LPT-Orsay

BSM Neutrino Physics confronted to LHC

- Neutrino data call for BSM
- Neutrino mass generation mechanisms
- Impact on observables, direct and indirect signatures
- High-energy / low-energy Complementarity

Les Rencontres de Blois, 26-31 May 2013

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☞ **Facts:** ν change flavours after propagating a finite distance

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

☞ **Indisputable:** νs are massive and mix

→ The minimal SM is incomplete!

▶ ν mixings pour oil on fire: add to the fermion flavour puzzle!

$$U_{CKM} = \begin{pmatrix} 1-\lambda^2/2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\lambda^2/2 & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix}, \lambda \sim 0.2, A \simeq 0.8, \rho \simeq 0.1, \eta \simeq 0.4$$

$\longrightarrow$ Quarks: small mixing angles, 1 Dirac CPV phase

$$U_{PMNS} = \begin{pmatrix} c_{13}c_{12} & c_{13}s_{12} & s_{13}e^{-i\delta} \\ -c_{23}s_{12} - s_{23}s_{13}c_{12}e^{i\delta} & c_{23}c_{12} - s_{23}s_{13}s_{12}e^{i\delta} & -s_{23}c_{13} \\ s_{23}s_{12} - c_{23}s_{13}c_{12}e^{i\delta} & -s_{23}c_{12} - c_{23}s_{13}s_{12}e^{i\delta} & c_{23}c_{13} \end{pmatrix} \times \mathrm{diag}\left(1, e^{i\alpha}, e^{i\beta}\right) ,$$

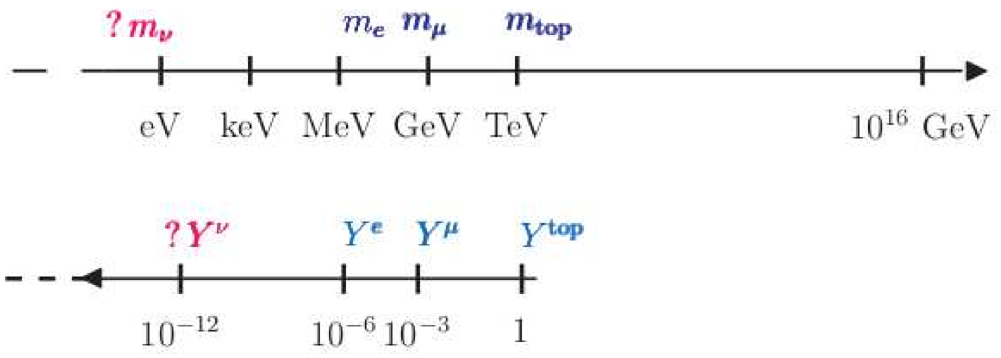
$\longrightarrow$ Leptons: 2 large mixing angles, 1 Dirac + 2 Majorana CPV phases

$\Longrightarrow$ Different mixing pattern for Leptons and Quarks

→ Is this related to lepton number violation and Majorana nature of νs?

- ν data make fermion hierarchy worse!

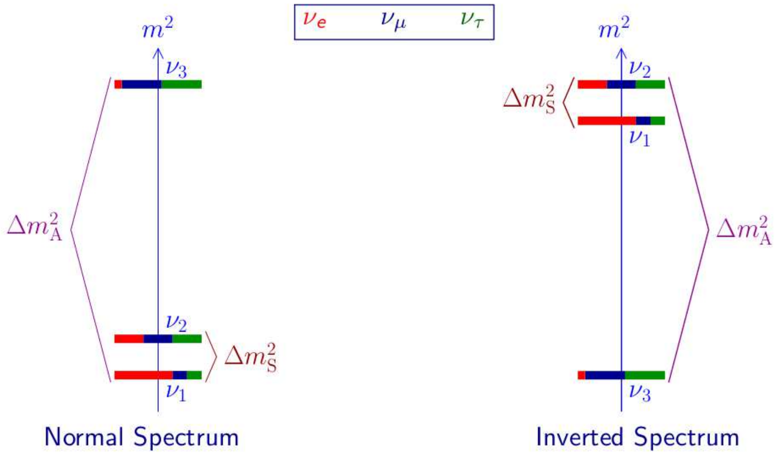
→ Why ν are so light?



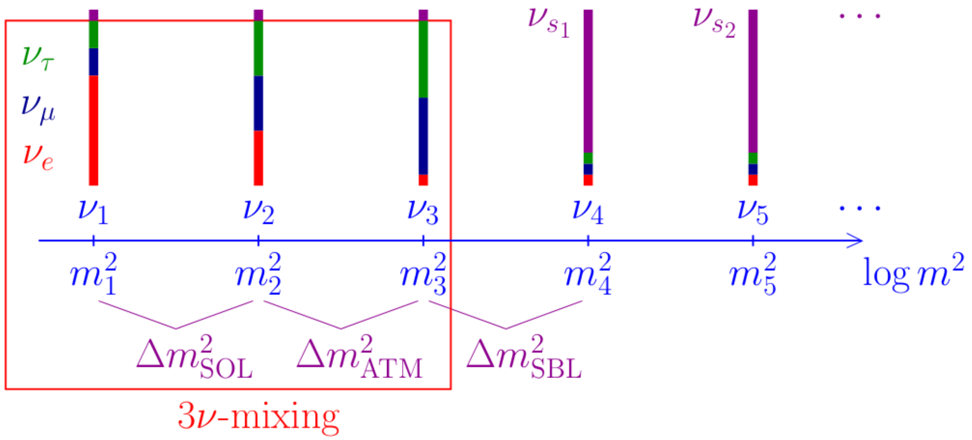
→ What is the absolute neutrino mass scale?

Oscillations	$m_{\nu_i} > \sqrt{\Delta m^2_{\rm atm}} \sim 5 \times 10^{-2}$ eV
Cosmology	$\sum_i m_{\nu_i} \lesssim$ eV
Tritium	$m_{\nu_e} \lesssim 2.2$ eV

- Are there some extra fermionic gauge singlets (steriles)?



3-ν mixing scheme

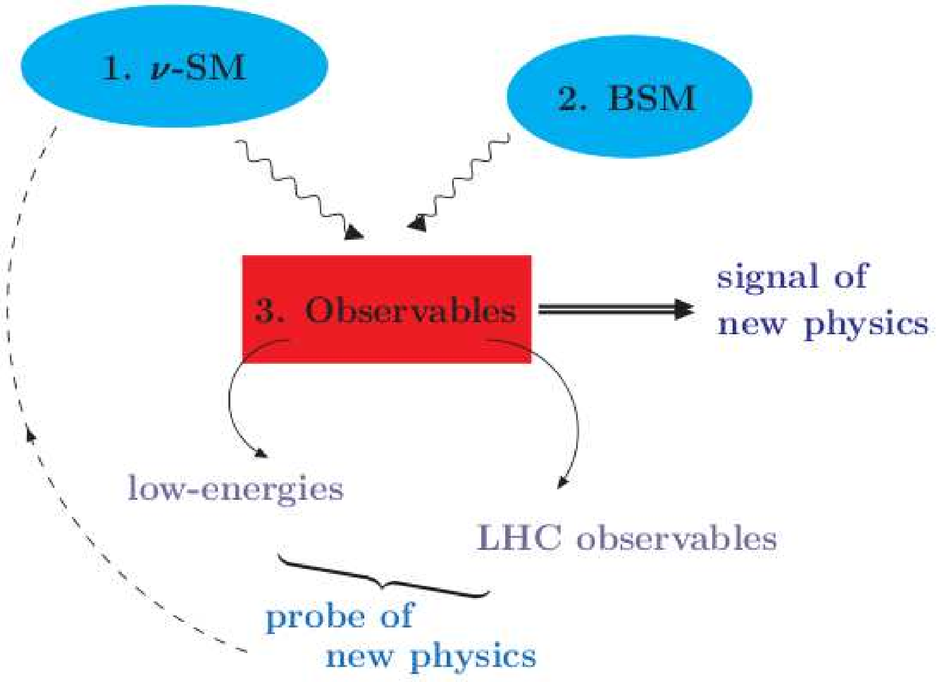


3+?-ν mixing schemes

→ Does this mean that U_{PMNS} is incomplete? Non Unitary ?

- ☞ SM cannot accommodate all these (ν) data ➙ **ν-SM (BSM)**
- ☞ **ν**-SM just to explain ν masses and mixings
  - Need other d.o.f, for instance Right-Handed Neutrinos
  - ν can be of Majorana nature ➙ **New physics scale $\neq$ EW scale**
  - what is the rôle of leptonic CP Violating phases? and what are they?
  - what is the hierarchy in the light neutrino spectrum?
  - unitarity violation? NSI, ...
- ☞ ν-SM will allow for many new phenomena
  - LFV in neutral sector. Why not in the charged sector? $\ell_i \to \ell_j\ \ell_k\ \ell_l$, $\ell_i \to \ell_j \gamma$, ...
  - Contributions to $g-2$, Lepton EDMs
  - Collider searches for new heavy states ...
- ☞ 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 ....

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



☞ How to proceed? Ingredients, Observables, Strategies

- Ingredients:
  1. mass generation mechanism (seesaw, radiative corrections, extra dim, ...)
  2. 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** ($\mu \to e\gamma$, $\mu \to eee$, $\mu - e$ (Nuclei), ...)
  - **Meson decays: violation of lepton flavour universality, LFV final states**

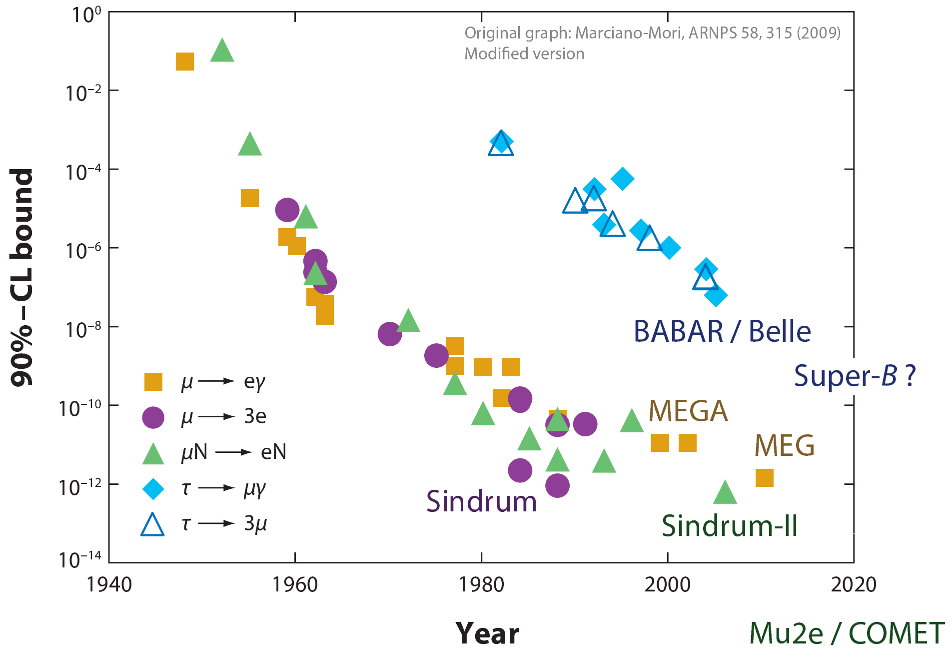
    lepton Number violating decays
  - **Rare (new) heavy particle decays (typically model-dependent):**

    $\Delta^{\pm\pm} \to \mu_i^{\pm}\, \tau_j^{\pm}$, $\chi_2^0 \to \chi_1^0 \,\tau\, \mu$, $H \to \tau\mu$, ...

    impact of LFV for new physics searches at colliders, ...
  - CP violation in the leptonic sector

Lepton Flavour Violation

- **A world-wide experimental effort** $>$ 60 years!



Process	present bound	future	
$\mu \to e\gamma$	2.4×10^{-12}	10^{-14}	MEG at PSI
$\mu \to eee$	1.0×10^{-12}	10^{-14}	Mu3e at PSI
$\mu - e$ (Au)	7×10^{-13}	–	SINDRUM-II
$\mu - e$ (Al)	–	10^{-16}	Mu2e/COMET
$\mu - e$ (Ti)	4.3×10^{-12}	10^{-18}	PRISM
$\tau \to e\gamma$	1.1×10^{-7}	$10^{-9} - 10^{-10}$	super KEKB/B
$\tau \to e\gamma$	3.6×10^{-8}	$10^{-9} - 10^{-10}$	super KEKB/B
$\tau \to \mu\gamma$	4.5×10^{-8}	$10^{-9} - 10^{-10}$	super KEKB/B
$\tau \to \mu\mu\mu$	3.2×10^{-8}	$10^{-9} - 10^{-10}$	super KEKB/B

(super) LHCb

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**

- **cLFV observed: compare with peculiar features of given model**

  ⇒ **predictions** for **cLFV observables**

  ⇒ **intrinsic patterns** of **correlations of observables**

- **Which New Physics ?**

  Generic BSM general MSSM, LHT, RS Extra D, ...

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

- **Use Effective Approach to study a given observable (cLFV)** - Model Independent

Effective approach

- Neutrino masses require new fields (or extremely tiny Y_ν)
- Effects at low energy: effective theorie approach

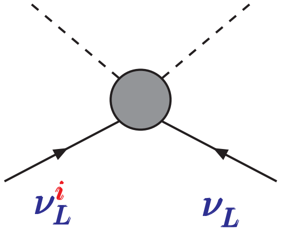
Effective operators obtained when expanding the heavy field propagators in $\frac{1}{M}$

☞ heavy fermion: $\frac{1}{\not{D}-M} \sim -\frac{1}{M} - \frac{1}{M}\not{D}\frac{1}{M} + \ldots$

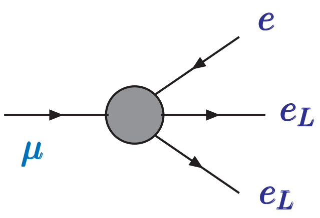
☞ heavy scalar : $\frac{1}{D^2-M^2} \sim -\frac{1}{M^2} - \frac{D^2}{M^4} + \ \ldots$

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

$\Delta\mathcal{L}^{d\geq5} = \frac{c^{d=5}}{M} \times$



$+ \frac{c^{d=6}_{\mu eee}}{M^2} \times$



$+ \frac{c^{d=6}_{\ell_i\ell_j\gamma}}{M^2} \ldots$

Distinguishing among BSM of Majorana neutrinos

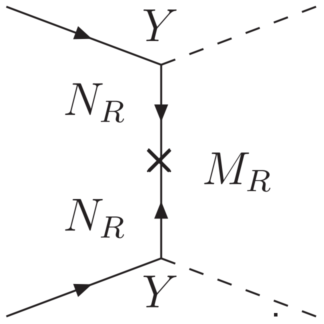
- The $\mathcal{O}^{d=5}$ operator is the same for all extensions incorporating massive MAJORANA neutrinos
- To distinguish among the SM extensions

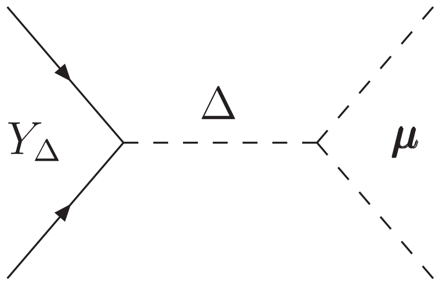
☞ **Study phenomenological fingerprints of $\mathcal{O}^{d=6}$ operators** (differ from model to model)

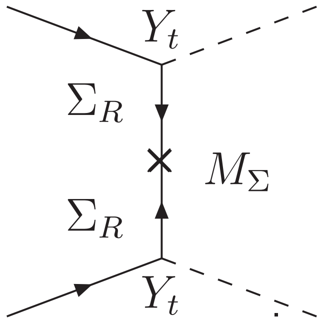
e.g. $\mu \to e\gamma$, $\ell \to \ell_i \ell_j \ell_k$, $\mu - e$ CR, unitarity violation, NSI, EW precision, t physics (LHC), ...

☞ **A specific example: Seesaw type II**

Generating tree level $\mathcal{O}^{d=5}$: Seesaw I, II, III







type I (fermionic singlet)

$$\boldsymbol{m_\nu} = -\tfrac{1}{2}v^2\, Y_N^T \frac{1}{M_N} Y_N$$

type II (scalar triplet)

$$\boldsymbol{m_\nu} = -2v^2 Y_\Delta \frac{\mu_\Delta}{M_\Delta^2}$$

type III (fermionic triplet)

$$\boldsymbol{m_\nu} = -\frac{v^2}{2} Y_\Sigma^T \frac{1}{M_\Sigma} Y_\Sigma$$

Minkowski, Gell-Man,

Ramond, Slansky

Yanagida, Glashow

Mohapatra, Senjanovic

Magg, Wetterich,

Nussinov

Mohapatra, Senjanovic

Schechter, Valle

Ma, Sarkar

Ma, Hambye et al.

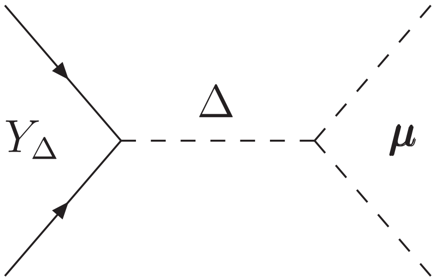
Bajc, Senjanovic, Lin

A.A., Biggio, Bonnet, Gavela,

Notari, Strumia, Papucci, Dorsn

Fileviez-Perez, Foot, Lew...

Case of scalar triplet (type II)



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

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:

$$\mu \; \phi^t_a \phi_b (i\tau_2\tau_\alpha) \left(\Delta^\dagger\right)^\alpha + h.c.$$

$$-M^2_\Delta \Delta^\dagger\Delta - \tfrac{1}{2}\lambda_2 \left(\Delta^\dagger\Delta\right)^2$$

$$-\lambda_3 \left(\phi^\dagger\phi\right)\left(\Delta^\dagger\Delta\right) + \ldots$$

d=5 Operator (Mass)

$$m_\nu = v^2 \, Y_\Delta \, \frac{\mu}{M^2_\Delta}$$

➔ 2 different scales μ, M_Δ

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

Low energy effects of dimension 6 operators:

$\frac{1}{2M_\Delta^2} Y_{\Delta ij} Y^\dagger_{\Delta kl} \left(\overline{l_{Li}} \gamma^\mu l_{Lk}\right) \left(\overline{l_{Lj}} \gamma_\mu l_{Ll}\right)$ → LFV, $g-2$, EDMs

constraints not suppressed by μ

$$\left.\begin{array}{l} -2\frac{\mu^2}{M_\Delta^4}\partial_\mu\left(\phi^\dagger\phi\right)\partial^\mu\left(\phi^\dagger\phi\right) \\ \\ 2\lambda_3\frac{\mu^2}{M_\Delta^4}\left(\phi^\dagger\phi\right)^3 \\ \\ 4\frac{\mu^2}{M_\Delta^4}\left[\phi^\dagger D_\mu\phi\right]^\dagger\left[\phi^\dagger D_\mu\phi\right] \end{array}\right\} \rightarrow$$

EW precision data,
couplings to gauge bosons

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

Reconstructing the Lagrangian?

- **Scalar triplet: bounds from low energy constraints**

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

☞ If observation of $\mu \to e\gamma$ at MEG (sensitivity of 10^{-13}?)

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

- **Scalar triplet: bounds form LHC**

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

LHC constraints on scalar triplet

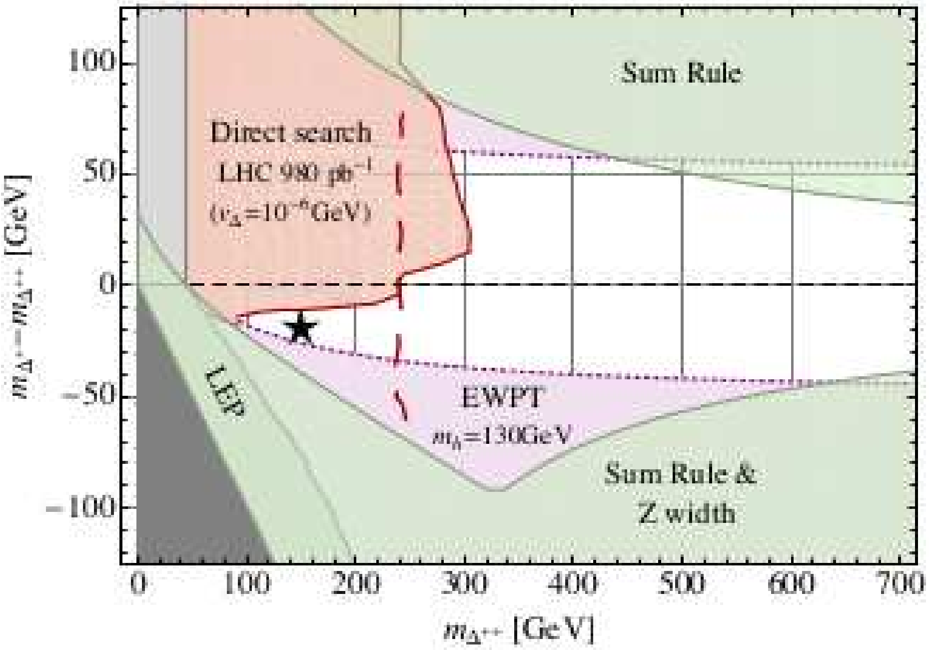
★ Production of Δ^{++} and Δ^{--}, decaying into pairs of same-sign leptons

➞ striking signals, free from SM backgrounds

- ▶ Drell-Yann Production $\begin{cases} M_{\Delta^{++}} \sim 200 \text{ GeV} \Rightarrow \ \sigma(\gamma^*, Z^* \to \Delta^{++}\Delta^{--}) \sim 100 \text{ fb} \\ M_{\Delta^{++}} \sim 900 \text{ GeV} \Rightarrow \ \sigma(\gamma^*, Z^* \to \Delta^{++}\Delta^{--}) \sim 0.1 \text{ fb} \end{cases}$

- ▶ Decay product $\begin{cases} \Gamma(\Delta^{\pm\pm} \to W^\pm W^\pm) \sim \mu^2 M_\Delta^3 \\ \Gamma(\Delta^{\pm\pm} \to \ell_i^\pm \ \ell_j^\pm) \sim Y_{\Delta ij} M_\Delta \end{cases}$

➞ **LHC:** so far, only **negative search** results ⇒ **constraints on parameter space** $(M_\Delta, \mu, Y_\Delta)$

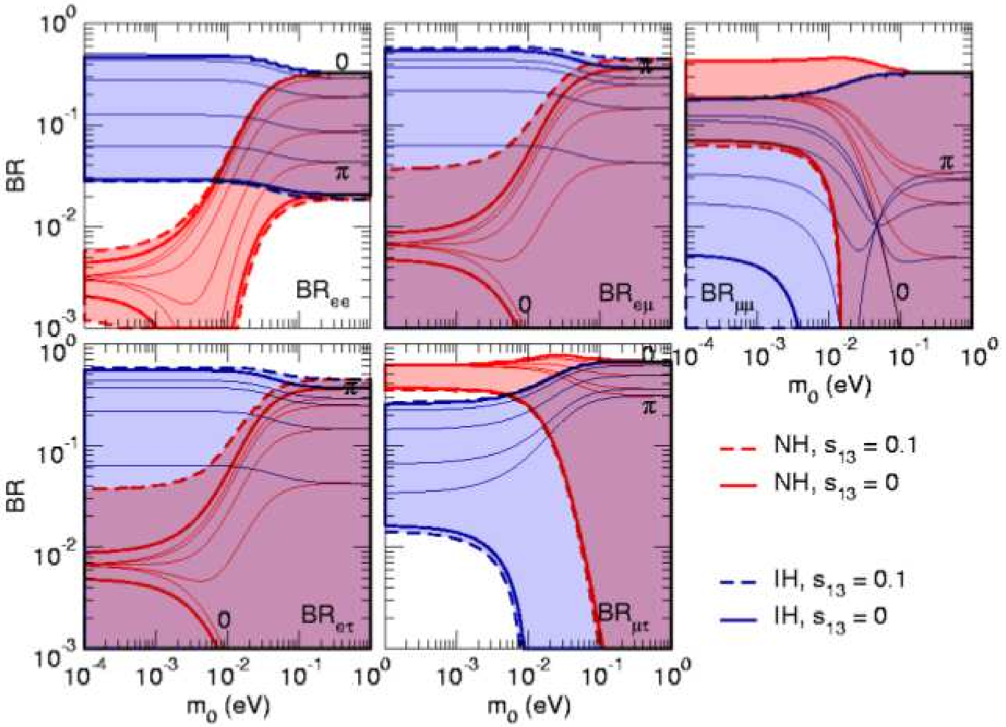


Melfo et.al., arXiv:1108.4416

LFV predictions for ν mass spectrum

- LFV in high-energy (LHC) + low-energy observables (e.g $\mu \to eee$)

$\Rightarrow$ **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

$\Rightarrow$ observe in addition at least three LFV processes (to measure and disentangle the individual $Y_{\Delta ij}$ couplings)

[Reconstruction of the Lagrangian at best only partially...]

Generic examples of such BSM extensions (m_ν + cLFV)

★ m_ν + mixings and cLFV in Little Higgs models (T-parity)

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

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

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

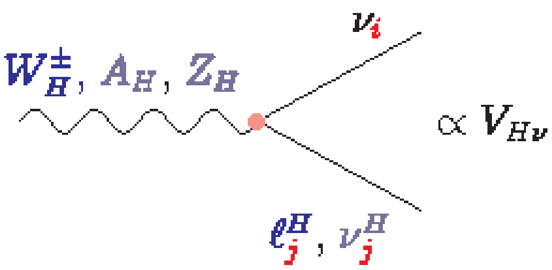
- **T parity** ⇒ prevents contributions to **EW observables** (tree-level)

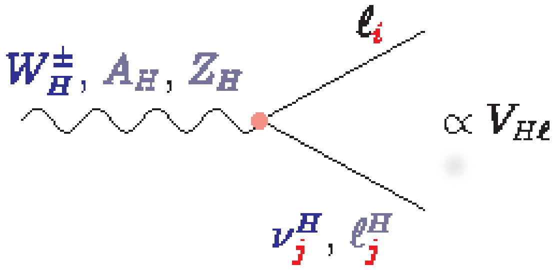
  Lightest T-odd particle stable ⇝ **dark matter candidate**

- **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

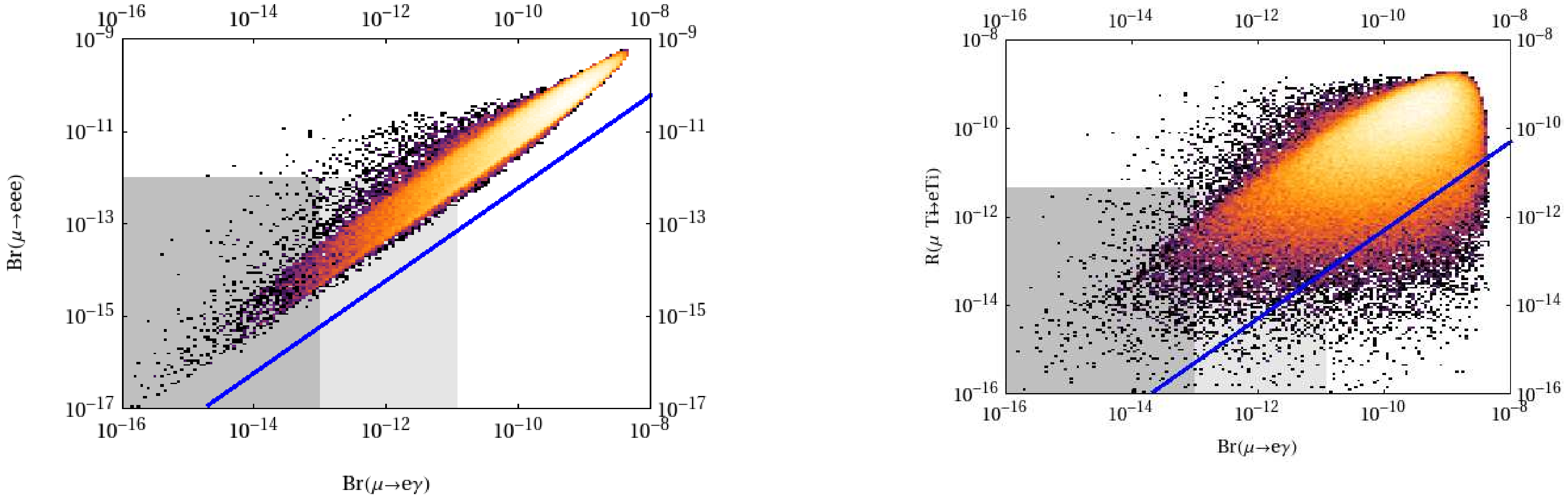




$$V_{H\nu}^\dagger V_{H\ell} = U_{\mathrm{PMNS}}^\dagger$$

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

★ m_ν + mixings and cLFV in Little Higgs models



[Blanke et al, 0906.5454]

- **Strong correlation** of some cLFV observables: $\mu \to e\gamma$ **and** $\mu \to 3e$
- **Asymmetries** for **polarised τ and μ** decays $\leftrightsquigarrow$ **chirality structure of LHT**

  [Goto et al, 1012.4385]

- Typically **large contributions to cLFV** $\rightsquigarrow$ some **fine-tuning required**

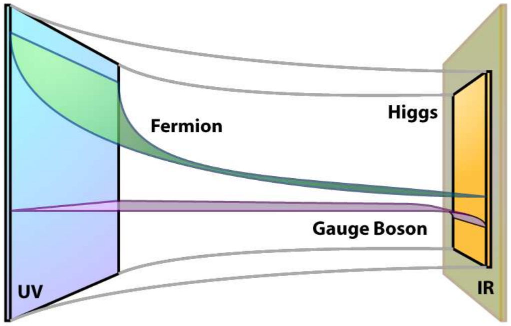
  hierarchical mixing matrices $(V_{H\ell}, V_{H\nu})$, quasi degenerate states, ...

★ 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 $\leftrightsquigarrow$ overlap of wave functions



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

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

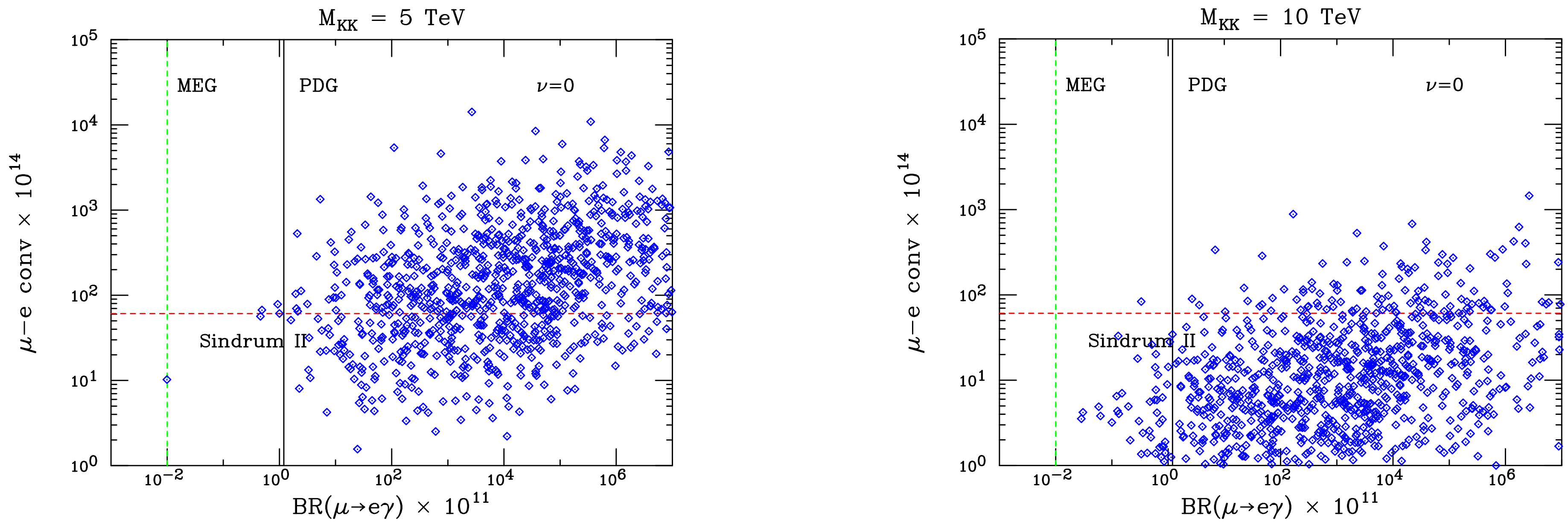
- **Circumvent pheno issues:** enlarge **bulk symmetry** (prevent violation of custodial SU(2));

  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]

★ m_ν + mixings and cLFV in RS warped extra dimensions



[Agashe et al, 0606021]

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

- ▶ **Electroweak precision observables: $M_{KK} \geq 3$ TeV ;**

  cLFV: $M_{KK} > 10$ **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)

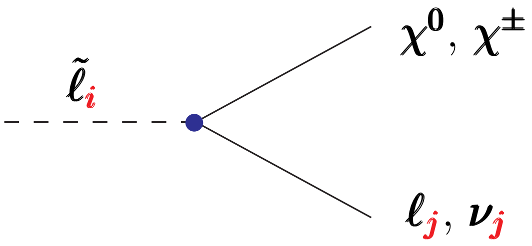
  non-diagonal masses for sleptons and sneutrinos $\quad (M^2_{\tilde{\ell}})_{ij} \neq 0! \quad (M^2_{\tilde{\nu}})_{ij} \neq 0!$

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

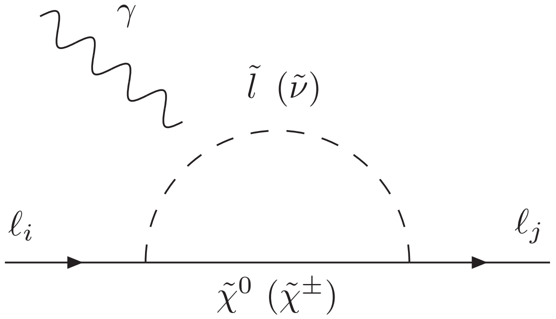
  $$\{\tilde{e}_L,\, \tilde{\mu}_L,\, \tilde{\tau}_L,\, \tilde{e}_R,\, \tilde{\mu}_R,\, \tilde{\tau}_R\} \quad \not\leftrightarrow \quad \{\tilde{\ell}_1,\, \ldots,\, \tilde{\ell}_6\}$$

  manifest in **neutral** and

  charged lepton-slepton interactions



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



- Sizable contributions to cLFV observables $\propto \delta^{\ell}_{ij} = \dfrac{(M^2_{\tilde{\ell}})_{ij}}{M^2_{\text{SUSY}}}$

"almost everything is possible - depending on the regime"...

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

[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
$\frac{\text{BR}(\mu\to eee)}{\text{BR}(\mu\to e\gamma)}$	$0.02\ldots 1$	$\sim 6\times 10^{-3}$	$\sim 6\times 10^{-3}$	$0.06\ldots\mathbf{2.2}$
$\frac{\text{BR}(\tau\to eee)}{\text{BR}(\tau\to e\gamma)}$	$0.04\ldots 0.4$	$\sim 1\times 10^{-2}$	$\sim 1\times 10^{-2}$	$0.07\ldots\mathbf{2.2}$
$\frac{\text{BR}(\tau\to \mu\mu\mu)}{\text{BR}(\tau\to \mu\gamma)}$	$0.04\ldots 0.4$	$\sim 2\times 10^{-3}$	$0.06\ldots 0.1$	$0.06\ldots\mathbf{2.2}$
$\frac{\text{BR}(\tau\to e\mu\mu)}{\text{BR}(\tau\to e\gamma)}$	$0.04\ldots 0.3$	$\sim 2\times 10^{-3}$	$0.02\ldots 0.04$	$0.03\ldots\mathbf{1.3}$
$\frac{\text{BR}(\tau\to \mu ee)}{\text{BR}(\tau\to \mu\gamma)}$	$0.04\ldots 0.3$	$\sim 1\times 10^{-2}$	$\sim 1\times 10^{-2}$	$0.04\ldots\mathbf{1.4}$
$\frac{\text{BR}(\tau\to eee)}{\text{BR}(\tau\to e\mu\mu)}$	$0.8\ldots 2$	$\boldsymbol{\sim 5}$	$0.3\ldots 0.5$	$1.5\ldots 2.3$
$\frac{\text{BR}(\tau\to \mu\mu\mu)}{\text{BR}(\tau\to \mu ee)}$	$0.7\ldots 1.6$	~ 0.2	$5\ldots 10$	$1.4\ldots 1.7$
$\frac{\text{CR}(\mu\,\text{Ti}\to e\,\text{Ti})}{\text{BR}(\mu\to e\gamma)}$	$10^{-3}\ldots 10^{2}$	$\sim 5\times 10^{-3}$	$0.08\ldots 0.15$	$10^{-12}\ldots 26$

[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 **disentagle 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:** $l_j \to l_i \gamma$, $l_j \to 3 l_i$, $\mu - e$ **in Nuclei** ⇒ **large rates** **[MEG,...]**
  - ⋆ **high-energies:** study **charged sleptons** from $\chi_2^0 \to \ell^\pm \ell^\mp \chi_1^0$ decays **[LHC, LC]**
    - ⇒ **sizable** $\tilde{e} - \tilde{\mu}$ **mass difference**, new edges in $m_{\ell\ell}$: $\chi_2^0 \to \tilde{\ell}^j_X \, \ell_i \to \chi_1^0 \, \ell_i \, \ell_i$ **[LHC]**
    - ⇒ **potential signal of cLFV** $e^+ e^- \to e^\pm \mu^\mp + 2\chi^0$, $e^- e^- \to e^- \mu^- + 2\chi^0$ **[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

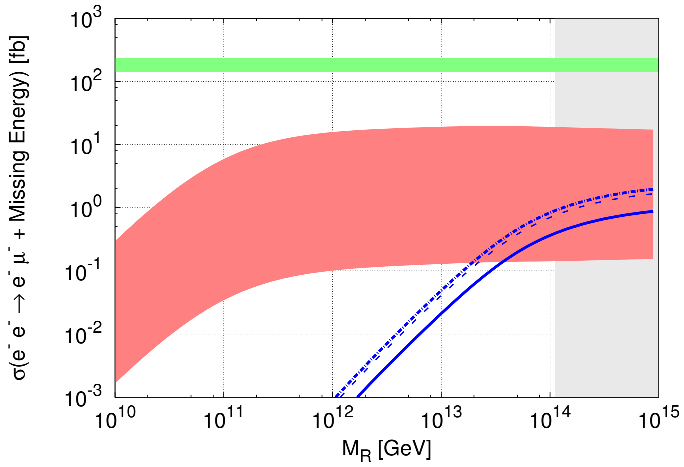
$$e^+ e^- \rightarrow \begin{cases} e^+ \mu^- + 2\,\chi_1^0 \\ e^+ \mu^- + 2\,\chi_1^0 + (2,4)\,\nu \\ e^+ \mu^- + (2,4)\,\nu \end{cases} \qquad e^- e^- \rightarrow \begin{cases} e^- \mu^- + 2\,\chi_1^0 \\ e^- \mu^- + 2\,\chi_1^0 + (2,4)\,\nu \\ e^- \mu^- + (2,4)\,\nu \end{cases}$$

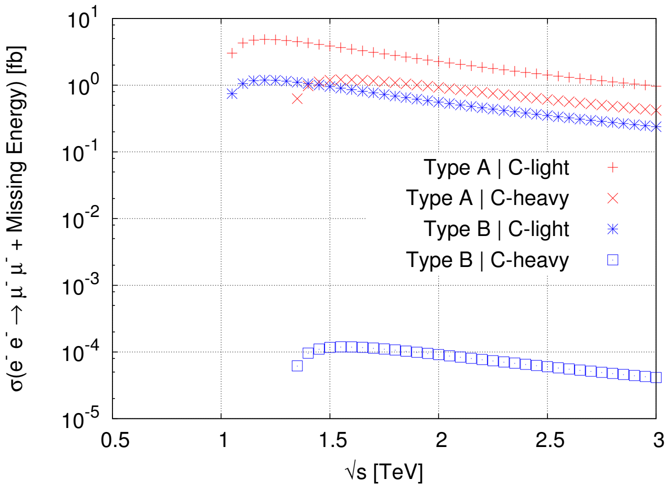
Signal

SUSY BKG

SM BKG

▶ Golden Channel $e^- e^- \rightarrow \mu^- \mu^- + E^T_{\text{miss}}$ Majorana nature of neutral exchanged superparticule





A A, A. Figueiredo, J. Romao, A.M. Teixeira, arXiv:1206.2306

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

☞ **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**: $\chi_2^0 \to \tilde{\ell}^i_{L,R}\,\ell^j \to \chi_1^0 \ell_j^+\,\ell_j^-$

▶ **Displaced** m_{ee}, $m_{\mu\mu}$ edges ⇒ **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: $\text{BR}(\ell_i \to \ell_j \gamma) \leftrightarrow \frac{\Delta m_{\tilde{\ell}}}{m_{\tilde{\ell}}}(\tilde{\ell}_i, \tilde{\ell}_j)$

▶ **New edges** in di-lepton mass distributions (LHC): $\chi_2^0 \to \left\{ \begin{array}{l} \tilde{\ell}^i_L\,\ell_i \\ \tilde{\ell}^i_R\,\ell_i \\ \tilde{\ell}^j_X\,\ell_i \end{array} \right\} \to \chi_1^0\,\ell_i\,\ell_i$

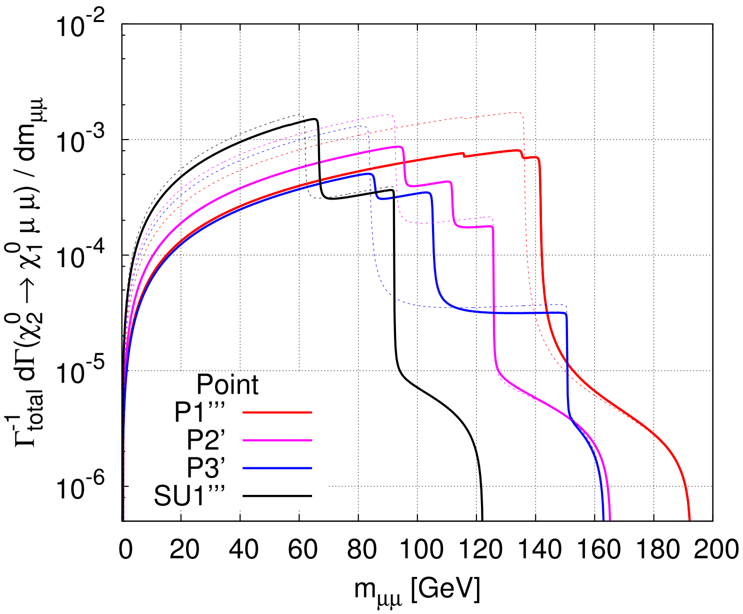
➞ Possible **direct FV** in **neutralino and slepton decays:** $\chi_2^0 \to \ell_i\,\ell_j\,\chi_1^0$

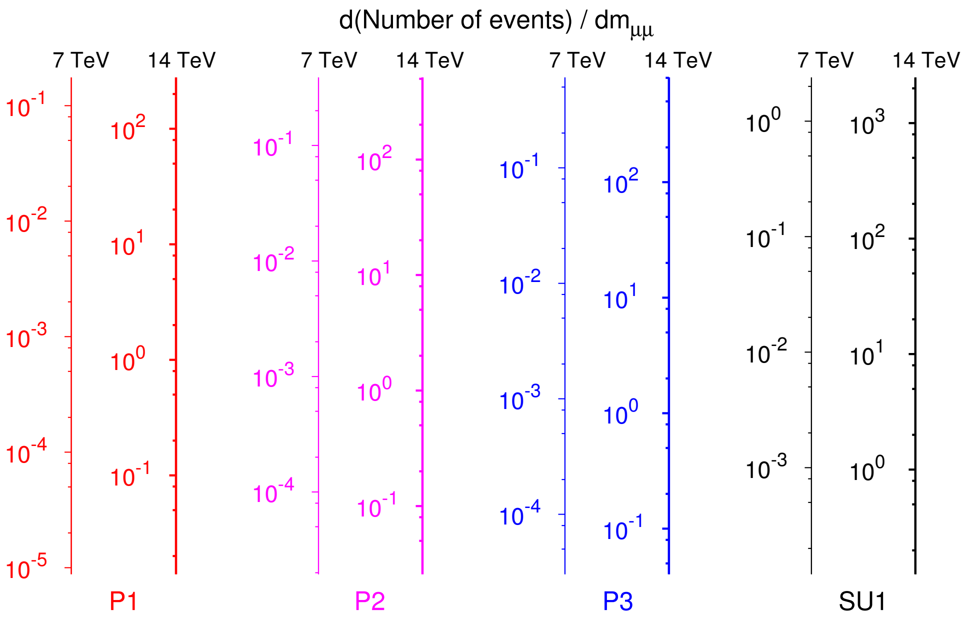
LFV at the LHC: di-lepton distributions in χ_2^0 decays

☞ CMSSM (no seesaw)

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





- ▶ **Displaced $m_{\mu\mu}$ and m_{ee} edges** $(\tilde{\ell}_L) \Leftrightarrow$ **sizable** $\frac{\Delta m_{\tilde{\ell}}}{m_{\tilde{\ell}}}(\tilde{e}_L\,,\tilde{\mu}_L)$ [⇝ flavour non-universality (?)]
- ▶ Appearance of **new edge** in $m_{\mu\mu}$ **: intermediate $\tilde{\tau}_2$** [⇝ flavour **violation!**]

A A, A. Figueiredo, J. Romao, A.M. Teixeira, arXiv:1007.48336

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 $\mathcal{L}_{\text{SUSY}}$...)

one source of flavour violation

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

BR($\mu \to e\gamma$) & CR($\mu - e$, Ti) & BR($\tau \to \mu\gamma$) within **future sensitivity**

$\Rightarrow$ **Intensely explore synergy** of **LFV at low-energies and at the LHC!**

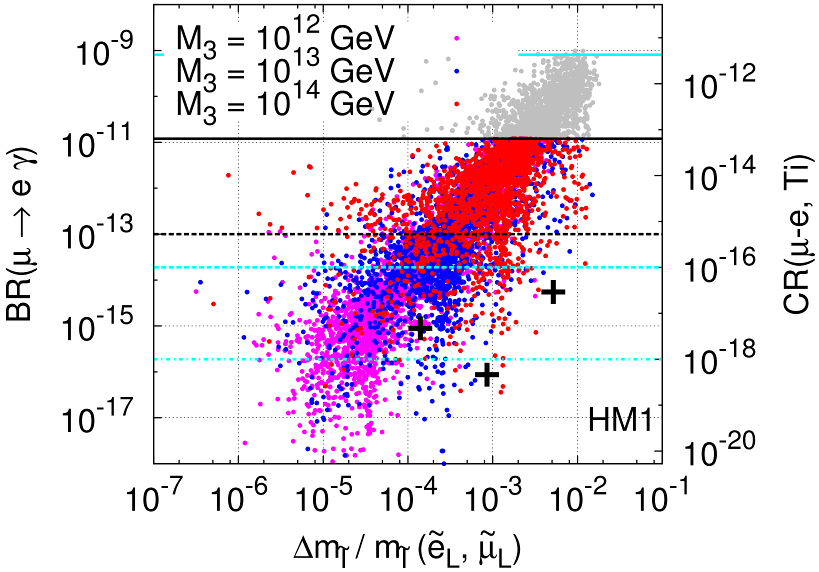
- ▶ $\Delta m(\tilde{e}_L, \tilde{\mu}_L)|_{\text{LHC}}$ and compatible BR($\mu \to e\gamma$)$|_{\text{MEG}}$, BR($\tau \to \mu\gamma$)$|_{\text{Belle II}}$

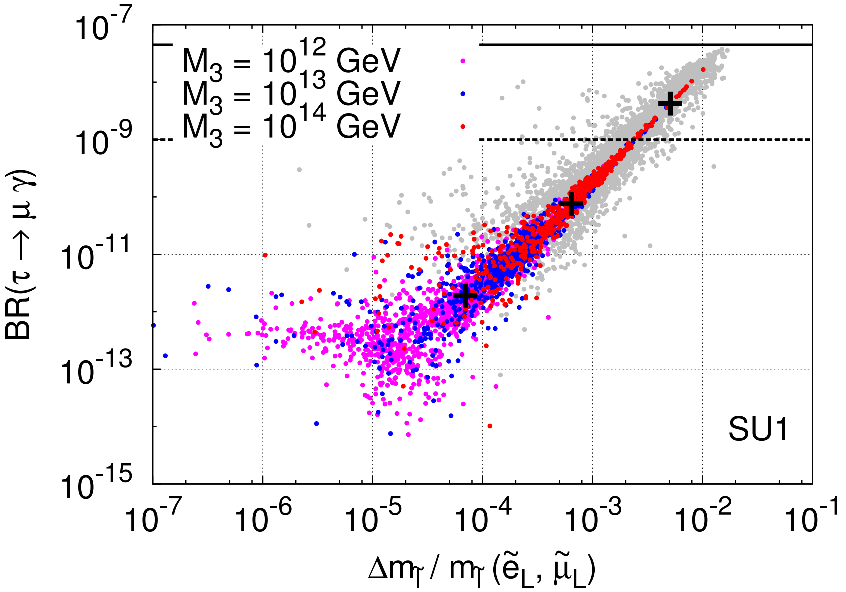
  $\Rightarrow$ **strengthen seesaw hypothesis**

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

  $\Rightarrow$ **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;**

- ▶ $\Delta m(\tilde{e}_L, \tilde{\mu}_L)|_{\text{LHC}} \sim (0.1-1)\% \rightsquigarrow \text{BR}(\mu \to e\gamma)|_{\text{MEG}}$

- ▶ $\Delta m(\tilde{e}_L, \tilde{\mu}_L)|_{\text{LHC}} \sim (0.1-1)\% \Rightarrow$ $\text{BR}(\tau \to \mu\gamma) \gtrsim 10^{-9}$ **(Super Belle ?)**

$\Rightarrow$ Hint towards scale of new physics ($M_{N_3} \gtrsim 10^{13}$ GeV)

Conclusions

- Neutrino masses and mixings: what is the generation mechanism?
- What is the scale of New Physics?
- What is the BSM extension?

Common tool: Interplay between high and low-energy observables.
Rich phenomenology from cLFV observables.