Theoretical aspects of LBL experiments and LBNO

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KITP

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Outline

1. **Theoretical implications of the mass ordering and CPV:**
    - **The origin of neutrino masses and mixing**
    - **Leptogenesis and the baryon asymmetry**

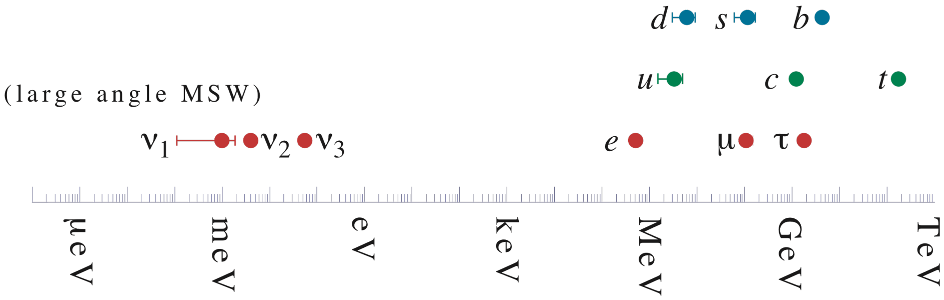
2. **LBL oscillation experiments physics goals:**
    - **Mass ordering**
    - **Leptonic CP-violation**
    - **Precision measurement of parameters**
    - **(Testing the 3-neutrino mixing scenario)**

3. **Conclusions**

Open window on Physics beyond the SM

Neutrino masses are *evidence* of physics BSM.

1. Origin of masses



Why neutrinos have mass?
Why are they so much lighter?
Why their hierarchy is at most mild?

2. Problem of flavour

$$\begin{pmatrix} \sim 1 & \lambda & \lambda^3 \\ \lambda & \sim 1 & \lambda^2 \\ \lambda^3 & \lambda^2 & \sim 1 \end{pmatrix} \quad \lambda \sim 0.2$$

$$\begin{pmatrix} 0.8 & 0.5 & 0.16 \\ -0.4 & 0.5 & -0.7 \\ -0.4 & 0.5 & 0.7 \end{pmatrix}$$

Why leptonic mixing is so different from quark mixing?

This points towards a different origin of neutrino masses and mixing from the ones of quarks:
a different window on the physics BSM.

Why should we search for the mass ordering and leptonic CP-violation (and the precise values of the mixing angles)?

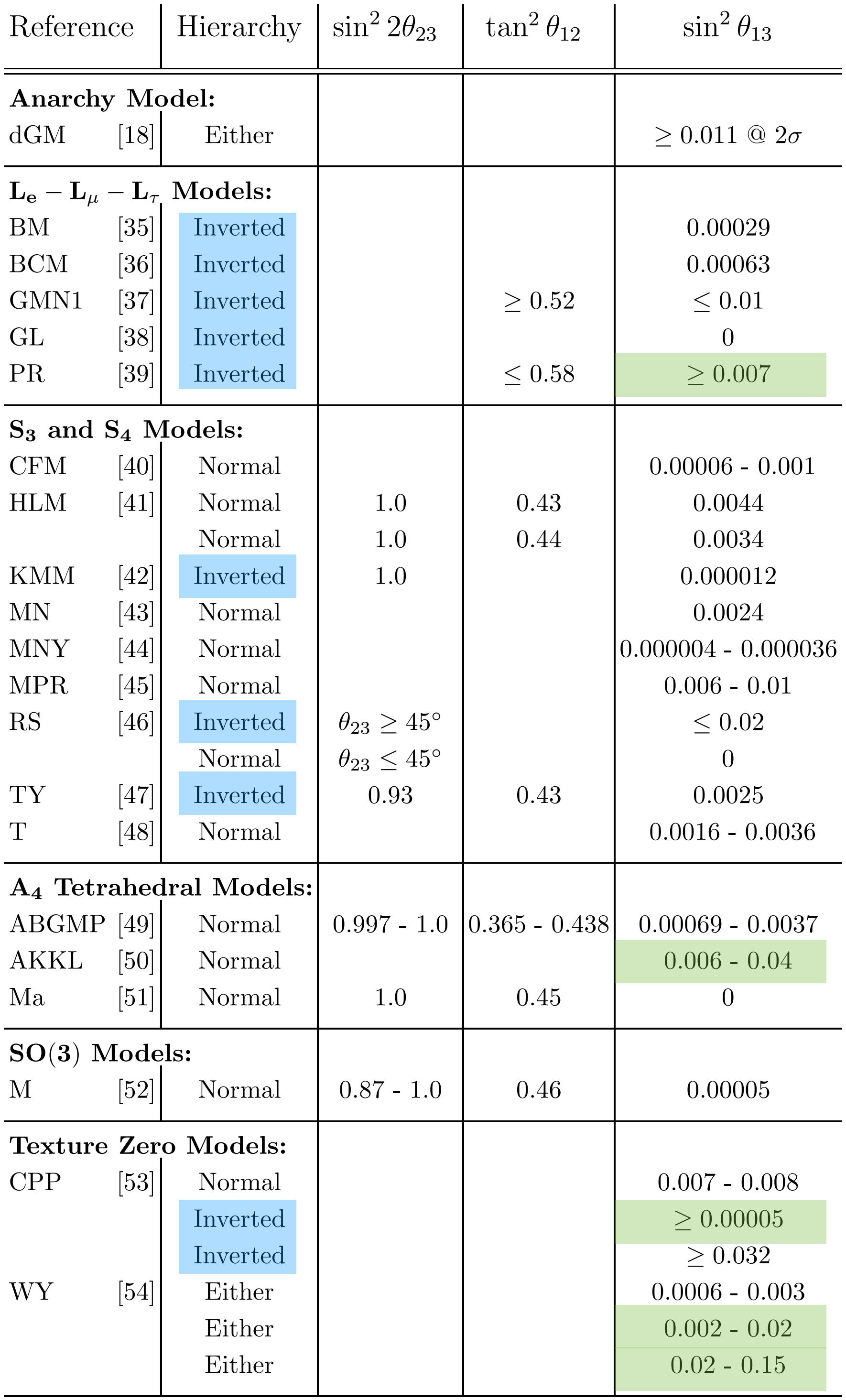
I:

The theoretical implications of the values of masses and mixing angles

Two necessary ingredients for testing flavour models:

- Precision measurements of the oscillation parameters at future experiments (including the delta phase!).

- The determination of the mass ordering and of the neutrino mass spectrum.



Reference	Hierarchy	$\sin^2 2\theta_{23}$	$\tan^2 \theta_{12}$	$\sin^2 \theta_{13}$
Anarchy Model:				
dGM [18]	Either			≥ 0.011 @ 2σ
$L_e - L_\mu - L_\tau$ Models:				
BM [35]	Inverted			0.00029
BCM [36]	Inverted			0.00063
GMN1 [37]	Inverted		≥ 0.52	≤ 0.01
GL [38]	Inverted			0
PR [39]	Inverted		≤ 0.58	≥ 0.007
S_3 and S_4 Models:				
CFM [40]	Normal			0.00006 - 0.001
HLM [41]	Normal	1.0	0.43	0.0044
	Normal	1.0	0.44	0.0034
KMM [42]	Inverted	1.0		0.000012
MN [43]	Normal			0.0024
MNY [44]	Normal			0.000004 - 0.000036
MPR [45]	Normal			0.006 - 0.01
RS [46]	Inverted	$\theta_{23} \geq 45°$		≤ 0.02
	Normal	$\theta_{23} \leq 45°$		0
TY [47]	Inverted	0.93	0.43	0.0025
T [48]	Normal			0.0016 - 0.0036
A_4 Tetrahedral Models:				
ABGMP [49]	Normal	0.997 - 1.0	0.365 - 0.438	0.00069 - 0.0037
AKKL [50]	Normal			0.006 - 0.04
Ma [51]	Normal	1.0	0.45	0
SO(3) Models:				
M [52]	Normal	0.87 - 1.0	0.46	0.00005
Texture Zero Models:				
CPP [53]	Normal			0.007 - 0.008
	Inverted			≥ 0.00005
	Inverted			≥ 0.032
WY [54]	Either			0.0006 - 0.003
	Either			0.002 - 0.02
	Either			0.02 - 0.15

Albright, Chen, PRD 74

Leptonic flavour structure

The mixing angles have special values: $\theta_{23} \simeq 45^o, \theta_{13} \ll \pi/4$
This can suggest an underlying pattern. **See Everett's talk**

Example: Tribimaximal mixing

$$\mathcal{U}_0 = \begin{pmatrix} \frac{\sqrt{2}}{\sqrt{3}} & \frac{1}{\sqrt{3}} & 0 \\ -\frac{1}{\sqrt{6}} & \frac{1}{\sqrt{3}} & \frac{1}{\sqrt{2}} \\ \frac{1}{\sqrt{6}} & -\frac{1}{\sqrt{3}} & \frac{1}{\sqrt{2}} \end{pmatrix} + \begin{pmatrix} \mathcal{O}(0.001) & -\mathcal{O}(0.01) & \mathcal{O}(0.1) \\ \mathcal{O}(0.1) & \mathcal{O}(0.05) & -\mathcal{O}(0.01) \\ -\mathcal{O}(0.1) & -\mathcal{O}(0.05) & \mathcal{O}(0.01) \end{pmatrix}$$

Harrison, Perkins, Scott

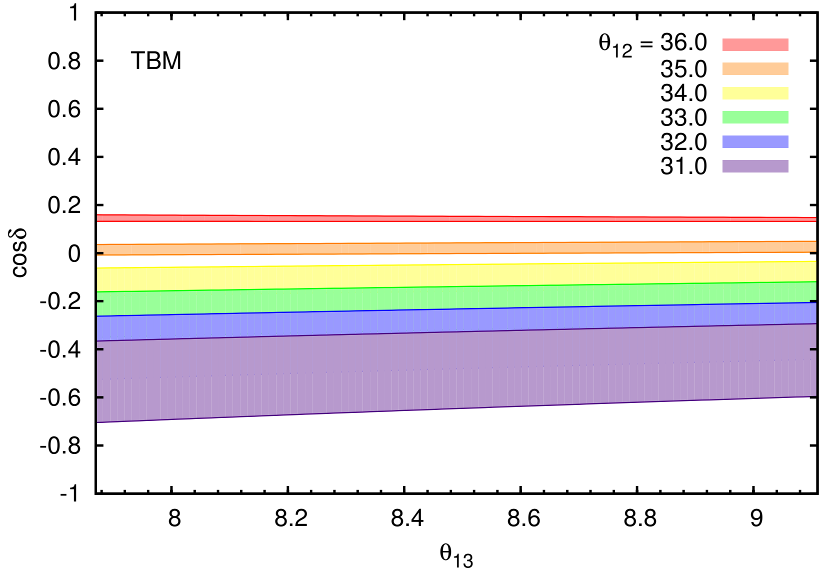
Large corrections to theta13 are needed.

Other possibilities: bimaximal mixing $(\theta_{12}|_0 = 45^o)$,
golden ratio $\left(\tan\theta_{12}|_0 = \frac{2}{1+\sqrt{5}}\right)$, and hexagonal $(\theta_{12}|_0 = 30^o)$.

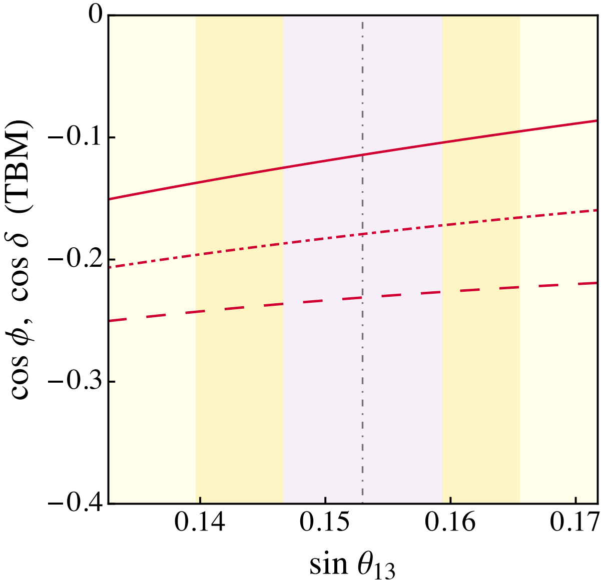
These basic patterns can emerge from specific flavour symmetries. M.-C. Chen and Mahanthappa; Girardi et al.; Petcov; Alonso, Gavela, Isidori, Maiani; Ding et al.; Ma; Hernandez, Smirnov; Feruglio et al.; Mohapatra, Nishi; Holthausen, Lindner, Schmidt; see also studies by Altarelli, Alonso, Ballett, Bazzocchi, Brahmachari, Branco, M.-C. Chen, Ding, Felipe, Ferreira, Feruglio, Fonseca, Frigerio, Gavela, Ge, Grimus, Gupta, Hagedorn, Hanlon, Hernandez, Holthausen, Hu, King, Joaquim, Joshipura, Ishimori, Lam, Lavoura, C.-C. Li, Lindner, Luhn, Ludl, B.-Q. Ma, E. Ma, Marzocca, Merle, Merlo, Meroni, Mohapatra, Morisi, Nishi, Ohlsson, Pascoli, Patel, H. Qu, Rebelo, Repko, Rigolin, Romanino, Roy, Schmidt, Sevilla, Silva-Marcos, Smirnov, Stamou, Stuart, Tanimoto, Valle, Villanova del Moral, Vitale, Zhang, Zhou, Ziegler...

Corrections to the basic pattern leads to predictions for the parameters and relations among them:

- charged lepton corrections to U_ν : $U_{\text{PMNS}} = U_e^\dagger U_\nu$
- Sum rules. E.g.: $\sin\theta_{23} - \frac{1}{\sqrt{2}} = a_0 + \lambda \sin\theta_{13}\cos\delta + \text{higher orders}$



P. Ballett et al., 1410.7573



I. Girardi, S. Petcov, A. Titov, 1410.8056

Measuring the oscillation parameters precisely would allow to distinguish between different models.

Why should we search for the mass ordering and leptonic CP-violation (and the precise values of the mixing angles)?

2:

The theoretical implications of CPV for the baryon asymmetry

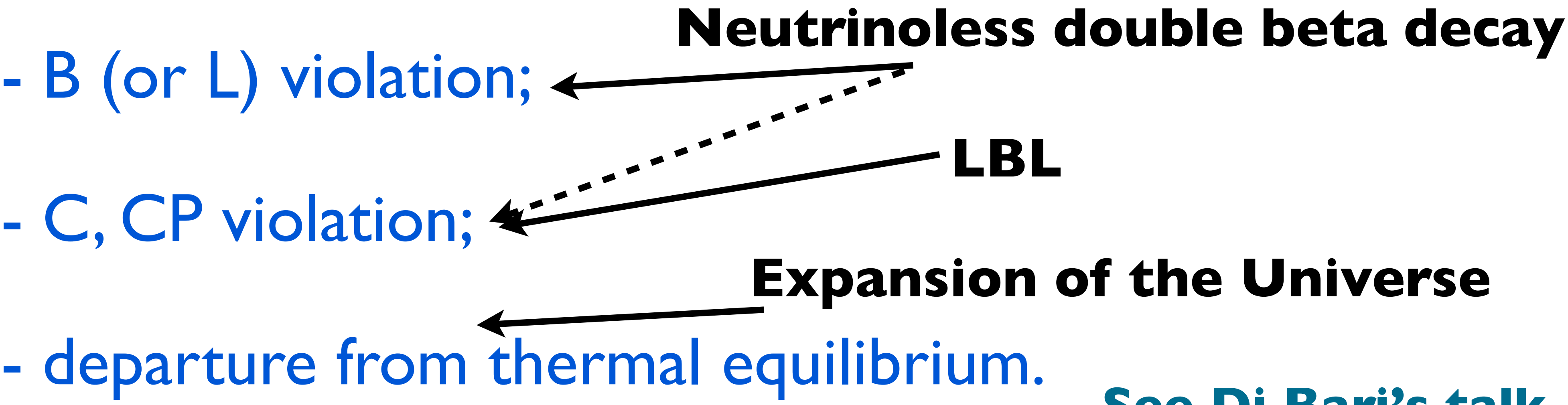
CPV and the Baryon asymmetry

There is evidence of the baryon asymmetry:

$$\eta_B \equiv \frac{n_B - n_{\bar{B}}}{n_\gamma} = (6.14 \pm 0.08) \times 10^{-10}$$

Planck, 1303.5076

In order to generate dynamically a baryon asymmetry, the Sakharov's conditions need to be satisfied:



Neutrinoless double beta decay

- B (or L) violation;

LBL

- C, CP violation;

Expansion of the Universe

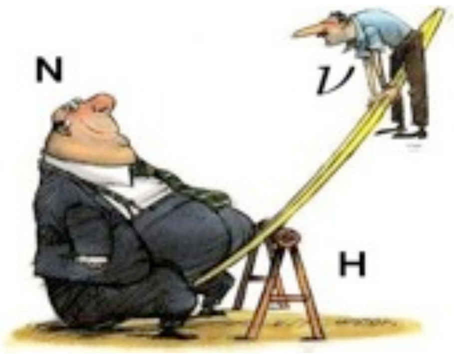
- departure from thermal equilibrium.

See Di Bari's talk

Leptogenesis in models at the origin of neutrino masses

An example of a connection between low energy CPV and leptogenesis

See-saw type I: Introduce a right handed neutrino **N**



$$\mathcal{L} = -Y_\nu \bar{N} L \cdot H - 1/2 \bar{N}^c M_R N$$

$$\begin{pmatrix} 0 & m_D \\ m_D^T & M_N \end{pmatrix}$$

$$m_\nu = \frac{Y_\nu^2 v_H^2}{M_N} \sim \frac{1\ \mathrm{GeV}^2}{10^{10}\mathrm{GeV}} \sim 0.1\ \mathrm{eV}$$

Minkowski; Yanagida; Glashow; Gell-Mann, Ramond, Slansky; Mohapatra, Senjanovic; et al.

Leptogenesis

$$\boxed{Y_B = \frac{k}{g^*} c_s \epsilon \sim 10^{-3} - 10^{-4} \epsilon}$$

with $\epsilon \equiv \dfrac{\Gamma(N \to \ell H) - \Gamma(N^c \to \ell^c H^c)}{\Gamma(N \to \ell H) + \Gamma(N^c \to \ell^c H^c)}$

For T < 10^{12} GeV, flavour effects are important.

Is there a connection between low energy CPV and the baryon asymmetry?

The general picture (see-saw type I)

ϵ depends on the CPV phases in Y_ν

$$\epsilon \propto \sum_j \Im(Y_\nu Y_\nu^\dagger)^2_{1j} \frac{M_j}{M_1}$$

and in the U mixing matrix via the see-saw formula.

$$m_\nu = U^* m_i U^\dagger = -Y_\nu^T M_R^{-1} Y_\nu v^2$$

Let's consider see-saw type I with 3 NRs.

High energy

M_R	3	0
Y_ν	9	6

Low energy

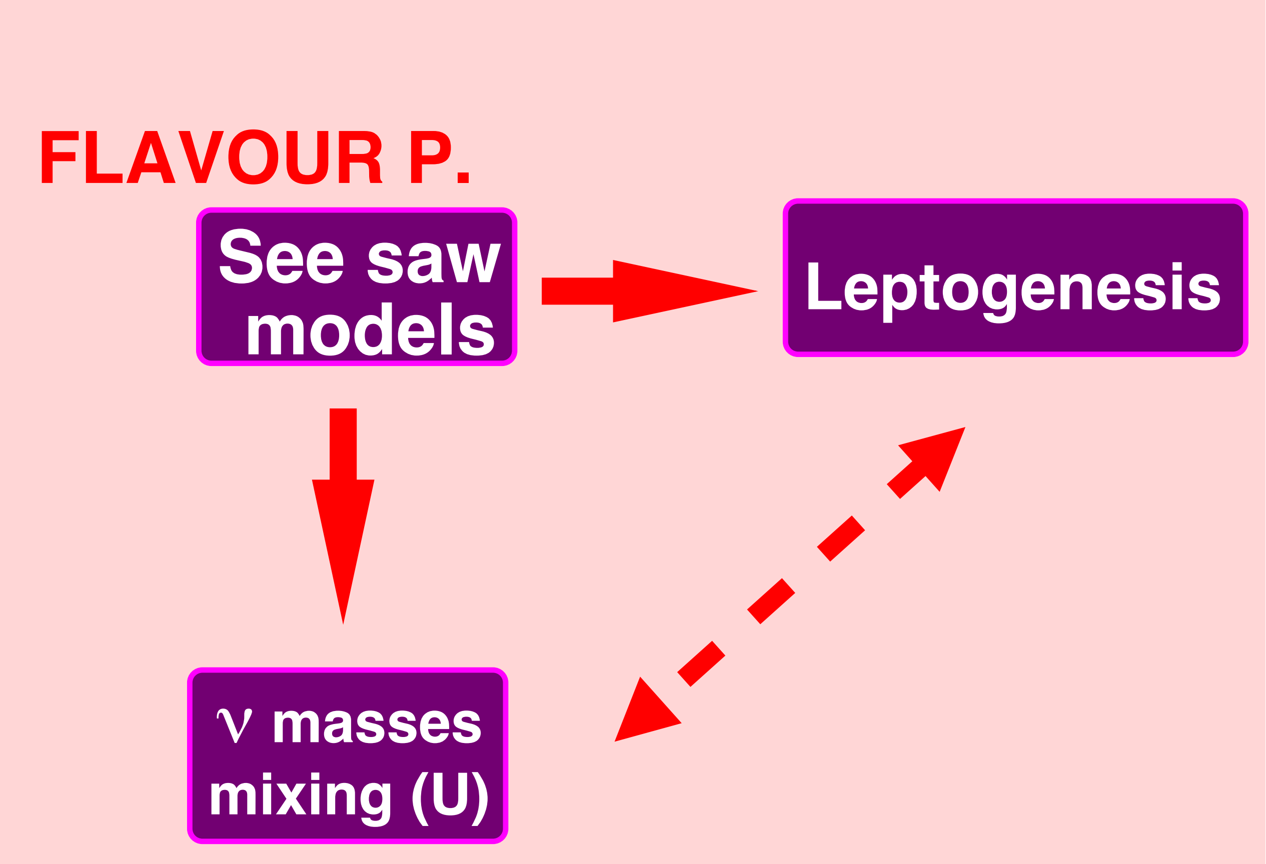
m_i	3	0
U	3	3

3 phases missing!

Specific flavour models

In understanding the origin of the flavour structure, the see-saw models have a reduced number of parameters.

It may be possible to predict the baryon asymmetry from the Dirac and Majorana phases.


FLAVOUR P.

See saw models

Leptogenesis

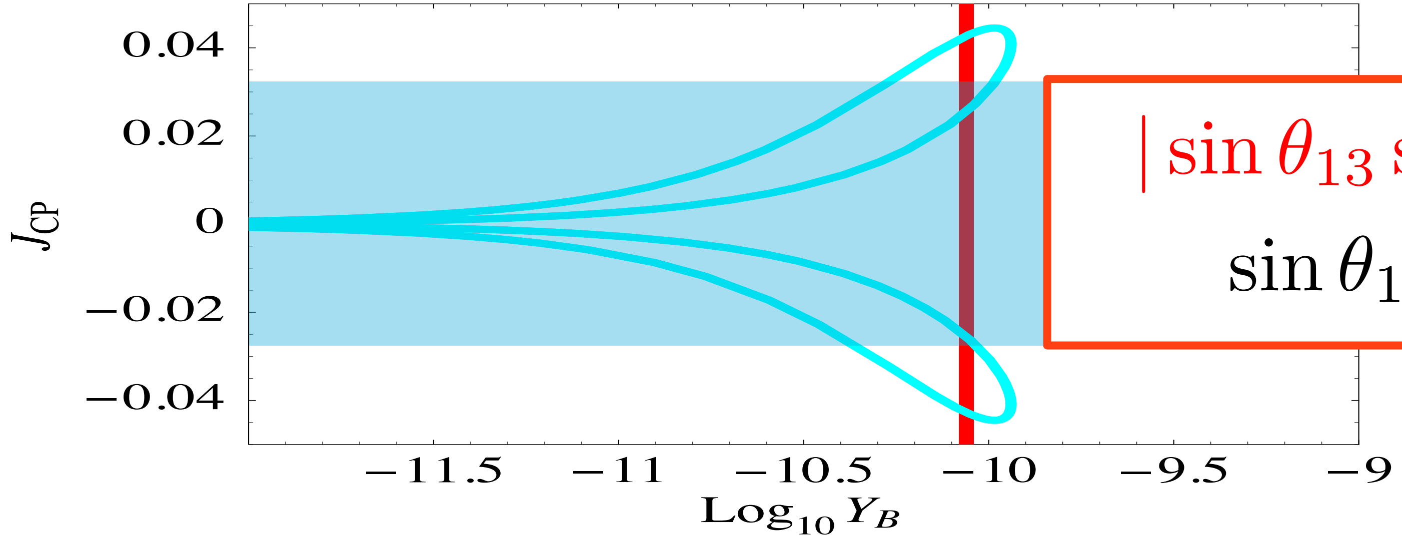
ν masses mixing (U)

Does observing low energy CPV imply a baryon asymmetry?

It has been shown that, thanks to flavour effects, the low energy phases enter directly the baryon asymmetry.

Example in see-saw type I, with NH (m1<< m2 <<m3), M1<<M2<<M3, M1~5 10^11 GeV:

$$\epsilon_\tau \propto M_1 f(R_{ij}) \left[c_{23} s_{23} c_{12} \sin\frac{\alpha_{32}}{2} - c_{23}^2 s_{12} s_{13} \sin(\delta - \frac{\alpha_{32}}{2}) \right]$$



$$|\sin\theta_{13}\sin\delta| > 0.11$$

$$\sin\theta_{13}|_{\exp} \simeq 0.15$$

SP, Petcov, Riotto,
PRD75 and NPB774

Large theta13 implies that delta can give an important (even dominant) contribution to the baryon asymmetry. Large CPV is needed and a NH spectrum.

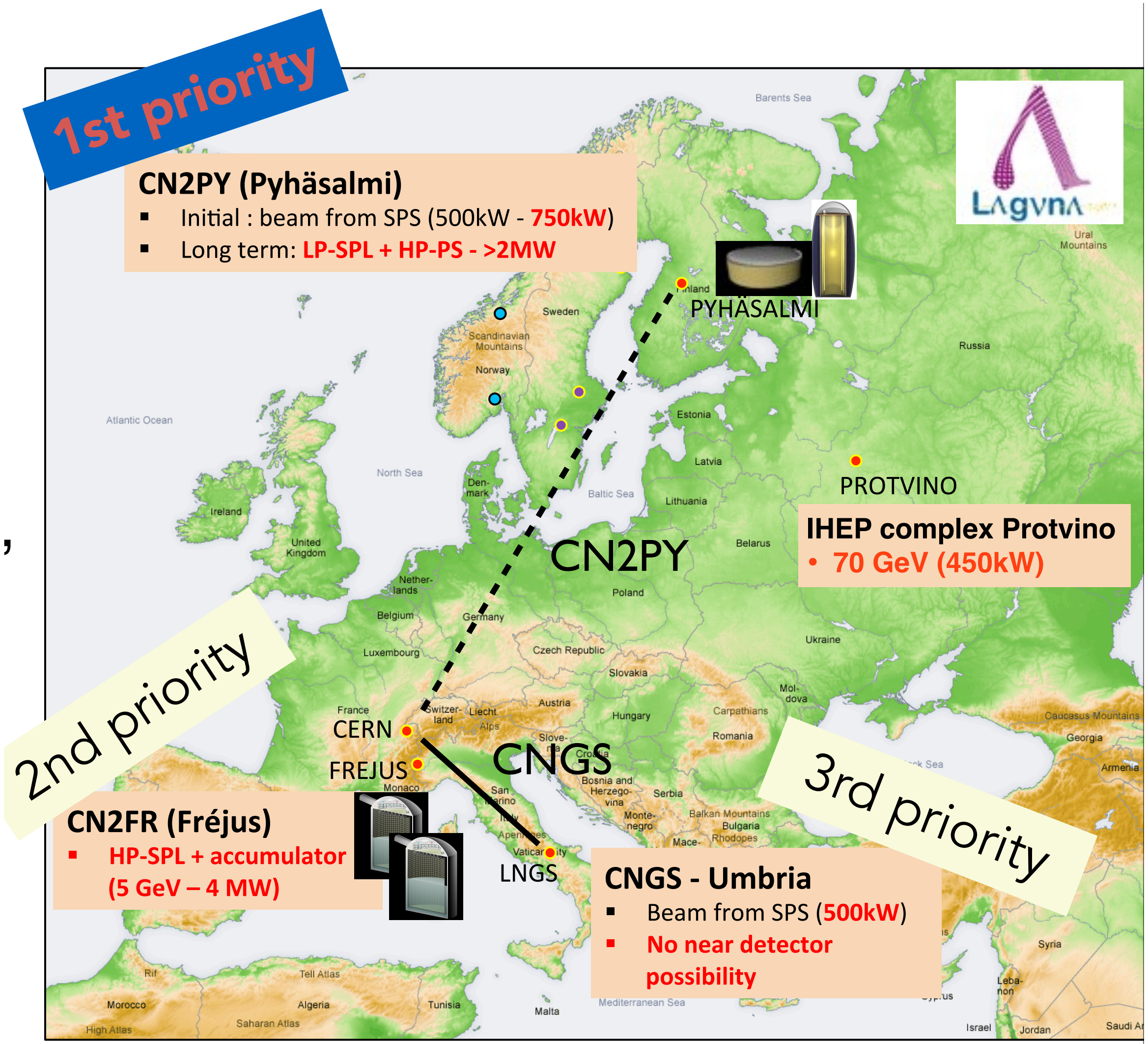
How can we search for the mass ordering and leptonic CP-violation?

How can we search for the mass ordering and leptonic CP-violation?

- Long-baseline neutrino oscillation experiments
- Reactor neutrinos
- Atmospheric neutrinos
- Neutrinoless double beta decay

LBNO

See Noah's talk



1st priority

CN2PY (Pyhäsalmi)
- Initial : beam from SPS (500kW - 750kW)
- Long term: LP-SPL + HP-PS - >2MW

IHEP complex Protvino
- 70 GeV (450kW)

2nd priority

CN2FR (Fréjus)
- HP-SPL + accumulator (5 GeV – 4 MW)

3rd priority

CNGS - Umbria
- Beam from SPS (500kW)
- No near detector possibility

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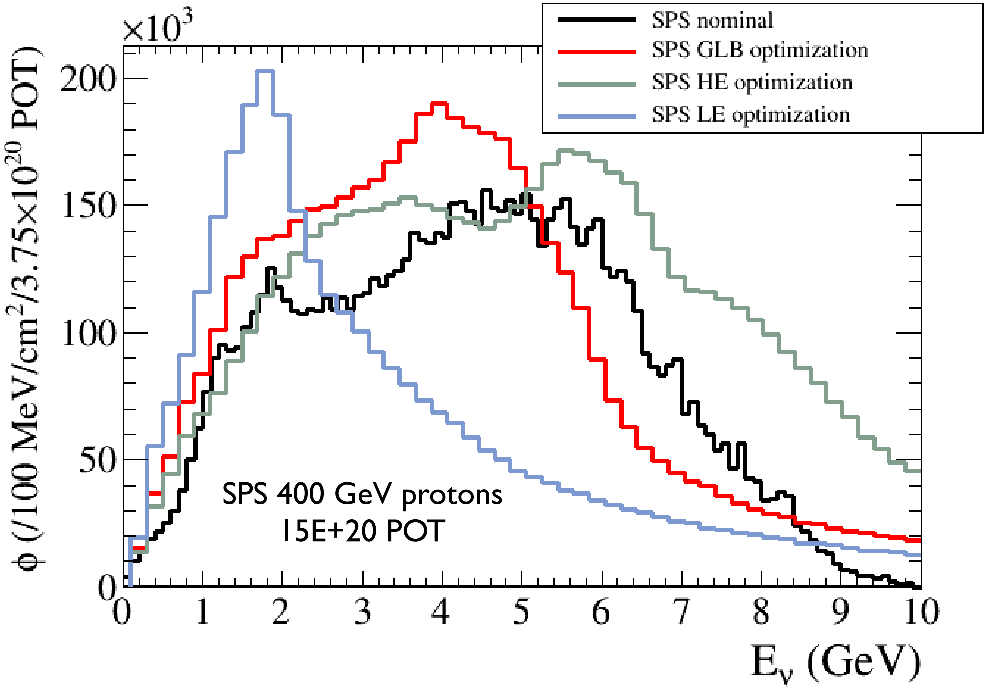
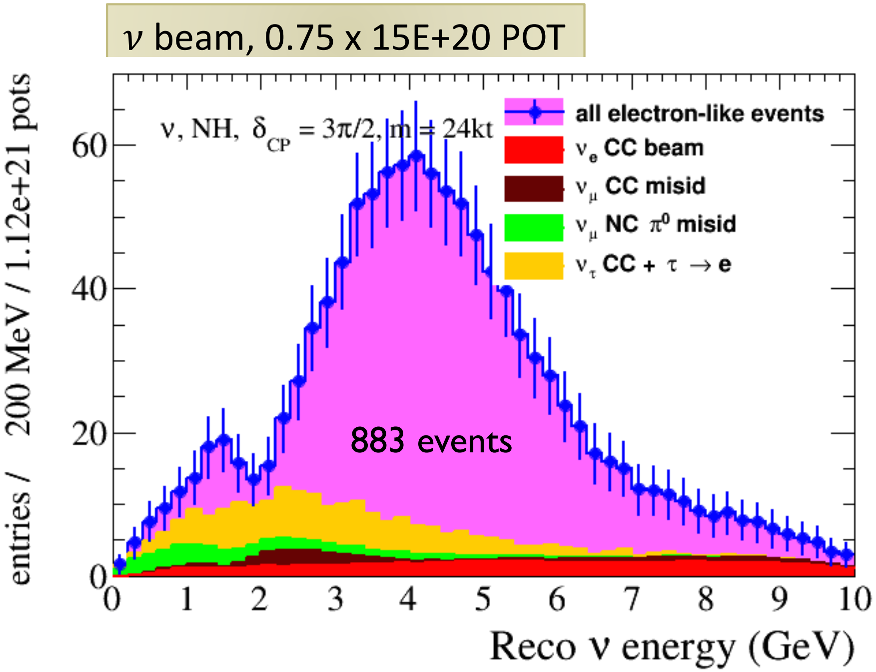
T. Patzak @Neutrino2014

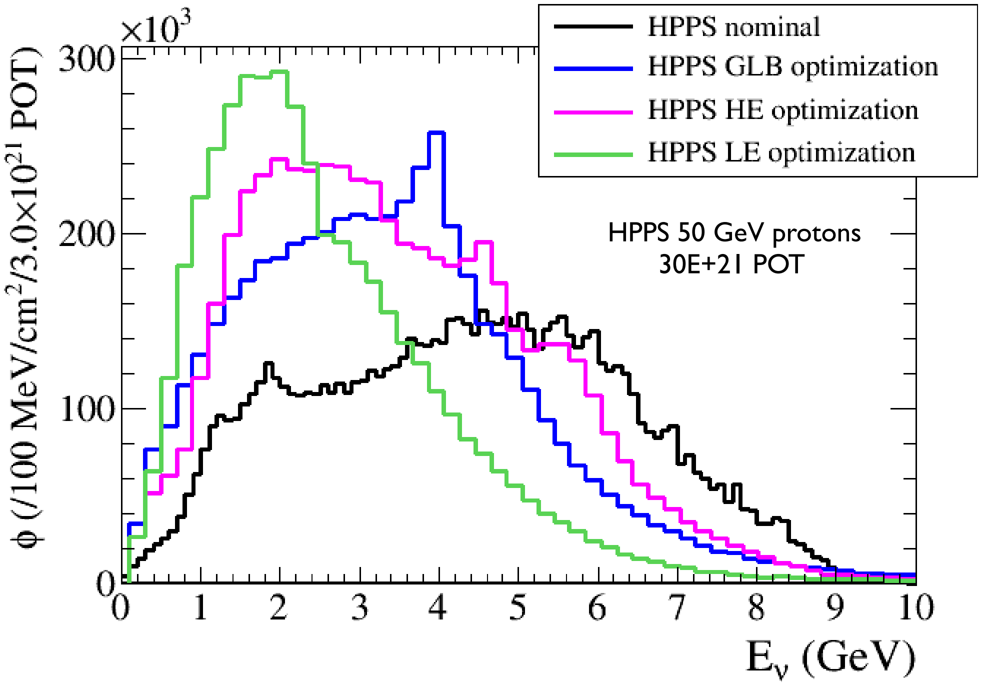
Phase I:
- 24 kton LAr + SPS beam (750 kW)

Phase II:
- 70 kton LAr + HPPS beam (2 MW) or Protvino beam

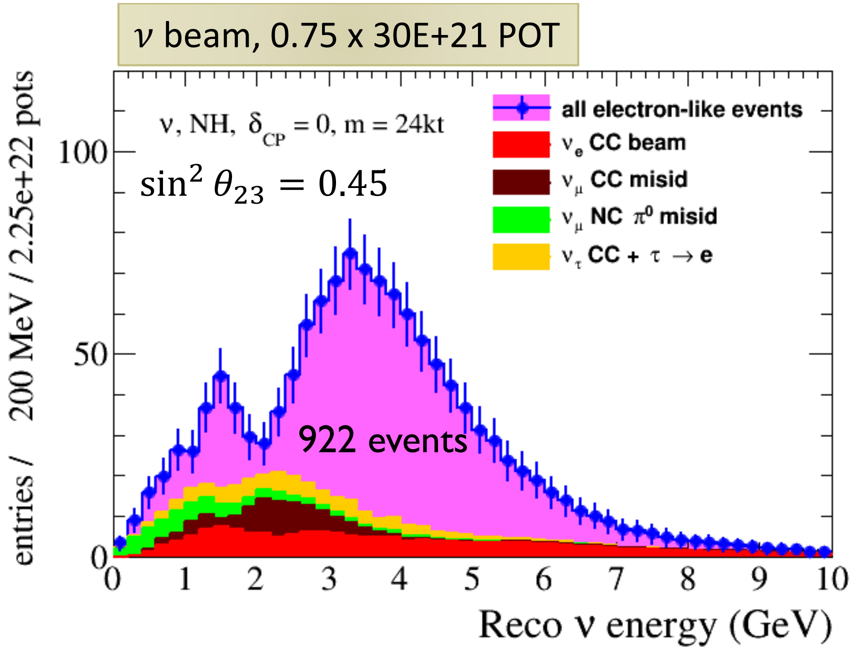


ν beam, 0.75 x 15E+20 POT





ν beam, 0.75 x 30E+21 POT



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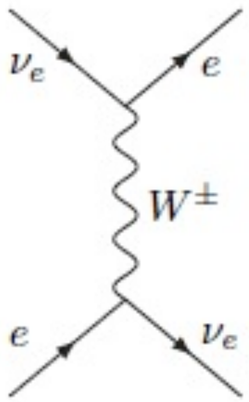
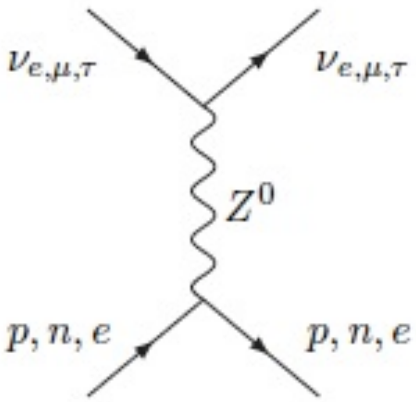
Mass ordering
in LBNO

Long-baseline neutrino oscillations and the ordering

- When neutrinos travel through a medium, they interact with the background of electron, proton and neutrons and acquire an effective mass.





- Typically the background is CP and CPT violating, e.g. the Earth and the Sun contain only electrons, protons and neutrons, and the resulting oscillations are CP and CPT violating.

See also Gandhi’s talk

The oscillation probability becomes (for constant density)

$$P_{\nu_\mu \to \nu_e} = \sin^2\theta_{23}\sin^2 2\theta_{13}^m \sin^2\frac{\Delta_{13}^m L}{2}$$

The mixing angle in matter is

$$\sin^2(2\theta_m) = \frac{\left(\frac{\Delta m^2}{2E}\sin(2\theta)\right)^2}{\left(\frac{\Delta m^2}{2E}\cos(2\theta) - \sqrt{2}G_F N_e\right)^2 + \left(\frac{\Delta m^2}{2E}\sin(2\theta)\right)^2}$$

- If $\boxed{\sqrt{2}G_F N_e = \frac{\Delta m^2}{2E}\cos 2\theta}$: resonance $\boxed{\theta_m = \pi/4}$
- The resonance condition can be satisfied for
  - neutrinos if $\Delta m^2 > 0$
  - antineutrinos if $\Delta m^2 < 0$

Matter effects modify the oscillation probability in LBL experiments.

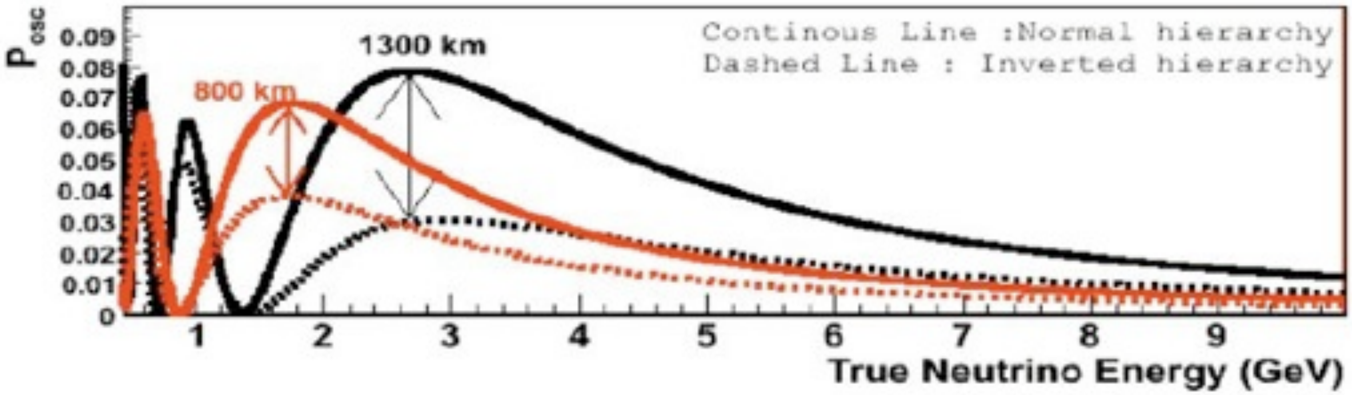
$$P_{\mu e} \simeq 4c_{23}^2 \boxed{s_{13}^2} \frac{1}{(1-\boxed{r_A})^2} \sin^2 \frac{(1-r_A)\Delta_{31}L}{4E}$$

$$+\sin 2\theta_{12} \sin 2\theta_{23} s_{13} \frac{\Delta_{21}L}{2E} \sin \frac{(1-r_A)\Delta_{31}L}{4E} \cos\left(\delta - \frac{\Delta_{31}L}{4E}\right)$$

$$+s_{23}^2 \sin^2 2\theta_{12} \frac{\Delta_{21}^2 L^2}{16E^2} - 4c_{23}^2 s_{13}^4 \sin^2 \frac{(1-r_A)\Delta_{31}L}{4E}$$

A. Cervera et al., hep-ph/0002108;
K. Asano, H. Minakata, 1103.4387;
S. K. Agarwalla et al., 1302.6773...

with $r_A \equiv \frac{2E}{\Delta m_{31}^2}\sqrt{2}G_F N_e$



Matter effects are stronger at high energies and at longer baselines.

Statistical issues for the mass hierarchy

Typical statements are:
“ LBNO will determine the mass ordering at x sigma”.

What is the “experiment”?
What does “determination” mean?
What is the meaning of “x sigma”?

From a statistics point of view, we are testing two alternative hypothesis: NO (true) vs IO (false) or viceversa.

Two errors:

1. reject NO when true (Ist kind),
2. accept IO when wrong (2nd kind).

One needs to quantify this using a test statistic T.

$$\alpha = \int_{T_c}^{\infty} p(T|NO)dT$$

prob. of rejecting NO when true

$1-\alpha$ confidence level

$$\beta = \int_{-\infty}^{T_c} p(T|IO)dT$$

prob. of accepting IO when wrong

$1-\beta$ power of the test

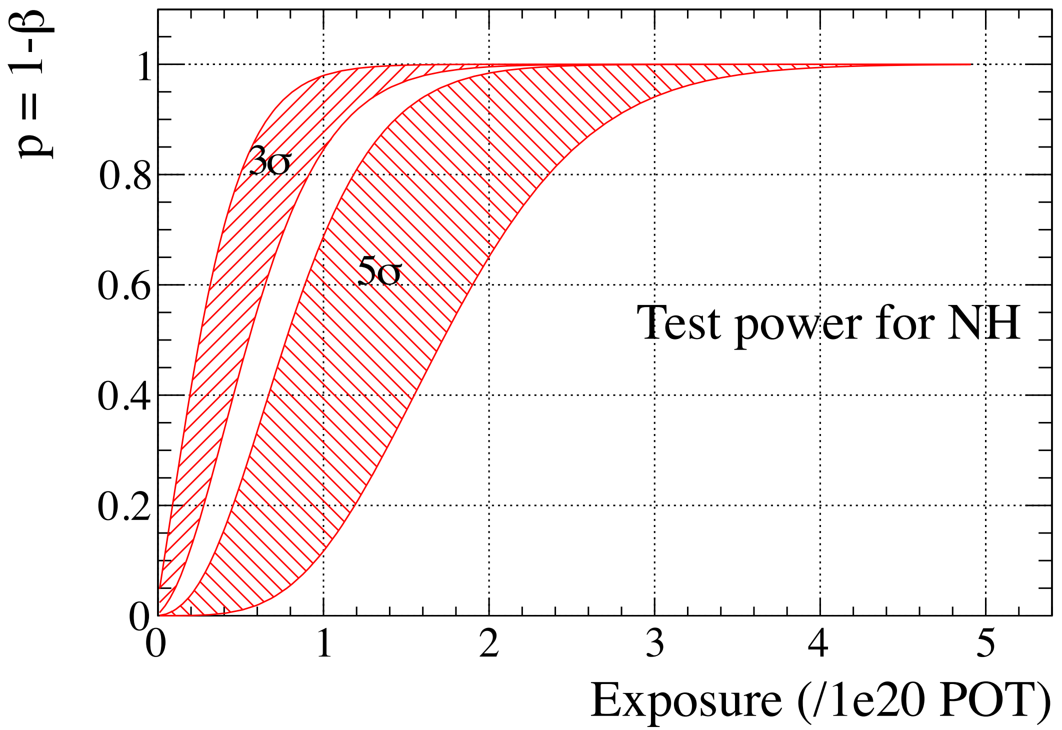
In the case of a simulated experiment:

$$T(\theta_0) = \min_{\theta_{IO}} \sum_i \frac{\left(\mu_i^{NO}(\theta_0) - \mu_i^{IO}(\theta)\right)^2}{\sigma_i^2}$$

No statistical fluctuations: "average" experiment.

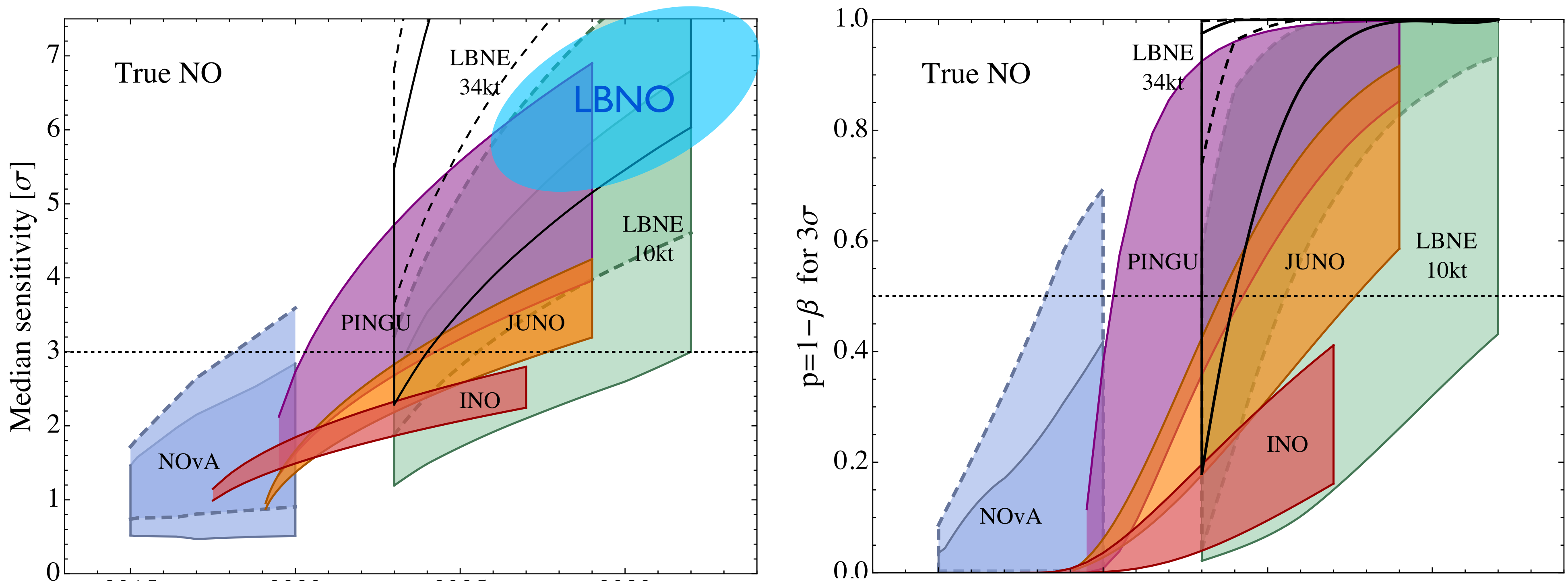
See M. Blennow et al., 1311.1822; X. Qian et al., 1210.3651, F. Capozzi, et al.,1309.1638; E. Ciuffoli, et al., 1305.5150; S.-F. Ge et al., 1210.8141.

The median sensitivity is the sensitivity with beta=50%: an experiment will reject the wrong mass ordering at x sigma with probability 50%.



LAGUNA-LBNO,
1312.6520

One can choose the beta at which one is confident in the predictions. But comparisons between experiments need to be consistent.



M. Blennow et al., 1311.1822

	Long baseline beam (e. g. LBNE)	**Atmospheric (e. g. PINGU)**	**Reactor long baseline**
Benefit	Robust, clean signal	Predictable timescale/cost	Independent technology
Risk (osc. params.)	δ_{CP}, θ_{23}	θ_{23}	-
Challenges	Timescale	Energy res., directional res., particle ID	Energy resolution!!!

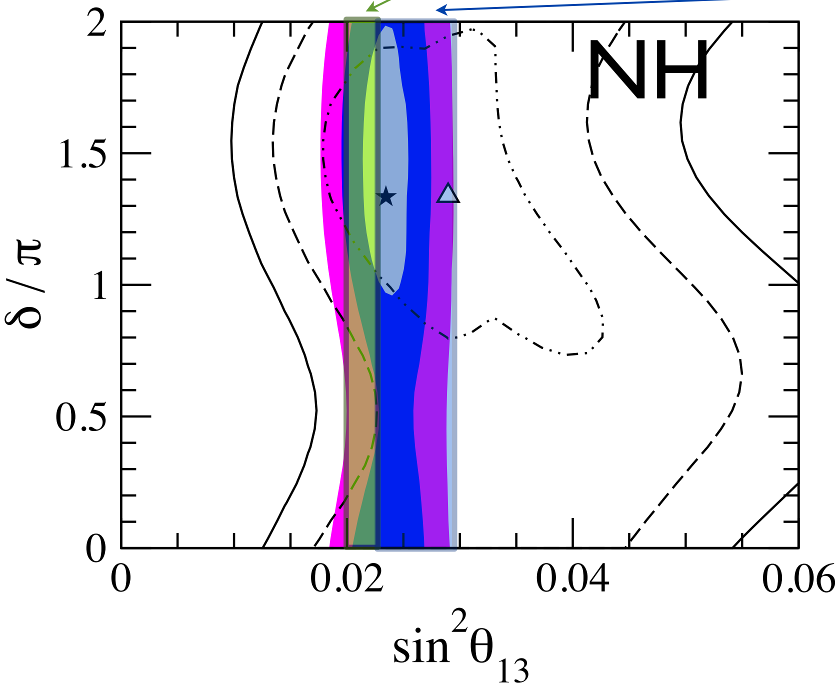
From W. Winter's talk at Neutrino 2014

CPV
in LBNO

CPV after Neutrino 2014

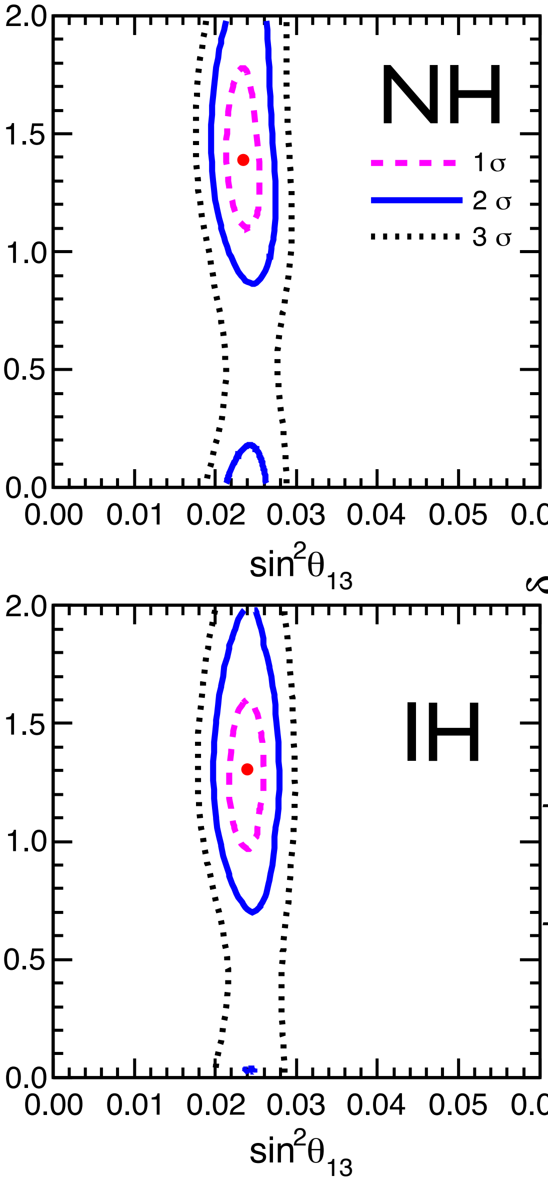
Neutrino 2014 Daya Bay results

Neutrino 2014 RENO results



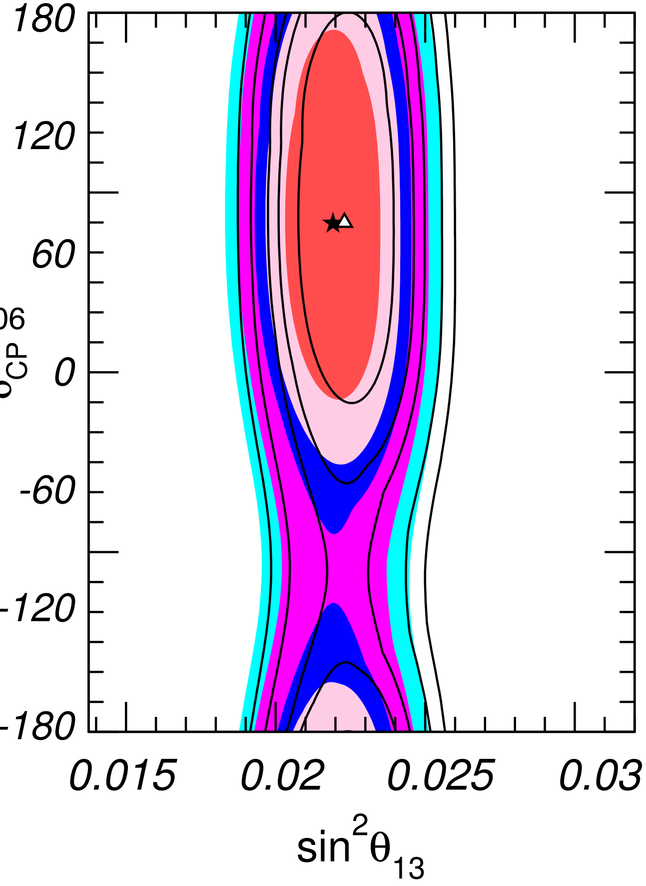
D.V. Forero et al., 1405.7540

There is a slight preference for CP-violation, which is mainly due to the combination of T2K and reactor neutrino data.



F. Capozzi et al., 1312.2878

After Neutrino 2014 and NOW 2014!



NuFIT 1.3 (2014)

NuFit: M. C. Gonzalez-Garcia et al., 1209.3023

CP-violation in LBL experiments

CP-violation will manifest itself in neutrino oscillations, due to the delta phase. The CP-asymmetry:

$$P(\nu_\mu \to \nu_e; t) - P(\bar{\nu}_\mu \to \bar{\nu}_e; t) =$$

$$= 4 s_{12} c_{12} s_{13} c_{13}^2 s_{23} c_{23} \sin\delta \left[\sin\left(\frac{\Delta m_{21}^2 L}{2E}\right) + \sin\left(\frac{\Delta m_{23}^2 L}{2E}\right) + \sin\left(\frac{\Delta m_{31}^2 L}{2E}\right) \right]$$

- CP-violation requires all angles to be nonzero.

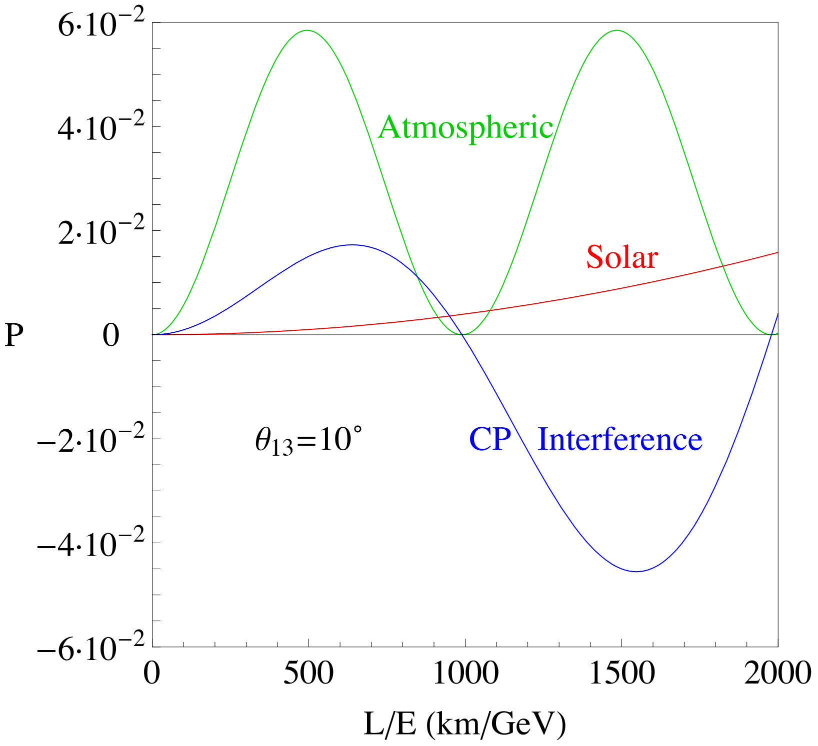
- It is proportional to the sine of the delta phase.

- Effective 2-neutrino probabilities are CP-symmetric. CPV needs to be searched for in LBL experiments which have access to 3-neutrino oscillations.

$$\begin{aligned}P_{\mu e} \simeq\ & 4c_{23}^2 \boxed{s_{13}^2} \frac{1}{(1-r_A)^2}\sin^2\frac{(1-r_A)\Delta_{31}L}{4E}\\ &+\sin 2\theta_{12}\sin 2\theta_{23}\boxed{s_{13}}\frac{\boxed{\Delta_{21}}L}{2E}\sin\frac{(1-r_A)\Delta_{31}L}{4E}\cos\left(\boxed{\delta}-\frac{\Delta_{31}L}{4E}\right)\\ &+s_{23}^2\sin^2 2\theta_{12}\frac{\Delta_{21}^2L^2}{16E^2}-4c_{23}^2 s_{13}^4\sin^2\frac{(1-r_A)\Delta_{31}L}{4E}\end{aligned}$$

A. Cervera et al., hep-ph/0002108;
K. Asano, H. Minakata, 1103.4387;
S. K. Agarwalla et al., 1302.6773...

- The CP asymmetry peaks for sin^2 2 theta13 ~0.001. Large theta13 makes its searches possible but not ideal.
- Impact of an unknown mass ordering.
- CPV effects are more pronounced at low energy.

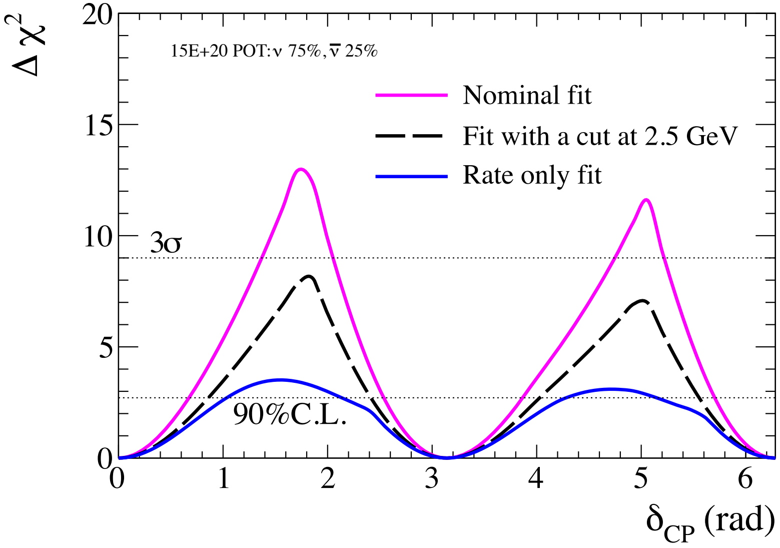


P. Coloma, E. Fernandez-Martinez, JHEP1204

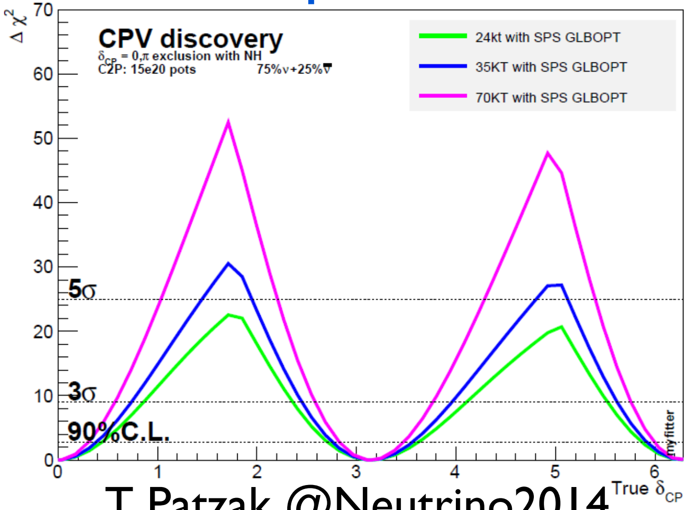
Sensitivity for LBNO

LBNO Coll., 1312.6520

Second oscillation maximum



Exposure



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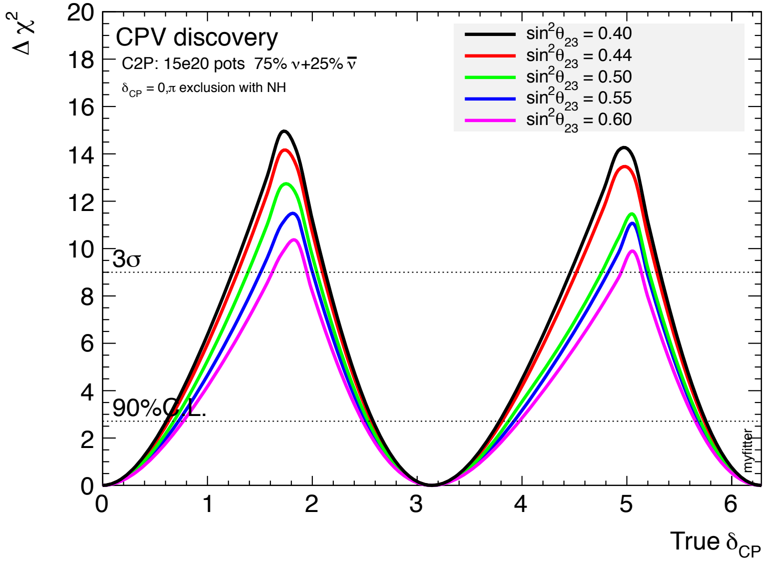
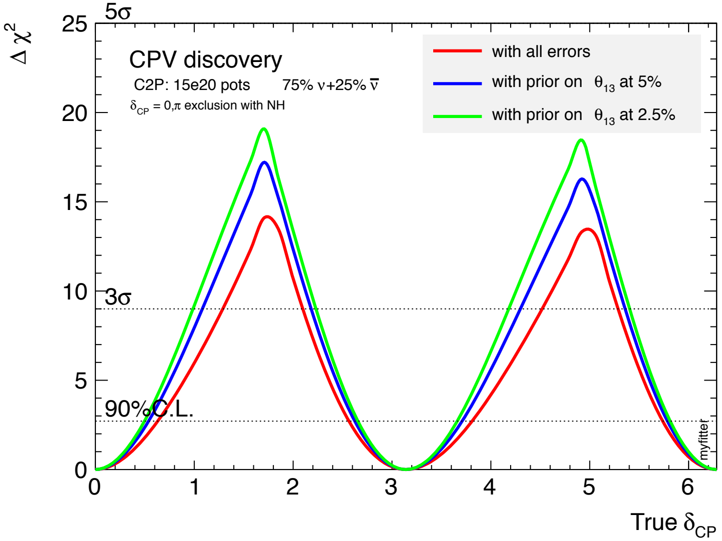
True values of parameters



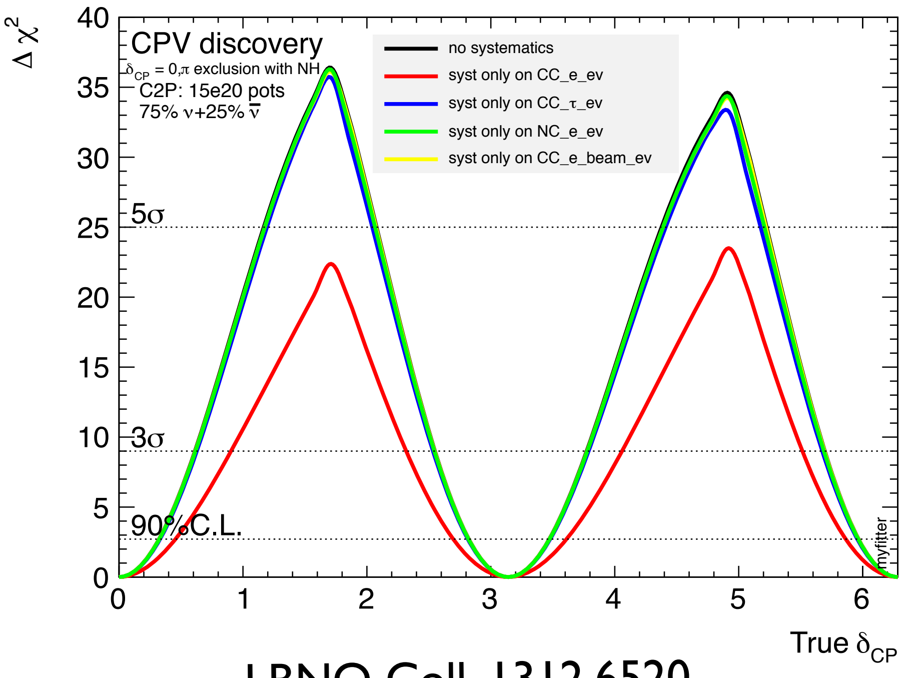
Error on oscillation parameters



Sensitivity to CPV depends on the experimental setup and theoretical assumptions.

Systematic errors

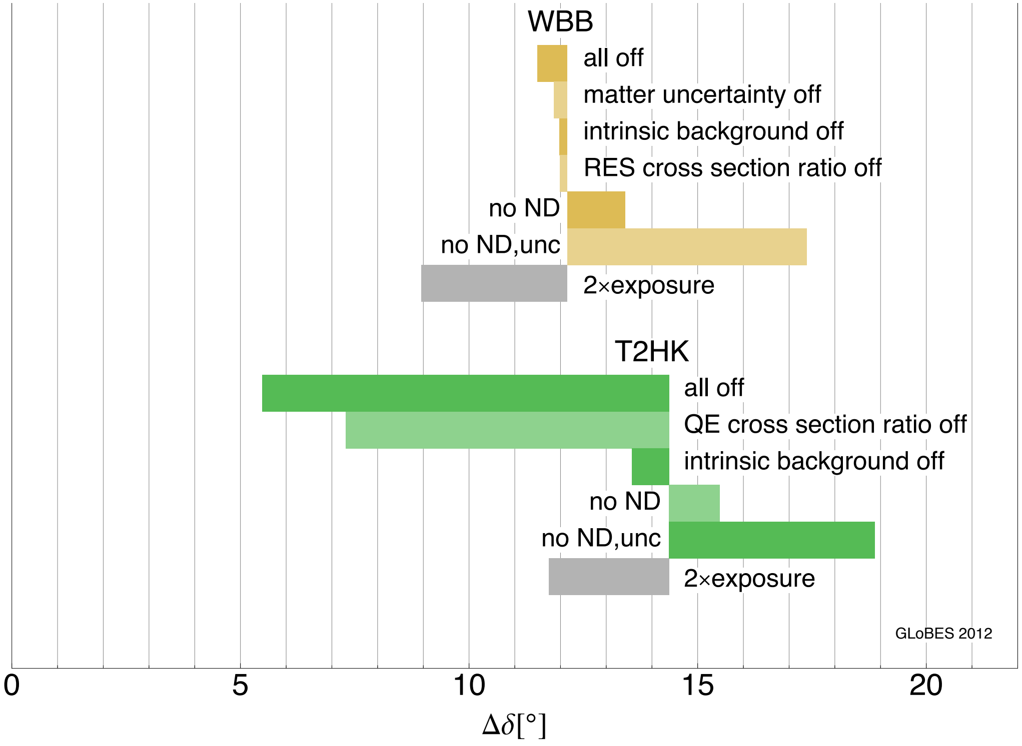
Systematic errors on the signal (flux, cross sections, fiducial volume) have a very strong impact on the sensitivity.



LBNO Coll.,1312.6520

A dedicated set of experiments is needed, in particular for measuring the cross sections.

The near detector plays a crucial role.



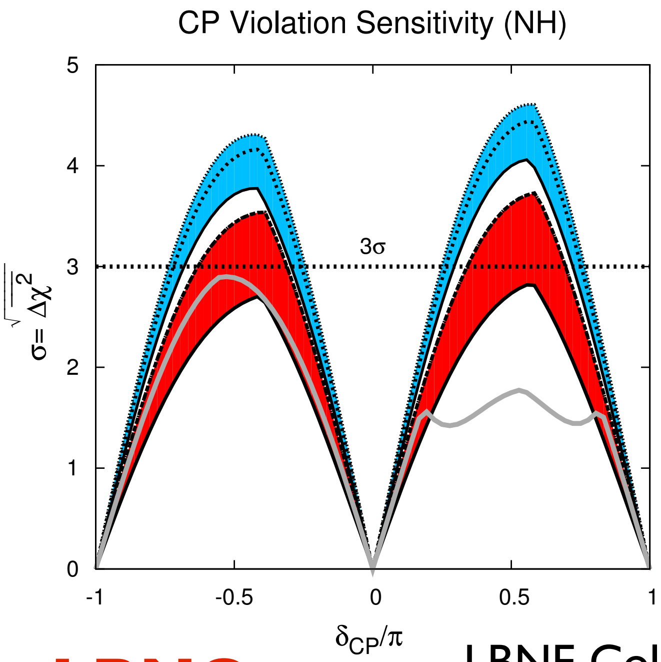
See also, e.g. Barger et al., 1307.2519.

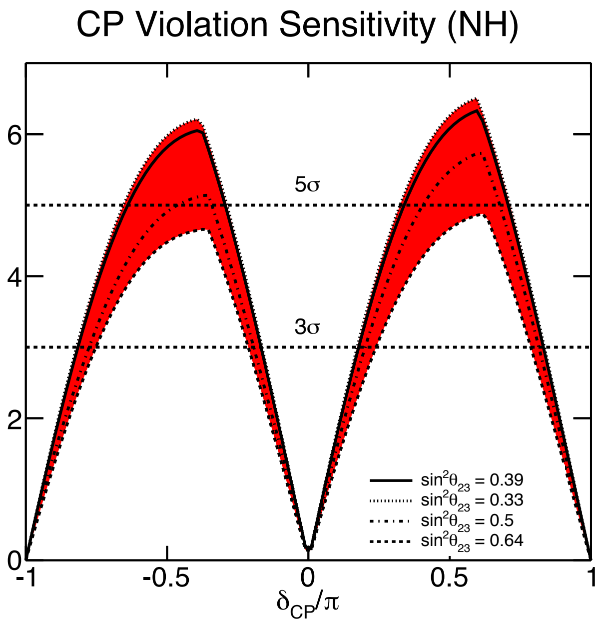
P. Coloma, P. Huber, J. Kopp, W. Winter, 1209.5973

LBNE-10Kton

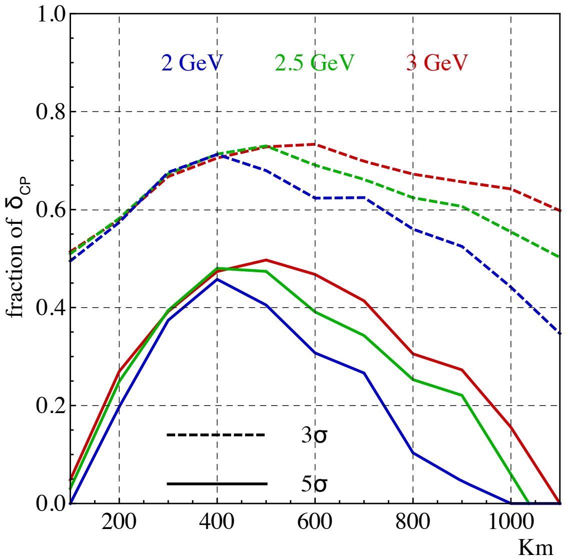
LBNE-34kton

ESSnuSB



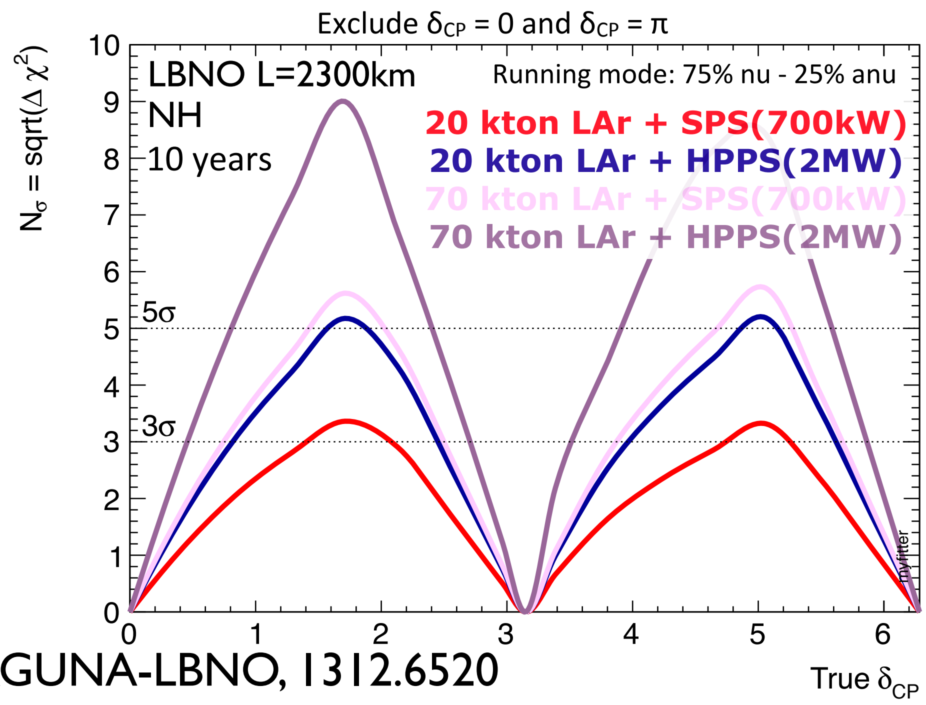


LBNE Coll., 1307.7335

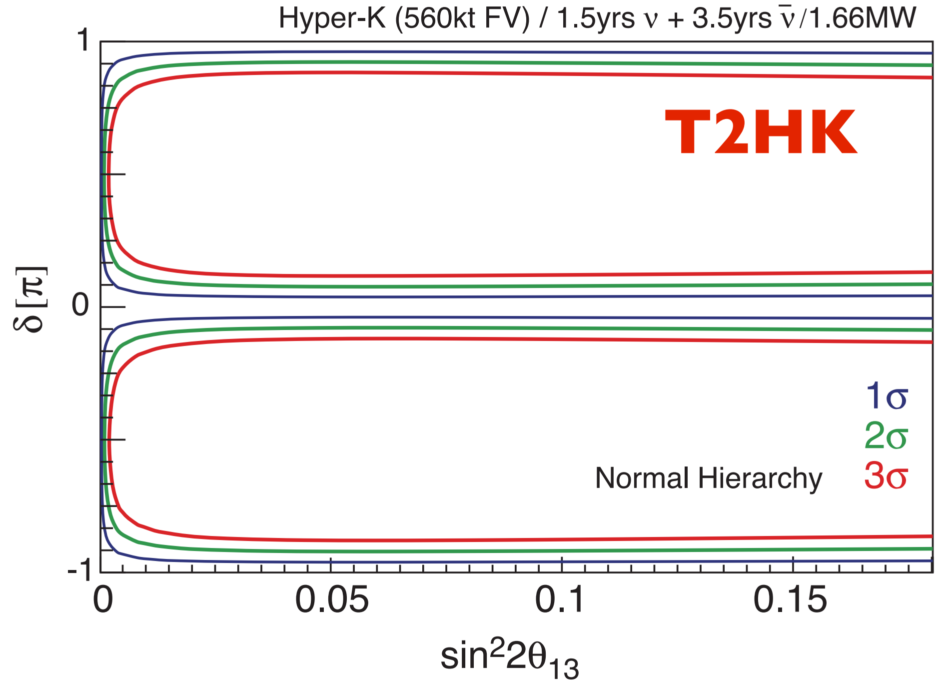


ESSnuSB, 1309.7022

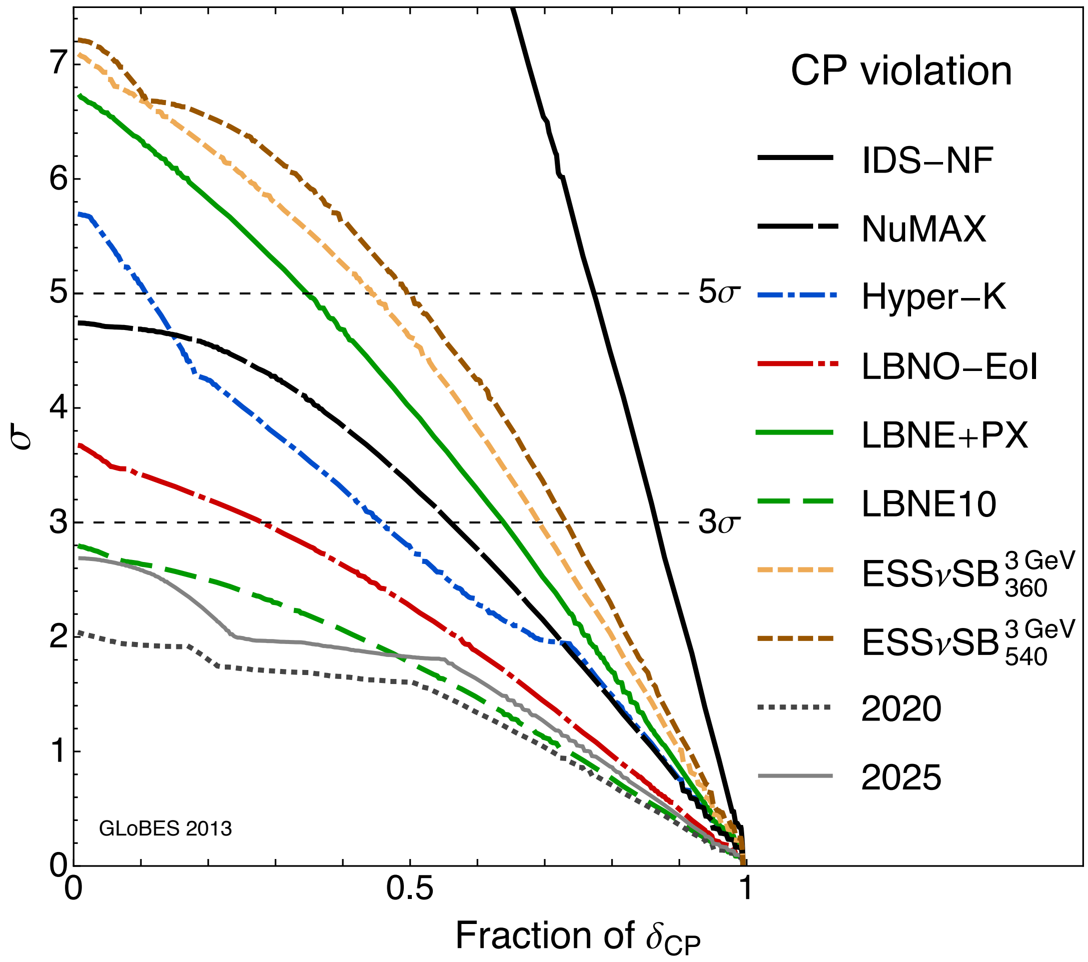
LBNO



LAGUNA-LBNO, 1312.6520



T2HK LoI, Abe et al., 1109.3262



NuFact

ESSnuSB, 1309.7022

Comparisons should be made with great care as they critically depend on:

- setup assumed: detector and its performance, beam...
- values of oscillation parameters and their errors;
- treatment of backgrounds and systematic errors.

Precision values of oscillation parameters in LBNO

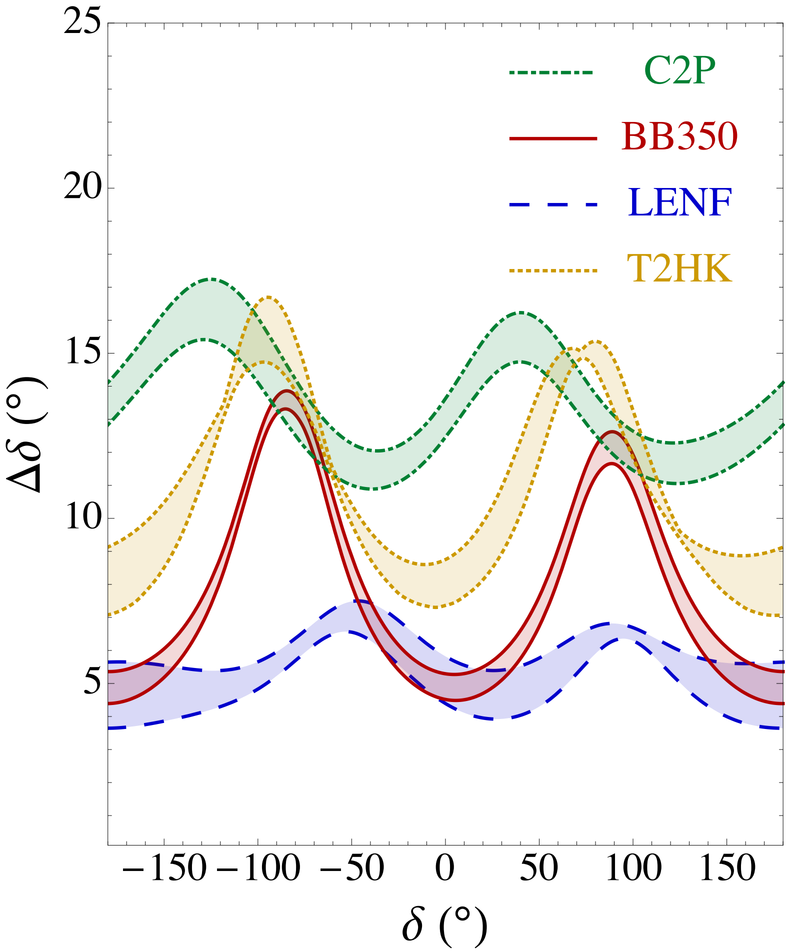
Precision measurements

An important goal will be the determination of the precise values of the parameters: theta23 and delta.

$$\Delta\delta \propto \sqrt{\frac{1}{1+\cos 2\delta}}$$

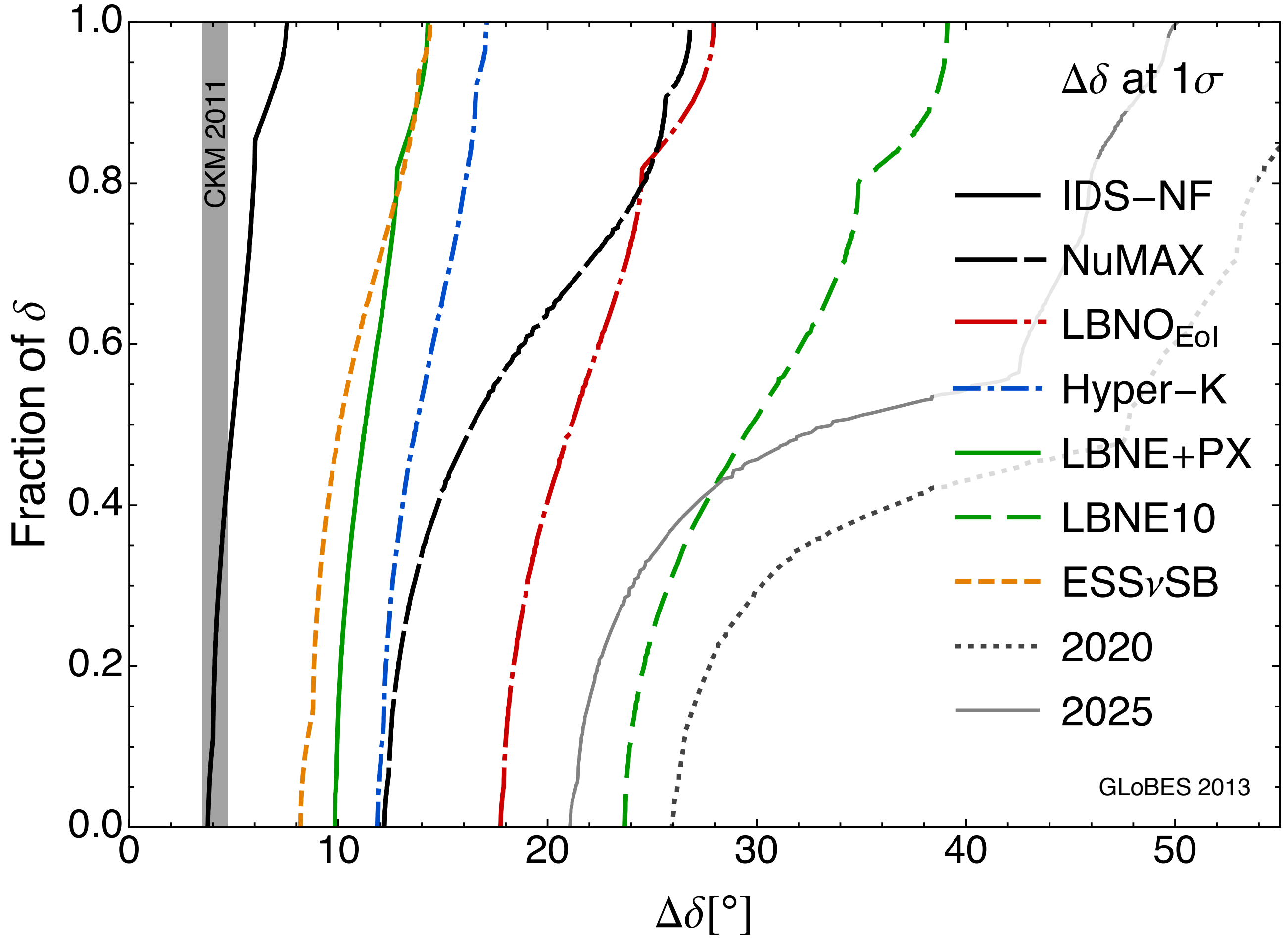
In vacuum, for neutrinos + antineutrinos, at 1st oscillation maximum

Matter effects modify this relation and information at different energies increases the precision achievable. Disappearance channel helps in improving the precision.



P. Coloma et al., 1203.5651

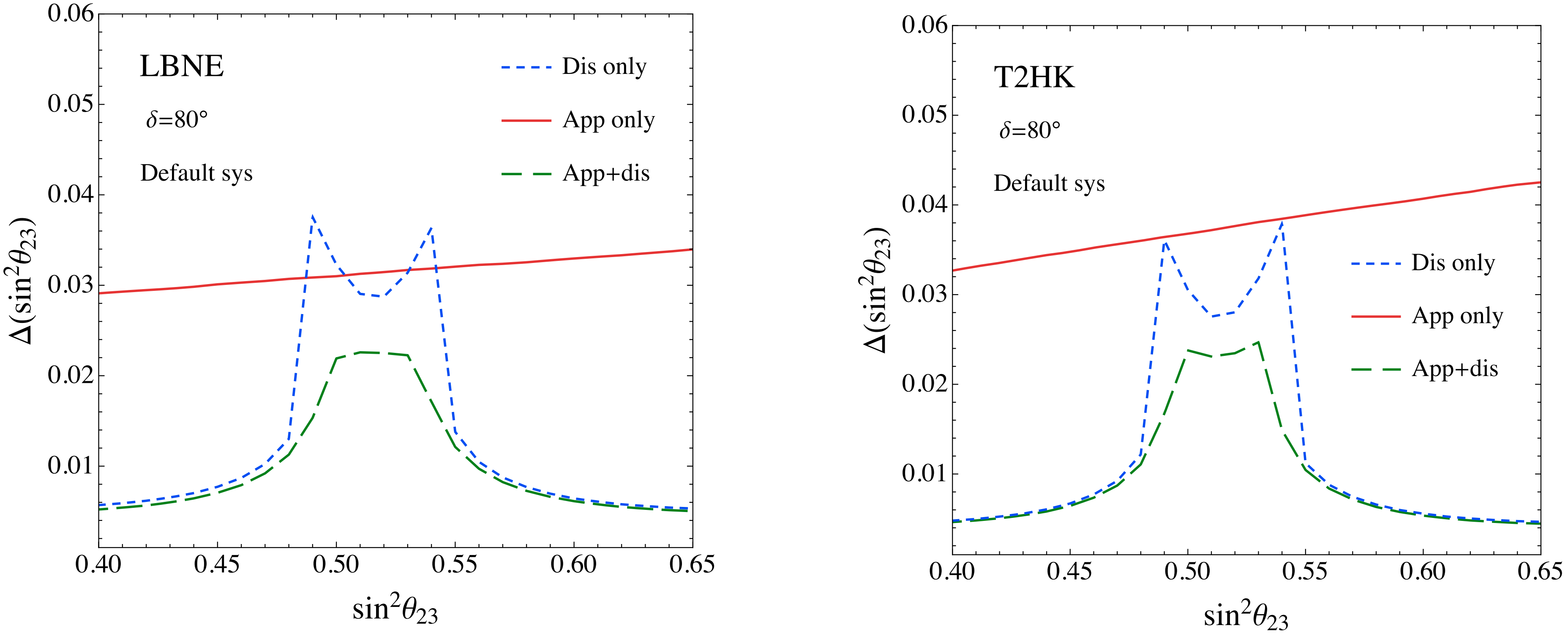
Crucial information in order to discriminate between different flavour models.



WG Report: Neutrinos, de Gouvea (Convener) et al., 1310.4340; see also, Coloma et al., JHEP 1206; Minakata, Parke, PRD87; D. Meloni, PLB728

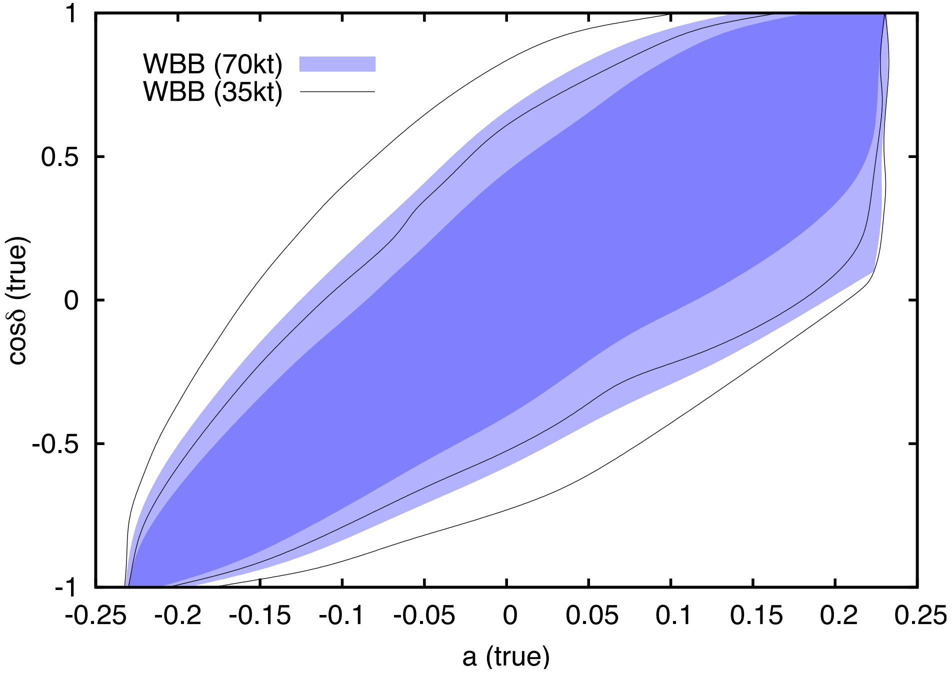
Precision on theta23

Degeneracies in the appearance and disappearance channels limit the precision on theta23 and delta. By combining the two channels and exploiting information at different L/E these degeneracies can be addressed.



P. Coloma, H. Minakata, S. Parke, 1406.2551. See also Minakata, Parke, 1303.6178.

Tests of flavour models



Atmospheric sum rule

$$\sin\theta_{23} - \frac{1}{\sqrt{2}} = a_0 + \lambda \sin\theta_{13}\cos\delta$$

Example: a0=0, lambda=1

Needed: precision LBL exp

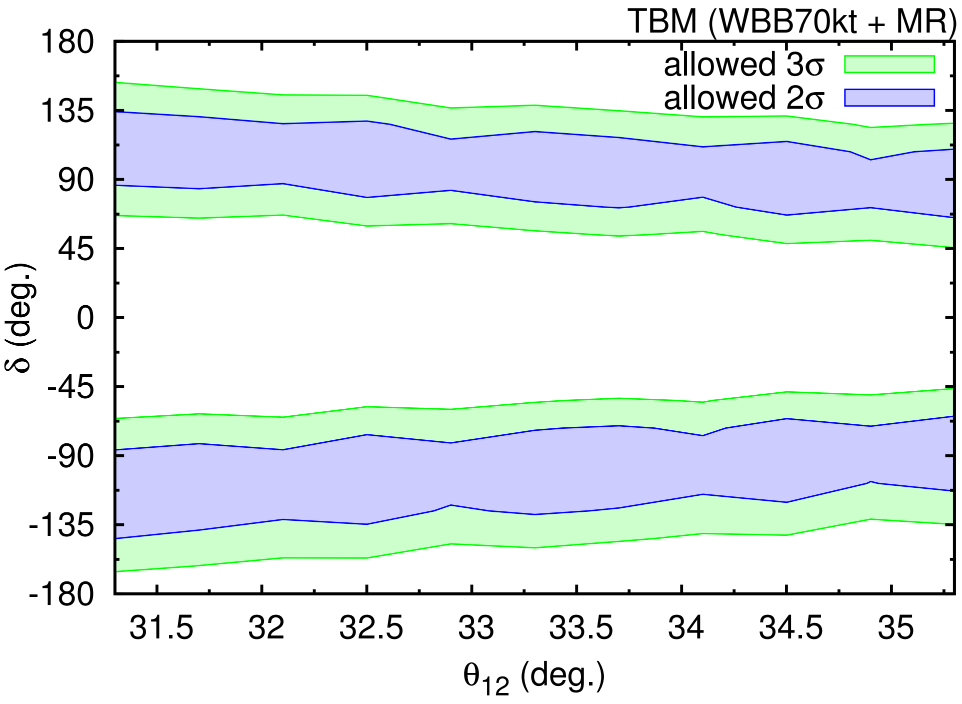
P. Ballett et al., 1308.4314. Also D. Meloni, 1308.4578

Solar sum rule

$$\cos\delta = \frac{t_{23}s_{12}^2 + s_{13}^2 c_{12}^2/t_{23} - s_{12}^{\nu 2}(t_{23} + s_{13}^2/t_{23})}{\sin 2\theta_{12} s_{13}}$$

Example for TBM: $s_{12}^{\nu} = 1/\sqrt{3}$

Synergy: precision LBL exp and future reactor exp



P. Ballett et al., 1410.7573

Conclusions

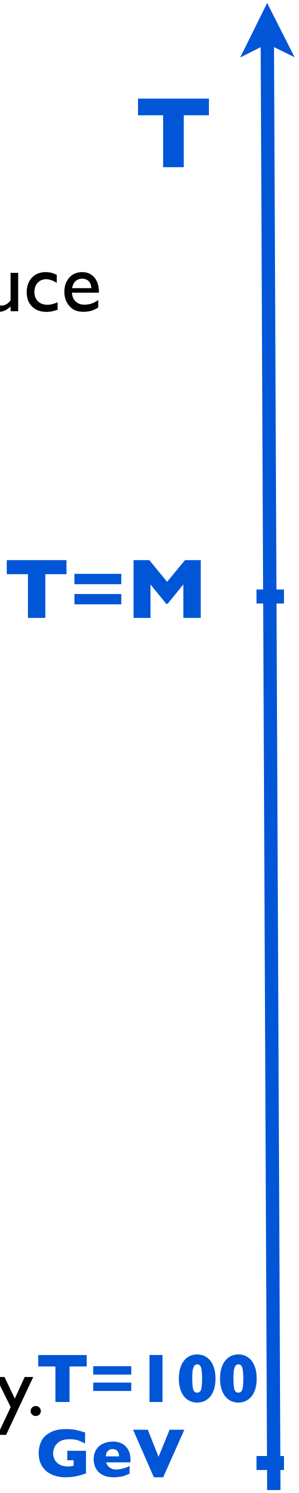
- LBL experiments can search for the mass ordering, CPV, precise values of the oscillation parameters and can provide tests of the 3-neutrino scenario.

- There is a strong synergy with non-accelerator searches (e.g. neutrinoless double beta decay, supernova neutrinos, cosmology,...).

- Precise information on the values of the masses, mixing angles and CPV phase is crucial to understand the origin of masses and mixing.

- The observation of L violation and of CPV in the lepton sector would be a strong indication (even if not a proof) of leptogenesis as the origin of the baryon asymmetry.

Leptogenesis



- At T>M, the right-handed neutrinos N are in equilibrium thanks to the processes which produce and destroy them:

$$N \leftrightarrow \ell H$$

- When T<M, N drops out of equilibrium

$$N \to \ell H \qquad\qquad N \to \ell^c H^c$$

- A lepton asymmetry can be generated if

$$\Gamma(N \to \ell H) \neq \Gamma(N \to \ell^c H^c)$$

- Sphalerons convert it into a baryon asymmetry.

Fukugita, Yanagida, PLB 174; Covi, Roulet, Vissani; Buchmuller, Plumacher; Abada et al., ...

In order to compute the baryon asymmetry:

1. evaluate the CP-asymmetry

$$\epsilon \equiv \frac{\Gamma(N \to \ell H) - \Gamma(N^c \to \ell^c H^c)}{\Gamma(N \to \ell H) + \Gamma(N^c \to \ell^c H^c)}$$

2. solve the Boltzmann equations to take into account the wash-out of the asymmetry

$$Y_L = k\epsilon$$

3. convert the lepton asymmetry into the baryon one

$$\boxed{Y_B = \frac{k}{g^*} c_s \epsilon \sim 10^{-3} - 10^{-4} \epsilon}$$

For T < 10^{12} GeV, flavour effects are important.