Lepton Flavour Violation: a brief overview

Ana M. Teixeira

Laboratoire de Physique Corpusculaire, LPC - Clermont

Laboratoire de Physique Corpusculaire de Clermont-Ferrand

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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 & discussion**

A first look at flavours in the SM

- **Quark sector:**

The SM electroweak interactions preserve u, d, etc flavours

After EWSB, there is a **misalignment** of physical and interaction eigenstates

Quark flavour violated by **charged current** interactions $V_{ij}^{\text{CKM}}\, W^{\pm}\, \bar{q}_i\, q_j$

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

[$\rightsquigarrow$ Yesterday's review by **J. Charles**]

- **Lepton sector:**

Original SM formulation only includes ν_L (no ν_R, no Higgs triplet)

$m_{\nu_i} = 0$ - **to all orders!** [accidental $U(1)_{B-L}$ symmetry]

Strict **conservation** of total lepton number (L) and lepton flavours (L_i)

- **Neutrino oscillations:** ν**s are massive and mix!**

Revisiting the SM lepton sector: leptonic mixing

- **Extend the SM** to accommodate $\nu_\alpha \leftrightsquigarrow \nu_\beta$

  A new lepton sector: flavour violated in **charged current** interactions

  Just as in the quark sector, **misalignment** of physical **(mass)** eigenstates

  and $SU(2)_L$ interaction eigenstates parametrised by **"mixing matrix"** *(à la V_{CKM})*

- **Pontecorvo-Maki-Nakagawa-Sakata matrix:** U_{PMNS}

$$\mathcal{L}^{\text{lepton}}_{\text{charged}} = U_{\text{PMNS}}\, \bar{\ell}_L\, W^{\pm}\, \nu_L \; + \text{h.c.}$$

$$(\nu_e,\, \nu_\mu,\, \nu_\tau) \overset{U_{\text{PMNS}}}{\leftrightsquigarrow} (\nu_1,\, \nu_2,\, \nu_3)$$

$$|\nu_\alpha\rangle = U^*_{\alpha i}\, |\nu_i\rangle$$

- **New degrees of freedom** must be added to the SM:

U_{PMNS} : **3 angles**	Solar	$\theta_{12},\, \theta_\odot$	**CPV phases**	Dirac	δ
	Atmospheric	$\theta_{23},\, \theta_@$		[Majorana	$\phi_{1,2}$]
	Reactor	$\theta_{13},\, \theta_{\text{Chooz}}$			

Neutrino masses: m_ν $\quad (\Delta m^2)$

[$\rightsquigarrow$ Yesterday's review by **E. Lisi**]

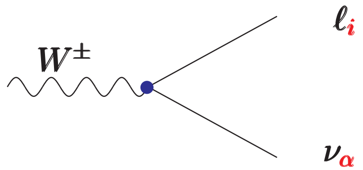
A second look at flavour violation in the SM

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

  Observed in many processes: $K^0 - \bar{K}^0$, $b \to s\gamma$, $D^+ \to \pi^+\mu^+\mu^-$ $(c\bar{d} \to u\bar{d})$...

- **Lepton sector:** **Charged currents** also **violate lepton flavour!** $U_{\mathrm{PMNS}} W^{\pm} \bar{\ell} \nu$

Assume most minimal extension SM_{m_ν}



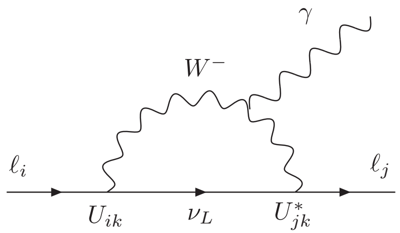
$\bullet \propto U_{\alpha i}^{\mathrm{PMNS}}$

$m_\nu \neq 0$

$\nu_\alpha = \sum_i U_{\alpha i} \nu_\beta$

[$\mathrm{SM}_{m_\nu} =$ "ad-hoc" m_ν, U_{PMNS}]

SM_{m_ν} - **cLFV possible??**



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

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

- **"Observable" cLFV $\Rightarrow$ New Physics in the lepton sector - beyond SM_{m_ν}**

- **Lepton flavour violation: Observables and facilities**

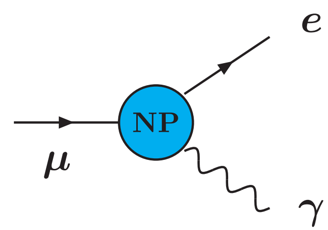
Signals of Lepton Flavour Violation

- **Neutrino oscillations** [ν-dedicated experiments]

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

  $\ell_i \to \ell_j \gamma$, $\ell_i \to 3\ell_j$, mesonic τ decays...

  nuclei (atomic) assisted $\mu - e$ transitions, Muonium channels...



- **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]

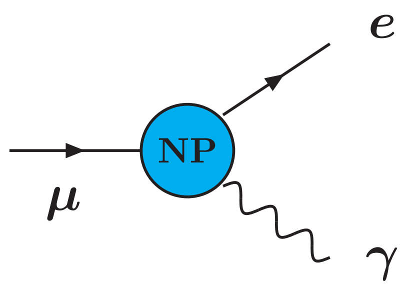
- **Rare (new) heavy particle decays (typically model-dependent)** [colliders]

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

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

- And many others ... **all without SM theoretical background!**

cLFV in muon channels: radiative decays



- **cLFV decay:** $\mu^+ \to e^+ \gamma$
- **Event signature:** $E_e = E_\gamma = m_\mu/2$ (~ 52.8 MeV)

  Back-to-back e^+ - γ ($\theta \sim 180°$); Time coincidence

- **Backgrounds** $\Rightarrow$ prompt physics & accidental

  Prompt: radiative μ decays $\mu \to e \nu_e \nu_\mu \gamma$ (very low E_ν) $[\propto R_\mu]$

  Accidental: coincidence of γ with positron from Michel decays $\mu \to e \nu_e \nu_\mu$; photon from $\mu \to e \nu_e \nu_\mu \gamma$; photon from in flight $e^+ e^-$ annihilation $[\propto R_\mu^2]$

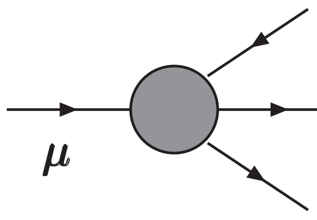
- **Current status:**

Collaboration	year	BR($\mu \to e\gamma$) 90% C.L.
LAMPF/MEGA	1999	1.2×10^{-11}
PSI/MEG	2011	2.8×10^{-11}
PSI/MEG	**2013**	$\mathbf{5.7 \times 10^{-13}}$

- **Future prospects:** **MEG II PSI** (proposal 2013) **sensitivity** $\mathbf{6 \times 10^{-14}}$

  ... intense proton beams: CERN (NuFact), FNAL (Project X), JPARC, ...

cLFV in muon channels: 3-body decays



- cLFV decay: $\mu^+ \to e^+ e^- e^+$
- Event signature: $\sum E_e = m_\mu$; $\sum \vec{P}_e = \vec{0}$

  common vertex; Time coincidence

- **Backgrounds** ⇒ physics & accidental

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

  Accidental: Bhabha scattering of Michel e^+ from $\mu \to e \nu \nu$ with atomic $e^+ e^-$;
  Michel positrons with $e^+ e^-$ from γ conversion...

- **Current status:**

Collaboration	year	BR($\mu \to eee$) 90% C.L.
LAMPF/Crystal Box	1988	3.5×10^{-11}
PSI/SINDRUM	1988	1.0×10^{-12}
JINR	1991	3.6×10^{-11}

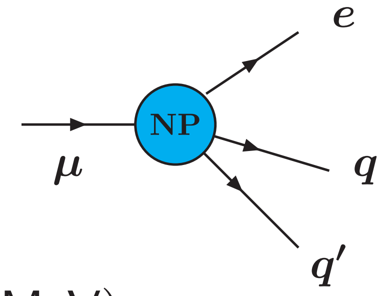
- **Future prospects: Mu3e Experiment** at **PSI**

  Phase I ($\sim$ 2017): 10^{-15} (πE5 μ source) ⇒ **Phase II ($>$ 2018): 10^{-16}** (H.I. μ-beam)

cLFV in "muonic" atoms: $\mu - e$ conversion

- **Muonic atoms:** 1s bound state formed when μ^- stopped in target

  SM-like processes: $\mu^- \to e^- \nu_\mu \bar{\nu}_e$ (decay in orbit) $\mu^- + (A,Z) \to \nu_\mu + (A, Z-1)$ (nuclear capture)



- **cLFV $\mu^- - e^-$ conversion:** $\boldsymbol{\mu^- + (A,Z) \to e^- + (A,Z)}$

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

  $E^{\text{N}}_{\mu e} = m_\mu - E_B(A,Z) - E_R(A,Z)$, $\quad E^{\text{Al, Pb, Ti}}_{\mu e} \approx \mathcal{O}(100\text{ MeV})$

  coherent conversion, increases with Z (maximal for $30 \leq Z \leq 60$)

- **Backgrounds** $\Rightarrow$ only **physics** (e.g. μ decay in orbit); beam (purity), cosmic rays, ...

- **Experimental status (present bounds and future prospects):**

CR($\mu - e$, N) bound	material	year
$\mathbf{4.3 \times 10^{-12}}$	**Ti**	1993
$\mathbf{4.6 \times 10^{-11}}$	**Pb**	1996
$\mathbf{7 \times 10^{-13}}$	**Au**	2006

Experiment (material)	future sensitivity	year
Mu2e (Al)	$\mathbf{3 \times 10^{-17}}$	$\sim$ 2021
COMET (Al) - Phase I (II)	$\mathbf{10^{-15}}$ $(\mathbf{10^{-17}})$	$\sim$ 2018(21)
PRISM/PRIME (Ti)	$\mathbf{10^{-18}}$	
DeeMee (SiC)	10^{-14}	

- **$\mu^- - e^+$ conversion** (cLFV & $\Delta L = 2$): $\boldsymbol{\mu^- + (A,Z) \to e^+ + (A, Z-2)^*}$

cLFV in "muonic" atoms: rare decays

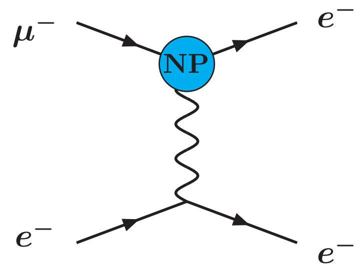
- **Muonic atom decay:** $\mu^- e^- \to e^- e^-$ [Koike et al, '10]

  Initial μ^- **and** e^-**: 1s** states bound in Coulomb field of the **muonic atom's nucleus**

- **Coulomb interaction** increases overlap between

  Ψ_{μ^-} and Ψ_{e^-} wave functions

  $$\Gamma(\mu^- e^- \to e^- e^-,\ \mathrm{N}) \propto \sigma_{\mu e \to ee} v_{\mathrm{rel}} \left[(Z-1)\,\alpha\, m_e\right]^3/\pi$$



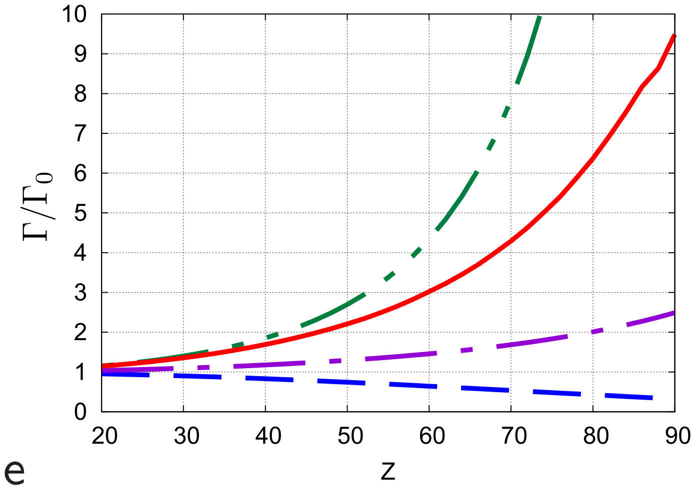
- **Clean experimental signature:** back-to-back electrons, $E_{e^-} \approx m_\mu/2$

  larger phase space than $\mu \to 3e$

- **Rate strongly enhanced** in **large Z atoms**

  $\Gamma/\Gamma_0 \gtrsim (Z-1)^3$ [Uesaka et al, '15]

  Consider experimental setups for **Pb, U !?**



- **Experimental status: New observable!**

  Hopefully included in **COMET**'s Phase II programme

cLFV in "muonic" atoms: Muonium

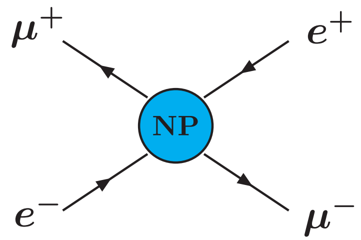
- **Muonium:** hydrogen-like **Coulomb bound state** $(e^-\mu^+)$; free of hadronic interactions!

- **Mu – $\overline{\text{Mu}}$** conversion

  Spontaneous conversion of a $(e^-\mu^+)$ into $(e^+\mu^-)$

  Reflects a **double lepton number violation:** $\Delta L_e = \Delta L_\mu = 2$

  Rate suppressed by external electromagnetic fields



- **Experimental status:** **P(Mu – $\overline{\text{Mu}}$)** $< 8.3 \times 10^{-11}$ [Willmann et al, 1999]

- **cLFV Mu decay:** Mu $\to e^+e^-$

  clear signal compared to SM decay Mu $\to e^+e^-\bar{\nu}_\mu\nu_e$ (no missing energy)

- **Experimental status:** no clear roadmap (nor bounds)...

  Hopefully included in **COMET**'s Phase II programme

Rare lepton processes: cLFV tau decays

- **Tau production and decay:** $e^+e^- \to \tau^+\tau^-$ $\rightsquigarrow$ signal hemisphere
  $\rightsquigarrow$ tagging hemisphere: e.g. $\tau \to \bar{\nu}_\tau \nu_e e^+$

- **Radiative decay:** $\tau^\pm \to \ell^\pm \gamma$
  - **Event signature:** $E_{\text{final}} - \sqrt{s}/2 = \Delta E \sim 0$;
    $M_{\text{final}} = M_{\ell\gamma} \sim m_\tau$
  - **Backgrounds** $\Rightarrow$ coincidence of isolated leptons with γ (ISR, FSR); mistagging

Process	BR (BaBar, 2010)
$\tau \to e\gamma$	3.3×10^{-8}
$\tau \to \mu\gamma$	4.4×10^{-8}

- **3-body decays:** $\tau^\pm \to \ell_i^\pm \ell_j^\mp \ell_k^\pm$
  - **Event signature:** $E_{3\ell} - \sqrt{s}/2 \sim 0$; $M_{3\ell} \sim m_\tau$
  - **Backgrounds** $\Rightarrow$ **No irreducible backgd!**
    small backgd from $q\bar{q}$ and Bhabha pairs...

3ℓ final state	BR (BaBar)	BR (Belle)
$e^-e^+e^-$	2.9×10^{-8}	2.7×10^{-8}
$\mu^-e^+e^-$	2.2×10^{-8}	1.8×10^{-8}
$\mu^-e^-e^-$	1.8×10^{-8}	1.5×10^{-8}
$e^+\mu^-\mu^-$	2.6×10^{-8}	1.7×10^{-8}
$e^-\mu^+\mu^-$	3.2×10^{-8}	2.7×10^{-8}
$\mu^-\mu^+\mu^-$	3.3×10^{-8}	2.1×10^{-8}

- **Future experimental prospects:** **SuperB (SuperBelle) and/or Tau-Charm factories**

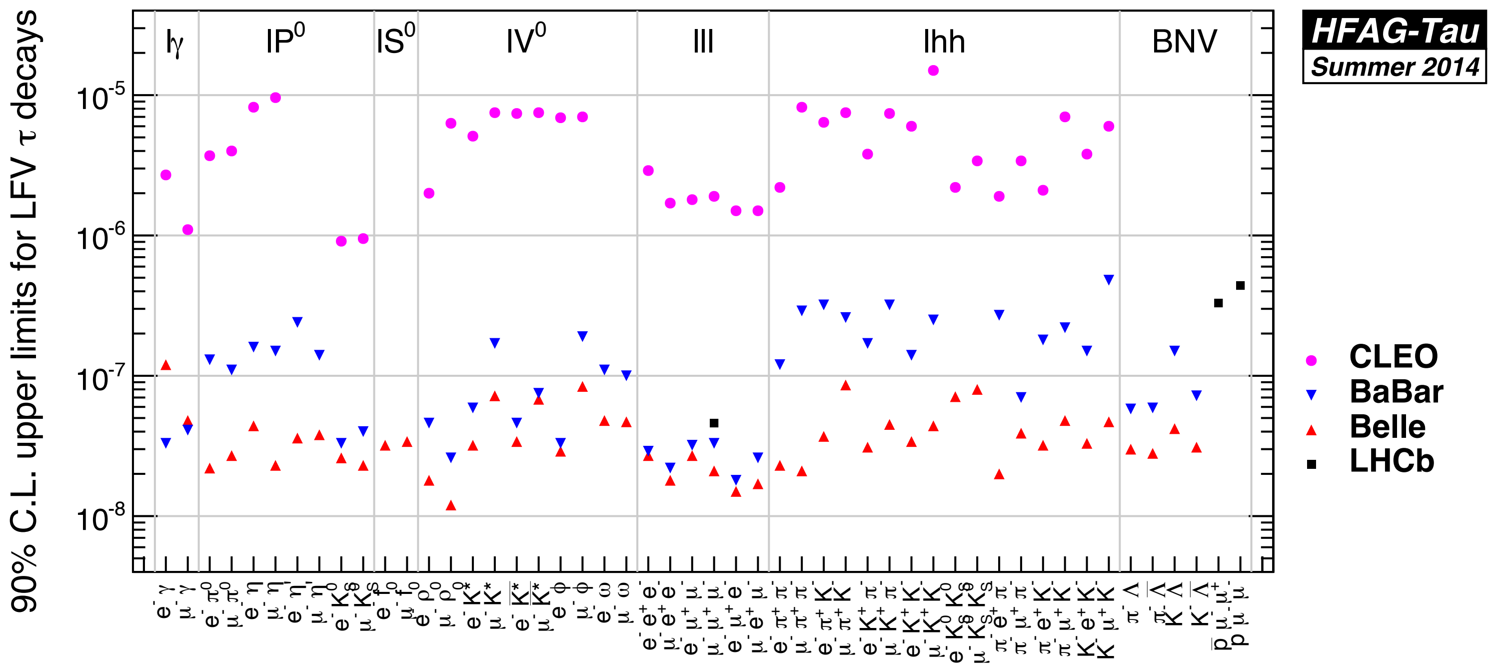
  BR$(\tau \to \ell\gamma) \leq 1 - 3 \times 10^{-9}$ **BR**$(\tau \to 3\ell) \leq 1 - 2 \times 10^{-10}$

Rare lepton processes: cLFV tau decays

- **cLFV tau decays into mesons:** "large" τ mass $\Rightarrow$ possible to have semi-leptonic decays
- **Meson & charged lepton:** $\tau \to \ell\, h^0$ pseudoscalar, scalar or vector neutral meson
- **3 body meson & charged lepton:** $\tau \to \ell\, h_i\, h_j$ $\quad h \leftrightsquigarrow \pi^\pm, K^\pm, K^0_s$
- **cLFV exotic modes:** violating total lepton number and baryon number

$$\tau^- \to \ell^+ h_i^\pm h_j^\pm \quad \text{where} \quad h^\pm = \pi^\pm, K^\pm \qquad \text{(LNV)}$$

$$\tau^- \to \Lambda\, h^- \quad \text{where} \quad h^\pm = \pi^\pm, K^\pm \qquad \text{and} \quad \tau \to p\,\mu\,\mu \qquad \text{(BNV)}$$



cLFV meson decays

- **Meson decays:** excellent testing grounds for lepton flavour dynamics! Examples...
  - **Lepton Universality Violation in K and π decays**

    $R_P = \frac{\Gamma(P\to e\nu)}{\Gamma(P\to\mu\nu)}$ comparison with **SM th predictions** $\Delta r_P = \frac{R_P^{\text{exp}}}{R_P^{\text{SM}}} - 1$

    - Limits from **NA62** at CERN: $\Delta r_K = (4 \pm 4) \times 10^{-3}$; $\Delta r_\pi = (-4 \pm 3) \times 10^{-3}$

      Future sensitivity: $\delta R_K / R_K \sim 0.1\% \Rightarrow$ measure $\Delta r_K \sim \mathcal{O}(10^{-3})$

  - **Lepton Universality Violation in B decays**

    $R_K^B = \frac{\text{BR}(B^+\to K^+\mu^+\mu^-)}{\text{BR}(B^+\to K^+e^+e^-)}$

    - **LHCb:** $R_K^B = 0.745 + 0.090 - 0.074(\text{stat}) \pm 0.036(\text{syst})$

      Also in $\bar{B}^0 \to D^*\ell\nu$ decays...

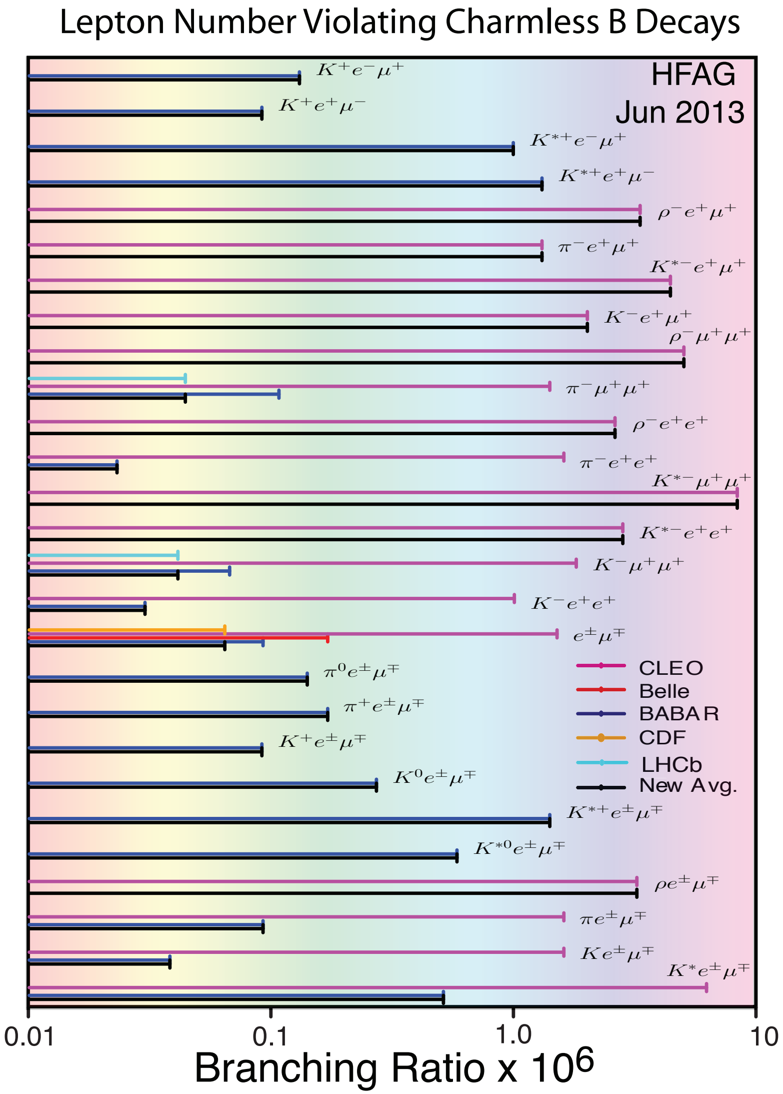
  - **cLFV & LNV** in **D and B meson decays** (Used as indirect test of Majorana mediators)
    - Abundant data from **LHCb, BNL, KTeV, BaBar, Cleo, Belle, ...**

      $\text{BR}(D^0 \to \mu e) < 1.5 \times 10^{-8}$; $\text{BR}(B \to \mu e) < 2.8 \times 10^{-9}$;

      $\text{BR}(B^- \to D^+\mu^-\mu^-) < 7 \times 10^{-7}$; $\text{BR}(B^- \to D^0\pi^+\mu^-\mu^-) < 2 \times 10^{-6}$, ...

cLFV meson decays

- **Many processes being searched for!** **From B-factories to high-energy colliders...**



Lepton flavour violating: Decay mode	BF UL 90% CL (10^{-6})
$D^+ \to \pi^+e^+\mu^-$	2.9
$D^+ \to \pi^+e^-\mu^+$	3.6
$D^+ \to K^+e^+\mu^-$	1.2
$D^+ \to K^+e^-\mu^+$	2.8
$D_s^+ \to \pi^+e^+\mu^-$	12
$D_s^+ \to \pi^+e^-\mu^+$	20
$D_s^+ \to K^+e^+\mu^-$	14
$D_s^+ \to K^+e^-\mu^+$	9.7
$\Lambda_c^+ \to pe^+\mu^-$	9.9
$\Lambda_c^+ \to pe^-\mu^+$	19

Lepton number violating: Decay mode	BF UL 90% CL (10^{-6})
$D^+ \to \pi^-e^+e^+$	1.9
$D^+ \to \pi^-\mu^+\mu^+$	2.0
$D^+ \to \pi^-e^+\mu^+$	2.0
$D^+ \to K^-e^+e^+$	0.9
$D^+ \to K^-\mu^+\mu^+$	10
$D^+ \to K^-e^+\mu^+$	1.9
$D_s^+ \to \pi^-e^+e^+$	4.1
$D_s^+ \to \pi^-\mu^+\mu^+$	14
$D_s^+ \to \pi^-e^+\mu^+$	8.4
$D_s^+ \to K^-e^+e^+$	5.2
$D_s^+ \to K^-\mu^+\mu^+$	13
$D_s^+ \to K^-e^+\mu^+$	6.1
$\Lambda_c^+ \to \bar{p}e^+e^+$	2.7
$\Lambda_c^+ \to \bar{p}\mu^+\mu^+$	9.4
$\Lambda_c^+ \to \bar{p}e^+\mu^+$	16

[BaBar, '12]

- **Also in Kaon decays!** e.g. $\mathrm{BR}(K_L \to \mu e) < 4.7 \times 10^{-12}$; $\mathrm{BR}(K^+ \to \pi^+\mu^+e^-) < 2.1 \times 10^{-11}$; ...

cLFV collider signatures: "heavy" SM decays

- **Z boson decays: $Z \to \ell_i \ell_j$**

  Z bosons abundantly produced at **LEP** and at the **LHC**

  - **Current bounds:** BR$(Z \to e\mu) < 7.5 \times 10^{-7}$ [ATLAS, 2014]

    BR$(Z \to \mu\tau) < 1.2 \times 10^{-5}$; BR$(Z \to e\tau) < 9.8 \times 10^{-6}$ [OPAL & DELPHI]

- **Higgs boson decays: $H \to \ell_i \ell_j$**

  A "Higgs-factory" at LHC - ability to study rare processes...

  - **Current bounds:** BR$(H \to \mu\tau) < 0.0157$ [CMS] Possible "signal" @ 2.4σ???...

- **Exotic top quark decays: $t \to \ell_i \ell_j q$**

  If present, possibly within reach - LHC "top-factory"... [Davidson et al, '14]

- **Future experimental prospects:** **Exciting ones from LHC Run 2 !!**

  Linear Collider / FCC-ee running at ZZ, HH, tt thresholds

cLFV collider signatures: "golden" channels for NP

- **At high energies, production of "on-shell" new physics states**

  $\Rightarrow$ **new interactions** open the way for cLFV decays

- **Multiplicity, composition,** ..., properties of final state **strongly model-dependent...**

  Many NP models introduce finals states containing "missing energy" EW states

- **Example (LHC): Supersymmetric cLFV extensions of the SM**

$$pp \to \begin{cases} \chi_2^0 \to \tilde{\ell}_i^\pm \, \ell_j^\mp \to \boldsymbol{\ell_i^\pm \, \ell_j^\mp \, \chi_1^0} \\ \chi_2^0 \to \boldsymbol{\ell_i^\pm \, \nu \, \chi_1^0} \end{cases}$$

  - **Event signature: 3 leptons**, of which 2 "opposite flavour opposite sign" **(OFOS)**

    plus missing transverse energy $\boldsymbol{E^T_{\text{miss}}}$ (LSP + ν)

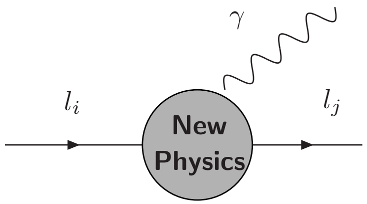
- **Example (LC): Supersymmetric cLFV extensions of the SM**

  - **Event:** $e^+ e^- \to \mu^\pm e^\mp + E_{\text{miss}}$ $(2\chi_1^0)$

- **After the experiments: understanding (negative) searches**

Interpreting experimental data (bounds & measurements)

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



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

cLFV $\Leftrightarrow$ **New Physics** (beyond SM_{m_ν}) $+$ **Lepton Flavour Mixing**

$\Lambda \sim \mathcal{O}(\text{TeV})$ — non-negligible $\theta_{\ell_i \ell_j}$

(testable at colliders ?) — (suggested by neutrino mixing ...)

- **Pheno approaches:**
  - **Effective approach (model-independent)**
  - **Model dependent (specific NP scenario)**

- **Many models:** well-motivated **SM extensions** to ease (some) of its th & exp problems

  generic cLFV extensions (SUSY, little Higgs, ...); models of ν **mass** generation;

  extended frameworks (gauge / flavour symmetries, extra dims, ...)

- **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 : **scale of new physics**

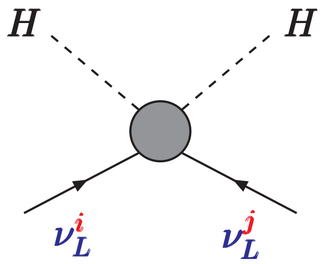
$\mathcal{C}^n$: **dimensionless couplings** - coupling constants, Yukawas, loop factors $((4\pi)^m)$, ...

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

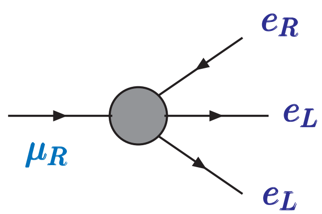
$\mathcal{O}^n$: **"external legs"** of the diagrams - **SM fields only!**

cLFV: the effective approach

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



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



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

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

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

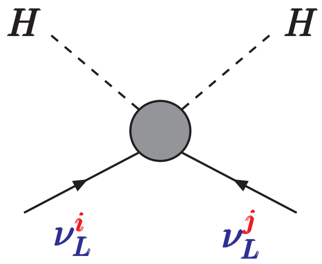
- **Dimension 6 $\Delta\mathcal{L}^6$:** kinetic corrections, **cLFV** **(dipole and 3-body)**, EW precision, t physics...

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

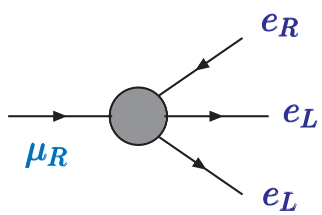
- **Higher order $\Delta\mathcal{L}^{7,8,..}$:** ν (transitional) magnetic moments, NSI, unitarity violation...

cLFV: the effective approach

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



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



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

▶ **Dimension 5 $\Delta\mathcal{L}^5$ (Weinberg):** a unique operator $\mathcal{O}^5_{ij} \sim (L_i.H)(H.L_j)$ $\quad \mathcal{C}^5_{ij} \sim (Y^\nu_{ij})^2$

▶ **Dimension 6 $\Delta\mathcal{L}^6$: 3 "types" of operators** relevant for **cLFV (dipole and 3-body)**

2 lepton-Higgs-photon: $\mathcal{O}^6_{\ell_i\ell_j\gamma} \sim L_i\sigma^{\mu\nu}e_j H F_{\mu\nu}$

$\mathcal{O}^6_{\ell_i\ell_i\gamma} \rightsquigarrow$ anomalous magnetic/electric moments $(\propto$ Re, Im $\mathcal{C}^6_{\ell_i\ell_i\gamma}/\Lambda^2)$

$\mathcal{O}^6_{\ell_i\ell_j\gamma} \rightsquigarrow$ **radiative decays** $\ell_i \to \ell_j\gamma$ $(\propto \mathcal{C}^6_{\ell_i\ell_j\gamma}/\Lambda^2)$

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

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

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

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

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

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

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

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

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

[Davidson, '12]

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

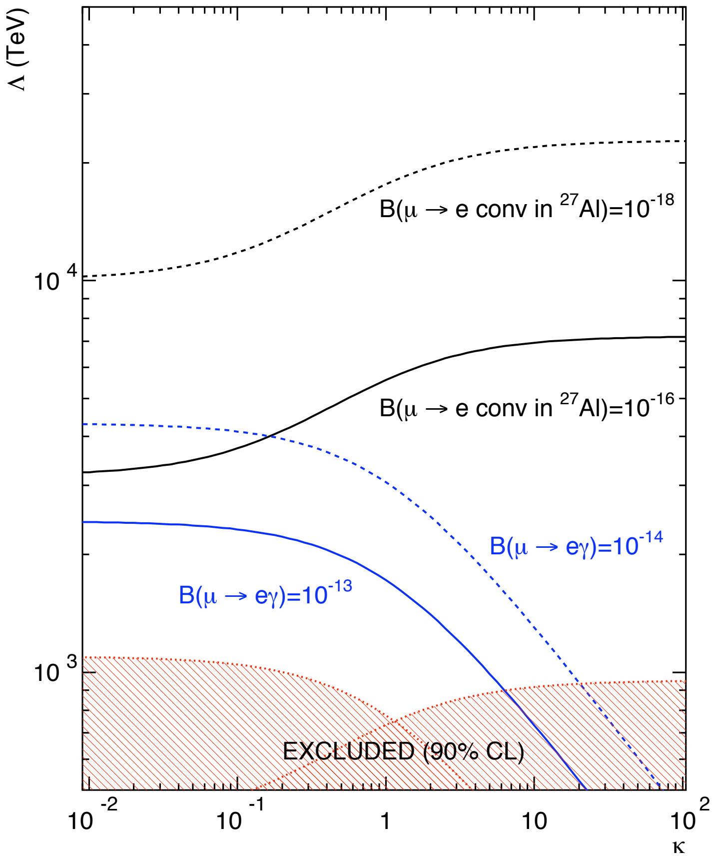
$$\text{BR}(\mu \to e\gamma) \leq 5.7 \times 10^{-13} \Rightarrow |\mathcal{C}^6_{\mu e}|^2 \lesssim 10^{-9} \times \left(\frac{1 \text{ TeV}}{\Lambda}\right)^2$$

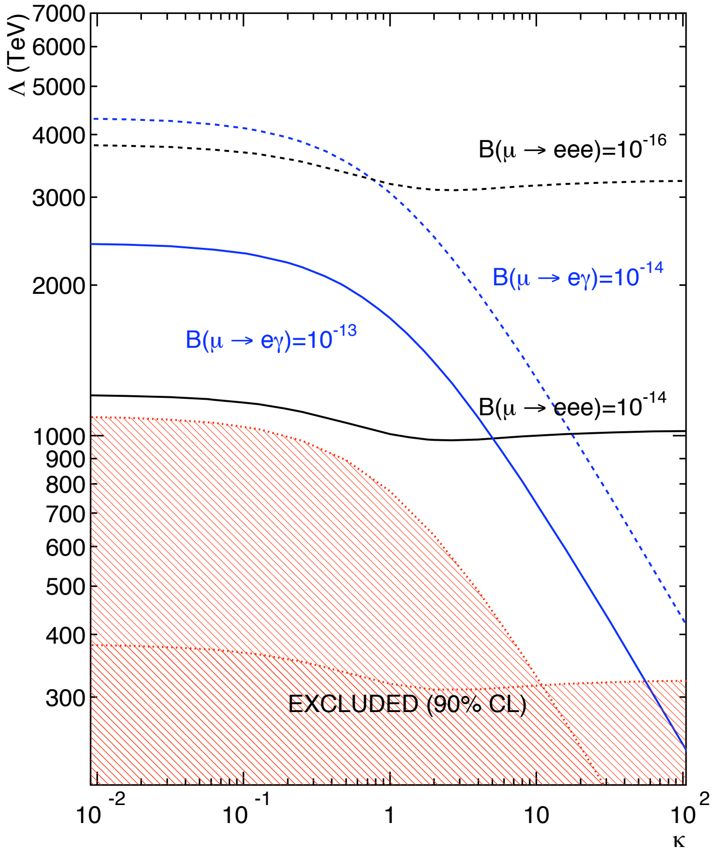
cLFV bounds and $\mathcal{L}^{\text{eff}}$

- Apply **experimental** bounds on **cLFV observables** to **constrain** $\mathcal{L}^{\text{eff}}$

$$\mathcal{L}^{\text{eff}}_{\kappa} \approx \frac{m_\mu}{\Lambda^2} \frac{1}{(\kappa+1)} \bar{\mu}_R \sigma_{\mu\nu} e_L F^{\mu\nu} + \frac{1}{\Lambda^2} \frac{\kappa}{(\kappa+1)} \left(\bar{\mu}_L \gamma_\mu e_L (\bar{e}\gamma^\mu e) + \bar{\mu}_L \gamma_\mu e_L (\bar{q}_L \gamma^\mu q_L) \right) + \ldots$$

$\kappa \rightsquigarrow$ "effective coupling"; relative weight of *"em vs 4f"* operators





[De Gouvea and Vogel, '13]

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

- **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**

$$\mathcal{L}^{\text{eff}} = \mathcal{L}^{\text{SM}} + \frac{1}{\Lambda_{\text{LNV}}}\,\mathcal{C}^5(m_\nu) + \frac{1}{\Lambda^2_{\text{LFV}}}\,\mathcal{C}^6(\ell_i \leftrightarrow \ell_j) + \ldots \quad \begin{cases} \Lambda_{\text{LNV}} \rightsquigarrow M_{\text{GUT}} \sim 10^{15}\ \text{GeV} \\ \Lambda_{\text{LFV}} \rightsquigarrow M_{\text{SUSY}} \sim\ \text{TeV} \end{cases}$$

- **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 $\Rightarrow$ **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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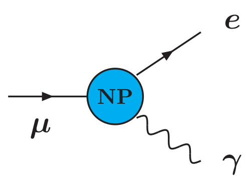
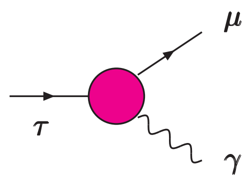
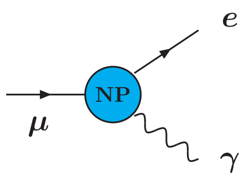
$$\frac{\mathrm{BR}(\mu\to e\gamma)}{\mathrm{BR}(\tau\to\mu\gamma)}$$

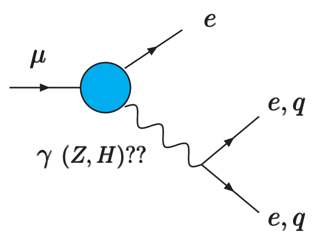




Probe NP flavour structure

$$\frac{\mathrm{BR}(\mu\to e\gamma)}{\mathrm{BR}(\mu\to 3e)}$$





Probe NP operator at work

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

- **An example: generic cLFV extensions - the MSSM**

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)

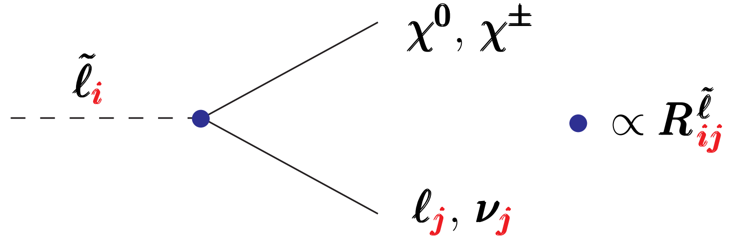
non-diagonal masses for sleptons and sneutrinos $(M^2_{\tilde{\ell}})_{ij} \neq 0!$ $(M^2_{\tilde{\nu}})_{ij} \neq 0!$

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

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

manifest in **neutral** and

charged lepton-slepton interactions



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

▶ 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"...

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

[Herrero et al, 1304.2783; Calibbi et al, 1502.07753]

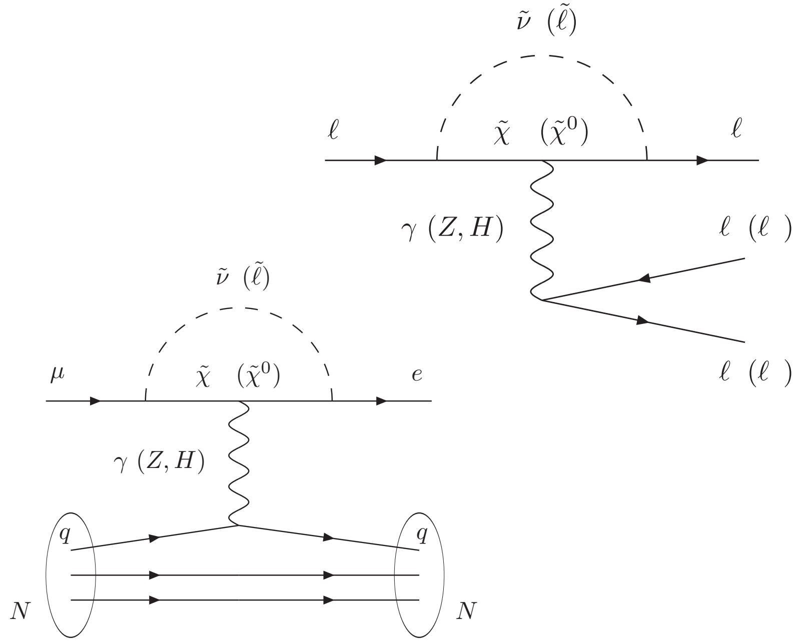
Correlation of observables in cLFV models (MSSM)

- Many **models - as the MSSM - predict/accommodate** extensive **ranges for observables**

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

- Are there peculiar patterns that might offer some hints?

Ratio	MSSM (dipole)	MSSM (Higgs)
$\frac{\text{BR}(\mu\to eee)}{\text{BR}(\mu\to e\gamma)}$	$\sim 6\times 10^{-3}$	$\sim 6\times 10^{-3}$
$\frac{\text{BR}(\tau\to eee)}{\text{BR}(\tau\to e\gamma)}$	$\sim 1\times 10^{-2}$	$\sim 1\times 10^{-2}$
$\frac{\text{BR}(\tau\to\mu\mu\mu)}{\text{BR}(\tau\to\mu\gamma)}$	$\mathbf{\sim 2\times 10^{-3}}$	$\mathbf{0.06\ldots0.1}$
$\frac{\text{BR}(\tau\to e\mu\mu)}{\text{BR}(\tau\to e\gamma)}$	$\sim 2\times 10^{-3}$	$0.02\ldots0.04$
$\frac{\text{BR}(\tau\to\mu ee)}{\text{BR}(\tau\to\mu\gamma)}$	$\sim 1\times 10^{-2}$	$\sim 1\times 10^{-2}$
$\frac{\text{BR}(\tau\to eee)}{\text{BR}(\tau\to e\mu\mu)}$	$\mathbf{\sim 5}$	$\mathbf{0.3\ldots0.5}$
$\frac{\text{BR}(\tau\to\mu\mu\mu)}{\text{BR}(\tau\to\mu ee)}$	$\mathbf{\sim 0.2}$	$\mathbf{5\ldots10}$
$\frac{\text{CR}(\mu\text{Ti}\to e\text{Ti})}{\text{BR}(\mu\to e\gamma)}$	$\mathbf{\sim 5\times 10^{-3}}$	$\mathbf{0.08\ldots0.15}$



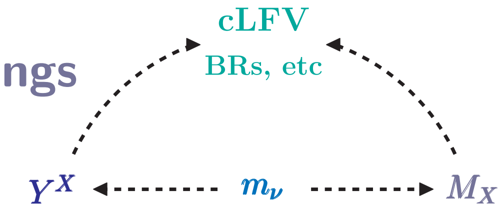
[Buras et al, 1006.5356]

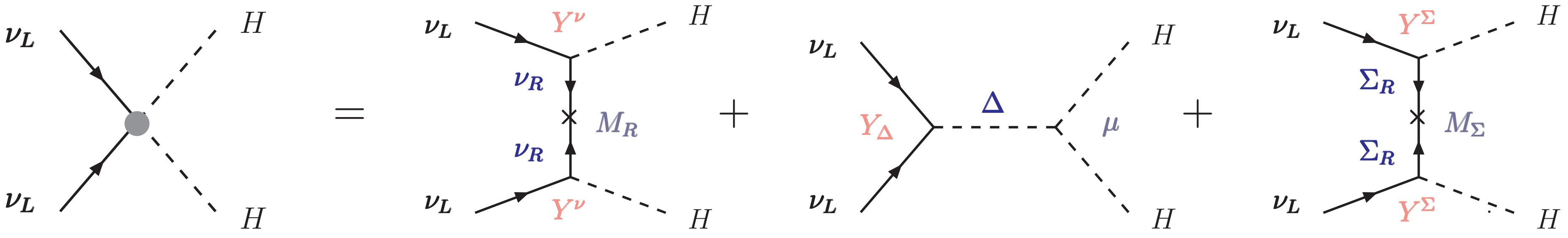
- **Correlations** might allow to **disentagle models of cLFV** in the absence of **discovery of new states!** ... or inability to **identify mechanism of LFV!**

▶ cLFV from 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**

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

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

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

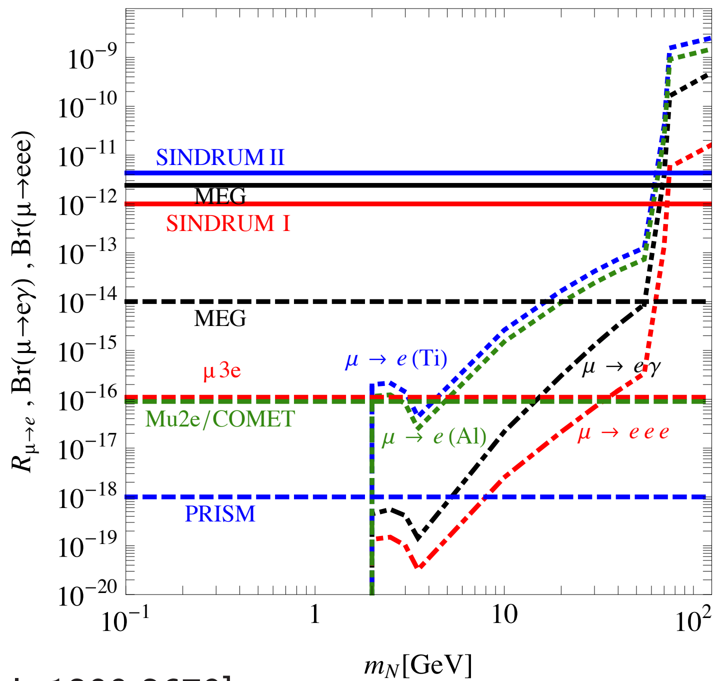
Low scale type I seesaw

- Addition of **3 "heavy" Majorana RH** neutrinos to SM; **MeV $\lesssim m_{N_i} \lesssim 10^{\text{few}}$TeV**
- **Spectrum and mixings:** $m_\nu \approx -v^2 Y_\nu^T M_N^{-1} Y_\nu$ $\quad U^T \mathcal{M}_\nu^{6\times6} U = \text{diag}(m_i)$

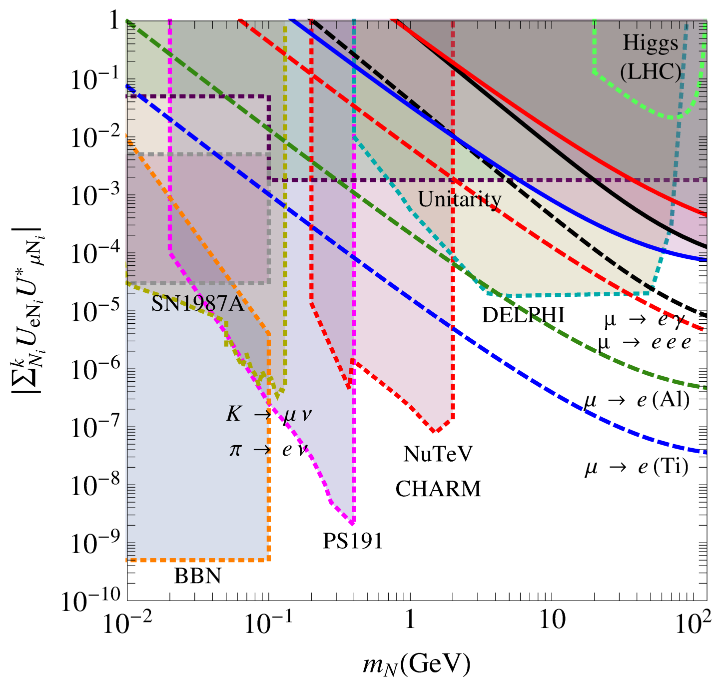
$$U = \begin{pmatrix} U_{\nu\nu} & U_{\nu N} \\ U_{N\nu} & U_{NN} \end{pmatrix} \qquad U_{\nu\nu} \approx (1-\varepsilon)\, U_{\text{PMNS}}$$

Non-unitary leptonic mixing $\tilde{U}_{\text{PMNS}}$!

- **Heavy states do not decouple** $\Rightarrow$ **modified neutral and charged leptonic currents**
- Rich phenomenology at **high-intensity/low-energy**



[Alonso et al, 1209.2679]



(see also Dinh et al, '12-'14)

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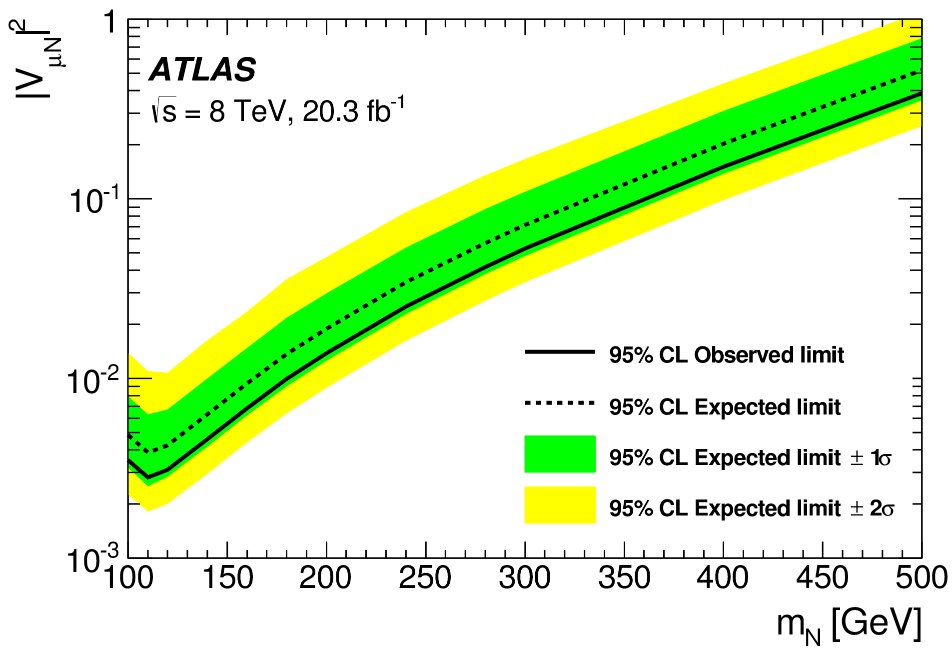
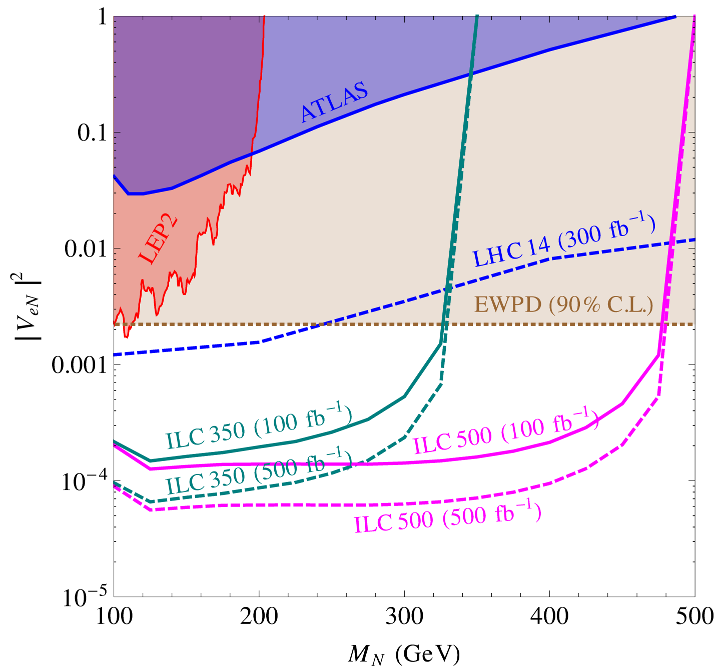
- **Heavy states do not decouple** $\Rightarrow$ **modified neutral and charged leptonic currents**
- Rich phenomenology at **high-energy colliders**



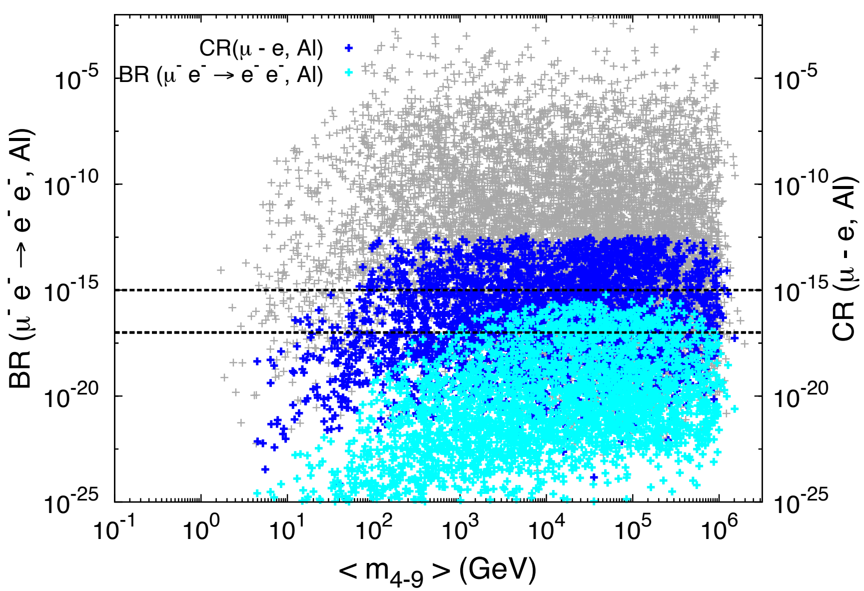
[ATLAS Collab., 1506.06020]

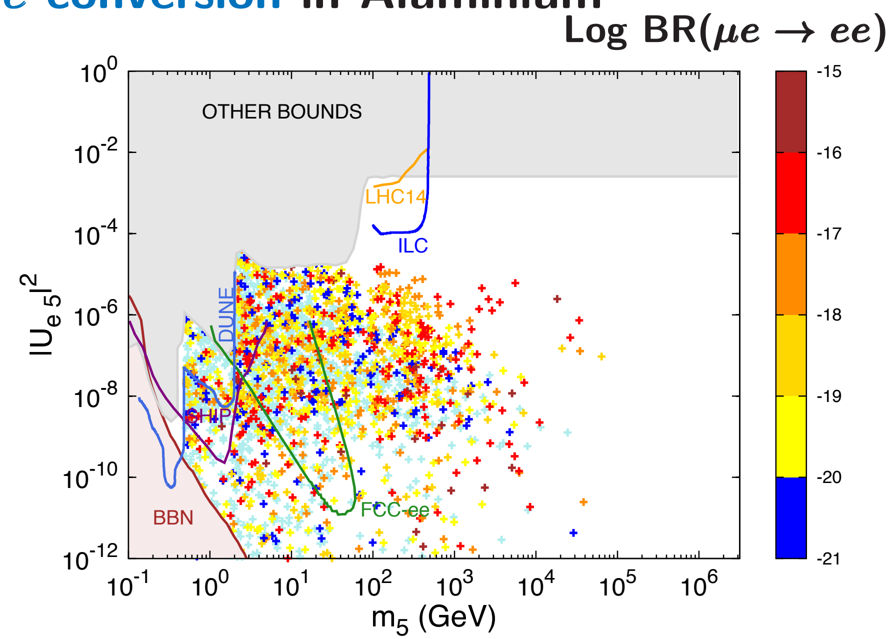


[Banerjee et al, 1503.05491]

Low scale: Inverse Seesaw (ISS)

- Addition of **3 "heavy" RH** neutrinos and **3 extra "sterile" fermions X** to the SM
- $\mathcal{M}^{9\times 9}_{\rm ISS} = \begin{pmatrix} 0 & Y_\nu v & 0 \\ Y_\nu^T v & 0 & M_R \\ 0 & M_R & \mu_X \end{pmatrix} \Rightarrow \begin{cases} \textbf{3 light } \nu : m_\nu \approx \frac{(Y_\nu v)^2}{(Y_\nu v)^2 + M_R^2} \mu_X \\ \textbf{3 pseudo-Dirac pairs} : m_{N^\pm} \approx M_R \pm \mu_X \end{cases}$
- **Non-unitarity $\tilde{U}_{\rm PMNS}$ $\Rightarrow$ modified neutral and charged leptonic currents**
- **New (virtual) states & modified couplings: cLFV,** non-universality, signals at colliders!
- **cLFV in muonic atoms: $\mu^- e^- \to e^- e^-$ vs $\mu - e$ conversion in Aluminium**

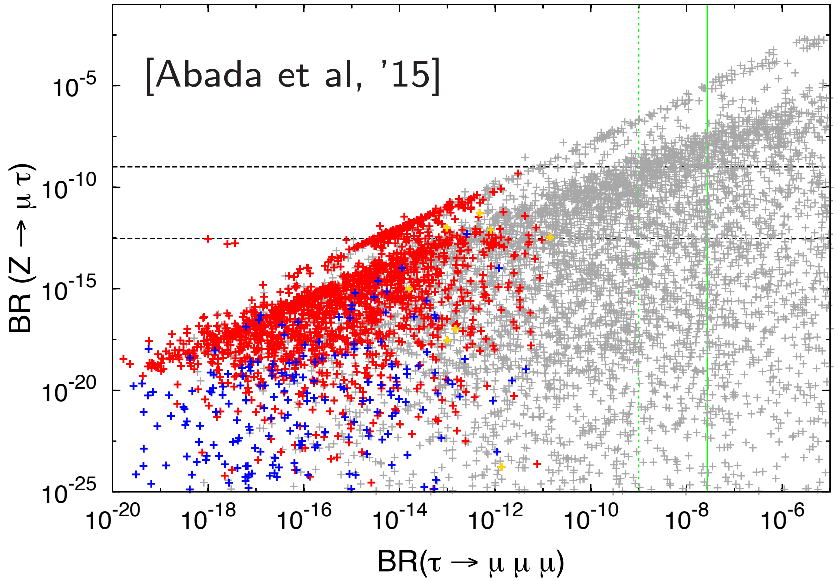




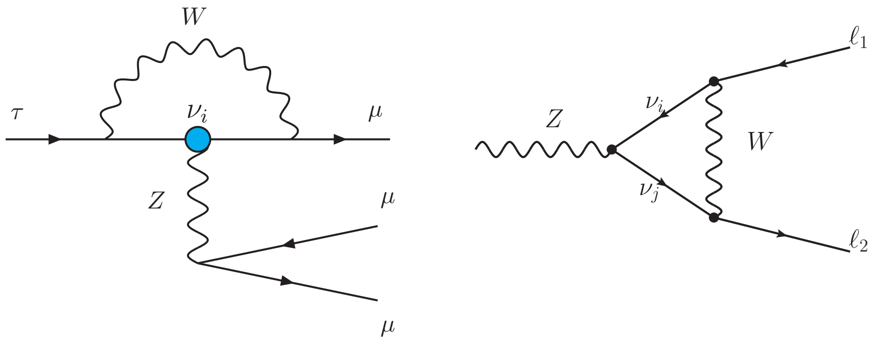
[Abada, DeRomeri, AMT, '15]

Low scale: Inverse Seesaw (ISS)

- **cLFV Z decays at FCC-ee vs 3 body decays $\ell_i \to 3\ell_j$**



- Dominated by Z **penguin** contributions



- Allows to **probe $\mu - \tau$ cLFV** beyond **SuperB reach**

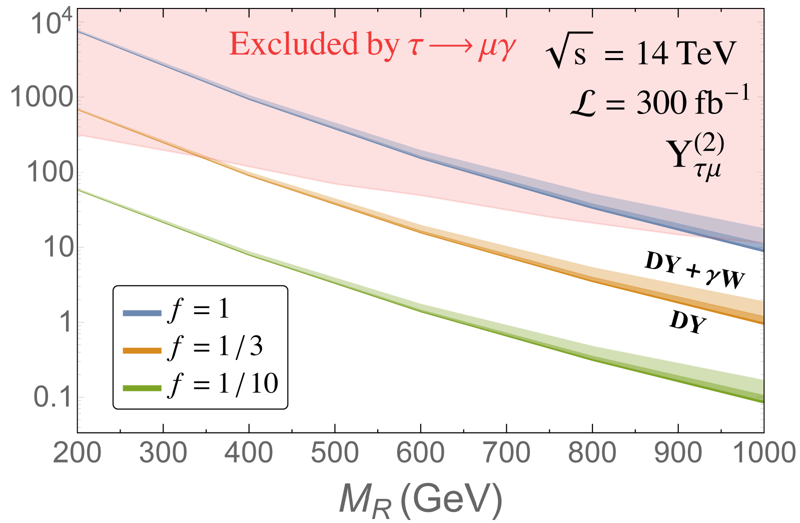
- **cLFV exotic events at the LHC**
  - Searches for **heavy N** at the LHC

$$q\,q' \to \tau\,\mu + 2\ \textbf{jets} \qquad \text{(no missing } E^T\text{!)}$$

  - After cuts, **significant number of events!**

- **cLFV Higgs decays: BR$(H \to \ell\tau) \lesssim 10^{-5}$..**

[Arganda et al, 1405.4300]



[Arganda et al, 1508.05074]

- **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...**

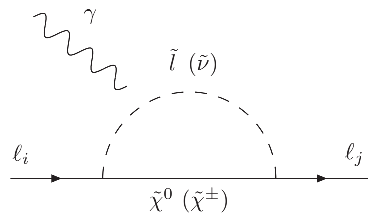
Still some **scenarios are falsifiable!**

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

SUSY seesaw: low-energy cLFV observables

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

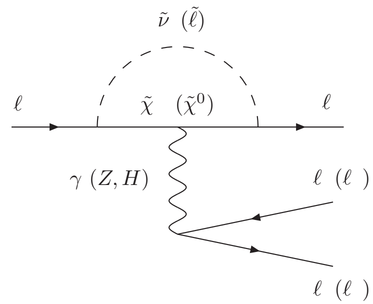
cLFV driven by the exchange of *virtual* **SUSY particles**



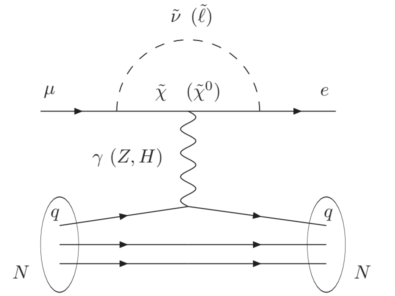
▶ **Flavour blind SUSY breaking: RGE running of Y^ν ($M_{\mathsf{GUT}} \to M_R$)**

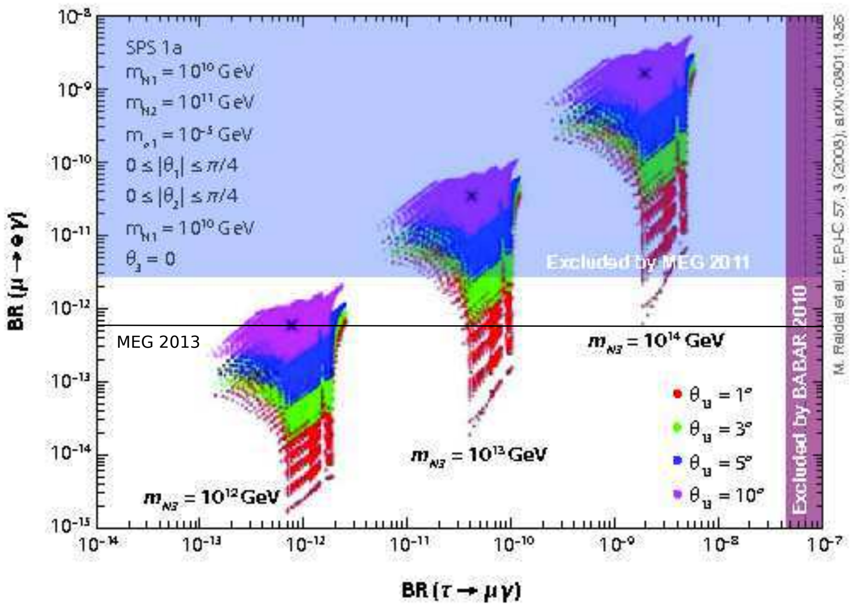
induces flavour-violating terms in slepton soft-breaking masses

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



▶ **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** $\leftrightsquigarrow$ *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 $\left\{ \right.$

- **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 $\left\{ \right.$

(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** $\chi_2^0 \to \ell_i\,\ell_j\,\chi_1^0$

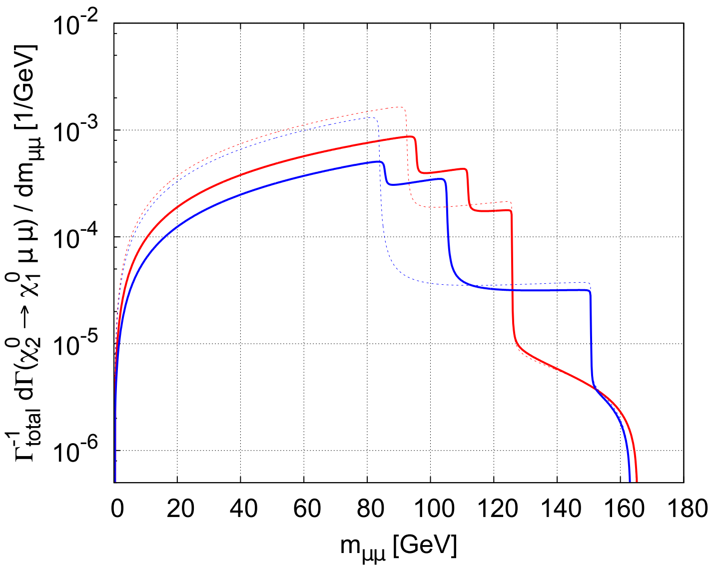
And many others: flavour violating Higgs decays, Lepton Number violating decays, etc ...

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

[Figueiredo and AMT, 1309.7951]

▶ Appearance of **new edge** in $m_{\mu\mu}$ **: intermediate** $\tilde{\tau}_2$

[$\rightsquigarrow$ flavour **violation!**]

▶ **LFV at the LHC:** $\chi_2^0 \to \tilde{\tau}_2\,\mu \to \chi_1^0\,\mu\,\mu$

- **Hints of an organising principle: additional symmetries**

Hints of a geometric principle: RS warped extra dimensions

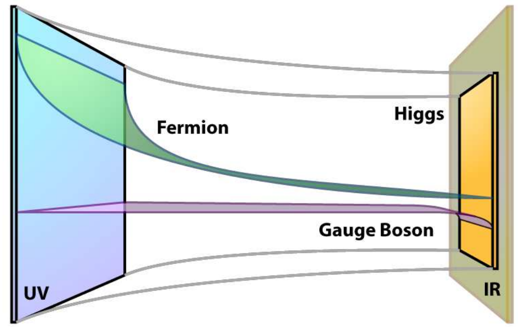
★ Embed **4dim space-time** into **5dim AdS space** (extra dim compactified on orbifold)

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

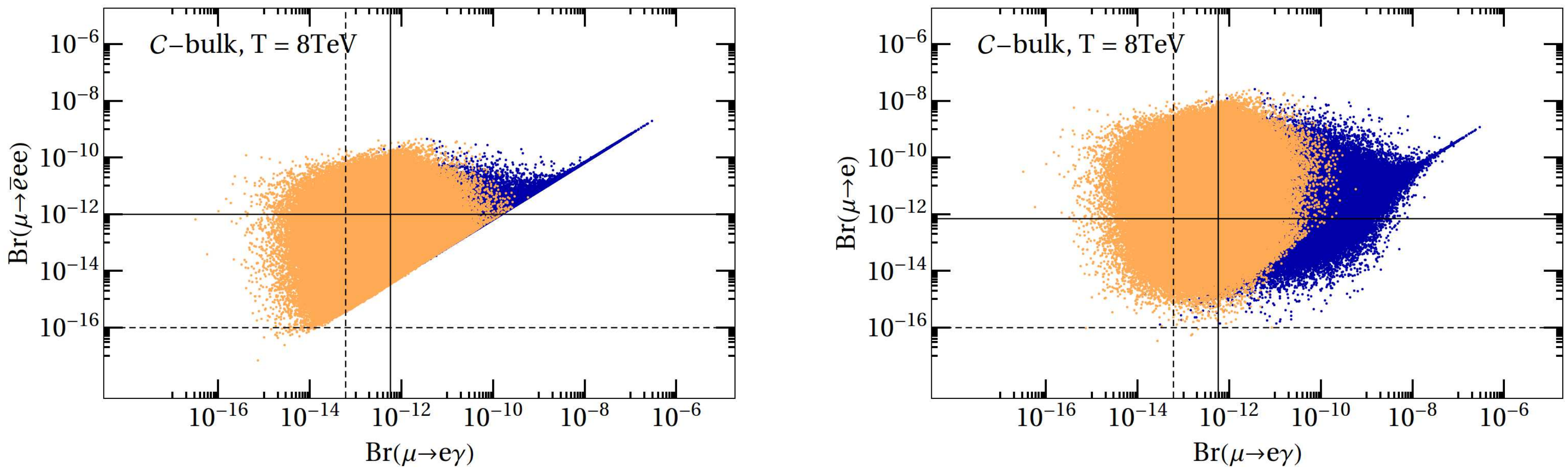
  additional **"rescue" ingredients** to **avoid excessive FCNCs,**

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

[Burdman '02; Agashe et al '04 -; Csaki et al '08; Blanke et al & Buras et al '08-'09;
Bauer et at, '10; Vempati et al, '12; Beneke et al, '12-'15]

Geometric cLFV: RS warped extra dimensions

- **Custodially protected model**; full inclusion of **all dim-6 operators**
- **Generic anarchic Yukawa couplings**
- cLFV processes mediated by **KK-lepton excitations, new gauge fields**



[Beneke et al, 1508.01705]

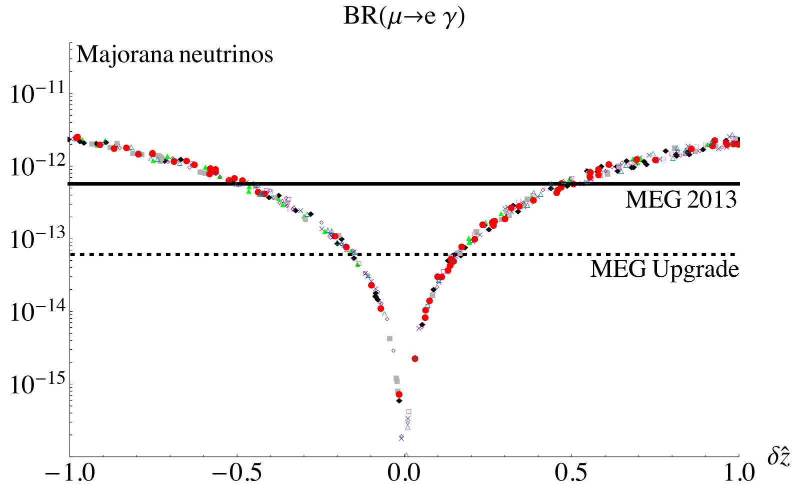
- Most **stringent constraints from $\mu \to e\gamma$ and $\mu - e$ conversion**

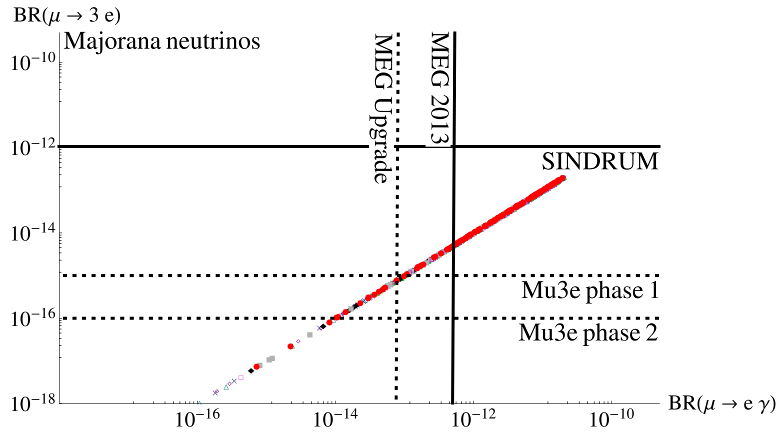
  τ **decays** comparatively less restrictive
- **Lower bounds on KK scales: 4 TeV** ($\rightsquigarrow$ 10 TeV for 1st KK-excitations)
- **Future cLFV sensitivities: exclude anarchic RS models** (without extra symmetries)

  up to **8 TeV** (KK gluon masses around 20 TeV)

Adding symmetry: composite Higgs and warped extra dims

- **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 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!**

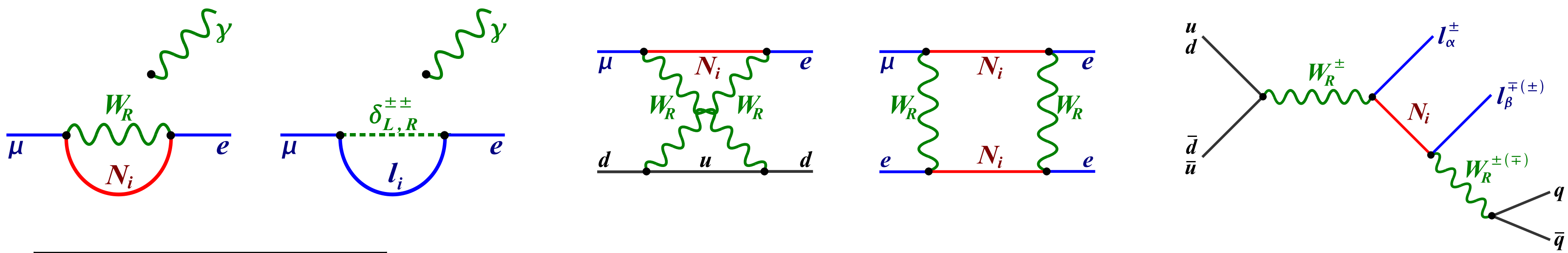
Hints of an organising principle: cLFV in Left-Right models

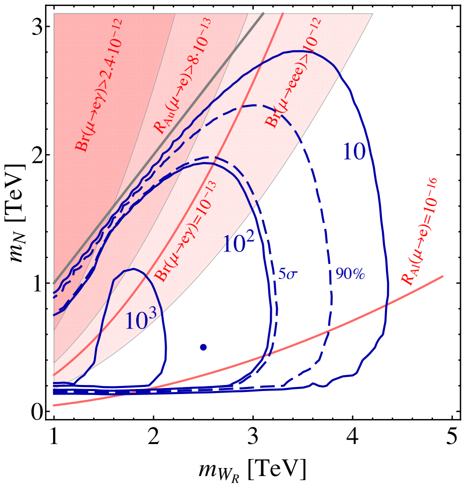
★ **Minimal Left-Right extension of the SM** (non-SUSY)

- 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 $pp \to W_R \to e^\pm \mu^\mp + 2$ 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**

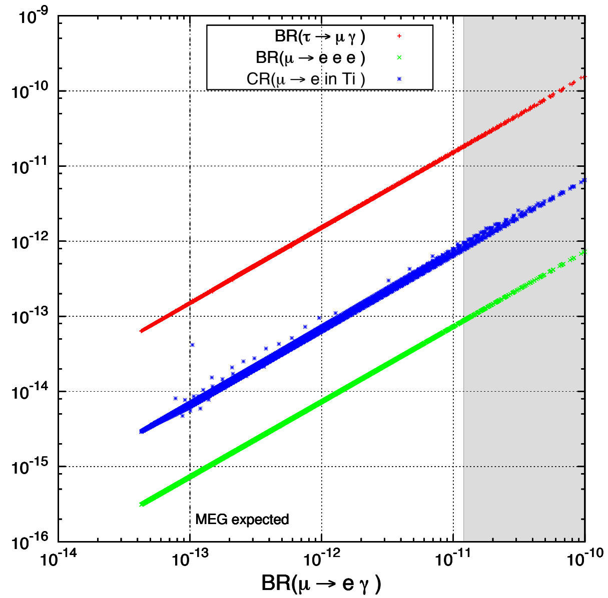
▶ **Reduce arbitrariness of Y^ν** [SO(10) CKM- and U_{PMNS}-inspired patterns..]

▶ **SO(10) type II SUSY seesaw example**

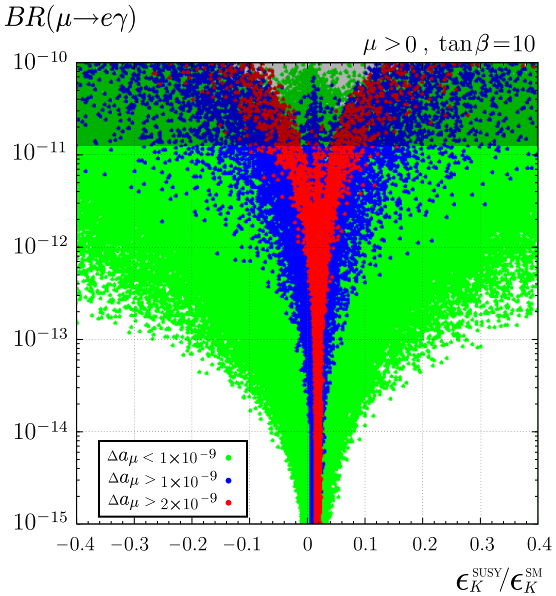
(leptogenesis motivated)

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?**

- **Xmas Workshop spirit:** roughly **1/2** of **1/2** of the **flavour questions...**

- **New Physics** can **be manifest via cLFV** even **before any direct discovery!**

  cLFV observables can provide (indirect) **information on the underlying NP model**

  Data from **cLFV** might even **exclude regimes/scenarios of SM extensions**

  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,**

  exploring diverse cLFV observables, of different origin, infer pattern/correlation

  $\Rightarrow$ **Unveil the underlying mechanism of flavour violation in the lepton sector!**

Discussion: the road ahead - "what if"s and "what then"s

- What if: cLFV from high-intensity experiments... and no NP at the LHC ?!
- What if: NP discovered at the LHC (maybe in lepton-like sector) and

  no cLFV at low-energies (near future) ?!

- What are the models accommodating these scenarios? Stick to m_ν models..?
- Can the scale of NP be very high? $\Lambda_{\text{cLFV}} > 10^{\text{several}}$ TeV?

  Can we accept that lepton flavour is only violated in neutrino oscillations??

- What then? Options for future colliders:

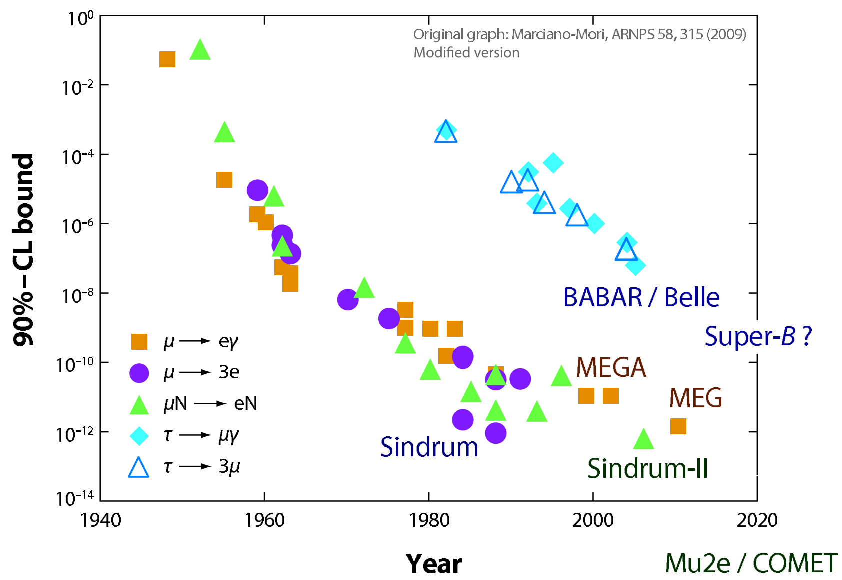
  100 TeV pp collider vs 3 TeV LC?

- Next generation of high-intensity machines!

  An unfathomable task:

  $\text{BR} \sim 10^{-18}\ldots \Rightarrow \sim 10^{-19}$ muons...

  as much as all the grains of sand in the world!



Happy Holidays!