Connection between $g-2$, EDMs, CLFV and LHC

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Open questions

- **The origin of flavour is still, to a large extent, a mystery. The most important open questions can be summarized as follow:**
  - **Which is the organizing principle behind the observed pattern of fermion masses and mixing angles?**
  - **Are there extra sources of flavour symmetry breaking beside the SM Yukawa couplings which are relevant at the TeV scale?**
- **Related important questions are:**
  - **Which is the role of flavor physics in the LHC era?**
  - **Do we expect to understand the (SM and NP) flavor puzzles through the synergy and interplay of flavor physics and the LHC?**

NP search strategies

- **High-energy frontier: A unique effort to determine the NP scale**

- **High-intensity frontier (flavor physics): A collective effort to determine the flavor structure of NP**

Where to look for New Physics at the low energy?

- **Processes very suppressed or even forbidden in the SM**
  - FCNC processes ($\mu \to e\gamma$, $\mu \to eee$, $\mu \to e$ in N, $\tau \to \mu\gamma$, $B^0_{s,d} \to \mu^+\mu^-$...)
  - CPV effects in the electron/neutron EDMs, $d_{e,n}$...
  - FCNC & CPV in $B_{s,d}$ & D decay/mixing amplitudes

- **Processes predicted with high precision in the SM**
  - EWPO as $(g-2)_{\mu,e}$: $a_\mu^{exp} - a_\mu^{SM} \approx (3 \pm 1) \times 10^{-9}$, a discrepancy at 3σ!
  - LU in $R_M^{e/\mu} = \Gamma(M \to e\nu)/\Gamma(M \to \mu\nu)$ with $M = \pi, K$

Experimental status

LFV process	Experiment	Future limits	Year (expected)
BR($\mu \to e\gamma$)	MEG	$\mathcal{O}(10^{-14})$	~ 2017
	Project X	$\mathcal{O}(10^{-15})$	> 2021
BR($\mu \to eee$)	Mu3e	$\mathcal{O}(10^{-15})$	~ 2017
	Mu3e	$\mathcal{O}(10^{-16})$	> 2017
	MUSIC	$\mathcal{O}(10^{-16})$	~ 2017
	Project X	$\mathcal{O}(10^{-17})$	> 2021
CR($\mu \to e$)	COMET	$\mathcal{O}(10^{-17})$	~ 2017
	Mu2e	$\mathcal{O}(10^{-17})$	~ 2020
	PRISM/PRIME	$\mathcal{O}(10^{-18})$	~ 2020
	Project X	$\mathcal{O}(10^{-19})$	> 2021
BR($\tau \to \mu\gamma$)	Belle II	$\mathcal{O}(10^{-8})$	> 2020
BR($\tau \to \mu\mu\mu$)	Belle II	$\mathcal{O}(10^{-10})$	> 2020
BR($\tau \to e\gamma$)	Belle II	$\mathcal{O}(10^{-9})$	> 2020
BR($\tau \to \mu\mu\mu$)	Belle II	$\mathcal{O}(10^{-10})$	> 2020

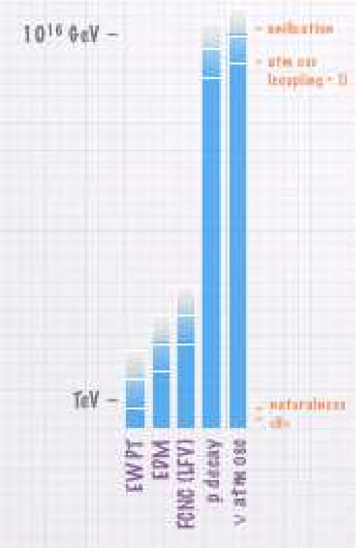
Table: Future sensitivities of next-generation experiments.

- **Gravity** $\Longrightarrow$ $\Lambda_{\text{Planck}} \sim 10^{18-19}\ \mathrm{GeV}$
- **Neutrino masses** $\Longrightarrow$ $\Lambda_{\text{see-saw}} \lesssim 10^{15}\ \mathrm{GeV}$
- **BAU**: evidence of CPV beyond SM
  - Electroweak Baryogenesis $\Longrightarrow$ $\Lambda_{NP} \lesssim \mathrm{TeV}$
  - Leptogenesis $\Longrightarrow$ $\Lambda_{\text{see-saw}} \lesssim 10^{15}\ \mathrm{GeV}$
- **Hierarchy problem**: $\Longrightarrow$ $\Lambda_{NP} \lesssim \mathrm{TeV}$
- **Dark Matter** $\Longrightarrow$ $\Lambda_{NP} \lesssim \mathrm{TeV}$

SM = effective theory at the EW scale

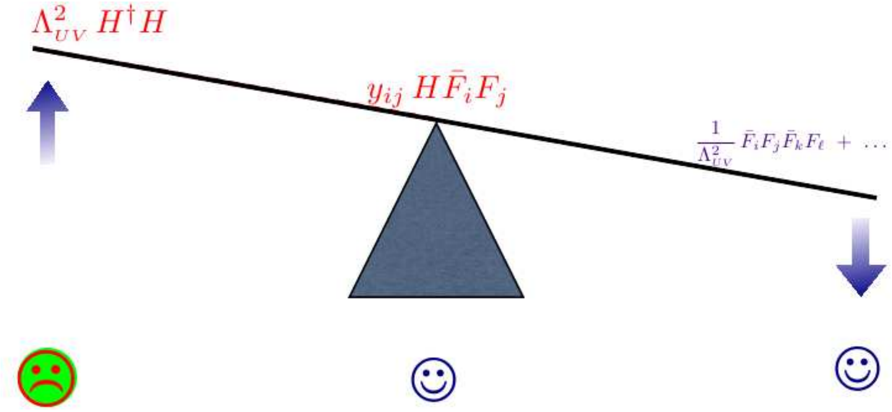
$$\mathcal{L}_{\rm eff} = \mathcal{L}_{\rm SM} + \sum_{d\geq 5} \frac{c_{ij}^{(d)}}{\Lambda_{NP}^{d-4}}\, O_{ij}^{(d)}$$

- $\mathcal{L}_{\rm eff}^{d=5} = \frac{y_\nu^{ij}}{\Lambda_{\rm see-saw}} L_i L_j \phi\phi$,
- $\mathcal{L}_{\rm eff}^{d=6}$ generates FCNC operators



$$\mathbf{BR}(\ell_i \to \ell_j\gamma) \sim \frac{v^4}{\Lambda_{NP}^4}$$

Hierarchy see-saw



- **Hierarchy problem**: $\Lambda_{\text{NP}} \lesssim \text{TeV}$
- **SM Yukawas**: $M_W \lesssim \Lambda_{\text{NP}} \lesssim M_P$
- **Flavor problem**: $\Lambda_{\text{NP}} \gg \text{TeV}$

Why LFV is interesting?

- **Neutrino Oscillation** $\Rightarrow m_{\nu_i} \neq m_{\nu_j} \Rightarrow$ **LFV**
- **see-saw**: $m_\nu \sim \frac{v^2}{M_R} \sim eV \Rightarrow M_R \sim 10^{14-16}$
- LFV transitions like $\mu \to e\gamma$ @ 1 loop with exchange of
  - W and ν in the SM with $\Lambda_{NP} \equiv M_R \equiv \Lambda_{see-saw}$

$$Br(\mu \to e\gamma) \sim \frac{v^4}{M_R^4} \leq 10^{-50} \qquad \textbf{GIM}$$

  - If $\Lambda_{NP} \ll \Lambda_{see-saw}$ ($\Lambda_{NP} \equiv m_{susy}$ in the MSSM)

$$Br(\mu \to e\gamma) \sim \frac{v^4}{\Lambda_{NP}^4}$$

$$\Downarrow$$

- LFV generally detectable in (multi) TeV scale NP scenarios like the MSSM, ...

The NP "scale" vs. LFV

$$\boxed{\mathcal{L}_{\rm eff} = \mathcal{L}_{\rm SM} + \sum_{d\geq 5} \frac{c_{ij}^{(d)}}{\Lambda_{NP}^{d-4}}\, O_{ij}^{(d)}}$$

$\boxed{\mathrm{BR}(\mu \to e\gamma) < 5 \times 10^{-14}}$

Process	Relevant operators	Present Bound on Λ (TeV)		Future Bound on Λ (TeV)	
		$C = 1/16\pi^2$	$C = 1$	$C = 1/16\pi^2$	$C = 1$
$\mu \to e\gamma$	$\frac{C}{\Lambda^2}\frac{m_\mu}{16\pi^2}\overline{\mu}_L\sigma^{\mu\nu}e_R F_{\mu\nu}$	50	—	90	—
$\mu \to eee$	$\frac{C}{\Lambda^2}(\overline{\mu}_L\gamma^\mu e_L)(\overline{e}_L\gamma^\mu e_L)$	17	210	170	2100
	$\frac{C}{\Lambda^2}(\overline{\mu}_L e_R)(\overline{e}_R e_L)$	10	120	100	1200
$\mu \to e$ in Ti	$\frac{C}{\Lambda^2}(\overline{\mu}_L\gamma^\mu e_L)(\overline{d}_L\gamma^\mu d_L)$	30	420	580	7300
	$\frac{C}{\Lambda^2}(\overline{\mu}_L e_R)(\overline{d}_R d_L)$	60	750	1000	13000

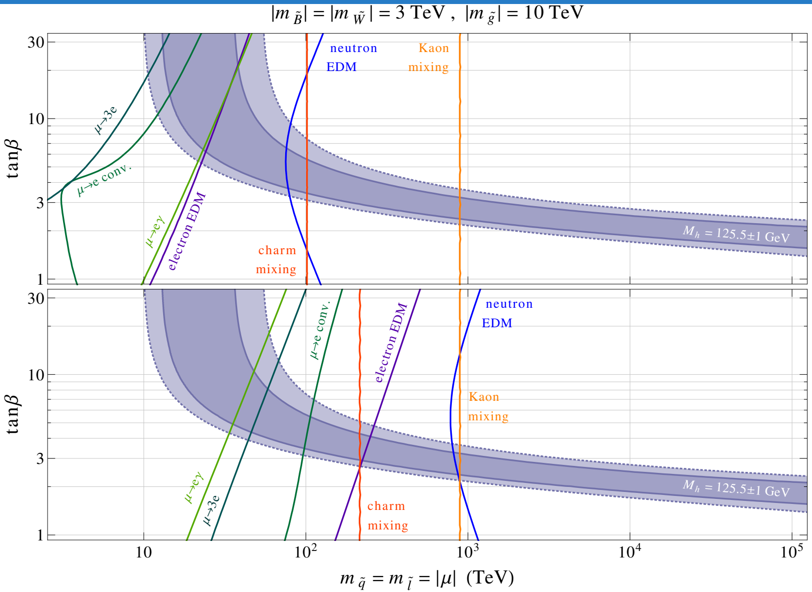
updated from LC Lalak Pokorski Ziegler '12

$\boxed{\mathrm{BR}(\mu \to eee) < 10^{-16}}$

$\boxed{\mathrm{CR}(\mu \to e \text{ in Ti}) < 5 \times 10^{-17}}$

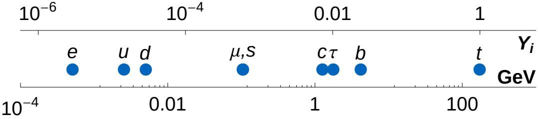
Calibbi @ IFAE2014

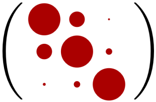
SUSY Flavour after the Higgs discovery



Low energy constraints fixing $(\delta_A)_{ij} = 0.3$. The upper (lower) plot gives the reach of current (projected future) experimental results [Altmannshofer, Harnik, & Zupan, '13]

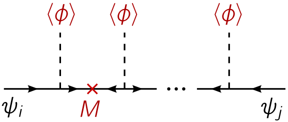
- Can the SM and NP flavour problems have a common explanation?



$V_{\text{CKM}} \sim$ 

- **Froggat-Nielsen ’79: Hierarchies from SSB of a Flavour Symmetry**

$$\epsilon = \frac{\langle\phi\rangle}{M} \ll 1 \Rightarrow Y_{ij} \propto \epsilon^{(a_i+b_j)}$$



- **Flavor protection from flavor models:** [Lalak, Pokorski & Ross ’10]

Operator	$U(1)$	$U(1)^2$	$SU(3)$	MFV
$(\overline{Q}_L X^Q_{LL} Q_L)_{12}$	λ	λ^5	λ^3	λ^5
$(\overline{D}_R X^D_{RR} D_R)_{12}$	λ	λ^{11}	λ^3	$(y_d y_s) \times \lambda^5$
$(\overline{Q}_L X^D_{LR} D_R)_{12}$	λ^4	λ^9	λ^3	$y_s \times \lambda^5$

- Is this flavor protection enough?

- Can we disentangle flavour models through flavour physics?

- **Why CP violation? Motivation:**
  - Baryogenesis requires extra sources of CPV
  - The QCD $\overline{\theta}$-term $\mathcal{L}_{CP} = \overline{\theta}\frac{\alpha_s}{8\pi}G\tilde{G}$ is a CPV source beyond the CKM
  - Most UV completion of the SM, e.g. the MSSM, have many CPV sources
  - However, TeV scale NP with $\mathcal{O}(1)$ CPV phases generally leads to EDMs many orders of magnitude above the current limits $\Rightarrow$ the New Physics CP problem.

- **How to solve the New Physics CP problem?**
  - Decoupling some NP particles in the loop generating the EDMs (e.g. hierarchical sfermions, split SUSY, 2HDM limit...)
  - Generating CPV phases radiatively $\phi^f_{CP} \sim \alpha_w/4\pi \sim 10^{-3}$
  - Generating CPV phases via small flavour mixing angles $\phi^f_{CP} \sim \delta_{fj}\delta_{fj}$ with $f = e, u, d$: maybe the suppression of FCNC processes and EDMs have a common origin?

Not only $\mu \to e\gamma$...

- **LFV** operators **@ dim-6**

$$\mathcal{L}_{\rm eff} = \mathcal{L}_{\rm SM} + \frac{1}{\Lambda^2_{\rm LFV}}\,\mathcal{O}^{\rm dim-6} + \ldots .$$

$$\mathcal{O}^{\rm dim-6} \ni \quad \bar{\mu}_R\,\sigma^{\mu\nu}\,H\,e_L\,F_{\mu\nu}\,, \quad (\bar{\mu}_L\gamma^\mu e_L)\left(\bar{f}_L\gamma^\mu f_L\right)\,, \quad (\bar{\mu}_R e_L)\left(\bar{f}_R f_L\right)\,, \; f = e,u,d$$

- the dipole-operator leads to $\ell \to \ell'\gamma$ while 4-fermion operators generate processes like $\ell_i \to \ell_j\bar{\ell}_k\ell_k$ and $\mu \to e$ conversion in Nuclei.
- When the dipole-operator is dominant:

$$\frac{\mathrm{BR}(\ell_i \to \ell_j\ell_k\bar{\ell}_k)}{\mathrm{BR}(\ell_i \to \ell_j\bar{\nu}_j\nu_i)} \simeq \frac{\alpha_{el}}{3\pi}\left(\log\frac{m^2_{\ell_i}}{m^2_{\ell_k}} - 3\right)\frac{\mathrm{BR}(\ell_i \to \ell_j\gamma)}{\mathrm{BR}(\ell_i \to \ell_j\bar{\nu}_j\nu_i)}\,,$$

$$\mathrm{CR}(\mu \to e \text{ in N}) \simeq \alpha_{\rm em} \times \mathrm{BR}(\mu \to e\gamma)\,.$$

- $\mathrm{BR}(\mu \to \mathbf{e}\gamma) \sim \mathbf{5} \times \mathbf{10^{-13}}$ implies

$$\frac{\mathrm{BR}(\mu \to \mathbf{3e})}{\mathbf{3} \times \mathbf{10^{-15}}} \approx \frac{\mathrm{BR}(\mu \to \mathbf{e}\gamma)}{\mathbf{5} \times \mathbf{10^{-13}}} \approx \frac{\mathrm{CR}(\mu \to \mathbf{e} \text{ in N})}{\mathbf{3} \times \mathbf{10^{-15}}}$$

- $\mu + N \to e + N$ on different N discriminates the operator at work [Okada et al. 2004].
- An angular analysis for $\mu \to eee$ can test operator which is at work.

Pattern of LFV in NP models

- **Ratios like** $Br(\mu \to e\gamma)/Br(\tau \to \mu\gamma)$ **probe the NP flavor structure**
- **Ratios like** $Br(\mu \to e\gamma)/Br(\mu \to eee)$ **probe the NP operator at work**

ratio	LHT	MSSM	SM4
$\frac{Br(\mu\to eee)}{Br(\mu\to e\gamma)}$	$0.02\ldots1$	$\sim 2\cdot10^{-3}$	$0.06\ldots2.2$
$\frac{Br(\tau\to eee)}{Br(\tau\to e\gamma)}$	$0.04\ldots0.4$	$\sim 1\cdot10^{-2}$	$0.07\ldots2.2$
$\frac{Br(\tau\to\mu\mu\mu)}{Br(\tau\to\mu\gamma)}$	$0.04\ldots0.4$	$\sim 2\cdot10^{-3}$	$0.06\ldots2.2$
$\frac{Br(\tau\to e\mu\mu)}{Br(\tau\to e\gamma)}$	$0.04\ldots0.3$	$\sim 2\cdot10^{-3}$	$0.03\ldots1.3$
$\frac{Br(\tau\to\mu ee)}{Br(\tau\to\mu\gamma)}$	$0.04\ldots0.3$	$\sim 1\cdot10^{-2}$	$0.04\ldots1.4$
$\frac{Br(\tau\to eee)}{Br(\tau\to e\mu\mu)}$	$0.8\ldots2$	~ 5	$1.5\ldots2.3$
$\frac{Br(\tau\to\mu\mu\mu)}{Br(\tau\to\mu ee)}$	$0.7\ldots1.6$	~ 0.2	$1.4\ldots1.7$
$\frac{\mathrm{R}(\mu\mathrm{Ti}\to e\mathrm{Ti})}{Br(\mu\to e\gamma)}$	$10^{-3}\ldots10^{2}$	$\sim 5\cdot10^{-3}$	$10^{-12}\ldots26$

[Buras et al., '07, '10]

- **NP effects are encoded in the effective Lagrangian**

$$\mathcal{L} = e\frac{m_\ell}{2}\left(\bar{\ell}_R \sigma_{\mu\nu} A_{\ell\ell'} \ell'_L + \bar{\ell}'_L \sigma_{\mu\nu} A^\star_{\ell\ell'} \ell_R\right) F^{\mu\nu} \qquad \ell, \ell' = e, \mu, \tau\,,$$

$$A_{\ell\ell'} = \frac{1}{(4\pi\,\Lambda_{\rm NP})^2}\left[\left(g^L_{\ell k}\, g^{L*}_{\ell' k} + g^R_{\ell k}\, g^{R*}_{\ell' k}\right) f_1(x_k) + \frac{v}{m_\ell}\left(g^L_{\ell k}\, g^{R*}_{\ell' k}\right) f_2(x_k)\right]\,,$$

  - Δa_ℓ **and leptonic EDMs are given by**

$$\Delta a_\ell = 2 m_\ell^2\, {\rm Re}(A_{\ell\ell}), \qquad \frac{d_\ell}{e} = m_\ell\, {\rm Im}(A_{\ell\ell})\,.$$

  - **The branching ratios of $\ell \to \ell'\gamma$ are given by**

$$\frac{{\rm BR}(\ell \to \ell'\gamma)}{{\rm BR}(\ell \to \ell' \nu_\ell \bar{\nu}_{\ell'})} = \frac{48\pi^3 \alpha}{G_F^2}\left(|A_{\ell\ell'}|^2 + |A_{\ell'\ell}|^2\right)\,.$$

- **"Naive scaling":**

$$\Delta a_{\ell_i}/\Delta a_{\ell_j} = m^2_{\ell_i}/m^2_{\ell_j}, \qquad d_{\ell_i}/d_{\ell_j} = m_{\ell_i}/m_{\ell_j}\,.$$

(for instance, if the new particles have an underlying SU(3) flavor symmetry in their mass spectrum and in their couplings to leptons, which is the case for gauge interactions).

[Giudice, P.P., & Passera, '12]

- $\mathrm{BR}(\ell_i \to \ell_j\gamma)$ **vs.** $(g-2)_\mu$

$$\mathrm{BR}(\mu \to e\gamma) \approx 3\times 10^{-13}\left(\frac{\Delta a_\mu}{3\times 10^{-9}}\right)^2 \left(\frac{\theta_{e\mu}}{10^{-5}}\right)^2,$$

$$\mathrm{BR}(\tau \to \mu\gamma) \approx 4\times 10^{-8}\left(\frac{\Delta a_\mu}{3\times 10^{-9}}\right)^2 \left(\frac{\theta_{\ell\tau}}{10^{-2}}\right)^2.$$

- **EDMs assuming "Naive scaling"** $d_{\ell_i}/d_{\ell_j} = m_{\ell_i}/m_{\ell_j}$

$$d_e \simeq \left(\frac{\Delta a_\mu}{3\times 10^{-9}}\right) 10^{-24}\ \tan\phi_e\ \ e\,\mathrm{cm}\,,$$

$$d_\mu \simeq \left(\frac{\Delta a_\mu}{3\times 10^{-9}}\right) 2\times 10^{-22}\ \tan\phi_\mu\ \ e\,\mathrm{cm}\,,$$

$$d_\tau \simeq \left(\frac{\Delta a_\mu}{3\times 10^{-9}}\right) 4\times 10^{-21}\ \tan\phi_\tau\ \ e\,\mathrm{cm}\,,$$

- $(g-2)_\ell$ **assuming "Naive scaling"** $\Delta a_{\ell_i}/\Delta a_{\ell_j} = m^2_{\ell_i}/m^2_{\ell_j}$

$$\Delta a_e = \left(\frac{\Delta a_\mu}{3\times 10^{-9}}\right) 0.7\times 10^{-13}\,, \qquad \Delta a_\tau = \left(\frac{\Delta a_\mu}{3\times 10^{-9}}\right) 0.8\times 10^{-6}.$$

[Giudice, P.P., & Passera, '12]

A concrete SUSY scenario: “Disoriented A-terms”

- **Challenge**: Large effects for $g-2$ keeping under control $\mu \to e\gamma$ and d_e
- **“Disoriented A-terms”** [Giudice, Isidori & P.P., ’12]:

$$(\delta_{LR}^{ij})_f \sim \frac{A_f \theta_{ij}^f m_{f_j}}{m_{\tilde{f}}} \qquad f = u, d, \ell \, ,$$

  - Flavor and CP violation is restricted to the trilinear scalar terms.
  - Flavor bounds of the down-sector are naturally satisfied thanks to the smallness of down-type quark/lepton masses.
  - This ansatz arises in scenarios with partial compositeness (where a natural prediction is $\theta_{ij}^\ell \sim \sqrt{m_i/m_j}$ [Rattazzi et al.,’12]) or, as shown in [Calibbi, P.P. and Ziegler,’13], in Flavored Gauge Mediation models [Shadmi and collaborators].

- $\mu \to e\gamma$ and d_e are generated only by $U(1)$ interactions

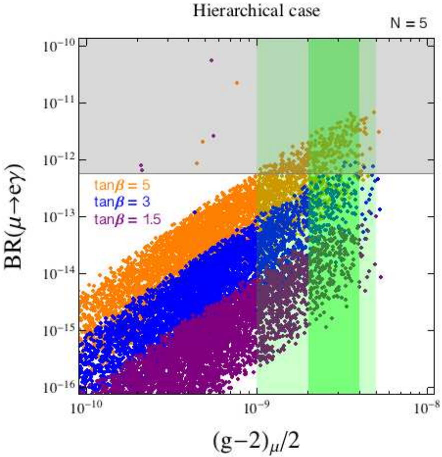
$$\mathrm{BR}(\mu \to e\gamma) \sim \left(\frac{\alpha}{\cos^2\theta_W}\right)^2 \left|\delta_{LR}^{\mu e}\right|^2 \, , \qquad \frac{d_e}{e} \sim \frac{\alpha}{\cos^2\theta_W} \, \mathrm{Im}\delta_{LR}^{ee} \, .$$

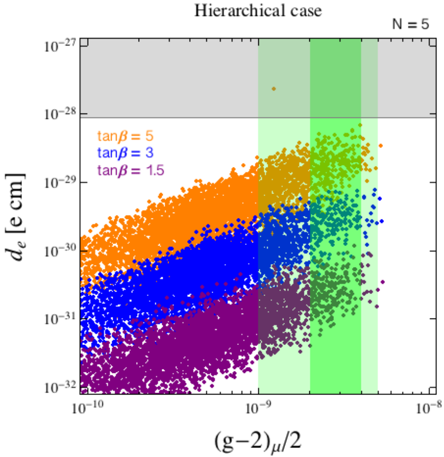
- $(g-2)_\mu$ is generated by $SU(2)$ interactions and is $\tan\beta$ enhanced

$$\Delta a_\ell \sim \frac{\alpha}{\sin^2\theta_W} \, \tan\beta$$

- $(g-2)_\mu$ is enhanced by $\approx 100 \times (\tan\beta/30)$ w.r.t. $\mu \to e\gamma$ and d_e amplitudes

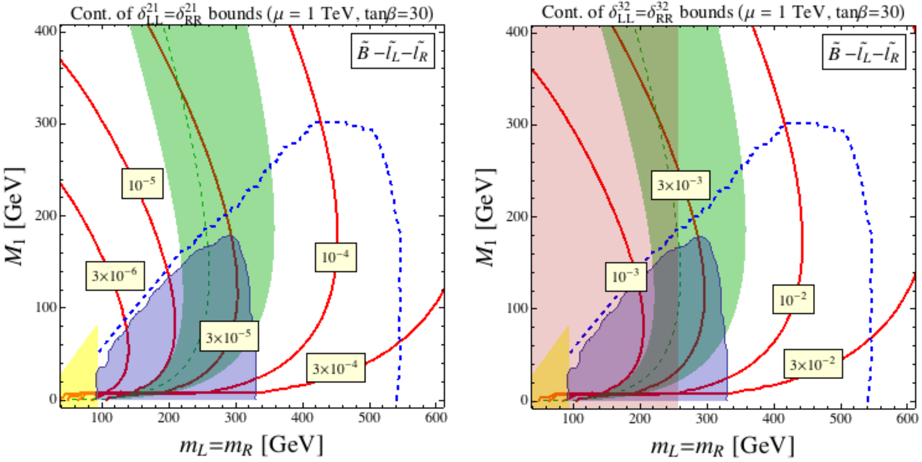
A concrete SUSY scenario: “Flavored Gauge Mediation”





- LFV processes with an undelying $\tau - \mu$ and $\tau - e$ are unobservable

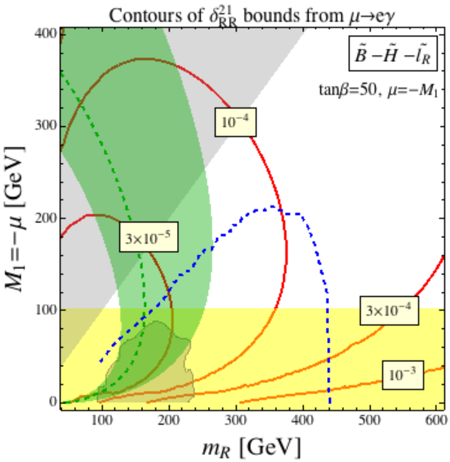
[Calibbi, P.P., & Ziegler, '14]



- The light-blue (yellow) area is excluded by ATLAS (LEP) and the dashed line refers to the limits by LHC14 with $\mathcal{L} = 100\ \mathrm{fb}^{-1}$. The green band explains the $(g-2)_\mu$ anomaly at 2σ. The red-shaded area is excluded by a stau LSP.

[Calibbi, Galon, Masiero, P.P., & Shadmi, '15]

LFV vs. LHC



- The light-blue (yellow) area is excluded by ATLAS (LEP) and the dashed line refers to the limits by LHC14 with $\mathcal{L} = 100\ \mathrm{fb}^{-1}$. The green band explains the $(g-2)_\mu$ anomaly at 2σ. In the grey area the LSP is not neutral.

[Calibbi, Galon, Masiero, P.P., & Shadmi, '15]

Conclusions and future prospects

- **Important questions in view of ongoing/future experiments are**:
  - What are the expected deviations from the SM predictions induced by TeV NP?
  - Which observables are not limited by theoretical uncertainties?
  - In which case we can expect a substantial improvement on the experimental side?
  - What will the measurements teach us if deviations from the SM are [not] seen?

- **(Personal) answers**:
  - The expected deviations from the SM predictions induced by NP at the TeV scale with generic flavor structure are already ruled out by many orders of magnitudes.
  - On general grounds, we can expect any size of deviation below the current bounds.
  - cLFV processes, leptonic EDMs and LFU observables $R^{e/\mu}_{K,\pi}$ do not suffer from theoretical limitations (clean th. observables).
  - On the experimental side there are still excellent prospects of improvements in several clean channels especially in the leptonic sector: $\mu \to e\gamma$, $\mu N \to eN$, $\mu \to eee$, τ-LFV, EDMs and leptonic $(g-2)$ and also $R^{e/\mu}_{K,\pi}$.
  - The the origin of the $(g-2)_\mu$ discrepancy can be understood testing new-physics effects in the electron $(g-2)_e$. This would require improved measurements of $(g-2)_e$ and more refined determinations of α in atomic-physics experiments.

Conclusions

The origin of flavour is still, to a large extent, a mystery. The most important open questions can be summarized as follow:

- **Which is the organizing principle behind the observed pattern of fermion masses and mixing angles?**

- **Are there extra sources of flavour symmetry breaking beside the SM Yukawa couplings which are relevant at the TeV scale?**

Irrespectively of whether the LHC will discover or not new particles, flavor physics in the leptonic sector (especially cLFV, leptonic $g-2$ and EDMs) will teach us a lot...