Theory and phenomenology of CP violation

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Outline

1. Present status of CP-violation

2. Searches for CP-violation
   - LBL experiments
   - Neutrinoless double beta decay

3. Leptogenesis

4. Is there a connection between low energy CPV and leptogenesis?

5. Conclusions

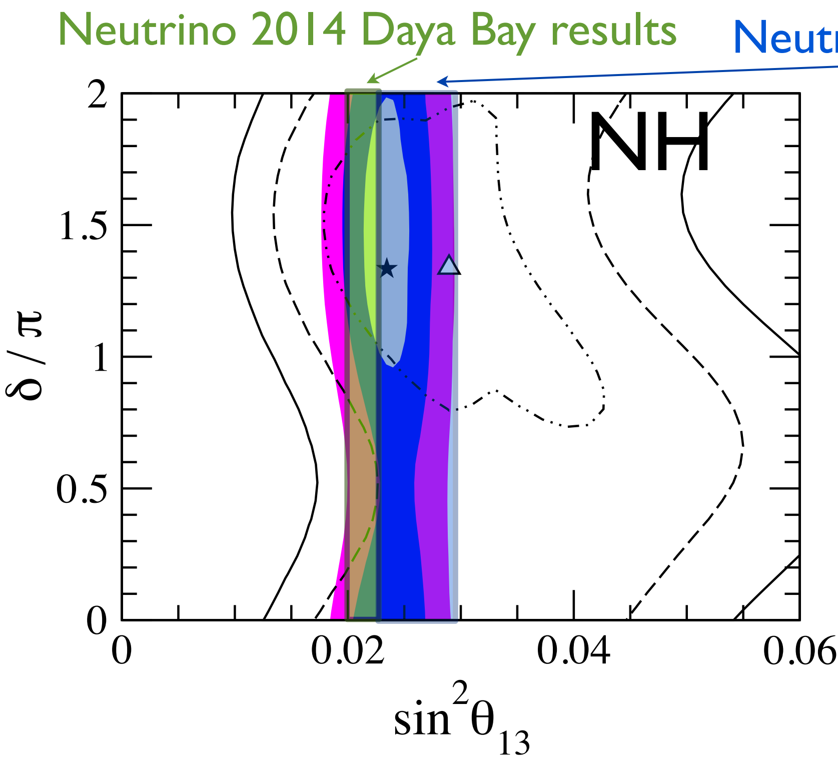
CP-violation in the leptonic sector

$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{-i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} 1 & 0 & 0 \\ 0 & e^{i\alpha_{21}/2} & 0 \\ 0 & 0 & e^{i\alpha_{31}/2} \end{pmatrix}$$

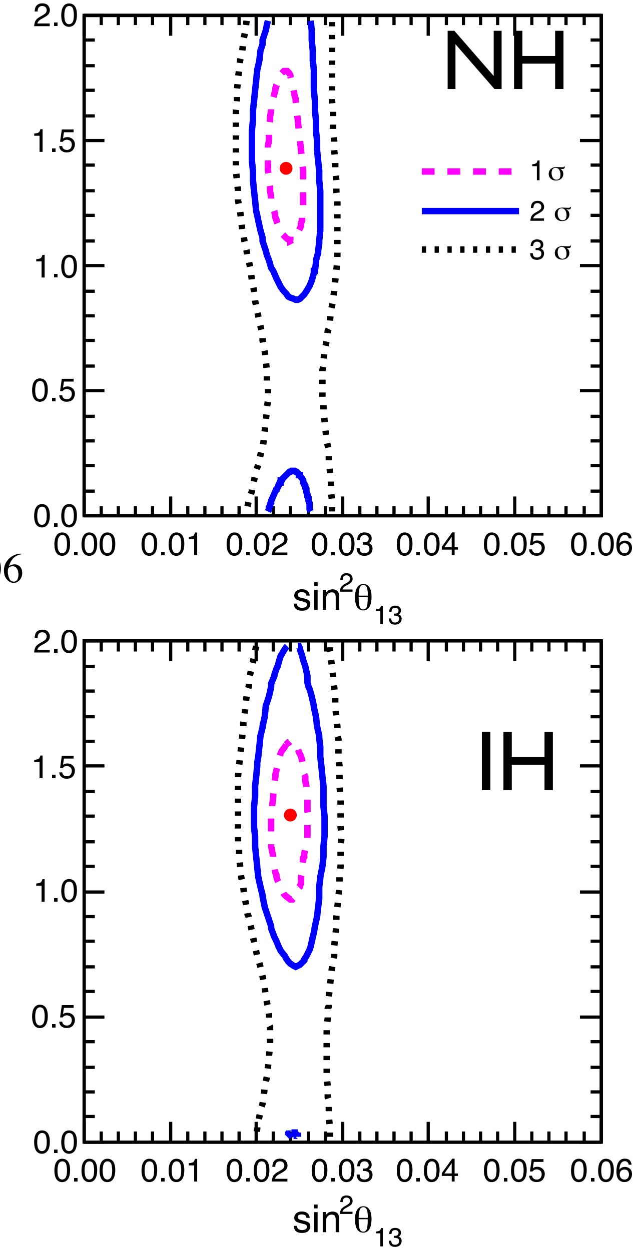
For antineutrinos, $U \rightarrow U^*$

CP-conservation requires U is real $\Rightarrow \delta = 0, \pi$

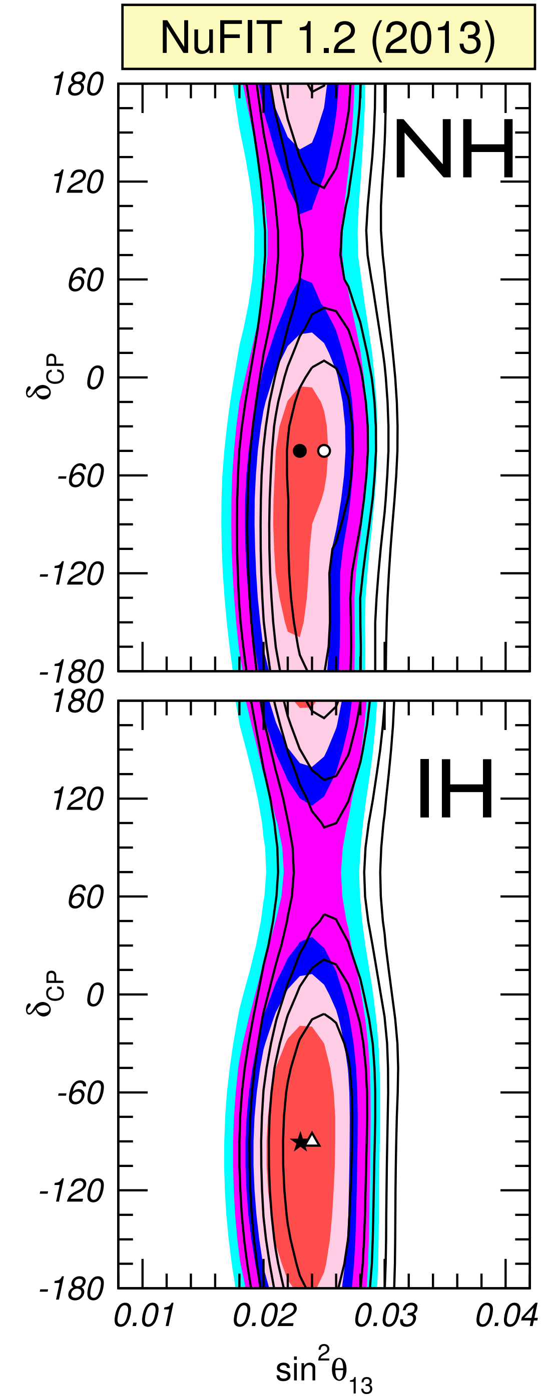
The delta phase can be tested in neutrino oscillations. The Majorana phases can enter only LNV processes and are currently completely unknown.



D.V. Forero et al., 1405.7540



F. Capozzi et al., 1312.2878



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

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

How can we search for leptonic CP-violation?

How can we search for leptonic CP-violation?

- Long baseline neutrino experiments
- (Atmospheric neutrinos)
- Neutrinoless double beta decay

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.
- If one can neglects Δm_{21}^2, the asymmetry goes to zero: effective 2-neutrino probabilities are CP-symmetric.

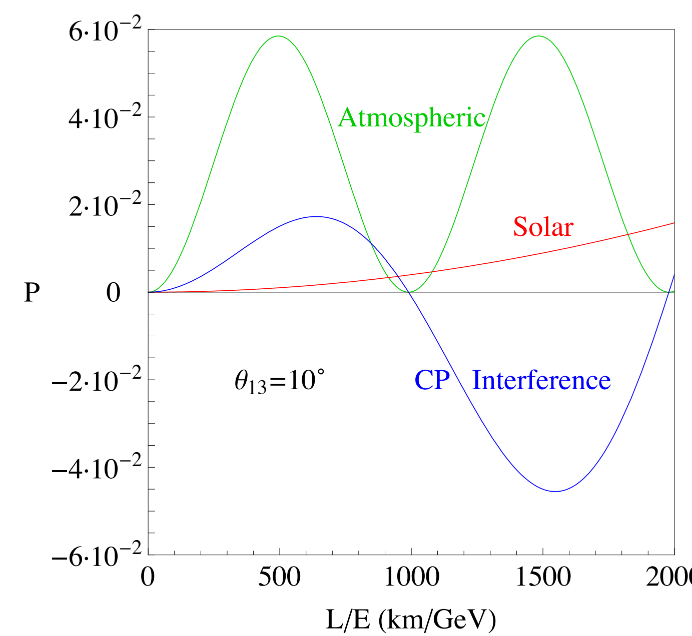
CPV needs to be searched for in long baseline neutrino experiments which have access to 3-neutrino oscillations.

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

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

See also W. Winter's talk

- The CP asymmetry peaks for sin^2 2 theta13 ~0.001. Large theta13 makes its searches possible but not ideal.
- Crucial to know mass ordering.
- CPV effects more pronounced at low energy.



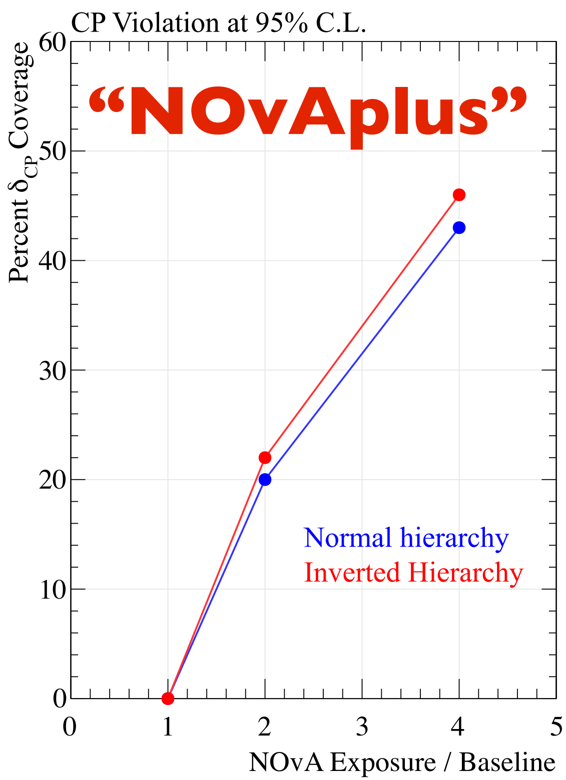
P. Coloma, E. Fernandez-Martinez, JHEP1204

Category	Experiment	Status	Oscillation parameters
Accelerator	MINOS+ [74]	Data-taking	MH/CP/octant
Accelerator	T2K [21]	Data-taking	MH/CP/octant
Accelerator	NOvA [108]	Commissioning	MH/CP/octant
Accelerator	RADAR [76]	Design/ R&D	MH/CP/octant
Accelerator	CHIPS [75]	Design/ R&D	MH/CP/octant
Accelerator	LBNE [87]	Design/ R&D	MH/CP/octant
Accelerator	Hyper-K [97]	Design/ R&D	MH/CP/octant
Accelerator	LBNO [109]	Design/ R&D	MH/CP/octant
Accelerator	ESSνSB [110]	Design/ R&D	MH/CP/octant
Accelerator	DAEδALUS [111]	Design/ R&D	CP

CPV Searches

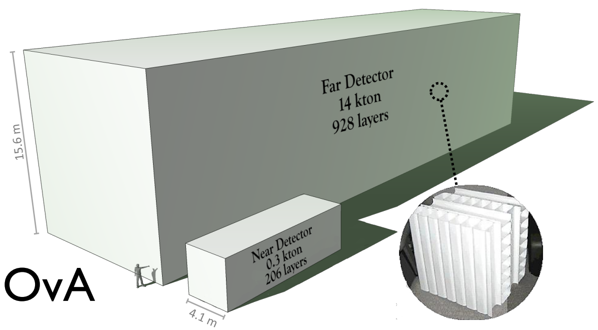
Near future: T2K and NOvA. Marginal sensitivity to CPV

WG Report: Neutrinos, de Gouvea (Convener) et al., 1310.4340

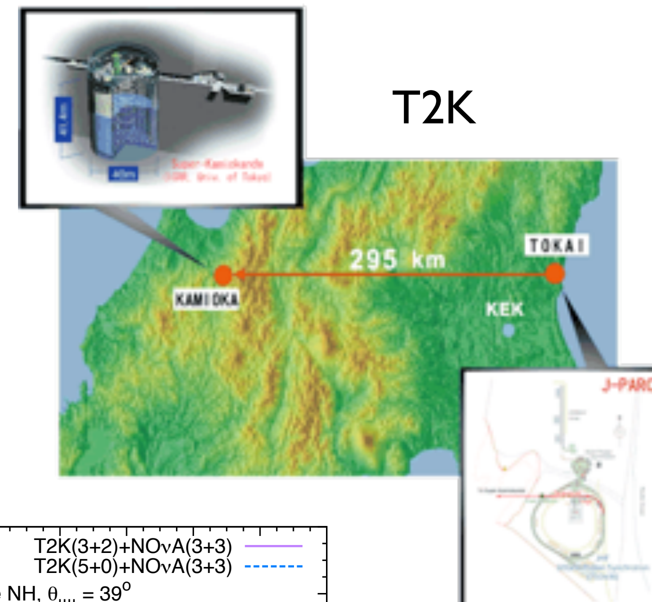


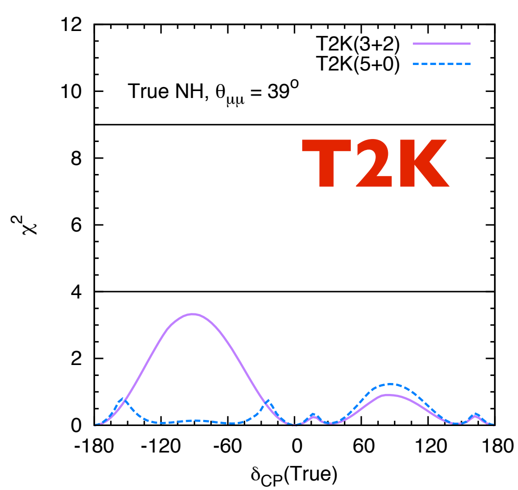
NOvA Coll., 1308.0106

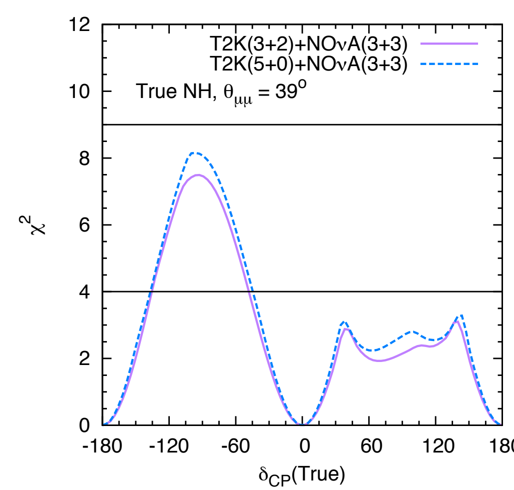
NOvA



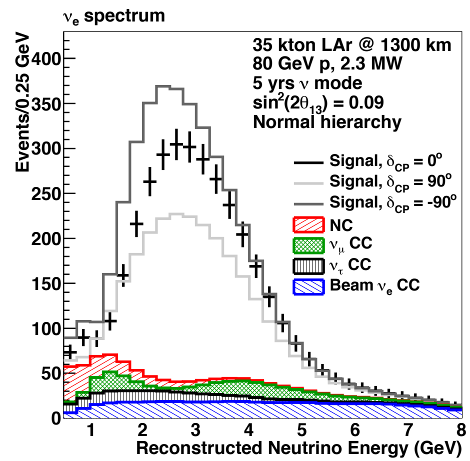
T2K

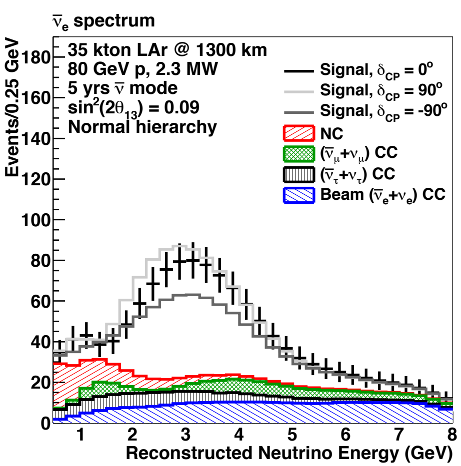




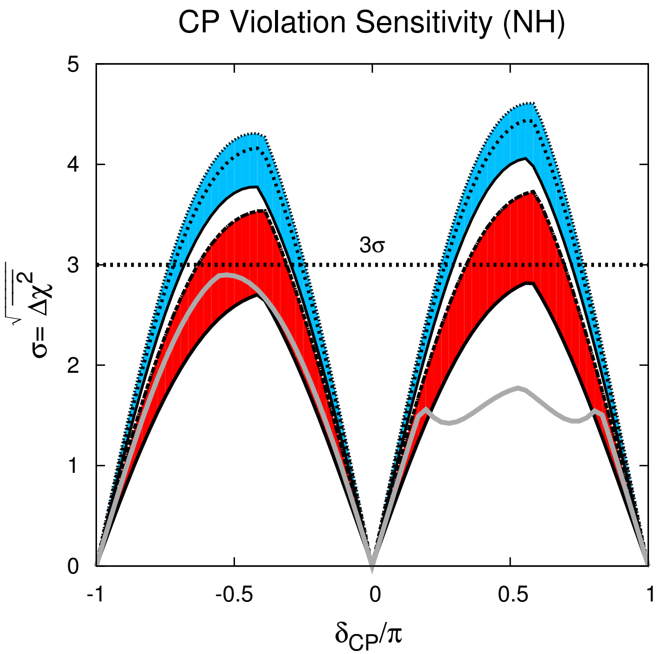


M. Gosh et al., 1401.7243; see also Machado et al.; Huber et al.

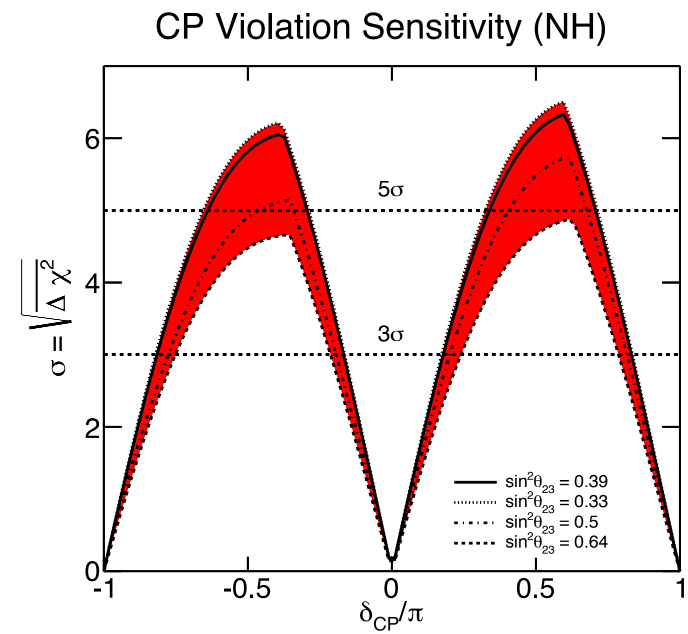




LBNE-10Kton

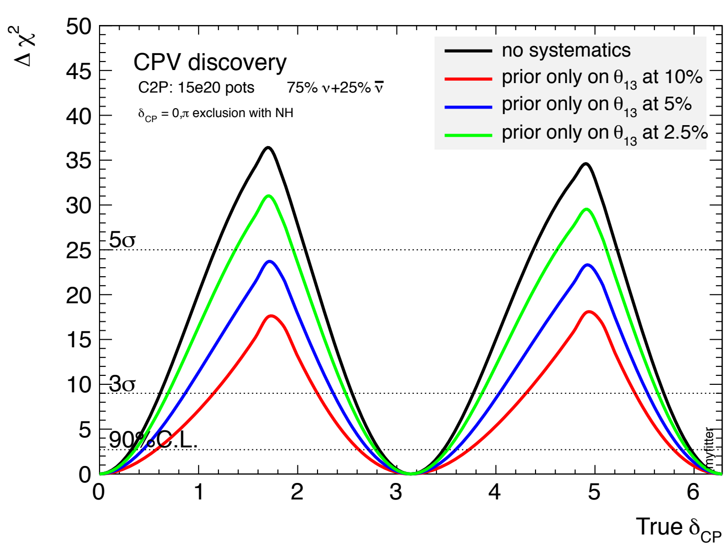


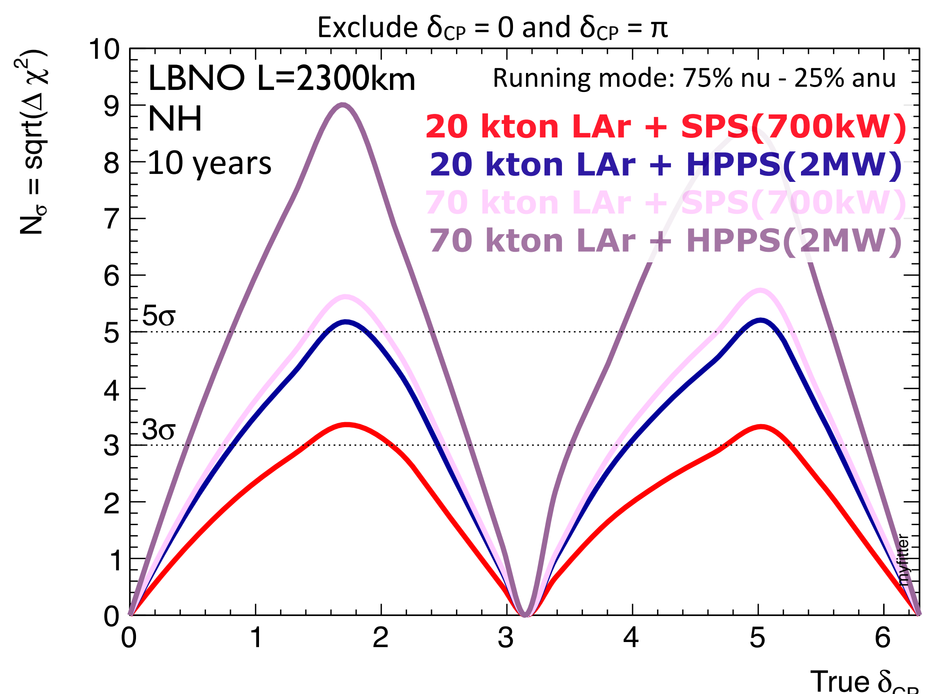
LBNE-34kton



LBNE Coll., 1307.7335

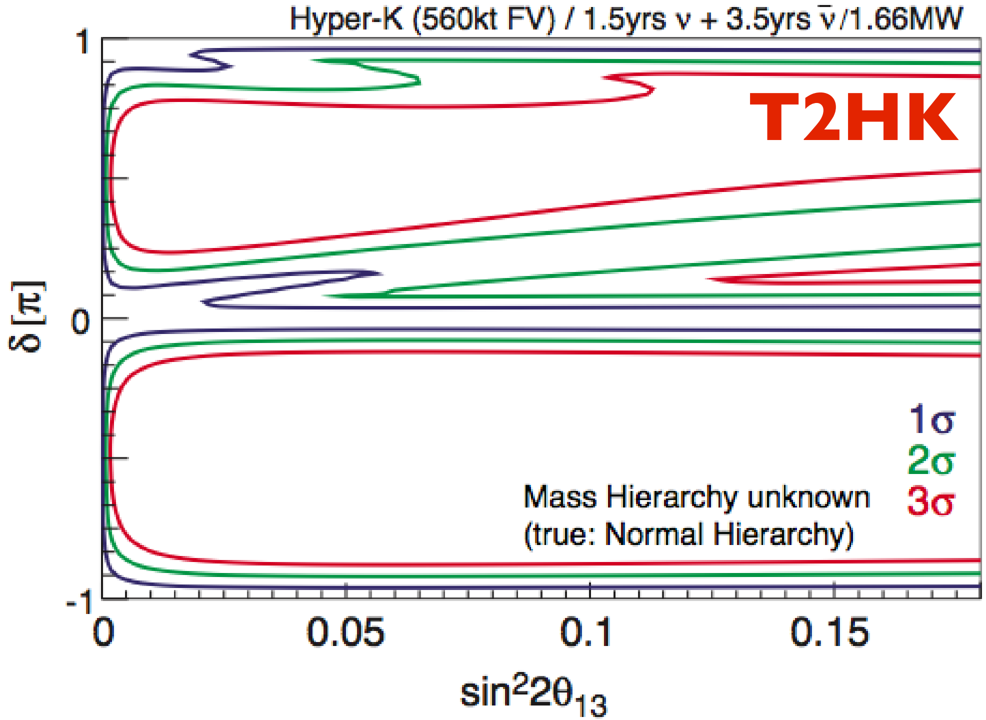
LBNO

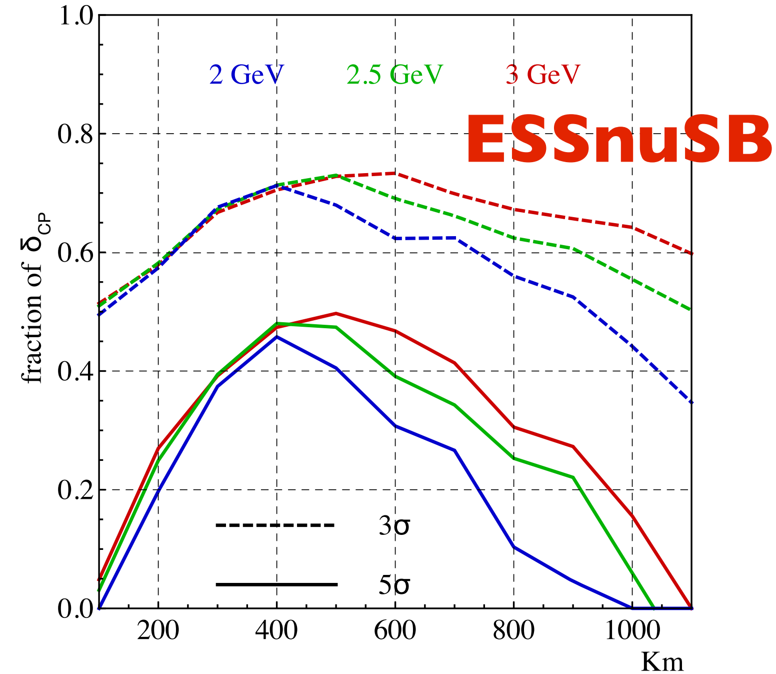




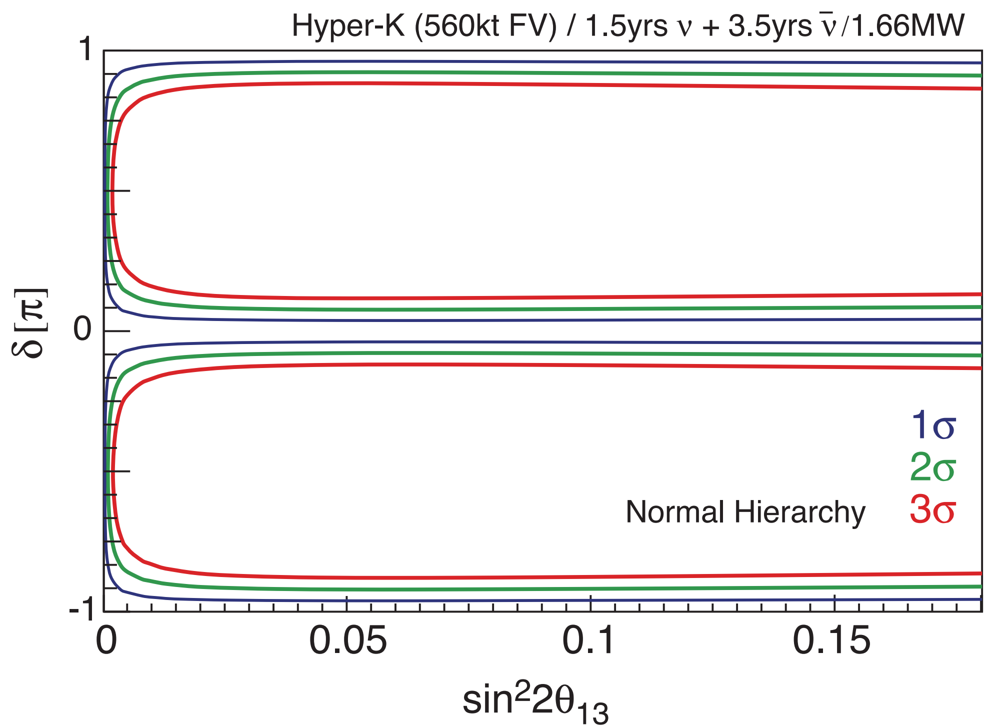
See T. Patzak's, R. Wilson's talk

LAGUNA-LBNO, 1312.6520





ESSnuSB, 1309.7022



T2HK:

The knowledge of the mass ordering is crucial (CPV-mass ordering degeneracy)

ESSnuSB:

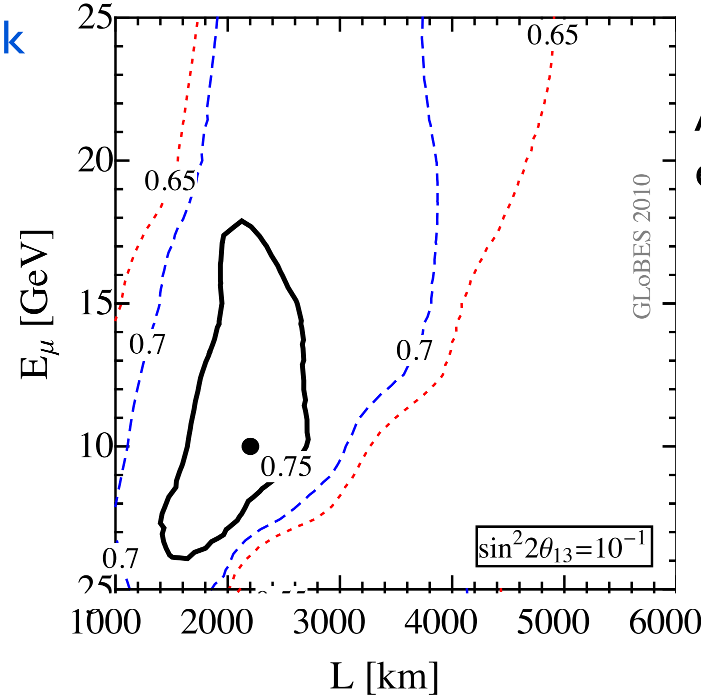
Use the information at low energy.

T2HK LoI, Abe et al., 1109.3262 See Y. Hayato's talk

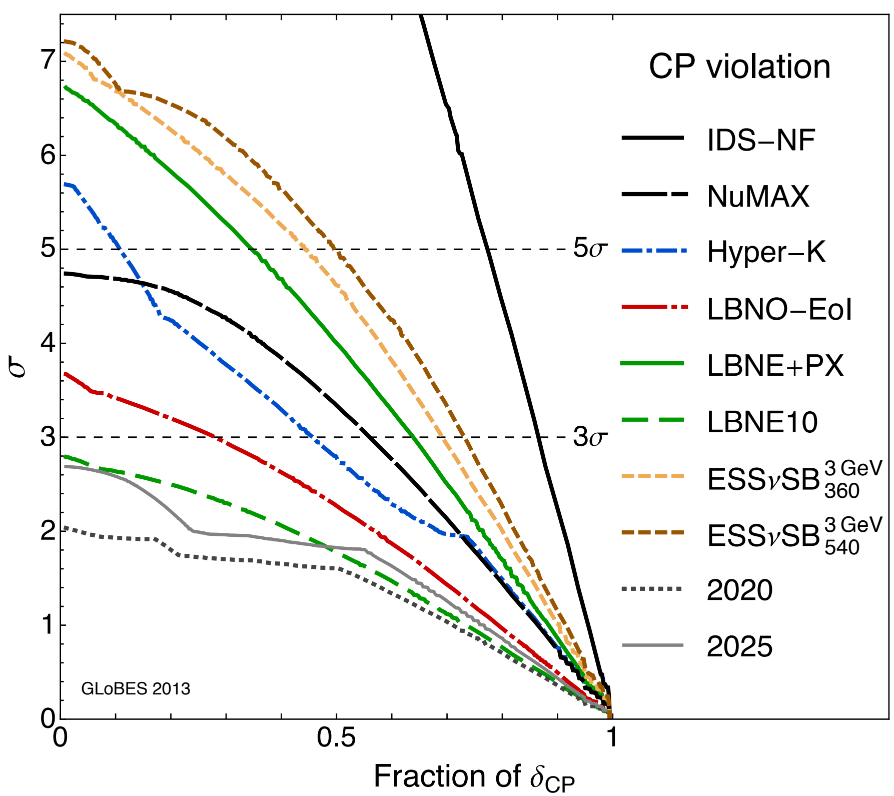
Neutrino factory

See P. Soler's talk

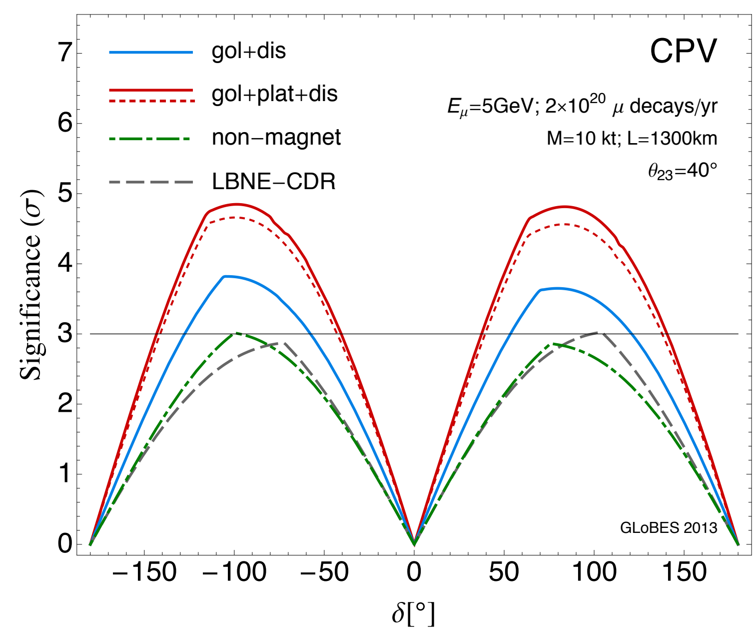
The neutrino factory has the best sensitivity to CPV. Due to large theta13, low energy muons and not-too-long baselines are needed.



Agarwalla et al., JHEP 1101



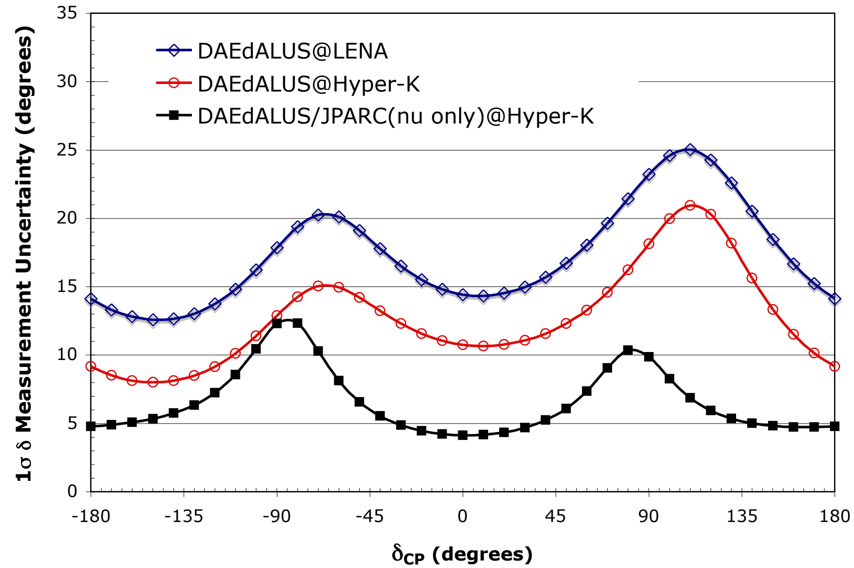
ESSnuSB, 1309.7022



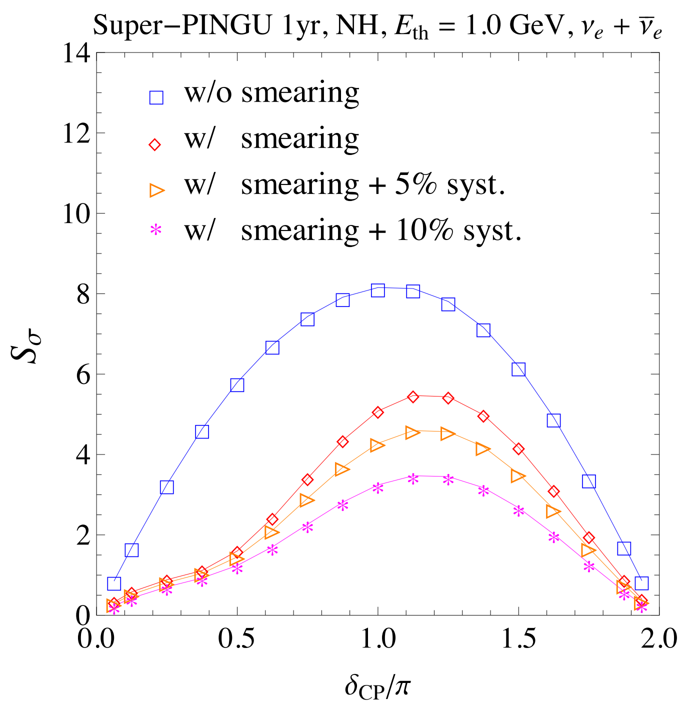
Christensen et al., PRL 111. See also Geer, Mena SP, PRD 75, Bross et al, PRD77; Fernandez-Martinez, Li, Mena, SP, PRD 81; and Rubbia et al., 2001; IDS-NF...

DAEdALUS

Uses the probability of oscillation of low energy muon antineutrino into electron antineutrinos at short baselines (1.5-20 Km).



DAEdALUS Coll., 1307.2949



Razzaque, Smirnov, to appear

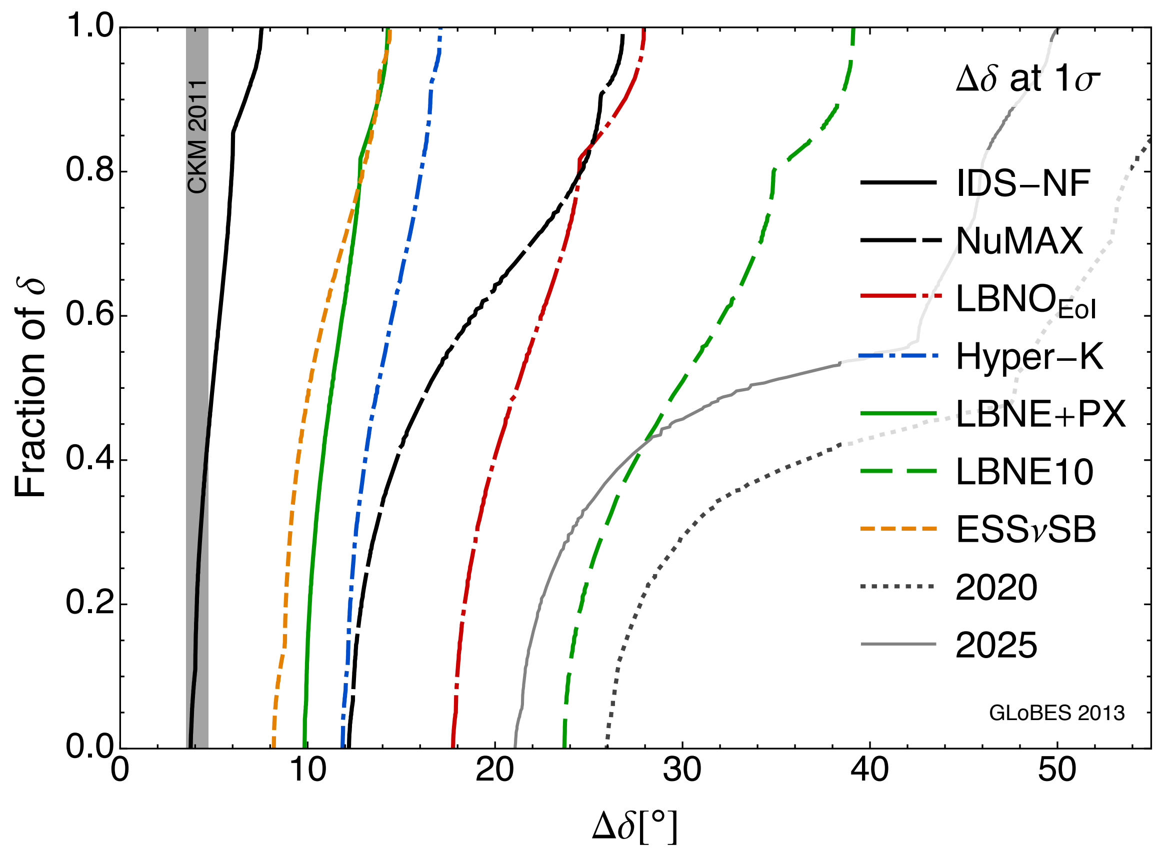
Atmospheric neutrinos

These experiments have access to a broad range of baselines and energies. Limited energy and angular resolution and nu-anti nu discrimination affect their reach.

Peres, Smirnov; Kimura et al., Gonzalez-Garcia, Maltoni; Akhmedov et al.; Mena et al.; Hay, Latimer; Agarwalla et al.; Ohlsson et al.; Ge et al.; Abe et al.; Kearns et al.; Adams et al; ...

Precision measurements of oscillation parameters

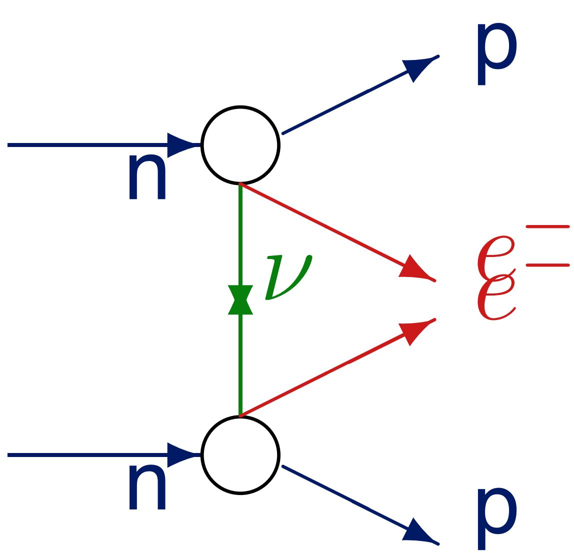
The precision measurement of the oscillation parameters will become very important once the mass hierarchy and CPV are established. LBL experiments can give information on $\theta_{23},\ \theta_{13},\ \delta$.



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

Neutrinoless double beta decay

Neutrinoless double beta decay, (A, Z) → (A, Z+2) + 2e, will test the nature of neutrinos.



This process has a special role in the study of neutrino properties as it probes lepton number violation and can provide information on neutrino masses and (possibly) on **CP-violation**.

The half-life time depends on neutrino properties

$$\left[T_{0\nu}^{1/2}(0^+ \rightarrow 0^+)\right]^{-1} \propto |M_F - g_A^2 M_{GT}|^2 \, |<m>|^2$$

- $|\langle m \rangle| = m_{ee}$: the effective Majorana mass parameter

$$|<m>| \equiv |\, m_1 |U_{e1}|^2 + m_2 |U_{e2}|^2 e^{i\alpha_{21}} + m_3 |U_{e3}|^2 e^{i\alpha_{31}} \,| ,$$

Mixing angles (known)

CPV phases (unknown)

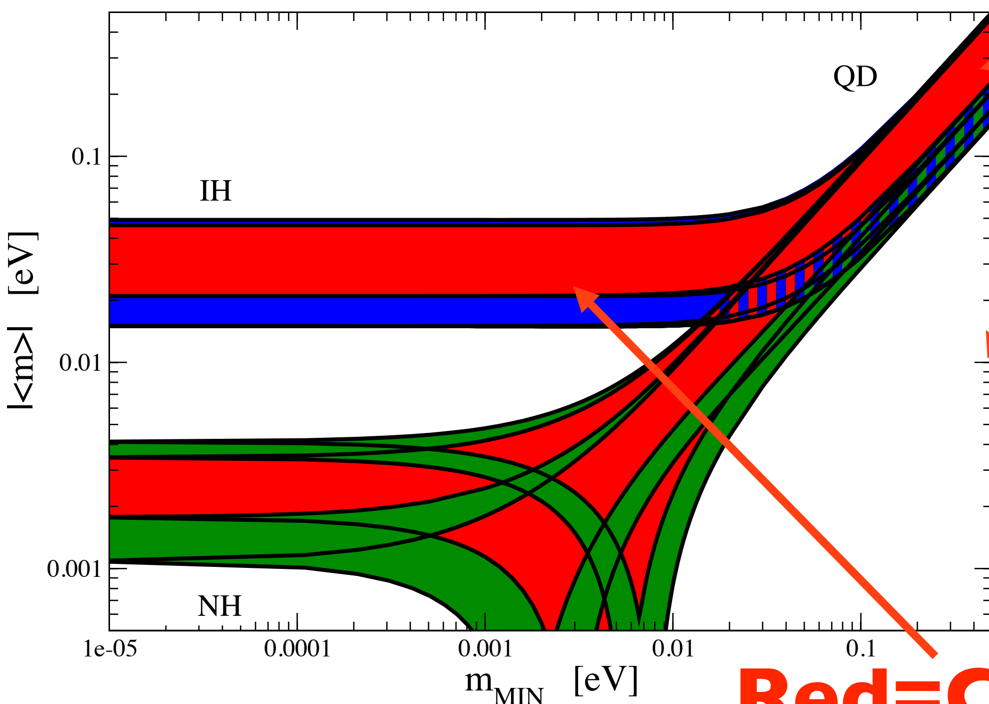
- $|M_F - g_A^2 M_{GT}|^2$: the nuclear matrix elements. They need to be computed theoretically.

See J. Engel's talk

Predictions for neutrinoless 2beta decay

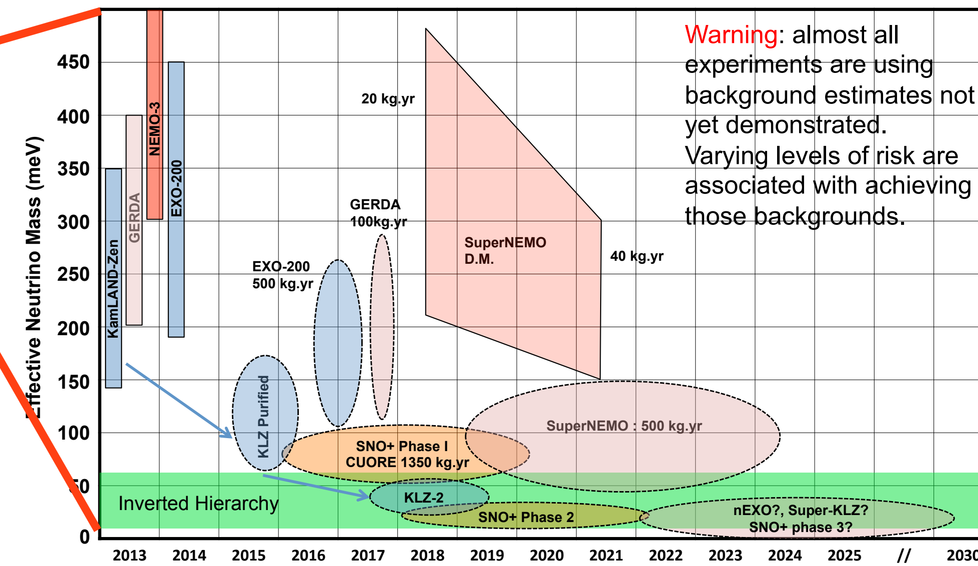
Example: QD (m1~m2~m3): 44 meV < |<m>| < m1

$$|\langle m\rangle| \simeq m_{\bar{\nu}_e}\left|\left(\cos^2\theta_\odot + \sin^2\theta_\odot e^{i\alpha_{21}}\right)\cos^2\theta_{13} + \sin^2\theta_{13}e^{i\alpha_{31}}\right|$$



Red=CPV

SP 2014, from Nakamura, Petcov review in PDG

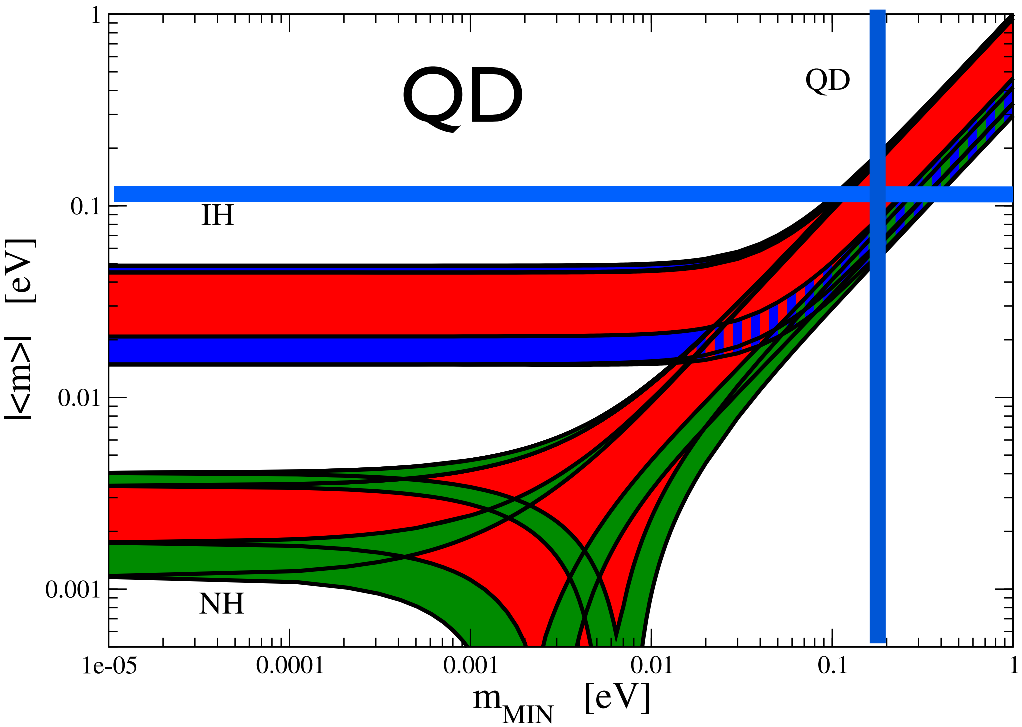


J. Hartnell, IOP meeting 2014

See Cremonesi's, Bongrand's, Schönert's, Shimizu's, Marino's, Winslow's talks

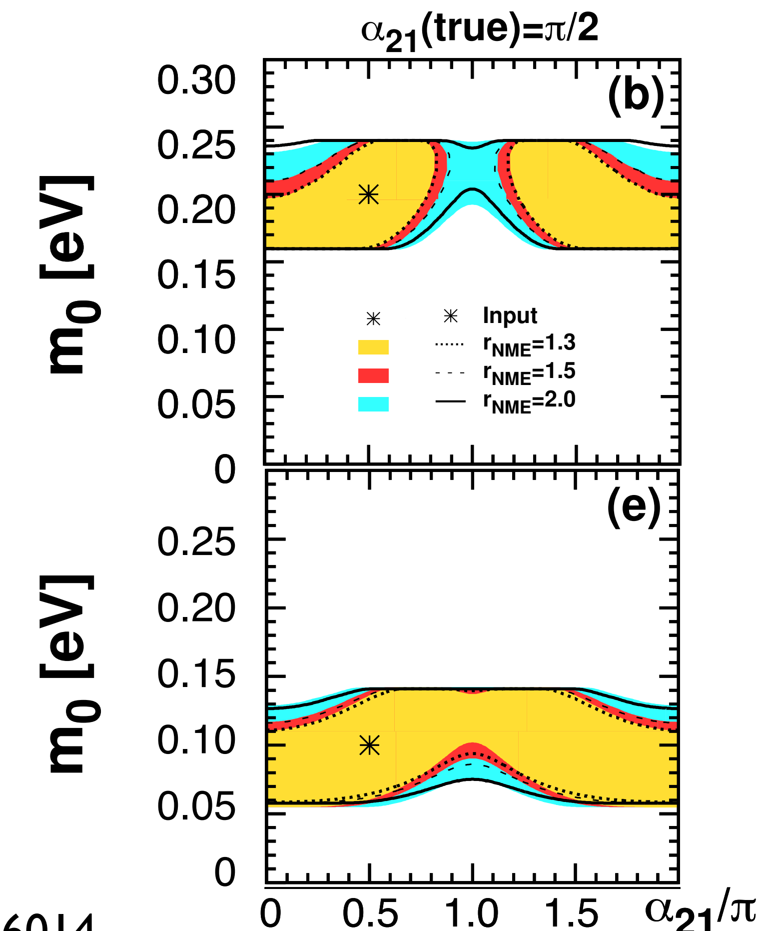
Broad experimental program for the future: **a positive signal would indicate that L is violated!**

Determining CP-violation with neutrinoless 2beta decay



If |<m>| and the masses are measured with sufficient precision, then it may be possible to establish CPV due to Majorana phases.

See also M. Hirsch's talk



However, this requires also a very precise determination of NME.

See also, SP, Petcov and Wolfenstein, PLB524.; SP, S. Petcov, T. Schwetz, NPB734; F. Simkovic, et al., PRD 87; Joniec, Zralek, PRD73; Deppisch et al, PRD72; Bahcall et al., PRD70; de Gouvea et al, PRD67; SP, et al., PLB579; Nunokawa et al., PRD66; Barger et al., PLB540.

H. Minakata et al., 1402.6014

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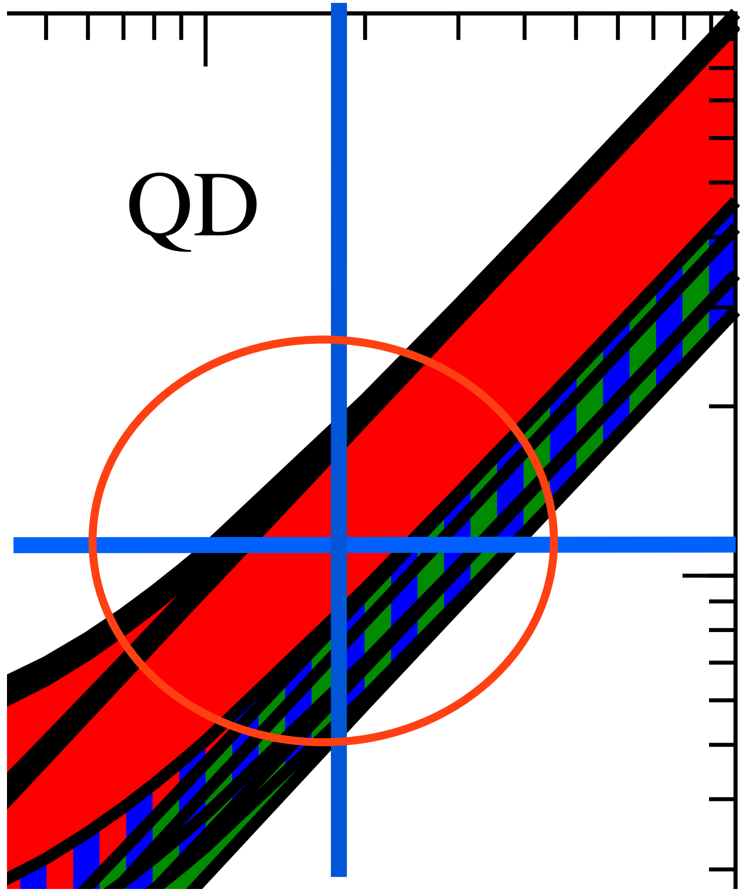

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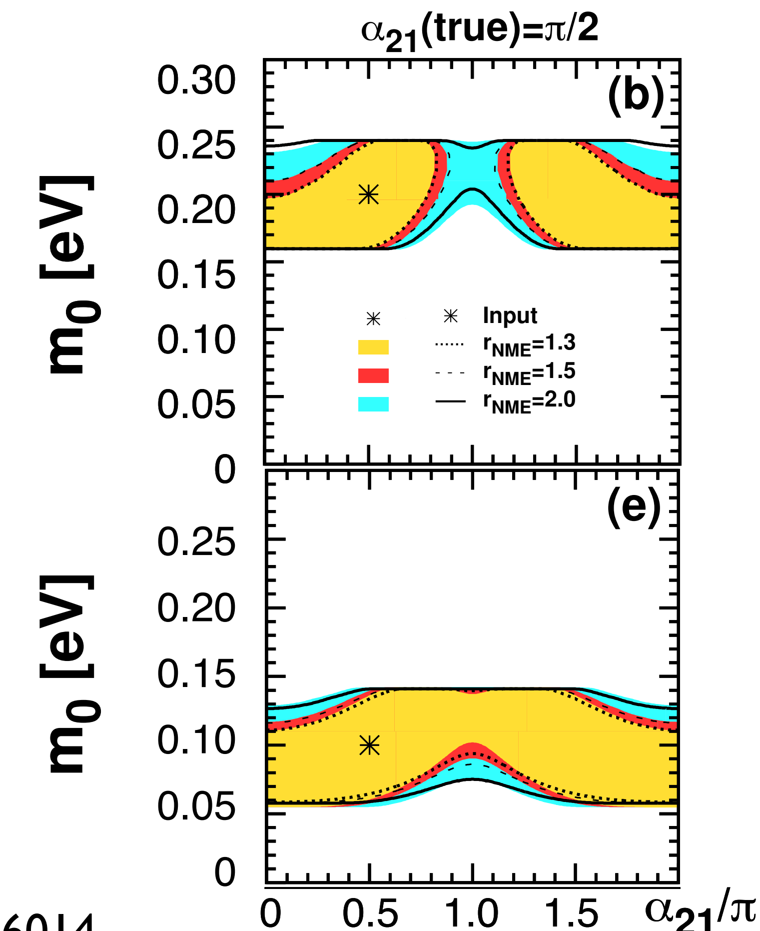

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H. Minakata et al., 1402.6014

Why is observing leptonic CP-violation important?

CP-violation has been observed in the quark sector. Does it occur also in the leptonic sector? and if so, what is its origin?

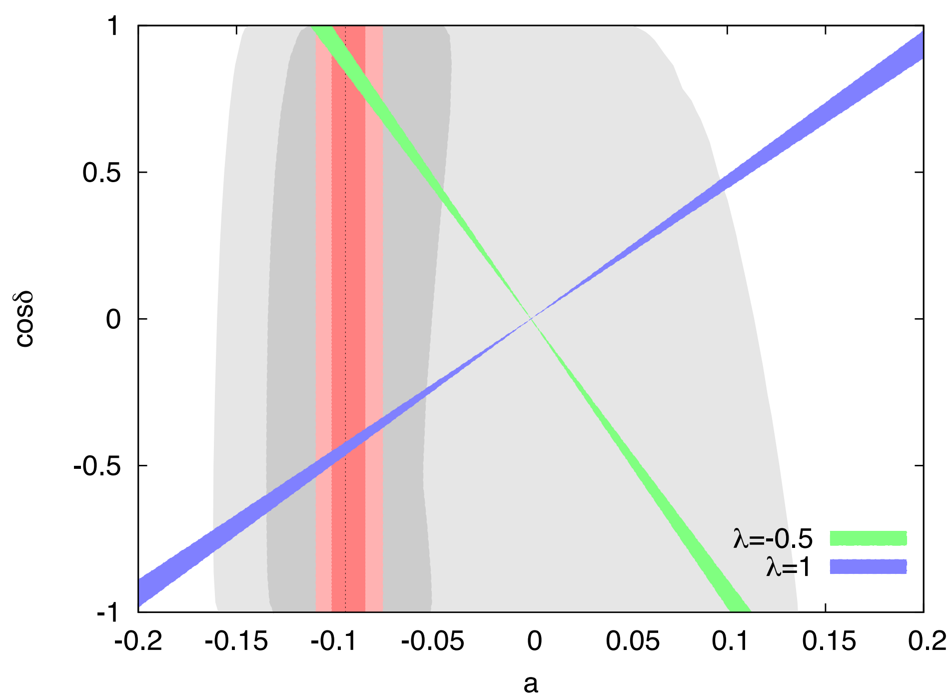
Different flavour models can lead to specific predictions for the value of the delta phase:

See M. Tanimoto's talk

- Sum rules: $\sin\theta_{12} = \frac{1+s}{\sqrt{3}}, \quad \sin\theta_{13} = \frac{r}{\sqrt{2}}, \quad \sin\theta_{23} = \frac{1+a}{\sqrt{2}}$ King, 0710.0530

$$a = a_0 + \lambda r \cos\delta + \text{higher orders}$$

- discrete symmetries models
- charged lepton corrections to U_ν : $U_{\rm PMNS} = U_e^\dagger U_\nu$



Ballett, King, Luhn, SP, Schmidt, PRD89

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, Otto Ludl, Pascoli, Patel, Petcov, H. Qu, Rebelo, Repko, Rigolin, Romanino, Roy, Schmidt, Sevilla, Silva-Marcos, Smirnov, Stamou, Stuart, Tanimoto, Valle, Villanova del Moral, Vitale, Wegman, Zhang, Zhou, Ziegler...

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:

- B (or L) violation;

- C, CP violation;

- departure from thermal equilibrium.

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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;

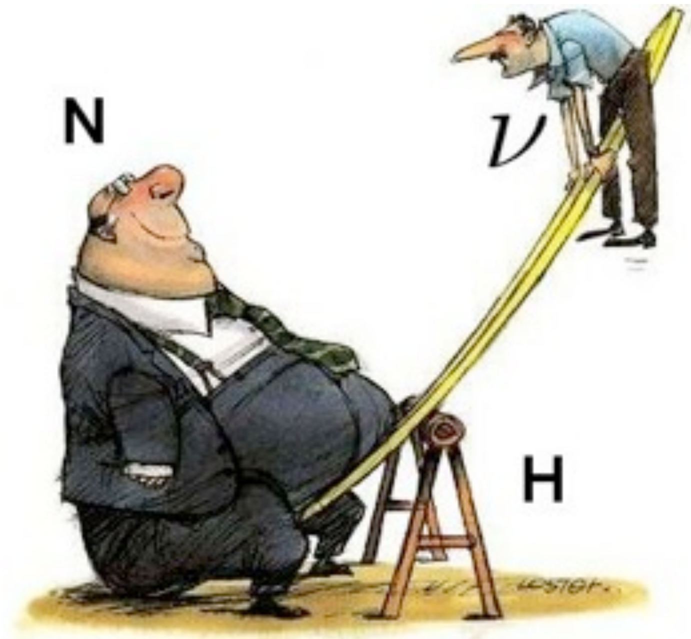
Expansion of the Universe

- departure from thermal equilibrium.

Leptogenesis in models at the origin of neutrino masses

Neutrino masses BSM: see saw mechanism type I

See Babu's talk



- Introduce a right handed neutrino **N**
- Couple it to the Higgs

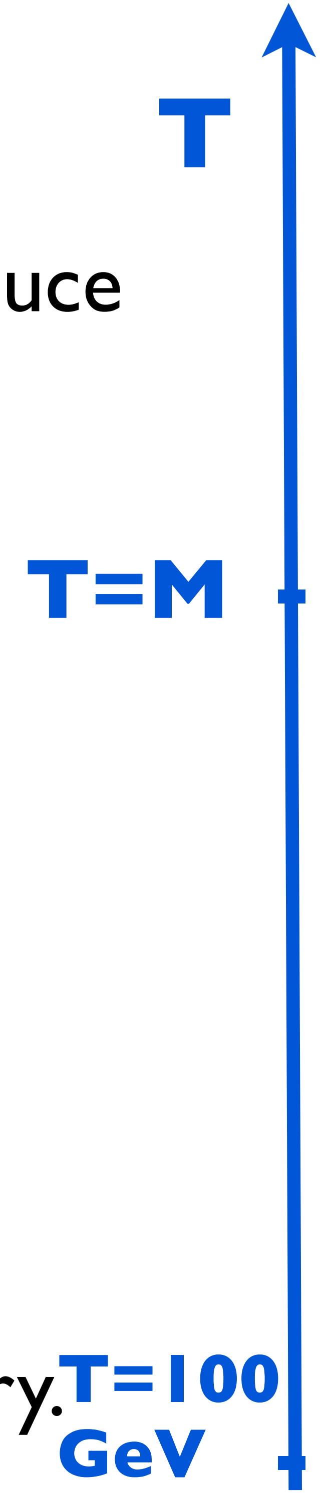
$$\mathcal{L} = -Y_\nu \bar{N} L \cdot H - 1/2 \bar{N}^c M_R N$$

$$\begin{pmatrix} 0 & m_D \\ m_D^T & M_N \end{pmatrix} \Rightarrow m_\nu = \frac{Y_\nu^2 v_H^2}{M_N} \sim \frac{1\ \mathrm{GeV}^2}{10^{10}\mathrm{GeV}} \sim 0.1\ \mathrm{eV}$$

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

See-saw type I models can be embedded in GUT theories and explain the baryon asymmetry via leptogenesis.

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

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

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

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

The general picture

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

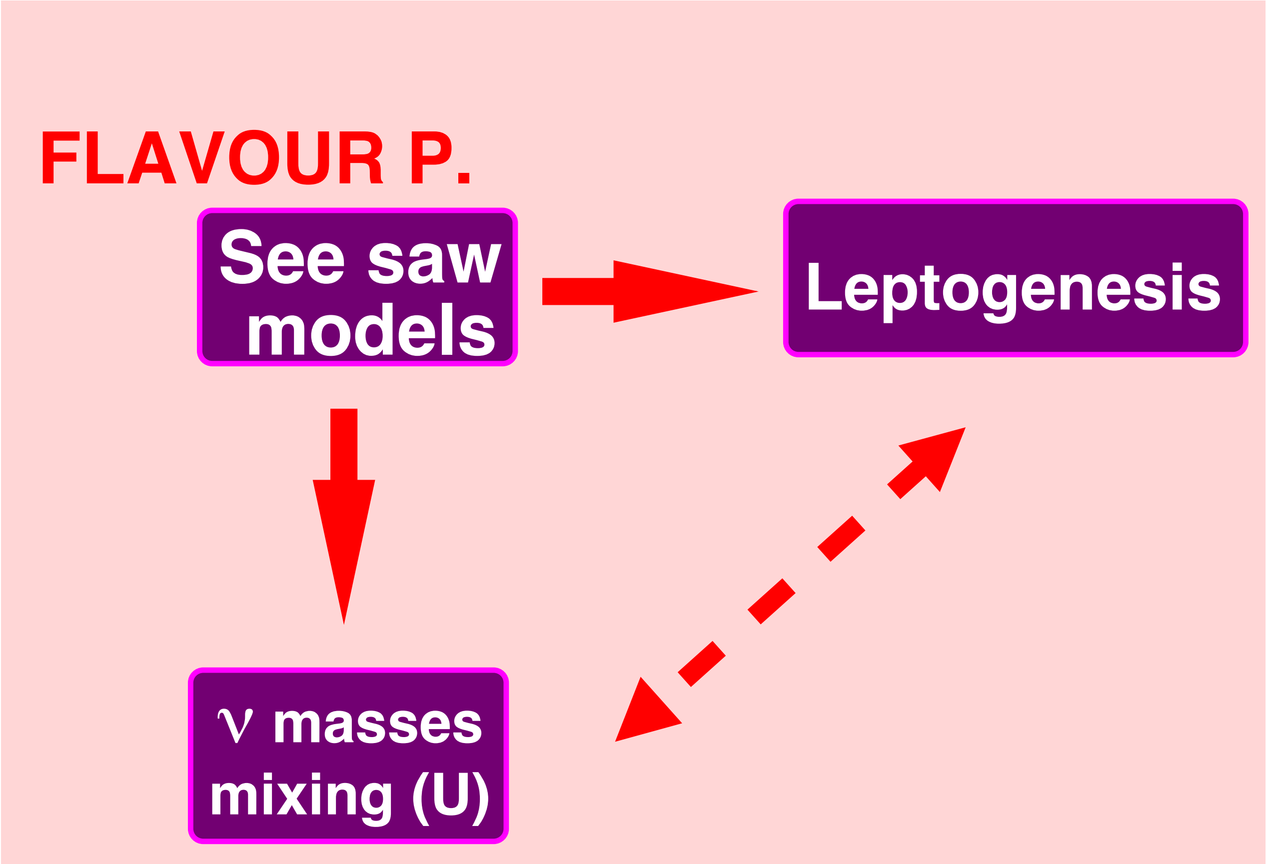
m_i	3	0
U	3	3

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.

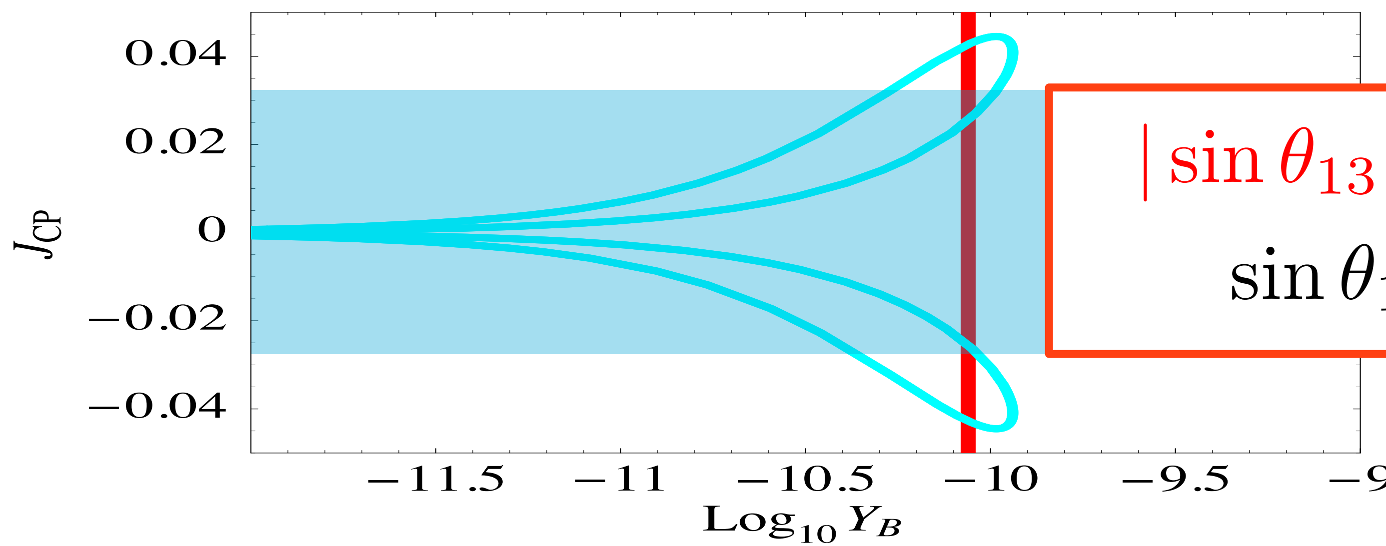


Does observing low energy CPV imply a baryon asymmetry?

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.

Conclusions

- There are current intriguing hints of CP-violation.

- Future LBL experiments will hunt for the delta phase and potentially measure it with precision. Neutrinoless double beta decay could point towards Majorana CPV.

- CP-violation, together with L violation, is the key ingredient of leptogenesis.

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.