# Lepton Flavour Violation

(Theoretical Aspects)

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# Outline



A comprehensive review can be found in:


- M. Raidal *et al.* , "Flavour physics of leptons and dipole moments", Eur. Phys. J. C **57** (2008) 13 [arXiv:0801.1826 [hep-ph]].

# Motivation

## Neutrino oscillations:

- Neutrino oscillations experimentally established (→ also implies LFV).
- Natural relation to New Physics from GUTs.
  - See-saw scale $\sim$ GUT scale $\sim$ scale of Lepton *Number* Violation (LNV).
  - Right-handed neutrino $\nu_R$ fits into 16-plet of $SO(10)$.
- Implications for Baryogenesis through Leptogenesis.

LNV $\Leftrightarrow$ New Physics at the GUT scale?

## Lepton Flavour Violation (LFV = in charged lepton decays):

- LFV violating effects tiny in minimally extended SM (← GIM mechanism):
  ( e.g. $\mathcal{B}[\mu \to e\gamma]_{\rm SM} \sim 10^{-54}$] compared to $\mathcal{B}[\mu \to e\gamma]_{\rm exp.} < 10^{-11(13)}$ )
- New sources for Lepton-Flavour Violation in generic NP models:

LFV $\Leftrightarrow$ NP at the TeV scale?

# Motivation

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LFV $\Leftrightarrow$ NP at the TeV scale?

# 1.1 Minimal Extensions of the SM Lepton Sector

- Yukawa sector in the (original) **SM**:

$$(Y_E)^{ij}\,(\bar{L}^i\,H)\,E_R^j \;+\; \text{h.c.}$$

  - massless (anti-) neutrinos with (positive) negative helicity
  - individual lepton flavour $(L_e, L_\mu, L_\tau)$ conserved $\to$ No Mixing

- SM plus right-handed **Dirac Neutrinos** (i.e. LN-conservation enforced):

$$(Y_E)^{ij}\,(\bar{L}^i\,H)\,E_R^j + (Y_\nu)^{ij}\,(\bar{L}^i\,\widetilde{H})\,\nu_R^j \;+\; \text{h.c.}$$

  - analogous to quark sector (CKM-like mixing)
  - phenomenologically and theoretically less interesting

- Minimally extended SM (as **Effective Theory**):

$$(Y_E)^{ij}\,(\bar{L}^i\,H)\,E_R^j + \frac{(g_\nu)^{ij}}{\Lambda_{\rm LNV}}\,(\bar{L}^i\widetilde{H})(\widetilde{H}^\dagger L^j)^c + \text{h.c.}$$

  - effective dim-5 operator $\to$ LNV.
  - mismatch between diagonalization of $Y_E$ and $g_\nu = g_\nu^T$ gives PMNS mixing matrix.

# 1.1 Minimal Extensions of the SM Lepton Sector

- SM plus right-handed **Majorana Neutrinos**:

$$(Y_E)^{ij}\,(\bar{L}^i\,H\,E_R^j) + (Y_\nu)^{ij}\,(\bar{L}^i\,\widetilde{H}\,\nu_R^j) + \frac{1}{2}\,M^{ij}\,(\nu_R^T)^i\,(\nu_R)^j + \text{h.c.}$$

  - Majorana mass term $\rightarrow$ LNV.
  - Integrating out $\nu_R$, yields dim-5 operator with

$$\frac{g_\nu}{\Lambda_{\rm LNV}} = Y_\nu\,(M)^{-1}\,Y_\nu^T \qquad \textbf{(type-I see-saw)}$$

- Alternatively:
  - Additional heavy scalar triplets **(type-II see-saw)**
  - Additional heavy fermion triplets **(type-III see-saw)**
  - Additional *light* sterile neutrinos ($\rightarrow$ LSND)
  - ...

## 1.2 Minimal Lepton Flavour Violation

[Cirigliano et al, hep-ph/0507001, hep-ph/0601111]

Idea:

- SM as Effective Theory (incl. LN-violating dim-5 operator).
- New dim $\geq$ 6 operators:

$$\mathcal{L}_{\rm eff} = \mathcal{L}_{\rm SM} + \frac{1}{\Lambda_{\rm LNV}} O^{\rm dim-5} + \frac{1}{\Lambda_{\rm LFV}^2} O^{\rm dim-6} + \ldots$$

with *independent* scales, $\Lambda_{\rm LFV} \ll \Lambda_{\rm LNV}$

- e.g. allowing for *generic* coupling constants for effective operators like

$$\frac{1}{\Lambda_{\rm LFV}^2} \bar{L}^i \sigma^{\mu\nu} H E_R^j F_{\mu\nu} ,$$

the bound on $\mu \to e\gamma$ would imply $\Lambda_{\rm LFV} > 10^5$ TeV.

$\Rightarrow$ Allowing for NP at the TeV scale requires specifically tuned LFV coefficients.

- Expand NP flavour matrices in terms of $Y_E$ and $g_\nu$ (with $\mathcal{O}(1)$ coefficients):

$\Rightarrow$ NP flavour coefficients related to SM masses and mixing angles.

# Formulation of MLFV from Flavour Symmetry Considerations

Lepton-flavour symmetry in (gauge sector of) minimally extended SM: $SU(3)_L \times SU(3)_{E_R}$

- Broken by flavour matrices (in the mass eigenbasis for charged leptons):

$$\text{Dim-5:} \quad g_\nu \sim (\bar{6}, 1) = \frac{\Lambda_{\rm LNV}}{v^2}\, U^* \,\mathrm{diag}[m_{\nu_i}]\, U^\dagger$$

$$\text{Yukawa:} \quad Y_E \sim (3, \bar{3}) = \frac{1}{v}\,\mathrm{diag}[m_\ell]$$

  with PMNS mixing matrix $U$.

- For the construction of MLFV operators, one needs

$$\Delta^i_j = (g_\nu^\dagger g_\nu)^i_j - \frac{1}{3}\delta^i_j\,\mathrm{tr}[g_\nu^\dagger g_\nu] \qquad \text{and} \qquad G^{kl}_{ij} = (g_\nu)_{ij}(g_\nu^*)^{kl} - \text{[trace terms]}$$

  appearing as the 8-tet and 27-plet in $\bar{6} \times 6 = 1 + 8 + 27$.

Leading LFV effect proportional to $\dfrac{\Delta m^2_{\rm atm}}{v^2}\,\dfrac{\Lambda_{\rm LNV}}{\Lambda_{\rm LFV}}$

(can be singled out by using a non-linear representation of MLFV. [TF/Mannel, arXiv:0806.0717])

## Dim-6 LFV Operators

- Dim-6 LFV operators in the minimally extended SM + M(L)FV (linear in $y_i$)

$$
\begin{aligned}
O_{LL}^{(1)} &= \Delta^i_j\; (\bar{L}_i \gamma^\mu L^j)\; H^\dagger i D_\mu H\,, \\
O_{LL}^{(2)} &= \Delta^i_j\; (\bar{L}_i \gamma^\mu \tau^a L^j)\; H^\dagger \tau^a i D_\mu H\,, \\
O_{LL}^{(3)} &= \Delta^i_j\; (\bar{L}_i \gamma^\mu L^j)\; (\bar{Q}_L \gamma_\mu Q_L)\,, \\
O_{LL}^{(4d)} &= \Delta^i_j\; (\bar{L}_i \gamma^\mu L^j)\; (\bar{D}_R \gamma_\mu D_R)\,, \\
O_{LL}^{(4u)} &= \Delta^i_j\; (\bar{L}_i \gamma^\mu L^j)\; (\bar{U}_R \gamma_\mu U_R)\,, \\
O_{LL}^{(5)} &= \Delta^i_j\; (\bar{L}_i \gamma^\mu \tau^a L^j)\; (\bar{Q}_L \gamma_\mu \tau^a Q_L)
\end{aligned}
$$

$$
\begin{aligned}
O_{RL}^{(1)} &= (Y_E^\dagger \Delta)^i_j\; g' H^\dagger\, (\bar{E}_{Ri} \sigma^{\mu\nu} L^j)\, B_{\mu\nu}\,, \\
O_{RL}^{(2)} &= (Y_E^\dagger \Delta)^i_j\; g H^\dagger\, (\bar{E}_{Ri} \sigma^{\mu\nu} \tau^a L^j)\, W^a_{\mu\nu}\,, \\
O_{RL}^{(3)} &= (Y_E^\dagger \Delta)^i_j\; (D_\mu H)^\dagger\, (\bar{E}_{Ri} D_\mu L^j)\,, \\
O_{RL}^{(4)} &= (Y_E^\dagger \Delta)^i_j\; (\bar{E}_{Ri} L^j)\, (\bar{Q}_L Y_D D_R)\,, \\
O_{RL}^{(5)} &= (Y_E^\dagger \Delta)^i_j\; (\bar{E}_{Ri} \sigma^{\mu\nu} L^j)\, (\bar{Q}_L \sigma_{\mu\nu} Y_D D_R)\,, \\
O_{RL}^{(6)} &= (Y_E^\dagger \Delta)^i_j\; (\bar{E}_{Ri} L^j)\, (\bar{U}_R Y_U^\dagger i\tau^2 Q_L)\,, \\
O_{RL}^{(7)} &= (Y_E^\dagger \Delta)^i_j\; (\bar{E}_{Ri} \sigma^{\mu\nu} L^j)\, (\bar{U}_R \sigma_{\mu\nu} Y_U^\dagger i\tau^2 Q_L)\,.
\end{aligned}
$$

for 2-lepton processes, and

$$
O_{LLRR}^{(4)} = \Delta^i_j\; (\bar{L}_i \gamma^\mu L^j)\; (\bar{E}_R \gamma_\mu E_R)\,,
$$

$$
\begin{aligned}
O_{LLLL}^{(3)} &= \left(\Delta^i_j \delta^{kl} + c\, G^{ik}_{jl}\right)\; (\bar{L}_i \gamma^\mu L^j)\; (\bar{L}_k \gamma_\mu L^l)\,, \\
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for 4-lepton processes.

[Cirigliano et al, hep-ph/0507001], [Dassinger/TF/Mannel/Turczyk, arXiv:0707.0988]

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for 2-lepton processes, and

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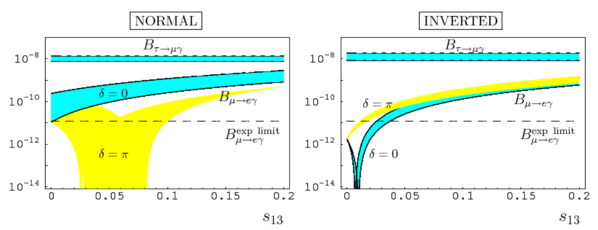
\end{aligned}
$$

for 4-lepton processes.

[Cirigliano et al, hep-ph/0507001], [Dassinger/TF/Mannel/Turczyk, arXiv:0707.0988]

## MLFV Phenomenology (example, minimal field content)

- LFV decay rates are sizeable, only if $\Lambda_{\rm LNV} \gg \Lambda_{\rm LFV}$ ,
  Example: $\mathcal{B}(\mu \to e\gamma) > 10^{-13}$ requires $\Lambda_{\rm LNV} > 10^{9} \cdot \Lambda_{\rm LFV}$ .
- $\Lambda_{\rm LNV}$ drops out in *ratios* of LFV decays, e.g. $\mathcal{B}(\mu \to e\gamma)/\mathcal{B}(\tau \to \mu\gamma)$




using $\Lambda_{\rm LNV} = 10^{10} \cdot \Lambda_{\rm LFV}$
[from Isidori, arXiv:0908.0404]

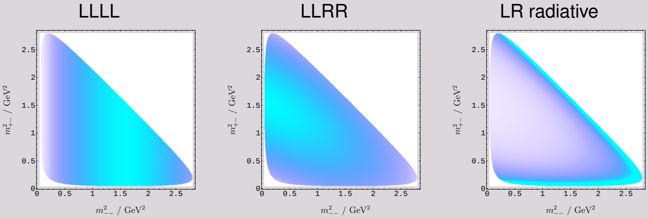
$\Rightarrow$ Better experimental prospects to observe $\mu \to e\gamma$ than $\tau \to \mu\gamma$.

- Alternative realizations of MLFV within see-saw constructions possible, see e.g. [Alonso et al. 11, Gavela et al. 09, Branco et al. 07, Davidson et al. 06]

## 1.3 LFV Observables $\leftrightarrow$ Flavour Coefficients of Effective Operators

- Radiative decays ($\mu \to e\gamma$, $\tau \to \mu(e)\gamma$)
- Decay to 3 charged leptons ($\mu \to 3e$, $\tau \to 3\mu$, etc.)
  - Different chiralities involved, including dipole operator with virtual photon.
  - Full-fledged analysis requires careful treatment of phase space.

E.g. phase space in $\tau \to 3\mu$: [Dassinger et al. 2007]




also: angular distributions [see, Giffels et al. 2008]

- also: Hadronic Decays, $\mu$-$e$ Conversion in Nuclei

Experimental Situation summarized in Talk by George Lafferty

# 2. LFV Phenomenology in Specific Models (top-down)

**In some detail:**

- (constrained) SUSY Models
- Littlest Higgs Model with T-Parity
- Sequential 4th Lepton Generation

Other (recently discussed) extensions:

- "Simplest Higgs model" [del Aguila et al. 11]
  (qualitatively similar results as for LHT)
- "AMEND" (neutrinos $\leftrightarrow$ dark matter)
  [Farzan/Pascoli/Schmidt 10]
- Non-universal $Z'$ [Mohanta 10]
- Higgs-triplet model [Akeroyd et al. 09]
  ...
- More results in review [Raidal et al. 08]

**Generic Questions:**

- Tree-level or loop-induced LFV ?
- Deviations from MLFV ?
- Comparison with present/foreseen experimental bounds ?
- Constraints on new sources of flavour violation, new-particle masses ?
- Correlations, e.g. $\tau \to \mu(e)\gamma$ vs. $\mu \to e\gamma$ ?
- ...

## 2.1 LFV in SUSY Models

**New Sources of Flavour Violation from Soft SUSY-breaking Sector:**

- Slepton Mass Matrices and Tri-linear Couplings
  - leading LFV via sneutrino-chargino and slepton-neutralino loops, coming from misalignment between leptons and sleptons.
- Non-holomorphic couplings of Higgs doublets $H_{u,d}$
  - LFV couplings to neutral Higgs bosons, relevant at large $\tan\beta = v_u/v_d$ ($\rightarrow$ general 2HDM).

- Generic MSSM: $\rightarrow$ mass insertion approximation. (off-diagonal slepton masses)
- Specific SUSY-breaking scenarios with universal slepton parameters $+$ RG.
- Additional constraints from (discrete) flavour symmetries.
- Specific assumptions on see-saw parameters.
- ...

# (a): Constrained MSSM with Type-I See-Saw

[Antusch et al. 06]

**Set-up:**

- cMSSM + 3 right-handed (s)neutrinos,
- hierarchical spectrum for heavy neutrinos,
- include constraints from baryogenesis through leptogenesis,

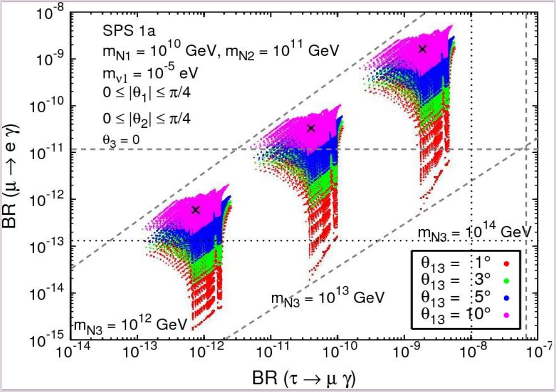
$\Rightarrow$ LFV originates from Neutrino Yukawa Matrices:

- Consider certain SPS benchmark points,
- Study dependence on neutrino mixing angle $\theta_{13}$
- also: Heavy Majorana masses and mixing angles.

# (a): Constrained MSSM with Type-I See-Saw [Antusch et al. 06]

## Correlation between $\mu \to e\gamma$ and $\tau \to \mu\gamma$

- as a function of $\theta_{13}$ and the heaviest Majorana mass $M_{N_3}$, for SPS 1A.

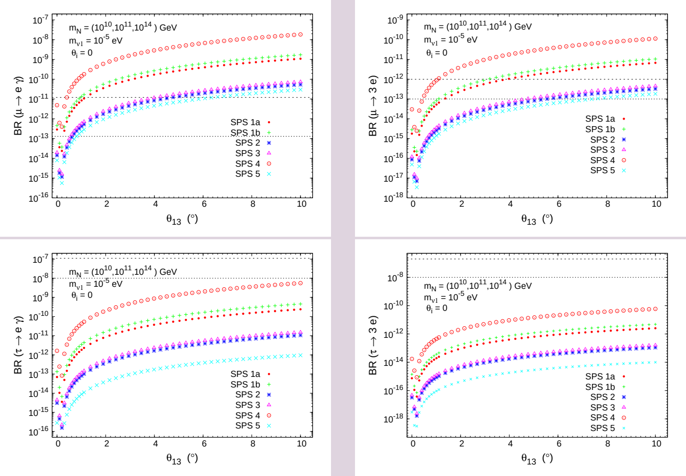



(for more on SUSY see-saw and LFV, see [J.C. Romao, talk at Moriond '11])

# (a): Constrained MSSM with Type-I See-Saw

[Antusch et al. 06]

## $\mu(\tau) \to e\gamma$ and $\mu(\tau) \to 3e$ for different SPS points

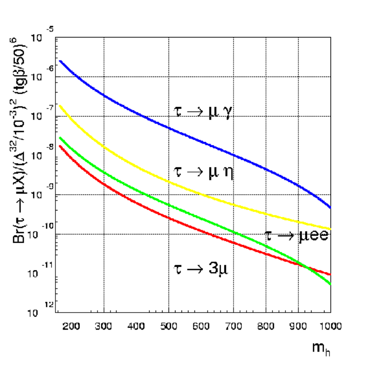


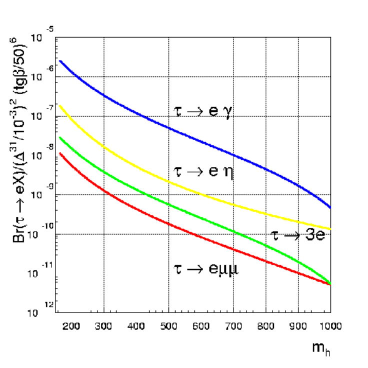

$B(\mu \to e\,\gamma)$ and $B(\mu \to 3\,e)$ as a function of $\theta_{13}$,

for SPS 1a $(\cdot)$, SPS 1b $(+)$, SPS 2 $(*)$, SPS 3 $(\triangle)$, SPS 4 $(\odot)$ and 5 $(\times)$.

## (b): Higgs-Mediated LFV in SUSY [Paradisi 06]

### Branching ratios for LFV $\tau$ decays (as a function of Higgs mass)




- "Non-decoupling limit": $\sin(\beta - \alpha) = 0$, $\tan\beta \gg 1$

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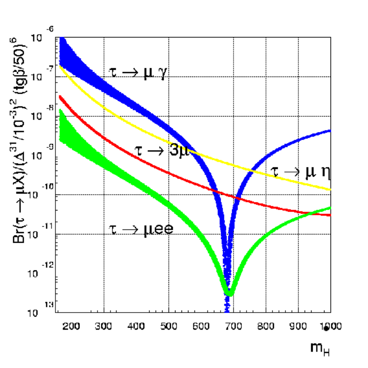
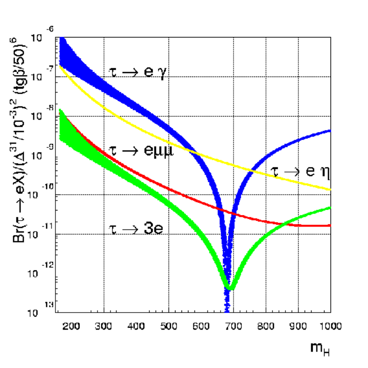



- "Decoupling limit": $\cos(\beta - \alpha) = 0$, $m_Z/m_A \to 0$ (2-loop effects important)

# (c) LFV in a SUSY Model with a discrete $A_4$ flavour symmetry

[Feruglio et al. arXiv:0911.3874]

## Motivation:

- Use specific symmetry group $(A_4 \times Z_3 \times U(1)_{\mathrm{FN}})$ to enforce near tri-bi-maximal neutrino mixing
- Implement into softly-broken SUSY context to realize NP at the TeV scale

## Relevant Parameters:

- Small expansion parameter classifying the breaking of the $A_4$ symmetry

$$u = \frac{\langle \phi_i \rangle}{\Lambda_f} \sim (0.01 - 0.05) \sim \theta_{13}$$

- Froggatt-Nielsen mechanism to explain the hierarchies of $y_\ell$, parametrized by

$$t = \frac{\langle \theta_{FN} \rangle}{\Lambda_f} \sim 0.05$$

- Ratio of Higgs VEVs restricted to small values: $2 \leq \tan\beta \leq 15$
- SUSY mass parameters $m_0$ and $m_{1/2}$

# (c) LFV in a SUSY Model with a discrete $A_4$ flavour symmetry

[Feruglio et al. arXiv:0911.3874]

## Essential Features:

- (right-handed) Slepton masses non-universal at flavour-symmetry breaking scale $\Lambda_f$.
- The ratios

$$R_{ij} = \frac{\mathcal{B}(\ell_i \to \ell_j \gamma)}{\mathcal{B}(\ell_i \to \ell_j \nu_i \bar{\nu}_j)}$$

are approximately universal, $R_{\mu e} \approx R_{\tau\mu} \approx R_{\tau e}$.

$\Rightarrow$ With the limit on $R_{\mu e}$, the decay $\tau \to \mu\gamma$ is not observable in the foreseeable future.

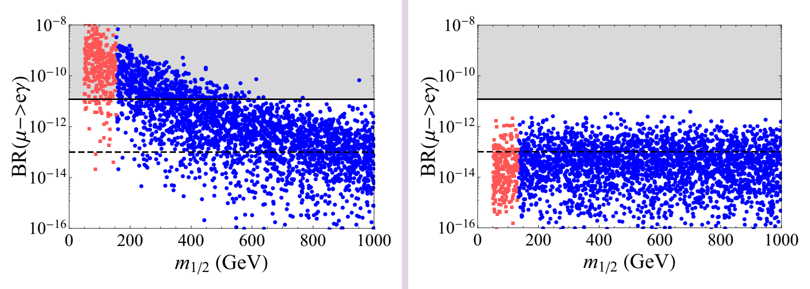
Experimental Constraints $\Rightarrow$

- small flavour-symmetry breaking parameter $u \sim 0.01$,
- and/or small $\tan\beta$,
- and/or large SUSY mass parameters (above 1 TeV).

# (c) LFV in a SUSY Model with a discrete $A_4$ flavour symmetry

[Feruglio et al. arXiv:0911.3874]

## Predictions for $\mu \to e\gamma$



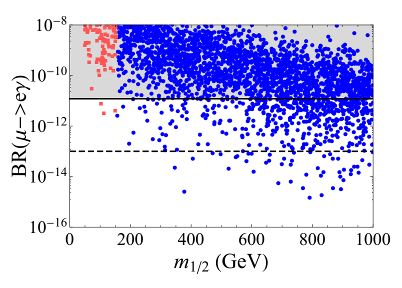

(a) $\tan\beta = 2$, $u = 0.01$ and $m_0 = 100$ GeV. (b) $\tan\beta = 2$, $u = 0.01$ and $m_0 = 1000$ GeV.

$BR(\mu \to e\gamma)$ as a function of $m_{1/2}$, for different values of $\tan\beta$, $u$ and $m_0$. The red points correspond to the mass of the lightest chargino being below the limit coming from direct searches. The horizontal lines show the current MEGA bound (continuous line) and the prospective MEG bound (dashed line).

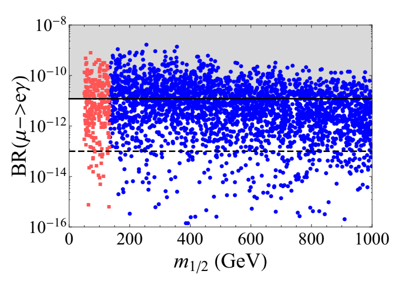
# (c) LFV in a SUSY Model with a discrete $A_4$ flavour symmetry

[Feruglio et al. arXiv:0911.3874]

## Predictions for $\mu \to e\gamma$




(c) $\tan\beta = 2$, $u = 0.05$ and $m_0 = 100$ GeV.




(d) $\tan\beta = 2$, $u = 0.05$ and $m_0 = 1000$ GeV.

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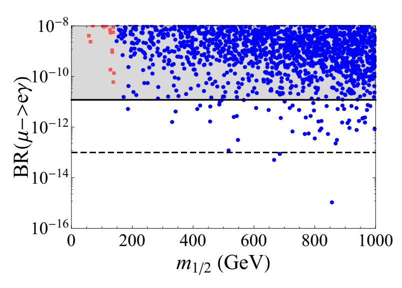
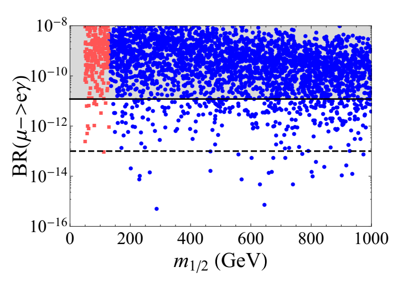



(e) $\tan\beta = 15$, $u = 0.05$ and $m_0 = 100$ GeV.

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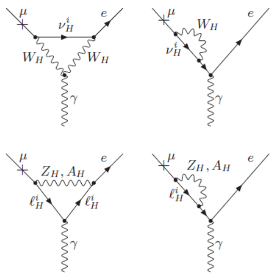
# 2.2 Littlest Higgs Model with $T$-parity (LHT)

[Low; Hubisz et al; Aquila et al; Blanke et al;Deandrea et al; Goto et al; . . . 2004++ ]

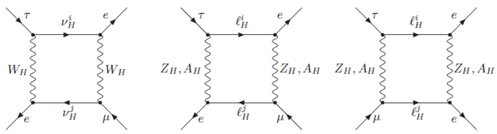
## General features:

- New Heavy Gauge Bosons ($W_H^{\pm}$, $Z_H$, $A_H$; detectable at the LHC).
- New Heavy Mirror Leptons $\begin{pmatrix} \nu_H^i \\ \ell_H^i \end{pmatrix}$ with masses of order TeV (and also quarks).

Diagrams for $\mu \to e\gamma$:




Diagrams contributing to $\tau^- \to e^- \mu^+ e^-$:



# 2.2 Littlest Higgs Model with $T$-parity (LHT)

[Low; Hubisz et al; Aquila et al; Blanke et al;Deandrea et al; Goto et al; ... 2004++ ]

**Input parameters:**

- LHT scale parameter: $f$
- mirror lepton masses: $M^{\ell}_{H1}$ , $M^{\ell}_{H1}$ , $M^{\ell}_{H1}$
- mirror-lepton mixing angles: $\theta^{\ell}_{12}$ , $\theta^{\ell}_{23}$ , $\theta^{\ell}_{13}$, new (Dirac) phases: $\delta^{\ell}_{12}$ , $\delta^{\ell}_{23}$ , $\delta^{\ell}_{13}$

$\rightarrow$ Potential LFV effects exceeding the SM by Many Orders of Magnitude.

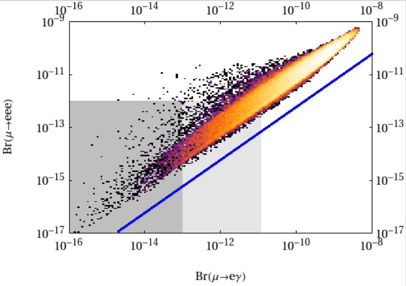
$\rightarrow$ Experimental Constraints $\Rightarrow$ Certain amount of Parameter Tuning:

- either, somewhat large LHT scale parameter,
- and/or small mirror-lepton mixing angles,
- and/or degenerate mirror lepton masses.

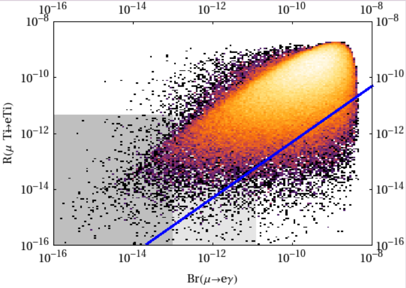
# LHT Correlations for LFV Decays and $\mu$-$e$ Conversion

[from Blanke et al. arXiv:0906.5454]

## $\mu \to 3e$ vs. $\mu \to e\gamma$:




## $\mu$-$e$ Conversion vs. $\mu \to e\gamma$:




- $f = 1$ TeV
- $300\ \mathrm{GeV} \leq M^{\ell}_{H_i} \leq 1.5\ \mathrm{TeV}$

– blue dots = dipole contribution from $\mu \to e\gamma^*$

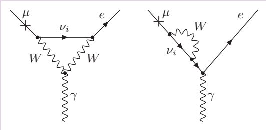
[for recent analysis, see also Y. Yamamoto: poster@BEAUTY2011]

## 2.3 A sequential 4$^{\text{th}}$ Lepton Generation (Dirac neutrinos)

- New heavy charged lepton $\tau'$ and (Dirac-)neutrino $\nu_{\tau'}$.
- $4 \times 4$ mixing matrix in the lepton sector $U_{ij}$

[Lacker/Menzel, arXiv:1003.4532]; [Buras et al, arXiv:1006.5356]

### Radiative $\mu$ and $\tau$ decays:




$$\frac{\mathcal{B}(\tau \to \mu\gamma)}{\mathcal{B}(\mu \to e\gamma)} \simeq \left|\frac{U_{\tau 4}}{U_{e4}}\right|^2 \mathcal{B}(\tau^- \to \nu_\tau \mu^- \bar\nu_\mu)$$

$$\frac{\mathcal{B}(\tau \to \mu\gamma)}{\mathcal{B}(\tau \to e\gamma)} \simeq \left|\frac{U_{\mu 4}}{U_{e4}}\right|^2 \frac{\mathcal{B}(\tau^- \to \nu_\tau \mu^- \bar\nu_\mu)}{\mathcal{B}(\tau^- \to \nu_\tau e^- \bar\nu_e)} \approx \left|\frac{U_{\mu 4}}{U_{e4}}\right|^2$$

$$\frac{\mathcal{B}(\tau \to e\gamma)}{\mathcal{B}(\mu \to e\gamma)} \simeq \left|\frac{U_{\tau 4}}{U_{\mu 4}}\right|^2 \mathcal{B}(\tau^- \to \nu_\tau e^- \bar\nu_e)$$

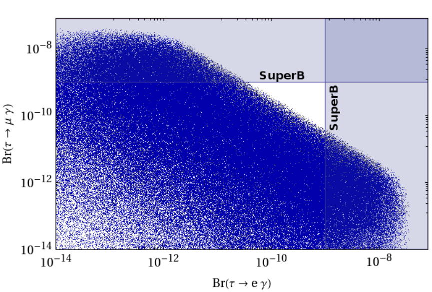
- stringent constraints on $|U_{i4}|$ elements, independent of heavy neutrino mass (!)

### $\mu$–$e$ conversion in nuclei:

- conversion rate directly proportional to $|U_{e4} U_{\mu 4}|^2$

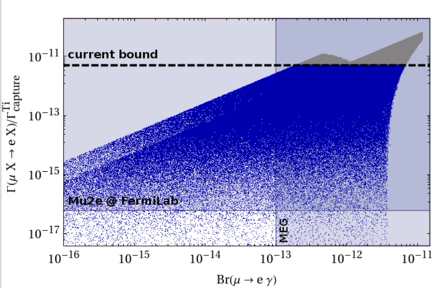
# 4G Correlations for Radiative Decays and $\mu$-$e$ Conversion

## $\tau \to \mu\gamma$ vs. $\tau \to e\gamma$




- within experimental reach, but not simultaneously (!)

## $\mu$–$e$ conversion vs. $\mu \to e\gamma$




- possible constraints on $|U_{e4} U_{\mu 4}|$ even tighter

[from Buras/Duling/TF/Heidsieck/Promberger 2010]

# Correlations and comparison of 4G with LHT and MSSM

| ratio | LHT | MSSM (dipole) | MSSM (Higgs) | 4G |
|---|---|---|---|---|
| $\frac{\mathcal{B}(\mu^- \to e^- e^+ e^-)}{\mathcal{B}(\mu \to e\gamma)}$ | 0.02...1 | $\sim 6 \cdot 10^{-3}$ | $\sim 6 \cdot 10^{-3}$ | 0.06...2.2 |
| $\frac{\mathcal{B}(\tau^- \to e^- e^+ e^-)}{\mathcal{B}(\tau \to e\gamma)}$ | 0.04...0.4 | $\sim 1 \cdot 10^{-2}$ | $\sim 1 \cdot 10^{-2}$ | 0.07...2.2 |
| $\frac{\mathcal{B}(\tau^- \to \mu^- \mu^+ \mu^-)}{\mathcal{B}(\tau \to \mu\gamma)}$ | 0.04...0.4 | $\sim 2 \cdot 10^{-3}$ | 0.06...0.1 | 0.06...2.2 |
| $\frac{\mathcal{B}(\tau^- \to e^- \mu^+ \mu^-)}{\mathcal{B}(\tau \to e\gamma)}$ | 0.04...0.3 | $\sim 2 \cdot 10^{-3}$ | 0.02...0.04 | 0.03...1.3 |
| $\frac{\mathcal{B}(\tau^- \to \mu^- e^+ e^-)}{\mathcal{B}(\tau \to \mu\gamma)}$ | 0.04...0.3 | $\sim 1 \cdot 10^{-2}$ | $\sim 1 \cdot 10^{-2}$ | 0.04...1.4 |
| $\frac{\mathcal{B}(\tau^- \to e^- e^+ e^-)}{\mathcal{B}(\tau^- \to e^- \mu^+ \mu^-)}$ | 0.8...2 | $\sim 5$ | 0.3...0.5 | 1.5...2.3 |
| $\frac{\mathcal{B}(\tau^- \to \mu^- \mu^+ \mu^-)}{\mathcal{B}(\tau^- \to \mu^- e^+ e^-)}$ | 0.7...1.6 | $\sim 0.2$ | 5...10 | 1.4...1.7 |
| $\frac{\mathrm{R}(\mu\mathrm{Ti} \to e\mathrm{Ti})}{\mathcal{B}(\mu \to e\gamma)}$ | $10^{-3} \ldots 10^{2}$ | $\sim 5 \cdot 10^{-3}$ | 0.08...0.15 | $10^{-12} \ldots 26$ |

Comparison of various ratios of branching ratios in

- the LHT model [Blanke et al. 2009],
- the MSSM without significant Higgs contributions [Ellis et al. 2002], [Brignole/Rossi 2004],
- the MSSM with significant Higgs contributions [Paradisi 2005-6],
- the 4G model [Buras et al. 2010].

[from Buras/Duling/TF/Heidsieck/Promberger 2010]

## Summary

- LFV in the Neutrino Sector well established.
  (Natural relation to physics at the GUT scale.)
- LFV in Charged Lepton Transitions tiny in the SM.
- Many models for NP at the TeV Scale predict sizeable LFV.

**If LFV (in charged lepton transitions) experimentally observed:**

- Physics beyond the (minimally extended) SM.
- Correlations among Observables distinguish between NP Models.

**If LFV experimentally further excluded:**

- Exclusion of NP parameter space / NP models.
- Another case pointing to a Symmetry Principle in the Flavour Sector.

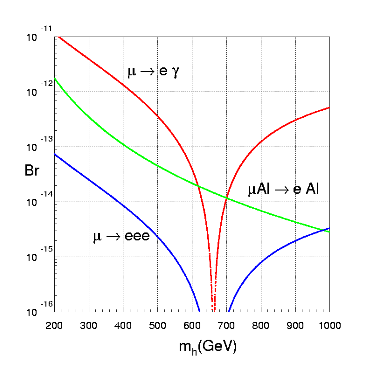
# Backup Slides . . .

# Higgs-Mediated vs. Gaugino-mediated LFV in SUSY

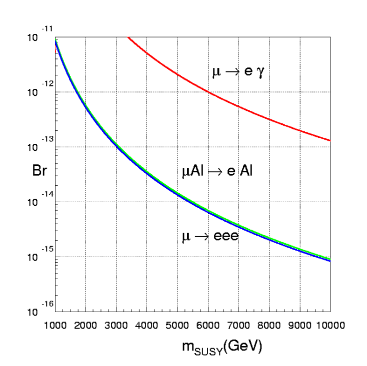
[Paradisi 06]

## For $\mu$ transitions

Higgs-mediated




Gaugino-mediated




$\tan_\beta = 50$ and $\delta_{LL}^{21} = 10^{-2}$

# Maximal branching ratios for LFV $\tau$ decays in LHT model

| decay | $f = 1000$ GeV | $f = 500$ GeV | SuperB sensitivity |
|---|---|---|---|
| $\tau \to e\gamma$ | $8 \cdot 10^{-10}$ | $2 \cdot 10^{-8}$ | $2 \cdot 10^{-9}$ |
| $\tau \to \mu\gamma$ | $8 \cdot 10^{-10}$ | $2 \cdot 10^{-8}$ | $2 \cdot 10^{-9}$ |
| $\tau^- \to e^- e^+ e^-$ | $1 \cdot 10^{-10}$ | $2 \cdot 10^{-8}$ | $2 \cdot 10^{-10}$ |
| $\tau^- \to \mu^- \mu^+ \mu^-$ | $1 \cdot 10^{-10}$ | $2 \cdot 10^{-8}$ | $2 \cdot 10^{-10}$ |
| $\tau^- \to e^- \mu^+ \mu^-$ | $1 \cdot 10^{-10}$ | $2 \cdot 10^{-8}$ | |
| $\tau^- \to \mu^- e^+ e^-$ | $1 \cdot 10^{-10}$ | $2 \cdot 10^{-8}$ | |
| $\tau^- \to \mu^- e^+ \mu^-$ | $6 \cdot 10^{-14}$ | $1 \cdot 10^{-13}$ | |
| $\tau^- \to e^- \mu^+ e^-$ | $6 \cdot 10^{-14}$ | $1 \cdot 10^{-13}$ | |
| $\tau \to \mu\pi$ | $4 \cdot 10^{-10}$ | $5 \cdot 10^{-8}$ | |
| $\tau \to e\pi$ | $4 \cdot 10^{-10}$ | $5 \cdot 10^{-8}$ | |
| $\tau \to \mu\eta$ | $2 \cdot 10^{-10}$ | $2 \cdot 10^{-8}$ | $4 \cdot 10^{-10}$ |
| $\tau \to e\eta$ | $2 \cdot 10^{-10}$ | $2 \cdot 10^{-8}$ | $6 \cdot 10^{-10}$ |
| $\tau \to \mu\eta'$ | $1 \cdot 10^{-10}$ | $2 \cdot 10^{-8}$ | |
| $\tau \to e\eta'$ | $1 \cdot 10^{-10}$ | $2 \cdot 10^{-8}$ | |

Upper bounds on LFV $\tau$ decay branching ratios in the LHT model, for two different values of the scale $f$, after imposing the constraints on $\mu \to e\gamma$ and $\mu \to eee$. For $f = 500$ GeV, also the bounds on $\tau \to \mu\pi$, $e\pi$ have been included.

[from Blanke et al. 2009]

# Maximal branching ratios for selected decays in the 4G model:

| decay | maximal value | exp. upper bound |
|---|---|---|
| $\mu \to e\gamma$ | $1.2 \cdot 10^{-11}$ $(6.8 \cdot 10^{-12})$ | $1.2 \cdot 10^{-11}$ |
| $\mu^- \to e^- e^+ e^-$ | $1.0 \cdot 10^{-12}$ $(1 \cdot 10^{-12})$ | $1.0 \cdot 10^{-12}$ |
| $\mathrm{R}(\mu\mathrm{Ti} \to e\mathrm{Ti})$ | $6.6 \cdot 10^{-11}$ $(5 \cdot 10^{-12})$ | $4.3 \cdot 10^{-12}$ |
| $\tau \to e\gamma$ | $3.9 \cdot 10^{-8}$ $(3.9 \cdot 10^{-8})$ | $3.3 \cdot 10^{-8}$ |
| $\tau \to \mu\gamma$ | $3.9 \cdot 10^{-8}$ $(3.9 \cdot 10^{-8})$ | $4.4 \cdot 10^{-8}$ |
| $\tau^- \to e^- e^+ e^-$ | $7.5 \cdot 10^{-8}$ $(7.5 \cdot 10^{-8})$ | $2.7 \cdot 10^{-8}$ |
| $\tau^- \to \mu^- \mu^+ \mu^-$ | $7.4 \cdot 10^{-8}$ $(7.1 \cdot 10^{-8})$ | $2.1 \cdot 10^{-8}$ |
| $\tau^- \to e^- \mu^+ \mu^-$ | $5 \cdot 10^{-8}$ $(5 \cdot 10^{-8})$ | $2.7 \cdot 10^{-8}$ |
| $\tau^- \to \mu^- e^+ e^-$ | $5 \cdot 10^{-8}$ $(5 \cdot 10^{-8})$ | $1.8 \cdot 10^{-8}$ |
| $\tau^- \to \mu^- e^+ \mu^-$ | $4.7 \cdot 10^{-17}$ $(4.7 \cdot 10^{-17})$ | $1.7 \cdot 10^{-8}$ |
| $\tau^- \to e^- \mu^+ e^-$ | $4.9 \cdot 10^{-17}$ $(4.9 \cdot 10^{-17})$ | $1.5 \cdot 10^{-8}$ |
| $\tau \to \mu\pi$ | $1.4 \cdot 10^{-7}$ $(1.4 \cdot 10^{-7})$ | $5.8 \cdot 10^{-8}$ |
| $\tau \to \mu\eta$ | $2.5 \cdot 10^{-8}$ $(2.5 \cdot 10^{-8})$ | $5.1 \cdot 10^{-8}$ |
| $\tau \to \mu\eta'$ | $2.9 \cdot 10^{-10}$ $(2.9 \cdot 10^{-8})$ | $5.3 \cdot 10^{-8}$ |

Maximal values for LFV decay branching ratios, after imposing the constraints on $\mathcal{B}(\mu \to e\gamma)$ and $\mathcal{B}(\mu^- \to e^- e^+ e^-)$.
The numbers given in brackets are obtained after imposing the additional constraint $\mathrm{R}(\mu\mathrm{Ti} \to e\mathrm{Ti}) < 5 \cdot 10^{-12}$.

The current experimental upper bounds are also given.

[from Buras/Duling/TF/Heidsieck/Promberger 2010]