Lepton flavour violation at high energies: the LHC and a Linear Collider

Ana M. Teixeira

Laboratoire de Physique Corpusculaire, LPC - Clermont

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Flavour violation in the SM

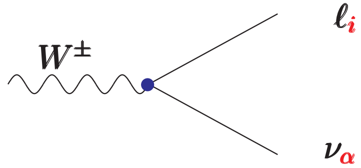
- **Quark sector:** **flavour** violated by **charged current** interactions $V_{ij}^{\text{CKM}} W^{\pm} \bar{q}_i q_j$

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

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

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

Charged currents violate lepton flavour!

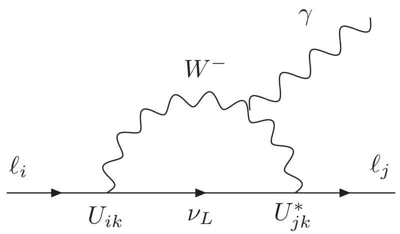


$\bullet \propto U_{\alpha i}^{\text{PMNS}}$

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

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

SM_{m_ν} - **cLFV possible??**



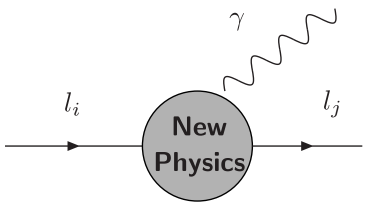
$$\text{BR}(\mu \to e\gamma) \propto \left| \sum U_{\mu i}^* U_{ei} \frac{m_{\nu_i}^2}{M_W^2} \right|^2 \sim 10^{-54}$$

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

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

LFV: which New Physics ?

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



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

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 ...)

Examples:

Generic cLFV extensions - general MSSM, LHT, RS, 4th generation, ...

cLFV from m_ν
- SM seesaw (TeV scale) - type II & inverse seesaw
- Extended frameworks - SUSY seesaw, GUTs, ...

cLFV: models of New Physics

- **All SM extensions** introduce **new particles**, **new flavour violating** couplings..
- Most **models predict/accommodate** extensive **ranges for observables**

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

- **cLFV** plays a **complementary rôle** to **direct searches:**
  - In the **absence** of **cLFV** (and other) **signals:**

    $\Rightarrow$ **constraints on parameter space (scale and couplings)**
  - **cLFV observed: compare with peculiar features of given model**

    $\Rightarrow$ **predictions** for **cLFV observables**

    $\Rightarrow$ **intrinsic patterns** of **correlations of observables**

Lepton Flavour Violation: Observables

- Many **candidate observables!** *(No SM theoretical background!)*

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

  - **Meson decays: violation of lepton flavour universality, LFV final states**

    lepton Number violating decays **[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, $H \to \tau\mu$, ...

    Impact of LFV for new physics searches at colliders, ...

  - Leptonic angular distributions; P- and T-odd asymmetries; leptonic CP violation, ...

Our approach ...

- **Consider a high-scale, type I seesaw mechanism**

  embedded into flavour conserving SUSY models

- **Address potential cLFV signals at colliders - LHC and LC**

  focusing on $\ell = e, \mu$ final states

- **Explore synergy between low- and high-energy cLFV observables**

  to probe the SUSY seesaw

Based on: A. Abada, A. Figueiredo, J. Romao and AMT

arXiv: 1007.4833 & 1206.2306

A. Figueiredo and AMT, arXiv: 1309.****

➠ M. Gómez talk (tomorrow) on general LFV final states !

New physics models: type I seesaw

- **Implement mechanism for ν-mass generation**

Seesaw mechanism $\leftrightsquigarrow$ If **Majorana ν**, a natural **explanation for small m_ν**

additional **singlet states** N (ν_R); new **dynamics**

- $-\mathcal{L}^{\text{lepton}}_{\text{mass}} = Y^\ell \, \bar{L} \, \phi \, e_R + Y^\nu \, \bar{L} \, \tilde{\phi} \, \boldsymbol{\nu_R} + \frac{1}{2} \, \boldsymbol{\bar{\nu}_R} \, \boldsymbol{M_R} \, \boldsymbol{\nu^c_R} + \text{h.c.}$ $[Y^\ell = Y^{\text{diag}}_\ell$ and $M_R = M^{\text{diag}}_R]$

- After **EW symmetry** breaking, an **effective neutrino** mass matrix M^ν [6×6]

$$M^\nu = \begin{pmatrix} 0 & \boldsymbol{m_D} \\ \boldsymbol{m_D^T} & \boldsymbol{M_R} \end{pmatrix}$$

$\boldsymbol{m_D} \to$ **Dirac** mass matrix; $m_D = vY^\nu$

$\boldsymbol{M_R} \to$ **Heavy neutrino** mass matrix - diag (m_{R_i})

- **Seesaw equation:** $\boldsymbol{m_\nu^{\text{light}}} = -\boldsymbol{m_D} \, \boldsymbol{M_R}^{-1} \, \boldsymbol{m_D^T}$

$\boldsymbol{m_D} \ll \boldsymbol{M_R}$

$M_R \sim$ few TeV $\Rightarrow$ $Y^\nu \sim Y^\ell$

$Y^\nu \sim 1 \Rightarrow \boldsymbol{M_R \sim \mathcal{O}(10^{15}}$ **GeV)**

experimentally unreachable / untestable (?)

New physics models: supersymmetric type I seesaw

- **SUSY:** appealing **theoretically** (hierarchy problem, unification of gauge couplings, ...)

  and **experimentally** (dark matter candidates, hopefully TESTABLE at colliders!, ...)

- **Embed the type I seesaw into models of flavour-blind SUSY breaking - e.g. cMSSM**

  only **SM** sources of **flavour and CP violation** (Y^f)

- **High-scale SUSY seesaw: 5 cMSSM parameters (e.g.) + ν dynamics**

- $$v_2 Y^\nu = i \sqrt{M_R^{\text{diag}}}\, R\, \sqrt{m_\nu^{\text{diag}}}\, U_{\text{MNS}}^\dagger \quad (\text{at } M_N)$$

  [Casas-Ibarra parameterisation]

  $$\begin{cases} U_{\text{MNS}}\ (\theta_{12}, \theta_{23}, \theta_{13}, \delta, \varphi_{1,2}) \\ m_\nu^{\text{diag}}\ (\Delta m^2_{\text{sol}}, \Delta m^2_{\text{atm}}, \sum m_{\nu_i}) \\ M_R^{\text{diag}} \ \text{heavy neutrino masses} \\ R(\theta_i) \ \text{3 complex angles} \end{cases}$$

- Before decoupling, **heavy RH neutrinos** leave imprint on **SUSY parameters** (slepton)

  $\Rightarrow$**Link slepton flavour violation with m_ν via high-scale dynamics**

Type-I SUSY seesaw: flavour violating slepton masses

- **mSUGRA-like SUSY seesaw:** Y^ν **unique source of FV**

- Even for **universal** soft-breaking terms **RGE running of** Y^ν $(M_{\text{GUT}} \to M_R)$

  induces flavour-violating terms in slepton soft-breaking masses

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

[Borzumati, Masiero; Hisano; ...]

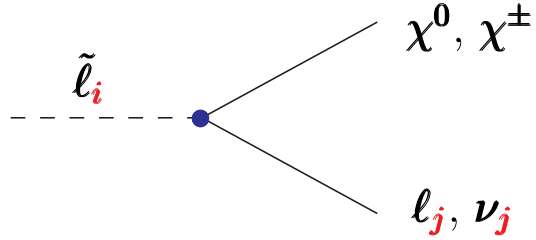
$$(M^2_{\tilde{\ell}})_{ij} \neq 0\,!$$

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

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

LFV manifest in **neutral** and

charged lepton-slepton interactions



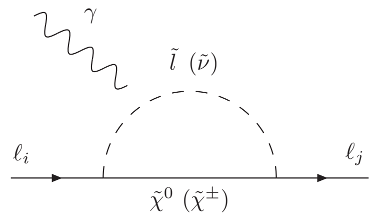
$\bullet \propto R^{\tilde{\ell}}_{ij}$

- **Expect many interesting** flavour violating **transitions in** charged leptons!

  [“observables” $\propto (Y^\nu)^n$; important degree of correlation ...]

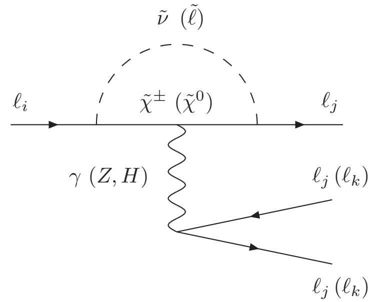
SUSY seesaw: low-energy cLFV observables

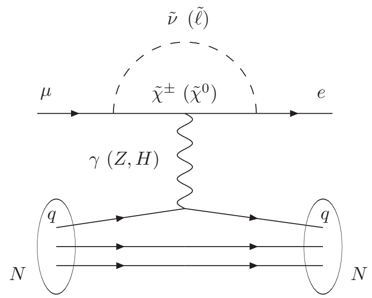
▶ **Large Y^ν: sizable contributions to cLFV observables**



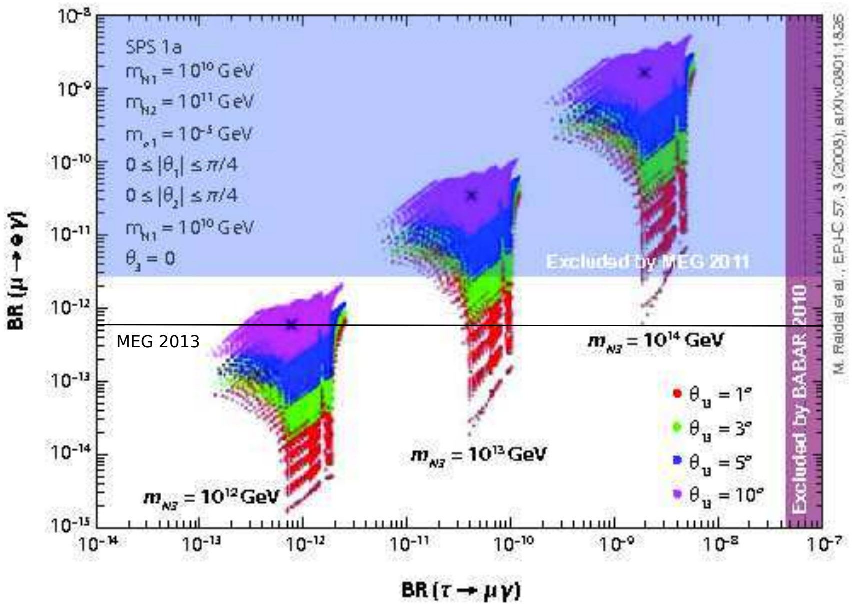
cLFV driven by the exchange of *virtual* **SUSY particles**

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





▶ **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

SUSY seesaw: high-energy cLFV observables

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

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

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

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

➠ M. Gómez talk

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

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

cLFV at the LHC: dilepton mass distributions

★ **At the LHC: $\tilde{\ell}$ production** from χ_2^0 **decays** ($\tilde{q} \to \chi_2^0 \to \tilde{\ell}$)

- Consider **dilepton invariant mass distributions** from $\chi_2^0 \to \tilde{\ell}_{L,R}\,\ell \to \chi_1^0 \ell\,\ell$
- **Shape** of $m_{\ell\ell}$ $\Rightarrow$ **info** on $\tilde{\ell}$ **spectrum** $\begin{cases} \text{position of edges} \rightsquigarrow \text{determine } m_{\tilde{\ell}} \\ \text{number of edges} \rightsquigarrow \text{number of } \tilde{\ell} \end{cases}$

★ cMSSM (no seesaw): $\chi_2^0 \to \tilde{\ell}^i_{L,R}\,\ell^i \to \chi_1^0\,\ell_i^+\,\ell_i^-$

- **Identical flavour** opposite-sign final state leptons
- **Two edges** in di-lepton mass distributions; **superimposed** m_{ee}, $m_{\mu\mu}$ **(degenerate $\tilde{e}$, $\tilde{\mu}$)**

★ **Impact of a type-I SUSY seesaw**: $\chi_2^0 \to \tilde{\ell}^i_{L,R}\,\ell^j \to \chi_1^0\,\ell_j^+\,\ell_k^-$

- **Displaced m_{ee}, $m_{\mu\mu}$ edges** $\Rightarrow$ **slepton mass splittings** $\frac{\Delta m_{\tilde{\ell}}}{m_{\tilde{\ell}}}(\tilde{e}_L, \tilde{\mu}_L)$
- **New edges** in **di-lepton mass distributions:** $\chi_2^0 \to \left\{ \begin{matrix} \tilde{\ell}^i_L\,\ell_i \\ \tilde{\ell}^i_R\,\ell_i \\ \tilde{\ell}^j_X\,\ell_i \end{matrix} \right\} \to \chi_1^0\,\ell_i\,\ell_i$

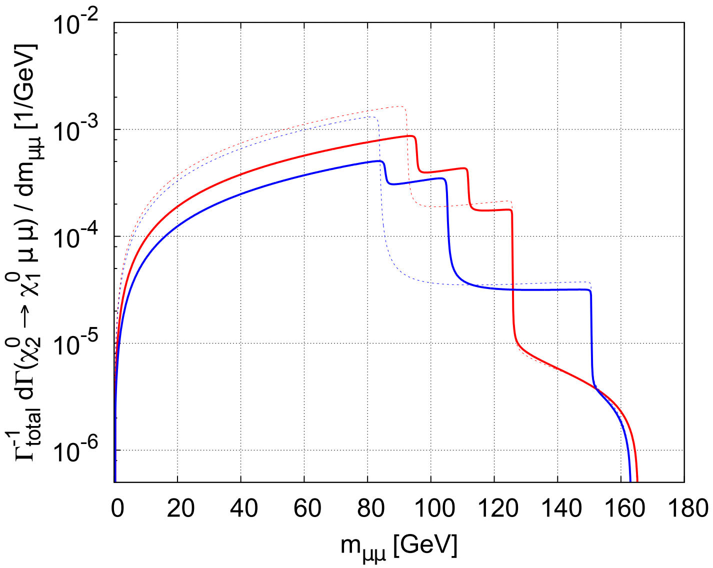
cLFV at the LHC: dilepton mass distributions

★ cMSSM (no seesaw)

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

▶ 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



▶ 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 (?)]

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

[$\rightsquigarrow$ flavour violation!]

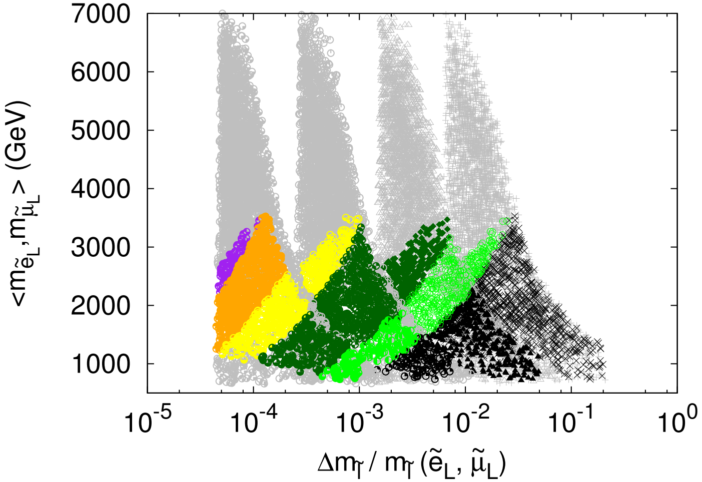
▶ LFV at the LHC: $\chi_2^0 \to \tilde{\tau}_2 \mu \to \chi_1^0 \mu \mu$

cLFV at the LHC: slepton mass splittings

- **Prospects** for **slepton mass reconstruction** at the **LHC** from $\chi_2^0 \to \tilde{\ell}$ **decays**

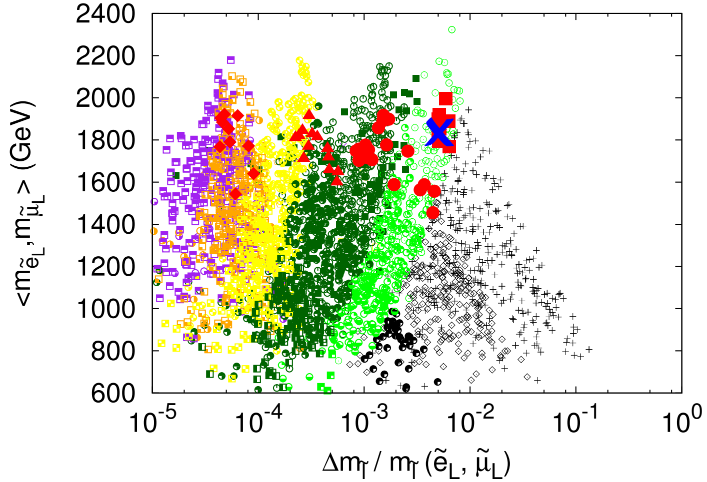
  [imposing 2013 experimental bounds: direct searches, SM-like H and flavour]

- Comparison of **strict mSUGRA-like** with **flavour-conserving relaxed universality**



BR($\mu \to e\gamma$)

- $\lesssim 10^{-17}$
- $[10^{-17}, 10^{-16}]$
- $[10^{-16}, 10^{-15}]$
- $[10^{-15}, 6 \times 10^{-14}]$
- $[6 \times 10^{-14}, 5.7 \times 10^{-13}]$
- $\gtrsim 5.7 \times 10^{-13}$
- m_h excluded



- **cMSSM:** $\frac{\Delta m_{\tilde{\ell}}}{m_{\tilde{\ell}}}(\tilde{e}_L, \tilde{\mu}_L) \gtrsim 1\% \Rightarrow m_{\tilde{\ell}} \gtrsim 2.5$ **TeV** [small region of $m_0 - M_{1/2}$ plane]

- **Relaxed universality** (lighter slepton sector, alleviates m_h tension):

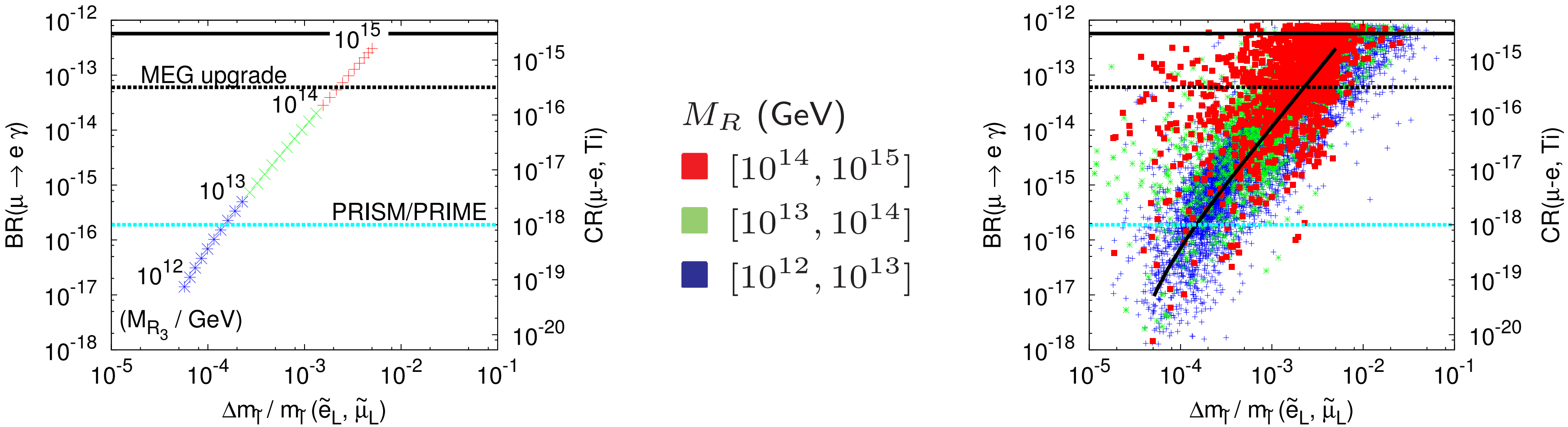
  $\frac{\Delta m_{\tilde{\ell}}}{m_{\tilde{\ell}}}(\tilde{e}_L, \tilde{\mu}_L) \gtrsim \mathcal{O}(0.5\%)$ **for** $m_{\tilde{\ell}} \sim$ **TeV and** BR($\mu \to e\gamma$) **at MEG!**

- **LHC slepton studies:** consider **semi-constrained SUSY models** $\longrightarrow$ "**X**"

cLFV at the LHC: synergy with low-energy observables

- **Probe the type I SUSY seesaw via interplay of low- and high-energy cLFV**

  (assume SUSY discovery - relaxed universality, explore full RH neutrino dynamics)



- **Sizable contributions** to **high- and low-energy observables - well within exp reach!**

- **Isolated cLFV** manifestations $\Rightarrow$ **high-scale SUSY seesaw** is **not unique cLFV source**

  e.g. $\frac{\Delta m_{\tilde{\ell}}}{m_{\tilde{\ell}}}(\tilde{e}_L, \tilde{\mu}_L) \gtrsim \mathcal{O}(0.5\%)$ and $\mu \to e\gamma|_{\text{MEG}}$ ✘: **disfavours seesaw hypothesis**

- **"Compatible" cLFV observations** $\Rightarrow$ **strengthens seesaw hypothesis !**

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

cLFV at high-energies: a Linear Collider

★ **Linear Colliders: ideal laboratory** for **slepton studies - LFV included** (if sizable $\sqrt{s}$ ...)

- **Exact nature of colliding particles is known; $e^{\pm}$ beam** options; beam **polarisation ...**
- **Direct $\tilde{\ell}$ production!** Study $\tilde{\ell} \to \ell$ decays in "short" chains
- **Beam polarisation: background** suppression; explore **chirality** aspects of **cLFV**

- **New cLFV** signals: e^-e^- **beam option** $\leftrightsquigarrow$ study **"clean" signals for LFV**
- **cLFV analysis** analogous to **LHC: new & displaced edges** in $m_{\ell\ell}$, **direct FV** in decays

  "Clean" environement $\Rightarrow$ **better resolution** in mass determination, **sharper** edges...

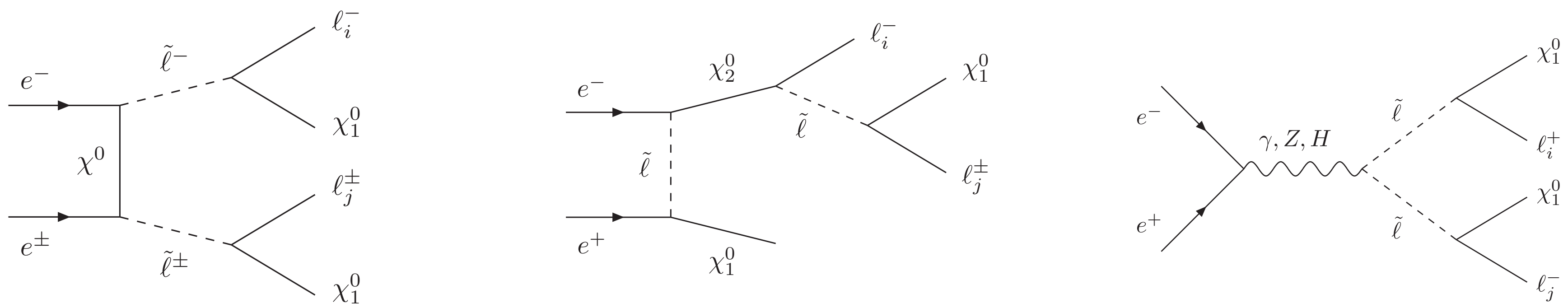
- **Here:** study $e^{\pm}e^- \to \ell^{\pm}\mu^- + E^T_{\text{miss}}$ $\quad (E^T_{\text{miss}} = \chi^0_1, \chi^0_1 + \nu, \nu)$

  LC operating at **500 GeV**$\lesssim \sqrt{s} \lesssim$ **3 TeV; benchmark** $\mathcal{L} = 0.5, 3\ \text{ab}^{-1}$

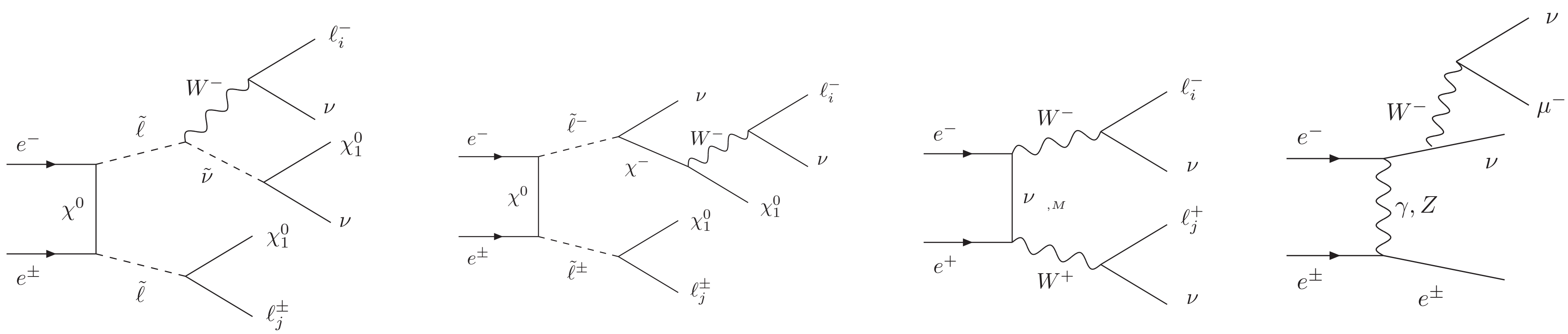
cLFV at a future LC: e^+e^- and e^-e^- beams

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

- **Signal events: dominated by LFV SUSY neutral currents**

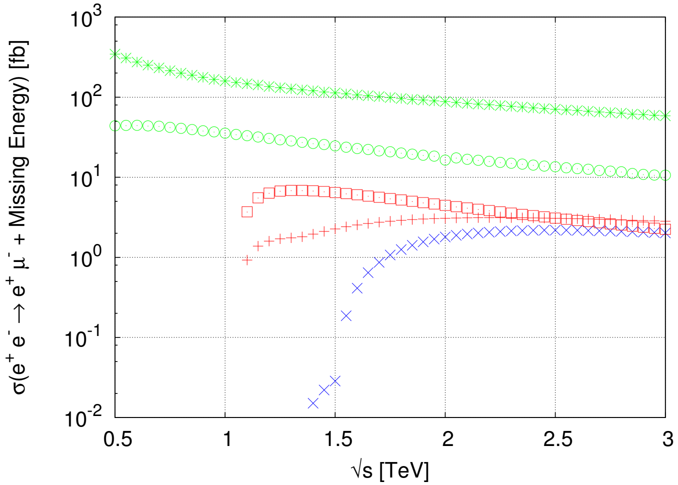


- **SUSY & SM$_{m_\nu}$ backg: cLFV from charged currents** - low-energy **leptonic mixing**



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

- Consider **illustrative example:** unpolarised and (ideal) fully polarised **LL** beams



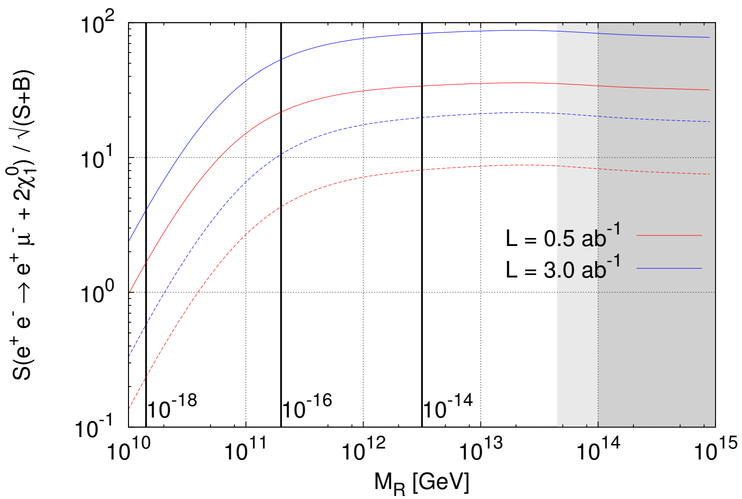
SM backg
cLFV signal
SUSY backg

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

m_i	GeV
χ^0_1	400
χ^0_2, $\chi^\pm_1$	760
$\tilde{\nu}_L$	656
$\tilde{\ell}_R$	410
$\tilde{\ell}_L$	663

- **Dominant** SM$_{m_\nu}$ backg (disentangled from SUSY events - cuts, etc);

  Polarisation: **enhance signal;** reduce (remove) SM$_{m_\nu}$ (**SUSY**) backg



- **Significance** for SUSY [–] and SUSY+SM$_{m_\nu}$ [$\cdots$] backg

  $\Rightarrow$ typically $\mathcal{S} \gtrsim$ **10** (unpolarised)

- For $\sqrt{s} = 2$ **TeV** and seesaw scale $M_R \sim 10^{12}$ **GeV:**

  $\mathcal{O}(10^3)$ **events** for $\mathcal{L} = 0.5$ **ab**$^{-1}$

  $\mathcal{O}(10^4)$ **events** for $\mathcal{L} = 3$ **ab**$^{-1}$

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

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

- **Signal events: $\tilde{\ell}$ production via t-channel χ^0 exchange**

  no s-channel exchanges (absence of doubly charged particles)

- **SUSY & SM_{m_ν} backg: dominated by W-strahlung** (tiny "$0\nu 2\beta$"-like...)

- **Same $\tilde{\ell}$ production** for **signal and background: smaller effect from beam polarisation**

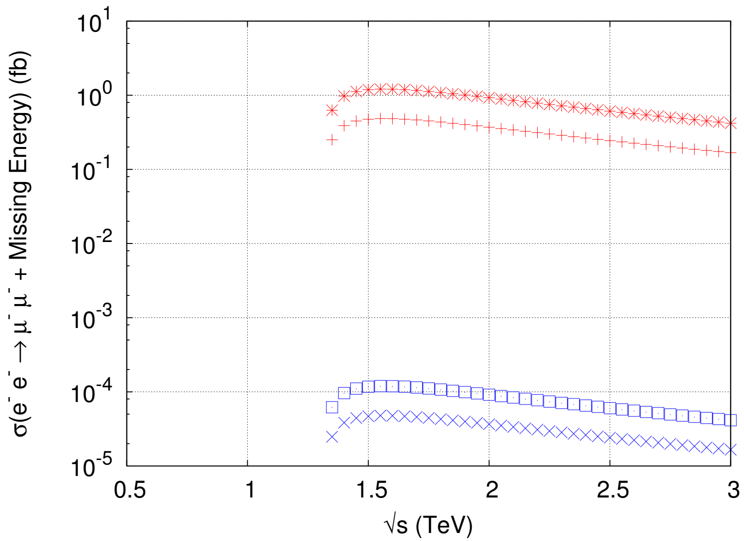
  Still expect a **large number of events** - $\mathcal{O}(10^3 - 10^5)$ **events** for $\sqrt{s} = 2$ **TeV**

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

cLFV at a future LC: the "golden channel"

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

SM$_{m_\nu}$ backg negligible ...



cLFV signal

SUSY backg

+, × → unpolarised

∗, □ → $e^-_L e^-_L$

- 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**

Summary

- **Observable cLFV $\Rightarrow$ evidence for New Physics beyond SM$_{m_\nu}$**

  cLFV complementary to **direct searches: bounds** on **NP scale and couplings**

- **Type I SUSY seesaw: one source of LFV $\leftrightsquigarrow$ correlated cLFV observables**

- **LFV at the LHC: new edges** in $m_{\ell\ell}$; **synergy between $\Delta m_{\tilde{e}_L,\tilde{\mu}_L}$** and **low-energy cLFV**

  constrained SUSY scenarios - worse prospects for LFV at the LHC (heavy $\tilde{\ell}$ spectrum)

- **Linear Collider: ideal for slepton and cLFV studies if $\sqrt{s}$ sufficiently large!**

  expect many $e^{\pm} e^{-} \to e^{\pm}\mu^{-} + E^{T}_{\text{miss}}$ **events; beam polarisation to reduce backgs**

- **Ideal cLFV discovery channel at a LC: $e^{-} e^{-} \to \mu^{-}\mu^{-} + E^{T}_{\text{miss}}$**