Charged Lepton Flavour in the MSSM Extended by a Type-II Triplet Seesaw

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23 July 2026

Outline

1. **Motivation: Why does the Standard Model fail for neutrino masses and cLFV?**
2. **Why Type-II seesaw and supersymmetry?**
3. **The MSSM extended by Type-II triplets**
4. **Numerical simulation results**
5. **Limitations and future extensions**

Why Does the Standard Model Need an Extension?

Neutrino mass

The minimal Standard Model contains no ν_R and no renormalizable Majorana operator:

$$m_\nu^{\text{minimal SM}} = 0. \tag{1}$$

Oscillation data instead require $\Delta m_{ij}^2 \neq 0$.

Charged-lepton flavour

Even after neutrino masses are included,

$$\mathcal{A}_{\text{SM}} \propto \sum_k U_{\mu k} U_{ek}^* \frac{m_{\nu_k}^2}{M_W^2} \simeq 0. \tag{2}$$

Observable cLFV would therefore reveal new flavour physics.

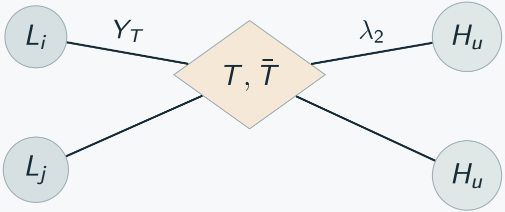
Neutrino oscillation → New mass mechanism → New flavour source → $\mu \to e\gamma$

Why a Type-II Seesaw?

Type-II seesaw generates a Majorana mass at tree level through a heavy electroweak triplet [4, 5]:

$$m_\nu = \frac{\lambda_2 v_u^2}{M_T} Y_T, \qquad Y_T = \frac{M_T}{\lambda_2 v_u^2} U^*_{\mathrm{PMNS}} m_\nu^D U^\dagger_{\mathrm{PMNS}}. \tag{3}$$

- $M_T \gg v$ naturally suppresses m_ν.
- No right-handed neutrino is required.
- Neutrino data fix the flavour structure of Y_T.



Why Supersymmetry?

Supersymmetry extends the Poincaré algebra by fermionic generators [1],

$$\{Q_\alpha, \bar{Q}_{\dot{\beta}}\} = 2\sigma^{\mu}_{\alpha\dot{\beta}} P_\mu, \qquad [P_\mu, Q_\alpha] = 0. \tag{4}$$

Algebraic consequence

- **Bosonic** $\leftrightarrow$ **Fermion**.
- Field - superpartner $\rightarrow$ supermultiplet.

Phenomenological consequence

- Softly broken SUSY $\rightarrow$ TeV-scale sleptons, neutralinos and charginos.
- Their loops avoid the ultra-light-neutrino suppression of the SM.

$$\boxed{\ell, \nu} \overset{Q}{\longleftrightarrow} \boxed{\widetilde{\ell}, \widetilde{\nu}} \qquad \boxed{W, B, H} \overset{Q}{\longleftrightarrow} \boxed{\widetilde{\chi}^{\pm}, \widetilde{\chi}^{0}}$$

How Is the MSSM Extended?

The MSSM superpotential is enlarged by a vector-like triplet pair:

$$W = W_{\rm MSSM} + \frac{1}{\sqrt{2}} Y_T^{ij} L_i T L_j + \frac{1}{\sqrt{2}} \lambda_1 H_d T H_d + \frac{1}{\sqrt{2}} \lambda_2 H_u \bar{T} H_u + M_T T \bar{T}. \qquad (5)$$

New superfields

$$T \sim (3, +1), \qquad \bar{T} \sim (3, -1). \qquad (6)$$

They contain scalar triplets and fermionic tripletinos.

Extended SUSY spectrum

- neutralinos: $4 \to 6$ states;
- charginos: $2 \to 3$ states;
- singly and doubly charged triplet scalars;
- triplet Yukawa soft terms A_T.

Why λ_2 and $\tan\beta$ Matter

$$W \supset \frac{\lambda_2}{\sqrt{2}} H_u \bar{T} H_u + M_T T \bar{T}, \qquad Y_T = \frac{M_T}{\lambda_2 v^2 \sin^2\beta} U^*_{\mathrm{PMNS}} m_\nu^D U^\dagger_{\mathrm{PMNS}}, \qquad \tan\beta = \frac{v_u}{v_d}. \tag{7}$$

Role of λ_2

- $H_u H_u \leftrightarrow \bar{T}$ coupling;
- fixes the seesaw normalization;
- $\lambda_2 \downarrow \Rightarrow Y_T \uparrow$.

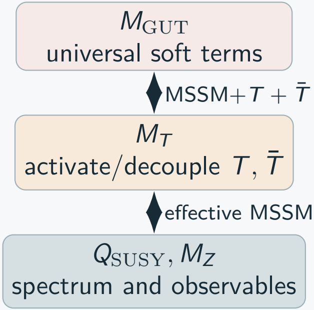
Role of $\tan\beta$

- $v_u = v \sin\beta$, $v_d = v \cos\beta$;
- weak effect on Y_T once $\sin\beta \simeq 1$;
- enhances chirality-sensitive SUSY loops.

$M_T \uparrow$ or $\lambda_2 \downarrow \Rightarrow Y_T \uparrow \Rightarrow$ stronger slepton mixing and tighter perturbativity/cLFV bounds.

Full RGE of Model

$$\frac{dX(Q)}{d\ln Q} = \frac{1}{16\pi^2}\beta_X, \qquad X = \{g_a, Y_f, Y_T, m_X^2, A_X, M_a, \ldots\}. \tag{8}$$



1. **Bottom-up:** low-energy inputs $\to M_T$; reconstruct Y_T.
2. **Boundary:** impose universal soft terms at M_{GUT} [2].
3. **Top-down:** generate flavour above M_T; match and decouple [5].
4. **Shooting:** update thresholds and repeat to convergence.

Output: converged masses, mixings and coherent loop amplitudes.

LLA as an Analytic Cross-Check

For $m^2_{\tilde{L}} = m_0^2 \mathbf{1}$ and $A_T = A_0 Y_T$ at $M_{\rm GUT}$,

$$(\Delta m^2_{\tilde{L}})_{ij} \simeq -\frac{3m_0^2 + A_0^2}{8\pi^2} (Y_T^\dagger Y_T)_{ij} \ln \frac{M_{\rm GUT}}{M_T}, \qquad i \neq j. \tag{9}$$

What LLA makes transparent

- source: $(Y_T^\dagger Y_T)_{ij}$;
- lever arm: $\ln(M_{\rm GUT}/M_T)$;
- soft scale: $3m_0^2 + A_0^2$.

How it is used

- checks sign and scaling;
- gives a fast RGE diagnostic;
- misses spectrum feedback and dip positions.

Dashed LLA: diagnostic. **Solid full RGE: prediction.**

MSSM Type II Seesaw - leading-log Approximation: Ref. [5].

Y_T Is the High-Scale Flavour Source

Standard Model

$$m_\nu, U_{\mathrm{PMNS}} \to W\text{–}\nu \text{ loop} \to \frac{m_\nu^2}{M_W^2} \simeq 0. \quad (10)$$

GIM cancellation and tiny m_ν make cLFV unobservable.

SUSY Type-II

$$Y_T^\dagger Y_T \to (m_{\tilde{L}}^2)_{ij} \to \tilde{\chi}\text{–}\tilde{\ell} \text{ loops.} \quad (11)$$

Neutrino flavour is transferred to the TeV-scale SUSY spectrum.

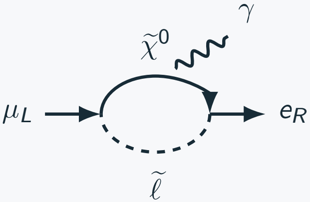
One spurion, three channels

$(Y_T^\dagger Y_T)_{12}$	$(Y_T^\dagger Y_T)_{13}$	$(Y_T^\dagger Y_T)_{23}$
$\Downarrow$	$\Downarrow$	$\Downarrow$
$\mu \to e\gamma$	$\tau \to e\gamma$	$\tau \to \mu\gamma$

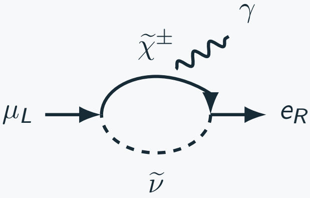
The (12) entry is the most tightly constrained.

Which Dipole-Loop Contributions Matter?

Neutralino–slepton



Chargino–sneutrino



$$\begin{aligned} A_L &= A_L^{\widetilde{\chi}^0} + A_L^{\widetilde{\chi}^\pm} + A_L^{\mathrm{H}^\pm,\mathrm{H}^{\pm\pm}}, \\ A_R &= A_R^{\widetilde{\chi}^0} + A_R^{\widetilde{\chi}^\pm}, \qquad A_R^{\mathrm{scalar}} \simeq 0, \\ \mathrm{BR}(\mu \to e\gamma) &\propto |A_L|^2 + |A_R|^2. \end{aligned} \tag{12}$$

Triplet-scalar background

$$A_{\mathrm{scalar}} \propto \frac{Y_T^\dagger Y_T}{M_T^2} \sim \frac{m_\nu^2}{\lambda_2^2 v_u^4}. \tag{13}$$

At fixed λ_2 and $\tan\beta$, $Y_T \propto M_T$ nearly cancels M_T^{-2}: a subleading background remains.

Numerical Scan and Physical Questions

M_T

Threshold and Y_T growth.

λ_2

Seesaw normalization: $Y_T \propto \lambda_2^{-1}$.

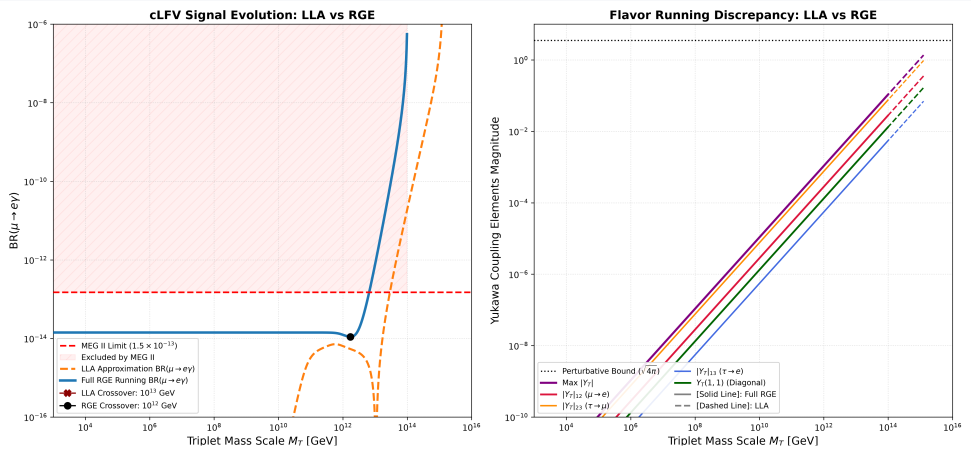
$\tan\beta$

Higgs VEVs, chirality and interference.

$$\{M_T, \lambda_2, \tan\beta\} \to Y_T \to \mathrm{RGE} \to \{m_X, Z_X\} \to A_{L,R} \to \mathrm{BR}(\mu \to e\gamma). \tag{14}$$

- Where do neutralino and chargino amplitudes cancel?
- Which regions survive MEG II?
- Where does Y_T lose perturbativity?

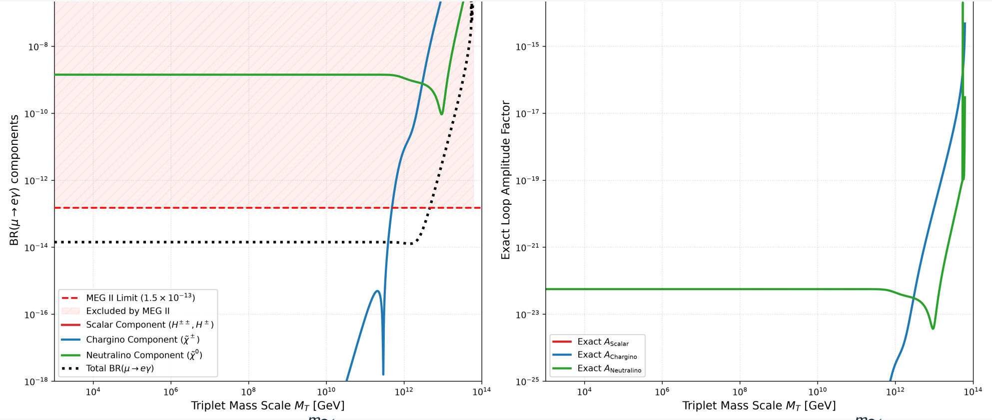
Full RGE versus LLA in the M_T Scan



$$(\Delta m^2_{\tilde{L}})^{\mathrm{LLA}}_{ij} \simeq -\frac{3m_0^2 + A_0^2}{8\pi^2}(Y_T^\dagger Y_T)_{ij} \ln \frac{M_{\mathrm{GUT}}}{M_T}$$

LLA fixes the analytic scaling; full RGE fixes the detailed spectrum and dip position.

The V-Dip Is an Interference Effect



$$A_L^{\tilde\chi^0} \sim \frac{N_L N_L^* F_1^N + N_L N_R^* \frac{m_{\tilde\chi^0}}{m_\mu} F_2^N}{32\pi^2 m_{\tilde\ell}^2} \qquad A_L^{\tilde\chi^\pm} \sim \frac{C_L C_L^* F_1^C + C_L C_R^* \frac{m_{\tilde\chi^\pm}}{m_\mu} F_2^C}{32\pi^2 m_{\tilde\nu}^2}$$

$$A_L = A_L^{\tilde\chi^0} + A_L^{\tilde\chi^\pm} + A_L^{\text{scalar}} \quad \Rightarrow \quad \text{coherent cancellation produces the V-dip.}$$

Lower and Higher M_T: Two Benchmark Trade-offs

Lower-M_T regime

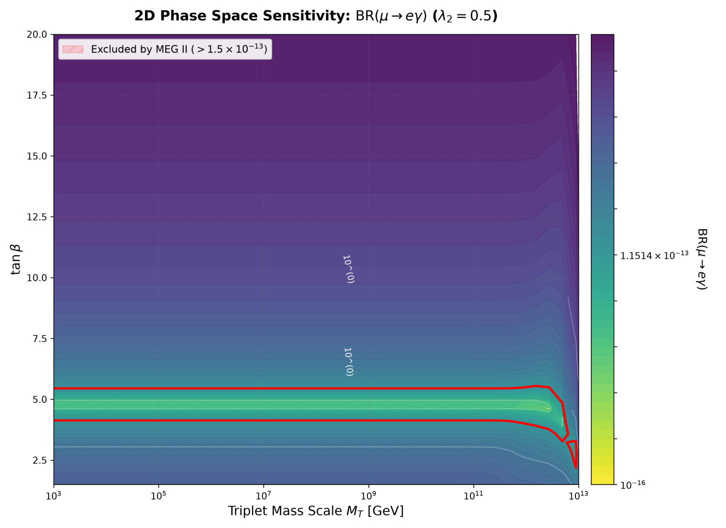
- Smaller Y_T at fixed λ_2: weaker RGE flavour.
- Low λ_2 or high $\tan\beta$ can restore cLFV tension.
- Heavier sleptons suppress cLFV; stop loops still lift m_h.

Higher-M_T regime

- Larger $Y_T \propto M_T/\lambda_2$: stronger slepton mixing.
- Perturbativity and MEG II become restrictive.
- Heavy sleptons can yield a hierarchical, split-like spectrum.

These are correlated benchmark choices—not parameter identities.

MEG II Isolates a $\tan\beta$ Corridor



- Red curve: MEG II 90% C.L. boundary [3].
- Cancellation corridor: $\tan\beta \sim 4$–5.
- It bends and narrows as M_T and Y_T grow.

Conclusions, Limitations and Future Work

Main result

$$m_\nu \to Y_T \to (m^2_{\tilde{L}})_{ij}$$
$$\Downarrow$$
$$\mu \to e\gamma$$

Neutralino–chargino interference generates the V-dip.

Current limitations

- fixed benchmark;
- low-dimensional scans;
- tree-level Higgs mass;
- dipole channel only.

Future extensions

- loop-corrected Higgs sector;
- global and split-spectrum scans;
- $\mu \to 3e$, μ–e conversion;
- CP phases.

Neutrino data become a predictive source of charged-lepton flavour violation.

Selected References

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Questions?

Neutrinos are light; the calculation code was not, therefore I AM suffered.