Neutrinos et physique au-delà du Modèle Standard

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- introduction
- origine des masses des neutrinos
- (propriétés non-standard des neutrinos)
- peut-on tester l'origine des masses des neutrinos?
- violation de la saveur leptonique (leptons chargés)
- leptogenèse et masses des neutrinos

Ecole de Gif 2011: Les Neutrinos
APC, 12-16 septembre 2011

Neutrinos et physique au-delà du Modèle Standard

Cours 2

- violation de la saveur leptonique (suite)
- leptogenèse et masses des neutrinos

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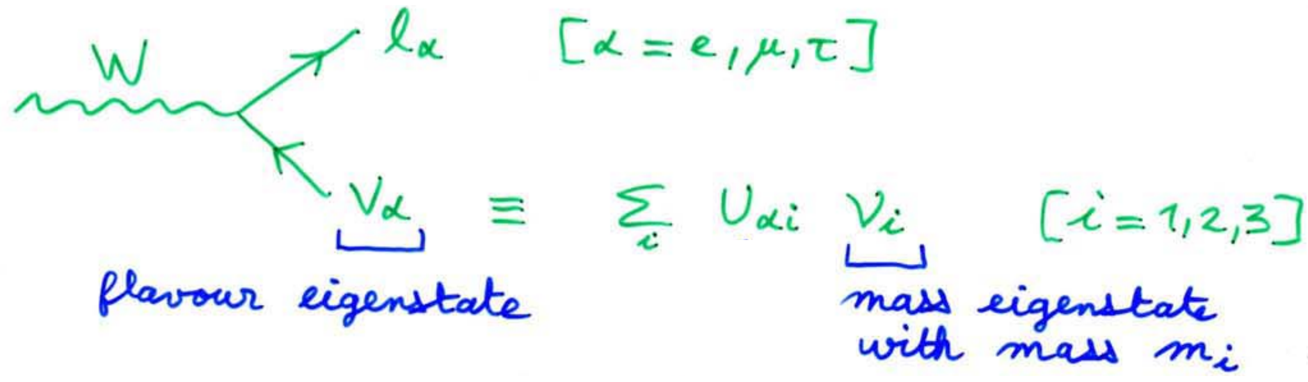
Lepton flavour violation (LFV)

We know that flavour is violated in the lepton sector, since neutrinos oscillate ($\nu_\mu \leftrightarrow \nu_e$ violates both Le and Lμ)



Since the PMNS matrix U appears in charged lepton current, would naively expect strong flavour violating effects in the charged lepton sector too (i.e. processes such as $\mu \to e\,\gamma$ and $\mu \to 3e$ should be observed).

This is not the case due to a GIM mechanism: LFV is strongly suppressed (and in practice unobservable) in the Standard Model

But we have good reasons to believe that there is new physics beyond the SM (neutrino masses, dark matter...) $\Rightarrow$ generally new sources of LFV

Indeed, many well-motivated new physics scenarios predict large flavour violations in the charged lepton sector:

- supersymmetry
- extra dimensions
- little Higgs models
- ...

→ the absence of sizeable SM contributions makes LFV a unique probe of new physics

Further motivation: connection with neutrino physics

The smallness of neutrino masses suggests a specific mechanism of mass generation ⇒ new particles with flavour violating couplings to leptons

→ LFV could tell us something about the origin of neutrino masses

Status of lepton flavour violation

So far lepton flavour violation has been observed only in the neutrino sector (oscillations). Experimental upper bounds on LFV processes involving charged leptons:

update from MEG (2011):

2.4×10^{-12}

Table 1.1: Present limits on rare μ decays.

mode	limit (90% C.L.)	year	Exp./Lab.
~~$\mu^+ \to e^+\gamma$~~	~~1.2×10^{-11}~~	~~2002~~	~~MEGA / LAMPF~~
$\mu^+ \to e^+e^+e^-$	1.0×10^{-12}	1988	SINDRUM I / PSI
$\mu^+e^- \leftrightarrow \mu^-e^+$	8.3×10^{-11}	1999	PSI
μ^- Ti $\to e^-$Ti	6.1×10^{-13}	1998	SINDRUM II / PSI
μ^- Ti $\to e^+$Ca*	3.6×10^{-11}	1998	SINDRUM II / PSI
μ^- Pb $\to e^-$Pb	4.6×10^{-11}	1996	SINDRUM II / PSI
μ^- Au $\to e^-$Au	7×10^{-13}	2006	SINDRUM II / PSI

[CERN flavour workshop –WG3 report]

Table 1.2: 90% C.L. upper limits on selected LFV tau decays by Babar and BELLE.

Channel	Babar $\mathcal{L}$ (fb^{-1})	Babar $\mathcal{B}_{UL}$ (10^{-8})	BELLE $\mathcal{L}$ (fb^{-1})	BELLE $\mathcal{B}_{UL}$ (10^{-8})
$\tau^\pm \to e^\pm \gamma$	232	11	535	12
$\tau^\pm \to \mu^\pm \gamma$	232	6.8	535	4.5
$\tau^\pm \to \ell^\pm \ell^\mp \ell^\pm$	92	11 - 33	535	2 - 4
$\tau^\pm \to e^\pm \pi^0$	339	13	401	8.0
$\tau^\pm \to \mu^\pm \pi^0$	339	11	401	12
$\tau^\pm \to e^\pm \eta$	339	16	401	9.2
$\tau^\pm \to \mu^\pm \eta$	339	15	401	6.5
$\tau^\pm \to e^\pm \eta'$	339	24	401	16
$\tau^\pm \to \mu^\pm \eta'$	339	14	401	13

[WG3 report]

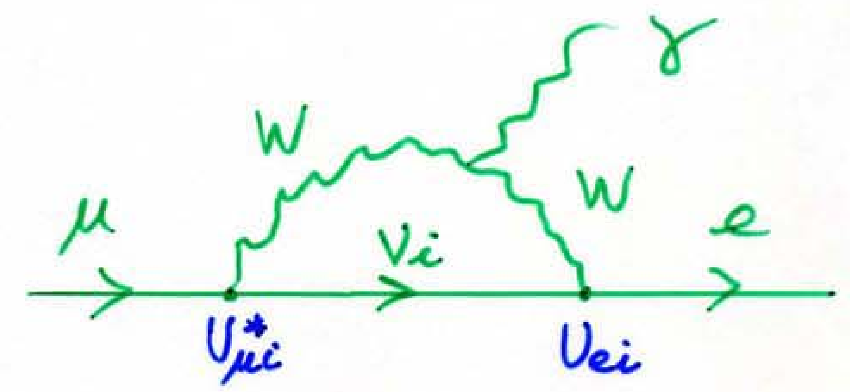
Also strong constraints on LFV rare decays of mesons:

$$\mathrm{BR}\,(K_L^0 \to \mu e) \; < \; 4.7 \times 10^{-12}$$

$$\mathrm{BR}\,(B_d^0 \to \mu e) \; < \; 1.7 \times 10^{-7} \qquad \text{[Belle]}$$

$$\mathrm{BR}\,(B_s^0 \to \mu e) \; < \; 6.1 \times 10^{-6} \qquad \text{[CDF]}$$

This is consistent with the Standard Model, in which LFV processes involving charged leptons are suppressed by the tiny neutrino masses



e.g. μ → e γ :

$$\mathrm{BR}\,(\mu \to e\gamma) \;=\; \frac{3\alpha}{32\pi}\left|\sum_i U^*_{\mu i} U_{ei}\,\frac{m^2_{\nu_i}}{M^2_W}\right|^2$$

Using known oscillations parameters (U = PMNS lepton mixing matrix) and $|U_{e3}| < 0.2$, this gives $\mathrm{BR}\,(\mu \to e\gamma) \;\lesssim\; 10^{-54}$: inaccessible to experiment!

This makes LFV a unique probe of new physics: the observation of e.g. μ → e γ would be an unambiguous signal of new physics (no SM background)

→ very different from the hadronic sector

Conversely, the present upper bounds on LFV processes already put strong constraints on new physics (same as hadronic sector)

Prospects for LFV experiments

μ → e γ :

- the experiment MEG at PSI has started taking data in sept. 2008
- 2011: reached a limit of 2.4×10^{-12}
- expects to reach a sensitivity of a few 10^{-13} (factor of 10 improvement) in the next years

μ → e conversion :

- the project mu2e is under study at FNAL - aims at $\mathcal{O}(10^{-16})$
- the project PRISM/PRIME at J-PARC aims at $\mathcal{O}(10^{-18})$

τ decays :

- LHC experiments limited to $\tau \to \mu\mu\mu$ – comparable to existing B fact.
- superB factories will probe the $10^{-9} - 10^{-10}$ level

Theoretical expectations/predictions

Many new physics scenarios predict "large" LFV rates: supersymmetry, extra dimensions, little Higgs models, ...

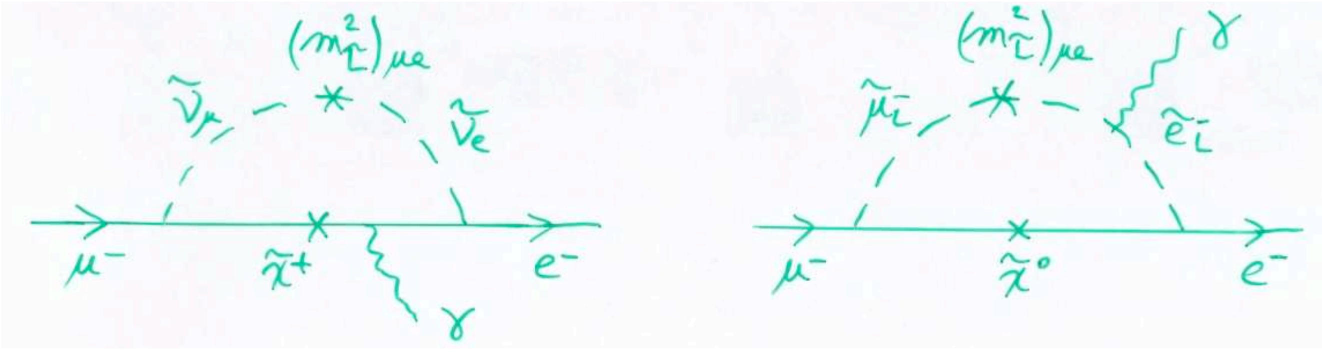
In (R-parity conserving) supersymmetric extensions of the Standard Model, LFV is induced by a misalignment between the lepton and slepton mass matrices, parametrized by the mass insertion parameters ($\alpha \neq \beta$):

$$\delta^{LL}_{\alpha\beta} \equiv \frac{(m^2_{\tilde{L}})_{\alpha\beta}}{m^2_L}\,, \qquad \delta^{RR}_{\alpha\beta} \equiv \frac{(m^2_{\tilde{e}})_{\alpha\beta}}{m^2_R}\,, \qquad \delta^{RL}_{\alpha\beta} \equiv \frac{A^e_{\alpha\beta} v_d}{m_R m_L}$$

(can be viewed as supersymmetric lepton mixing angles)

$\Rightarrow$ typical $\mu \to e\,\gamma$ rate: $B(\mu \to e\gamma) \sim 10^{-5}\, \frac{M_W^4}{M_{SUSY}^4}\, |\delta^{LL}_{12}|^2 \tan^2\beta$

where $\tan\beta \equiv \langle H^0_u \rangle / \langle H^0_d \rangle$



[Masina, Savoy]

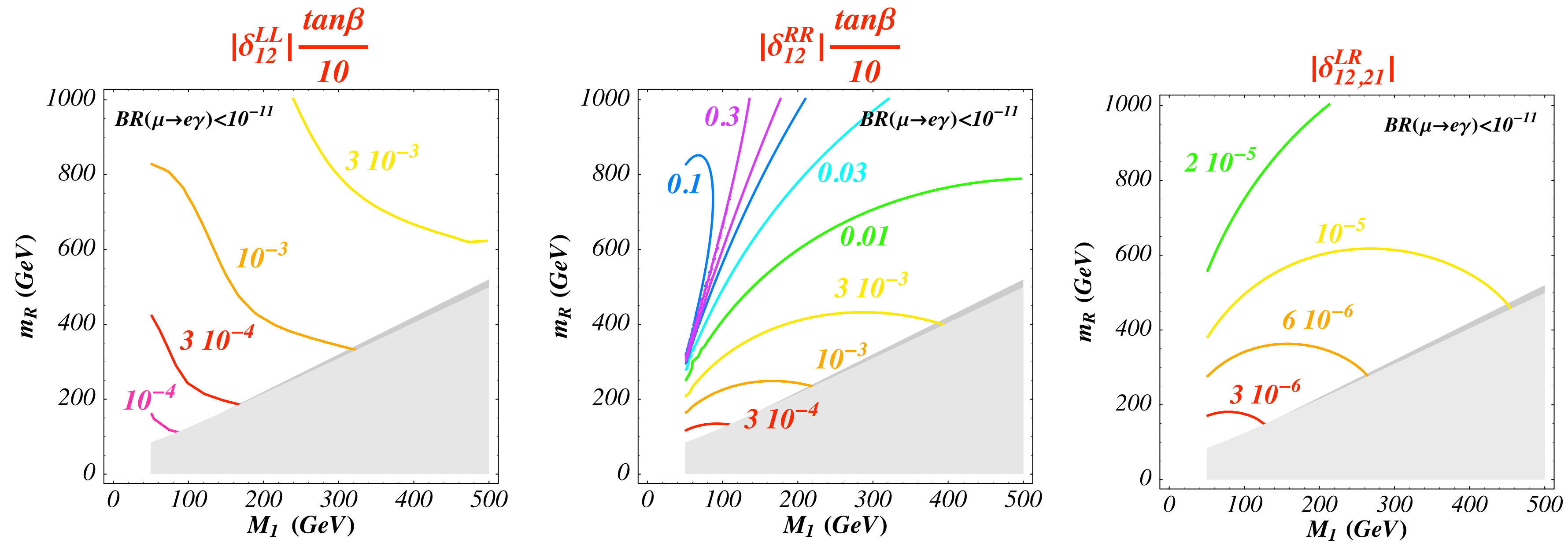


Fig. 5.3: Upper limits on δ_{12}'s in mSUGRA. Here M_1 and m_R are the bino and right-slepton masses, respectively.

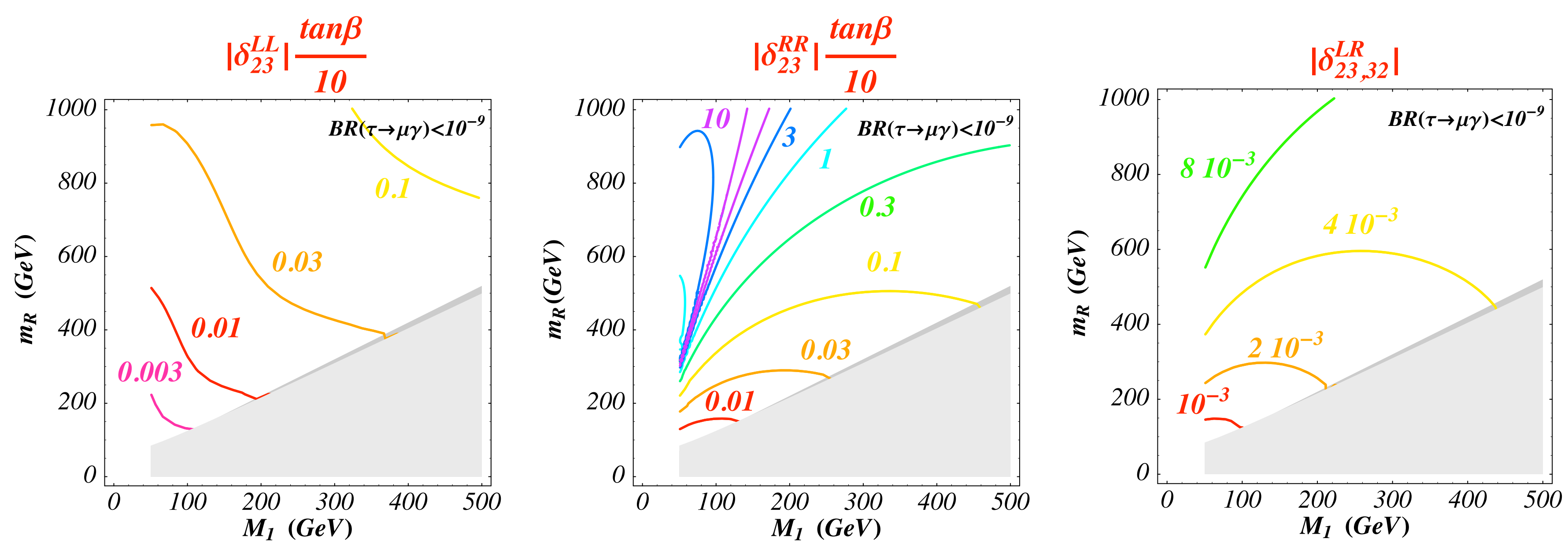


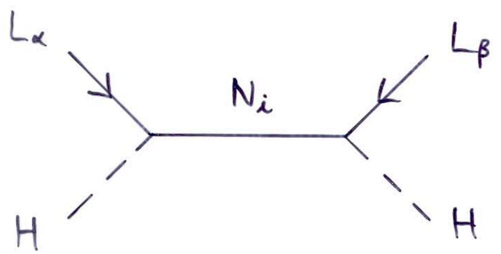
Fig. 5.4: Upper limits on δ_{23}'s in mSUGRA. Here M_1 and m_R are the bino and right-slepton masses, respectively.

Important difference with the quark sector: even if slepton mass matrices are flavour diagonal at some high scale, radiative corrections may induce large LFV [quark sector: controlled by CKM, pass most flavour constraints]

Such large corrections are due to heavy states with FV couplings to SM leptons, whose presence is suggested by $m_\nu << m_l$ [Borzumati, Masiero]

Well-known example: (type I) seesaw mechanism

$$\mathcal{L}_{seesaw} = -\frac{1}{2} M_i \bar{N}_i N_i - \left(\bar{N}_i Y_{i\alpha} L_\alpha H + \text{h.c.} \right)$$



$$\Longrightarrow \quad (M_\nu)_{\alpha\beta} = -\sum_i \frac{Y_{i\alpha} Y_{i\beta}}{M_i} v^2 \quad (v = \langle H \rangle)$$

Assuming universal slepton masses at M_U, one obtains at low energy:

$$(m^2_{\tilde{L}})_{\alpha\beta} \simeq -\frac{3m_0^2 + A_0^2}{8\pi^2} C_{\alpha\beta} , \quad (m^2_{\tilde{e}})_{\alpha\beta} \simeq 0 , \quad A^e_{\alpha\beta} \simeq -\frac{3}{8\pi^2} A_0 y_{e\alpha} C_{\alpha\beta}$$

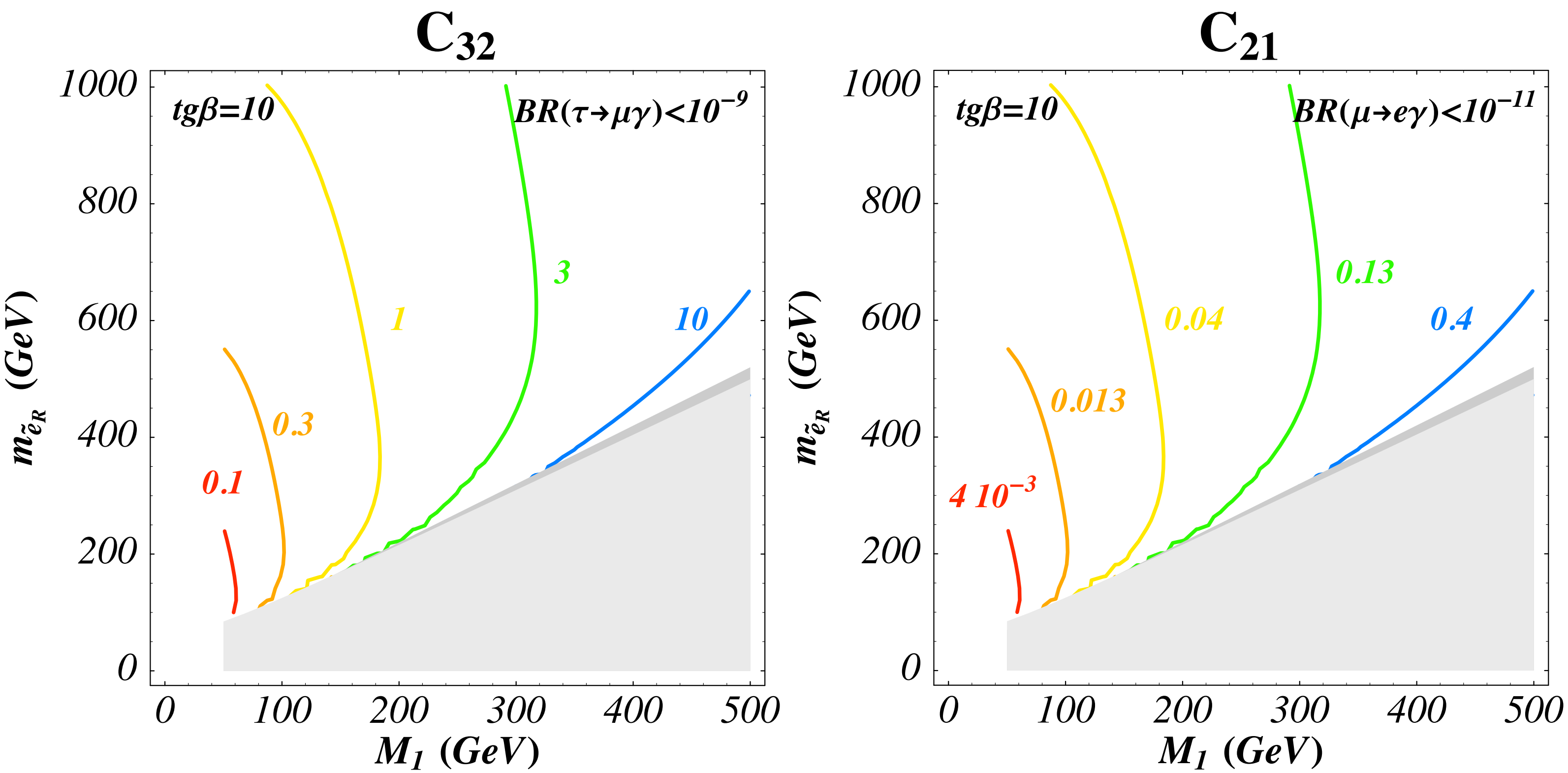
where $C_{\alpha\beta} \equiv \sum_k Y^\star_{k\alpha} Y_{k\beta} \ln(M_U/M_k)$ encapsulates all the dependence on the seesaw parameters

$$\text{BR}\left(l_\alpha \to l_\beta \gamma\right) \propto |C_{\alpha\beta}|^2$$

$$\mathrm{BR}\,(l_\alpha \to l_\beta \gamma) \;\propto\; |C_{\alpha\beta}|^2$$

$$C_{\alpha\beta} \;\equiv\; \sum_k Y^\star_{k\alpha} Y_{k\beta} \ln(M_U/M_k)$$

[SL, Masina, Savoy]



Thus, in the supersymmetric seesaw mechanism, LFV processes probe the seesaw parameters

In general, however, cannot disentangle LFV induced by supersymmetry breaking from seesaw-induced LFV

Even in mSUGRA, there is no straightforward correlation between the measured neutrino parameters and the LFV rates, due to the degeneracy of seesaw parameters

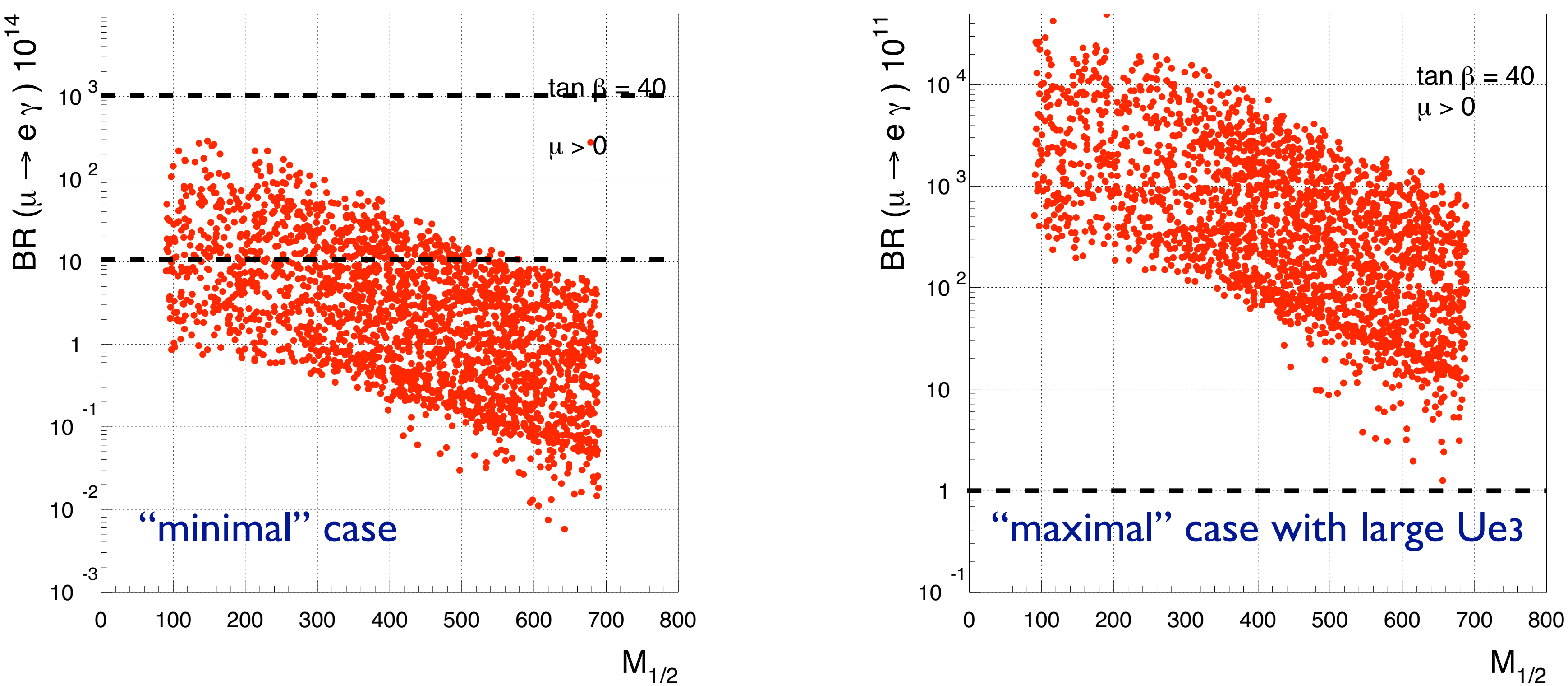
It is therefore fair to say that there is no definite prediction of the supersymmetric (type I) seesaw scenario for LFV processes, even in the mSUGRA case. This explains why different models give different predictions, although large rates are generic.

One can embed the supersymmetric seesaw in a Grand Unified Theory in order to reduce the arbitrariness in the seesaw parameters

Example [Masiero, Vempati, Vives]: SO(10)-motivated ansätze for the seesaw parameters

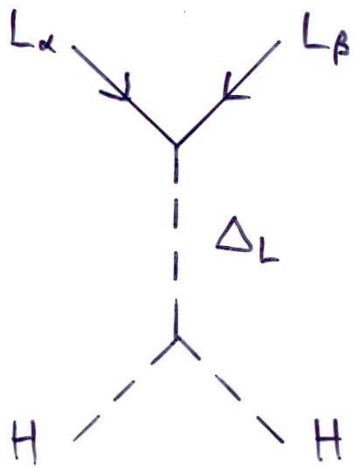
“minimal case”: CKM-like mixing in the Dirac couplings Yij

“maximal case”: PMNS-like mixing in the Dirac couplings Yij – $\mu \to e\gamma$ scales as U_{e3}^2 for $U_{e3}^2 \gtrsim 4 \times 10^{-5}$



More predictive version of the seesaw mechanism:

Type II seesaw [heavy scalar SU(2)L triplet exchange]



$$\frac{1}{\sqrt{2}} Y_T^{ij} L_i T L_j + \frac{1}{\sqrt{2}} \lambda\, H_u \bar{T} H_u + M_T\, T \bar{T}$$

$$\Rightarrow \quad M_\nu^{ij} = \lambda\, Y_T^{ij} \frac{v_u^2}{M_T}$$

The radiative corrections to soft slepton masses are now controlled by

$$(Y_T^\dagger Y_T)_{\alpha\beta} \ln(M_U / M_T) \;\propto\; \sum_i m^2_{\nu_i} U_{i\alpha} U^*_{i\beta}$$

$\Rightarrow$ predictive (up to an overalll scale) and leads to correlations between LFV observables (correlations controlled by the neutrino parameters)

[A. Rossi]

$$\frac{\mathrm{BR}(\tau\to\mu\gamma)}{\mathrm{BR}(\mu\to e\gamma)} \approx \left|\frac{(m^2_{\tilde{L}})_{\tau\mu}}{(m^2_{\tilde{L}})_{\mu e}}\right|^2 \frac{\mathrm{BR}(\tau\to\mu\nu_\tau\bar{\nu}_\mu)}{\mathrm{BR}(\mu\to e\nu_\mu\bar{\nu}_e)} \approx \begin{cases} 300 & [s_{13}=0] \\ 2\,(3) & [s_{13}=0.2] \end{cases}$$

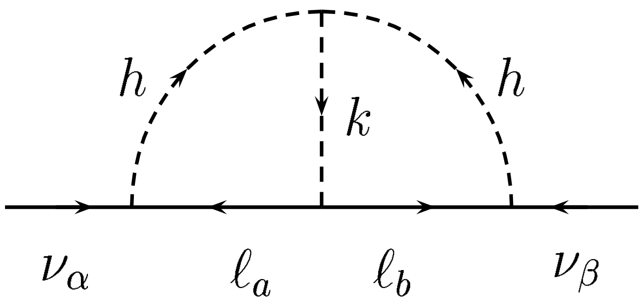
$$\frac{\mathrm{BR}(\tau\to e\gamma)}{\mathrm{BR}(\mu\to e\gamma)} \approx \left|\frac{(m^2_{\tilde{L}})_{\tau e}}{(m^2_{\tilde{L}})_{\mu e}}\right|^2 \frac{\mathrm{BR}(\tau\to e\nu_\tau\bar{\nu}_e)}{\mathrm{BR}(\mu\to e\nu_\mu\bar{\nu}_e)} \approx \begin{cases} 0.2 & [s_{13}=0] \\ 0.1\ (0.3) & [s_{13}=0.2] \end{cases}$$

LFV in non-supersymmetric mechanisms of neutrino mass generation

<u>Example of a radiative model: Zee-Babu model</u>

introduce 2 charged SU(2) singlet scalars, h^+ and k^{++}, with couplings to leptons:

$$f_{\alpha\beta}\, L_\alpha^T C i\sigma^2 L_\beta h^+ + h'_{\alpha\beta} e_{R\alpha}^T C e_{R\beta} k^{++} + \mathrm{h.c.}$$



Lepton number is violated by scalar couplings: $\mu\, h^+ h^+ k^{--} + \mathrm{h.c.}$

Neutrino mass matrix: $(M_\nu)_{\alpha\beta} \sim \dfrac{8\mu}{(16\pi^2)^2 m_h^2} f_{\alpha\gamma} m_{e_\gamma} h_{\gamma\delta} m_{e_\delta} f_{\delta\beta}$

In addition to new exotic scalars, this mechanism predicts flavour-violating processes involving charged leptons, such as $\mu \to e\,\gamma$:

$$Br(\mu \to e\gamma) \simeq 4.5 \cdot 10^{-10} \left(\frac{\varepsilon^2}{h_{\mu\mu}^2 \mathscr{I}(r)^2}\right)\left(\frac{m_\nu}{0.05\ \mathrm{eV}}\right)^2 \left(\frac{100\ \mathrm{GeV}}{m_h}\right)^2$$

$\epsilon \equiv f_{e\tau}/f_{\mu\tau}$

$\mathcal{J}(r)$ = loop function

D. Aristizabal Sierra, M. Hirsch

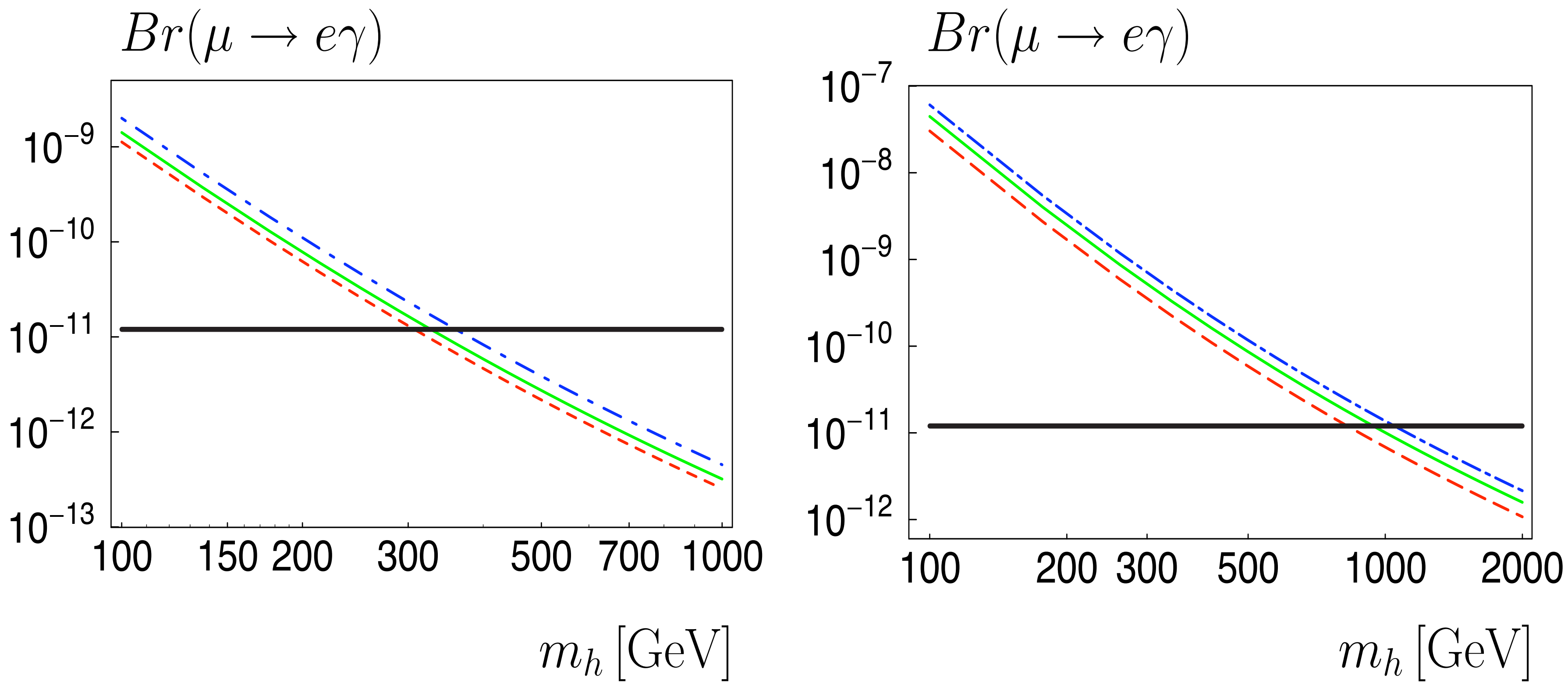


Fig. 2 Conservative lower limit on the branching ratio Br($\mu \to e\gamma$) as a function of the charged scalar mass m_h for normal hierarchy (left plot) and inverted hieraracthy (right plot). The three lines are for the current solar angle $\sin^2\theta_{12}$ best fit value (full line) and 3 σ lower (dashed line) and upper (dot-dashed line) bounds. Other parameters fixed at $\sin^2\theta_{23} = 0.5$, $\sin^2\theta_{13} = 0.040$ and $\Delta m^2_{\rm Atm} = 2.0 \cdot 10^{-3}$ eV^2.

Example of a low-scale seesaw model: inverse seesaw

Conventional type I seesaw: loop contribution of the heavy Majorana neutrinos to $\mu \to e\,\gamma$ are suppressed by the large Majorana masses and/or by the small Dirac couplings

$$m_\nu \sim Y_N \frac{1}{M_N} Y_N^T v^2 \qquad \Gamma(\mu \to e\gamma) \propto Y_N^4 \frac{m_\mu^5}{M_N^4} \text{ very suppressed!!}$$

Inverse seesaw:

example with n N_1 and n N_2: $L_{N_1} = +1\,,\ L_{N_2} = -1$

$$\begin{array}{c|ccc} & \nu_L & N_1 & N_2 \\ \hline \nu_L & 0 & Y_N \frac{v}{\sqrt{2}} & 0 \\ N_1 & Y_N \frac{v}{\sqrt{2}} & 0 & M_N \\ N_2 & 0 & M_N & 0 \end{array}$$

"inverse seesaw" as in
Mohapatra, Valle '86
Gonzalez-Garcia, Valle '89
Branco, Grimus, Lavoura '89
Kersten, Smirnov '07
Abada, Biggio, Bonnet, Gavela, T.H. '07

slide borrowed from Th. Hambye

if Y_N is large, M_N not too high:

$$Br(\mu \to e\gamma) \sim 10^{-11} \sim \text{experimental upper limit}$$

$$m_\nu = 0$$

no L violation

example with n N_1 and n N_2: $L_{N_1} = +1\,,\;\; L_{N_2} = -1$

$$\begin{array}{c c} & \begin{array}{ccc} \nu_L & N_1 & N_2 \end{array} \\ \begin{array}{c} \nu_L \\ N_1 \\ N_2 \end{array} & \begin{pmatrix} 0 & Y_N \frac{v}{\sqrt{2}} & 0 \\ Y_N \frac{v}{\sqrt{2}} & 0 & M_N \\ 0 & M_N & \mu \end{pmatrix} \end{array}$$

soft L breaking

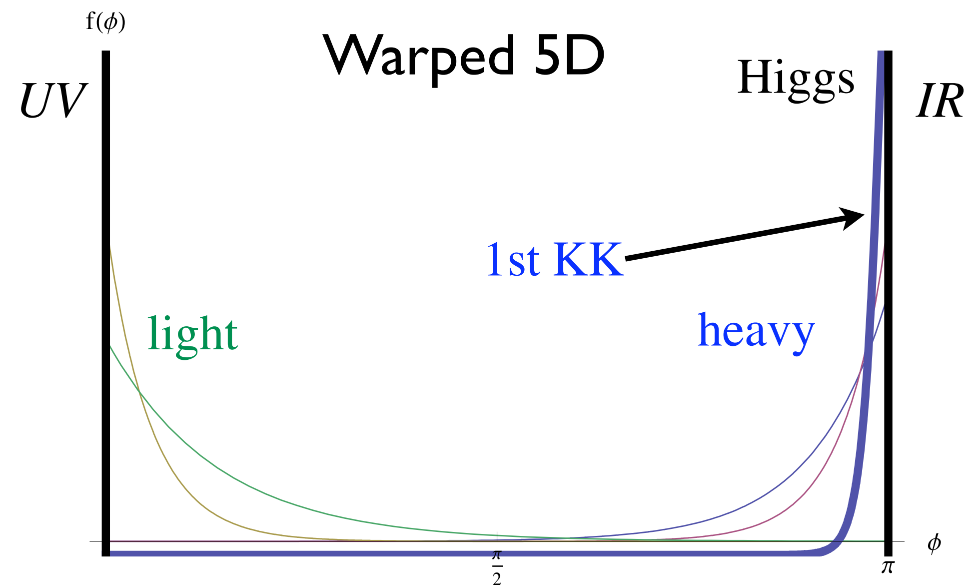
"inverse seesaw" as in
Mohapatra, Valle '86
Gonzalez-Garcia, Valle '89
Branco, Grimus, Lavoura '89
Kersten, Smirnov '07
Abada, Biggio, Bonnet, Gavela, T.H. '07

if Y_N is large, M_N not too high:

$$Br(\mu \to e\gamma) \sim 10^{-11} \sim \text{experimental upper limit}$$

$$m_\nu = -Y_N^T \frac{\mu}{M_N^2} Y_N\, v^2 \sim 0.1\,\text{eV}$$

LFV in extra-dimensional scenarios



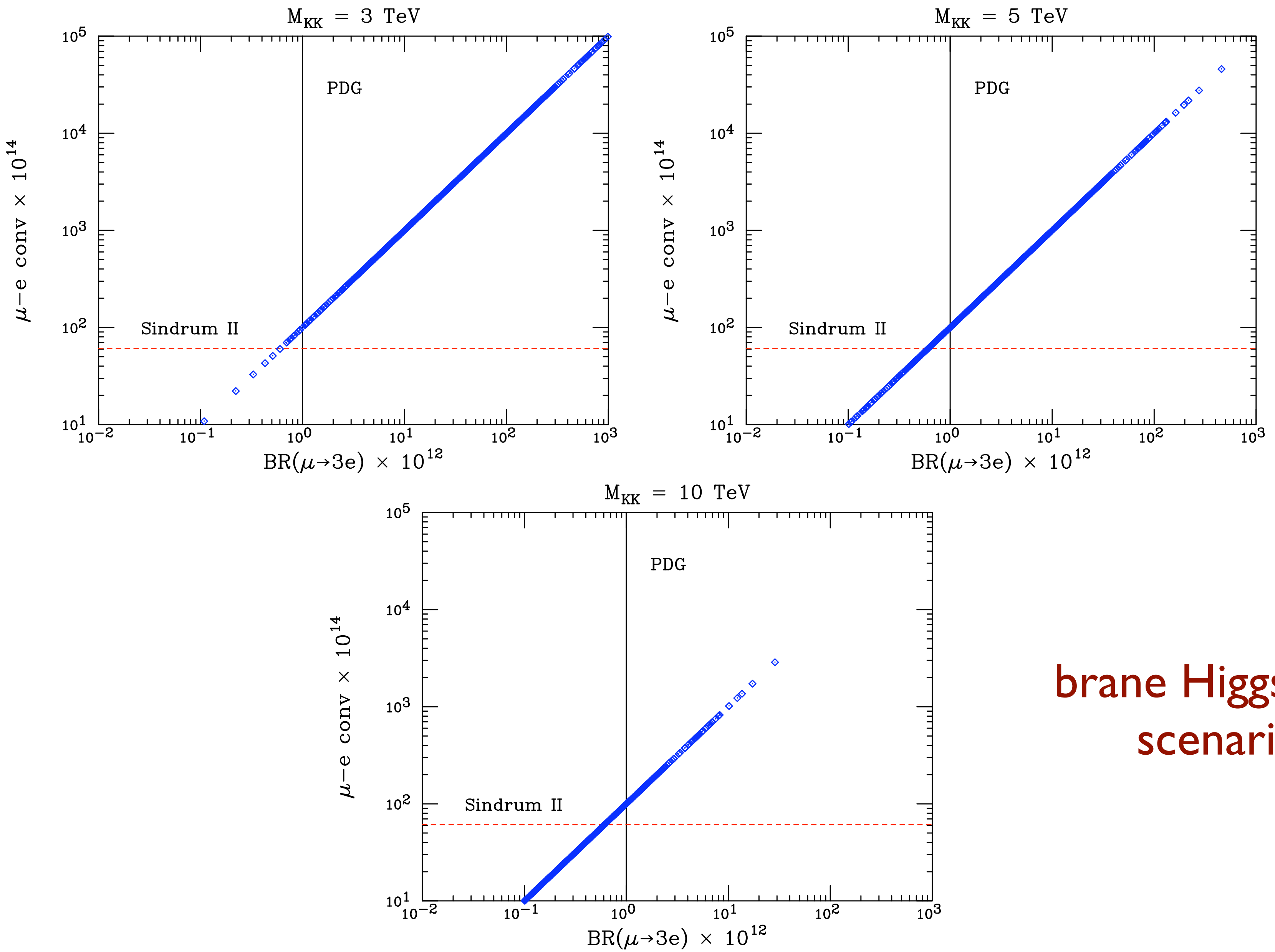
Source of flavour violation = couplings of light fermions to Kaluza-Klein excitations

Milder flavour violation in warped (Randal-Sundrum) models in which the fermion mass hierarchies are accounted for by different fermion localizations in extra dimensions (small overlap with KK wavefunction)

<u>Agashe, Blechman, Petriello</u>: RS model with Higgs propagating in the bulk ($l_i \to l_j \gamma$ UV sensitive if Higgs localized on the IR brane)

Present bounds on LFV processes compatible with O(1 TeV) KK masses, with however some tension between loop-induced $l_i \to l_j \gamma$ and tree-level $\mu \to e$ conversion [can be improved with different lepton reps (2009)]

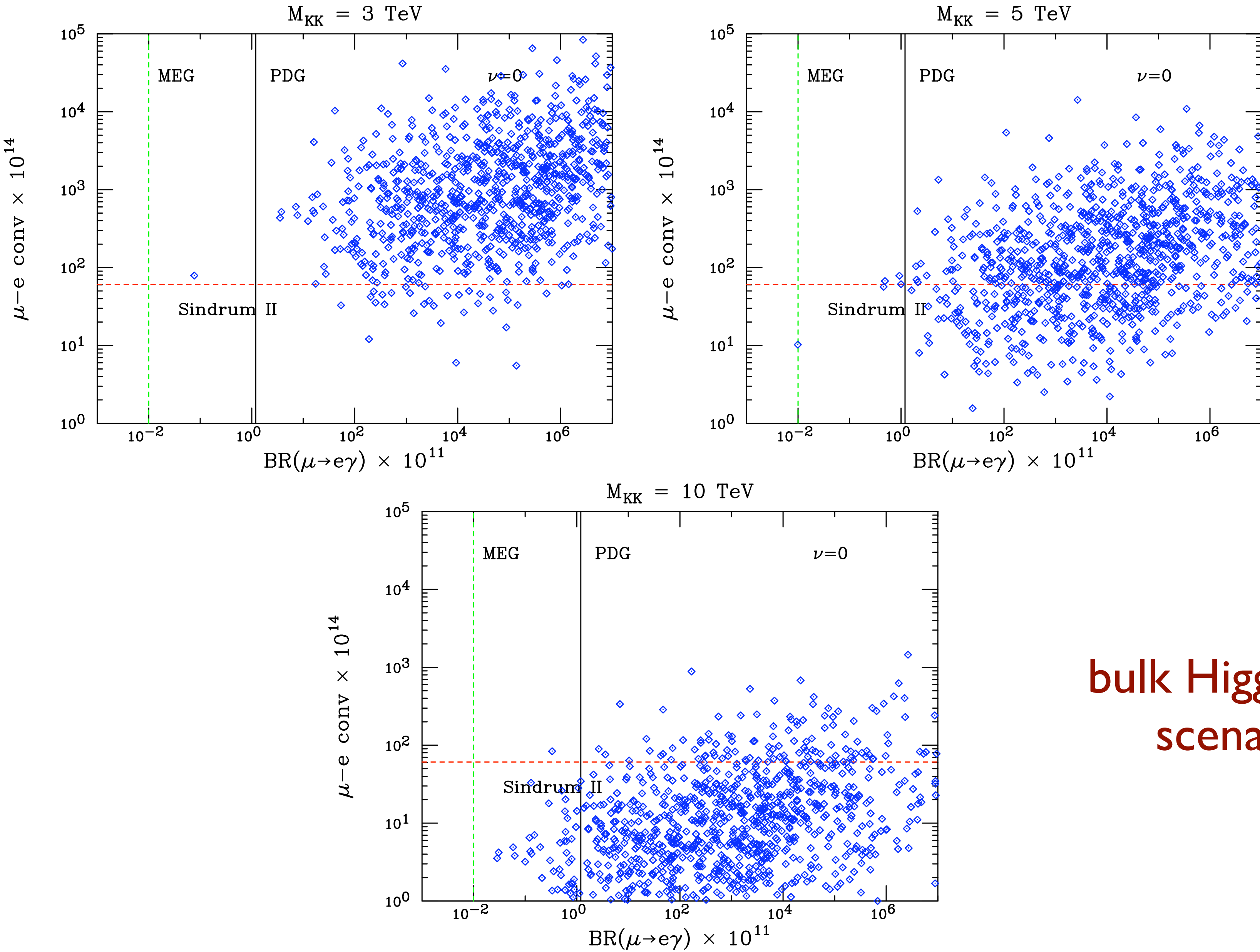
[Agashe, Blechman, Petriello]



brane Higgs field scenario

FIG. 4: Scan of the $\mu \to 3e$ and $\mu - e$ conversion predictions for $M_{KK} = 3, 5, 10$ TeV. The solid and dashed lines are the PDG and SINDRUM II limits, respectively.

[Agashe, Blechman, Petriello]



bulk Higgs field scenario

FIG. 6: Scan of the $\mu \to e\gamma$ and $\mu - e$ conversion predictions for $M_{KK} = 3, 5, 10$ TeV and $\nu = 0$. The solid line denotes the PDG bound on $BR(\mu \to e\gamma)$, while the dashed lines indicate the SINDRUM II limit on $\mu - e$ conversion and the projected MEG sensitivity to $BR(\mu \to e\gamma)$.

LFV in the littlest Higgs model with T-parity

Littlest Higgs model with T-parity (LHT) = model with a Higgs boson as a pseudo-Goldstone boson of a spontaneously broken global symmetry

The origin of LFV is the FV couplings of the mirror leptons to the SM leptons (via the heavy gauge bosons) = new flavour mixing matrices $V_{H\nu}$ and V_{Hl}, related by the PMNS matrix

Generally find large rate $\Rightarrow$ constraints on the mirror lepton parameters

After imposing these constraints, find correlations between LFV processses that differ from the MSSM expectations

Blanke, Buras, Duling, Recksiegel, Tarantino

Ratios of LFV Branching Ratios

BBDRT, 0903.xxxx

	LHT	MSSM
$\frac{Br(\mu^- \to e^- e^+ e^-)}{Br(\mu \to e\gamma)}$	0.02. . . 1	$\sim 6 \cdot 10^{-3}$
$\frac{Br(\tau^- \to e^- e^+ e^-)}{Br(\tau \to e\gamma)}$	0.04. . . 0.4	$\sim 1 \cdot 10^{-2}$
$\frac{Br(\tau^- \to \mu^- \mu^+ \mu^-)}{Br(\tau \to \mu\gamma)}$	0.04. . . 0.4	$\sim 2 \cdot 10^{-3}$ ❇
$\frac{Br(\tau^- \to e^- \mu^+ \mu^-)}{Br(\tau \to e\gamma)}$	0.04. . . 0.3	$\sim 2 \cdot 10^{-3}$ ❇
$\frac{Br(\tau^- \to \mu^- e^+ e^-)}{Br(\tau \to \mu\gamma)}$	0.04. . . 0.3	$\sim 1 \cdot 10^{-2}$

❇ can be significantly enhanced by Higgs contributions

Paradisi, hep-ph/0508054, hep-ph/0601100

Leptogenesis

- the baryon asymmetry of the Universe
- conditions for baryogenesis
- electroweak baryogenesis in the Standard Model
- leptogenesis

The baryon asymmetry of the Universe

The matter-antimatter asymmetry of the Universe is measured by the baryon-to-photon ratio:

$$\eta \equiv \frac{n_B}{n_\gamma} \simeq \frac{n_B - n_{\bar{B}}}{n_\gamma}$$

Since the photon density is not preserved in the early Universe, one also considers:

$$Y_B \equiv \frac{n_B - n_{\bar{B}}}{s}$$

s = entropy density = 7.04 n_γ today

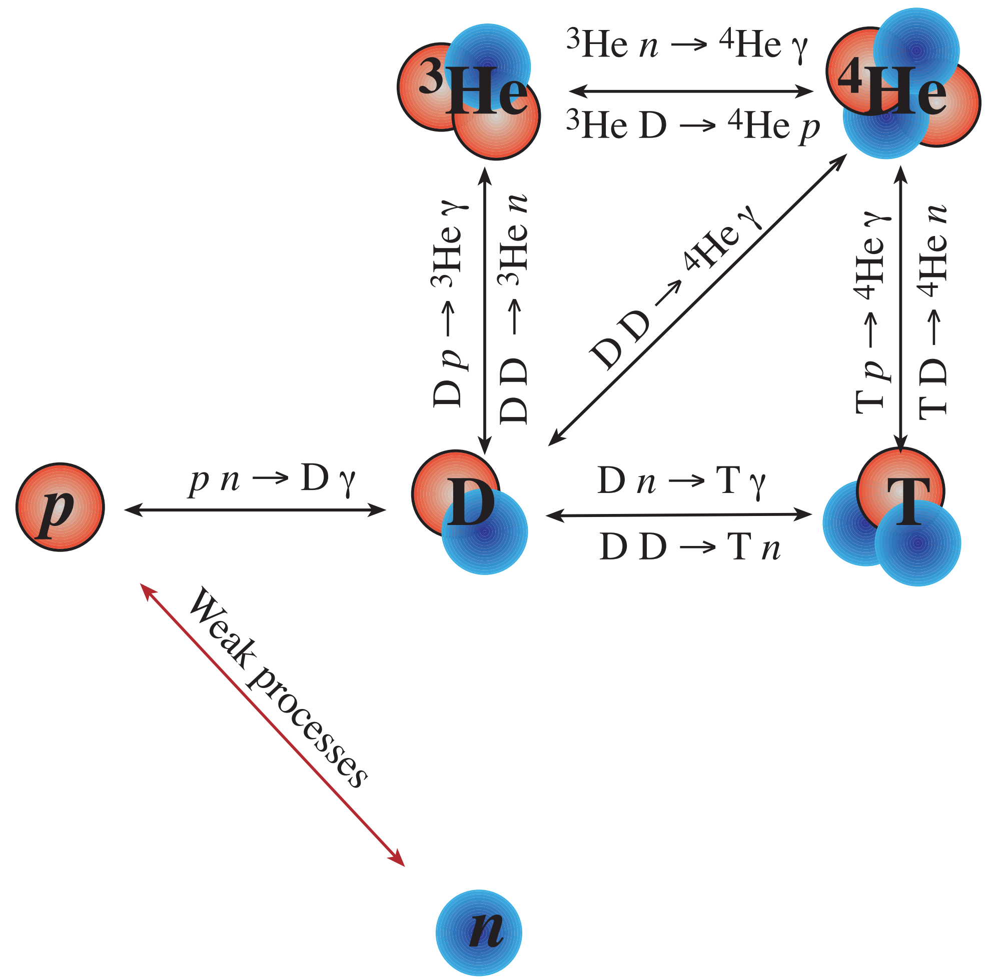
2 independent determinations of Y_B:

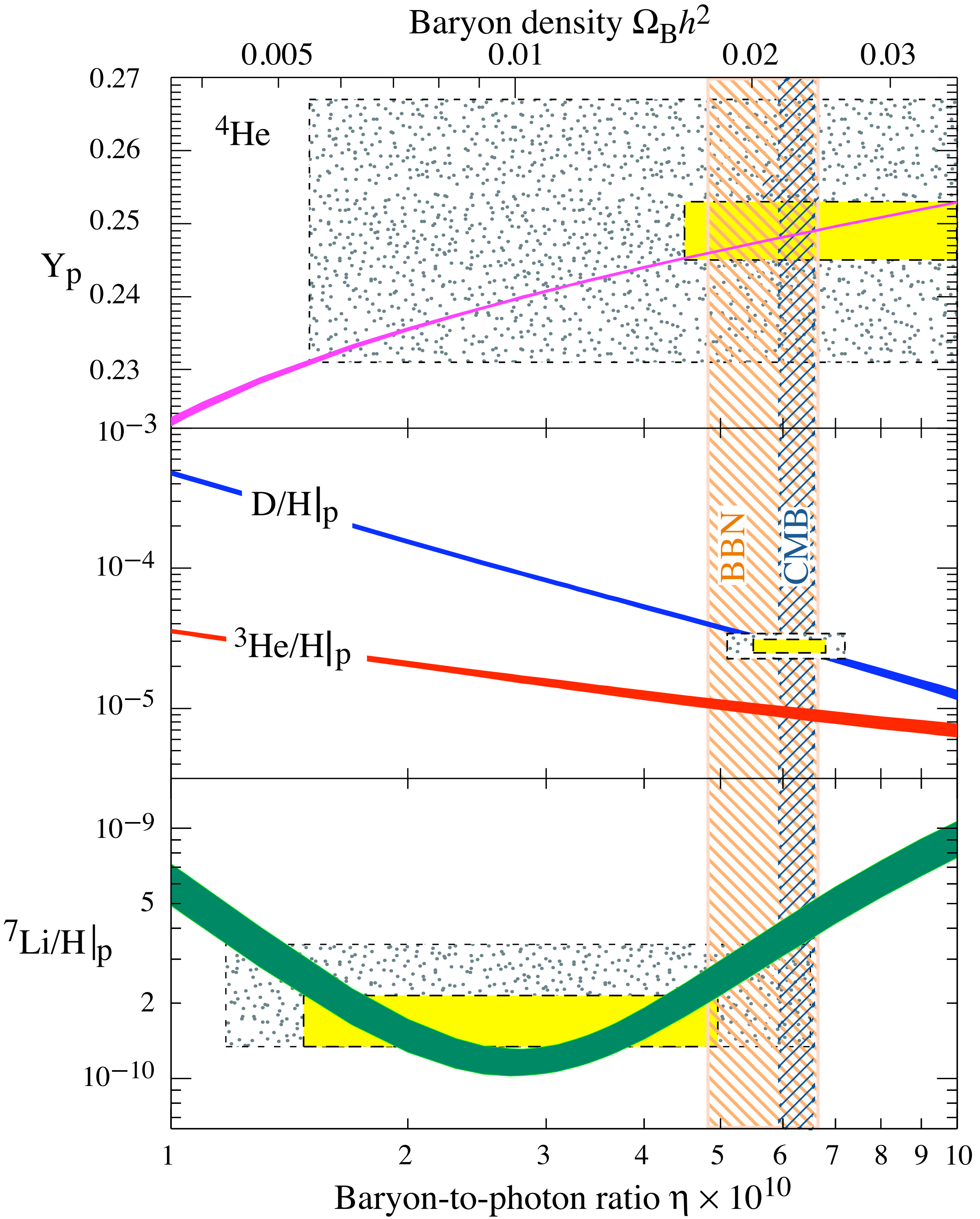
(i) light element abundances

(ii) anisotropies of the cosmic microwave background (CMB)

Big Bang nucleosynthesis predicts the abundances of the light elements (D, ^{3}He, ^{4}He and ^{7}Li) as a function of η:

The abundances of D and ^{3}He are very sensitive to η, since a larger η accelerates the synthesis of D and ^{3}He, which are themselves needed for the synthesis of ^{4}He, resulting in final lower abundances for D and ^{3}He

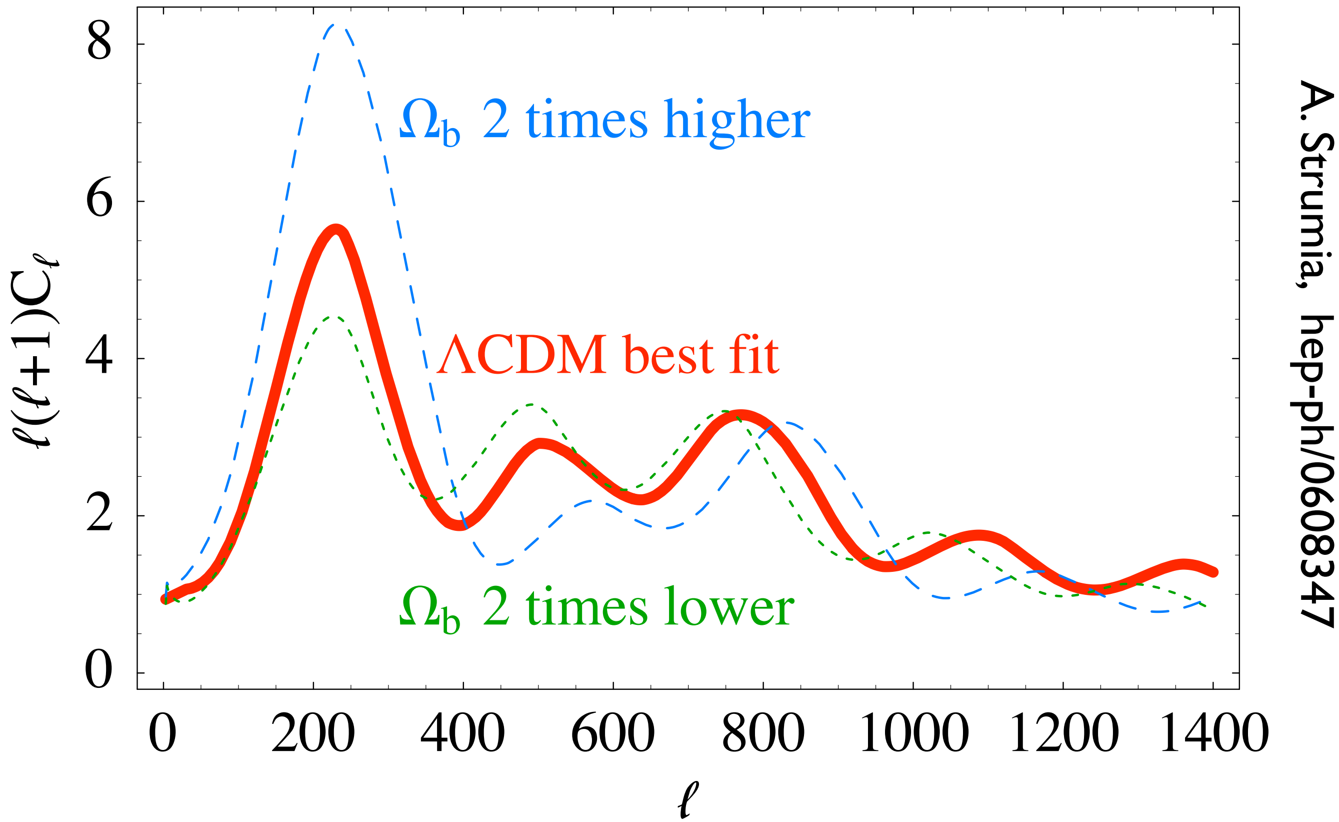




The fact that there is a range of values for η consistent with all observed abundances (“concordance”) is a major success of Big Bang cosmology

$$\eta = (4.7 - 6.5) \times 10^{-10}$$

- bands = 95% C.L.
- smaller boxes = ±2σ statistics
- larger boxes = ±2σ statistics and systematics



Information on the cosmological parameters can be extracted from the temperature anisotropies

In particular, the anisotropies are affected by the oscillations of the baryon-photon plasma before recombination, which depend on η (or $\Omega_b h^2$)

$$\Rightarrow \quad \eta = (6.23 \pm 0.17) \times 10^{-10} \;\; \text{(WMAP 5y)}$$

$\Rightarrow$ remarkable agreement between the CMB and BBN determinations of the baryon asymmetry: another success of standard Big Bang cosmology

$$\eta = (4.7 - 6.5) \times 10^{-10} \qquad \text{(BBN)}$$

$$\eta = (6.23 \pm 0.17) \times 10^{-10} \qquad \text{(WMAP 5y)}$$

Although this number might seem small, it is actually very large:

in a baryon-antibaryon symmetric Universe, annihilations would leave a relic abundance

$$n_B/n_\gamma = n_{\bar{B}}/n_\gamma \approx 5 \times 10^{-19}$$

The necessity of a dynamical generation

In a baryon-antibaryon symmetric Universe, annihilations would leave a relic abundance $n_B/n_\gamma = n_{\bar{B}}/n_\gamma \approx 5 \times 10^{-19}$

Since at high temperatures $n_q \sim n_{\bar{q}} \sim n_\gamma$, one would need to fine-tune the initial conditions in order to obtain the observed baryon asymmetry as a result of a small primordial excess of quarks over antiquarks:

$$\frac{n_q - n_{\bar{q}}}{n_q} \approx 3 \times 10^{-8}$$

Furthermore, our Universe most probably underwent a phase of inflation, which would have exponentially diluted the initial conditions

$\Rightarrow$ need a mechanism to dynamically generate the baryon asymmetry

Baryogenesis!

Conditions for baryogenesis

Sakharov's conditions [1967]:

(i) baryon number (B) violation
(ii) C and CP violation
(iii) departure from thermal equilibrium

(i) is obvious

(ii) C and CP violation

If C were conserved, any processes creating n baryons would occur at the same rate as the C-conjugated process creating n antibaryons, resulting in a vanishing net baryon asymmetry

C violation is not enough. If CP were conserved, even with C violated, processes creating baryons and antibaryons would balance each other once integrated over phase space

(iii) departure from thermal equilibrium

At thermal equilibrium, any process creating baryons occurs at the same rate than the inverse process which destroys baryons, resulting in a vanishing net baryon asymmetry

Quite remarkably, the Standard Model (SM) of particle physics satisfies all three Sakharov's conditions:

(i) B is violated by non-perturbative processes known as sphalerons

(ii) C and CP are violated by SM interactions
(CP violation due to the CKM phase)

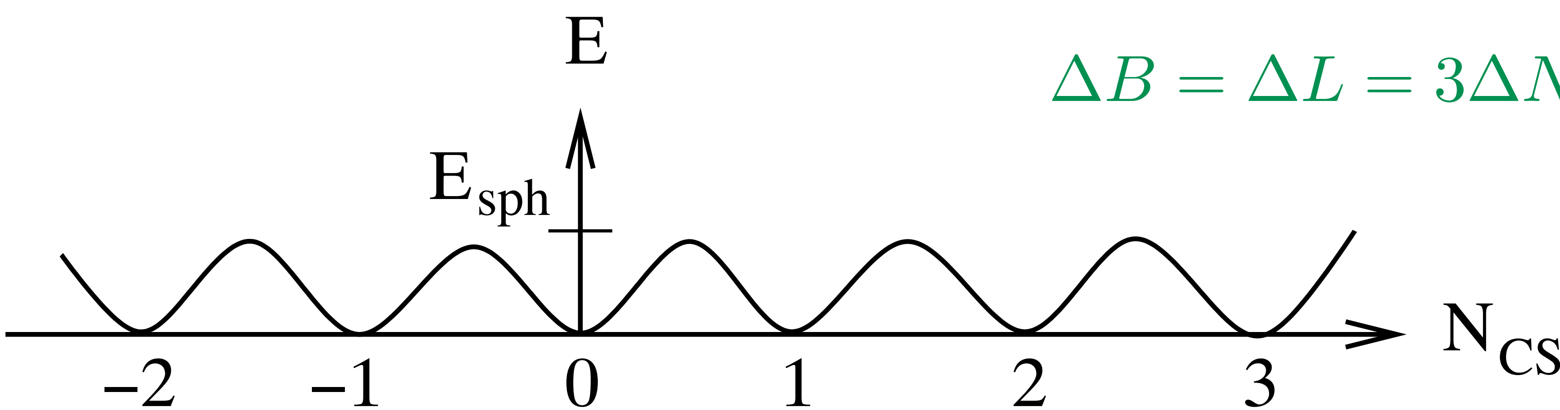
(iii) departure from thermal equilibrium can occur during the electroweak phase transition

→ ingredients of electroweak baryogenesis

Baryon number violation in the Standard Model

The baryon (B) and lepton (L) numbers are accidental global symmetries of the SM Lagrangian ⇒ all perturbative processes preserve B and L

However, B+L is violated at the quantum level (anomaly)
⇒ non-perturbative transitions between vacua of the electroweak theory characterized by different values of B+L [but B-L is conserved]



$$\Delta B = \Delta L = 3\Delta N_{CS}$$

At T=0, transitions by tunneling: $\Gamma(T=0) \sim e^{-16\pi^2/g^2} \sim 10^{-150}$ ['t Hooft]

⇒ extremely suppressed: no baryogenesis?

However, this is different at finite temperature

- above the electroweak phase transition [$T > T_{EW} \sim 100\,\mathrm{GeV}$],
  i.e. in the unbroken phase [$\langle\phi\rangle = 0$], (B+L) violation is unsuppressed:

$$\Gamma(T > T_{EW}) \sim \alpha_W^5 T^4 \qquad\qquad \alpha_W \equiv g^2/4\pi$$

[Kuzmin, Rubakov, Shaposhnikov]

- below the electroweak transition [$0 < T < T_{EW}, \langle\phi\rangle \neq 0$]:

$$\Gamma(T < T_{EW}) \propto e^{-E_{sph}(T)/T}$$

[Arnold, McLerran - Khlebnikov, Shaposhnikov]

where E_{sph} (T) is the energy of the gauge field configuration ("sphaleron") that interpolates between two vacua [Klinkhamer, Manton]

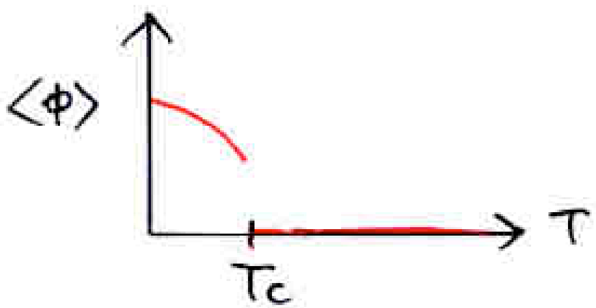
$\Rightarrow$ electroweak baryogenesis [=baryogenesis at the electroweak phase transition] becomes possible

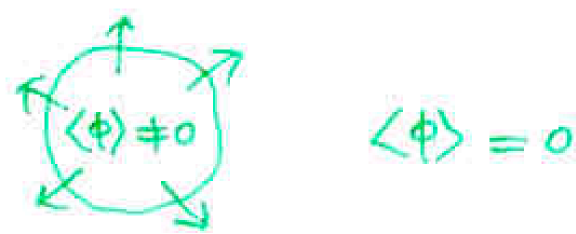
Baryogenesis in the Standard Model: rise and fall of electroweak baryogenesis

The order parameter of the electroweak phase transition is the Higgs vev:

- $T > T_{EW}, \langle\phi\rangle = 0$ unbroken phase
- $T < T_{EW}, \langle\phi\rangle \neq 0$ broken phase

If the phase transition is first order, the two phases coexist at $T = T_c$ and the phase transition proceeds via bubble nucleation





[Cohen, Kaplan, Nelson]

Sphalerons are in equilibrium outside the bubbles, and out of equilibrium inside the bubbles (rate exponentially suppressed by $E_{sph}(T) / T$)

CP-violating interactions in the wall together with unsuppressed sphalerons outside the bubble generate a B asymmetry which diffuses into the bubble

For the mechanism to work, it is crucial that sphalerons are suppressed inside the bubbles (otherwise will erase the generated B+L asymmetry)

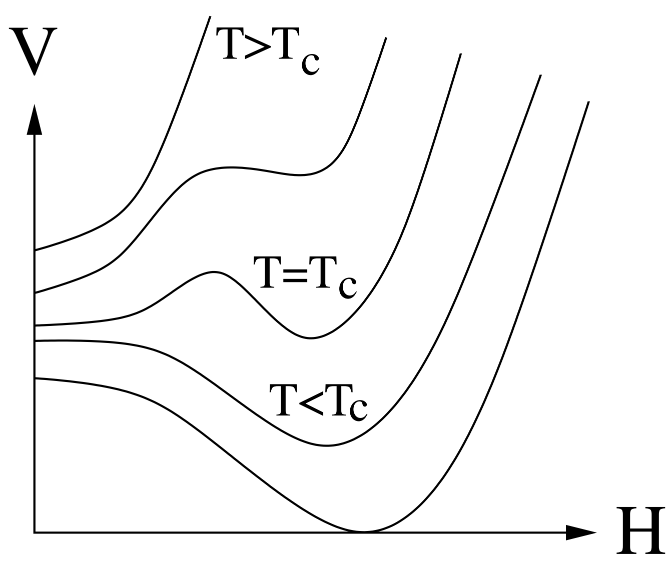
$$\Gamma(T < T_{EW}) \propto e^{-E_{sph}(T)/T} \quad \text{with} \quad E_{sph}(T) \approx (8\pi/g)\,\langle\phi(T)\rangle$$

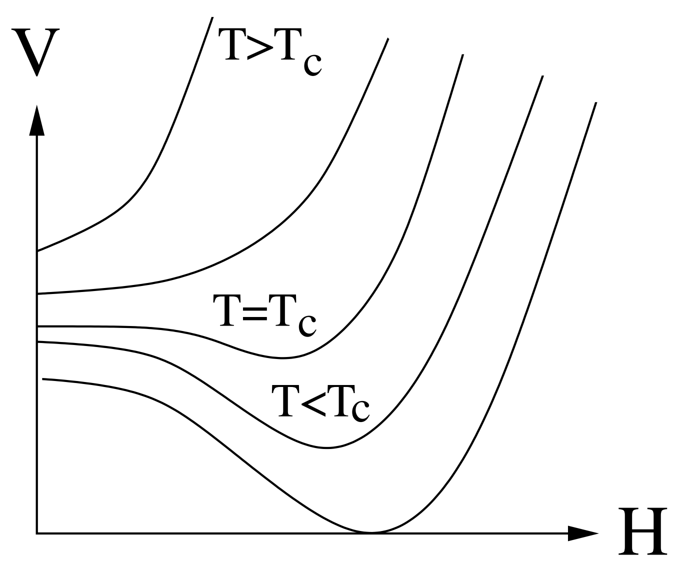
The out-of-equilibrium condition is

$$\frac{\langle\phi(T_c)\rangle}{T_c} \gtrsim 1$$

⇒ strongly first order phase transition required!

To determine whether this is indeed the case, need to study the 1-loop effective potential at finite temperature





To determine whether this is indeed the case, need to study the 1-loop effective potential at finite temperature. The out-of-equilibrium condition $\Phi(T_c)/T_c > 1$ then translates into:

$$m_H \lesssim 40\,\mathrm{GeV}$$ condition for a strong first order transition

$\Rightarrow$ <u>(standard) electroweak baryogenesis excluded by LEP</u>

It is also generally admitted that CP-violating effects are too small in the SM for successfull electroweak baryogenesis (small Jarlskog invariant)

[Gavela, Hernandez, Orloff, Pène]

$\Rightarrow$ standard electroweak baryogenesis fails: the observed baryon asymmetry requires new physics beyond the Standard Model

The observed baryon asymmetry requires new physics beyond the SM

⇒ 2 approaches:

1) modify the dynamics of the electroweak phase transition [+ new source of CP violation needed]

- MSSM with a light top squark (+ CP violation from the chargino sector)

- NMSSM, 2 Higgs doublet model...

- model-independent approach [Grojean, Servant, Wells]: add a Φ^6 term in the Higgs potential

2) generate a B-L asymmetry at $T > T_{EW}$, which is then converted into a baryon asymmetry by sphaleron processes

- GUT baryogenesis: out-of-equilibrium decays of heavy gauge bosons (however conflict with inflation)

- leptogenesis: generation of a lepton asymmetry in out-of-equilibrium decays of heavy states

- other mechanisms, e.g. Affleck-Dine

A link with neutrino masses: Baryogenesis via leptogenesis

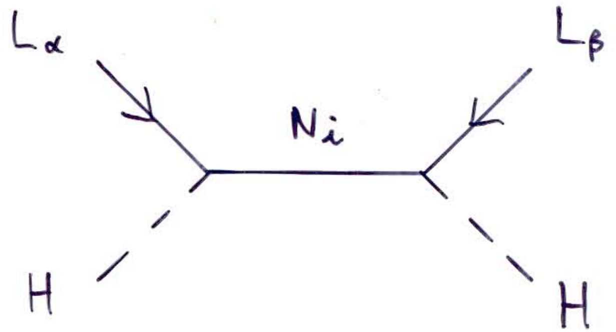
The observation of neutrino oscillations from different sources (solar, atmospheric and accelerator/reactor neutrinos) has led to a well-established picture in which neutrinos have tiny masses and there is flavour mixing in the lepton sector (as in the quark sector)

The tiny neutrino masses can be interpreted in terms of a high scale:

$$m_\nu = \frac{v_{EW}^2}{M} \qquad M \sim 10^{14}\,\mathrm{GeV}$$

Several mechanisms can realize this mass suppression. The most popular one (type I seesaw mechanism) involves heavy Majorana neutrinos:

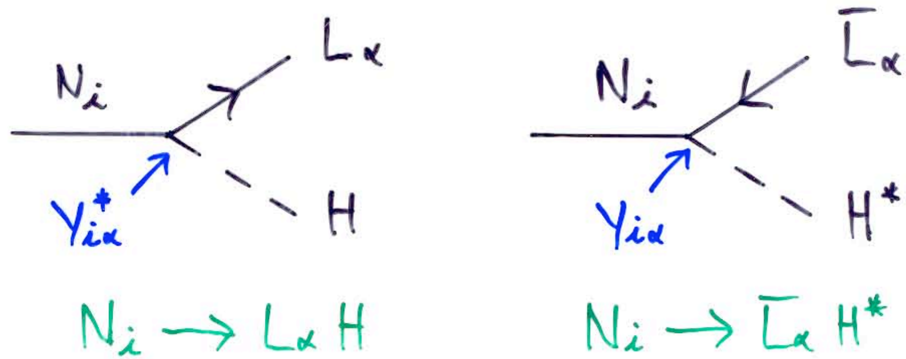
Minkowski - Gell-Mann, Ramond, Slansky
Yanagida - Glashow - Mohapatra, Senjanovic



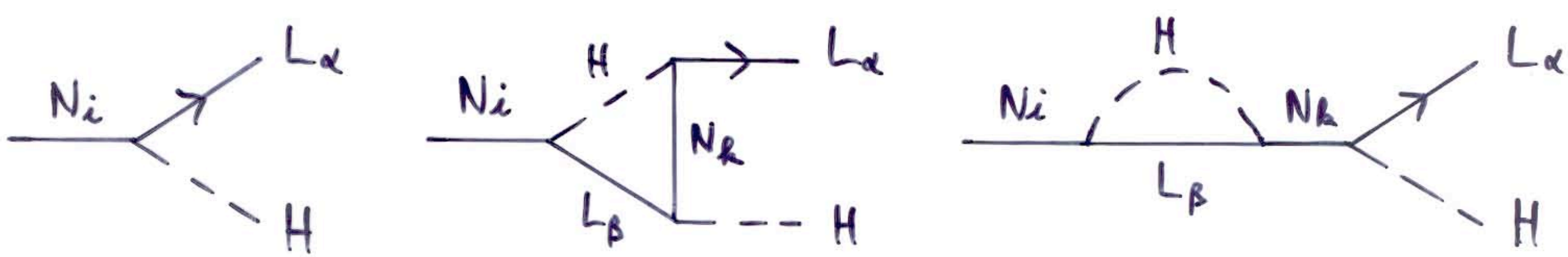
$$\Longrightarrow \qquad m_\nu \sim \frac{y^2 v^2}{M_R}$$

Interestingly, this mechanism contains all required ingredient for baryogenesis: out-of-equilibrium decays of the heavy Majorana neutrinos can generate a lepton asymmetry (L violation replaces B violation and is due to the Majorana masses) if their couplings to SM leptons violate CP

<u>CP violation</u>: being Majorana, the heavy neutrinos are CP-conjugated and can decay both into l^+ and into l^-



The decay rates into l^+ and into l^- differ due to quantum corrections

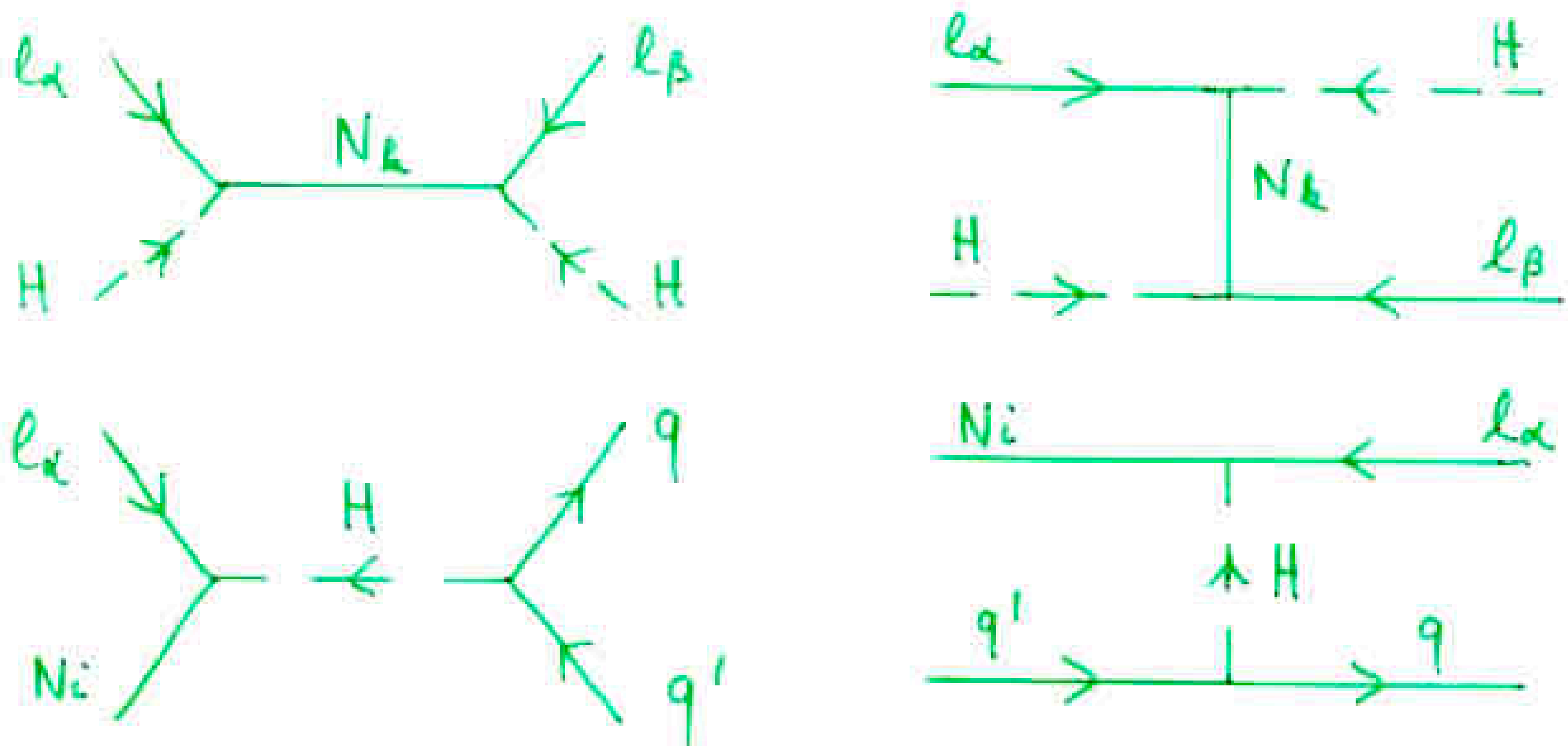


$$\Rightarrow \quad \Gamma(N_i \to LH) \neq \Gamma(N_i \to \bar{L}H^\star)$$

$\Gamma(N_i \to LH) \neq \Gamma(N_i \to \bar{L}H^\star)$ results in an asymmetry between leptons and antileptons, which is partially washed out by L-violating processes and converted into a baryon asymmetry by the sphalerons

⚠ "wash-out processes" [$\ell H \rightleftarrows \ell^c H^c$, $\ell N \rightleftarrows q \bar{q}'$]

éliminent l'asymétrie créée



⇒ doivent rester hors d'équilibre

$\Gamma(N_i \to LH) \neq \Gamma(N_i \to \bar{L}H^\star)$ results in an asymmetry between leptons and antileptons, which is partially washed out by L-violating processes and converted into a baryon asymmetry by the sphalerons

The final baryon asymmetry can be expressed as:

$$Y_B = -0.42\, C\, \frac{\eta\, \epsilon_{N_1}}{g_\star} = -1.4 \times 10^{-3}\, \eta\, \epsilon_{N_1} \quad \text{(SM)}$$

C = conversion factor by sphaleron (28/79 in the SM)

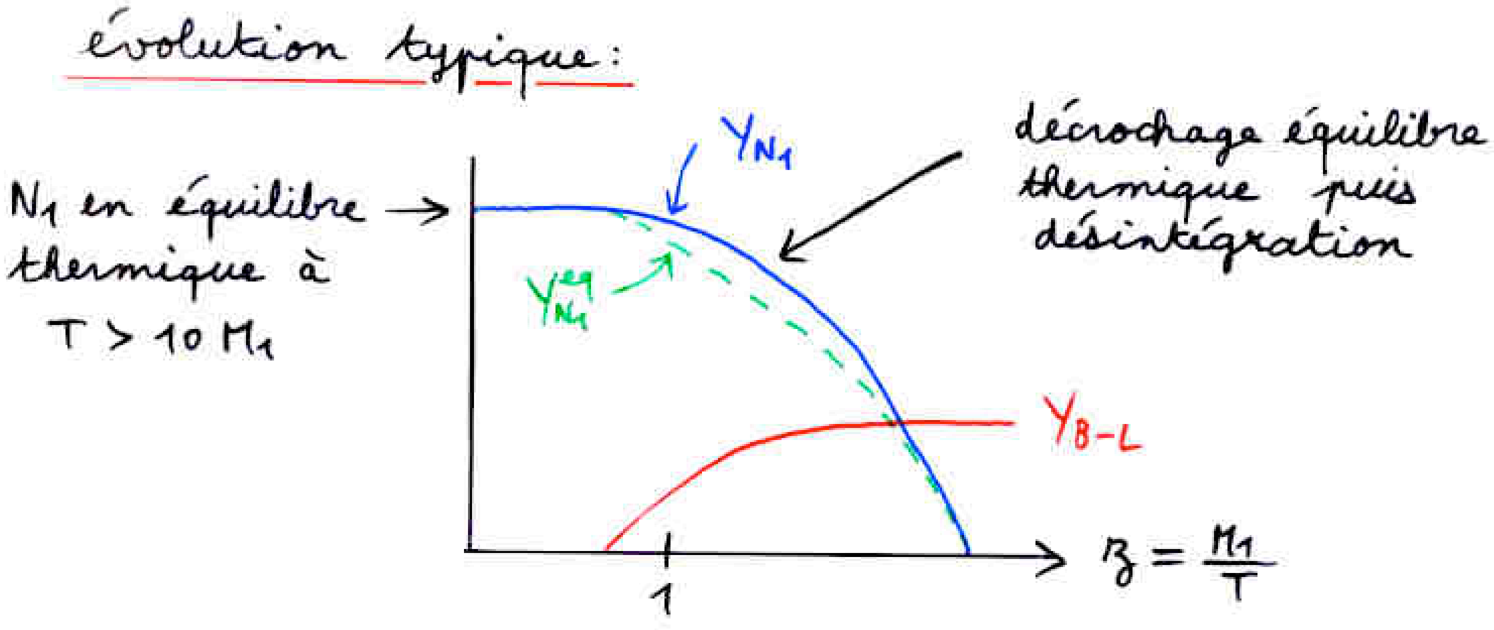
$$< Y_B >_T = C < Y_{B-L} >_T \qquad\qquad C = \frac{8N_f + 4N_H}{22N_f + 13N_H} = \frac{28}{79} \quad \text{(SM)}$$

g_* = total number of relativistic d.o.f. (g_* = 106.75 in the SM)

ε_{N_1} = CP asymmetry in N_1 decays

η = efficiency factor that takes into account the dilution of the lepton asymmetry by L-violating processes ($LH \to N_1,\ LH \leftrightharpoons \bar{L}H^\star \cdots$)

→ baryogenesis via leptogenesis



Can leptogenesis explain the observed baryon asymmetry?

$\Rightarrow$ must compare Y_B computed from leptogenesis with observed value

- η essentially depends on M_1 and on $\tilde{m}_1 \equiv (YY^\dagger)_{11} v^2 / M_1$, which controls the out-of-equ. decay condition / strength of washout processes:

$$\Gamma_{N_1} < H(T = M_1) \quad \Longleftrightarrow \quad \tilde{m}_1 < \tilde{m}_1^\star = 2.2 \times 10^{-3}\,\text{eV}$$

- ε_{N_1} depends on the N_i masses and couplings, but is bounded by a simple function of M_1, m_1, m_3 and $\tilde{m}_1$ [case $M_1 \ll M_2, M_3$]:

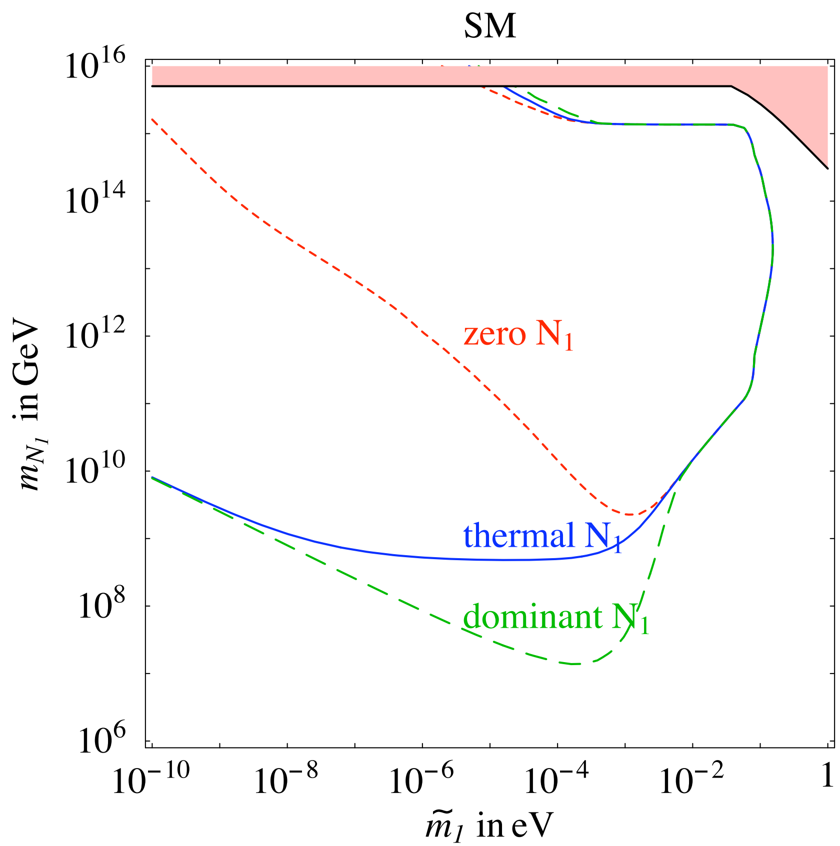
$$|\epsilon_{N_1}| \leq \frac{3}{16\pi} \frac{M_1 (m_3 - m_1)}{v^2} f\left(\frac{m_1}{\tilde{m}_1}\right) \qquad 0 \leq f\left(\frac{m_1}{\tilde{m}_1}\right) \leq 1$$

Davidson, Ibarra
Hambye et al.

The requirement that leptogenesis generates the observed baryon asymmetry puts constraints on the seesaw parameters:

Case $M_1 \ll M_2, M_3$

[Giudice et al., hep-ph/0310123]



$\Rightarrow M_1 \geq (0.5 - 2.5) \times 10^9\,\mathrm{GeV}$ depending on the initial conditions

[Davidson, Ibarra]

Case $M_1 \approx M_2$: if $|M_1 - M_2| \sim \Gamma_2$, the self-energy part of ε_{N_1} has a resonant behaviour, and $M_1 \ll 10^9\,\mathrm{GeV}$ is compatible with successful leptogenesis ("resonant leptogenesis") [Covi, Roulet, Vissani - Pilaftsis]

peut-on tester expérimentalement la leptogénèse ?

- Y_B dépend de $\epsilon_1 \propto \sum_{k=2,3} \frac{\mathrm{Im}\left[(YY^\dagger)^2_{k1} \right]}{(YY^\dagger)_{11}} \frac{M_1}{M_k}$

  → sensible aux phases de $YY^\dagger$

- CP à basse énergie (oscillations, $(\beta\beta)_{0\nu}$) :

  → phases de U_{MNS} $\begin{cases} \delta \to \text{oscillations} \\ \phi_2, \phi_3 \to (\beta\beta)_{0\nu} \end{cases}$

  → sont-elles reliées ?

réponse :

$$Y = \underbrace{\begin{pmatrix} \sqrt{M_1} & & \\ & \sqrt{M_2} & \\ & & \sqrt{M_3} \end{pmatrix}}_{3 \text{ masses } N_R} R \underbrace{\begin{pmatrix} \sqrt{m_1} & & \\ & \sqrt{m_2} & \\ & & \sqrt{m_3} \end{pmatrix} U^\dagger}_{9 \text{ paramètres basse énergie}}$$

(Casas, Ibarra)

Y : base où M_e, M_R diag.

R complexe, $R^T R = 1 \Rightarrow$ 3 param. complexes

→ leptogénèse : $YY^\dagger = \begin{pmatrix} \sqrt{M_1} & & \\ & \sqrt{M_2} & \\ & & \sqrt{M_3} \end{pmatrix} R \begin{pmatrix} m_1 & & \\ & m_2 & \\ & & m_3 \end{pmatrix} R^\dagger \begin{pmatrix} \sqrt{M_1} & & \\ & \sqrt{M_2} & \\ & & \sqrt{M_3} \end{pmatrix}$

$\Rightarrow \epsilon_i \longleftrightarrow$ phases de R

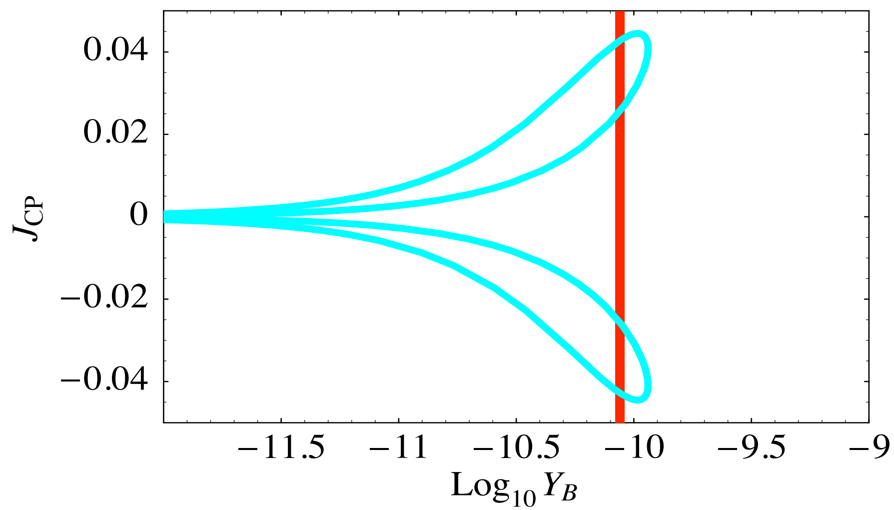
→ dans le cadre du Modèle Standard (ou du MSSM), leptogénèse indépendante de CP à basse énergie

However, if lepton flavour effects play an important role, the high-energy and low-energy phases both contribute to the CP asymmetry and cannot be disentangled. Leptogenesis possible even if all high-energy phases (R) vanish

Asymmetry in the flavour lα:

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

leptogenesis from PMNS phase δ



[Pascoli, Petcov, Riotto]

FIG. 1. The invariant $J_{\rm CP}$ versus the baryon asymmetry varying (in blue) $\delta = [0, 2\pi]$ in the case of hierarchical RH neutrinos and NH light neutrino mass spectrum for $s_{13} = 0.2$, $\alpha_{32} = 0$, $R_{12} = 0.86$, $R_{13} = 0.5$ and $M_1 = 5 \times 10^{11}$ GeV . The red region denotes the 2σ range for the baryon asymmetry.

cependant, dans des théories / modèles plus contraints, les phases de U et de R peuvent être reliées

exemple (ad hoc) : seesaw avec 2 N_R

(Frampton, Glashow, Yanagida - Endoh et al.)

$$M_R = \begin{pmatrix} M_1 & 0 \\ 0 & M_2 \end{pmatrix} \qquad Y = \begin{pmatrix} Y_{11} & Y_{12} & Y_{13} \\ Y_{21} & Y_{22} & Y_{23} \end{pmatrix}$$

$$Y = P_R V_R^T \begin{pmatrix} 0 & y_2 & 0 \\ 0 & 0 & y_3 \end{pmatrix} P_L V_L$$

P_R → 1 phase ϕ_R ; P_L → 1 phase ϕ_L ; V_L → 1 phase δ_L

→ 3 phases :
- leptogenèse ↔ ϕ_R
- U : 2 phases ($m_1 = 0$) ↔ ϕ_R, ϕ_L, δ_L

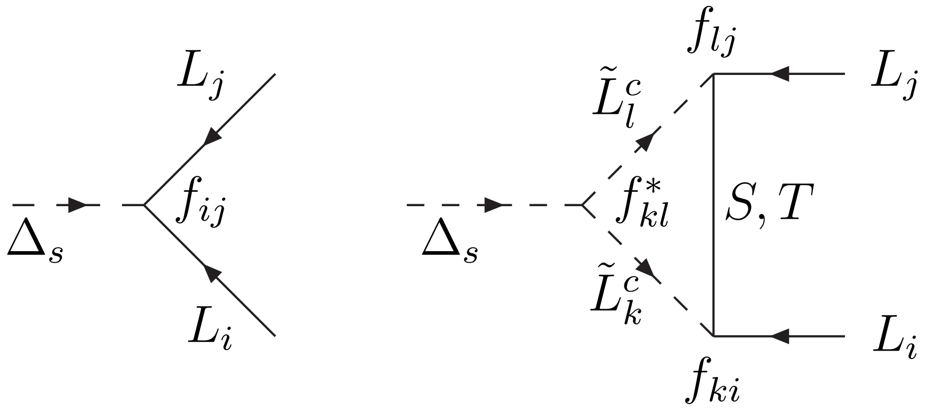
→ cas $Y_{21} = Y_{13} = 0$: Y contient une seule phase

⇒ la même phase contribue à Y_B et J (signes de Y_B et J corrélés)

→ " modèle de seesaw minimal " (juste assez de paramètres pour reproduire les données et autoriser $\not{CP}$)

A theoretically more motivated possibility [Calibbi, Frigerio, SL, Romanino]:
SO(10) models with non-standard embedding of SM matter (16 and 10)

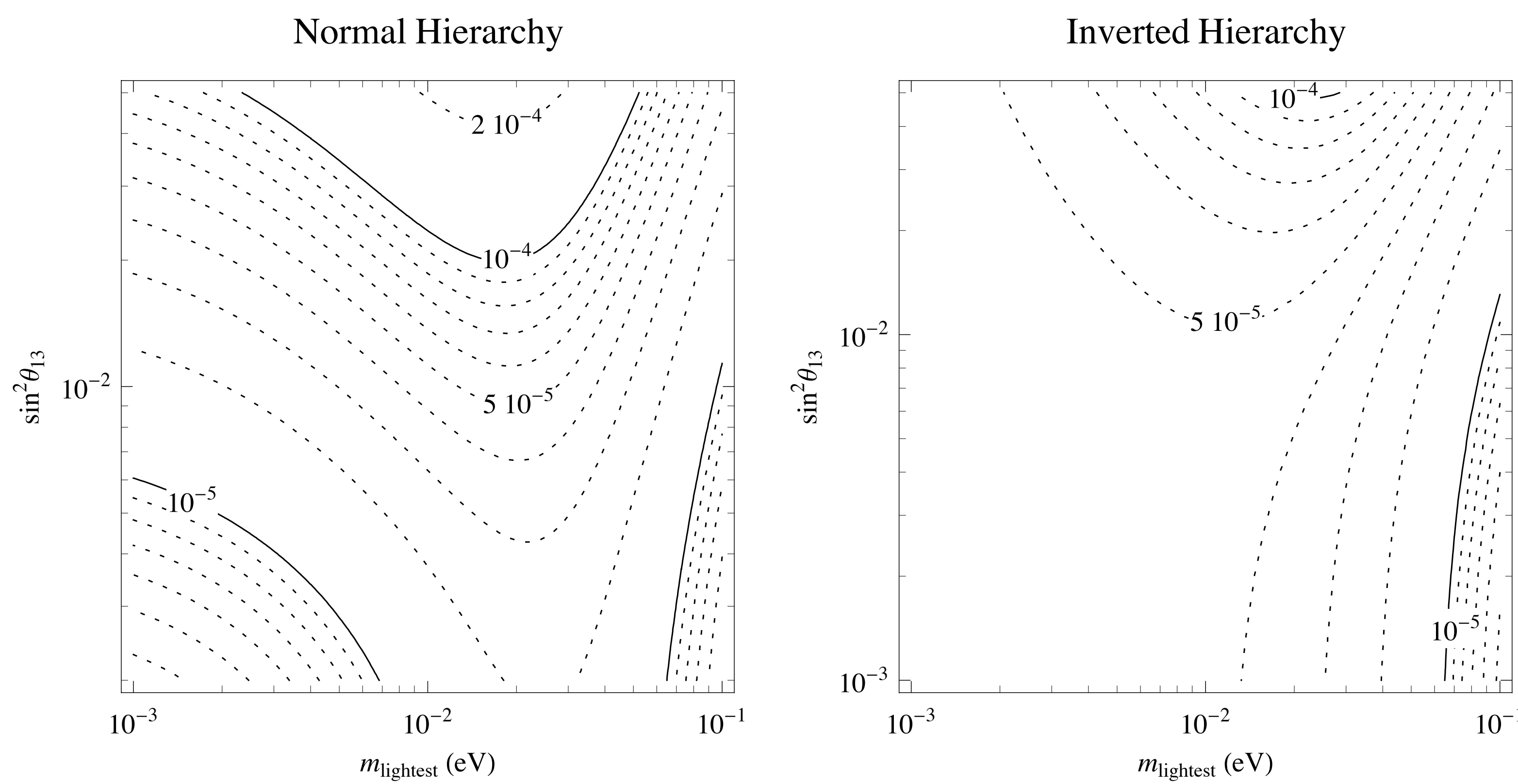
Neutrino masses and leptogenesis from a type II seesaw mechanism (heavy scalar $SU(2)_L$ triplet)



$$\epsilon_\Delta \simeq \frac{1}{10\pi} \frac{M_\Delta}{M_{24}} \frac{\lambda_L^4}{\lambda_L^2 + \lambda_{L_1^c}^2 + \lambda_{H_u}^2 + \lambda_{H_d}^2} \frac{\mathrm{Im}[M_{11}(M^* M M^*)_{11}]}{(\sum_i m_i^2)^2}$$

$$\frac{\mathrm{Im}[M_{11}(M^* M M^*)_{11}]}{\overline{m}^4} = -\frac{1}{\overline{m}^4} \Big\{ c_{13}^4 c_{12}^2 s_{12}^2 \sin(2\rho)\, m_1 m_2 \Delta m_{21}^2$$
$$+ c_{13}^2 s_{13}^2 c_{12}^2 \sin 2(\rho - \sigma)\, m_1 m_3 \Delta m_{31}^2 - c_{13}^2 s_{13}^2 s_{12}^2 \sin(2\sigma)\, m_2 m_3 \Delta m_{32}^2 \Big\}$$

$$U_{ei} = (c_{13} c_{12} e^{i\rho}, c_{13} s_{12}, s_{13} e^{i\sigma})$$



Isocontours of the CP asymmetry in units of λ_L^2 in the $(\sin^2\theta_{13}, m_{\text{lightest}})$ plane, maximized with respect to the CP-violating phases and to M_Δ/M_{24}

Conclusion: in general, leptogenesis depends both on high-energy and low-energy (i.e. PMNS) phases, thanks to lepton flavour effects.

Low-energy CP violation in the lepton sector is not a necessary condition for leptogenesis

Still leptogenesis would gain support from:

- observation of neutrinoless double beta decay: $(A,Z) \to (A,Z+2)\, e^- e^-$ [proof of the Majorana nature of neutrinos - necessary condition]

- observation of CP violation in the lepton sector, e.g. in neutrino oscillations [not necessary though]

- experimental exclusion of new physics electroweak baryogenesis scenarios [e.g. MSSM without a light stop and/or small CP violation in the chargino sector]

Back-up slides

In the context of Grand Unification, other heavy states may induce flavour violation in the slepton (and in the squark) sector [Barbieri, Hall, Strumia]

e.g. minimal SU(5) with type I seesaw: coloured Higgs triplets couple to RH quarks and leptons with the same Yukawa couplings as the Higgs doublets

$$\frac{1}{2}Y^u_{ij}Q_iQ_jH_c + Y^u_{ij}\overline{U}_i\overline{E}_jH_c + Y^d_{ij}Q_iL_j\overline{H}_c + Y^d_{ij}\overline{U}_i\overline{D}_j\overline{H}_c + Y^\nu_{ij}\overline{D}_i\overline{N}_jH_c$$

$\Rightarrow$ potentially large radiative corrections to the soft terms of the singlet squarks and sleptons (absent in the MSSM at leading order); in particular, comtributions to $(m^2_{\tilde{e}})_{ij}$ controlled by the top Yukawa:

$$(m^2_{\tilde{e}})_{ij} \;\simeq\; -\mathrm{e}^{i\varphi_{d_{ij}}}V_{3i}V^\star_{3j}\,\frac{3Y_t^2}{(4\pi)^2}\,(3m_0^2 + A_0^2)\,\log\left(\frac{M_G^2}{M^2_{H_c}}\right)$$

and contributions to $(m^2_{\tilde{d}})_{ij}$ controlled by the RHN couplings $\Rightarrow$ correlation between leptonic and hadronic flavour violations [Hisano, Shizimu - Ciuchini et al.]

$$(m^2_{\tilde{d}})_{23} \;\simeq\; \mathrm{e}^{i\varphi_{d_{23}}}(m_{\tilde{L}^2})^*_{23}\left(\log\frac{M_G^2}{M^2_{H_c}}\Big/\log\frac{M_G^2}{M^2_{N_3}}\right)$$

Similar effects (although of different origin) in SO(10) models with type II seesaw [Calibbi, Frigerio, SL, Romanino, in progress]

Since radiative corrections to slepton soft terms are large, interfere with possible non-universal contributions from supersymmetry breaking (different from quark sector)

⇒ difficult to disentangle them, unless correlations characteristic of a given scenario are observed

An interesting scenario: type II seesaw with the triplet [extended to a (15, 15*) of SU(5)] mediating supersymmetry breaking [Joaquim, Rossi]

$$W_{(15,\overline{15})} \;=\; \frac{1}{\sqrt{2}}(Y_{15}\,\bar{5}\,15\,\bar{5} + \lambda\,5_H\,\overline{15}\,5_H) + \xi\,X\,15\,\overline{15}$$

$$\langle X\rangle \;=\; \langle S_X\rangle + \langle F_X\rangle\theta^2 \quad \Rightarrow \quad \xi\langle X\rangle \;=\; M_{15} - B_{15}M_{15}\theta^2$$

⇒ gauge and Yukawa-mediated supersymmetry breaking (controlled by gauge couplings and $Y_{15} = Y_T$)

⇒ soft terms determined by M_{15}, B_{15} [the F_X / X of gauge mediation], Y_{15} and λ : predictive scenario (can trade Y_{15} for the neutrino mass matrix)

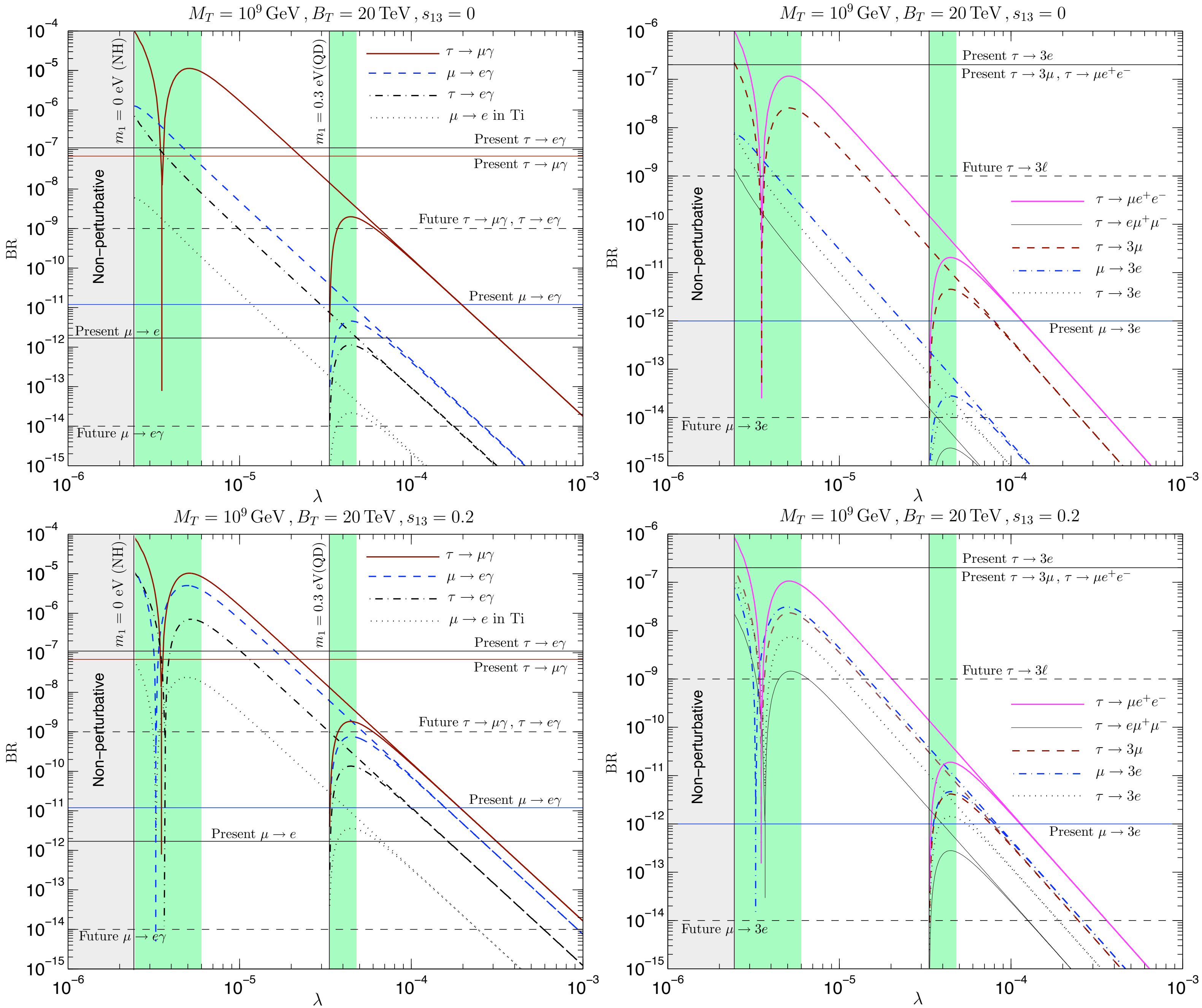


Fig. 5.28: Branching ratios of several LFV processes as a function of λ. The left (right) vertical line indicates the lower bound on λ imposed by requiring perturbativity of the Yukawa couplings $Y_{T,S,Z}$ when $m_1 = 0\,(0.3)$ eV [normal-hierarchical (quasi-degenerate) neutrino mass spectrum]. The regions in green (grey) are excluded by the $m_{\tilde{\ell}_1} > 100$ GeV constraint (perturbativity requirement when $m_1 = 0$).

[Joaquim, Rossi]

Leptogenesis and Unification

Right-handed neutrinos are suggestive of SO(10) unification:

(i) $\mathbf{16} \;=\; (Q, \bar{u}, \bar{d}, L, \bar{e}) \oplus \bar{N}$

(ii) B-L is a generator of SO(10) $\Rightarrow$ the mass scale of the N_R is associated with the breaking of the gauge group $\Rightarrow$ $M_R >> M_{weak}$ natural

However, successful leptogenesis is not so easy to achieve in SO(10) models with a type I seesaw mechanism:

$M_D \propto M_u \Rightarrow$ very hierarchical right-handed neutrino masses

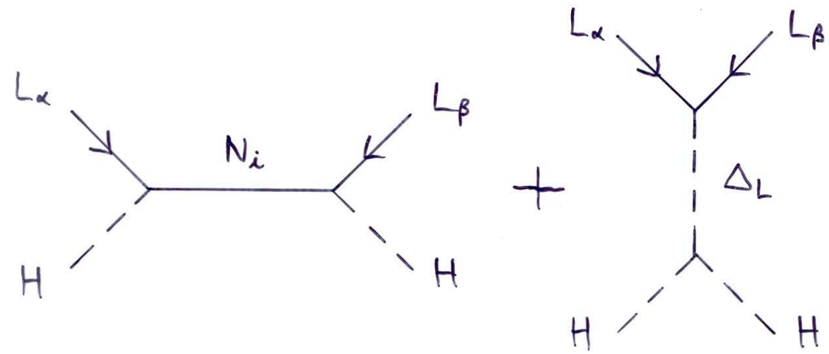
$\Rightarrow M_1 << 10^8$ GeV , below the Davidson-Ibarra bound

Ways out:

- flavour-dependent N_2 leptogenesis [Vives]: N_2 decays generate an asymmetry in a lepton flavour that is only mildly washed out by N_1
- large corrections to $M_D = M_u$
- other versions of the seesaw mechanism: type II (heavy scalar $SU(2)_L$ triplet exchange), type I + II (left-right symmetric seesaw mechanism)

SO(10) models with a left-right symmetric seesaw

Type I+II seesaw mechanism:



Δ_L = SU(2)$_L$ triplet with couplings f_{Lij} to lepton doublets

$$M_\nu \;=\; \frac{\lambda v^2}{M_\Delta} f_L - \frac{v^2}{v_R} Y^T f_R^{-1} Y$$

v_R = scale of B-L breaking (NR mass matrix: $M_R \;=\; f_R v_R$)

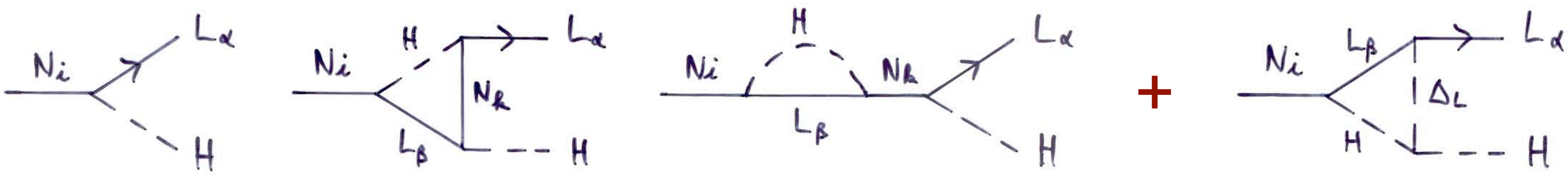
In a broad class of theories with underlying left-right symmetry (such as SO(10) with a $\overline{126}_H$), one has $Y = Y^T$ and $f_L = f_R \equiv f$:

$$M_\nu \;=\; v_L\, f - \frac{v^2}{v_R} Y f^{-1} Y$$

→ left-right symmetric seesaw mechanism

In explicit SO(10) models, Y is related to charged fermion Yukawa couplings
⇒ predictive framework

The $SU(2)_L$ triplet also contributes to leptogenesis. If $M_1 \ll M_\Delta$, it mainly affects leptogenesis by contributing to the CP asymmetry in N_1 decays:

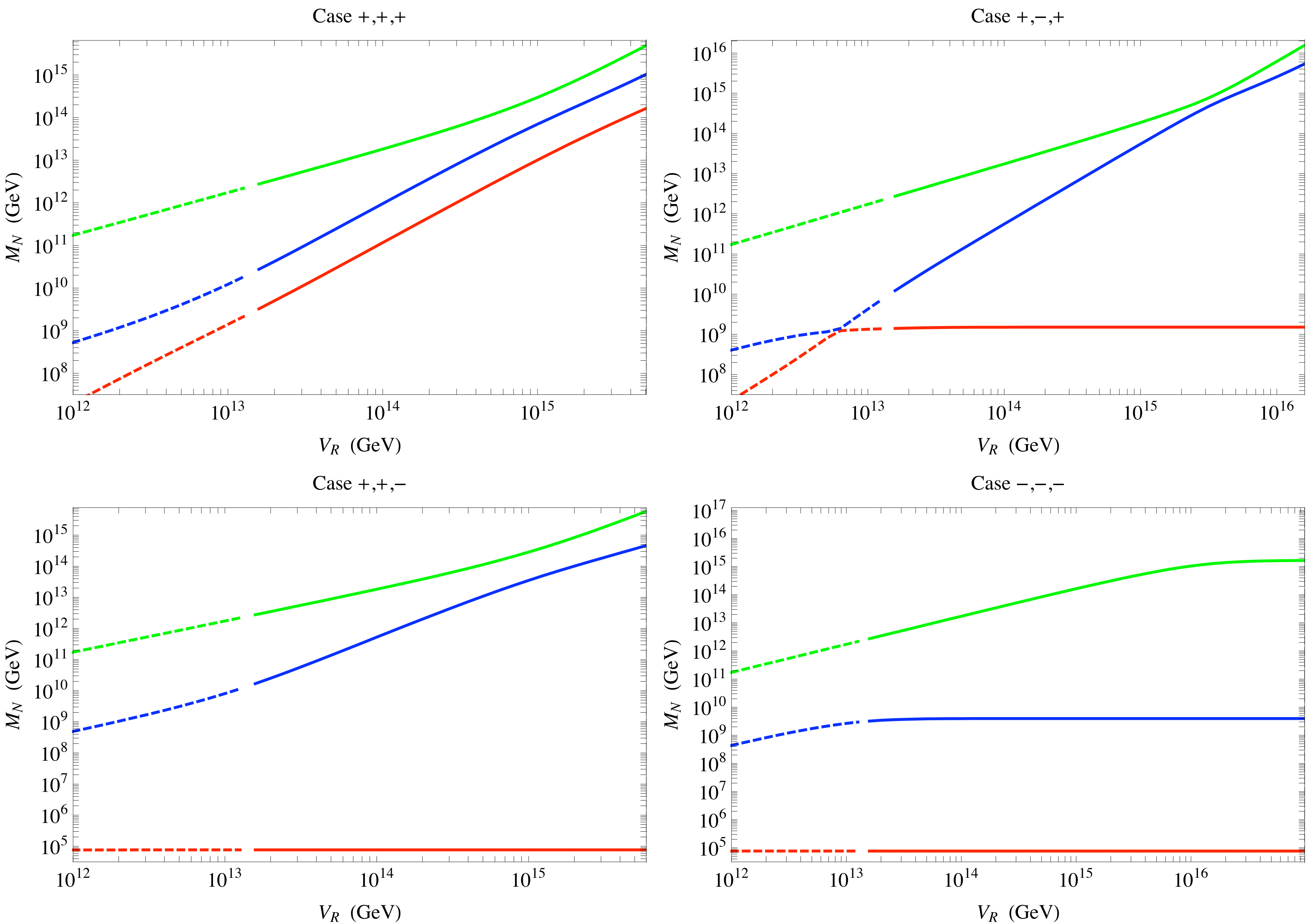


Hambye, Senjanovic – Antusch, King

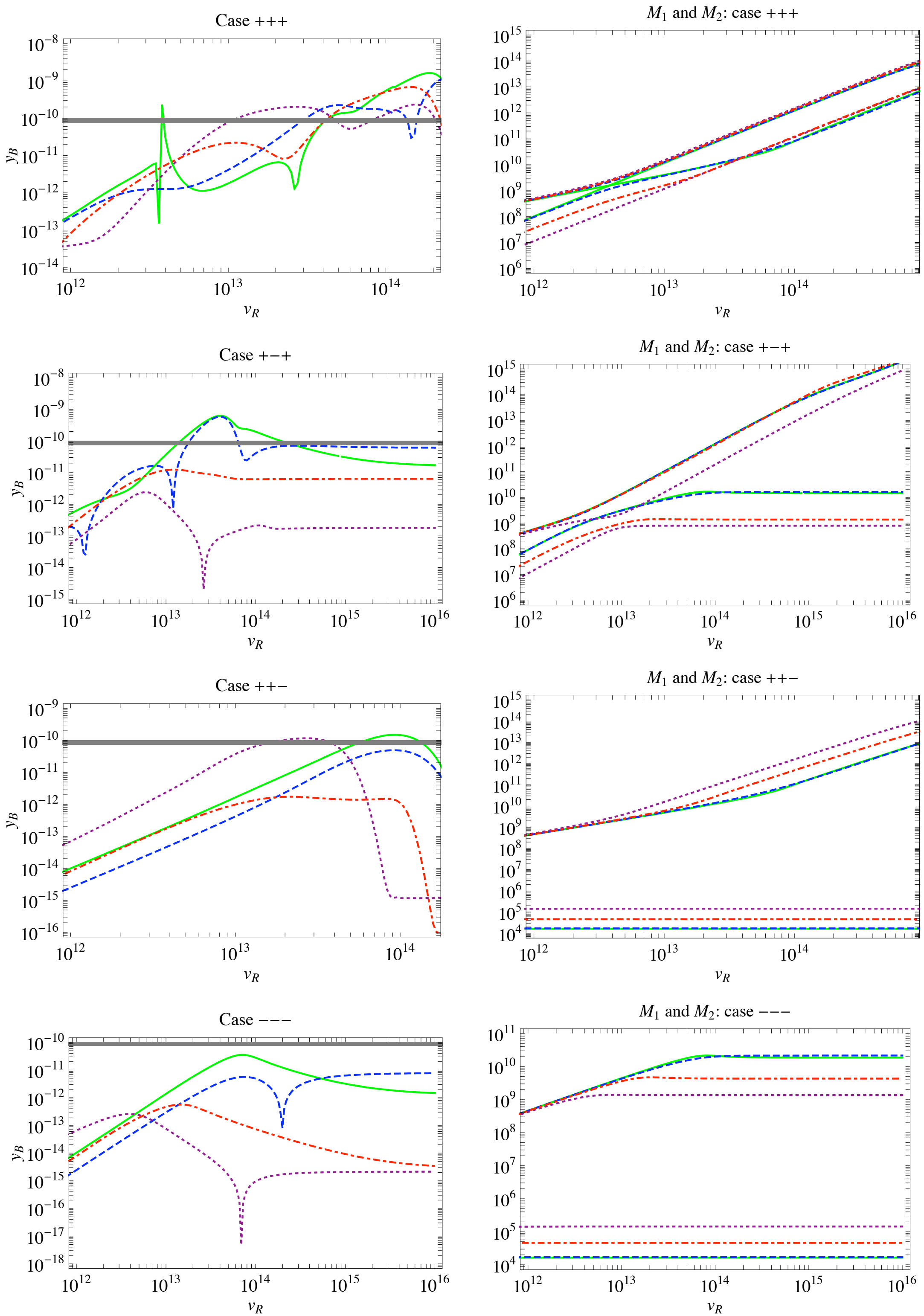
In a theory that predicts the Y_{ij}, can reconstruct the f_{ij} (which determine both the triplet couplings and the N_R mass matrix) as a function of v_L, v_R and of the light neutrino parameters (in principe accessible to experiment) $\Rightarrow$ 8 solutions

Detailed analysis of leptogenesis in Susy SO(10) models with a LR symmetric seesaw mechanism [Abada, Hosteins, Josse-Michaux, SL]:

- flavour-dependent Boltzmann equations (independent evolution of the lepton asymmetry in the e, μ and τ flavours)
- contribution of N_2
- corrections to $M_d = M_e$ from non-renormalizable operators
- flavour-dependent "N_2 leptogenesis" in the solutions with a light N_1: N_2 decays generate an asymmetry in a flavour that is only mildly washed out by N_1 inverse decays



Case +,+,+
Case +,−,+
Case +,+,−
Case −,−,−
M_N (GeV)
V_R (GeV)



Case +++
M_1 and M_2: case +++
Case +−+
M_1 and M_2: case +−+
Case ++−
M_1 and M_2: case ++−
Case −−−
M_1 and M_2: case −−−
y_B
v_R

If impose $T_{RH} < 10^{10}$ GeV, only 4 solutions survive (generically)

No successful realization of "N2 leptogenesis"

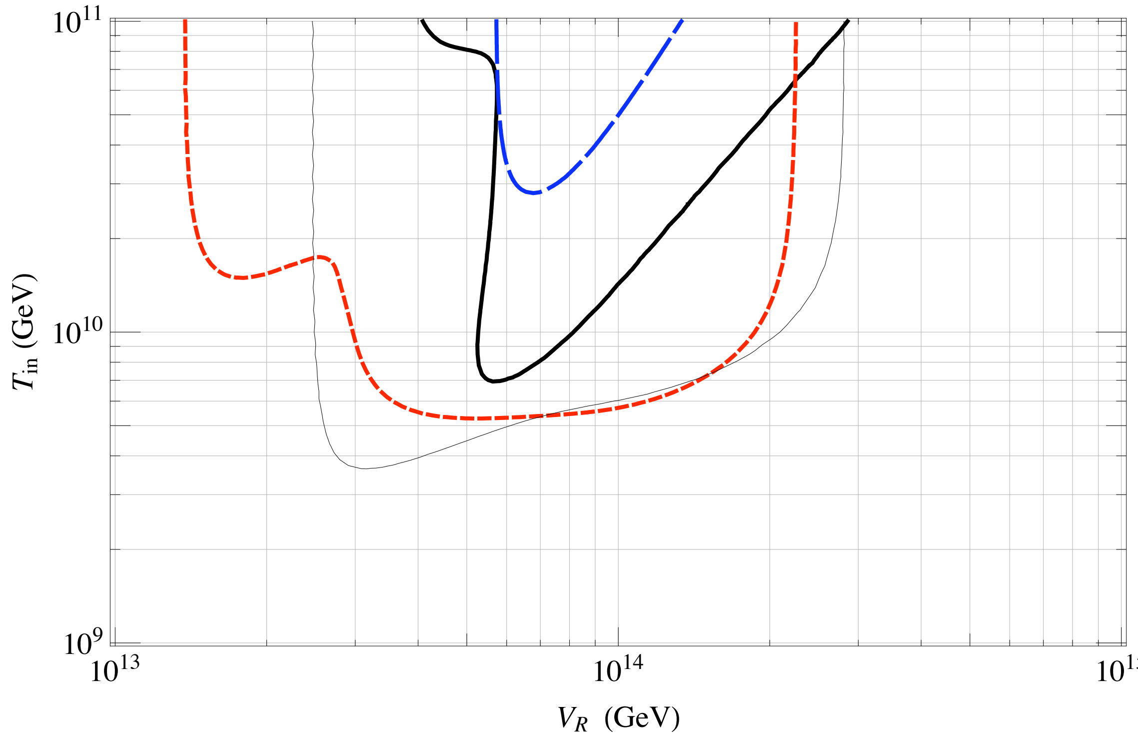


Figure 10: Regions of the (v_R, T_{in}) parameter space where $|Y_B| > Y_B^{WMAP}$ for solutions $(+,+,+)$, $(+,-,+)$ and $(+,+,-)$, and where $|Y_B| > 0.1\, Y_B^{WMAP}$ for solution $(-,-,-)$. These regions are delimited by the thick black contour in the $(+,+,+)$ case, the dashed red contour for $(+,-,+)$, the long-dashed blue contour for $(+,+,-)$, and the thin black contour for $(-,-,-)$. Inputs: set 1 of the Appendix for U_m and the high-energy phases; other input parameters as in Fig. 2.

Impact of corrections to MD = Mu

(if impose $T_{RH} < 10^{10}$ GeV, solution (-,-,-) fails)

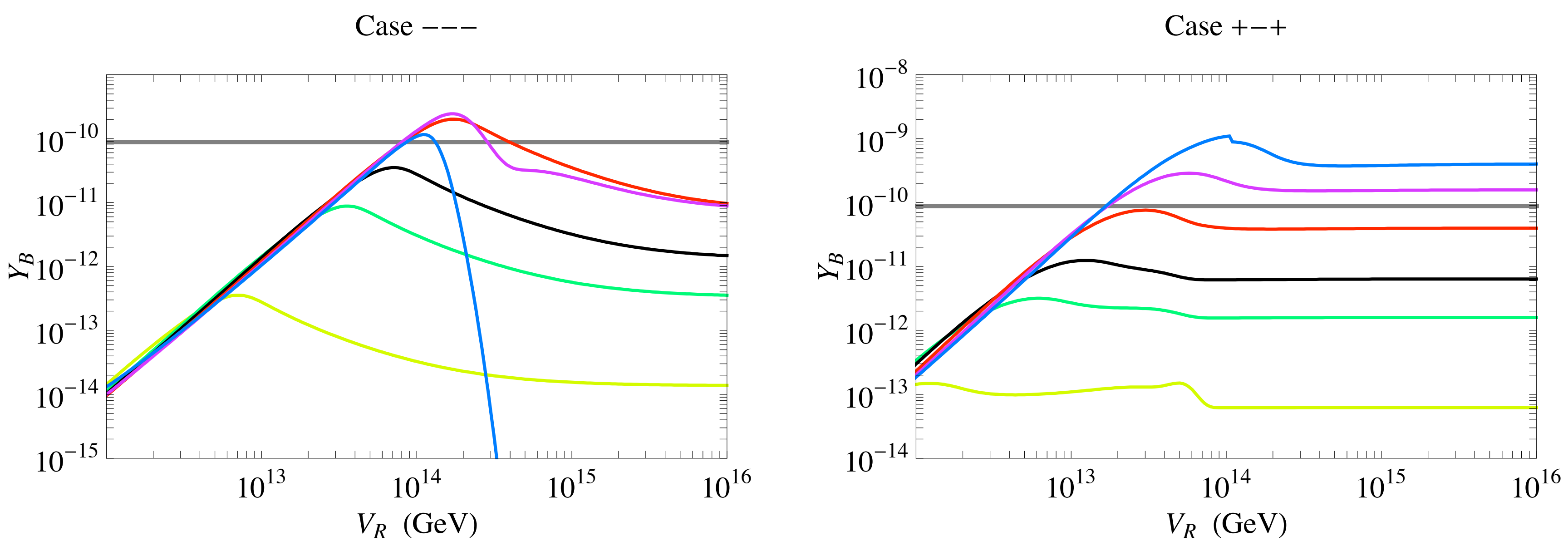


Figure 9: The final baryon asymmetry as a function of v_R for different values of y_2, from $y_2/y_c(M_{GUT}) = 0.1$ (yellow/light grey) to $y_2/y_c(M_{GUT}) = 10$ (blue/dark grey). The reference case $y_2 = y_c$ is plotted in black. Left panel: solution $(-,-,-)$, set 1 for U_m and the high-energy phases; right panel: solution $(+,-,+)$, set 4 for U_m and the high-energy phases. The other input parameters are as in Fig. 2.