# Lepton flavour violation: a phenomenological overview


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“What is $\nu$?” INVISIBLES 2012 GGI, Firenze, 26 June 2012

# Lepton Flavour Violation: LFV@2012

★ What **we do know** about **Lepton Flavour Violation** [experiment]

- **Neutral leptons** ⇝ **neutrino oscillations** $\nu_\alpha \leftrightsquigarrow \nu_\beta$

  3 mixing angles ($U_{\text{PMNS}}$) - solar, atmospheric, reactor $\theta_\odot$, $\theta_@$, $\theta_{13}$ $[\Delta m_i^2]$

- **Charged leptons** ⇝ so far, **only upper bounds** ... on "possible" observables!

| LFV process | Present bound | Future sensitivity |
|---|---|---|
| BR($\mu \to e\gamma$) | $2.4 \times 10^{-12}$ | $10^{-13}$ |
| BR($\tau \to e\gamma$) | $3.3 \times 10^{-8}$ | $10^{-9}$ |
| BR($\tau \to \mu\gamma$) | $4.4 \times 10^{-8}$ | $10^{-9}$ |
| BR($\mu \to 3e$) | $1.0 \times 10^{-12}$ | $\mathcal{O}(10^{-16})$ |
| BR($\tau \to 3e$) | $2.7 \times 10^{-8}$ | $2 \times 10^{-10}$ |
| BR($\tau \to 3\mu$) | $2.1 \times 10^{-8}$ | $8 \times 10^{-10}$ |
| BR($\tau \to \ell P$) | $(2-5) \times 10^{-3}$ | |

| LFV process | Present bound | Future sensitivity |
|---|---|---|
| CR($\mu - e$, Ti) | $4.3 \times 10^{-12}$ | $\mathcal{O}(10^{-16(-18)})$ |
| CR($\mu - e$, Au) | $7 \times 10^{-13}$ | |
| CR($\mu - e$, Al) | | $\mathcal{O}(10^{-16})$ |
| BR($\bar{K}_L^0 \to \mu e$) | $4.7 \times 10^{-12}$ | |
| BR($B^+ \to K^+ \tau\mu$) | $7.7 \times 10^{-5}$ | |
| ... and many others! | | |

But a huge experimental commitment!

*(Y. Kuno's review)*

▶ **Will cLFV be observed soon? How to accommodate such a signal? Which origin?**

# A first look at flavours in the SM

- **Quark sector:** **flavour** violated by **charged current** interactions $V_{ij}^{\mathsf{CKM}} W^{\pm} \bar{q}_i q_j$

  Observed in many oscillation/decay processes: **very good agreement with SM!**

SM QFV: **Th vs Exp**

Little room for *"beyond SM"* contributions (eg $B_s \to \mu\mu$)

$\Rightarrow$ **strong constraints** on *"beyond SM"* dynamics!

# A first look at flavours in the SM

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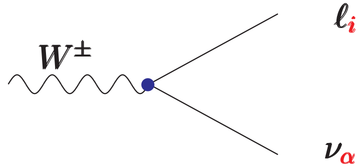
- **Lepton sector:** **neutral** & **charged** **lepton flavours** **strictly conserved**

  $\Rightarrow$ **Extend the SM** to accommodate $\boldsymbol{\nu_\alpha \leftrightsquigarrow \nu_\beta}$ [$\text{SM}_{m_\nu} =$ "ad-hoc" $m_\nu$, $U_{\text{PMNS}}$]

  **Charged currents** violate lepton flavour!

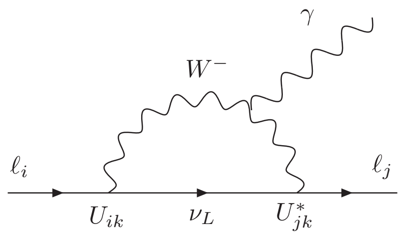



$\bullet \propto U_{\alpha i}^{\text{PMNS}}$

$\boldsymbol{m_\nu \neq 0}$

$\boldsymbol{\nu_\alpha = \sum_i U_{\alpha i} \nu_i}$

$\text{SM}_{m_\nu}$ - **cLFV viable??**




$$\textbf{BR}(\mu \to e\gamma) \propto \left| \sum U_{\mu i}^* U_{ei} \frac{m_{\nu_i}^2}{M_W^2} \right|^2 \sim 10^{-54}$$

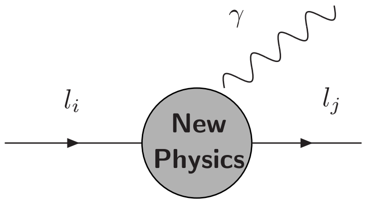
**Viable** - **yes...** but **not observable!!**

- **"Observable" cLFV $\Rightarrow$ New Physics in the lepton sector - beyond $\text{SM}_{m_\nu}$**

# A few thoughts on lepton flavour violation

★ Huge **experimental effort: MEG, PRISM/PRIME, SuperB, JPARC, ...**

What is **required** of a **SM extension** to have **"observable" cLFV?**




$\rightsquigarrow$ $\mathbf{BR(\mu \to e\gamma)} = 10^{-12} \times (2 \text{ TeV}/\Lambda)^4 \times (\theta_{\mu e}/0.01)^2$

| | | | New Physics (beyond $\text{SM}_{m_\nu}$) | + | Lepton Flavour Mixing |
|---|---|---|---|---|---|
| ▶ | **cLFV** | $\Leftrightarrow$ | $\Lambda \sim \mathcal{O}(\text{TeV})$ | | non-negligible $\theta_{\ell_i \ell_j}$ |
| | | | (testable at colliders ?) | | (suggested by neutrino mixing ...) |

▶ Many reasons support considering **BSM $\mathcal{O}$(TeV) scenarios of New Physics**

Hierarchy - Higgs FT problem; dark matter candidate; neutrino mass generation (?); ...

▶ Smallness of $m_\nu$ (and nature - **Majorana!?**) $\rightsquigarrow$ **new mechanism of mass generation**

▶ **Is Nature hidding clues of BSM in cLFV processes? How to unravel them?**

# cLFV beyond the SM - road map

- **Assume existence** of **New Physics (couplings, dynamics, states)** and

- Evaluate **impact of New Physics** for *all* possible signatures:

  **"SM" collider signals, cascade decays, EW precision tests, CP violation,**

  **anomalous moments ($\vec{E}$, $\vec{B}$), qFV, LFV, unitarity, dark matter...**

  at **high-energies, high-intensities** and **astro/cosmo frontier**

- ***All* cLFV observables:** $\ell_i \to \ell_j \gamma$, $\ell_i \to 3\ell_j$ (and angular distributions, T-, P-odd asymmetries),

  $\mu - e, N$ (different nuclei) ..., **meson decays**, ...

- **Synergy** of **observables** - peculiar patterns, dominances - **id/exclude candidates...**

- **Approaches:** 
  - **Effective approach**
  - **Model dependent**

## ▶ Effective Approach

# cLFV: the effective approach

- At **higher scales** (TeV? $M_{\text{GUT}}$? $M_{\text{Planck}}$?) additional **"heavy" degrees of freedom**
- **Integrate out "new heavy fields"** (e.g. as possibly required to generate $\nu$ masses)

- **Effective Lagrangian: "vestigial" (new) interactions** with **SM fields** at **low-energies**

$$\mathcal{L}^{\text{eff}} = \mathcal{L}^{\text{SM}} + \text{ higher order (non-renormalisable) terms}$$

$$\Delta\mathcal{L}^{d\geq 5} \sim \sum_{n\geq 5} \frac{1}{\Lambda^{n-4}}\, \mathcal{C}^n(g, Y, \ldots)\, \mathcal{O}^n(\ell, q, H, \gamma, \ldots)$$

$\Lambda$ : mass **scale of new physics**

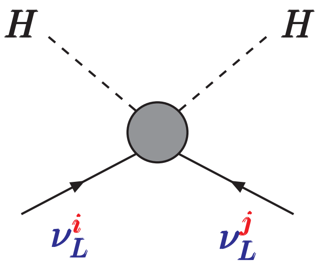
$\mathcal{C}^n$ : **dimensionless couplings** - gauge couplings, Yukawas, loop factors $((4\pi)^m)$, ...

$\Rightarrow \mathcal{C}^n_{ij}$ : *matrices in flavour space!*

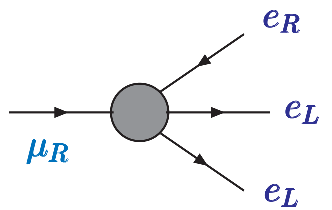
$\mathcal{O}^n$ : **"external legs"** of the diagrams - **SM fields only!**

# cLFV: the effective approach

$\Delta\mathcal{L}^{d\geq 5} = \quad \mathcal{C}^5_{\text{Weinberg}}\,\frac{1}{\Lambda} \times$




$+\ \mathcal{C}^6_{\mu eee}\,\frac{1}{\Lambda^2} \times$




$+\ \dots$

- **Dimension 5 $\Delta\mathcal{L}^5$ (Weinberg): neutrino masses** $(\Delta L = 2)$

  Common to all models with Majorana neutrinos [seesaws, radiative (Zee, RpV), ...]

- **Dimension 6 $\Delta\mathcal{L}^6$ :** kinetic corrections, cLFV **(dipole and 3-body)**, EW precision, $t$ physics...

  Differs from model to model - used to **disentangle scenarios...**

- **Higher order $\Delta\mathcal{L}^{7,8,..}$ :** $\nu$ (transitional) magnetic moments, NSI, ...

# cLFV bounds and $\mathcal{L}^{\text{eff}}$

▶ Apply **experimental** bounds on **cLFV observables** to **constrain** $\sim \frac{1}{16\pi^2} \mathcal{C}^6_{ij} \frac{1}{\Lambda^2}$

1. hypothesis on **size** of **"new couplings"** and/or 2. hypothesis on **scale** of **"new physics"**

▶ **Natural** values of the **couplings** $\mathcal{C}^6_{ij} \sim \mathcal{O}(1)$

$$\text{BR}(\mu \to e\gamma)|_{\text{MEG}} \Rightarrow \Lambda \lesssim 50 \text{ TeV}; \quad \text{BR}(\mu \to 3e) \Rightarrow \Lambda \lesssim 15 \text{ TeV}$$

$$\text{BR}(\tau \to \ell\gamma) \Rightarrow \Lambda \lesssim 3 \text{ TeV}; \quad \text{BR}(\tau \to 3\ell) \Rightarrow \Lambda \lesssim 1 \text{ TeV}$$

[from La Thuile '12]

▶ **Natural scale?** more delicate - **well motivated:** direct discovery, ...

Example: **discovery of type II seesaw** (scalar triplet) mediator at LHC, $M_\Delta \sim 1$ **TeV**

$$\text{BR}(\mu \to e\gamma)|_{\text{MEG}} \Rightarrow |Y^{\Delta\dagger}_{\mu\mu} Y^{\Delta}_{\mu e} + Y^{\Delta\dagger}_{\tau\mu} Y^{\Delta}_{\tau e}| \lesssim 2 \times 10^{-3}$$

[from 0707.4058]

▶ **Can we reconstruct the New Physics Lagrangian?** not likely...

We can **identify operators** (combining distinct observables) and

learn about **flavour structure** (same observable, different flavours)

# cLFV bounds and $\mathcal{L}^{\text{eff}}$

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- **Can we reconstruct the New Physics Lagrangian?** not likely...

- **Be prepared!** - master **"theoretical expectations"** of model **M376XV** to **falsify** it!

# Models of New Physics

**But** **"theoretical expectations"** is an *oxymoron:*

**different theorists** expect **different New Physics** at the **TeV scale** because it is

- motivated by the **naturalness** of the weak scale

- motivated by precision **unification of couplings**

- not motivated, but **why not**

- to their personal **taste or prejudice!**

[cf. Jäger, NA62 Workshop, '09]

▶ **Here:** consider **examples** of (well motivated?) models

$\rightsquigarrow$ with **potentially observable cLFV implications!**

among many, many possibilities

- **Models of New Physics and cLFV**

# cLFV: models of New Physics

- **New physics at TeV: Higgs** fine-tuning - **hierarchy problem**

  **Dark matter** candidates

  Within **experimental reach!**

- **SM extensions** introduce **new particles**, **new flavour violating** couplings..

- *Recall:* contributions to **quark FV strongly constrained** (dominated by SM)

  **No "SM background" for cLFV contributions!**

- **Examples:**

  **Generic cLFV extensions** - general MSSM, Little Higgs, Xdim, 4th generation, ...

  **cLFV from $m_\nu$**
  - SM seesaw (TeV scale) - e.g. type II
  - Extended frameworks - SUSY seesaw, GUTs, ...

- **Find cLFV-footprints to probe the nature of the model!**

# cLFV-footprints: unveiling the NP model

- In the **absence** of cLFV (and other) **signals:**

  ⇒ **constraints on parameter space (scale and couplings)**

- **cLFV observed: compare with peculiar features of given model**

  ⇒ **predictions** for **low-energy cLFV observables** (& CPV, $(g-2)_\mu$, ...)

  ⇒ **intrinsic patterns** of **correlations of observables**

  ⇒ possible **high-energy (collider) cLFV** observables; **further correlations!**

  ⇒ If present, explore **links to $\nu$ data and dark matter**

- **One keyword: synergy of observables !**

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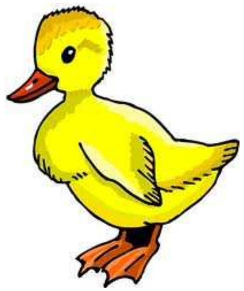
- **One keyword: synergy of observables !**

*And at the end: "If it looks like a duck, swims like a duck,*

*and quacks like a duck, then it probably is a duck."*



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- **One keyword: synergy of observables !**

*And at the end: "If it exhibits the observed pattern for cLFV observables,*
*explains the issues of the SM, is in agreement with everything...*
*it might be the correct New Physics model !"*

- **Generic cLFV extensions**

# Example: cLFV in Little Higgs models (T-parity) [LHT]

★ **Higgs** is a **pseudo-Goldstone** boson of **spontaneously broken** global symmetry

- SU(5) $\to$ SO(5) **(@ TeV scale); augmented gauge group** $[\mathrm{SU}(2)\times\mathrm{U}(1)]^2$

  $\Rightarrow$ **new (heavy) gauge bosons** - $A_H$, $Z_H$, $W_H^\pm$

- T parity $\Rightarrow$ prevents contributions to **EW observables** (tree-level)

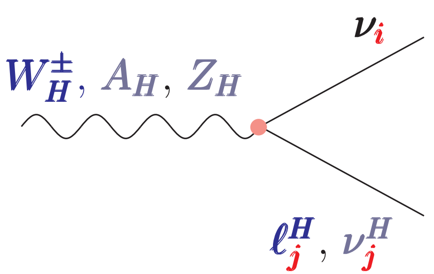
  **Lightest T-odd particle stable** $\leftrightsquigarrow$ **dark matter candidate**

- T-odd sector: **3 doublets of mirror quarks** and **leptons**

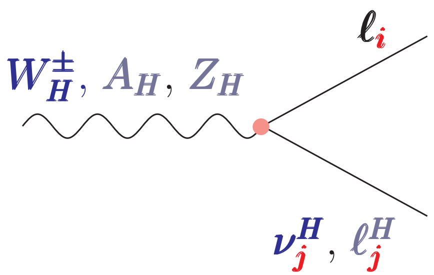
  (couple to SM via **new gauge bosons**)

- Only **10 new parameters** in flavour sector, only **SM operators relevant**

- **Sources of cLFV:** couplings of **leptons - mirror leptons - heavy gauge bosons**




$\propto V_{H\nu}$

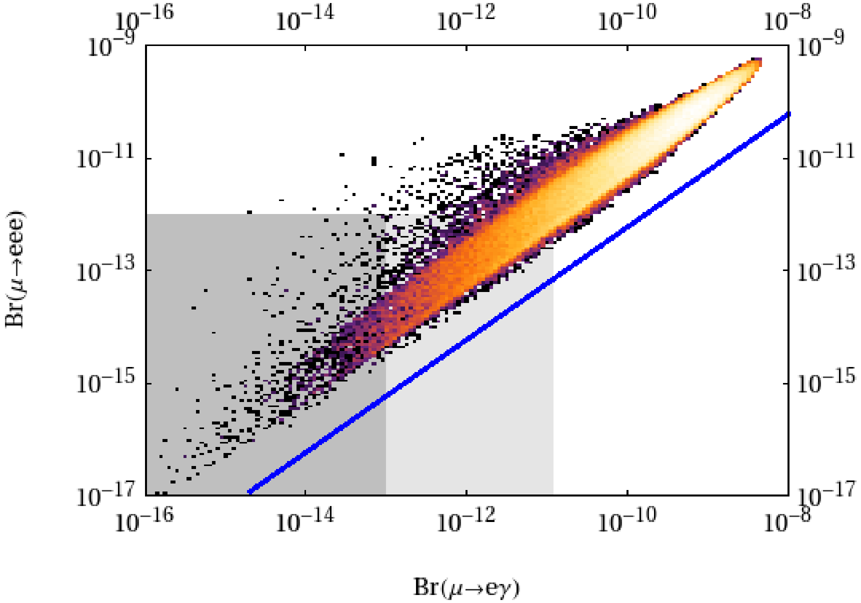


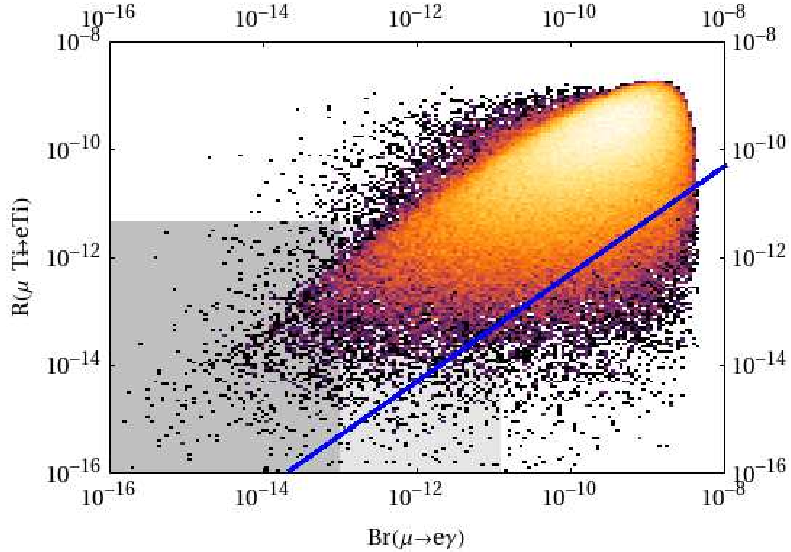

$\propto V_{H\ell}$

$$V_{H\nu}^\dagger V_{H\ell} = U_{\mathrm{PMNS}}^\dagger$$

[Many people, ...]

# cLFV in Little Higgs models (T-parity): an example




[from Blanke et al, 0906.5454]

- **Strong correlation** of some cLFV observables: $\mu \to e\gamma$ **and** $\mu \to 3e$
- Negligible **dipole** contributions
- **Chirality structure of LHT** $\leftrightsquigarrow$ **Asymmetries** for **polarised** $\tau$ **and** $\mu$ decays [1012.4385]
- Typically **large contributions to cLFV** $\rightsquigarrow$ some **fine-tuning required**

  hierarchical mixing matrices $(V_{H\ell}, V_{H\nu})$, quasi degenerate states, ...

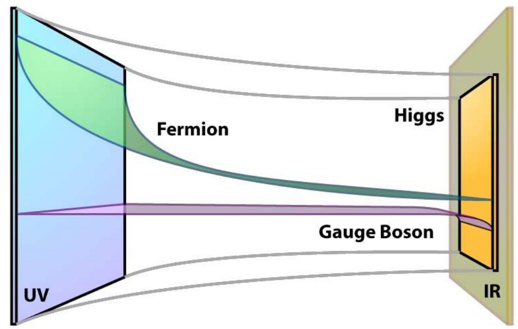
# Geometric flavour violation: RS warped extra dimensions

★ Embed **4dim space-time** into **higher dim AdS space** (extra dims compactified on orbifold)

- **Two branes** (UV, IR) and **bulk** between; $M_{\text{TeV}} = M_{\text{Planck}} e^{-\pi L_x}$
- Localise fields: **Higgs** close to **IR brane** (hierarchy problem);

  **e.g.** **SM fermions and gauge bosons** on **bulk**

  **KK excitations** of **SM fields** close to **IR brane**
- **Interactions of fields: overlap of wave functions**




- An example - **Geometrical distribution** of **fermions** in bulk:

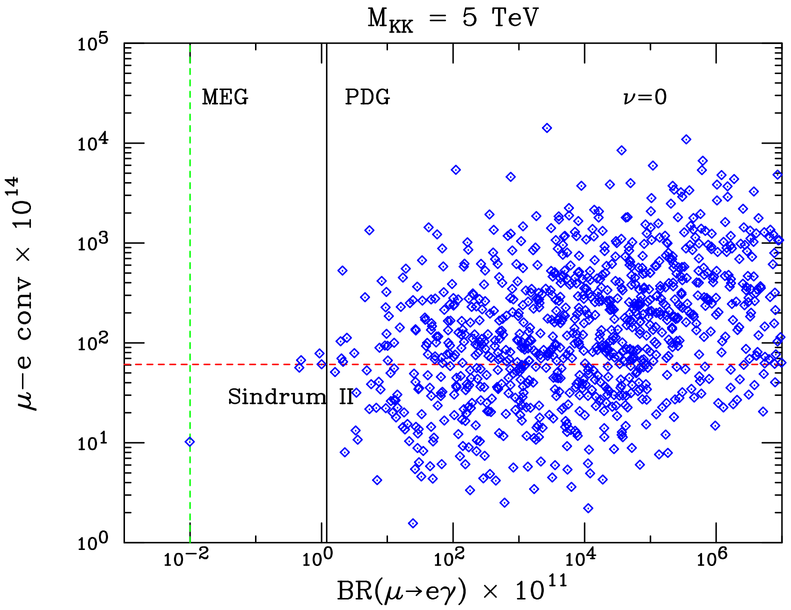
  **hierarchy in 4dim Yukawas** for **"anarchic"** $\mathcal{O}(1)$ **higher dim couplings**
- **Circumvent pheno issues:** enlarge **bulk symmetry** (prevent violation of custodial SU(2));

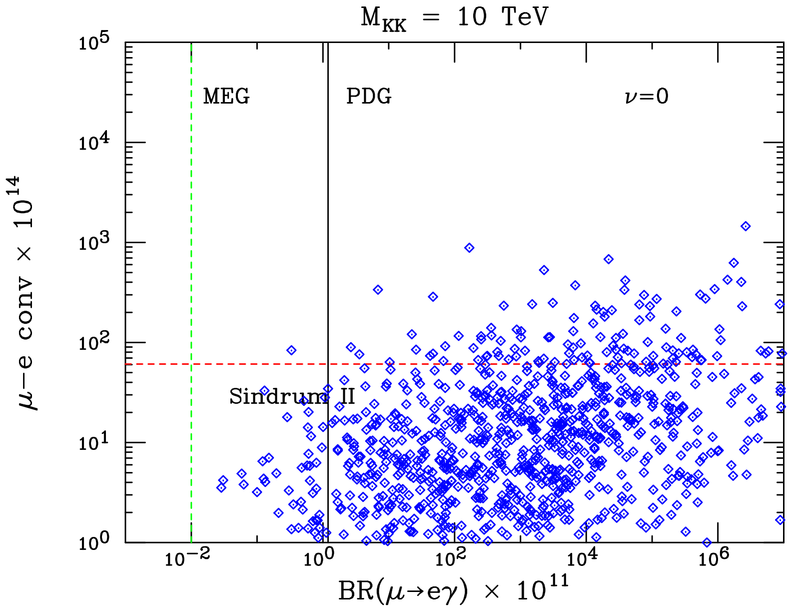
  additional **"rescue" ingredients** to **avoid excessive FCNCs,**

  protect **EW precision observables,** ...

[ ... also many people!]

# Geometric flavour violation: RS warped extra dimensions




[from Agashe et al, 0606021]

- **Electroweak precision observables:** $\boldsymbol{M_{KK} \geq 3}$ **TeV** [models with custodial sym.]
- **Purely geometrical** description (quarks$|_{\varepsilon_K}$) $\Rightarrow$ $\boldsymbol{M_{KK} \geq 20}$ **TeV** $\xrightarrow{\text{some FT}}$ $\boldsymbol{M_{KK} \geq 3}$ **TeV**
- **cLFV processes** mediated by **KK-lepton excitations, new gauge fields**

  **cLFV:** $\boldsymbol{M_{KK} \geq 10}$ **TeV** (5 TeV only marginally compatible)
- Possible ways out... flavour structure (non-geometrical), increase gauge symmetry, ...

# General Minimal Supersymmetric extension of the SM

- **Supersymmetry is broken in Nature:** different masses for SM particles and superpartners

  **Generic soft-SUSY breaking terms** introduce new sources of flavour violation ($q$ and $\ell$)

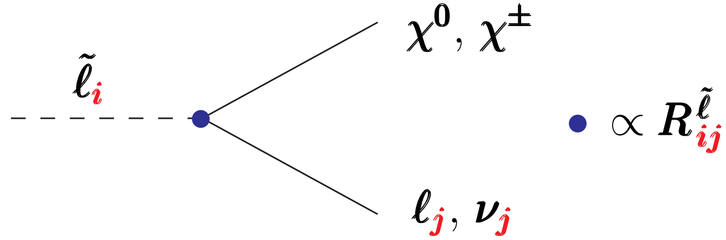
  non-diagonal masses for sleptons and sneutrinos $\quad (M^2_{\tilde{\ell}})_{ij} \neq 0! \quad (M^2_{\tilde{\nu}})_{ij} \neq 0!$

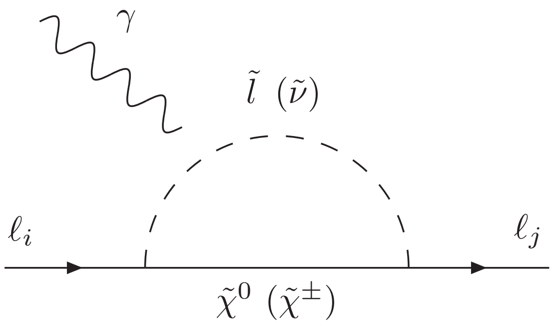
- **Misalignement** of **flavour** and **physical** eigenstates: $\quad R^{\tilde{\ell}\,\dagger}\, M^2_{\tilde{\ell}}\, R^{\tilde{\ell}} = \text{diag}(m^2_{\tilde{\ell}_i}) \quad R^{\tilde{\ell}} \neq 1!$

  $\{\tilde{e}_L, \tilde{\mu}_L, \tilde{\tau}_L, \tilde{e}_R, \tilde{\mu}_R, \tilde{\tau}_R\} \not\leftrightarrow \{\tilde{\ell}_1, \dots, \tilde{\ell}_6\}$

  manifest in **neutral** and

  **charged lepton-slepton** interactions




- Sizable contributions to **cLFV observables** $\propto \delta^{\ell}_{ij} = \frac{(M^2_{\tilde{\ell}})_{ij}}{M^2_{\text{SUSY}}}$

"almost everything is possible - depending on the regime"...

e.g. $\mathbf{BR}(\mu \to e\gamma) \sim \frac{\alpha}{4\pi} \left(\frac{M_W}{M_{\text{SUSY}}}\right)^4 \sin^2\theta_{\tilde{e}\tilde{\mu}} \left(\frac{\Delta m^2_{\tilde{\ell}}}{M^2_{\text{SUSY}}}\right)^2$

[... really a lot of people - a crowd!]

# 4th generation* - and beyond!

- **Extend the SM** via a **fourth family*** of quarks and **leptons** (Dirac or Majorana $\nu$s)

  ***LHC excluded??**

- **Additional mixing angles** and CP phases in the **lepton sector**
- **Radiative and 3-body decays:** all **as large as current bounds (not simultaneously)**
- **Distinctive patterns for correlations** of observables in **SM4**

**[... still many people, decreasing?]**

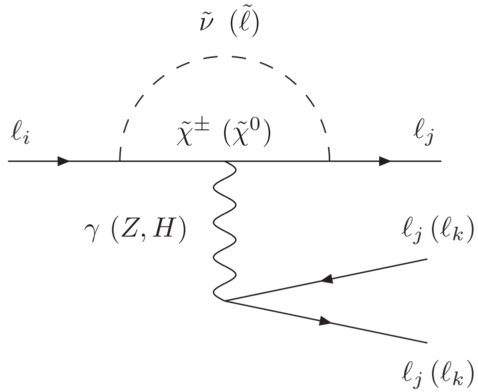
⋆ ⋆ ⋆ ⋆ ⋆ ⋆ ⋆ ⋆ ⋆ ⋆

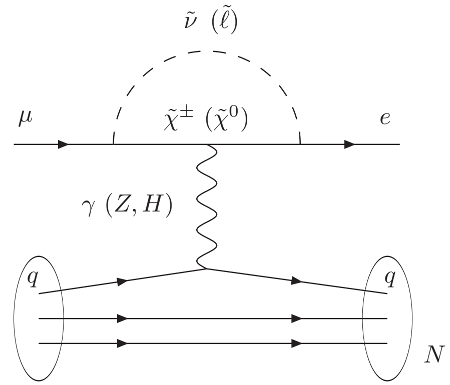
*And many other models ... LR symmetric, multiHiggs, Leptoquarks, ...*

**[... a whole population! ]**

# Comparing predictions - finding fingerprints

| ratio | LHT | MSSM (dipole) | MSSM (Higgs) | SM4 |
|---|---|---|---|---|
| $\frac{BR(\mu^- \to e^- e^+ e^-)}{BR(\mu \to e\gamma)}$ | 0.02...1 | $\sim 6 \times 10^{-3}$ | $\sim 6 \times 10^{-3}$ | $0.06 \ldots \mathbf{2.2}$ |
| $\frac{BR(\tau^- \to e^- e^+ e^-)}{BR(\tau \to e\gamma)}$ | 0.04...0.4 | $\sim 1 \times 10^{-2}$ | $\sim 1 \times 10^{-2}$ | $0.07 \ldots \mathbf{2.2}$ |
| $\frac{BR(\tau^- \to \mu^- \mu^+ \mu^-)}{BR(\tau \to \mu\gamma)}$ | 0.04...0.4 | $\sim 2 \times 10^{-3}$ | $0.06 \ldots 0.1$ | $0.06 \ldots \mathbf{2.2}$ |
| $\frac{BR(\tau^- \to e^- \mu^+ \mu^-)}{BR(\tau \to e\gamma)}$ | 0.04...0.3 | $\sim 2 \times 10^{-3}$ | $0.02 \ldots 0.04$ | $0.03 \ldots \mathbf{1.3}$ |
| $\frac{BR(\tau^- \to \mu^- e^+ e^-)}{BR(\tau \to \mu\gamma)}$ | 0.04...0.3 | $\sim 1 \times 10^{-2}$ | $\sim 1 \times 10^{-2}$ | $0.04 \ldots \mathbf{1.4}$ |
| $\frac{BR(\tau^- \to e^- e^+ e^-)}{BR(\tau^- \to e^- \mu^+ \mu^-)}$ | 0.8...2 | $\boldsymbol{\sim 5}$ | 0.3...0.5 | $1.5 \ldots 2.3$ |
| $\frac{BR(\tau^- \to \mu^- \mu^+ \mu^-)}{BR(\tau^- \to \mu^- e^+ e^-)}$ | 0.7...1.6 | $\sim 0.2$ | 5...10 | $1.4 \ldots 1.7$ |
| $\frac{R(\mu Ti \to e Ti)}{BR(\mu \to e\gamma)}$ | $10^{-3} \ldots 10^{2}$ | $\sim 5 \times 10^{-3}$ | $0.08 \ldots 0.15$ | $10^{-12} \ldots 26$ |




[from Buras et al, 1006.5356]

- Most **models predict/accommodate** extensive **ranges for observables**

  (no new physics yet discovered, only bounds on new scale!)

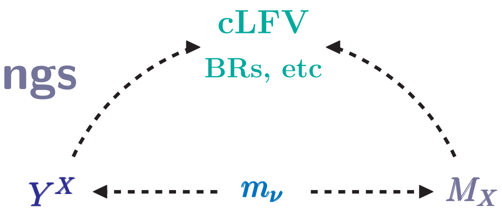
- But... **Peculiar patterns** to **correlation of observables** (model-specific)

**Correlations** might allow to **disentagle models of cLFV** in the absence of **discovery of new states!** ... or inability to **identify mechanism of LFV!**

## ▶ cLFV from $\nu$ mass generation mechanisms - seesaw

# cLFV and the "SM" seesaw mechanism

★ **Seesaw mechanism:** explain **small $\nu$ masses** with **"natural" couplings** via **new dynamics** at **"heavy" scale**




| Seesaw | $\tilde{\mathcal{C}}_5$ | New Physics scales | cLFV-$\tilde{\mathcal{C}}_6$ | cLFV obs |
|---|---|---|---|---|
| Fermionic singlet (type I) | $Y_N^T \frac{1}{M_N} Y_N$ | $Y_N \sim \mathcal{O}(1) \Rightarrow M_N \approx 10^{15}$GeV $M_N \sim M_{\text{GUT}}???$ | $\left(Y_N^\dagger \frac{1}{M_N^\dagger} \frac{1}{M_N} Y_N\right)_{\alpha\beta}$ | ... not enough... (?) |
| Fermionic triplet (type III) | $Y_\Sigma^T \frac{1}{M_\Sigma} Y_\Sigma$ | $M_\Sigma \gg$ TeV | $\left(Y_\Sigma^\dagger \frac{1}{M_\Sigma^\dagger} \frac{1}{M_\Sigma} Y_\Sigma\right)_{\alpha\beta}$ | ... not enough... (?) |
| **Scalar triplet** (type II) | $4 Y_\Delta \frac{\mu_\Delta}{M_\Delta^2}$ | **$Y_\Delta \sim \mathcal{O}(1) \Rightarrow M_\Delta \approx$ TeV** **($\mu_\Delta \ll 1$!)** | $\frac{1}{M_\Delta^2} Y_{\Delta\alpha\beta} Y^\dagger_{\Delta\gamma\delta}$ | **maybe large...** **constrain model!** |

- cLFV in type II seesaw: **predictive** (correlations), **observable cLFV!**
- **cLFV bounds $\Rightarrow$ constraints on $Y_\Delta$ and $M_\Delta$; $\mu \to eee$: $Y_\Delta \sim \mathcal{O}(1) \Rightarrow M_\Delta \leq 300$ TeV**

  [from 0707.4058]
- **If $M_\Delta \sim$ TeV** (smaller $Y_\Delta$), possible **discovery at LHC**
- **"Inverse seesaw":** similar decorrelation between $m_\nu$ suppression and cLFV - large BRs (?)

  ... and many other variations!

[... a very sizable community! ]

- **cLFV from $m_\nu$ in extended frameworks**

# The supersymmetric seesaw(s) and cLFV

★ **Embed seesaw in the framework** of (otherwise) **flavour-conserving SUSY models**

(cMSSM, supergravity-inspired, etc)

- In addition to

| | | | |
|---|---|---|---|
| **Right-handed $\nu$** | $\rightsquigarrow$ | $\tilde{\nu}_R$ | [Type I] |
| **Scalar triplets** | $\rightsquigarrow$ | **"triplinos"** | [Type II] |
| **Fermion triplets** | $\rightsquigarrow$ | **"s-triplets"** | [Type III] |

with **same couplings, same interactions!**

- **But!** preserve nice SUSY feature of **"gauge coupling unification"**

"gauge non-singlets" below $M_{\text{GUT}}$ $\rightsquigarrow$ running of $g_i$

$\Rightarrow$ embed superfields into **complet GUT** (e.g. SU(5)) **representations**

- **SUSY introduces degrees of freedom active at "seesaw" scales**

$\Rightarrow$ **indirect probe of the seesaw!**

- **Even if correlations, etc... - difficult to disentangle from "generic" MSSM cLFV...**

On the other hand $\Rightarrow$ some scenarios are falsifiable!

**[... and many many many people!]**

# What is so special about the SUSY Seesaw?

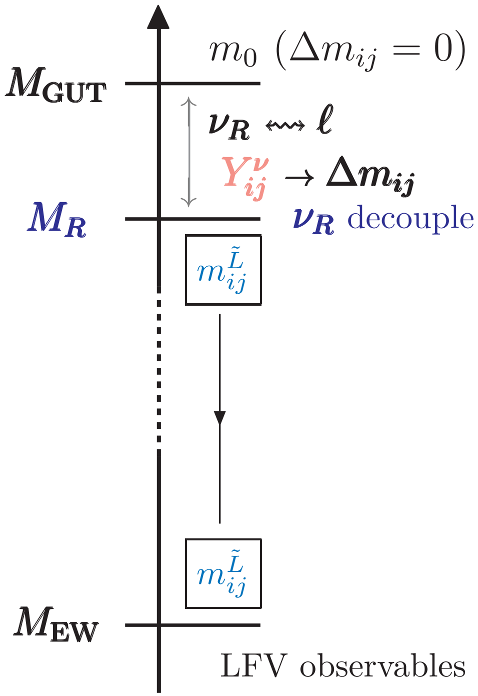
- To accommodate **data on $\nu$-oscillations**, $\boldsymbol{Y^\nu}$ cannot be **diagonal**!

**cLFV originates from large size and non-trivial structure of $Y^\nu$!**

- Even for **universal** soft-breaking terms @ $M_{\text{GUT}}$ (SUSY flavour problem),

  **RGE running of $Y^\nu$** from $M_{\text{GUT}}$ down to **Seesaw scale** $M_R$

  induces flavour-violating terms in **slepton soft-breaking masses**




- If **Majorana** $\nu$s, if **seesaw scale** $\sim \mathcal{O}(10^{15}$ GeV$) \rightsquigarrow \boldsymbol{Y^\nu}$ can be $\boldsymbol{\mathcal{O}(1)}$

  **Large flavour violation in slepton sector**

$$(\Delta m^2_{\tilde{L}})_{ij} = -\frac{1}{8\,\pi^2}\,(3\,m_0^2 + A_0^2)\,(Y^{\nu\dagger}\,L\,Y^\nu)_{ij}$$

$L = \log(M_{\text{GUT}}/M_R)$

$$\text{BR}(\ell_i \to \ell_j \gamma) \propto \left|\left(Y^{\nu\dagger} \log \frac{M_{\text{GUT}}}{M_R}\, Y^\nu\right)_{ij}\right|^2$$

- **Large SUSY contributions to cLFV observables, within experimental reach!**

# One source of flavour violation in the lepton sector

- **mSUGRA-like SUSY seesaw:** $Y^\nu$ **unique source of FV**

  (all observables strongly related)

  ⋆ **low-energies:** $l_j \to l_i \gamma$, $l_j \to 3l_i$, $\mu - e$ **in Nuclei**

  ⇒ **large rates potentially observable!**

  ⋆ **high-energies [LHC]:** study **charged sleptons** from $\chi_2^0 \to \ell^\pm \ell^\mp \chi_1^0$ decays

  ⇒ **sizable** $\tilde{e} - \tilde{\mu}$ **mass differences**, new edges in $m_{\ell\ell}$: $\chi_2^0 \to \left\{ \begin{array}{c} \tilde{\ell}^i_L \, \ell_i \\ \tilde{\ell}^i_R \, \ell_i \\ \tilde{\ell}^j_X \, \ell_i \end{array} \right\} \to \chi_1^0 \, \ell_i \, \ell_i$

  ⋆ **high-energies - lepton colliders:** cLFV in $e^\pm e^- \to e^\pm \mu^- + E^T_{\text{miss}}$

  ⇒ **possibily cLFV-seesaw golden channel** $e^- e^- \to \mu^- \mu^- + 2\chi_1^0$

- **If LFV indeed observable (large BRs & CR),**

**expect interesting slepton phenomena at colliders!**

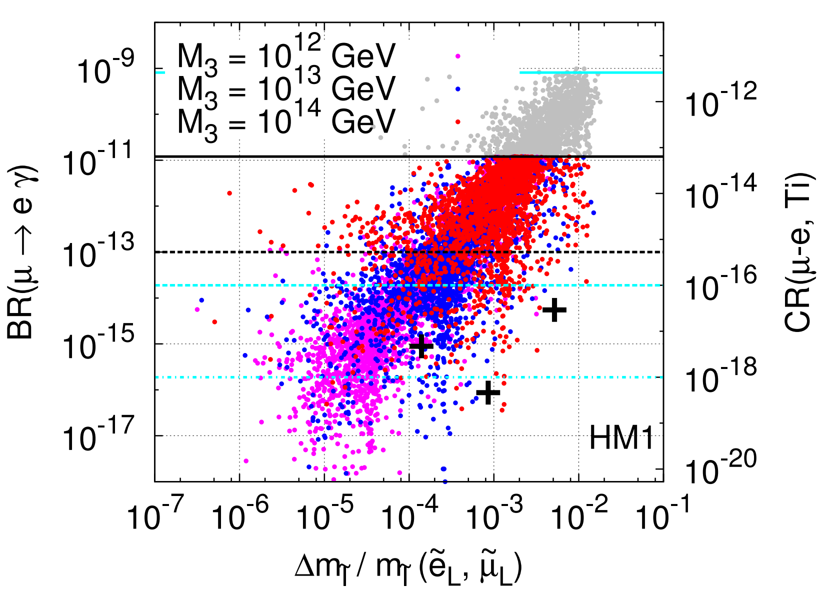
**... strengthen / disfavour seesaw hypothesis !**

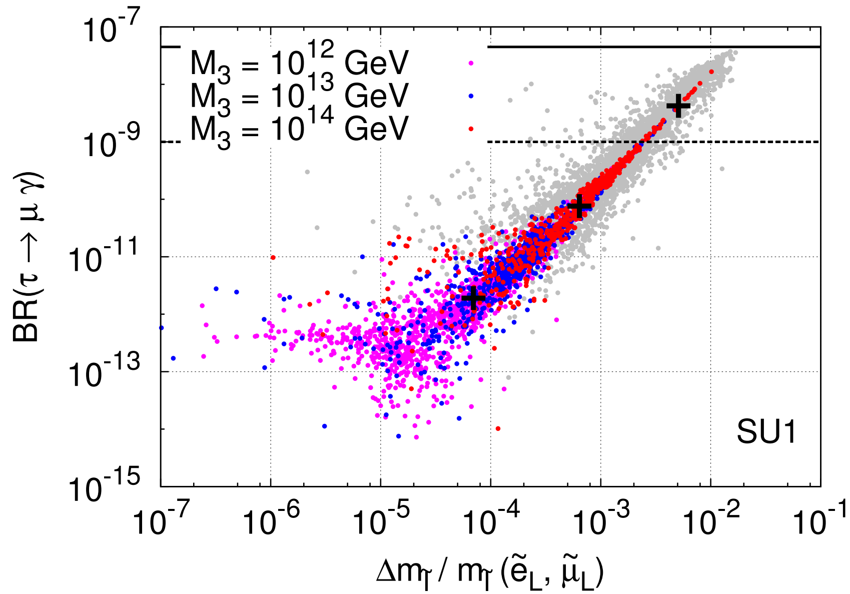
**[... a large group!]**

# LFV at low- and high-energies: general overview

**cMSSM: CMS point HM1** {180, 850, 0, 10, +1} and **ATLAS point SU1** {70, 350, 0, 10, +1}

**Seesaw:** general $\boldsymbol{R}$ (vary $|\theta_i|, \arg\theta_i \in [-\pi, \pi]$), $\boldsymbol{M_{R_3}} = 10^{12,13,14}$ GeV; $\boldsymbol{\theta_{13}} = 0.1^\circ$




[from AFRT, 1007.4833]

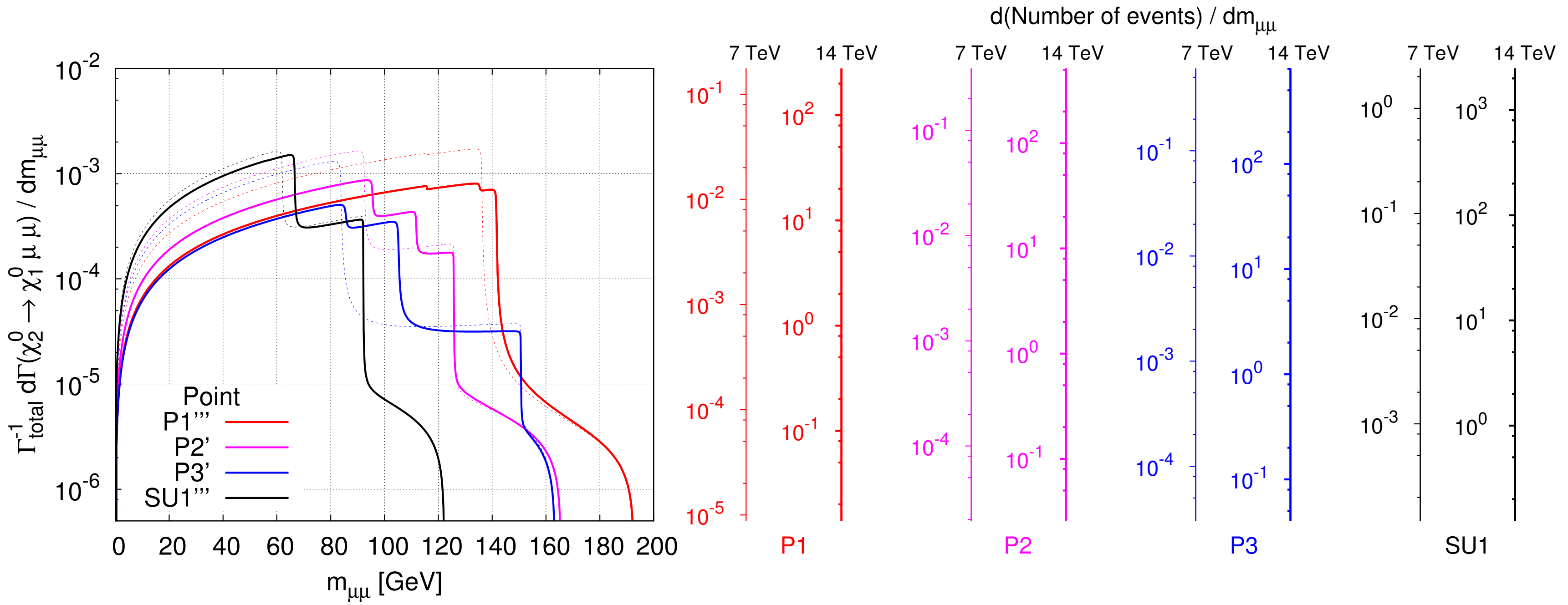
- **If type-I seesaw and SUSY ⇒ LFV observables within experimental reach**
- **HM1:** $\Delta m(\tilde{e}_L, \tilde{\mu}_L)|_{\text{LHC}} \sim 0.1 - 1\% \rightsquigarrow$ **BR**$(\mu \to e\gamma)|_{\text{MEG}}$
- **SU1:** $\Delta m(\tilde{e}_L, \tilde{\mu}_L)|_{\text{LHC}} \sim 0.1 - 1\% \Rightarrow$ **BR**$(\tau \to \mu\gamma) \gtrsim 10^{-9}$ **(SuperB)**

⇒ Hint towards scale of new physics ($M_{N_3} \gtrsim 10^{13}$ GeV)

# LFV at the LHC: di-lepton distributions in $\chi_2^0$ decays

Impact of **type-I SUSY seesaw** for **di-lepton distributions** $\chi_2^0 \to \tilde{\ell}^i_{L,R}\, \ell_i \to \chi_1^0\, \ell_i\, \ell_i$

**Seesaw:** $R = 1$, $P'^{('''')}_{M_R}$ ={$10^{10}$, $5 \times 10^{10}$ ($10^{12}$), $5 \times 10^{13}$ ($10^{15}$)} GeV, $\theta_{13} = 0.1°$

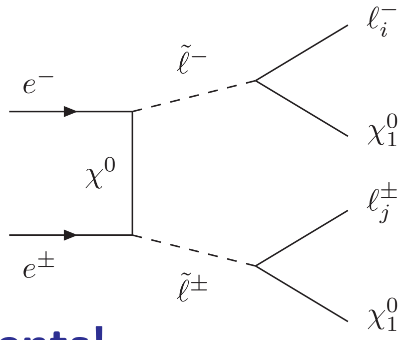



[from AFRT, 1007.4833]

- **Displaced** $m_{\mu\mu}$ and $m_{ee}$ **edges** $(\tilde{\ell}_L) \Leftrightarrow$ **sizable** $\frac{\Delta m_{\tilde{\ell}}}{m_{\tilde{\ell}}}(\tilde{e}_L, \tilde{\mu}_L)$ [⇝ flavour non-universality (?)]
- Appearance of **new edge** in $m_{\mu\mu}$ : **intermediate** $\tilde{\tau}_2$ [⇝ flavour **violation!**]
- **LFV at the LHC:** $\chi_2^0 \to \tilde{\tau}_2\, \mu \to \chi_1^0\, \mu\, \mu$

# cLFV at Linear Colliders

★ **Seesaw-induced cLFV final states** from $e^{\pm}e^{-} \to e^{\pm}\mu^{-}$ +**missing energy**

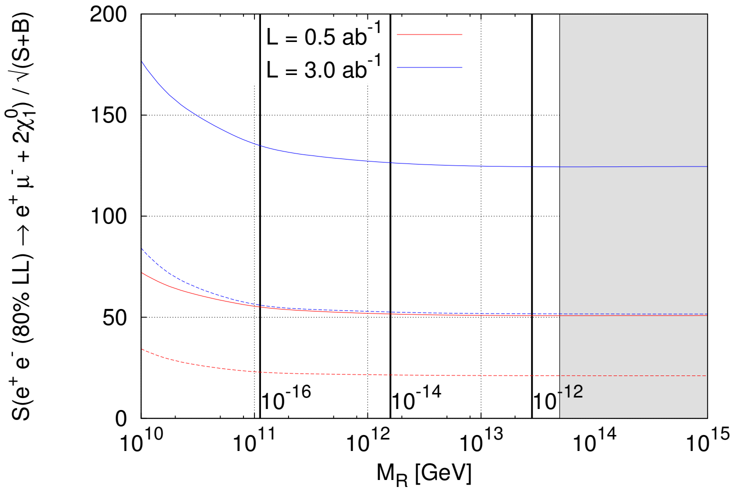



- Potential **backgrounds from SM$_{m_\nu}$ & SUSY$_{m_\nu}$ charged currents ...**

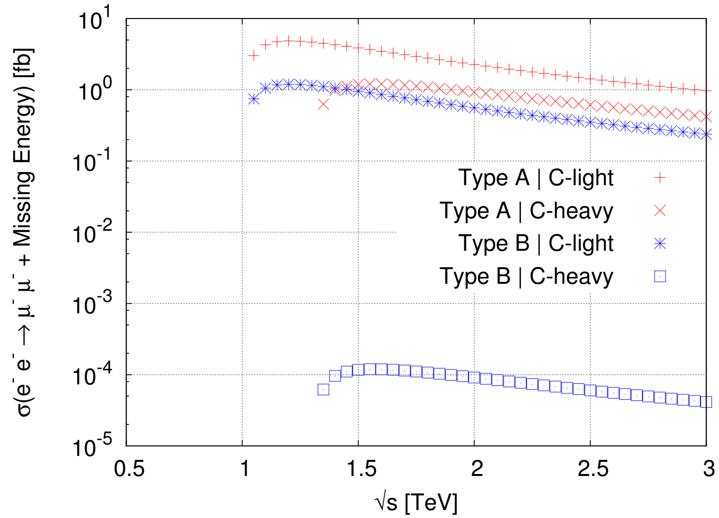
  explore electron and positron **beam polarisation!**

- **Statistical significance** of **"raw" signal** ⇒ **feasible observation of events!**

$e^+e^- \to e^+\mu^- + E^T_{\text{miss}}$




$e^-e^- \to \mu^-\mu^- + E^T_{\text{miss}}$




⇝ **Number events**

C-I 1000 (6000)

C-H 500 (3000)

$\mathcal{L} = 0.5\ (3)$ ab$^{-1}$

[from AFRT, 1206.2306]

★ **Golden channel (?) : $e^-e^- \to \mu^-\mu^-$** + missing energy

- **Small background... ⇒ signal clear probe type I** of **SUSY seesaw**

  (if unique source of LFV!)

# Beyond the type I SUSY seesaw: examples ...

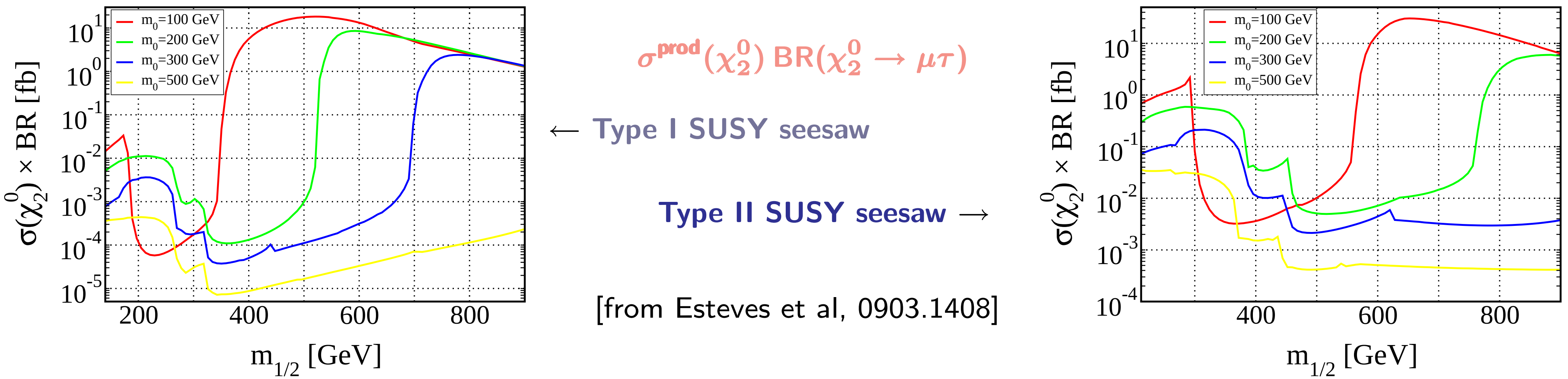
★ **Type II SUSY seesaw**

▶ **More predictive** (up to overall scale) - $(\Delta m^2_{\tilde{L}})_{ij} \propto m^2_{\nu\alpha} U_{\alpha i} U^*_{\beta j}$

**correlations** between cLFV observables controled by **$\nu$-parameters !**

[... large community!]

▶ **Distinctive prospects for cLFV at colliders**




$\sigma^{\text{prod}}(\chi^0_2)\, \text{BR}(\chi^0_2 \to \mu\tau)$

← Type I SUSY seesaw

Type II SUSY seesaw →

[from Esteves et al, 0903.1408]

▶ Non-singlet SUSY seesaw: "force" gauge coupling unification - embed into GUTs, etc

★ **Type III SUSY seesaw, Inverse SUSY seesaw, hybrid...**

[... really large community!]

# Beyond the type I SUSY seesaw: examples ...

★ **Supersymmetric Grand Unified Theories**

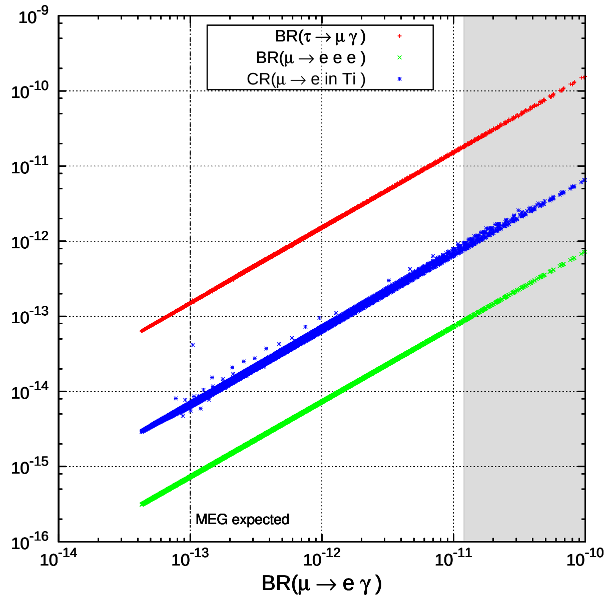
▶ **Reduce arbitrariness of $Y^\nu$** [CKM- and $U_{\text{PMNS}}$-inspired patterns... Symmetries...]

▶ **SO(10) type II example**

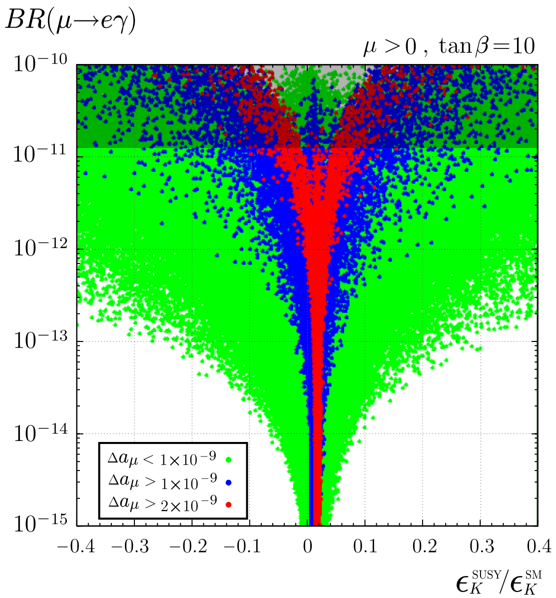
(leptogenesis motivated)

**highly correlated cLFV observables!**

[from Calibbi et al, 0910.0377]




▶ **SU(5) + RH neutrinos SUSY GUTs**




**correlated CPV and FCNCs observables**

**in lepton and hadron sectors!**

[from Buras et al, 1011.4853]

# Overview

- Flavour violated in **neutral leptons (and quarks)...**

  only **logical and natural** that charged lepton flavour also violated in **Nature!**

  and **great!** **New Physics beyond SM + massive $\nu$s!**

- Many (interesting) **models predict** cLFV - some in relation with **$\nu$-mass generation**

  cLFV **can play a unique rôle** in **disentangling models**, **info on $\nu$-dynamics**

  *"prefer" those with "some tension" between theory and near future data!*

- **Nature** has been **"kind"** - **large Chooz angle...** maybe $0\nu2\beta$? or **NP** at LHC?

- While waiting: **explore new avenues,** as many as possible! *(here - just "tip of iceberg!")*

  **different models, cLFV observables, correlations...**

  and **"indirect links"** to other problems: **dark matter, supernovae, BAU...**

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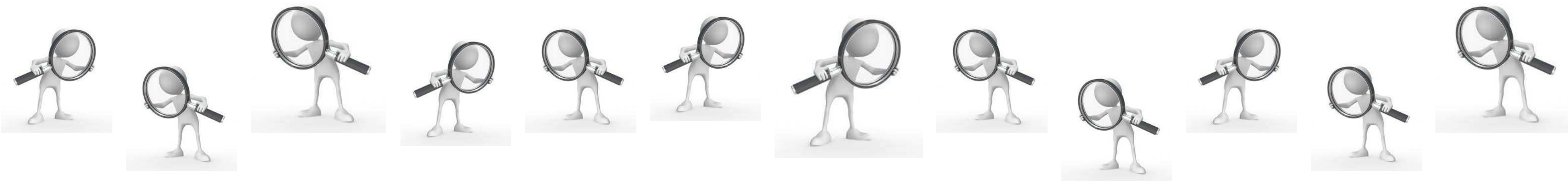
- Joint effort of **so many many people**, working in **so many interesting cLFV models**



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**And then one day** ... **cLFV is observed** and *"we will come up with a theory so simple, so beautiful, so elegant - that it can only be true!"*

One day... - maybe 2013?

Delivered to some British castle via a very Invisible $g^3$-mail?

... “The new Standard Model of Particle Physics” ...

[$g^3$-mail : three-ghost mail (triplet, s-triplet, triplino representation!)]