Neutrino scattering uncertainties and CP violation measurements

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Based on a collaboration with Huber, Kopp, Winter,
Phys. Rev. D 87, 033004 (2013)

Intensity Frontier Neutrino Subgroup Workshop
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Neutrino mixing

Knowns

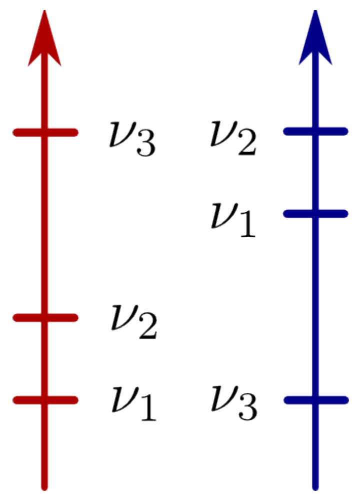
$$
\begin{aligned}
\theta_{12} &= 33.36^\circ \\
\theta_{23} &= 40^\circ/50.4^\circ \\
\theta_{13} &= 8.66^\circ \\
\Delta m^2_{21} &= 7.5\times 10^{-5} \\
\Delta m^2_{31} &= 2.473\times 10^{-3}(NH)
\end{aligned}
$$

Unknowns

δ

$\downarrow$

CP violation?



Gonzalez-Garcia, Maltoni, Salvado and Schwetz, 1209.3023 [hep-ph]
(see also 1205.5254 [hep-ph] and 1205.4018 [hep-ph])

Future oscillation experiments

- Muon-based neutrino beams (NuFact,NuSTORM)
  - Low uncertainties, no intrinsic bg, flavor rich
- Pion-based neutrino beams (T2K,NOvA,LBNE,...)
  - Intrinsic bg, large flux and cross section uncertainties
  - Technology already well-known
  - No magnetization is required
- Beta-decay neutrino beams (beta-beams)
  - Technologically very demanding
  - Muon disappearance unavailable

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)

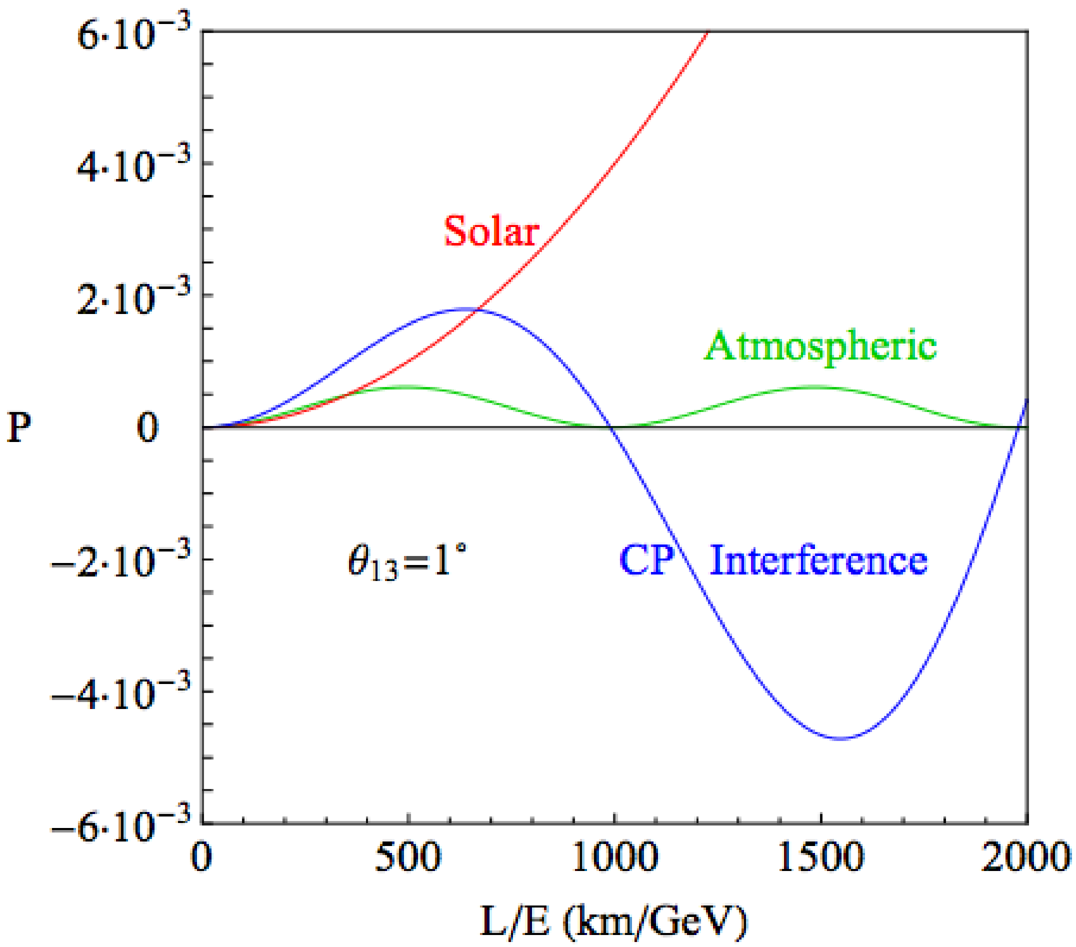
The golden channel

The best chance to measure CPV is through:

$$P^{\pm}_{e\mu}(\theta_{13}, \delta) = X_{\pm} \sin^2 2\theta_{13}$$
$$+ Y_{\pm} \cos\theta_{13} \sin 2\theta_{13} \cos\left(\pm\delta - \frac{\Delta_{31} L}{2}\right)$$
$$+ Z$$

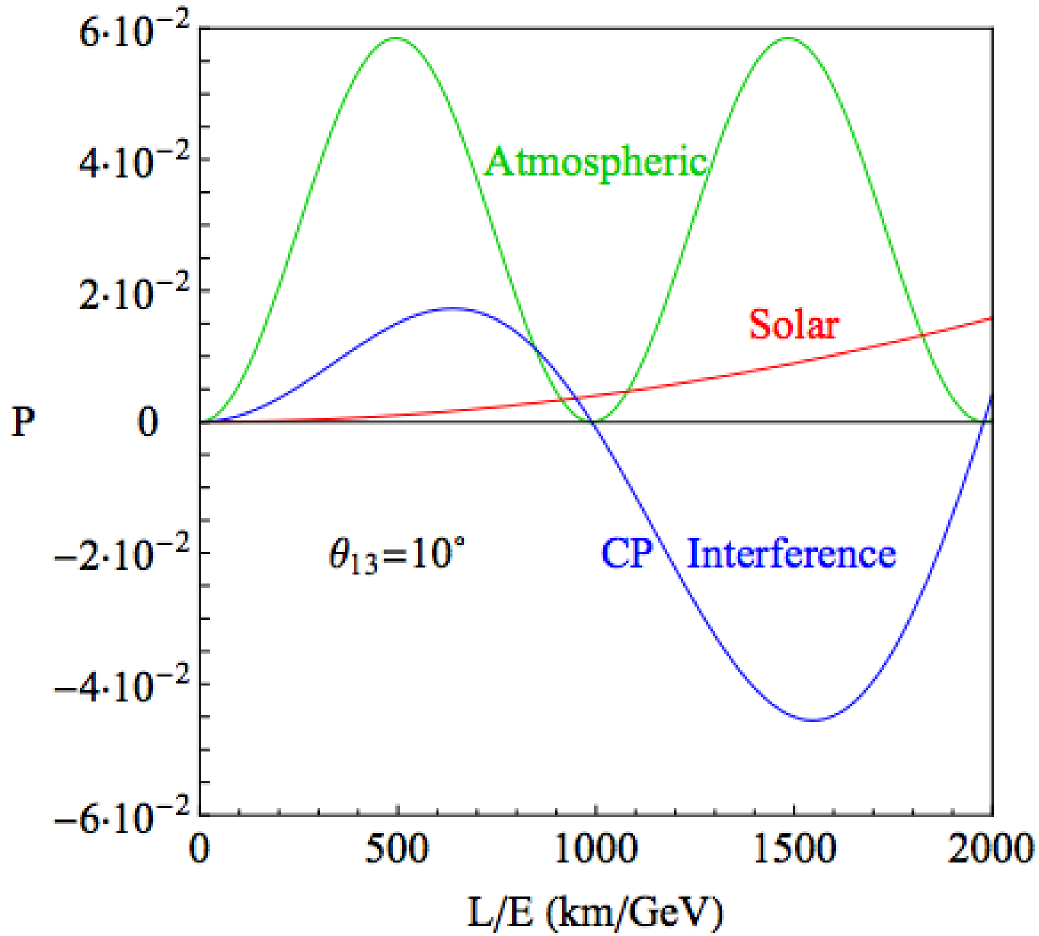
$$X_{vac} \propto \sin^2\left(\frac{\Delta m^2_{31} L}{4E}\right)$$
$$Y_{vac} \propto \sin\left(\frac{\Delta m^2_{31} L}{4E}\right) \sin\left(\frac{\Delta m^2_{21} L}{4E}\right)$$

Impact of systematics on CPV

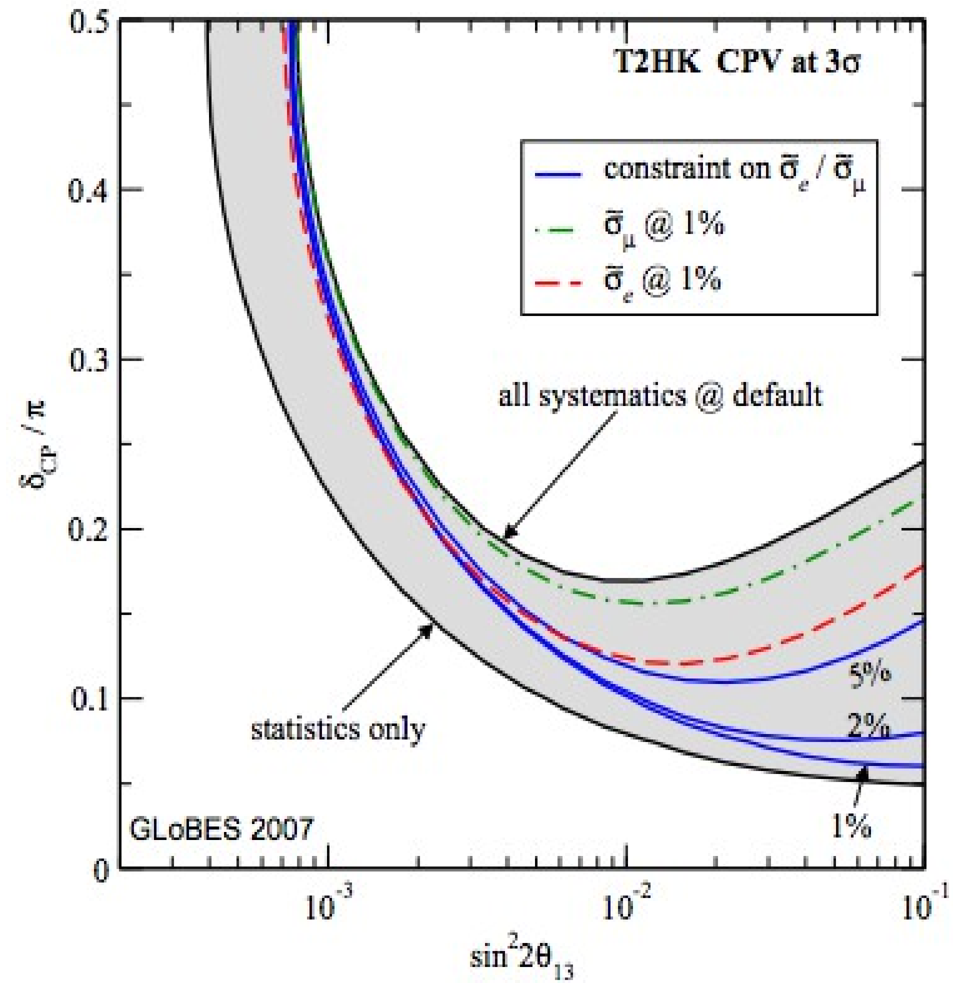


Coloma and Fernandez-Martinez,
1110.4583 [hep-ph]

Impact of systematics on CPV



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



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

Systematics

- Possible ways to reduce their impact:
  - Measure final flavor cross sections at the near det

    If this cannot be done, put constraints on ratios between different flavors Day, McFarland, 1206.6745 [hep-ph]
  - Combining different experiments (BB+SPL)
  - Measure intrinsic backgrounds at the near det
  - Use disappearance data from the far detector

Correlations

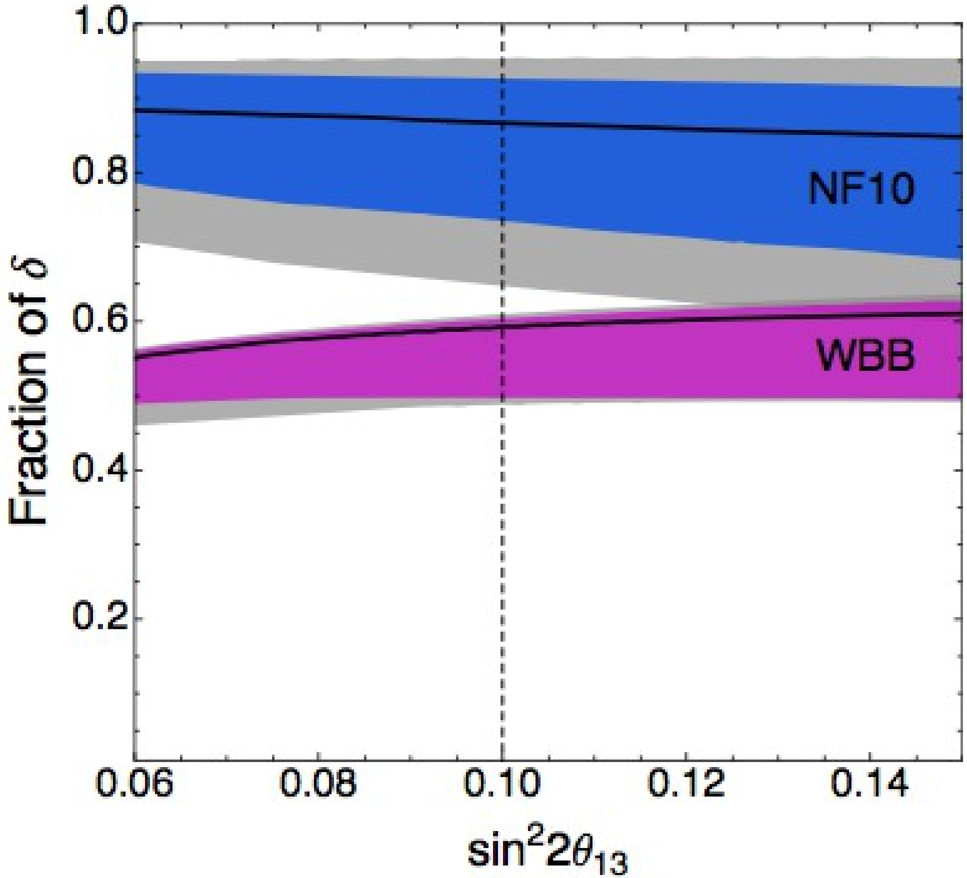
$$\mu^- \to e^- \bar{\nu}_e \nu_\mu$$

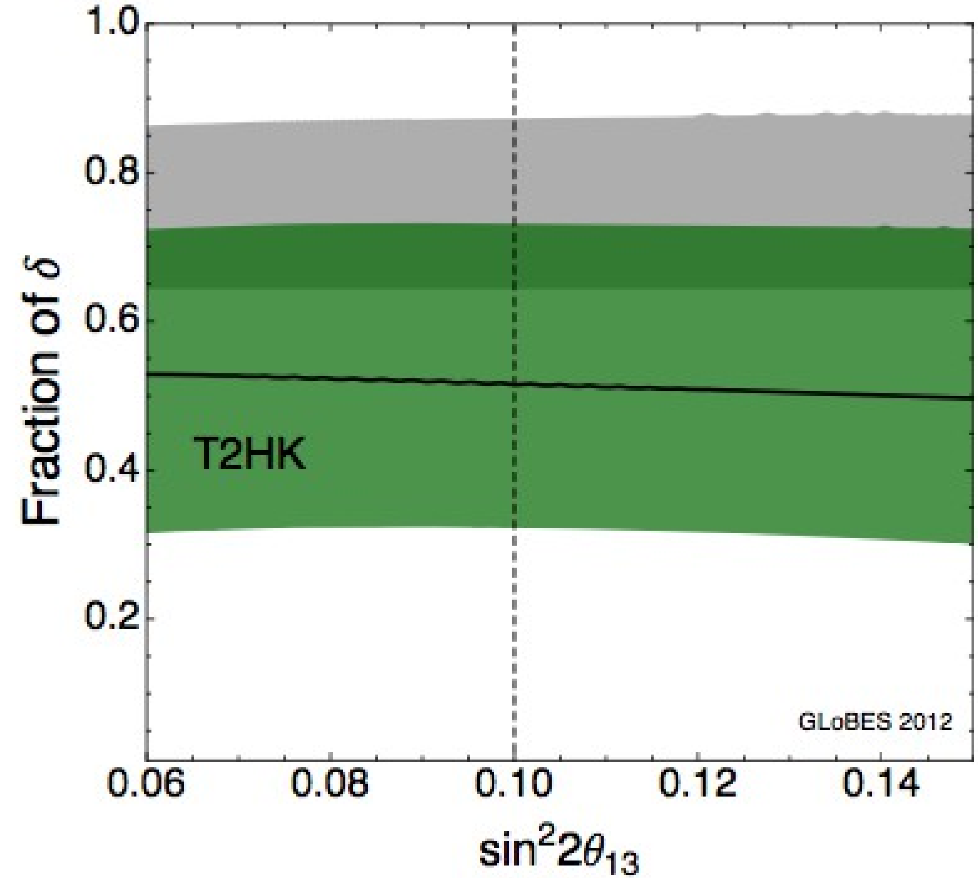
	$\bar{\nu}_e \to \bar{\nu}_\mu$	ϕ_-	V_{far}	Matter	Xsec
ND:	$\nu_\mu \to \nu_\mu$	ϕ_-	V_{near}	Vacuum	Xsec
	$\bar{\nu}_\mu \to \bar{\nu}_\mu$	ϕ_+	V_{near}	Vacuum	Xsec
FD:	$\nu_\mu \to \nu_\mu$	ϕ_-	V_{far}	Matter	Xsec
	$\bar{\nu}_\mu \to \bar{\nu}_\mu$	ϕ_+	V_{far}	Matter	Xsec

Simulation details

Systematics	SB			BB			NF		
	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 × 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%

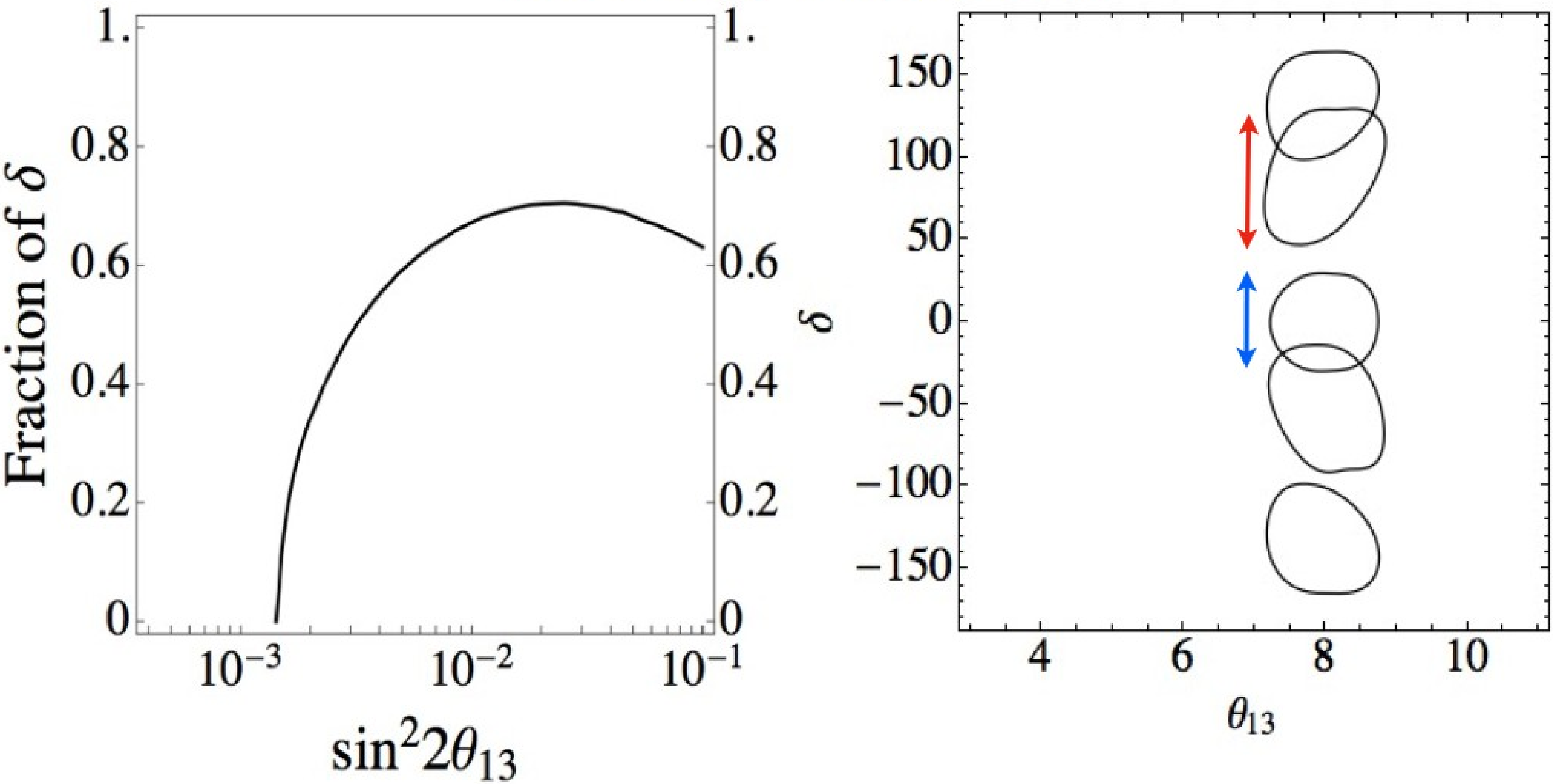
Impact of systematics on CPV





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

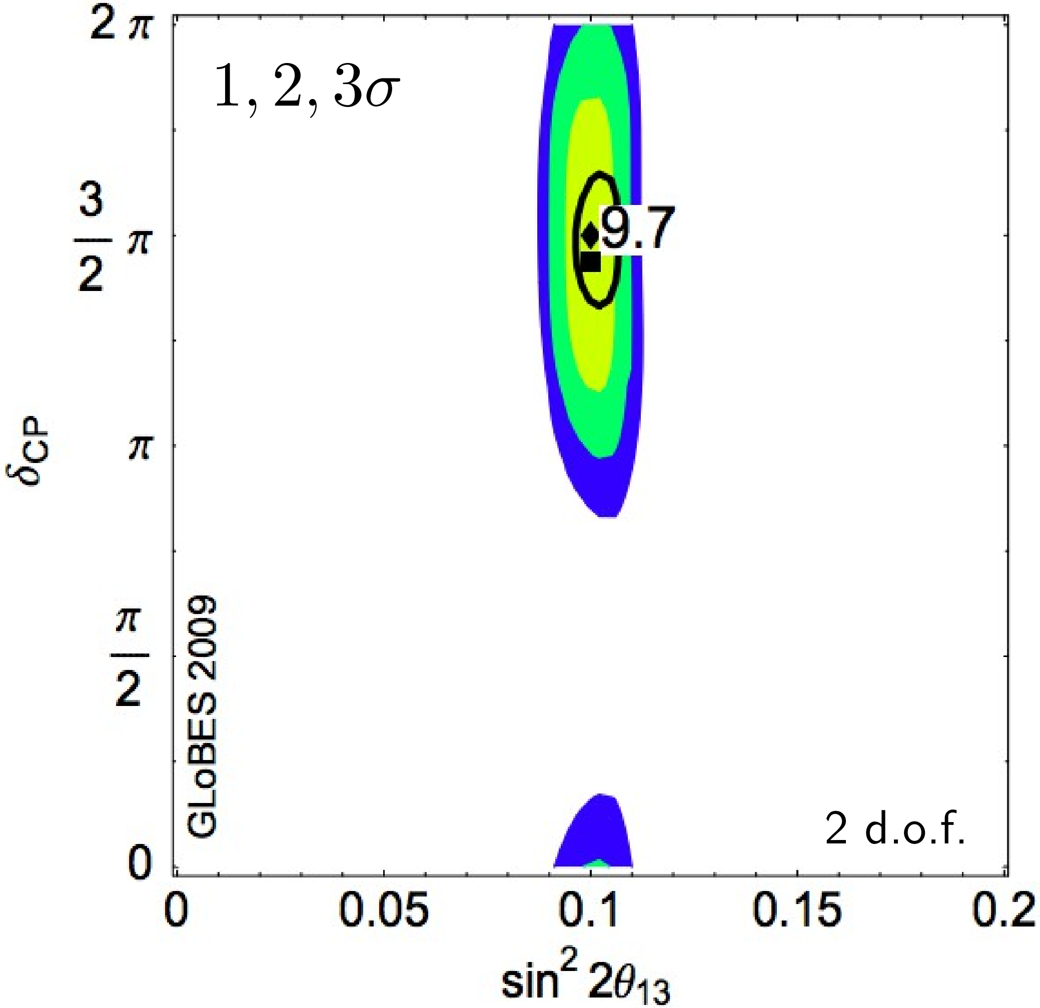
Discovery vs precision

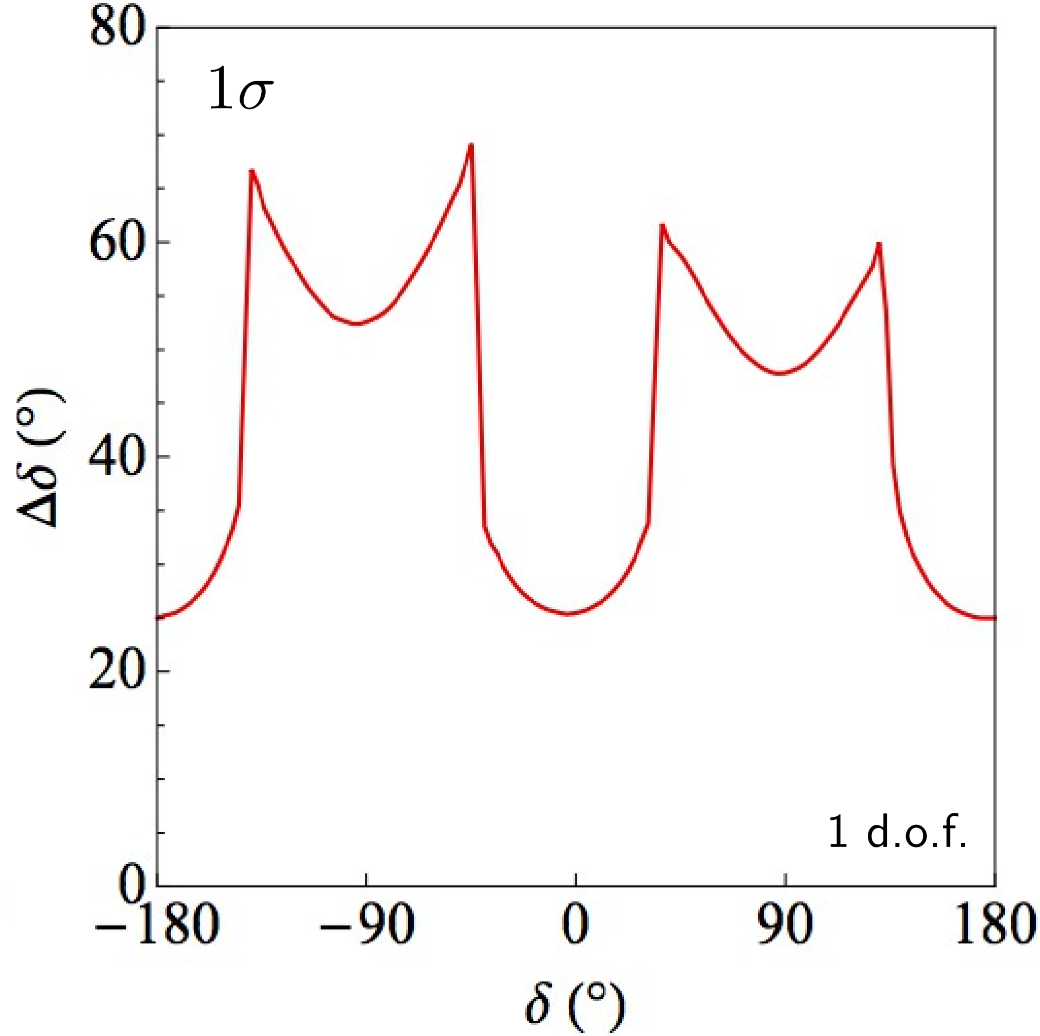


Why precision? $\rightarrow$ see Huber's talk

Precision

T2K + NOvA + Reactors:

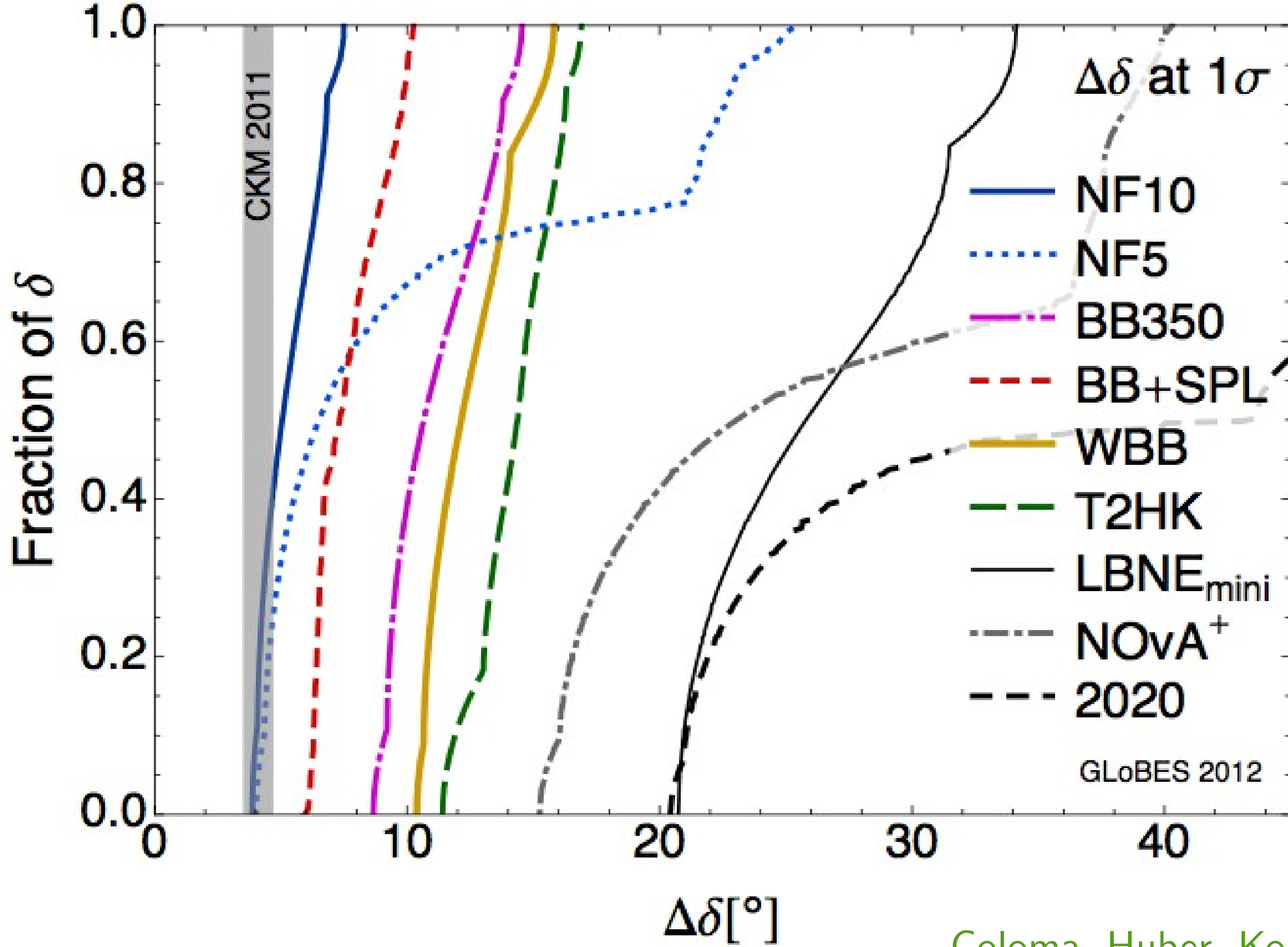




Huber Lindner, Schwetz and Winter, 0907.1896 [hep-ph]

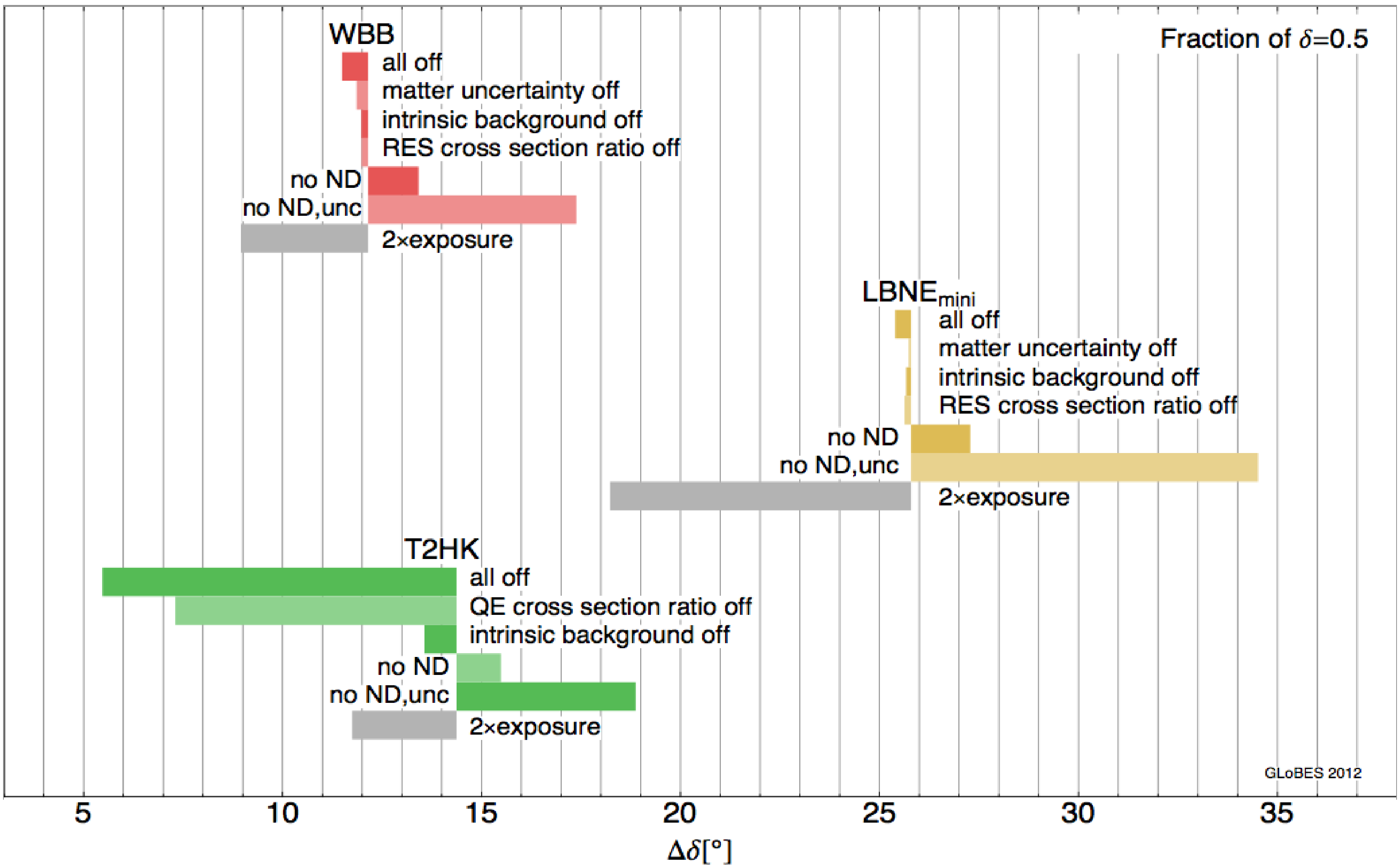
Coloma, Donini, Fernandez-Martinez and Hernandez, 1203.5651 [hep-ph]

Precision



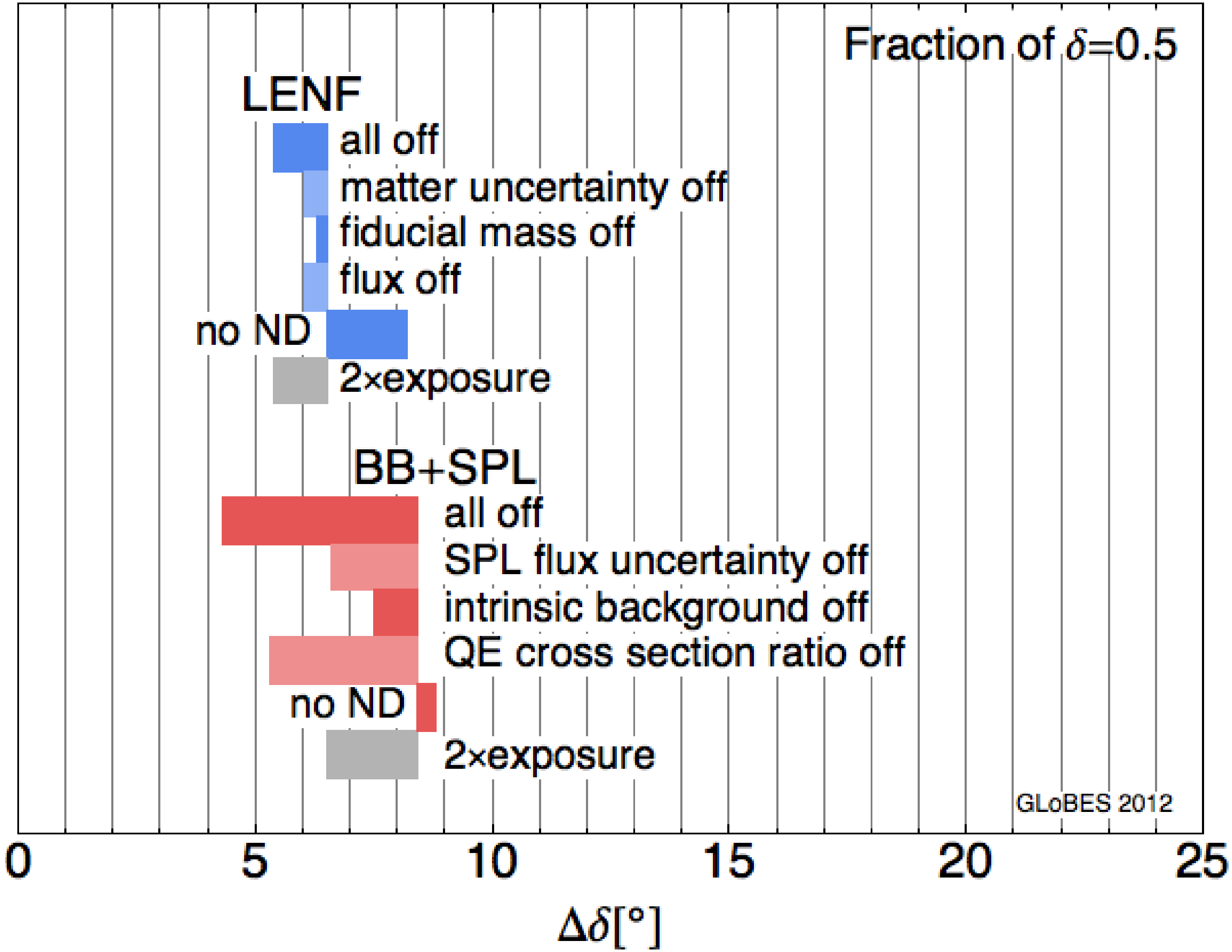
Coloma, Huber, Kopp, Winter, 1209.5973 [hep-ph]

Precision, systematics and near dets



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

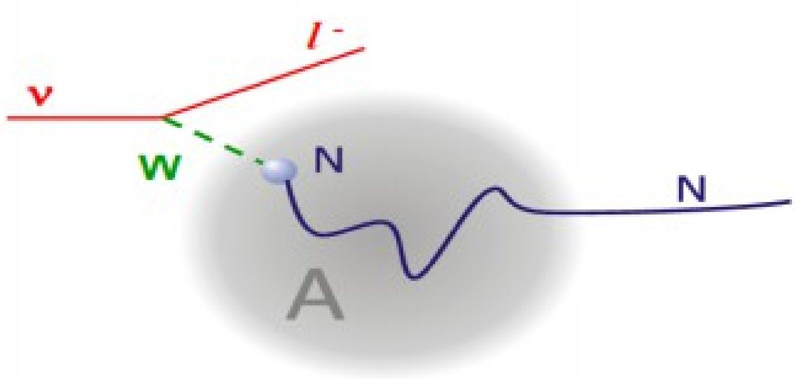
Precision, systematics and near dets

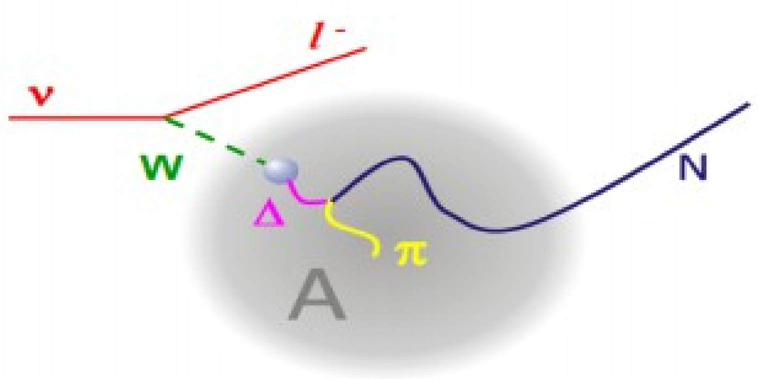


Coloma, Huber, Kopp, Winter, 1209.5973 [hep-ph]

However...

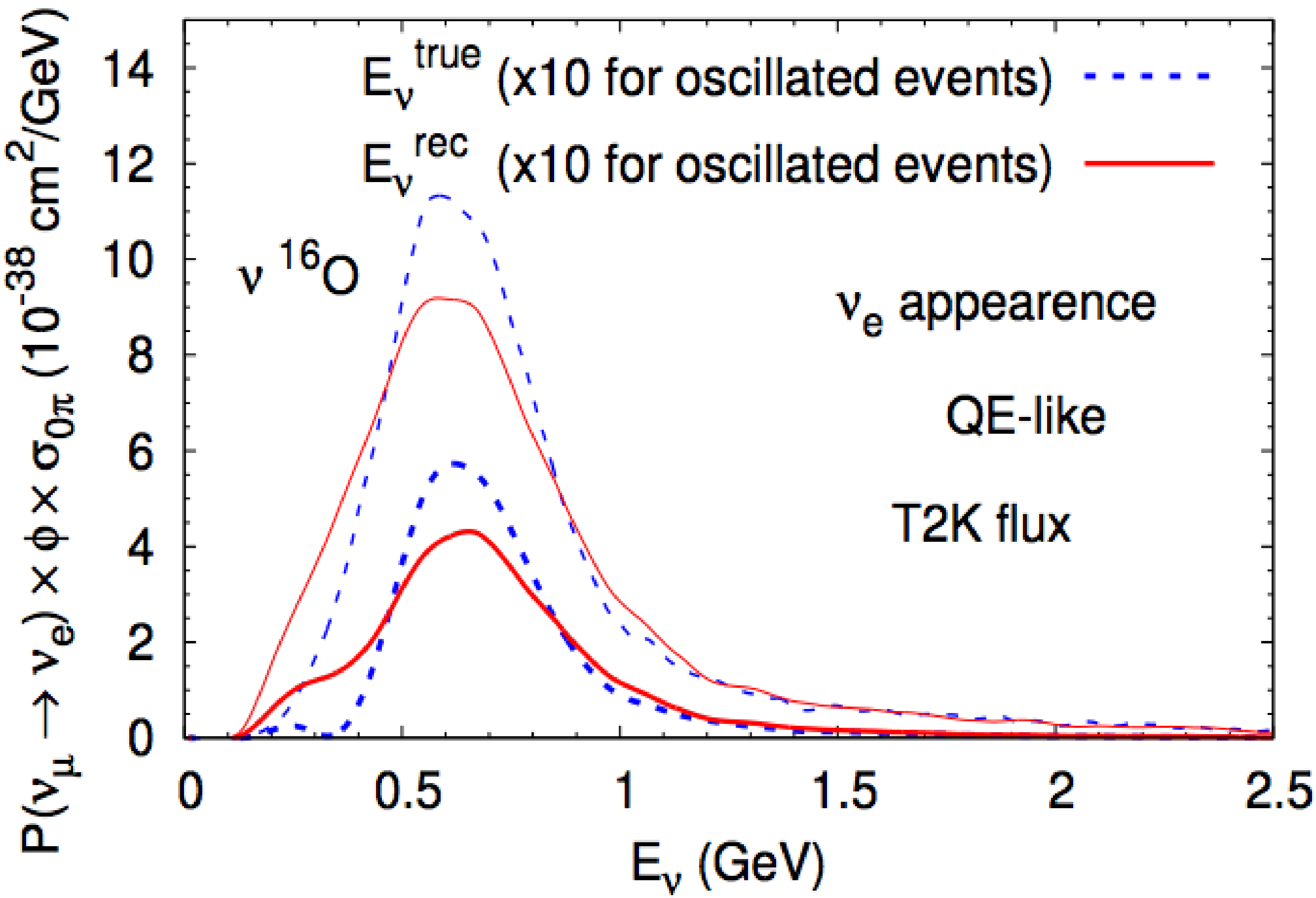
- These results assumed identical near and far spectra
- No shape uncertainties on the cross section were considered
- If this is not the case, the situation can be far more complicated, since what is truly measurable is a convolution of cross section and flux





See talks by Mariani, Morfin and Mosel

Nuclear effects and FSI



Nuclear effects and FSI have a non-negligible effect on the neutrino energy spectrum.

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

More in Mosel's talk

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)

Toy model

- Super-Beam with peak energy around 1 GeV, L=730 km

500 kton WC detector $\rightarrow$ QE events only (1-ring)

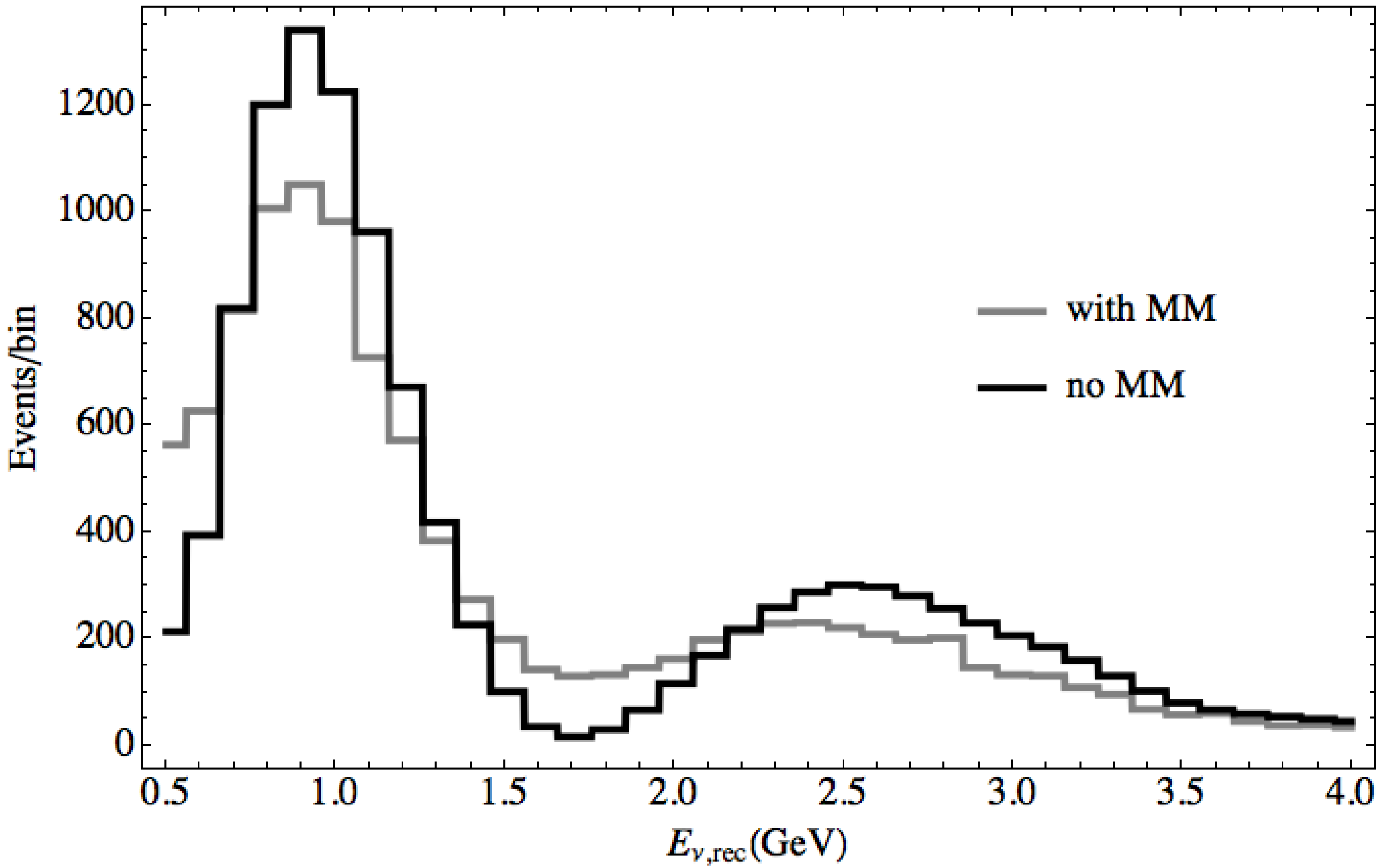
- Use migration matrix for ^{16}O produced with GiBUU

http://gibuu.physik.uni-giessen.de/GiBUU/wiki

- Muon neutrino disappearance only $\rightarrow$ fit to atmospheric parameters
- Inclusion of bin-dependent systematics to be able to fit shape errors

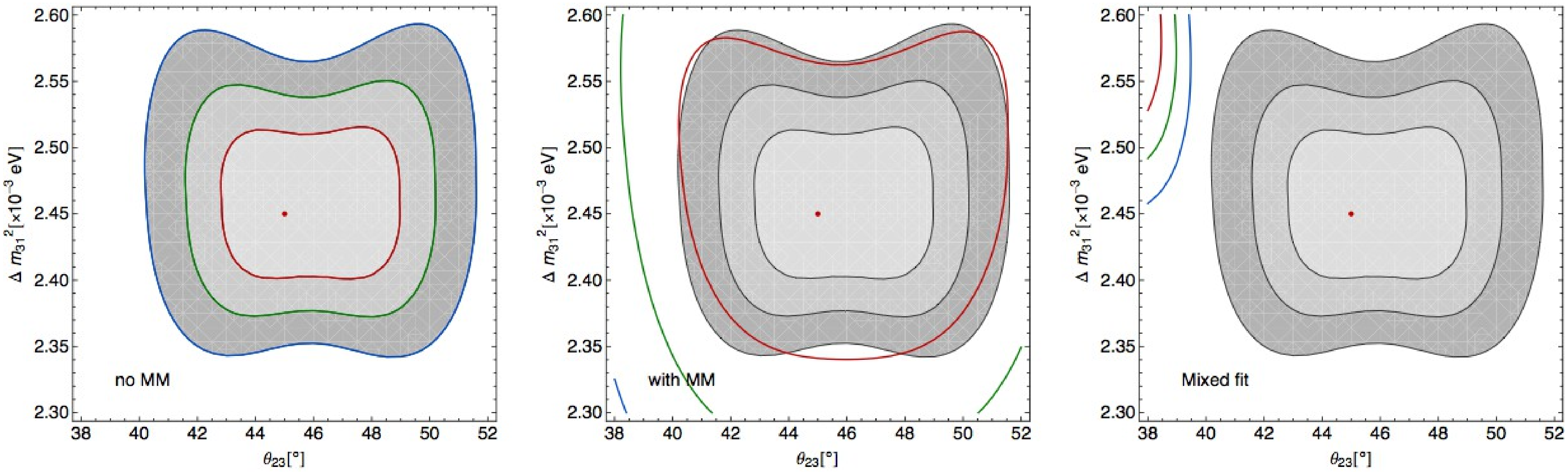
P. Coloma and P. Huber, work in progress

Toy model



P. Coloma and P. Huber, work in progress

Toy model



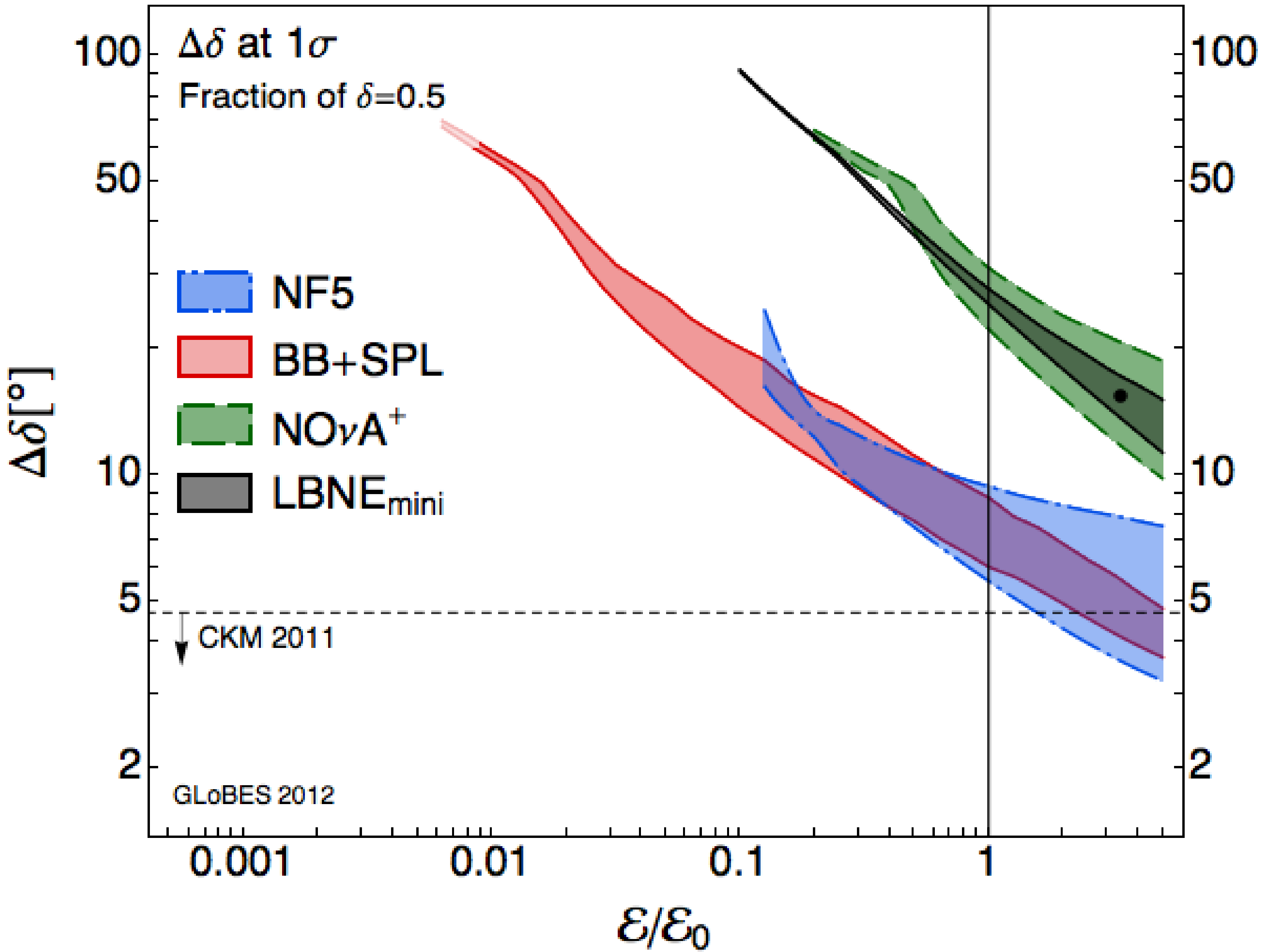
P. Coloma and P. Huber, work in progress

Conclusions

- The most relevent systematics on LBL exps are those related to cross sections
  - Unavailability of final flavor at the near det may be a problem
- Systematic effects can be kept under control if:
  - no flux shape uncertainties
  - no cross section shape uncertainties
- If these are present both effects cannot be disentangled
  - this could lead to a wrong fit for the oscillation parameters!

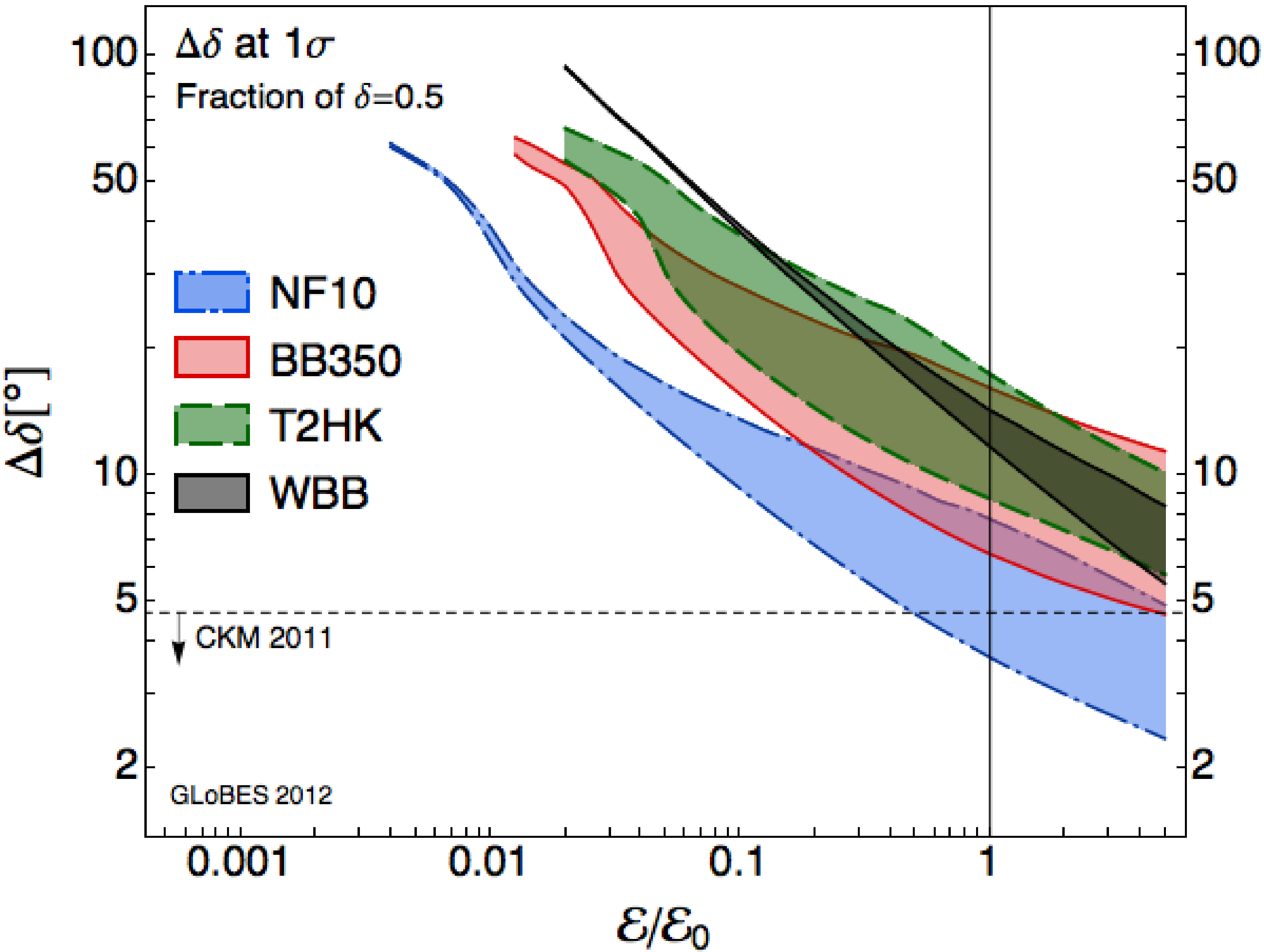
Thank you!

Exposure



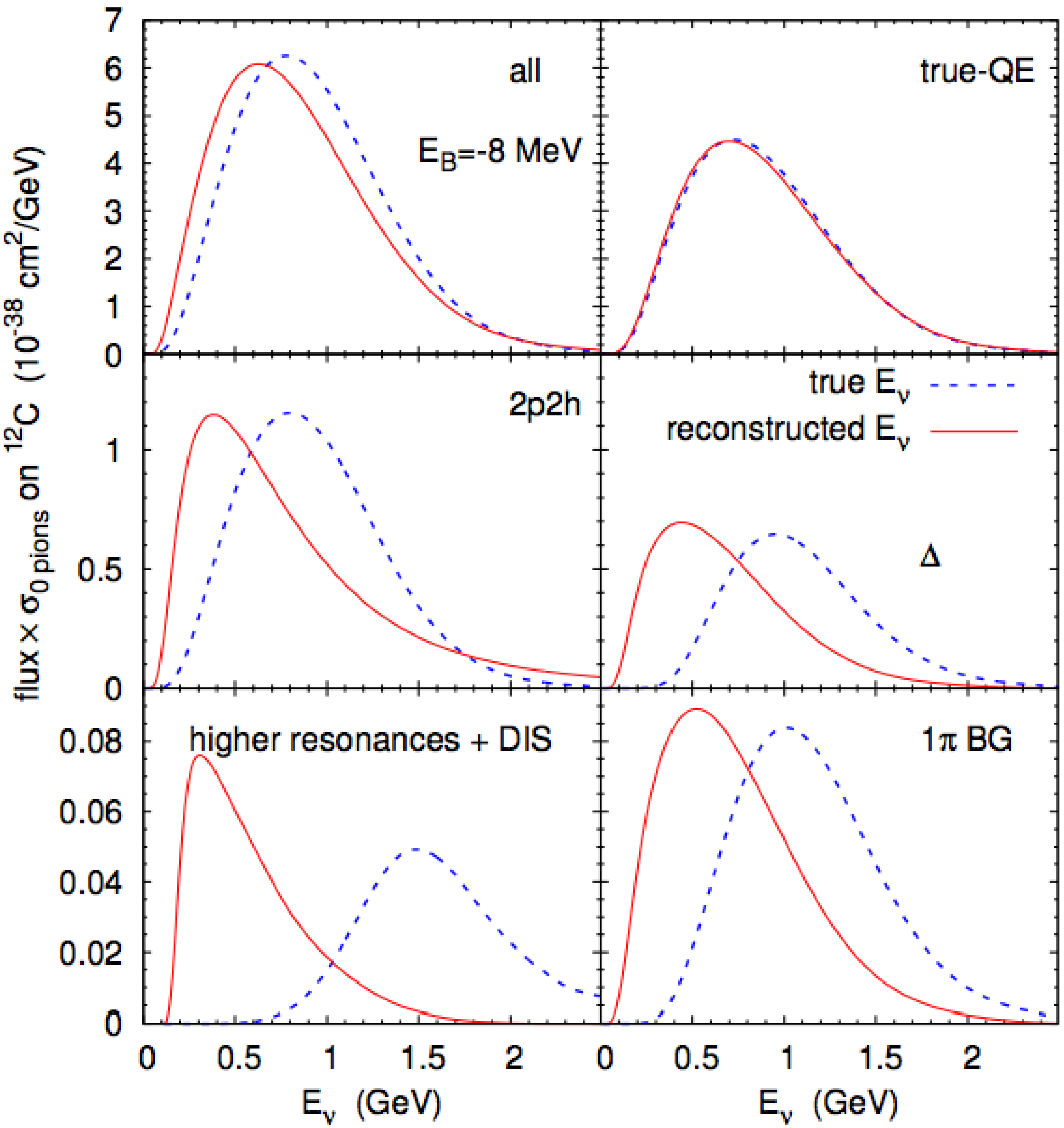
Δδ at 1σ
Fraction of δ=0.5
NF5
BB+SPL
NOνA+
LBNEmini
CKM 2011
GLoBES 2012
Δδ[°]
100
50
10
5
2
0.001
0.01
0.1
1
ℰ/ℰ0

Exposure



Δδ at 1σ
Fraction of δ=0.5
NF10
BB350
T2HK
WBB
CKM 2011
GLoBES 2012
100
50
10
5
2
Δδ[°]
0.001
0.01
0.1
1
ℰ/ℰ0

Nuclear effects and FSI



Nuclear effects and FSI have a non-negligible effect on the neutrino energy spectrum.

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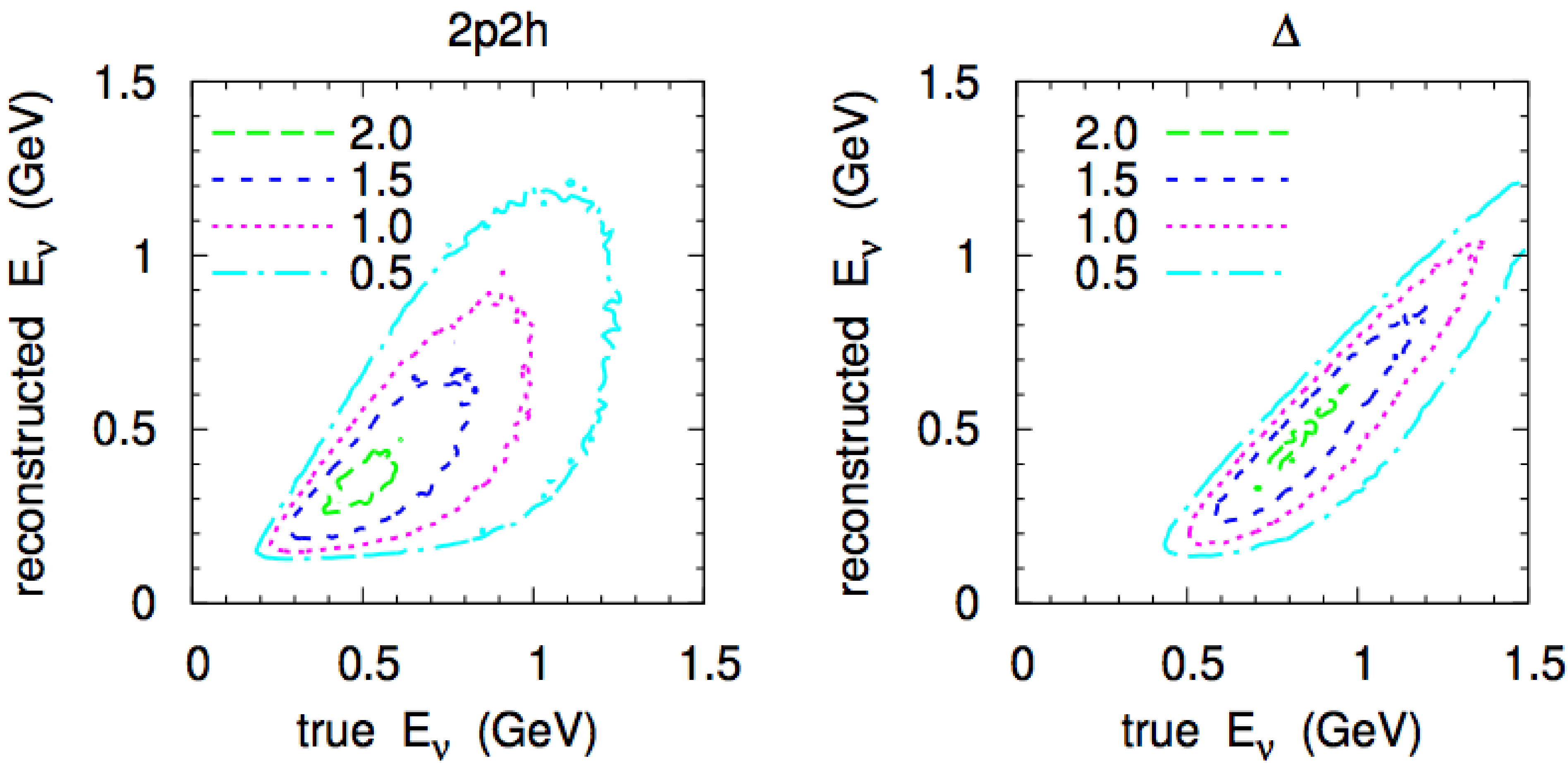
More in Mosel's talk

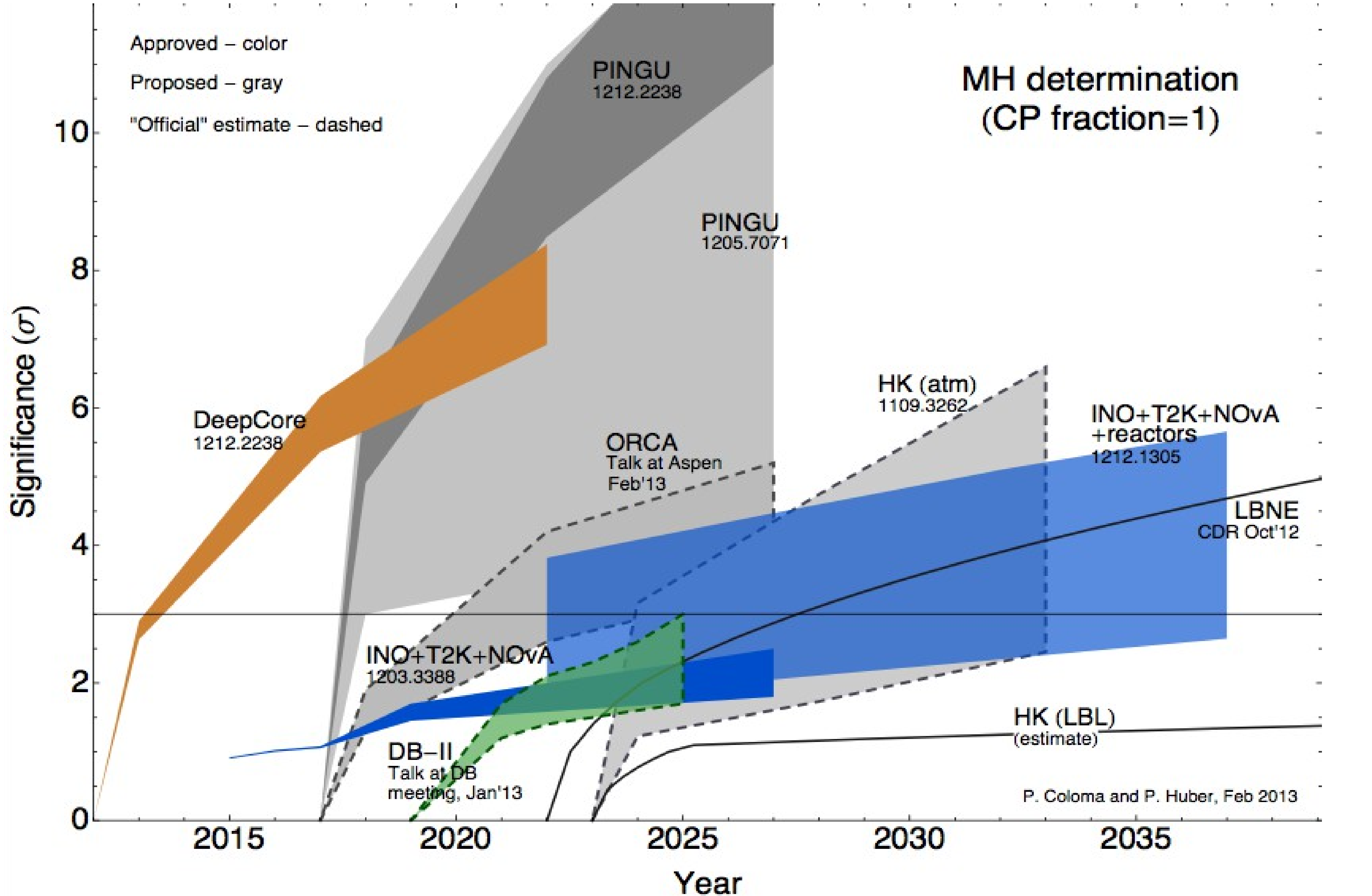
1208.3678
(see also 1202.4745, 1204.5404,1302.0703,...)

Nuclear effects and FSI



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

Will the hierarchy be measured soon?



Precision

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

Statistical limit:

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

Systematics on the signal:

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

Background error:

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

Precision

Statistical limit:

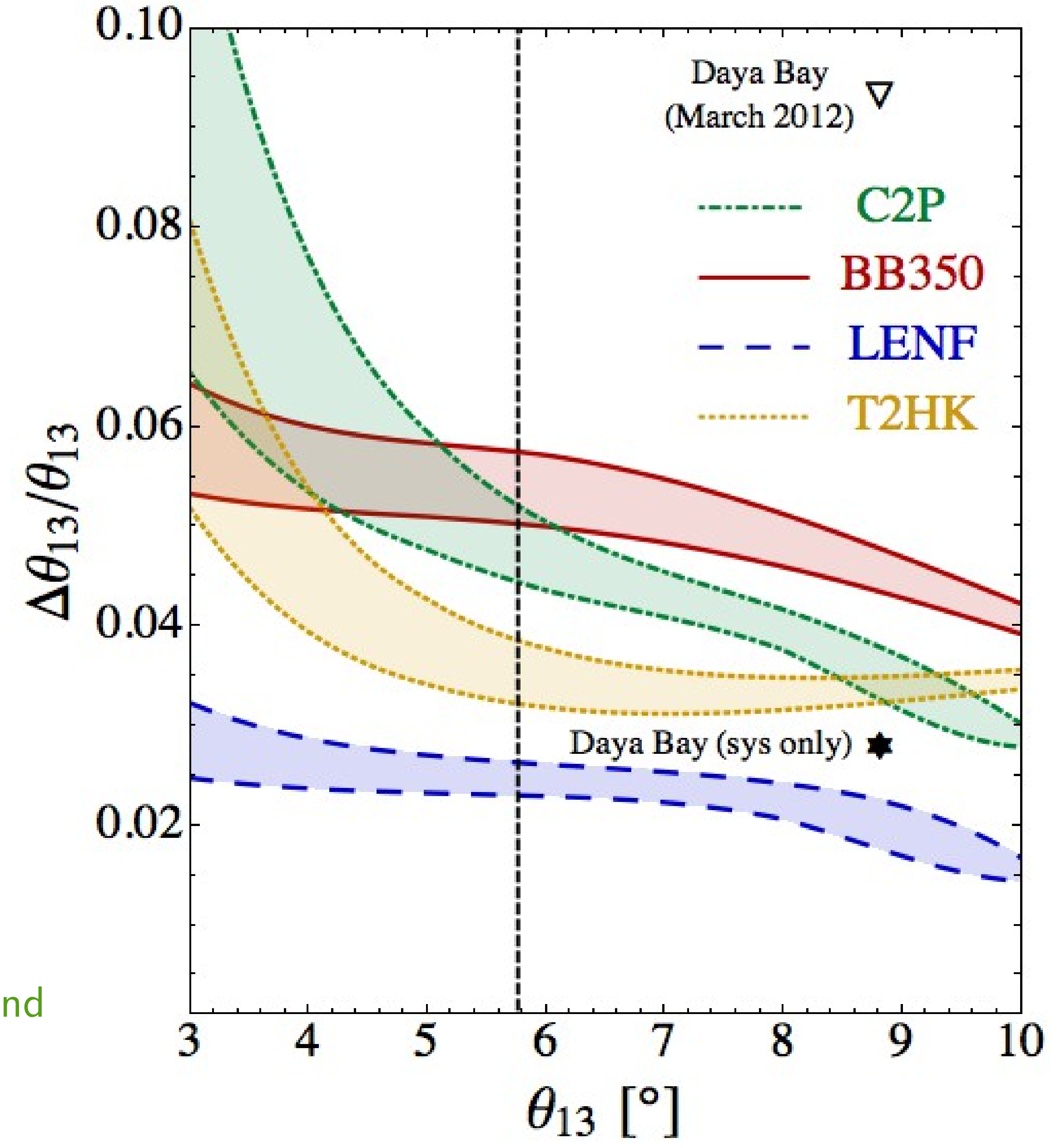
$$\frac{\Delta\theta_{13}}{\theta_{13}} \propto \frac{1}{\theta_{13}}$$

Systematics on the signal:

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

Background error:

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



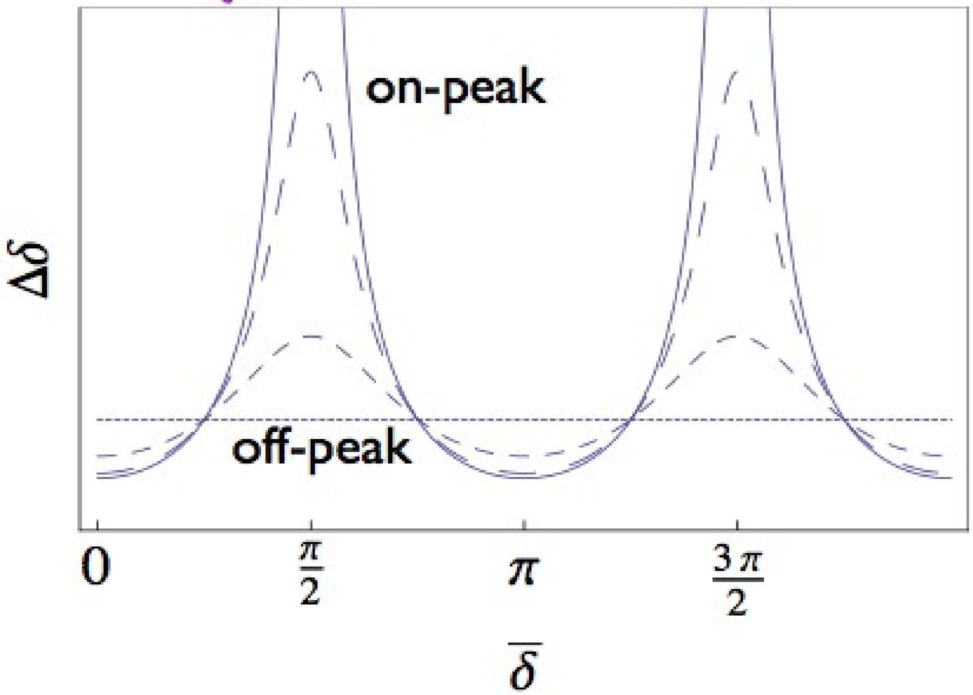
Coloma, Donini, Fernandez-Martinez and Hernandez, 1203.5651 [hep-ph]

Precision

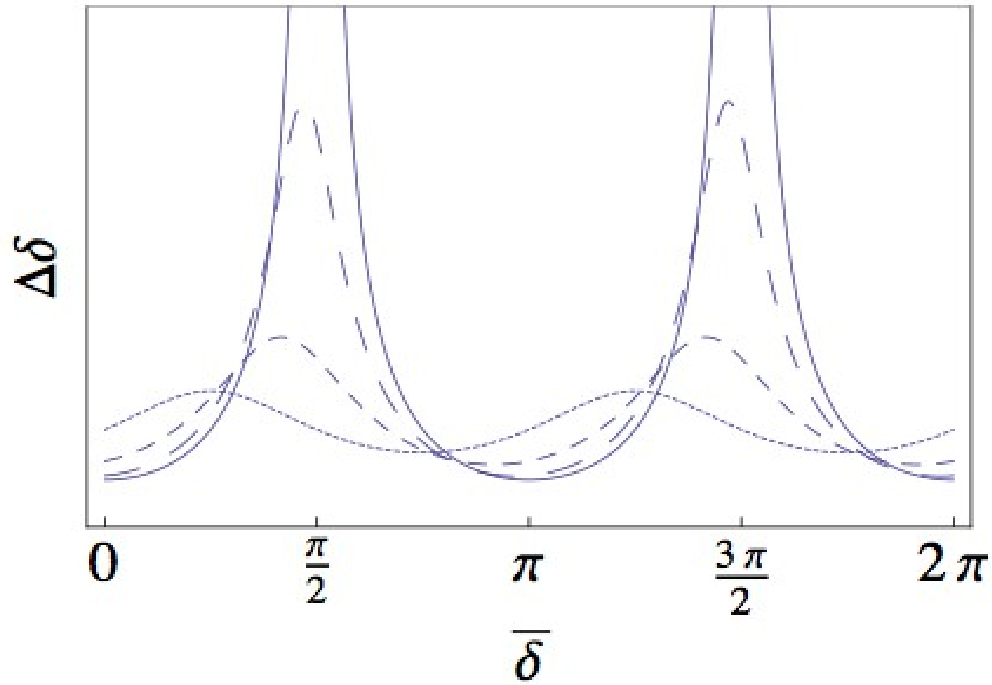
VACUUM

$$(\Delta\delta)_{\pm} \propto f[\Delta]\frac{1}{\sin\left(\frac{\pi}{2} \mp \delta\right)}$$

equal nu and nubar events



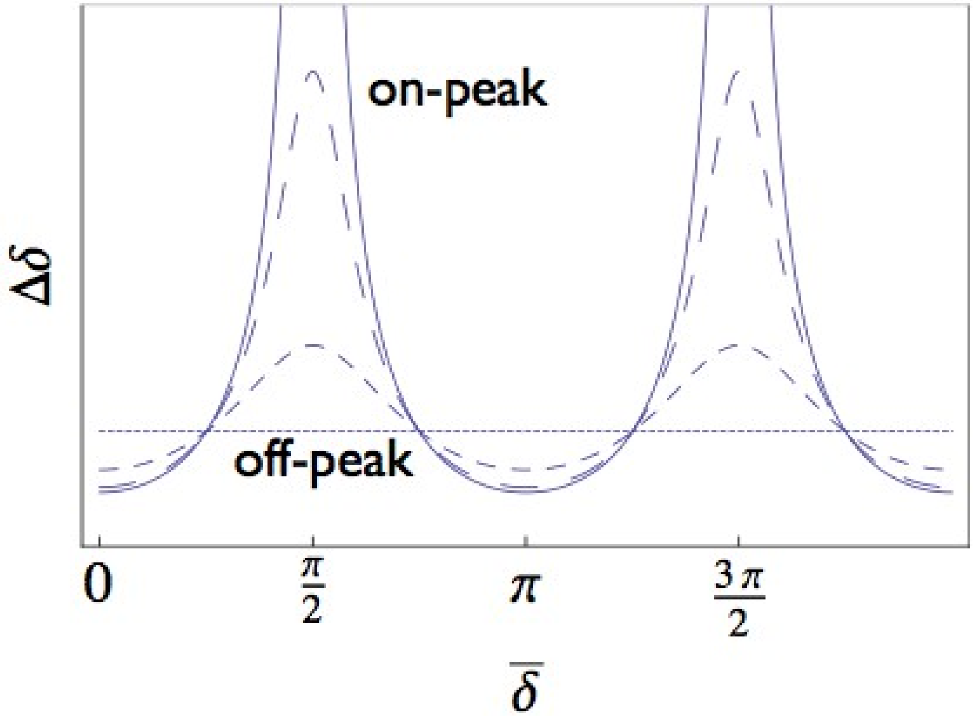
less nubar than nu events



Precision

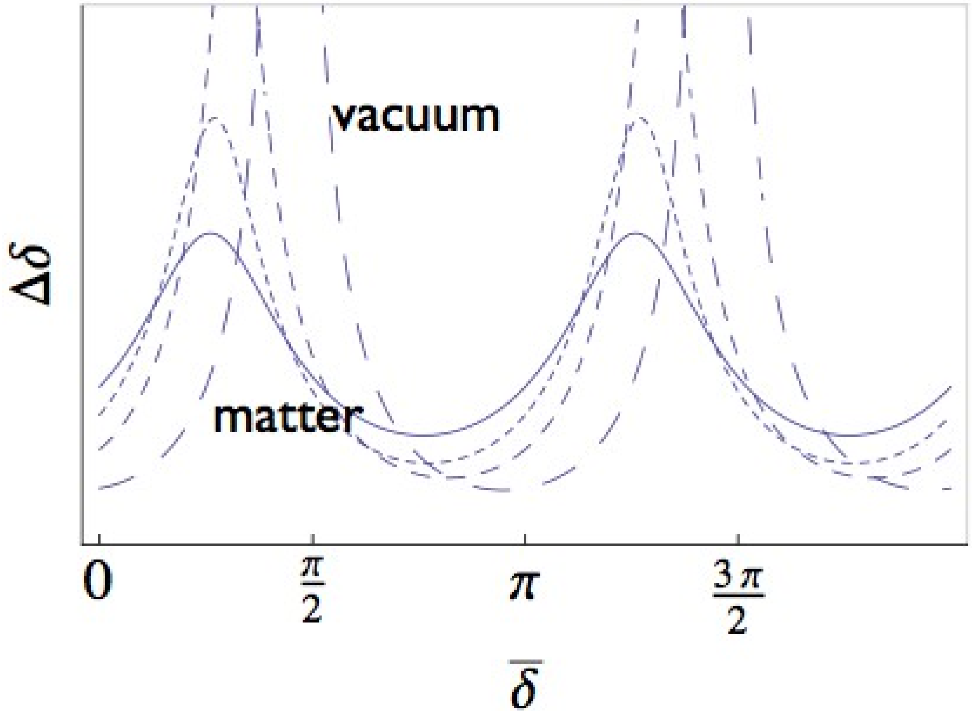
VACUUM

$$(\Delta\delta)_{\pm} \propto f[\Delta]\frac{1}{\sin\left(\frac{\pi}{2} \mp \delta\right)}$$



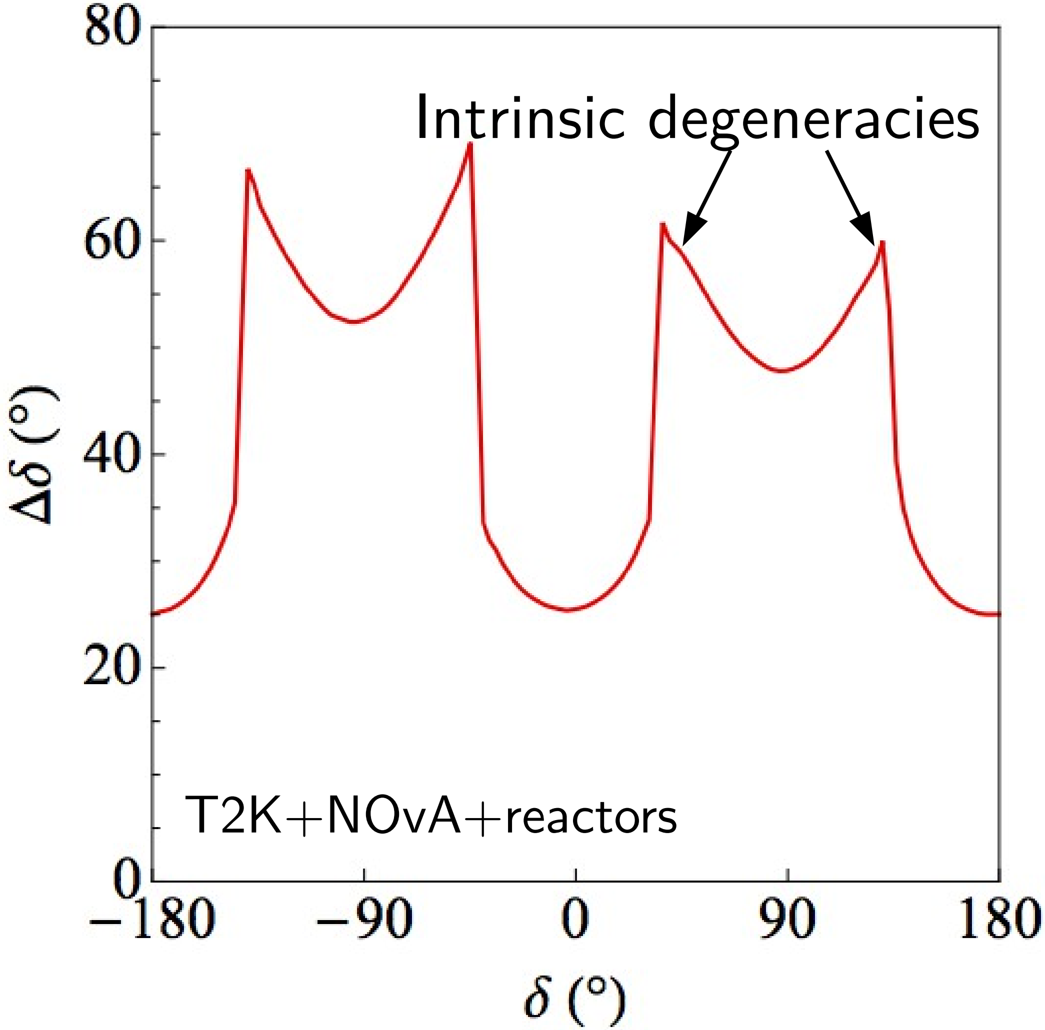
MATTER

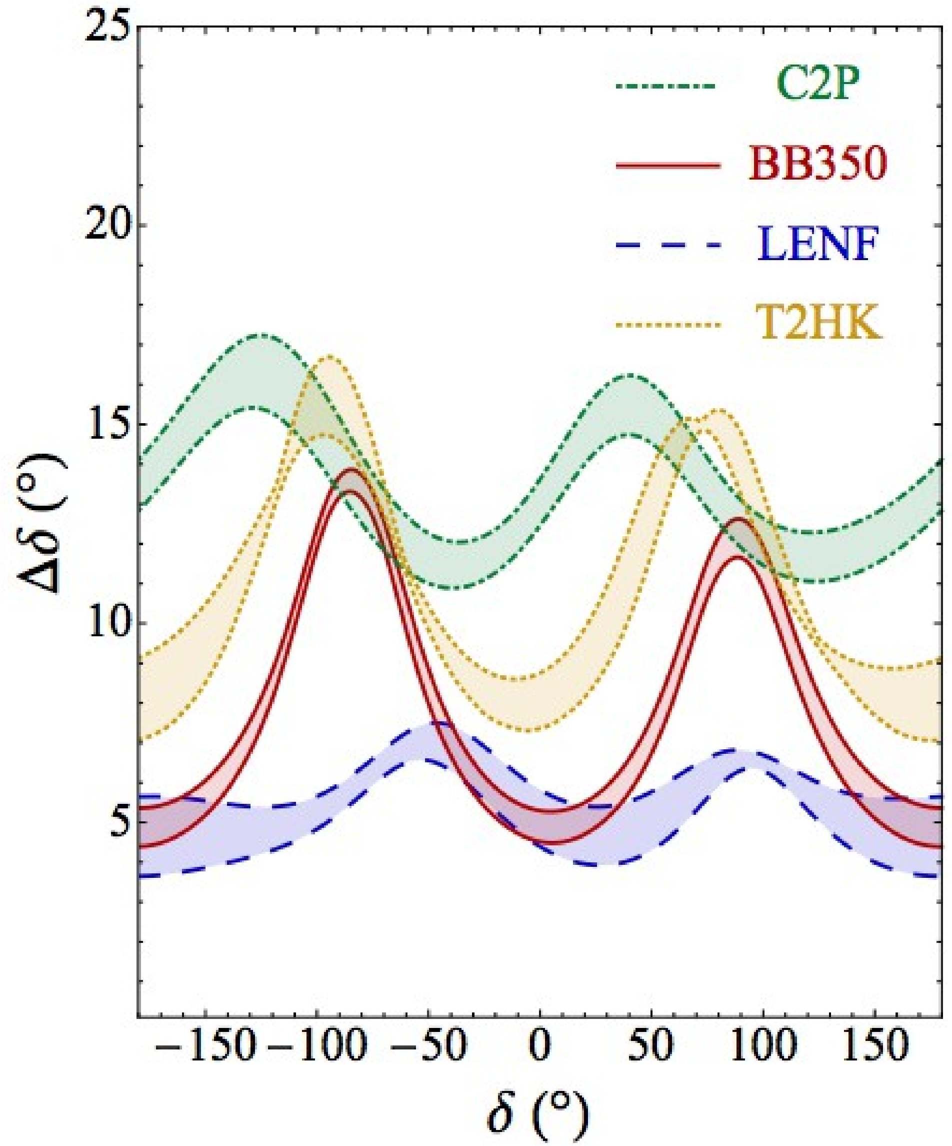
$$(\Delta\delta)_{\pm} \propto \tilde{f}[\Delta, \hat{A}]\frac{1}{\sin\left(\frac{\pi}{2}\frac{\hat{A}}{(1\mp\hat{A})} \mp \delta\right)}$$



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

Precision at 1σ





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

Present generation

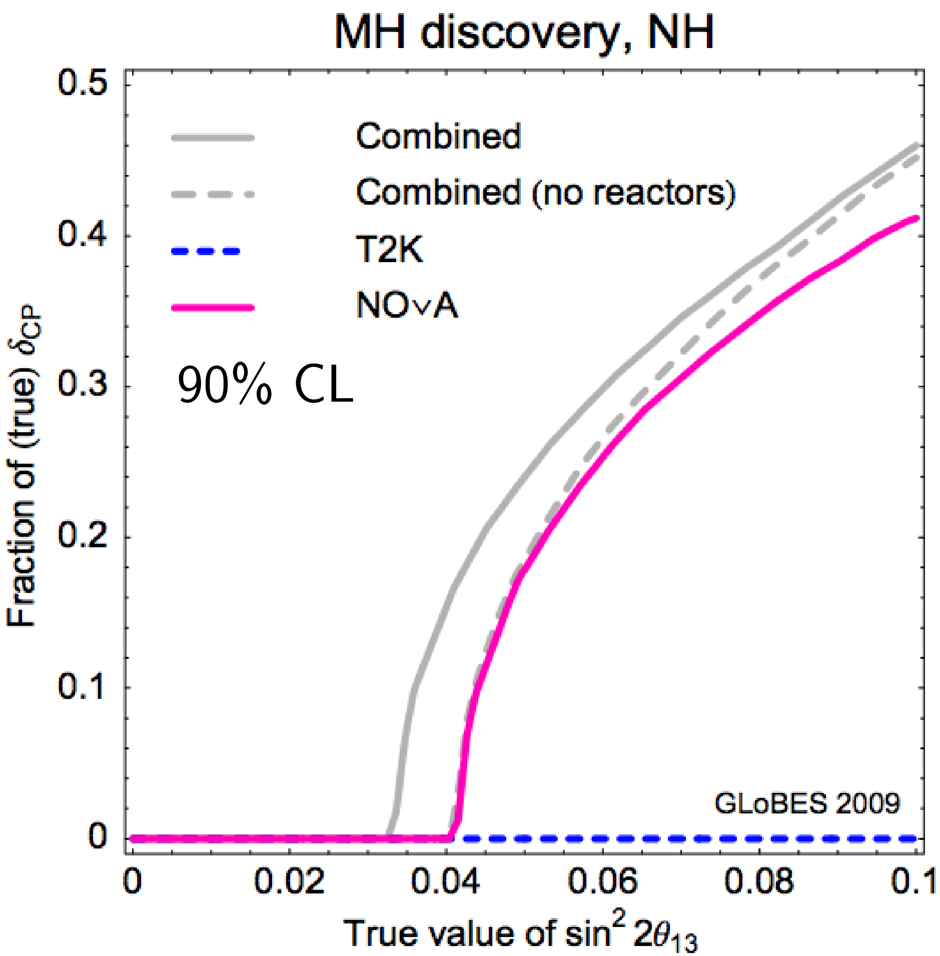
- T2K: target power is 750 kW, uses SK as detector (22.5 kt) at 295 km. Off-axis by 2.5deg

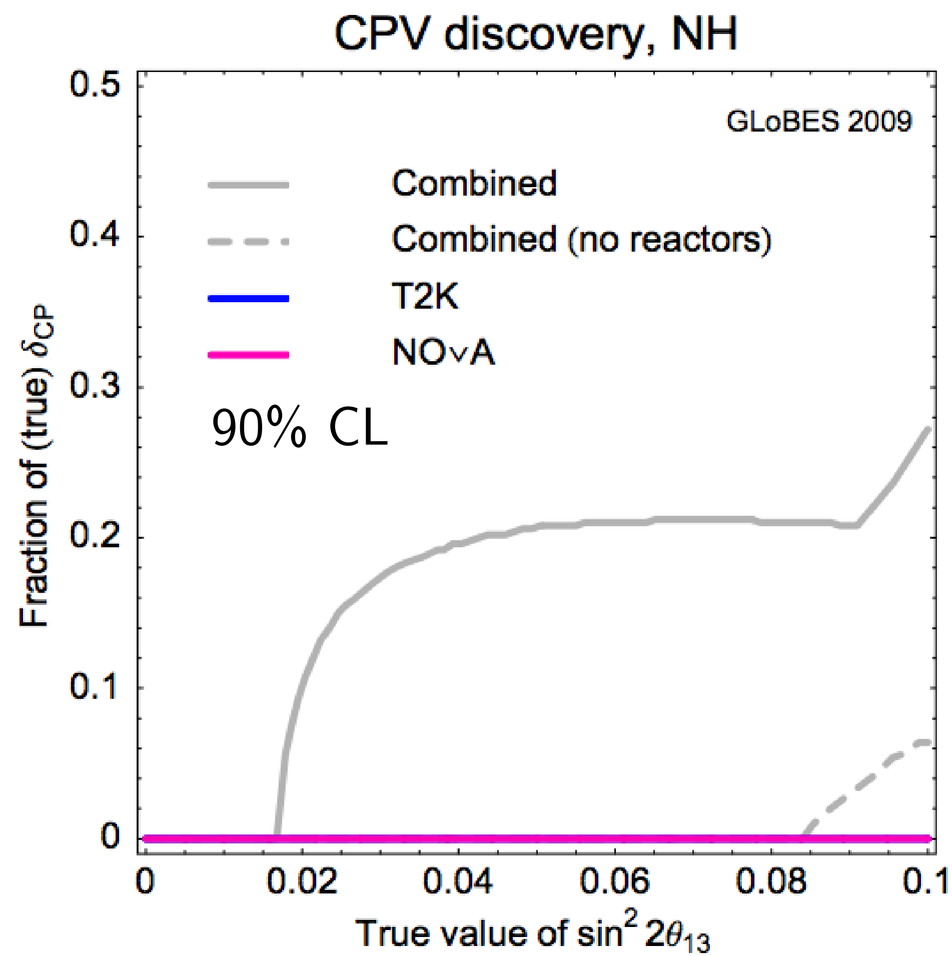
already taking data: 2.5 and 3.2 sigma evidences for nonzero θ_{13} reported in 1106.2822 and at ICHEP2012

- NOvA: target power is 700 kW, uses 14 kton TASD detector at 810 km. Off-axis by 0.8 deg

data taking expected to start in May 2013
1209.0716 [hep-ex]

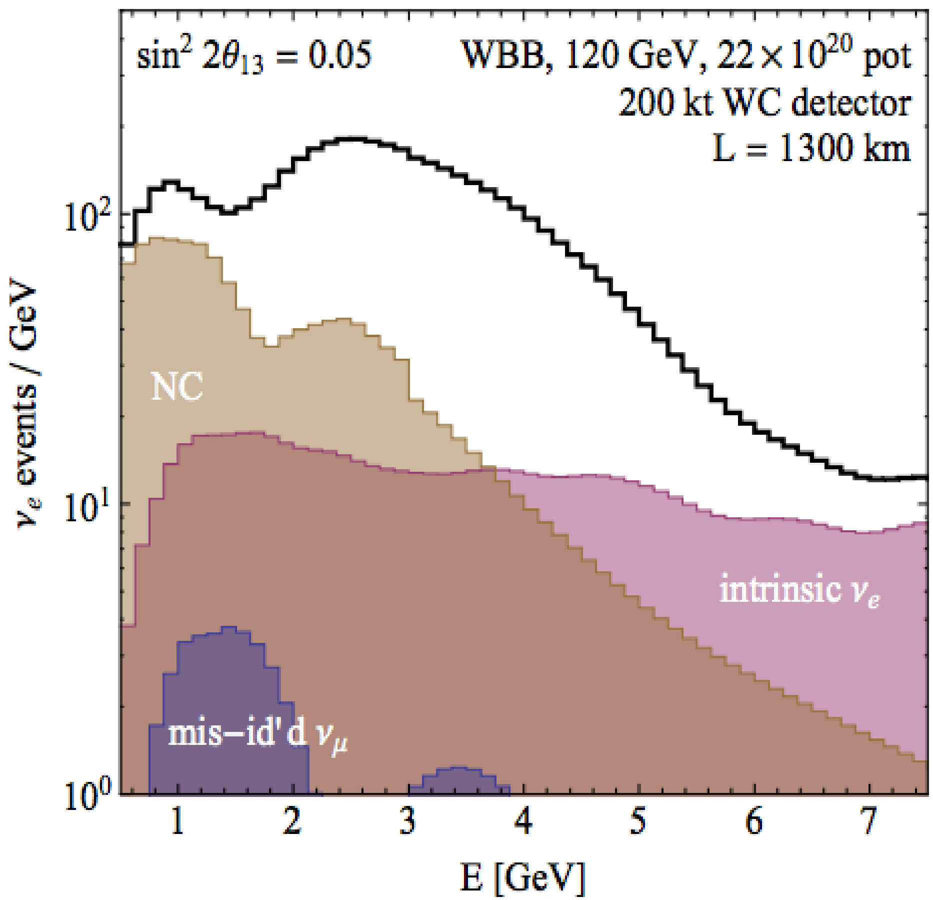
Present generation

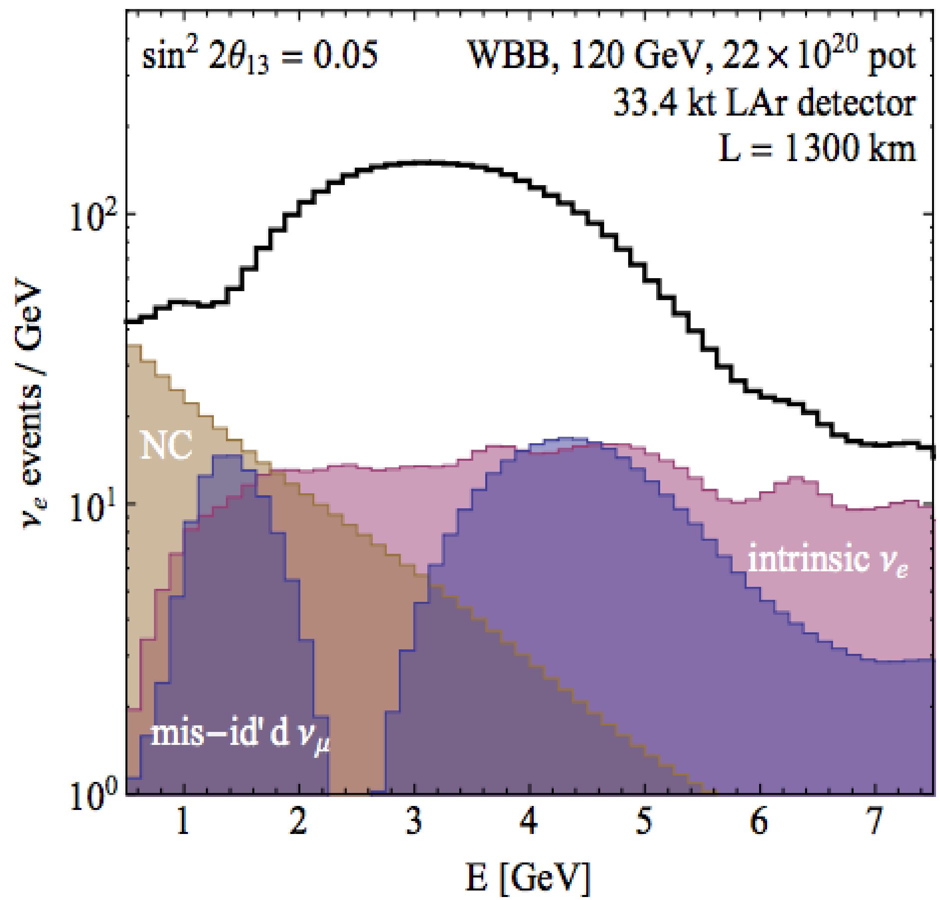




Huber et al, 0907.1896 [hep-ph]

1st vs 2nd oscillation maxima





Huber and Kopp,
1010.3706[hep-ph]