Lepton Flavour Violation in Neutrino Seesaw Scenarios

Anna Rossi (Padova University)

Flavour in the era of LHC – CERN March 27, 2007

- -S. Antusch
- -S. Davidson
- -Han
- -M.J. Herrero
- -A. Ibarra
- -F. R. Joaquim
- -A. Masiero
- -S. Petcov
- -A. Pilaftsis
- -M. Raidal
- -A.R.
- -Y.Takanishi

- **The Seesaw paradigm for the neutrino mass:**
  Singlet versus Triplet realizations
- **Lepton Flavour Violation (LFV):**
  comparing different Seesaw's without and with SUSY
- **Triplet as Messenger of SUSY breaking:**
  Novel predictive picture relating

ν Masses | **LFV** | **Sparticle and Higgs boson spectrum**

Electroweak Symmetry Breaking (EWSB)

What we know about LFV: the experimental side

- **All data from solar, atmospheric, accelerator and reactor neutrino experiments can be interpreted as**

ν **Oscillations and Adiabatic resonant conversion in matter**

$$\nu_e \longrightarrow \nu_\mu \ , \ \nu_\mu \longrightarrow \nu_\tau$$

↓

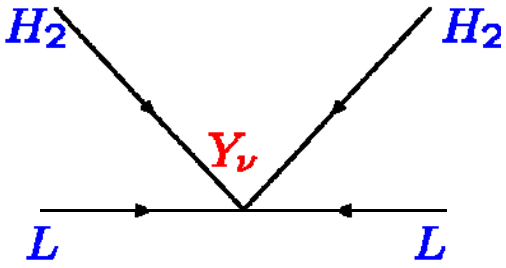
- **Evidence of Lepton Flavour Violation**

$$|\Delta L_e| = |\Delta L_\mu| = |\Delta L_\tau| = 1$$

What we know about LFV in the (MS)SM: the theory side

- **LFV emerges from** $m_\nu \neq 0, \quad \theta_{ij} \neq 0 \quad (i \neq j)$
- **This is understood from** $L = L_e + L_\mu + L_\tau$ **Violating d=5 operator**

S.Weinberg,1979



$$\frac{1}{M_L} Y_\nu^{ij} (L_i H_2)(L_j H_2)$$

$$\downarrow \langle H_2 \rangle = v_2$$

$$m_\nu^{ij} = \frac{v_2^2}{M_L} Y_\nu^{ij}$$

$$m_\nu \sim 0.1\,\text{eV} \rightarrow \frac{M_L}{Y_\nu} \sim \mathcal{O}(10^{14}\,\text{GeV})$$

$M_L > M_Z$

M_L **scale suppression**

$$m_\nu = U^* m_\nu^D U^\dagger$$

Charged leptons

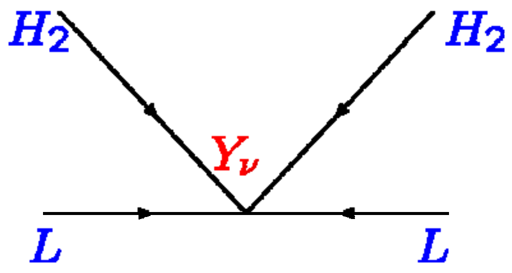
$$m_\ell = \text{diag}(m_e, m_\mu, m_\tau)$$

$$m_\nu^D = \text{diag}(m_1, m_2, m_3) \qquad U = V(\theta_{12}, \theta_{23}, \theta_{13}, \delta) \times \text{diag}(1, e^{i\alpha_1}, e^{i\alpha_2})$$

3 masses + 3 angles + 3 phases = 9 independent parameters
provided by low-energy experiments

How to get the neutrino d=5 operator ?

The d=5 Seesaw effective operator



Additional heavy degrees of freedom decouple at M_L

Tree-level Seesaw realizations

I decoupling fermion singlets N **('right-handed')**

P.Minkowski,1977; M.Gell-Mann, P.Ramond,R,Slanski,1979; T.Yanagida,1979; R.N.Mohapatra, G.Senjanovic, 1980

II decoupling $SU(2)_W$ **scalar triplets** $T = (T^0, T^+, T^{++})$ **(Y=1)**

R.Barbieri,D.Nanopoulos, 1980; M.Magg, C.Wetterich,1980; G.Lazarides, Q.Shafi, C.Wetterich, 1981; R.N.Mohapatra, G.Senajanovic, 1981

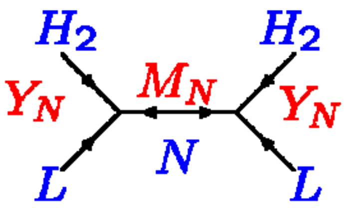
III decoupling $SU(2)_W$ **fermion triplets** $F = (F^0, F^\pm)$ **(Y=0)**

R.Foot,H.Lew,X.G.He,G.C.Joshi, 1989; E.Ma, 1998; B.Brahmachari, E.Ma, U.Sarkar, 2001

Comparing different Seesaw's

Seesaw with fermion Singlets $N \sim (1,0)$

$$W_N = Y_N^{ij} H_2 N_i L_j + \frac{1}{2} M_N^{ij} N_i N_j$$



$$m_\nu = \frac{v_2^2}{M_L} Y_\nu = v_2^2 Y_N^T M_N^{-1} Y_N$$

- 3 N needed
- 2 LFV sources Y_N, M_N

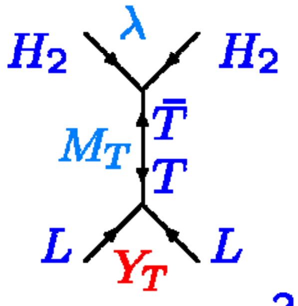
  i.e. 12 reals + 6 phases

Seesaw with fermion Triplets $F \sim (3,0)$

Replace $N_i \to F_i$, $Y_N^{ij} \to Y_F^{ij}, M_N^{ij} \to M_F^{ij}$

Seesaw with scalar Triplets $T, \bar{T} \sim (3, \pm 1)$

$$W_T = Y_T^{ij} L_i T L_j + \lambda H_2 \bar{T} H_2 + M_T T \bar{T}$$



$$m_\nu = \frac{v_2^2}{M_L} Y_\nu = v_2^2 \frac{\lambda}{M_T} Y_T$$

- 1 pair $(T, \bar{T})$ enough
- 1 LFV source Y_T (symmetric)

  i.e. 6 reals + 3 phases

Low-energy neutrino data reconstruct Y_ν i.e. 9 parameters

Not possible to fix univocally Y_N , M_N

A.Casas, A.Ibarra,2001

One-to-one matching: $Y_\nu \Leftrightarrow Y_T$

A.R., 2002

LFV Low-Energy Processes with Charged Leptons

$$\ell_j \to \ell_i + \gamma\,,\ \ell_j \to \ell_i \ell_i \ell_i \text{ etc.}$$

- **In the effective theory** $(\mu < M_L)$

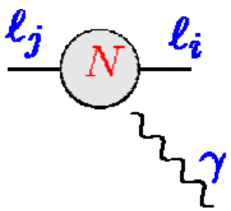
LFV in Y_ν (or m_ν) does not give sizeable effects … Suppressed by $\frac{m_\nu^2}{M_W^2}$
(except for ν oscillations)

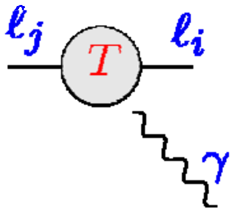
'leptonic' GIM-mechanism

- **In the 'complete' theory** $(\mu > M_L)$

LFV encoded in either Y_N, M_N or Y_T can induce sizeable effects through the one-loop decoupling of the heavy states, either N or T

★ **directly in the amplitudes of the processes, e.g.**





★ **In the SUSY extension of the SM, indirectly via its effect in the slepton mass matrix m_L^2 or in the scalar couplings A_e**

Detecting such LFV processes is a clear NEW Physics evidence

LFV Low-Energy Processes with Charged Leptons

LFV processes: Present and Future View

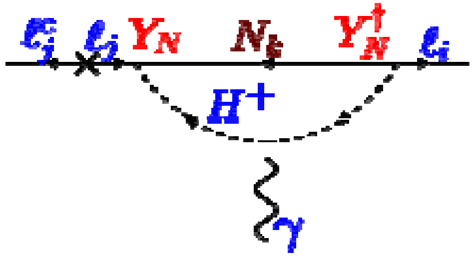
BR	Present limits	Future sensitivity
$\mu^- \to e^- \gamma$	1.2×10^{-11}	10^{-14}
$\tau^- \to \mu^- \gamma$	4.5×10^{-8}	10^{-9}
$\tau^- \to e^- \gamma$	1.1×10^{-7}	10^{-9}
$\mu^- \to e^- e^+ e^-$	1.0×10^{-12}	10^{-14}
$\tau^- \to \mu^- \mu^+ \mu^-$	1.9×10^{-7}	10^{-9}
$\tau^- \to \mu^- e^+ e^-$	1.9×10^{-7}	10^{-9}
$\tau^- \to e^- e^+ e^-$	2.0×10^{-7}	10^{-9}
$\tau^- \to e^- \mu^+ \mu^-$	3.3×10^{-7}	10^{-9}
CR($\mu \to e$; Ti)	1.7×10^{-12}	10^{-18}

Direct LFV effects: N-Seesaw

Exchanging at 1-loop the singlets N

T.P.Cheng, LF.Li., 1980;
A.Ilakovac, A.Pilaftsis, 1995...

e.g. $\ell_j \to \ell_i + \gamma$



$+ \quad \ldots = D_{ij} \propto \frac{(Y_N^\dagger M_N^{-2} Y_N)_{ij}}{16\pi^2}$

• **LFV** structure $Y_N^\dagger M_N^{-2} Y_N$ not directly linked to Y_ν or m_ν ⇓ **more (model dependent) assumptions needed to draw any prediction** ☆	• sizeable effects need $\frac{Y_N}{M_N} \sim 10^{-3}\,\text{GeV}^{-1}$ ⇒ Low-scale seesaw versus m_ν requiring $\frac{Y_N^2}{M_N} \sim 10^{-14}\,\text{GeV}^{-1}$ ⇓ **Generically not phenomenologically relevant** ☆

☆ **Special models with some enhanced Y_N entries and $M_N \sim \text{TeV}$ (small ν masses due to an approximate U(1) symm.) provide testable $\mu - e$ LFV : e.g. $\text{BR}(\mu \to e + \gamma) \sim 10^{-12}$**

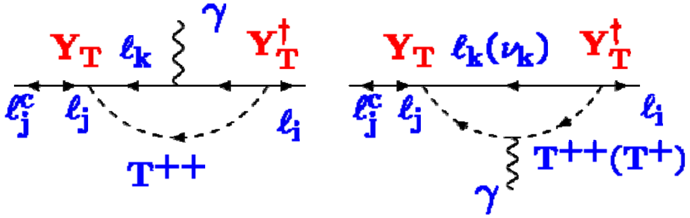
A.Pilaftsis, T.Underwood, 2005

Direct LFV effects: T-Seesaw

E.Ma, M.Raidal,2000;F.Cuypers,S.Davidson, 1998; E.J.Chun,K.Y.Lee,S.C.Park,2003; M.Kakizaki,Y.Ogura,F.Shima,2003

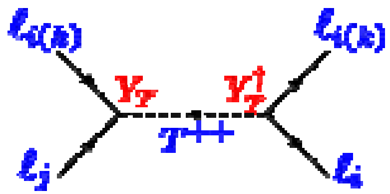
Exchanging the scalar Triplets

$\ell_j \to \ell_i + \gamma$



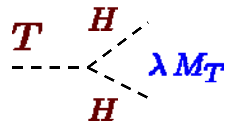
$$D_{ij} \propto \frac{(Y_T^\dagger Y_T)_{ij}}{16\pi^2 M_T^2}$$

$\ell_j \to \ell_i \ell_{i(k)} \ell_{i(k)}$



$$A \propto \frac{Y^\dagger_{T\,ii(k)} Y_{T\,ji(k)}}{M_T^2}$$

- Minimal **LFV** structure: direct link $Y_T \leftrightarrow m_\nu$



$$D \propto \frac{(Y_T^\dagger Y_T)_{ij}}{16\pi^2 M_T^2} \sim \frac{(m_\nu^\dagger m_\nu)_{ij}}{16\pi^2 \lambda^2 v^4} \sim \frac{[V(m_\nu^D)^2 V^\dagger]_{ij}}{16\pi^2 \lambda^2 v^4}$$

$$A \propto \frac{Y^\dagger_{T\,ii(k)} Y_{T\,ji(k)}}{M_T^2} \sim \frac{m^\dagger_{\nu\,ii(k)} m_{\nu\,ji(k)}}{\lambda^2 v^4}$$

⇒ **LFV** structure determined by low-energy ν parameters

- Sizeable **LFV** effects are possible for $\lambda \sim 10^{-10}$ and in particular for $M_T \lesssim \mathcal{O}(TeV)$ ⟹ the triplets can be produced at e+ e- coll. and LHC

LFV features in T-Seesaw

T-Seesaw provides a realization of truly Minimal LFV: $Y_T^\dagger Y_T \propto V (m_\nu^D)^2 V^\dagger$

Relative LFV size predicted in a model-independent way: depends only on the neutrino masses (m_1, m_2, m_3) and mixing angles (V) measured at low-energy

$$\frac{(Y_T^\dagger Y_T)_{\tau\mu}}{(Y_T^\dagger Y_T)_{\mu e}} \approx \frac{[V (m_\nu^D)^2 V^\dagger]_{\tau\mu}}{[V (m_\nu^D)^2 V^\dagger]_{\mu e}}, \qquad \frac{(Y_T^\dagger Y_T)_{\tau e}}{(Y_T^\dagger Y_T)_{\mu e}} \approx \frac{[V (m_\nu^D)^2 V^\dagger]_{\tau e}}{[V (m_\nu^D)^2 V^\dagger]_{\mu e}}$$

plugging the neutrino exp data

$$\left|\frac{(Y_T^\dagger Y_T)_{\tau\mu}}{(Y_T^\dagger Y_T)_{\mu e}}\right| \approx 40, \quad \left|\frac{(Y_T^\dagger Y_T)_{\tau e}}{(Y_T^\dagger Y_T)_{\mu e}}\right| \approx 1 \quad , \quad [\sin\theta_{13} = 0]$$

$$\left|\frac{(Y_T^\dagger Y_T)_{\tau\mu}}{(Y_T^\dagger Y_T)_{\mu e}}\right| \approx 0.8\ (1.2), \quad \left|\frac{(Y_T^\dagger Y_T)_{\tau e}}{(Y_T^\dagger Y_T)_{\mu e}}\right| \approx 3.2\ (3.8) \quad , \quad [\sin\theta_{13} = 0.2]$$

A.R.,2002

For the Normal Hierarchy NH, Quasi Degenerate DG (Inverted Hierarchy IH) neutrino spectra

LFV features in T-Seesaw (continuing)

T-Seesaw : strict predictions for the ratio of LFV Branching Ratios given the neutrino parameters

$$\frac{BR(\tau\to\mu\gamma)}{BR(\mu\to e\gamma)} \approx \left|\frac{(Y_T^\dagger Y_T)_{\tau\mu}}{(Y_T^\dagger Y_T)_{\mu e}}\right|^2 \frac{BR(\tau\to\mu\nu_\tau\bar\nu_\mu)}{BR(\mu\to e\nu_\mu\bar\nu_e)} \approx \begin{cases} 300 & [s_{13}=0] \\ 2\,(3) & [s_{13}=0.2] \end{cases}$$

$$\frac{BR(\tau\to e\gamma)}{BR(\mu\to e\gamma)} \approx \left|\frac{(Y_T^\dagger Y_T)_{\tau e}}{(Y_T^\dagger Y_T)_{\mu e}}\right|^2 \frac{BR(\tau\to e\nu_\tau\bar\nu_e)}{BR(\mu\to e\nu_\mu\bar\nu_e)} \approx \begin{cases} 0.2 & [s_{13}=0] \\ 0.1\ (0.3) & [s_{13}=0.2] \end{cases}$$

Notice: Major uncertainty from θ_{13}

A.R., 2002

For LFV directly induced: $\mu \to eee$ occurs at tree-level

M.Kakizaki, Y.Ogura, F.Shima, 2003

$\mu \to e\gamma$ occurs at one-loop

$BR(\mu \to eee) \gtrsim BR(\mu \to e\gamma)$ ⟹ and τ–μ LFV BRs $\lesssim \mathcal{O}(10^{-10})$

LFV in SUSY Standard Model

The SUSY extension of the SM (MSSM) offers new LFV sources:

The soft SUSY breaking (SSB) parameters $m^2_{\tilde{L}}$ and A_e

Provided

the slepton mass matrix $m^2_{\tilde{L}}$ is not aligned to the lepton mass matrices

What about $m^2_{\tilde{L}}$?

- **Mass scale not far from the EW scale**
- **Flavour structure: theoretically unknown (…more general and open issue) though phenomenologically constrained**

How to proceed to do phenomenology ?

Take a conservative approach inspired by

Certain Minimal SUGRA or (High Scale) Gauge Mediation Scenarios

- **Universality/Flavour-Conservation at high (SUSY -- mediation) scale M_X**

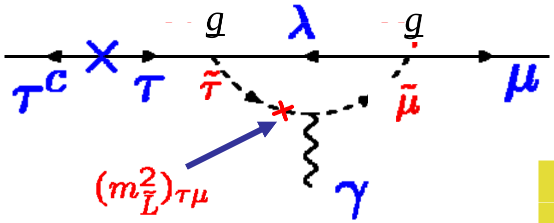
$$m^2_{\tilde{L}} = m^2_0 \mathbb{1}$$

- **At lower energy Renormalization-Group (RG) effects induced by LFV Yukawa couplings, either Y_N or Y_T, via the one-loop exchange of either N or T, spoil universality/flavour conservation**

$$(m^2_{\tilde{L}})_{ij} \neq 0$$

L.Hall, V.Kostelecky, S.Raby,1986, F.Borzumati, A.Masiero,1986; A.R.,2002

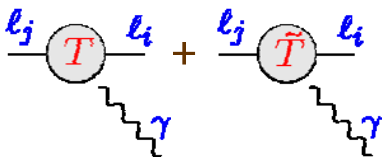
'Indirect LFV effects':



$$D \sim \frac{g^2}{16\pi^2} \frac{(m^2_{\tilde{L}})_{\tau\mu}}{\tilde{m}^4}$$

No suppression for $\tilde{m} \lesssim$ Tev

'Direct LFV effects' ?



$$\propto \frac{(Y_T^\dagger Y_T)_{ij}}{16\pi^2} \frac{\tilde{m}^2}{M_T^4}$$

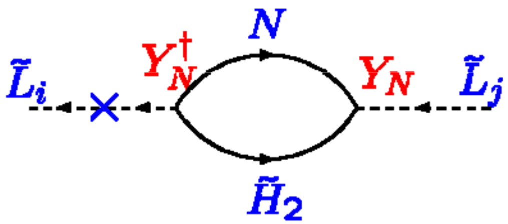
Negligible for $M_T \gg \tilde{m}$

Generating LFV in $(\tilde{L}^\dagger m^2_{\tilde{L}} \tilde{L})$ from Susy Seesaw

N- Seesaw

RG running from M_X to M_N

e.g.



$$(m^2_{\tilde{L}})_{ij} \sim \frac{m_0^2}{16\pi^2} (Y_N^\dagger \ln \frac{M_X}{M_N} Y_N)_{ij}$$

- LFV encoded in $Y_N^\dagger \ln \frac{M_X}{M_N} Y_N$ not directly linked to m_ν
- More assumptions are needed to specify $(m^2_{\tilde{L}})_{ij}$

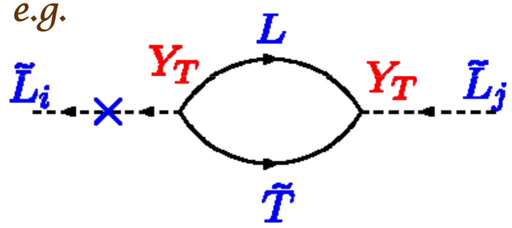
LFV structure of $m^2_{\tilde{L}}$ is a model-dependent issue

A.Casas, A.Ibarra,2001
S.Davidson,A.Ibarra,2001

T- Seesaw

RG running from M_X to M_T

e.g.



$$(m^2_{\tilde{L}})_{ij} \sim \frac{m_0^2}{16\pi^2} (Y_T^\dagger Y_T)_{ij} \ln \frac{M_X}{M_T}$$

- LFV encoded in $Y_T^\dagger Y_T$ directly linked to m_ν

$$(m^2_{\tilde{L}})_{ij} \sim \frac{m_0^2}{16\pi^2} \left(\frac{M_T}{\lambda v_2^2}\right)^2 \left[V (m_\nu^D)^2 V^\dagger\right]_{ij} \ln \frac{M_X}{M_T}$$

- $m^2_{\tilde{L}}$ inherits the low-energy Flavour structure A.R., 2002

Mixed singlet-triplet seesaw (left-right or SO(10) inspired) also addressed, *e.g.* P.Hosteins,S.Lavignac,C.Savoy 2006

LFV in SUSY N-Seesaw: ~ Bottom-up analysis

A.Casas,
A.Ibarra,2001

$$Y_N = D_{\sqrt{M}}\, R\, D_{\sqrt{k}} U^{\dagger}$$

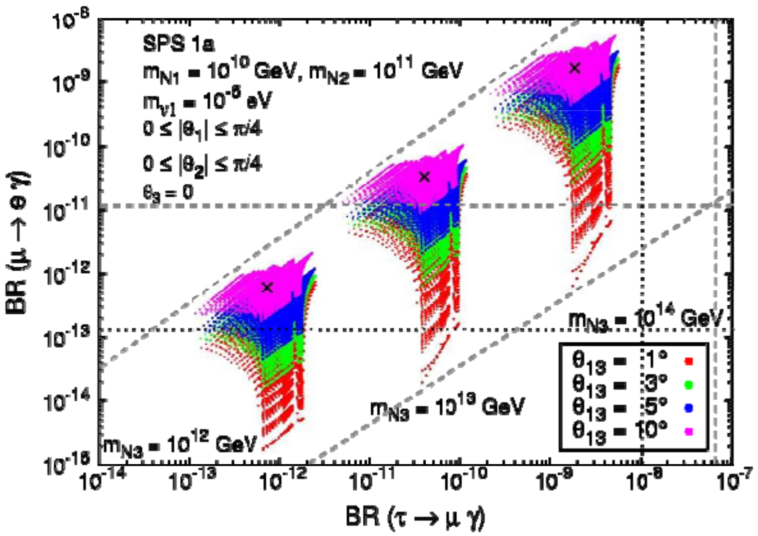
$\kappa = m_\nu / v^2$
Known structure

$D_M = \mathrm{diag}(M_{N1}, M_{N2}, M_{N3})$
Unknown: not related to m_ν

complex, $RR^T = 1$
Unknown:not related to m_ν

Correlation pattern of $BR(\mu \to e\gamma)$ & $BR(\tau \to \mu\gamma)$

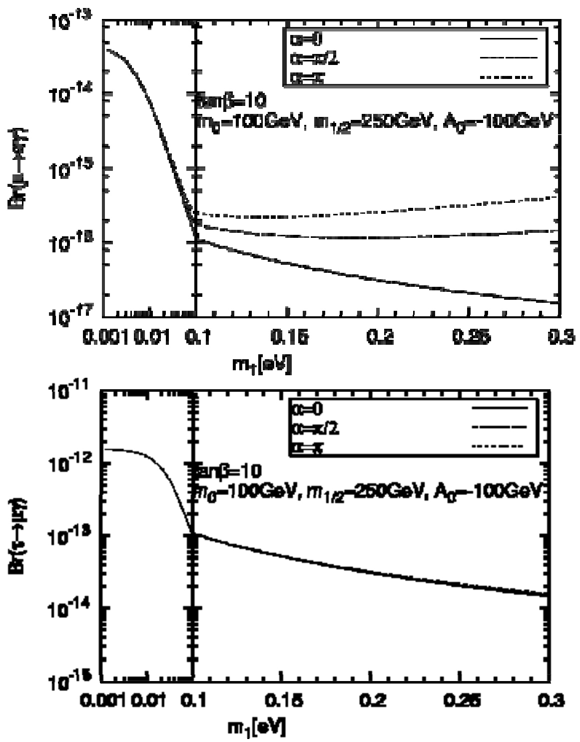
S.Antusch,E.Aganda,M.J.Herrero,A.Teixeira,06



$R \neq 1$

Given θ_{13} and M_{N3}, the correlation spreads out due to the unknown angles of R

S.T.Petcov,T.Shindou,Y.Takanishi,05



$R = 1$
$M_{N3} = 2 \cdot 10^{13}$ GeV
$\theta_{13} = 0$

BR's and relative correlation depend on m_1 and on the Majorana phases

LFV in SUSY N-Seesaw: ~ Top-down analysis

Assume a High-Energy 'model': e.g. SO(10)-inspired

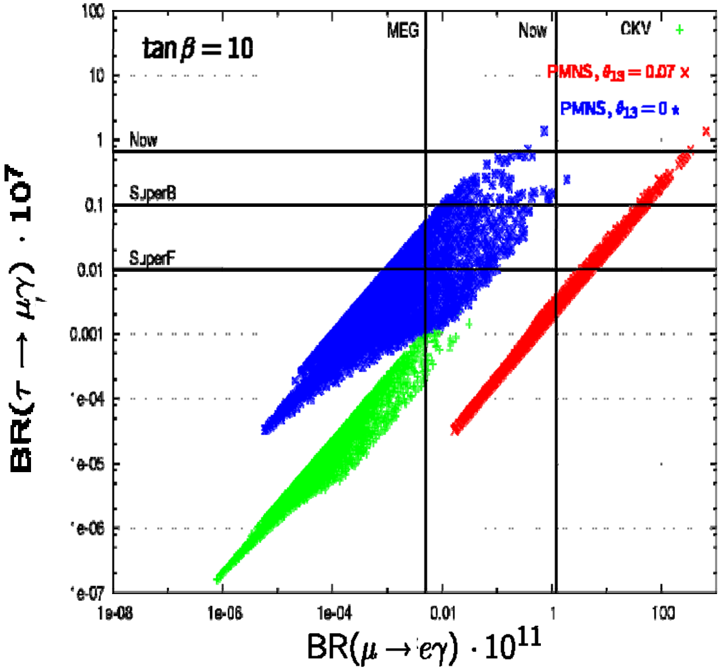
All matter field reps are unified as $\mathbf{16} = (q, u^c, d^c, L, e^c, N)$

Yukawa's are related, although in a model dependent way. Two extreme cases:

$$Y_N = Y_{\rm up}\, U \quad \text{or} \quad Y_N = Y_{\rm up}\, V_{\rm ckm}$$

$$Y_{\rm up} = {\rm diag}(Y_u, Y_c, Y_t)$$

Correlation pattern of $BR(\mu \to e\gamma)$ & $BR(\tau \to \mu\gamma)$



L.Calibbi, A.Faccia, A.Masiero, S.Vempati, 06

The correlation depends on θ_{13}, and the spread is due to the scanning of LHC accessible parameter space

Detecting both signals (at MEG and SuperB) points to tiny θ_{13}

LFV in SUSY T-Seesaw

The relevant LFV structure is Minimal : $(m^2_{\tilde{L}})_{ij} \propto Y_T^\dagger Y_T \propto V (m_\nu^D)^2 V^\dagger$

Relative LFV size predicted in a model-independent way - ***i.e.* no dependence** on either the seesaw parameters, M_T, λ , or the SUSY ones, m_0, $M_{1/2}\dots$ but **only dependence** on the low-energy neutrino parameters A.R.,2002

Notice: no dependence on the lightest ν mass m_1 and on the Majorana phases

$$\frac{BR(\tau\to\mu\gamma)}{BR(\mu\to e\gamma)} \approx \left|\frac{(m^2_{\tilde{L}})_{\tau\mu}}{(m^2_{\tilde{L}})_{\mu e}}\right|^2 \frac{BR(\tau\to\mu\nu_\tau\bar{\nu}_\mu)}{BR(\mu\to e\nu_\mu\bar{\nu}_e)} \approx \begin{cases} 300 & [s_{13}=0] \\ 2\,(3) & [s_{13}=0.2] \end{cases}$$

$$\frac{BR(\tau\to e\gamma)}{BR(\mu\to e\gamma)} \approx \left|\frac{(m^2_{\tilde{L}})_{\tau e}}{(m^2_{\tilde{L}})_{\mu e}}\right|^2 \frac{BR(\tau\to e\nu_\tau\bar{\nu}_e)}{BR(\mu\to e\nu_\mu\bar{\nu}_e)} \approx \begin{cases} 0.2 & [s_{13}=0] \\ 0.1\ (0.3) & [s_{13}=0.2] \end{cases}$$

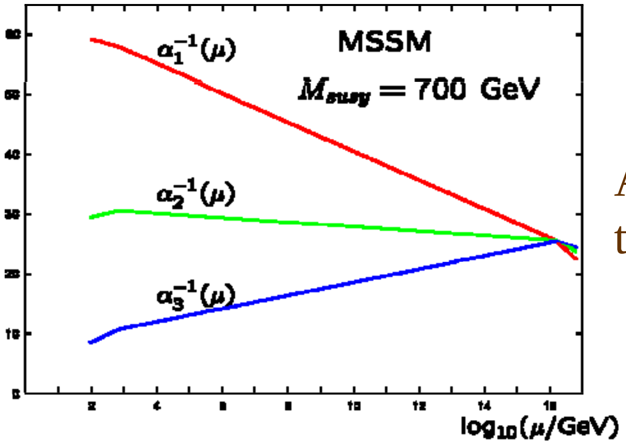
$$\frac{BR(\tau\to\mu\mu\mu)}{BR(\mu\to eee)} \approx \left|\frac{(m^2_{\tilde{L}})_{\tau\mu}}{(m^2_{\tilde{L}})_{\mu e}}\right|^2 \left(\frac{\ln\frac{m^2_{\tau}}{m^2_{\mu}}-\frac{11}{4}}{\ln\frac{m^2_{\mu}}{m^2_{e}}-\frac{11}{4}}\right) \frac{BR(\tau\to\mu\nu_\tau\bar{\nu}_\mu)}{BR(\mu\to e\nu_\mu\bar{\nu}_e)} \approx \begin{cases} 100 & [s_{13}=0] \\ 0.6\ (0.9) & [s_{13}=0.2] \end{cases}$$

Similarly for other LFV-decays

SUSY T-Seesaw : Calling for a GUT extension

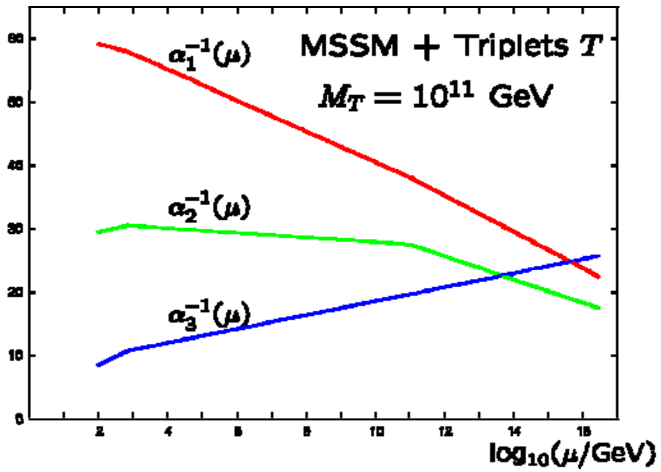
$SU(2)_W$ **Triplet states below M_G alter (simple) gauge coupling unification**

MSSM (w/o $T, \bar{T}$)



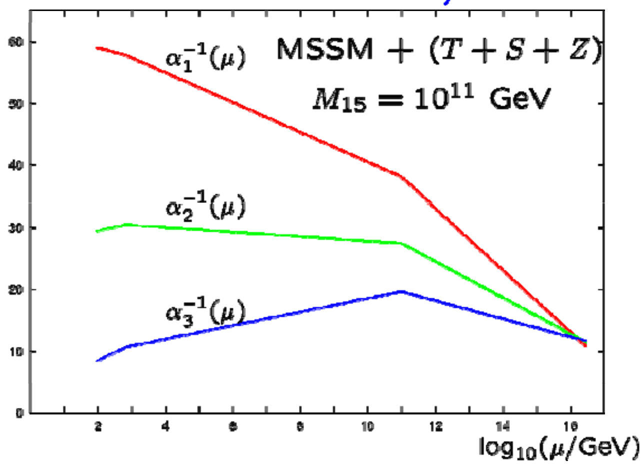
Adding the triplets

MSSM with $T, \bar{T}$



Unification recovered by adding extra states to complete a GUT supermultiplet: *T* + …

MSSM with $15, \overline{15}$



Minimal extension: SUSY SU(5) with $T \subset 15$:

$$15 = S + T + Z$$

$SU(3)_c \times SU(2)_W \times U(1)_Y$ decomposition

$$S \sim (6, 1, -\frac{2}{3}), \quad T \sim (1, 3, 1), \quad Z \sim (3, 2, \frac{1}{6})$$

…which implications for Flavour Violation ?

SUSY SU(5) T-Seesaw : Flavour Violation

SUSY SU(5) with 15 = *T* + *S* + *Z*

Relevant Yukawa term $Y_{15}\,\bar{5}\,15\,\bar{5} = Y_T L\,T\,L + Y_S d^c\,S\,d^c + Y_Z d^c\,Z\,L$

$\bar{5} = (d^c, L)$

All Yukawa's Y_T, Y_S, Y_Z induce FV through RG effects in both the (s)lepton and (s)quark sector .

$$(m^2_{\tilde{d}})_{ij} \approx \frac{m_0^2}{16\pi^2}\left(Y_T^\dagger Y_T\right)_{ij} \ln\frac{M_X}{M_T} \sim \frac{m_0^2}{16\pi^2}\left(\frac{M_T}{\lambda v_2^2}\right)^2\left[V(m_\nu^D)^2 V^\dagger\right]_{ij} \ln\frac{M_X}{M_T}$$

Possible direct connection between Quark and Lepton FV (from GUT symmetry)

$$(m^2_{\tilde{d}})_{ij} \sim (m^2_{\tilde{L}})_{ij}$$

$$\frac{(m^2_{\tilde{L}})_{\tau\mu}}{(m^2_{\tilde{L}})_{\mu e}} \sim \frac{(m^2_{\tilde{d}})_{bs}}{(m^2_{\tilde{d}})_{sd}} \sim \frac{\left[V(m_\nu^D)^2 V^\dagger\right]_{\tau\mu}}{\left[V(m_\nu^D)^2 V^\dagger\right]_{\mu e}} \quad , \quad \frac{(m^2_{\tilde{L}})_{\tau e}}{(m^2_{\tilde{L}})_{\mu e}} \sim \frac{(m^2_{\tilde{d}})_{bd}}{(m^2_{\tilde{d}})_{sd}} \sim \frac{\left[V(m_\nu^D)^2 V^\dagger\right]_{\tau e}}{\left[V(m_\nu^D)^2 V^\dagger\right]_{\mu e}}$$

A.R.,2002

A different way to generate LFV $(m^2_{\tilde{L}})_{ij} \neq 0$

BEFORE: in 2 (unrelated) steps

1) Flavour universal overall SSB mass m_0 generated at the SUSY mediation scale (unrelated to the dynamics of the triplets T)

2) LFV $(m^2_{\tilde{L}})_{ij}$ structure generated by RG quantum effects due to the triplet Yukawa Y_T

NOW: Even more economical and predictive approach

1 Single step

1) Both the overall SSB mass scale and the LFV $(m^2_{\tilde{L}})_{ij}$ structure are generated at the scale M_T by exchanging the triplets T at the quantum level

F.R.Joaquim, A.R. – PRL 97 (2006) 181801; NPB 765 (2007) 71

Novel SUSY SU(5) T-Seesaw : Flavour Violation & SSB

Basic observation: $15 \subset T + \ldots$ **exchange can generate all SSB masses**

Provided 15 interacts with a superfield *X* breaking SUSY

$$W_{SU(5)} = \xi X 15\ \overline{15} + Y_{15}\ \bar{5}\ 15\ \bar{5} + \lambda 5_H\ \overline{15}\ 5_H + Y_5\ 10\ \bar{5}\ \bar{5}_H + Y_{10}\ 10\ 10\ 5_H + M_5 \bar{5}_H\ 5_H$$

B - L is conserved

$10 = (u^c, d^c, Q);\ \bar{5} = (d^c, L)$
$5_H = (t, H_2)\,,\ \bar{5}_H = (\bar{t}, H_1)$

X **is a singlet with B – L charge and VEV:** $\langle X \rangle = \langle S_X \rangle + \theta^2 \langle F_X \rangle$

$\langle S_X \rangle \neq 0$ **breaks B – L :**

$$\xi \langle S_X \rangle = M_{15} \longrightarrow W \supset M_{15}\ 15\ \overline{15}$$

$\langle F_X \rangle \neq 0$ **breaks SUSY and B – L :**

$$\xi \langle F_X \rangle = B_{15} M_{15} \longrightarrow \mathcal{L}_{SSB} = B_{15} M_{15}\ 15\ \overline{15}$$

This is the only SSB term at M_G

F.Joaquim, A.R. 2006

Novel SUSY SU(5) T-Seesaw : …(continuing)

At M_G SU(5) breaks: → $W_{SU(5)} = W_{MSSM} + W_T + W_{S,Z}$

- $W_{MSSM} = Y_d\, d^c H_1 Q + Y_e e^c H_1 L + Y_u u^c Q H_2 + \mu H_1 H_2$
- $W_T = Y_T\, LTL + \lambda H_2 \bar{T} H_2 + M_T T\bar{T}$
- $W_{S,Z} = Y_S\; d^c S d^c + Y_Z\, d^c Z L + M_Z Z\bar{Z} + M_S S\bar{S}$

SSB terms $\mathcal{L}_{SSB} = -B_T M_T (T\bar{T} + S\bar{S} + Z\bar{Z}) + \text{h.c.}$

$B_T M_T = B_{15} M_{15}$

At $M_T < M_G$

- Only $T, \bar{T}$ are messengers of $\not{L}$ at tree-level → ν masses

  coloured $S, \bar{S}, T, \bar{T}$ are not messengers of $\not{B}$

- All $T, \bar{T}, S, \bar{S}, Z, \bar{Z}$ are messengers of $\not{\text{SUSY}}$ at the quantum level

→ All SSB masses are obtained as FINITE CONTRIBUTIONS

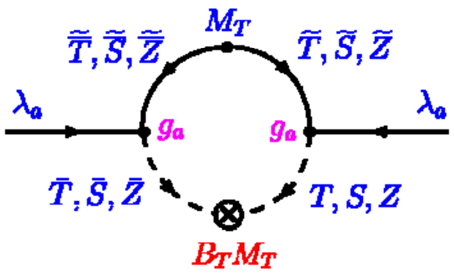
- At 1-loop: Gaugino masses, Trilinear couplings A_f , bilinear Higgs parameter B_H
- At 2-loop: all sfermion masses, and $m^2_{H_1}, m^2_{H_2}$

Novel SUSY SU(5) T-Seesaw : …(continuing)

SSB parameters: The Boundary conditions at M_T

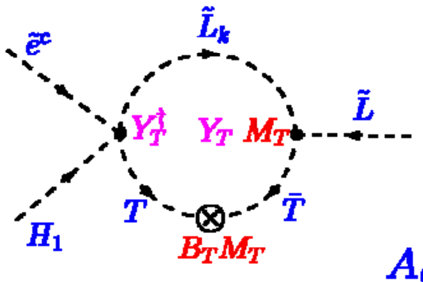
1-loop examples

For gaugino masses



$$M_a \propto \frac{B_T}{16\pi^2} g_a^2$$

For trilinear A_e



$$A_e \propto \frac{B_T}{16\pi^2} Y_T^\dagger Y_T$$

$$A_e = \frac{3B_T}{16\pi^2} Y_e (Y_T^\dagger Y_T + Y_Z^\dagger Y_Z)$$

$$A_d = \frac{2B_T}{16\pi^2} (Y_Z Y_Z^\dagger + 2 Y_S Y_S^\dagger) Y_d; \qquad A_u = \frac{3B_T}{16\pi^2} Y_u |\lambda|^2$$

$$M_a = \frac{7B_T}{16\pi^2} g_a^2; \qquad B_H = \frac{3B_T}{16\pi^2} |\lambda|^2$$

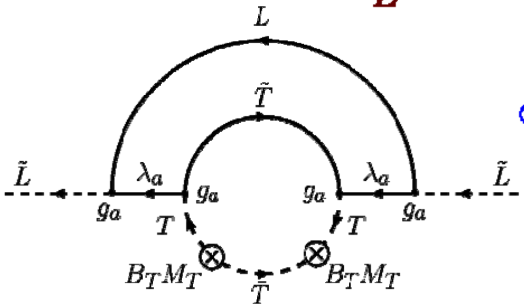
- Y_T , Y_S , Y_Z mediate Flavour Violation in A_e , A_d

Novel SUSY SU(5) T-Seesaw : …(continuing)

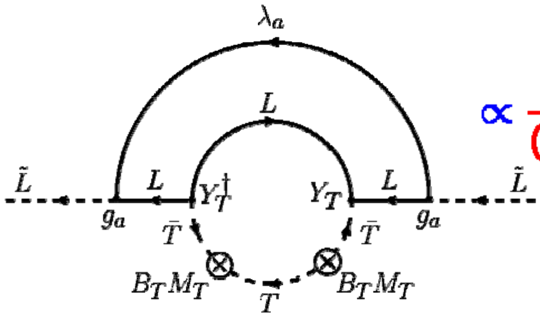
SSB parameters: The Boundary conditions at M_T

2-loop examples

For slepton masses $m^2_{\tilde L}$



$\propto \left(\frac{B_T}{16\pi^2}\right)^2 g_a^4$



$\propto \frac{|B_T|^2}{(16\pi^2)^2} g_a^2 Y_T^\dagger Y_T$

$$m^2_{\tilde L} = \frac{|B_T|^2}{(16\pi^2)^2}\left[\frac{21}{10}g_1^4 + \frac{21}{2}g_2^4 - (\frac{27}{5}g_1^2 + 21 g_2^2)Y_T^\dagger Y_T - (\frac{21}{15}g_1^2 + 9 g_2^2 + 16 g_3^2)Y_Z^\dagger Y_Z + \mathcal{O}(Y^4)\right]$$

$$m^2_{\tilde d^c} = \frac{|B_T|^2}{(16\pi^2)^2}\left[\frac{14}{15}g_1^4 + \frac{56}{3}g_3^4 - (\frac{16}{5}g_1^2 + 48 g_3^2)Y_S^\dagger Y_S - (\frac{14}{15}g_1^2 + 6 g_2^2 + \frac{32}{3} g_3^2)Y_Z Y_Z^\dagger + \mathcal{O}(Y^4)\right]$$

$$m^2_{\tilde Q} = \frac{|B_T|^2}{(16\pi^2)^2}\left[\frac{7}{30}g_1^4 + \frac{21}{2}g_2^4 + \frac{56}{3}g_3^4 + \mathcal{O}(Y^4)\right], \quad m^2_{\tilde u^c} = \frac{|B_T|^2}{(16\pi^2)^2}\left[\frac{56}{15}g_1^4 + \frac{56}{3}g_3^4 + \mathcal{O}(Y^4)\right]$$

$$m^2_{\tilde e^c} = \frac{|B_T|^2}{(16\pi^2)^2}\left[\frac{42}{5}g_1^4 + \mathcal{O}(Y^4)\right], \quad m^2_{H_1} = \frac{|B_T|^2}{(16\pi^2)^2}\left[\frac{21}{10}g_1^4 + \frac{21}{2}g_2^4 + \mathcal{O}(Y^4)\right]$$

$$m^2_{H_2} = \frac{|B_T|^2}{(16\pi^2)^2}\left[\frac{21}{10}g_1^4 + \frac{21}{2}g_2^4 - (\frac{27}{5}g_1^2 + 21 g_2^2)\lambda^2 + 9\lambda^2 Y_t^2 + \mathcal{O}(Y^4)\right]$$

- gauge $g_a\ (a = 1, 2, 3)$ **mediate Flavour blind SUSY : like in pure Gauge Mediation Models**
- Y_T, Y_S, Y_Z **mediate Flavour Violation in $m^2_{\tilde L}, m^2_{\tilde d^c}$: at variance with pure Gauge Mediation Models**

Novel SUSY SU(5) T-Seesaw : …(continuing)

PREDICTIVE SET-UP: 3 free parameters B_T, M_T, λ

B_T : Effective SUSY-breaking mass, fixing all SSB masses $\tilde{m} \sim \frac{B_T}{16\pi^2}$

$$\tilde{m} \sim \mathcal{O}(100 \text{ GeV}) \longrightarrow B_T \sim \mathcal{O}(10 \text{ TeV})$$

M_T : Triplet mass & SUSY-breaking Mediation scale

Gauge coupling perturbativity up to M_G $\longrightarrow$ $M_T \geq 10^7$ GeV

Bottom-up approach to determine

$Y_T = U m_\nu^D U^\dagger \frac{M_T}{\lambda v_2^2}$ (as well as Y_S, Y_Z) from low-energy neutrino params.

μ and $\tan\beta$ from the radiative EWSB conditions

→ Flavour Violation is univocally predicted in the SSB masses

$$(m^2_{\tilde{L}})_{ij} \propto (Y_T^\dagger Y_T + Y_Z^\dagger Y_Z)_{ij} \propto (m_\nu^\dagger m_\nu)_{ij}; \quad (m^2_{\tilde{d}^c})_{ij} \propto (Y_S Y_S^\dagger + Y_Z Y_Z^\dagger)_{ij} \propto (m_\nu^\dagger m_\nu)_{ij}$$

→ Correlation between LFV and QFV is also predicted

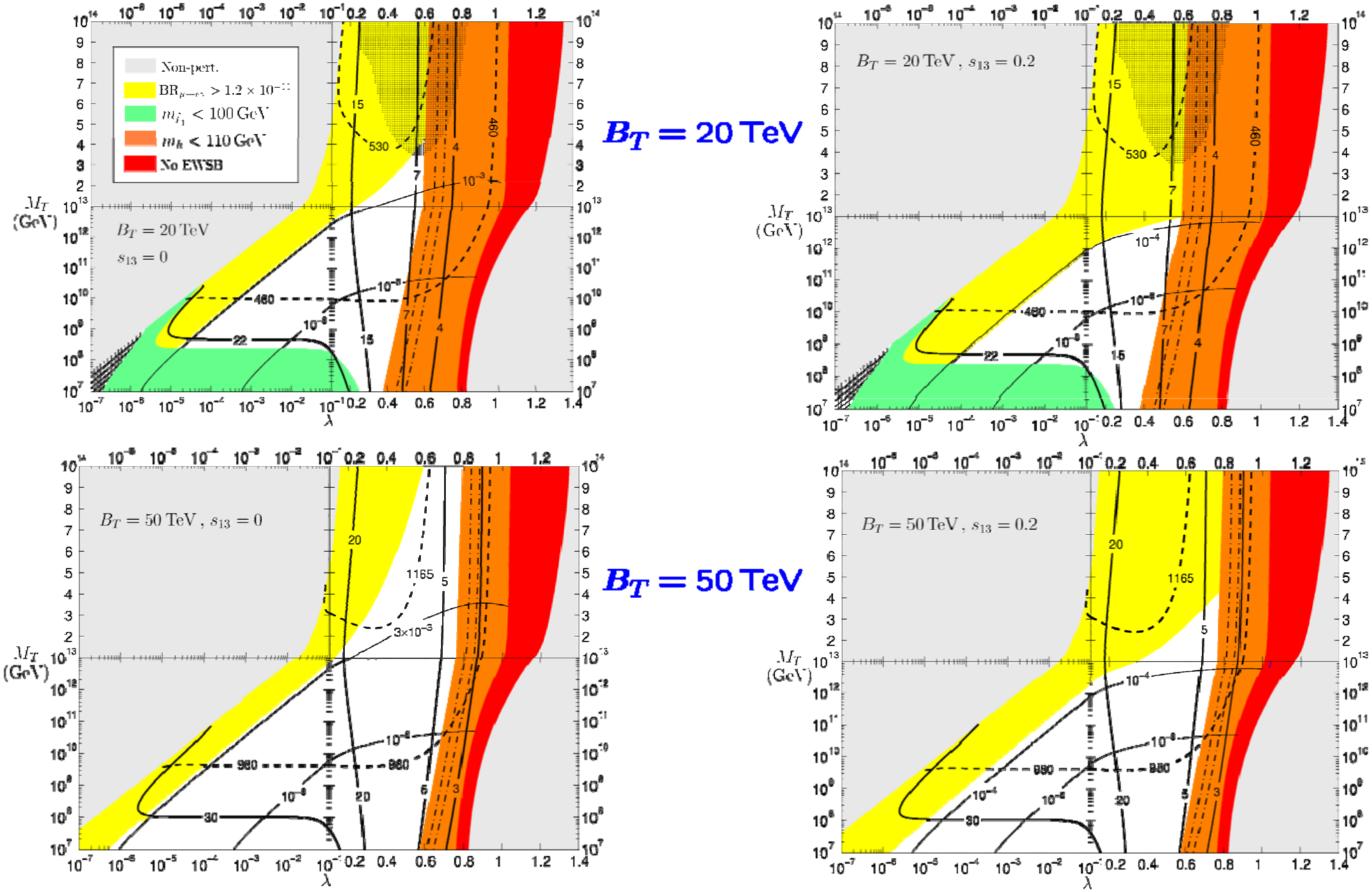
Novel SUSY SU(5) T-Seesaw : …(continuing)

IS ALL THIS PHENOMENOLOGICALLY VIABLE ?

$(B_T\,,M_T\,,\,\lambda)$ PARAMETER SPACE EXPLORATION

Next slide

Novel SUSY SU(5) T-Seesaw : …(continuing)



The model is compatible with experiments for $M_T \geq 10^7 - 10^8$ GeV and $B_T \geq 20$ TeV

PROBING THE ALLOWED PARAMETER SPACE

BY PREDICTIONS ON

MSSM Sparticle and Higgs Boson Spectrum

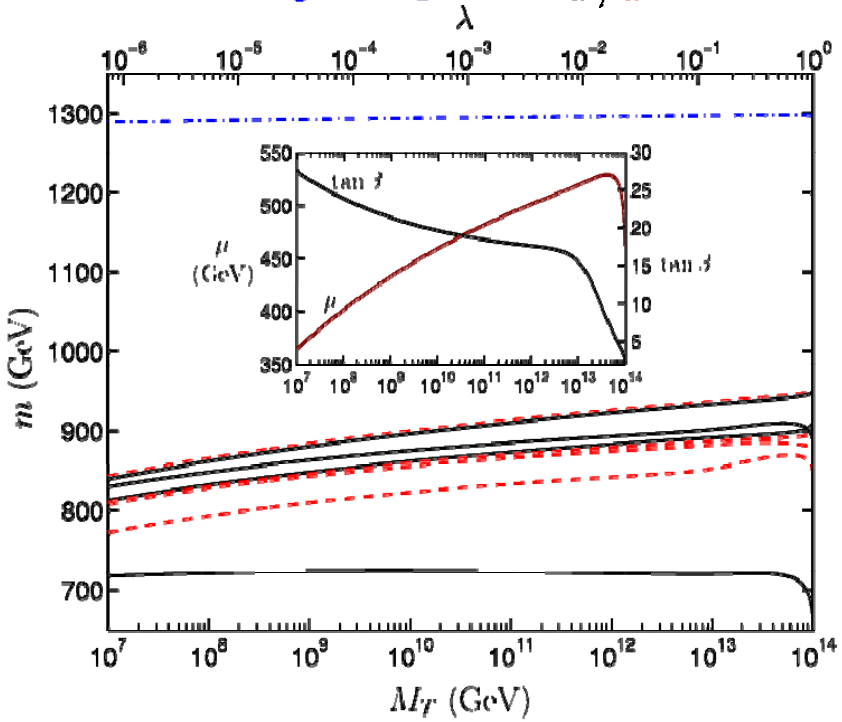
LFV Processes

Next slide

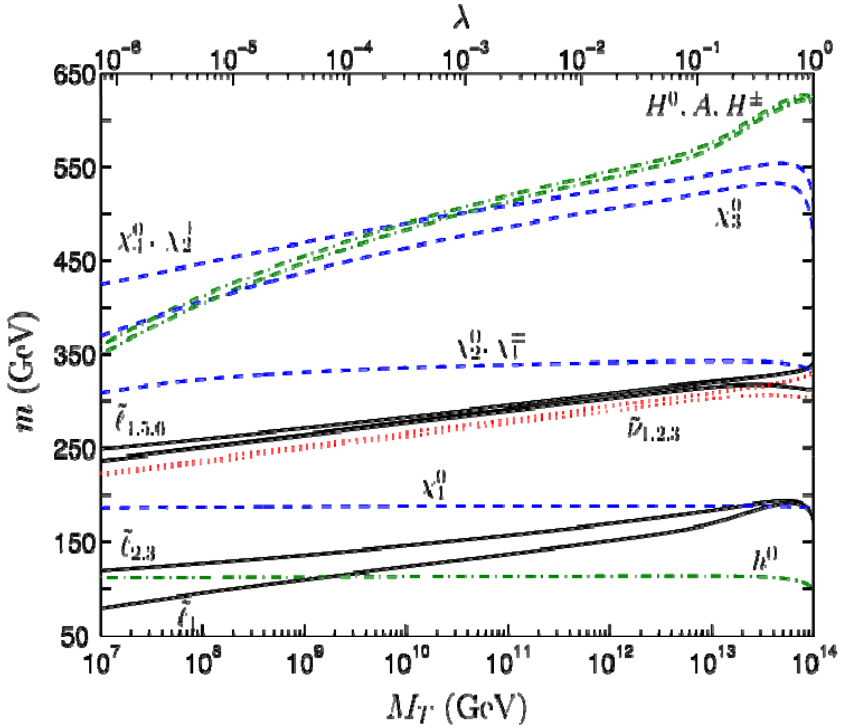
Novel SUSY SU(5) T-Seesaw : …(continuing)

THE SPECTRUM $(B_T = 20\,\text{TeV})$

Gluino $\tilde{g}$, Squarks $\tilde{u}$, $\tilde{d}$



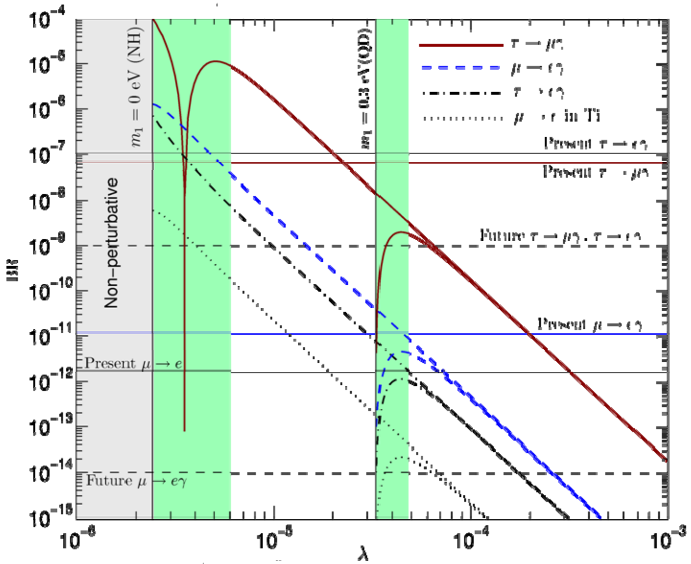
Sleptons, neutralinos, charginos and Higgs



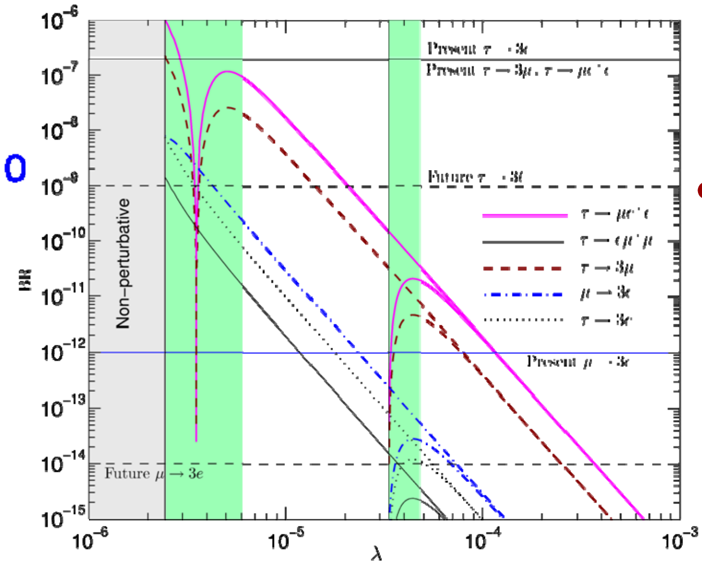
- The sparticle masses are within the discovery reach of LHC
- The gluino is the heaviest sparticle, $M_{\tilde{g}} \sim 1.3\,\text{TeV}$
- The slepton $\tilde{\ell}_1$ is the lightest ★ Gravitino is LSP
- 1-light SM-like Higgs (h^0) + 3 heavy Higgs $(H^0\ A, H^\pm)$

Novel SUSY SU(5) T-Seesaw : ...(continuing)

Predictions for LFV Processes $(B_T = 20\,\text{TeV}\,,\, M_T = 10^9\,\text{TeV})$ NH ν spectrum



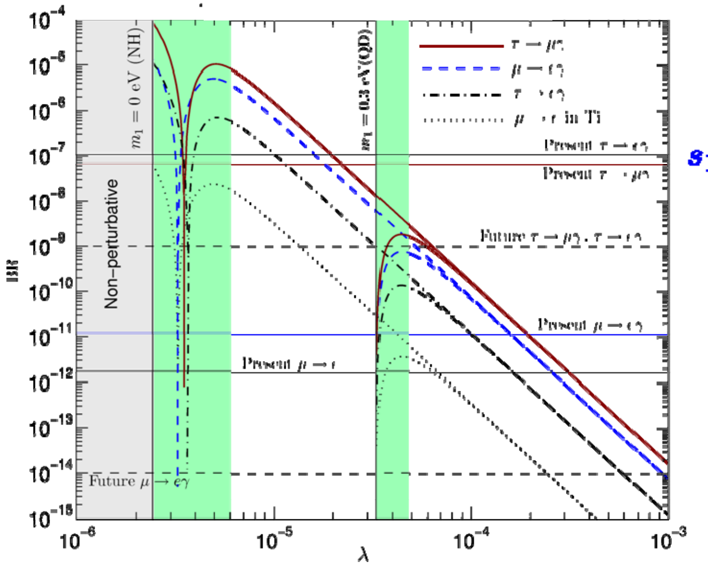
$s_{13} = 0$



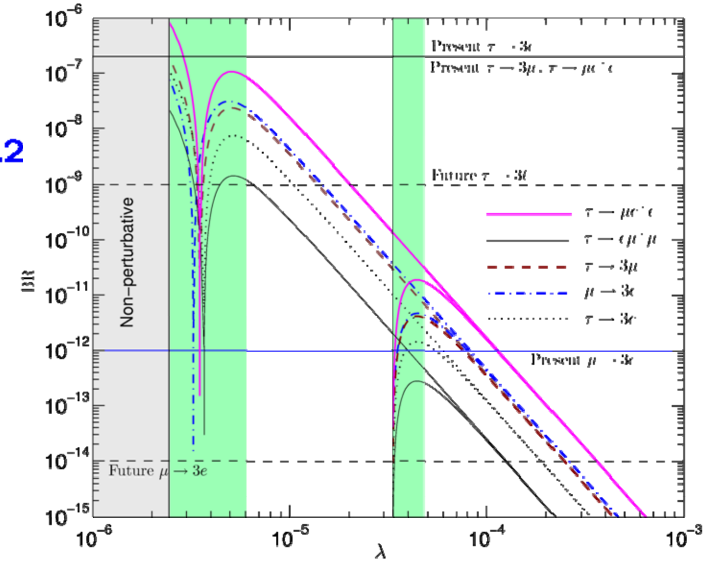
NOTICE

- **Constant ratios of LFV BRs** ***e.g.***

$$\frac{BR(\tau\to\mu\gamma)}{BR(\mu\to e\gamma)} \sim 300$$



$s_{13} = 0.2$



$$\frac{BR(\tau\to\mu\gamma)}{BR(\mu\to e\gamma)} \sim 2$$

Novel SUSY SU(5) T-Seesaw : …(continuing)

LFV Correlation pattern taking $\mathrm{BR}(\mu \to e\gamma) = 1.2 \times 10^{-11}$

Expectation	$s_{13} = 0$	$s_{13} = 0.2$
$\mathrm{BR}(\tau^- \to \mu^- \gamma)$	3×10^{-9}	$2\,(3) \times 10^{-11}$
$\mathrm{BR}(\tau^- \to e^- \gamma)$	2×10^{-12}	$1\,(3) \times 10^{-12}$
$\mathrm{BR}(\mu^- \to e^- e^+ e^-)$	6×10^{-14}	6×10^{-14}
$\mathrm{BR}(\tau^- \to \mu^- \mu^+ \mu^-)$	7×10^{-12}	$4\,(6) \times 10^{-14}$
$\mathrm{BR}(\tau^- \to \mu^- e^+ e^-)$	3×10^{-11}	$2\,(3) \times 10^{-13}$
$\mathrm{BR}(\tau^- \to e^- e^+ e^-)$	2×10^{-14}	$1\,(3) \times 10^{-14}$
$\mathrm{BR}(\tau^- \to e^- \mu^+ \mu^-)$	3×10^{-15}	$2\,(4) \times 10^{-15}$
$CR(\mu \to e;\, \mathrm{Tl})$	6×10^{-14}	6×10^{-14}

Upcoming exp.sensitivity will allow to detect

- $s_{13} \ll 0.2$: $\mathrm{BR}(\mu \to e\gamma)$, $\mathrm{BR}(\mu \to eee)$, $CR(\mu \to e; Ti)$, $\mathrm{BR}(\tau \to \mu\gamma)$
- $s_{13} \lesssim 0.2$: $\mathrm{BR}(\mu \to e\gamma)$, $\mathrm{BR}(\mu \to eee)$, $CR(\mu \to e; Ti)$

Conclusions

The Seesaw mechanism gives a) neutrino masses, b) sizeable LFV effects by exchaning heavy states, either singlets *N* or triplets *T* ☆

LFV decays are sensitive probes of the SUSY parameter space:
complementarity between LHC and LFV exps

Unambiguous predictions on LFV rates needs a 'high-energy' model for
1) Seesaw and 2) SUSY Mediation mechanism

- **N-Seesaw**: needs 1) and 2) to tell LFV rates. Bottom-up analysis are important to scan the parameter space and so to envisage/pinpoint the underlying high-energy theory (once LFV processes are detected)

- **T-Seesaw**: 1) is already OK, high-energy LFV = low-energy LFV
  ⟶ relative size of LFV rates is predicted . Overall size needs also 2).

Novel proposal : *T* playing also the role of SUSY Messengers
⟶ **1) and 2) are related** ⟶ Strong correlations among:

ν parameters, LFV/QFV , Sparticle spectrum and Higgs spectrum

Nicely testable at LHC !!

☆**also important for leptogenesis**