CP Violation and Leptogenesis

05 March 2015

Neutrino Telescopes 2015

Venice

Silvia Pascoli

IPPP – Durham University

Two compelling observations

1. Neutrino oscillations (first evidence in 1998) imply:
neutrinos have mass and mix (CPV?)!
This requires new physics BSM which might be lepton number violating.

2. There is evidence of the baryon asymmetry:

$$\eta_B \equiv \frac{n_B - n_{\bar{B}}}{n_\gamma} = (6.18 \pm 0.06) \times 10^{-10}$$

Planck, 1502.01589

Is there a link between light neutrino physics and the baryon asymmetry?

Outline

1. Baryogenesis and leptogenesis: Sakharov's conditions

2. Searches for
- **Lepton Number Violation**
- **CP-violation**

3. Leptogenesis

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

5. Conclusions

The baryon asymmetry. The theory

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

- B (or L) violation;

- C, CP violation;

- departure from thermal equilibrium.

B (or L) violation

$$X^c \to \bar{q}q \qquad X \to \bar{q}q$$

$$X \to \ell q \qquad X^c \to \bar{\ell}\bar{q}$$

$$X \to \bar{q}q \qquad X \to \ell q$$

In the SM also L is violated at the non-perturbative level, while B-L is conserved. A lepton asymmetry is converted into a baryon asymmetry by sphaleron effects, at T>100 GeV.

If neutrinos are Majorana particles, L is violated.

See-saw models require L violation (typically the Majorana mass of a heavy right-handed neutrino).
In SUSY models without R-parity, L can be violated and neutrino masses generated.

C, CP violation

$$X^c \to \bar{q}q \qquad X \to \bar{q}q$$
$$X \to \ell q \qquad X^c \to \bar{\ell}\bar{q}$$
$$X \to \bar{q}q \qquad X \to \ell q$$

If C were conserved:

$$\Gamma(X^c \to Y^c + B^c) = \Gamma(X \to Y + B)$$

and no baryon asymmetry generated:

$$\frac{dB}{dt} \propto \Gamma(X^c \to Y^c + B^c) - \Gamma(X \to Y + B)$$

We have observed CPV in quark sector (too small) and we can search for it in the leptonic sector.

Out of equilibrium

$$X^c \leftrightarrow \bar{q}q \qquad X \leftrightarrow \bar{q}q$$

$$X \leftrightarrow \ell q \quad X^c \leftrightarrow \bar{\ell}\bar{q}$$

$$X \leftrightarrow \bar{q}q \qquad X \leftrightarrow \ell q$$

In equilibrium

$$\Gamma(X \to Y + B) = \Gamma(Y + B \to X)$$

A generated baryon asymmetry is cancelled exactly by the antibaryon asymmetry.
When particles get out of equilibrium, this does not happen.

$$T < M_X$$

Out of equilibrium

$$X^c \to \bar{q}q \qquad X \to \bar{q}q$$

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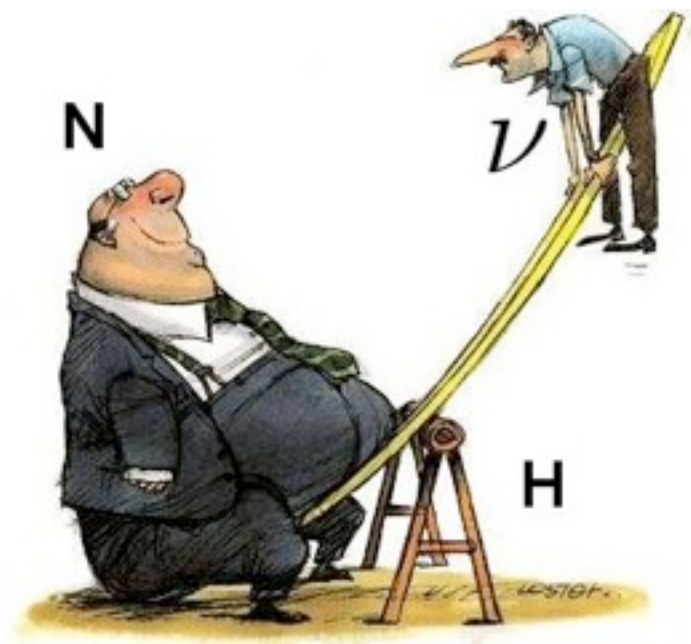
A successful model of baryogenesis:

Leptogenesis in models at the origin of neutrino masses

Neutrino masses BSM: see saw type I



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

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

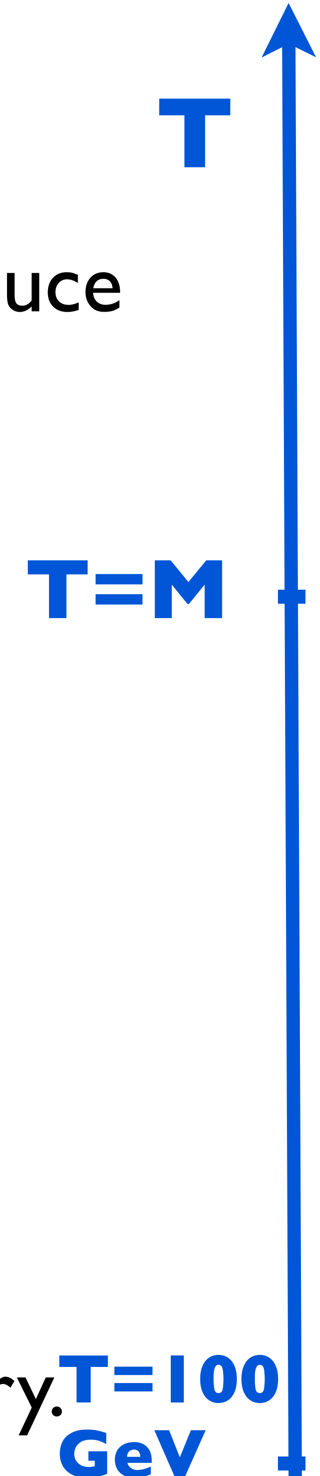
$$\begin{pmatrix} 0 & m_D \\ m_D^T & M_N \end{pmatrix}$$

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

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

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

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

Can we "test" Leptogenesis?

First of all, we can look for the ingredients needed:
- L violation
- CP violation
- out of equilibrium ✔

expansion of the Universe

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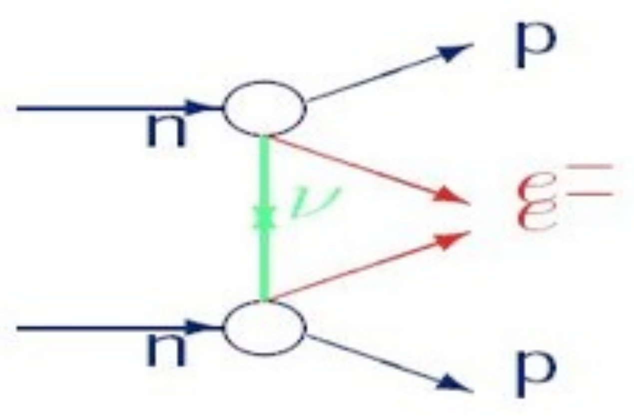
Lepton number violation?

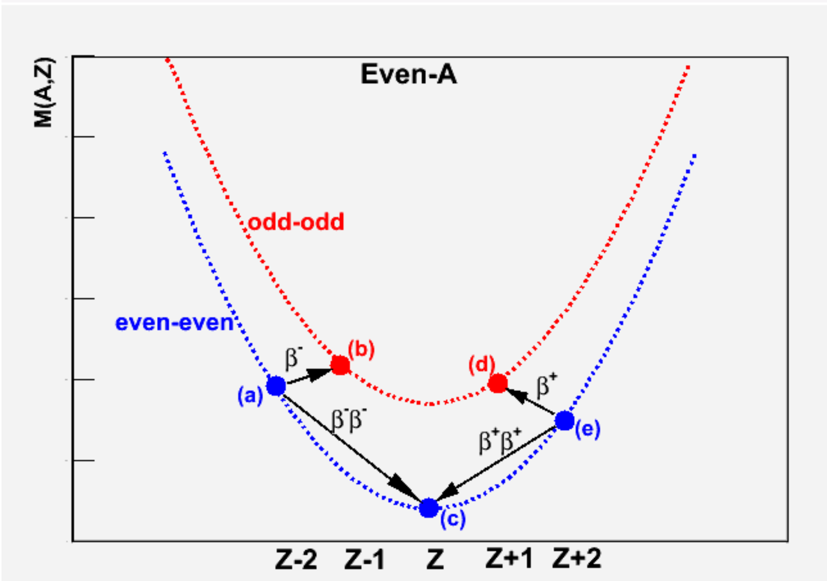
- At low energy, **neutrinoless double beta decay,** (A, Z) → (A, Z+2) + 2 e



- LNV tau and meson decays (requires masses in the 100s MeVs-GeV range)

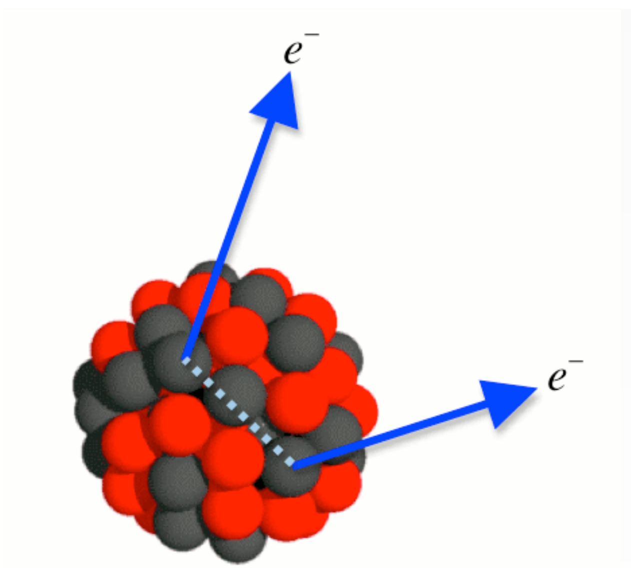
- LNV at colliders (if masses in the 10s GeV-TeV range)

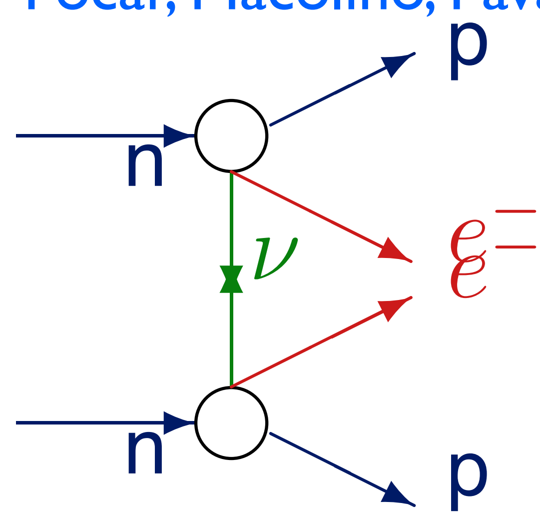
Neutrinoless double beta decay



Neutrinoless double beta decay proceeds in nuclei in which single beta decay is kinematically forbidden but double beta decay (A, Z) → (A, Z+2) + 2 e + 2 v is allowed.

See talks by Pocar, Macolino, Pavan, Remoto





At the fundamental level, exchange of light Majorana neutrino (or other exotic mechanism).

The half-life time depends on neutrino properties

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

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

$$| < m > | \simeq |m_1 \sin^2\theta_{12} + m_2 \cos^2\theta_{12} e^{i\alpha_{21}} + m_3 \sin^2\theta_{13} e^{i\alpha_{31}}$$

Mixing angles (known)

CPV phases (unknown)

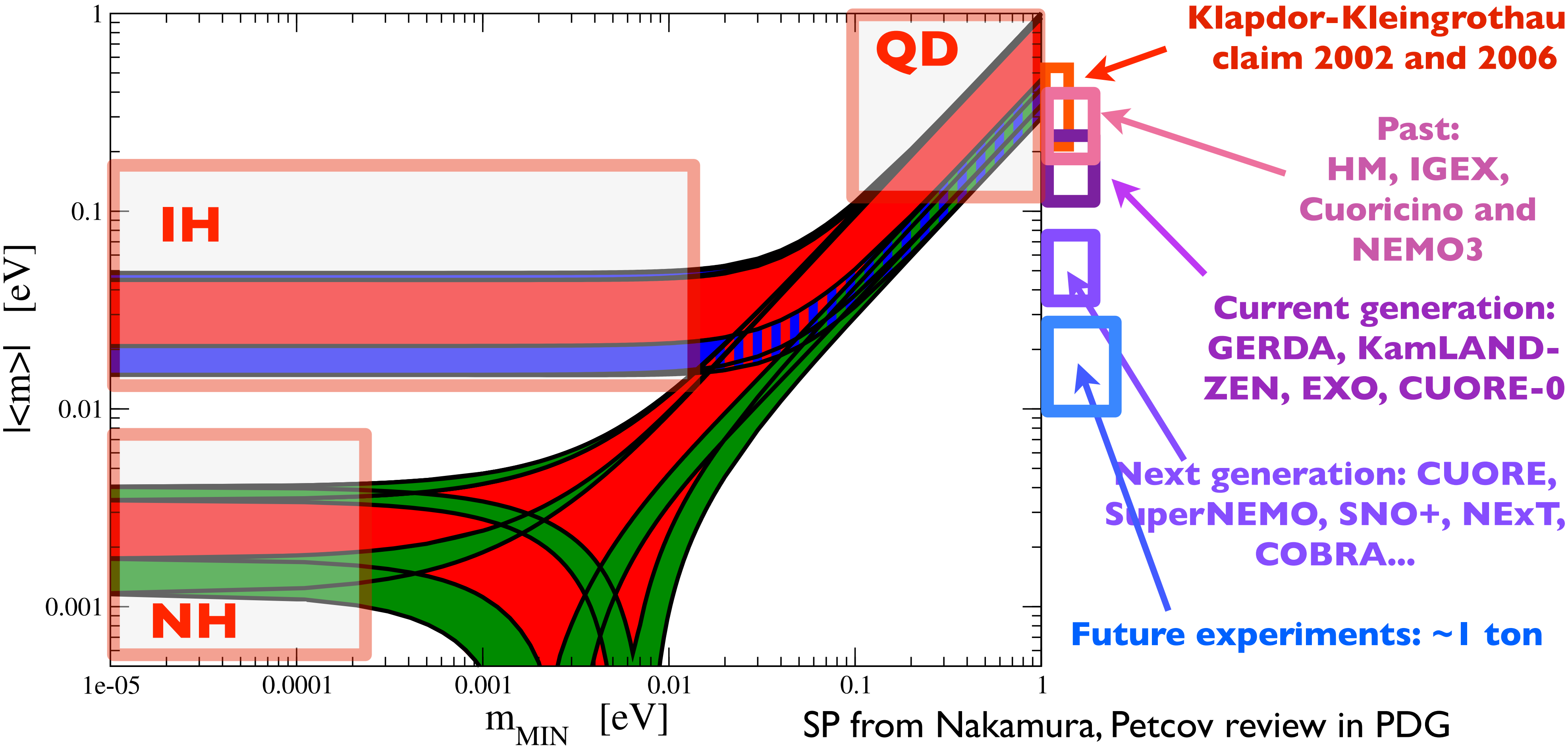
Masses (partially known)

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

See talk by Iachello

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

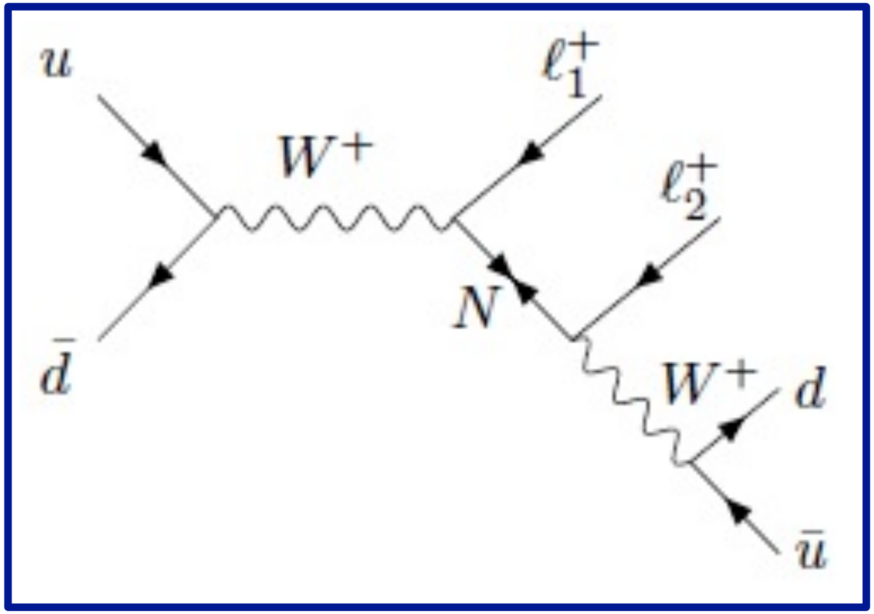
$$|<m>| \simeq m_{\bar{\nu}_e} \left| \left(\cos^2\theta_\odot + \sin^2\theta_\odot e^{i\alpha_{21}} \right) \cos^2\theta_{13} + \cancel{\sin^2}\theta_{13} e^{i\alpha_{31}} \right|$$

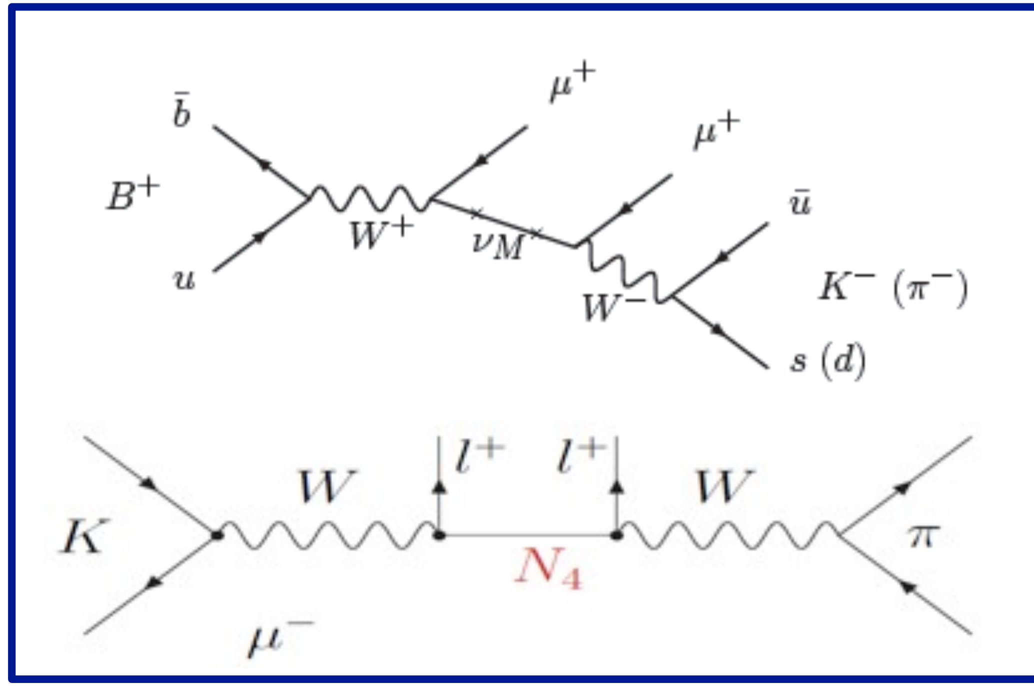


SP from Nakamura, Petcov review in PDG

Wide experimental program for the future: **a positive signal would indicate that L is violated! Independently from NME and from mediator.**

LNV searches at LHC and in meson/tau decays





At colliders, same-sign leptons and no missing E_T.

CMS and ATLAS searches have reported no signal.

Tau and Meson LNV decays.

They get resonantly enhanced for M~ 100 MeV - few GeV.

Channel	Observed 95% CL
$K^+\mu^-\mu^-$	5.4×10^{-8}
$D^+\mu^-\mu^-$	6.9×10^{-7}
$D^{*+}\mu^-\mu^-$	2.4×10^{-6}
$\pi^+\mu^-\mu^-$	1.3×10^{-8}
$D_s^+\mu^-\mu^-$	5.8×10^{-7}
$D^0\pi^+\mu^-\mu^-$	1.5×10^{-6}

LHC-b

PRL 108 and PRD 85.

Can we "test" Leptogenesis?

First of all, we can look for the ingredients needed:

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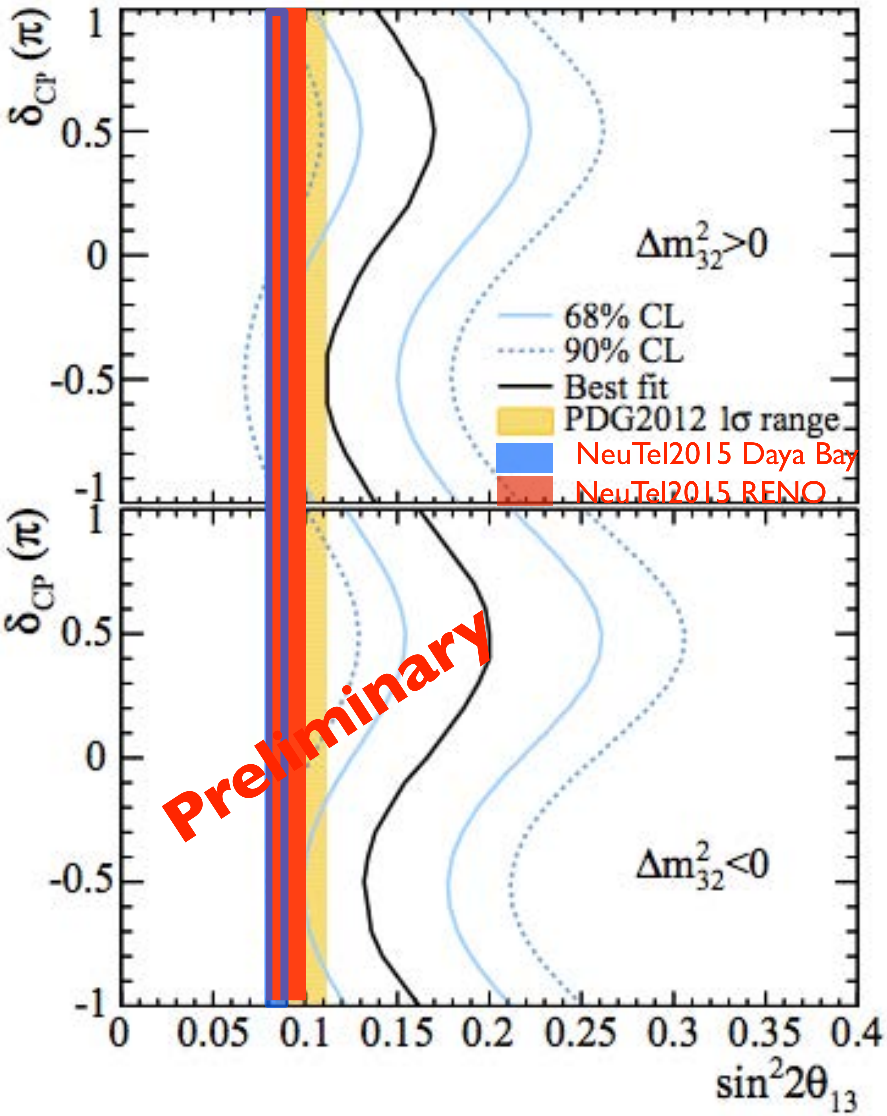
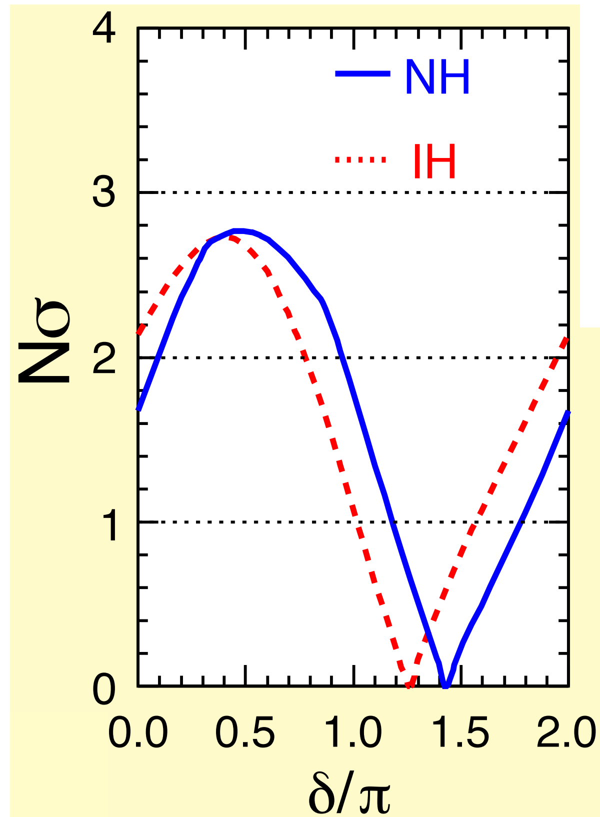
- out of equilibrium ✓

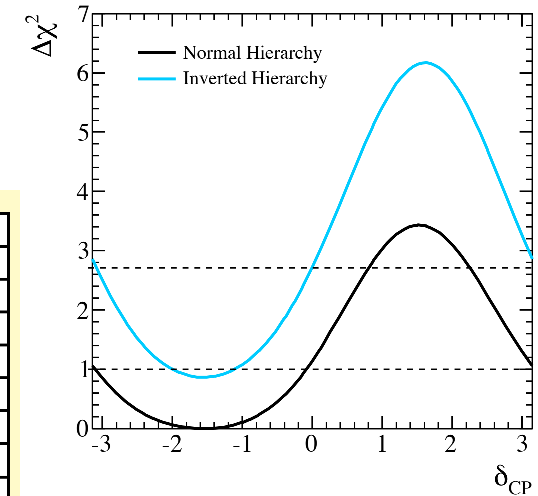
expansion of the Universe

Hints of leptonic CP-violation?



T2K Coll. PRL 112, 061802 (2014)





T2K Coll. 1502.01550

Thanks to G. Fogli

See results in talks by S.-H. Seo, L. Zhan

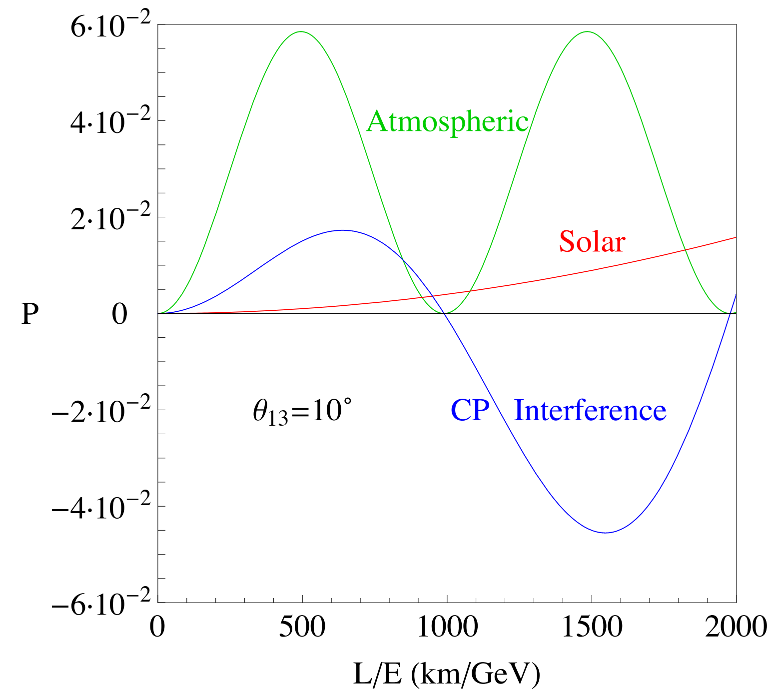
There is a slight preference for CP-violation, which is mainly due to the combination of T2K and reactor neutrino data.

CP-violation in LBL experiments

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

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

- 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

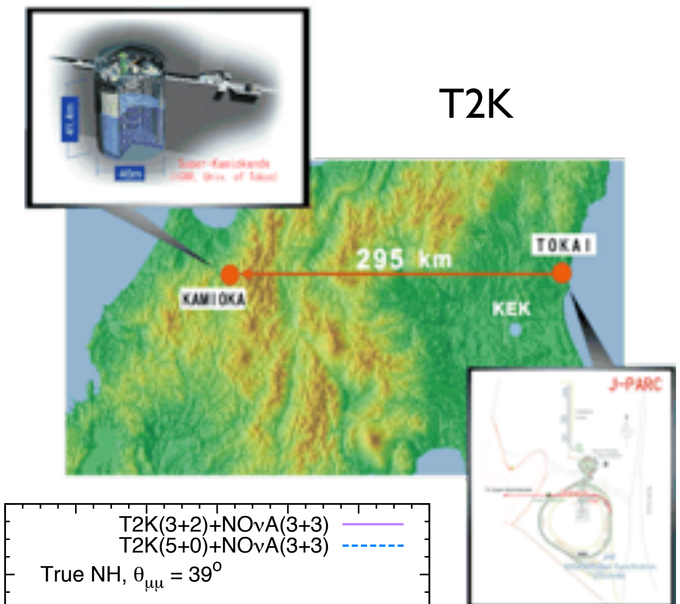
CPV Searches

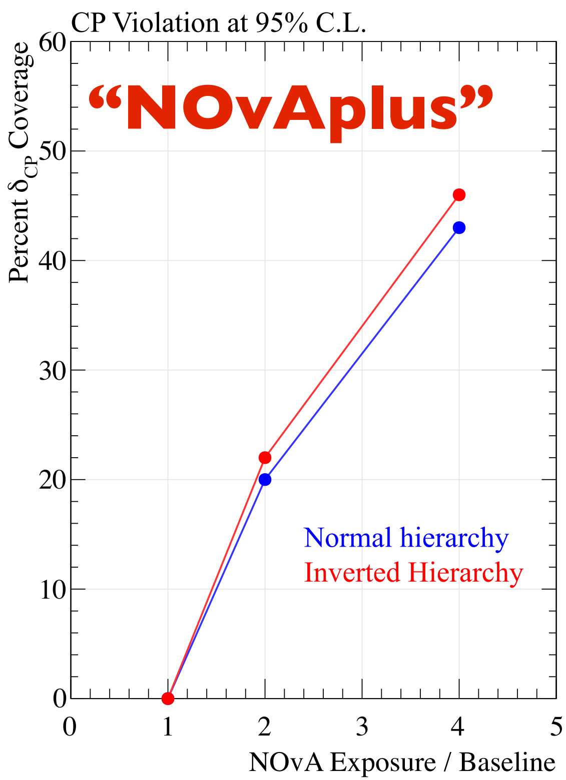
Category	Experiment	Status	Oscillation parameters
Accelerator	MINOS+ [74]	Data-taking	MH/CP/octant
Accelerator	T2K [21]	Data-taking	MH/CP/octant
Accelerator	NOvA [108]	Commissioning	MH/CP/octant
Accelerator	RADAR [76]	Design/ R&D	MH/CP/octant
Accelerator	CHIPS [75]	Design/ R&D	MH/CP/octant
Accelerator	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

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

Near future: T2K and NOvA. Marginal sensitivity to CPV

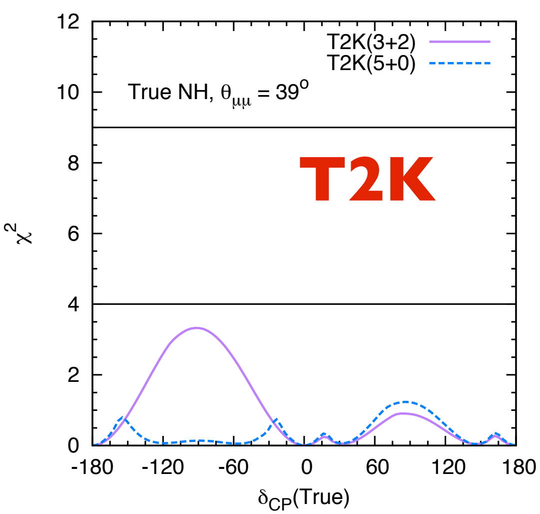
See talks by Yokoyama, Pawlosky

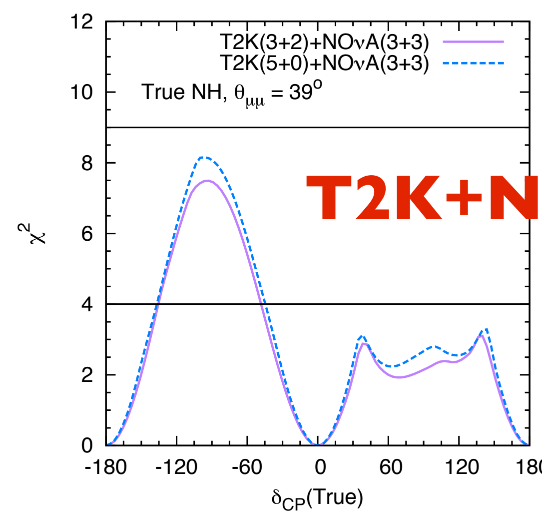




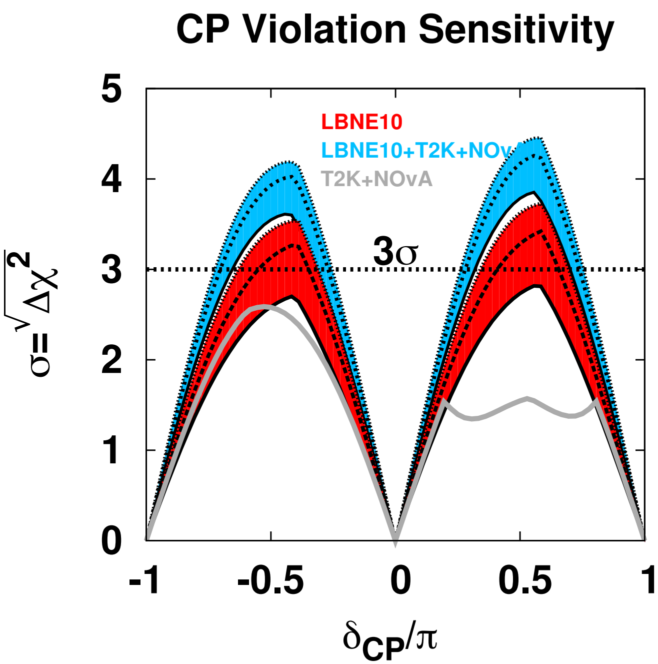
NOvA Coll., 1308.0106

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



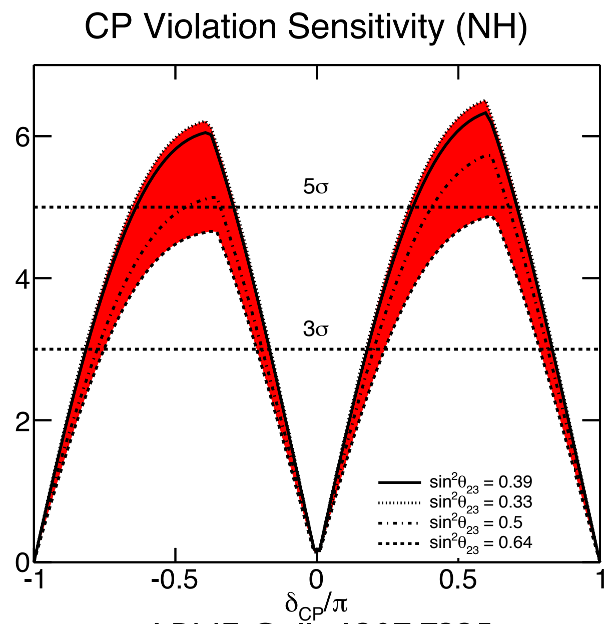


LBNE-10Kton



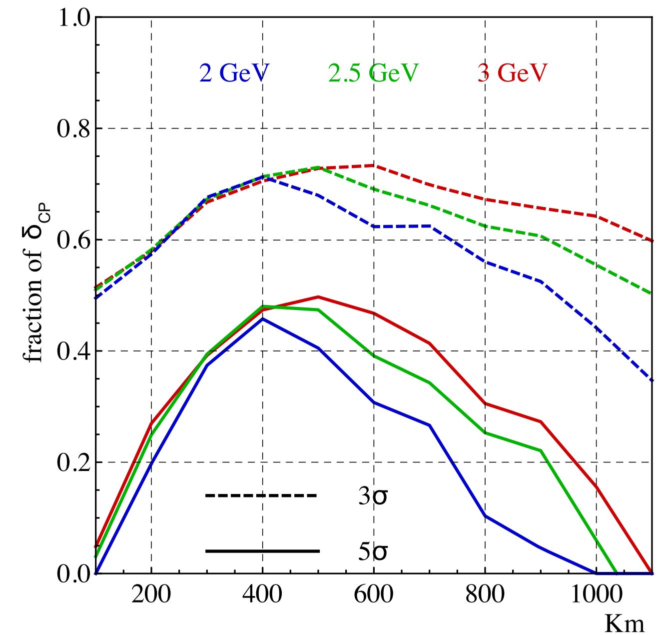
fermilab-conf-13-300.pdf

LBNE-34kton



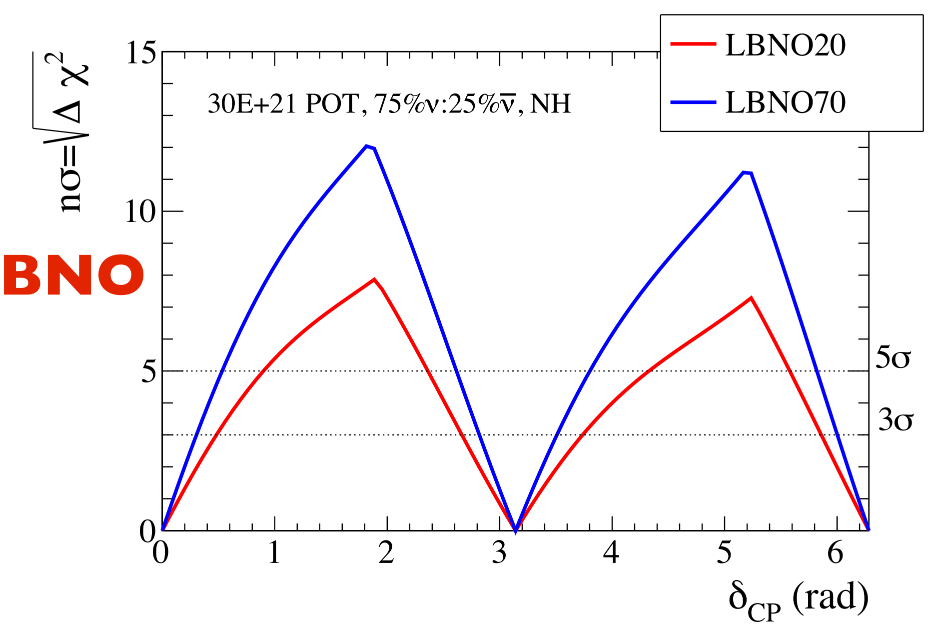
LBNE Coll., 1307.7335

ESSnuSB



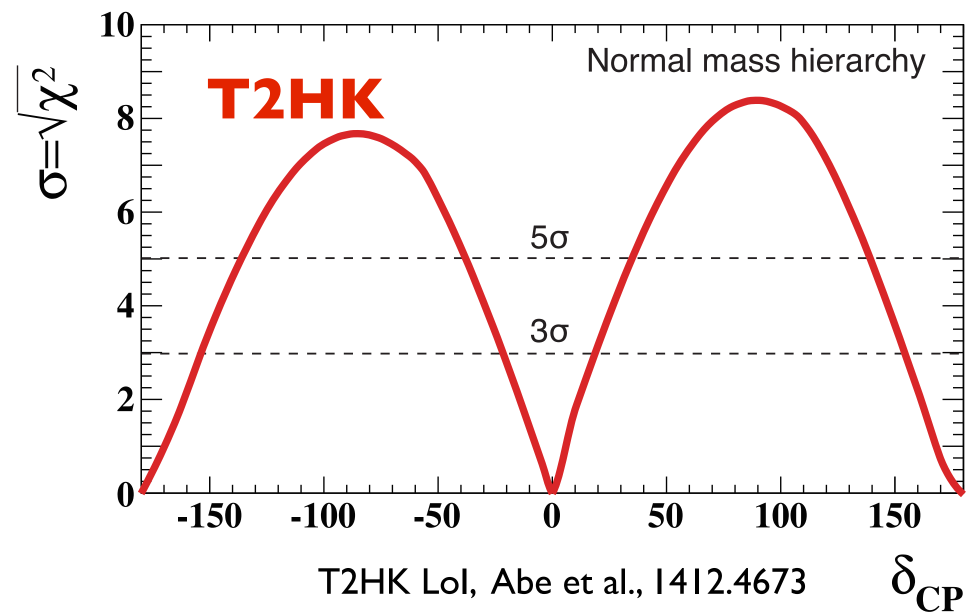
ESSnuSB, 1309.7022

LBNO



LAGUNA-LBNO, 1412.0593. See also 1312.6520

T2HK

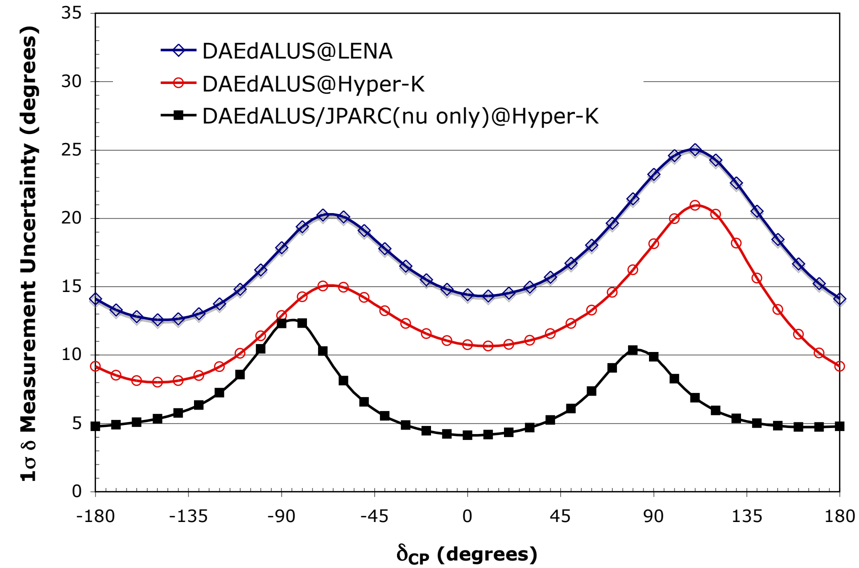


T2HK LoI, Abe et al., 1412.4673

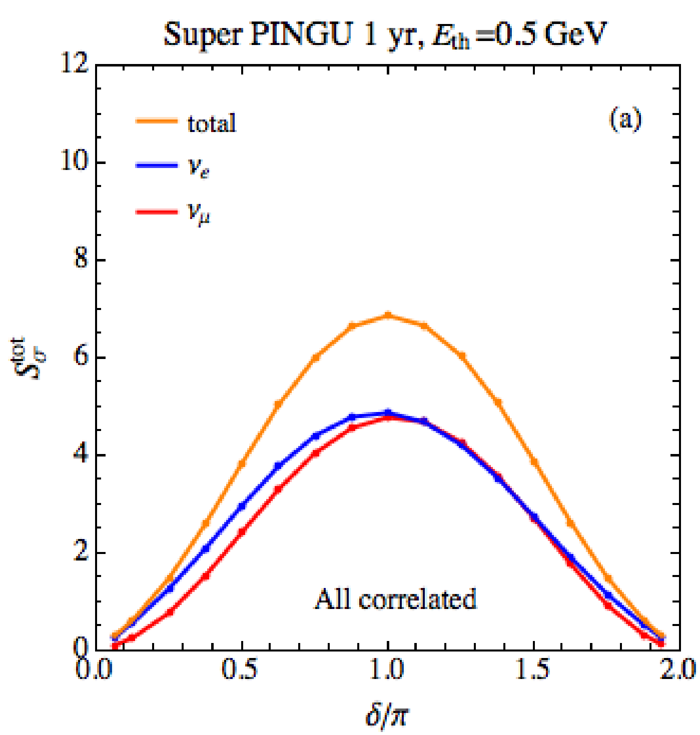
See talks by Strait, Shiozawa, Dracos

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



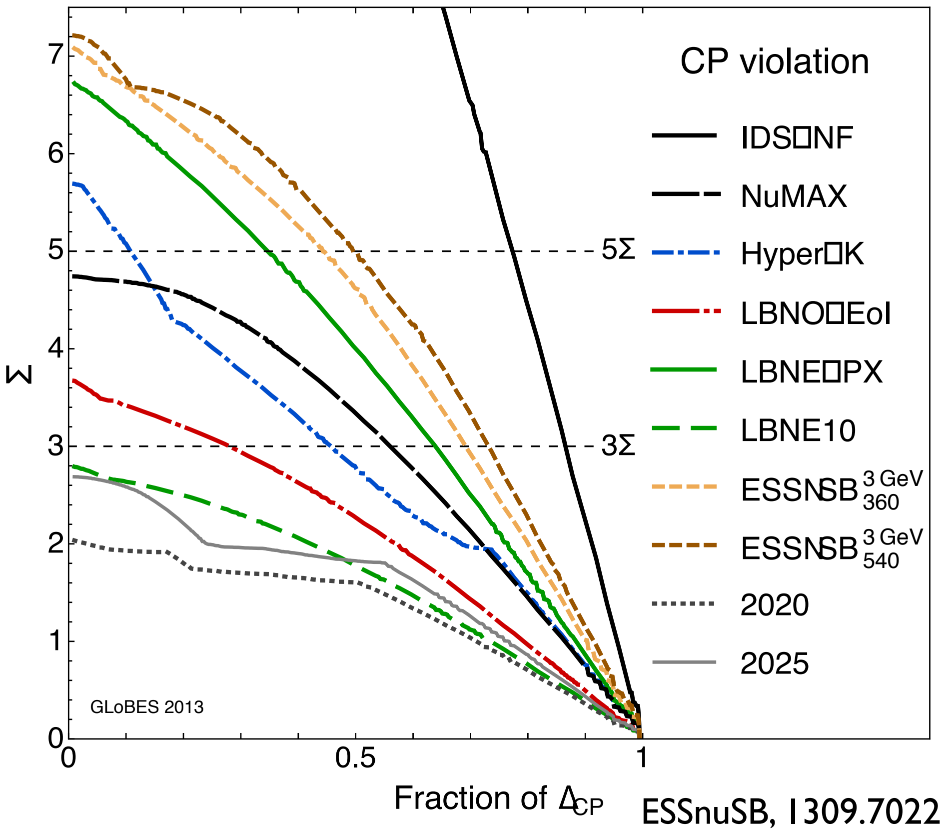
Razzaque, Smirnov, 1406.1407

Atmospheric neutrinos

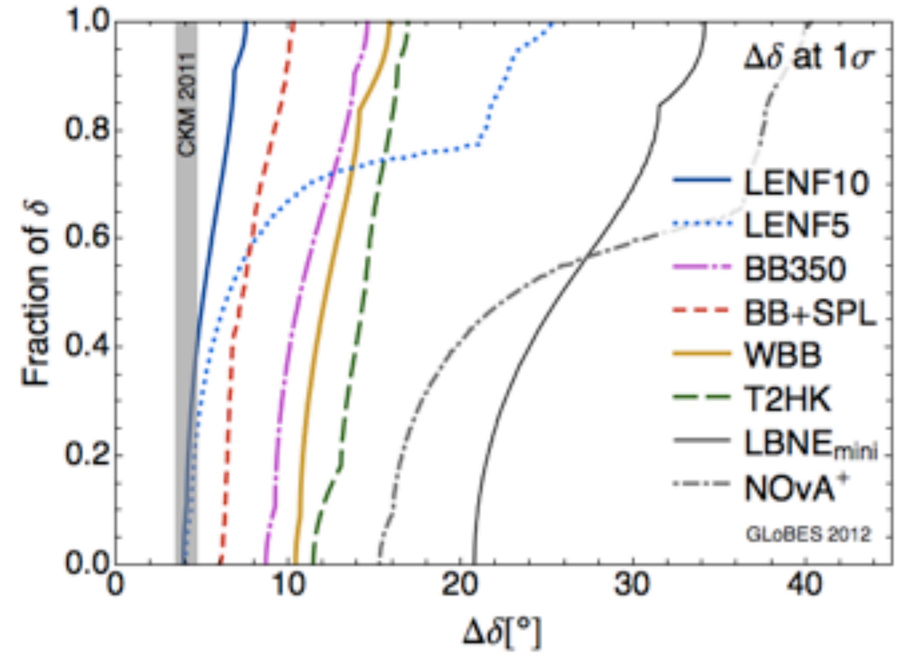
These experiments have access to a broad range of baselines and energies. Limited energy and angular resolution and nu-anti nu discrimination affect their reach.

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; ...

NuFact



ESSnuSB, 1309.7022

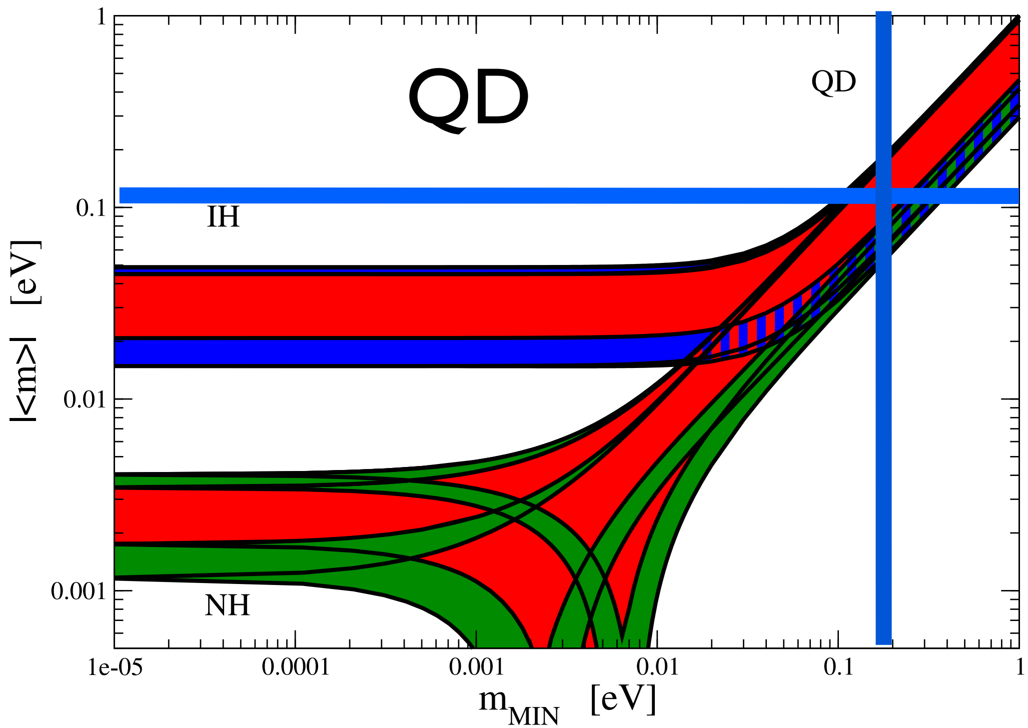


Coloma, et al. 1209.5973

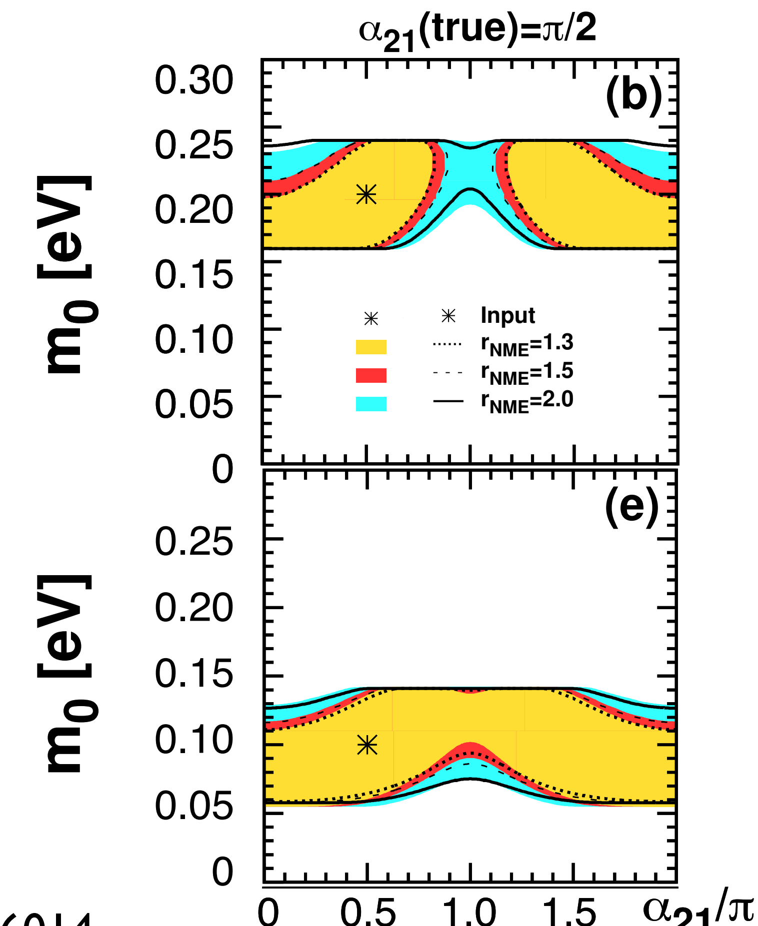
Comparisons should be made with great care as they critically depend on:

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

Determining CPV with nuless 2beta decay



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

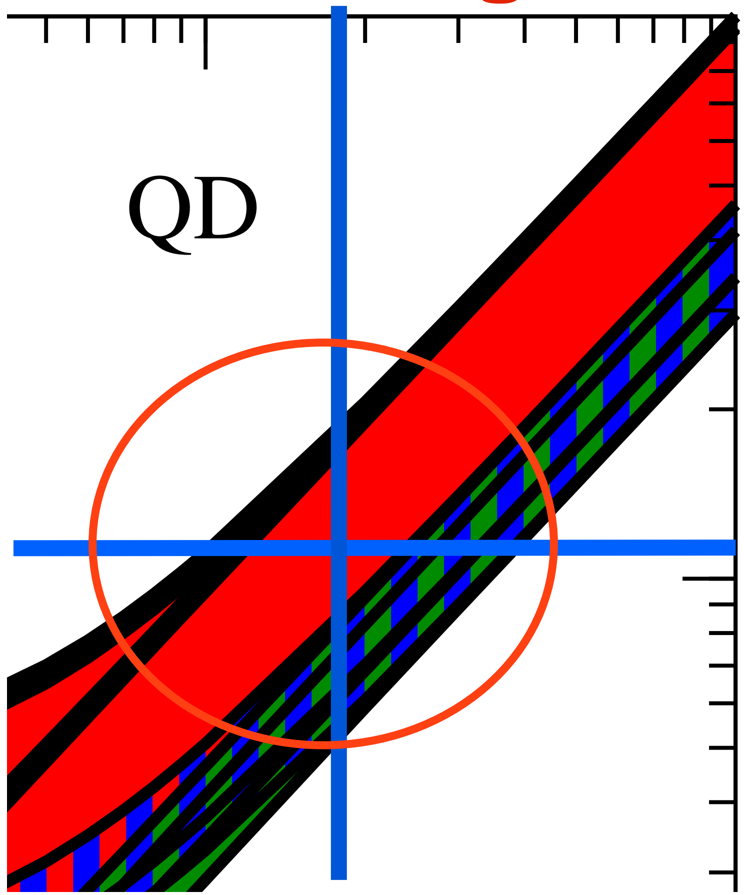


However, this requires also a very precise determination of NME.

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

Determining CPV with nuless 2beta decay



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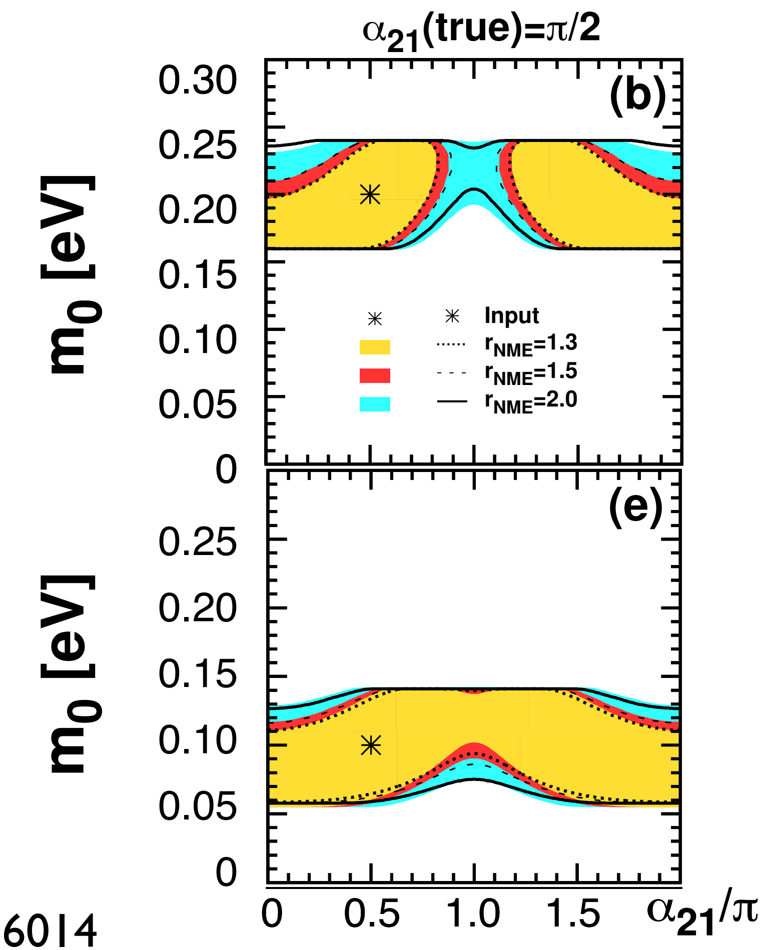

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H. Minakata et al., 1402.6014

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

The general picture (see-saw type I at high scale)

ϵ depends on the CPV phases in Y_ν

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

One flavour approximation

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

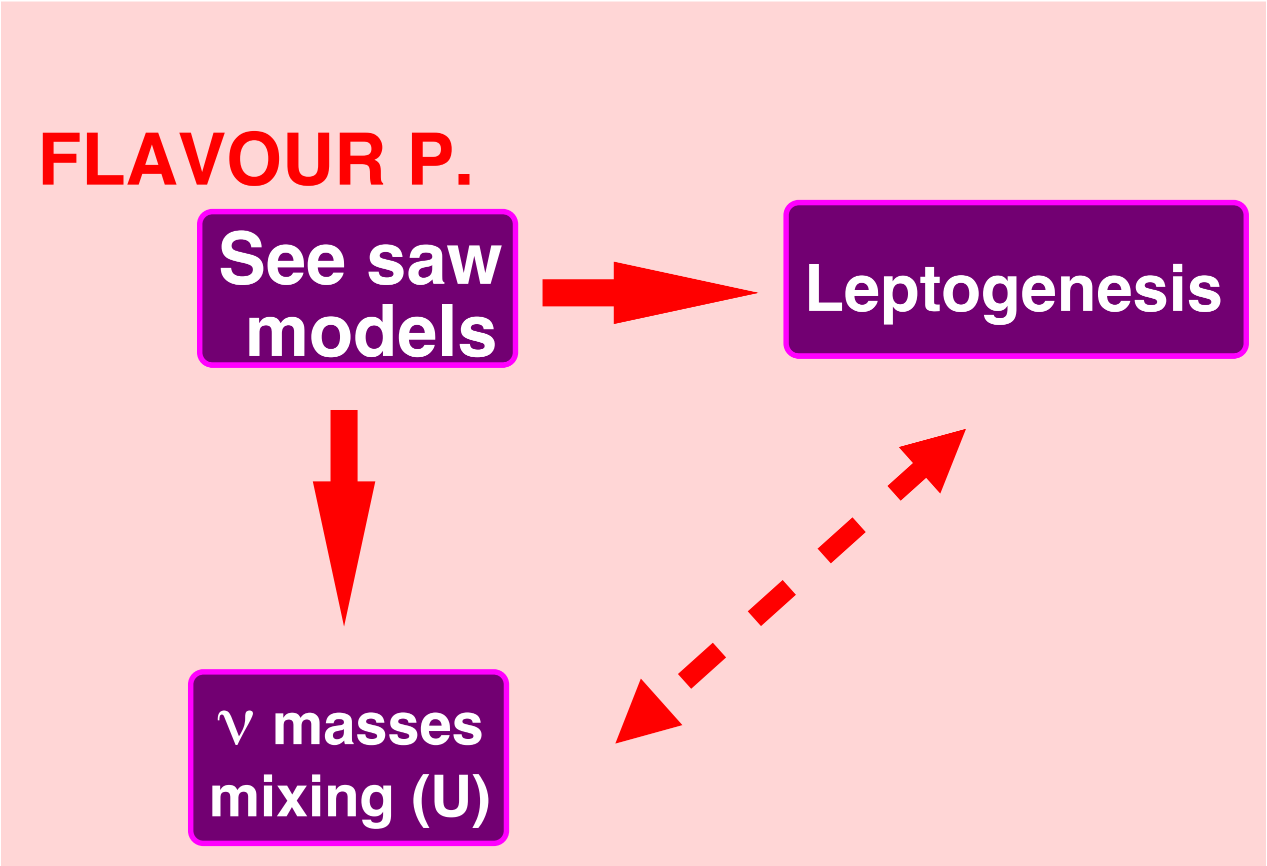
m_i	3	0
U	3	3

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.



See talk by Hagedorn

More details on the low-high energy connection

We try to separate the low energy parameters (measurable in experiments) and the high energy ones on which one cannot get information.

The Casas-Ibarra parameterization is useful:

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

$$U^* \sqrt{m_i} \sqrt{m_i} U^\dagger = -Y_\nu^T \sqrt{M_R^{-1}} \underbrace{R R^T}_{=1} \sqrt{M_R^{-1}} Y_\nu v^2$$

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

$$\boxed{Y_\nu v \simeq i \sqrt{M_R} R \sqrt{m_i} U_{\mathrm{PMNS}}^\dagger}$$

high energy untestable parameters

low energy parameters

More details on the low-high energy connection

With $$Y_\nu v \simeq i\sqrt{M_R}R\sqrt{m_i}U^\dagger_{\mathrm{PMNS}}$$

As example, M1<< M2<<M3. In the one flavour case (M1≳10^12 GeV)

$$\varepsilon_1 = -\frac{3M_1}{16\pi v^2}\frac{\mathrm{Im}\left(\sum_{\alpha\beta\rho} m_\rho^{1/2} m_\beta^{3/2} \cancel{U^*_{\alpha\rho} U_{\alpha\beta}} R_{1\beta} R_{1\rho}\right)}{\sum_\beta m_\beta \left|R_{1\beta}\right|^2} = -\frac{3M_1}{16\pi v^2}\frac{\mathrm{Im}\left(\sum_\rho m_\rho^2 R_{1\rho}^2\right)}{\sum_\beta m_\beta \left|R_{1\beta}\right|^2}$$

The low energy phases do not enter directly: observing CPV DOES NOT imply a baryon asymmetry.

If flavours can be distinguished (M1≪10^12 GeV), the low energy phases enter directly the baryon asymmetry.

$$\varepsilon_\alpha = -\frac{3M_1}{16\pi v^2}\frac{\mathrm{Im}\left(\sum_{\beta\rho} m_\beta^{1/2} m_\rho^{3/2} U^*_{\alpha\beta} U_{\alpha\rho} R_{1\beta} R_{1\rho}\right)}{\sum_\beta m_\beta \left|R_{1\beta}\right|^2}$$

Does observing low energy CPV imply a baryon asymmetry?

In see-saw type I, let's consider the case of CPV due only to low energy phases, for instance delta (R real):

$$|Y_B| \cong 2.4 \times 10^{-11} \, |\sin\delta| \left(\frac{s_{13}}{0.15}\right) \left(\frac{M_1}{10^{11}\ \mathrm{GeV}}\right)$$

M1<<M2<<M3, for NH spectrum, maximising w.r.t. R

Imposing M1< 5 10^{11} GeV

preliminary

$$\boxed{|\sin\delta| \geq 0.7 \quad \Rightarrow |45^o \leq \delta \leq 135^o|}$$

SP, Petcov, Riotto, PRD and NPB 2007; SP 2014

If flavour effects fully develop for smaller M1, delta even closer to maximal.

Large theta13 implies that delta can give an important (even dominant) contribution to the baryon asymmetry.
For Majorana CPV, effects enhanced by a factor of ~10.

Conclusions

• CP-violation and L violation, are the key ingredients of leptogenesis (together with the departure from equilibrium).

• 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.

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.