The search for leptonic CP violation

Enrique Fernández Martínez

νProbes

Mostly based on collaborations with P. Coloma

Oscillation Parameters

- What we already know (1σ)
  - Solar sector $\begin{cases} \Delta m_{21}^2 = 7.45_{-0.16}^{+0.19} \cdot 10^{-5} \mathrm{eV}^2 \\ \sin^2\theta_{12} = 0.306_{-0.012}^{+0.012} \end{cases}$
  - Atm. sector $\begin{cases} \Delta m_{31}^2 = 2.417_{-0.013}^{+0.013} \cdot 10^{-3} / -2.410_{-0.062}^{+0.062} \cdot 10^{-3}\ \mathrm{eV}^2 \\ \sin^2\theta_{23} = 0.446_{-0.007}^{+0.007} / 0.587_{-0.037}^{+0.032} \end{cases}$
  - $\sin^2\theta_{13} = 0.0229_{-0.0019}^{+0.002}$

- What we still don't know
  - $\delta = ?$
  - Mass hierarchy $s_{atm} = sign\left(\Delta m_{31}^2\right)$

M. C. Gonzalez-Garcia, M. Maltoni, J. Salvado, T. Schwetz 1209.3023 www.nu-fit.org
See also: D. V. Forero, M. Tortola, J. Valle 1205.4018
G.L. Fogli, E. Lisi, A. Marrone, D. Montanino, A. Palazzo, A.M. Rotunno 1205.5254

The Golden channel in matter

$$P\left(\overset{(-)}{\nu}_e \to \overset{(-)}{\nu}_\mu\right) = s_{23}^2 \sin^2 2\theta_{13} \left(\frac{\Delta_{atm}}{\tilde{B}_\mp}\right)^2 \sin\left(\frac{\tilde{B}_\mp L}{2}\right)^2$$ "atmospheric"

$$+ c_{23}^2 \sin^2 2\theta_{12} \left(\frac{\Delta_{sol}}{A}\right)^2 \sin^2\left(\frac{AL}{2}\right)$$ "solar"

"interference" $$+ \tilde{J} \frac{\Delta_{sol}}{A} \frac{\Delta_{atm}}{\tilde{B}_\mp} \sin\left(\frac{AL}{2}\right) \sin\left(\frac{\tilde{B}_\mp L}{2}\right) \cos\left(\pm\delta - \frac{\Delta_{atm} L}{2}\right)$$

Expanded in

$$\sin 2\theta_{13} \sim 0.3 \qquad \left(\frac{\Delta_{sol} L}{2}\right) \cong 0.05$$

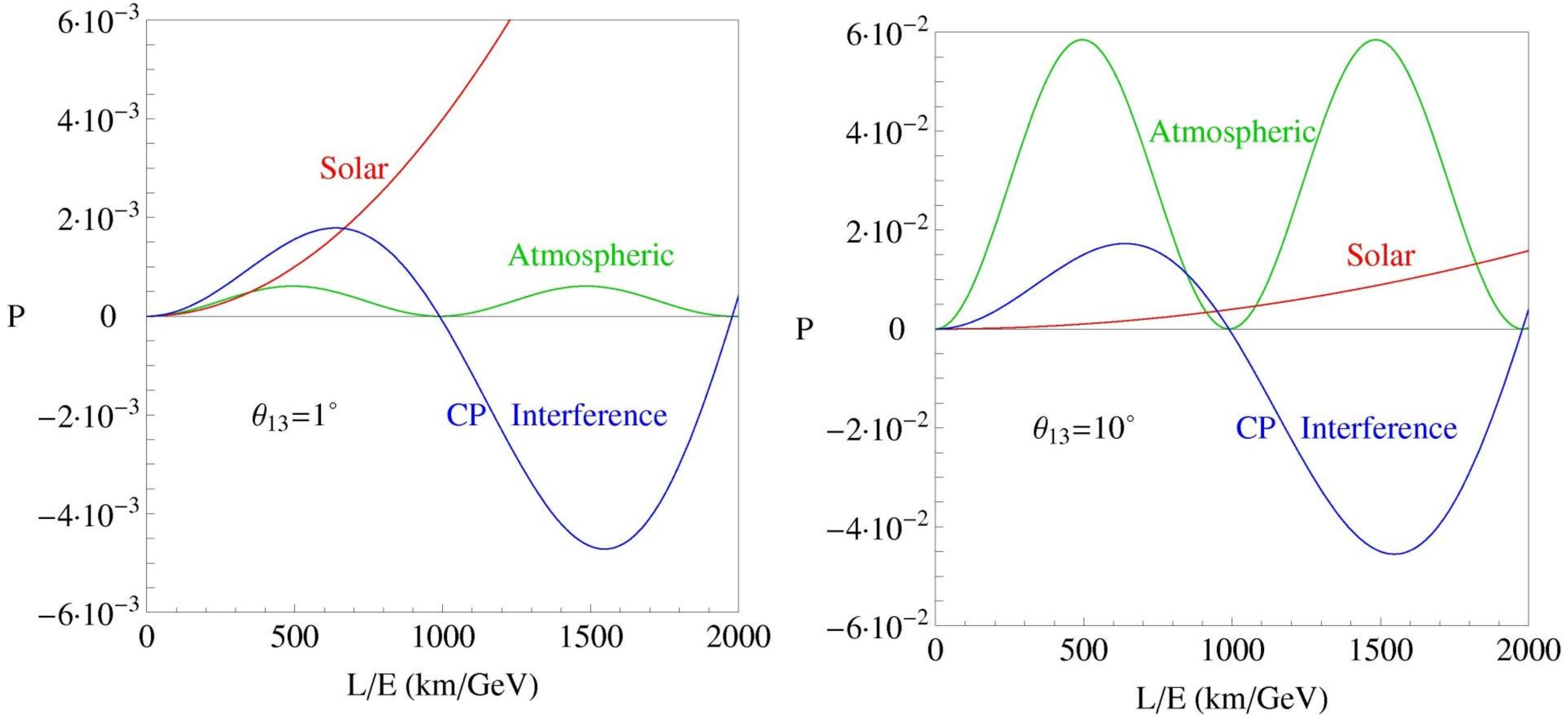
where

$$\tilde{J} = \cos\theta_{13} \sin 2\theta_{13} \sin 2\theta_{12} \sin 2\theta_{23} \qquad \Delta_{atm} = \frac{\Delta m_{23}^2}{2E} \qquad \Delta_{sol} = \frac{\Delta m_{12}^2}{2E}$$

$$A = \sqrt{2} G_F n_e \qquad \tilde{B}_\mp = \left| A \mp \Delta_{atm} \right|$$

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

Optimization of facilities for large θ_{13}

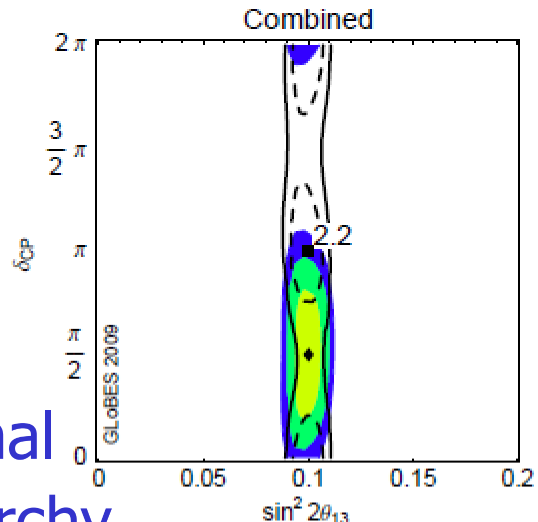


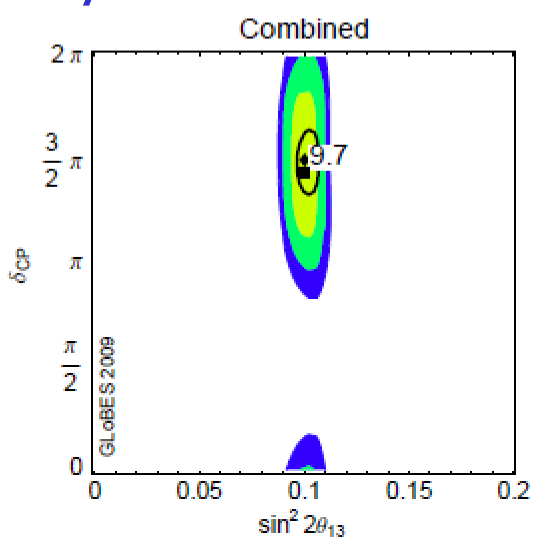
Signal systematics and not stats becomes the bottleneck for large θ_{13}, explore second peak? P. Coloma and EFM 1110.4583

Sensitivities with present experiments

1, 2 and 3 σ

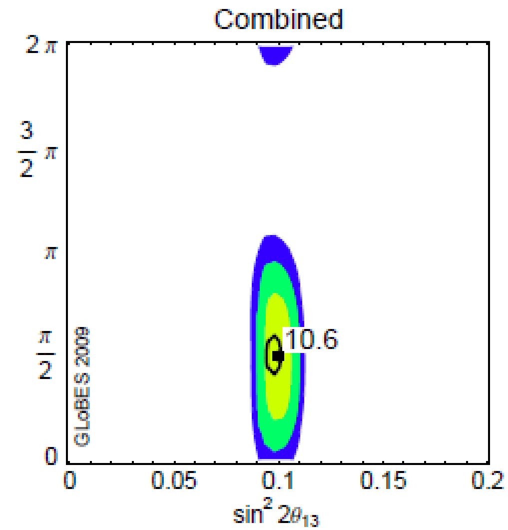
Normal hierarchy

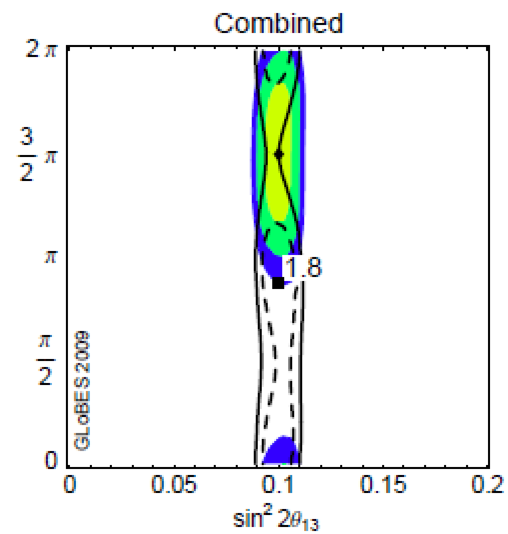




T2K+
Nova+
Daya Bay

Inverted hierarchy





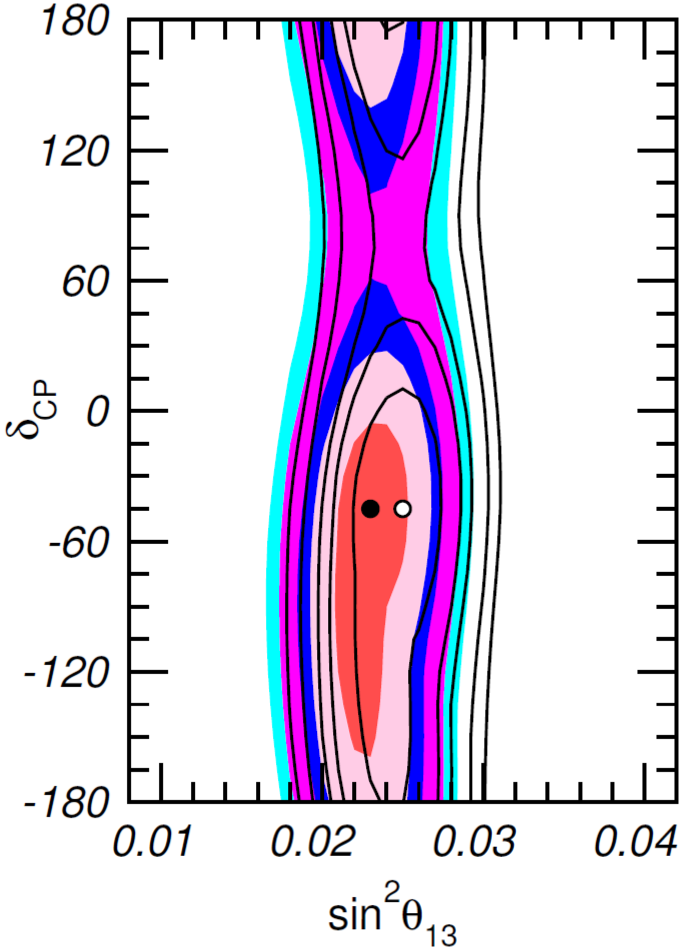
From P. Huber *et al.* 0907.1896

Sensitivities with present experiments

Normal hierarchy

1 σ, 90%, 2 σ, 99% and 3 σ

Inverted hierarchy



mainly
T2K+
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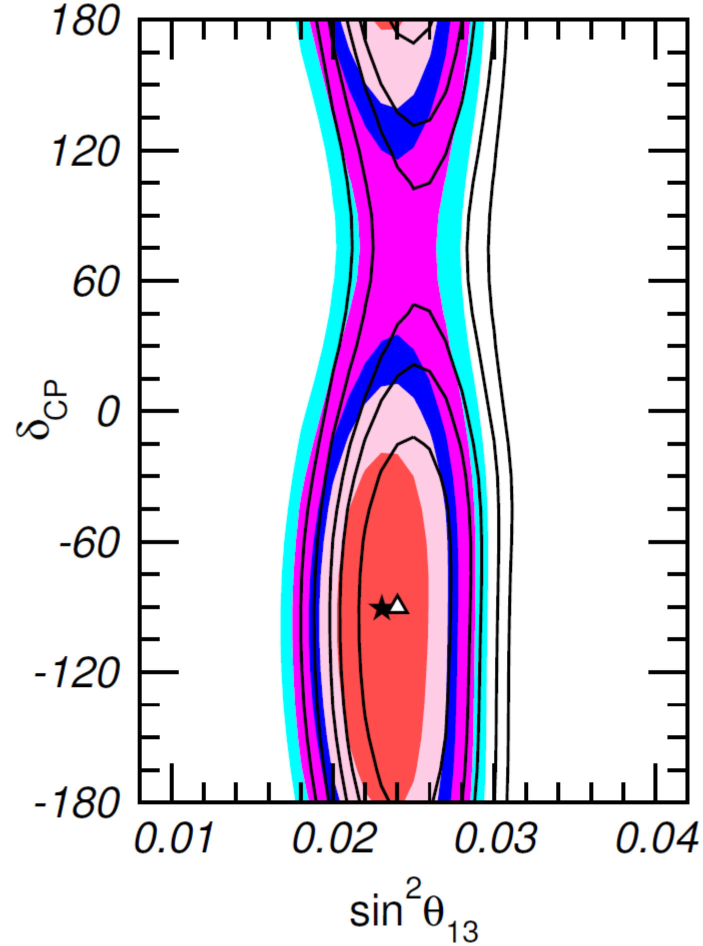


From M. C. Gonzalez-Garcia, M. Maltoni, J. Salvado, T. Schwetz 1209.3023 www.nu-fit.org

Shoplist of future facilities

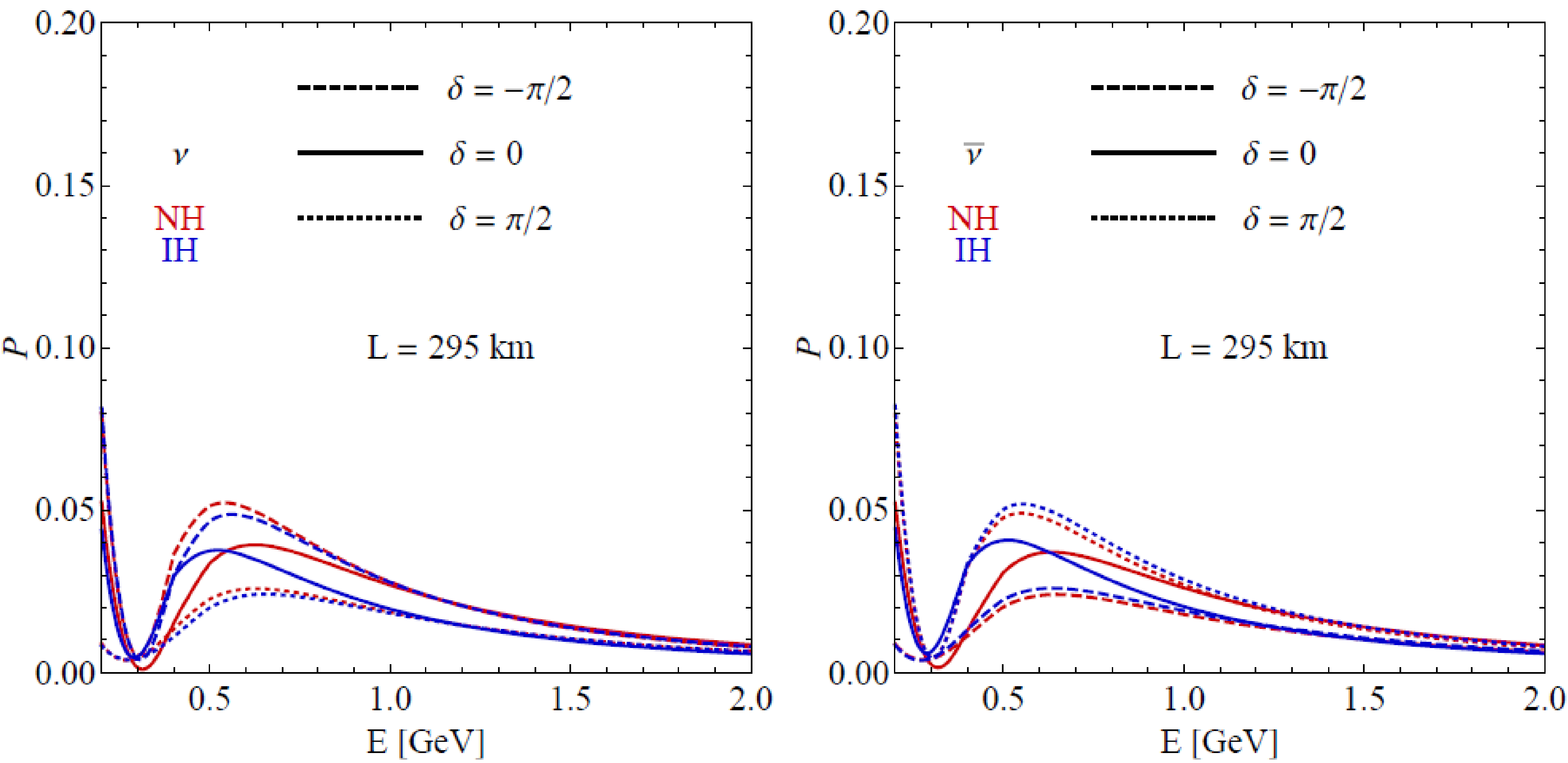
Big WC detectors, low energies, small matter effects

	detector vol. (kt)/type	dist. (km)	power (MW)	proton driver energy (GeV)	years $\nu/\bar{\nu}$
ESSνSB-360	500/WC	360	5	2.0/3.0	2/8
ESSνSB-540	500/WC	540	5	2.0/3.0	2/8
Hyper-K	560/WC	295	0.75	30	3/7
LBNE-10	10/LAr	1290	0.72	120	5/5
LBNE-PX	34/LAr	1290	2.2	120	5/5
LBNO-EoI	20/LAr	2300	0.7	400	5/5
IDS-NF	100/MIND	2000	4	10*	10**
NuMAX	10/LAr (magnetized)	1300	1	5*	5/5

LAr detectors, high energies and broad beams, big matter effects

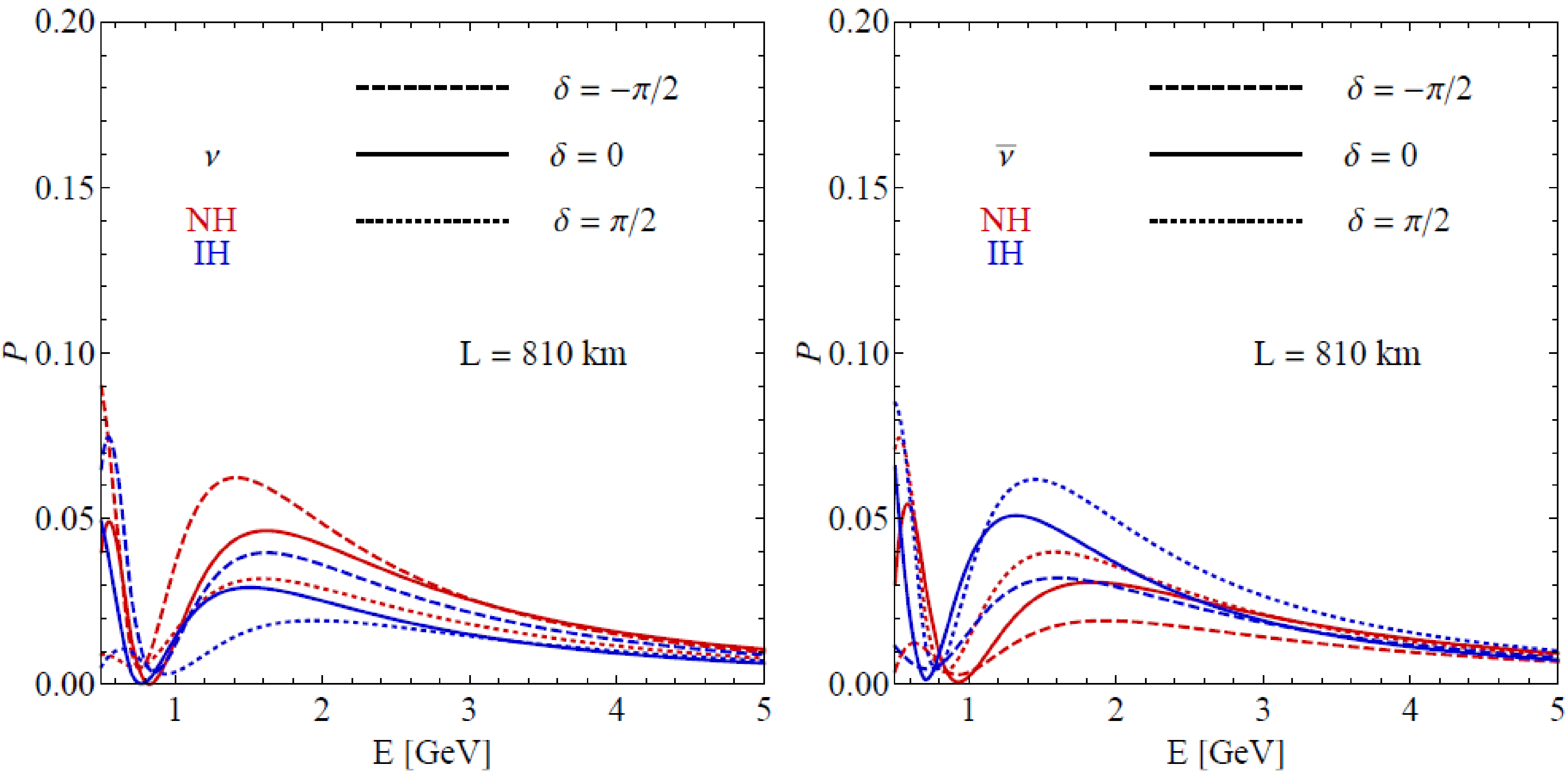
E. Baussan et al 1309.7022

Probabilities



Plot from the Physics Briefing Book: Input for the Strategy Group to the European Strategy for Particle Physics

Probabilities



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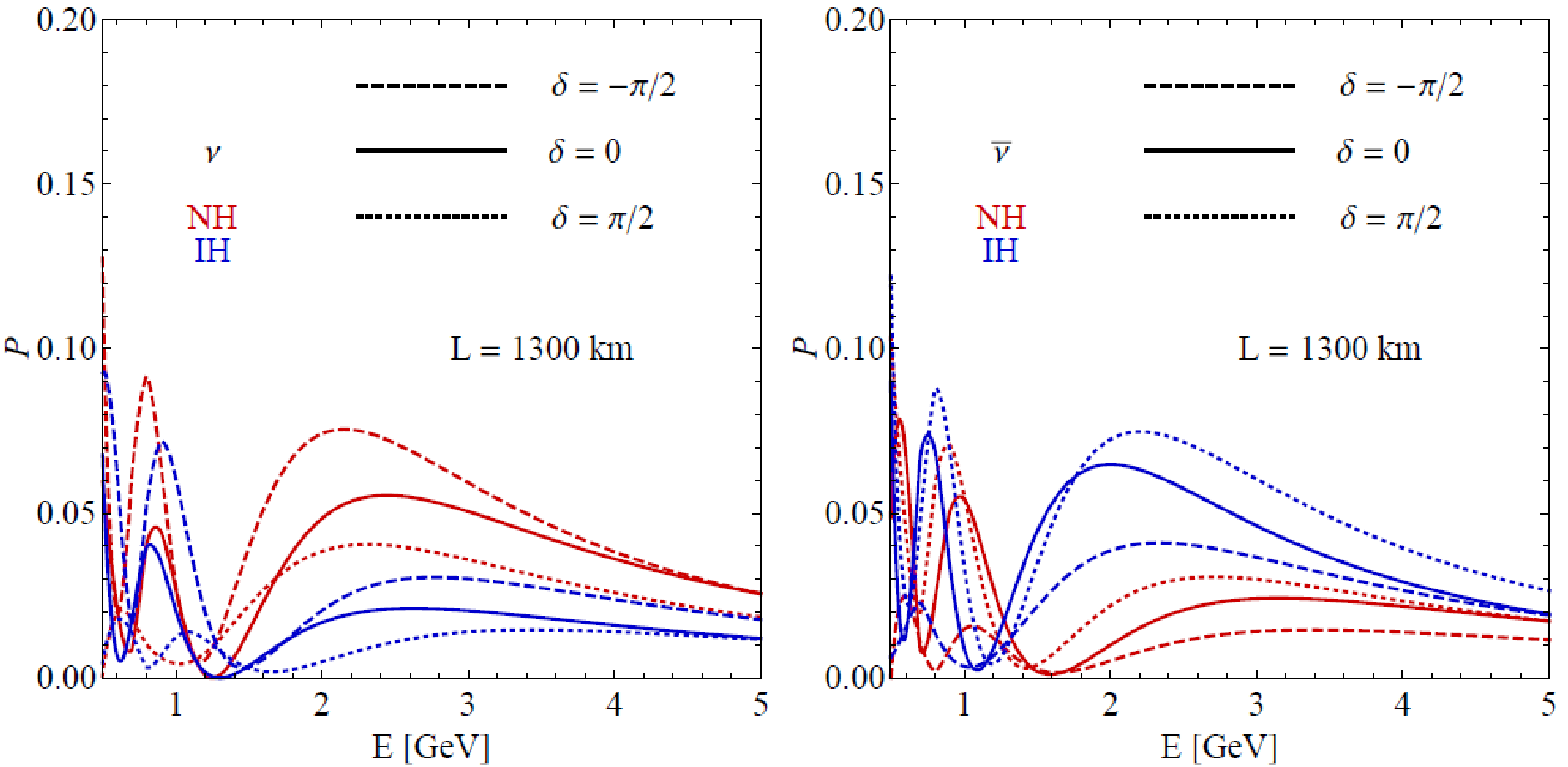

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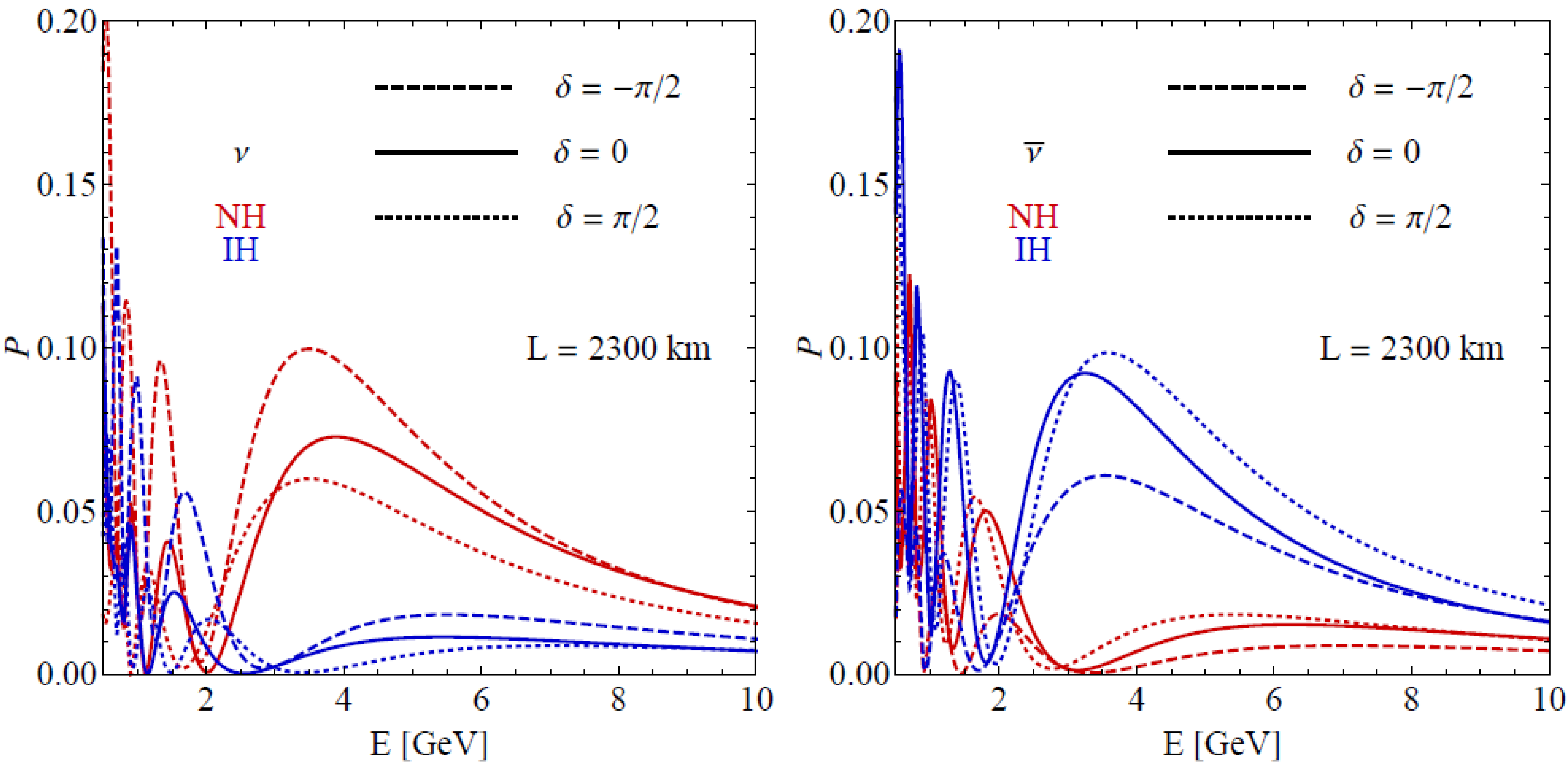

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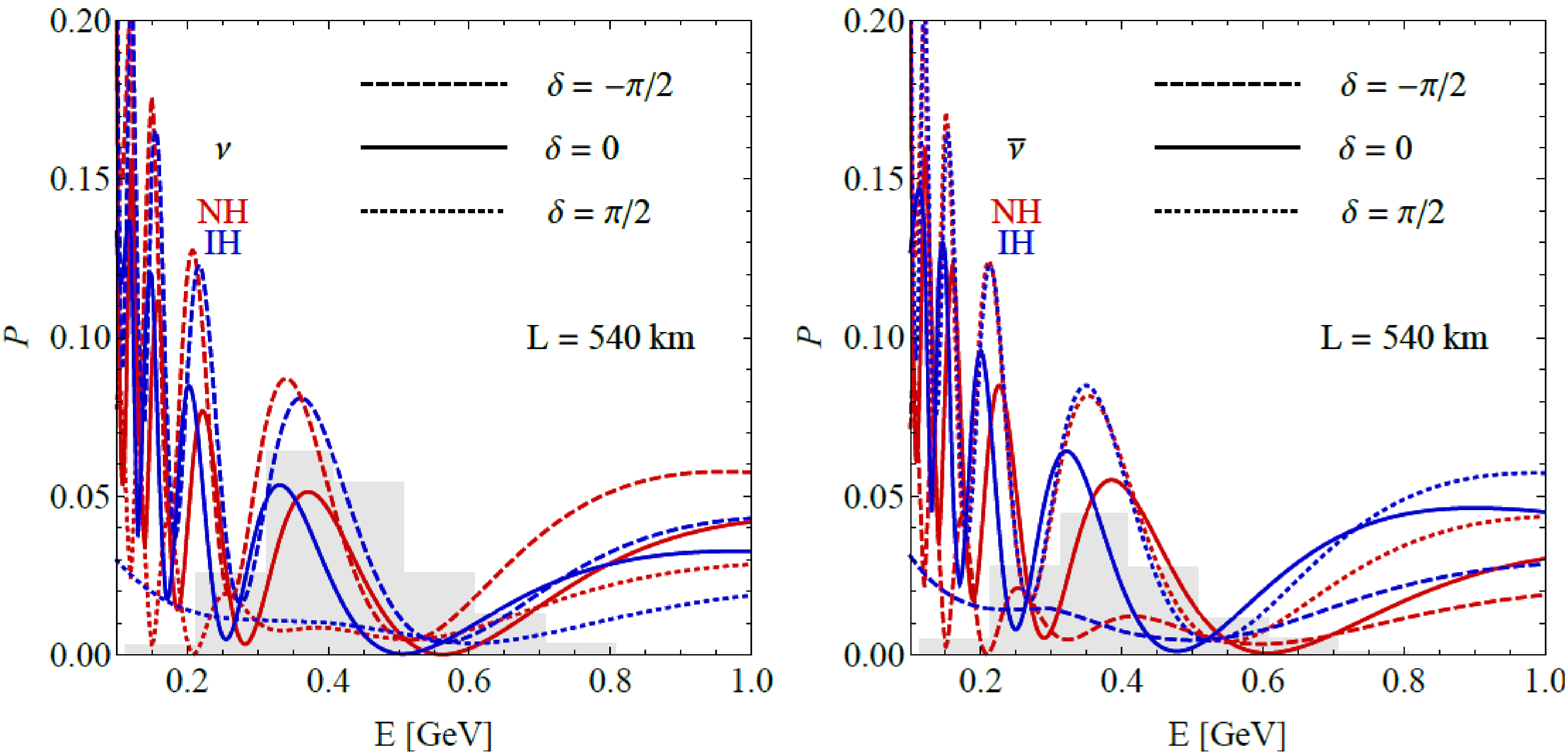
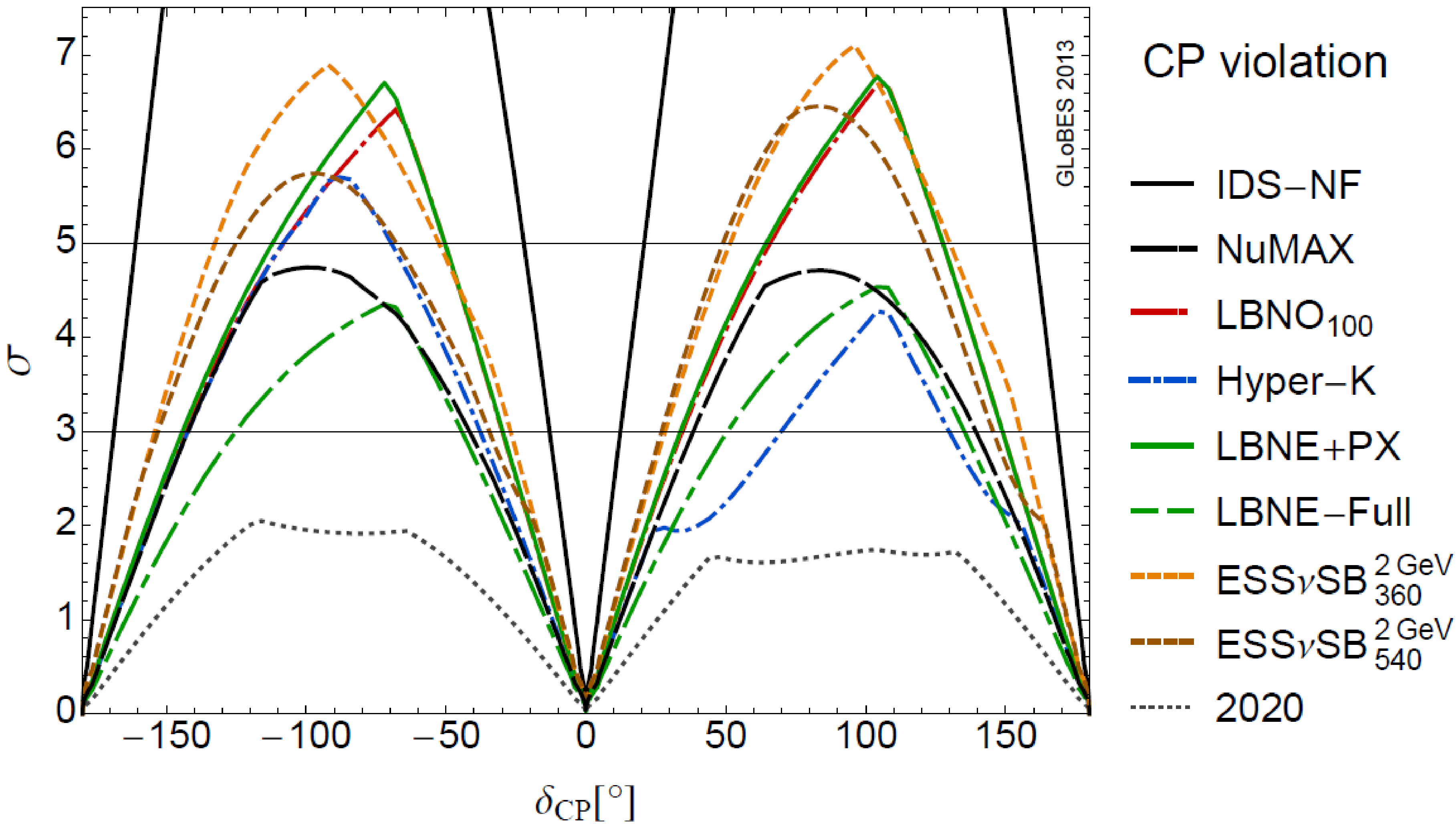
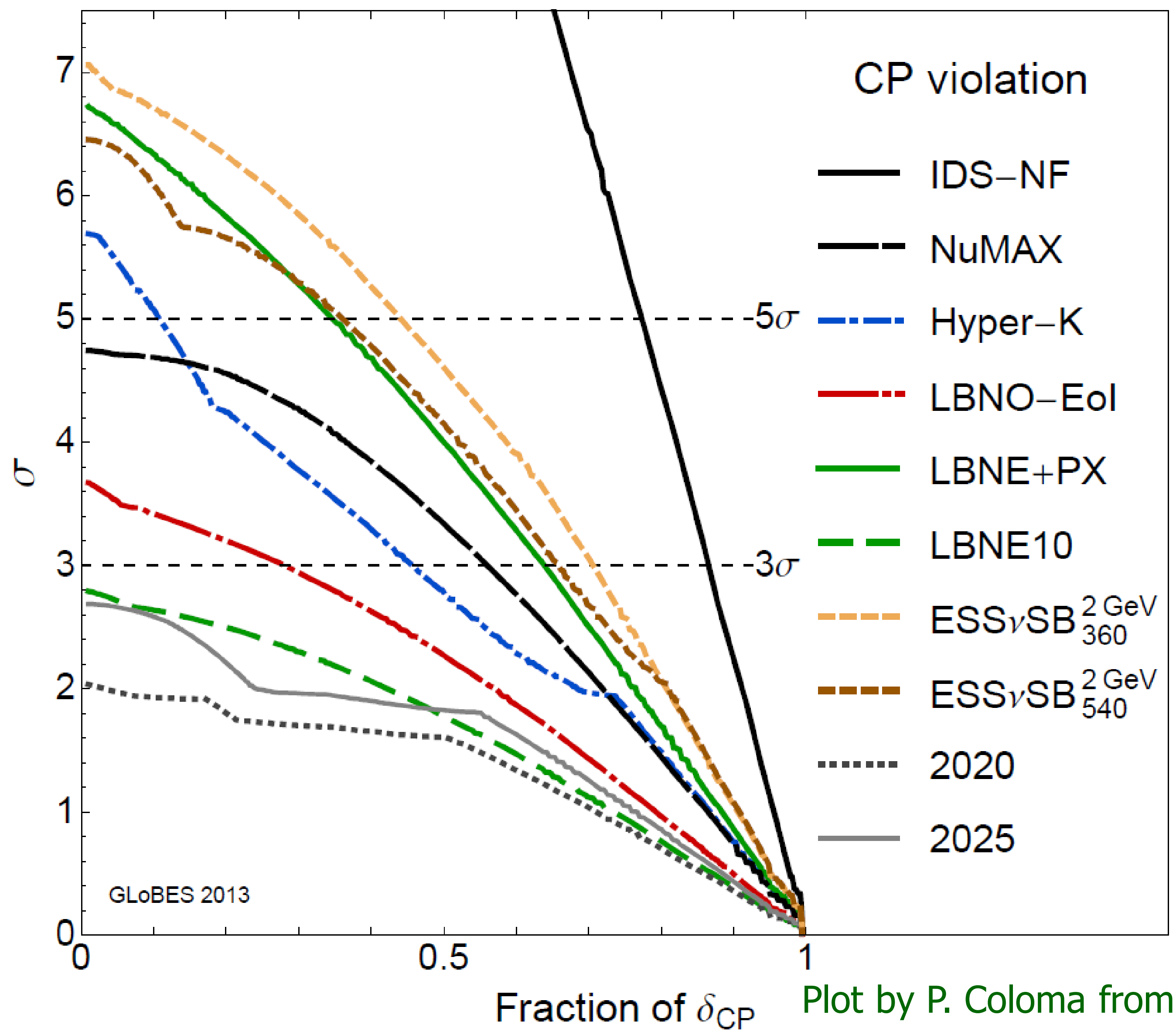


Sensitivities to CPV



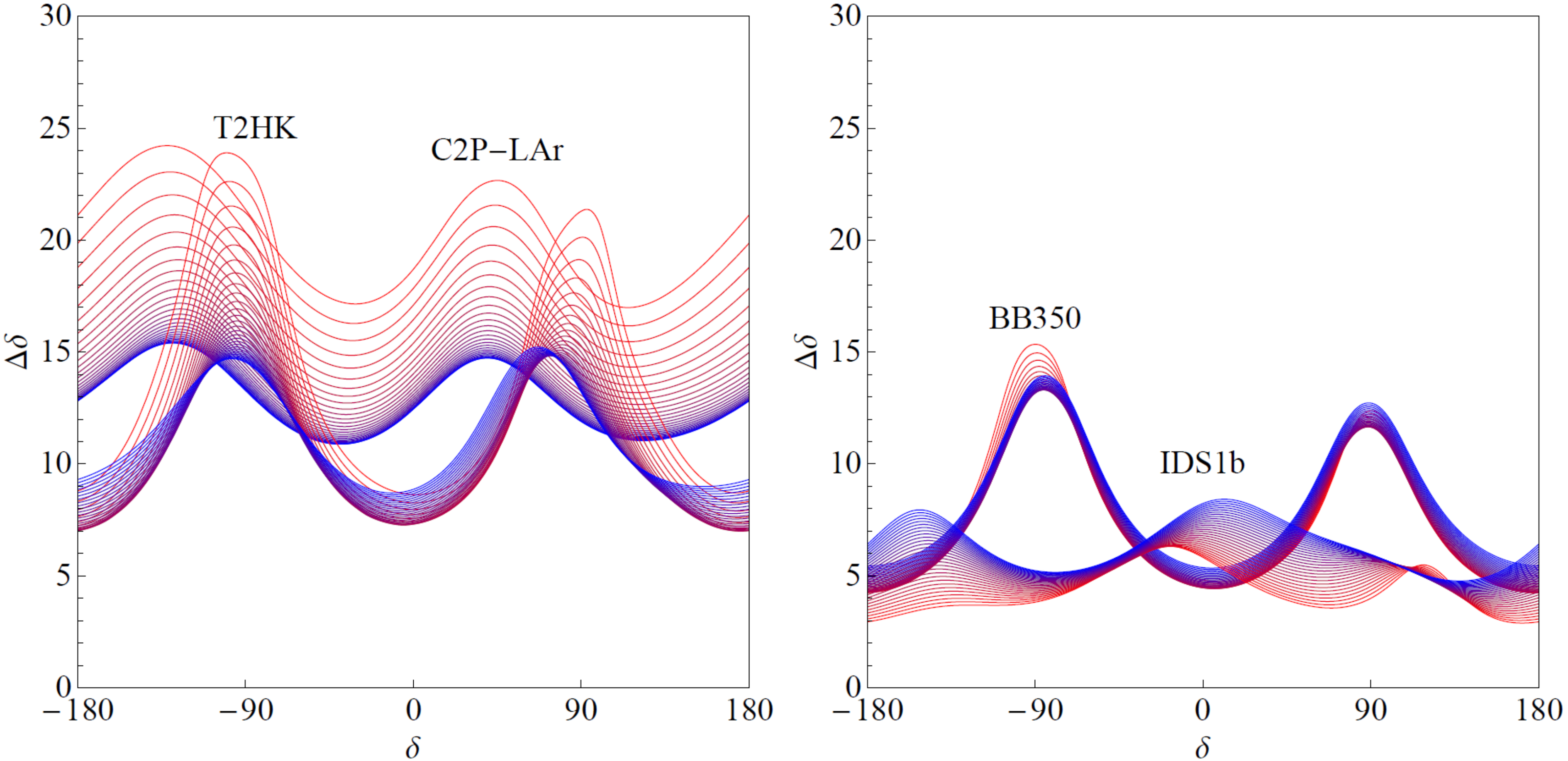
Plot by P. Coloma

Sensitivities to CPV



Plot by P. Coloma from 1309.7022

Precision



θ_{13}: 3º - 10º

P. Coloma, A. Donini, EFM and P. Hernandez 1203.5651

Sensitivities with future experiments

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4. Repeat for as many "true values" as you want and plot

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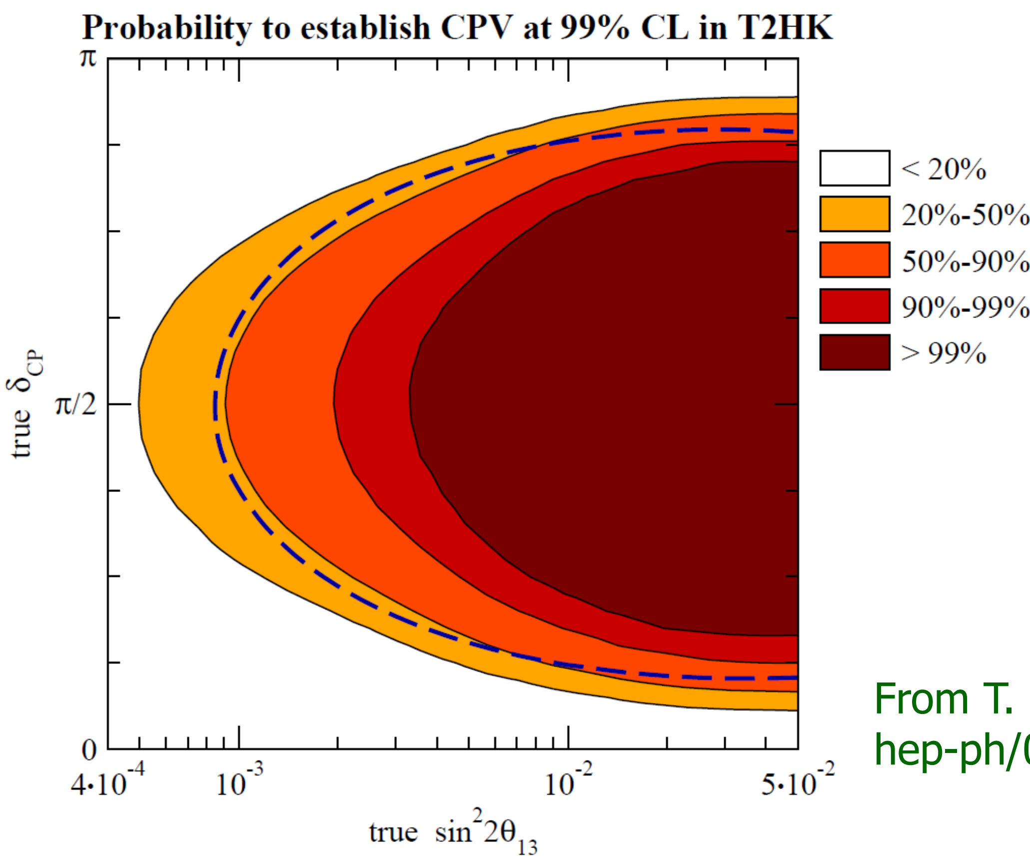

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From T. Schwetz
hep-ph/0612223

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Not so interested in knowing that a facility is expected to provide 4.5 σ or 8 σ. It is more interesting to know the probability for the facility to achieve 5 σ!

The first could get lucky, the second unlucky…

Naturally the two things are correlated

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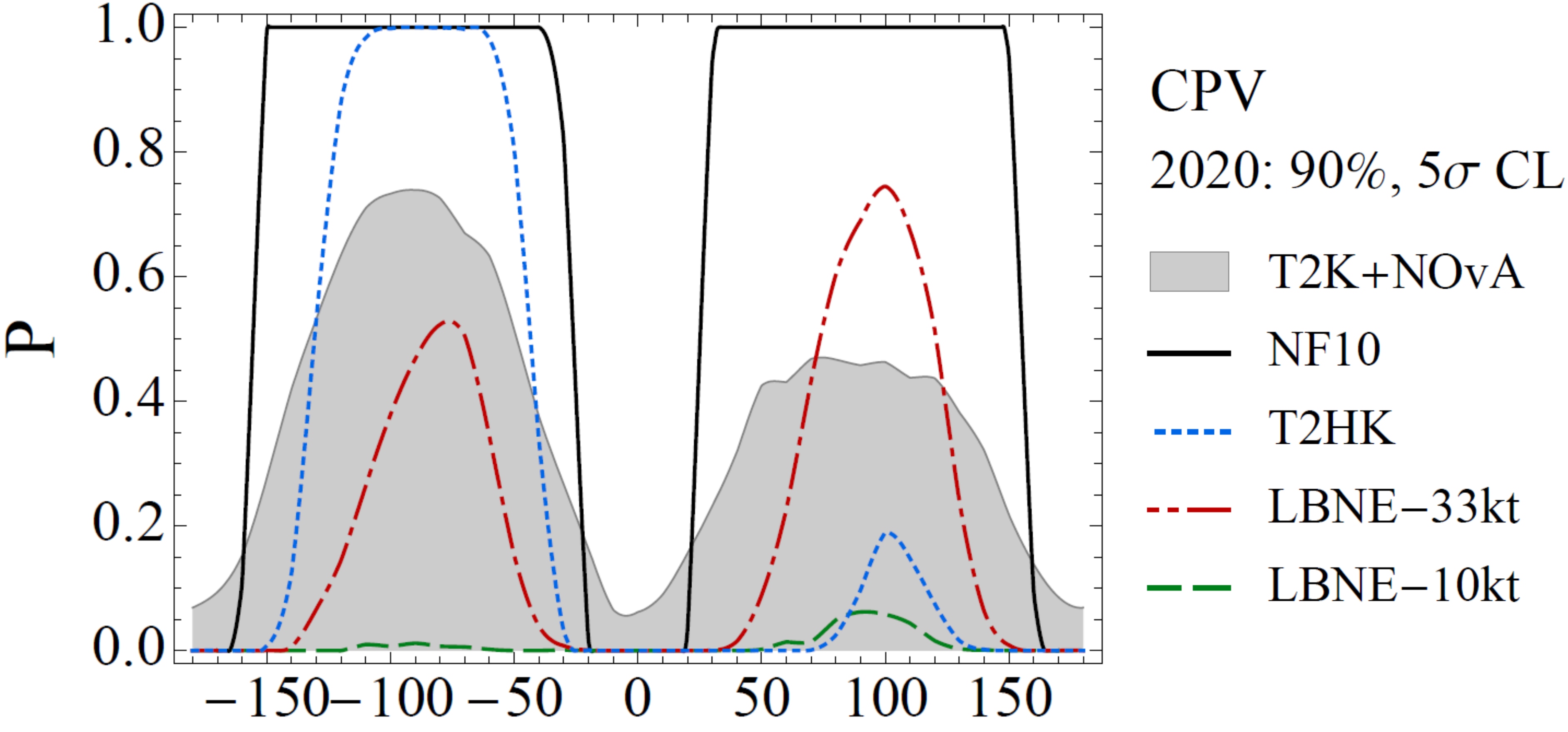
2. Generate a large (~1000) number of realizations of that experiment with the expected mean and deviation

3. Compute the χ^2 between each realization and the "null hypothesis" and check if the target CL was reached for that realization. Count how many, that gives and estimation of the success probability.

4. Repeat for as many "true values" as you want and plot

Probabilities for CPV discovery



M. Blennow, P. Coloma, A. Donini and EFM 1303.0003

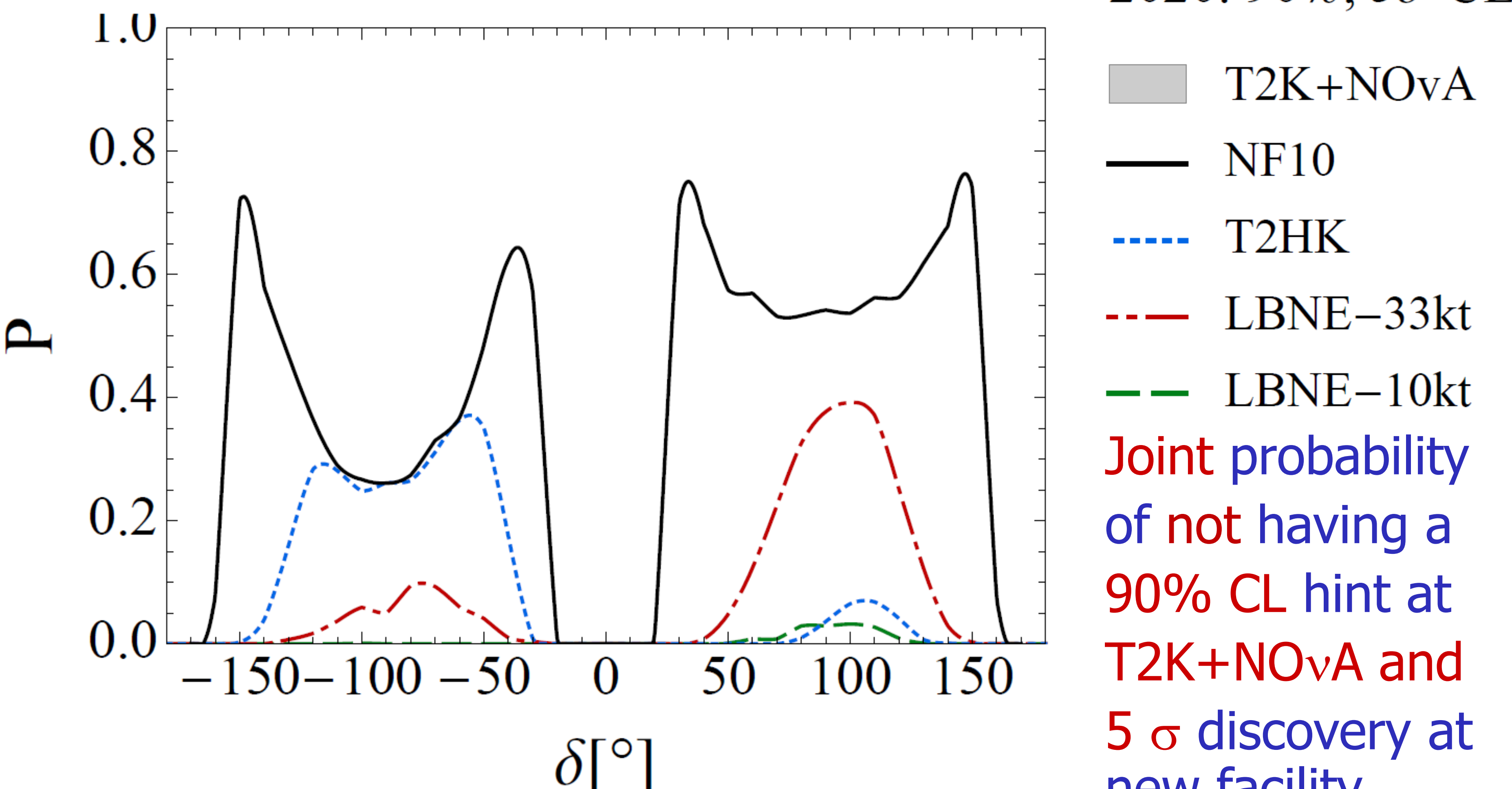
90 % CL for T2K+NOνA, 5 σ for the rest

Sensitivity peaked around ±90º for all

Probabilities for CPV discovery

Sensitivity peaked around ±90º for all

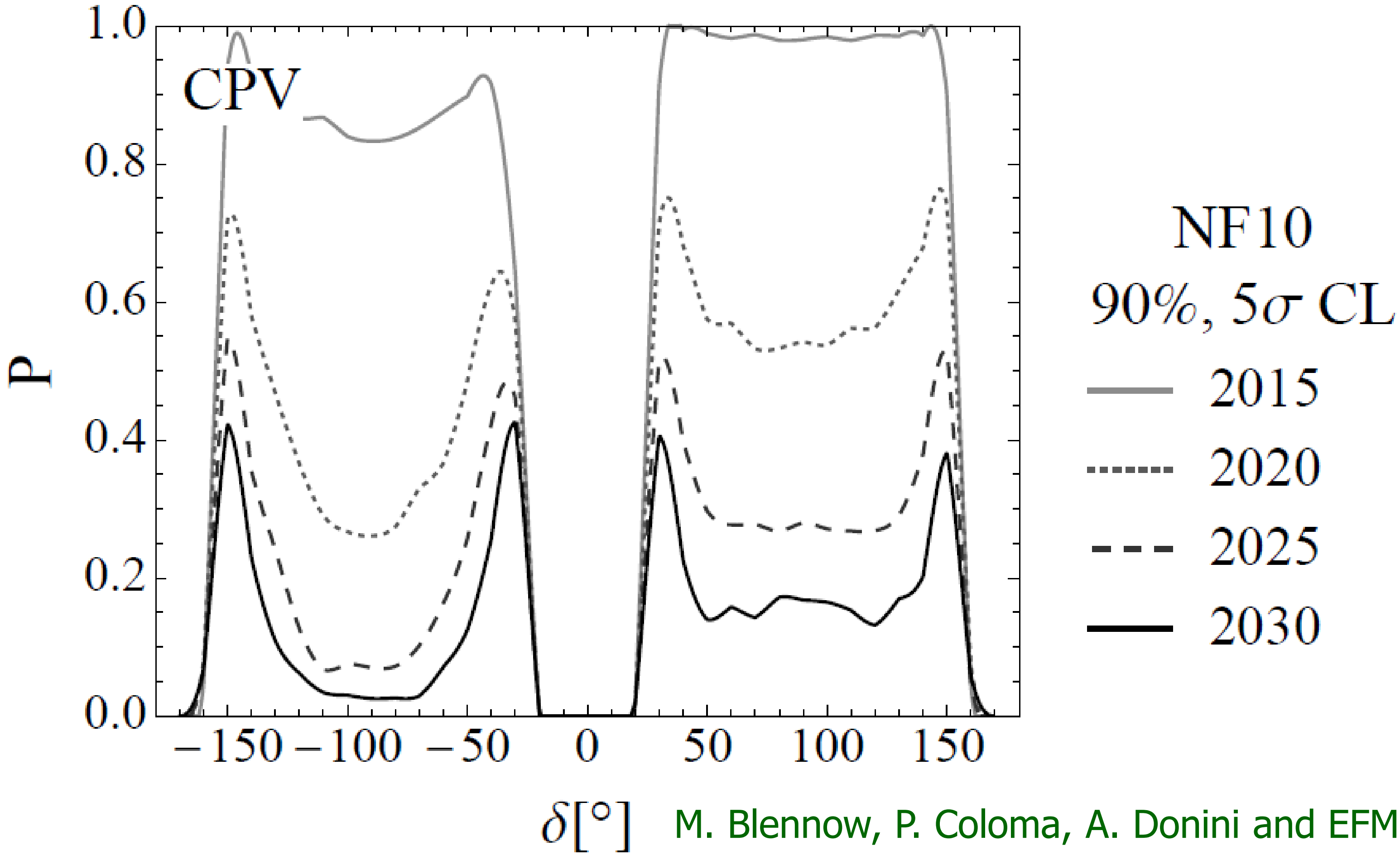
If T2K+NOνA dont see, will the others see?



M. Blennow, P. Coloma, A. Donini and EFM 1303.0003

Joint probability of not having a 90% CL hint at T2K+NOνA and 5 σ discovery at new facility

Probabilities for CPV discovery



M. Blennow, P. Coloma, A. Donini and EFM 1303.0003

Joint probability of not having a 90% CL hint at T2K+NOνA and 5 σ discovery at new facility. Less and less likely when increasing T2K+NOνA running time if no hint.

Conditional probability

The results from T2K+NOνA will constrain our prior knowledge of δ for the next facilities

Negative results will make CPV values of δ less likely

$$P\left(\delta \mid T2K + NO\nu A\right)$$

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The probability of discovery of the new facility contidioned to T2K+NOνA results:

$$P(disc \mid T2K + NO\nu A) = \int P(disc \mid T2K + NO\nu A, \delta) P(\delta \mid T2K + NO\nu A) d\delta$$

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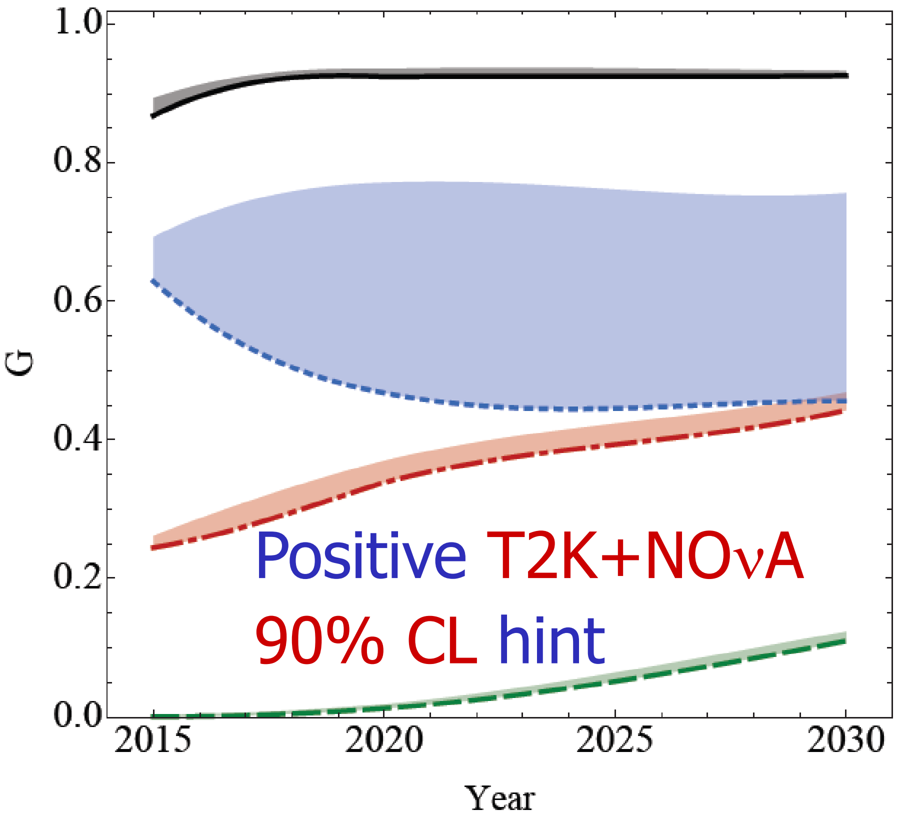
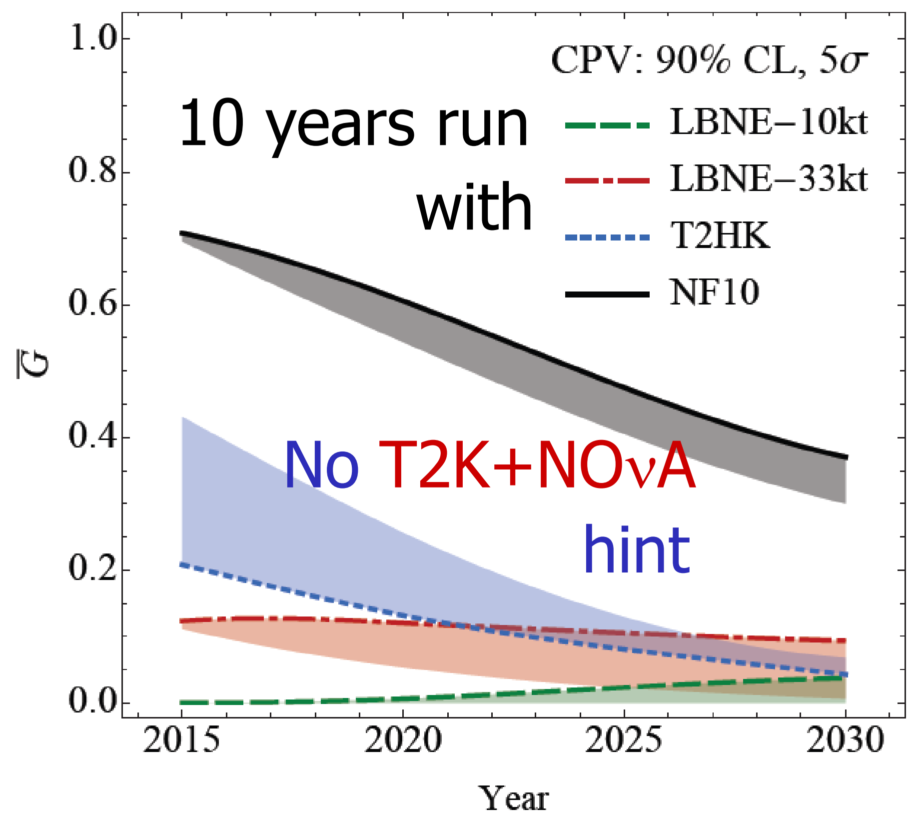
Can be easily computed from the joint prob:

$$P(disc \mid T2K + NO\nu A) = \frac{P(disc, T2K + NO\nu A)}{P(T2K + NO\nu A)}$$

Conditional probability





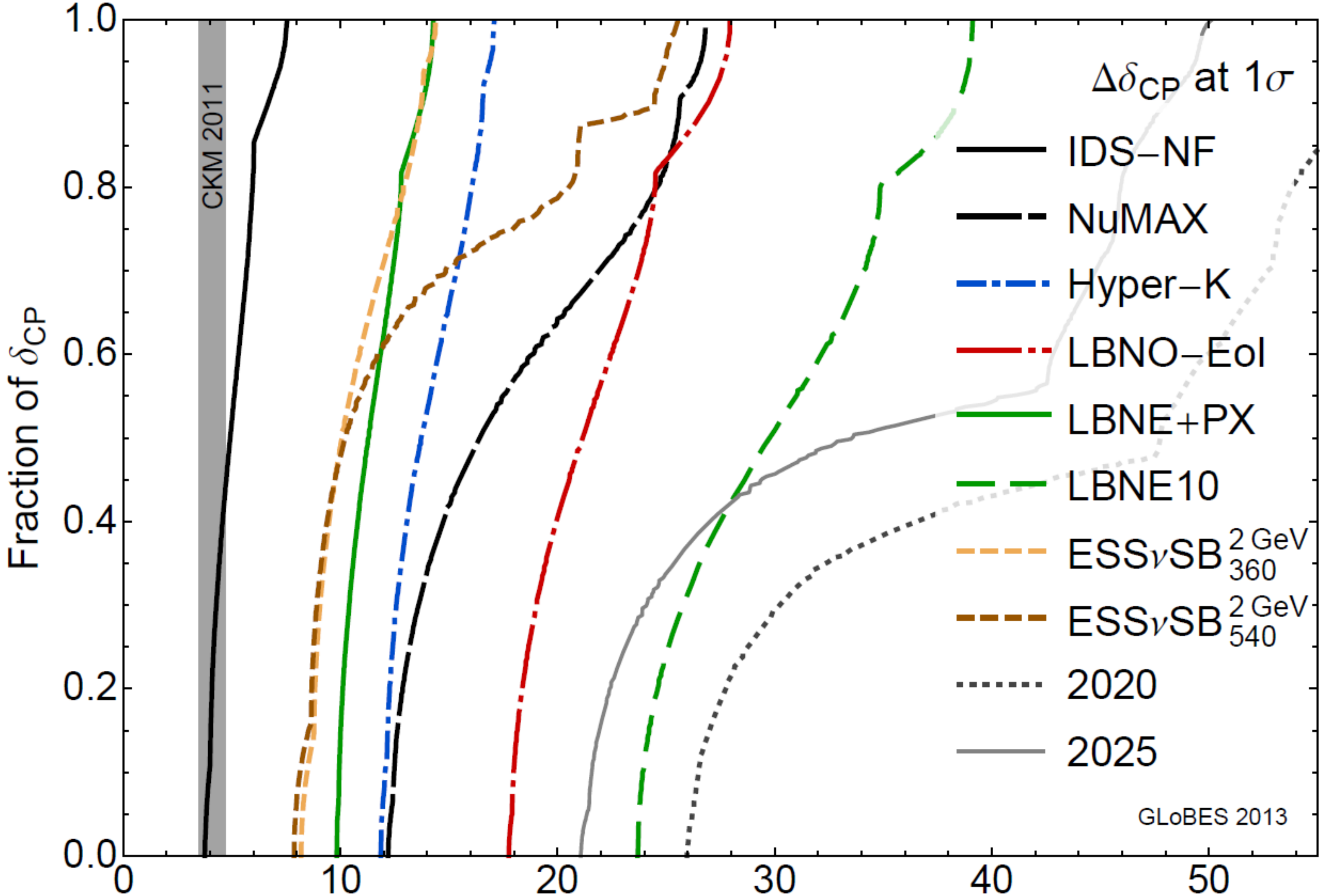
Assuming a uniform probability distribution of δ, how likely is a discovery (5σ) by a new facility if T2K+NOνA (dont) have a 90% hint by the year X? Upper (lower) end of band for (un)known hierarchy

M. Blennow, P. Coloma, A. Donini and EFM 1303.0003

Conclusions

- The large value of θ_{13} discovered opens the window to the measurement of the neutrino mass hierarchy and leptonic CP violation.
- T2K and Noνa will provide the first ~90% CL indications over the next years. In order to reach discovery, upgraded or new facilities will be needed.
- The optimization strategy for CPV changes for large θ_{13}: importance of systematic errors and the second oscillation peak over statistics and backgrounds.

Precision in δ



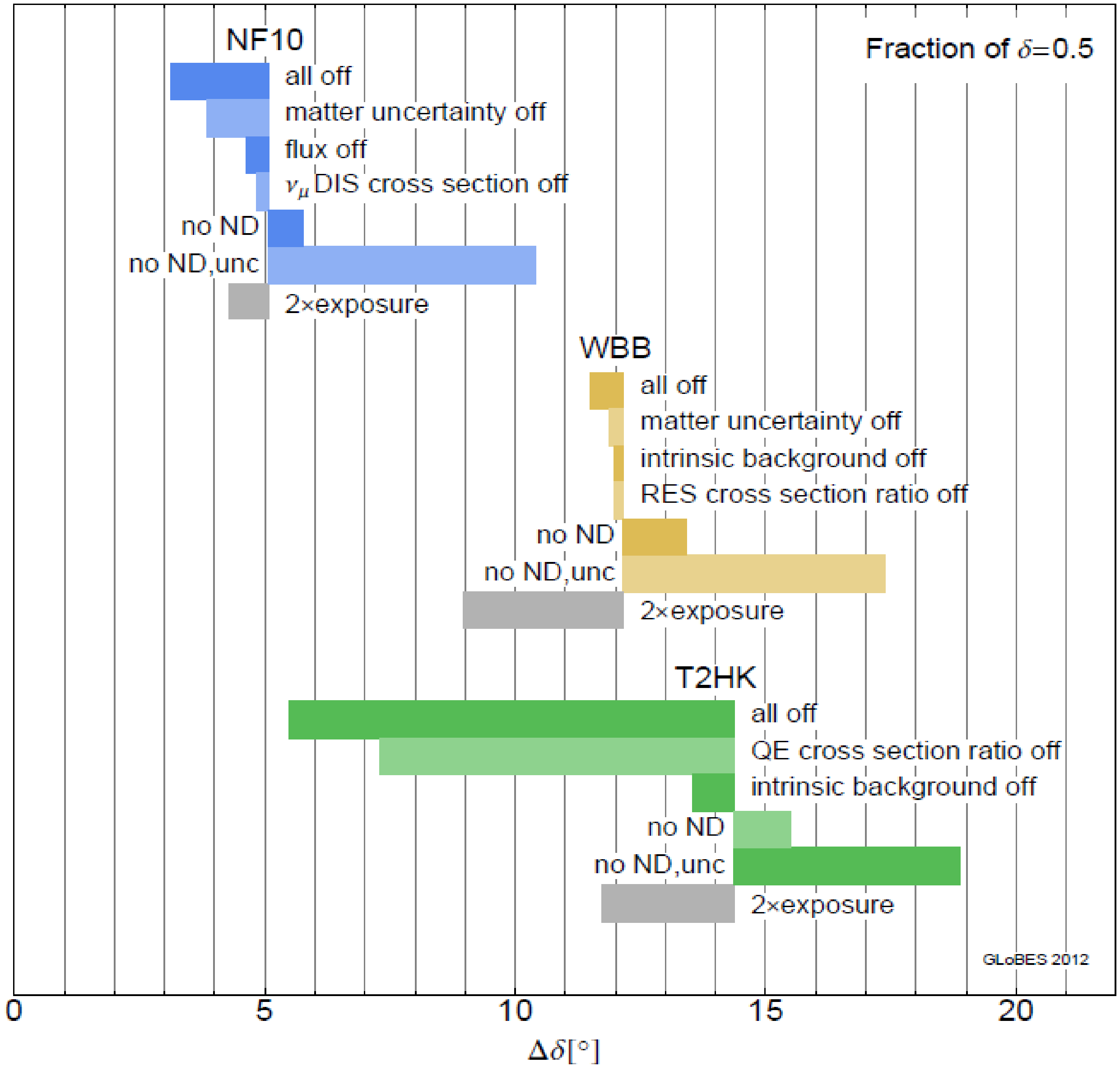
Plot by P. Coloma from 1309.7022

Systematics

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

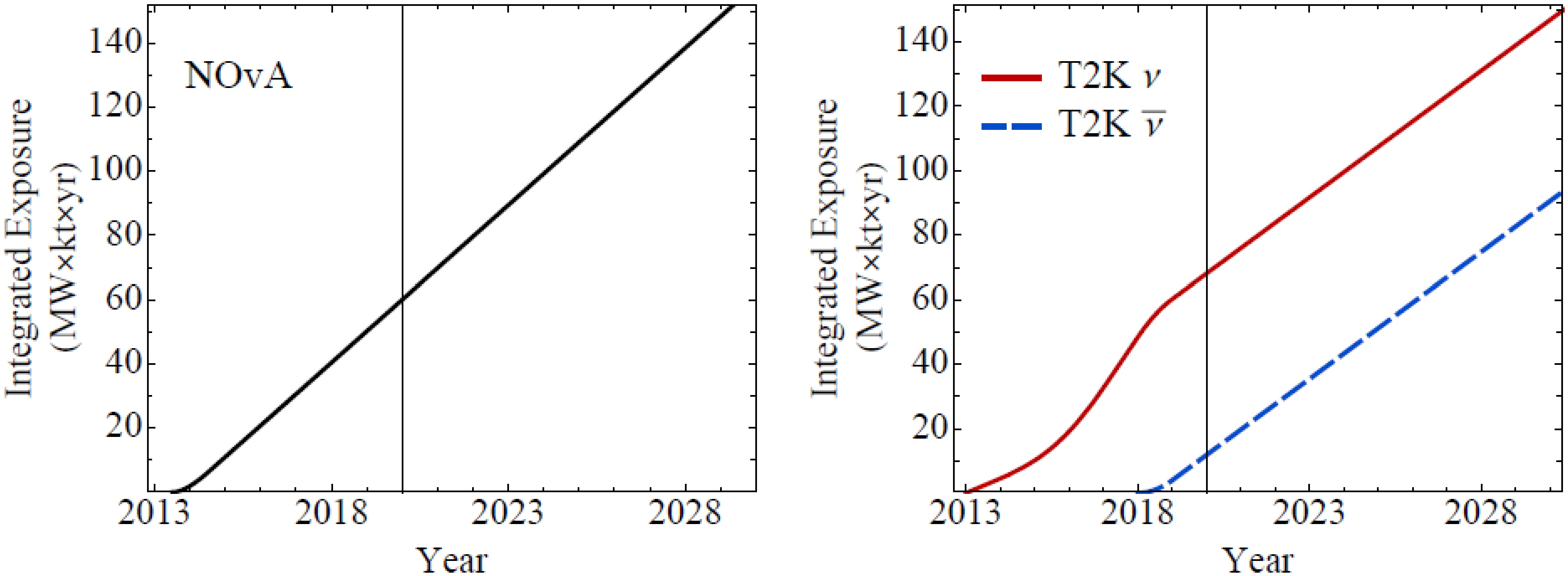
P. Coloma et al 1209.5973

Systematics

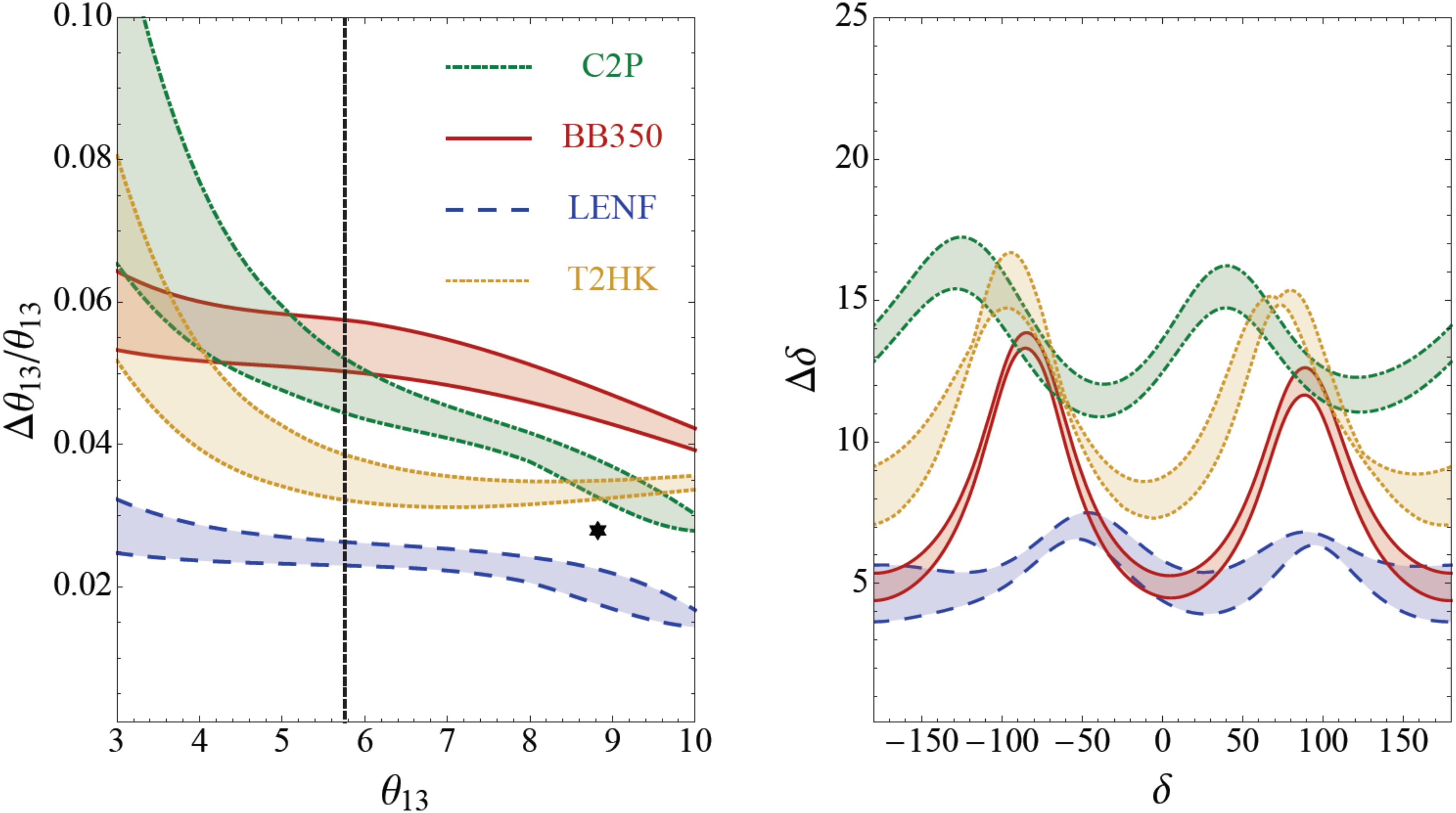


P. Coloma et al 1209.5973

T2K+NOνA Running time



Precision



P. Coloma, A. Donini, EFM and P. Hernandez 1203.5651