Resonant Single Slepton Production

in R-parity violating SUSY Models

with a $\tilde{\tau}$-LSP

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Outline

- **Introduction**

  R-parity violating ($\not{R}_p$) SUSY models

- **R-parity Violation and $\tilde{\tau}$-LSP Phenomenology**

  dynamical generation of $\not{R}_p$ couplings

  impact on $\tilde{\tau}$-LSP decays

- **Single Slepton Production at the LHC**

  like-sign dimuon events

- **Summary**

SUSY and R-Parity Violation

Consider **supersymmetric (SUSY) extension** of the Standard Model with a **minimal particle content**:

$\longrightarrow$ most general **superpotential** W**:** $\quad W = W_{R_p} + W_{\not{R}_p}$

$$W_{\not{R}_p} = \kappa_i L_i H_U + \frac{1}{2} \lambda_{ijk} L_i L_j \bar{E}_k + \lambda'_{ijk} L_i Q_j \bar{D}_k + \frac{1}{2} \lambda''_{ijk} \bar{U}_i \bar{D}_j \bar{D}_k$$

- $\kappa_i, \lambda, \lambda'$: induce Lepton number violation,
  λ'' : Baryon number violation

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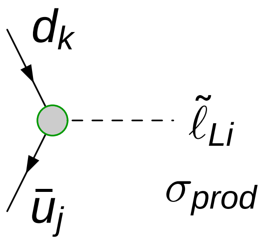
- **MSSM**: $W_{\not R_p}$ suppressed by ad-hoc introduced **R-parity**
  $\hookrightarrow$ sparticles produced in pairs, **L**ightest **S**USY **P**article is stable
- also allowed: R-parity violation ($\not R_p$) but **Baryon-Triality** ($\lambda'' = 0$)
  $\hookrightarrow$ single sparticle production possible, LSP unstable

$\lambda'_{ijk} L_i Q_j \bar{D}_k$: $\tilde{q}$ prod. at *ep* colliders & $\tilde{\ell}_i$ **prod.** at **hadron colliders**



$\sigma_{prod} \propto |\lambda'|^2$

Considered Model: mSUGRA + λ'_{ijk} + $\tilde{\tau}$-LSP

- SUSY has **many free parameters**,
  $\mathcal{O}(100)$ if R-parity is conserved, $\mathcal{O}(200)$ if R-parity is violated

- Simplify life: assume **boundary conditions** at the GUT scale

  mSUGRA: M_0, $M_{1/2}$, A_0, $\tan\beta$, sgn μ + λ'_{ijk}

- low-energy spectrum given by Renormalization Group Equations (**RGEs**)

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  mSUGRA: M_0, $M_{1/2}$, A_0, $\tan\beta$, sgn μ + λ'_{ijk}

  $\lambda'_{ijk} \neq 0 : \longrightarrow$ lepton number violating processes take place
  $\hookrightarrow$ LSP decays, needs not to be neutral
  here: **$\tilde{\tau}$-LSP scenarios** (decay e.g. $\tilde{\tau} \to \tau\, \ell_i\, u_j\, \bar{d}_k$)

- low-energy spectrum given by Renormalization Group Equations (**RGEs**)

  $\lambda'_{ijk} \neq 0 :$ $\longrightarrow$ moderate changes for sparticle masses
  $\longrightarrow$ neutrino masses are generated ($\longrightarrow$ bounds)
  $\longrightarrow$ CKM mixing: RGEs of $R\!\!\!/_p$ couplings are coupled
  $\hookrightarrow$ **new $R\!\!\!/_p$ couplings generated** at lower scales (λ'_{imn}, λ_{ill})

Dynamical generation of $\not{R}_p$ couplings

- approximated one-loop RGEs:
  - $\longrightarrow$ assume a single $\lambda'_{ijk} \neq 0|_{GUT}$
  - $\longrightarrow$ neglect products of two or more $\not{R}_p$ couplings
  - $\longrightarrow$ consider hierarchical structure of Yukawa couplings

$$16\pi^2 \frac{d}{dt}\lambda'_{ijk} = \lambda'_{ijk} \Big[-\frac{7}{15}g_1^2 - 3g_2^2 - \frac{16}{3}g_3^2 \\ + \left(\mathbf{Y}_D\right)^2_{33} \left(2\delta_{k3} + \delta_{j3} + 3\,\delta_{j3}\,\delta_{k3}\right) + \left(\mathbf{Y}_U\right)^2_{33}\,\delta_{j3} + \left(\mathbf{Y}_E\right)^2_{33}\,\delta_{i3}\Big],$$

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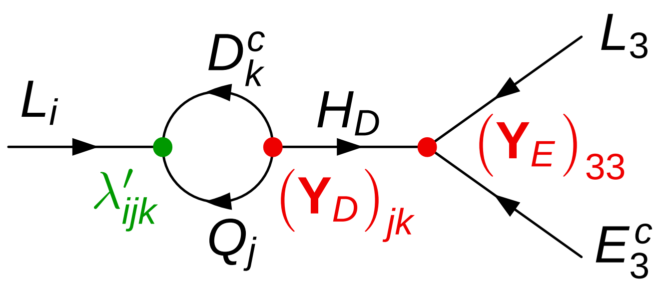
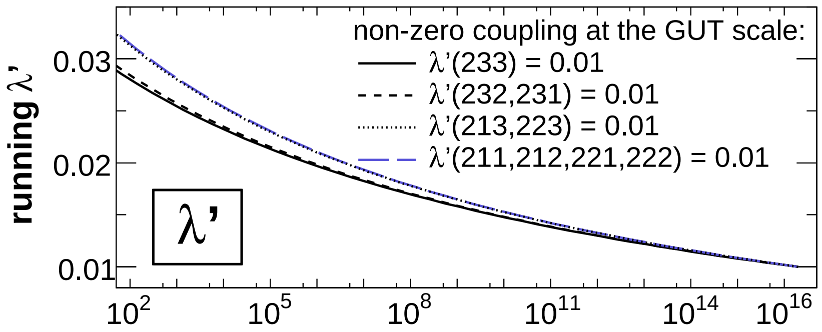
$$16\pi^2 \frac{d}{dt} \boldsymbol{\lambda}_{i33} = \boldsymbol{\lambda}_{i33} \Big[-\frac{9}{5} g_1^2 - 3g_2^2 + 4\left(\mathbf{Y}_E\right)^2_{33} \Big] + 3\,\boldsymbol{\lambda}'_{ijk} \left(\mathbf{Y}_E\right)_{33} \left(\mathbf{Y}_D\right)_{jk}.$$

- dynamical generation of λ_{i33} via $\boldsymbol{\lambda}'_{ijk}$

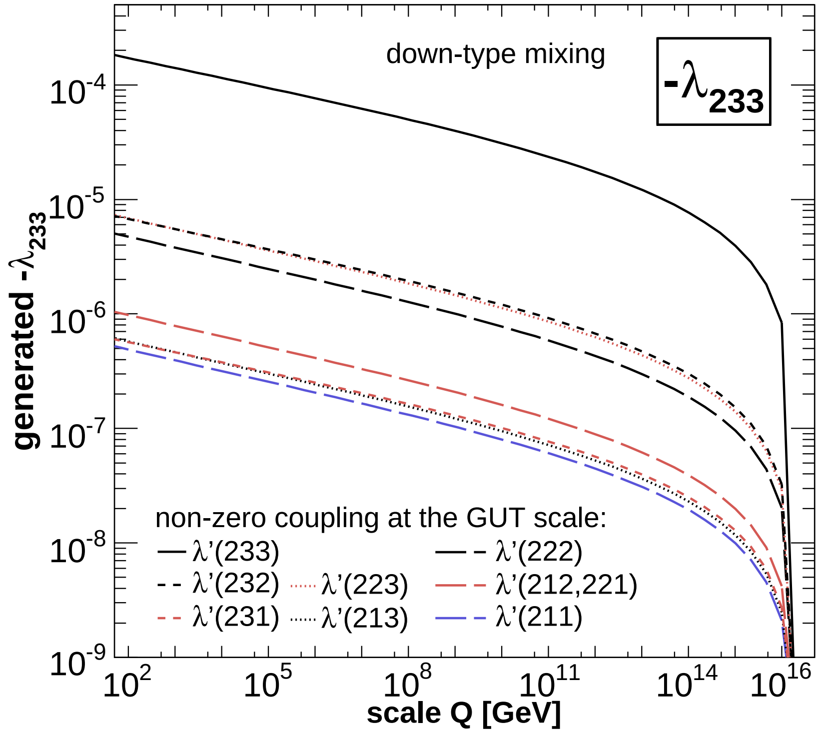


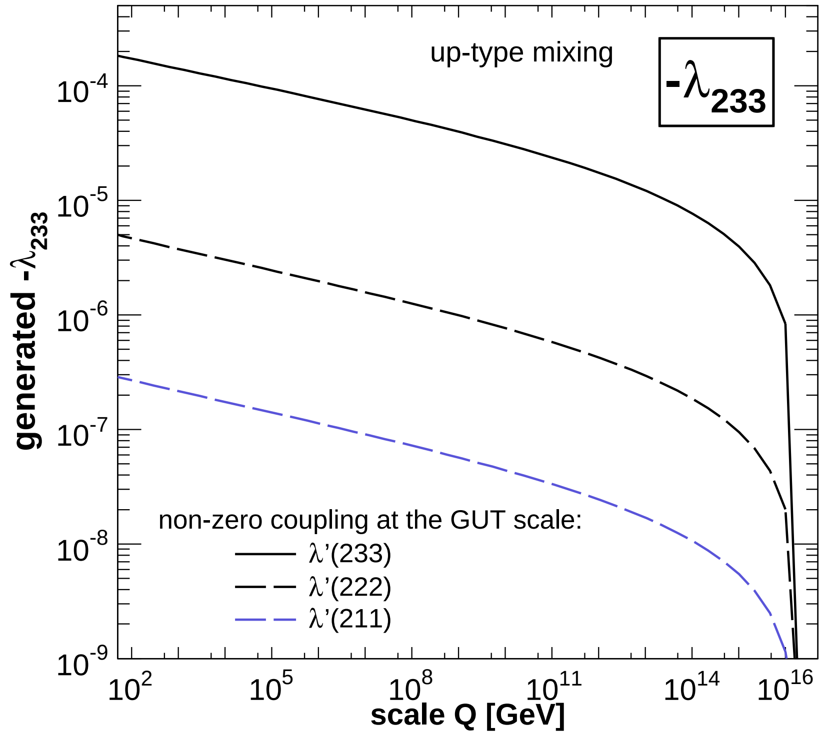
λ_{i33} interesting for $\tilde{\tau}$-LSP decays!
e.g. $\tilde{\boldsymbol{\tau}} \to \tau \nu_i$

RGE running: $\boldsymbol{\lambda}'_{2jk} \neq 0|_{GUT}$ generates $\boldsymbol{\lambda}_{233} \neq 0|_Q$



Set A: $M_0 = 0\,\text{GeV}$, $M_{1/2} = 500\,\text{GeV}$,
$A_0 = 600\,\text{GeV}$,
$\tan\beta = 13$, $\text{sgn}(\mu) = +1$
one $\boldsymbol{\lambda}'_{2jk} = 0.01|_{GUT}$

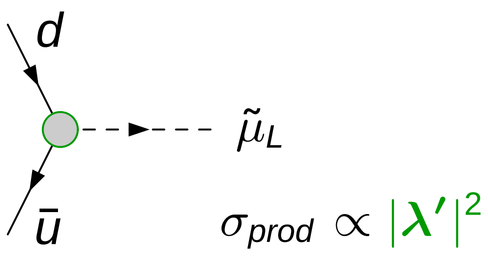




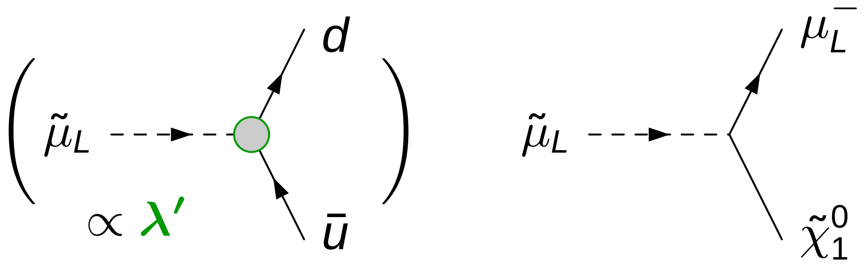
$$16\pi^2 \frac{d}{dt}\boldsymbol{\lambda}_{233} = \boldsymbol{\lambda}_{233}\left[-\frac{9}{5}g_1^2 - 3g_2^2 + 4\left(\mathbf{Y}_E\right)^2_{33}\right] + 3\,\boldsymbol{\lambda}'_{2jk}\,\left(\mathbf{Y}_E\right)_{33}\boxed{\left(\mathbf{Y}_D\right)_{jk}}$$

What is special about $\tilde{\ell}$ prod. in $\tilde{\tau}$-LSP scenarios?

Hadronic slepton production (via λ'_{211})



Slepton decay modes:



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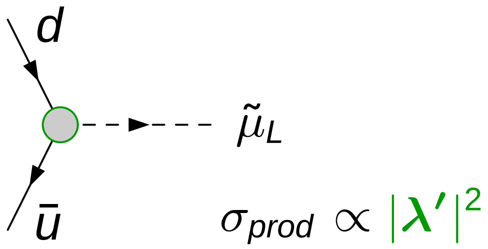

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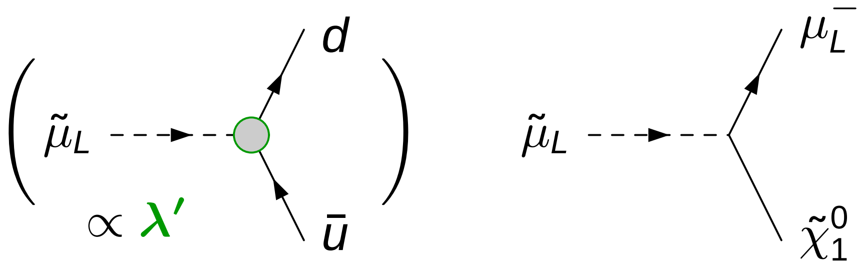
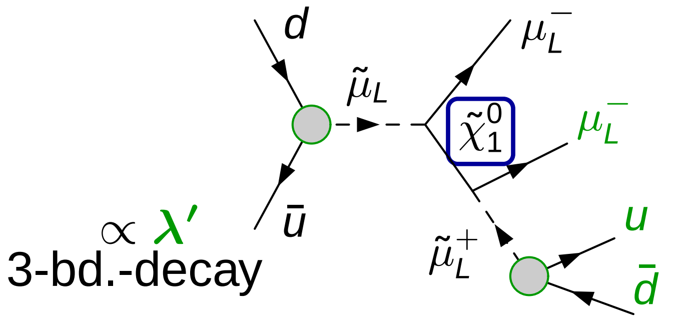
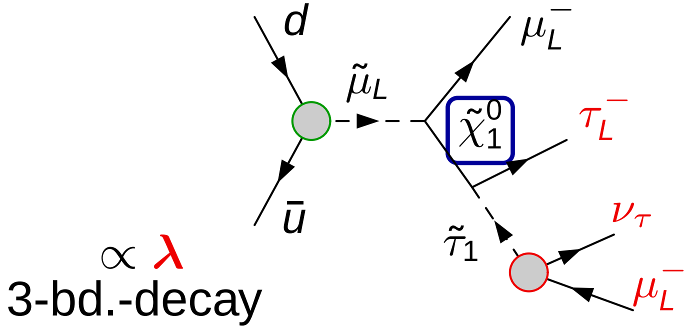


$\tilde{\chi}_1^0$-LSP





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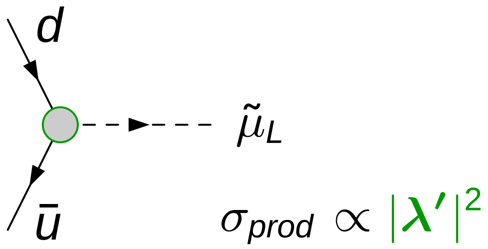

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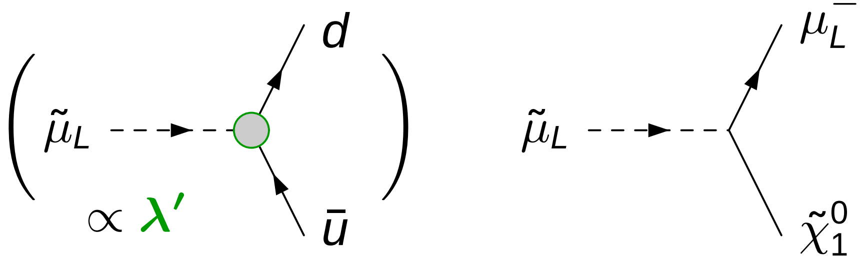

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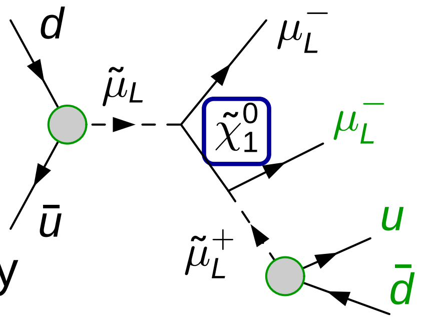
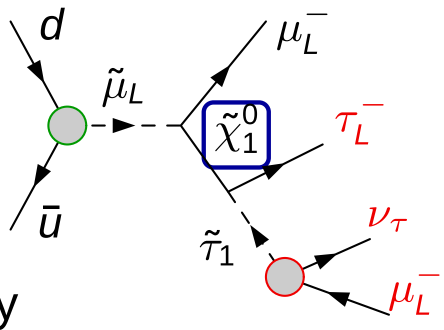


$\propto \lambda'$
3-bd.-decay



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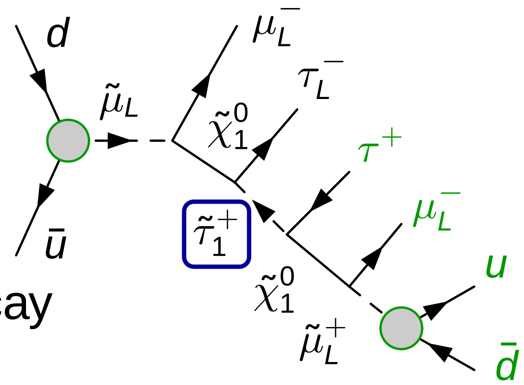
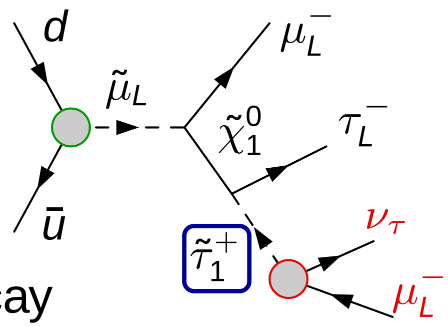
$\tilde{\tau}_1$-LSP



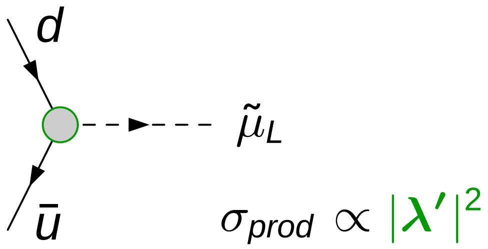
$\propto \lambda'$
4-bd.-decay



$\propto \lambda$
2-bd.-decay

What is special about $\tilde{\ell}$ prod. in $\tilde{\tau}$-LSP scenarios?

Hadronic slepton production (via λ'_{211})



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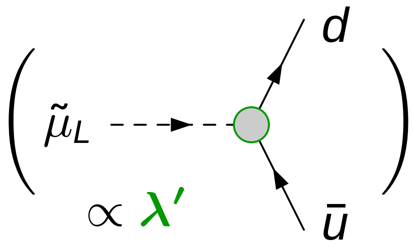

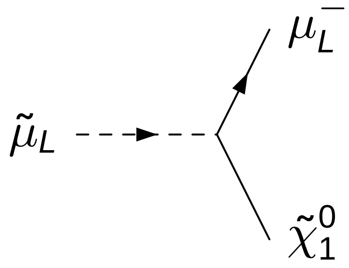

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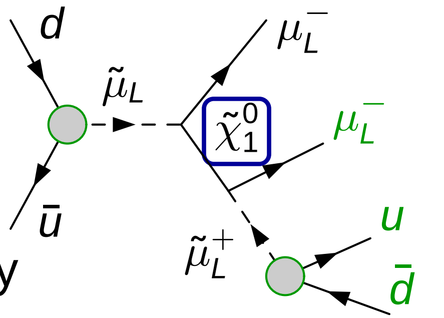

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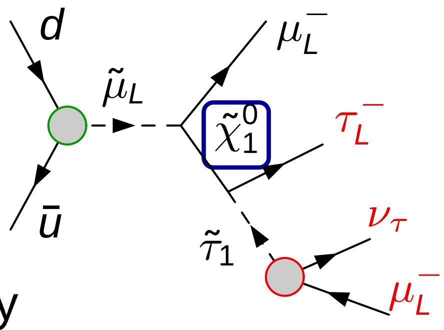

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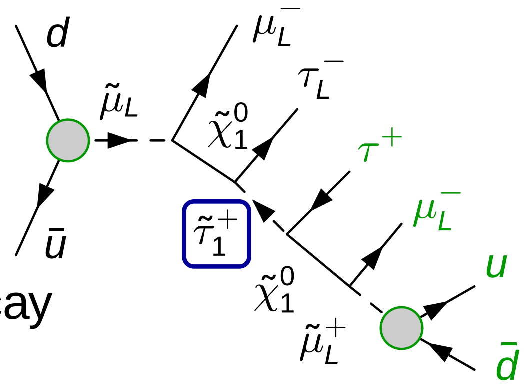

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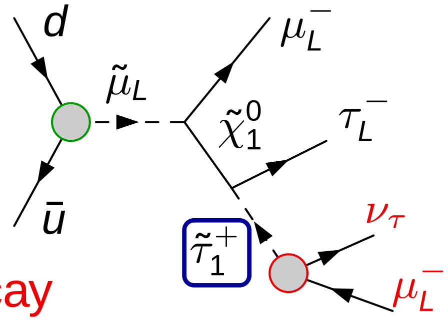
4-bd.-decay



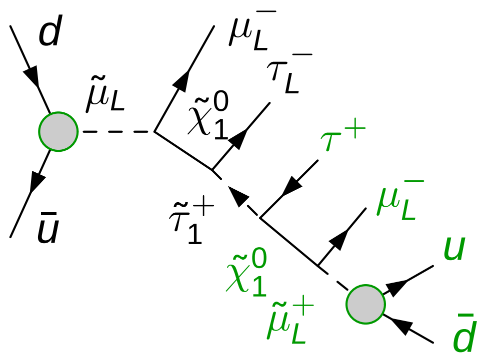
$\propto \lambda$
2-bd.-decay

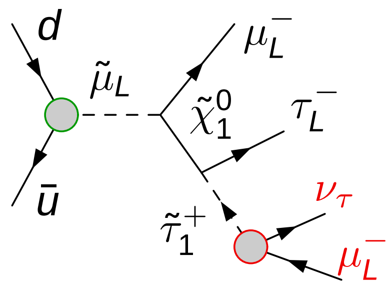
$\Rightarrow$ can be important!

Single Slepton Production: Possible Signatures

$\lambda'_{2jk} \neq 0|_{GUT}$

	$\bar{u}_j\, d_k \to \tilde{\mu}_L^- \to \mu^- \tilde{\chi}_1^0$ or $\bar{d}_j\, d_k \to \tilde{\nu}_\mu \to \nu_\mu \tilde{\chi}_1^0$	
	$\tilde{\chi}_1^0 \to \tau^+\, \tilde{\tau}_1^-$ $\left[\tilde{\chi}_1^0 \to \tau^+\, \tilde{\tau}_1^-\, \ell^+ \ell^-\right]$	$\tilde{\chi}_1^0 \to \tau^-\, \tilde{\tau}_1^+$ $\left[\tilde{\chi}_1^0 \to \tau^-\, \tilde{\tau}_1^+\, \ell^- \ell^+\right]$
λ'_{2jk}	$\tilde{\tau}_1^- \to \tau^- \mu^-\, u_j\, \bar{d}_k$ $\tilde{\tau}_1^- \to \tau^- \mu^+ \bar{u}_j d_k$ $\tilde{\tau}_1^- \to \tau^- \nu_\mu\, d_j\, \bar{d}_k$ $\tilde{\tau}_1^- \to \tau^- \bar{\nu}_\mu\, \bar{d}_j\, d_k$	$\tilde{\tau}_1^+ \to \tau^+ \mu^+\, \bar{u}_j\, d_k$ $\tilde{\tau}_1^+ \to \tau^+ \mu^-\, u_j\, \bar{d}_k$ $\tilde{\tau}_1^+ \to \tau^+ \bar{\nu}_\mu\, \bar{d}_j\, d_k$ $\tilde{\tau}_1^+ \to \tau^+ \nu_\mu\, d_j\, \bar{d}_k$
λ_{233}	$\tilde{\tau}_1^- \to \tau^- \nu_\mu$ $\tilde{\tau}_1^- \to \tau^- \bar{\nu}_\mu$ $\tilde{\tau}_1^- \to \mu^- \nu_\tau$	$\tilde{\tau}_1^+ \to \tau^+ \bar{\nu}_\mu$ $\tilde{\tau}_1^+ \to \tau^+ \nu_\tau$ $\tilde{\tau}_1^+ \to \mu^+ \bar{\nu}_\tau$





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	$\tilde{\chi}_1^0 \to \tau^+\, \tilde{\tau}_1^-$ $\left[\tilde{\chi}_1^0 \to \tau^+\, \tilde{\tau}_1^-\, \ell^+ \ell^-\right]$	$\tilde{\chi}_1^0 \to \tau^-\, \tilde{\tau}_1^+$ $\left[\tilde{\chi}_1^0 \to \tau^-\, \tilde{\tau}_1^+\, \ell^- \ell^+\right]$
λ'_{2jk}	$\tilde{\tau}_1^- \to \tau^- \mu^-\, u_j\, \bar{d}_k$	$\tilde{\tau}_1^+ \to \tau^+ \mu^+\, \bar{u}_j\, d_k$
	$\tilde{\tau}_1^- \to \tau^- \mu^+ \bar{u}_j d_k$	$\tilde{\tau}_1^+ \to \tau^+ \mu^-\, u_j\, \bar{d}_k$
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λ_{233}	$\tilde{\tau}_1^- \to \tau^- \nu_\mu$	$\tilde{\tau}_1^+ \to \tau^+ \bar{\nu}_\mu$
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	$\tilde{\tau}_1^- \to \mu^- \nu_\tau$	$\tilde{\tau}_1^+ \to \mu^+ \bar{\nu}_\tau$

$\tilde{\mu}$ production

λ'_{2jk}	$\tau^+\tau^-$	$\mu^-\mu^\mp$		jj
	$\tau^+\tau^-$	μ^-	$\not{E}_T$	jj
λ_{233}	$\tau^+\tau^-$	μ^-	$\not{E}_T$	
	$\tau^\pm$	$\mu^-\mu^\mp$	$\not{E}_T$	

$\tilde{\nu}_\mu$ production

λ'_{2jk}	$\tau^+\tau^-$	$\mu^\mp$	$\not{E}_T$	jj
	$\tau^+\tau^-$		$\not{E}_T$	jj
λ_{233}	$\tau^+\tau^-$		$\not{E}_T$	
	$\tau^\pm$	$\mu^\mp$	$\not{E}_T$	

- 2-body decays: **purely leptonic** final states
- $\tilde{\mu}$ prod.: promising final state signatures: **like-sign dimuons**!

Like-Sign Dimuon Events

$$\bar{u}_j d_k \xrightarrow{\lambda'} \tilde{\mu}_L^- \xrightarrow{100\%} \mu^- \tilde{\chi}_1^0, \quad \tilde{\chi}_1^0 \nearrow \tau^+ \tilde{\tau}_1^-, \quad \tilde{\tau}_1^- \xrightarrow{\lambda} \nu_\tau \mu^- , \quad \tilde{\tau}_1^- \xrightarrow{\lambda'} \tau^- \mu^- u_j \bar{d}_k$$

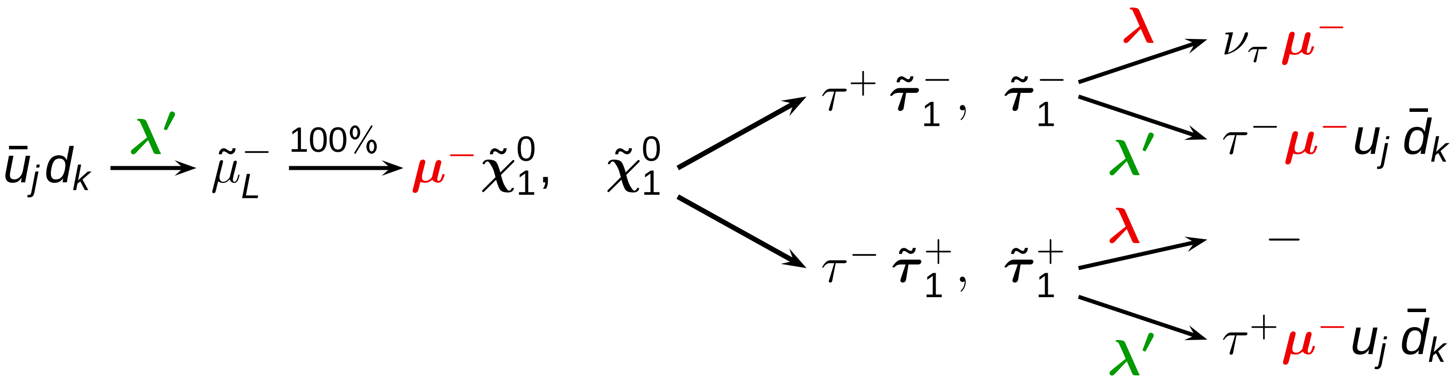
$$\tilde{\chi}_1^0 \searrow \tau^- \tilde{\tau}_1^+, \quad \tilde{\tau}_1^+ \xrightarrow{\lambda} \; - , \quad \tilde{\tau}_1^+ \xrightarrow{\lambda'} \tau^+ \mu^- u_j \bar{d}_k$$

σ @ NLO QCD + SUSY-QCD

[Choudhury, Majhi, Ravindran ’03],
[Yang, Li, Liu, Li ’05],
[Dreiner, Grab, Krämer, MT ’07],
[Chen, Han, Si ’07]

BRs: $\not{R}_p$ version of Herwig

Like-Sign Dimuon Events



Set A: $\tan\beta = 13$, $A_0 = 600\,\text{GeV}$, $M_{1/2} = 500\,\text{GeV}$, $M_0 = 0\,\text{GeV}$; $+\lambda'_{2jk} = 0.002|_{GUT}$
Set B: $\tan\beta = 26$, $A_0 = 1150\,\text{GeV}$, $M_{1/2} = 700\,\text{GeV}$, $M_0 = 0\,\text{GeV}$; $+\lambda'_{2jk} = 0.01|_{GUT}$

$\mathcal{L}$=10 fb^{-1}:

up mix.	Set A $N_{\lambda'}$	Set A N_{λ}	Set B $N_{\lambda'}$	Set B N_{λ}
λ'_{211}	305	20	30	2890
λ'_{221}	110	–	840	–
λ'_{212}	195	–	1640	–

down mix.	Set A $N_{\lambda'}$	Set A N_{λ}	Set B $N_{\lambda'}$	Set B N_{λ}
λ'_{211}	270	60	5	2910
λ'_{221}	60	55	–	890
λ'_{212}	110	95	–	1725

$(\mathbf{Y}_D)_{kk} \neq 0$: only λ'_{2kk} generate λ_{233}
4-body decays dominate

$(\mathbf{Y}_D)_{jk} \neq 0$: all λ'_{2jk} generate λ_{233}
Set B / large $\tan\beta$: 2-bd.-decays dominate

Summary

- Model: mSUGRA + **R-parity violation** ($\lambda'_{ijk} \neq 0$) + $\tilde{\tau}$**-LSP**
- **modified RGEs**: dynamical generation of new $\not{R}_p$ couplings,
  λ'_{ijk} generate λ_{i33}, relevant for $\tilde{\tau}$**-LSP decay**
  since dominant λ' decay is phase-space suppressed
- **sleptons** can be **produced singly** at hadron colliders
- interesting final state signatures: **like-sign dimuons**,
  $\tilde{\tau}$-LSP decays via λ_{233} contribute considerably

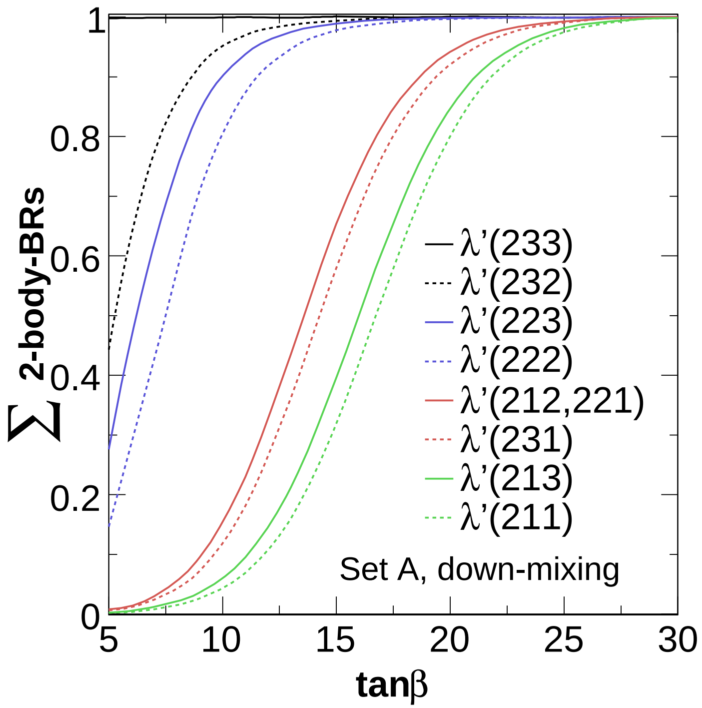
Backup

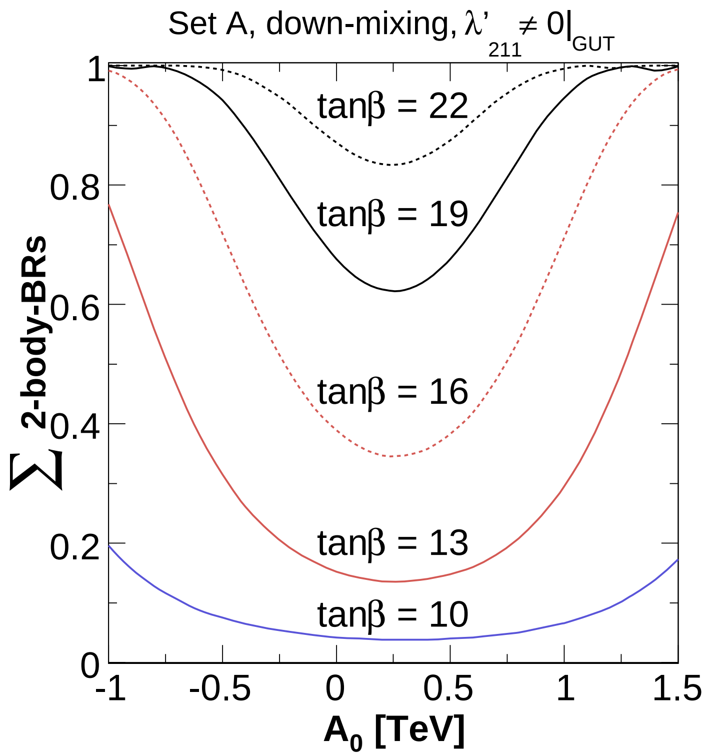
2-body versus 4-body $\tilde{\tau}$-LSP decays

- When do the 2-body decays dominate?

$$\Gamma_{\text{2body}} \propto \boldsymbol{\lambda}_{i33}^2\, m_{\tilde{\tau}_1} \;\leftrightarrow\; \Gamma_{\text{4body}} \propto \boldsymbol{\lambda}_{ijk}^{\prime 2}\, \frac{m_{\tilde{\tau}_1}^7}{m_{\tilde{\chi}}^2\, m_{\tilde{f}}^4}$$

$BR_2 = \Sigma\Gamma_2/(\Sigma\Gamma_2 + \Sigma\Gamma_4)$





$$16\pi^2 \frac{d}{dt} \boldsymbol{\lambda}_{i33} = \boldsymbol{\lambda}_{i33} \left[\ldots \right] + 3\, \boldsymbol{\lambda}'_{ijk} \left(\mathbf{Y}_E \right)_{33} \left(\mathbf{Y}_D \right)_{jk}$$

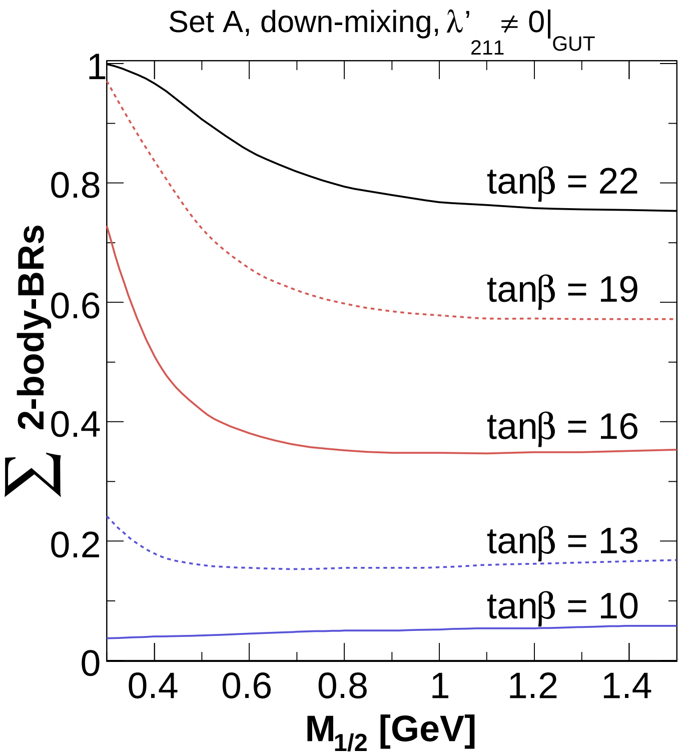
stau mass mixing:

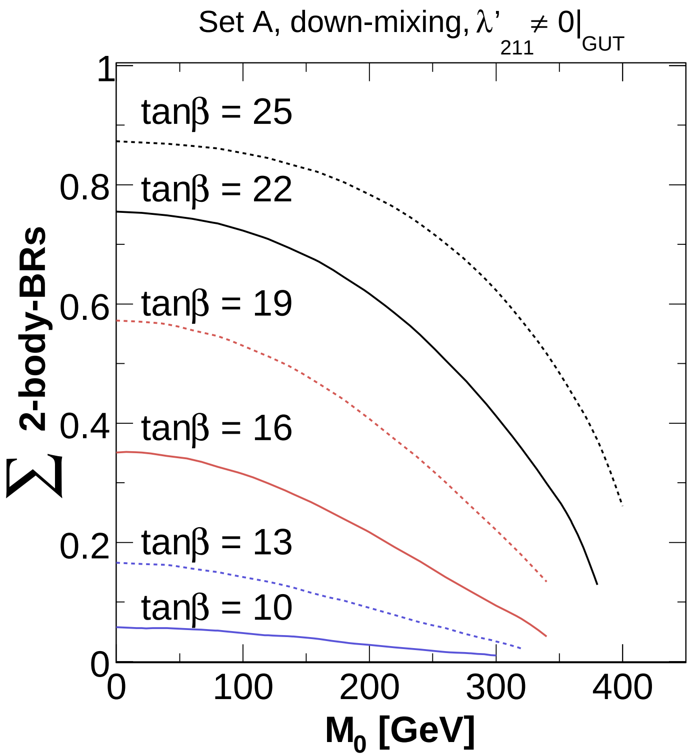
$$m_{\tilde{\tau}_1}^2 - m_{\tilde{\tau}_2}^2 \propto A_\tau - \mu \tan\beta$$

2-body versus 4-body $\tilde{\tau}$-LSP decays II

- When do the 2-body decays dominate?

$$\Gamma_{\text{2body}} \propto \lambda_{i33}^2\, m_{\tilde{\tau}_1} \quad \leftrightarrow \quad \Gamma_{\text{4body}} \propto \lambda_{ijk}'^2 \frac{m_{\tilde{\tau}_1}^7}{m_{\tilde{\chi}}^2\, m_{\tilde{f}}^4}$$





$$m_{\tilde{\chi}}^2 \propto M_{1/2}; \quad m_{\tilde{f}}^2 \propto M_0^2 + aM_{1/2}^2$$
$$\Gamma_4/\Gamma_2 \propto m_{\tilde{\tau}_1}^6 / m_{\tilde{\chi}}^2\, m_{\tilde{f}}^4$$

$$\Rightarrow \lim_{M_{1/2}\to\infty}(\Gamma_4/\Gamma_2) = \text{const.}$$
$$\Rightarrow \lim_{M_0\to\infty}(\Gamma_4/\Gamma_2) = \mathcal{O}(M_0^2)$$

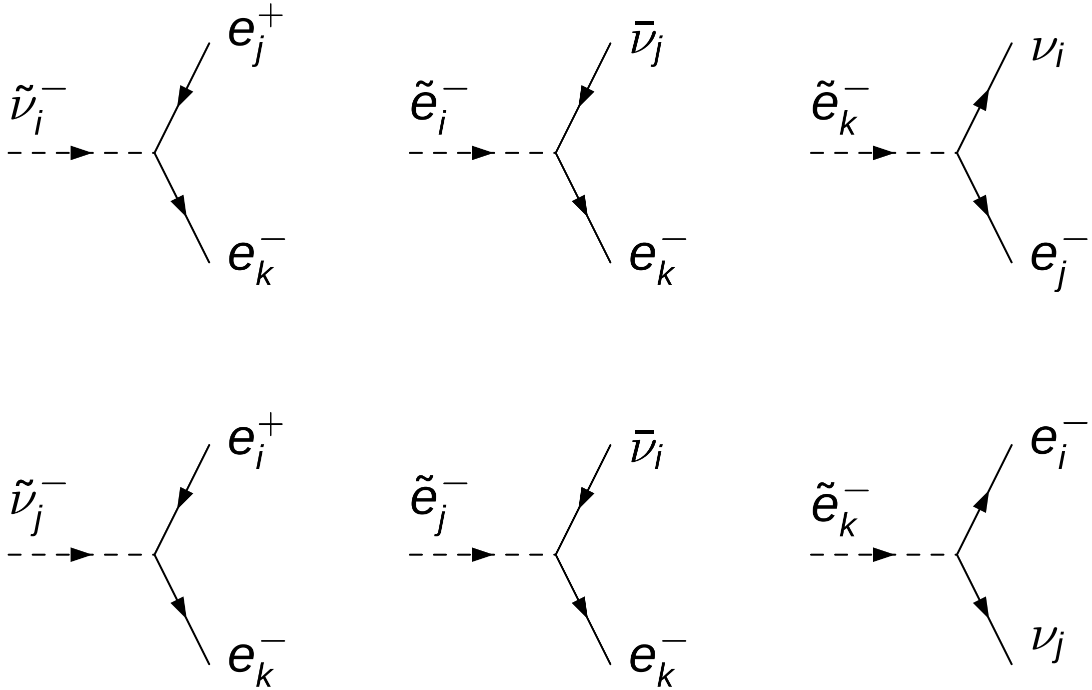
Sparticle Masses for Set A & Set B

	masses [GeV]			masses [GeV]	
	Set A	Set B		Set A	Set B
$\tilde{\tau}_1$	179	146	$\tilde{\chi}_1^0$	203	290
$\tilde{e}_R$	193	266	$\tilde{\chi}_2^0$	380	544
$\tilde{\tau}_2$	340	453	$\tilde{\chi}_3^0$	571	754
$\tilde{e}_L$	340	471	$\tilde{\chi}_4^0$	587	765
$\tilde{\nu}_\tau$	326	437	$\tilde{\chi}_1^\pm$	383	549
$\tilde{\nu}_e$	329	461	$\tilde{\chi}_1^\pm$	583	761
$\tilde{t}_1$	841	1160	h^0	113	115
$\tilde{b}_1$	970	1300	H^0	643	795
$\tilde{u}_R$	1010	1370	A^0	642	795
$\tilde{t}_2$	1010	1340	H^+	648	799
$\tilde{b}_2$	995	1340			
$\tilde{u}_L$	1040	1410	$\tilde{g}$	1150	1560

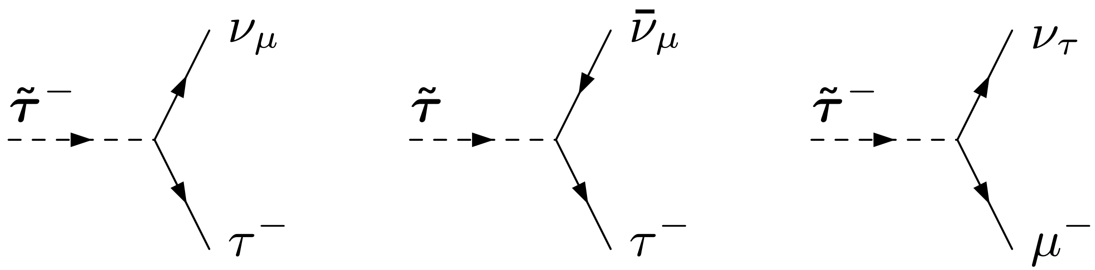
[using Softsusy 2.0.10;
variation due to different $\lambda'_{ijk} \neq 0|_{\mathrm{GUT}}$ and
quark mixing below percent level;
masses in 1st & 2nd generation coincide.]

$LL\bar{E}$ induced 2-body decays of the $\tilde{\tau}$-LSP

- processes induced by the $\not{R}_p$ operator $L_i\, L_j\, \bar{E}_k$:

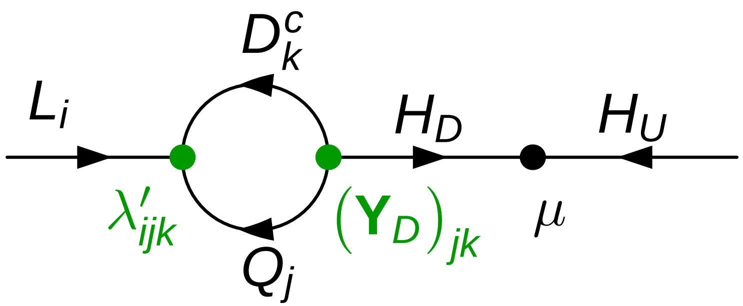


- i. e. the following $\tilde{\tau}$ decay modes exist for $ijk = 233$:



Dynamical generation of the $\not{R}_p$ coupling κ_i

- dynamical generation of κ_i via $\boldsymbol{\lambda}'_{ijk}$



- $16\,\pi^2 \frac{d}{dt}\kappa_i =$

$$\kappa_i \left[-\tfrac{6}{10} g_1^2 - 3 g_2^2 + 3 (\mathbf{Y}_U)^2_{33} + (\mathbf{Y}_E)^2_{33} \right] + \mu \left[3 \boldsymbol{\lambda}'_{ijk} (\mathbf{Y}_D)^*_{jk} + \boldsymbol{\lambda}_{ill} (\mathbf{Y}_E)^*_{ll} \right]$$

- superpotential W:

$$W = W_{R_p} + W_{\not{R}_p}$$

$$W_{R_p} = (\mathbf{Y}_E)_{ij}\, L_i\, H_d\, \bar{E}_j + (\mathbf{Y}_D)_{ij}\, Q_i\, H_d\, \bar{D}_j + (\mathbf{Y}_U)_{ij}\, Q_i\, H_u\, \bar{U}_j + \mu\, H_d\, H_u\,,$$

$$W_{\not{R}_p} = \boldsymbol{\kappa}_i\, L_i\, H_u + \tfrac{1}{2}\, \boldsymbol{\lambda}_{ijk}\, L_i\, L_j\, \bar{E}_k + \boldsymbol{\lambda}'_{ijk}\, L_i\, Q_j\, \bar{D}_k + \tfrac{1}{2}\, \boldsymbol{\lambda}''_{ijk}\, \bar{U}_i\, \bar{D}_j\, \bar{D}_k$$

i,j,k family indices; $Q_i\,, L_i$ quark–/lepton SU(2)-dublet superfields;
$\bar{U}_i\,, \bar{D}_i\; \bar{E}_i$ up/down-type quark–/lepton SU(2)-singlet superfields; $H_{U\,/\,D}$ Higgs superfields