



Theoretical aspects of lepton flavour violation

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Rencontres de Physique des Particules
IPHC - Strasbourg, 21 January 2014

Lepton flavour violation: brief summary

- ▶ **LFV observables and experimental status**
- ▶ **Model-independent approaches to LFV**
- ▶ **LFV in models of New Physics**
 - Flavour violating extensions of the Standard Model
 - Models of neutrino mass generation (SM-like and larger frameworks)
 - Hints of an organising principle: LFV and symmetries
- ▶ **Overview**

Signals of Lepton Flavour Violation

► Neutrino oscillations

[ν -dedicated experiments]

► Rare leptonic decays and transitions

[high-intensity facilities]

$\ell_i \rightarrow \ell_j \gamma$, $\ell_i \rightarrow 3\ell_j$, $\mu - e$ conversion, mesonic τ decays...

► Meson decays: violation of lepton flavour universality (e.g. R_K)

lepton Number violating decays - $B \rightarrow D \mu^- \mu^-$, ...

lepton flavour violating decays - $B \rightarrow \tau \mu$, ... [high-intensity; LHCb]

► Rare (new) heavy particle decays (typically model-dependent)

[colliders]

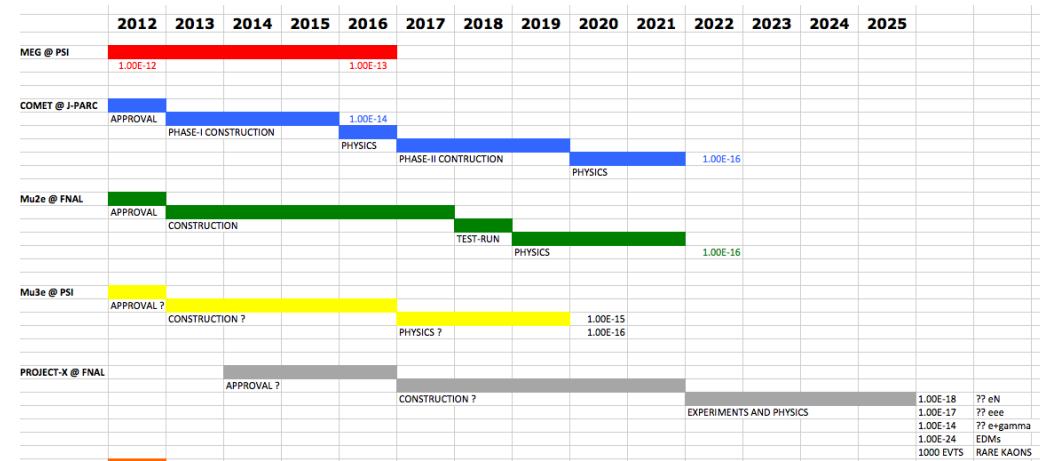
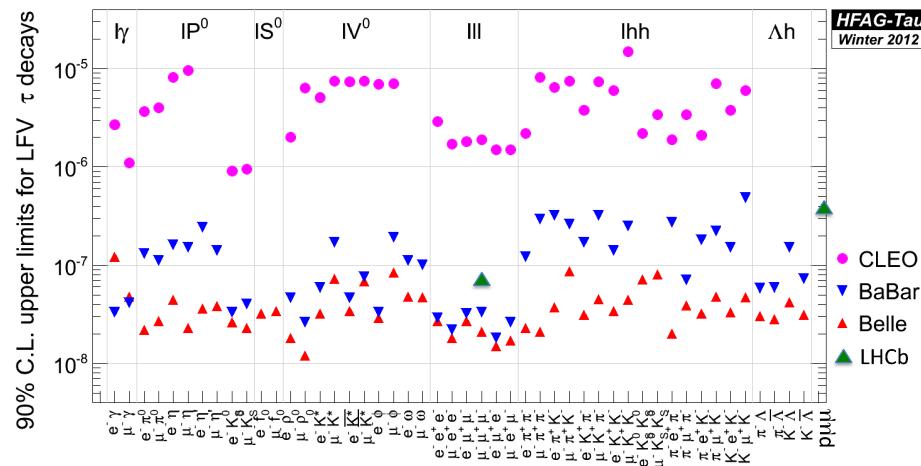
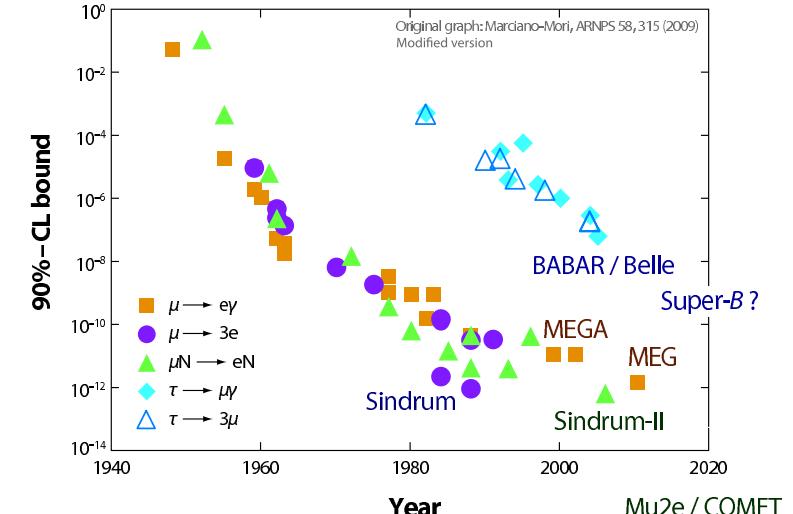
SUSY $\tilde{\ell}_i \rightarrow \ell_j \chi^0$, FV KK-excitation decays, $H \rightarrow \tau \mu$, ...

LFV final states: for example, $e^\pm e^- \rightarrow e^\pm \mu^- + E_{\text{miss}}^T$

► And many others ...

LFV observables: experimental status

	90% C.L. upper-limit	Future Sensitivity
$\text{BR}(\mu \rightarrow e\gamma)$	5.7×10^{-13} (MEG, '13)	6×10^{-14} (MEG)
$\text{BR}(\tau \rightarrow \mu\gamma)$	4.4×10^{-8} (BaBar, '10)	$10^{-(9-10)}$ (Super-KEKB)
$\text{BR}(\tau \rightarrow e\gamma)$	3.3×10^{-8} (BaBar, '10)	$10^{-(9-10)}$ (Super-KEKB)
$\text{CR}(\mu - e, \text{Ti})$	4.3×10^{-12} (SINDRUM II, '93)	10^{-18} (PRISM/PRIME)
$\text{CR}(\mu-e, \text{Au})$	7.0×10^{-13} (SINDRUM II, '06)	—
$\text{CR}(\mu-e, \text{Al})$	—	10^{-16} (Mu2e/COMET)
$\text{BR}(\mu \rightarrow 3e)$	1.0×10^{-12} (SINDRUM, '88)	10^{-14} (Mu3e)



► Impressive sensitivity to rare processes: $10^{-18} \leftrightarrow$ about 10^{19} muons
 (... and circa 10^{19} grains of sand on Earth ...)

LFV observables as a sign of New Physics

► Flavour violation in the neutral sector

SM: $m_\nu = 0 \Rightarrow$ no oscillations, lepton number and flavour strictly conserved

SM $_{m_\nu}$ “ad-hoc extension” $\rightsquigarrow m_\nu \nu_L \nu_R$ (Dirac)

Lepton flavour violated by charged currents: $U_{ij}^{\text{PMNS}} W \ell_i \nu_j$

Negligible charged Lepton Flavour Violation (**cLFV**):

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

► Flavour violation in charged lepton sector: **Physics beyond SM $_{m_\nu}$!**

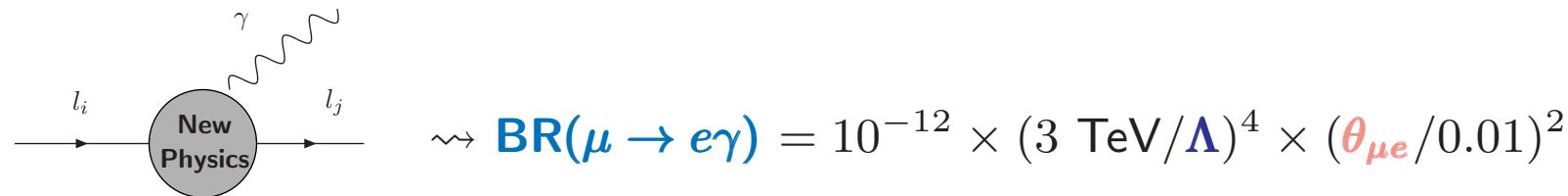
Are neutral and charged LFV related?

Does cLFV arise from ν -mass mechanism? Or entirely different nature?

► Lepton number violation: models of NP with Majorana fermions

Interpreting experimental data (bounds & measurements)

- What is required of a **SM extension** to have “**observable**” cLFV?



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

- **Pheno approaches:** $\left\{ \begin{array}{l} \text{Effective approach (model-independent)} \\ \text{Model dependent (specific NP scenario)} \end{array} \right.$
- **Many models:** generic cLFV extensions (general MSSM, LHT, RS, composite Higgs, ...);
models of massive ν s; extended frameworks ...

- ▶ cLFV: effective approach

cLFV: the effective approach

- At higher scales (TeV? M_{GUT} ? M_{Planck} ?) additional “heavy” degrees of freedom
- Integrate out “new heavy fields” (as those required to generate ν masses)
- Effective Lagrangian: “vestigial” (new) interactions with SM fields at low-energies

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

[e.g. to break SM $B - L$ accidental symmetry, $m_\nu \neq 0$]

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

Λ : scale of new physics

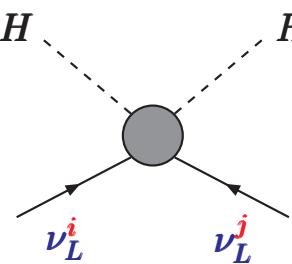
\mathcal{C}^n : dimensionless couplings - coupling constants, Yukawas, loop factors $((4\pi)^m)$, ...

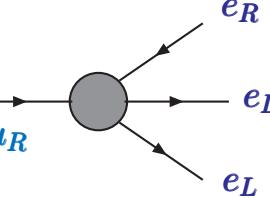
$\Rightarrow \mathcal{C}_{ij}^n$: matrices in flavour space!

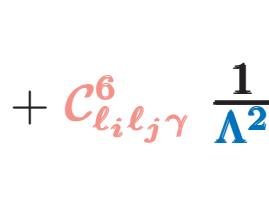
\mathcal{O}^n : “external legs” of the diagrams - SM fields only!

cLFV: the effective approach

$$\Delta\mathcal{L}^{d \geq 5} = C_{\text{Weinberg}}^5 \frac{1}{\Lambda} \times \begin{array}{c} H \\ \diagdown \quad \diagup \\ \text{---} \end{array} + C_{\mu eee}^6 \frac{1}{\Lambda^2} \times \begin{array}{c} \mu_R \\ \longrightarrow \quad \longrightarrow \\ \text{---} \end{array} + C_{\ell_i \ell_j \gamma}^6 \frac{1}{\Lambda^2} \dots$$







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

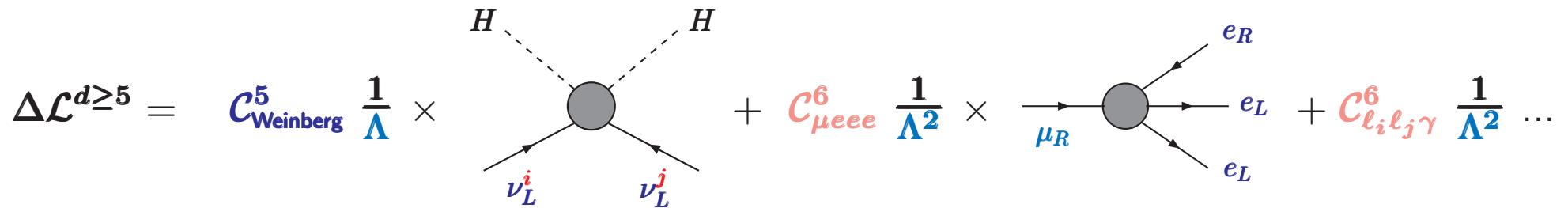
Common to all models with Majorana neutrinos [seesaws, radiative (Zee, RpV), ...]

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

C_{ij}^6 differ from model to model - used to **disentangle scenarios...**

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

cLFV: the effective approach



- **Dimension 5 $\Delta\mathcal{L}^5$ (Weinberg):** a unique operator $\mathcal{O}_{ij}^5 \sim (L_i.H)(H.L_j)$ $\mathcal{C}_{ij}^5 \sim (Y_{ij}^\nu)^2$
- **Dimension 6 $\Delta\mathcal{L}^6$:** 3 “types” of operators relevant for **cLFV** (dipole and 3-body)
 - 2 lepton-Higgs-photon:** $\mathcal{O}_{\ell_i \ell_j \gamma}^6 \sim L_i \sigma^{\mu\nu} e_j H F_{\mu\nu}$
 - $\mathcal{O}_{\ell_i \ell_i \gamma}^6 \rightsquigarrow$ anomalous magnetic/electric moments ($\propto \text{Re}, \text{Im } \mathcal{C}_{\ell_i \ell_i \gamma}^6 / \Lambda^2$)
 - $\mathcal{O}_{\ell_i \ell_j \gamma}^6 \rightsquigarrow$ radiative decays $\ell_i \rightarrow \ell_j \gamma$ ($\propto \mathcal{C}_{\ell_i \ell_j \gamma}^6 / \Lambda^2$)

4 lepton: $\mathcal{O}_{\ell_i \ell_j \ell_k \ell_l}^6 \sim (\ell_i \gamma_\mu P_{L,R} \ell_j)(\ell_k \gamma^\mu P_{L,R} \ell_l)$ **3-body decays** $\ell_i \rightarrow \ell_j \ell_k \ell_l, \dots$

2 lepton-2 quarks: $\mathcal{O}_{\ell_i \ell_j q_k q_l}^6 \sim (\ell_i \gamma_\mu P_{L,R} \ell_j)(q_k \gamma^\mu P_{L,R} q_l)$ $\mu - e$ in Nuclei, meson decays, ...

cLFV bounds and \mathcal{L}^{eff}

- Apply **experimental** bounds on **cLFV observables** to constrain $\frac{\mathcal{C}_{ij}^6}{\Lambda^2}$

$$\text{BR}(\ell_i \rightarrow \ell_j \gamma) = \frac{12\sqrt{2}\pi^3 \alpha}{G_F^3 m_{\ell_i}^2 \Lambda^2} (|\mathcal{C}_{ij}^6|^2 + |\mathcal{C}_{ij}^6|^2)$$

1. hypothesis on **size** of “new couplings”
2. hypothesis on **scale** of “new physics”

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

$$\text{BR}(\mu \rightarrow e\gamma)|_{\text{MEG}} \Rightarrow \Lambda \gtrsim 10^5 \text{ TeV}; \quad \text{BR}(\mu \rightarrow 3e) \Rightarrow \Lambda \gtrsim 15 \text{ TeV}$$

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

- **Natural scale?** more delicate - **well motivated**: direct discovery (LHC - TeV), ...

$$\text{BR}(\mu \rightarrow e\gamma) \leq 5.7 \times 10^{-13} \Rightarrow |\mathcal{C}_{\mu e}^6|^2 \lesssim 10^{-9} \times \left(\frac{1 \text{ TeV}}{\Lambda}\right)^2$$

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

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

[Abada et al, '07-'09]

cLFV bounds and \mathcal{L}^{eff}

- ▶ Despite its generality, caution in interpreting limits from effective approach!
 - limits assume **dominance of one operator**; NP leads to several (interference...)
 - contributions from **higher order operators** may be non-negligible if Λ is low...
 - **multiple “new physics” scales:** example of the **high-scale SUSY seesaw**

$$\mathcal{L}^{\text{eff}} = \mathcal{L}^{\text{SM}} + \frac{1}{\Lambda_{\text{LNV}}} \mathcal{C}^5(m_\nu) + \frac{1}{\Lambda_{\text{LFV}}^2} \mathcal{C}^6(\ell_i \leftrightarrow \ell_j) + \dots \quad \left\{ \begin{array}{l} \Lambda_{\text{LNV}} \rightsquigarrow M_{\text{GUT}} \sim 10^{15} \text{ GeV} \\ \Lambda_{\text{LFV}} \rightsquigarrow M_{\text{SUSY}} \sim \text{TeV} \end{array} \right.$$

- ▶ 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: scenarios of New Physics**

Models of New Physics

- Models of **New Physics** can change SM's predictions, introducing:
 - (i) new sources of **flavour violation** (corrections to SM vertices, new SM-NP interactions)
 - (ii) new **Lorentz structure** in the “four-fermion” interaction ⇒ new **effective operators**
- So far, **no experimental evidence!**

Most models can account for **extensive ranges** for cLFV observables...
However, **specific patterns** (**correlation** of observables, **dominance** of regimes)
might be used to **favour** a specific model!
- Model-independent approach is quite “hard” ...

... model-dependent \rightsquigarrow master “**theoretical expectations**” of **N** models!
- **Here:** consider **examples** of (well motivated) **models of New Physics**

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

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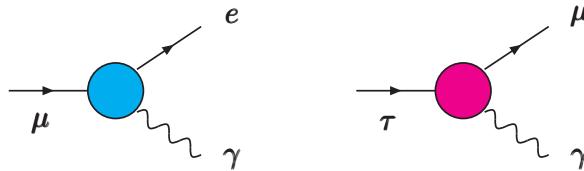
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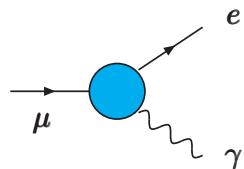
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$$\frac{\text{BR}(\mu \rightarrow e\gamma)}{\text{BR}(\tau \rightarrow \mu\gamma)}$$

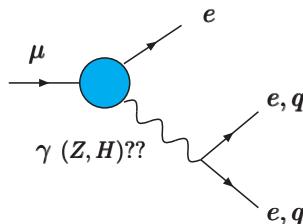


Probe NP **flavour structure**

$$\frac{\text{BR}(\mu \rightarrow e\gamma)}{\text{BR}(\mu \rightarrow 3e)}$$



Probe NP **operator at work**



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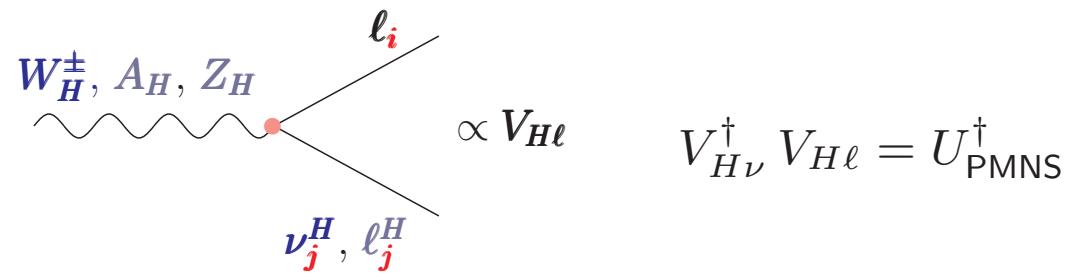
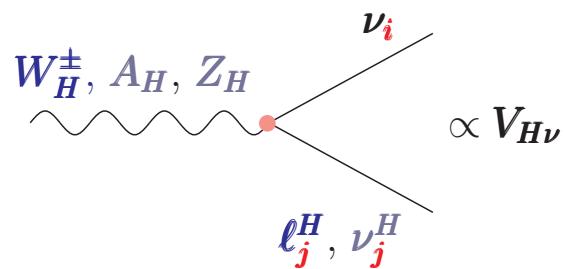
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Generic cLFV extensions

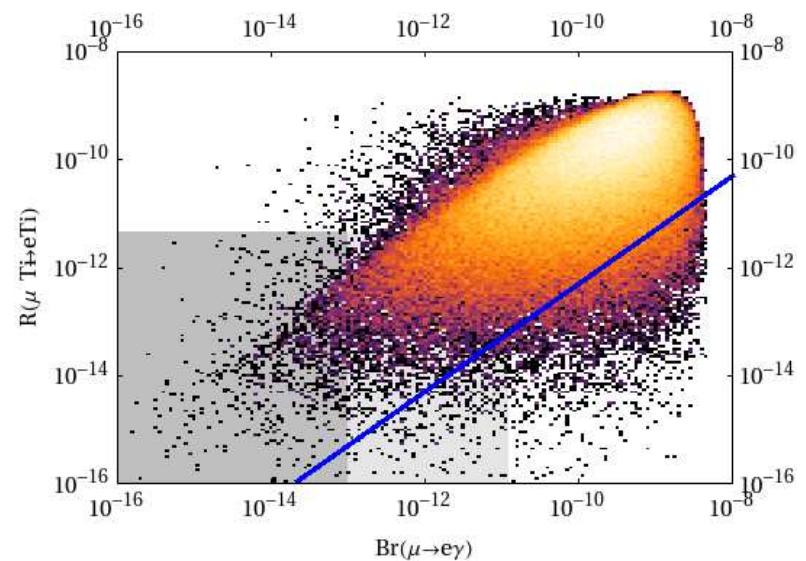
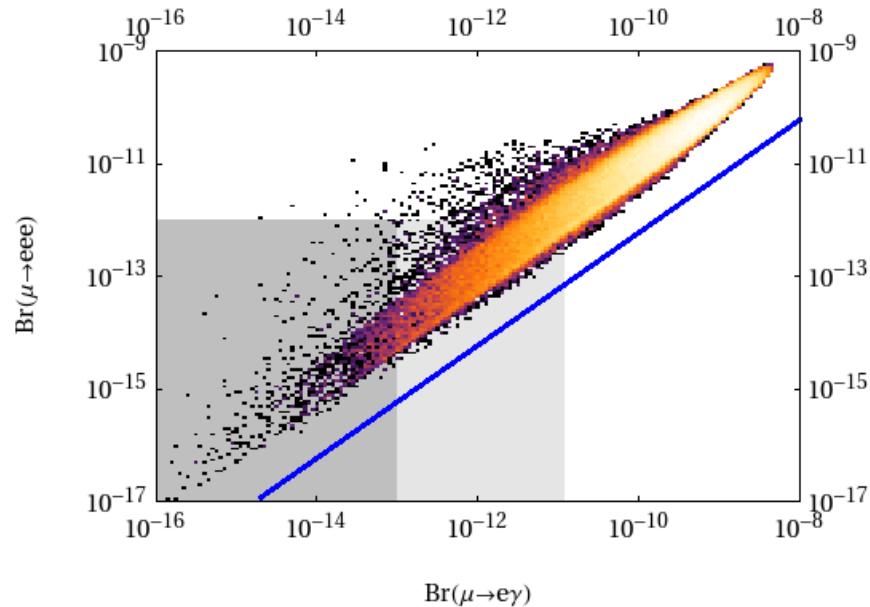
cLFV in Little Higgs models (T-parity)

- ★ Higgs is a **pseudo-Goldstone** boson of spontaneously broken global symmetry
- $SU(5) \rightarrow SO(5)$ (@ TeV scale); augmented gauge group $[SU(2) \times U(1)]^2$
 \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 \rightsquigarrow dark matter candidate
- New scale as low as **500 GeV** [$f \sim$ decay const of NL sigma model (NG)]
- Only **10 new parameters** in flavour sector, only **SM operators relevant**
- Sources of **cLFV**: couplings of leptons - mirror leptons - heavy gauge bosons



[Hubisz et al '05; Blanke et al '06-'09; Ray et al '07; Goto et al '09-'11, del Aguila et al '09-'10, ...]

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



[Blanke et al, 0906.5454]

- Strong correlation of some cLFV observables: $\mu \rightarrow e\gamma$ and $\mu \rightarrow 3e$
- Asymmetries for polarised τ and μ decays \rightsquigarrow chirality structure of LHT

[Goto et al, 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 5dim AdS space (extra dim compactified on orbifold)

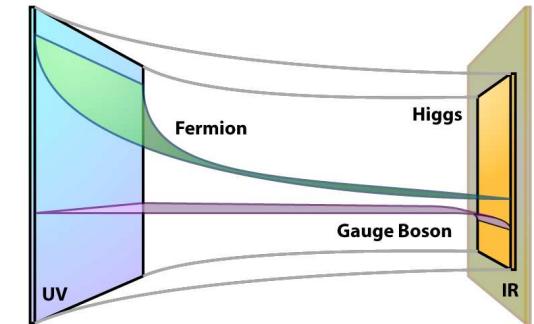
► Two branes (UV, IR) and bulk between; $M_{\text{TeV}} = M_{\text{Planck}} e^{-\pi L_5}$

► Localise fields: Higgs close to IR brane

SM fermions and gauge bosons on bulk

KK excitations of SM fields close to IR brane

interactions \leftrightarrow overlap of wave functions



► Geometrical distribution of fermions in bulk:

hierarchy in 4dim Yukawas for “anarchic” $\mathcal{O}(1)$ couplings!

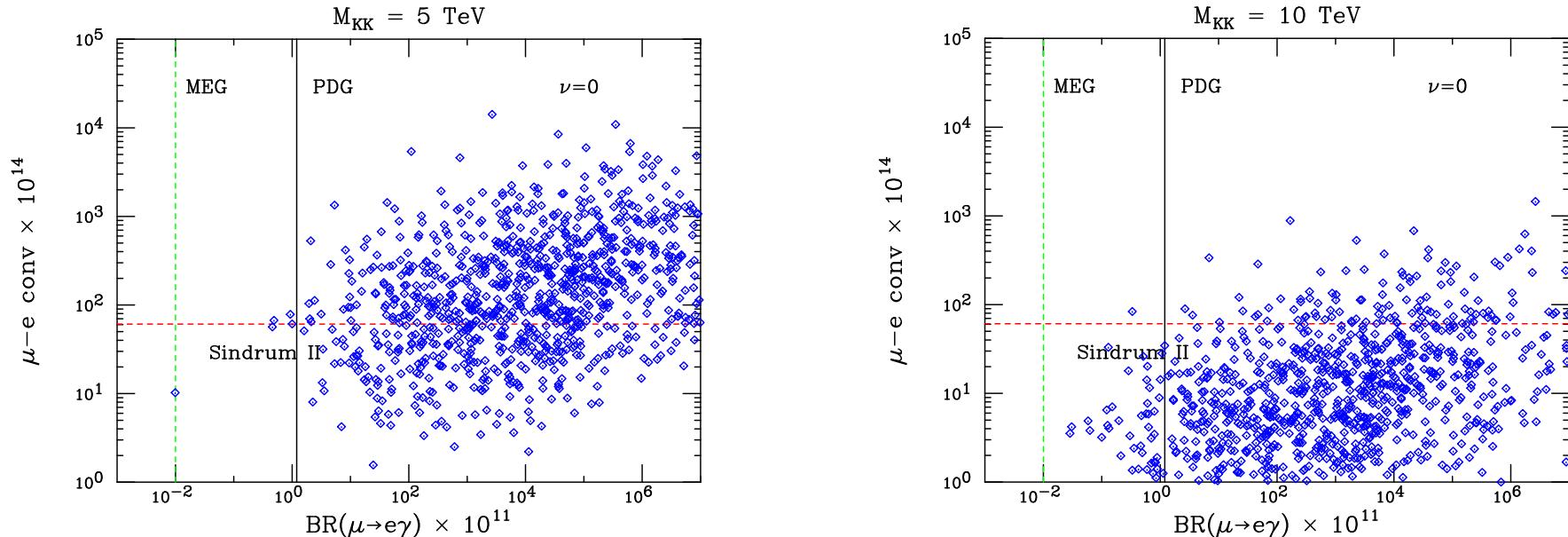
► Circumvent pheno issues: enlarge bulk symmetry (prevent violation of custodial SU(2));

additional “rescue” ingredients to avoid excessive FCNCs,

protect EW precision observables, ...

[Burdman '02; Agashe et al '04 -; Csaki et al '08; Blanke et al & Buras et al '08-'09]

Geometric flavour violation: RS warped extra dimensions



[Agashe et al, 0606021]

- ▶ **cLFV processes** mediated by **KK-lepton excitations, new gauge fields**
- ▶ Electroweak precision observables: $M_{KK} \geq 3 \text{ TeV}$;
cLFV: $M_{KK} \geq 10 \text{ TeV}$ (5 TeV only marginally compatible)
- ▶ Possible ways out... flavour structure (non-geometrical), increase gauge symmetry, ...

[see also Vempati et al, 1206.4383]

General Minimal Supersymmetric extension of the SM

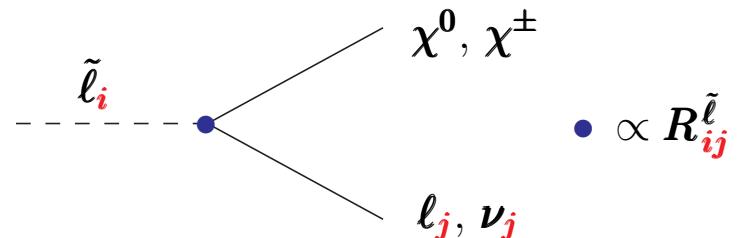
- **Supersymmetry is broken in Nature:** different masses for SM particles and superpartners
Generic soft-SUSY breaking terms introduce new sources of flavour violation (q and ℓ)
 non-diagonal masses for sleptons and sneutrinos $(M_{\tilde{\ell}}^2)_{ij} \neq 0!$ $(M_{\tilde{\nu}}^2)_{ij} \neq 0!$

- Misalignment of **flavour** and **physical** eigenstates: $R^{\tilde{\ell}\dagger} M_{\tilde{\ell}}^2 R^{\tilde{\ell}} = \text{diag}(m_{\tilde{\ell}_i}^2)$ $R^{\tilde{\ell}} \neq 1!$

$$\{\tilde{e}_L, \tilde{\mu}_L, \tilde{\tau}_L, \tilde{e}_R, \tilde{\mu}_R, \tilde{\tau}_R\} \leftrightarrow \{\tilde{\ell}_1, \dots, \tilde{\ell}_6\}$$

manifest in **neutral** and

charged lepton-slepton interactions



	S1	S2	S3
$ \delta_{12}^{LL} _{\max}$	10×10^{-5}	7.5×10^{-5}	5×10^{-5}
$ \delta_{12}^{LR} _{\max}$	2×10^{-6}	3×10^{-6}	4×10^{-6}
$ \delta_{12}^{RR} _{\max}$	1.5×10^{-3}	1.2×10^{-3}	1.1×10^{-3}
$ \delta_{13}^{LL} _{\max}$	5×10^{-2}	5×10^{-2}	3×10^{-2}
$ \delta_{13}^{LR} _{\max}$	2×10^{-2}	3×10^{-2}	4×10^{-2}

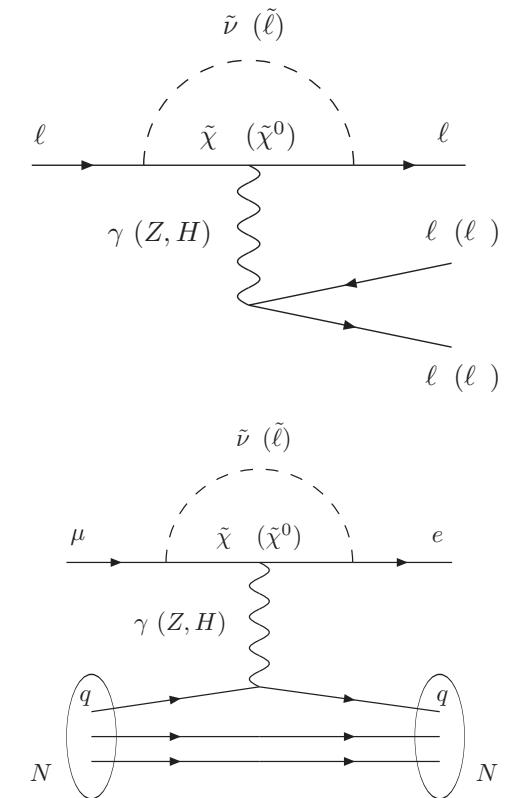
[Herrero et al, 1304.2783]

- Sizable contributions to **cLFV observables** $\propto \delta_{ij}^\ell = \frac{(M_{\tilde{\ell}}^2)_{ij}}{M_{\text{SUSY}}^2}$
 “almost everything is possible - depending on the regime” ...

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

Correlation of observables in NP models: peculiar patterns

ratio	LHT	MSSM (dipole)	MSSM (Higgs)	SM4
$\frac{\text{BR}(\mu \rightarrow eee)}{\text{BR}(\mu \rightarrow e\gamma)}$	$0.02 \dots 1$	$\sim 6 \times 10^{-3}$	$\sim 6 \times 10^{-3}$	$0.06 \dots 2.2$
$\frac{\text{BR}(\tau \rightarrow eee)}{\text{BR}(\tau \rightarrow e\gamma)}$	$0.04 \dots 0.4$	$\sim 1 \times 10^{-2}$	$\sim 1 \times 10^{-2}$	$0.07 \dots 2.2$
$\frac{\text{BR}(\tau \rightarrow \mu\mu\mu)}{\text{BR}(\tau \rightarrow \mu\gamma)}$	$0.04 \dots 0.4$	$\sim 2 \times 10^{-3}$	$0.06 \dots 0.1$	$0.06 \dots 2.2$
$\frac{\text{BR}(\tau \rightarrow e\mu\mu)}{\text{BR}(\tau \rightarrow e\gamma)}$	$0.04 \dots 0.3$	$\sim 2 \times 10^{-3}$	$0.02 \dots 0.04$	$0.03 \dots 1.3$
$\frac{\text{BR}(\tau \rightarrow \mu ee)}{\text{BR}(\tau \rightarrow \mu\gamma)}$	$0.04 \dots 0.3$	$\sim 1 \times 10^{-2}$	$\sim 1 \times 10^{-2}$	$0.04 \dots 1.4$
$\frac{\text{BR}(\tau \rightarrow eee)}{\text{BR}(\tau \rightarrow e\mu\mu)}$	$0.8 \dots 2$	~ 5	$0.3 \dots 0.5$	$1.5 \dots 2.3$
$\frac{\text{CR}(\mu Ti \rightarrow e Ti)}{\text{BR}(\mu \rightarrow e\gamma)}$	$10^{-3} \dots 10^2$	$\sim 5 \times 10^{-3}$	$0.08 \dots 0.15$	$10^{-12} \dots 26$



[Buras et al, 1006.5356]

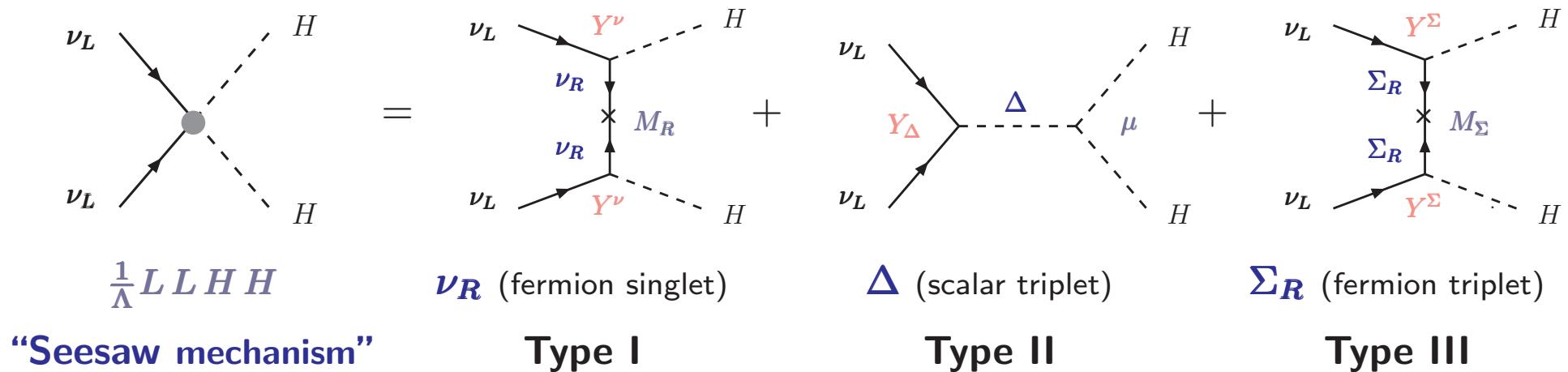
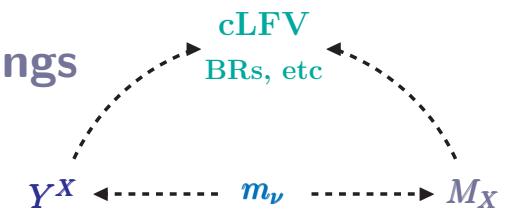
- Most **models predict/accommodate** extensive **ranges for observables**
(no new physics yet discovered, only bounds on new scale!)
- **Correlations** might allow to **disentangle models of cLFV** in the absence of
discovery of new states! ... or inability to **identify mechanism of LFV!**



- ▶ cLFV from ν mass generation mechanisms - seesaw

cLFV and the seesaw mechanism

★ **Seesaw mechanism:** explain **small ν masses** with “natural” couplings via new dynamics at “heavy” scale



- **LFV observables:** depend on **powers of Y^ν** \rightsquigarrow large rates \Rightarrow sizable Y^ν and on the **mass of the (virtual) NP propagators**

- **Fermionic seesaws:** $Y^\nu \sim \mathcal{O}(1) \Rightarrow M_{\text{new}} \approx 10^{13-15} \text{ GeV!}$

Suppression of LFV rates due to the large mass of the mediators!

cLFV and the seesaw mechanism

Seesaw	$\tilde{\mathcal{C}}_5$	New Physics scales	$\tilde{\mathcal{C}}_6$	cLFV obs
Fermionic singlet (type I)	$Y_N^T \frac{1}{M_N} Y_N$	$Y_N \sim \mathcal{O}(1) \Rightarrow M_N \approx 10^{15} \text{ GeV}$ $M_N \sim M_{\text{GUT}} ???$	$\left(Y_N^\dagger \frac{1}{M_N^\dagger} \frac{1}{M_N} Y_N \right)_{\alpha\beta}$...
Fermionic triplet (type III)	$Y_\Sigma^T \frac{1}{M_\Sigma} Y_\Sigma$	“ ”	$\left(Y_\Sigma^\dagger \frac{1}{M_\Sigma^\dagger} \frac{1}{M_\Sigma} Y_\Sigma \right)_{\alpha\beta}$...
Scalar triplet (type II)	$4Y_\Delta \frac{\mu_\Delta}{M_\Delta^2}$	$Y_\Delta \sim \mathcal{O}(1) \Rightarrow M_\Delta \approx \text{TeV}$ $(\mu_\Delta \ll 1!)$	$\frac{1}{M_\Delta^2} Y_{\Delta\alpha\beta} Y_{\Delta\gamma\delta}^\dagger$	large BRs ! constrain model!

- Low scale seesaws: rich phenomenology (also at LHC), observable cLFV!

decorrelate m_ν from LFV rates \rightsquigarrow suppressed LNV and enhanced LFV

- Type II: cLFV constraints on Y_Δ and M_Δ ; $\mu \rightarrow eee$: $Y_\Delta \sim \mathcal{O}(1) \Rightarrow M_\Delta \geq 300 \text{ TeV}$

[for a review: 0707.4058]

- “Inverse seesaw”: similar decorrelation between m_ν , suppression and cLFV

Contribution to many observables (e.g. violation of LFU, EWPT...) \rightsquigarrow see C. Weiland's talk!

- Other realisations: symmetry-inspired Y^ν ansatz, low scale type I, “scotogenic”, ...

[TeV-scale seesaws recent review: Dinh et al 1205.4671]

- ▶ cLFV from m_ν in extended frameworks

The supersymmetric seesaw(s) and cLFV

- ★ Embed seesaw in the framework of (otherwise) **flavour-conserving SUSY models**
(cMSSM, supergravity-inspired, etc)

Right-handed ν $\rightsquigarrow \tilde{\nu}_R$ [Type I]

► In addition to Scalar triplets \rightsquigarrow "triplinos" [Type II]

Fermion triplets \rightsquigarrow "s-triplets" [Type III]

with **same couplings, same interactions!**

► In general "radiatively" generated cLFV: $(\Delta m_{\tilde{L}}^2)_{ij} = (\Delta m_{\tilde{L}}^2(Y^\nu))_{ij}$

► Maybe difficult to disentangle from "generic" MSSM cLFV...

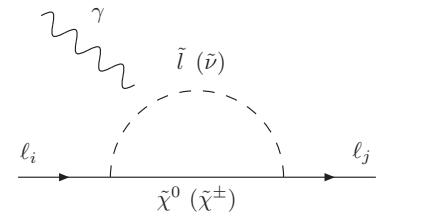
Still some **scenarios are falsifiable!**

► Here: focus on **type I SUSY seesaw**

SUSY seesaw: low-energy cLFV observables

- Large Y^ν : sizable contributions to cLFV observables

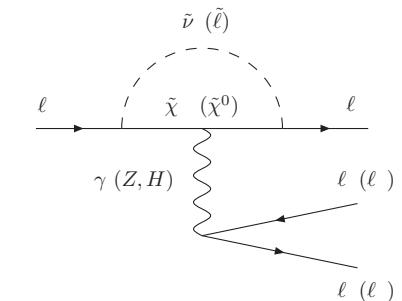
cLFV driven by the exchange of *virtual SUSY particles*



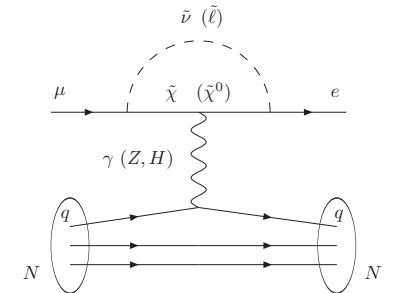
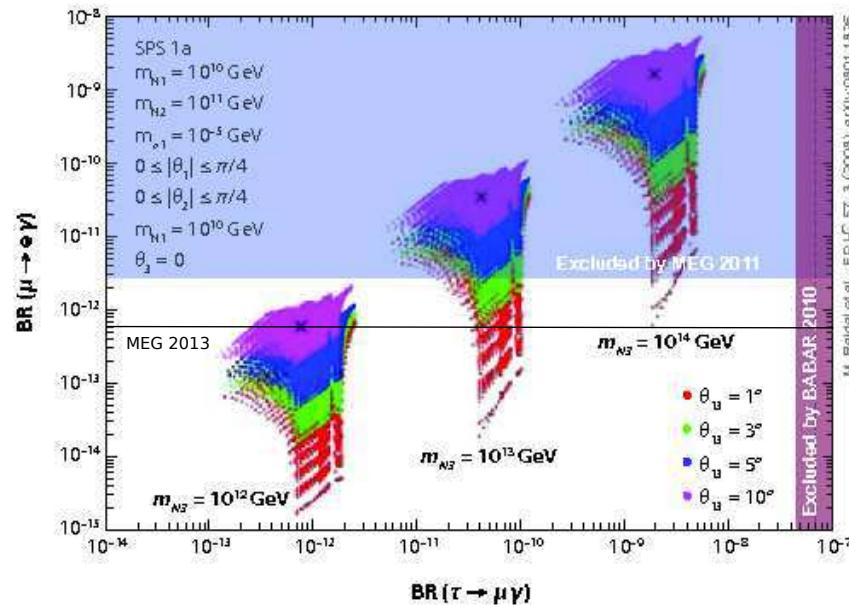
- Flavour blind SUSY breaking: RGE running of Y^ν ($M_{\text{GUT}} \rightarrow M_R$)

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

$$(\Delta m_{\tilde{L}}^2)_{ij} = -\frac{1}{8\pi^2} (3m_0^2 + A_0^2) (Y^\nu \dagger L Y^\nu)_{ij} \quad L = \log(M_{\text{GUT}}/M_N)$$



- Y^ν unique source of FV: all observables strongly related



- Synergy of low-energy observables

⇒ hints on seesaw scale M_R !

[Antusch, Arganda, Herrero and AMT, '06 - '07]

SUSY seesaw: high-energy cLFV observables

- **High-energy coliders:** direct access to slepton sector \rightsquigarrow *on-shell* $\tilde{\ell}$
- **cLFV** in **SUSY neutral current** interactions $\chi^0 - \tilde{\ell}_i - \ell_j$
cascade decays involving $\tilde{\ell}$ (direct production, or favourable decays e.g. χ_2^0)

LC: $\tilde{\ell}^\pm \rightarrow \ell^\pm + E_{\text{miss}}^T$ decays

$e^+ e^- \rightarrow e^\pm \mu^\mp + 2\chi^0$ $e^- e^- \rightarrow e^- \mu^- + 2\chi^0$ “golden channel” $e^- e^- \rightarrow \mu^- \mu^- + 2\chi^0$	$\left\{ \begin{array}{l} \text{multiple edges in } m_{\ell\ell} \\ \text{direct FV decays} \end{array} \right.$
------------------------------------------------------------------------------------------------------------------------------------------------------------	------------------------------------------------------------------------------------------------------------------

[Abada, Figueiredo, Romão, AMT, 1206.2306]

LHC: $\chi_2^0 \rightarrow \ell^\pm \ell^\mp + E_{\text{miss}}^T$ cascades
 $(\chi_2^0 \text{ from } \tilde{q} \text{ production})$

$\left\{ \begin{array}{l} \text{flavoured slepton mass differences } (\tilde{e} - \tilde{\mu}) \\ \text{multiple edges in dilepton mass distributions } m_{\ell\ell} \\ \text{direct FV final states } \chi_2^0 \rightarrow \ell_i \ell_j \chi_1^0 \end{array} \right.$

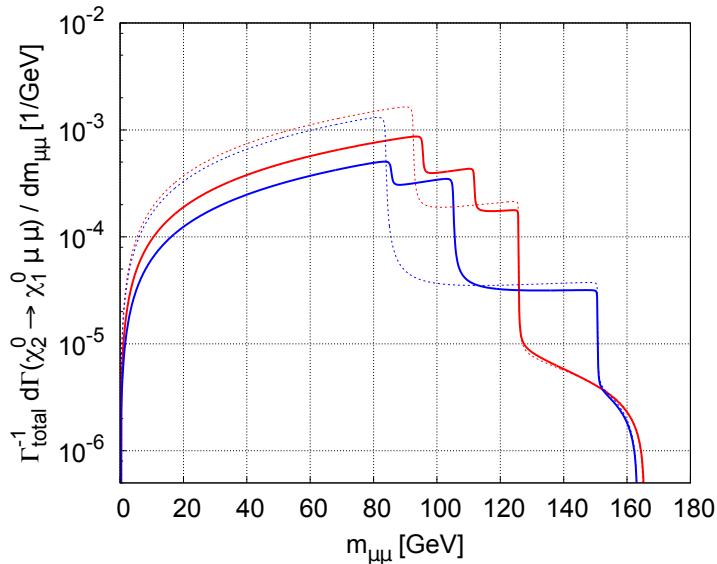
And many others: flavour violating Higgs decays, Lepton Number violating decays, etc ...

cLFV at the LHC: dilepton mass distributions

★ cMSSM (no seesaw)

- Double-triangular distributions: intermediate $\tilde{\mu}_L, \tilde{\mu}_R$ in $\chi_2^0 \rightarrow \tilde{\mu} \mu \rightarrow \chi_1^0 \mu \mu$
- Approximately superimposed $\tilde{\ell}_{L,R}$ edges for $m_{\mu\mu}$ and m_{ee} : “degenerate” $\tilde{\mu}, \tilde{e}$

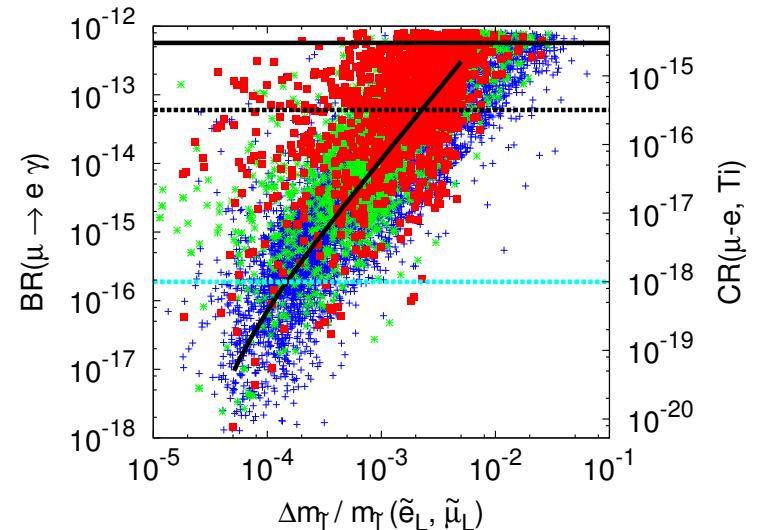
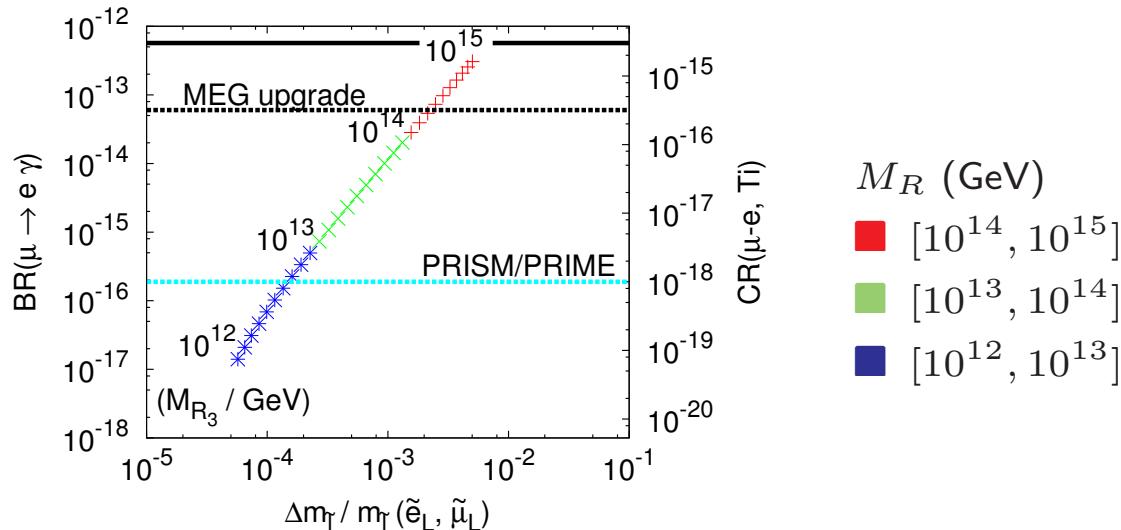
★ Impact of type-I SUSY seesaw: an example



[Abada, Figueiredo, Romão, AMT, 1007.4833]

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

cLFV at the LHC: slepton mass splittings



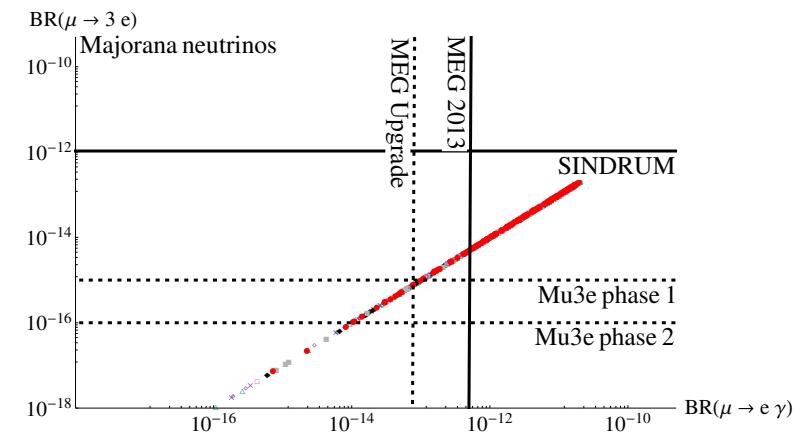
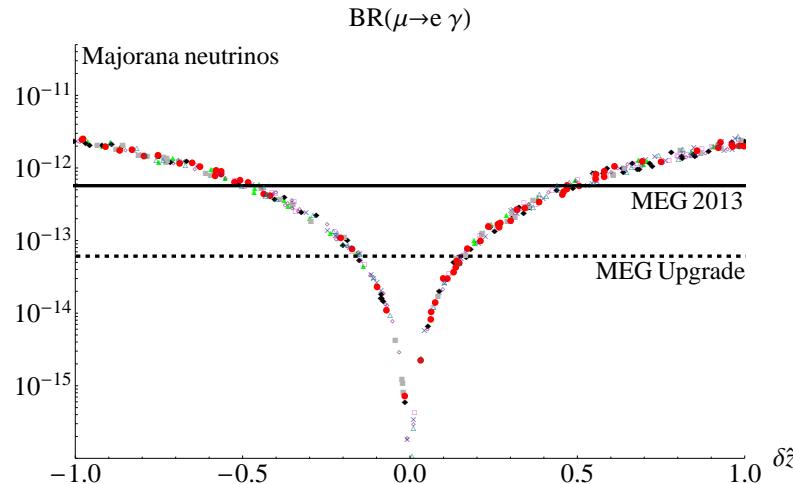
[Figueiredo, AMT, 1309.7951]

- ▶ **Sizable contributions** to **high- and low-energy observables** - **within exp reach!**
- ▶ Isolated cLFV manifestations \Rightarrow **high-scale SUSY seesaw** is **not unique cLFV source**
e.g. $\frac{\Delta m_{\tilde{\ell}}}{m_{\tilde{\ell}}}(\tilde{e}_L, \tilde{\mu}_L) \gtrsim \mathcal{O}(0.5\%)$ and $\mu \rightarrow e\gamma|_{\text{MEG}}$ ✗: disfavours seesaw hypothesis
- ▶ “**Compatible**” cLFV observations \Rightarrow **strengthens** seesaw hypothesis !
 $\frac{\Delta m_{\tilde{\ell}}}{m_{\tilde{\ell}}}(\tilde{e}_L, \tilde{\mu}_L) \gtrsim \mathcal{O}(0.5\%)$ and $\mu \rightarrow e\gamma|_{\text{MEG}}$ ✓ !! **Hints on the seesaw scale:** $M_R \sim 10^{14}$ GeV

- ▶ Hints of an organising principle: additional symmetries

Composite Higgs and warped extra dimensions

- **Holographic composite Higgs** models based on $G_f = X \times Z_N$ $[X = S_4, A_4, \Delta(96, 384)]$
- **Symmetries** allow to **predict lepton mixing pattern (masses unconstrained)**
- Apply to **5D model in warped space**; models for *both Dirac and Majorana* ν s



[Hagedorn and Serone, '11-'12]

- **cLFV observables** (and EDMs) typically **below experimental bounds**, $M_{KK} \sim 3.5$ TeV
- **MEG results on $\text{BR}(\mu \rightarrow e\gamma)$** \rightsquigarrow **constraints size of boundary kinetic terms!**

Hints of an organising principle: cLFV in Left-Right models

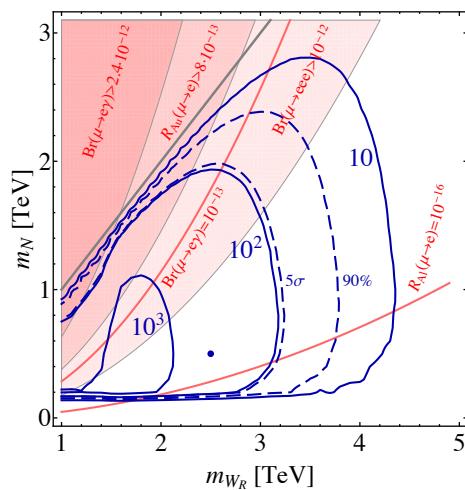
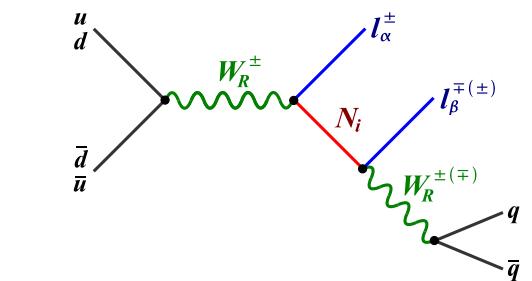
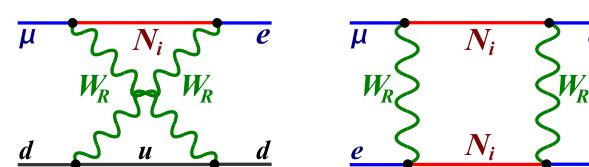
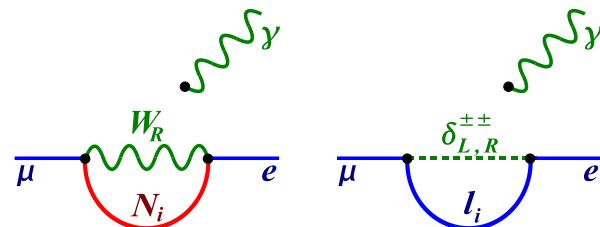
★ Minimal Left-Right extension of the SM (non-SUSY)

► extend SM gauge group: $SU(2)_L \otimes U(1) \Rightarrow SU(2)_L \otimes SU(2)_R \otimes U(1)_{B-L}$

► RH neutrinos automatically included $M_\nu \approx \begin{pmatrix} y_M v_L & y_D m_{EW} \\ y_D^T m_{EW} & y_M v_R \end{pmatrix}$

bi-doublet and triplet Higgs; new Z_R , W_R bosons

► New contributions to cLFV observables at low- and high-energies



► If LHC \sqrt{s} above heavy neutrino threshold:
dilepton LFV signatures $pp \rightarrow W_R \rightarrow e^\pm \mu^\mp + 2 \text{ jets}$

► Complementarity studies of LHC signatures and
low-energy rare decays

[Das et al, 1206.0656]

Hints of an organising principle: cLFV and SUSY GUTs

★ Supersymmetric Grand Unified Theories

- Reduce arbitrariness of Y^ν [SO(10) CKM- and U_{PMNS} -inspired patterns..]

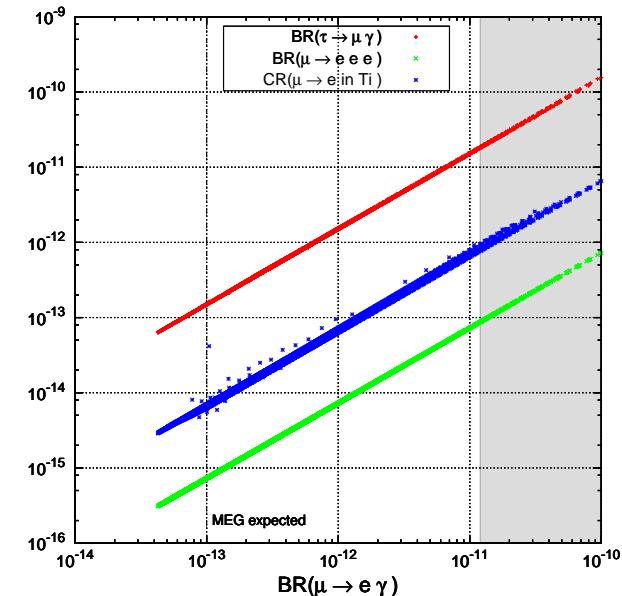
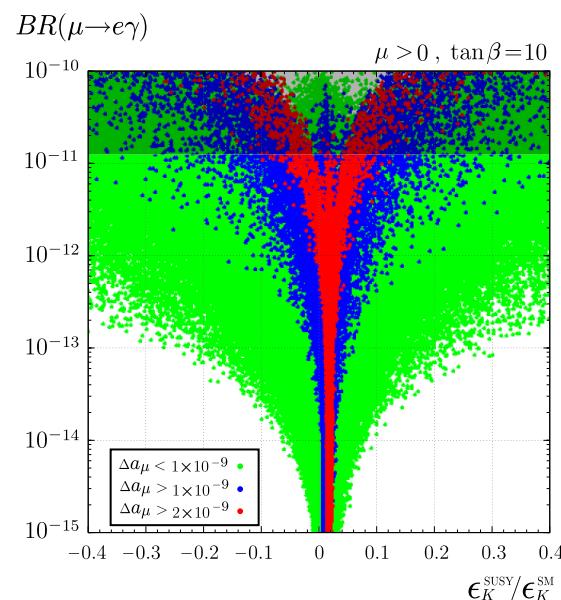
► SO(10) type II example

(leptogenesis motivated)

highly correlated cLFV observables!

[Calibbi et al, 0910.0377]

► SU(5) + RH neutrinos SUSY GUTs



correlated CPV and FV observables

in lepton and hadron sectors!

[Buras et al, 1011.4853]



Concluding remarks

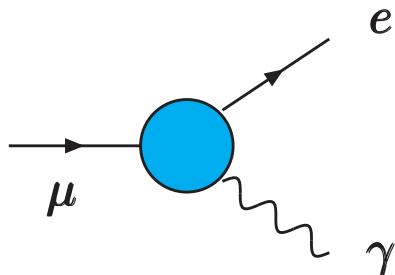
Charged lepton flavour violation: outlook

- ▶ Flavour violation observed in quarks & neutral leptons...
why should Nature “conserve” charged lepton flavour?
- ▶ cLFV observables can provide (indirect) information on the underlying NP model
New Physics can be manifest via cLFV even before any direct discovery!
Lepton sector of BSM remains comparatively unexplored...
- ▶ Numerous observables that can be (are) searched for ⇒ intensify the exp effort!
Closely follow with theoretical studies and phenomenological analyses,
exploring diverse cLFV observables, of different origin, infer pattern/correlation
⇒ Unveil the underlying mechanism of flavour violation in the lepton sector!



Backup

Lepton Flavour Violation: $\mu \rightarrow e\gamma$



- **Event signature:** $E_e = E_\gamma = m_\mu/2$ (~ 52.8 MeV)
Back-to-back $e^+ - \gamma$ ($\theta \sim 180^\circ$); Time coincidence

- **Backgrounds** ⇒ prompt physics & accidental

Prompt: radiative μ decays $\mu \rightarrow e\nu_e\nu_\mu\gamma$ (very low E_ν)

Accidental: positron from $\mu \rightarrow e\nu_e\nu_\mu$;

photon from $\mu \rightarrow e\nu_e\nu_\mu\gamma$; photon from in flight e^+e^- annihilation

- **MEG Experiment:** $3 \times 10^7 \mu/\text{s}$ at **PSI** (Switzerland)

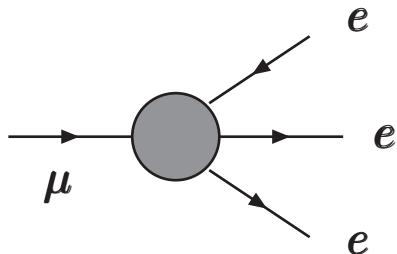
2.7 ton liquid Xenon scintillation detector (good time, position and energy resolution)

2009 + 2010 data: 2.4×10^{-12} Upper Limit (90% CL)

2011 + 2012 data: 10^{-13} Upper Limit (90% CL)

- **MEG II** (proposal to appear 2013): **sensitivity** $\approx 10^{-14}$

Lepton Flavour Violation: $\mu \rightarrow eee$



► **Event signature:** $\sum E_e = m_\mu$; $\sum \vec{P}_e = \vec{0}$
common vertex; Time coincidence

► **Backgrounds** \Rightarrow physics & accidental

Physics: $\mu \rightarrow ee\nu\nu e$ decay (very low E_ν)

Accidental: positrons from $\mu \rightarrow e\nu\nu$;

electrons from $\mu \rightarrow eee\nu\nu$ and/or $\mu \rightarrow e\nu\nu\gamma$; ...

► **Mu3e Experiment at PSI** (Switzerland)

Stage I (2014 - 2017): $2 \times 10^8 \mu/\text{s}$ at II E5 muon source

Stage II (2018 -): $2 \times 10^9 \mu/\text{s}$ at new muon source

Future sensitivity: $\approx 10^{-14}$

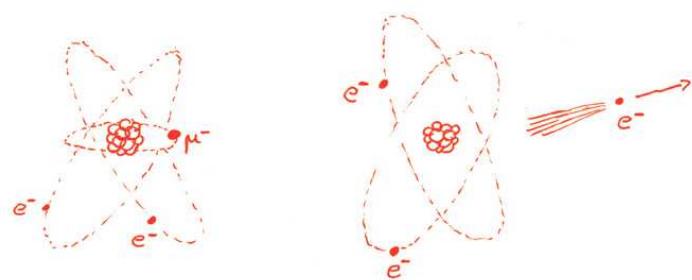
Lepton Flavour Violation: $\mu - e$ conversion in atoms

- ▶ Consider the fate of a **1s μ -state in a muonic atom:**

SM-like muon decay in orbit $\mu^- \rightarrow e^- \nu \bar{\nu}$

SM-like nuclear muon capture $\mu^- + (A, Z) \rightarrow \nu_\mu + (A, Z - 1)$

Beyond SM - neutrinoless muon nuclear capture



$$\mu^- + (A, Z) \rightarrow e^- + (A, Z)$$

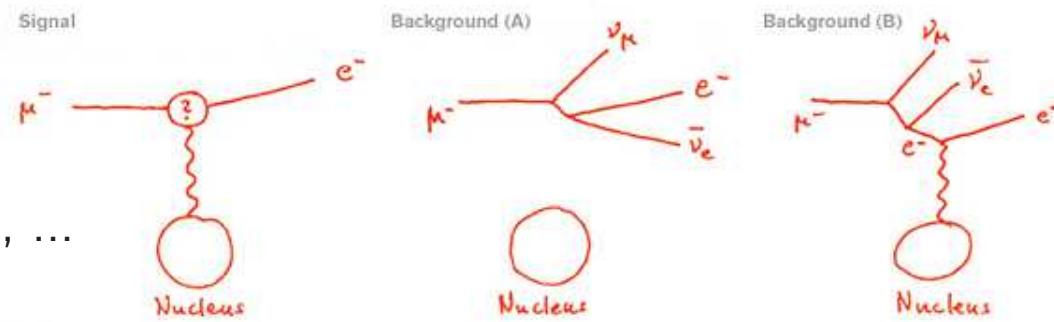
- ▶ **Event signature:** single mono-energetic electron

$$E_e \sim 100 \text{ MeV}$$

- ▶ **Backgrounds** ⇒

Physics (e.g. muon decay in orbit);

beam-related; cosmic rays; false tracking, ...



- ▶ **SINDRUM-II at PSI** (max $10^8 \mu/\text{s}$ beam intensity): $\text{CR}(\mu - e, \text{Au}) < 7 \times 10^{-13}$

Improving the bound $\rightsquigarrow \mathcal{O}(10^{-17})$: increase beam intensity $10^{11} \mu/\text{s}$ (10^7 sec running)

improve background rejection...

Lepton Flavour Violation: $\mu - e$ conversion in atoms

- **Mu2e** at Fermilab: $\text{CR}(\mu - e, \text{AI}) < 10^{-16}$ (90% CL)

Reincarnation of MECO at BNL;

Approved, CDO 2009, CD1 review 2012; *data taking 2019*

- **COMET (E21)** at J-PARC: $\text{CR}(\mu - e, \text{AI}) < 6 \times 10^{-17}$ (90% CL)

10^{11} muon stops/s for 56kW proton beam power

Stage-I approved in 2009

- **DeeMe** at J-PARC/MLF: $\text{CR}(\mu - e, \text{Si}) < 3.5 \times 10^{-14}$ (90% CL)

SiC target; 15×10^9 muon stopped for 2×10^7 s running

quick and not expensive... *not yet stage-I approved...*

Beyond the type I SUSY seesaw: examples ...

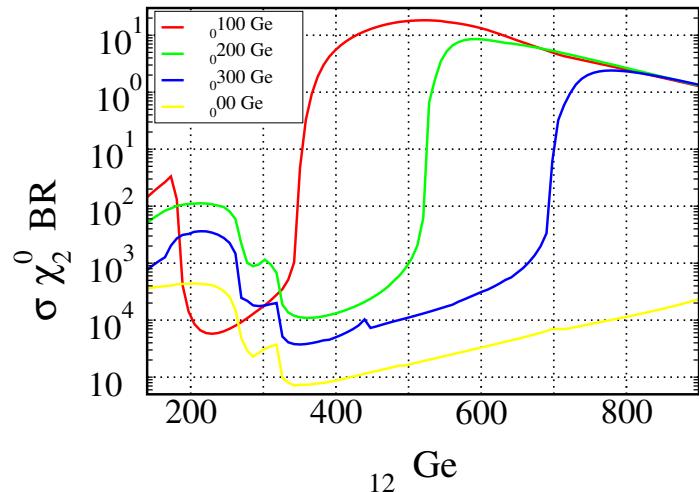
★ Type II SUSY seesaw

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

correlations between cLFV observables controled by ν -parameters !

[Rossi et al, ...]

► Distinctive prospects for cLFV at colliders

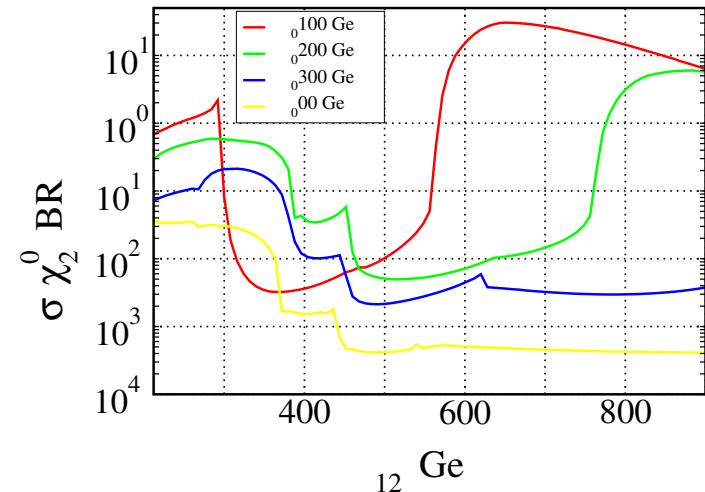


$\text{BR}(\chi_2^0 \rightarrow \mu\tau)$

← Type I SUSY seesaw

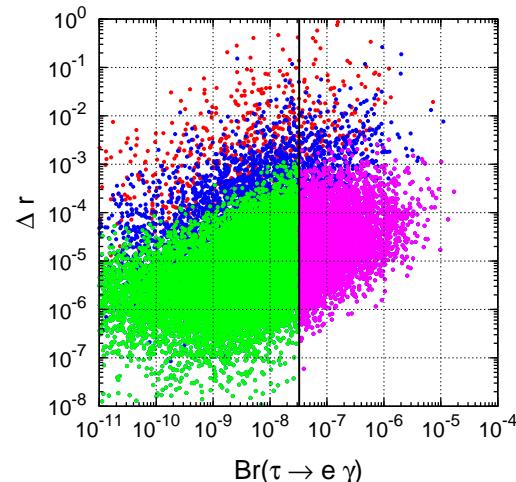
Type II SUSY seesaw →

[Esteves et al, 0903.1408]



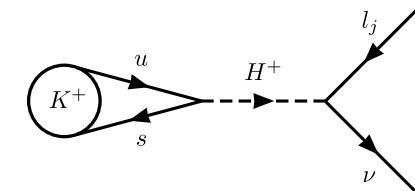
Inverse seesaw: flavour universality violation in kaon decays

- $R_K \equiv \frac{\Gamma(K \rightarrow e\nu)}{\Gamma(K \rightarrow \mu\nu)}$ $\rightsquigarrow \Delta r_K = R_K^{\text{exp}} / R_K^{\text{SM}} - 1$ NA62: $\Delta r_K = (4 \pm 4) \times 10^{-3}$
- Models of new physics (2HDM, SUSY, etc) typically lead to $\Delta r_K < \mathcal{O}(10^{-3}, -4)$



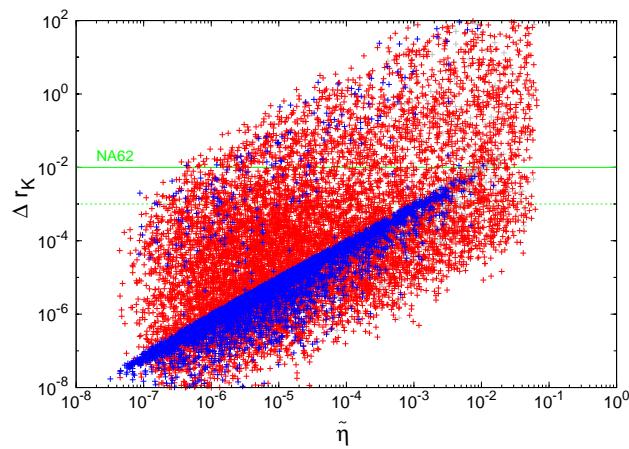
- Unconstrained MSSM: LFV corrections to $H^+ l \nu$ vertex

[■ \rightsquigarrow viable points]

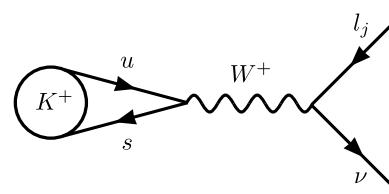


Maximise Δr_K : explicit LFV δ_{31}^{RR} , low mass regimes

[Fonseca, Romão, AMT, 1205.1411]



- Inverse seesaw: corrections to $W^+ l \nu$ vertex



$$\Delta r_K \sim \mathcal{O}(1)$$

$\tilde{\eta}$: “non-unitarity” of U_{PMNS} due to extra sterile ν s

$$M_R \in [0.1 \text{ MeV}, 10^6] \text{ GeV}$$

[Abada, AMT, Vicente, Weiland, 1311.2830]

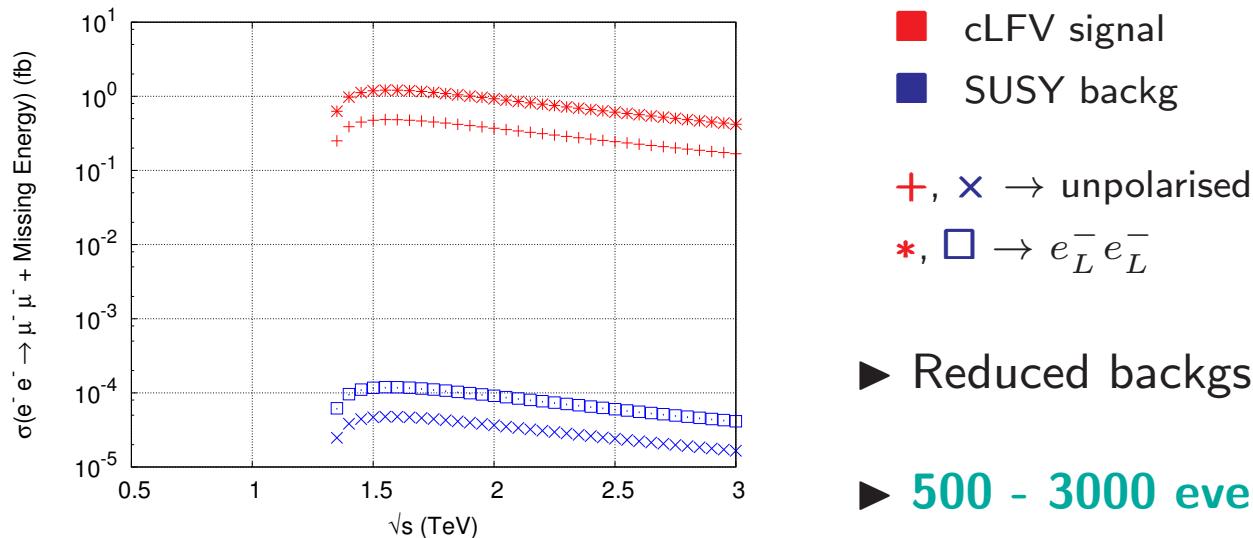
cLFV at a future LC: e^-e^- beam option

- Consider $e^-e^- \rightarrow e^-\mu^- + E_{\text{miss}}^T \rightsquigarrow \begin{cases} e^-\mu^- + 2\chi_1^0 & \text{(signal)} \\ e^-\mu^- + 2\chi_1^0 + (2,4)\nu & \text{(SUSY backg)} \\ e^-\mu^- + (2,4)\nu & \text{(SM}_{m_\nu}\text{ backg)} \end{cases}$
- **Signal** events: $\tilde{\ell}$ production via t-channel χ^0 exchange
no s-channel exchanges (absence of doubly charged particles)
- **SUSY & SM $_{m_\nu}$ backg:** dominated by W -strahlung (tiny “ $0\nu2\beta$ ”-like...)
- **Same $\tilde{\ell}$ production for signal and background:** smaller effect from beam polarisation
Still expect a **large number of events** - $\mathcal{O}(10^3 - 10^5)$ events for $\sqrt{s} = 2$ TeV
- **Ideal beam option** for a “golden channel” of cLFV at Linear Colliders ...

cLFV at a future LC: the “golden channel”

- ▶ Consider $e^- e^- \rightarrow \mu^- \mu^- + E_{\text{miss}}^T \leftrightarrow \begin{cases} \mu^- \mu^- + 2 \chi_1^0 & \text{(signal)} \\ \mu^- \mu^- + 2 \chi_1^0 + (2, 4) \nu & \text{(SUSY backg)} \end{cases}$

SM_{m_ν} backg negligible ...



- ▶ Reduced backgs: subdominant SUSY $\mathcal{O}(10^{-4})$
- ▶ **500 - 3000 events** for $\mathcal{L} = 0.5 - 3 \text{ ab}^{-1}$

[Abada, Figueiredo, Romão, AMT, 1206.2306]

- ▶ **Ideal cLFV discovery channel** $\Rightarrow e^- e^- \rightarrow \mu^- \mu^- + E_{\text{miss}}^T$ [provided \sqrt{s} large ...]
- ▶ Confirm t-channel exchange of **Majorana particle**
- ▶ **RR-polarised e^- can test seesaw hypothesis:** $\tilde{\ell}$ cLFV predominantly **LL phenomenon**