



LPT-Orsay



Charged leptons and lepton flavour violation

- 👉 Lepton Flavour Violation (Neutrino data) call for BSM
- 👉 LFV Observables and Experimental status
- 👉 BSM (with/without m_ν) impact on LFV observables
- 👉 High-energy / Low-energy Complementarity

FPCP 2014, Marseille, 29 May 2014

Asmaa Abada

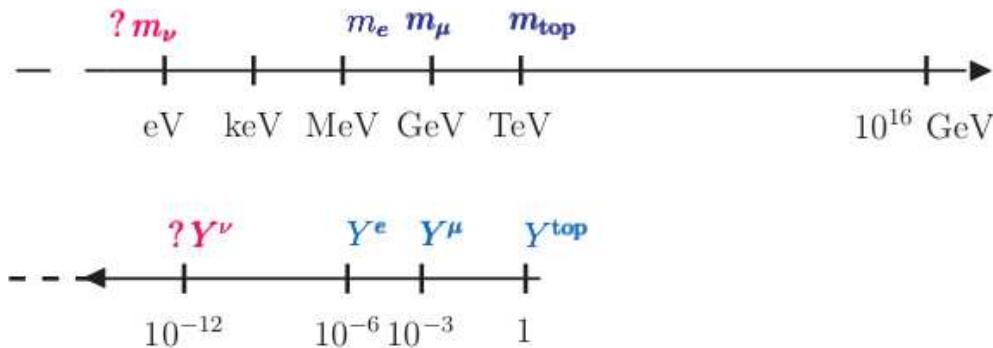
👉 Facts: ν change flavours after propagating a finite distance

Solar	$\Delta m_{\text{sol}}^2 \simeq 7.6 \times 10^{-5} \text{ eV}^2$	SNO, BOREXino, Super-Kamiokande,
$\nu_e \rightarrow \nu_{\mu,\tau}$	$\sin^2 \theta_{\text{sol}} \simeq 0.30$	GALLEX/GNO, SAGE, Homestake, Kamiokande
Atmospheric		IMB, MAcro, Soudan-2,
$\nu_\mu \rightarrow \nu_\tau$		Kamiokande, Super-Kamiokande
LBL Accelerator	$\Delta m_{\text{atm}}^2 \simeq 2.4 \times 10^{-3} \text{ eV}^2$	
ν_μ disappearance	$\sin^2 \theta_{\text{atm}} \simeq 0.50$	K2K, T2K, MINOS
LBL Accelerator		
$\nu_\mu \rightarrow \nu_\tau$		Opera
LBL Accelerator		
$\nu_\mu \rightarrow \nu_e$	Δm_{atm}^2	T2K, MINOS
LBL Reactor	$\sin^2 \theta_{\text{Chooz}} \simeq 0.023$	Daya Bay, RENO
$\bar{\nu}_e$ disappearance		Double Chooz
SBL Accelerator		
$\nu_\mu (\bar{\nu}_\mu) \rightarrow \nu_e (\bar{\nu}_e)$	$\Delta m^2 \simeq 1 \text{ eV}^2$ (?)	LSND, MiniBooNE
SBL Reactor	$\sin^2 \theta \simeq 0.1$ (?)	++ Solar: GALLEX, SAGE++
$\bar{\nu}_e$ disappearance		Bugey, ILL, Rovno,...

👉 **Indisputable:** ν s are massive and mix

→ The minimal SM is incomplete!

- ★ ν data pour oil on fire: add to the fermion flavour puzzle!
- ★ Different mixing pattern for Quarks and Leptons
- ★ ν data make fermion hierarchy worse!



👉 SM has other issues that call for BSM

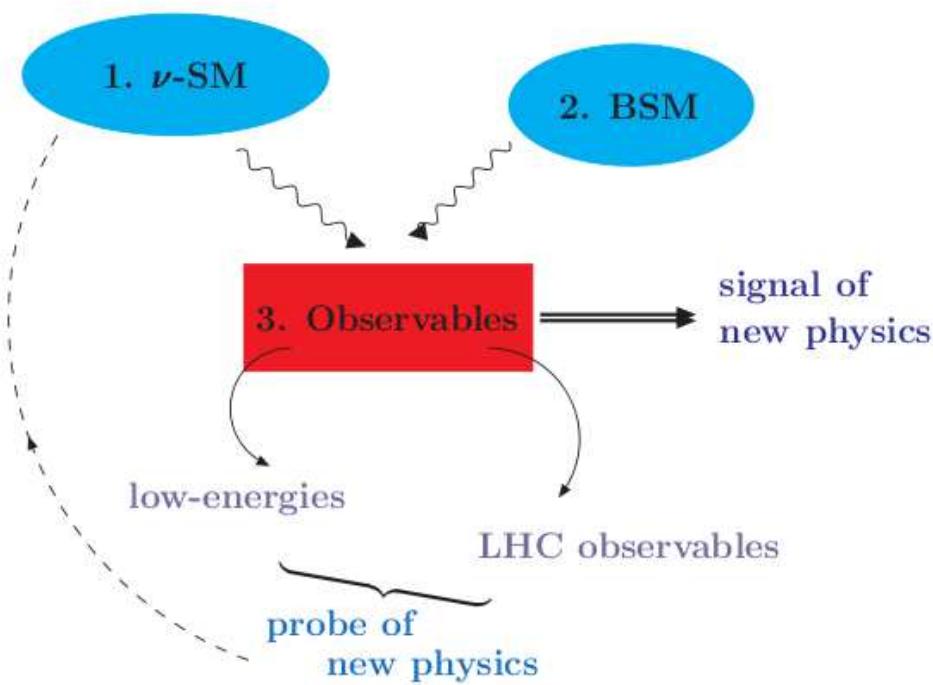
- * observational problems (ν masses & mixings): BAU and Dark Matter
- * theoretical caveats: fine-tuning, hierarchy and flavour problems

👉 BSM will allow for many new phenomena

- ★ LFV in neutral sector, why not in the charged sector?
 $\ell_i \rightarrow \ell_j \ell_k \ell_k$, $\ell_i \rightarrow \ell_j \gamma$, $B \rightarrow \ell_i \ell_j$, $H \rightarrow \tau \mu$, ...
- ★ Contributions to $g - 2$, Lepton EDMs
- ★ New heavy states at Colliders

Determination of ν -SM/BSM model requires combinations of \neq observables

How to proceed? Ingredients, Observables, Strategies



★ Ingredients:

- a mass generation mechanism (**seesaw**, radiative corrections, extra dim, ...)
- and/or, extension of SM: SM + new d.o.f, or BSM (e.g. SUSY, ...)

★ Observables (peculiar to these extensions):

- Produce directly new d.o.f at LHC (if accessible)
- Or study impact of 1. (and 1. + 2.) on e.g. **cLFV observables** at low- energy (MEG, ...) and high-energy (LHC, LC)

★ Probe New Physics: interplay between low- and high-energy observables [cLFV]

Observables: Lepton Flavour Violation

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

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

$\mu - e$ conversion (Nuclei), $\mu \rightarrow e\gamma$, $\mu \rightarrow eee$, mesonic τ decays, ...

★ Meson decays:

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

violation of lepton flavour universality - R_K , ...

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

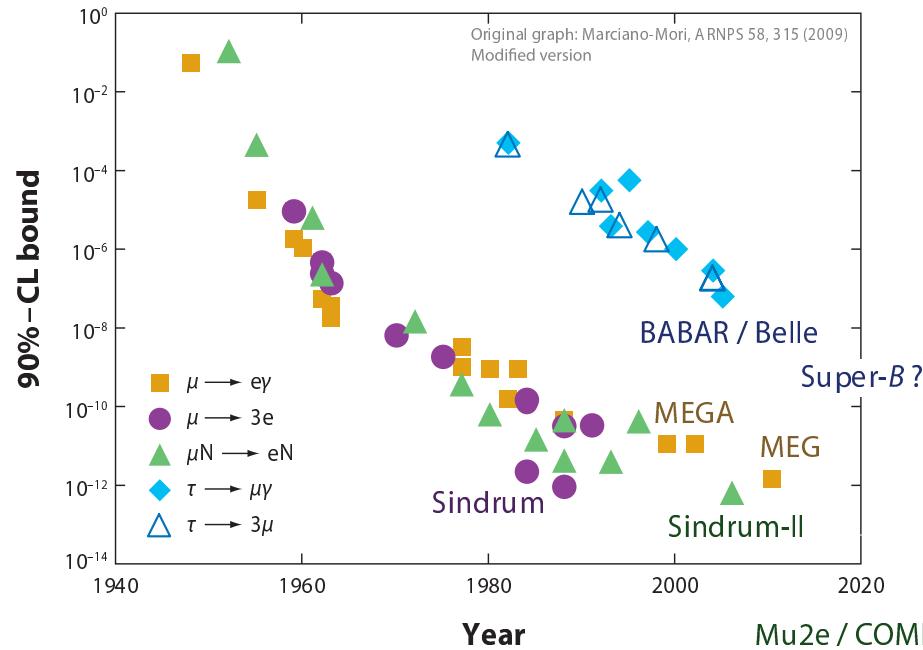
★ Rare (new) heavy particle decays (model-dependent) → [colliders]

$\tilde{\ell}_i \rightarrow \ell_j \chi^0$, $\chi_2^0 \rightarrow \chi_1^0 \tau \mu$, $H \rightarrow \tau \mu$, $\Delta^{\pm\pm} \rightarrow \mu_i^\pm \tau_j^\pm$, ...

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

Lepton Flavour Violation

★ A world-wide experimental effort > 60 years!



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

cLFV: observables of New Physics

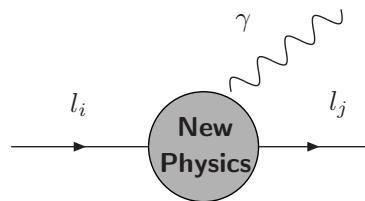
★ In the **absence of cLFV [and other]** signals:

- ⇒ constraints on parameter space (scale and couplings)
- ⇒ i.e. constraint the neutrino mass generation mechanism

★ if **cLFV observed**: compare with **peculiar features** of given model

- ⇒ predictions for **cLFV observables**
- ⇒ intrinsic patterns of **correlations of observables**

★ to have an **observable cLFV**:



$$\text{BR}(\mu \rightarrow e\gamma) = 10^{-13} \times (1.7 \text{ TeV}/\Lambda)^4 \times (\theta_{\mu e}/0.01)^2$$

→ New Physics $\Lambda \sim \mathcal{O}(\text{TeV})$ (LHC?), and sizable Lepton Flavour Mixing $\theta_{\ell_i \ell_j}$ ($m_\nu \neq 0?$)

Which New Physics?

- ★ cLFV from Generic BSM models: general MSSM, LHT, RS, composite Higgs, ...;
- ★ cLFV from m_ν :
$$\left\{ \begin{array}{l} \text{SM seesaw (TeV scale) - type II, inverse seesaw, ...} \\ \text{Extended frameworks - SUSY seesaw, GUTs, ...} \end{array} \right.$$
- ★ Use Effective Approach to study a given (cLFV) observable - [example: type II seesaw]

Effective approach

★ **BSM** (or SM + m_ν) require new fields (or extremely tiny Y_ν)

★ Effects at low energy: effective theory approach

Effective operators obtained when expanding the heavy field propagators in $\frac{1}{M}$

👉 heavy fermion: $\frac{1}{p-M} \sim -\frac{1}{M} - \frac{1}{M} \not{D} \frac{1}{M} + \dots$

👉 heavy scalar : $\frac{1}{D^2-M^2} \sim -\frac{1}{M^2} - \frac{D^2}{M^4} + \dots$

$$\rightarrow \mathcal{L}_{\text{eff}} = \mathcal{L}_{\text{SM}} + \frac{1}{M} c^{d=5} \mathcal{O}^{d=5} + \frac{1}{M^2} c^{d=6} \mathcal{O}^{d=6} + \dots$$

$$\Delta \mathcal{L}^{d \geq 5} = \frac{c^{d=5}}{M} \times \begin{array}{c} \text{---} \\ \diagup \quad \diagdown \\ \text{---} \end{array} \quad + \quad \frac{c_{\mu eeee}^{d=6}}{M^2} \times \begin{array}{c} \text{---} \\ \mu \quad \quad \quad e \\ \diagup \quad \diagdown \\ e_L \quad e_L \end{array} \quad + \quad \frac{c_{\ell_i \ell_j \gamma}^{d=6}}{M^2} \dots$$

Higher order operators

👉 $\mathcal{O}^{d=5}$ operator: same for all SM extensions incorporating massive MAJORANA

👉 3 “types” of Dimension 6 operators relevant for **cLFV (dipole and 3-body)**

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

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

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

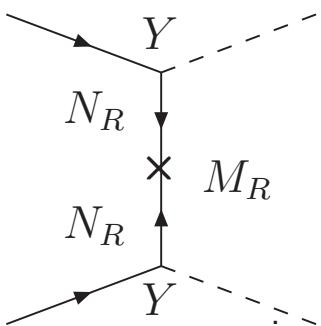
4 lepton: $\mathcal{O}_{\ell_i \ell_j \ell_k \ell_l}^6 \sim (\ell_i \gamma_\mu P_{L,R} \ell_j)(\ell_k \gamma^\mu P_{L,R} \ell_l) \rightsquigarrow$ 3-body decays $\ell_i \rightarrow \ell_j \ell_k \ell_l, \dots$

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

(Higher order $\mathcal{O}^{d=7,8,\dots}$: ν (transitional) magnetic moments, NSI, unitarity violation, ...)

👉 A specific example: Seesaw type II

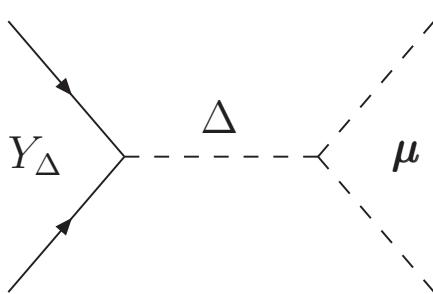
Seesaw I, II, III



type I (fermionic singlet)

$$\mathbf{m}_{\nu} = -\frac{1}{2}v^2 Y_N^T \frac{1}{M_N} Y_N$$

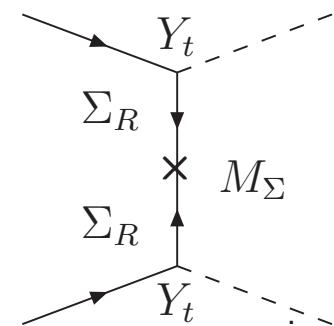
Minkowski, Gell-Man,
Ramond, Slansky
Yanagida, Glashow
Mohapatra, Senjanovic



type II (scalar triplet)

$$\mathbf{m}_{\nu} = -2v^2 Y_{\Delta} \frac{\mu_{\Delta}}{M_{\Delta}^2}$$

Magg, Wetterich,
Nussinov
Mohapatra, Senjanovic
Schechter, Valle
Ma, Sarkar

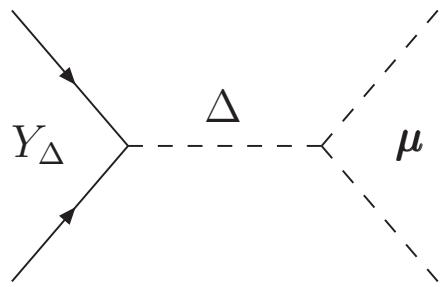


type III (fermionic triplet)

$$\mathbf{m}_{\nu} = -\frac{v^2}{2} Y_{\Sigma}^T \frac{1}{M_{\Sigma}} Y_{\Sigma}$$

Ma, Hambye et al.
Bajc, Senjanovic, Lin
A.A., Biggio, Bonnet, Gavela,
Notari, Strumia, Papucci, Dorsner
Fileviez-Perez, Foot, Lew...

Case of scalar triplet (type II)



$$\Delta = \begin{pmatrix} \Delta^{++} \\ \Delta^+ \\ \Delta^0 \end{pmatrix} \sim (1, 3, 2) \quad L_\Delta = -2$$

Yukawa couplings:

$$Y_{\Delta ij} \overline{(l_L)^c}_{ia} (l_L)_{jb} (i\tau_2 \tau_\alpha)_{ab} \Delta^\alpha + h.c.$$

Scalar coupling:

$$\mu \phi_a^t \phi_b (i\tau_2 \tau_\alpha) (\Delta^\dagger)^\alpha + h.c.$$

$$\begin{aligned} & -M_\Delta^2 \Delta^\dagger \Delta - \frac{1}{2} \lambda_2 (\Delta^\dagger \Delta)^2 \\ & - \lambda_3 (\phi^\dagger \phi) (\Delta^\dagger \Delta) + \dots \end{aligned}$$

d=5 Operator (Mass)

$$m_\nu = v^2 Y_\Delta \frac{\mu}{M_\Delta^2} \rightarrow 2 \text{ different scales } \mu, M_\Delta$$

possible to have $Y_\Delta \sim \mathcal{O}(1)$ $M_\Delta \sim 1 \text{ TeV}$ ($\mu \sim 100 \text{ eV}$)

Low energy effects of dimension 6 operators:

$\frac{1}{2M_\Delta^2} Y_{\Delta ij} Y_{\Delta kl}^\dagger (\overline{l_{Li}} \gamma^\mu l_{Lk}) (\overline{l_{Lj}} \gamma_\mu l_{Ll}) \rightarrow \text{LFV, } g - 2, \text{ EDMs}$
 constraints not suppressed by μ

$$\left. \begin{array}{c} -2 \frac{\mu^2}{M_\Delta^4} \partial_\mu (\phi^\dagger \phi) \partial^\mu (\phi^\dagger \phi) \\ 2 \lambda_3 \frac{\mu^2}{M_\Delta^4} (\phi^\dagger \phi)^3 \\ 4 \frac{\mu^2}{M_\Delta^4} [\phi^\dagger D_\mu \phi]^\dagger [\phi^\dagger D_\mu \phi] \end{array} \right\} \rightarrow \text{EW precision data, couplings to gauge bosons}$$

$-2 \frac{\mu^2}{M_\Delta^4} (\phi^\dagger \phi) \{ Y_e \bar{l} e_R \phi + Y_d \bar{q} d \phi - Y_u \bar{q} i \tau_2 u \phi + h.c. \} \rightarrow \text{top physics...}$

Constraining the type II seesaw

★ Scalar triplet: bounds from low energy constraints

↳ $Y_\Delta \lesssim 10^{-1} \times \left(\frac{M_\Delta}{1 \text{ TeV}}\right)$ or stronger

↳ If observation of $\mu \rightarrow e\gamma$ at MEG (sensitivity of 10^{-13})

- for $Y_\Delta \sim \mathcal{O}(1)$ → $15 \text{ TeV} < M_\Delta < 50 \text{ TeV}$
- for $Y_\Delta \sim \mathcal{O}(10^{-2})$ → $0.15 \text{ TeV} < M_\Delta < 0.50 \text{ TeV}$

★ Scalar triplet: bounds from LHC

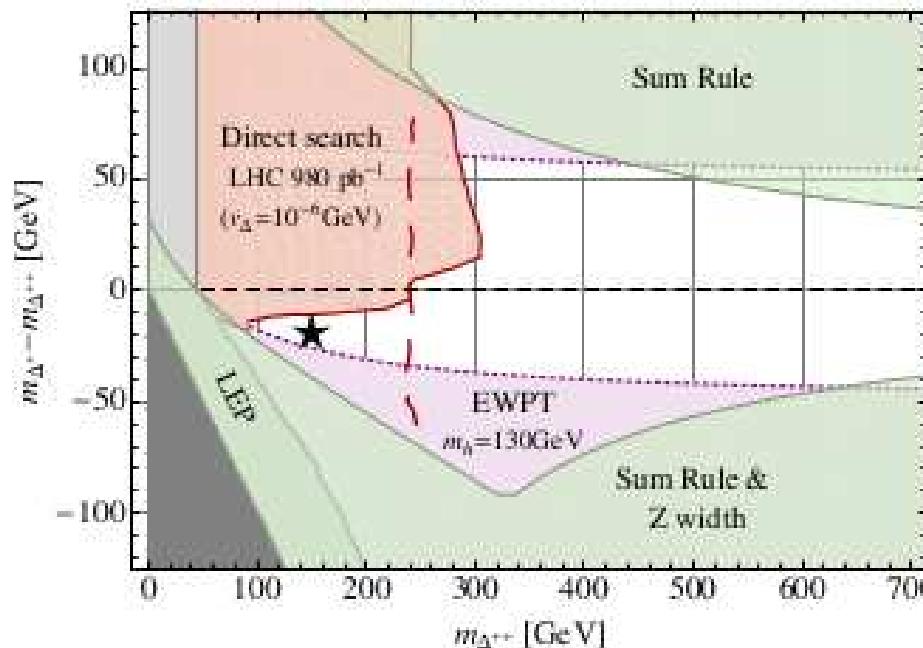
↳ If M_Δ turns out to be as low as $\mathcal{O}(\text{TeV})$ → possibility of clean signals in colliders (LHC)

LHC constraints on scalar triplet

- ★ Production of Δ^{++} and Δ^{--} , decaying into pairs of same-sign leptons
 - striking signals, free from SM backgrounds

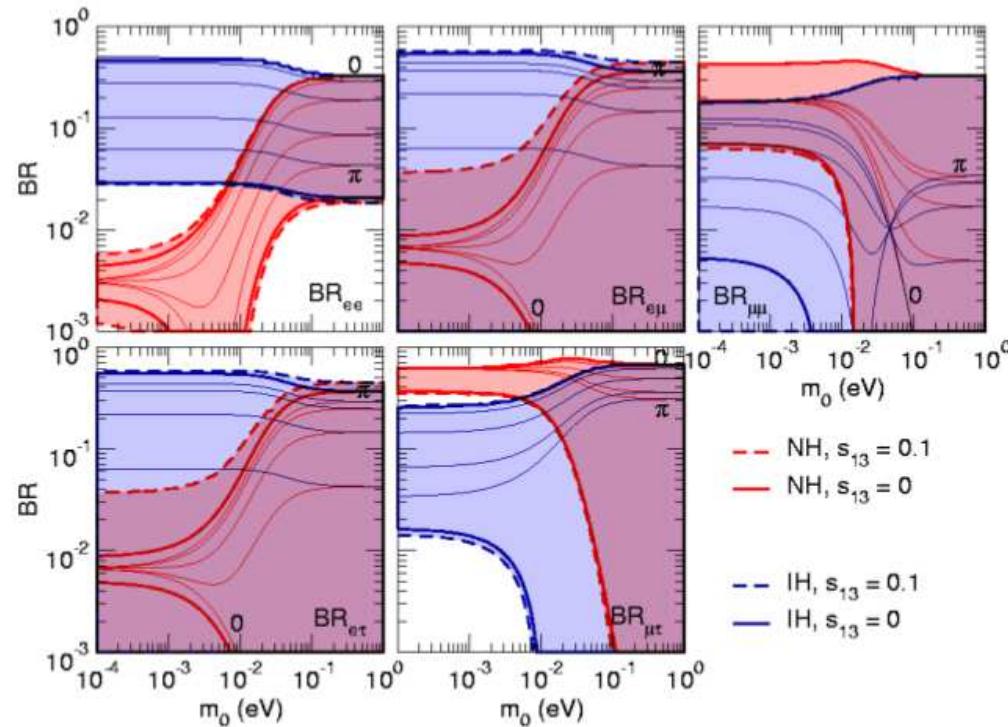
$$\begin{aligned} \star \text{ Drell-Yann Production} & \left\{ \begin{array}{l} M_{\Delta^{++}} \sim 200 \text{ GeV} \Rightarrow \sigma(\gamma^*, Z^* \rightarrow \Delta^{++}\Delta^{--}) \sim 100 \text{ fb} \\ M_{\Delta^{++}} \sim 900 \text{ GeV} \Rightarrow \sigma(\gamma^*, Z^* \rightarrow \Delta^{++}\Delta^{--}) \sim 0.1 \text{ fb} \end{array} \right. \\ \star \text{ Decay product} & \left\{ \begin{array}{l} \Gamma(\Delta^{\pm\pm} \rightarrow W^\pm W^\pm) \sim \mu^2 M_\Delta^3 \\ \Gamma(\Delta^{\pm\pm} \rightarrow \ell_i^\pm \ell_j^\pm) \sim Y_{\Delta ij} M_\Delta \end{array} \right. \end{aligned}$$

→ **LHC:** so far, only **negative search results** ⇒ **constraints on parameter space** (M_Δ, μ, Y_Δ)



LFV predictions for ν mass spectrum

- ★ LFV in high-energy (LHC) + low-energy observables (e.g $\mu \rightarrow eee$)
 - ⇒ predictions for ν mass spectrum, CP phases ...



Garayoa, Schwetz, arXiv:0712.1453

- 👉 If Δ observed, must verify whether a scalar-mediated seesaw is at work
 - ⇒ observe in addition at least three LFV processes (to measure and disentangle the individual $Y_{\Delta ij}$ couplings)

- CLFV plays important rôle in disentangling between models
[Reconstruction of the Lagrangian at best only partially...]

Generic examples of BSM extensions (cLFV)

★ cLFV in Little Higgs models (T-parity)

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

★ $SU(5) \rightarrow SO(5)$ (@ TeV scale); augmented gauge group $[SU(2) \times U(1)]^2$

⇒ new (heavy) gauge bosons - A_H, Z_H, W_H^\pm

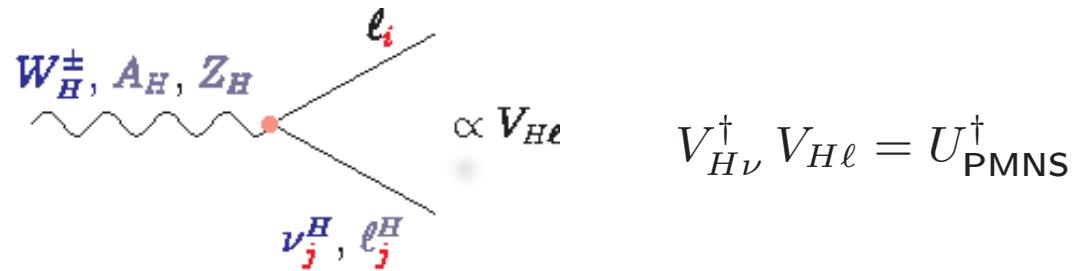
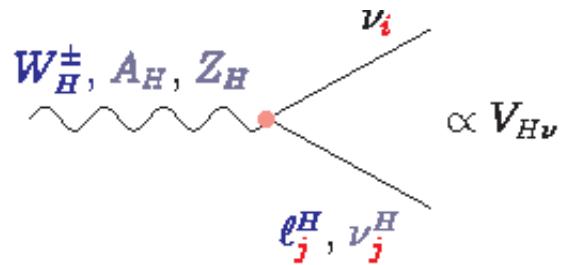
★ T parity ⇒ prevents contributions to **EW observables** (tree-level)

Lightest T-odd particle **stable** ⇔ dark matter candidate

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

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

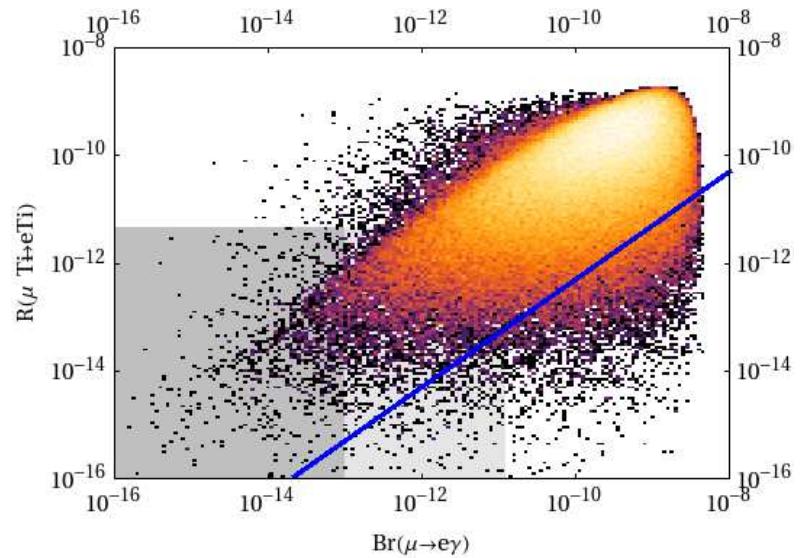
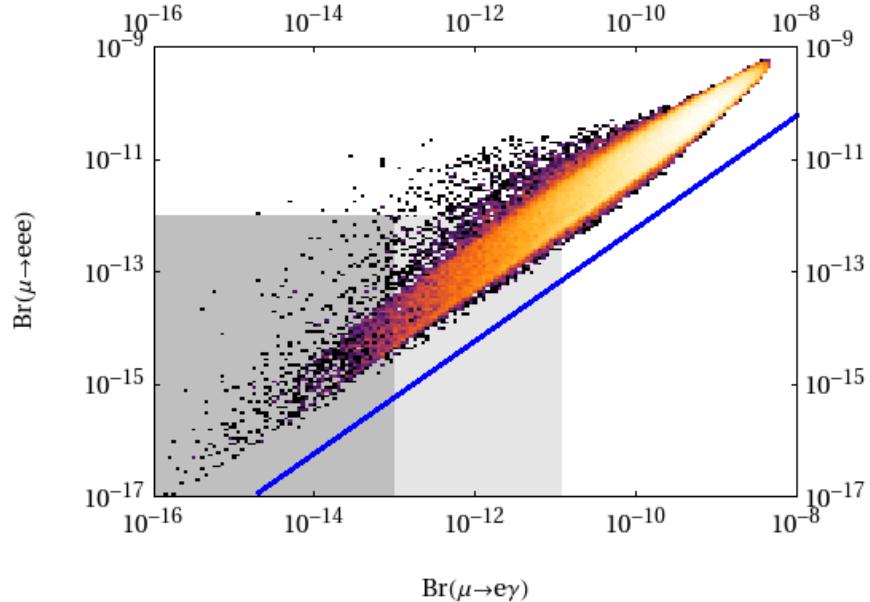
★ Sources of **LFV** (m_ν and cLFV): couplings of leptons - mirror leptons - heavy gauge bosons



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



cLFV in Little Higgs models



[Blanke et al, 0906.5454]

★ Strong correlation of some cLFV observables: $\mu \rightarrow e\gamma$ and $\mu \rightarrow 3e$

★ Asymmetries for polarised τ and μ decays \leftrightarrow chirality structure of LHT

[Goto et al, 1012.4385]

★ Typically large contributions to cLFV → some fine-tuning required

hierarchical mixing matrices ($V_{H\ell}, V_{H\nu}$), quasi degenerate states, ...



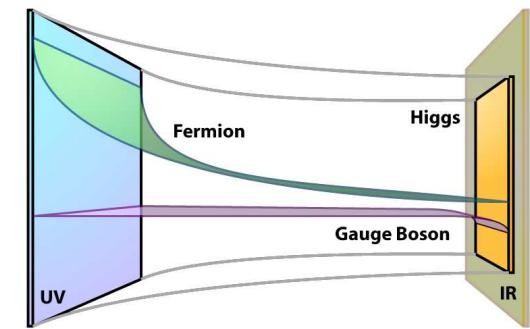
RS warped extra dimensions

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

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

★ Localise fields:

interactions \leftrightarrow overlap of wave functions



★ Geometrical distribution of fermions in bulk:

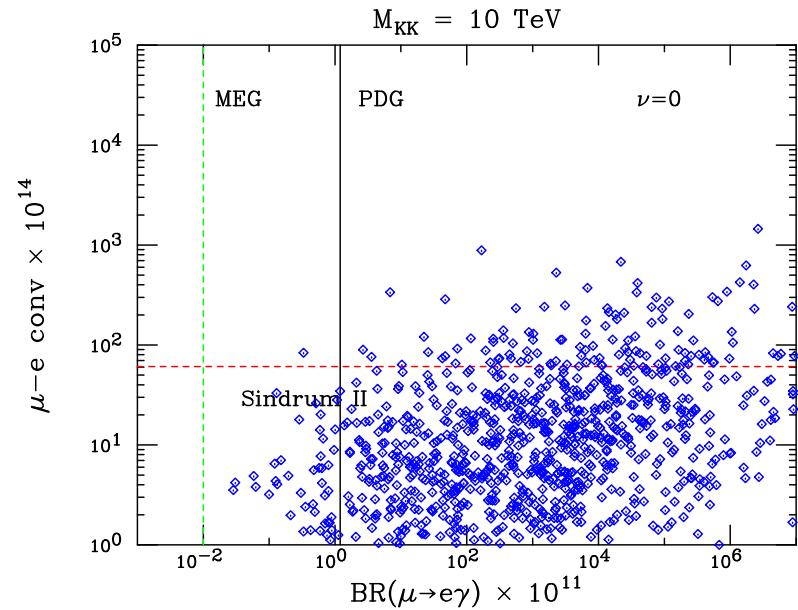
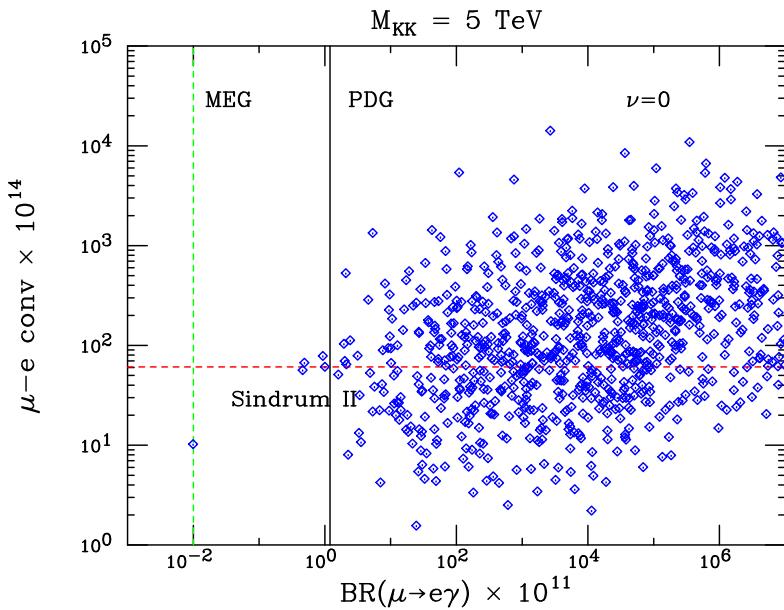
hierarchy in 4dim Yukawas for “anarchic” $\mathcal{O}(1)$ couplings!

★ Circumvent pheno issues: enlarge bulk symmetry (prevent violation of custodial SU(2));
additional “rescue” ingredients to avoid excessive FCNCs,
protect EW precision observables, ...

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



cLFV in RS warped extra dimensions



[Agashe et al, 0606021]

★ cLFV processes mediated by KK-lepton excitations, new gauge fields

★ Electroweak precision observables: $M_{KK} \geq 3 \text{ TeV}$;

cLFV: $M_{KK} > 10 \text{ TeV}$ (10 TeV only marginally compatible)

★ Possible ways out... flavour structure (non-geometrical), increase gauge symmetry, ...

[Vempati et al, 1206.4383]

★ General Minimal Supersymmetric extension of the SM

★ **Supersymmetry is broken in Nature:** different masses for SM particles and superpartners

Generic soft-SUSY breaking terms introduce new sources of flavour violation (q and ℓ)

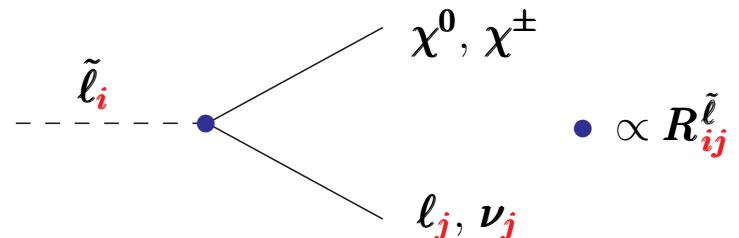
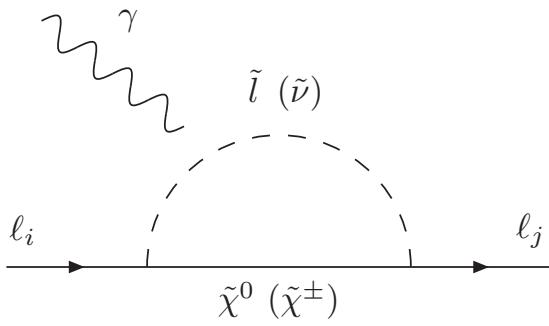
non-diagonal masses for sleptons and sneutrinos $(M_{\tilde{\ell}}^2)_{ij} \neq 0!$ $(M_{\tilde{\nu}}^2)_{ij} \neq 0!$

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

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

manifest in **neutral** and

charged lepton-slepton interactions



★ Sizable contributions to **cLFV observables** $\propto \delta_{ij}^{\tilde{\ell}} = \frac{(M_{\tilde{\ell}}^2)_{ij}}{M_{\text{SUSY}}^2}$

“almost everything is possible - depending on the regime”...

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

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

but no neutrino mass!

Comparing predictions - finding fingerprints

ratio	LHT	MSSM (dipole)	MSSM (Higgs)	SM4
$\frac{\text{BR}(\mu \rightarrow eee)}{\text{BR}(\mu \rightarrow e\gamma)}$	$0.02 \dots 1$	$\sim 6 \times 10^{-3}$	$\sim 6 \times 10^{-3}$	$0.06 \dots 2.2$
$\frac{\text{BR}(\tau \rightarrow eee)}{\text{BR}(\tau \rightarrow e\gamma)}$	$0.04 \dots 0.4$	$\sim 1 \times 10^{-2}$	$\sim 1 \times 10^{-2}$	$0.07 \dots 2.2$
$\frac{\text{BR}(\tau \rightarrow \mu\mu\mu)}{\text{BR}(\tau \rightarrow \mu\gamma)}$	$0.04 \dots 0.4$	$\sim 2 \times 10^{-3}$	$0.06 \dots 0.1$	$0.06 \dots 2.2$
$\frac{\text{BR}(\tau \rightarrow e\mu\mu)}{\text{BR}(\tau \rightarrow e\gamma)}$	$0.04 \dots 0.3$	$\sim 2 \times 10^{-3}$	$0.02 \dots 0.04$	$0.03 \dots 1.3$
$\frac{\text{BR}(\tau \rightarrow \mu ee)}{\text{BR}(\tau \rightarrow \mu\gamma)}$	$0.04 \dots 0.3$	$\sim 1 \times 10^{-2}$	$\sim 1 \times 10^{-2}$	$0.04 \dots 1.4$
$\frac{\text{BR}(\tau \rightarrow eee)}{\text{BR}(\tau \rightarrow e\mu\mu)}$	$0.8 \dots 2$	~ 5	$0.3 \dots 0.5$	$1.5 \dots 2.3$
$\frac{\text{BR}(\tau \rightarrow \mu\mu\mu)}{\text{BR}(\tau \rightarrow \mu ee)}$	$0.7 \dots 1.6$	~ 0.2	$5 \dots 10$	$1.4 \dots 1.7$
$\frac{\text{CR}(\mu \text{Ti} \rightarrow e \text{Ti})}{\text{BR}(\mu \rightarrow e\gamma)}$	$10^{-3} \dots 10^2$	$\sim 5 \times 10^{-3}$	$0.08 \dots 0.15$	$10^{-12} \dots 26$

[Buras et al, 1006.5356]

★ Most models predict/accommodate extensive ranges for observables

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

★ But... Peculiar patterns of correlation of observables (model-specific)

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

LFV from m_ν in extended frameworks

Interplay between high and low-energy observables

An example: the supersymmetric seesaw(s) and cLFV

A A, A. Figueiredo, J. Romao, A.M. Teixeira

SUSY seesaw(s) and cLFV

- 👉 Embed seesaw in the framework of (otherwise) **flavour-conserving SUSY models**
(cMSSM, supergravity-inspired, etc)
- ★ **mSUGRA-like SUSY seesaw:** Y^ν unique source of LFV → observables strongly related
 - * **low-energies:** $l_j \rightarrow l_i \gamma$, $l_j \rightarrow 3l_i$, $\mu - e$ in Nuclei ⇒ large rates [MEG,...]
 - * **high-energies:** study charged sleptons from $\chi_2^0 \rightarrow \ell^\pm \ell^\mp \chi_1^0$ decays [LHC, LC]
 - ⇒ sizable $\tilde{e} - \tilde{\mu}$ mass difference, new edges in $m_{\ell\ell}$: $\chi_2^0 \rightarrow \tilde{\ell}_X^j \ell_i \rightarrow \chi_1^0 \ell_i \ell_i$ [LHC]
 - ⇒ potential signal of cLFV $e^+ e^- \rightarrow e^\pm \mu^\mp + 2\chi^0$, $e^- e^- \rightarrow e^- \mu^- + 2\chi^0$ [LC]
- ★ Even if correlations, etc... - difficult to disentangle from “generic” MSSM cLFV...
On the other hand ⇒ some scenarios are falsifiable!

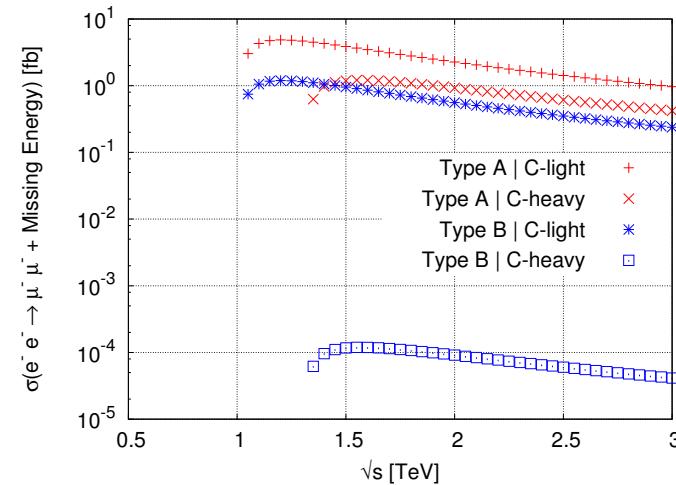
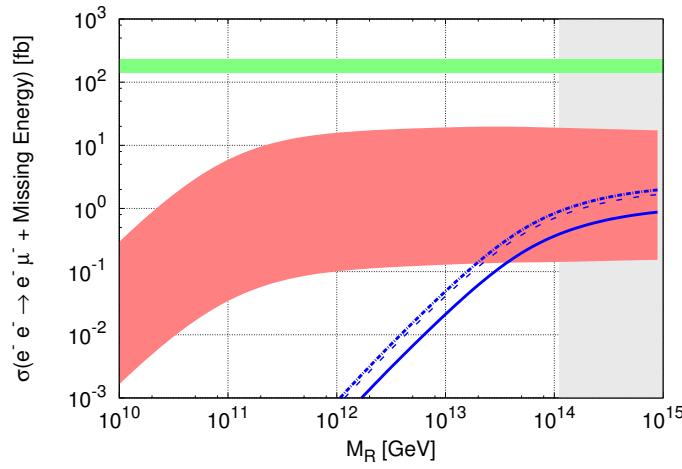
Type I SUSY seesaw cLFV in a Linear collider

👉 LFV also at a Linear collider

$$e^+ e^- \rightarrow \begin{cases} e^+ \mu^- + 2 \chi_1^0 \\ e^+ \mu^- + 2 \chi_1^0 + (2, 4) \nu \\ e^+ \mu^- + (2, 4) \nu \end{cases} \quad e^- e^- \rightarrow \begin{cases} e^- \mu^- + 2 \chi_1^0 \\ e^- \mu^- + 2 \chi_1^0 + (2, 4) \nu \\ e^- \mu^- + (2, 4) \nu \end{cases}$$

Signal
SUSY BKG
SM BKG

★ Golden Channel $e^- e^- \rightarrow \mu^- \mu^- + E_{\text{miss}}^T$ Majorana nature of neutral exchanged superparticle



Type I SUSY seesaw cLFV: from χ_2^0 decays in LHC

☞ **cMSSM** (no seesaw): $\chi_2^0 \rightarrow \tilde{\ell}_{L,R}^i \ell^i \rightarrow \chi_1^0 \ell_i^+ \ell_i^-$

- ★ **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:** $\chi_2^0 \rightarrow \tilde{\ell}_{L,R}^i \ell^j \rightarrow \chi_1^0 \ell_j^+ \ell_i^-$

- ★ **Displaced** $m_{ee}, m_{\mu\mu}$ edges \Rightarrow **slepton mass splittings** $\frac{\Delta m_{\tilde{\ell}}}{m_{\tilde{\ell}}}(\tilde{e}_L, \tilde{\mu}_L) \sim \mathcal{O}(10\%)$

strongly correlated with low-energy cLFV: $\text{BR}(\ell_i \rightarrow \ell_j \gamma) \leftrightarrow \frac{\Delta m_{\tilde{\ell}}}{m_{\tilde{\ell}}}(\tilde{\ell}_i, \tilde{\ell}_j)$

- ★ **New edges** in di-lepton mass distributions (LHC): $\chi_2^0 \rightarrow \left\{ \begin{array}{l} \tilde{\ell}_L^i \ell_i \\ \tilde{\ell}_R^i \ell_i \\ \tilde{\ell}_X^j \ell_i \end{array} \right\} \rightarrow \chi_1^0 \ell_i \ell_i$

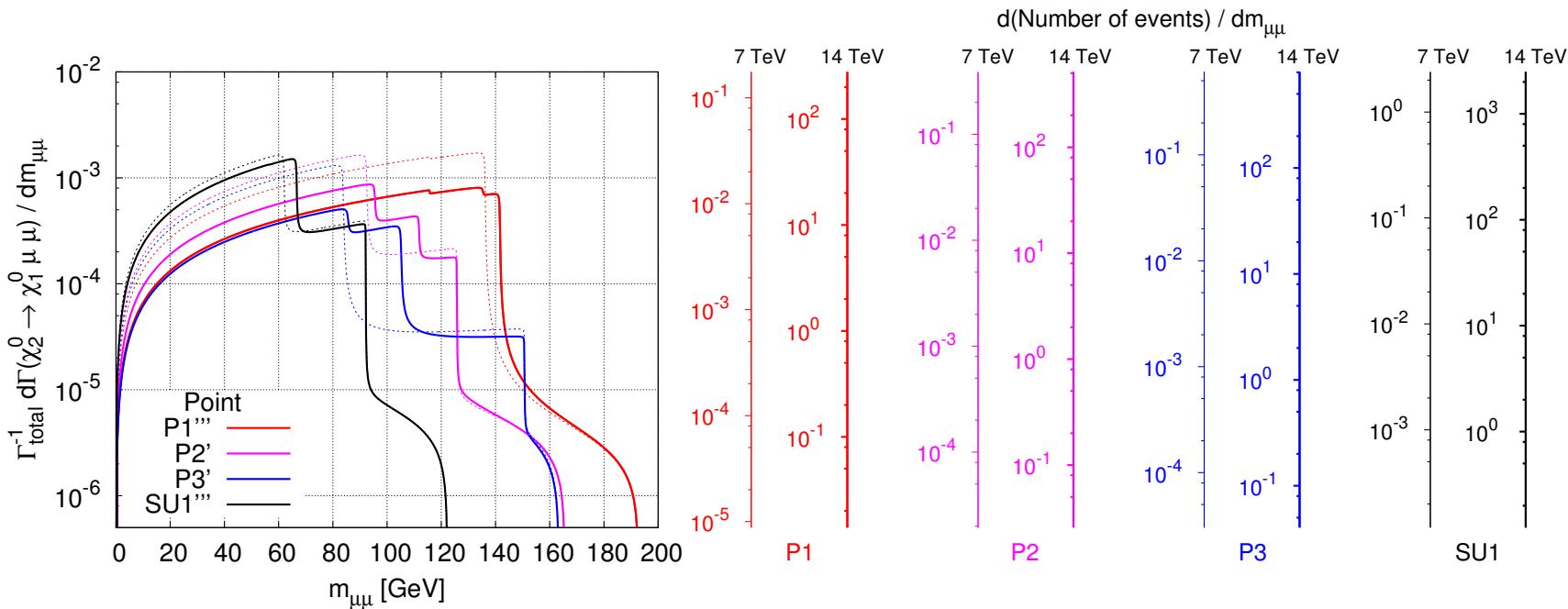
→ Possible **direct FV** in neutralino and slepton decays: $\chi_2^0 \rightarrow \ell_i \ell_j \chi_1^0$

LFV at the LHC: di-lepton distributions in χ_2^0 decays

👉 CMSSM (no seesaw)

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

👉 Impact of type-I SUSY seesaw



- ★ Displaced $m_{\mu\mu}$ and m_{ee} edges ($\tilde{\ell}_L$) \Leftrightarrow 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 low- and high-energies: strategies to probe seesaw

Working Hypothesis: mSUGRA-like cMSSM and type-I seesaw

discovery of **SUSY** at **LHC** (reconstruction of $\mathcal{L}_{\text{SUSY}}\dots$)

one source of flavour violation

SUSY seesaw: $\Delta m(\tilde{e}_L, \tilde{\mu}_L)$, within LHC reach, *correlated with*

$\text{BR}(\mu \rightarrow e\gamma)$ & $\text{CR}(\mu - e, \text{Ti})$ & $\text{BR}(\tau \rightarrow \mu\gamma)$ within **future sensitivity**

⇒ Intensely explore synergy of **LFV at low-energies and at the LHC!**

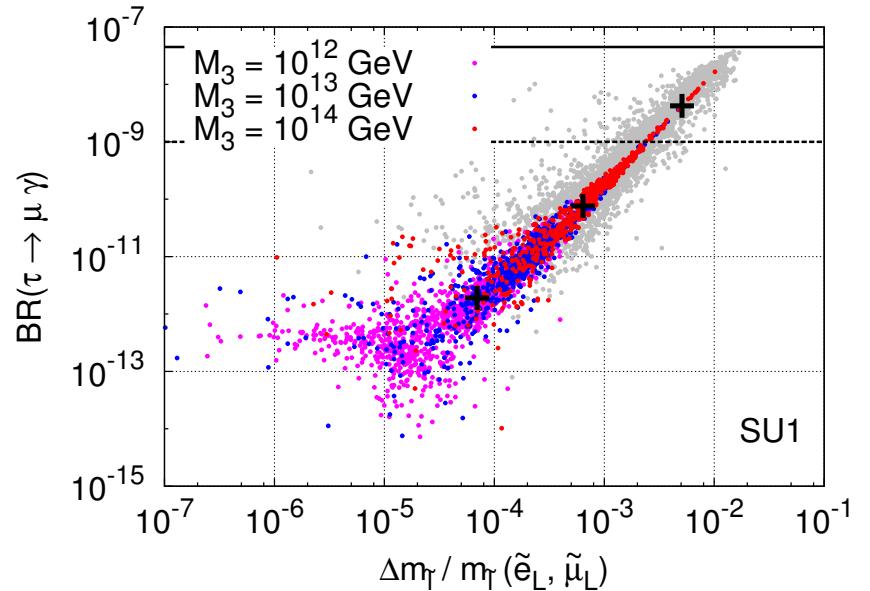
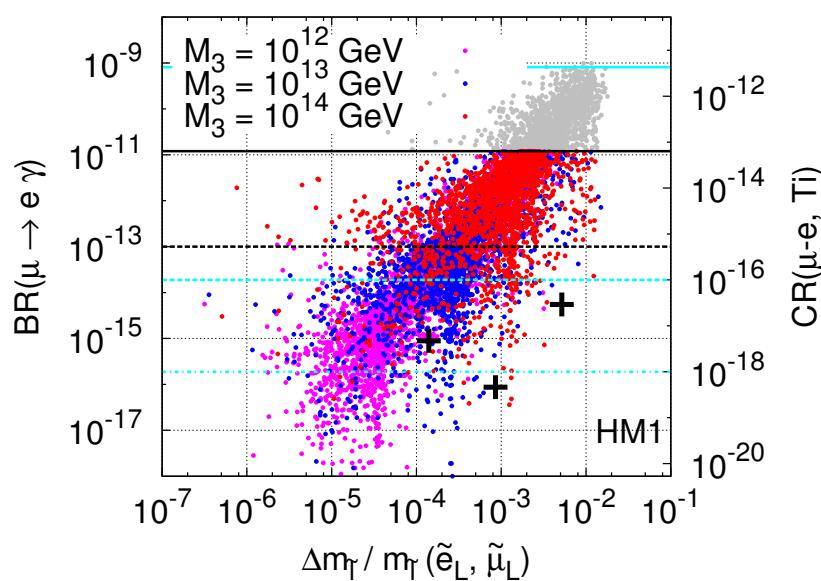
★ $\Delta m(\tilde{e}_L, \tilde{\mu}_L)|_{\text{LHC}}$ and compatible $\text{BR}(\mu \rightarrow e\gamma)|_{\text{MEG}}$, $\text{BR}(\tau \rightarrow \mu\gamma)|_{\text{Belle II}}$

⇒ strengthen seesaw hypothesis

★ $\Delta m(\tilde{e}_L, \tilde{\mu}_L)|_{\text{LHC}}$ excluded by BRs, CR or observed BRs/CR for negligible Δm

⇒ suggests distinct (or additional) source of flavour violation

LFV at low- and high-energies: general overview



If type-I seesaw indeed at work and SUSY

- ★ LFV observables **within experimental reach**;
- ★ $\Delta m(\tilde{e}_L, \tilde{\mu}_L)|_{\text{LHC}} \sim (0.1 - 1)\%$ $\rightarrow BR(\mu \rightarrow e\gamma)|_{\text{MEG}}$
- ★ $\Delta m(\tilde{e}_L, \tilde{\mu}_L)|_{\text{LHC}} \sim (0.1 - 1)\% \Rightarrow BR(\tau \rightarrow \mu\gamma) \gtrsim 10^{-9}$ (Super Belle ?)
 \Rightarrow Hint towards scale of new physics ($M_{N_3} \gtrsim 10^{13} \text{ GeV}$)

Conclusions

- ★ Flavour violation in quarks and neutral leptons..., expected in the charged lepton sector
- ★ cLFV observables can provide (indirect) information on the underlying NP model
- ★ New Physics can be manifest via cLFV even before any direct discovery!
- ★ Numerous observables of different origin, infer pattern, correlation if unique LFV source

Common tool: Interplay between high and low-energy observables.

Rich phenomenology from cLFV observables.