On the relationship between Leptogenesis and low energy observables

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Based on Works done in collaboration With

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Flavour puzzle

Origin of fermion masses mixing and CP violation

Attempts at solving the flavour puzzle

symmetries

texture zeros

Universal strength of Yukawa couplings

(more)

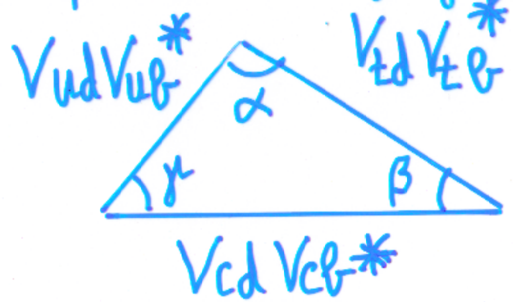
Increasingly higher precision in the determination of the elements of fermion mixing matrices

→ great challenge to flavour models

All experimental data on flavour physics and CP violation in quark sector seem to be in agreement with the SM and its KM mechanism with a few hints for potencial deviations

→ account for a large number of data with a small number of parameters

"the consistency of $|V_{ub}|/|V_{cb}|$ and $\sin 2\beta$ is not very good" PDG 08



(β_s) $\chi = \arg(-V_{ts}V_{cb}V_{tb}^*V_{cs}^*)$

$B_s \to J/\psi\,\phi$

$D^0-\bar{D}^0$ mixing if long distance contributions are not dominant

Botella, Branco, Nebot 2008

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Why, Where Physics Beyond the SM

- SM leaves many open questions
- Is there a Higgs (a scalar) boson? What else?

  Strength of ~~CP~~ not sufficient to generate BAU

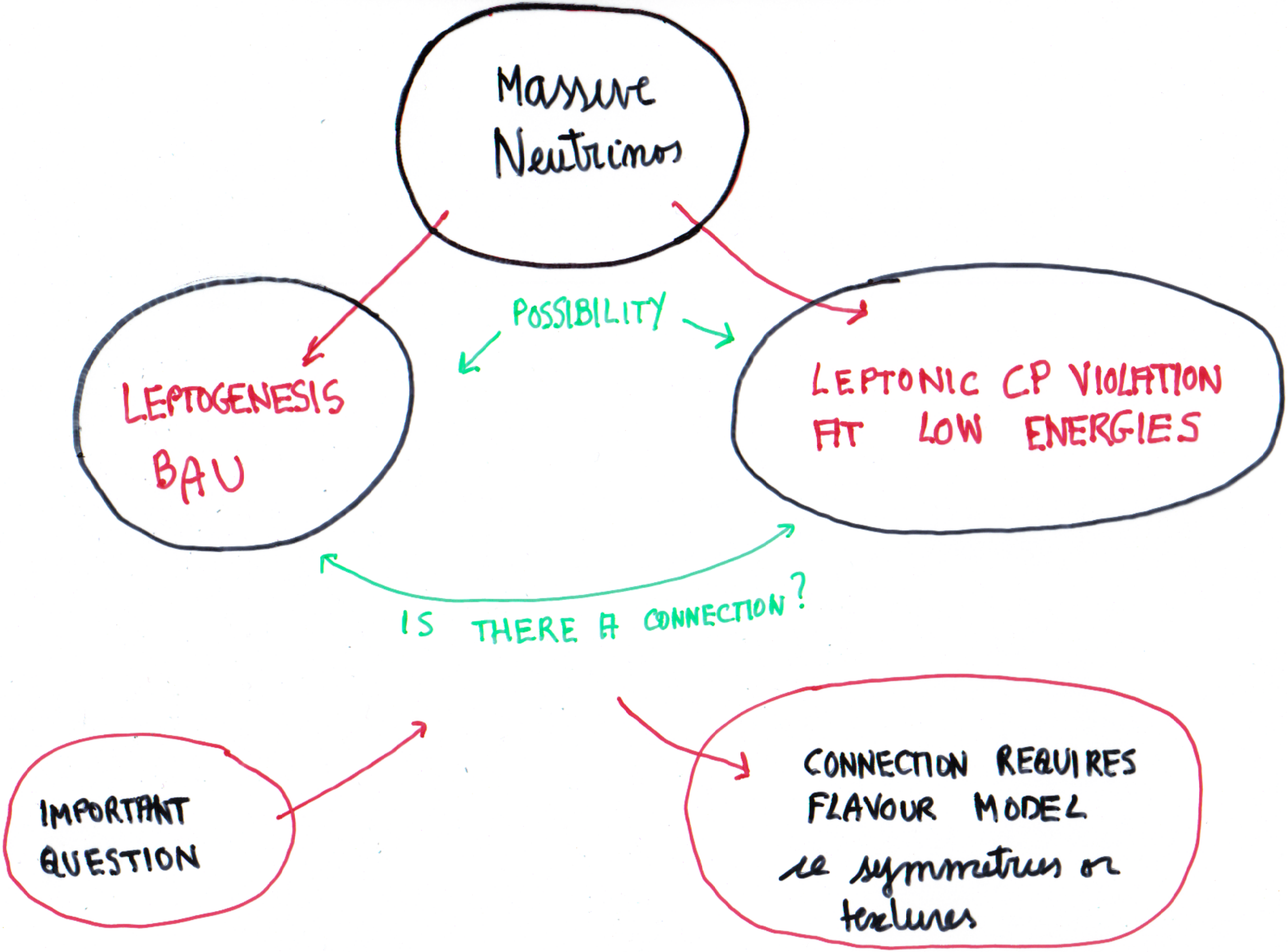
  Almost all extensions of SM, including SUSY, have new sources of CP violation

  Many New Physics scenarios have FCNC

- Dark Matter candidates

- NEUTRINOS ARE MASSIVE

  Physics Beyond SM!!!


Massive Neutrinos
LEPTOGENESIS
BAU
POSSIBILITY
LEPTONIC CP VIOLATION AT LOW ENERGIES
IS THERE A CONNECTION?
IMPORTANT QUESTION
CONNECTION REQUIRES FLAVOUR MODEL
ie symmetries or textures

Flavour Models, e.g. texture zeros are WB dependent
also symmetries are only explicit in special WB

WB: all gauge currents are real and flavour diagonal

$$\mathcal{L}_W = -\frac{g}{\sqrt{2}} W_\mu \overline{\ell^0_{iL}} \gamma^\mu \nu^0_{iL} + h.c$$

i - family index

WB transformation

(d_L) $\quad \ell^0_L \to U \ell^0_L \quad , \quad \ell^0_R \to V \ell^0_R$

(u_L) $\quad \nu^0_L \to U \nu^0_L \quad , \quad \nu^0_R \to W \nu^0_R$

Obviously two sets of leptonic mass matrices (quark mass matrices) related by a WB transformation contain the same physics

Example

$S_{3L} \times S_{3R}$ symmetry

Dirac type matrices $\lambda\Delta = \lambda \begin{pmatrix} 1 & 1 & 1 \\ 1 & 1 & 1 \\ 1 & 1 & 1 \end{pmatrix}$

Majorana type matrices
$M_R = \mu\,(\Delta + a\mathbb{I})$

$$U, V = \begin{pmatrix} \frac{2}{\sqrt{3}} & \frac{1}{\sqrt{3}} & 0 \\ -\frac{1}{\sqrt{6}} & \frac{1}{\sqrt{3}} & 1/\sqrt{2} \\ -\frac{1}{\sqrt{6}} & \frac{1}{\sqrt{3}} & -1/\sqrt{2} \end{pmatrix} \qquad U^T \Delta U = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 3 & 0 \\ 0 & 0 & 0 \end{pmatrix}$$

symmetry is no longer obvious

SM neutrinos are strictly massless

Incorporation of ν masses

- extensions of scalar sector
- extension of fermionic sector

We work with "minimal" extension (one ν_R per generation)

$$\mathcal{L}_{mass} = -\left[\overline{\nu_L^0}\, m_D\, \nu_R^0 + \frac{1}{2} \nu_R^{0T} C\, M_R\, \nu_R^0 + \overline{\ell_L^0}\, m_\ell\, \ell_R^0 \right] + h.c.$$

in WB: $\mathcal{L}_W = -\frac{g}{\sqrt{2}} W_\mu\, \overline{\ell_{L_i}^0} \gamma^\mu \nu_{L_i}^0 + h.c.$ real diagonal

$M_D \equiv M$

$\mathcal{O}(M_R) \gg \mathcal{O}(m_D)$ Seesaw Mechanism

$$\mathcal{L}_W = -\frac{g}{\sqrt{2}} \left(\overline{\ell_{iL}} \gamma^\mu \underline{K_{ij}}\, \nu_{jL} + \overline{\ell_{iL}} \gamma_\mu G_{ij} N_{jL} \right) W^\mu + h.c.$$

G suppressed $\mathcal{O}\left(\frac{m_D}{M_R}\right)$; K almost unitary

Excellent approximation: $\underbrace{-K^\dagger m_D \frac{1}{M_R} m_D^T K^* = d}_{\text{seesaw formula}}$

$U_\nu^\dagger m_{eff} U_\nu^* = d$

Possible choice of WB

M_R and m_ℓ real and diagonal

All CP violating phases in m_D

Possibility of studying CP properties still in WB (any WB)

no need to go to physical bases:

inspection of mass matrices m_D, m_ℓ, $M \equiv M_R$

Technique: Build WB invariant CP odd conditions

(Bernabeu, Branco, Gronau, 1986)

Symmetries and texture zeros in general imply

- reduction in # CP violating phases
- with implications for WB invariant CP-odd conditions

Therefore these CP-odd conditions may

- allow to recognize special flavour models
- allow to study CP violation at low energies
- allow to detect presence of CP violation relevant for leptogenesis

CP violation still in a WB

most general CP transformation

$\ell_L^0 \to U \gamma^0 C \bar{\ell}_L^{0\,T}$ $\qquad$ $\ell_R^0 \to V \gamma^0 C \bar{\ell}_R^{0\,T}$

$\nu_L^0 \to U \gamma^0 C \bar{\nu}_L^{0\,T}$ $\qquad$ $\nu_R^0 \to W \gamma^0 C \bar{\nu}_R^{0\,T}$

CP invariance of mass terms requires

$W^T M_R W = - M_R^*$ (1) $(\nu_R^{0\,T} C M_R \nu_R^0)$

$U^\dagger m_D W = m_D^*$ (2) $(\bar{\nu}_L^0 m_D \nu_R^0)$; $U^\dagger m_\ell V = m_\ell^*$ (3) $(\bar{\ell}_L^0 m_\ell \ell_R^0)$

Search for W, U, V not simple task ; go to physical basis ...

Alternative strategy (Bernabeu, Branco, Gronau, 1986)

(2) $\Rightarrow W^\dagger h_D W = h_D^*$ $\quad (h_D = m_D^\dagger m_D)$

(3) $\Rightarrow U^\dagger h_\ell U = h_\ell^*$ $\quad (h_\ell = m_\ell m_\ell^\dagger)$

(1) $\Rightarrow W^\dagger H_R W = H_R^*$ $\quad (H_R = M_R^\dagger M_R)$

Combined together (multiplication, addition, subtraction) and applying traces, determinants (W, U, V eliminated)

Examples of WB invariants relevant for low energies

$$U_\nu = \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\ \times & \times & s_{23}c_{13} \\ \times & \times & c_{23}c_{13} \end{pmatrix} \begin{pmatrix} 1 & & \\ & e^{i\alpha} & \\ & & e^{i\beta} \end{pmatrix}$$

Dirac and Majorana-type CP violation

$$\mathrm{Tr}\left[m_{eff}\, m_{eff}^\dagger,\, h_\ell\right]^3 = 0\,, \quad m_{eff} = -m_D \frac{1}{M_R} m_D^T\ ; \quad h_\ell = m_\ell m_\ell^\dagger$$

sensitive to Dirac type phase

$$\mathrm{Im}\,\mathrm{Tr}\, Q = 0 \qquad Q \equiv h_\ell\, m_{eff}\, m_{eff}^*\, m_{eff}\, h_\ell^*\, m_{eff}^*$$

sensitive to Majorana-type CP violation
(two generations of Majorana neutrinos Branco, Lavoura, MNR, 1986)

$$\mathrm{Tr}\left[\left(m_{eff}^*\, h_\ell\, m_{eff}\right),\, h_\ell^*\right]^3 = 0$$

sensitive to Majorana-type CP violation
(e.g. three degenerate neutrinos Branco, MNR, Silva-Marcos 1998)

(Dreiner, Kim, Lebedev, Thormeier, 2007)

Ingredients required to produce BAU (Sakharov, 1967)

- Baryon number violation $B=0 \rightarrow B \neq 0$
- C and CP violation (different behaviour particles, anti-p)
- Out of equilibrium dynamics

In the SM

C violation; CP violation (CKM mechanism) (too small)

B and L are not conserved due to chiral nature of Weak interactions $(\Delta B - \Delta L = 0)$ ('t Hooft, 1976)

at $T=0$ no observable effect

$100\,\text{GeV} < T < 10^{12}\,\text{GeV}$ $B+L=0$ restored with $B-L$ conserved.

(Kuzmin, Rubakov, Shaposhnikov 1985)

$M_H > 72\,\text{GeV}$ EW phase transition in equilibrium, $\Delta B = 0$

BAU requires Physics Beyond SM

Challenge: non observation of proton decay

SM non perturbative effects do not mediate proton decay

Leptogenesis $L=0 \rightarrow L \neq 0 \xrightarrow{\text{sphalerons}} B \neq 0$

Leptogenesis

Initial condition $B=0$, $L=0$

Out of equilibrium decay of N_j in $\langle v \rangle = 0$ phase

$M(\nu_R) \neq 0$, no other fermions have mass

$L \neq 0$ generated while $B=0$

$\Delta A_i^j = N_i^j - \bar{N}_i^j$

opposite charged leptons i

Still in sym phase, sphalerons restore $B+L=0$ ($B-L$ invariant)

Baryon asymmetry is generated

Next, smooth phase transition $\Rightarrow v \neq 0$ and B unchanged

Further constraints competition between production processes and washout processes. Boltzmann equations

Buchmüller et al

Davidson, Ibarra

Minimal version $M_1 \ll M_2, M_3$, unflavoured

lower bound $M_1 \sim 10^7$ or 10^8 GeV

Upper bound on light neutrino masses

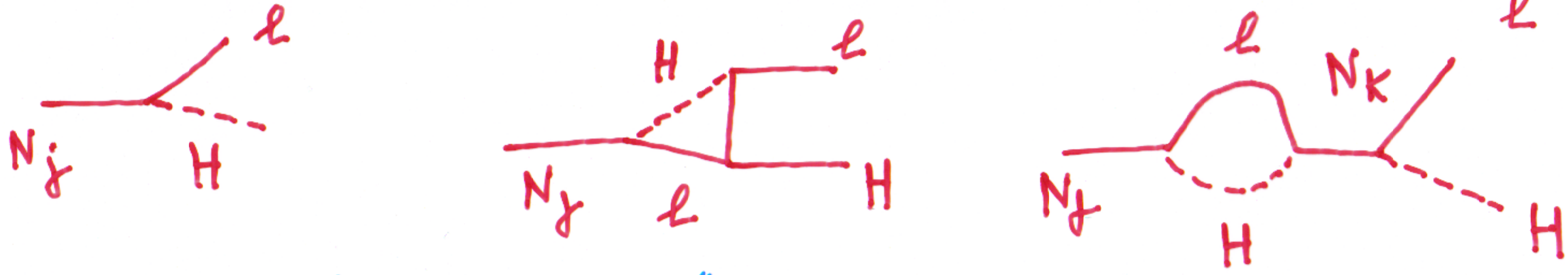
$m_i < 0.1\,\text{eV}$ $(0.15\,\text{eV})$

Leptogenesis

Fukugita, Yanagida (1986)

L asymmetry generated through CP violating decays

$$N \to \ell + H \qquad (\bar{\ell}\, H^{+})$$



Covi, Roulet, Vissani
Flanz, Paschos, Sarkar

Plümacher, Buchmüller

Pilaftsis

Unflavoured leptogenesis

(M_R diagonal real)

$$A^j = \frac{\sum_i (N_i^j - \bar{N}_i^j)}{\sum_i (N_i^j + \bar{N}_i^j)} \propto \sum_{k \neq j} \mathrm{Im}\left[(m_D^\dagger m_D)_{jk} (m_D^\dagger m_D)_{jk} \right]^{ck}$$

$m_D^\dagger m_D$ is Hermitian, only three phases

Flavoured leptogenesis

(M_R, m_ℓ diagonal real)

$$\mathrm{Im}\,(m_D^\dagger m_D)_{kk'} (m_D^*)_{ik} (m_D)_{ik'}$$

$$\mathrm{Im}\,(m_D^\dagger m_D)_{k'k} (m_D^*)_{ik} (m_D)_{ik'}$$

Additional sources of CP violation in flavoured leptogenesis

$$m_D \frac{1}{D_R} m_D^\dagger = -U_\nu d U_\nu^T \Rightarrow \left(m_D \frac{1}{\sqrt{D_R}}\right)\left(m_D \frac{1}{\sqrt{D_R}}\right)^T = \left(i U_\nu \sqrt{d}\right)\left(i U_\nu \sqrt{d}\right)^T$$

$$m_D \frac{1}{\sqrt{D_R}} = i U_\nu \sqrt{d} R \,, \quad R R^T = \mathbb{1} \Rightarrow m_D = i U_\nu \sqrt{d} R \sqrt{D_R}$$

Casas and Ibarra, 2001

Unflavoured Leptogenesis

$$m_D^\dagger m_D = -\sqrt{D_R} R^\dagger \sqrt{d}^T \sqrt{d} R \sqrt{D_R}$$ leptogenesis independent of U_ν

U_ν may be real

It is possible to have leptogenesis with no low energy $\not{CP}$

MNR, 2003

Flavoured leptogenesis

In addition to R the matrix U_ν does not cancel out in $(m_D^*)_{ik} (m_D)_{ik}$

possibility of having viable leptogenesis even in the case of R being a real matrix

Branco, Buras, Jager, Uhlig, Weiler (2006)

Pascoli, Petcov, Riotto (2006), Branco, Gonzalez-Felipe, Joaquim (2006)

Examples of WB invariants relevant for leptogenesis
(Branco, Morozumi, Nobre, MNR 2001)

Unflavoured leptogenesis, only phases in $m_D^\dagger m_D$ relevant

$$I_1 \equiv \mathrm{Im\,Tr}\left[h_D H M^* h_D^* M\right] = 0 \qquad h_D = m_D^\dagger m_D$$

$$H = M^\dagger M \qquad M \equiv M_R$$

$$I_2 \equiv \mathrm{Im\,Tr}\left[h_D H^2 M^* h_D^* M\right] = 0$$

$$I_3 \equiv \mathrm{Im\,Tr}\left[h_D H^2 M^* h_D^* M H\right] = 0$$

sufficient to guarantee CP conservation in $m_D^\dagger m_D$

Flavoured leptogenesis, also phases in $(m_D^*)_{ik}(m_D)_{ik'}$

replace h_D by $\bar{h} = m_D^\dagger h_e m_D$ where $h_e = m_e m_e^\dagger$

for example

$$\bar{I}_1 = \mathrm{Im\,Tr}\left[m_D^\dagger h_e m_D H M^* m_D^T h_e^* m_D^* M\right]$$

Texture zeros in $m_D \Rightarrow$ reduction in number of parameters $\Rightarrow$ physical implications

- possible low energy constraints
- connection between leptogenesis and low energy physics

NOTE: WB where M_R and m_ℓ are real diagonal

Casas and Ibarra parametrization

$$m_D \frac{1}{D_R} m_D^T = - U_\nu d U_\nu^T \Rightarrow m_D = i\, U_\nu \sqrt{d}\, R \sqrt{D_R}$$

R orthogonal complex matrix

$$(m_D)_{ij} = 0 \quad \Rightarrow (U_\nu)_{ik} \sqrt{d_{k\ell}}\, R_{\ell j} = 0$$

"orthogonality" condition between row of $U_\nu \sqrt{d}$ and column of R

Two interesting examples, two righthanded ν's only

Frampton, Glashow, Yanagida 2002

$$\begin{pmatrix} y_{11} & 0 \\ y_{21}e^{i\delta} & y_{22} \\ 0 & y_{32} \end{pmatrix} \qquad \begin{pmatrix} y_{11} & 0 \\ 0 & y_{22} \\ y_{31}e^{i\delta} & y_{32} \end{pmatrix}$$

only one CP violating phase

most economical extension of SM leading to leptogenesis

THE SIGN OF THE BARYON ASYMMETRY OF THE UNIVERSE IS UNIQUELY RELATED TO CP VIOLATION IN ν OSCILLATION EXPERIMENTS

Ibarra, Ross (2004) studied predictions for all two texture zeros : fifteen cases, only five allowed

- one zero texture only: no low energy constraints yet fixes R up to a reflection
- two zero textures: already impose constraints at low energies

All fifteen two zero textures, two righthand ν's only
(G. Branco, Silva-Marcos, MNR 2005)

imply $\quad I_1 \equiv \mathrm{Tr}\left[m_D M_R^\dagger M_R m_D^\dagger, h_\ell\right]^3 = 0$

Converse is true with arbitrary phases and no relation between M_R and m_D

Two zeros in m_D allow for CP violation at low and at high energies

Three righthanded neutrinos and three texture zeros

$I_1 = 0$ provided two rows of m_D orthogonal, e.g. $m_D = \begin{pmatrix} 0 & 0 & a_3 \\ b_1 & b_2 & 0 \\ c_1 & c_2 & c_3 \end{pmatrix}$
(one zero in m_{eff}, low energy constraint)

$I_2 \equiv \mathrm{Tr}\left[M_R^\dagger M_R, m_D^\dagger m_D\right]^3 = 0$
provided two columns of m_D orthogonal, eg $\begin{pmatrix} 0 & a_2 & a_3 \\ 0 & b_2 & b_3 \\ c_1 & 0 & c_3 \end{pmatrix}$
one zero in $m_D^\dagger m_D$, high energy constraint

$m_D = \begin{pmatrix} 0 & 0 & a_3 \\ 0 & b_2 & b_3 \\ c_1 & c_2 & c_3 \end{pmatrix}$ connection yet each sector can be "freely" chosen (separately)

Systematic study of four zeros in m_D

Maximal number of texture zeros compatible with observed leptonic mixing provided no neutrino mass vanishes

(Branco, Emmanuel-Costa, MNR, Roy, 2008)

Two categories

i) Those with two orthogonal rows

One off diagonal entry in meff is zero

A Merle, W Rodejohann hep-ph/0603111

ii) Those with two orthogonal columns (no orth rows)

One subdeterminant condition

$$(m_{eff})_{ii}\,(m_{eff})_{jk} = (m_{eff})_{ij}\,(m_{eff})_{ik}$$

i, j, k different from each other no sum implied

ith row has two zeros

simple exact low energy relations

Relating leptogenesis to low energy physics

In both categories the matrix R is fully determined in terms of light neutrino masses and mixing

e.g. $(\vec{R}_\ell)_i = \left(\varepsilon_{ijk} U_{pj}\sqrt{m_j}\; U_{qk}\sqrt{m_k}\right)\frac{1}{N_\ell}$ (column i)

p, q rows with zeros in column ℓ

$$\begin{pmatrix} 0 & 0 & x \\ 0 & x & 0 \\ x & x & x \end{pmatrix}$$

e.g. $(\vec{R}_a)_i = \left(\varepsilon_{ijk} U_{rj}\sqrt{m_j}\,(R_\ell)_k\right)\frac{1}{N_a}$

r, s rows where the zeros are in columns a and b

$(a, r) \to (b, s)$

Extremely important to constrain leptogenesis

Zeros in m_D versus zeros in m_{eff}

Conclusions

The Problem of Flavour is one of the fundamental problems in Particle Physics

ν masses are the only direct evidence for physics beyond SM

Is there a connection between the quark and lepton sectors?

great expectations for LHC

We need guidelines from LHC to focus our research