Resonant Single Slepton Production

in R-parity violating SUSY Models

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

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Outline

- **Introduction**
  Supersymmetry and R-parity violation
- **R-parity Violation and $\tilde{\tau}$-LSP Phenomenology**
  dynamical generation of λ_{233}
- **Single Slepton Production at the LHC**
  like-sign dimuon events
- **Summary**

Supersymmetry (SUSY) and R-Parity Violation

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

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

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

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

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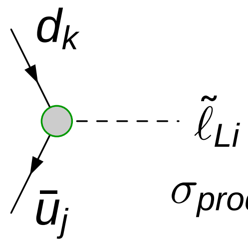
- **MSSM**: $W_{\not R_p}$ suppressed by ad-hoc introduced **R-parity**
  $\hookrightarrow$ SUSY particles produced in pairs, **L**ightest **S**USY **P**article is stable
- also allowed: R-parity violation ($\not R_p$) + **Baryon-Triality** ($\lambda'' = 0$)
  $\hookrightarrow$ single SUSY particle production 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 parameters are given by Renormalization Group Equations (**RGEs**)

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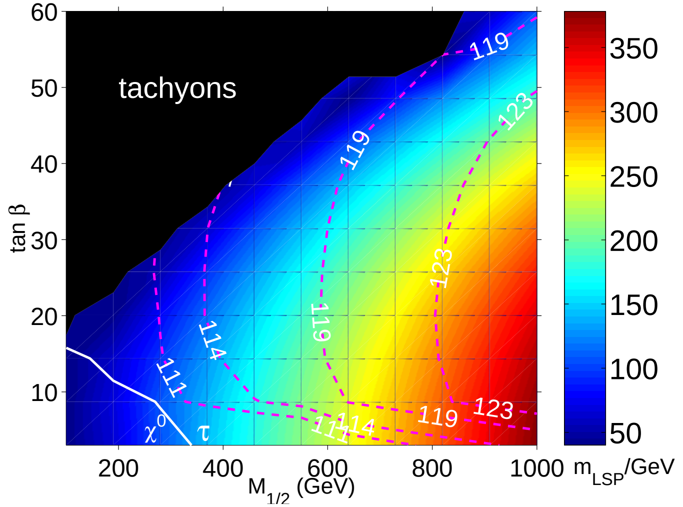
- low-energy parameters are given by Renormalization Group Equations (**RGEs**)

- $\tilde{\tau}_1$**-LSP scenarios** arise naturally!

  excluded if R-parity is conserved since LSP needs to be neutral

  but **allowed in $\not{R}_p$ models**, where the **LSP** may be **charged**

$M_0 = A_0 = 0$ GeV



[Allanach, Dedes, Dreiner '04]

Phenomenology of $\not{R}_p$ models

- Lepton- or baryon number violating processes take place
- neutrino masses are generated

  $\hookrightarrow$ **bounds** on $\not{R}_p$ couplings ($< \mathcal{O}(0.01) - \mathcal{O}(0.1)$)

- **single sparticle production** is possible
- **LSP** is **unstable** ($\longrightarrow$ can be charged)

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  - moderate changes for sparticle masses
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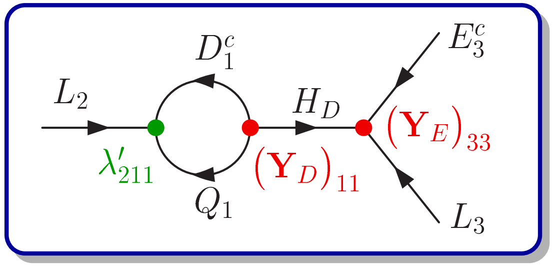


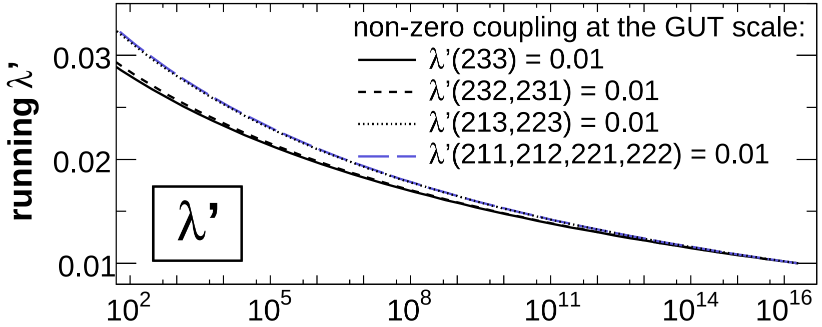
approx.:

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

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

$\Rightarrow \tilde{\tau}$ decay

RGEs: Running of $\not{R}_p$ couplings



Set A: $M_0 = 0\,\text{GeV}$, $M_{1/2} = 500\,\text{GeV}$,
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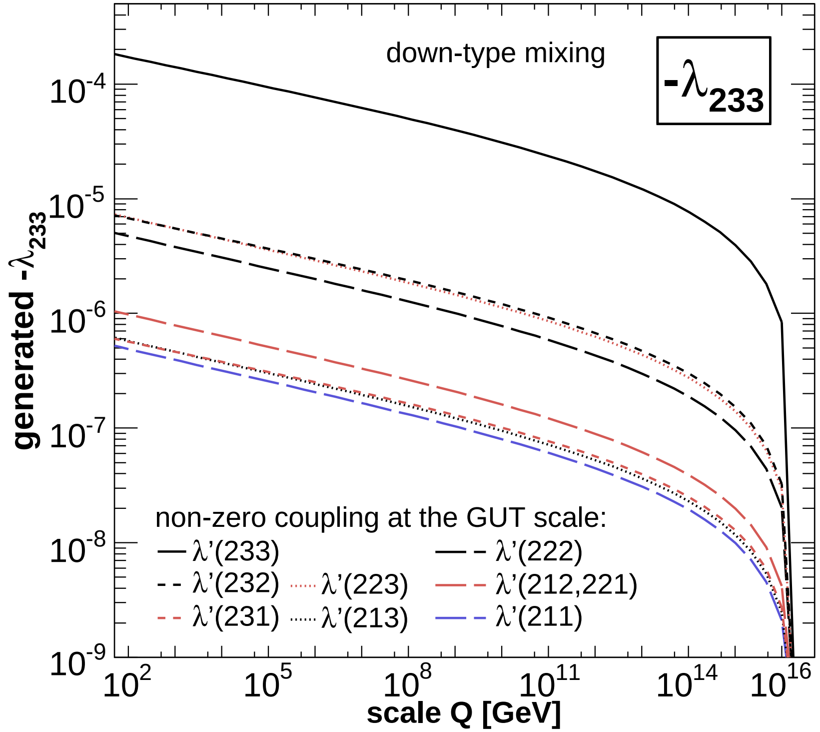
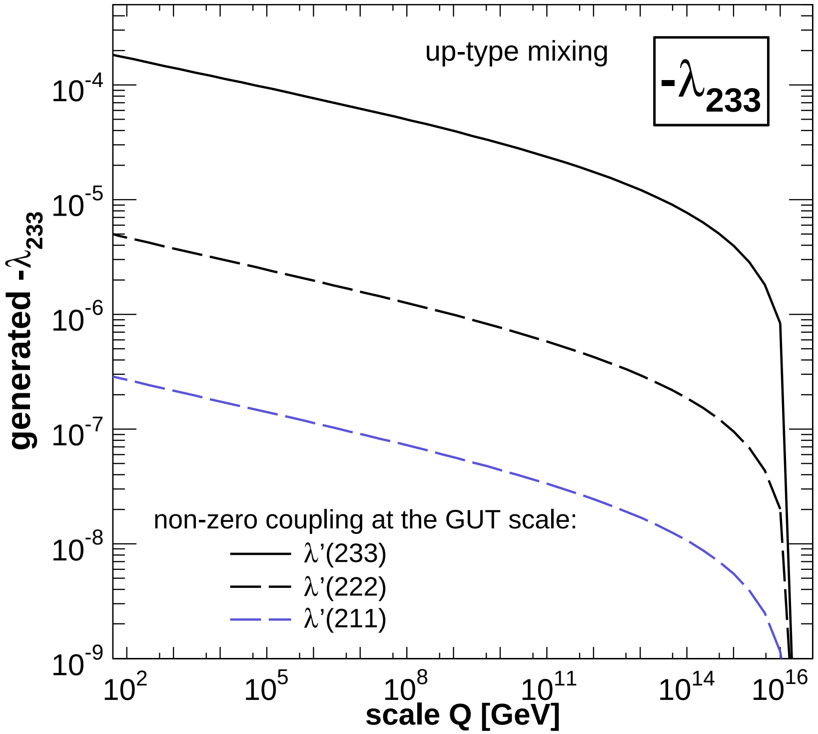
one $\lambda'_{2jk} = 0.01|_{GUT}$





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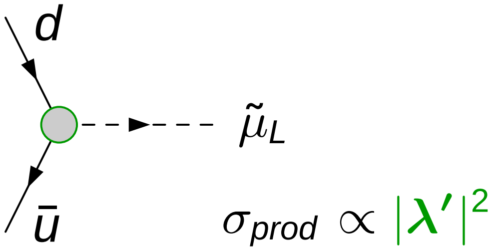
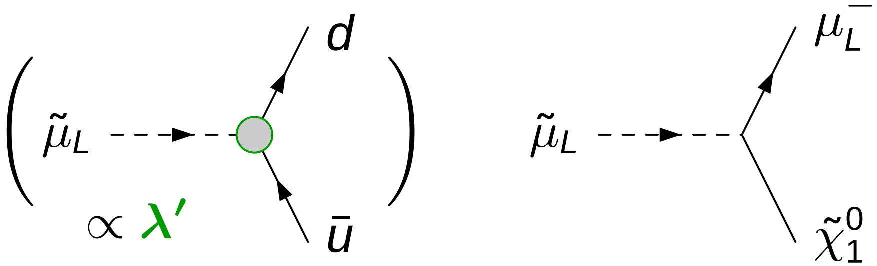
Why considering $\tilde{\ell}$ prod. in $\tilde{\tau}$-LSP scenarios?

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



Slepton decay modes:



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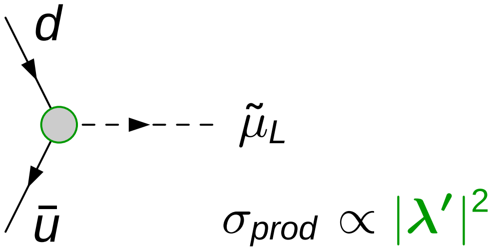

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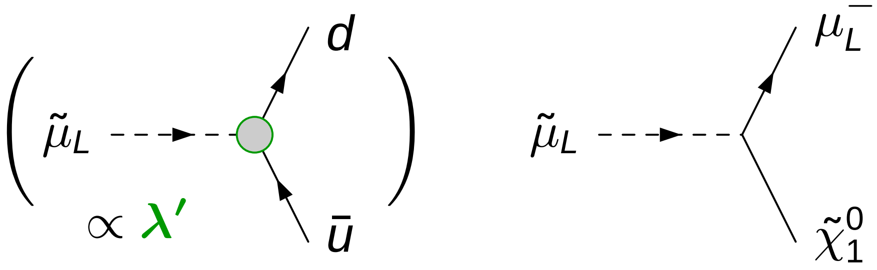
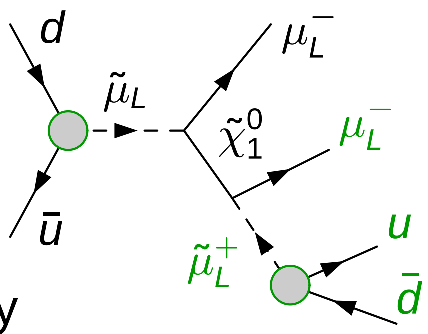
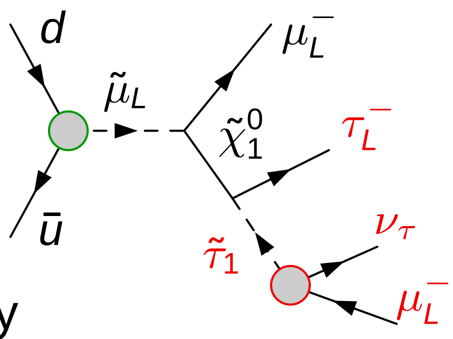


$\tilde{\chi}_1^0$-LSP



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



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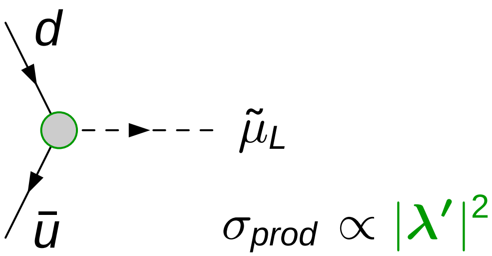

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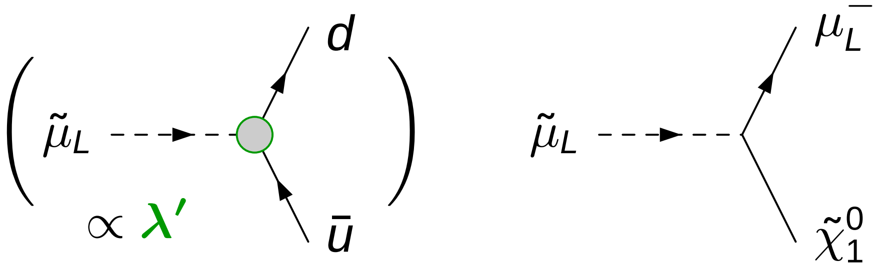

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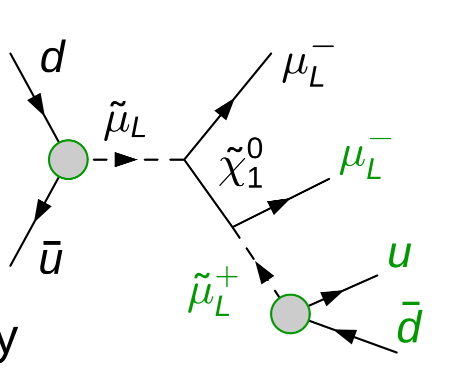

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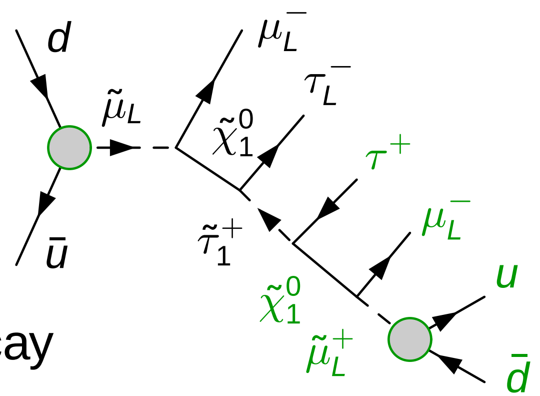
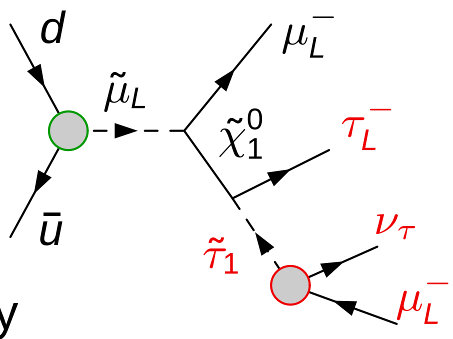
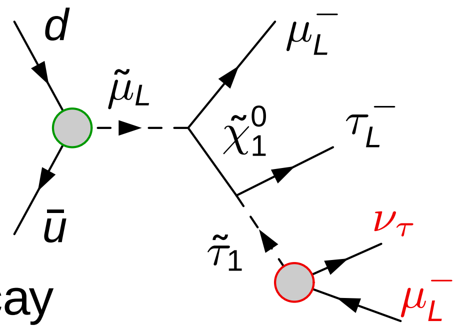
$\tilde{\tau}_1$-LSP



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



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



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

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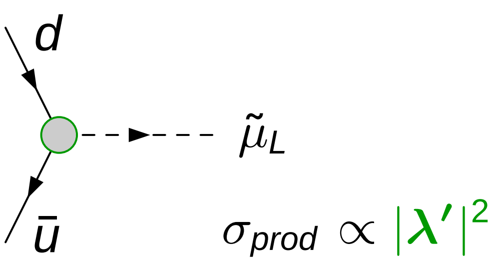

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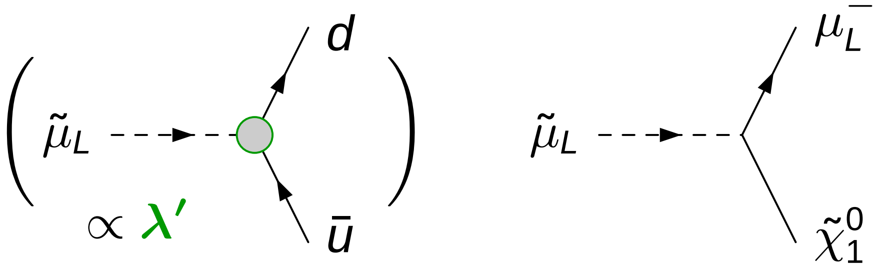

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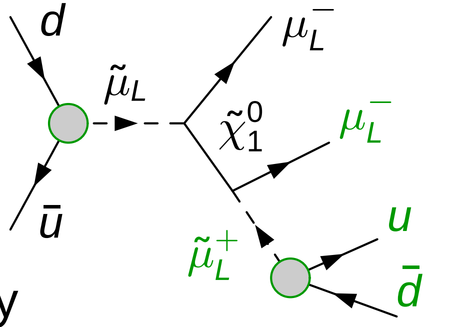
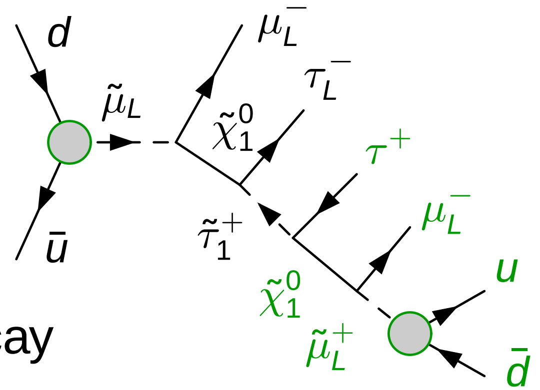
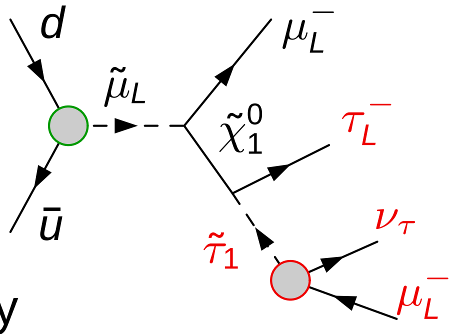


$\propto \lambda'$
3-bd.-decay

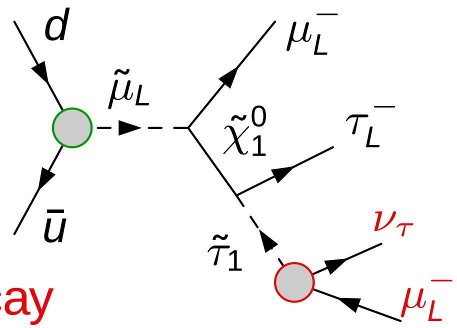
$\tilde{\tau}_1$-LSP



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



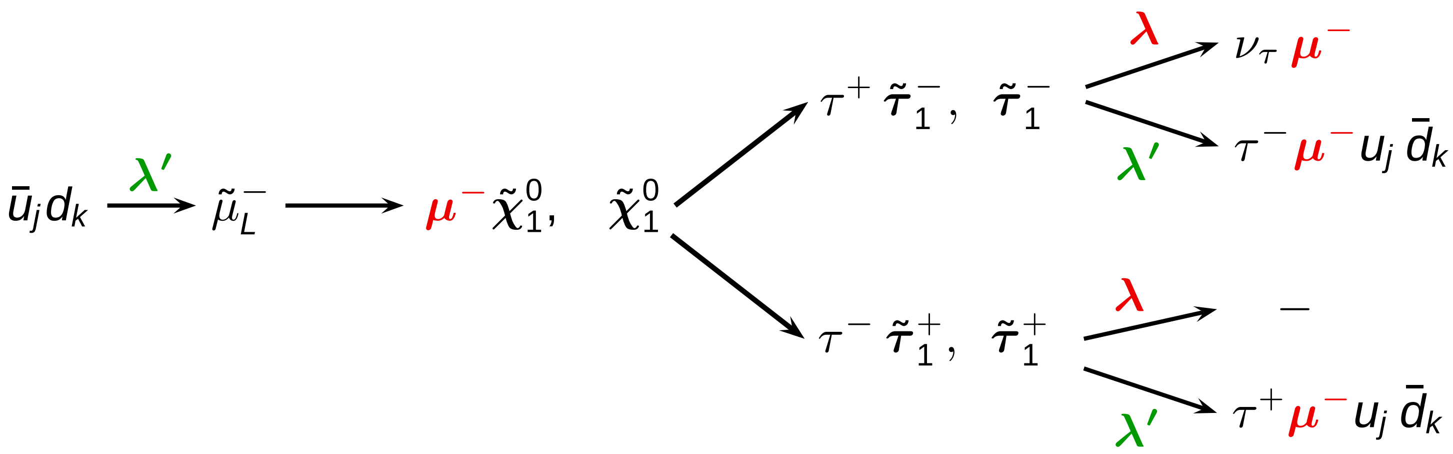
$\propto \lambda$
3-bd.-decay



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

$\Rightarrow$ can be important!

Like-Sign Dimuon Events



Like-Sign Dimuon Events

Set A: $M_0 = 0\,\text{GeV}$, $M_{1/2} = 500\,\text{GeV}$, $A_0 = 600\,\text{GeV}$,
$\tan\beta = 13$, $\text{sgn}(\mu) = +1$
$\lambda'_{211} = 0.002|_{GUT}$

$$\bar{u}_j d_k \xrightarrow{\lambda'} \tilde{\mu}_L^- \xrightarrow{100\%} \mu^- \tilde{\chi}_1^0, \quad \tilde{\chi}_1^0 \xrightarrow{30\%} \tau^+ \tilde{\tau}_1^-, \quad \tilde{\chi}_1^0 \xrightarrow{30\%} \tau^- \tilde{\tau}_1^+$$

$\sigma_{prod}(\tilde{\mu}_L^-) = 62\,\text{fb}$
$\sigma_{prod}(\tilde{\mu}_L^+) = 110\,\text{fb}$

Decay	Coupling	$BR(\tilde{\tau}_1)$ up	$BR(\tilde{\tau}_1)$ down
$\tilde{\tau}_1^- \to \nu_\tau \mu^-$	λ	8%	3%
$\tilde{\tau}_1^- \to \tau^- \mu^- u_j \bar{d}_k$	λ'	12%	13%
$\tilde{\tau}_1^+ \to$ –	λ		
$\tilde{\tau}_1^+ \to \tau^+ \mu^- u_j \bar{d}_k$	λ'	25%	29%

Like-Sign Dimuon Events

Set B: $M_0 = 0\,\text{GeV}$, $M_{1/2} = 700\,\text{GeV}$, $A_0 = 1150\,\text{GeV}$,
$\tan\beta = 26$, $\text{sgn}(\mu) = +1$
$\lambda'_{211} = 0.01|_{GUT}$

$$\bar{u}_j d_k \xrightarrow{\lambda'} \tilde{\mu}_L^- \xrightarrow{100\%} \mu^- \tilde{\chi}_1^0, \quad \tilde{\chi}_1^0$$

$$\tilde{\chi}_1^0 \xrightarrow{43\%} \tau^+ \tilde{\tau}_1^-, \quad \tilde{\tau}_1^- \xrightarrow{\lambda} \nu_\tau \mu^-, \quad \tilde{\tau}_1^- \xrightarrow{\lambda'} \tau^- \mu^- u_j \bar{d}_k$$

$$\tilde{\chi}_1^0 \xrightarrow{43\%} \tau^- \tilde{\tau}_1^+, \quad \tilde{\tau}_1^+ \xrightarrow{\lambda} -, \quad \tilde{\tau}_1^+ \xrightarrow{\lambda'} \tau^+ \mu^- u_j \bar{d}_k$$

	$BR(\tilde{\tau}_1)$ up	$BR(\tilde{\tau}_1)$ down
$\nu_\tau \mu^-$	49%	49%
$\tau^- \mu^- u_j \bar{d}_k$	0.1%	–
–		
$\tau^+ \mu^- u_j \bar{d}_k$	0.4%	0.1%

$\sigma_{prod}(\tilde{\mu}_L^-) = 475\,\text{fb}$
$\sigma_{prod}(\tilde{\mu}_L^+) = 885\,\text{fb}$

Like-Sign Dimuon Events

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$\sigma_{prod}(\tilde{\mu}_L^-) = 475$ fb
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Decay	$BR(\tilde{\tau}_1)$ up	$BR(\tilde{\tau}_1)$ down
$\tilde{\tau}_1^- \xrightarrow{\lambda} \nu_\tau \mu^-$	49%	49%
$\tilde{\tau}_1^- \xrightarrow{\lambda'} \tau^- \mu^- u_j \bar{d}_k$	0.1%	–
$\tilde{\tau}_1^+ \xrightarrow{\lambda}$ –		
$\tilde{\tau}_1^+ \xrightarrow{\lambda'} \tau^+ \mu^- u_j \bar{d}_k$	0.4%	0.1%

down mix.	Set A σ_{λ}	Set A $\sigma_{\lambda'}$	Set B σ_{λ}	Set B $\sigma_{\lambda'}$
λ'_{211}	4 fb	19 fb	290 fb	–
λ'_{221}	4 fb	4 fb	87 fb	–
λ'_{212}	7 fb	8 fb	170 fb	–
λ'_{213}	2 fb	5 fb	89 fb	–

up mix.	Set A σ_{λ}	Set A $\sigma_{\lambda'}$	Set B σ_{λ}	Set B $\sigma_{\lambda'}$
λ'_{211}	–	21 fb	283 fb	3 fb
λ'_{221}	–	7.5 fb	–	83 fb
λ'_{212}	–	14 fb	–	162 fb
λ'_{213}	–	8 fb	–	85 fb

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

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

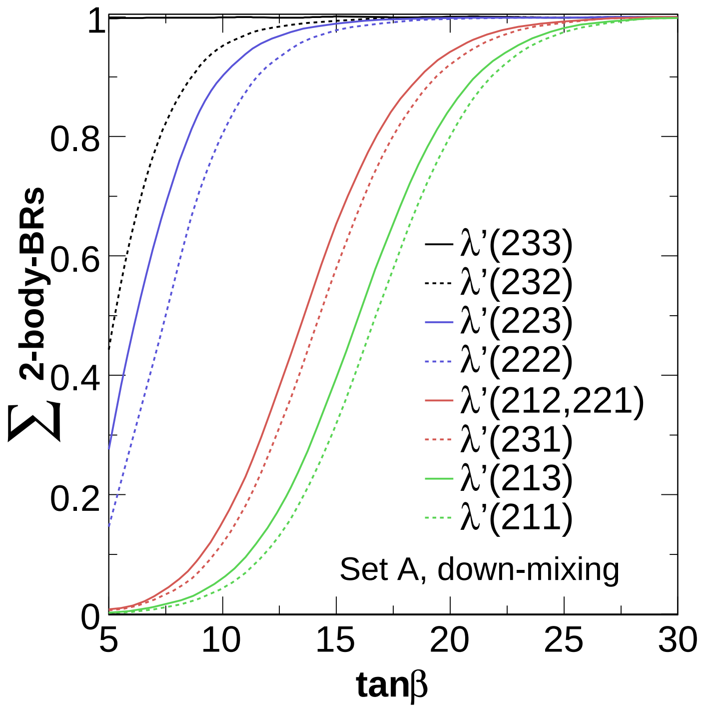
Backup

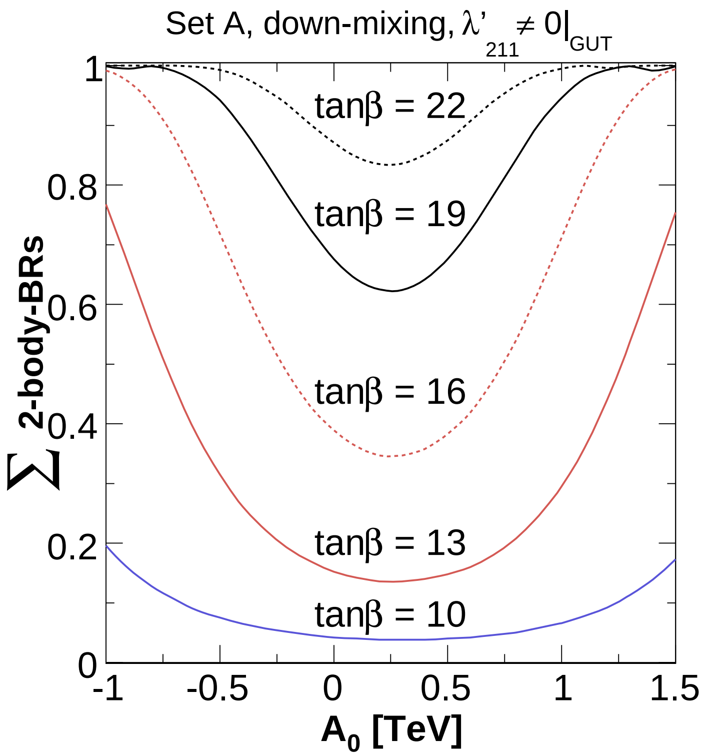
2-body versus 4-body $\tilde{\tau}$-LSP decays

- When do the 2-body decays dominate?

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

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





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

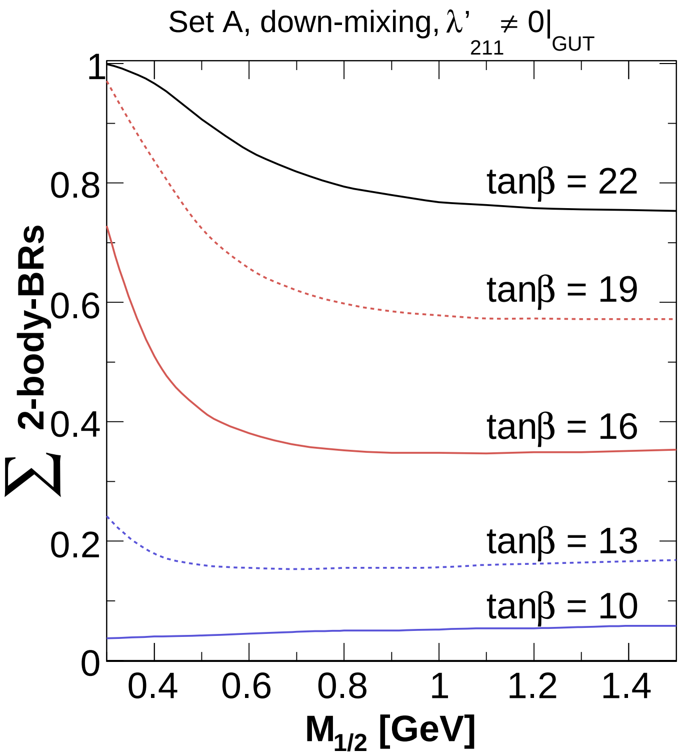
stau mass mixing:

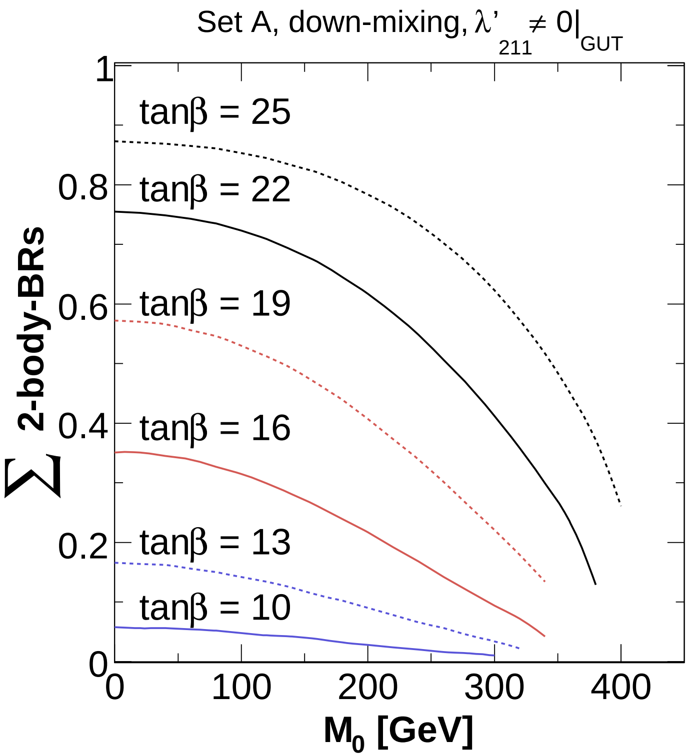
$$m_{\tilde{\tau}_1}^2 - m_{\tilde{\tau}_2}^2 \propto A_\tau - \mu \tan\beta$$

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

- When do the 2-body decays dominate?

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



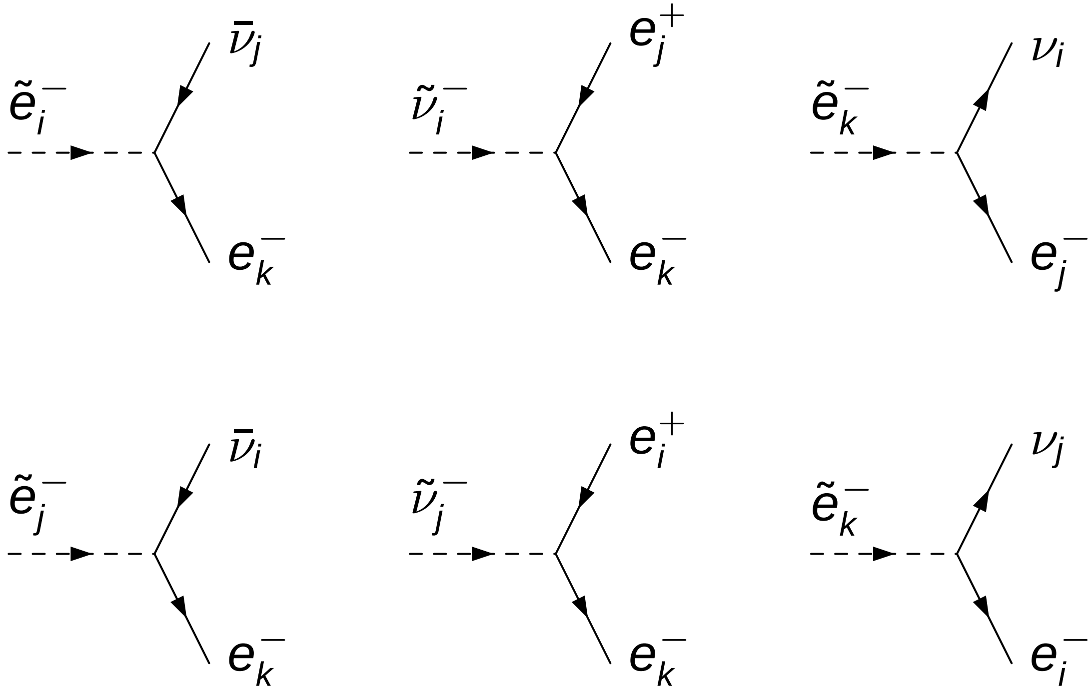


$$m^2_{\tilde{\chi}} \propto M_{1/2}; \quad m^2_{\tilde{f}} \propto M_0^2 + a M^2_{1/2}$$
$$\Gamma_4/\Gamma_2 \propto m^6_{\tilde{\tau}_1}/m^2_{\tilde{\chi}}\, m^4_{\tilde{f}}$$

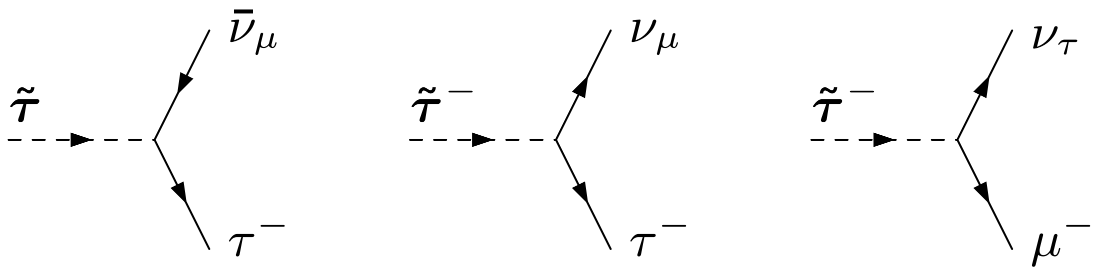
$$\Rightarrow \lim_{M_{1/2}\to\infty}(\Gamma_4/\Gamma_2) = \text{const.}$$
$$\Rightarrow \lim_{M_0\to\infty}(\Gamma_4/\Gamma_2) = \mathcal{O}(M_0^2)$$

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

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

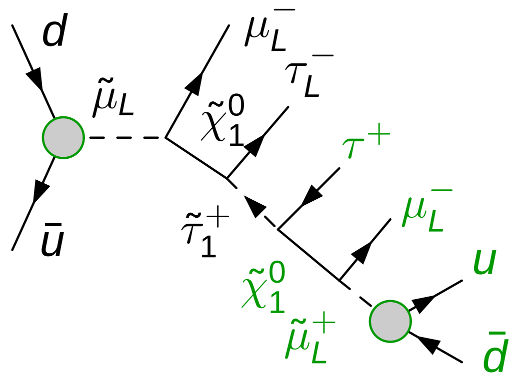


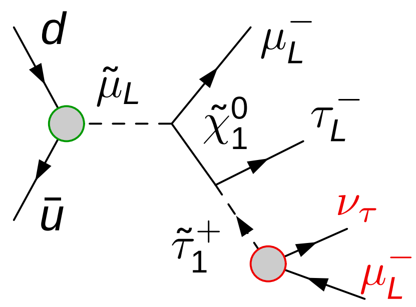
- i. e. the following $\tilde{\tau}$ decay modes exist for $ijk = 233$:



Single Slepton Production: Possible Signatures

	$\bar{u}_j\, d_k \to \tilde{\mu}_L^- \to \mu^- \tilde{\chi}_1^0$ 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}	$\tilde{\tau}_1^- \to \tau^- \nu_\mu$ $\tilde{\tau}_1^- \to \tau^- \bar{\nu}_\mu$ $\tilde{\tau}_1^- \to \mu^- \nu_\tau$	$\tilde{\tau}_1^+ \to \tau^+ \bar{\nu}_\mu$ $\tilde{\tau}_1^+ \to \tau^+ \nu_\tau$ $\tilde{\tau}_1^+ \to \mu^+ \bar{\nu}_\tau$





Single Slepton Production: Possible Signatures

	$\bar{u}_j\, d_k \to \tilde{\mu}_L^- \to \mu^- \tilde{\chi}_1^0$ 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}	$\tilde{\tau}_1^- \to \tau^- \nu_\mu$ $\tilde{\tau}_1^- \to \tau^- \bar{\nu}_\mu$ $\tilde{\tau}_1^- \to \mu^- \nu_\tau$	$\tilde{\tau}_1^+ \to \tau^+ \bar{\nu}_\mu$ $\tilde{\tau}_1^+ \to \tau^+ \nu_\tau$ $\tilde{\tau}_1^+ \to \mu^+ \bar{\nu}_\tau$

$\tilde{\mu}$ production

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

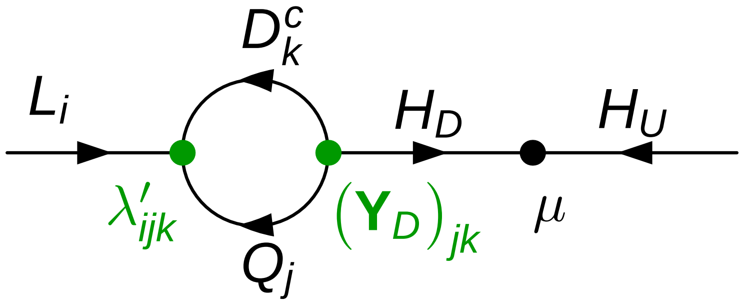
$\tilde{\nu}_\mu$ production

λ'_{2jk}	$\tau^+\tau^-$	μ	$\not{E}_T$	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**!

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

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



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

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

- superpotential W:

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

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

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

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