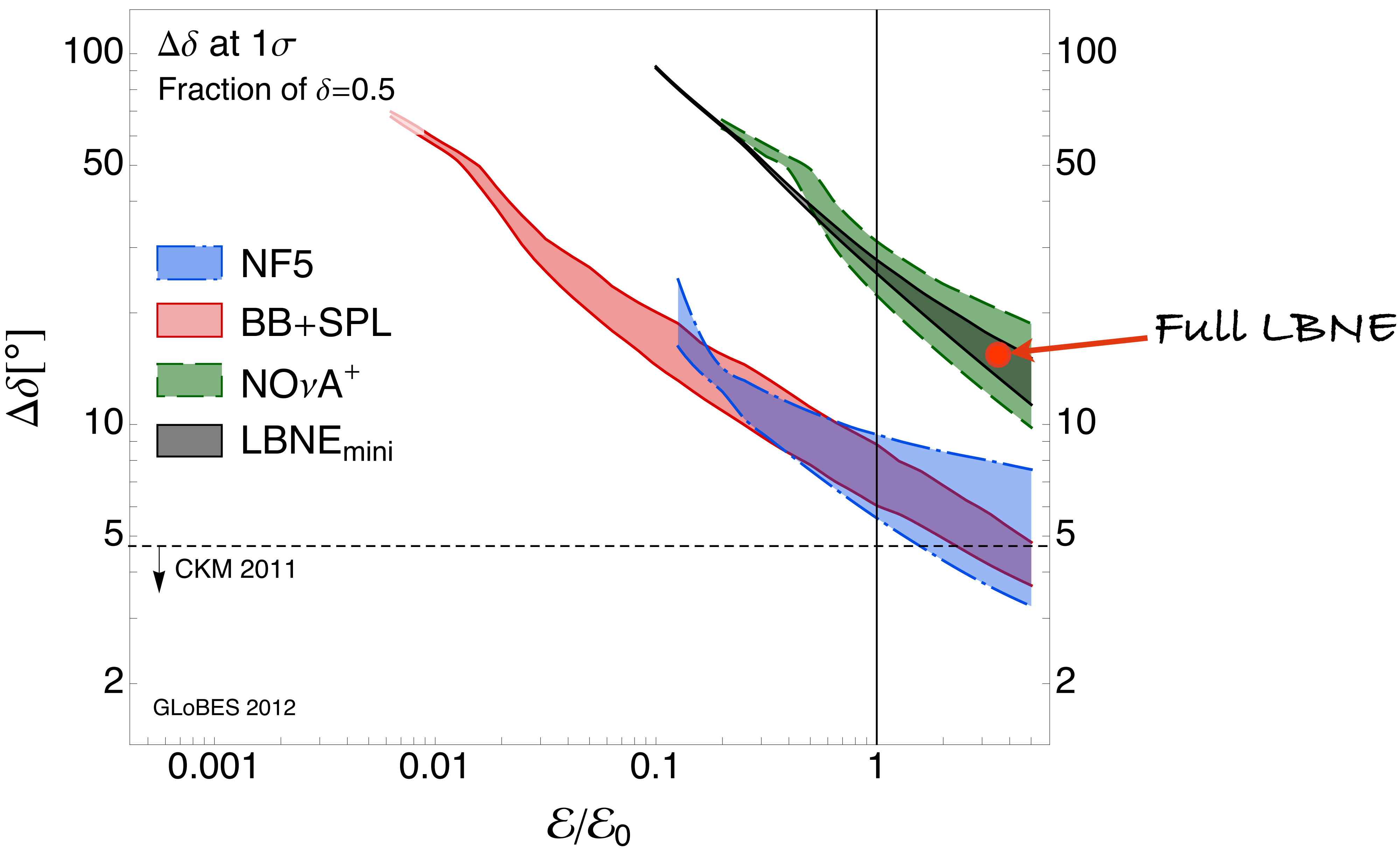


Coloma, Huber, Kopp, Winter, 1209.5973 [hep-ph]

Conclusions

- The precision on θ_{13} obtained at Daya Bay will most likely not be exceeded by any beam experiment. For δ the situation is more complicated, though:
    - ideally, an experiment in vacuum would have the best reach for CPV; however, this is not optimal for precision...
    - maybe a combination of the two?
- Low energy setups are generally more affected by systematics
    - theoretical assumptions on cross section ratios are critical (Exception! BB+SPL)

Conclusions

- The impact of a ND does not seem so relevant if data from disappearance at the FD is used (under certain assumptions!)
  - migration due to nuclear effects is not included
  - if NP is present, a ND is crucial
  - we assume only norm errors (an "effective" shape error is done for the xsecs only)
  - effectiveness of this method depends on the statistics
- In some cases, it may a be better path to increase statistics than reduce systematics...
- LENF is the only facility able to achieve similar precision to quark sector

Backup

Impact of systematics

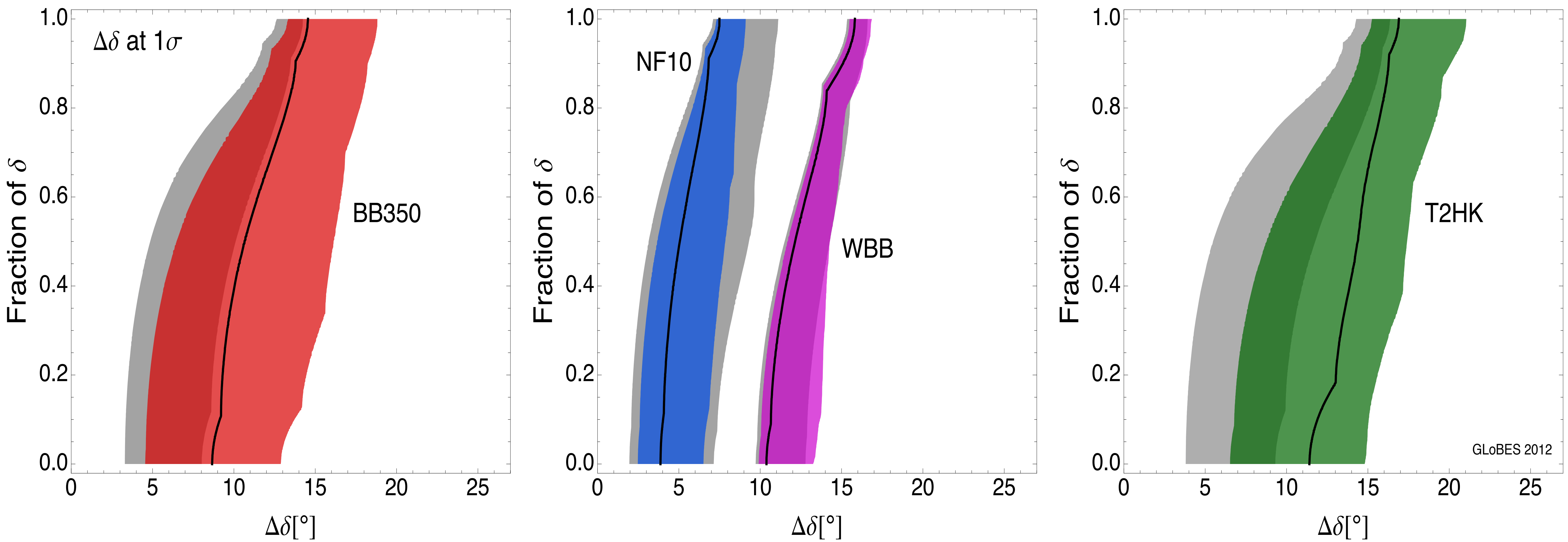
Systematics become a problem for large q13 since the leading term in the probability grows quadratically

$$P_{e\mu}^{\pm} = X_{\pm} \sin^2 2\theta_{13} + Z$$

$$+ Y_{\pm} \cos\theta_{13} \sin 2\theta_{13} \cos\left(\pm\delta - \frac{\Delta_{31} L}{2}\right)$$

Impact of systematics

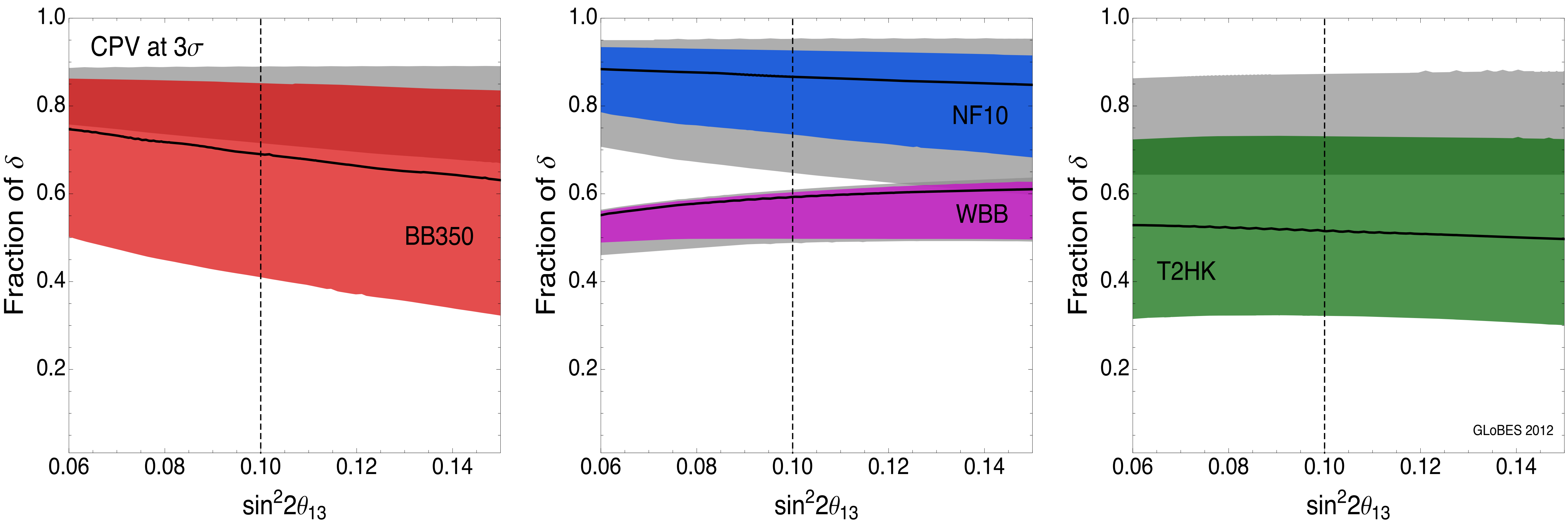
Variation between optimistic and conservative assumptions:



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

Impact of systematics

Variation between optimistic and conservative assumptions:



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

Mass hierarchy

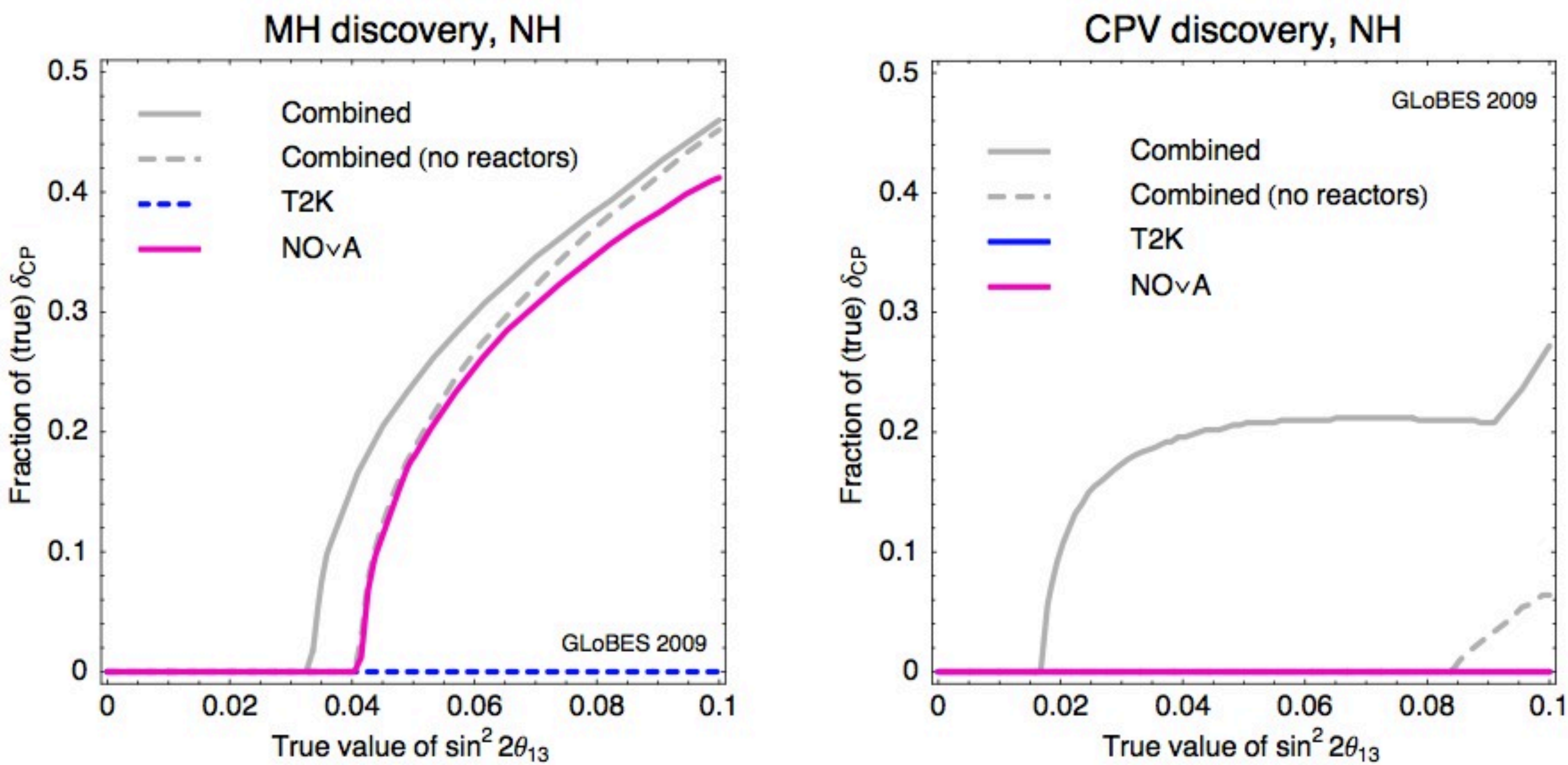
Mass hierarchy may be obtained through:

- T2K+NOvA+INO 1203.3388 [hep-ph]
- Atmospheric data at future exps 1109.3262 [hep-ex]
- PINGU 1205.7071 [hep-ph]
- Daya Bay II hep-ph/0112074
- combination of precise reactor+LBL data hep-ph/0503283
- ...

...or a combination of all of them!

Present oscillation facilities

Discovery potential at the 90% CL

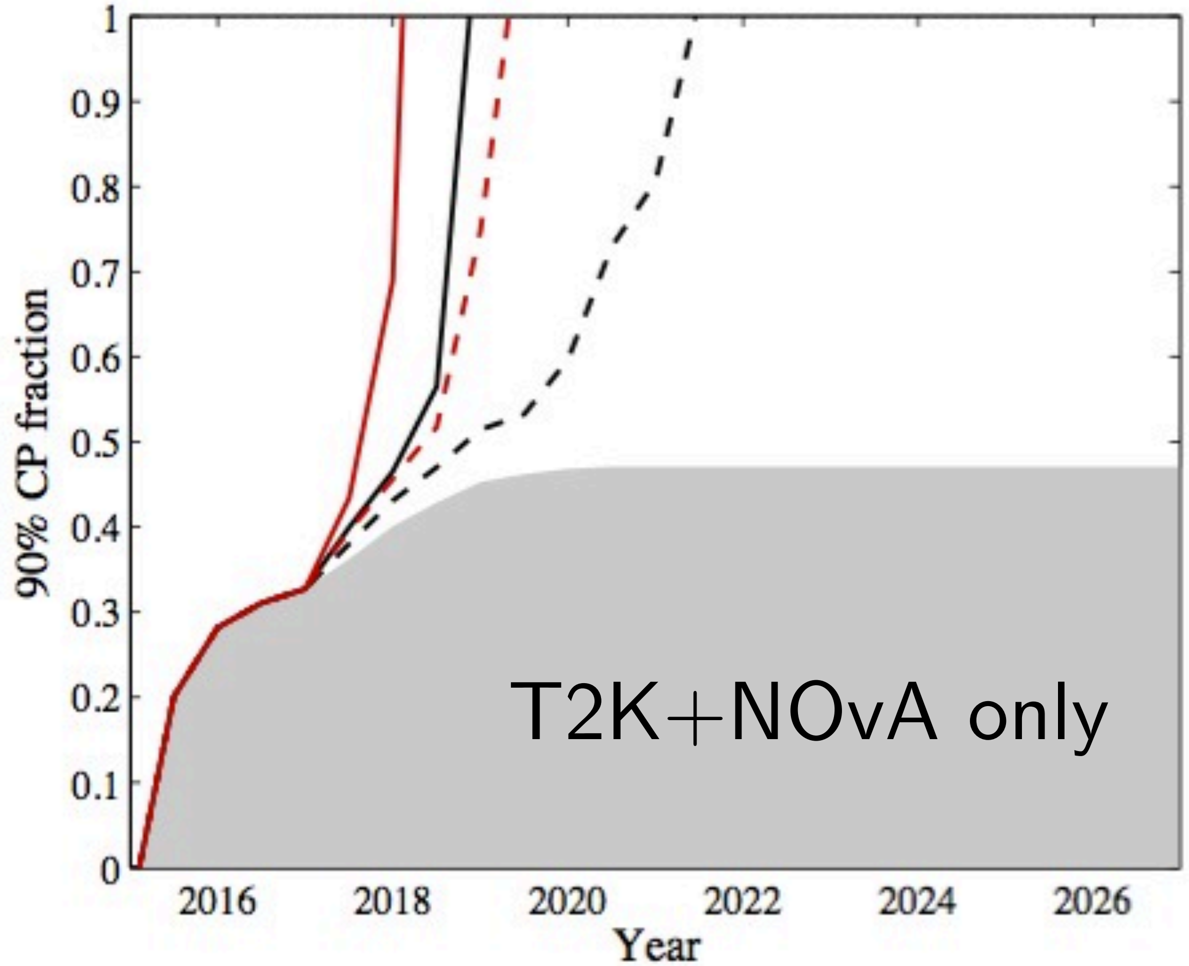


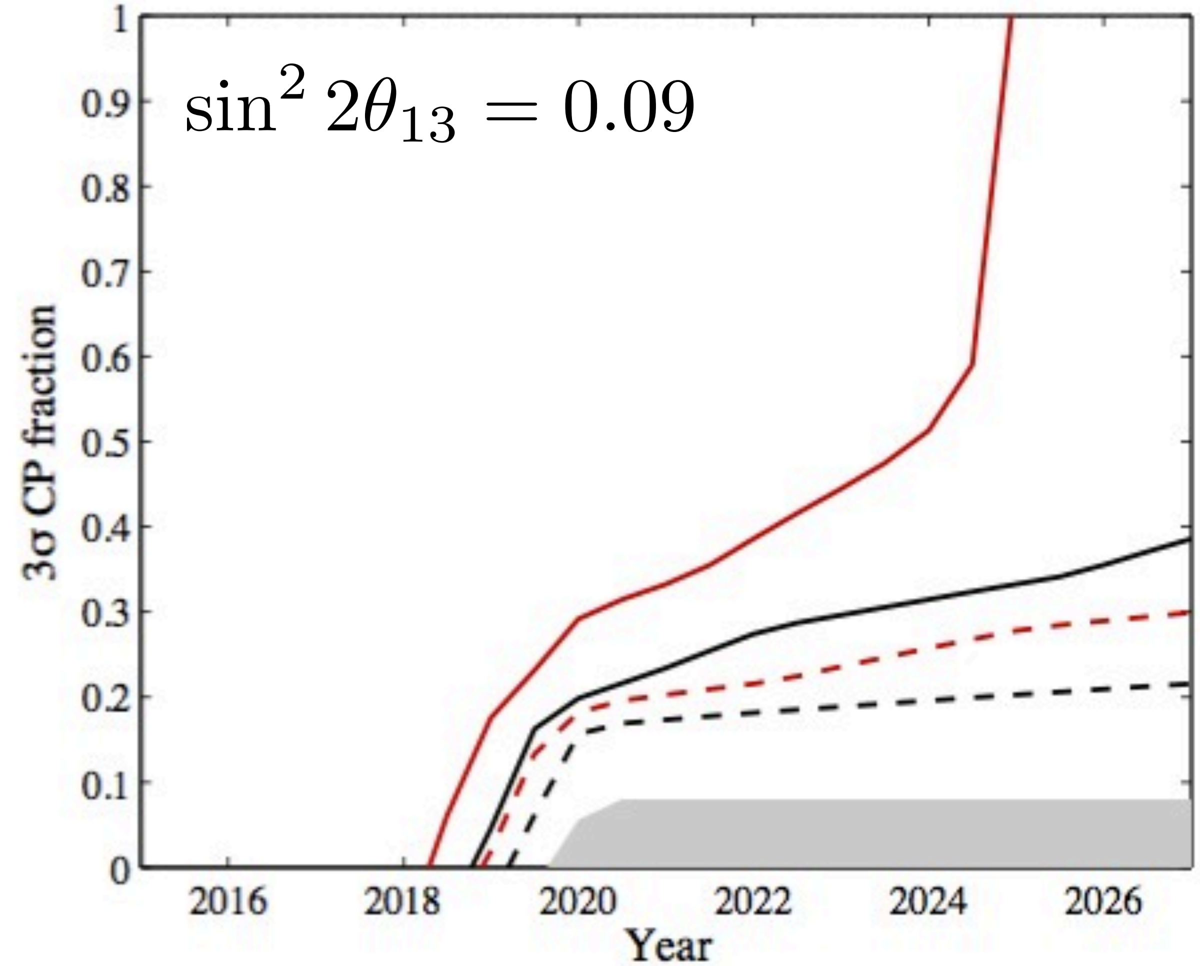
Huber, Lindner, Schwetz, Winter, 0907.1896 [hep-ph]

Present oscillation facilities

T2K+NOvA+INO

(50kt/100kt; low/high res)

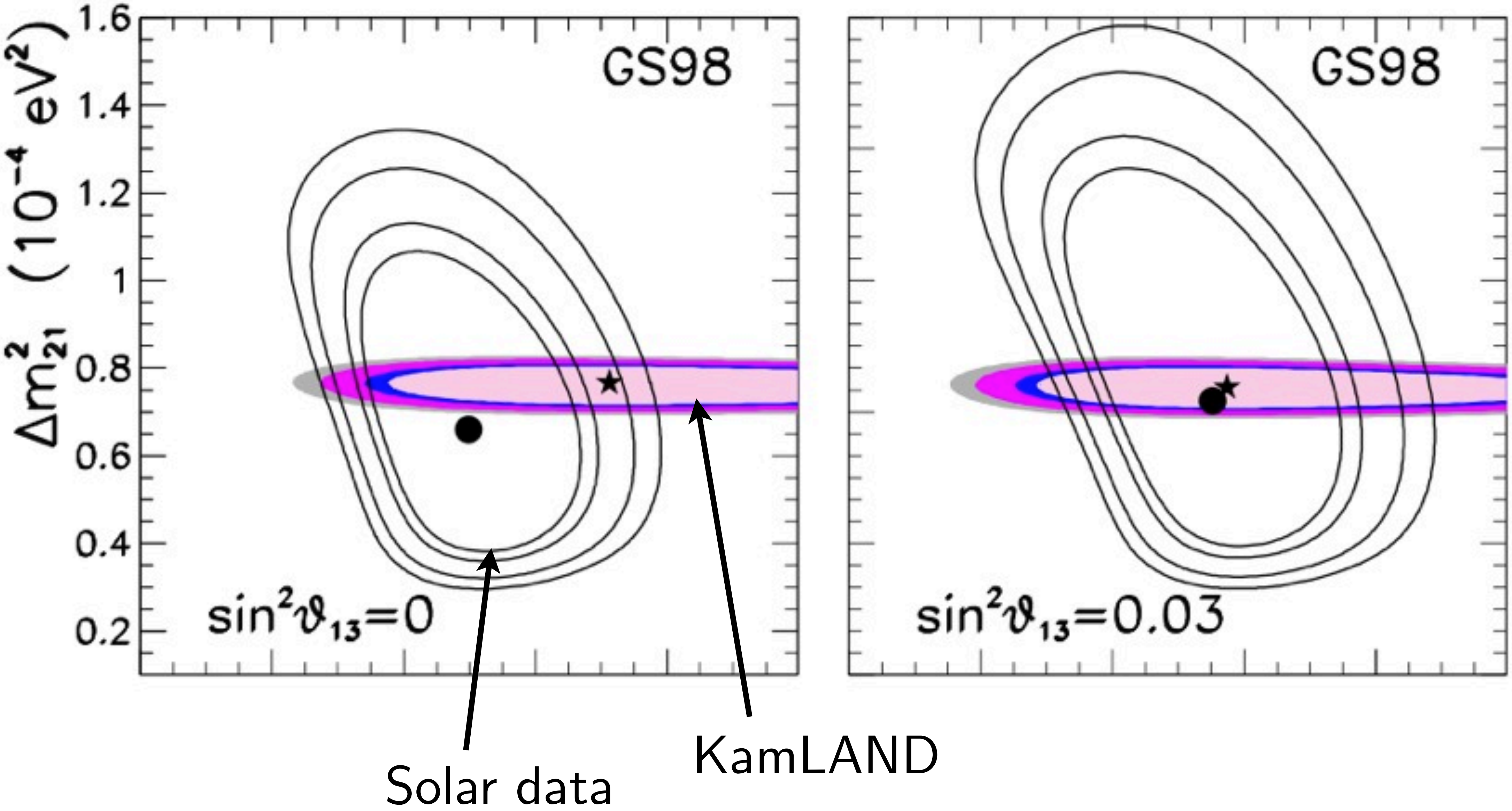




Blennow, Schwetz, 1203.3388 [hep-ph]

Previous hints on θ_{13}

Previous hints from global fits pointed to nonzero θ_{13}...



González-García, Maltoni,Salvado, 1001.4524 [hep-ph]