Lepton Flavour Violation and the Flavour Puzzle

Stefan Antusch

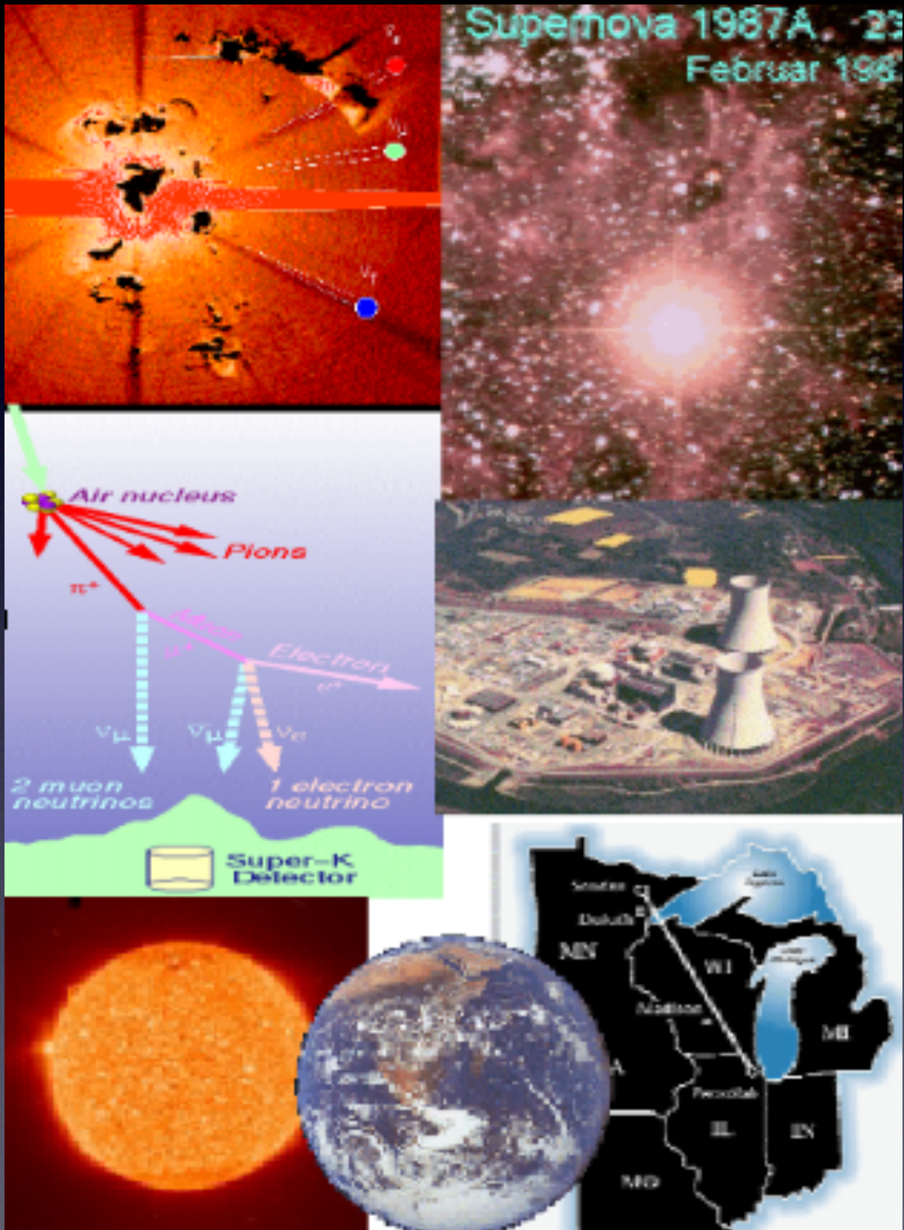
University of Basel
Department of Physics

Max-Planck-Institut für Physik
(Werner-Heisenberg-Institut)

Beauty 2013, Bologna

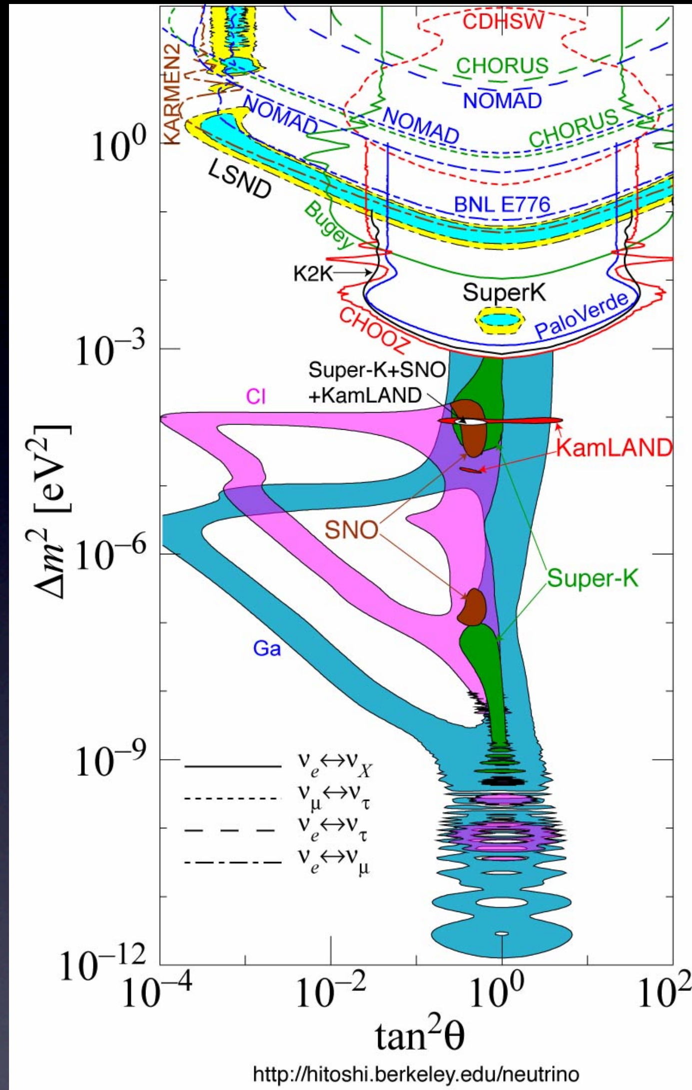
April 9, 2013

LFV exists ...



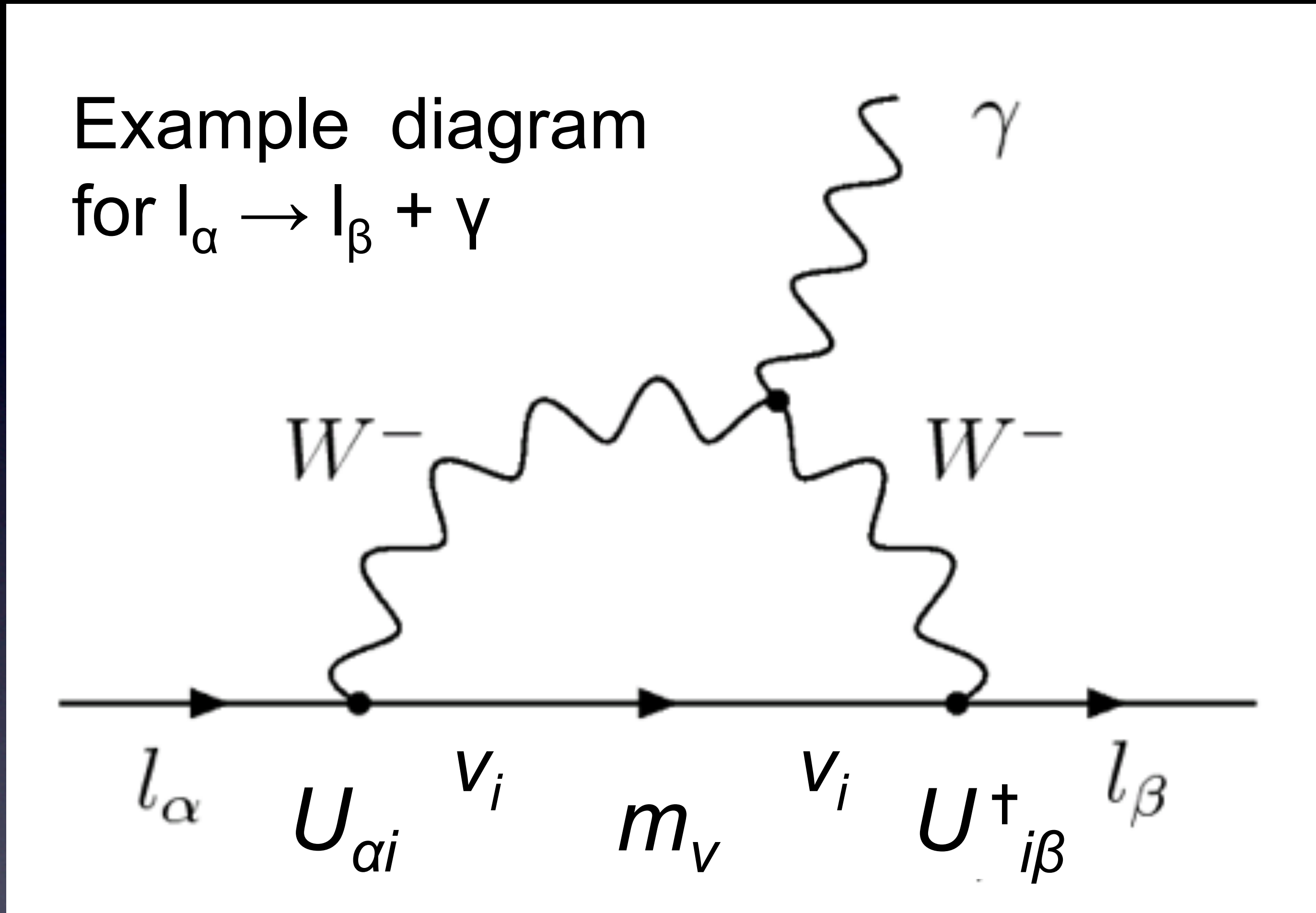
Neutral LFV is observed!

<u>ν oscillations</u> imply neutrino masses



⇒ also charged LFV exists ...

LFV in the SM + neutrino masses



E.g. in the SM + d=5 operator

However, it is well known that the branching ratios are suppressed by $(m_\nu/M_W)^4$ for unitary U (↔ GIM mechanism) and thus unobservably small ...

However, as soon as one extends the SM by a mechanism to generate the neutrino masses, charged LFV is typically induced at a much larger rate ... !

(Some of) the pieces of the flavour puzzle

I) The SM
flavour puzzle

II) The neutrino
flavour puzzle

III) The "new physics"
flavour puzzle

IV) The puzzle of
CP violation

(Some of) the pieces of the flavour puzzle

I) The SM flavour puzzle

II) The neutrino flavour puzzle

this talk

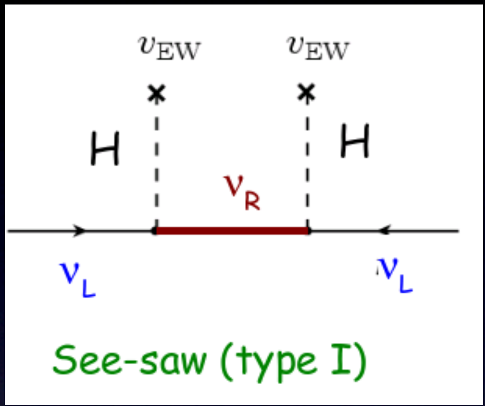
III) The "new physics" flavour puzzle

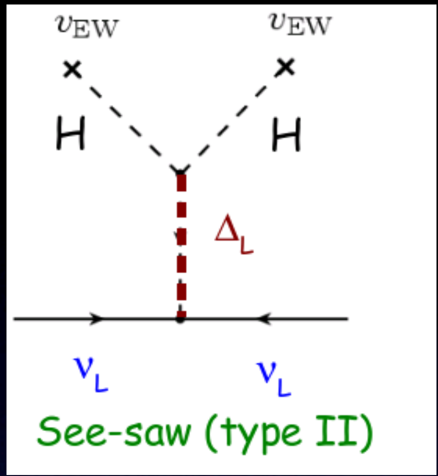
IV) The puzzle of CP violation

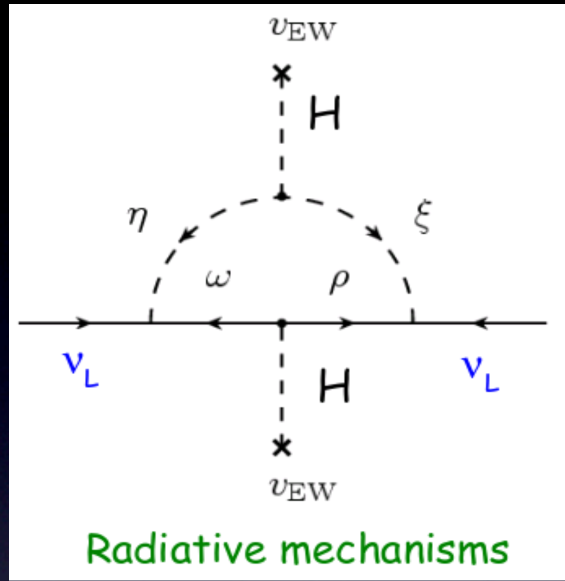
Overview: Two examples ...

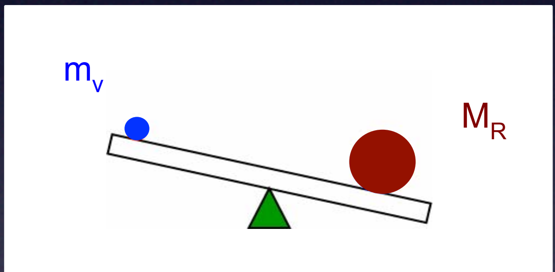
- Botton-up example: LFV & non-unitarity of the leptonic mixing matrix
- Top-down example: LFV in SUSY GUT models of flavour

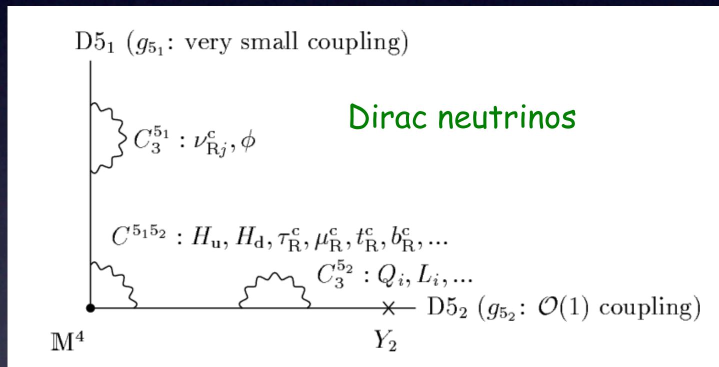
Neutrino masses:
How to extend the SM?

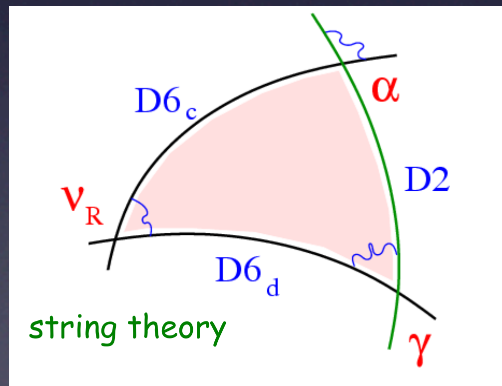




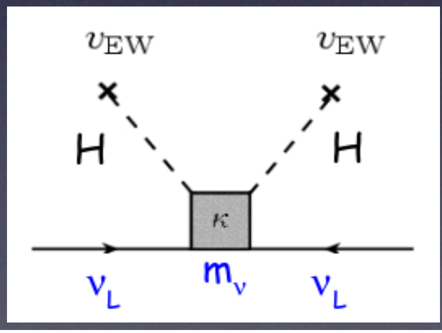


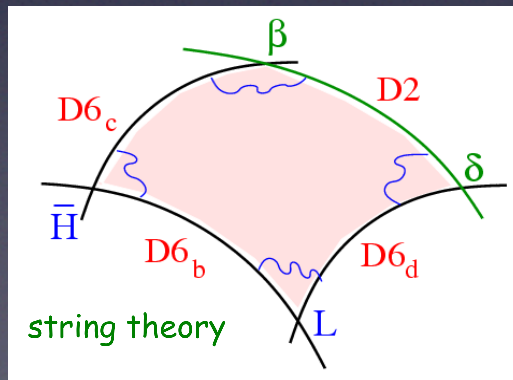






Effective theory:
d=5 operator





$$\delta\mathcal{L}^{d=5} = \frac{1}{2}\, c^{d=5}_{\alpha\beta} \left(\overline{L^c}_\alpha \tilde{\phi}^*\right) \left(\tilde{\phi}^\dagger L_\beta\right) + h.c.$$

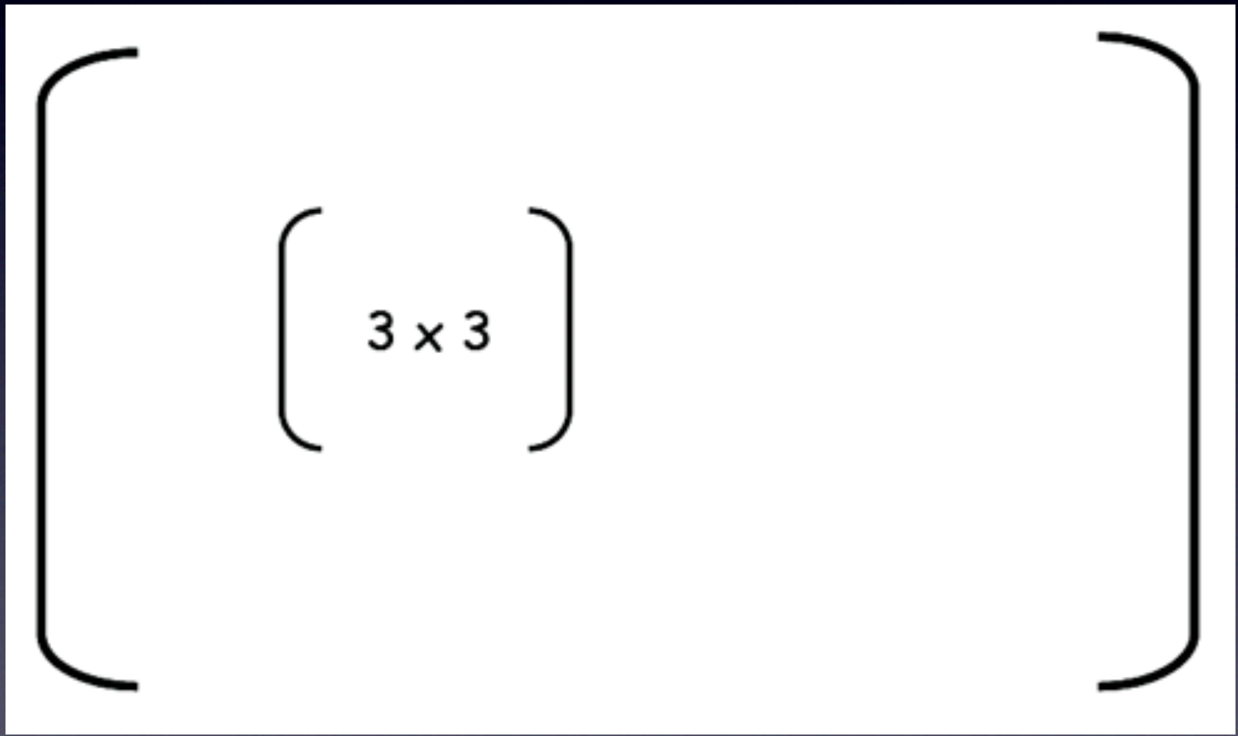
A comparatively model-independent consequence of new physics introduced to generate the observed neutrino masses:

Non-unitarity of the leptonic mixing matrix ...

Non-unitary leptonic mixing

- Typical situation, intuitively:

(Effective) mixing matrix of light neutrinos is submatrix of a larger unitary mixing matrix (mixing with additional heavy particles)



Langacker, London ('88)

$\Rightarrow U_{PMNS} \equiv N$ is non-unitary

Examples with possible large non-unitarity: 'inverse' seesaw or 'multiple' seesaw at TeV energies, SUSY with R-parity violation, large extra dimensions, ...

Non-unitary leptonic mixing

- Lagrangian in the mass basis ...

kinetic term → neutrino mass term → charged current interaction → non-unitary mixing matrix N

$$\mathcal{L}^{eff} = \frac{1}{2}\left(\bar{\nu}_i i \partial\!\!\!/ \nu_i - \overline{\nu^c}_i m_i \nu_i + h.c.\right) - \frac{g}{2\sqrt{2}}\left(W^+_\mu \bar{l}_\alpha \gamma_\mu (1-\gamma_5) N_{\alpha i} \nu_i + h.c.\right)$$
$$- \frac{g}{2\cos\theta_W}\left(Z_\mu \bar{\nu}_i \gamma^\mu (1-\gamma_5) (N^\dagger N)_{ij} \nu_j + h.c.\right) + \ldots$$

+ modification in neutral current interaction in minimal schemes (MUV), to be explained later ...

Non-unitary leptonic mixing

- ... now when we change to the flavour basis:

non-canonical kinetic terms

$$\begin{aligned}\mathcal{L}^{eff} \;=\; & \frac{1}{2}\left(i\,\bar{\nu}_\alpha\,\partial\!\!\!/\,(NN^\dagger)^{-1}_{\alpha\beta}\,\nu_\beta - \overline{\nu^c}_\alpha\,[(N^{-1})^t m N^{-1}]_{\alpha\beta}\,\nu_\beta + h.c.\right) \\ & - \frac{g}{2\sqrt{2}}\left(W^+_\mu\,\bar{l}_\alpha\,\gamma^\mu\,(1-\gamma_5)\,\nu_\alpha + h.c.\right) \\ & - \frac{g}{2\cos\theta_W}\left(Z_\mu\,\bar{\nu}_\alpha\,\gamma^\mu\,(1-\gamma_5)\,\nu_\alpha + h.c.\right) + \ldots\,,\end{aligned}$$

Non-unitarity of the leptonic mixing matrix corresponds to non-canonical kinetic terms in the flavour basis!

Non-unitary leptonic mixing

- There is a unique gauge invariant d=6 effective operator which leads to non-canonical kinetic terms only for the neutrinos:

$$\delta\mathcal{L}^{d=6} = c^{d=6}_{\alpha\beta} \left(\overline{L}_\alpha \tilde{\phi}\right) i\partial\!\!\!/ \left(\tilde{\phi}^\dagger L_\beta\right)$$

- After EW symmetry breaking it results in a non-unitary leptonic mixing matrix with:

De Gouvea, Giudice, Strumia, Tobe ('01), Broncano, Gavela, Jenkins ('02)

$$|NN^\dagger - 1|_{\alpha\beta} = \frac{v^2}{2} |c^{d=6}|_{\alpha\beta}$$

S.A., Biggio, Fernandez-Martinez, Gavela, Lopez-Pavon ('06)

- + modification of the NC interaction shown earlier ...

Non-unitary leptonic mixing

- A minimal way to introduce neutrino masses and non-unitary leptonic mixing thus consists in adding a d=5 and a d=6 operator to the SM:

$$\mathcal{L}^{eff} = \mathcal{L}_{SM} + \delta\mathcal{L}^{d=5} + \delta\mathcal{L}^{d=6} + \ldots$$

MUV scheme: Minimal Unitarity Violation

S.A., Biggio, Fernandez-Martinez, Gavela, Lopez-Pavon ('06)

Neutrino masses (violates L)

$$\delta\mathcal{L}^{d=5} = \frac{1}{2}\, c^{d=5}_{\alpha\beta} \left(\overline{L^c}_\alpha \tilde{\phi}^*\right)\left(\tilde{\phi}^\dagger L_\beta\right) + h.c.$$

Non-unitarity (conserves L)

$$\delta\mathcal{L}^{d=6} = c^{d=6}_{\alpha\beta} \left(\overline{L}_\alpha \tilde{\phi}\right) i\partial\!\!\!/ \left(\tilde{\phi}^\dagger L_\beta\right)$$

not necessarily suppressed by the smallness of the neutrino masses

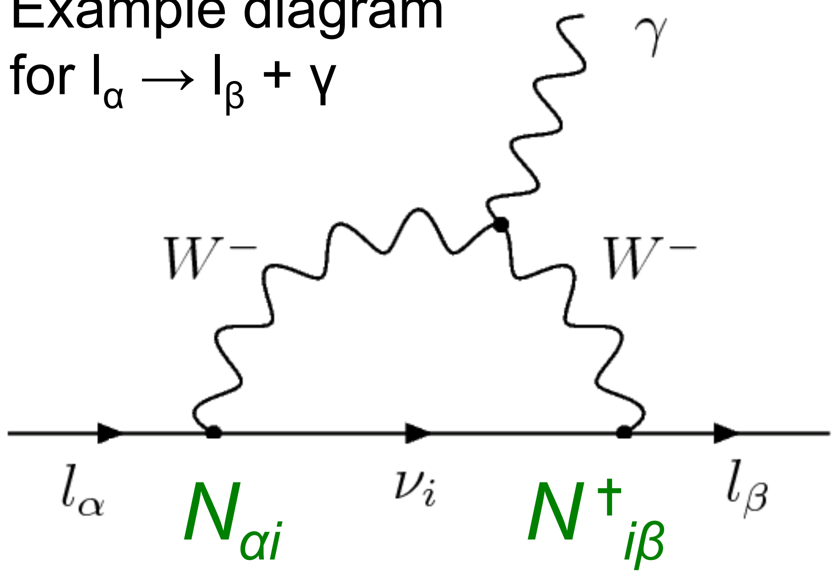
Consequences of leptonic non-unitarity

- In the SM as an effective theory, the data should in principle be analyzed with a general, non-unitary leptonic mixing matrix N ...
- From neutrino oscillations alone, the general, non-unitary leptonic mixing matrix is quite poorly determined!
- However, leptonic non-unitarity gets constrained by various other physical processes ..., e.g. by
  - invisible Z decays
  - W decays
  - processes which are also used as universality tests
  - LFV processes

Constraints on leptonic non-unitarity

- Important part of the constraints stems from LFV μ and τ decays (and in the future maybe also from μ → 3e and/or from μ → e conversion in nuclei):

Example diagram for $l_\alpha \to l_\beta + \gamma$



$$\frac{\Gamma(\ell_\alpha \to \ell_\beta \gamma)}{\Gamma(\ell_\alpha \to \nu_\alpha \ell_\beta \overline{\nu}_\beta)} = \frac{3\alpha}{32\pi} \frac{|\sum_k N_{\alpha k} N^\dagger_{k\beta} F(x_k)|^2}{(NN^\dagger)_{\alpha\alpha}(NN^\dagger)_{\beta\beta}}$$

irrelevant for unitary mixing matrix, but can lead to sizable Br's for non-unitary N!

$$F(x) \equiv \frac{\boxed{10} - 43x + 78x^2 - 49x^3 + 4x^4 + 18x^3 \ln x}{3(x-1)^4}$$

where:

$$x_k \equiv m_k^2 / M_W^2$$

m_k: light neutrinos' masses

Constraints on leptonic non-unitarity

- LFV bounds result in strong constraints on the off diagonal elements

$$(N\,N^{\dagger})_{\alpha\beta}$$

- In summary (from a global fit to all data), the constraints are:

from $\mu \rightarrow e\,\gamma$

$$|(NN^{\dagger})_{\alpha\beta} - \delta_{\alpha\beta}| = \frac{v^2}{2}|c^{d=6,kin}_{\alpha\beta}| < \begin{pmatrix} 4.0 \cdot 10^{-3} & 1.2 \cdot 10^{-4} & 3.2 \cdot 10^{-3} \\ 1.2 \cdot 10^{-4} & 1.6 \cdot 10^{-3} & 2.1 \cdot 10^{-3} \\ 3.2 \cdot 10^{-3} & 2.1 \cdot 10^{-3} & 5.3 \cdot 10^{-3} \end{pmatrix}$$

Note: Latest MEG bounds not yet included ...

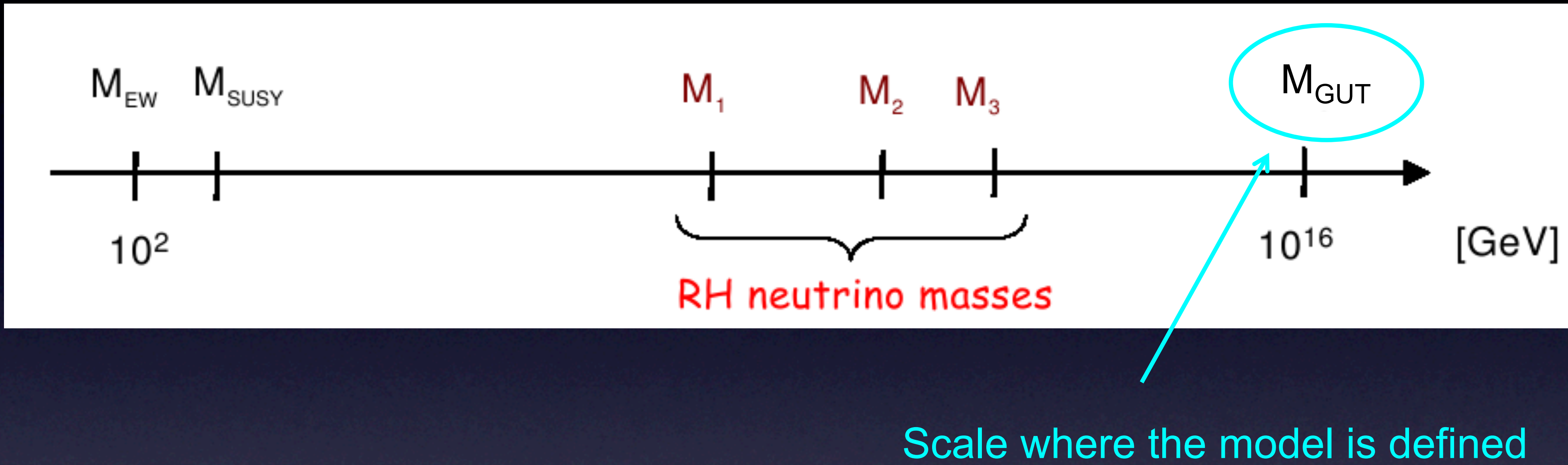
S.A., Biggio, Fernandez-Martinez, Gavela, Lopez-Pavon ('06)
S.A., Baumann, Fernandez-Martinez ('08)

Now changing to a top-down motivated approach:

In (supersymmetric) GUTs, neutrino masses are typically generated via the seesaw mechanism at high energies.

In SUSY GUT models of flavour, there are two effects inducing charged LFV …

For example: Scales in the type I seesaw scenario:



I) Non-universal soft SUSY breaking parameters (e.g. slepton masses) at high energies (= intrinsic non-universalities)

E.g.:

$$\tilde{m}_{LL}^{\text{High Scale}} = \begin{pmatrix} (m^2_{\tilde{L}L})_{11} & (\Delta_{LL})_{12} & (\Delta_{LL})_{13} \\ (\Delta_{LL})_{21} & (m^2_{\tilde{L}L})_{22} & (\Delta_{LL})_{23} \\ (\Delta_{LL})_{31} & (\Delta_{LL})_{32} & (m^2_{\tilde{L}L})_{33} \end{pmatrix}$$

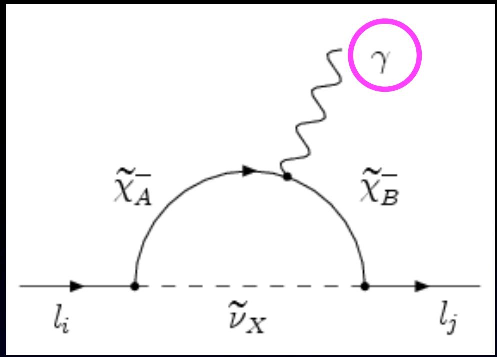
II) Non-universalities induced by RG effects from Y_ν

Borzumati, Masiero ('86), Hisano et al ('96)

$$m^2_{\tilde{L}_{ij}} = m_0^2 \begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{pmatrix} + \delta m^2_{\tilde{L}_{ij}} \xleftarrow{\text{RG running}} m^2_{\tilde{L}_{ij}} = m_0^2 \begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

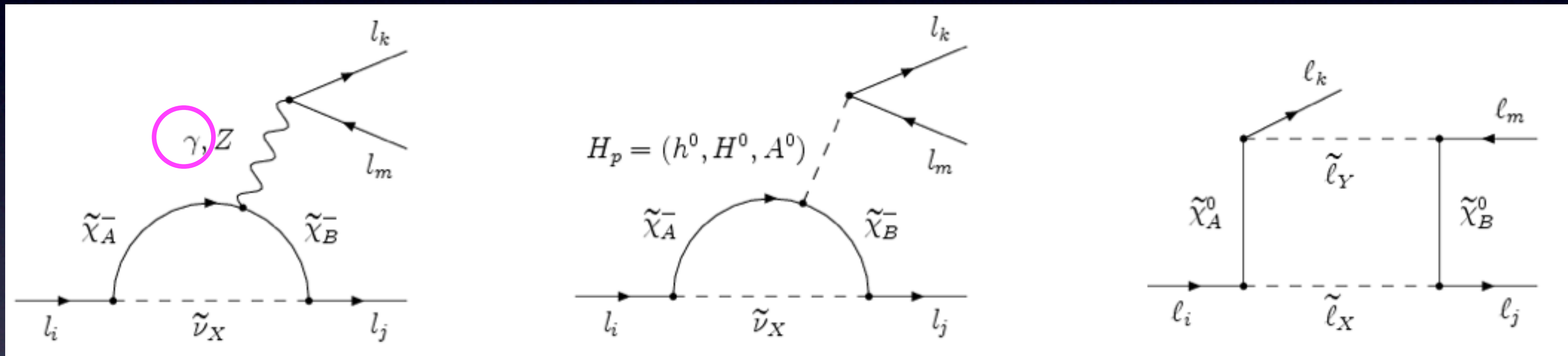
LFV processes in SUSY extensions

- $l_\alpha \rightarrow l_\beta + \gamma$

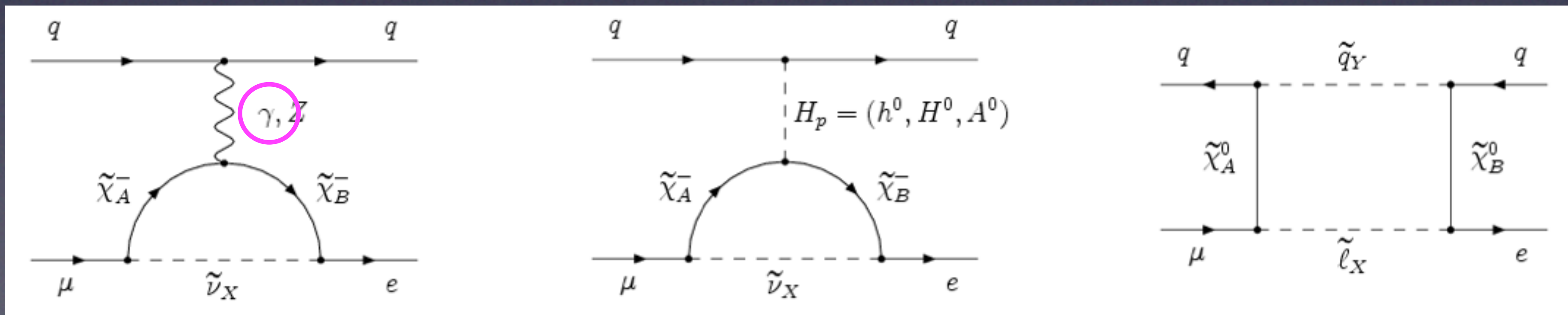


<u>Remark:</u> Typically close relations between the Br's for these processes if the γ diagrams dominate …

- $l_\alpha \rightarrow 3\, l_\beta$

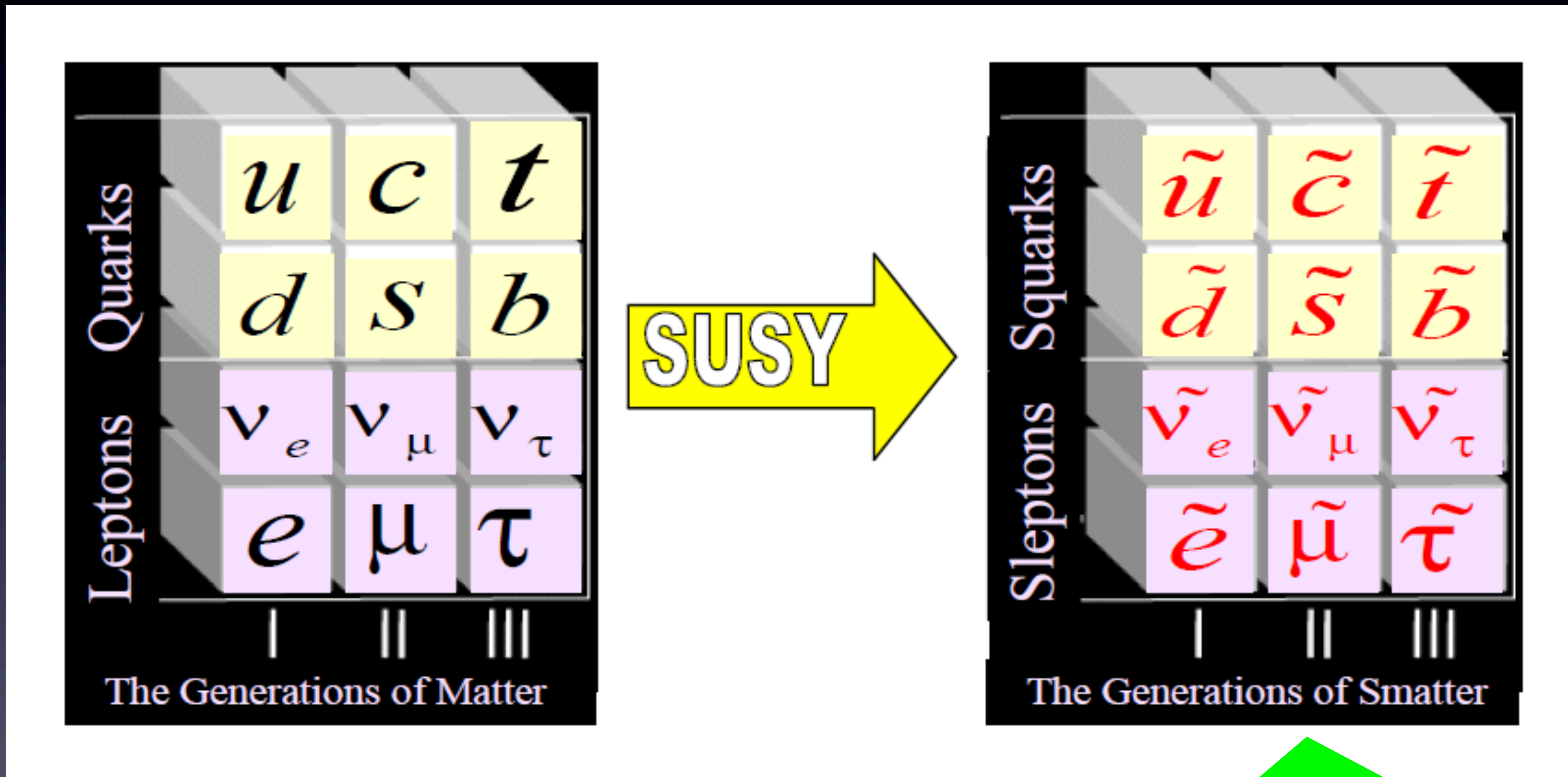


- $\mu \rightarrow e$ conversion in nuclei



I) LFV from the model at high energies

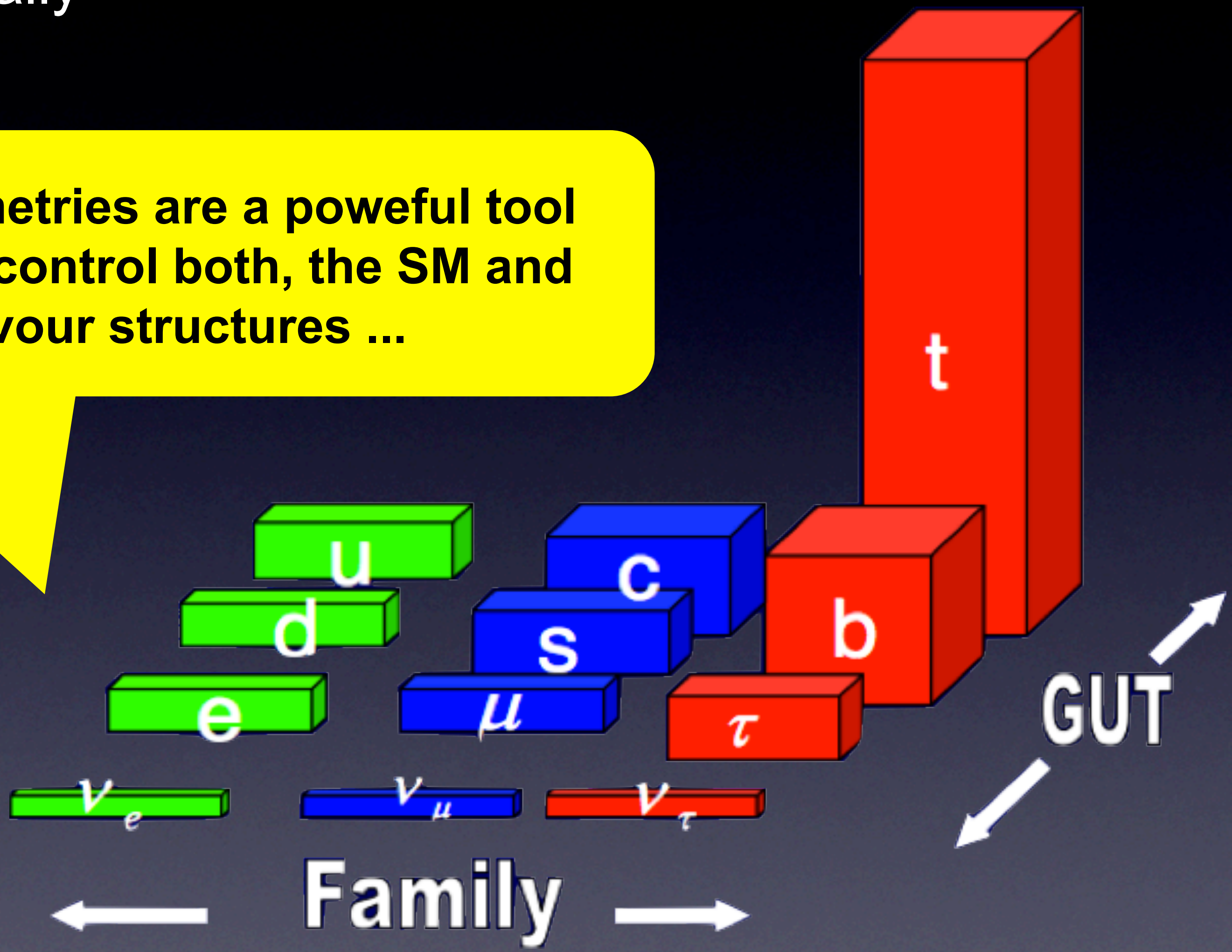
- SUSY is broken: SUSY particles have their own flavour structure
  → New souces of LFV!



What can control the flavour structure of the SUSY particles?

- GUT symmetries unify “vertically”, family symmetries unify “horizontally”

Family symmetries are a poweful tool to constrain/control both, the SM and the SUSY flavour structures ...



Family symmetries and the SUSY flavour structure

Particularly efficient: Non-Abelian family symmetries where all familie are in 3 of G_{Fam}!

- Explain flavour structure in the SM, e.g.:

Abel, Khalil, Lebedev ('01)
Ross, Vives ('02),
Ross, Velasco-Sevilla, Vives ('04)
S.A., King, Malinsky ('07)
...

$$M_d \sim \begin{pmatrix} 0 & \varepsilon_1\varepsilon_2 & \varepsilon_1\varepsilon_2 \\ \varepsilon_1\varepsilon_2 & \varepsilon_2^2 & \varepsilon_2^2 \\ \varepsilon_1\varepsilon_2 & \varepsilon_2^2 & \varepsilon_3^2 \end{pmatrix} v_\mathrm{d}$$

- Generate flavour stucture of the SUSY particles:

SUSY flavour "problem" can be resolved in SUGRA: S.A., King, Ross, Malinsky ('08)

$$\widetilde{M}_{d_R} \sim \begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{pmatrix} m_0 + \begin{pmatrix} \varepsilon_1^2 & \varepsilon_1^2 & \varepsilon_1^2 \\ \varepsilon_1^2 & \varepsilon_2^2 & \varepsilon_2^2 \\ \varepsilon_1^2 & \varepsilon_2^2 & \varepsilon_3^2 \end{pmatrix} m_0$$

Universality (at LO) is enforced by the family symmetry!

$$A_d \sim \begin{pmatrix} 0 & \varepsilon_1\varepsilon_2 & \varepsilon_1\varepsilon_2 \\ \varepsilon_1\varepsilon_2 & \varepsilon_2^2 & \varepsilon_2^2 \\ \varepsilon_1\varepsilon_2 & \varepsilon_2^2 & \varepsilon_3^2 \end{pmatrix} A_0$$

SUSY flavour structure related to the one of the SM

Altmannshofer, Buras, Gori, Paradisi, Straub ('09)

Flavour physics effects = "DNA" of flavour models

	AC	RVV2	AKM	δLL	FBMSSM	LHT	RS
$D^0 - \bar{D}^0$	★★★	★	★	★	★	★★★	?
ϵ_K	★	★★★	★★★	★	★	★★	★★★
$S_{\psi\phi}$	★★★	★★★	★★★	★	★	★★★	★★★
$S_{\phi K_S}$	★★★	★★	★	★★★	★★★	★	?
$A_{\rm CP}(B \to X_s\gamma)$	★	★	★	★★★	★★★	★	?
$A_{7,8}(B \to K^*\mu^+\mu^-)$	★	★	★	★★★	★★★	★★	?
$A_9(B \to K^*\mu^+\mu^-)$	★	★	★	★	★	★	?
$B \to K^{(*)}\nu\bar{\nu}$	★	★	★	★	★	★	★
$B_s \to \mu^+\mu^-$	★★★	★★★	★★★	★★★	★★★	★	★
$K^+ \to \pi^+\nu\bar{\nu}$	★	★	★	★	★	★★★	★★★
$K_L \to \pi^0\nu\bar{\nu}$	★	★	★	★	★	★★★	★★★
$\mu \to e\gamma$	★★★	★★★	★★★	★★★	★★★	★★★	★★★
$\tau \to \mu\gamma$	★★★	★★★	★	★★★	★★★	★★★	★★★
$\mu + N \to e + N$	★★★	★★★	★★★	★★★	★★★	★★★	★★★
d_n	★★★	★★★	★★★	★★	★★★	★	★★★
d_e	★★★	★★★	★★	★	★★★	★	★★★
$(g-2)_\mu$	★★★	★★★	★★	★★★	★★★	★	?

Table 8: "DNA" of flavour physics effects for the most interesting observables in a selection of SUSY and non-SUSY models ★★★ signals large effects, ★★ visible but small effects and ★ implies that the given model does not predict sizable effects in that observable.

Recent analysis in a class of flavour models …

- Model class: G_{GUT} = SU(5); G_{Fam} = SO(3), spontaneoulsy broken by flavour Higgs fields (in representations 3 of SO(3)) with vacuum expectation values pointing in the following flavour directions:

S.A., Calibbi, Maurer, Spinrath ('11)

$$\frac{\langle\phi_1\rangle}{\Lambda} \sim \begin{pmatrix} 1 \\ 1 \\ -1 \end{pmatrix} \varepsilon_1 \quad \frac{\langle\phi_2\rangle}{\Lambda} \sim \begin{pmatrix} 0 \\ 1 \\ 1 \end{pmatrix} \varepsilon_2$$

CP violation in the quark sector with a right angled UT (i.e. with α = 90°)

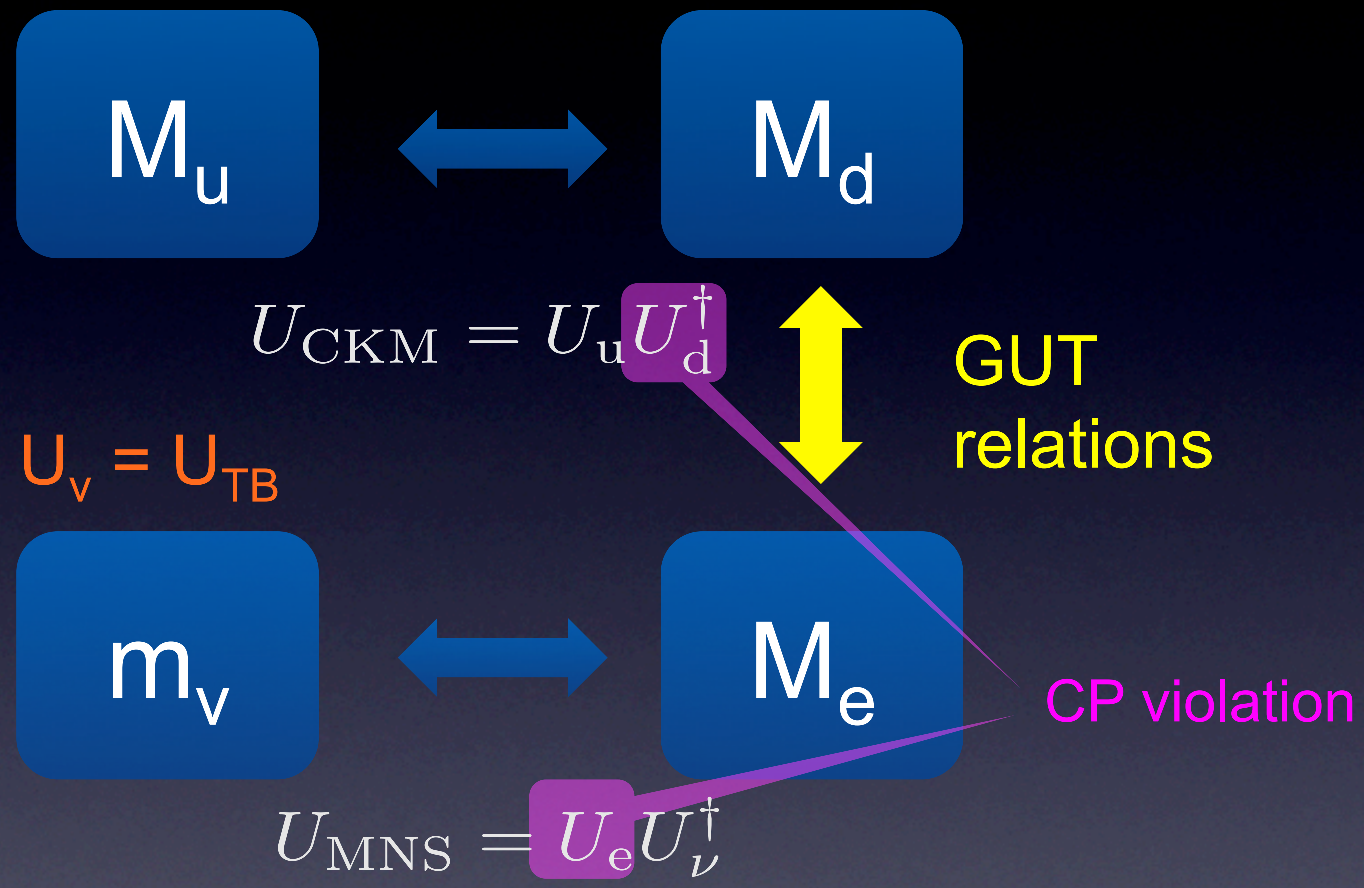
In leading order: Large "Tri-Bimaximal" mixing (in the neutrino-sector)

$$\frac{\langle\phi_3\rangle}{\Lambda} \sim \begin{pmatrix} 0 \\ 0 \\ 1 \end{pmatrix} \varepsilon_3 \quad \frac{\langle\phi_4\rangle}{\Lambda} \sim \begin{pmatrix} 0 \\ i \\ O(1) \end{pmatrix} \tilde{\varepsilon}_4$$

+ sequestering in the Kähler potential

ϕ_3 and ϕ_4 in 24 of SU(5) ⇒ GUT relations, e.g. $m_\tau/m_b = 3/2$ and $m_\mu/m_s = 9/2$

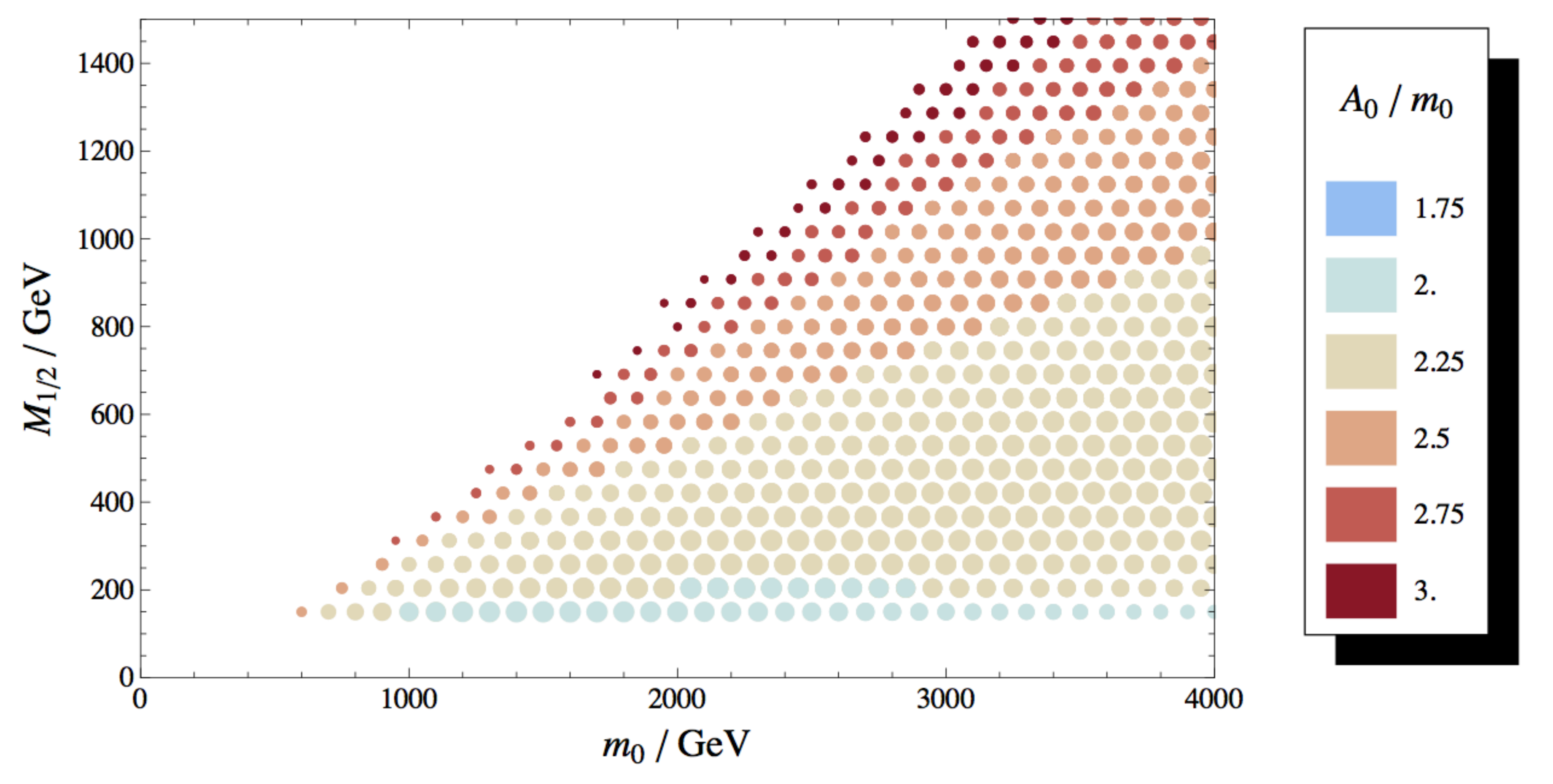
→ **Quark and lepton flavour structure (including CP violation)**



✓ Good fit to the experimental data; Predictions: $\delta^{MNS} \sim \pm 90°$, SUSY spectrum, SUSY flavour structure; non-zero θ_{13}^{PMNS} from charged lepton mixing effects

Constraints on the SUSY spectrum

CMSSM-like (+ non-universalities)



S.A., Calibbi, Maurer, Spinrath ('11)

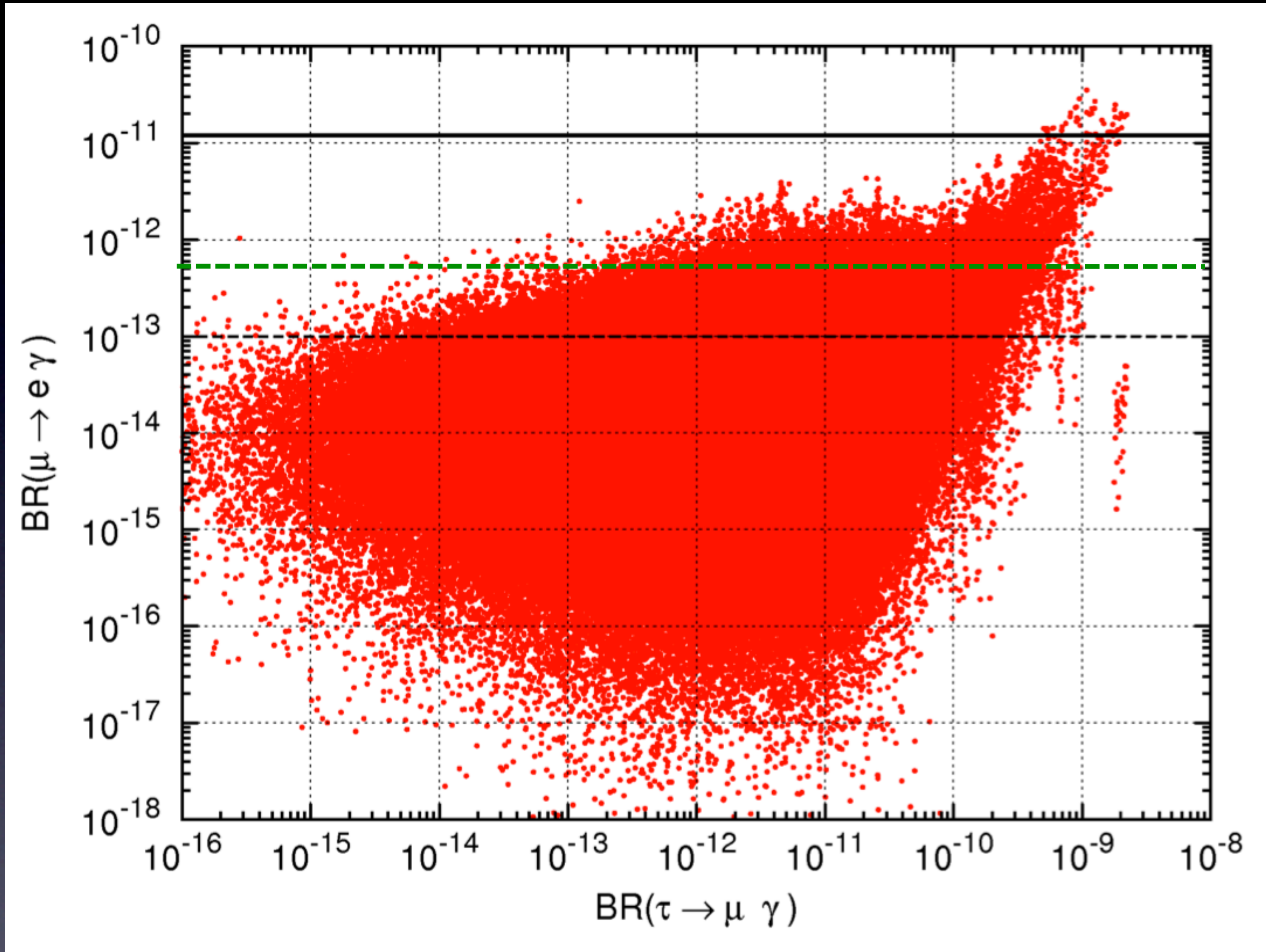
→ Comparatively heavy SUSY preferred

→ Higgs mass m_h ~ 125 GeV can be accommodated

Charged LFV in a SUSY GUT "toy model"

S.A., Calibbi, Maurer, Spinrath ('11)

Here: The intrinsic non-universalities at M_{GUT} are the dominant source of LFV!



MEG (2013): $Br(\mu \to e\gamma) < 5.7 \times 10^{-13}$ (@ 90% CL)

Although flavour effects are suppressed by comparatively heavy SUSY:
Nevertheless, charged LFV provides one of the most promising signals …

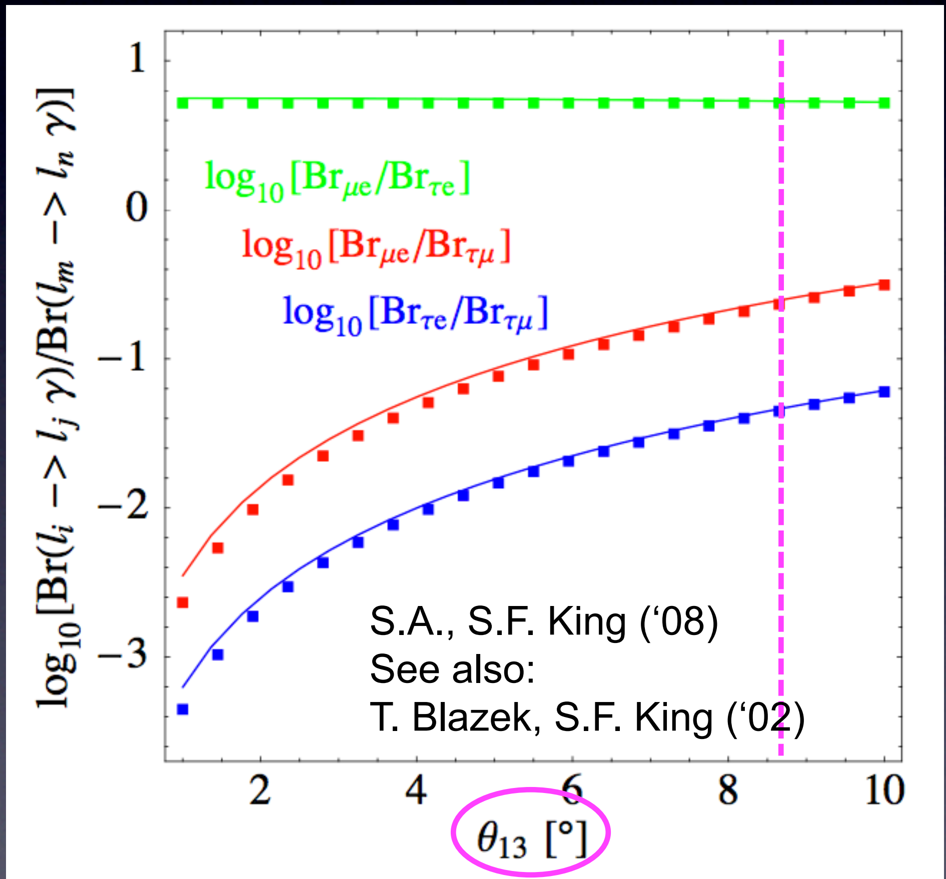
Even in the presence of a mechanism which enforces a universal flavour structure at high energies, there is still LFV induced by RG running

→ In this case: LFV can offers a window into the flavour structure of the SUSY seesaw …

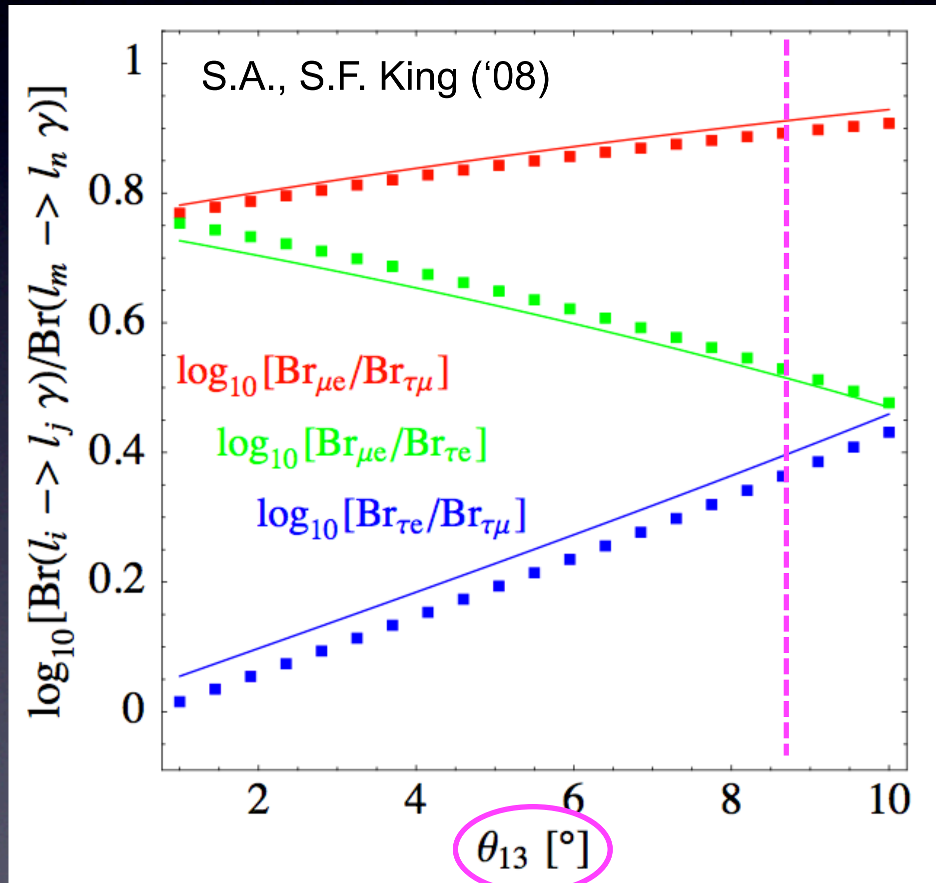
Borzumati, Masiero (‘86), Hisano et al (’96), ...
various works by many authors on this subject

Example: Classes of neutrino mass models predict very different ratios of Br's …

A: Heavy Sequential Dominance



B: Intermediate Sequential Dominance



Note: $\theta_{13}^{PMNS} = 8.6° \pm 0.5°$ has recently been measured! T2K, Minos, DoubleCHOOZ. DayaBay, RENO

Also, when constraints are imposed on the SUSY seesaw, e.g. from leptogenesis:

MEG (2013):
Br(μ → e γ)
< 5.7 x 10^{-13}
(@ 90% CL)

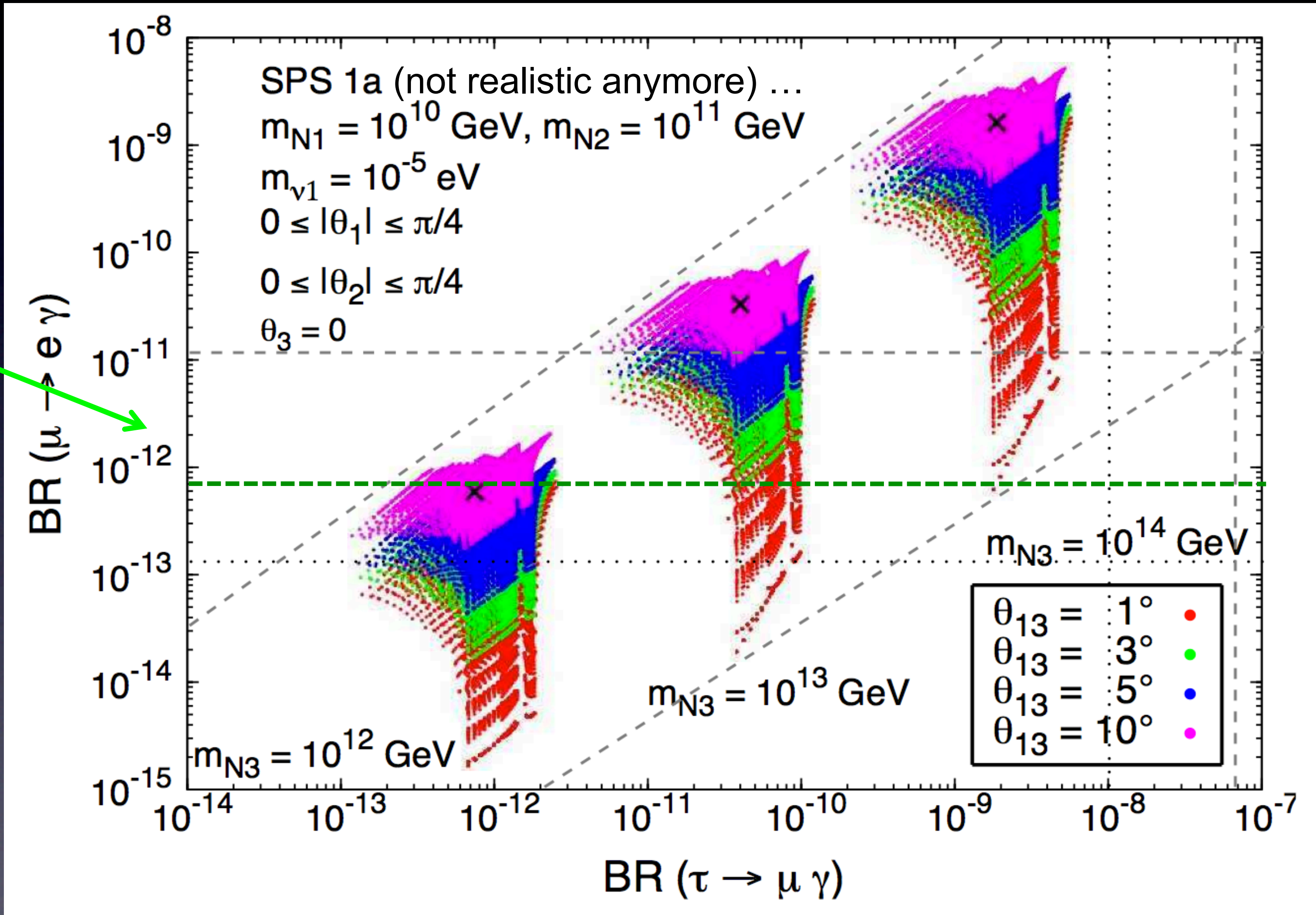


Figure from:
S.A., Arganda, Herrero, Teixeira ('06)

→ Correlations between observables → Constraints on seesaw parameters

Summary and concluding remarks

- Charged LFV processes provide important channels to search for physics beyond the SM
- Many new physics scenarios receive strong constraints from/ predict observable rates for LFV processes
  - Bottom-up example: Strong constraints on the possible non-unitarity of the leptonic mixing matrix from LFV
  - Top-down example: LFV in SUSY GUT flavour models
- New insights expected from the future experimental results … !

Thanks for your attention!