# Lepton Flavor Violation and neutrino physics: beyond the Standard Model

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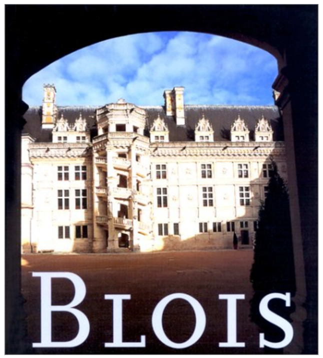


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# Beyond the Standard Model

- **Observations not accounted for** in the **Standard Model:**

  **Baryon asymmetry of the Universe;** **Dark matter component of the Universe**

  **Neutrino oscillations** (massive $\nu$s that mix)

- **Neutrino oscillations** provided the 1st laboratory **evidence of New Physics**

  $\Rightarrow$ **SM must be clearly extended** (or embedded in a larger framework)!

  Several **possible models** successfully **account for $\nu$ data**

  such extensions might even allow **to address SM caveats**

  hints to the **flavour puzzle ?** **BAU via leptogenesis ?** **DM candidates ?**

- Gateway to new **experimental signals** (deviation from SM) in the **lepton sector:**

  **Lepton Number Violation** (if **Majorana**) - **$0\nu2\beta$, meson decays, colliders, ...**

  **Lepton flavour universality violation** - weak boson and meson decays.. **(e.g. $R_K$)**

  **Electric dipole moments** and **Anomalous magnetic moments**

  **Violation of lepton flavour** - **in charged sector as well?**

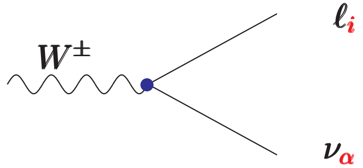
# LFV observables as a sign of New Physics

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

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

  **[Similar to quark sector?!?]**

Assume most minimal extension $\text{SM}_{m_\nu}$



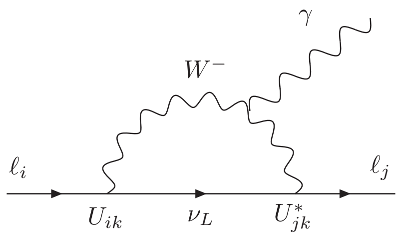

$\bullet \propto U^{\text{PMNS}}_{\alpha i}$

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

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

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

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




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

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

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

**Are neutral and charged LFV related?**

**Does cLFV arise from $\nu$-mass mechanism? Or entirely different nature?**

# 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

  Hints of an organising principle: LFV and symmetries

  $\Rightarrow$ **Models of neutrino mass generation (SM-like and larger frameworks)**

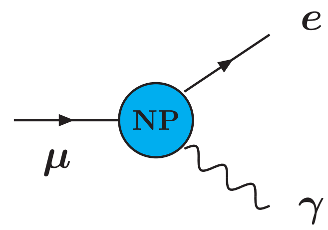
- **Overview & discussion**

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

# Signals of Lepton Flavour Violation

- **Neutrino oscillations** [$\nu$-dedicated experiments] [ ⇝ Review by **K. Scholberg** ]

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




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

  **nucleus 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]

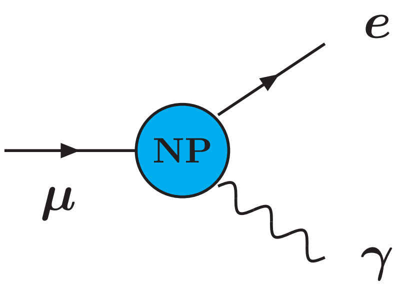
  **SM boson decays: $H \to \tau\mu$, $Z \to \ell_i \ell_j$**

  **SUSY $\tilde{\ell}_i \to \ell_j \chi^0$; FV KK-excitation decays; ...**

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

- And many others ... **all absent in the SM!**

# cLFV in muon channels: radiative decays




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

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

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

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

  **Accidental:** coincidence of $\gamma$ 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 $[\propto R_\mu^2]$

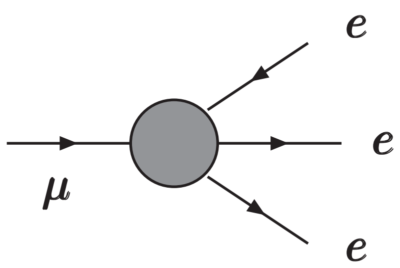
- **Current status:**

| Collaboration | year | BR($\mu \to e\gamma$) 90% C.L. |
|---|---|---|
| LAMPF/MEGA | 1999 | $1.2 \times 10^{-11}$ |
| PSI/MEG | 2011 | $2.8 \times 10^{-11}$ |
| **PSI/MEG** | **2016** | $\mathbf{4.2 \times 10^{-13}}$ |

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

  common vertex; Time coincidence

- **Backgrounds** ⇒ physics & accidental

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

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

- **Current status:**

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

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

  **Phase I ($\sim$ 2017): $10^{-15}$** ($\pi$E5 $\mu$ source) ⇒ **Phase II ($>$ 2018): $10^{-16}$** (H.I. $\mu$-beam)

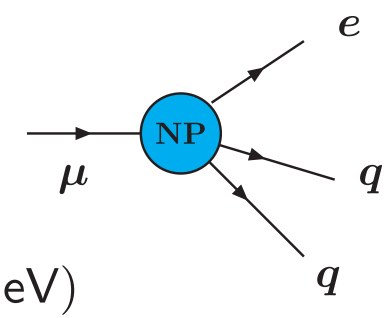
# cLFV in "muonic" atoms: $\mu - e$ conversion

- **Muonic atoms:** 1s bound state formed when $\mu^-$ stopped in target

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

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




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

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

- **Backgrounds** $\Rightarrow$ only **physics** (e.g. $\mu$ 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) | $\mathbf{10^{-18}}$ | |
| DeeMe (SiC) | $10^{-14}$ | |

# cLFV in "muonic" atoms: Coulomb enhanced decays

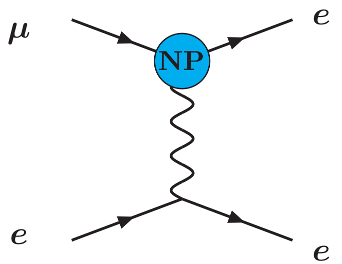
- **Muonic atom decay:** $\boldsymbol{\mu^- e^- \to e^- e^-}$ [Koike et al, '10]

  Initial $\mu^-$ **and** $e^-$**: 1s** state bound in Coulomb field of the **muonic atom's nucleus**

- **Coulomb interaction** increases overlap between

  $\Psi_{\mu^-}$ and $\Psi_{e^-}$ wave functions

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



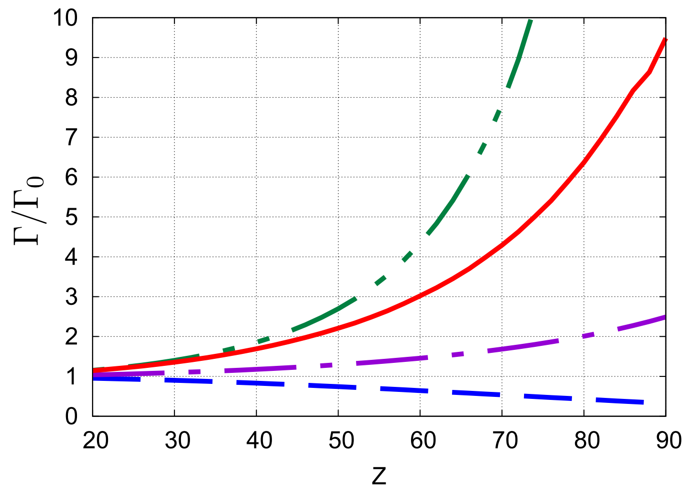

- **Clean experimental signature:** back-to-back electrons, $E_{e^-} \approx m_\mu/2$

  larger phase space than $\boldsymbol{\mu \to 3e}$

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

  $\boldsymbol{\Gamma/\Gamma_0 \gtrsim (Z-1)^3}$ [Uesaka et al, '15-'16]

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




- **Experimental status: New observable!**

  Hopefully included in **COMET**'s Physics 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:** $\boldsymbol{\tau^\pm \to \ell^\pm \gamma}$
  - **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 $\gamma$ (ISR, FSR); mistagging

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

- **3-body decays:** $\boldsymbol{\tau^\pm \to \ell_i^\pm \ell_j^\mp \ell_k^\pm}$
  - **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...

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

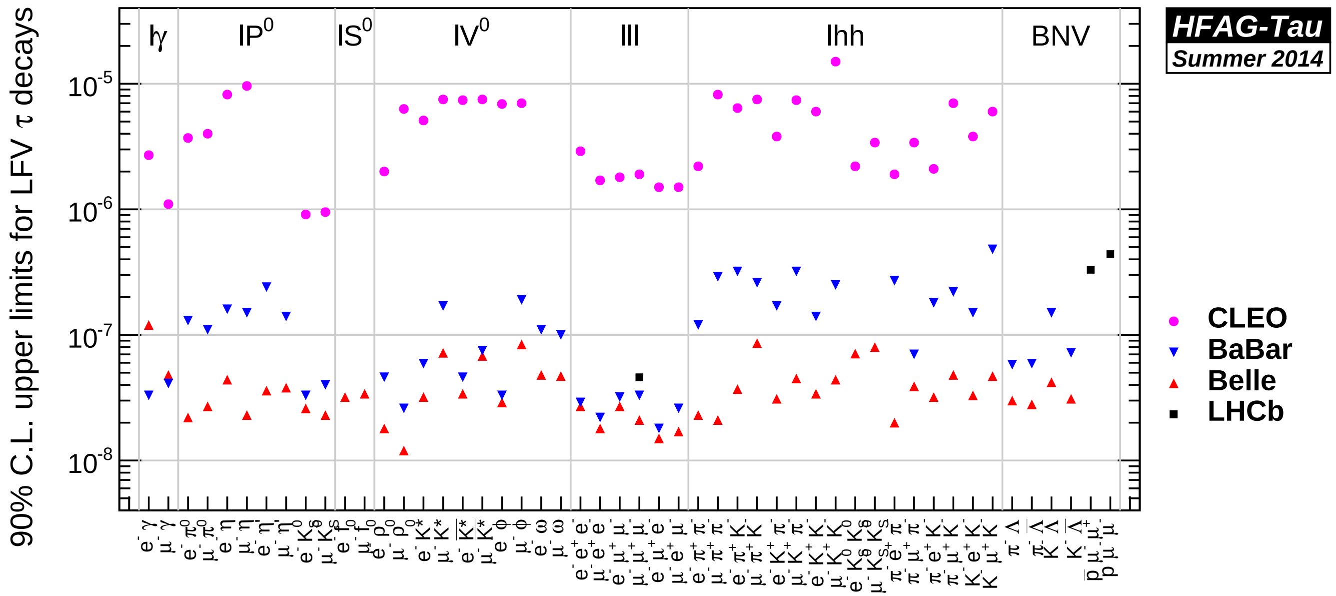
- **Future experimental prospects: SuperB (SuperBelle) and/or Tau-Charm factories**

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

# Rare processes: (semi)leptonic decays

**cLFV tau decays into mesons:** "large" $\tau$ mass $\Rightarrow$ possible to have semi-leptonic decays

- **Meson(s) & charged lepton:** $\tau \to \ell h^0$; $\quad \tau \to \ell h_i h_j$
- **cLFV exotic modes:** $\tau^- \to \ell^+ h_i^- h_j^-$; $\quad \tau \to p \mu \mu$




**Meson decays:** excellent testing grounds for lepton flavour dynamics - **cLFV** & **LNV**

- **$K$, $D$ and $B$ meson decays:** **abundant data [LHCb, BNL, KTeV, BaBar, Cleo, Belle, ...]**

$$\text{BR}(K_L \to \mu e) < 4.7 \times 10^{-12}; \quad \text{BR}(K^+ \to \pi^+ \mu^+ e^-) < 2.1 \times 10^{-11}$$

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

# cLFV collider signatures: “heavy” SM & NP decays

- **$Z$ boson decays: $Z \to \ell_i \ell_j$** $\rightsquigarrow$ $Z$s abundantly produced at **LEP** and at the **LHC**
  - **Current bounds:** $\text{BR}(Z \to e\mu) < 7.5 \times 10^{-7}$ [ATLAS, 2014]

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

- **Higgs boson decays: $H \to \ell_i \ell_j$** $\rightsquigarrow$ “Higgs-factory” at LHC - study rare processes...
  - **Current data:** $\mathbf{BR}(H \to \mu\tau) \approx 0.84\%$ [CMS] **Possible cLFV “hint” @ $2.6\sigma$???...**

- **Production of “on-shell” NP states** $\Rightarrow$ **new interactions** induce cLFV **decays**

  Multiplicity, composition, $E_{\text{miss}}$, ...: properties of final state strongly model-dependent...

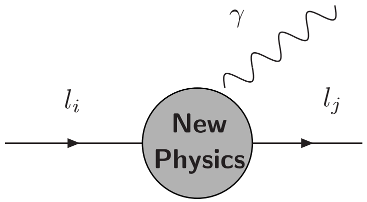
- **Future experimental prospects:** **Exciting ones from LHC Run 2 !!**

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

- **After the experiments: which NP model of cLFV?**

# 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$_{m_\nu}$) + **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

## ▶ cLFV: effective approach

# cLFV: the effective approach

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

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

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

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

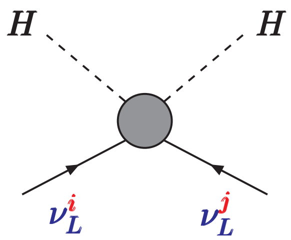
$\Lambda$ : **scale of new physics**

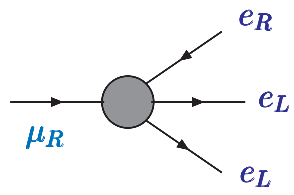
$\mathcal{C}^n$ : **dimensionless couplings** - coupling constants, Yukawas, loop factors $((4\pi)^m)$, ...

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

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

# cLFV: the effective approach

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

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

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

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

  a unique operator $\mathcal{O}^5_{ij} \sim (L_i\, H)(H\, L_j)$

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

  **3 "types" of operators** relevant for **cLFV**

  **Dipole:** $\mathcal{O}^6_{\ell_i \ell_j \gamma} \sim L_i \sigma^{\mu\nu} e_j H F_{\mu\nu}$ **radiative decays** $\ell_i \to \ell_j \gamma$

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

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

  **Vector/scalar:** $\mathcal{O}^6_{HH\ell_i \ell_j} \sim (H^\dagger i \overleftrightarrow{D}_\mu H)(\ell_i \gamma_\mu \ell_j)$ **3-body decays** $\ell_i \to \ell_j \ell_k \ell_l$, ...

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

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

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

Hypotheses on:

1. **size** of **"new couplings"**

   $\Rightarrow$ **Natural couplings**

   $\mathcal{C}^6_{ij} \sim \mathcal{O}(1)$

2. **scale** of **"new physics"**

   $\Rightarrow$ **Natural scale** - delicate..

   direct discovery $\Lambda \sim$ TeV

| Effective coupling (example) | Bounds on $\Lambda$ (TeV) (for $\lvert\mathcal{C}^6_{ij}\rvert = 1$) | Bounds on $\lvert\mathcal{C}^6_{ij}\rvert$ (for $\Lambda = 1$ TeV) | Observable |
|---|---|---|---|
| $\mathcal{C}^{\mu e}_{e\gamma}$ | $6.3 \times 10^4$ | $2.5 \times 10^{-10}$ | $\mu \to e\gamma$ |
| $\mathcal{C}^{\tau e}_{e\gamma}$ | $6.5 \times 10^2$ | $2.4 \times 10^{-6}$ | $\tau \to e\gamma$ |
| $\mathcal{C}^{\tau\mu}_{e\gamma}$ | $6.1 \times 10^2$ | $2.7 \times 10^{-6}$ | $\tau \to \mu\gamma$ |
| $\mathcal{C}^{\mu eee}_{\ell\ell,ee}$ | $207$ | $2.3 \times 10^{-5}$ | $\mu \to 3e$ |
| $\mathcal{C}^{e\tau ee}_{\ell\ell,ee}$ | $10.4$ | $9.2 \times 10^{-5}$ | $\tau \to 3e$ |
| $\mathcal{C}^{\mu\tau\mu\mu}_{\ell\ell,ee}$ | $11.3$ | $7.8 \times 10^{-5}$ | $\tau \to 3\mu$ |
| $\mathcal{C}^{\mu e}_{(1,3)H\ell}, \mathcal{C}^{\mu e}_{He}$ | $160$ | $4 \times 10^{-5}$ | $\mu \to 3e$ |
| $\mathcal{C}^{\tau e}_{(1,3)H\ell}, \mathcal{C}^{\tau e}_{He}$ | $\approx 8$ | $1.5 \times 10^{-2}$ | $\tau \to 3e$ |
| $\mathcal{C}^{\tau\mu}_{(1,3)H\ell}, \mathcal{C}^{\tau\mu}_{He}$ | $\approx 9$ | $\approx 10^{-2}$ | $\tau \to 3\mu$ |

[Feruglio et al, 2015]

- **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 **$\Lambda$ is low...**
  - **multiple "new physics" scales:** $\mathcal{L}^{\text{eff}} = \mathcal{L}^{\text{SM}} + \frac{1}{\Lambda_{\text{LNV}}}\, \mathcal{C}^5(m_\nu) + \frac{1}{\Lambda^2_{\text{LFV}}}\, \mathcal{C}^6(\ell_i \leftrightarrow \ell_j) + \ldots$

- **New Physics models: cLFV**

# Models of New Physics

- Models of **New Physics** can lead to "observable cLFV", introducing:

  **(i) new sources of flavour violation** (corrections to SM vertices, new SM-NP interactions)

  **(ii) new Lorentz structure** other than "standard" interactions ⇒ **new operators**

- Little hints on **preferred NP model;** most lead to **extensive ranges** for cLFV observables...

- **cLFV** can be a powerful probe to **test NP realisations!** Some examples...

  **Generic cLFV extensions of the SM** - supersymmetric (SUSY) extensions of the SM

  **"Geometric" cLFV** - extra dimensional Randall-Sundrum models

  **cLFV and compositness** - Little(st) Higgs; Holographic composite Higgs;...

  **Simple SM extensions and cLFV** - Multi-Higgs doublet, Leptoquarks, additional $Z'$, ...

  **Additional symmetries and cLFV** - Flavour symmetries; Left-Right symmetric models;

  - Extended gauge groups and GUTs

# Models of New Physics and cLFV: some examples

- **cLFV** can be a powerful probe to **test NP realisations!** Some examples...

**cLFV from $\nu$-mass generation** - **Standard seesaws** [type I, type II, type III]

**(little impact from high-scale realisations)**

- **Low scale seesaws** (rich cLFV phenomenology!)

**Low-scale type I, $\nu$MSM, ...**

**Inverse Seesaw (ISS)**

- **Extended frameworks:** embeddings into RS, ...

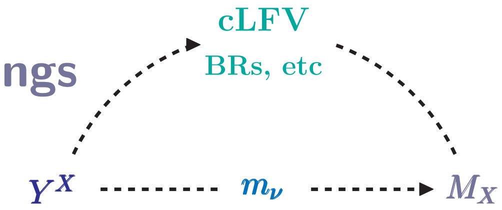
**SUSY seesaw**

[ $\rightsquigarrow$ Review by **S. King** for $\nu$-mass models!]

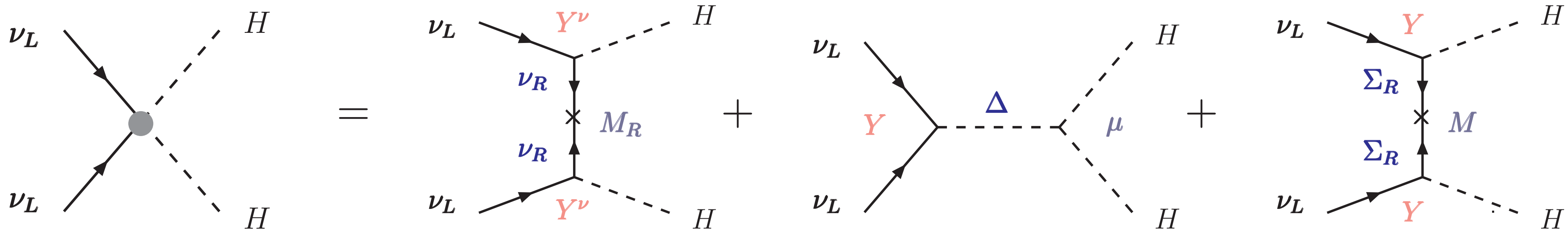
- **cLFV** can provide **valuable hints** on the underlying mechanism of **$\nu$-mass generation**

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

# cLFV and the seesaw mechanism




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




| $\frac{1}{\Lambda} L\, L\, H\, H$ | $\nu_R$ (fermion singlet) | $\Delta$ (scalar triplet) | $\Sigma_R$ (fermion triplet) |
|---|---|---|---|
| **"Seesaw mechanism"** | **Type I** | **Type II** | **Type III** |

▶ **LFV observables:** depend on **powers of $Y^\nu$** $\rightsquigarrow$ large rates $\Rightarrow$ sizable $Y^\nu$
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!**

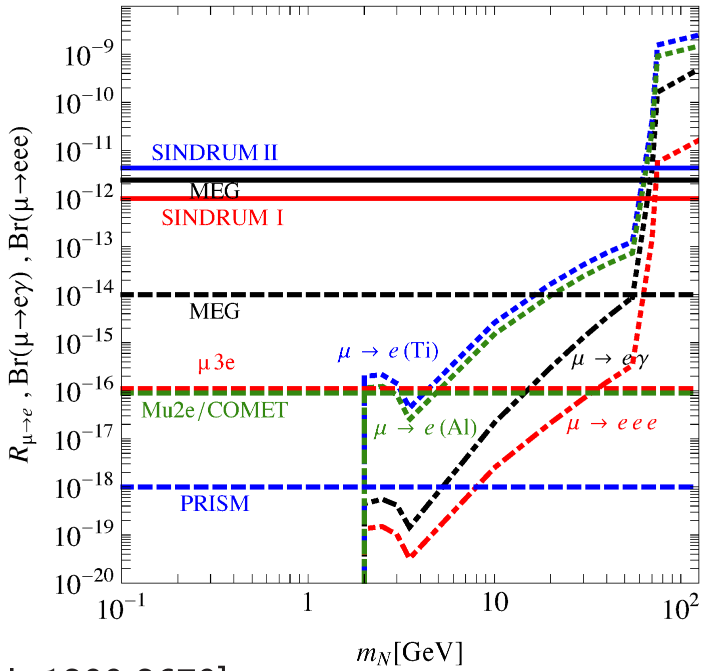
# Low scale type I seesaw

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

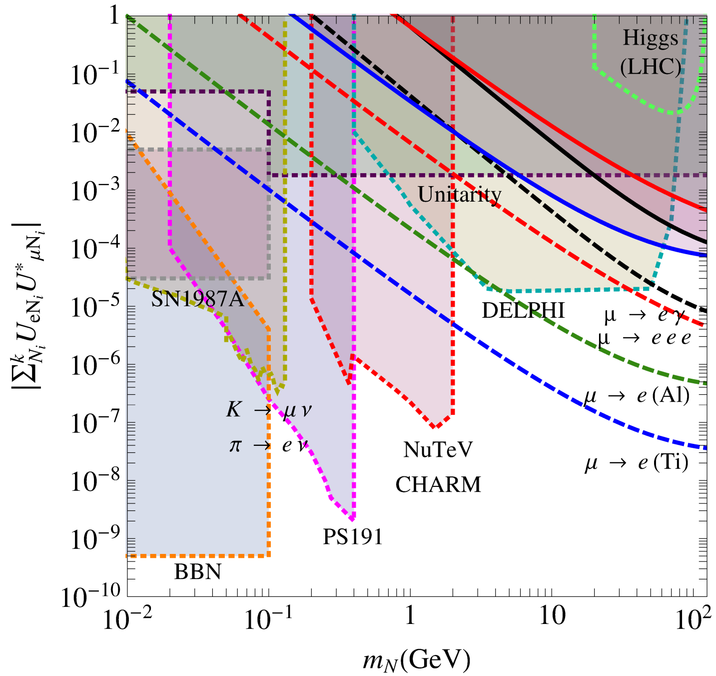
$$U = \begin{pmatrix} U_{\nu\nu} & U_{\nu N} \\ U_{N\nu} & U_{NN} \end{pmatrix} \qquad U_{\nu\nu} \approx (1-\varepsilon)\, U_{\text{PMNS}}$$

**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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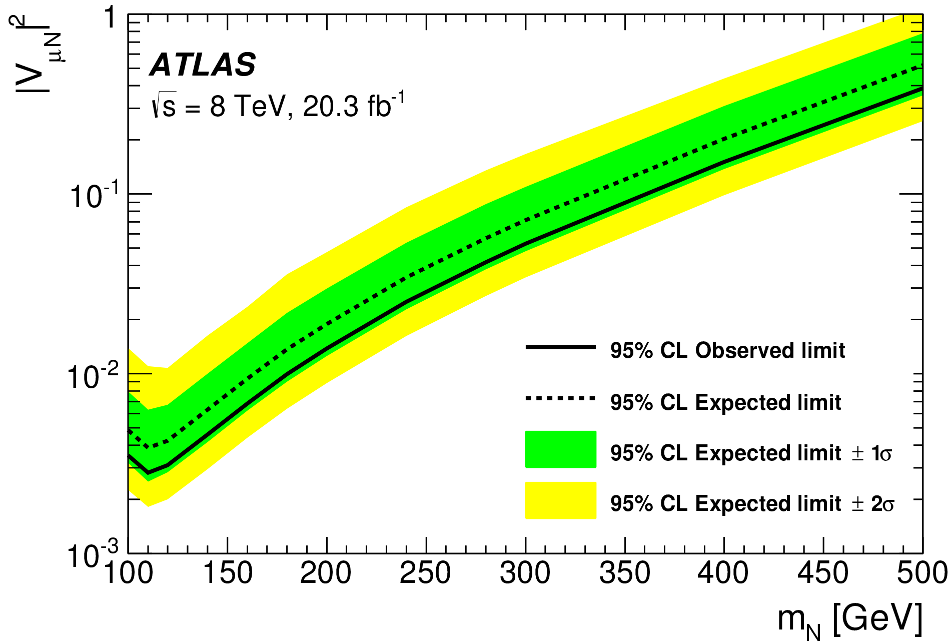
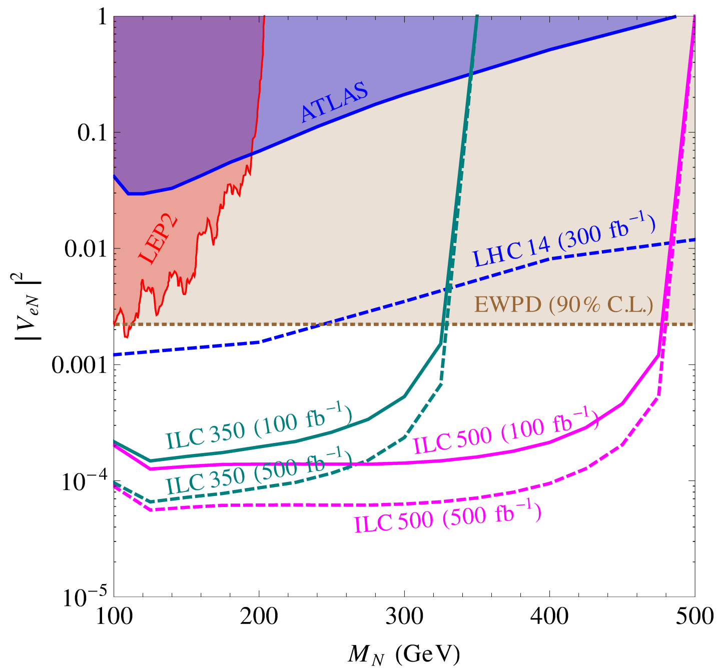


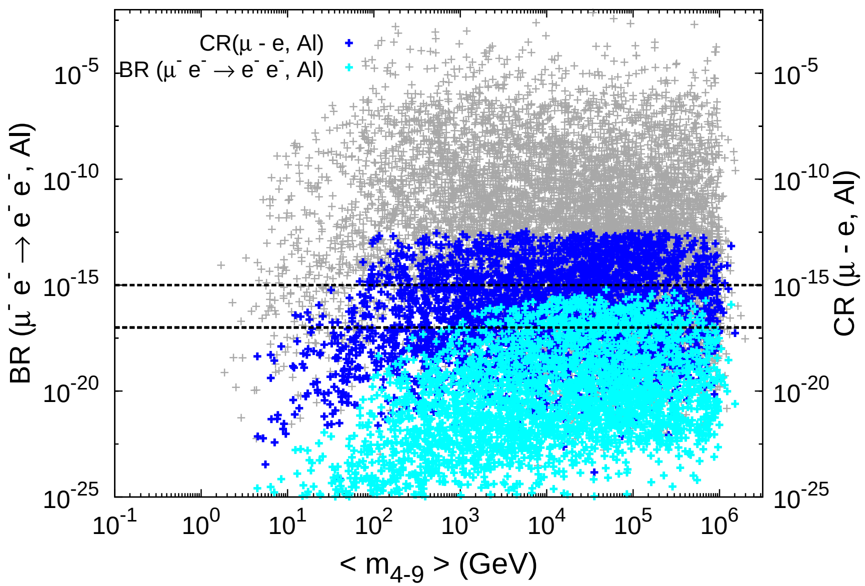

[ATLAS Collab., 1506.06020]

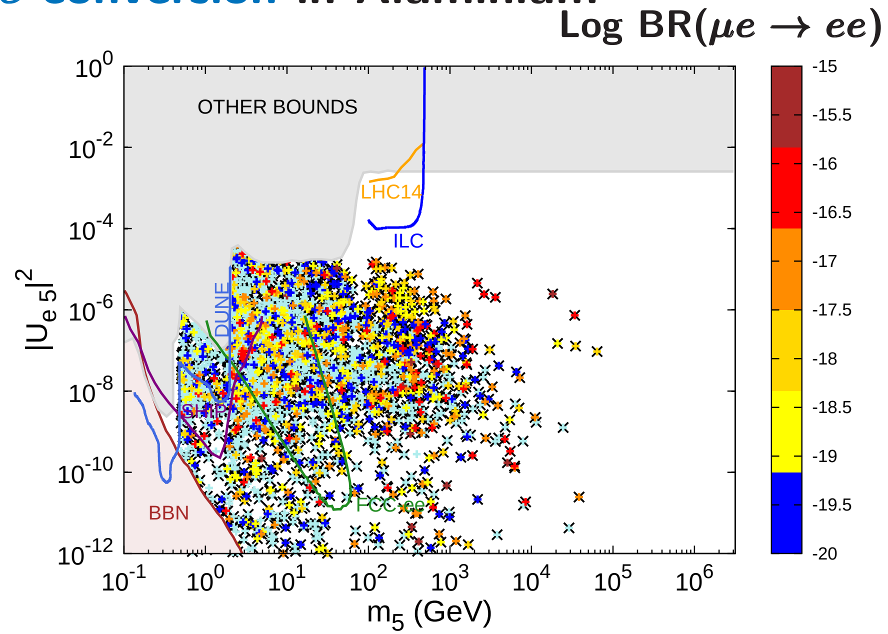



[Banerjee et al, 1503.05491]

# Low scale: Inverse Seesaw (ISS)

- Addition of **3 "heavy" RH** neutrinos and **3 extra "sterile" fermions $X$** to the SM
- $\mathcal{M}^{9\times 9}_{\text{ISS}} = \begin{pmatrix} 0 & Y_\nu v & 0 \\ Y_\nu^T v & 0 & M_R \\ 0 & M_R & \mu_X \end{pmatrix} \Rightarrow \begin{cases} \textbf{3 light } \nu : m_\nu \approx \frac{(Y_\nu v)^2}{(Y_\nu v)^2 + M_R^2} \mu_X \\ \textbf{3 pseudo-Dirac pairs} : m_{N^\pm} \approx M_R \pm \mu_X \end{cases}$
- **Non-unitarity $\tilde{U}_{\text{PMNS}}$ $\Rightarrow$ 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**

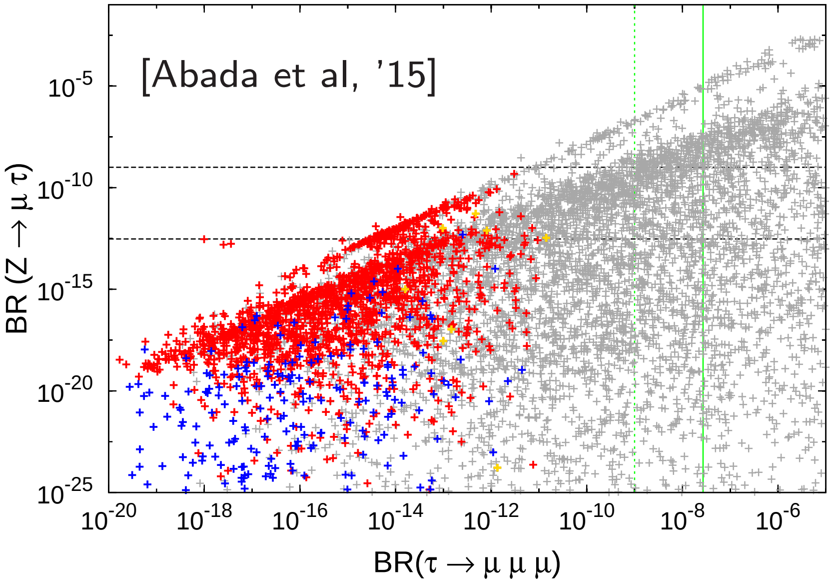


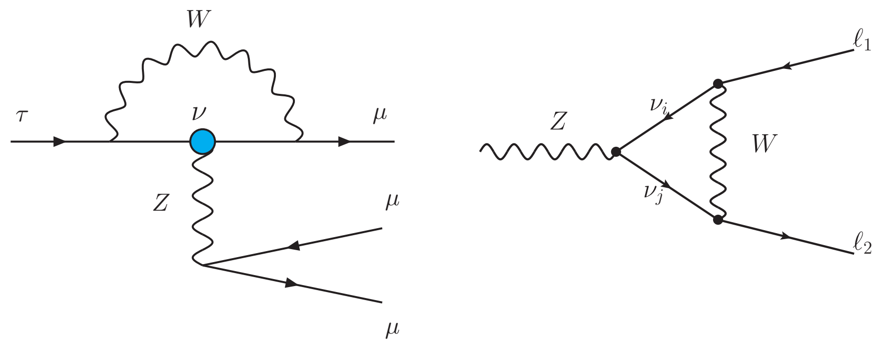

[Abada, DeRomeri, AMT, '15]

# 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

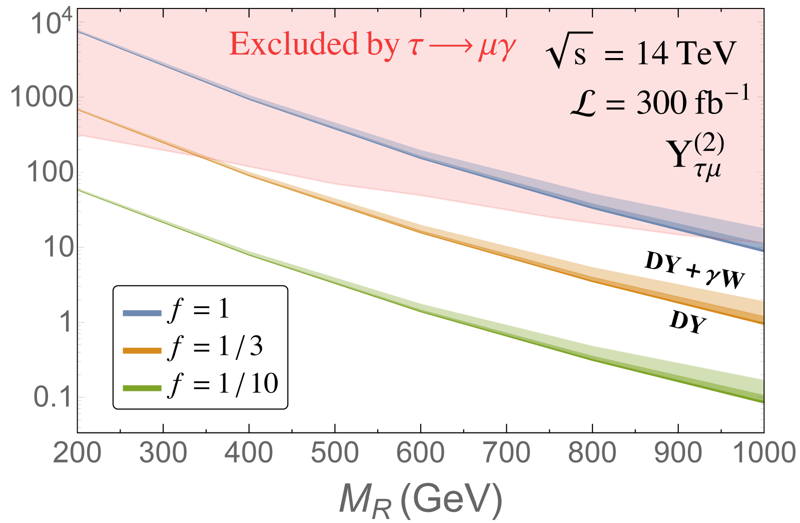



- Allows to **probe $\mu - \tau$ cLFV** beyond **SuperB reach**

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

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

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




[Arganda et al, 1508.05074]

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

[Arganda et al, 1405.4300]

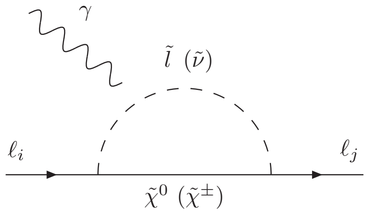
- **cLFV from $\nu$ mass in extended frameworks - SUSY seesaw**

# SUSY seesaw: cLFV at low- and high energies

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

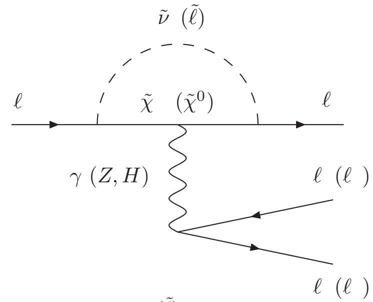
- **Large $Y^\nu$: sizable contributions to cLFV observables**

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

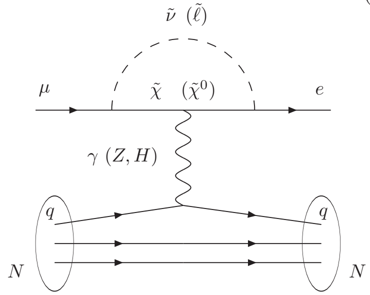


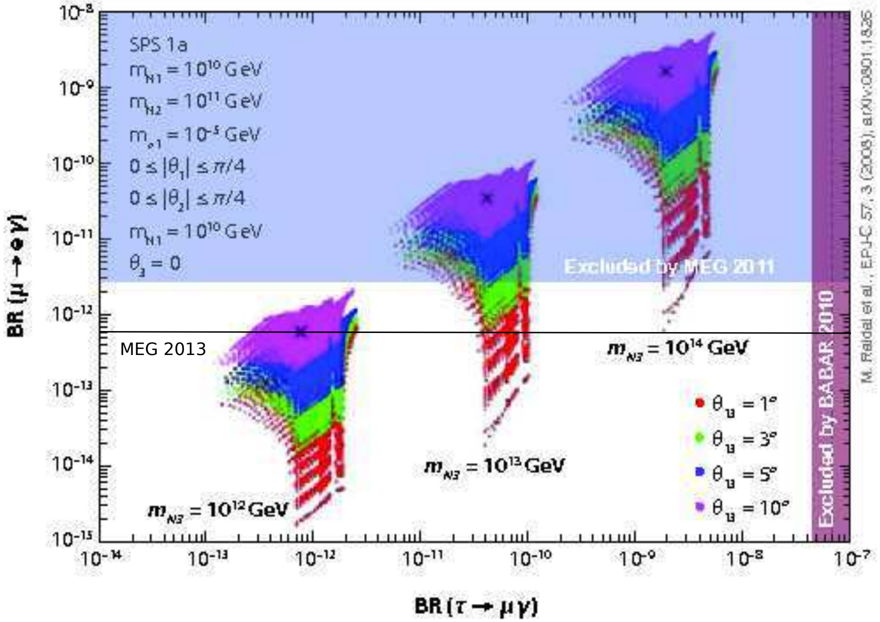

- **Flavour blind SUSY breaking: RGE running of $Y^\nu$** $(M_{\text{GUT}} \to M_R)$

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




- **$Y^\nu$ unique source of FV: all observables strongly related**




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

- **Synergy of low-energy observables**

  **$\Rightarrow$ hints on seesaw scale $M_R$!**

  **$\Rightarrow$ disfavour the model**

# SUSY seesaw: cLFV at low- and high energies

- **High-energy colliders: direct access to slepton sector** $\rightsquigarrow$ *on-shell* $\tilde{\ell}$
- **cLFV** in **SUSY neutral current** interactions $\chi^0$ - $\tilde{\ell}_i$ - $\ell_j$

**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"** $e^-e^- \to \mu^-\mu^- + 2\chi^0$

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

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

# SUSY seesaw: cLFV at low- and high energies

- **High-energy coliders: direct access to slepton sector** $\leftrightsquigarrow$ *on-shell* $\tilde{\ell}$
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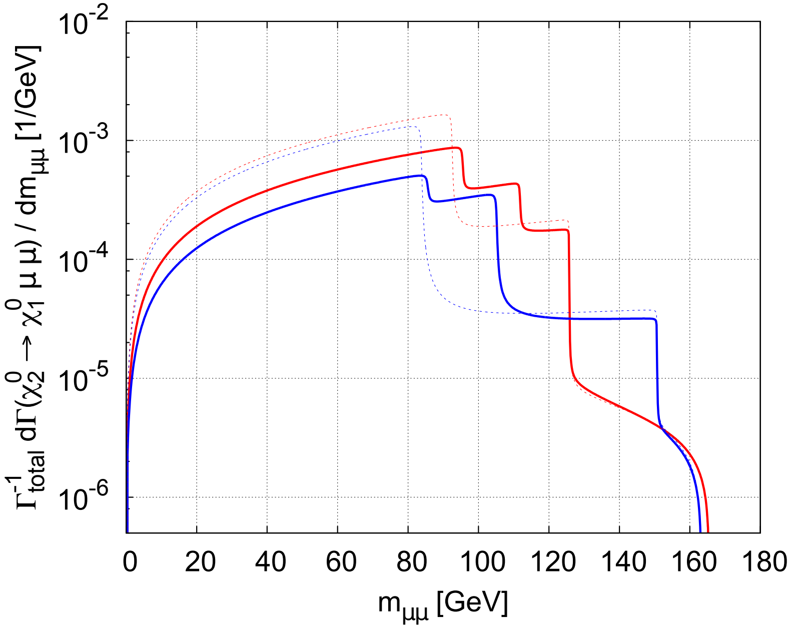
**LHC:** $\chi_2^0 \to \ell^\pm \ell^\mp + E_{\text{miss}}^T$ cascades - **new edges in dilepton mass distributions** $m_{\ell\ell}$




[Abada, Figueiredo, Romão, AMT, '10]

- **Flavour conserving case:**

  Double triangular distributions (2 edges)

  $$\chi_2^0 \to \tilde{\mu}_{L,R}\, \mu \to \chi_1^0\, \mu\, \mu$$

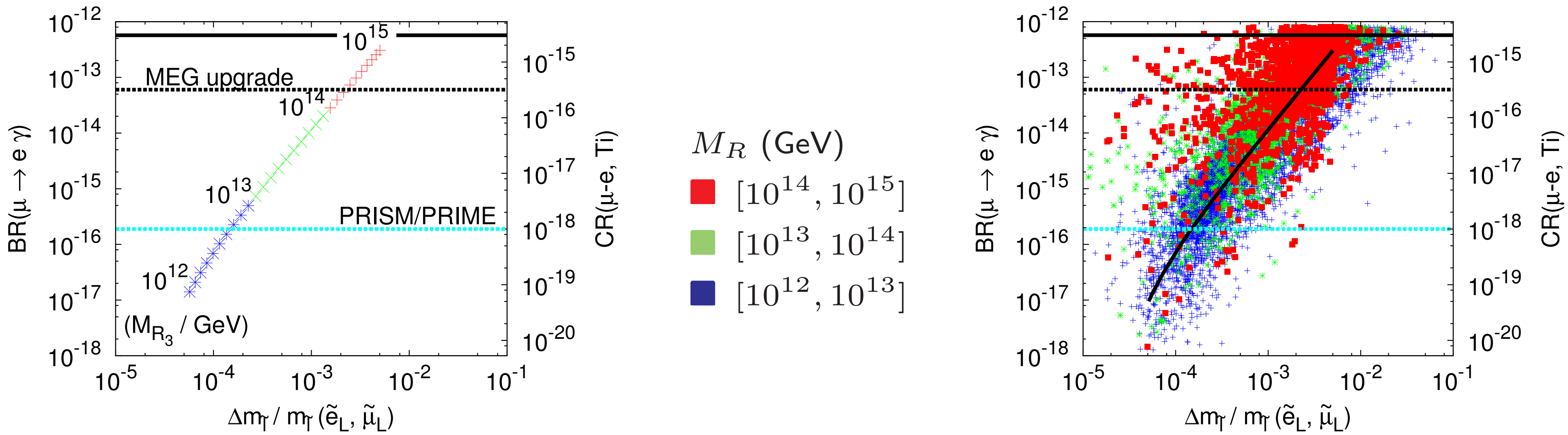
- **cLFV:** in parallel to other observables...

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

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

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

# SUSY seesaw: cLFV at low- and high energies




*"Type I SUSY seesaw post LHC run 1 and MEG"* [Figueiredo and AMT, '13]

- **Synergy** of **high- and low-energy observables** - **probe the SUSY seesaw!**

- **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 $\mu \to e\gamma|_{\text{MEG}}$ ✘: **disfavours SUSY seesaw hypothesis**

- **"Compatible" cLFV observations** $\Rightarrow$ **strengthen SUSY 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**

- **Concluding remarks**

# Charged lepton flavour violation: outlook

- **Flavour violation observed in quarks & neutral leptons...**

  why should **Nature "conserve" charged lepton flavour?**

- **Confirmed observations** and several **"tensions"** suggest the need to go **beyond the SM**

  In the lepton sector, **$\nu$-masses** provided the 1st laboratory **evidence of NP**

  Many experimental **"tensions"** nested in **lepton-related observables**

- **Lepton physics** might offer valuable hints in **constructing and probing NP models**

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

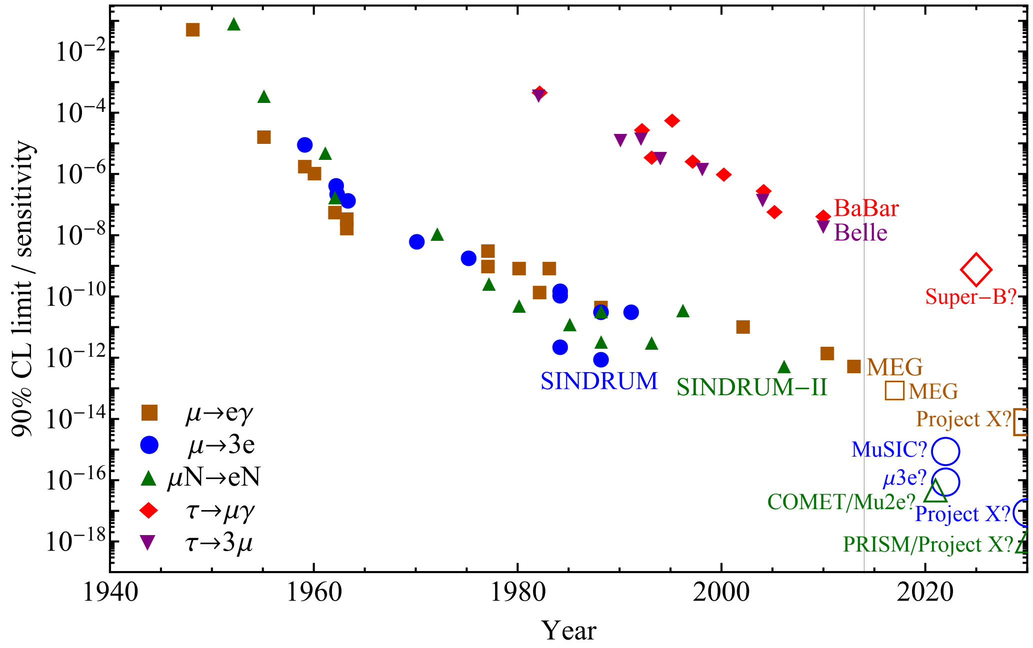
  **cLFV observables** can provide (indirect) **information on the underlying NP model**

# Charged lepton flavour violation: outlook

- ▶ **Lepton sector** of **BSM remains comparatively unexplored...**

  Numerous observables are being addressed: massive **experimental effort**

  closely followed by **theoretical studies and phenomenological analyses**




⇒ **Unveil the underlying mechanism of flavour violation in the lepton sector!**