Towards the measurements of mass hierarchy and CP violation in neutrino oscillations

Frontiers in Particle Physics:
From Dark Matter to the LHC and Beyond

Aspen, USA

Jan. 18-24, 2014

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Deutsche Forschungsgemeinschaft

Contents

- Current knowledge of neutrino oscillations
- Mass hierarchy determination
- Measurement of the CP phase
- Summary

Neutrino oscillations
(two flavors)

- Two parameters:

$$U = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix}$$

Evidence for massive neutrinos!

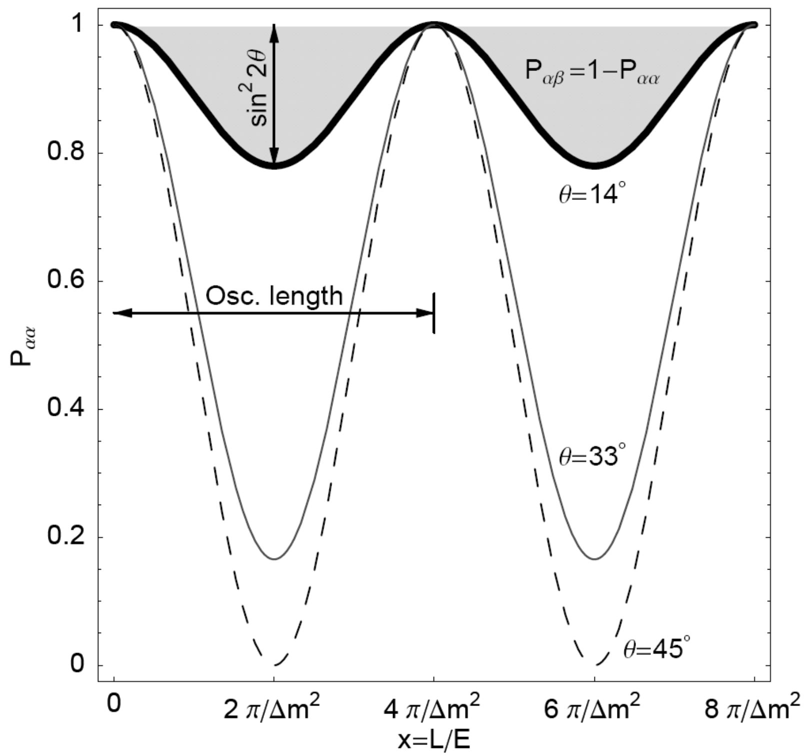
$$\Delta m^2 \equiv m_2^2 - m_1^2$$

- **Disappearance** or **survival** probability

$$P_{\alpha\alpha} = 1 - \sin^2 2\theta \, \sin^2\left(\frac{\Delta m^2 L}{4E}\right)$$

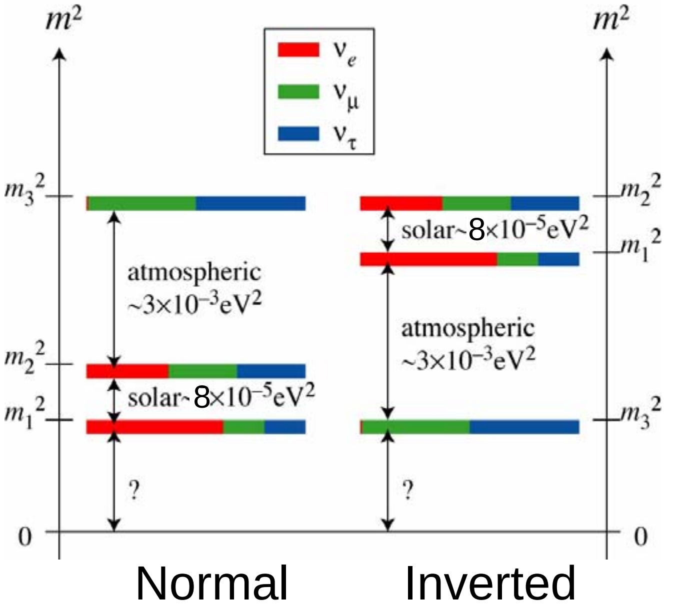
Appearance probability

$$P_{\alpha\beta} = \sin^2 2\theta \, \sin^2\left(\frac{\Delta m^2 L}{4E}\right)$$



Three flavors: Masses and mixings

- Two independent mass squared splittings, typically
  Δm^2_{21} (solar)
  Δm^2_{31} (atmospheric)



- Mixing: Use same parameterization as for CKM matrix (4 params)

($s_{ij} = \sin\theta_{ij}$ $c_{ij} = \cos\theta_{ij}$)

Potential CP violation ~ θ_{13}

$$U_{\mathrm{PMNS}} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}\, e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}\, e^{i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} .$$

Observation of Mixing Angle θ_{13}

in the Daya Bay Reactor Antineutrino Experiment

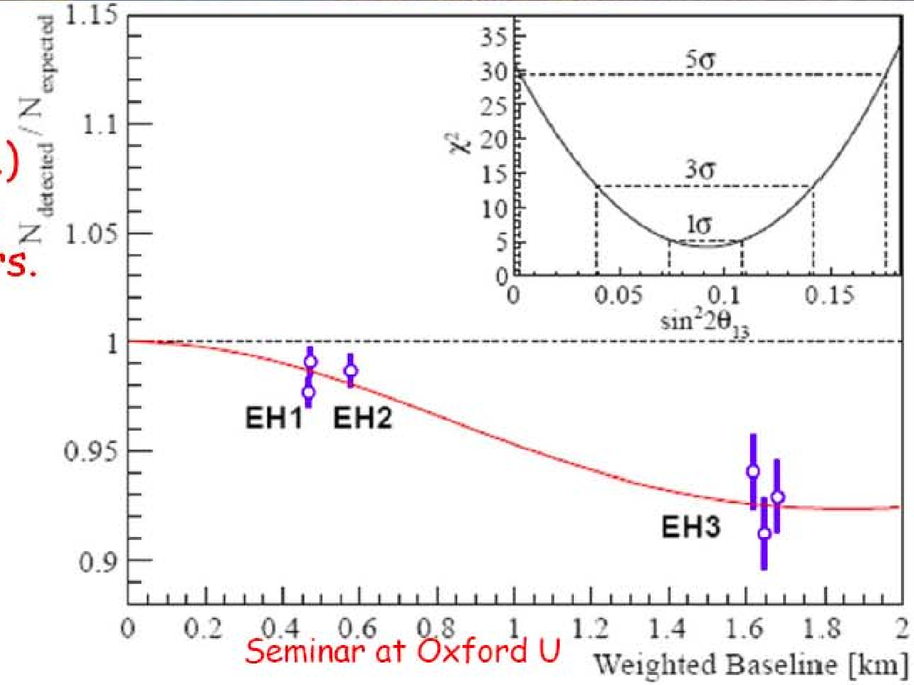
$$P_{\bar{e}\bar{e}} \simeq 1 - \sin^2(2\theta_{13})\sin^2\Delta_{31}$$

(short distance)

Kirk T McDonald
Princeton U
(April 24, 2012)
on behalf of the Daya Bay Collaboration

We observe that
$\sin^2 2\theta_{13}$ = 0.092 ± 0.016 (stat.) ± 0.005 (syst.)
after 55 days of operation with 6 detectors
at 3 sites close to 3 pairs of ~ 3 GW reactors.

F.P. Ahn *et al.*
Phys. Rev. Lett. **108**, 171803 (2012).



(also: T2K, Double Chooz, RENO)

Precision of parameters?

Gonzalez-Garcia, Maltoni, Salvado, Schwetz, JHEP 1212 (2012) 123

NuFIT 1.2 (2013)

	bfp $\pm 1\sigma$	3σ range
$\sin^2\theta_{12}$	$0.306^{+0.012}_{-0.012}$	$0.271 \to 0.346$
$\theta_{12}/^\circ$	$33.57^{+0.77}_{-0.75}$	$31.38 \to 36.01$
$\sin^2\theta_{23}$	$0.446^{+0.007}_{-0.007} \oplus 0.587^{+0.032}_{-0.037}$	$0.366 \to 0.663$
$\theta_{23}/^\circ$	$41.9^{+0.4}_{-0.4} \oplus 50.0^{+1.9}_{-2.2}$	$37.2 \to 54.5$
$\sin^2\theta_{13}$	$0.0229^{+0.0020}_{-0.0019}$	$0.0170 \to 0.0288$
$\theta_{13}/^\circ$	$8.71^{+0.37}_{-0.38}$	$7.50 \to 9.78$
$\delta_{CP}/^\circ$	265^{+56}_{-61}	$0 \to 360$
$\frac{\Delta m^2_{21}}{10^{-5}\ \text{eV}^2}$	$7.45^{+0.19}_{-0.16}$	$6.98 \to 8.05$
$\frac{\Delta m^2_{31}}{10^{-3}\ \text{eV}^2}$ (N)	$+2.417^{+0.013}_{-0.013}$	$+2.247 \to +2.623$
$\frac{\Delta m^2_{32}}{10^{-3}\ \text{eV}^2}$ (I)	$-2.410^{+0.062}_{-0.062}$	$-2.602 \to -2.226$

± 2%

± 4% (or better)

± 4%

± 3%

± 3%

⇨ More details: talk by R. Patterson

Age of the **precision flavor physics of the lepton sector**

Open issues:
- Degeneracies (mass ordering, octant)
- CP phase

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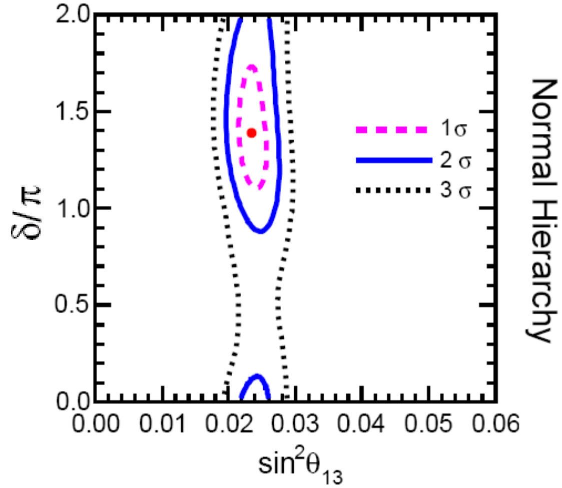
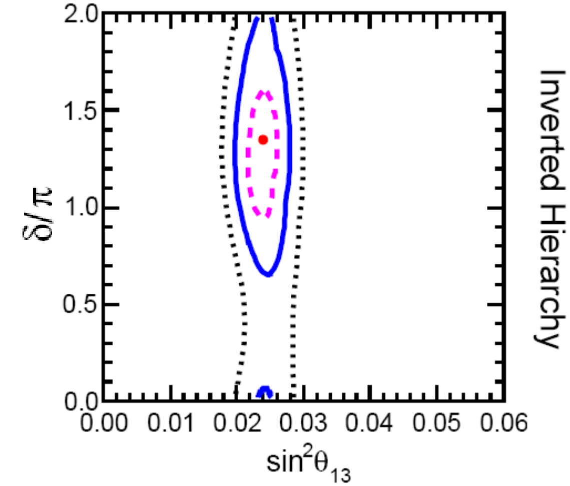
Latest fits vs. projection

- Indication for δ_{CP}, no evidence for mass hierarchy

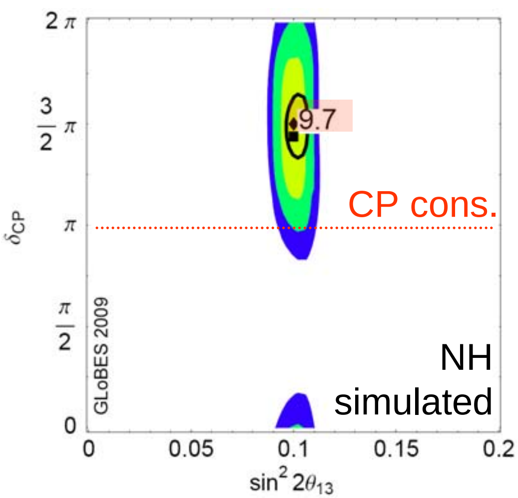


LBL Acc + Solar + KL
+ SBL Reactors
+ SK Atm

Capozzi, Fogli, Lisi, Marrone, Montanino, Palazzo, arXiv:1312.2878



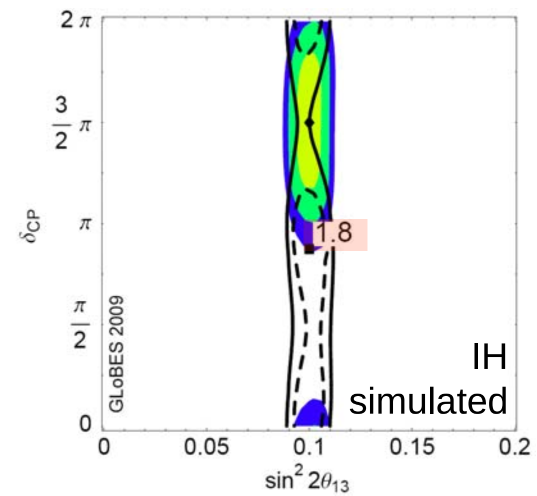
- Potential of existing equipment



T2K, NOvA,
Double Chooz, Daya Bay;
5 years each

High CL determination requires new equipment

Huber, Lindner, Schwetz, Winter, JHEP 0911 (2009) 044



Short-distance anomalies

... unresolved 2.0

$\Delta m^2_{41} L/(4E)$

Example: 3+1 scenario

$$P_{ee} = 1 - 4|U_{e4}|^2(1-|U_{e4}|^2)\sin^2\Delta_{41}\,, \quad ?$$

$$P_{\mu\mu} = 1 - 4|U_{\mu 4}|^2(1-|U_{\mu 4}|^2)\sin^2\Delta_{41}\,,$$

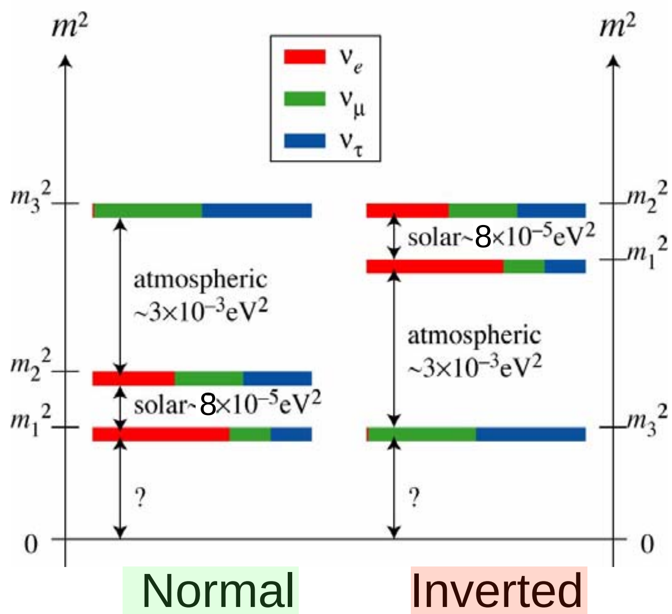
$$P_{e\mu} = P_{\mu e} = 4|U_{e4}|^2|U_{\mu 4}|^2\sin^2\Delta_{41}\,,$$

⇨ MiniBooNE

- Well known tension between appearance and disapp. data (appearance ⇨ disapp. in both channels)
- Need one or more new experiments which can test
  - ν_e disappearance (Gallium, reactor anomalies)
  - ν_μ disappearance (overconstrains 3+N frameworks)
  - ν_e-ν_μ oscillations (LSND, MiniBooNE)
  - Neutrinos and antineutrinos separately (CP violation? Gallium vs reactor?)
- Summary of options: Appendix of white paper **arXiv:1204.5379**
- Example: completely self-consistent test at **νSTORM - Neutrinos from STORed Muons**

Mass hierarchy determination

Why would one like to measure the mass hierarchy?



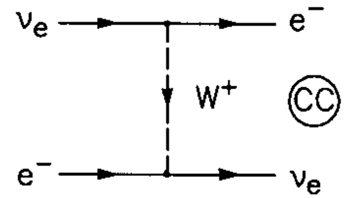
- Mass hierarchy is a good model discriminator **(Albright, Chen, 2006)** →
- Leading indicator for flavor model?
  [determines structure of couplings in hierarchical models]

Reference		Hierarchy
Anarchy Model:		
dGM	[18]	Either
$\mathbf{L_e - L_\mu - L_\tau}$ **Models:**		
BM	[35]	Inverted
BCM	[36]	Inverted
GMN1	[37]	Inverted
GL	[38]	Inverted
PR	[39]	Inverted
$\mathbf{S_3}$ **and** $\mathbf{S_4}$ **Models:**		
CFM	[40]	Normal
HLM	[41]	Normal
		Normal
KMM	[42]	Inverted
MN	[43]	Normal
MNY	[44]	Normal
MPR	[45]	Normal
RS	[46]	Inverted
		Normal
TY	[47]	Inverted
T	[48]	Normal
$\mathbf{A_4}$ **Tetrahedral Models:**		
ABGMP	[49]	Normal
AKKL	[50]	Normal
Ma	[51]	Normal
SO(3) Models:		
M	[52]	Normal
Texture Zero Models:		
CPP	[53]	Normal
		Inverted
		Inverted
WY	[54]	Either
		Either
		Either

Parameter mapping

… for two flavors, constant matter density

- Oscillation probabilities in
  vacuum: $P_{\alpha\alpha} = 1 - \sin^2 2\theta \, \sin^2 \frac{\Delta m^2 L}{4E}$
  matter: $P_{\alpha\alpha} = 1 - \sin^2 2\tilde{\theta} \, \sin^2 \frac{\Delta \tilde{m}^2 L}{4E}$



(Wolfenstein, 1978; Mikheyev, Smirnov, 1985)

$$\Delta\tilde{m}^2 = \xi \cdot \Delta m^2, \quad \sin 2\tilde{\theta} = \frac{\sin 2\theta}{\xi},$$

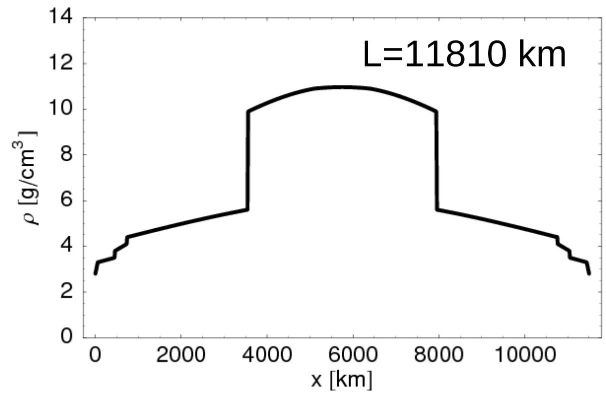
$$\xi \equiv \sqrt{\sin^2 2\theta + \left(\cos 2\theta - \hat{A}\right)^2},$$

$$\hat{A} = \frac{2EV}{\Delta m^2} = \frac{\pm 2\sqrt{2} E \, G_F \, n_e}{\Delta m^2}$$

⇨ **MH**

Resonance energy (from $\hat{A} \to \cos 2\theta$):

$$E_{\rm res}\,[\text{GeV}] \sim 13\,200 \, \cos 2\theta \, \frac{\Delta m^2\,[\text{eV}^2]}{\rho\,[\text{g/cm}^3]}$$

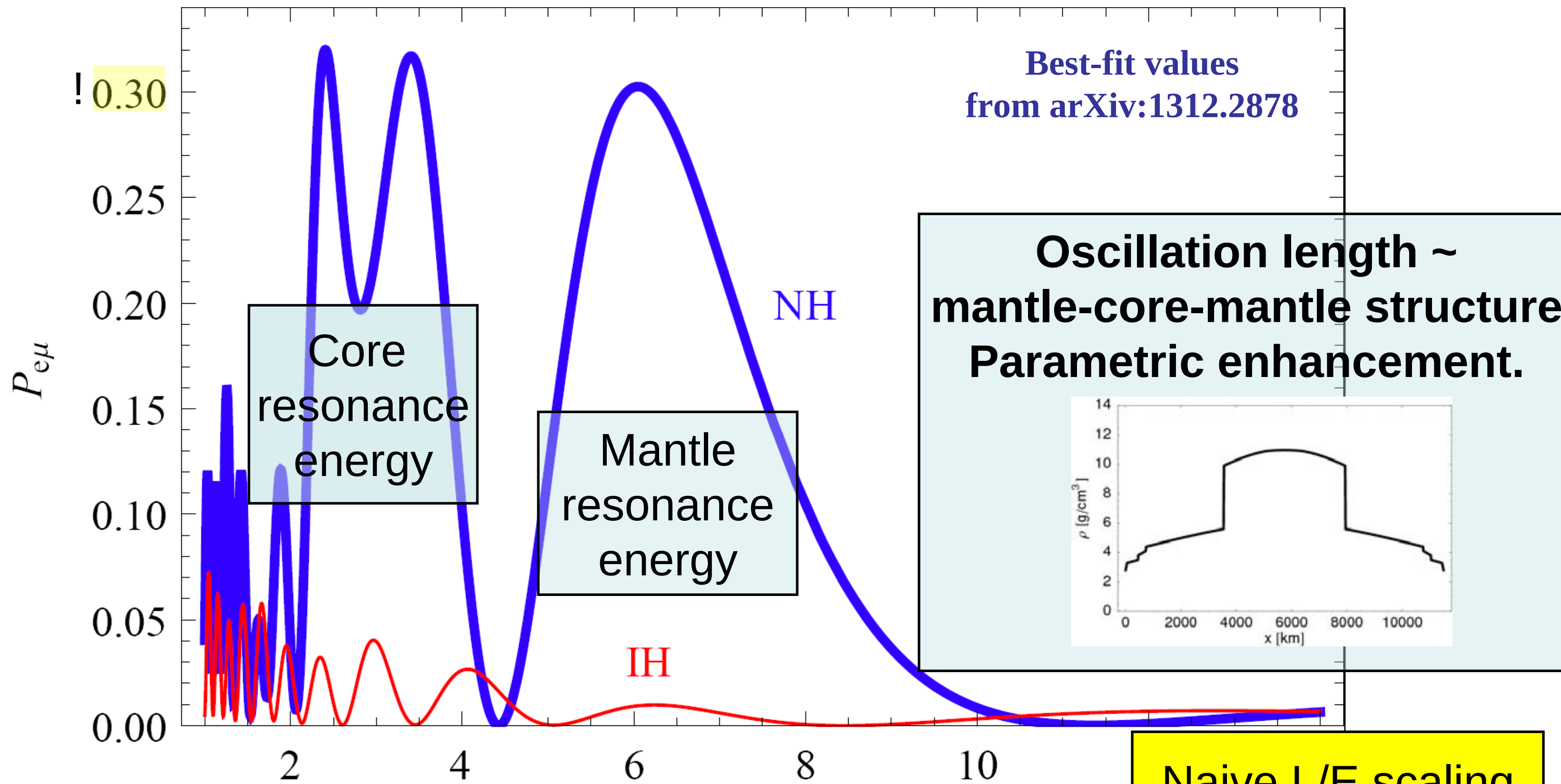


For ν_μ appearance, Δm_{31}^2:
- $\rho \sim 4.7$ g/cm³ (Earth's mantle): **E_{res} ~ 6.4 GeV**
- $\rho \sim 10.8$ g/cm³ (Earth's outer core): **E_{res} ~ 2.8 GeV**

Mantle-core-mantle

(Parametric enhancement: Akhmedov, 1998; Akhmedov, Lipari, Smirnov, 1998; Petcov, 1998)

- Probability for L=11810 km

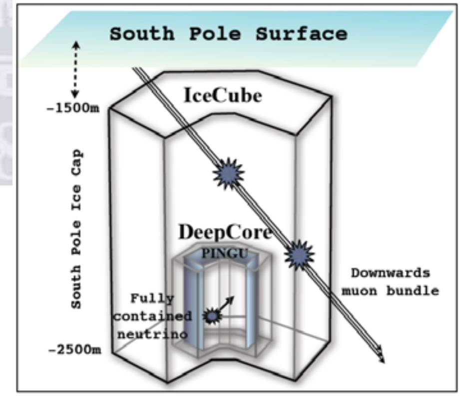


Oscillation length ~ mantle-core-mantle structure Parametric enhancement.

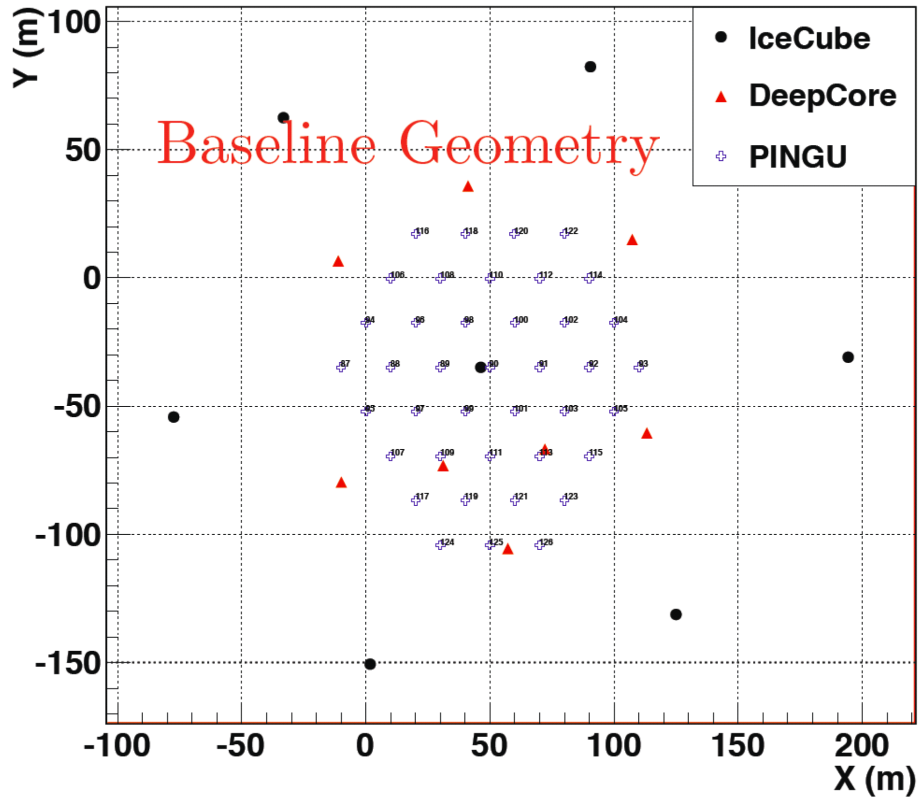
Naive L/E scaling does not apply!

Threshold effects expected at: 2 GeV 4-5 GeV

Emerging technologies:
PINGU



- Fill in IceCube/DeepCore array with additional strings
  - ➢ Lower threshold
  - ➢ Particle physics!?
- PINGU
  ("Precision IceCube Next Generation Upgrade"):
- 40 additional strings, 60 optical modules each
- Modest cost,
  US part ~ 55-80 M$,
  foreign ~ 25 M$
  (including contingency)
- Completion 2019/2020?



(PINGU LOI, arXiv:1401.2046)

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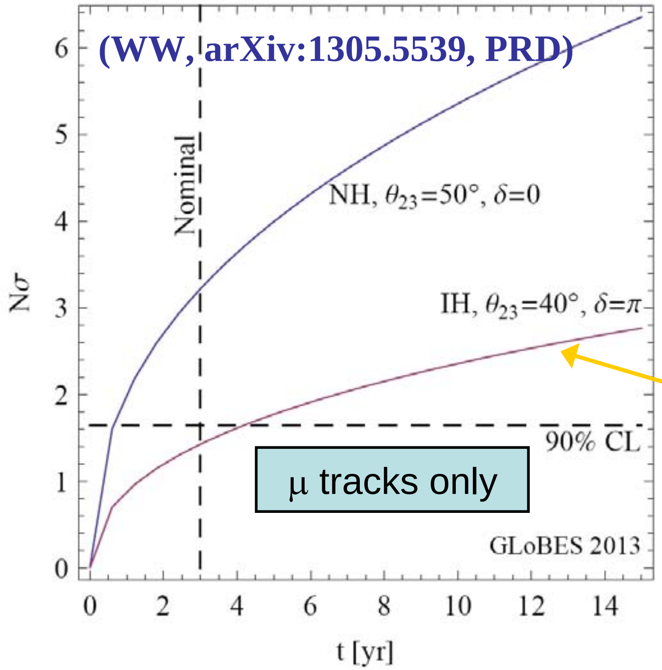
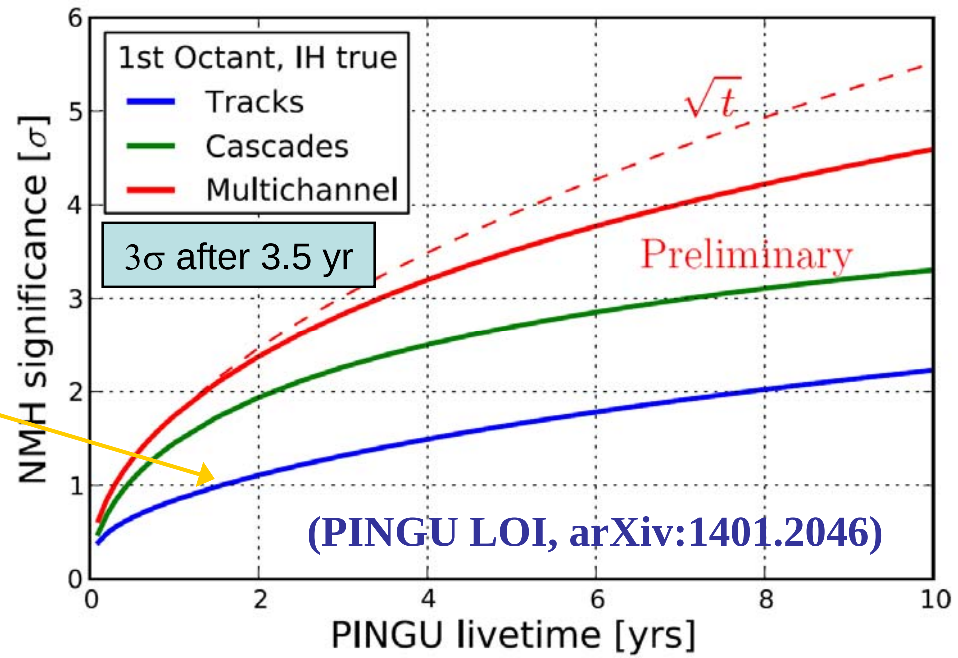
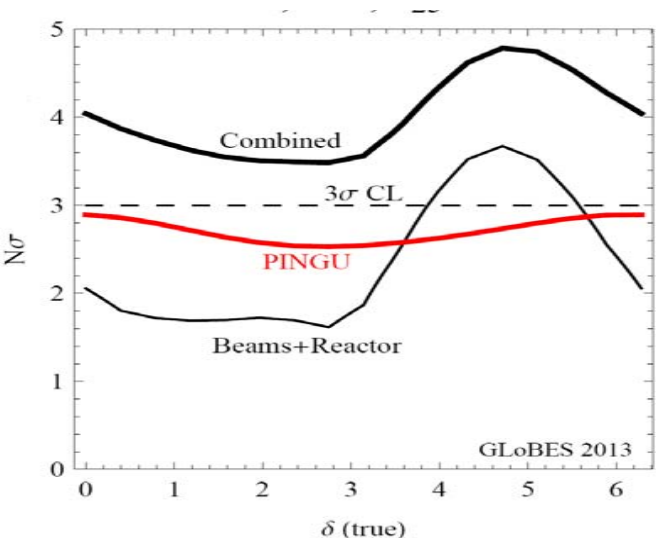
Mass hierarchy measurment

… PINGU, using atmospheric neutrinos





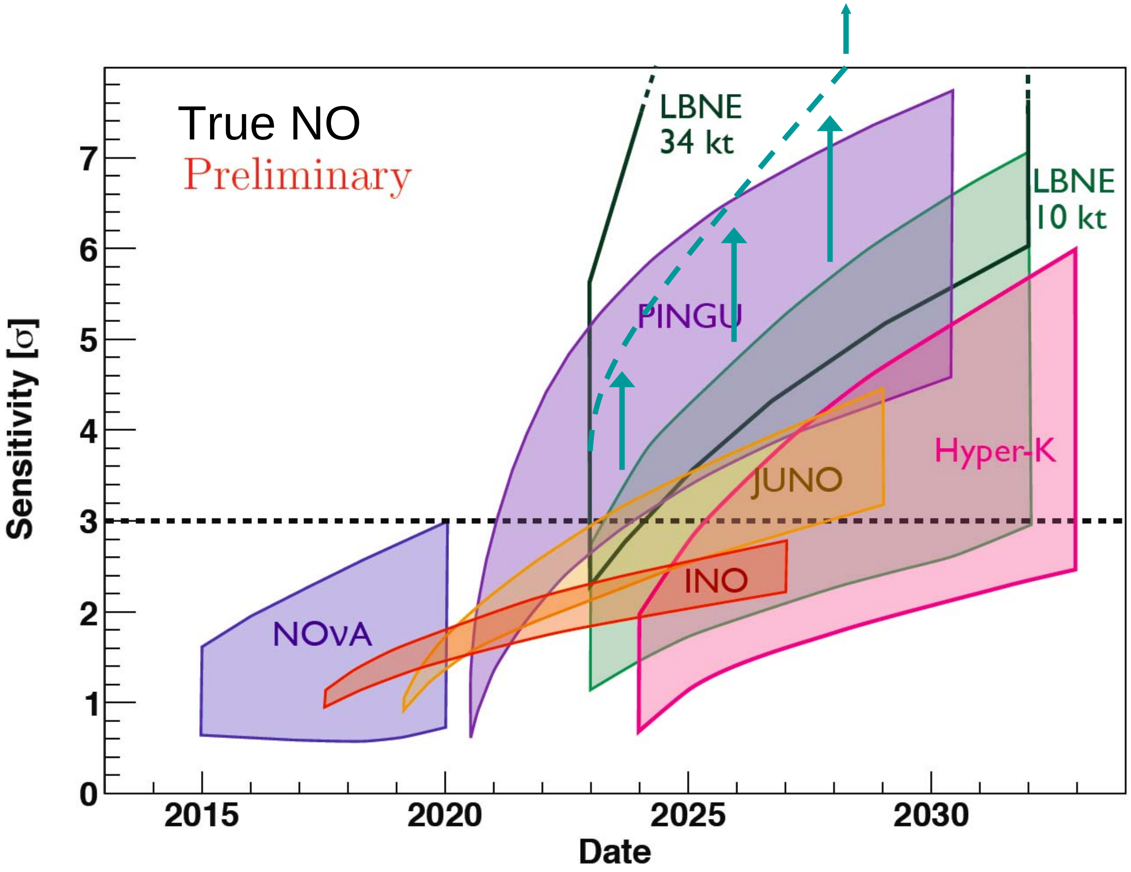
- 3σ conceivable after three years of operation
- Complementary to beams+reactor



(WW, arXiv:1305.5539, PRD)

Global context

LBNE 10kt if θ_{23} varied as well
⇨ **Fig. 9 in arXiv:1305.5539**



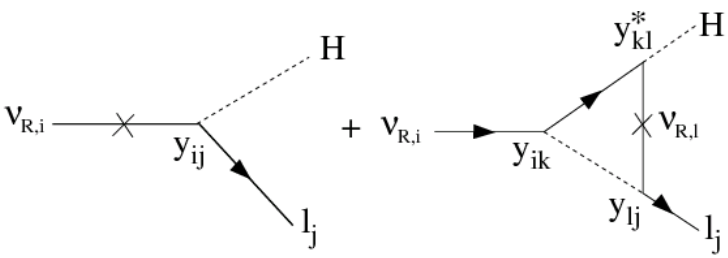
- Bands: risk wrt θ_{23} (PINGU, INO), δ_{CP} (NOvA, LBNE), energy resolution (JUNO)
- LBNE and sensitivity also scales with θ_{23}!

(version from PINGU LOI, arXiv:1401.2046, based on Blennow, Coloma, Huber, Schwetz, arXiv:1311.1822)

Measurement of δ_{CP}

Why is δ_{CP} interesting?

- **CP violation** **sinδ**
  Necessary condition for successful baryogenesis
  (dynamical mechanism to create matter-antimatter asymmetry of the universe)
  ⇨ thermal leptogenesis by decay of heavy see-saw partner?



- **Model building** **cosδ**

$$U_{\mathrm{PMNS}} = U_\ell^\dagger U_\nu$$

⇨ C. Hagedorn

Correction leading to non-zero θ_{13}?

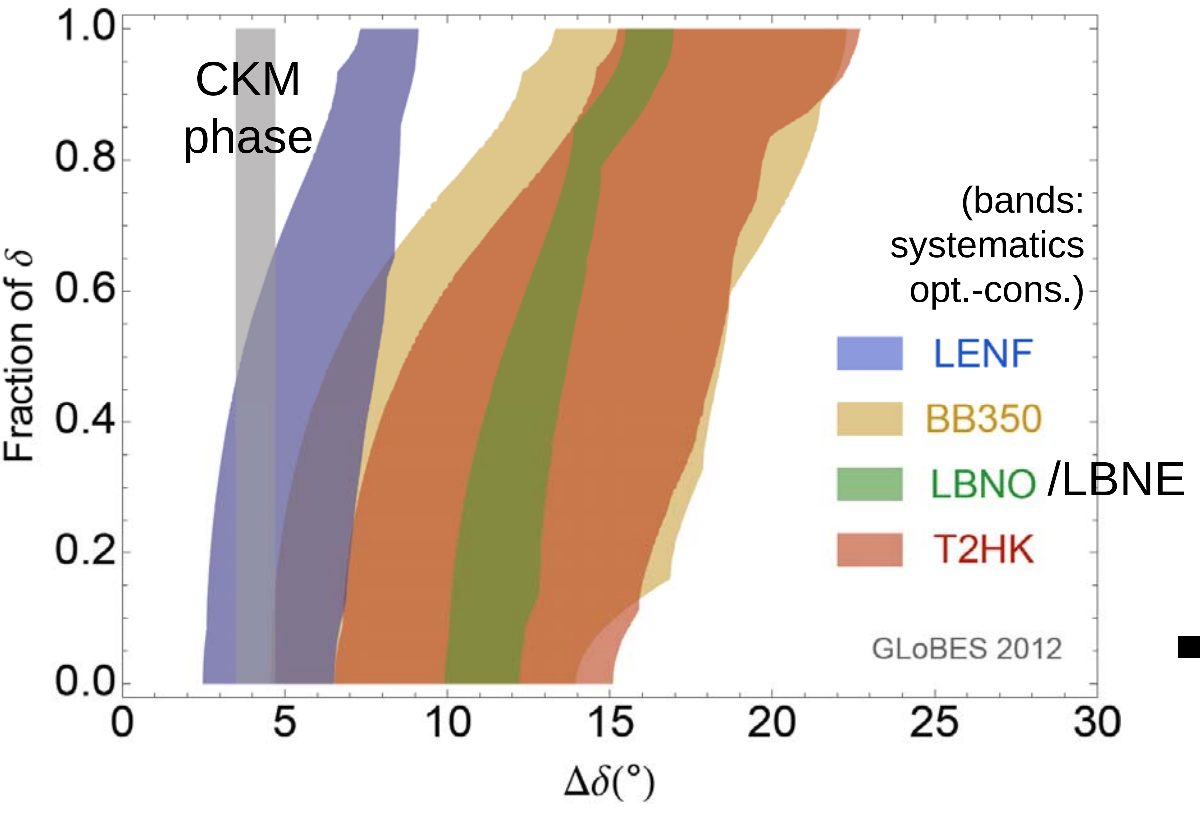
Symmetry e.g. TBM, BM, …? ⇨ $\theta_{13}=0$

e.g. TBM sum rule: $\theta_{12} = 35° + \theta_{13}$ **cosδ** (Antusch, King, …)

➢ Discuss precision of δ_{CP} rather than CP violation

Precision of δ_{CP}

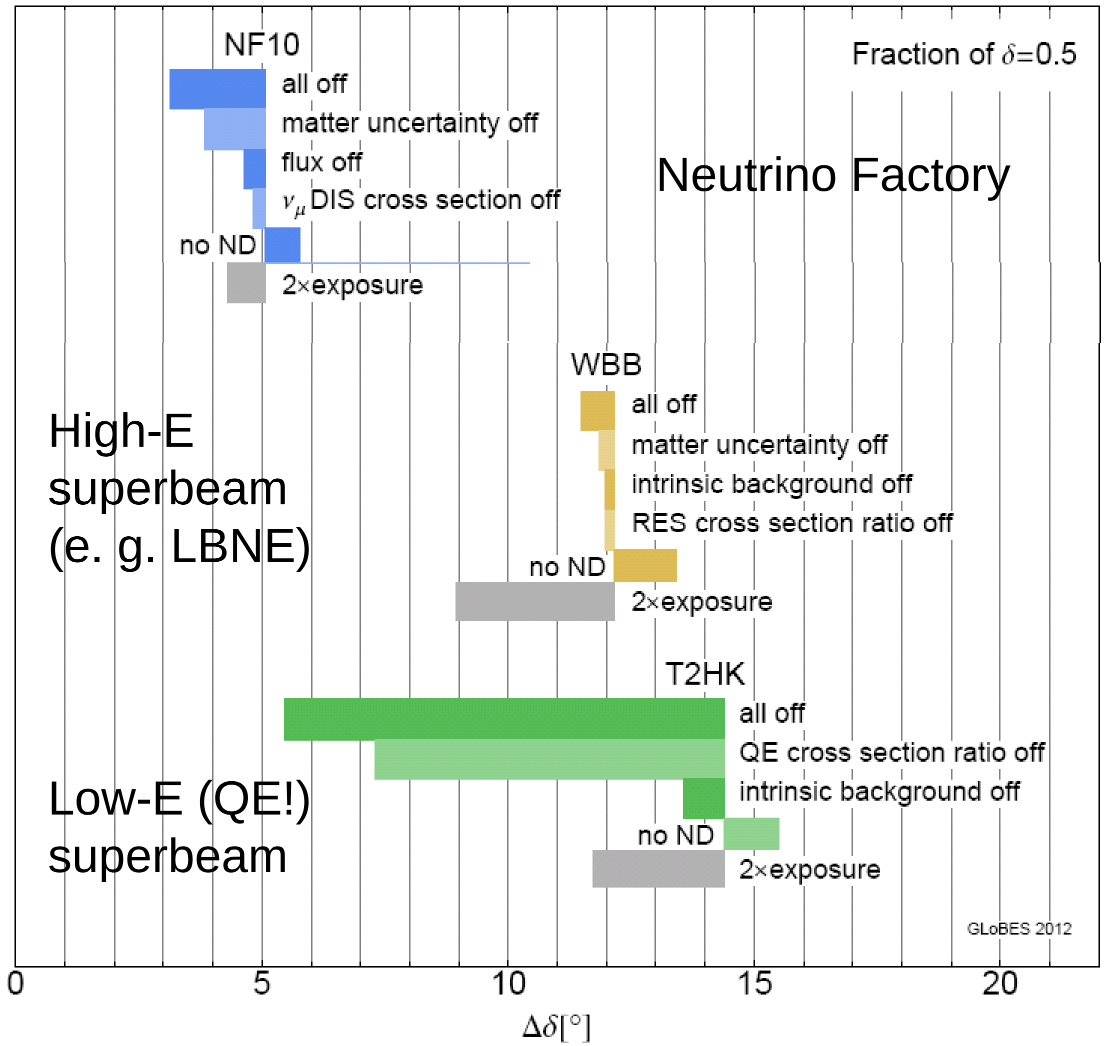
⇨ **More details: talk by A. Sousa**



(Coloma, Huber, Kopp, Winter, arXiv:1209.5973)

- Systematics important
  - Use explicit near-far detector simulations
  - Use same knowledge for cross sections for all experiments
  - Use same assumptions for systematics implementation!
- **The NF can measure δ_{CP} with a precision comparable to the quark sector**

Main challenges for δ_{CP}



(Coloma, Huber, Kopp, Winter, arXiv:1209.5973)

Robust wrt systematics

Main impact:
Matter density uncertainty

Operate in statistics-limited regime

Exposure more important than near detector

QE ν_e X-sec critical: cannot be measured in near detector

Theory: ν_e/ν_μ ratio?
Experiment: νSTORM

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

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Perspectives for neutrino oscillations

- Mass hierarchy: may be tested in beginning of 2020s by "emerging technologies", such as PINGU or JUNO
- CP violation: requires a new long-baseline experiment, such as LBNE, T2HK, NuFact
- Other issues: θ_{23} maximal? Octant? Sun and Earth tomography? New physics?
- Light sterile neutrinos - best candidate for physics BνSM? Test short-baseline anomalies, measure neutrino X-secs, …

Backup

Options

	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)
	$\text{LBNE}_{\text{mini}}$	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)

+ Daya Bay

(Coloma, Huber, Kopp, Winter, arXiv:1209.5973)

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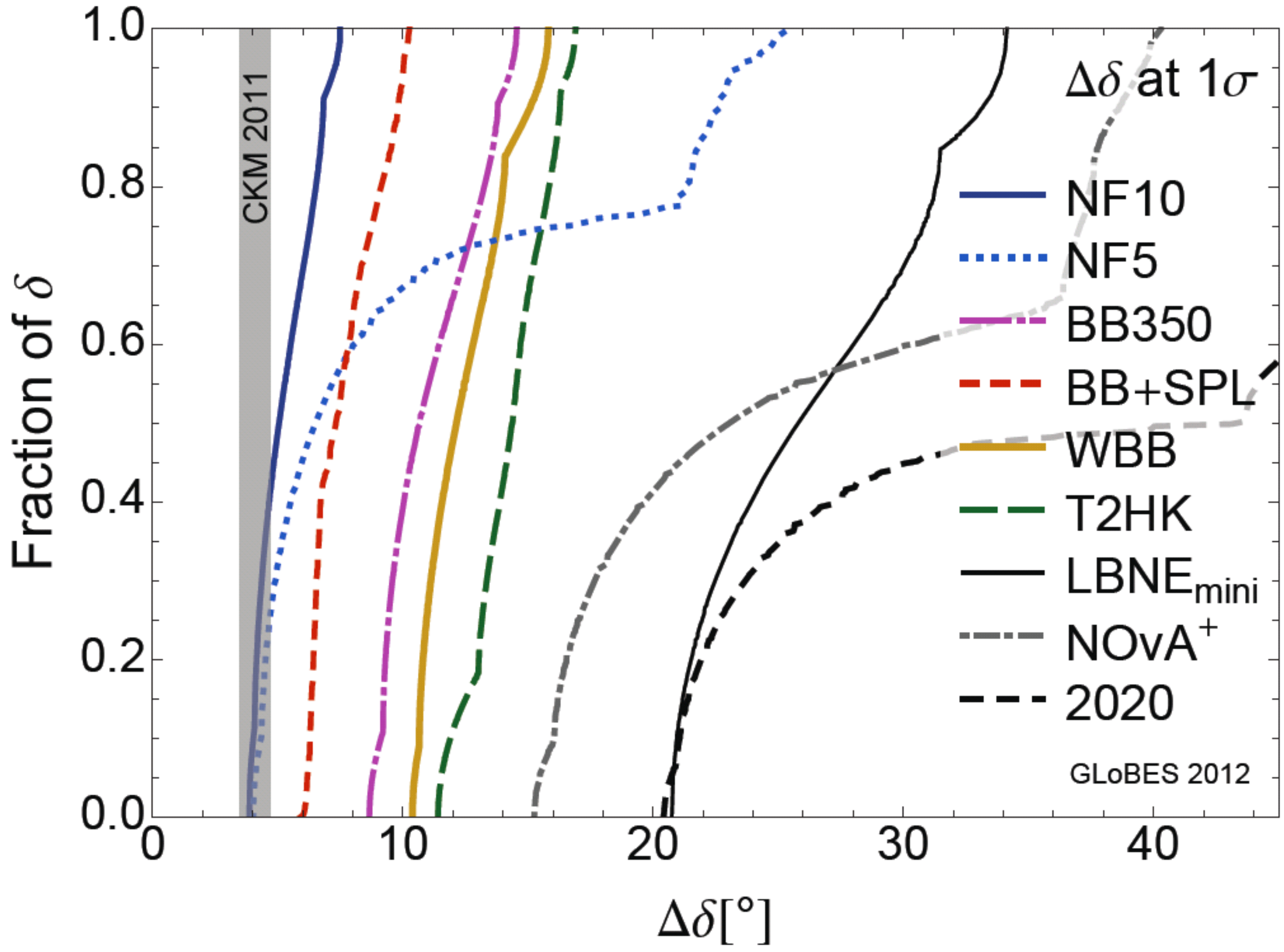
Systematics

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 $\times$ 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, arXiv:1209.5973)

Interesting alternatives

- Comparison at default systematics:

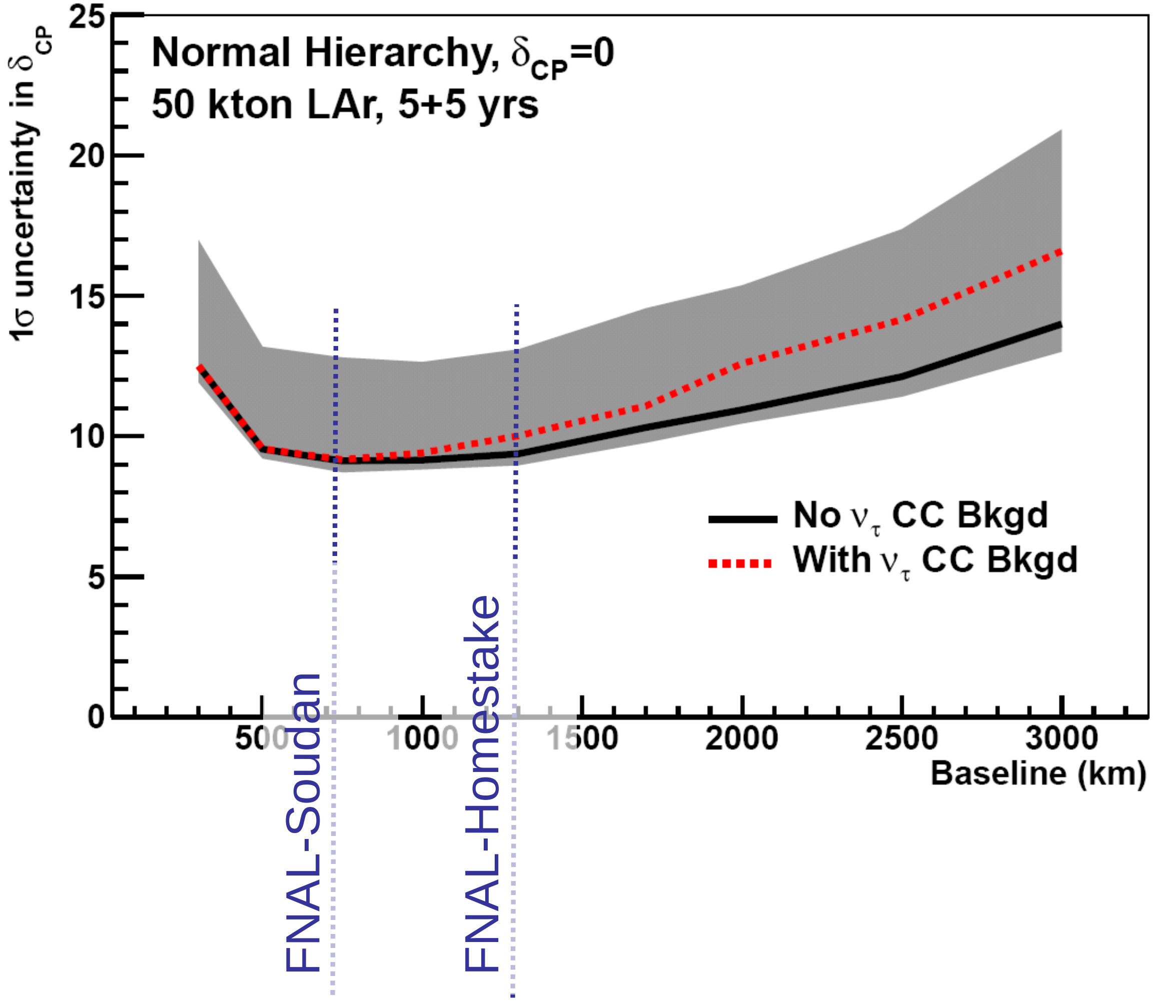


NF5 exhibits strong dependence on δ_{CP} (some dependence on binning!)

BB100+SPL is the only setup comparable with NuFact

(Coloma, Huber, Kopp, Winter, arXiv:1209.5973)

LBNE: Optimal baseline?



- For δ_{CP}: ~500 – 1300 km
- For MH, octant > 1000 km

(LBNE, arXiv:1311.0212; see also: arXiv:hep-ph/0607177; arXiv:hep-ph/0703029)