

Leptogenesis and low-energy
leptonic physics

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Standard Model and Beyond - Standard Cosmology

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Based on Works

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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

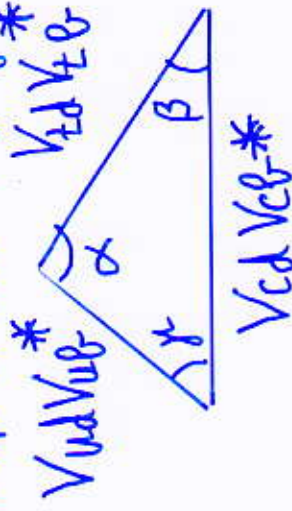
great challenge
to flavour models

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 potential 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



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

$$B_s \rightarrow J/\psi \phi$$

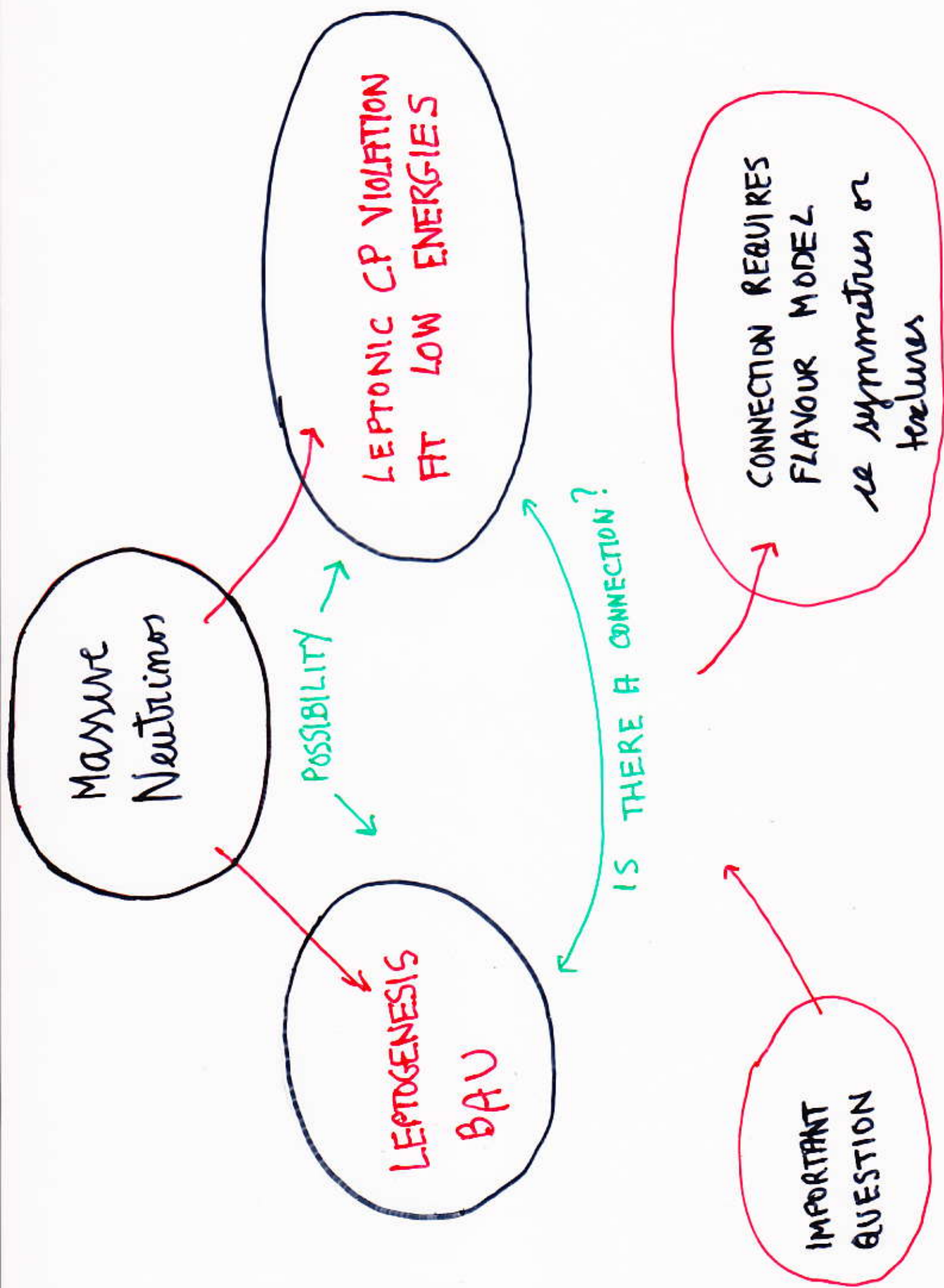
$D^0 - \bar{D}^0$ mixing of long distance contributions are not dominant

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 BAO
- 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!!!



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

$$\mathcal{L}_W = -\frac{g}{\sqrt{2}} W_\mu \bar{l}_L^\mu \gamma^\mu \nu_L^\mu + h.c$$

i -family index

WB transformation

$$(d_L) \quad l_L^0 \rightarrow U l_L^0, \quad l_R^0 \rightarrow V l_R^0$$

$$(u_L) \quad \nu_L^0 \rightarrow U \nu_L^0, \quad \nu_R^0 \rightarrow W \nu_R^0$$

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

$$M_R = \mu (\Delta + a \mathbb{I})$$

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

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)

$$\mathcal{L}_{\text{mass}} = - \left[\bar{\nu}_L^0 m_D \nu_R^0 + \frac{1}{2} \nu_R^{0T} C^{-1} M_R \nu_R^0 + \bar{\ell}_L^0 m \ell_R^0 \right] + \text{h.c.}$$

$$\text{in WB: } \mathcal{L}_W = - \frac{g}{\sqrt{2}} W_\mu \bar{\ell}_{Li}^0 \gamma^\mu \nu_{Li}^0 + \text{h.c.} \quad \text{real diagonal}$$

$$M_D \equiv M$$

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

$$\mathcal{L}_W = - \frac{g}{\sqrt{2}} \left(\bar{\ell}_{Li} \gamma^\mu K_{ij} \nu_{jL} + \bar{\ell}_{LiL} \gamma^\mu G_{ij} N_{jL} \right) W^\mu + \text{h.c.}$$

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

Excellent approximation:

$$- K^\dagger m_D \frac{1}{M_R} m_D^T K^* = d$$

seesaw formula

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

$$\mathcal{L}_{\text{mass}} = - \left[\frac{1}{2} m_L^T \bar{c}^{-1} \mathcal{H}^* n_L + \bar{e}_L^0 m_e \bar{e}_R^0 \right] + \text{h.c.}$$

$$n_L = \begin{pmatrix} \nu_L^0 \\ (\nu_R^0)^c \end{pmatrix}$$

$$\mathcal{H} = \begin{pmatrix} 0 & m_D \\ m_D^T & m_R \end{pmatrix}$$

$$V^T \mathcal{H}^* V = \mathcal{Q}$$

$$V = \begin{pmatrix} K & G & T \\ S & & \end{pmatrix}$$

$$\mathcal{Q} = \begin{pmatrix} d & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix}$$

$$\psi^c = \gamma_0 C \psi^*$$

Possible choice of WB
MR and m_L real and diagonal
All CP violating phases in m_D

Possibility of studying CP properties still in WB (only WB)
no need to go to physical basis :
inspection of mass matrices m_D, m_L , $M \equiv MR$

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

Warning :

Not all texture zero sets have
physical content

Some special cases are just a choice
of WB

also in the quark sector

CP violation still in a WB

most general CP transformation

$$\ell_L^0 \rightarrow U \gamma^0 C \bar{\ell}_L^{0T} \quad \ell_R^0 \rightarrow V \gamma^0 C \bar{\ell}_R^{0T}$$

$$\nu_L^0 \rightarrow U \gamma^0 C \bar{\nu}_L^{0T} \quad \nu_R^0 \rightarrow W \gamma^0 C \bar{\nu}_R^{0T}$$

CP invariance of mass terms requires

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

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

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

Alternative strategy (Bernabeu, Branco, Gronau, 1986)

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

$$(3) \Rightarrow U^T h_e U = h_e^* \quad (h_e = m_e m_e^+)$$

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

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

Examples of WB invariants relevant for low energies

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

Dirac and
Majorana-type
CP violation

$$\text{Tr} [m_{\text{eff}}^{\dagger} m_{\text{eff}}, h_e]^3 = 0, \quad m_{\text{eff}} = -m_D \frac{1}{M_R} m_D^T; \quad h_e = m_e m_e^{\dagger}$$

sensitive to Dirac type phase

$$\text{Im Tr } Q = 0 \quad Q \equiv h_e m_{\text{eff}}^{\dagger} m_{\text{eff}} h_e^{\dagger}$$

sensitive to Majorana-type CP violation
(two generations of Majorana neutrinos)

Blanco, Lavoue, MNR, 1986)

$$\text{Tr} [(m_{\text{eff}}^{\dagger} h_e m_{\text{eff}}), h_e^{\dagger}]^3 = 0$$

sensitive to Majorana-type CP violation
(e.g. three degenerate neutrinos)

Blanco, MNR, Silva-Marcos 1998)

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 $L=0 \rightarrow L \neq 0$ sphalerons $B \neq 0$

Leptogenesis

Initial Condition $B=0$, $L=0$

Out of equilibrium decay of N_i in $\langle v \rangle = 0$ phase
 $M(\nu_k) \neq 0$, no other fermions have mass

$L \neq 0$ generated while $B=0$ $\Delta H_i^{\dot{}} = N_i^{\dot{}} - \bar{N}_i^{\dot{}}$

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
Dardson, Ibarra

Minimal version $M_1 < M_2, M_3$, unflavoured

Buchmüller et al

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

Grudic et al

Upper bound on light neutrino masses

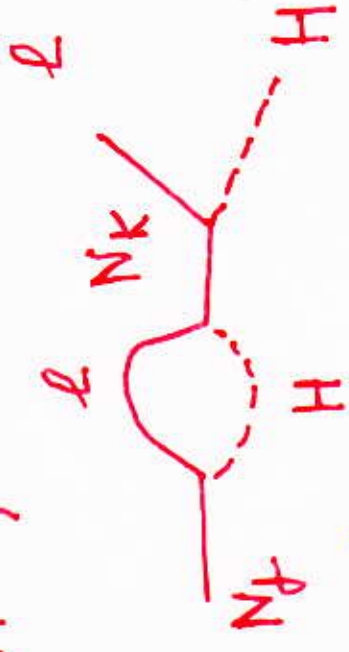
$m_i < 0.1 \text{ eV}$ (0.15 eV)

Leptogenesis

Fukugita, Yanagida (1986)

L asymmetry generated through CP violating decays

$$N \rightarrow \ell + H \quad (\bar{\ell} H^+)$$



Covi, Roulet, Vinanzi
Flanz, Paschos, Sarkar

Plümacher, Buchmüller

Pilaftsis

Unflavoured leptogenesis

(M_R diagonal real)

$$A_i^\dagger = \frac{\sum_j (N_{ij}^\dagger - \bar{N}_{ij}^\dagger)}{\sum_j (N_{ij}^\dagger + \bar{N}_{ij}^\dagger)}$$

$$\propto \sum_{k \neq i}$$

$$\text{Im} \left[(m_D^\dagger m_D)_{jk} (m_D^\dagger m_D)_{ik} \right] \epsilon_k$$

$m_D m_D^\dagger$ is Hermitian, only three phases (M_R, m_e diagonal real)

Flavoured leptogenesis

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

$$\text{Im} (m_D^\dagger m_D)_{ik} (m_D^{*})_{ik} (m_D)_{ik'}$$

Additional sources of CP violation in flavoured leptogenesis

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

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

Casas and Ibarra, 2001

Unflavoured Leptogenesis

$$m_D^+ m_D = -\sqrt{D_R} R^T \sqrt{d}^T \sqrt{d} R \sqrt{D_R} \quad \text{leptogenesis independent of } U_\nu$$

U_ν may be real

It is possible to have leptogenesis with no low energy 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, Weber (2006)

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

Examples of WB invariants relevant for leptogenesis

(Branco, Morozumi, Nohre, HNR 2001)

Unflavoured leptogenesis, only phases in $m_D^+ m_D$ relevant

$$\begin{aligned} I_1 &\equiv \text{Im Tr} [h_D H M^* h_D^* M] = 0 & h_D &= m_D^+ m_D \\ I_2 &\equiv \text{Im Tr} [h_D H^2 M^* h_D^* M] = 0 & H &= M^\dagger M & M &\equiv M_R \\ I_3 &\equiv \text{Im Tr} [h_D H^2 M^* h_D^* M H] = 0 \end{aligned}$$

sufficient to guarantee CP conservation in $m_D^+ m_D$

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

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

$$I_1 = \text{Im Tr} [m_D^+ h_e m_D H M^* m_D^T h_e^* m_D^* M]$$

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_e 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

$$(m_D)_{ij} = 0 \Rightarrow (U_\nu)_{ik} \sqrt{d_{kl}} R_{lj} = 0$$

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

Two interesting examples, two right-handed ν 's only
 Frampton, Glashow, Yanagida 2002

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

only one CP violating phase leading to leptogenesis
 most economical extension of SM leading to leptogenesis
 THE SIGN OF THE BARYON ASYMMETRY OF THE UNIVERSE IS
 RELATED TO CP VIOLATION IN ν OSCILLATION EXPERIMENTS
 UNIQUELY

Ghavra, Ross (2004) studied production 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

Example: One texture zero, two ν_R 's

$$m_D = \begin{pmatrix} a_1 & 0 \\ b_1 & b_2 \\ c_1 & c_2 \end{pmatrix}, \quad R = \begin{pmatrix} \cos Z & \pm \sin Z \\ -\sin Z & \pm \cos Z \end{pmatrix}$$

$$m_{D11} = i U_{\nu 12} \sqrt{m_2} (\cos Z) \sqrt{M_1} + i U_{\nu i3} \sqrt{m_3} (-\sin Z) \sqrt{M_1}$$

$$m_{D12} = i U_{\nu 12} \sqrt{m_2} (\pm \sin Z) \sqrt{M_2} + i U_{\nu i3} \sqrt{m_3} (\pm \cos Z) \sqrt{M_2}$$

$$m_{D12} = 0$$

$$\lambda_{12} c_{13} e^{i \frac{\alpha}{2}} \sqrt{m_2} (\pm \sin Z) + \lambda_{13} \sqrt{m_3} (\pm \cos Z) = 0$$

With standard parametrization for U_2

One equation, one unknown (Z)

All fifteen two zero textures, two right-handed ν 's only
 (G. Branco, Silva-Marcos, MNR 3 2005)

$$\text{imply } I_1 \equiv \text{Tr} [m_D M_R^\dagger M_R m_D^\dagger h_e] = 0$$

Converse is true with arbitrary phases and no relation between MR and MD

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

Three right-handed neutrinos and three texture zeros

$$I_1 = 0 \quad \text{provided two rows of MD orthogonal, e.g. } m_D = \begin{pmatrix} 0 & 0 & a_3 \\ b_1 & b_2 & 0 \\ c_1 & c_2 & c_3 \end{pmatrix}$$

(one zero in m_{eff} , low energy constraint)

$$I_2 \equiv \text{Tr} [M_R^\dagger M_R m_D^\dagger m_D]^3 = 0$$

provided two columns of MD orthogonal, e.g.
 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 zero in m_D
Maximal number of texture zeros compatible with
observed leptonic mixing provided no neutrino mass vanishes
(Branco, Emmanuel-Genta, MNR, Roy, 2008)

Two categories

i) Those with two orthogonal rows

One off diagonal entry in m_{eff} is zero

Ahmed, 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
 i th row has two zeros

simple exact low energy relation

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. $(\vec{R}_L)_i = (\epsilon_{ijk} U_{pj} \sqrt{m_j} U_{qk} \sqrt{m_k}) \frac{1}{N_L} \text{ (column } L)$

P, Q rows with zeros in column L

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

$$L=1$$

$$P, Q=1, 2$$

$$(\vec{R}_A)_i = (\epsilon_{ijk} U_{pj} \sqrt{m_j} (R_L)_k) \frac{1}{N_A}$$

e.g.

n, λ rows where the zeros are in columns a and b
 $(a, \lambda) \rightarrow (b, \lambda)$

Extremely important to constrain leptogenesis
 R can only be complex if there is CP violation at low energies

$$a=2$$

$$n=1$$

$$b=3$$

$$\lambda=2$$

(to examples studied in detail in Barnes, Gongalvez Felipe, Joaquim, Marzola, MNR, Savoy 2003)

Zeros in m_D versus zero in m_{eff}

Before going to the Conclusions

A Comment on Symmetries

Tri-maximal Mixing and A_4 symmetry

Ma, Rajasekaran, Babu, Valle, Altarelli, Feruglio, Lin
He, Keum, Volkas, Varzielas, King, Ross, Hirsch, Misiak
Meloni, Bellazzini, di Bari, Nardi, Hagedorn, Molinaro, Petcov
Jenkins, Manohar, ...

Resonant Leptogenesis

Branco, Gonzalez-Felipe, MNR, Soudo

Type I seesaw

effective theory with an $A_4 \times Z_3 \times Z_4$ symmetry.
spontaneous symmetry breakdown
at high scale $\gg$ EW scale:

exact tribimaximal mixing with phases
exact degeneracy of heavy Neutrino masses

Leptogenesis (flavoured) after lifting degeneracy

Radiative Leptogenesis

Through soft breaking (possibility of unflavoured ^{lept.})

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

Flavoured leptogenesis (2006)

Abada, Davidson, Josse-Michaux,
Losada, Riotto

Nardi, Nir, Racker, Roulet

Washout processes, minimal
leptogenesis

Buchmüller, Di Bari, Plümacher (2002,
2004)

Davinson, Ibarra (2002, 2003)

Giudice, Notari, Randal, Riotto,
Strumia (2003)

Leptogenesis from low energy phases
(flavoured)

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

Pascoli, Petcov, Riotto (2006)

Branco, Gonzalez Felipe, Joaquim (2006)

Flavoured leptogenesis

R. Barbieri, P. Giaminelli, A. Strumia, N. Tetradis (2000)

T. Endoh, T. Morozumi, Z. Xiong (2004)

T. Fujihara, S. Kametoko, S. Kang, D. Kimura, T. Morozumi,
M. Tamamoto (2005)