Non-Neutralino LSPs in mSUGRA with R-Parity Violation and their Signatures at Hadron Colliders

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Outline

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:

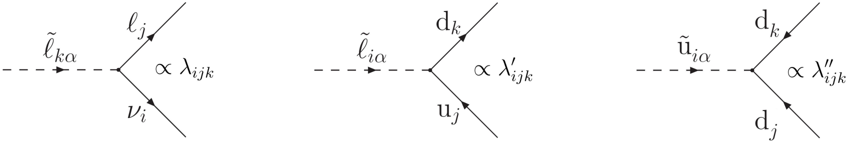
SM Particles	Superfields	spin 0	spin 1/2	spin 1
Quarks	Q_i	$(\tilde{u}_{L_i}, \tilde{d}_{L_i})$	(u_{L_i}, d_{L_i})	
	$\bar{U}_i$	$\tilde{u}^c_{R_i}$	$u^c_{R_i}$	
	$\bar{D}_i$	$\tilde{d}^c_{R_i}$	$d^c_{R_i}$	
Leptons	L_i	$(\tilde{\nu}_i, \tilde{e}_{L_i})$	(ν_i, e_{L_i})	
	$\bar{E}_i$	$\tilde{e}^c_{R_i}$	$e^c_{R_i}$	
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_u^0)	$(\tilde{H}_u^+, \tilde{H}_u^0)$	
	H_d	(H_d^0, H_d^-)	$(\tilde{H}_d^0, \tilde{H}_d^-)$	

MSSM with R-parity violation

General superpotential of the MSSM superfields:

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

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



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.

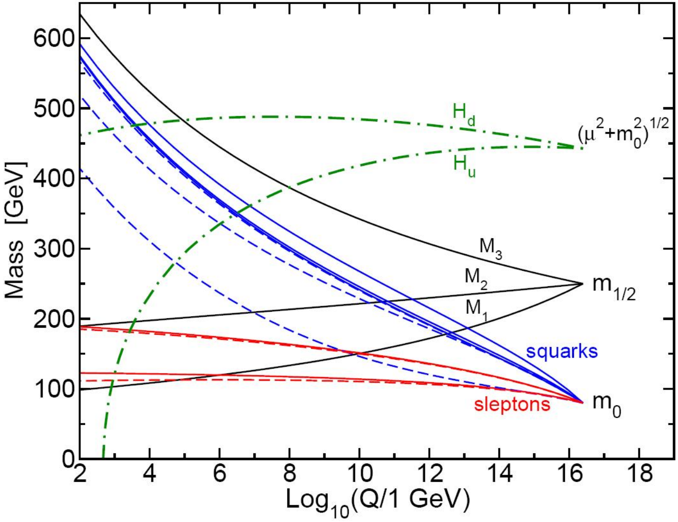
mSUGRA parameter space

- 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.

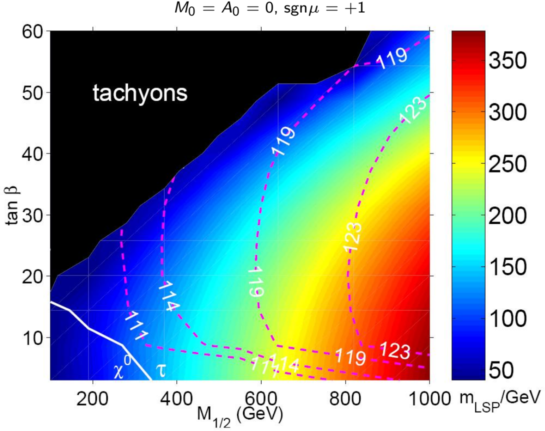
Running masses in mSUGRA

[Martin, hep-ph/9709356]



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

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

Differences to R_p conserving mSUGRA:

- In principle, any SUSY particle could be the LSP.
  $\Rightarrow$ $\tilde{\tau}_1$ LSP region allowed.
- Further R_p violating couplings are generated through RGEs at M_{EW}.
  $\Rightarrow$ 2-body and 4-body decays of $\tilde{\tau}_1$ LSP.
- R_p violating RGEs change the SUSY mass spectrum at M_{EW}.
  $\Rightarrow$ $\tilde{\nu}$, $\tilde{\mu}_R$, $\tilde{e}_R$, $\tilde{q}_R$ LSP.
- Single sparticle production is possible.
  $\Rightarrow$ single slepton production.
- Neutrino masses are generated.

What is the phenomenology of a $\tilde{\tau}_1$ LSP scenario at hadron colliders?

- $\tilde{\tau}_1$ LSP decays (2-body & 4-body).
  [Dreiner, SG, Trenkel, arXiv:0808.3079]
- Example: Sparticle pair production.
  [Allanach, Bernhardt, Dreiner, SG, Kom, Richardson, arXiv:0710.2034]

Typical mass ordering for $\tilde{\tau}_1$ LSP scenarios.

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

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.

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

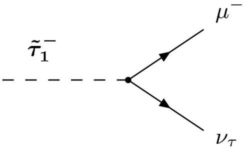
If $\mathbf{\Lambda} \geq \mathcal{O}(10^{-2})$

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

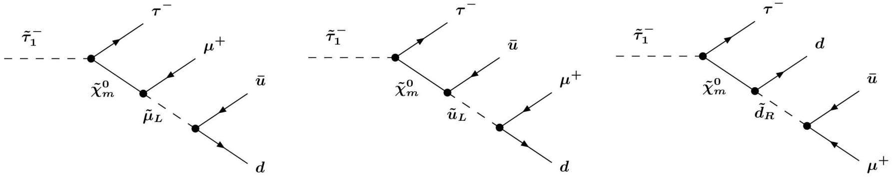
RPV decays of the $\tilde{\tau}_1$ LSP (naive picture)

- 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: $L_{i\neq 3} L_{j\neq 3} \bar{E}_{k\neq 3}$, $L_{i\neq 3} Q_j \bar{D}_k$ or $\bar{U}_i \bar{U}_j \bar{D}_k$.
  $\Rightarrow$ 4-body decays.

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

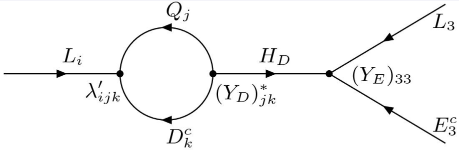


For example $\lambda'_{211} \neq 0$:



Dynamical generation of R_p violating couplings

Generation of λ_{i33} via λ'_{ijk}



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

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:

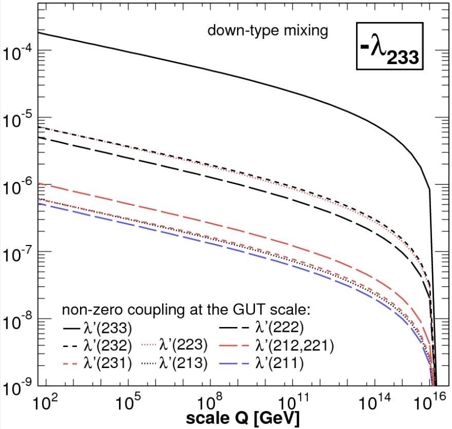
$$\mathbf{Y}_U(M_Z) \times v_u = \mathbf{V}^{+}_{CKM}\text{diag}(m_u, m_c, m_t)\mathbf{V}_{CKM},$$
$$\mathbf{Y}_D(M_Z) \times v_d = \text{diag}(m_d, m_s, m_b)$$

down-mixing:

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

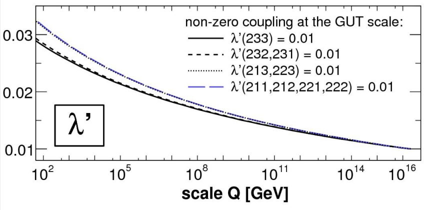
Running of R_p violating couplings: down-mixing

Dynamical generation of λ_{233}



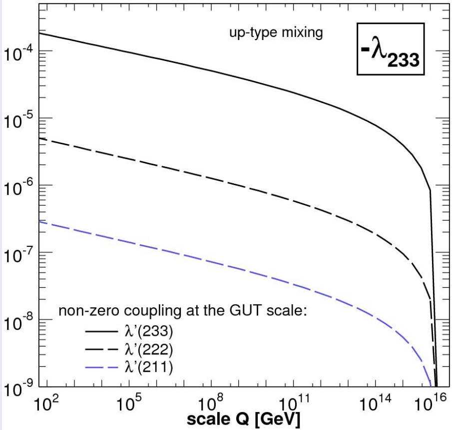
For comparison:

Running of λ'_{2jk}



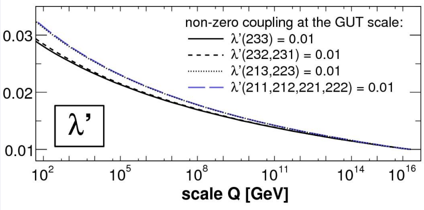
Running of R_p violating couplings: up-mixing

Dynamical generation of λ_{233}



For comparison:

Running of λ'_{2jk}



Decays of the $\tilde{\tau}_1$ 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.

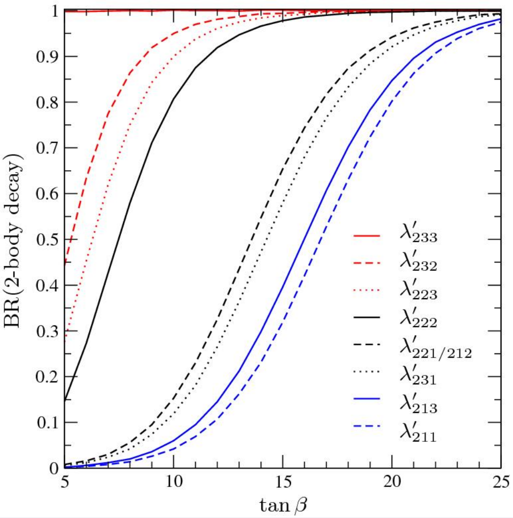
But: λ'_{2jk} will generate λ_{233}.

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



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

$$\frac{d\lambda_{i33}}{dt} \propto (\mathbf{Y}_E)_{33}(\mathbf{Y}_D)_{jk} \propto \tan^2\beta$$

$$\Rightarrow \Gamma_2 \propto \tan^4\beta$$

$\tilde{\tau}_1$ LSP phenomenology

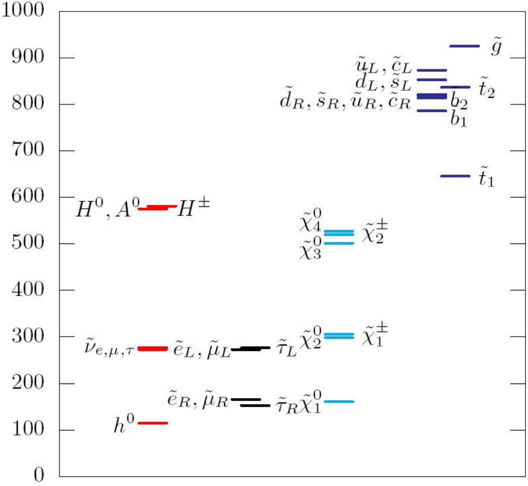
Example:
Sparticle pair production at the LHC.

Benchmark scenario BC1

BC1

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

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



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

$\sigma(\text{sparticle pair production}) = 4.8\,\text{pb}$

e^+ or μ^+	e^- or μ^-	τ^+	τ^-	event fraction
2	2	2	2	35 %
3	2	2	2	12 %
2	3	2	2	8.3 %
3	3	2	2	7.3 %
2	2	2	1	4.7 %
2	2	3	2	4.3 %
2	2	3	3	1.4 %
4	3	2	2	1.1 %

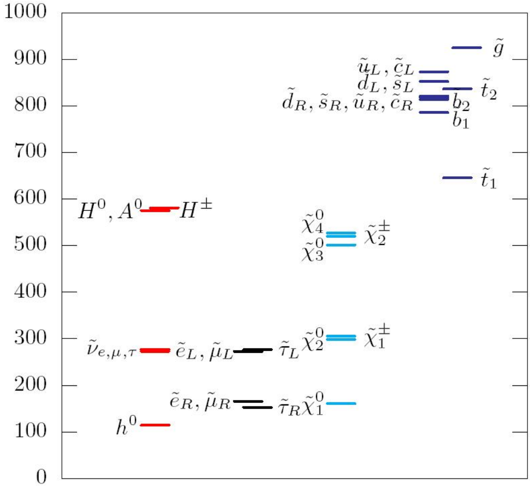
- Multi-lepton final states ($\approx$ 8 leptons).
- Multi-tau final states ($\approx$ 4 taus).
- 2-4 jets

Benchmark scenario BC2

BC2

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

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



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	$\tilde{\chi}_1^0\tau^-$ $h^0\tilde{\tau}_1^-$	63 % 15 %	$Z^0\tilde{\tau}_1^-$	18 %

Signal rates of benchmark scenario BC2

$$\sigma(\text{sparticle pair production}) = 4.8\,\text{pb}$$

e^+ or μ^+	e^- or μ^-	τ^+	τ^-	event fraction
0	0	1	1	14 %
0	0	2	0	7.1 %
0	0	0	2	6.8 %
1	0	1	1	6.5 %
0	0	1	1	4.5 %
1	0	0	2	3.3 %
1	0	2	0	3.2 %
1	1	1	1	2.4 %

- Like-sign τ events.
- 6-8 jets
- Less missing p_T.
- Detached vertex, i.e. $c \cdot \tau_{\tilde{\tau}_1} = 0.3$ mm.

So far:
$\tilde{\tau}_1$ LSP in $\not{R}_p$ mSUGRA.

Now:
Sneutrino, Smuon or Squarks as the LSP in $\not{R}_p$ mSUGRA.

[Bernhardt, Dreiner, SG, Das, arXiv:0810.3423]

[Dreiner, SG, arXiv:0811.0200]

So far:
$\tilde{\tau}_1$ LSP in $\not{R}_p$ mSUGRA.

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[Bernhardt, Dreiner, SG, Das, arXiv:0810.3423]

[Dreiner, SG, arXiv:0811.0200]

Effects of R_p violation

What will change due to one additional $\not{R}_p$ coupling at the GUT scale?

The RGEs get additional contributions.

$\Rightarrow$ Additional $\not{R}_p$ couplings at M_{EW}.

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

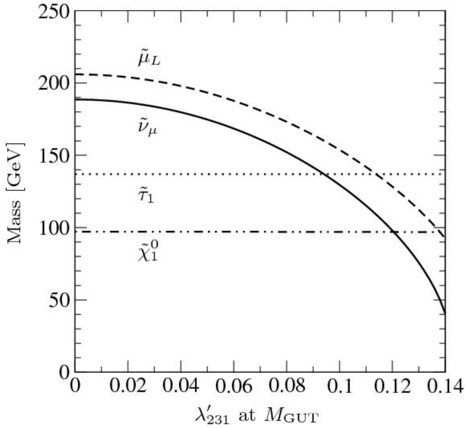
running sneutrino mass

$$
\begin{aligned}
16\pi^2 \frac{d(m^2_{\tilde{\nu}_i})}{dt} &= -\left(\frac{6}{5}g_1^2|M_1|^2 + 6g_2^2|M_2|^2 + \frac{3}{5}g_1^2 S\right) \\
&\quad +6\lambda'^2_{ijk}\left[(\mathbf{m}_{\tilde{\mathbf{L}}})^2_{ii} + (\mathbf{m}_{\tilde{\mathbf{Q}}})^2_{jj} + (\mathbf{m}_{\tilde{\mathbf{D}}})^2_{kk}\right] + 6(\mathbf{h}_{\mathbf{D}^k})^2_{ij} \\
\text{with} \quad (\mathbf{h}_{\mathbf{D}^k})_{ij} &= \lambda'_{ijk} \cdot A_0 \quad \text{at } M_{GUT}, \\
S &= f(\tilde{m}^2).
\end{aligned}
$$

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

What is the LSP?

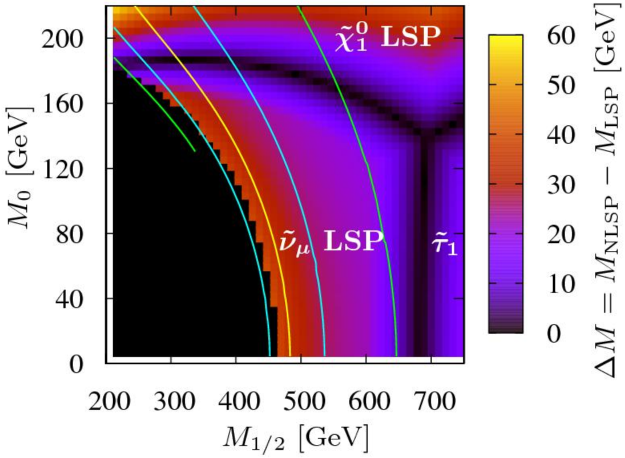
A non-vanishing coupling $\lambda'(M_{GUT})$ leads to a new LSP candidate.
For SPS1a:



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

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

$\lambda'_{231}(M_{GUT}) = 0.11$, $A_0 = -600$ GeV, $\tan\beta = 10$, $\mu > 0$.



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

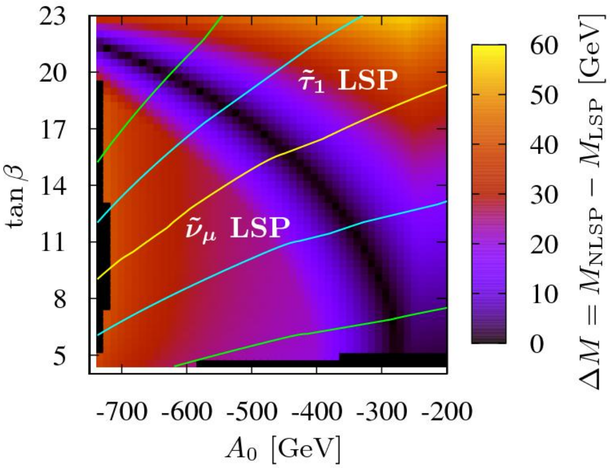
Different LSP regions because:

- $m^2_{\tilde{\tau}_R} = M_0^2 + 0.15 M_{1/2}^2 + \dots$.
  (right-handed stau couples only via U(1) charges.)
- $m^2_{\tilde{\nu}_\mu} = M_0^2 + 0.52 M_{1/2}^2 + \dots$.
  (left-handed sneutrino couples via U(1) & SU(2) charges.)
- $m^2_{\tilde{\chi}_1^0} \simeq M_1^2 = 0.17 M_{1/2}^2$.
  ($\tilde{\chi}_1^0$ is bino-like.)

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

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

$\lambda'_{231}(M_{GUT}) = 0.11$, $M_0 = 50$ 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 $\not{R}_p$ mSUGRA parameter space.

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

Sneutrino LSP phenomenology

Example: $\lambda'_{231}(M_{GUT}) = 0.11$, $M_0 = 110$ GeV, $M_{1/2} = 450$ GeV, $A_0 = -600$ GeV, $\tan\beta = 10$, $\mu > 0$.

$\sigma_{LHC}(PP \rightarrow 2 \text{ Sparticles}) = 3.0$ pb .

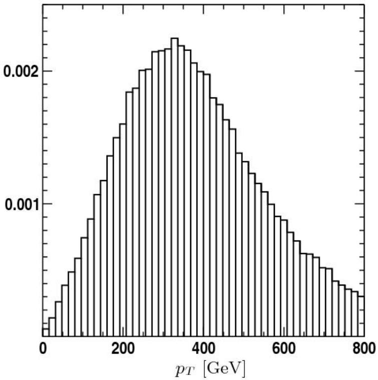
Characteristic signatures

- $\gtrsim$ 4 jets ($\approx$ 2 b-jets).
- Not necessarily missing p_T. (20% of events).
- High-p_T muon. (11% of events)

	mass	channel	BR
$\tilde{\nu}_\mu$	124	$\bar{b}d$	100 %
$\tilde{\mu}_L^-$	147	$W^-\bar{b}d$	79 %
		$\bar{c}d$	21 %
$\tilde{\chi}_1^0$	184	$\tilde{\nu}_\mu\bar{\nu}_\mu$	36 %
		$\tilde{\mu}_L^-\mu^+$	14 %
$\tilde{\nu}_e$	319	$\tilde{\chi}_1^0\nu_e$	100 %
$\tilde{e}_L^-$	329	$\tilde{\chi}_1^0 e^-$	100 %
$\tilde{t}_1$	650	$\tilde{\chi}_1^+ b$	42 %
		$\tilde{\chi}_1^0 t$	34 %
		$\mu^+ d$	11 %
$\tilde{d}_R$	897	$\nu_\mu b$	45 %
		$\mu^- t$	42 %
		$\tilde{\chi}_1^0 d$	13 %

High-p_T muons

Muon p_T from the decays $\tilde{d}_R \to \mu t$ and $\tilde{t}_{1/2} \to \mu d$:



- High-p_T muon can be used to discover BSM physics
- and to distinguish $\not{R}_p$ from R_p SUSY.
- $\tilde{\nu}_\tau$ LSP $\Rightarrow$ high-p_T taus $\Rightarrow$ detached vertex of $\mathcal{O}$(1cm).

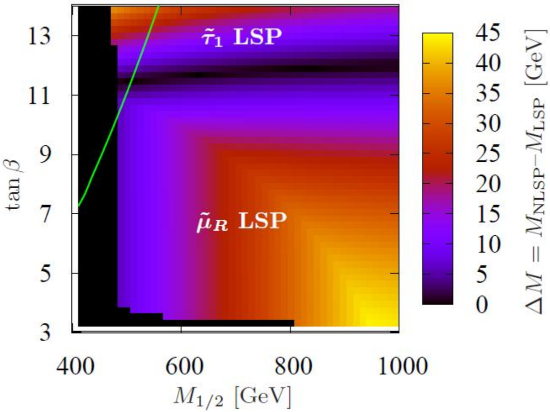
So far:
$\tilde{\nu}$ LSP via $\lambda' = \mathcal{O}(0.1)$.

Can we obtain new LSP candidates
via $\lambda = \mathcal{O}(0.1)$ or $\lambda'' = \mathcal{O}(0.1)$?

[Dreiner, SG, arXiv:0811.0200]

$\tilde{\mu}_R$ LSP parameter space: $M_{1/2}$–$\tan\beta$ plane

$\lambda_{132}(M_{GUT}) = 0.09$, $A_0 = -1500$ GeV, $M_0 = 170$ GeV, $\mu > 0$.



$\tilde{\mu}_R$ LSP phenomenology

Remarks

- $M_{1/2} > 500$ GeV. Reason: $\lambda_{132}(M_{GUT}) \leq 0.05 \times (m_{\tilde{\mu}_R}/100\,\text{GeV})$.
  $\Rightarrow$ Heavy SUSY spectrum.
- $\lambda_{231}(M_{GUT}) = 0.1 \Rightarrow \tilde{e}_R$ LSP.

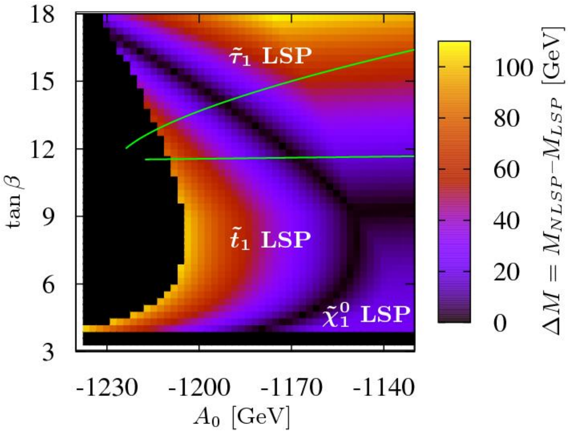
Promising LHC signatures:

$$PP \longrightarrow \tilde{q}_R\tilde{q}_R$$
$$\longrightarrow (q\tilde{\chi}_1^0)(q\tilde{\chi}_1^0)$$
$$\longrightarrow (q\mu\tilde{\mu}_R)(q\mu\tilde{\mu}_R)$$
$$\xrightarrow{\lambda} (q\mu e\nu_\tau)(q\mu\tau\nu_e)$$

$\Rightarrow$ 4 leptons in the final state!

$\tilde{t}_1$ LSP parameter space: A_0–$\tan\beta$ plane

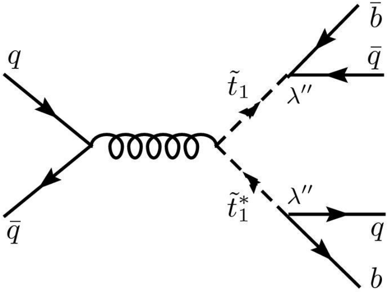
$\lambda''_{323}(M_{GUT}) = 0.35$, $M_0 = 120$ GeV, $M_{1/2} = 480$ GeV, $\mu > 0$.



$\tilde{t}_1$ LSP phenomenology

$\tilde{t}_1$ can be light, *i.e.* LEP bound $m_{\tilde{t}_1} \gtrsim 94$ GeV.

at Tevatron and LHC:

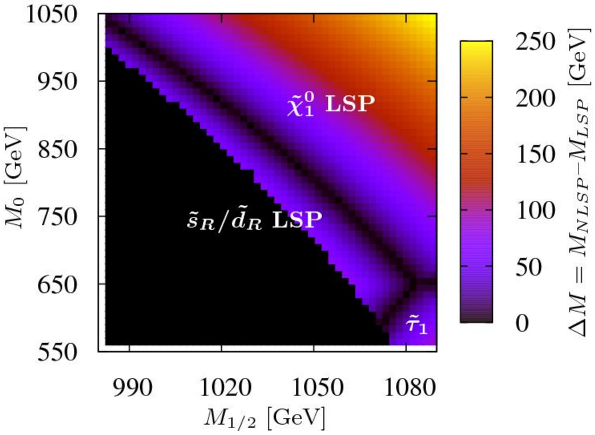


[Choudhury et al., Phys. Rev. D73, 055013]:

$\Rightarrow$ $\tilde{t}_1$ LSPs up to 210 GeV can be tested at the Tevatron!

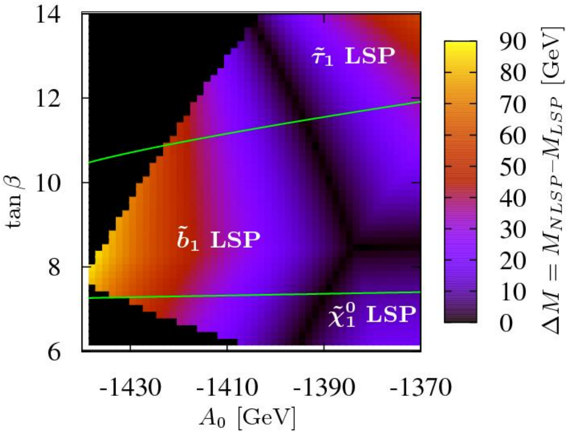
$\tilde{s}_R/\tilde{d}_R$ LSP parameter space: $M_{1/2}$–M_0 plane

$\lambda''_{212}(M_{GUT}) = 0.5$, $A_0 = -3700$ GeV, $\tan\beta = 19$ GeV, $\mu > 0$.



$\tilde{b}_1$ LSP parameter space: A_0–$\tan\beta$ plane

$\lambda''_{223}(M_{GUT}) = 0.5$, $M_0 = 120$ GeV, $M_{1/2} = 400$ GeV, $\mu > 0$.



Summary and Outlook

Summary

- Including R-parity violation allows $\tilde{\tau}_1$ LSP in mSUGRA.
- Including R-parity violation changes RGEs in mSUGRA.
  $\Rightarrow$ 2-body versus 4-body $\tilde{\tau}_1$ decays.
  $\Rightarrow$ $\tilde{\nu}$, $\tilde{\mu}_R$, $\tilde{e}_R$, $\tilde{t}_1$, $\tilde{b}_1$ $\tilde{d}_R$, $\tilde{s}_R$ LSP possible.
- Promising hadron collider signatures:
  - $\tilde{\tau}_1$ LSP: detached vertices, multi-lepton final states.
  - $\tilde{\nu}$ LSP: high-p_T muons.
  - $\tilde{\mu}_R$ LSP: multi-lepton final states.
  - $\tilde{t}_1$ LSP: 4-jet events at Tevatron.

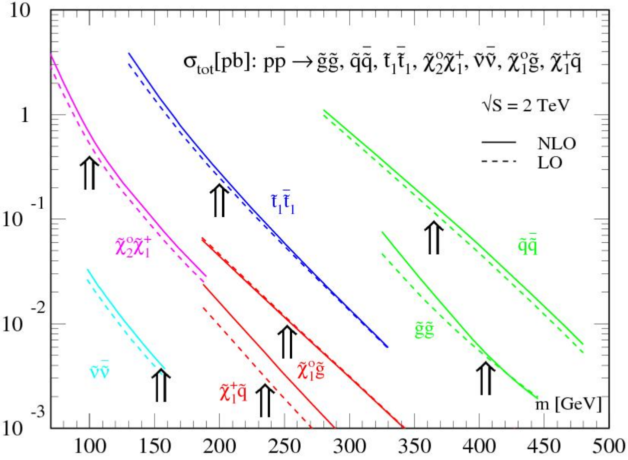
Outlook

- Detailed anlaysis including background, detector simulations and data.

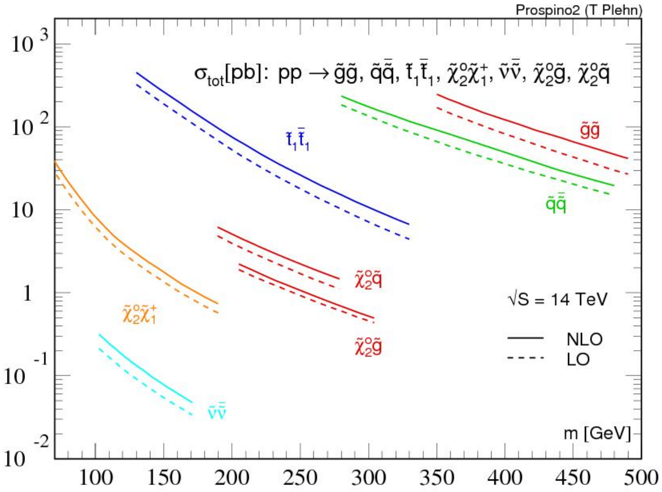
backup slides

Sparticle Pair Production at the Tevatron

[Plehn, PROSPINO]



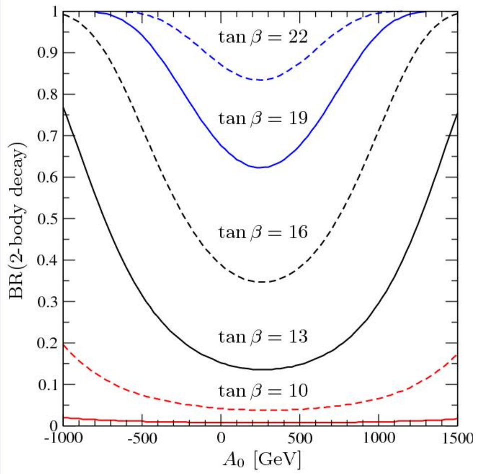
Sparticle Pair Production at the LHC



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

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

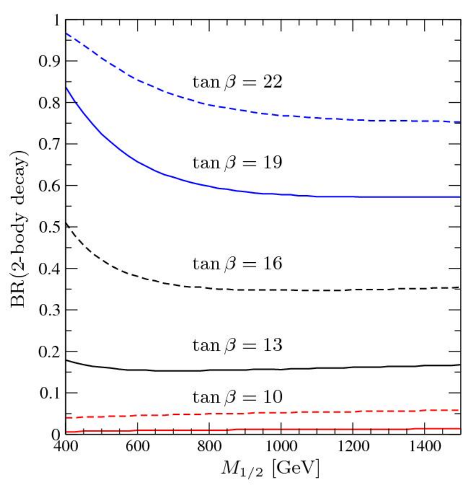
$$\Gamma_4 \propto \lambda'^2_{2jk} \frac{m^7_{\tilde{\tau}_1}}{m^2_{\tilde{\chi}} m^4_{\tilde{f}}}$$

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

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

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

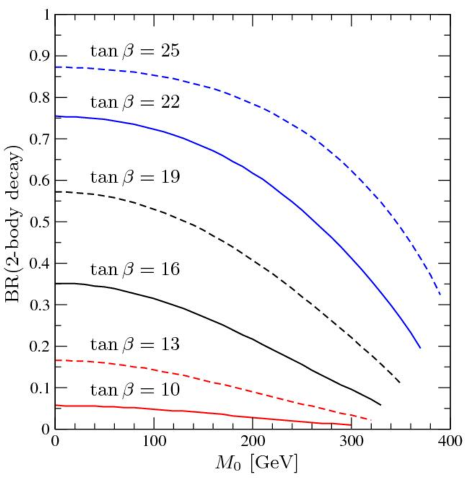
$$\Gamma_4 \propto \lambda'^2_{2jk}\, \frac{m^7_{\tilde{\tau}_1}}{m^2_{\tilde{\chi}} m^4_{\tilde{f}}}$$

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

2-body versus 4-body decay: M_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

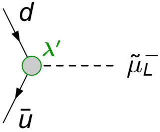
$$\Gamma_2 \propto \lambda_{233}^2 \, m_{\tilde{\tau}_1}$$

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

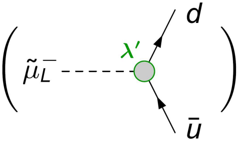
$$\Rightarrow \Gamma_4/\Gamma_2 \propto m_{\tilde{\tau}_1}^6$$

Single slepton production via λ'_{ijk}

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

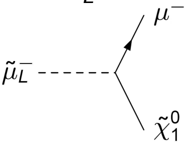


$\tilde{\mu}_L^-$ decay via λ'_{211}:



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:

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

$\tilde{\tau}$ LSP:

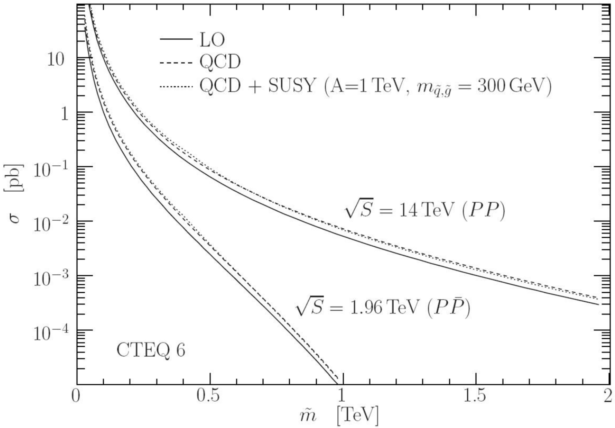
$$\tilde{\mu}_L^- \to \mu^- \mu^- \tau^+ \tau^- u\bar{d} \quad \text{(4-body decay).}$$
$$\tilde{\mu}_L^- \to \mu^- \mu^- \tau^+ \nu_\tau \quad \text{(2-body decay).}$$

$\Rightarrow$ Promising signature: Like-sign muon final states!

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

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

Possible Signatures

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

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.

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

⇒ Multi-lepton final states, e.g. four μ in final state.

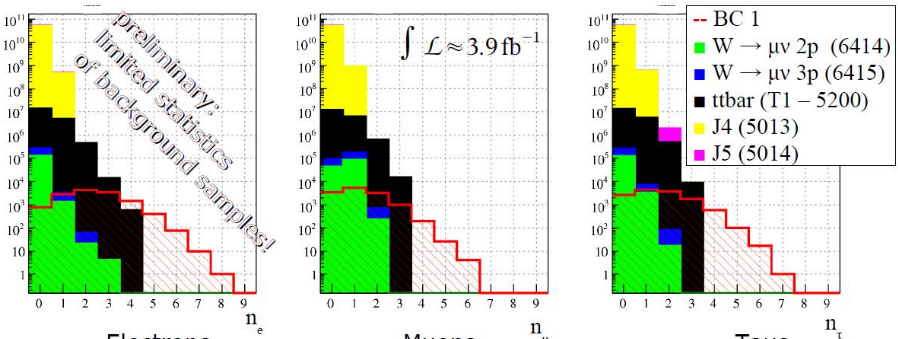
⇒ Like sign-muon events.

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]

Number of leptons in BC1

[Desch, Fleischmann, Wienemann]



Electrons $p_T > 10$ GeV

Muons $p_T > 10$ GeV

Taus $p_T > 10$ GeV

RPV couplings leading to a sneutrino LSP

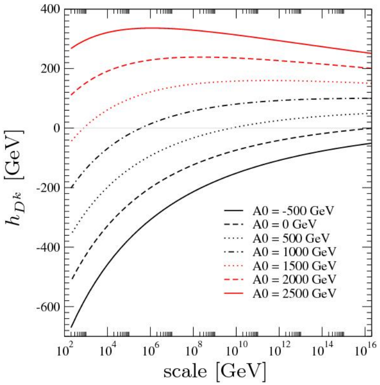
couplings λ'_{ijk} with upper bounds of $\mathcal{O}(0.1 - 1)$ at M_{EW}

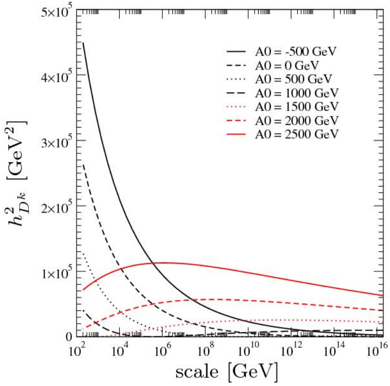
coupling	LSP
λ'_{112}	$\tilde{\nu}_e$
λ'_{121}	$\tilde{\nu}_e$
λ'_{131}	$\tilde{\nu}_e$
λ'_{212}	$\tilde{\nu}_\mu$
λ'_{221}	$\tilde{\nu}_\mu$
λ'_{231}	$\tilde{\nu}_\mu$
λ'_{312}	$\tilde{\nu}_\tau$
λ'_{321}	$\tilde{\nu}_\tau$
λ'_{331}	$\tilde{\nu}_\tau$

and up-mixing.

Charm physics, e.g. $D_0 - \bar{D}_0$ mixing, will test couplings λ'_{i21} & λ'_{i12}.

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

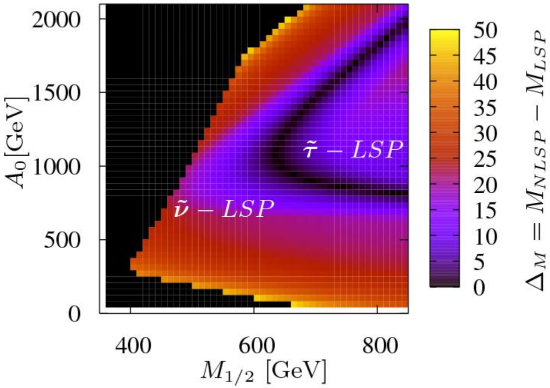




$$
\begin{aligned}
16\pi^2 \frac{d(\mathbf{h_{D^k}})_{ij}}{dt} &= -(\mathbf{h_{D^k}})_{ij} \left(\frac{7}{15} g_1^2 + 3 g_2^2 + \frac{16}{3} g_3^2 \right) \\
&\quad + \lambda'_{ijk} \left(\frac{14}{15} M_1^2 + 6 M_2^2 + \frac{32}{3} M_3^2 \right) .
\end{aligned}
$$

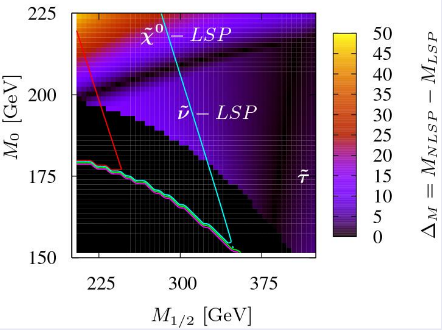
A_0 dependence

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

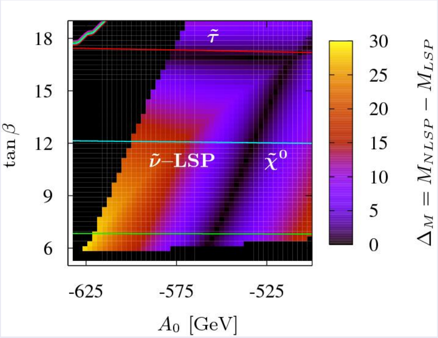


$\tilde{\nu}_\tau$ LSP parameter space

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



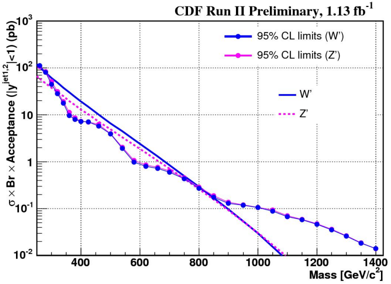
$\lambda'_{331}(M_{GUT}) = 0.12,\ M_0 = 200$ GeV, $M_{1/2} = 270$ GeV, $\mu > 0.$

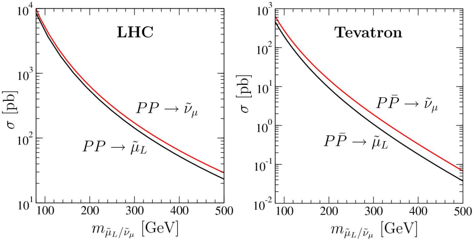


muon anomalus magnetic moment: $\delta a_\mu = a_\mu|_{exp} - a_\mu|_{SM} = 2.95 \times 10^{-9}$.
$\Leftrightarrow$ 3.4σ deviation to SM prediction!

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

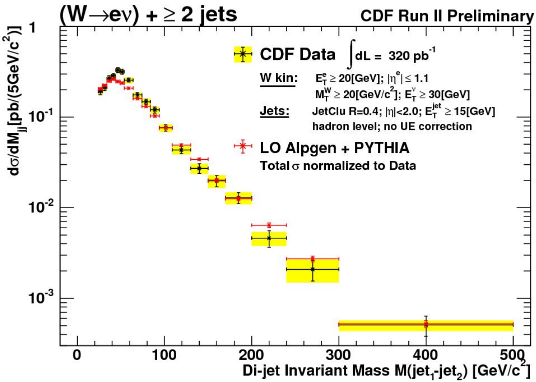
Single $\tilde{\mu}_L$ and $\tilde{\nu}_\mu$ production via λ'_{221}



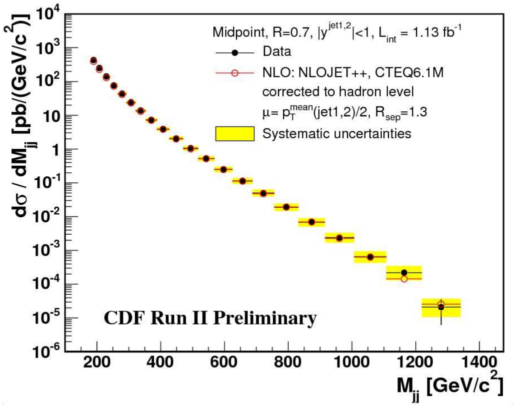


Problem: Large QCD background.

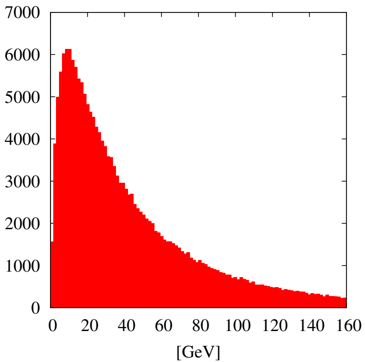
$W+ \geq 2$ jets at the Tevatron



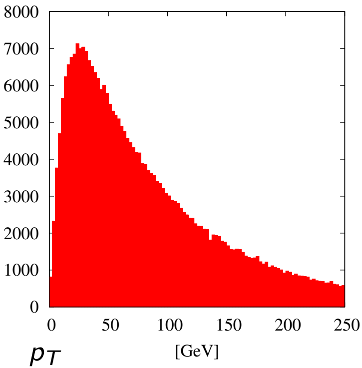
Dijet production at the Tevatron



p_T distributions in benchmark scenario BC1



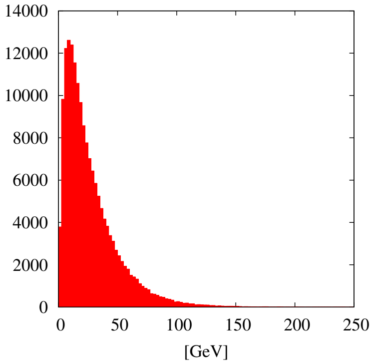
p_T distribution of the τ from $\tilde{\tau}_1$ decays.



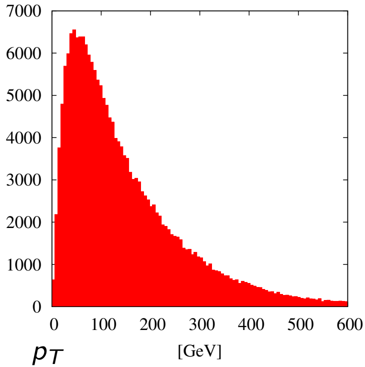
p_T distribution of the neutrinos.

- 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.

p_T distributions in benchmark scenario BC2



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



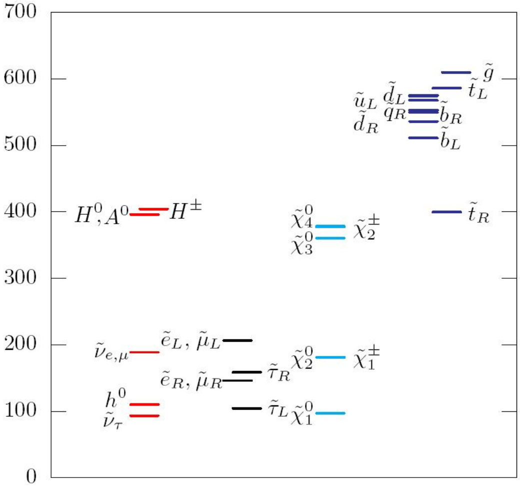
p_T distribution of the d-jets from $\tilde{\tau}_1$ decays.

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

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	$\bar{\tilde{\nu}}_\tau \nu_\tau$	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	$\bar{\tilde{\nu}}_\tau \nu_\tau$	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 %		

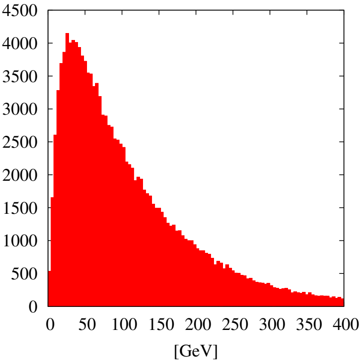
Signal rates of benchmark scenario BC3

$$\sigma(\text{sparticle pair production}) = 4.7 \cdot 10^4 \text{fb}$$

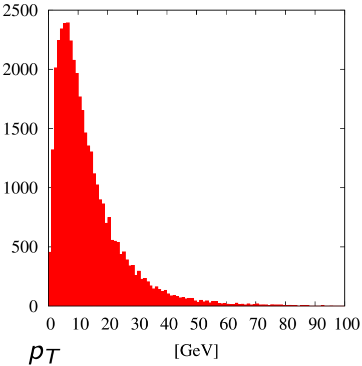
e^+ or μ^+	e^- or μ^-	τ^+	τ^-	$\not{p}_T$	event fraction
0	0	0	0	yes	27 %
0	0	1	0	yes	19 %
0	0	0	1	yes	16 %
0	0	1	1	yes	14 %
0	0	1	1	no	4.4 %
0	0	2	1	yes	4.0 %
0	0	1	2	yes	3.0 %
1	0	0	1	yes	1.9 %

- 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



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



p_T

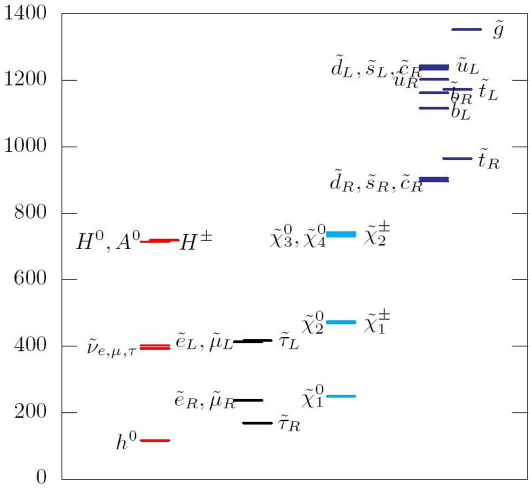
distribution of the τ from $\tilde{\tau}_1$ decays.

- 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
- $\mathrm{sgn}(\mu) = +1.$



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 %

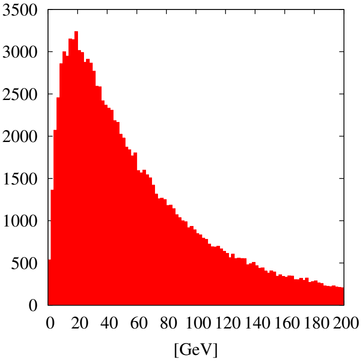
Signal rates of benchmark scenario BC4

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

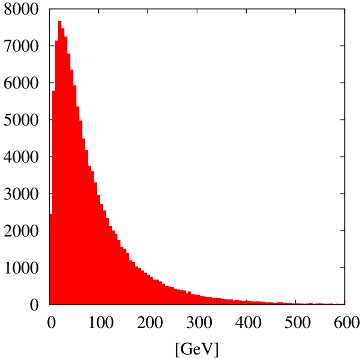
e^+ or μ^+	e^- or μ^-	τ^+	τ^-	$\not{p}_T$	event fraction
0	0	1	1	no	23 %
0	0	0	0	no	18 %
0	0	2	2	no	8.0 %
1	0	2	2	yes	5.6 %
0	0	2	1	yes	4.1 %
1	1	2	2	no	3.7 %
1	0	1	1	yes	3.6 %
0	1	2	2	yes	3.2 %

- 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



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

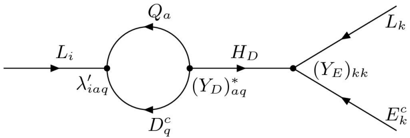


p_T distribution of the d-jets from $\tilde{\tau}_1$ decay.

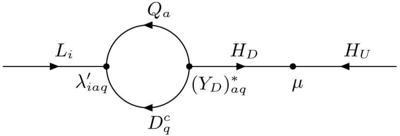
- Triggering to taus should be possible.

Dynamical generation of RPV couplings

Dynamical generation of λ_{ikk}



Dynamical generation of κ_i



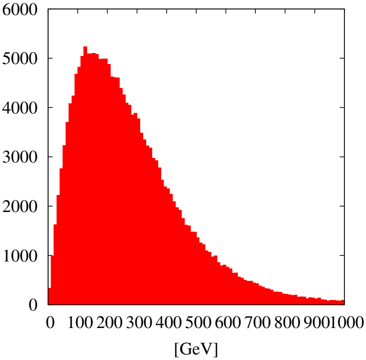
$$16\pi^2 \frac{d}{dt}\lambda_{ikk} = (Y_E)_{kk}[3\lambda'_{iaq}(Y_D)^*_{aq} + \lambda_{ill}(Y_E)^*_{ll}]$$

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

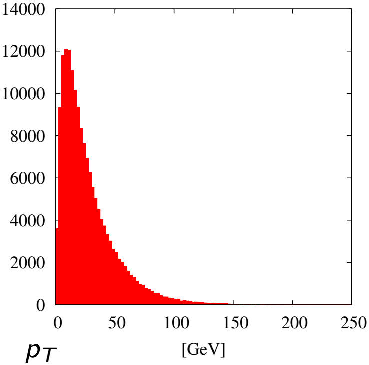
$$16\pi^2 \frac{d}{dt}\kappa_i = \mu[3\lambda'_{iaq}(Y_D)^*_{aq} + \lambda_{ill}(Y_E)^*_{ll}].$$

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

More p_T distributions in benchmark scenario BC1

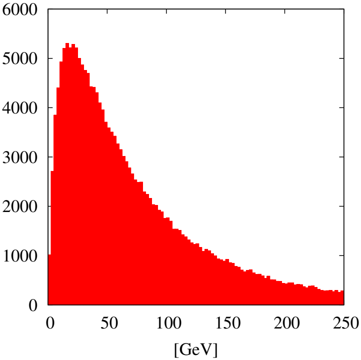


distribution of the $\tilde{\tau}_1$.

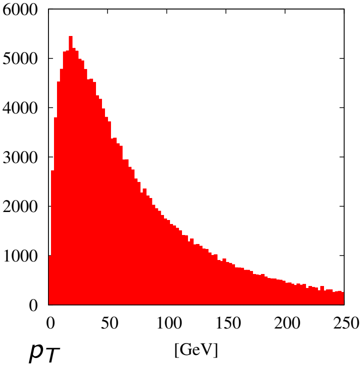


p_T distribution of τ coming from $\tilde{\chi}^0_m$ decays.

More p_T distributions in benchmark scenario BC1



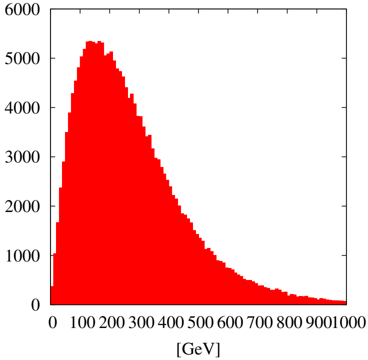
distribution of the ℓ^+ coming from $\tilde{\tau}_1$ decays.



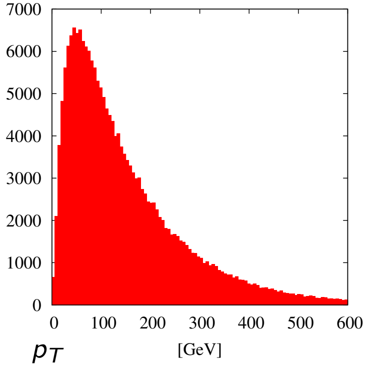
p_T

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

More p_T distributions in benchmark scenario BC2

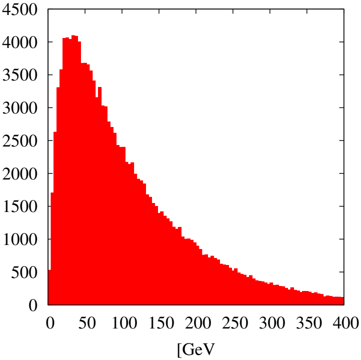


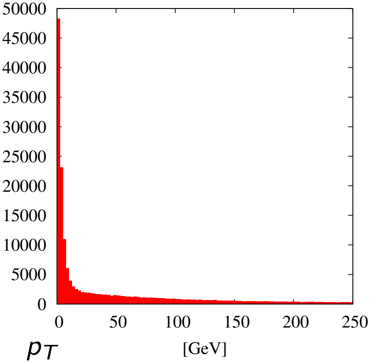
distribution of the $\tilde{\tau}_1$.



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

More p_T distributions in benchmark scenario BC3

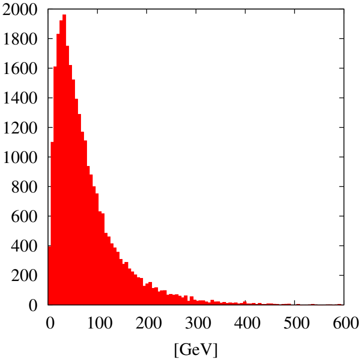




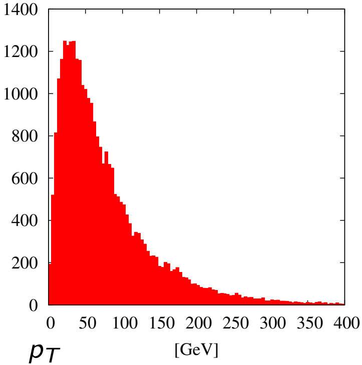
p_T distribution of the d-jets from $\tilde{\nu}_\tau$ decays.

p_T distribution of the neutrinos.

More p_T distributions in benchmark scenario BC3

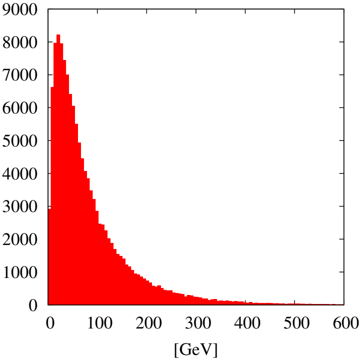


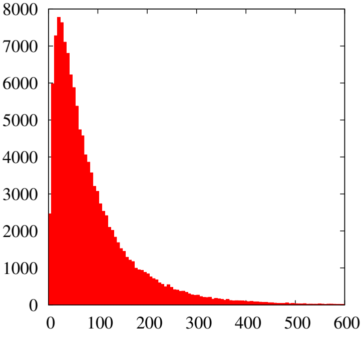
p_T distribution of the d-jets from $\tilde{\tau}_1$ decays.



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

More p_T distributions in benchmark scenario BC4



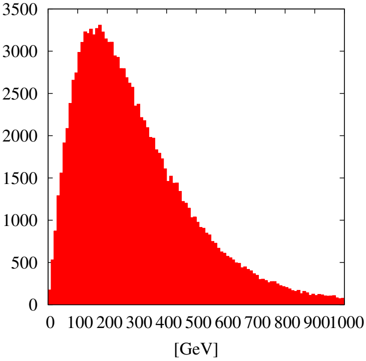


p_T

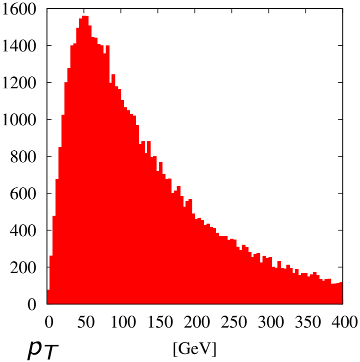
distribution of the c-jets from $\tilde{\tau}_1$ decay.

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

More p_T distributions in benchmark scenario BC4

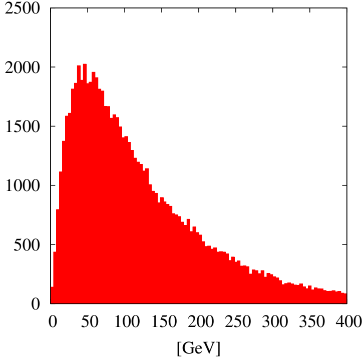


distribution of the $\tilde{\tau}_1$.

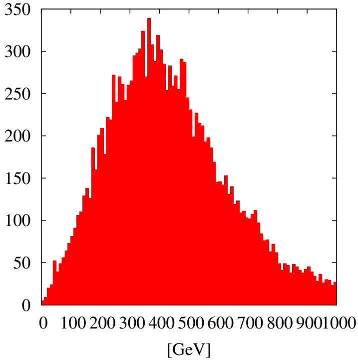


p_T distribution of the neutrinos.

More p_T distributions in benchmark scenario BC4



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



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