Sneutrino or Stau as the Lightest Supersymmetric Particle in mSUGRA with R-parity Violation

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   - Minimal supergravity (mSUGRA) with RPV
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   - Single slepton production
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3. Sneutrino as the LSP
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Supersymmetry (SUSY)

Why SUSY?

- Higgs mass is protected from quadratic divergencies.
- Unification of gauge couplings at $M_{GUT} = \mathcal{O}(10^{16})$ GeV.

What is SUSY?

$$Q\,|boson\rangle = |fermion\rangle$$
$$\overline{Q}\,|fermion\rangle = |boson\rangle$$

- Q doesn't change gauge charges.
- Q doesn't change mass.

No SUSY partners observed so far.

$\Rightarrow$ SUSY must be broken.

Particle content of the MSSM

Minimal supersymmetric extension of the SM:

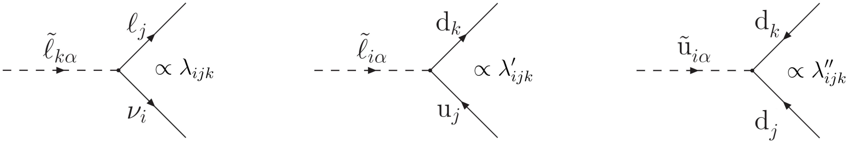
SM Particles	Superfields	spin 0	spin 1/2	spin 1
Quarks	Q_i	$(\tilde{u}_{L_i}, \tilde{d}_{L_i})$	(u_{L_i}, d_{L_i})	
	$\bar{U}_i$	$\tilde{u}^c_{R_i}$	$u^c_{R_i}$	
	$\bar{D}_i$	$\tilde{d}^c_{R_i}$	$d^c_{R_i}$	
Leptons	L_i	$(\tilde{\nu}_i, \tilde{e}_{L_i})$	(ν_i, e_{L_i})	
	$\bar{E}_i$	$\tilde{e}^c_{R_i}$	$e^c_{R_i}$	
Gauge Bosons	V_1		$\tilde{B}^0$	B^0
	V_2		$\tilde{W}^\pm, \tilde{W}^0$	$W^\pm, W^0$
	V_3		$\tilde{g}_a$	g_a
Higgs	H_u	(H^+_u, H^0_u)	$(\tilde{H}^+_u, \tilde{H}^0_u)$	
	H_d	(H^0_d, H^-_d)	$(\tilde{H}^0_d, \tilde{H}^-_d)$	

MSSM with R-parity violation (RPV)

General Superpotential of the Minimal Supersymmetric extension of the SM (MSSM):

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

$$W_{\not{R}_p} = \underbrace{\frac{1}{2}\lambda_{ijk} L_i L_j \bar{E}_k + \lambda'_{ijk} L_i Q_j \bar{D}_k}_{\Delta L \neq 0} + \underbrace{\frac{1}{2}\lambda''_{ijk} \bar{U}_i \bar{D}_j \bar{D}_k}_{\Delta B \neq 0} + \underbrace{\kappa_i L_i H_u}_{\Delta L \neq 0} .$$



The lepton/baryon number violating terms lead to proton decay.
It is sufficient to suppress $\Delta L \neq 0$ or $\Delta B \neq 0$ terms to keep proton stable.
[Dreiner, Luhn, Thormeier, Phys.Rev.D73:075007,2006]

Minimal supergravity (mSUGRA)

number of new parameters

- $\mathcal{O}(100)$ if R_p is conserved.
- $\mathcal{O}(200)$ if R_p is violated.

Assume simple boundary conditions at the scale $M_{GUT} = \mathcal{O}(10^{16})$ GeV.

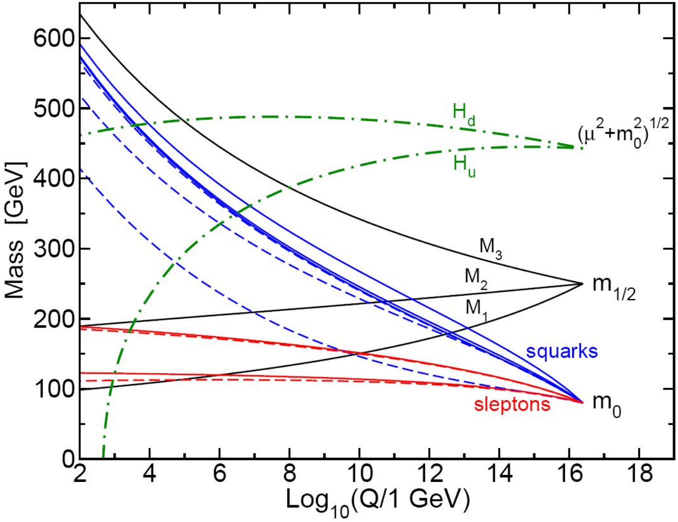
mSUGRA parameter space

- M_0 : Universal soft breaking scalar mass.
- $M_{1/2}$: Universal gaugino soft breaking mass.
- A_0 : Universal trilinear scalar interaction.
- $\tan\beta$: Ratio of vevs. of the two Higgs doublets H_u, H_d.
- $\text{sgn}\,\mu$: Solution of EW symmetry breaking scalar potential.

Parameters at the scale $M_{EW} = \mathcal{O}(10^2)$ GeV are obtained by RGEs.
Programs: `Softsusy`, `SPheno`, `Suspect`, `Isajet` etc.

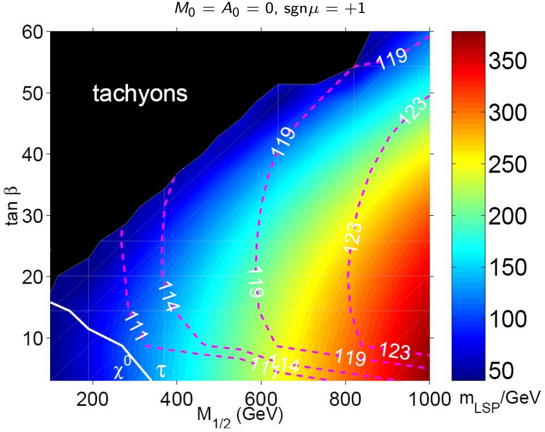
Running masses in mSUGRA

[Martin, hep-ph/9709356]



$\tilde{\chi}_1^0$ LSP versus $\tilde{\tau}$ LSP

[Allanach, Dedes, Dreiner, Phys.Rev.D69:115002,2004]



- If R_p conserved: Scenario is excluded.
  (neutral LSP & $m_{h^0} > 114$ GeV).
- If R_p violated: Most of the $\tilde{\tau}$ LSP region is allowed.

Add one parameter at M_{GUT}: $\mathbf{\Lambda} \in \{\lambda_{ijk}, \lambda'_{ijk}, \lambda''_{ijk}\}$.

$\Rightarrow$ **R-parity violating mSUGRA**

mSUGRA with R-parity violation (RPV)

We add one parameter at M_{GUT}: $\mathbf{\Lambda} \in \{\lambda_{ijk}, \lambda'_{ijk}, \lambda''_{ijk}\}$.

Differences to R_p conserving mSUGRA:

- Further R_p violating couplings are generated through RGEs at M_{EW}.
  $\Rightarrow$ 2-body and 4-body decays of $\tilde{\tau}$ LSP.
- Single sparticle production is possible.
  $\Rightarrow$ single slepton production.
- In principle, any SUSY particle could be the LSP.
  $\Rightarrow$ $\tilde{\tau}$ LSP region allowed.
- R_p violating RGEs change the SUSY mass spectrum at M_{EW}.
  $\Rightarrow$ $\tilde{\nu}$ LSP.
- Neutrino masses are generated.

What is the phenomenology of a $\tilde{\tau}$ LSP scenario at hadron colliders?

- $\tilde{\tau}$ LSP decays (2-body & 4-body).
  [Dreiner, SG, Trenkel, work in progress]
- First example: Resonant single slepton production.
  [Dreiner, SG, Trenkel, work in progress]
- Second example: Sparticle pair production.
  [Allanach, Bernhardt, Dreiner, SG, Kom, Richardson, arXiv:0710.2034]

Typical mass ordering for $\tilde{\tau}$ LSP scenarios.

$$m_{\tilde{g}} > m_{\tilde{q}_2} > m_{\tilde{q}_1} > m_{\tilde{\chi}_2^+} > m_{\tilde{\chi}_1^+} \approx m_{\tilde{\ell}_2} > m_{\tilde{\chi}_1^0} \approx m_{\tilde{\mu}_1} \approx m_{\tilde{e}_1} > m_{\tilde{\tau}_1}$$

If $\mathbf{\Lambda} \leq \mathcal{O}(10^{-3})$

- Sparticles are produced in pairs via gauge interactions, e.g. $\tilde{g}\tilde{g}$, $\tilde{q}\tilde{q}$.
- Sparticle undergo 2-body decays to the $\tilde{\tau}_1$ via gauge interactions.

$$\begin{aligned}
\tilde{g} \rightarrow & \tilde{t}\bar{t} \\
& \hookrightarrow \tilde{\chi}_1^+ b \\
& \qquad \hookrightarrow \tilde{\nu}_\mu \mu^+ \\
& \qquad\qquad \hookrightarrow \tilde{\chi}_1^0 \nu_\mu \\
& \qquad\qquad\qquad \hookrightarrow \tilde{\tau}_1^- \tau^+
\end{aligned}$$

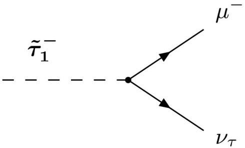
If $\mathbf{\Lambda} \geq \mathcal{O}(10^{-2})$

- Single sparticle production may dominate.
- RPV 2-body decays may alter the decay chains.

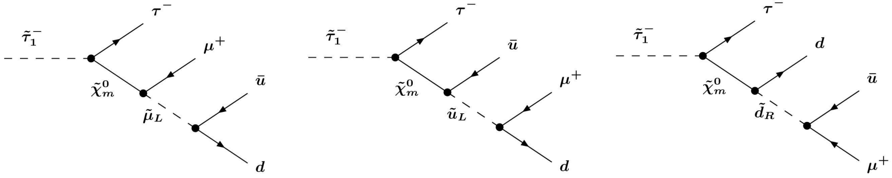
RPV decays of the $\tilde{\tau}$ LSP (naive picture)

- The dominant operator is: $L_3 L_j \bar{E}_k, L_i L_3 \bar{E}_k$, $L_i L_j \bar{E}_3$ or $L_3 Q_j \bar{D}_k$.
  $\Rightarrow$ 2-body decays.
- The dominant operator is: $L_{i\neq3} L_{j\neq3} \bar{E}_{k\neq3}$, $L_{i\neq3} Q_j \bar{D}_k$ or $\bar{U}_i \bar{U}_j \bar{D}_k$.
  $\Rightarrow$ 4-body decays.

For example $\lambda_{233} \neq 0$:

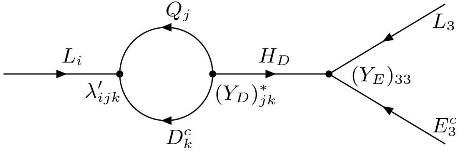


For example $\lambda'_{211} \neq 0$:



Dynamical generation of RPV couplings

Generation of λ_{i33} via λ'_{ijk}



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

Assume: $\mathbf{Y}_E = \text{diag} \Rightarrow$ e.g. if you break only L_e then $L_{\mu/\tau}$ will not be broken via RGEs.

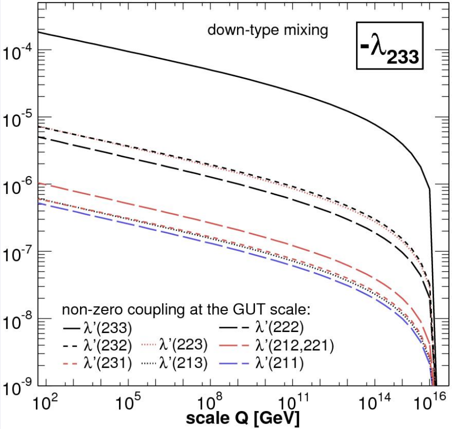
Quark mixing: We know $\mathbf{V}_{CKM} = V_{uL}^{+} V_{dL}$.

up-mixing:
$$\mathbf{Y}_U(M_Z) \times v_u = \mathbf{V}^{+}_{CKM}\text{diag}(m_u, m_c, m_t)\mathbf{V}_{CKM},$$
$$\mathbf{Y}_D(M_Z) \times v_d = \text{diag}(m_d, m_s, m_b)$$

down-mixing:
$$\mathbf{Y}_U(M_Z) \times v_u = \text{diag}(m_u, m_c, m_t),$$
$$\mathbf{Y}_D(M_Z) \times v_d = \mathbf{V}_{CKM}\text{diag}(m_d, m_s, m_b)\mathbf{V}^{+}_{CKM}.$$

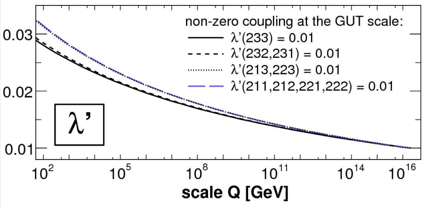
Running of RPV couplings: down-mixing

Dynamical generation of λ_{233}



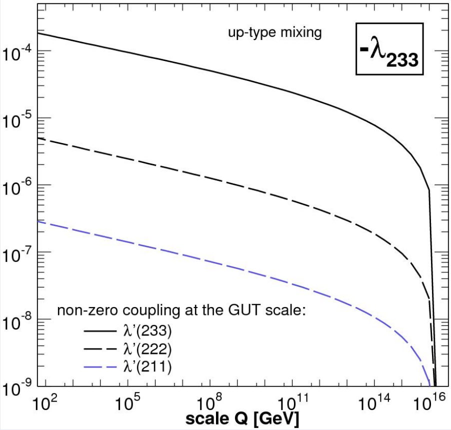
For comparison:

Running of λ'_{2jk}



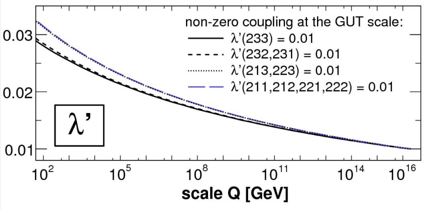
Running of RPV couplings: up-mixing

Dynamical generation of λ_{233}



For comparison:

Running of λ'_{2jk}



Decays of the $\tilde{\tau}$ LSP

Naive picture

- The dominant operator is: $L_3 L_j \bar{E}_k, L_i L_3 \bar{E}_k$, $L_i L_j \bar{E}_3$ or $L_3 Q_j \bar{D}_k$, e.g. $\lambda_{233} \neq 0 \Rightarrow$ 2-body decays.
- The dominant operator is: $L_{i\neq 3} L_{j\neq 3} \bar{E}_{k\neq 3}$, $L_{i\neq 3} Q_j \bar{D}_k$ or $\bar{U}_i \bar{U}_j \bar{D}_k$, e.g. $\lambda'_{2jk} \neq 0 \Rightarrow$ 4-body decays.

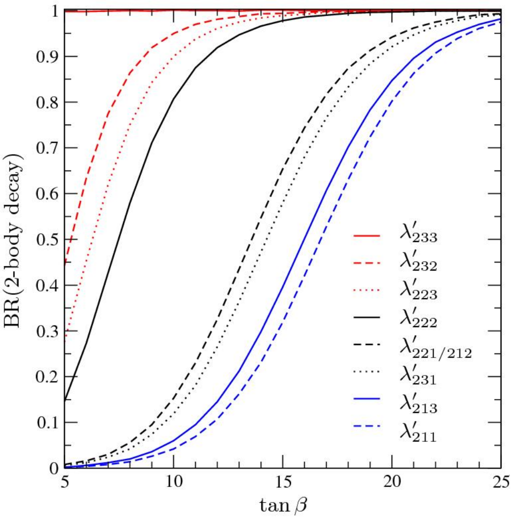
But: λ'_{2jk} will generate λ_{233}.

Question: 2-body or 4-body decay dominant?

2-body versus 4-body decays

BR(2-body decay), down-mixing

$M_0 = 0$ GeV, $M_{1/2} = 500$ Gev, $A_0 = 600$ GeV, sgnμ=+1



$$BR_2 = \frac{1}{1 + \Gamma_4/\Gamma_2}$$

with

$$\Gamma_2 \propto \lambda^2_{233}\, m_{\tilde{\tau}_1}$$

$$\Gamma_4 \propto \lambda'^2_{2jk}\, \frac{m^7_{\tilde{\tau}_1}}{m^2_{\tilde{\chi}}\, m^4_{\tilde{f}}}$$

$$\Rightarrow \Gamma_4/\Gamma_2 \propto m^6_{\tilde{\tau}_1}$$

$m_{\tilde{\tau}_1}$ dependence on $\tan\beta$

Recall: $\Gamma_4/\Gamma_2 \propto m^6_{\tilde{\tau}_1}$

$$M^2_{\tilde{\tau}} = \begin{pmatrix} m^2_{\tilde{\tau}_R} & m_{\tilde{\tau}_{RL}} m_\tau \\ m_{\tilde{\tau}_{RL}} m_\tau & m^2_{\tilde{\tau}_L} \end{pmatrix}$$

with

$$\begin{aligned} m^2_{\tilde{\tau}_R} &= m^2_\tau + M^2_0 + 0.15 M^2_{1/2} - 0.23 M^2_z \cos 2\beta - 2/3 X_\tau \\ m^2_{\tilde{\tau}_L} &= m^2_\tau + M^2_0 + 0.52 M^2_{1/2} - 0.27 M^2_z \cos 2\beta - 1/3 X_\tau \\ m_{\tilde{\tau}_{RL}} &= A_\tau - \mu \tan\beta \end{aligned}$$

where

$$X_\tau = 10^{-4}(1 + \tan^2\beta)(M^2_0 + 0.15 M^2_{1/2} + 0.33 A^2_0)$$

[Drees, Martin, 1995]

tanβ increase $\Rightarrow m_{\tilde{\tau}_1}$ decrease $\Rightarrow BR_2 = 1/(1 + \Gamma_4/\Gamma_2)$ increase.

$\tilde{\tau}$ LSP phenomenology

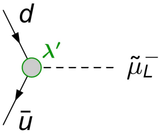
So far: $\tilde{\tau}$ LSP decays.

First Example: Resonant single slepton production.

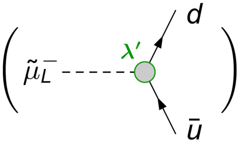
Resonant single slepton production was only investigated for $\tilde{\chi}_1^0$ LSP!
e.g. [Allanach et al., Searching for R parity violation at Run II of the Tevatron, 1999]

Single slepton production via λ'_{ijk}

$\tilde{\mu}_L^-$ production via λ'_{211}:

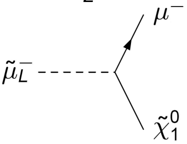


$\tilde{\mu}_L^-$ decay via λ'_{211}:



suppressed if $\lambda' \leq \mathcal{O}(10^{-2})$

RPC $\tilde{\mu}_L^-$ decay:



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

- $\tilde{\chi}_1^0$ decays via λ'_{211}. (3-body decay)

$\tilde{\tau}$ LSP

- $\tilde{\chi}_1^0 \rightarrow \tilde{\tau}_1 \tau$.
- $\tilde{\tau}_1$ decays via λ'_{211} or λ_{233}.

Promising signatures at hadron colliders

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

$$\tilde{\mu}_L^- \rightarrow \mu^- \mu^- u\bar{d}.$$

$\tilde{\tau}$ LSP:

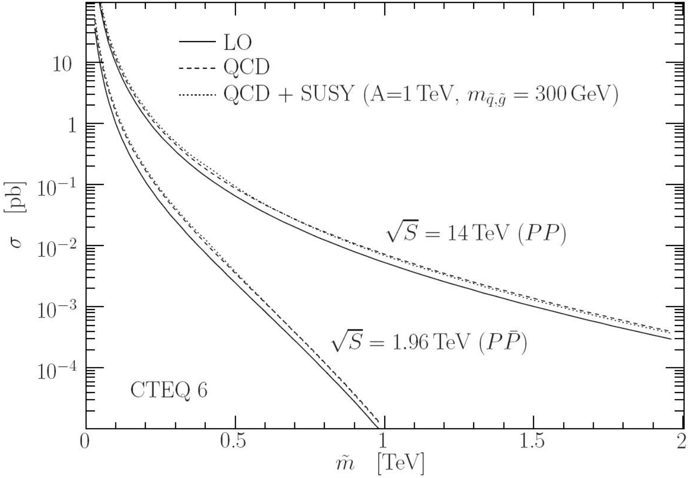
$$\tilde{\mu}_L^- \rightarrow \mu^- \mu^- \tau^+ \tau^- u\bar{d} \quad \text{(4-body decay).}$$
$$\tilde{\mu}_L^- \rightarrow \mu^- \mu^- \tau^+ \nu_\tau \quad \text{(2-body decay).}$$

⇒ Promising signature: Like-sign muon final states!

⇒ Low SM background: 5 events at LHC for 10 fb^{-1} after cuts!
[Dreiner, Richardson, Seymour, Phys.Rev.D63:055008,2001]

Cross sections at hadron colliders.

$PP(\bar{P}) \to \tilde{\mu}_L^+ + X$ via $\lambda'_{211} = 0.01$ at M_{EW}.



Note: $\lambda'_{211} = 0.01$ at M_{GUT} $\Rightarrow$ $\lambda'_{211} \approx 0.03$ at M_{EW}.

Numerical example for LHC

$M_0 = 0$ GeV, $M_{1/2} = 700$ GeV, $A_0 = 1150$ GeV, $tan\beta = 26$, sgn$\mu = +1$.

- σ_{prod}: Cross section for $\tilde{\mu}_L$ production.
- $\sigma_{\lambda'}$: $\sigma_{prod} \times BR(\tilde{\mu}_L \to \mu^\pm \mu^\pm + X)$ & $\tilde{\tau}_1$ decay via λ'.
- σ_{λ}: $\sigma_{prod} \times BR(\tilde{\mu}_L \to \mu^\pm \mu^\pm + X)$ & $\tilde{\tau}_1$ decay via λ.

$m_{\tilde{\mu}_L} = 470$ GeV		σ_{prod} [fb]	up mixing $\sigma_{\lambda'}$ [fb]	up mixing σ_{λ} [fb]	down mixing $\sigma_{\lambda'}$ [fb]	down mixing σ_{λ} [fb]
$\lambda'_{211} = 1 \times 10^{-2}$	$\mu^- \mu^-$	476	1.02	99.2	–	100
	$\mu^+ \mu^+$	885	1.90	184	–	186
$\lambda'_{221} = 1 \times 10^{-2}$	$\mu^- \mu^-$	309	61.8	–	–	65.1
	$\mu^+ \mu^+$	105	21.1	–	–	22.2

- Final state might reveal quark mixing and $\tan\beta$.
- Ratio $(\#\mu^+\mu^+)/(\#\mu^-\mu^-)$ can reveal the indices j, k of λ'_{ijk}.

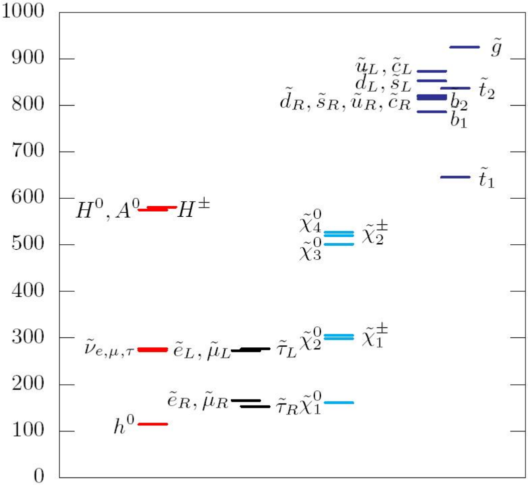
$\tilde{\tau}$ LSP phenomenology

First Example:
Resonant single slepton production.

Second example:
Sparticle pair production at the LHC.

Benchmark scenario BC1

[Allanach et. al., Phys.Rev.D75:035002,2007]



BC1

- $M_0 = A_0 = 0$
- $\lambda_{121}(M_{GUT}) = 0.032$
- $\tan\beta = 13$
- $M_{1/2} = 400$ GeV
- $\text{sgn}(\mu) = +1.$

Branching ratios in benchmark scenario BC1

	mass [GeV]	channel	BR	channel	BR
$\tilde{\tau}_1$	148	$\mu^+\bar{\nu}_e e^-\tau^-$	32 %	$e^+\bar{\nu}_\mu e^-\tau^-$	32 %
		$\mu^-\nu_e e^+\tau^-$	18 %	$e^-\nu_\mu e^+\tau^-$	18 %
$\tilde{e}_R$	161	$e^-\nu_\mu$	50 %	$\mu^-\nu_e$	50 %
$\tilde{\mu}_R$	161	$\tilde{\tau}^+\mu^-\tau^-$	51 %	$\tilde{\tau}^-\mu^-\tau^+$	49 %
$\tilde{\chi}_1^0$	162	$\tilde{\tau}_1^+\tau^-$	50 %	$\tilde{\tau}_1^-\tau^+$	50 %
$\tilde{\nu}_\tau$	265	$\tilde{\chi}_1^0\nu_\tau$	67 %	$W^+\tilde{\tau}_1$	33 %
$\tilde{\nu}_e(\tilde{\nu}_\mu)$	266	$\tilde{\chi}_1^0\nu_e(\nu_\mu)$	92 %	$\mu^+(e^+)e^-$	7.5 %
$\tilde{e}_L^-(\tilde{\mu}_L^-)$	280	$\tilde{\chi}_1^0 e^-(\mu^-)$	92 %	$e^-\bar{\nu}_\mu(\bar{\nu}_e)$	8.1 %
$\tilde{\tau}_2$	283	$\tilde{\chi}_1^0\tau^-$	63 %	$Z^0\tilde{\tau}_1^-$	18 %
		$h^0\tilde{\tau}_1^-$	19 %		

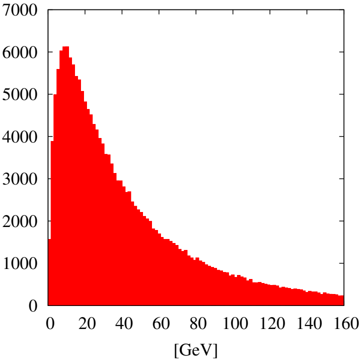
Signal rates of benchmark scenario BC1

$\sigma(\text{total sparticle pair production}) = 4.8 \cdot 10^3$ fb

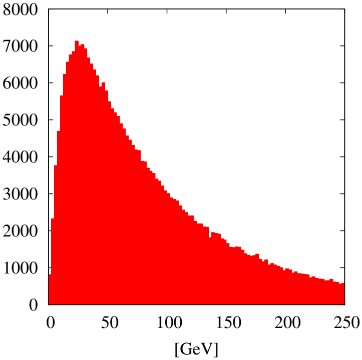
e^+ or μ^+	e^- or μ^-	τ^+	τ^-	$\not{p}_T$	event fraction
2	2	2	2	yes	35 %
3	2	2	2	yes	12 %
2	3	2	2	yes	8.3 %
3	3	2	2	yes	7.3 %
2	2	2	1	yes	4.7 %
2	2	3	2	yes	4.3 %
2	2	3	3	yes	1.4 %
4	3	2	2	yes	1.1 %

- Multi-lepton final states ($\approx$ 8 leptons).
- Multi-tau final states ($\approx$ 4 taus).
- 2-4 jets
- Missing p_T due to neutrinos from $\tilde{\tau}_1$ decay.

p_T distributions in benchmark scenario BC1



p_T distribution of the τ from $\tilde{\tau}_1$ decays.

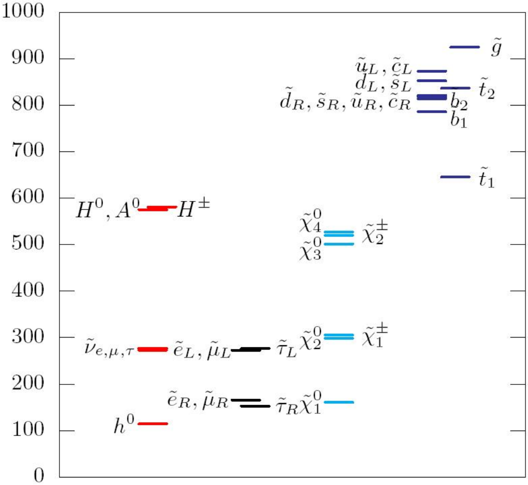


p_T distribution of the neutrinos.

- Taus with $p_T > 30$ GeV might be usefull to identify the scenario.
- Missing p_T is less than in the R_p conserving MSSM.

Benchmark scenario BC2

[Allanach et. al., Phys.Rev.D75:035002,2007]



BC2

- $M_0 = A_0 = 0$
- $\lambda'_{311}(M_{GUT}) = 3.5 \cdot 10^{-7}$
- $\tan\beta = 13$
- $M_{1/2} = 400$ GeV
- $\text{sgn}(\mu) = +1.$

Branching ratios in benchmark scenario BC2

	mass [GeV]	channel	BR	channel	BR
$\tilde{\tau}_1$	148	$\bar{u}d$	100 %		
$\tilde{e}_R(\tilde{\mu}_R)$	161	$\tilde{\tau}_1^+ e^-(\mu^-)\tau^-$	51 %	$\tilde{\tau}_1^- e^-(\mu^-)\tau^+$	49 %
$\tilde{\chi}_1^0$	162	$\tilde{\tau}_1^+ \tau^-$	50 %	$\tilde{\tau}_1^- \tau^+$	50 %
$\tilde{\nu}_\tau$	265	$\tilde{\chi}_1^0 \nu_\tau$	67 %	$W^+ \tilde{\tau}_1$	33 %
$\tilde{\nu}_e(\tilde{\nu}_\mu)$	266	$\tilde{\chi}_1^0 \nu_e(\nu_\mu)$	100 %		
$\tilde{e}_L^-(\tilde{\mu}_L^-)$	280	$\tilde{\chi}_1^0 e^-(\mu^-)$	100 %		
$\tilde{\tau}_2$	283	$\tilde{\chi}_1^0 \tau^-$	63 %	$Z^0 \tilde{\tau}_1^-$	18 %
		$h^0 \tilde{\tau}_1^-$	15 %		

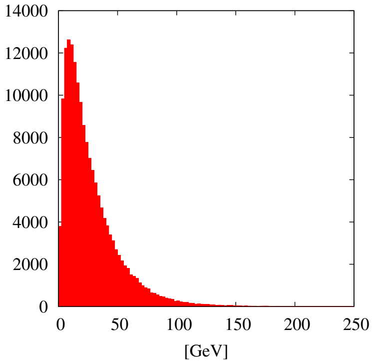
Signal rates of benchmark scenario BC2

$$\sigma(\text{sparticle pair production}) = 4.8 \cdot 10^3 \text{ fb}$$

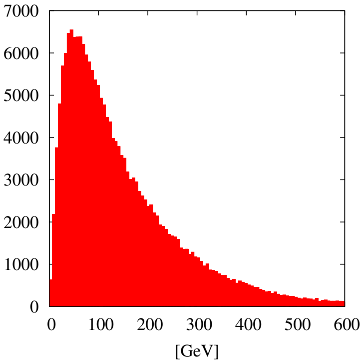
e^+ or μ^+	e^- or μ^-	τ^+	τ^-	$\not{p}_T$	event fraction
0	0	1	1	no	14 %
0	0	2	0	no	7.1 %
0	0	0	2	no	6.8 %
1	0	1	1	yes	6.5 %
0	0	1	1	yes	4.5 %
1	0	0	2	yes	3.3 %
1	0	2	0	yes	3.2 %
1	1	1	1	yes	2.4 %

- Like-sign τ events.
- 6-8 jets
- Not necessarily missing p_T signature.
- Detached vertex, i.e. $c \cdot \tau_{\tilde{\tau}_1} = 0.3$ mm.

p_T distributions in benchmark scenario BC2



p_T distribution of the τ from $\tilde{\chi}_1^0$ decays.



p_T distribution of the d-jets from $\tilde{\tau}_1$ decays.

- Tau identfication is difficult but possible.
- Reconstruction of the $\tilde{\tau}_1$ mass is possible via the two jets.

So far:
$\tilde{\tau}$ LSP in mSUGRA.

Now:
Sneutrino as the lightest supersymmetric particle in mSUGRA.

[Bernhardt, Dreiner, SG, Das, work in progress]

Effects of RPV

What will change due to one additional RPV coupling at the GUT scale?

The RGEs get additional contributions.

$\Rightarrow$ Additional RPV couplings at M_{EW}.

$\Rightarrow$ Sparticle masses can change at M_{EW}.

running sneutrino mass

$$16\pi^2 \frac{d(m^2_{\tilde{\nu}_i})}{dt} = -\left(\frac{6}{5}g_1^2|M_1|^2 + 6g_2^2|M_2|^2 + \frac{3}{5}g_1^2 S\right) +6\lambda'^2_{ijk}\left[m^2_{\tilde{\nu}_i} + (\mathbf{m}^2_{\tilde{\mathbf{Q}}})_{jj} + (\mathbf{m}^2_{\tilde{\mathbf{D}}})_{kk}\right] + 6(\mathbf{h}_{\mathbf{D}^k})^2_{ij}$$

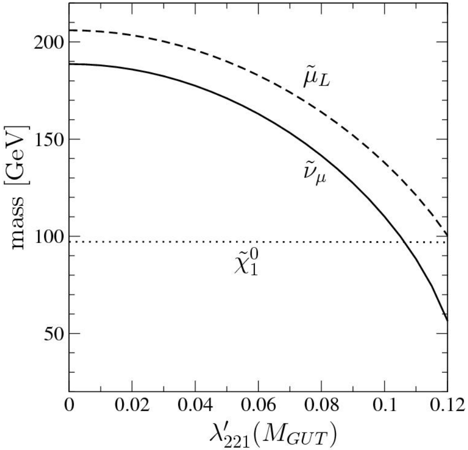
$$\text{with} \quad (\mathbf{h}_{\mathbf{D}^k})_{ij} = \lambda'_{ijk} \cdot A_0 \quad \text{at } M_{GUT},$$

$$S = f(\tilde{m}^2).$$

Note: Contribution of $(\mathbf{h}_{\mathbf{D}^k})_{ij}$ can dominate for negative A_0.

What is the LSP?

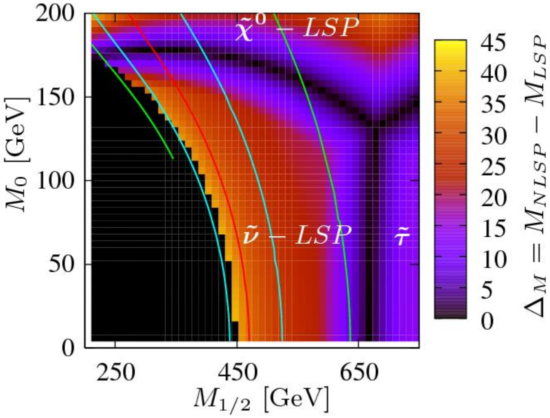
A non-vanishing coupling $\lambda'_{221}(M_{GUT})$ leads to a new LSP candidate.
For SPS1a:



$\Rightarrow$ $\tilde{\nu}_\mu$ LSP; also possible: $\tilde{\nu}_e$ & $\tilde{\nu}_\tau$ LSP.

$\tilde{\nu}_\mu$ LSP parameter space: M_0-$M_{1/2}$ plane

$$\lambda'_{221}(M_{GUT}) = 0.1,\ A_0 = -500 \text{ GeV},\ \tan\beta = 10,\ \mu > 0.$$



$\tilde{\nu}_\mu$ LSP parameter space: M_0-$M_{1/2}$ plane

Different LSP regions because:

- $m^2_{\tilde{\tau}_R} = M_0^2 + 0.15 M^2_{1/2} + \ldots$.
  (right-handed stau couples only via U(1) charges.)

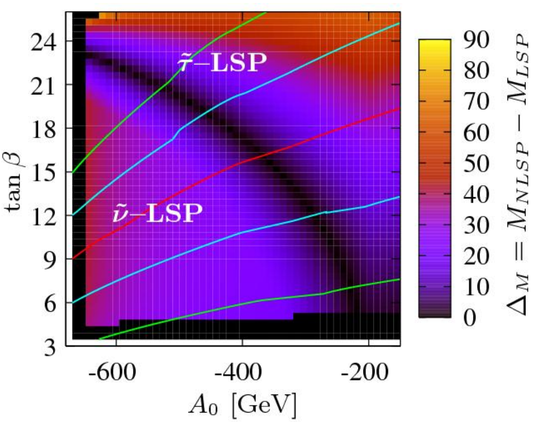
- $m^2_{\tilde{\nu}_\mu} = M_0^2 + 0.52 M^2_{1/2} + \ldots$.
  (left-handed sneutrino couples via U(1) & SU(2) charges.)

- $m^2_{\tilde{\chi}_1^0} \simeq M_1^2 = 0.17 M^2_{1/2}$.
  ($\tilde{\chi}_1^0$ is bino-like.)

[Ibanez, Lopez, Munoz, Nucl.Phys.B256,1985]

$\tilde{\nu}_\mu$ LSP parameter space: A_0-tan β plane

$\lambda'_{221}(M_{GUT}) = 0.1,\ M_0 = 50$ GeV, $M_{1/2} = 500$ GeV, $\mu > 0$.



$\tilde{\nu}_\mu$ LSP parameter space: A_0-$\tan\beta$ plane

Different LSP regions because:

- $m^2_{\tilde{\tau}_R} = m^2_\tau + M_0^2 + 0.15 M^2_{1/2} - 0.23 M_z^2 \cos 2\beta - 2/3 X_\tau$
  with
  $X_\tau = 10^{-4}(1 + \tan^2\beta)(M_0^2 + 0.15 M^2_{1/2} + 0.33 A_0^2)$
- $m_{\tilde{\tau}_{RL}} = A_\tau - \mu \tan\beta$.
- $16\pi^2 \frac{dm^2_{\tilde{\nu}_i}}{dt} = 6(\mathbf{h_{D^k}})^2_{ij} + \ldots$
  with
  $(\mathbf{h_{D^k}})_{ij} = \lambda'_{ijk} \cdot A_0$ at M_{GUT}.

So far:
$\tilde{\nu}$ LSP in extended regions
of RPV mSUGRA parameter space.

Now: Phenomenology of a $\tilde{\nu}$ LSP at hadron colliders.

- Sparticle pair production.
- Single slepton production.

Sparticle pair production at LHC

Example: $\lambda'_{221}(M_{GUT}) = 0.1$, $\tan\beta = 10$, $\mu > 0$, $M_0 = 110$ GeV, $M_{1/2} = 440$ GeV, $A_0 = -500$ GeV.

$$\sigma_{LHC}(PP \to 2 \text{ Sparticles}) = 3.2 \text{ pb} .$$

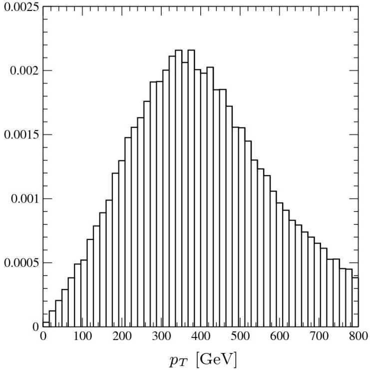
	mass	channel	BR
$\tilde{\nu}_\mu$	135	$\bar{s}d$	100 %
$\tilde{\mu}_L^-$	157	$\bar{c}d$	100 %
$\tilde{\chi}_1^0$	179	$\tilde{\nu}_\mu\bar{\nu}_\mu$	39 %
		$\tilde{\mu}_L^-\mu^+$	11 %
$\tilde{\tau}_1^-$	192	$\tilde{\chi}_1^0\tau^-$	100 %
$\tilde{\nu}_e$	316	$\tilde{\chi}_1^0\nu_e$	100 %
$\tilde{d}_R$	881	$\mu^- c$	44 %
		$\nu_\mu s$	44 %
		$\tilde{\chi}_1^0 d$	12 %
$\tilde{c}_L$	931	$\tilde{\chi}_1^+ s$	55 %
		$\tilde{\chi}_2^0 c$	27 %
		$\mu^+ d$	17 %

Characteristic signatures

- Not necessarily missing p_T. (22% of events).
- 4-7 non b-jets and 0-2 b-jets.
- High p_T muon plus high p_T jet. (10% of events)

High-p_T muons

Muon p_T distributions from the decays $\tilde{d}_R \to \mu^- c$ and $\tilde{c}_L \to \mu^+ d$:



$m_{\tilde{d}_R} = 881$ GeV, $m_{\tilde{c}_L} = 931$ GeV.

- Squark mass can be reconstracted via high p_T muon and high p_T jet.
- $\tilde{\nu}_\tau$ LSP $\Rightarrow$ high p_T taus.

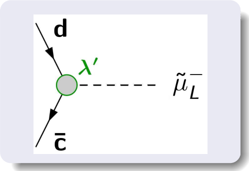
$\tilde{\nu}$ LSP phenomenology

So far: Sparticle pair production

Now: Resonant single slepton production.

Resonant single slepton production was only investigated for $\tilde{\chi}_1^0$ LSP!
e.g. [Allanach et al., Searching for R parity violation at Run II of the Tevatron, 1999]

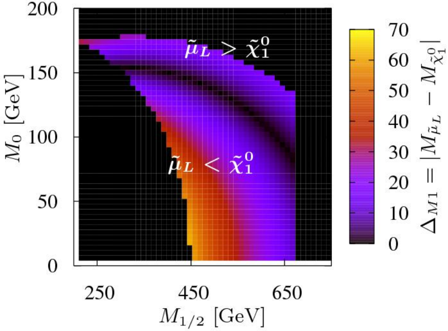
Single $\tilde{\mu}_L$ and $\tilde{\nu}_\mu$ production via λ'_{221}

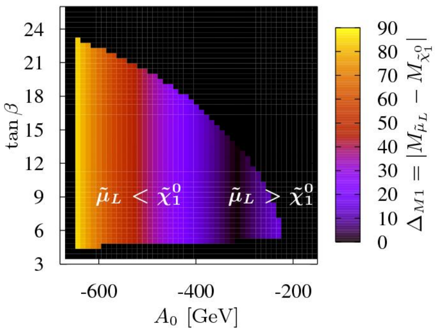


$\Rightarrow$

$$PP(\bar{P}) \to \tilde{\nu}_\mu + X$$
$$\hookrightarrow \bar{s}d$$

$$PP(\bar{P}) \to \tilde{\mu}_L^- + X$$
$$\hookrightarrow \bar{c}d$$
$$\hookrightarrow \tilde{\chi}_1^0 \; \mu^-$$
$$\hookrightarrow \tilde{\nu}_\mu \nu_\mu$$
$$\hookrightarrow \bar{s}d$$





Single $\tilde{\mu}_L$ and $\tilde{\nu}_\mu$ production via λ'_{221}

$\lambda'_{221}(M_{GUT}) = 0.1$, $M_0 = 170$ GeV, $M_{1/2} = 300$ GeV, $A_0 = -500$ GeV, $\tan\beta = 10$, $\mu > 0$.

$\Rightarrow M_{\tilde{\mu}_L} = 140$ GeV, $M_{\tilde{\chi}_1^0} = 120$ GeV

Tevatron

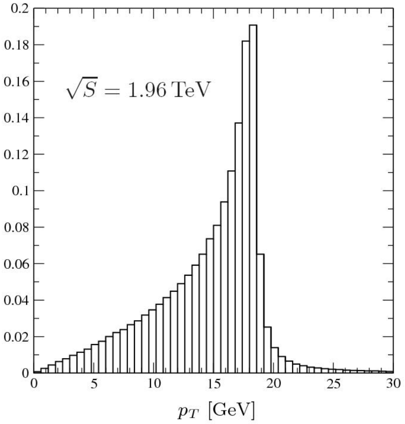
$\sigma(P\bar{P} \to \tilde{\mu}_L \to \tilde{\chi}_1^0 \mu) = 1.2$ pb.

LHC

$\sigma(P\bar{P} \to \tilde{\mu}_L \to \tilde{\chi}_1^0 \mu) = 29$ pb.

$\Rightarrow \tilde{\nu}$ LSP scenarios might be found at the Tevatron!

Bottleneck: Small p_T of Muons.



Muon p_T from $P\bar{P} \to \tilde{\mu}_L \to \tilde{\chi}_1^0 \mu$ at the Tevatron

Summary and Outlook

Summary

- Including R-parity violation allows $\tilde{\tau}$ LSP in mSUGRA.
- Including R-parity violation changes RGEs in mSUGRA.
  $\Rightarrow$ 2-body versus 4-body $\tilde{\tau}$ decays.
  $\Rightarrow$ $\tilde{\nu}$ LSP possible.
- Single slepton production can test λ' and λ at the same time.
- Promising hadron collider signatures for $\tilde{\tau}$ LSP:
  detached vertices, multi-lepton final states, like-sign leptons.
- Promising hadron collider signatures for $\tilde{\nu}$ LSP:
  high-p_T muons, muons from single slepton production.
  $\Rightarrow$ Tevatron might find $\tilde{\nu}$ LSP scenarios.

Outlook

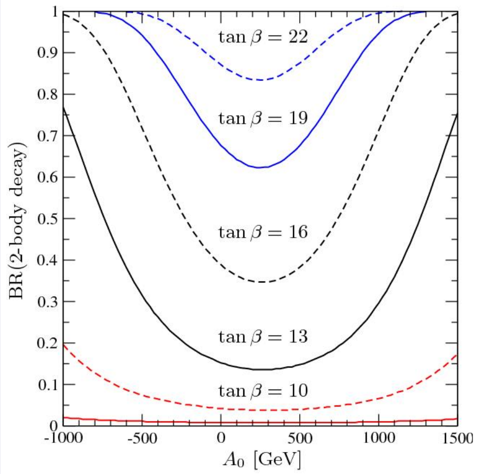
- Detailed anlaysis including background, detector simulations and data.
- Additional LSP candidates: $\tilde{e}_R$ with λ, $\tilde{t}_1$ with λ''.

backup slides

2-body versus 4-body decay: A_0-dependence

BR(2-body decay), down-mixing

$\lambda'_{211} = 0.01$, $M_0 = 0$ GeV, $M_{1/2} = 500$ Gev, sgnμ=+1



$$BR_2 = \frac{1}{1 + \Gamma_4/\Gamma_2}$$

with

$$\Gamma_2 \propto \lambda^2_{233}\, m_{\tilde{\tau}_1}$$

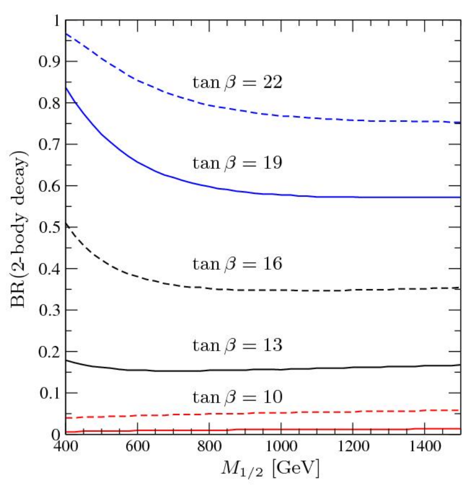
$$\Gamma_4 \propto \lambda'^2_{2jk}\, \frac{m^7_{\tilde{\tau}_1}}{m^2_{\tilde{\chi}}\, m^4_{\tilde{f}}}$$

$$\Rightarrow \Gamma_4/\Gamma_2 \propto m^6_{\tilde{\tau}_1}$$

2-body versus 4-body decay: $M_{1/2}$-dependence

BR(2-body decay), down-mixing

$\lambda'_{211} = 0.01$, $M_0 = 0$ GeV, $A_0 = 600$ Gev, sgnμ=+1



$$BR_2 = \frac{1}{1 + \Gamma_4/\Gamma_2}$$

with

$$\Gamma_2 \propto \lambda_{233}^2 \, m_{\tilde{\tau}_1}$$

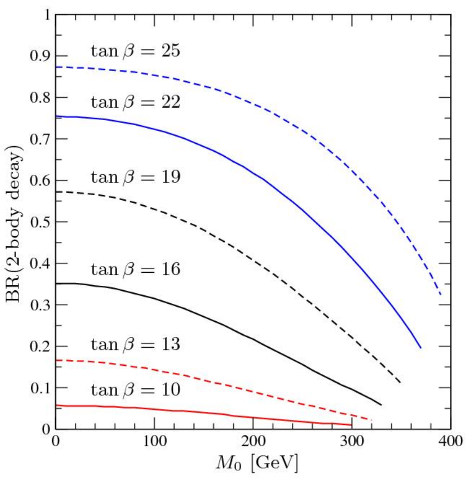
$$\Gamma_4 \propto \lambda'^2_{2jk} \frac{m_{\tilde{\tau}_1}^7}{m_{\tilde{\chi}}^2 m_{\tilde{f}}^4}$$

$$\Rightarrow \Gamma_4/\Gamma_2 \propto m_{\tilde{\tau}_1}^6$$

2-body versus 4-body decay: M_0-dependence

BR(2-body decay), down-mixing

$\lambda'_{211} = 0.01$, $A_600 = 0$ GeV, $M_{1/2} = 1400$ Gev, sgnμ=+1



$$BR_2 = \frac{1}{1 + \Gamma_4/\Gamma_2}$$

with

$$\Gamma_2 \propto \lambda_{233}^2 \, m_{\tilde{\tau}_1}$$

$$\Gamma_4 \propto \lambda'^2_{2jk} \frac{m^7_{\tilde{\tau}_1}}{m^2_{\tilde{\chi}} m^4_{\tilde{f}}}$$

$$\Rightarrow \Gamma_4/\Gamma_2 \propto m^6_{\tilde{\tau}_1}$$

Possible Signatures

$\tilde{\tau}_1$ decay	$\tilde{\mu}_L$ production					$\tilde{\nu}_\mu$ production				
via λ'_{2jk}	$\tau^+\tau^-$	$\mu^-\mu^\pm$	$[\ell^+\ell^-]$		jj	$\tau^+\tau^-$	$\mu^\pm$	$[\ell^+\ell^-]$	$\not{E}_T$	jj
	$\tau^+\tau^-$	μ^-	$[\ell^+\ell^-]$	$\not{E}_T$	jj	$\tau^+\tau^-$		$[\ell^+\ell^-]$	$\not{E}_T$	jj
via λ_{233}	$\tau^+\tau^-$	μ^-	$[\ell^+\ell^-]$	$\not{E}_T$		$\tau^+\tau^-$		$[\ell^+\ell^-]$	$\not{E}_T$	
	$\tau^\pm$	$\mu^-\mu^\mp$	$[\ell^+\ell^-]$	$\not{E}_T$		$\tau^\pm$	$\mu^\mp$	$[\ell^+\ell^-]$	$\not{E}_T$	

with $\ell = e, \mu$ if decays $\tilde{\chi}_1^0 \to \tilde{\ell}_R^\pm \ell^\mp$ and $\tilde{\ell}_R^- \to \ell^- \tau^\pm \tilde{\tau}_1^\mp$ allowed.

$$\bar{u}_j\, d_k \xrightarrow{\lambda'} \tilde{\mu}_L^- \to \mu^- \tilde{\chi}_1^0,$$
$$\hookrightarrow \tau^+\, \tilde{\tau}_1^-$$
$$\overset{\lambda'}{\hookrightarrow} \tau^- \mu^-\, u_j\, \bar{d}_k$$
$$\overset{\lambda}{\hookrightarrow} \nu_\tau\, \mu^-,$$
$$\hookrightarrow \tau^-\, \tilde{\tau}_1^+$$
$$\overset{\lambda'}{\hookrightarrow} \tau^+ \mu^-\, u_j\, \bar{d}_k$$

$\Rightarrow$ Multi-lepton final states, e.g. four μ in final state.

$\Rightarrow$ Like sign-muon events.

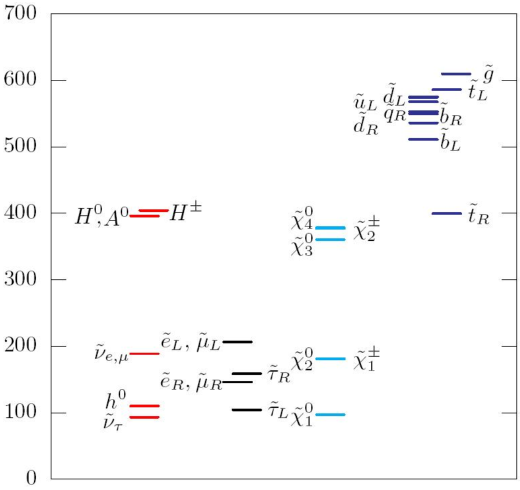
SM background for $\mu^\pm\mu^\pm$ events

4.9 ± 1.6 like-sign μ events after cuts at the LHC for $10 fb^{-1}$. [Dreiner, Richardson, Seymour, Phys.Rev.D63:055008]

Benchmark scenario BC3

BC3

- $M_0 = 100$ GeV
- $A_0 = -100$ GeV
- $\lambda'_{331}(M_{GUT}) = 0.122$
- $\tan\beta = 10$
- $M_{1/2} = 250$ GeV
- $\mathrm{sgn}(\mu) = +1.$



Branching ratios in benchmark scenario BC3

	mass [GeV]	channel	BR	channel	BR
$\tilde{\nu}_\tau$	93	$\bar{b}d$	100 %		
$\tilde{\chi}_1^0$	97	$\tilde{\bar{\nu}}_\tau \nu_\tau$	50 %	$\tilde{\nu}_\tau \bar{\nu}_\tau$	50%
$\tilde{\tau}_1^-$	105	$\nu_\tau b\bar{d}\tau^-$	37 %	$\bar{\nu}_\tau \bar{b}d\tau^-$	37 %
		$\tilde{\chi}_1^0\tau^-$	26 %		
$\tilde{e}_R^-(\tilde{\mu}_R^-)$	146	$\tilde{\chi}_1^0 e^-(\mu^-)$	100 %		
$\tilde{\tau}_2^-$	159	$\tilde{\chi}_1^0\tau^-$	100 %		
$\tilde{\chi}_2^0$	181	$\tilde{\bar{\nu}}_\tau \nu_\tau$	27 %	$\tilde{\nu}_\tau \bar{\nu}_\tau$	27 %
		$\tilde{\tau}_1^+\tau^-$	22 %	$\tilde{\tau}_1^-\tau^+$	22 %
$\tilde{\chi}_1^-$	181	$\tilde{\nu}_\tau \tau^-$	63 %	$\tilde{\tau}_1^-\nu_\tau$	35 %
$\tilde{\nu}_e(\tilde{\nu}_\mu)$	189	$\tilde{\chi}_1^0\nu_e(\nu_\mu)$	85 %	$\tilde{\chi}_1^+ e^-(\mu^-)$	11 %
$\tilde{e}_L^-(\tilde{\mu}_L^-)$	206	$\tilde{\chi}_1^0 e^-(\mu^-)$	48 %	$\tilde{\chi}_1^- \bar{\nu}_e(\bar{\nu}_\mu)$	33 %
		$\tilde{\chi}_2^0 e^-(\mu^-)$	19 %		

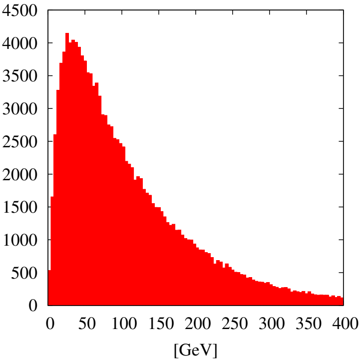
Signal rates of benchmark scenario BC3

σ(sparticle pair production) $= 4.7 \cdot 10^4$fb

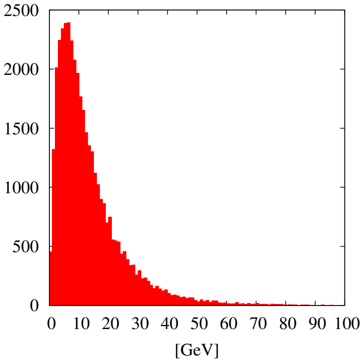
e^+ or μ^+	e^- or μ^-	τ^+	τ^-	$\not{p}_T$	event fraction
0	0	0	0	yes	27 %
0	0	1	0	yes	19 %
0	0	0	1	yes	16 %
0	0	1	1	yes	14 %
0	0	1	1	no	4.4 %
0	0	2	1	yes	4.0 %
0	0	1	2	yes	3.0 %
1	0	0	1	yes	1.9 %

- Most difficult scenario to trigger, although light spectrum.
- 4.7 million sparticle events at the LHC with $\int \mathcal{L} = 100\,\text{fb}^{-1}$.
- b-tagging should be possible.

p_T distributions in benchmark scenario BC3



p_T distribution of the b-jets from $\tilde{\nu}_\tau$ decays.



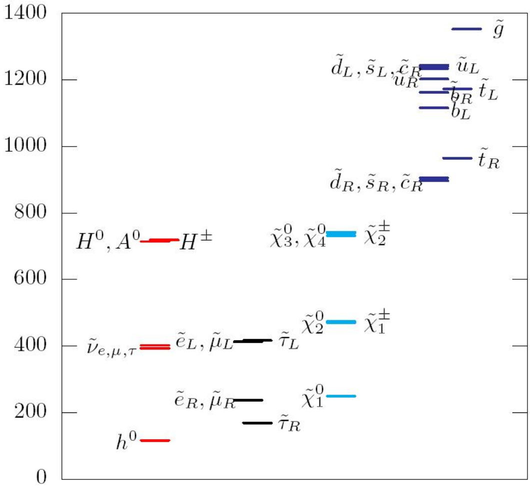
p_T distribution of the τ from $\tilde{\tau}_1$ decays.

- b-tagging should be possible.
- Most of the taus from $\tilde{\tau}_1$ decays are invisble ($p_T \leq 30$ GeV).

Benchmark scenario BC4

BC4

- no-scale mSUGRA
- $\lambda''_{212}(M_{GUT}) = 0.5$
- $\tan\beta = 30$
- $M_{1/2} = 600$ GeV
- $\text{sgn}(\mu) = +1$.



Branching ratios in benchmark scenario BC4

	mass [GeV]	channel	BR	channel	BR
$\tilde{\tau}_1$	169	$cds\tau^-$	79 %	$\bar{c}\bar{d}\bar{s}\tau^-$	21 %
$\tilde{e}_R(\tilde{\mu}_R)$	236	$\tilde{\tau}_1^+ e^-(\mu^-)\tau^-$	58 %	$\tilde{\tau}_1^- e^-(\mu^-)\tau^+$	42 %
$\tilde{\chi}_1^0$	249	$\tilde{\tau}_1^+\tau^-$	47 %	$\tilde{\tau}_1^-\tau^+$	47 %
$\tilde{\nu}_\tau$	393	$W^+\tilde{\tau}_1$	89 %	$\tilde{\chi}_1^0\nu_\tau$	12 %
$\tilde{\nu}_e(\tilde{\nu}_\mu)$	402	$\tilde{\chi}_1^0\nu_e(\nu_\mu)$	100 %		
$\tilde{e}_L^-(\tilde{\mu}_L^-)$	413	$\tilde{\chi}_1^0 e^-(\mu^-)$	100 %		
$\tilde{\tau}_2$	417	$Z^0\tilde{\tau}_1^-$	48 %	$h^0\tilde{\tau}_1^-$	38 %
		$\tilde{\chi}_1^0\tau^-$	15 %		
$\tilde{d}_R(\tilde{s}_R)$	897	$\bar{c}\bar{s}(\bar{d})$	99 %	$\tilde{\chi}_1^0 d(s)$	1.2 %
$\tilde{c}_R$	906	$\bar{s}\bar{d}$	95 %	$\tilde{\chi}_1^0 c$	4.7 %

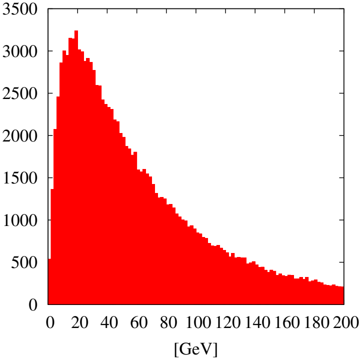
Signal rates of benchmark scenario BC4

$$\sigma(\text{sparticle pair production}) = 7.1 \cdot 10^2 \text{fb}$$

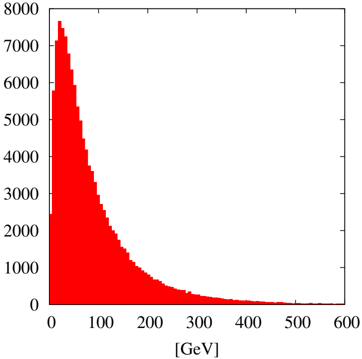
e^+ or μ^+	e^- or μ^-	τ^+	τ^-	$\not{p}_T$	event fraction
0	0	1	1	no	23 %
0	0	0	0	no	18 %
0	0	2	2	no	8.0 %
1	0	2	2	yes	5.6 %
0	0	2	1	yes	4.1 %
1	1	2	2	no	3.7 %
1	0	1	1	yes	3.6 %
0	1	2	2	yes	3.2 %

- Many jets in final state (6-8 jets).
- Very little missing p_T.
- Heavy spectrum.
- First two generations of $\tilde{q}_R$ undergo RPV decays.

p_T distributions in benchmark scenario BC4



p_T distribution of the τ from $\tilde{\tau}_1$ decay.

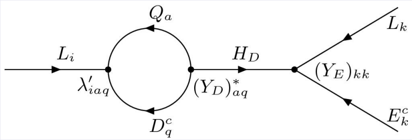


p_T distribution of the d-jets from $\tilde{\tau}_1$ decay.

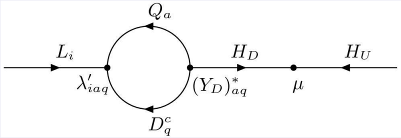
- Triggering to taus should be possible.

Dynamical generation of RPV couplings

Dynamical generation of λ_{ikk}



Dynamical generation of κ_i



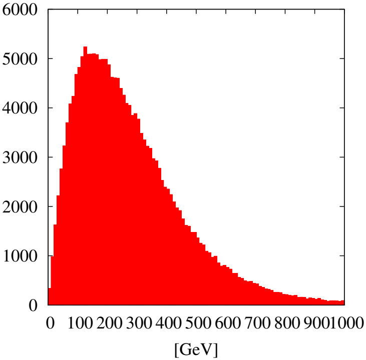
$$16\pi^2 \frac{d}{dt}\lambda_{ikk} = (Y_E)_{kk}[3\lambda'_{iaq}(Y_D)^*_{aq} + \lambda_{ill}(Y_E)^*_{ll}]$$

$$16\pi^2 \frac{d}{dt}\lambda'_{ijk} = \lambda'_{ijl}2(Y_D^\dagger Y_D)_{kl} + \lambda'_{ilk}[(Y_D Y_D^\dagger)_{lj} + (Y_U Y_U^\dagger)_{lj}] + 3\lambda'_{iaq}(Y_D)^*_{aq}(Y_D)_{jk} + \lambda_{iaa}(Y_E)^*_{aa}(Y_D)_{jk}$$

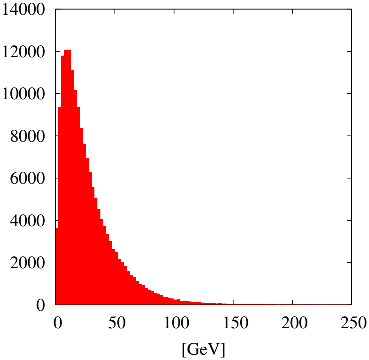
$$16\pi^2 \frac{d}{dt}\kappa_i = \mu[3\lambda'_{iaq}(Y_D)^*_{aq} + \lambda_{ill}(Y_E)^*_{ll}].$$

Breaking of one lepton number does not break the two other lepton numbers.

More p_T distributions in benchmark scenario BC1

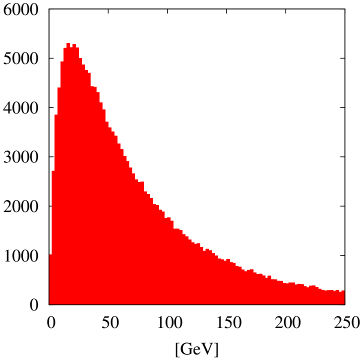


p_T distribution of the $\tilde{\tau}_1$.

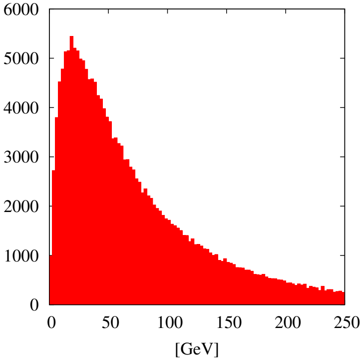


p_T distribution of τ coming from $\tilde{\chi}^0_m$ decays.

More p_T distributions in benchmark scenario BC1

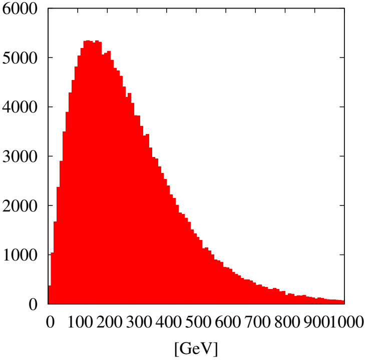


p_T distribution of the ℓ^+ coming from $\tilde{\tau}_1$ decays.

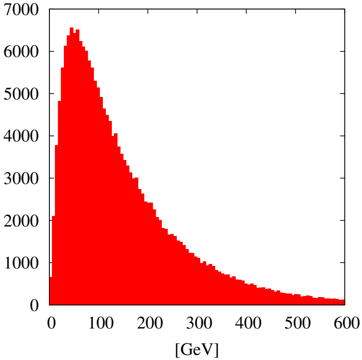


p_T distribution of the ℓ^- coming from $\tilde{\tau}_1$ decays.

More p_T distributions in benchmark scenario BC2

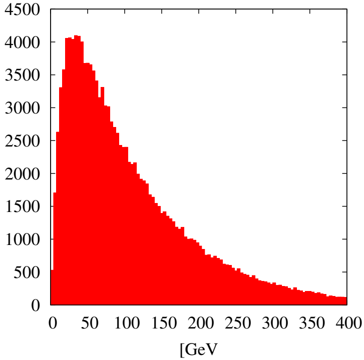


p_T distribution of the $\tilde{\tau}_1$.

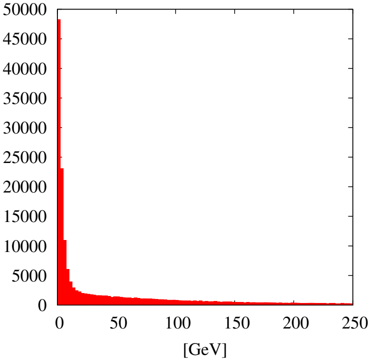


p_T distribution of the u-jets from $\tilde{\tau}_1$ decays.

More p_T distributions in benchmark scenario BC3

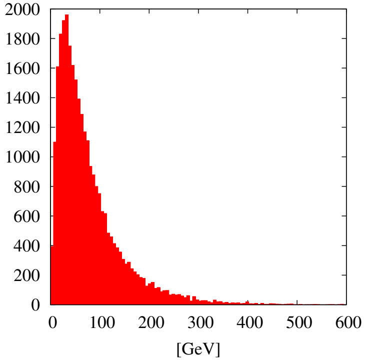


p_T distribution of the d-jets from $\tilde{\nu}_\tau$ decays.

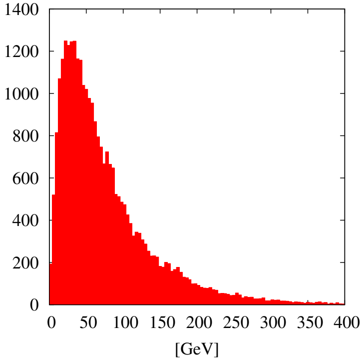


p_T distribution of the neutrinos.

More p_T distributions in benchmark scenario BC3

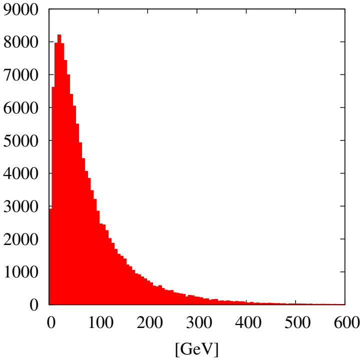


p_T distribution of the d-jets from $\tilde{\tau}_1$ decays.

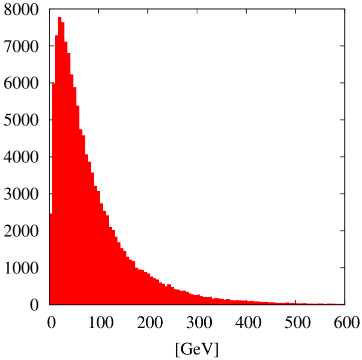


p_T distribution of the s-jets from $\tilde{\tau}_1$ decays.

More p_T distributions in benchmark scenario BC4

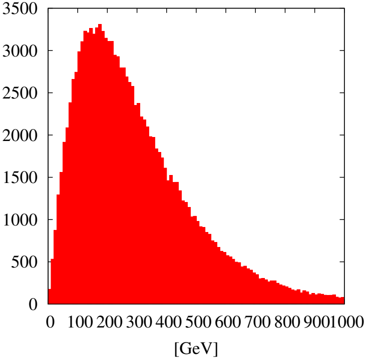


p_T distribution of the c-jets from $\tilde{\tau}_1$ decay.

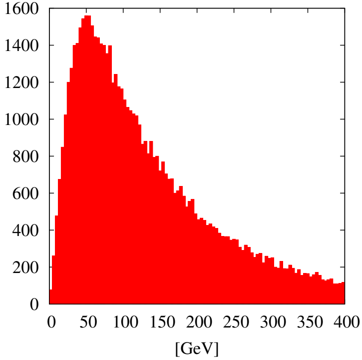


p_T distribution of the s-jets from $\tilde{\tau}_1$ decay.

More p_T distributions in benchmark scenario BC4

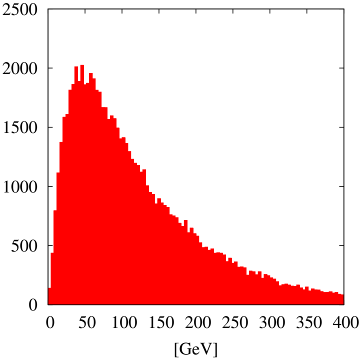


p_T distribution of the $\tilde{\tau}_1$.

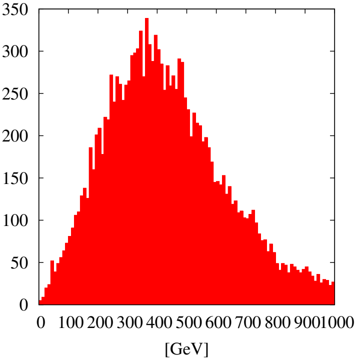


p_T distribution of the neutrinos.

More p_T distributions in benchmark scenario BC4



p_T distribution of τ from $\tilde{\chi}_m^0$ decays.



p_T distribution of the d-jets from $\tilde{c}_R$ decay.

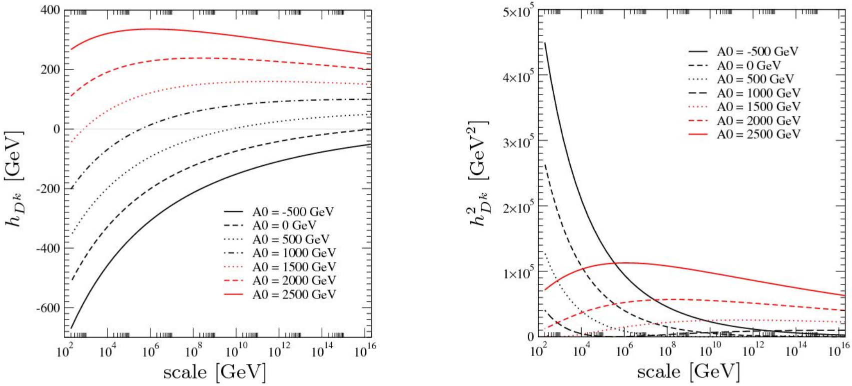
RPV couplings leading to a sneutrino LSP

strongest bounds at M_{EW}
(for $m_{\tilde{\ell}} = 200$ GeV, $m_{\tilde{q}} = 500$ GeV)

coupling	bound	LSP
λ'_{112}	0.10	$\tilde{\nu}_e$
λ'_{121}	0.15	$\tilde{\nu}_e$
λ'_{131}	0.15	$\tilde{\nu}_e$
λ'_{212}	0.30	$\tilde{\nu}_\mu$
λ'_{221}	0.37	$\tilde{\nu}_\mu$
λ'_{231}	0.90	$\tilde{\nu}_\mu$
λ'_{312}	0.37	$\tilde{\nu}_\tau$
λ'_{321}	0.37	$\tilde{\nu}_\tau$
λ'_{331}	1.60	$\tilde{\nu}_\tau$

and up-mixing.

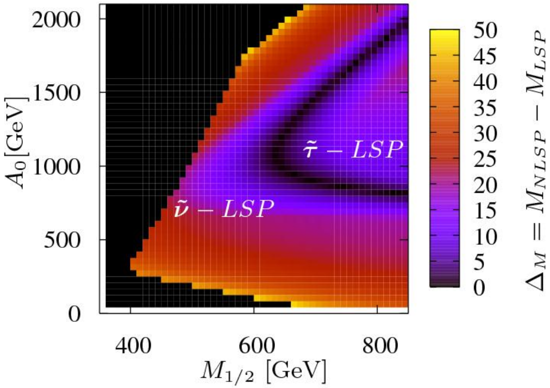
Running of $(h_{D^k})_{ij}$ $\lambda'_{ijk}(M_{GUT}) = 0.1,\ M_{1/2} = 500$ GeV



$$16\pi^2 \frac{d(\mathbf{h}_{\mathbf{D}^k})_{ij}}{dt} = -(\mathbf{h}_{\mathbf{D}^k})_{ij}\left(\frac{7}{15}g_1^2 + 3g_2^2 + \frac{16}{3}g_3^2\right) + \lambda'_{ijk}\left(\frac{14}{15}M_1^2 + 6M_2^2 + \frac{32}{3}M_3^2\right).$$

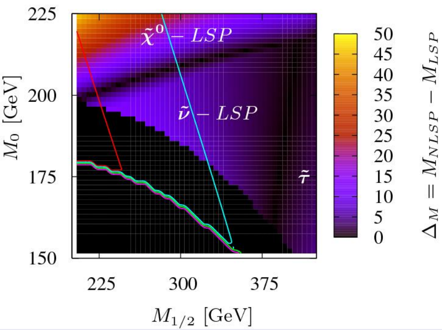
A_0 dependence

$\lambda'_{221}(M_{GUT}) = 0.149$, $M_0 = 50$ GeV, $\tan\beta = 10$.

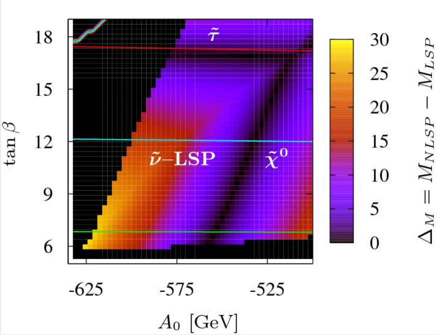


$\tilde{\nu}_\tau$ LSP parameter space

$\lambda'_{331}(M_{GUT}) = 0.12$, $A_0 = -550$ GeV, $\tan\beta = 14$, $\mu > 0$.



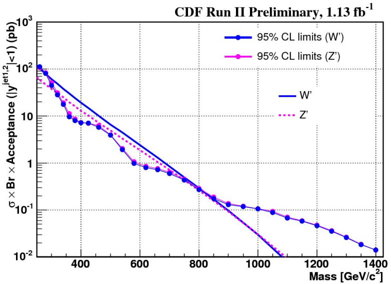
$\lambda'_{331}(M_{GUT}) = 0.12$, $M_0 = 200$ GeV, $M_{1/2} = 270$ GeV, $\mu > 0$.

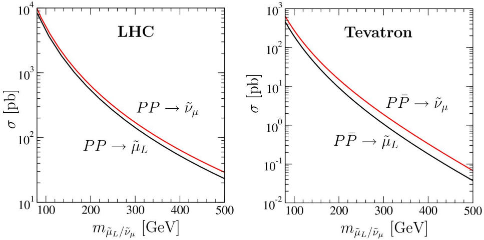


muon anomalus magnetic moment: $\delta a_\mu = a_\mu|_{exp} - a_\mu|_{SM} = 2.95 \times 10^{-9}$.
$\Leftrightarrow$ 3.4σ deviation to SM prediction!

$\delta a_\mu|_{SUSY} = 2.95 \times 10^{-9}$ (red line), $\pm 1\sigma$, $\pm 2\sigma$.

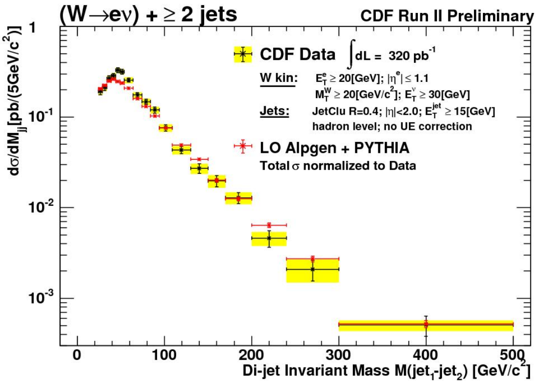
Single $\tilde{\mu}_L$ and $\tilde{\nu}_\mu$ production via λ'_{221}





Problem: Large QCD background.

$W+ \geq 2$ jets at the Tevatron



Dijet production at the Tevatron