Theoretical aspects of lepton flavour violation

Ana M. Teixeira

Laboratoire de Physique Corpusculaire, LPC - Clermont

UK HEP Forum “Quarks and Leptons”

The Cosener’s House, 15 November 2013

Signals of Lepton Flavour Violation

- Neutrino oscillations [ν-dedicated experiments]

- Rare leptonic decays and transitions [high-intensity facilities]

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

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

  lepton Number violating decays - $B \to D\mu^- \mu^-, \ldots$

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

- Rare (new) heavy particle decays (typically model-dependent) [colliders]

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

  LFV final states: for example, $e^\pm e^- \to e^\pm \mu^- + E^T_{\text{miss}}$

- And many others ...

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):

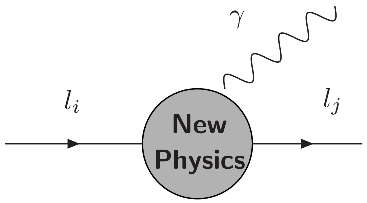
$$\text{BR}(\mu \to e\gamma) \propto \left| \sum U^*_{\mu i} U_{ei} \frac{m^2_{\nu_i}}{M_W^2} \right|^2 \sim 10^{-54}$$

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

- 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?**



$\rightsquigarrow$ **BR($\mu \to e\gamma$)** $= 10^{-12} \times (3\ \text{TeV}/\Lambda)^4 \times (\theta_{\mu e}/0.01)^2$

		New Physics (beyond SM_{m_ν})	+	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 ...)

- **Pheno approaches:** $\begin{cases} \textbf{Effective approach (model-independent)} \\ \textbf{Model dependent (specific NP scenario)} \end{cases}$

- **Many models:** generic cLFV extensions (general MSSM, LHT, RS, 4th generation, ...);

  models of massive νs; 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, $m_\nu \neq 0$]

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

Λ : mass **scale of new physics**

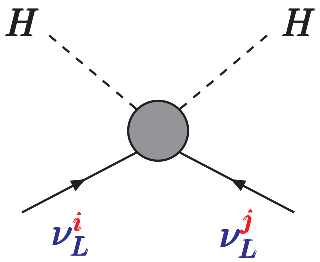
$\mathcal{C}^n$: **dimensionless couplings** - coupling constants, Yukawas, loop factors ($(4\pi)^m$), ...

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

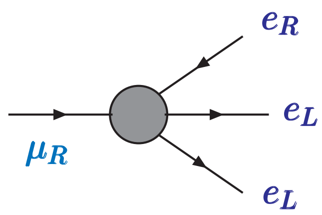
$\mathcal{O}^n$: **"external legs"** of the diagrams - **SM fields only!**

cLFV: the effective approach

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



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



$+\; C^6_{\ell_i\ell_j\gamma}\,\frac{1}{\Lambda^2}\;\dots$

- **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...

  $$C^6_{\mu e\gamma}\frac{1}{\Lambda^2}\,\bar{\mu}_L\sigma^{\mu\nu}F_{\mu\nu}\,\phi\,e_R \quad + \quad C^6_{\mu eN}\frac{1}{\Lambda^2}\,\bar{\mu}_L e_R\,\bar{q}_L u_R \quad + \quad \dots$$

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

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

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

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

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

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

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

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

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

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

  $\text{BR}(\mu \to e\gamma)|_{\text{MEG}} \Rightarrow |Y^{\Delta\dagger}_{\mu\mu} Y^{\Delta}_{\mu e} + Y^{\Delta\dagger}_{\tau\mu} Y^{\Delta}_{\tau e}| \lesssim \mathbf{2 \times 10^{-3}}$ [Abada et al, '07-'09]

- **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 ⇝ master **"theoretical expectations"** of **N** models!

- **Here:** consider **examples** of (well motivated) **models of New Physics**

  ⇝ with **potentially observable cLFV implications!**

- **Generic cLFV extensions**

cLFV in Little Higgs models (T-parity)

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

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

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

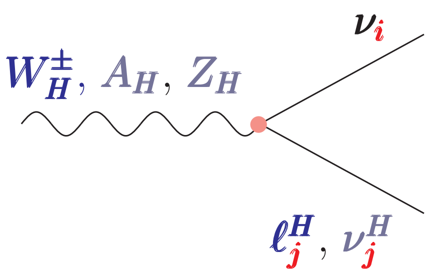
- T parity $\Rightarrow$ prevents contributions to **EW observables** (tree-level)

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

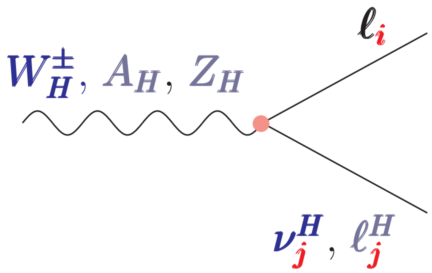
- **New scale** as low as **500 GeV** [$f \sim$ decay const of NL sigma model (NG)]

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

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



$\propto V_{H\nu}$

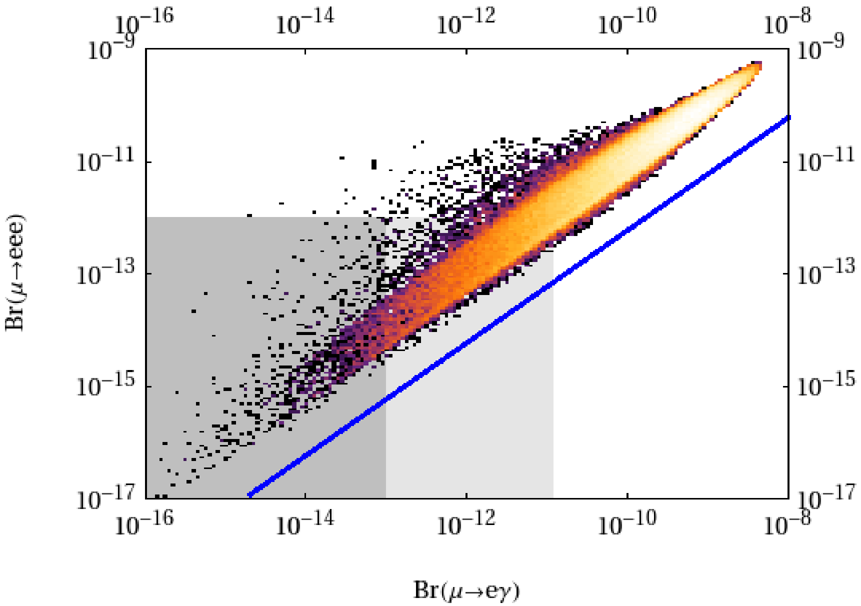


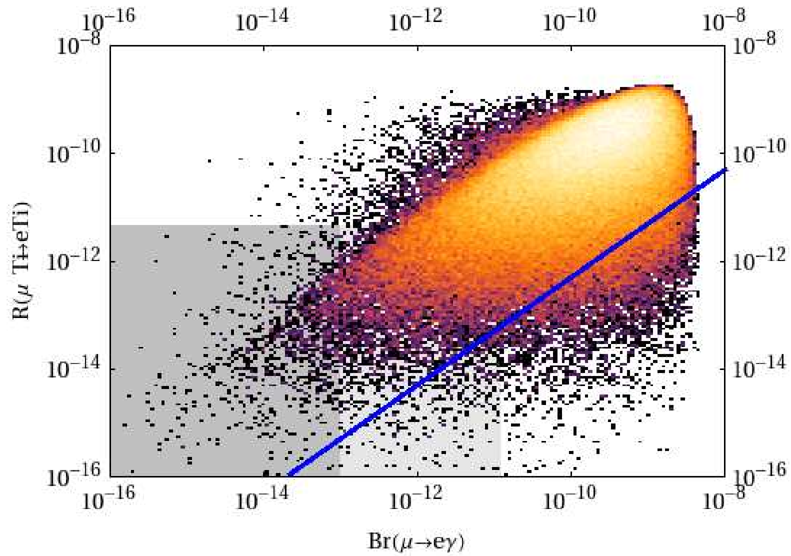
$\propto V_{H\ell}$

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

[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: $\boldsymbol{\mu \to e\gamma}$ **and** $\boldsymbol{\mu \to 3e}$
- **Asymmetries** for **polarised** $\boldsymbol{\tau}$ **and** $\boldsymbol{\mu}$ decays $\leftrightsquigarrow$ **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

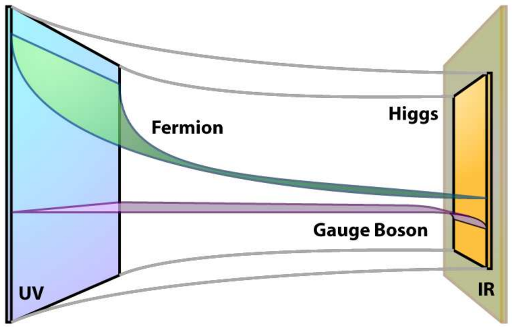
★ Embed **4dim space-time** into **5dim AdS space** (extra dim compactified on orbifold)

- **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 ⇝ **overlap of wave functions**



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

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

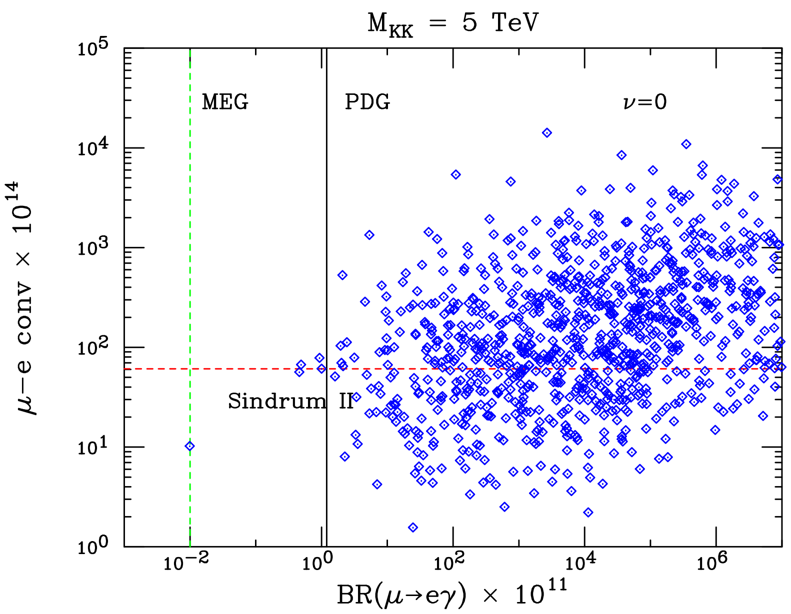
- **Circumvent pheno issues:** enlarge **bulk symmetry** (prevent violation of custodial SU(2));

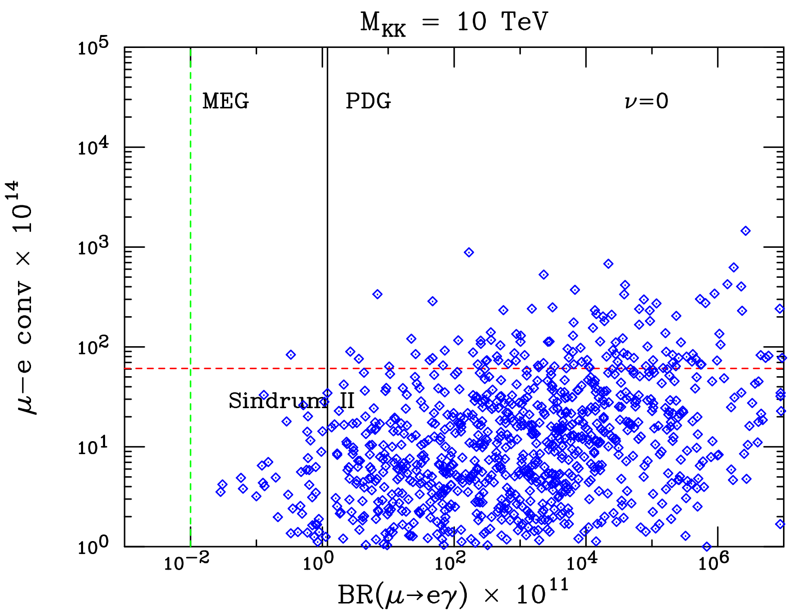
  additional **"rescue" ingredients** to **avoid excessive FCNCs,**

  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]

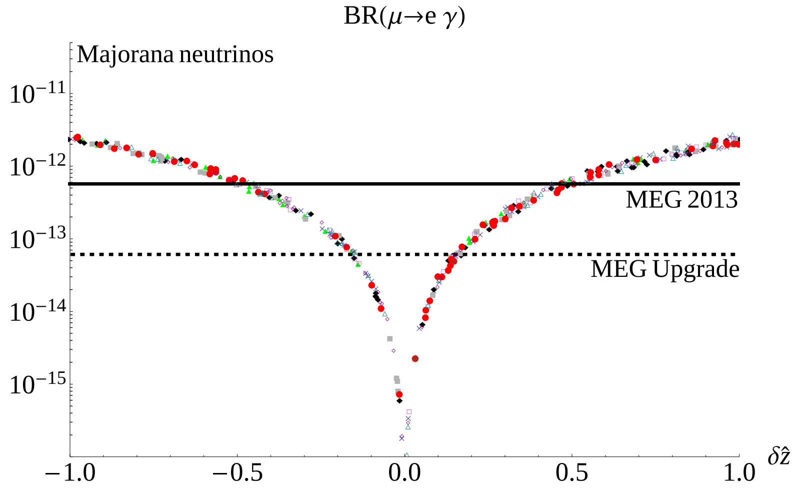
- cLFV processes mediated by **KK-lepton excitations, new gauge fields**
- **Electroweak precision observables: $M_{KK} \geq 3$ TeV ;**

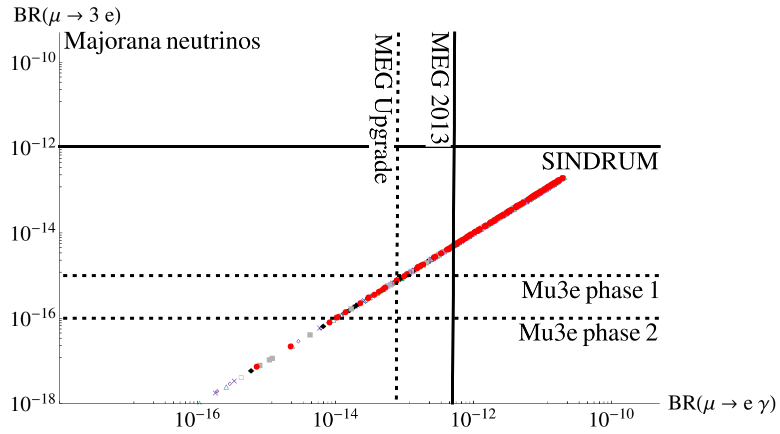
  cLFV: $M_{KK} \geq 10$ **TeV** (5 TeV only marginally compatible)
- Possible ways out... flavour structure (non-geometrical), increase gauge symmetry, ...

[see also Vempati et al, 1206.4383]

Composite Higgs and warped extra dimensions

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





[Hagedorn and Serone, '11-'12]

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

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)

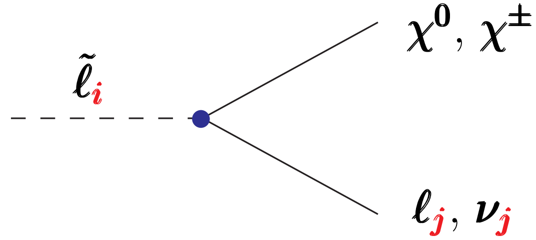
  non-diagonal masses for sleptons and sneutrinos $\quad (M^2_{\tilde{\ell}})_{ij} \neq 0\,! \quad (M^2_{\tilde{\nu}})_{ij} \neq 0\,!$

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

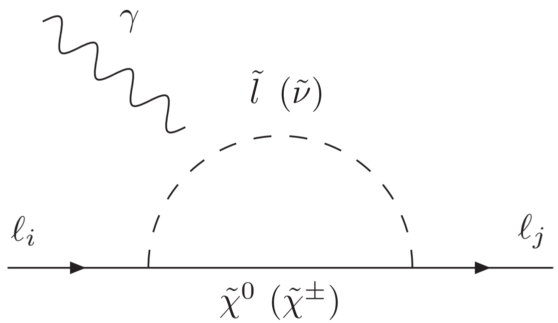
  $\{\tilde{e}_L, \tilde{\mu}_L, \tilde{\tau}_L, \tilde{e}_R, \tilde{\mu}_R, \tilde{\tau}_R\} \quad \not\leftrightarrow \quad \{\tilde{\ell}_1, \ldots, \tilde{\ell}_6\}$

  manifest in **neutral** and

  charged lepton-slepton interactions



$\bullet \propto R^{\tilde{\ell}}_{ij}$



- 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"...

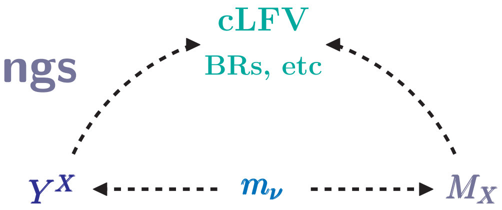
e.g. $\mathbf{BR}(\mu \to e\gamma) \sim \frac{\alpha}{4\pi} \left(\frac{M_W}{M_{\text{SUSY}}}\right)^4 \sin^2\theta_{\tilde{e}\tilde{\mu}} \left(\frac{\Delta m^2_{\tilde{\ell}}}{M^2_{\text{SUSY}}}\right)^2$

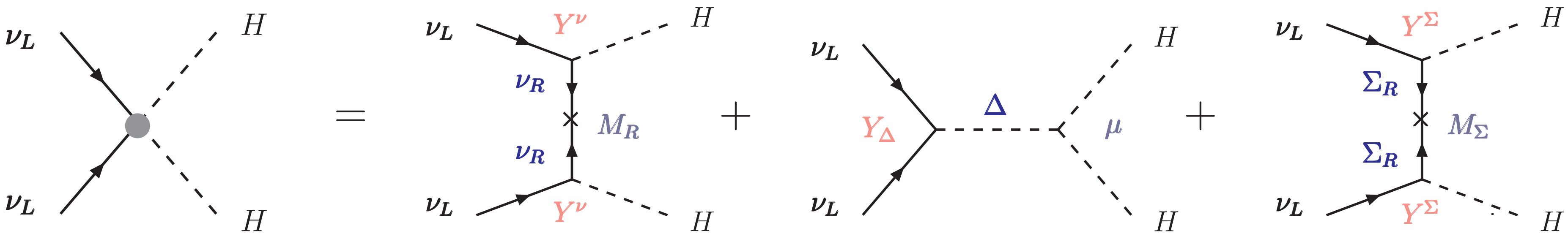
[Ellis et al, Hisano et al, Lavignac et al, Raidal et al, Brignole & Rossi, Paradisi, Buras et al, Herrero et al...]

▶ 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**

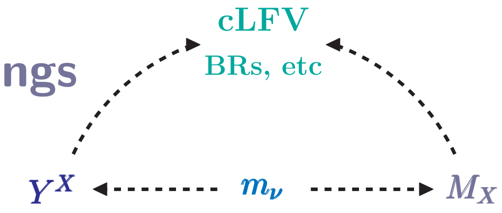




$\frac{1}{\Lambda} L\,L\,H\,H$	ν_R (fermion singlet)	Δ (scalar triplet)	Σ_R (fermion triplet)
"Seesaw mechanism"	**Type I**	**Type II**	**Type III**

cLFV and the seesaw mechanism

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



Seesaw	$\tilde{\mathcal{C}}_5$	New Physics scales	$\tilde{\mathcal{C}}_6$	cLFV obs
Fermionic singlet (type I)	$Y_N^T \frac{1}{M_N} Y_N$	$Y_N \sim \mathcal{O}(1) \Rightarrow M_N \approx 10^{15}$ **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)	$4 Y_\Delta \frac{\mu_\Delta}{M_\Delta^2}$	$Y_\Delta \sim \mathcal{O}(1) \Rightarrow M_\Delta \approx$ **TeV** $(\mu_\Delta \ll 1!)$	$\frac{1}{M_\Delta^2} Y_{\Delta\alpha\beta} Y^\dagger_{\Delta\gamma\delta}$	**large BRs !** **constrain model!**

- ▶ **Type II seesaw: rich phenomenology, predictive, observable cLFV!**
- ▶ **cLFV bounds** $\Rightarrow$ **constraints on Y_Δ and M_Δ; $\mu \to eee$: $Y_\Delta \sim \mathcal{O}(1) \Rightarrow M_\Delta \geq 300$ TeV**

[for a review: 0707.4058]

- ▶ **"Inverse seesaw":** similar decorrelation between m_ν suppression and cLFV

Interesting effects for violation of lepton flavour universality (e.g. R_K) and cLFV!

[Abada, AMT, Vicente, Weiland, 1311.2830]

- **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)

▶ In addition to

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

with **same couplings, same interactions!**

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

▶ **Maybe difficult to disentangle from "generic" MSSM cLFV...**

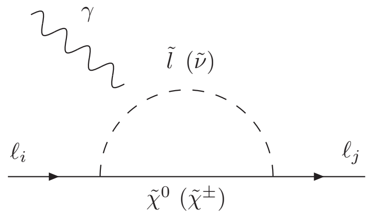
Still some **scenarios are falsifiable!**

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

SUSY seesaw: low-energy cLFV observables

- **Large Y^ν: sizable contributions to cLFV observables**

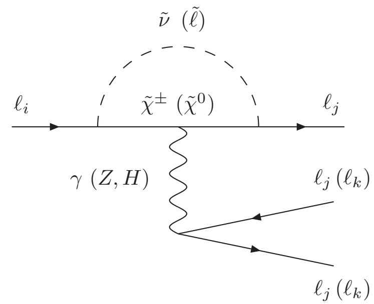
  cLFV driven by the exchange of *virtual* **SUSY particles**



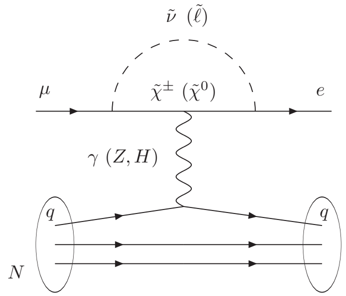
- **Flavour blind SUSY breaking: RGE running of Y^ν $(M_{\text{GUT}} \to M_R)$**

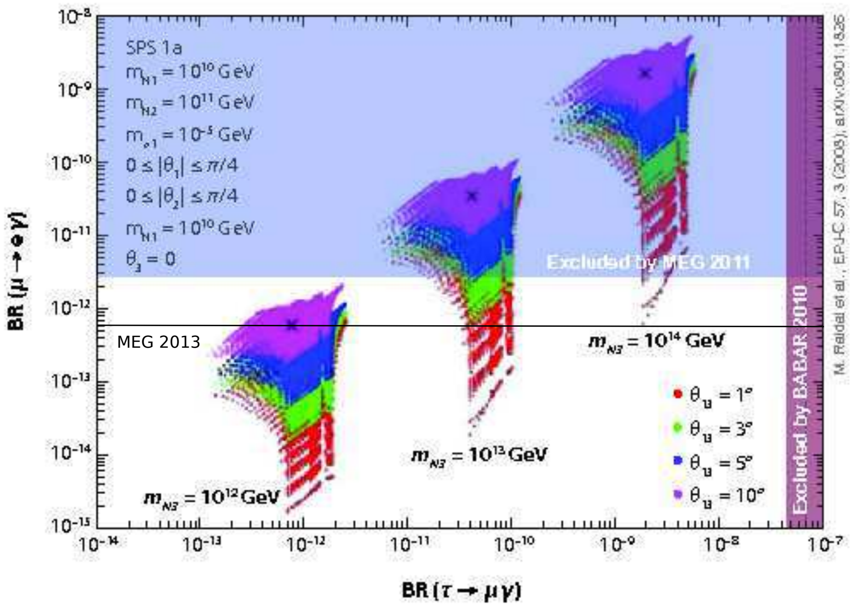
  induces flavour-violating terms in slepton soft-breaking masses

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



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





- **Synergy of low-energy observables**

  $\Rightarrow$ hints on seesaw scale M_R!

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

SUSY seesaw: high-energy cLFV observables

- **High-energy coliders: direct access to slepton sector** $\leftrightsquigarrow$ *on-shell* $\tilde{\ell}$

- cLFV in **SUSY neutral current** interactions χ^0 - $\tilde{\ell}_i$ - ℓ_j

  cascade decays involving $\tilde{\ell}$ (direct production, or favourable decays e.g. χ_2^0)

LC: $\tilde{\ell}^{\pm} \to \ell^{\pm} + E^T_{\text{miss}}$ decays

- **multiple edges in** $m_{\ell\ell}$
- **direct FV decays** $e^+e^- \to e^{\pm}\mu^{\mp} + 2\chi^0$, $e^-e^- \to e^-\mu^- + 2\chi^0$
- **"golden channel"** $e^-e^- \to \mu^-\mu^- + 2\chi^0$

[Abada, Figueiredo, Romão, AMT, 1206.2306]

LHC: $\chi_2^0 \to \ell^{\pm}\,\ell^{\mp} + E^T_{\text{miss}}$ cascades

(χ_2^0 from $\tilde{q}$ production)

- **flavoured slepton mass differences** $(\tilde{e} - \tilde{\mu})$
- **multiple edges in dilepton mass distributions** $m_{\ell\ell}$
- **direct FV final states** $\chi_2^0 \to \ell_i\,\ell_j\,\chi_1^0$

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

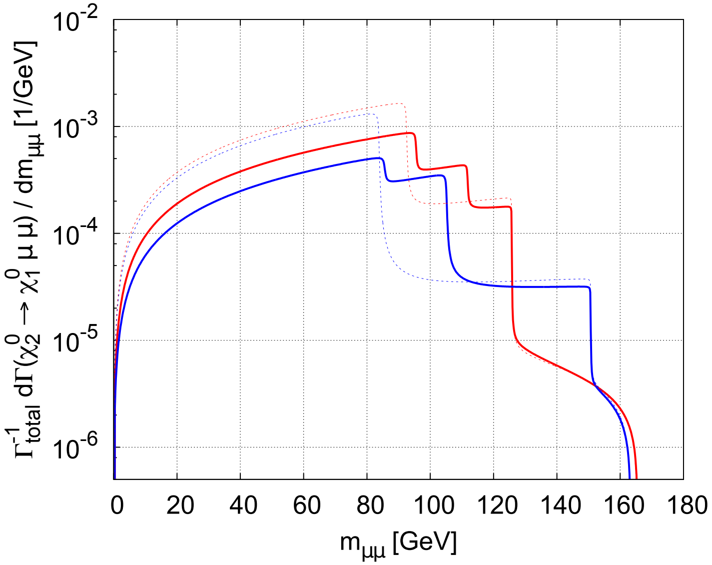
cLFV at the LHC: dilepton mass distributions

★ cMSSM (no seesaw)

▶ **Double-triangular distributions:** intermediate $\tilde{\mu}_L\,,\ \tilde{\mu}_R$ in $\chi_2^0 \to \tilde{\mu}\,\mu \to \chi_1^0\,\mu\,\mu$

▶ 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** $(\tilde{\ell}_L)$

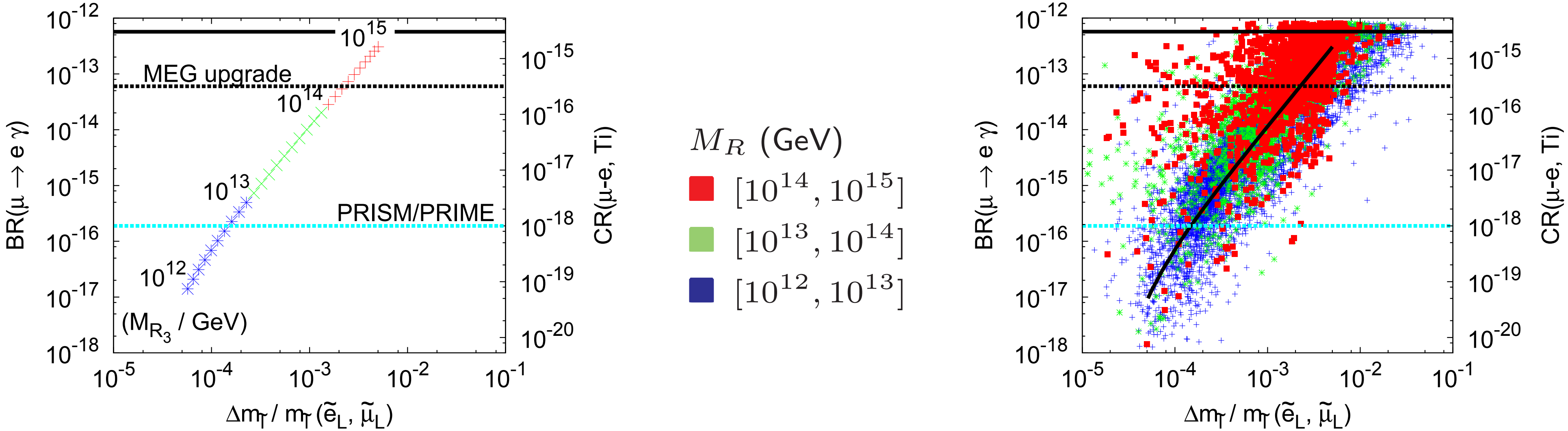
$\Rightarrow$ **sizable** $\frac{\Delta m_{\tilde{\ell}}}{m_{\tilde{\ell}}}(\tilde{e}_L, \tilde{\mu}_L)$ [⇝ flavour non-universality (?)]

▶ 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 the LHC: slepton mass splittings



[Figueiredo, AMT, 1309.7951]

- **Sizable contributions** to **high- and low-energy observables** - **within exp reach!**
- **Isolated cLFV** manifestations ⇒ **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 $\mu \to e\gamma|_{\text{MEG}}$ ✘: disfavours seesaw hypothesis

- **“Compatible” cLFV observations** ⇒ **strengthens seesaw hypothesis !**

  $\frac{\Delta m_{\tilde{\ell}}}{m_{\tilde{\ell}}}(\tilde{e}_L, \tilde{\mu}_L) \gtrsim \mathcal{O}(0.5\%)$ **and** $\mu \to e\gamma|_{\text{MEG}}$ ✔ !! **Hints on the seesaw scale:** $M_R \sim 10^{14}$ **GeV**

Hints of an organising principle: cLFV and SUSY GUTs

★ Supersymmetric Grand Unified Theories

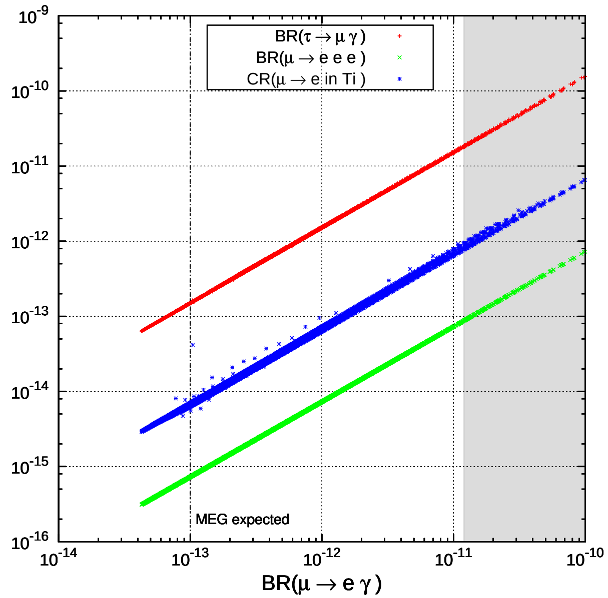
▶ **Reduce arbitrariness of Y^ν** [SO(10) CKM- and $U_{\rm PMNS}$-inspired patterns..]

▶ **SO(10) type II example**

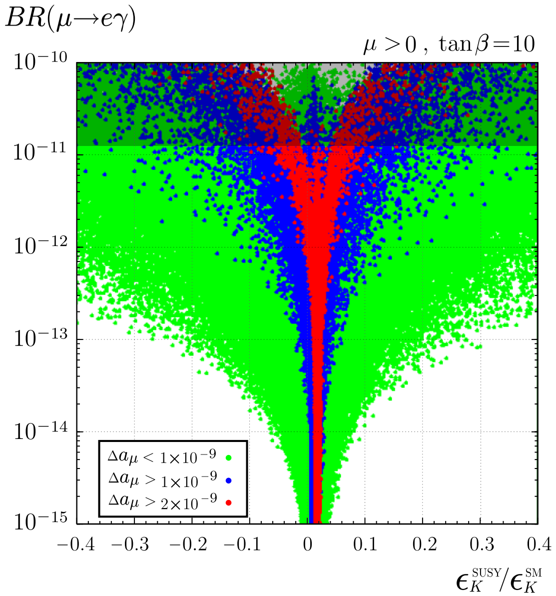
(leptogenesis motivated)

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 $\Rightarrow$ intensify the exp effort!**

  Closely follow with **theoretical studies and phenomenological analyses**

Backup

Beyond the type I SUSY seesaw: examples ...

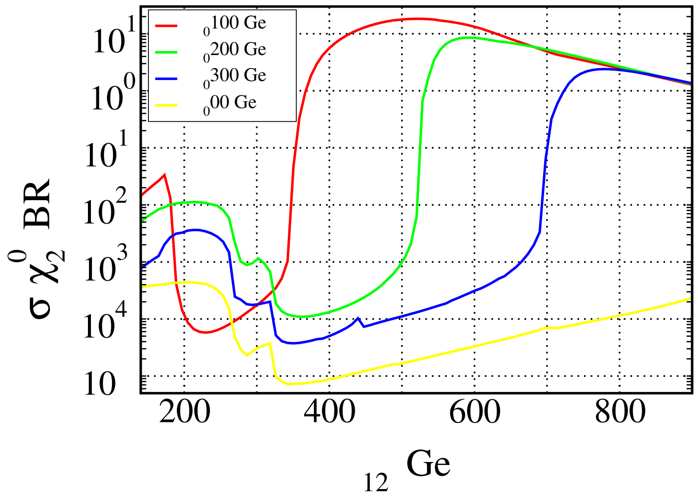
★ **Type II SUSY seesaw**

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

correlations between cLFV observables controled by **ν-parameters !**

[Rossi et al, ...]

▶ **Distinctive prospects for cLFV at colliders**

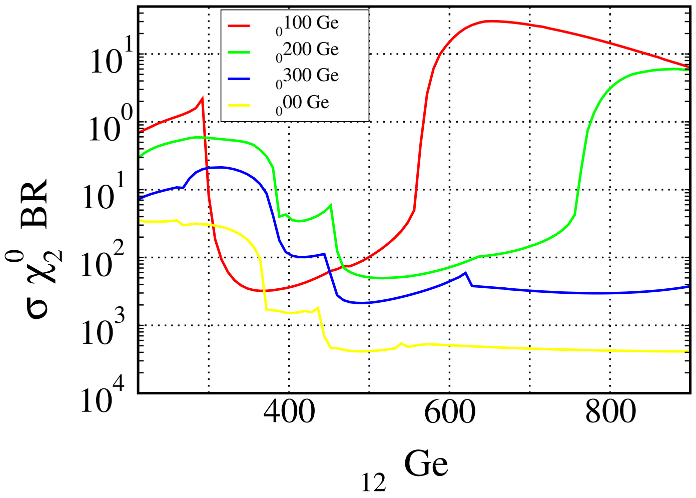


$\mathrm{BR}(\chi^0_2 \to \mu\tau)$

← Type I SUSY seesaw

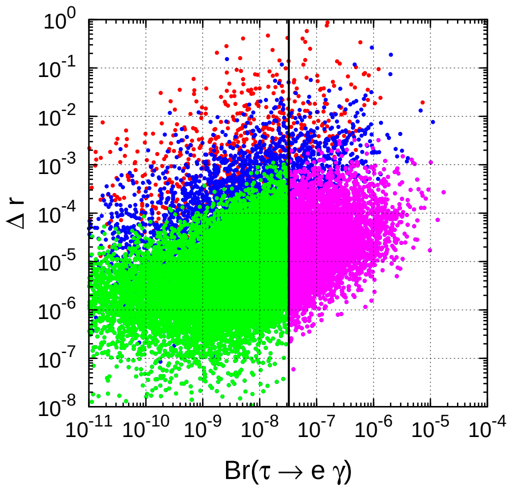
Type II SUSY seesaw →

[Esteves et al, 0903.1408]



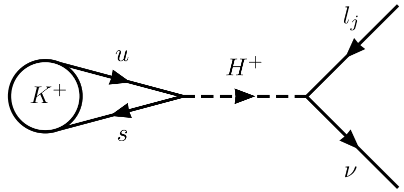
Inverse seesaw: flavour universality violation in kaon decays

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



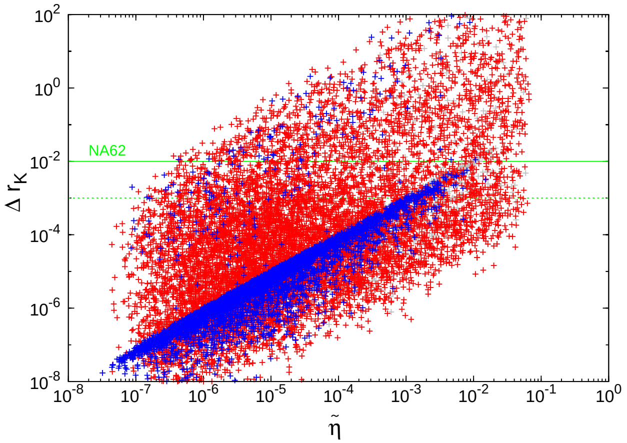
- **Unconstrained MSSM: LFV corrections to $H^+\ell\nu$ vertex**

[■ $\rightsquigarrow$ viable points]

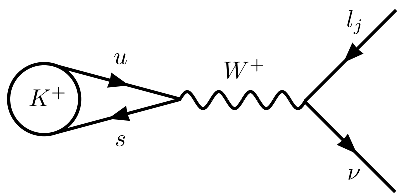


Maximise Δr_K: explicit LFV δ_{31}^{RR}, low mass regimes

[Fonseca, Romão, AMT, 1205.1411]



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



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

$\tilde{\eta}$: **"non-unitarity" of U_{PMNS}** due to **extra sterile νs**

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

[Abada, AMT, Vicente, Weiland, 1311.2830]

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

- **Consider** $e^- \, e^- \to e^- \mu^- + E^T_{\text{miss}} \rightsquigarrow \begin{cases} e^- \, \mu^- + 2\,\chi^0_1 & \text{(signal)} \\ e^- \, \mu^- + 2\,\chi^0_1 + (2,4)\,\nu & \text{(SUSY backg)} \\ e^- \, \mu^- + (2,4)\,\nu & \text{(SM}_{m_\nu}\text{ backg)} \end{cases}$

- **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**

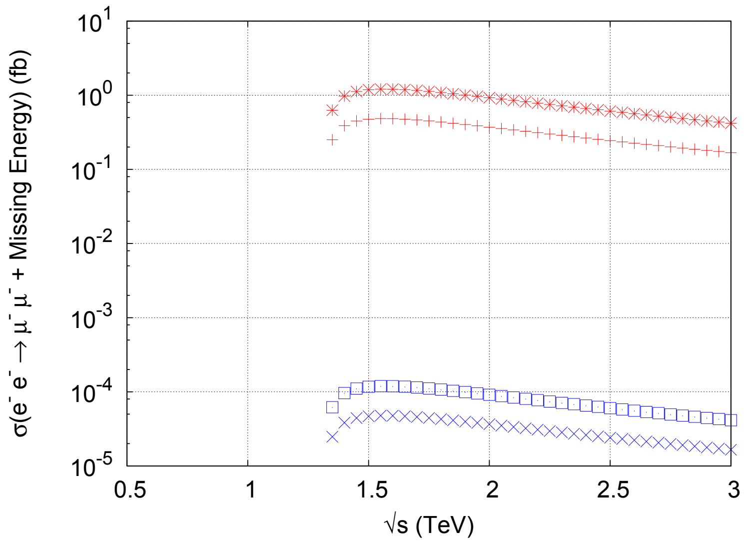
  Still expect a **large number of events** - $\mathcal{O}(10^3 - 10^5)$ **events** for $\sqrt{s} = 2$ **TeV**

- **Ideal beam option** for a **"golden channel" of cLFV** at **Linear Colliders ...**

cLFV at a future LC: the "golden channel"

- **Consider** $e^- e^- \to \mu^-\mu^- + E^T_{\text{miss}} \leftrightsquigarrow \begin{cases} \mu^-\mu^- + 2\,\chi^0_1 & \text{(signal)} \\ \mu^-\mu^- + 2\,\chi^0_1 + (2,4)\,\nu & \text{(SUSY backg)} \end{cases}$

SM_{m_ν} backg negligible ...



■ cLFV signal
■ SUSY backg

$+$, $\times$ $\to$ unpolarised
$*$, $\square$ $\to$ $e^-_L e^-_L$

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

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