Lepton flavour violation in supersymmetric models

Stéphane Lavignac (IPhT Saclay)

- introduction
- experimental status of lepton flavour violation
- theoretical expectations/predictions
- a predictive SO(10) scenario for leptogenesis and flavour violation

<u>based on:</u>

- M. Frigerio, P. Hosteins, S.L. and A. Romanino, Nucl. Phys. B806 (2009) 84
- L. Calibbi, M. Frigerio, S.L. and A. Romanino, JHEP 0912 (2009) 057

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Introduction

There are good reasons to believe that the Standard Model is an incomplete theory, and to expect New Physics around the TeV scale (dark matter, baryon asymmetry of the universe, EWSB, hierarchy problem...)

In the quest for this New Physics, flavour physics is complementary to collider searches and astroparticle (dark matter) experiments:

- provides some information about the flavour structure of NP (which will be difficult to extract from LHC data)
- sensitive to NP scales / regions of NP parameter space that will not be accessible at the LHC

Already strong constraints from present data, e.g. in the kaon sector: requiring $(\Delta m_K)_{\mathrm{SM+NP}}$ $(\varepsilon_K^{\mathrm{SM+NP}})$ within the exp. and th. errors gives

$$\Lambda_{\mathrm{NP}} \gtrsim \begin{cases} 2 \times 10^4\,\mathrm{TeV} & (C = 1) \\ 2 \times 10^3\,\mathrm{TeV} & \left(C = \frac{\alpha_S}{4\pi}\right) \end{cases} \qquad \frac{C}{\Lambda_{\mathrm{NP}}^2}(\bar{s}d)(\bar{s}d)$$

implying that NP should come with suppressed flavour-violating couplings if it lies in the TeV region

$\Lambda_{\rm NP} \lesssim 1\,{\rm TeV}$ can be made consistent with constraints in the quark sector if the minimal flavour violation (MFV) principle is assumed: Yukawa couplings are the only source of flavour symmetry breaking [D'Ambrosio, Giudice, Isidori, Strumia]

$Y_u \sim (3, \bar{3}, 1)\,,\ Y_d \sim (3, 1, \bar{3})$ under $SU(3)_{Q_L} \times SU(3)_{u_R} \times SU(3)_{d_R}$

Then the effective operator $(\bar{s}_L \gamma^\mu d_L)(\bar{s}_L \gamma_\mu d_L)$ comes with a flavour suppression $\left[(Y_u Y_u^\dagger)_{sd}\right]^2 \simeq \left[V_{ts}^* V_{td}\, y_t^2\right]^2$ as in the SM, which together with a loop factor is enough to bring the lower bound on $\Lambda_{\rm NP}$ down to 0.5 TeV

The MSSM with flavour-blind supersymmetry breaking satisfies MFV

Strong constraints also in the charged lepton sector, but noticeable differences with the quark sector:

- the SM predicts no observable flavour violation in the charged lepton sector. The observation of any LFV process, e.g. $\mu \to e\,\gamma$, would be an unambiguous signal of New Physics

- there is no model-independent definition of MFV in the lepton sector: depends on the way neutrino masses are generated (several possibilities if Majorana, many of which involve new flavour-violating couplings)

Experimental 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:

Table 8.1: Present limits on rare μ decays.

mode	upper 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
$\mu^-\ \mathrm{Ti} \to e^-\mathrm{Ti}$	6.1×10^{-13}	1998	SINDRUM II / PSI
$\mu^-\ \mathrm{Ti} \to e^+\mathrm{Ca}^*$	3.6×10^{-11}	1998	SINDRUM II / PSI
$\mu^-\ \mathrm{Pb} \to e^-\mathrm{Pb}$	4.6×10^{-11}	1996	SINDRUM II / PSI
$\mu^-\ \mathrm{Au} \to e^-\mathrm{Au}$	7×10^{-13}	2006	SINDRUM II / PSI

[WG3 report of the CERN "Flavour in the Era of the LHC" workshop]

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

Channel	Babar $\mathcal{L}$ (fb^{-1})	Babar $\mathcal{B}_{\text{UL}}$ (10^{-8})	BELLE $\mathcal{L}$ (fb^{-1})	BELLE $\mathcal{B}_{\text{UL}}$ (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]

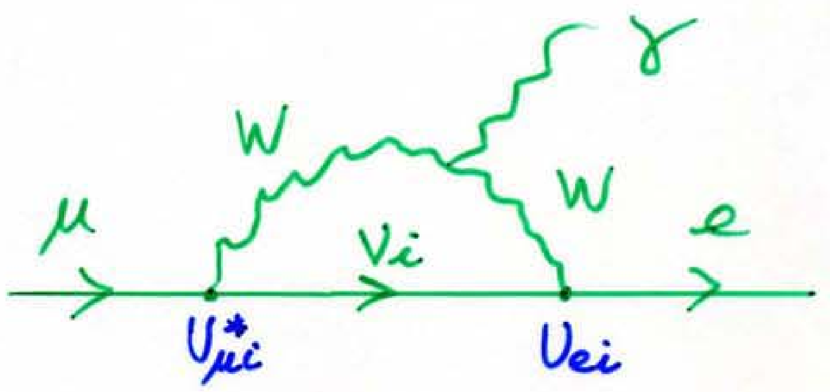
Also strong constraints on LFV rare decays of mesons:

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

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

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

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



e.g. $\mu \to e\,\gamma$:

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

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. $\mu \to e\,\gamma$ 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)

In terms of effective Lagrangian operators:

<u>$\mu \to e\gamma$:</u> $$\frac{C^M_{\mu e\gamma}}{\Lambda^2_{NP}} \langle H^0 \rangle \, \bar{e}\sigma^{\mu\nu} P_M \mu \, F_{\mu\nu} \; + \; \text{h.c.}$$ (M = L,R)

The exp. upper bound $\mathrm{BR}\,(\mu \to e\gamma) \; < \; 1.2 \times 10^{-11}$ translates into

$$\Lambda_{NP} \; > \; \begin{cases} 1.7 \times 10^4 \, \text{TeV} & (C = 1) \\ 860 \, \text{TeV} & (C = \frac{\alpha_W}{4\pi}) \end{cases}$$

<u>$\mu \to e\,e\,e$:</u> $$\frac{C^{MN}_{eee\mu}}{\Lambda^2_{NP}} \; (\bar{e}\gamma^\mu P_M e)\,(\bar{e}\gamma^\mu P_N \mu) \; + \; \text{h.c.}$$ (M,N = L,R)

The exp. upper bound $\mathrm{BR}\,(\mu \to eee) \; < \; 10^{-12}$ translates into

$$\Lambda_{NP} \; > \; \begin{cases} 210 \, \text{TeV} & (C = 1) \\ 11 \, \text{TeV} & (C = \frac{\alpha_W}{4\pi}) \end{cases}$$

→ strong constraint on new physics at the TeV scale

Indeed, many new physics scenarios predict “large” LFV rates

Prospects for LFV experiments

$\mu \to e\gamma$:

- the experiment MEG at PSI has started taking data in sept. 2008
- first results published in summer 2009 (3.0×10^{-11} at 90% CL)
- expects to reach a sensitivity of a few 10^{-13} (factor of 100 improvement) in 3 years of acquisition time

$\mu \to e$ 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, ... (focus on Susy in this talk)

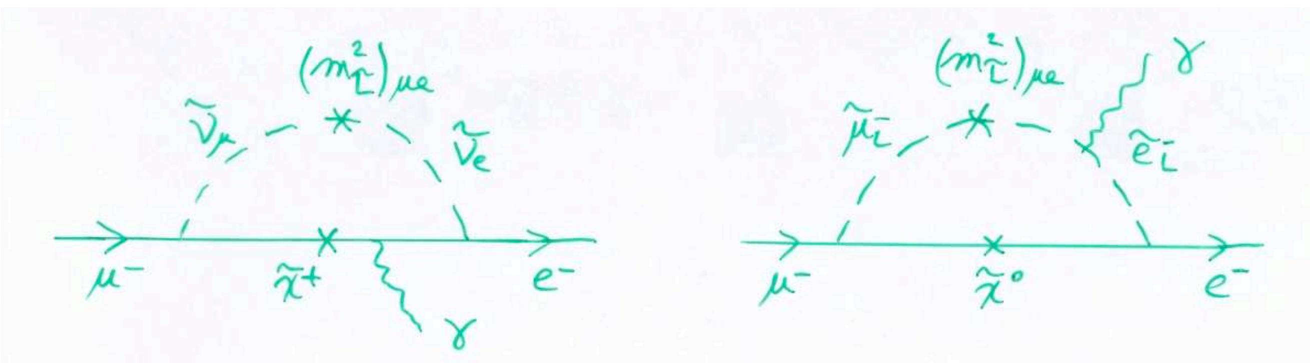
In (R-parity conserving) supersymmetric extensions of the Standard Model, LFV is induced by a misalignment between the lepton and slepton mass matrices, parametrized by the mass insertion parameters ($\alpha \neq \beta$):

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

In the mass insertion approximation, the branching ratio for $\mu \to e\,\gamma$ reads

$$\mathrm{BR}\,(\mu \to e\gamma) \;=\; \frac{3\pi\alpha^3}{4G_F^2\cos^4\theta_W}\;\left\{\left|f_{LL}\,\delta^{LL}_{12} + f_{LR}\,\delta^{LR}_{12}\right|^2 + \left|f_{RR}\,\delta^{RR}_{12} + f^\star_{LR}\,\delta^{LR\star}_{21}\right|^2\right\}\;\tan^2\beta$$

with f_L, f_R functions of the superpartner masses and of tan β. For moderate to large tan β, the branching ratio approximately scales as $\tan^2\beta$



[Masina, Savoy]

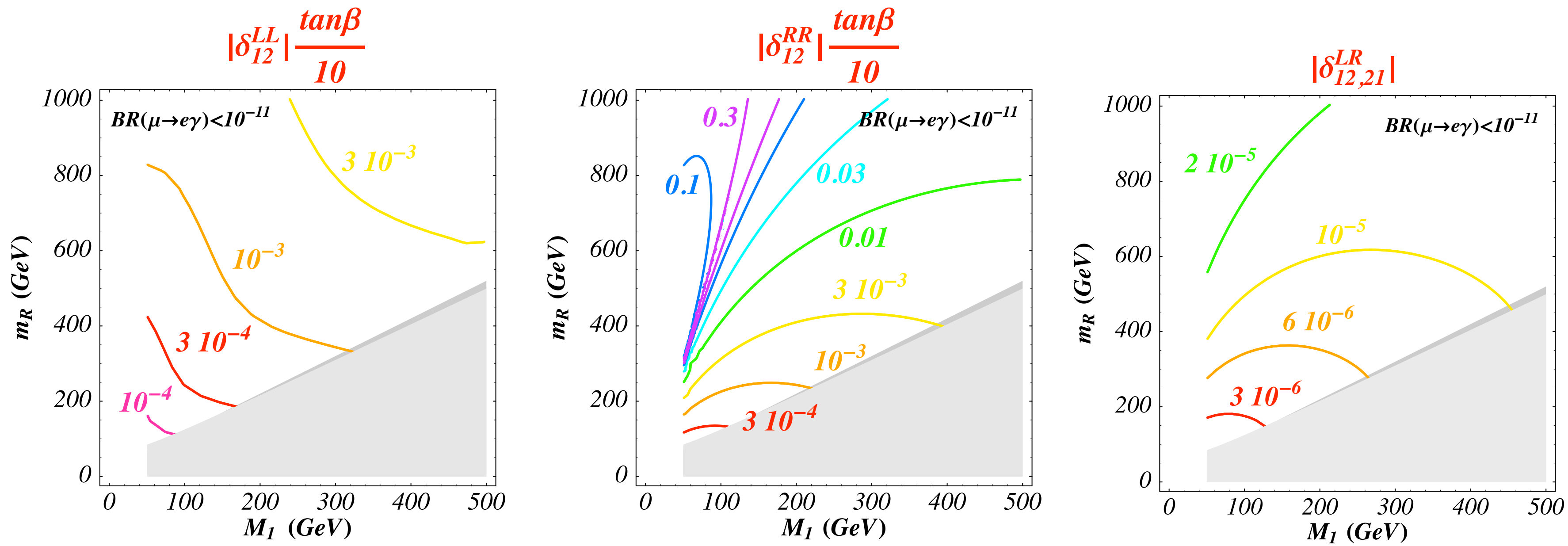


Fig. 5.3: Upper limits on δ_{12}'s in mSUGRA. Here M_1 and m_R are the bino and right-slepton masses, respectively.

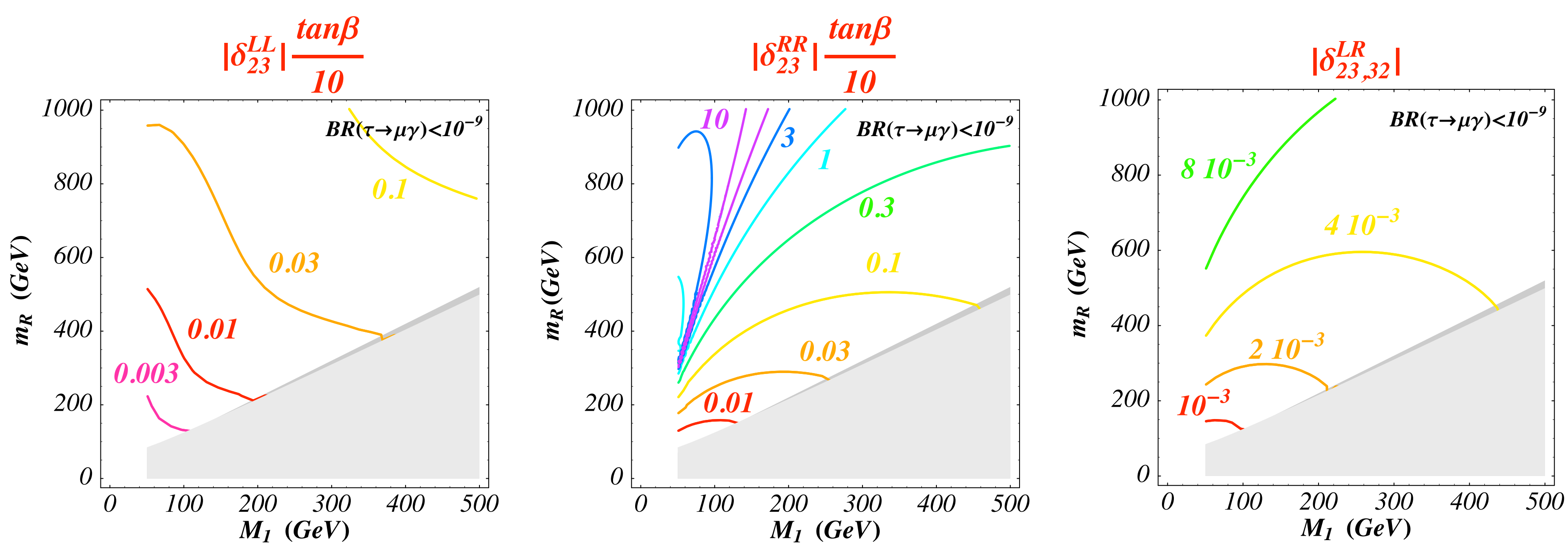


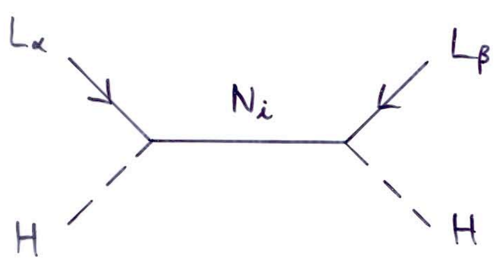
Fig. 5.4: Upper limits on δ_{23}'s in mSUGRA. Here M_1 and m_R are the bino and right-slepton masses, respectively.

Important difference with the quark sector: even if slepton soft terms are flavour universal 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]

Most celebrated example: (type I) seesaw mechanism

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



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

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

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

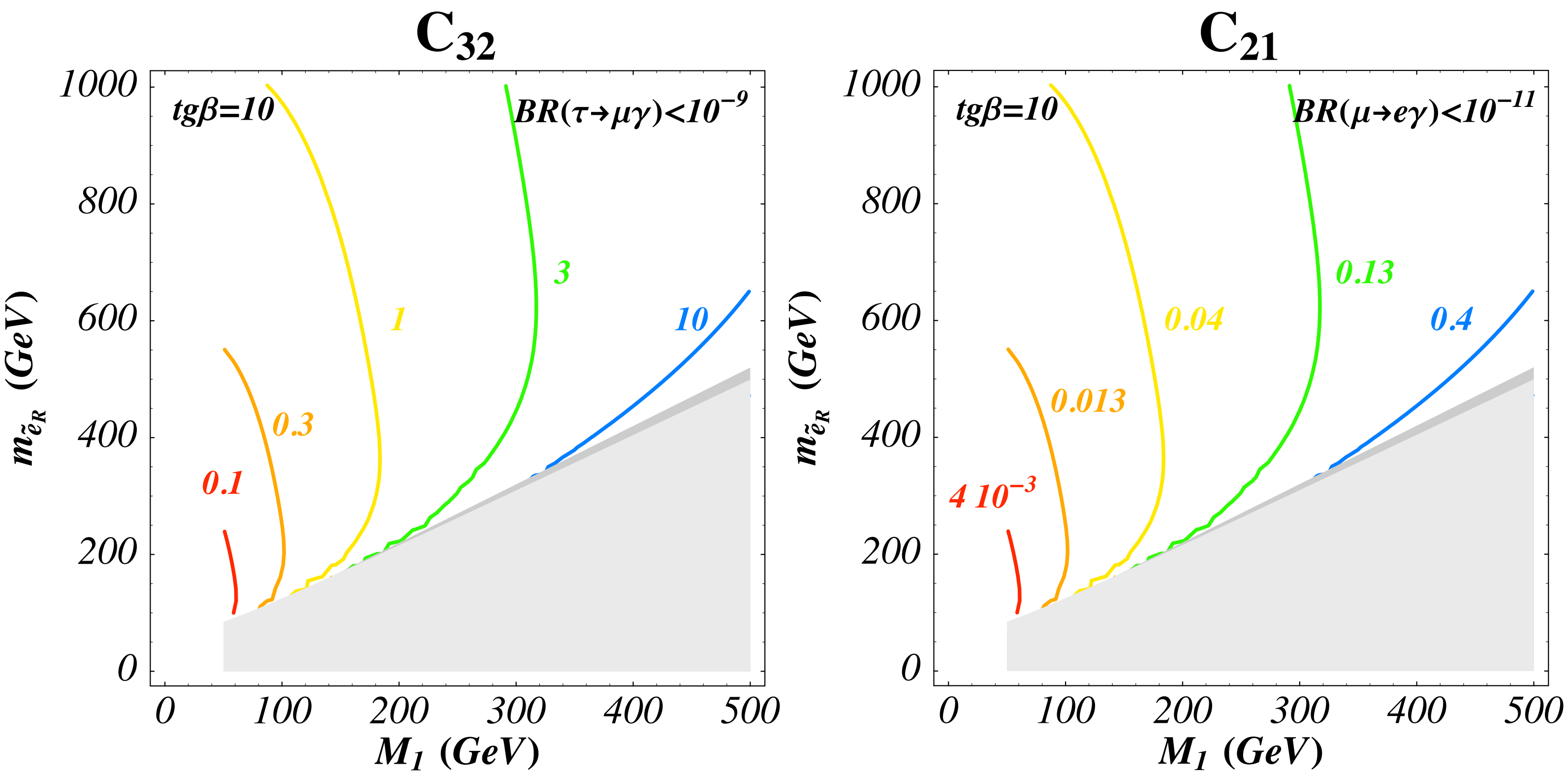
where $C_{\alpha\beta} \equiv \sum_k Y^\star_{k\alpha} Y_{k\beta} \ln(M_U/M_k)$ encapsulates all the dependence on the seesaw parameters

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

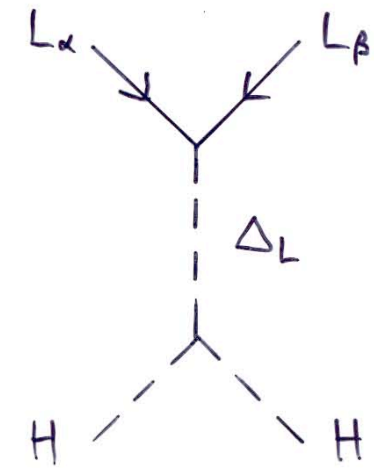
$$\mathrm{BR}\,(l_\alpha \to l_\beta \gamma) \;\propto\; |C_{\alpha\beta}|^2$$

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

[SL, Masina, Savoy]



Other example: type II seesaw mechanism [A. Rossi]



= heavy scalar SU(2)L triplet exchange

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

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

(simplest realization of MFV in the lepton sector)

The radiative corrections to soft slepton masses are now controlled by

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

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

[A. Rossi]

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

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

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

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

⇒ 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:

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

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

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

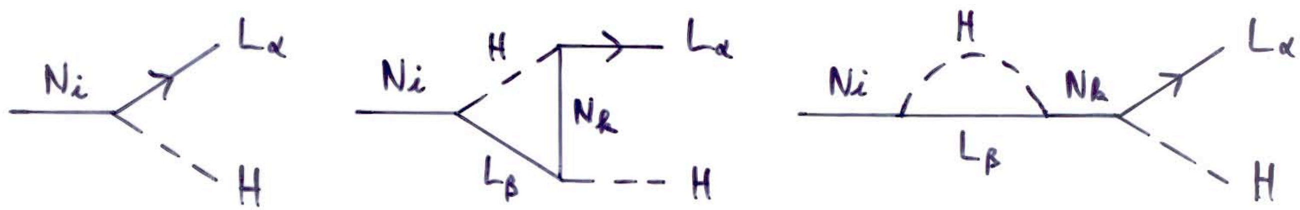
Similar effects (although of different origin) in SO(10) models with type II seesaw [see later]

Since radiative corrections to slepton soft terms can be large, interfere with possible non-universal contributions from supersymmetry breaking

$\Rightarrow$ difficult to disentangle them, unless correlations characteristic of a given scenario are observed

A preditive SO(10) scenario for leptogenesis and LFV

The type I seesaw mechanism is attractive because it can explain both the light neutrino masses and the baryon asymmetry of the Universe (leptogenesis)



Fukugita, Yanagida

$$\epsilon_{N_1} \equiv \frac{\Gamma(N_1 \to LH) - \Gamma(N_1 \to \bar{L}H^\star)}{\Gamma(N_1 \to LH) + \Gamma(N_1 \to \bar{L}H^\star)} \simeq \frac{3}{16\pi} \sum_k \frac{\mathrm{Im}[(YY^\dagger)^2_{k1}]}{(YY^\dagger)_{11}} \frac{M_k}{M_1}$$

Covi, Roulet, Vissani
Buchmüller, Plümacher

But difficult to test: no connection in general between the CP asymmetry and low-energy observables (18 seesaw parameters for 9 low-energy parameters, m_i and U_{PMNS}), nor between these and seesaw-induced LFV. Davidson et al. – Petcov et al.

The type II seesaw mechanism is more predictive: the triplet-induced LFV is controlled by the light neutrino parameters. Triplet leptogenesis also possible, but to get a non-vanishing CP asymmetry need another heavy state with couplings $g_{ij} \neq f_{ij}$ to lepton doublets $\Rightarrow$ direct connection with low-energy parameters lost

$$\epsilon_\Delta \propto \mathrm{Im}\left[\mathrm{Tr}\left(M_\nu^{(\Delta)\dagger} M_\nu^{(H)}\right)\right] \qquad M_\nu = M_\nu^{(\Delta)} + M_\nu^{(H)}$$

Hambye, Raidal, Strumia

However, such a connection can be recovered if the type II seesaw mechanism is realized in a SO(10) GUT

Type II seesaw in non-standard SO(10) unification

Not easy to avoid the type I contribution: RHNs belong to the matter representation (16), hence are always around and couple to lepton doublets

Way out: "non-standard" embedding of the SM fermions into SO(10) representations

$$16_i = 10_i \oplus . \oplus 1_i$$
$$10_i = . \oplus \bar{5}_i^{10}$$

Hisano, Murayama, Yanagida
Nomura, Yanagida - Rosner
Asaka - Berezhiani, Tavartkiladze
Berezhiani, Rossi - Malinsky

$(5_i^{10}, \bar{5}_i^{16})$ form a (heavy) vector-like pair of matter fields

Motivation: E6? $27_i = 16_i \oplus 10_i \oplus 1_i$

How to achieve this? $$W = \frac{1}{2} y_{ij} 16_i 16_j 10 + h_{ij} 16_i 10_j 16$$

SU(5) singlet in the 16: $V_1^{16} \neq 0 \Rightarrow$ GUT-scale masses for $(5_i^{10}, \bar{5}_i^{16})$

$5_i^{10} \equiv (L_i^c, D_i)$ heavy anti-lepton doublets and quark singlets

SM matter fields: $10_i^{16} = (Q_i, u_i^c, e_i^c), \quad \bar{5}_i^{10} = (L_i, d_i^c), \quad 1_i^{16} = \nu_i^c$

$$W = \frac{1}{2} y_{ij} 16_i 16_j 10 + h_{ij} 16_i 10_j 16$$

Quark and lepton masses: $M_u = y\, v_u^{10}$ $\quad M_d = M_e^T = h\, v_d^{16}$

No neutrino Dirac couplings at tree level: RHNs couple to heavy leptons

The heavy leptons (quarks) have hierarchical masses proportional to down-type fermion masses: $M_i = h_i V_1^{16} = m_{e_i} V_1^{16} / v_d^{16}$

Neutrino masses: $W_{II} = \frac{1}{2} f_{ij} 10_i 10_j 54 + \frac{1}{2} \sigma 10\, 10\, 54 + \frac{1}{2} M_{54} 54^2$

$$\Rightarrow \quad \frac{1}{2} f_{ij} L_i L_j \Delta + \frac{1}{2} \sigma H_u^{10} H_u^{10} \bar{\Delta} + M_\Delta \Delta \bar{\Delta} + \ldots$$

where $54 = 15 \oplus \overline{15} \oplus 24\,, \quad 15 = (\Delta, Z, \Sigma)\,, \quad \Delta = (1,3)_{+2}$

$\Rightarrow$ type II seesaw: $M_\nu = \frac{\sigma (v_u^{10})^2}{2 M_\Delta} f$

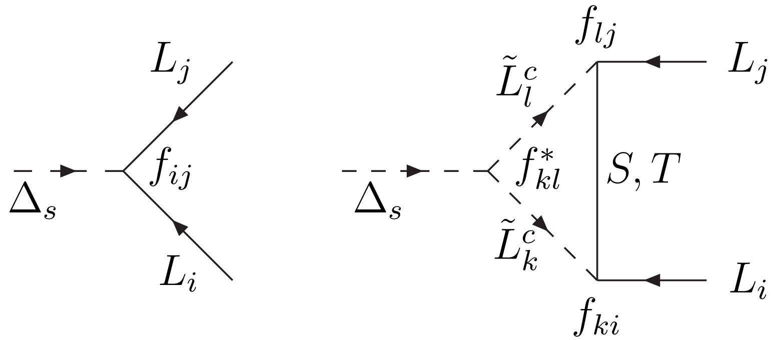
Assumed:
- matter parity
- no mass term $10_i\ 10_j$, no 54 vev $\Rightarrow$ no mixing $\bar{5}_i^{10} / \bar{5}_i^{16}$

Leptogenesis

Requires a CP asymmetry in triplet decays. In standard triplet leptogenesis, need another heavy state with couplings $g_{ij} \neq f_{ij}$ to lepton doublets, otherwise

$$\epsilon_\Delta \propto \mathrm{Im}[\mathrm{Tr}(f f^* f f^*)] = 0 \qquad \Rightarrow \text{lose predictivity}$$

In our scenario, $g_{ij} = f_{ij}$ but the heavy leptons in the loop have hierarchical masses and the trace is incomplete as soon as $M_3 > M_\Delta/2$:



$S, T \in 24$

$$\epsilon_\Delta \propto \sum_{k,l} \theta(M_\Delta - M_k - M_l)\, C_{kl}\, \mathrm{Im}[f_{kl}(f^* f f^*)_{kl}]$$

Assuming $M_1 \ll M_\Delta < M_1 + M_2$ and $M_S = M_T = M_{24} \gg M_\Delta$, one obtains:

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

$$\lambda_L^2 \equiv \sum_{i,j=1}^3 |f_{ij}|^2, \quad \lambda_{L_1^c}^2 \equiv |f_{11}|^2, \quad \lambda_{H_{u,d}}^2 \equiv |\sigma\, \alpha_{u,d}^2|^2$$

Dependence on the light neutrino parameters

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

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

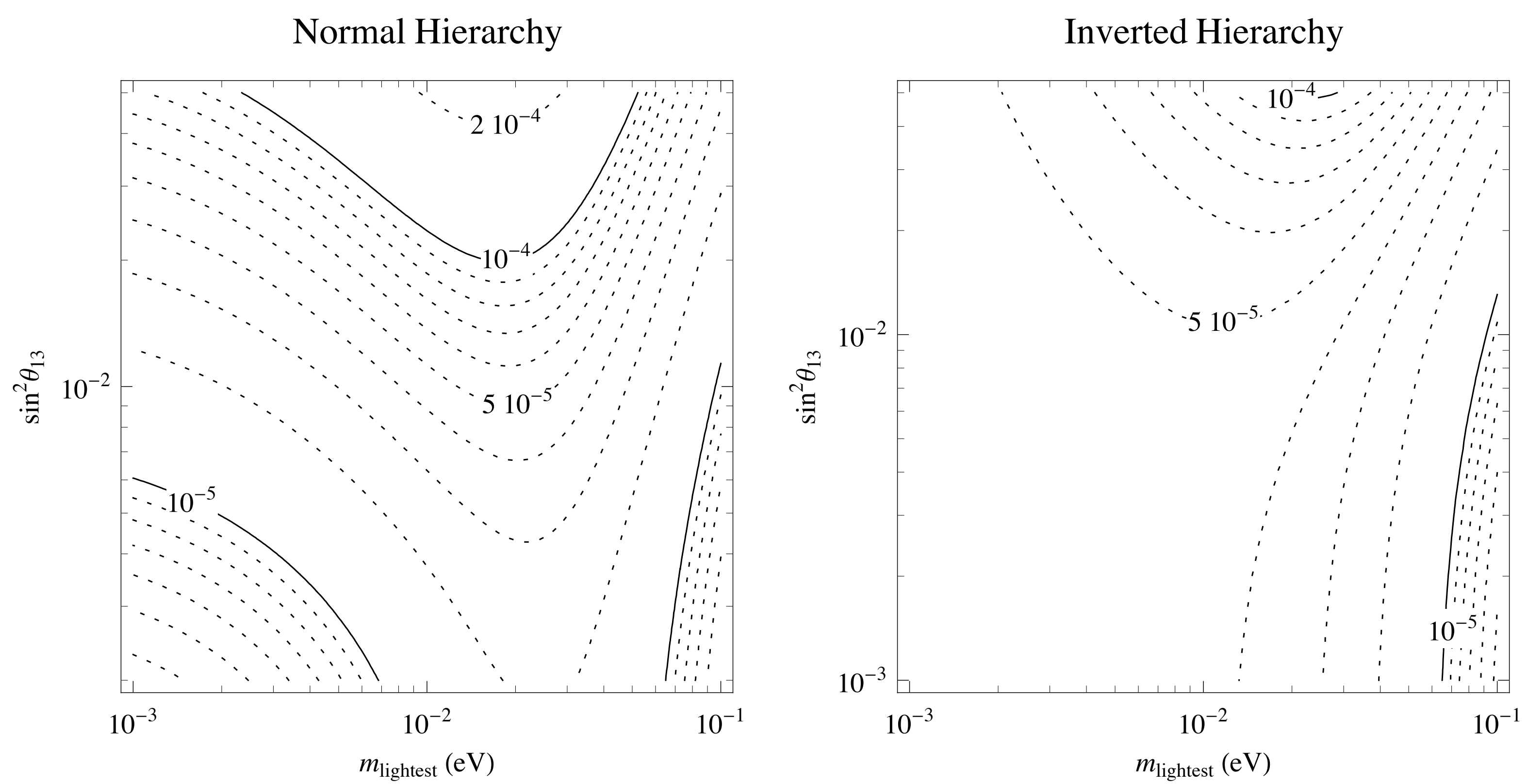
→ ϵ_Δ does not depend on high-scale flavour parameters - only on the light neutrino parameters and on $\lambda_L, \lambda_{H_u}, \lambda_{H_d}, M_\Delta/M_{24}$

→ the CP violation needed for leptogenesis is provided by the CP-violating phases of the PMNS matrix

[the Majorana phases ρ and σ in the case $M_1 < M_\Delta < M_1 + M_2$]

→ ϵ_Δ can be large (λ_L^2 is bounded by perturbativity):

$$\begin{aligned}\epsilon_\Delta^{\max} &\simeq 2.2\times 10^{-4}\,\lambda_L^2 \qquad (\text{maximum}\,\theta_{13})\ ,\\ &\simeq 3.4\times 10^{-5}\,\lambda_L^2 \qquad (\text{vanishing}\,\theta_{13})\ ,\end{aligned}$$



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

$\frac{n_B}{s} \; = \; 7.62 \times 10^{-3}\, \eta\, \epsilon_\Delta$ agrees with the WMAP value $(8.82 \pm 0.23) \times 10^{-11}$

if $\eta\, \epsilon_\Delta \approx 10^{-8}$ ⇒ the efficiency factor η can be as small as $10^{-5} - 10^{-4}$ in the region where the CP asymmetry is maximal

This regime must be studied numerically. There is also a large efficiency regime that can be discussed analytically, where

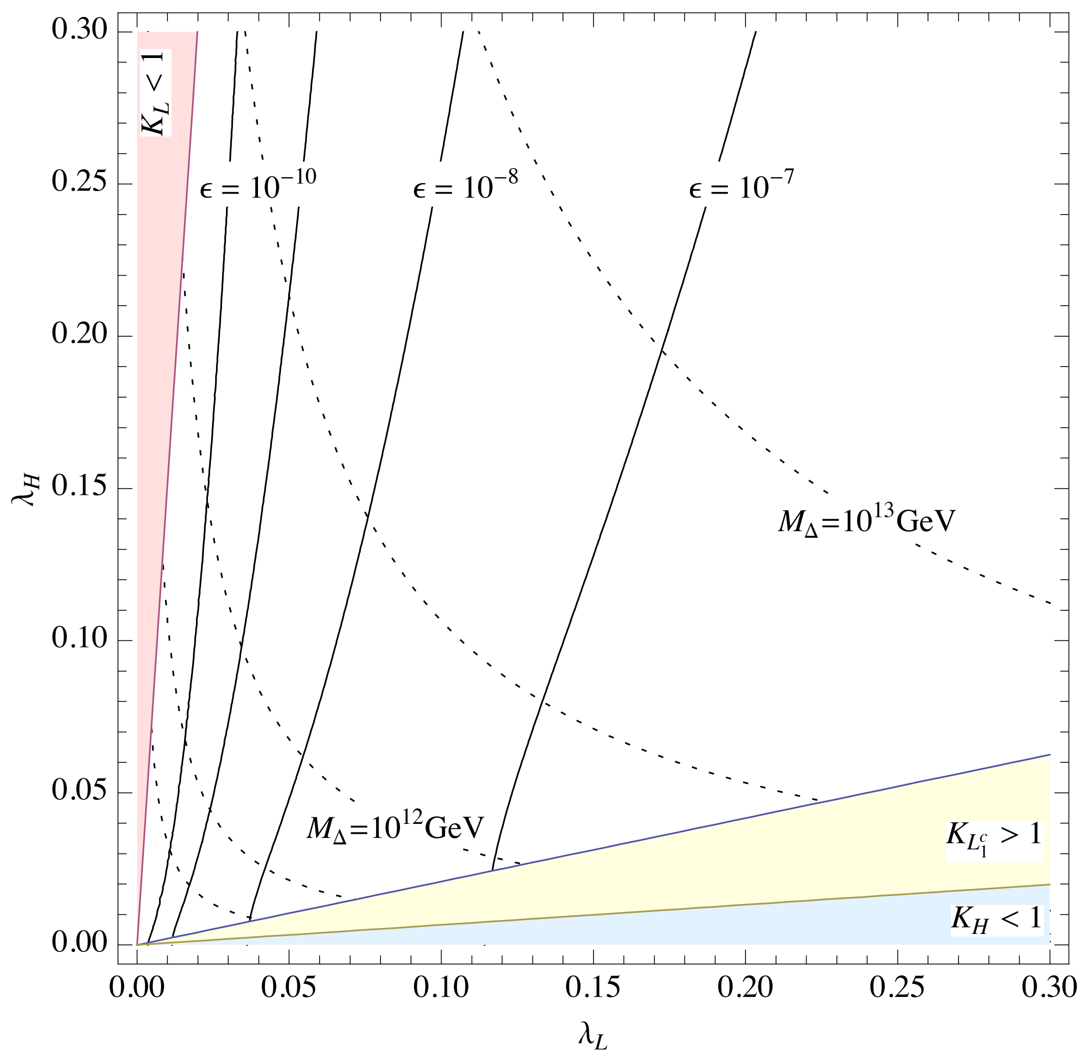
$$K_{L_1^c} \ll 1 \qquad \text{and} \qquad K_L,\, K_{H_u} \gtrsim 1$$

with $K_a \, \equiv \, \Gamma(\Delta_s \to aa)/H(M_\Delta) \quad (a = \tilde{L}_1^c, \bar{L}, H_u)$

Even though triplet decays are in equilibrium, a large lepton asymmetry is generated thanks to $K_{L_1^c} \ll 1$ and η ~ 1 can be obtained [Hambye, Raidal, Strumia]

[the CP asymmetry in the channel $\Delta_s \to \tilde{L}_1^c \tilde{L}_1^c$ is $-\epsilon_\Delta$]

The condition $K_{L_1^c} \ll 1$ tends to suppress the CP asymmetry, which can be compensated for by increasing the triplet mass



Normal hierarchy with $m_1 \ll m_2,\ \sin^2\theta_{13} = 0.05$ and $\sin 2\sigma = 1$

$\tan\beta = 10,\ \lambda_{H_d} = 0$ and $M_\Delta / M_{24} = 0.1$

In the large efficiency regime, successful leptogenesis requires:

- a normal light neutrino hierarchy
- a large value of θ_{13}
- large Majorana phases

$\rightarrow$ the scenario can be excluded on the basis of neutrino experiments!

Predictions for flavour violation

The squark and slepton soft terms receive flavour-violating radiative corrections from:

- the heavy triplets and their SO(10) partners (components of the 54)
  ⇒ controlled by the fij's ($f_{ij} 10_i 10_j 54$)
- the heavy quarks and leptons (heavy components of the 16i and 10i)
  ⇒ controlled by the up-quark Yukawa couplings ($y_{ij} 16_i 16_j 10$)

→ flavour structure of the radiative corrections predicted in terms of low-energy parameters [up quark and neutrino masses, quark and lepton mixing]

Their absolute size also depends on a few high-energy parameters [λ_H, masses of the 54 components, absolute scale of the heavy quarks and leptons fixed by $V_1^{16} / \sin\theta_H$, where θ_H is defined by $H_d^{light} = \sin\theta_H H_d^{16} + \cos\theta_H H_d^{10}$]

Also mild model dependence associated with the non-renormalizable operators needed to correct the mass relation $M_d = M_e^T$: in general spoil the relation between the heavy and light down quark/charged lepton mass matrices. However the dependence on the heavy masses is logarithmic

Assuming universal soft terms at the GUT scale, we obtain in the leading-log approximation (in matrix form):

$$\delta m_L^2 = -\frac{3m_0^2 + A_0^2}{16\pi^2}\, f^\dagger \left(3 \ln \frac{M_{\rm GUT}^2}{M_{15}^2} + \frac{9}{10} \ln \frac{M_{\rm GUT}^2}{M_{24}^2 + M_{L^c}^T M_{L^c}^*} + \frac{3}{2} \ln \frac{M_{\rm GUT}^2}{M_{24}^2 + M_D^T M_D^*} \right) f$$

$$\delta m_{d^c}^2 = -\frac{3m_0^2 + A_0^2}{16\pi^2}\, f^\dagger \left(3 \ln \frac{M_{\rm GUT}^2}{M_{15}^2} + \ln \frac{M_{\rm GUT}^2}{M_{24}^2 + M_{L^c}^\dagger M_{L^c}} + \frac{7}{5} \ln \frac{M_{\rm GUT}^2}{M_{24}^2 + M_D^\dagger M_D} \right) f$$

The first term in the bracket is present in the SU(5) version of the type II seesaw [A. Rossi], the next two are due to the presence of the heavy quarks and leptons

Contrary to the standard type II seesaw, flavour violation is also induced in the singlet slepton and doublet squark sectors:

$$\delta m_{e^c}^2 = -\frac{3m_0^2 + A_0^2}{16\pi^2}\, \cos^2\theta_H\, y^\dagger \left(2 \ln \frac{M_{\rm GUT}^2}{M_{L^c}^* M_{L^c}^*} \right) y$$

$$\delta m_Q^2 = -\frac{3m_0^2 + A_0^2}{16\pi^2}\, \cos^2\theta_H\, y^\dagger \left(\ln \frac{M_{\rm GUT}^2}{M_D M_D^\dagger} \right) y$$

δm_Q^2 has the same flavour structure as the MSSM radiative corrections

Model-building aspects of the model

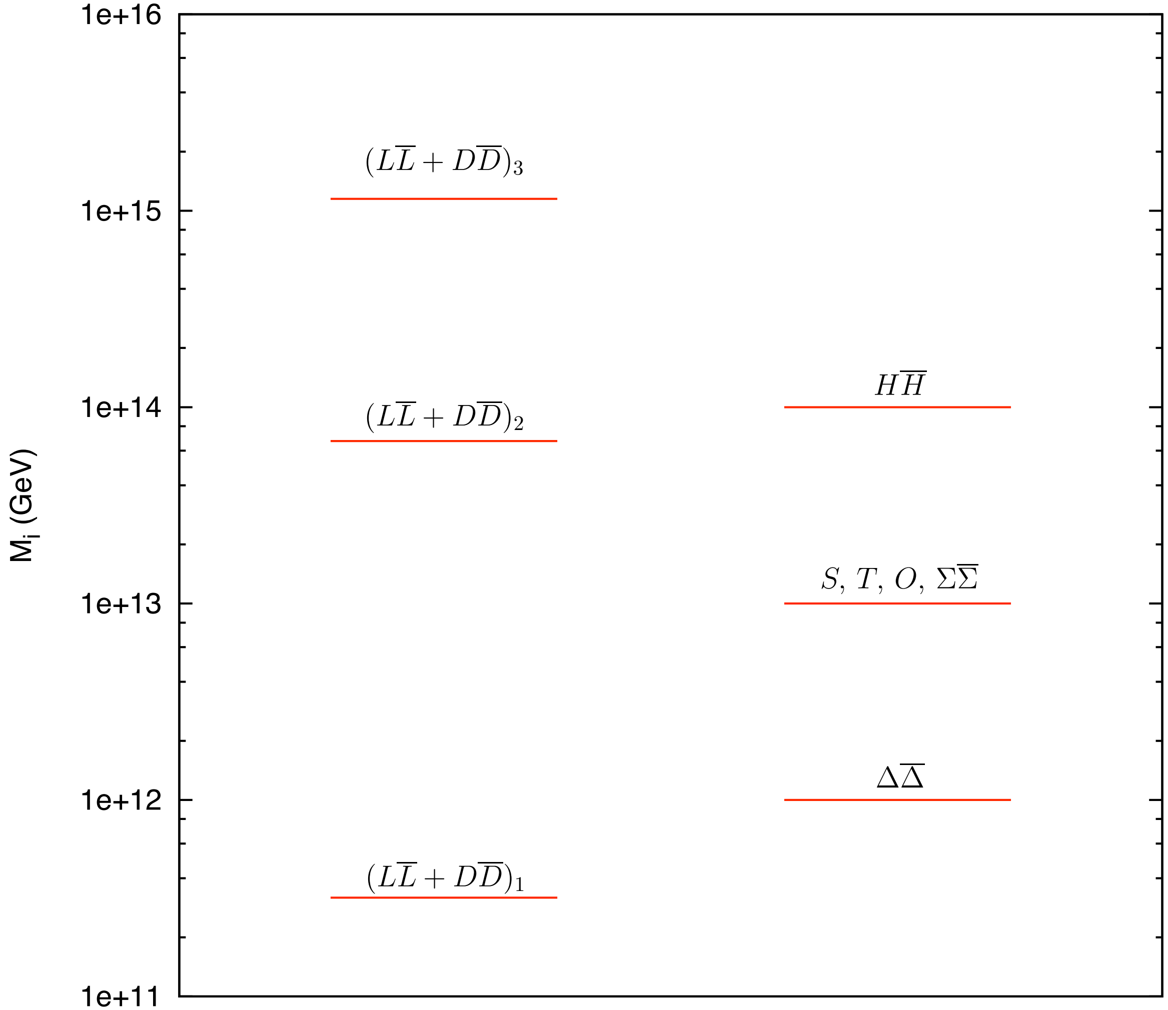
- SO(10) is broken down to the SM gauge group by a 54', two 45 with vevs aligned in the T_{3R} and B-L directions, and the $\mathbf{16} \oplus \overline{\mathbf{16}}$ which breaks the rank
- the 10 and $\mathbf{16} \oplus \overline{\mathbf{16}}$ contain both Higgs doublets and colour triplets. The doublet-triplet splitting is realized à la Dimopoulos-Wilczek using the 45_{B-L}
- to suppress proton decay from coloured triplet exchange, one pair of Higgs doublets must have a mass $M_H \lesssim 10^{14}\,\mathrm{GeV}$

The intermediate pair of Higgs doublets spoils gauge coupling unification. This can be cured by splitting the components of the $\mathbf{15} \oplus \overline{\mathbf{15}}$ and 24 SU(5) multiplets inside the 54 (which also has the advantage of keeping unification perturbative). 2 possibilities emerge (both with $M_H = 10^{14}\,\mathrm{GeV}$ and $M_T / M_\Delta = 10$, motivated by leptogenesis):

(i) all components of the 54 have GUT-scale masses but $(\mathbf{\Delta}, \bar{\mathbf{\Delta}}), (\mathbf{\Sigma}, \bar{\mathbf{\Sigma}})$ and T (with $M_\Sigma = M_\Delta$ and $M_T / M_\Delta = 10$ fixed)

(ii) all components of the 54 have GUT-scale masses but $(\mathbf{\Delta}, \bar{\mathbf{\Delta}}), (\mathbf{\Sigma}, \bar{\mathbf{\Sigma}})$, S, T and O (with $M_\Delta < M_\Sigma$, $M_S = M_T = M_O$ and $M_T / M_\Delta = 10$ fixed)

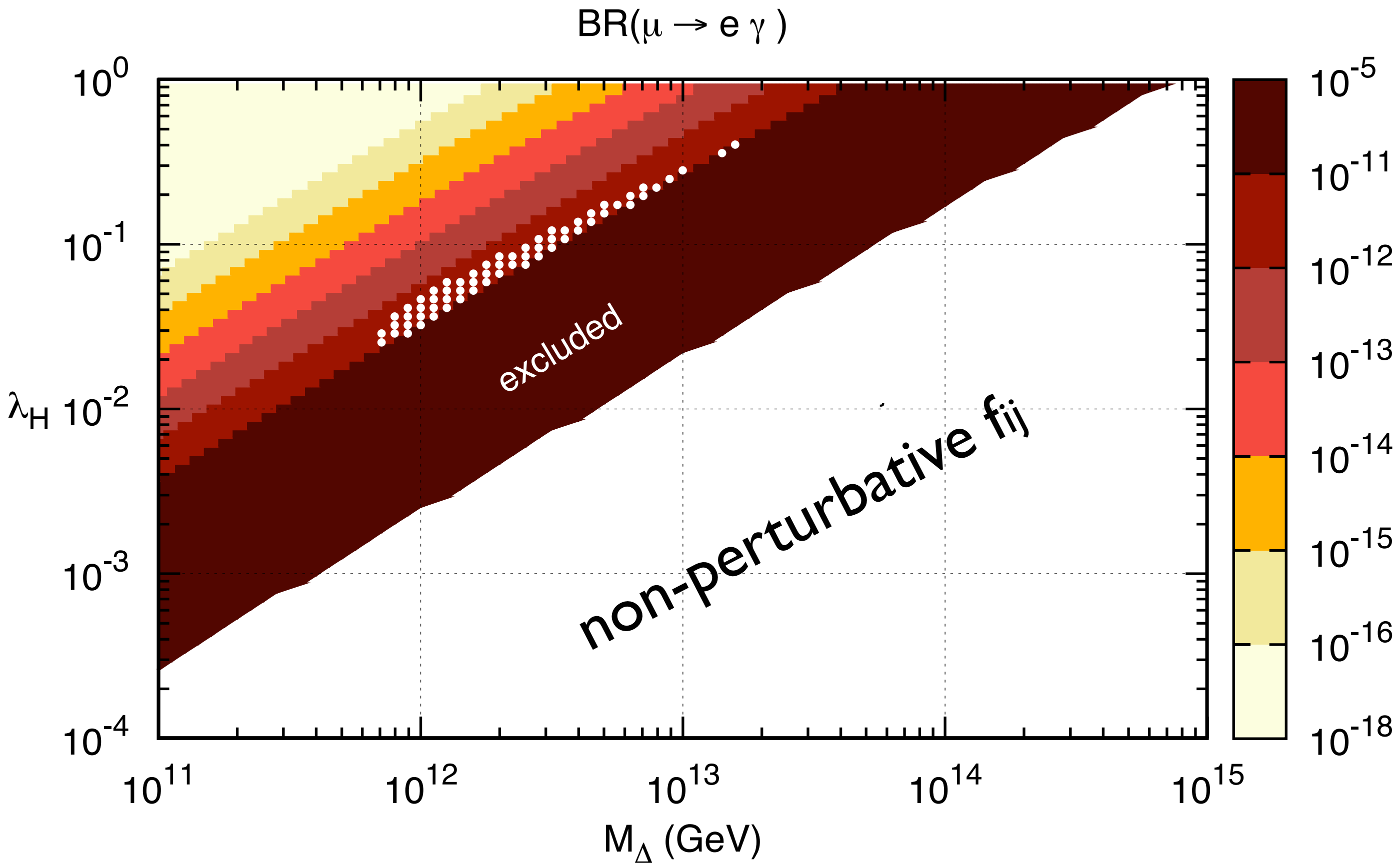
Both restore unification at one loop [with however a too low M_{GUT} in case (i): must rely on 2-loop RGEs and GUT threshold effects to increase it]



Spectrum of heavy states [scenario (ii) with $M_\Delta = 10^{12}\,\mathrm{GeV}$, $\lambda_H = 0.045, V_1^{16} = M_{GUT}, \tan\theta_H = 1, \tan\beta = 10$]

Numerical results

- we assume universal soft terms at MGUT, with A0 = 0 and μ > 0
- we require radiative electroweak symmetry breaking and impose the experimental limits on the Higgs and superpartner masses and on $\mathrm{BR}\,(b \to s\gamma), \mathrm{BR}\,(B^0_{d,s} \to \mu^+\mu^-), \Delta m_K, \Delta m_D, \Delta m_B$ and Δm_{B_s}
- we choose values of the light neutrino parameters favoured by leptogenesis: $m_{\nu_1} = 0.005\,\mathrm{eV}$, $\sin^2\theta_{13} = 0.05$, $\rho = \pi/4$, $\sigma = \pi/2$ $[\delta = 0]$
- we consider scenario (ii) [scenario (i) would give similar results] with $V_1^{16} = M_{GUT}$ and $\tan\theta_H = 1$

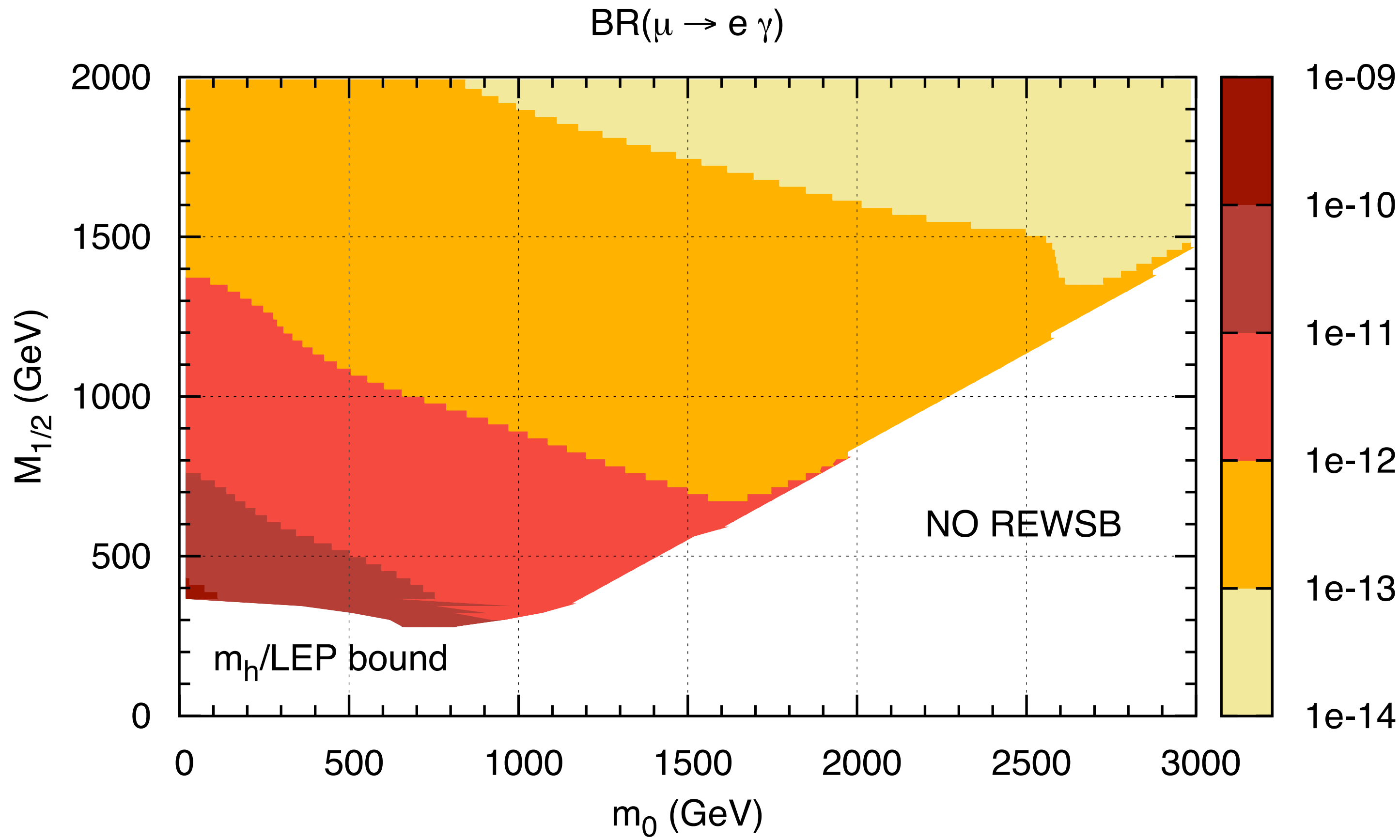


Susy parameters: $m_0 = M_{1/2} = 700\,\mathrm{GeV},\ A_0 = 0,\ \tan\beta = 10,\ \mu > 0$

Strong dependence of $\mathrm{BR}\,(\mu \to e\gamma)$ on the seesaw parameters:

$$\mathrm{BR}\,(\mu \to e\gamma) \sim |(m_L^2)_{21}|^2 \sim |(f^\dagger f)_{21}|^2 \sim (M_\Delta/\lambda_H)^4$$

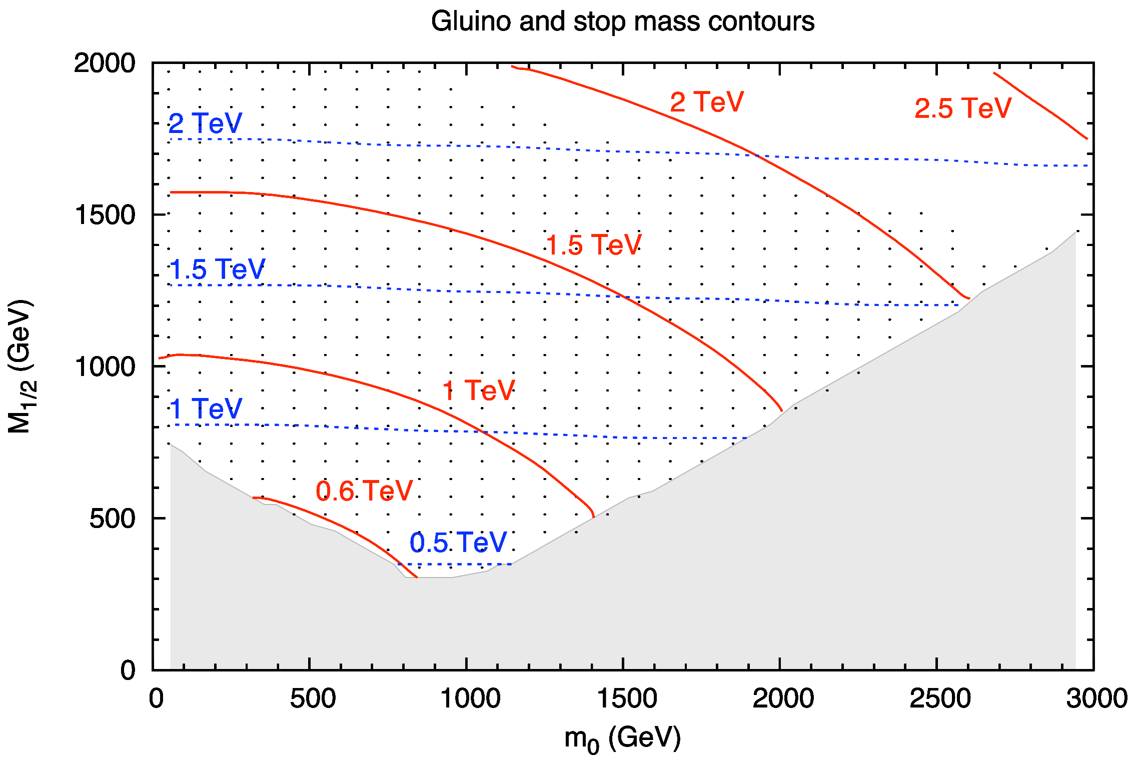
Large values of the f_{ij}'s excluded $\Rightarrow$ leptogenesis can work only in a small region of the seesaw parameter space (otherwise ε_Δ too small)

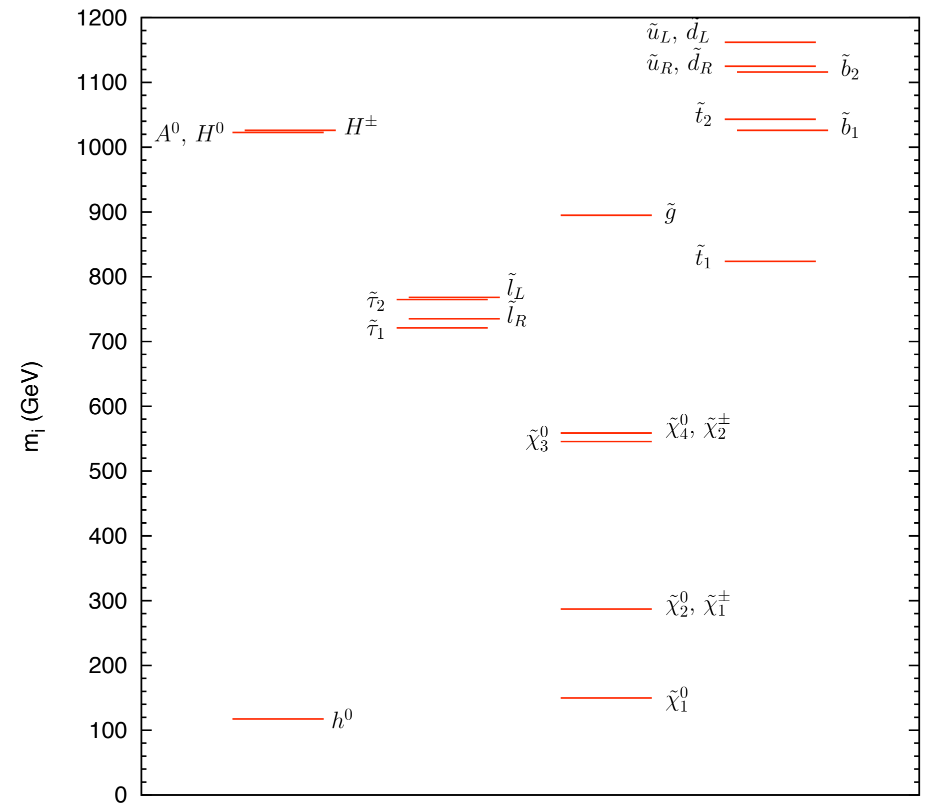


From now on, choose a point in the region of the seesaw parameter space not excluded by $\mu \to e\,\gamma$ where leptogenesis can work:

$$M_\Delta = 10^{12}\,\mathrm{GeV},\;\; \lambda_H = 0.045$$

The ongoing experiment MEG (which will reach a sensitivity of 10^{-13}) will probe most of the Susy parameter space for this point





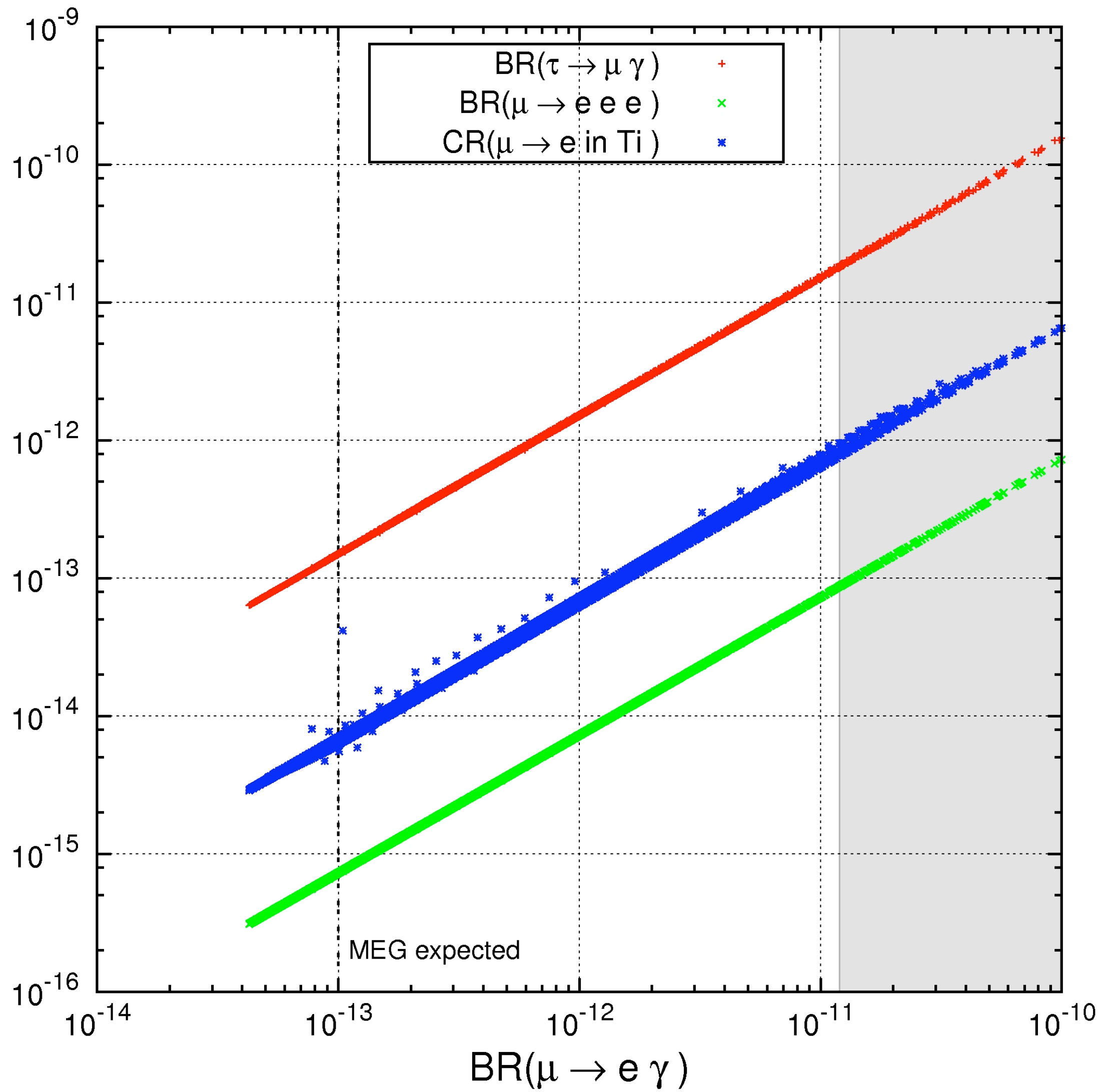
— gluino

— lightest stop

$$m_0 = M_{1/2} = 700\,\mathrm{GeV},$$
$$A_0 = 0,\ \tan\beta = 10$$

The region of the Susy parameter space that will be probed by MEG will also be accessible at the LHC

Sleptons are heavy – the lightest neutralino is always the LSP



— $\tau \to \mu\,\gamma$

— $\mu\,\mathrm{Ti} \to e\,\mathrm{Ti}$

— $\mu \to e\,e\,e$

Correlations between $\mu \to e\,\gamma$ and other LFV processes

Susy parameters: $m_0 = M_{1/2} = 700\,\mathrm{GeV},\ A_0 = 0,\ \tan\beta = 10,\ \mu > 0$

$\mathrm{BR}\,(\tau \to \mu\gamma) \lesssim 2 \times 10^{-11}$: not competitive with $\mu \to e\,\gamma$ (out of reach of super B factories)

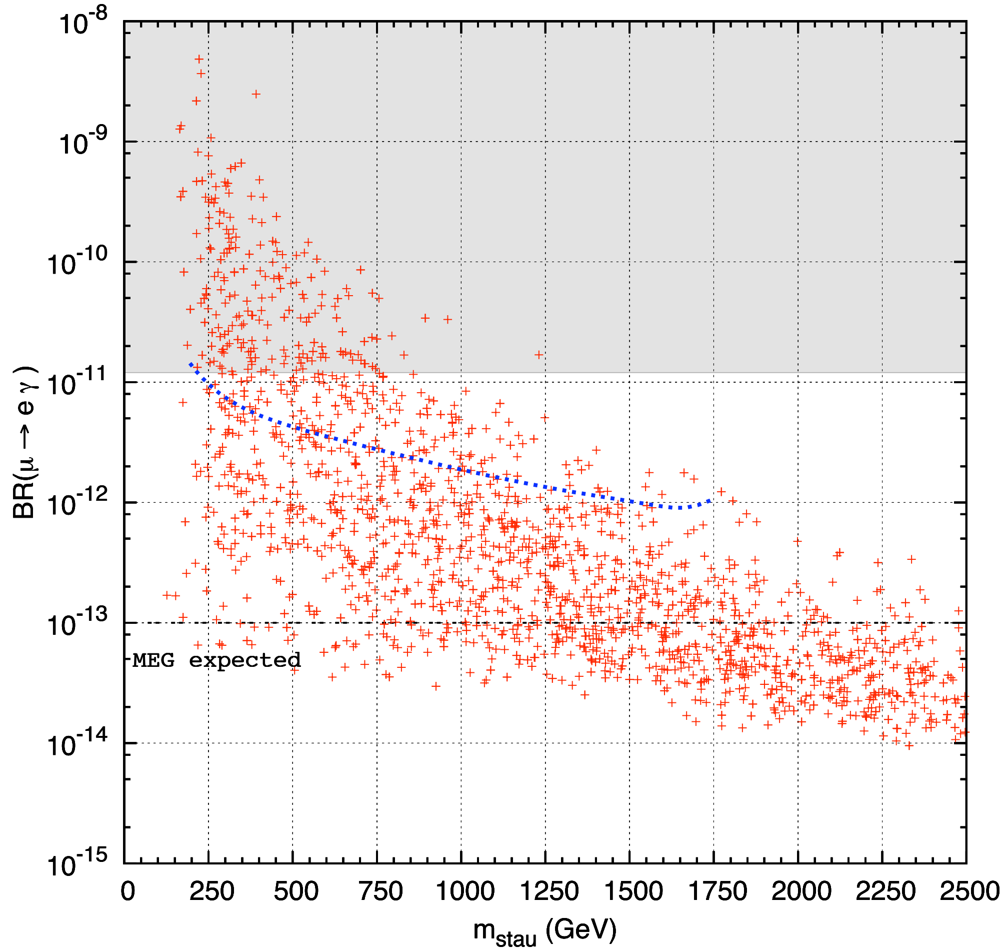
The correlation between $\mu \to e\,\gamma$ and $\tau \to \mu\,\gamma$ is characteristic of the supersymmetric type II seesaw:

$$\frac{\mathrm{BR}\,(\tau \to \mu\gamma)}{\mathrm{BR}\,(\mu \to e\gamma)} \approx 0.17 \left| \frac{(m_L^2)_{32}}{(m_L^2)_{21}} \right|^2 \approx 0.17 \left| \frac{(M_\nu^\dagger M_\nu)_{32}}{(M_\nu^\dagger M_\nu)_{21}} \right|^2 \approx 1.5$$

for θ_{13} close to its experimental upper limit

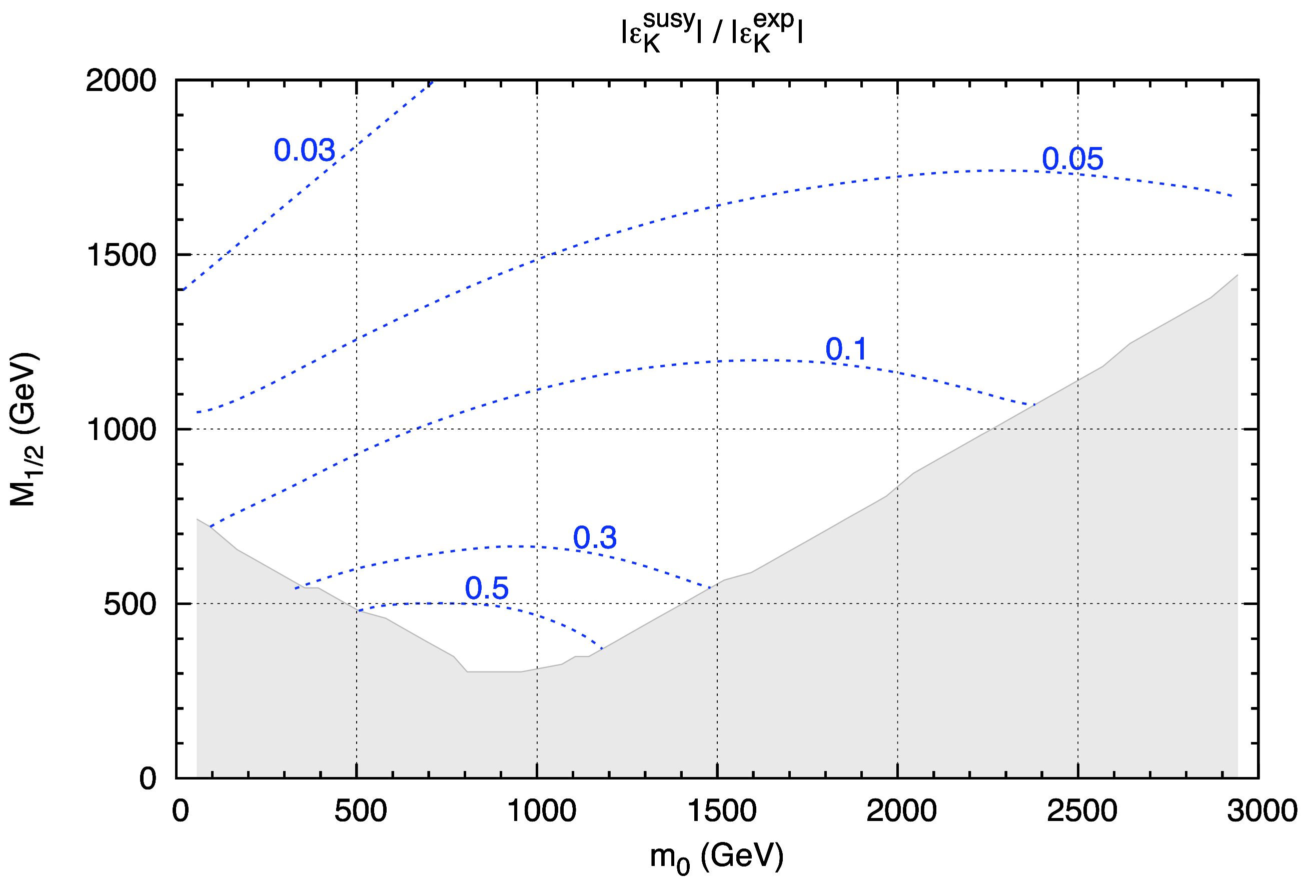
$\mu - e$ conversion looks more promising: the projects Mu2e at FNAL and PRISM/PRIME at J-PARC aim at 10^{-16} and 10^{-18} (the present upper limit is 4.3×10^{-12}) – would be a more powerful probe than MEG

Finally, $\mathrm{BR}\,(\mu \to 3e) \lesssim 10^{-13}$ (the present upper limit is 1.0×10^{-12})



Effect of relaxing the universality of soft scalar masses (keeping them flavour blind), for $M_{1/2} = 700\,\mathrm{GeV},\ A_0 = 0,\ \tan\beta = 10$

Most points remain within the reach of MEG, unless the lightest slepton is very heavy



The only hadronic observable that may receive a significant contribution (in the presence of a large phase, here $\arg\left((m^2_{d^c})_{12}\right) = 0.5$) is ϵ_K

The supersymmetric contribution could easily reach the 10^{-4} level, enough to account for 10% - 20% of the observed value, $(2.229 \pm 0.012) \times 10^{-3}$

[the SM contribution is estimated to be $(1.78 \pm 0.25) \times 10^{-3}$ by Buras and Guadagnoli, arXiv:0901.2056]

Conclusions

- embedding the SM fermions in both 16 and 10 representations makes it possible to realize the type II seesaw mechanism in SO(10) GUTs and leads to a predictive scenario of leptogenesis
- the pattern of flavour violation in this scenario shows some difference with the standard type II seesaw due to the presence of heavy quark and lepton fields
- in the region of seesaw parameters where leptogenesis can work, definite predictions for LFV processes which can be tested by the ongoing MEG experiment (barring cancellations with other sources of LFV, e.g. from supersymmetry breaking)
- in the absence of a positive signal at MEG, the discovery of a relatively light superpartner spectrum at the LHC would strongly disfavour this scenario

Back-up slides

schematically:

At T < M$_\Delta$, decays start to dominate over gauge scatterings $\Delta\Delta^* \to \cdots$

Since $K_L, K_{H_u} \gtrsim 1$, triplets keep close to thermal equilibrium but a $\tilde{L}_1^c$ asymmetry develops due to $K_{\tilde{L}_1^c} \ll 1$

This in turn induces an asymmetry between triplets and antitriplets, which transferred to Δ_L and Δ_{H_u} through their decays

The final B-L asymmetry then reads:

$$Y_{B-L} \simeq \frac{Y_{H_u}^{eq}}{Y_L^{eq} + Y_{H_u}^{eq}} \Delta_{\tilde{L}_1^c} = \frac{4}{7} \Delta_{\tilde{L}_1^c}$$

where $\Delta_{\tilde{L}_1^c} = \eta_0 \, \epsilon_\Delta (Y_\Delta^{eq} + Y_{\Delta^*}^{eq}) \, (T \gg M_\Delta)$

and $\eta_0 \sim 1$ due to $\gamma_A \ll \gamma_D$ and $K_{\tilde{L}_1^c} \ll 1$

We find that successful leptogenesis is possible for $M_\Delta \gtrsim 10^{12}\,\mathrm{GeV}$

This scale is problematic in view of the gravitino problem, which requires $T_{RH} \lesssim (10^9 - 10^{10})\,\mathrm{GeV}$ in the most favourable cases (unstable gravitino with $m_{3/2} \gtrsim 10\,\mathrm{TeV}$ or gravitino LSP with harmless NLSP for BBN)

<u>Ways out:</u>

- very light gravitino (< 16 eV required by WMAP)
- very heavy gravitino (>> 100 TeV)
- non-thermal production of the triplets ($T_{RH} \ll M_\Delta$)
- non-supersymmetric scenario with a real 54

In the following, we consider a supersymmetric scenario with soft terms generated at the GUT scale, and we rely on possibility 2 or 3

SO(10) gauge symmetry breaking

The superpotential

$$\frac{1}{2} f_1 \mathbf{54}' \mathbf{45}_1 \mathbf{45}_1 + (\lambda_{12} \mathbf{S} + f_{12} \mathbf{54}') \mathbf{45}_1 \mathbf{45}_2 + \frac{1}{3} \lambda\, \mathbf{54}' \mathbf{54}' \mathbf{54}' + \overline{\mathbf{16}} (M_{16} + g \mathbf{45}_1) \mathbf{16}$$

leads to the vacuum

$$V_{B-L}^{(1)} = V_R^{(2)} = 0 \ , \qquad V_R^{(1)} = \frac{1}{2g} M_{16} \ , \qquad V_{B-L}^{(2)} = -\frac{3\sqrt{3} f_1}{10\sqrt{2} f_{12} g} M_{16} \ ;$$

$$V_{54'}^2 = -\frac{3 f_1}{8 \lambda g^2} M_{16}^2 \ , \qquad S = -\frac{\sqrt{3} f_{12}}{2\sqrt{5} \lambda_{12}} V_{54'} \ , \qquad V_1^{\overline{16}} V_1^{16} = \frac{\sqrt{3} f_1}{8\sqrt{5} g^2} V_{54'} M_{16}$$

SO(10) is broken in one step down to the SM gauge group if all dimensionless couplings are of order one

Doublet-triplet splitting

Introduce and additional 10'

$$W_{\rm DT} \;=\; \frac{1}{2}\,M_{10'}\,\mathbf{10}'\mathbf{10}' + h\mathbf{10}'\mathbf{45}_2\mathbf{10} + \overline{\mathbf{16}}(M_{16} + g\mathbf{45}_1)\mathbf{16} + \frac{1}{2}\,\bar{\eta}\,\overline{\mathbf{16}}\,\overline{\mathbf{16}}\,\mathbf{10}$$

Doublet and triplet mass matrices:

$$M_D \;=\; \begin{pmatrix} 0 & 0 & -\bar{\eta}V_1^{\overline{16}} \\ 0 & M_{10'} & 0 \\ 0 & 0 & M_{16} \end{pmatrix} \qquad M_T \;=\; \begin{pmatrix} 0 & \frac{h}{\sqrt{6}}V_{B-L} & -\bar{\eta}V_1^{\overline{16}} \\ -\frac{h}{\sqrt{6}}V_{B-L} & M_{10'} & 0 \\ 0 & 0 & M_{16} + 2gV_R \end{pmatrix}$$

Light Higgs doublets:

$$h_u \;=\; H_u^{10} \qquad h_d \;=\; \cos\theta_H H_d^{10} + \sin\theta_H H_d^{16} \qquad \tan\theta_H \;=\; \frac{\bar{\eta}V_1^{\overline{16}}}{M_{16}}$$

D=5 proton decay operator proportional to:

$$\left(M_T^{-1}\right)_{T^{10}\overline{T}^{16}} \;=\; \frac{3\bar{\eta}V_1^{\overline{16}}M_{10'}}{M_{16}\left(hV_{B-L}\right)^2}$$

$\Rightarrow$ «conservative» upper bound: $M_{10'} \lesssim 10^{14}\,\mathrm{GeV}$