Phenomenology of a Selectron-LSP in mSUGRA with R-Parity Violation

Herbi Dreiner[12] Sebastian Grab[2] **Tim Stefaniak**[13]

[1]BCTP Bonn, University of Bonn

[2]SCIPP, University of California, Santa Cruz

[3]II. Physikalisches Institut, University of Göttingen

18th International Conference on Supersymmetry and Unification of Fundamental Interactions (SUSY10)

Bonn, 27^{th} August 2010

Outline

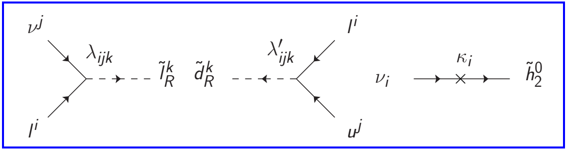
1. Supersymmetry with R-Parity Violation
2. How to get a $\tilde{e}_R$-LSP
   - RGE running of the $\tilde{e}_R$-mass
   - $\tilde{e}_R$-LSP parameter space in B_3-mSUGRA
3. Collider phenomenology of $\tilde{e}_R$-LSP models
   - Signatures and prospects at LHC
   - Mass reconstruction
4. Summary & Conclusions

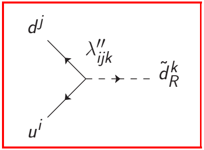
Superpotential of the SSM

Write down all renormalizable (gauge-invariant) interactions:

- $W_{P_6} = (\mathbf{Y}_E)_{ij} L_i H_1 \bar{E}_j + (\mathbf{Y}_D)_{ij} Q_i H_1 \bar{D}_j + (\mathbf{Y}_U)_{ij} Q_i H_2 \bar{U}_j + \mu H_1 H_2$
  - These terms gives mass to the quarks and leptons. But there is more:

- $W_{\not P_6} = \underbrace{\lambda_{ijk} L_i L_j \bar{E}_k + \lambda'_{ijk} L_i Q_j \bar{D}_k + \kappa_i L_i H_2}_{\text{Lepton Number Violating}} + \underbrace{\lambda''_{ijk} \bar{U}_i \bar{D}_j \bar{D}_k}_{\text{Baryon Number Violating}}$





However: LNV + BNV lead to **proton decay!**

$\Rightarrow$ We will use a model which prohibits $\bar{U}\bar{D}\bar{D}$ (Baryon Triality)

[H. Dreiner, C. Luhn, M. Thormeier, Phys.Rev.D73:075007 (2006)]

Minimal Supergravity with baryon triality (B_3-mSUGRA)

Assume simple boundary conditions at the scale $M_{GUT} = 2 \cdot 10^{16}$ GeV:

B_3-mSUGRA parameter [B. C. Allanach, A. Dedes, H. K. Dreiner, Phys.Rev.D69:115002 (2004)]

- 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_1, H_2
- $\mathrm{sgn}(\mu)$: Sign of the Higgs mixing parameter
- $\mathbf{\Lambda}$: One R-Parity violating coupling $\mathbf{\Lambda} \in \{\lambda_{ijk}, \lambda'_{ijk}\}$

Parameters at the scale $M_W = \mathcal{O}(10^2)$ GeV are obtained by B_3-RGEs.

Spectrum Calculator: *Softsusy 3.0.13*

[B.C. Allanach, M. Bernhardt, Comput.Phys.Commun.181:232-245 (2010)]

General Aspects of R-Parity Violation (RPV)

- Sparticles can be produced singly, possibly at resonance.
- Neutrino masses can be generated.
- The RGEs get additional contributions.
- The lightest supersymmetric particle (LSP) is **not** stable.
  - The LSP is **not** a dark matter (DM) candidate.
  - The LSP can be charged.

LSP candidates in B_3-mSUGRA [H. K. Dreiner, S. Grab: Phys.Lett.B 679:45-50 (2009)]

$$\tilde{\chi}_1^0,\ \tilde{e}_R^\pm,\ \tilde{\mu}_R^\pm,\ \tilde{\tau}_1^\pm,\ \tilde{\nu}_i$$

Potential other DM candidates in RPV models:

- Axino [Chun, Kim, Phys.Rev.D 60:095006 (1999)]
- Lightest U-parity particle (LUP) [Lee, Phys.Lett.B 663:255 (2008)]

How to get a $\tilde{e}_R$-LSP

RGE running of the $\tilde{e}_R$-mass

Dominant contributions to the right-handed slepton mass RGE's:

$$16\pi^2 \frac{d(m^2_{\tilde{j}_k})}{d(\ln Q)} = \underbrace{-\frac{24}{5}g_1^2|M_1|^2 + \frac{6}{5}g_1^2\mathcal{S}}_{\text{present in mSUGRA}} + \underbrace{2\lambda_{ijk}{}^2\left[2(\mathbf{m}_{\tilde{\mathbf{L}}}{}^2)_{ii} + 2(\mathbf{m}_{\tilde{\mathbf{L}}}{}^2)_{jj} + (\mathbf{m}_{\tilde{\mathbf{E}}}{}^2)_{kk}\right] + 2(\mathbf{h}_{\mathbf{E}^k})_{ij}{}^2}_{\text{additional contributions in RPV-mSUGRA}}$$

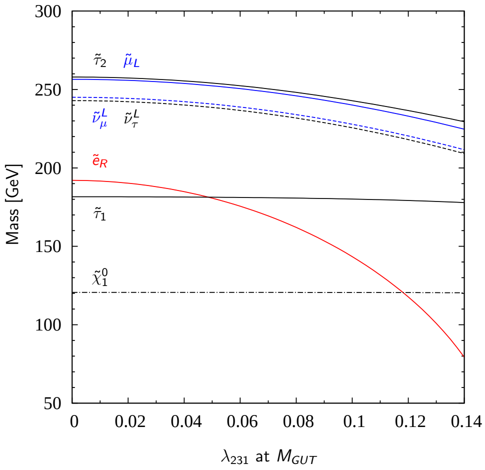
with $(\mathbf{h}_{\mathbf{E}^k})_{ij} \equiv \lambda_{ijk} \times A_0$ at M_{GUT} and $\mathcal{S} = f(\tilde{m}^2)$.

- Large λ-couplings ($\lambda_{121}, \lambda_{131}, \lambda_{231}$) change RGE running of the $\tilde{e}_R$ mass.
- Contribution of $(\mathbf{h}_{\mathbf{E}^k})_{ij}$ can dominate for large magnitude of (negative) A_0.

$\Rightarrow$ Both contributions *lower* the resulting $\tilde{e}_R$-mass at M_W!

RGE running of the $\tilde{e}_R$-mass

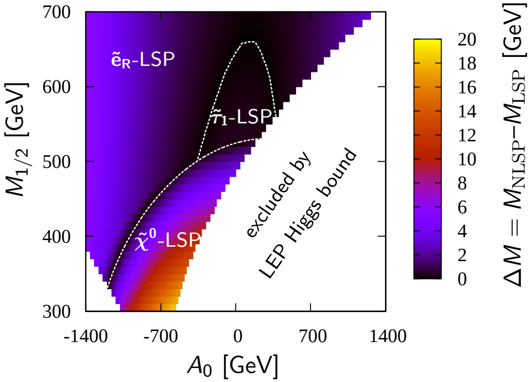
$M_0 = 150$ GeV, $M_{1/2} = 300$ GeV, $A_0 = -1000$ GeV, $\tan\beta = 5$, $\mu > 0$



In general: $\tilde{e}_R$-LSP with a RPV coupling $\lambda \gtrsim \mathcal{O}(10^{-2})$ at M_{GUT}.

$\tilde{e}_R$-LSP parameter space in B_3-mSUGRA

$M_0 = 80$ GeV, $\tan\beta = 5$, $\mu > 0$, $\lambda_{231}|_{\mathrm{GUT}} = 0.05$



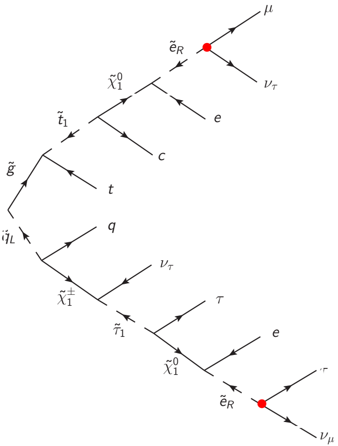
Mass hierarchies:

- $M_{\tilde{e}_R} < M_{\tilde{\chi}_1^0} < M_{\tilde{\tau}_1}$
- $M_{\tilde{e}_R} < M_{\tilde{\tau}_1} < M_{\tilde{\chi}_1^0}$

$\Rightarrow$ These lead to different phenomenology!

Signatures and prospects at LHC

Signatures at hadron colliders



Example cascade decay with $\lambda_{231} \neq 0$

- Squark and gluino production dominant (at LHC)
- Mostly cascade decays into $\tilde{e}_R$-LSP
- $\tilde{e}_R$-LSP decays via λ_{231}:
  - $\tilde{e}_R \to \mu\nu_\tau,\ \tau\nu_\mu$
- Some other RPV decays via λ_{231}:
  - $\tilde{\nu}_\tau^L \to \mu^+ e^-$
  - $\tilde{\tau}_1 \to e\nu_\mu$
- Typical signatures:

$$2e + 2\,\text{jets} + \not{E}_T + \begin{cases} 2\,\mu \\ \mu\,\tau \\ 2\,\tau \end{cases}$$

- Similar signatures for other λ_{ijk}-couplings

$\Rightarrow$ **Look for multi-leptonic events (plus jets)!**

Benchmark points

BE1:

$M_0 = 80$ GeV $\tan\beta = 5$
$M_{1/2} = 350$ GeV $\mu > 0$
$A_0 = -1200$ GeV $\lambda_{231}|_{\rm GUT} = 0.05$

$\sigma_{\rm LHC}$ @ 14 (7) TeV = 21.8 (2.6) pb

	mass [GeV]	channel	BR	channel	BR
$\tilde{e}_R^-$	140.3	$\mu^-\nu_\tau$	**50%**	$\tau^-\nu_\mu$	**50%**
$\tilde{\chi}_1^0$	142.0	$\tilde{e}_R^- e^+$	50%	$\tilde{e}_R^+ e^-$	50%
$\tilde{\tau}_1^-$	143.4	$e^-\bar{\nu}_\mu$	**100%**		
$\tilde{\mu}_R^-$	159.4	$\tilde{\chi}_1^0\mu^-$	100%		

BE2:

$M_0 = 50$ GeV $\tan\beta = 8$
$M_{1/2} = 450$ GeV $\mu > 0$
$A_0 = -1000$ GeV $\lambda_{231}|_{\rm GUT} = 0.07$

$\sigma_{\rm LHC}$ @ 14 (7) TeV = 2.9 (0.18) pb

	mass [GeV]	channel	BR	channel	BR
$\tilde{e}_R^-$	156.3	$\mu^-\nu_\tau$	**50%**	$\tau^-\nu_\mu$	**50%**
$\tilde{\tau}_1^-$	157.4	$e^-\bar{\nu}_\mu$	**100%**		
$\tilde{\mu}_R^-$	181.9	$\tilde{e}_R^-\mu^- e^+$	93%	$\tilde{\tau}_1^+\mu^-\tau^-$	4%
		$\tilde{\tau}_1^-\mu^-\tau^+$	3%		
$\tilde{\chi}_1^0$	184.9	$\tilde{e}_R^- e^+$	26%	$\tilde{e}_R^+ e^-$	26%
		$\tilde{\tau}_1^-\tau^+$	23%	$\tilde{\tau}_1^+\tau^-$	23%
		$\tilde{\mu}_R^-\mu^+$	$<1\%$	$\tilde{\mu}_R^+\mu^-$	$<1\%$

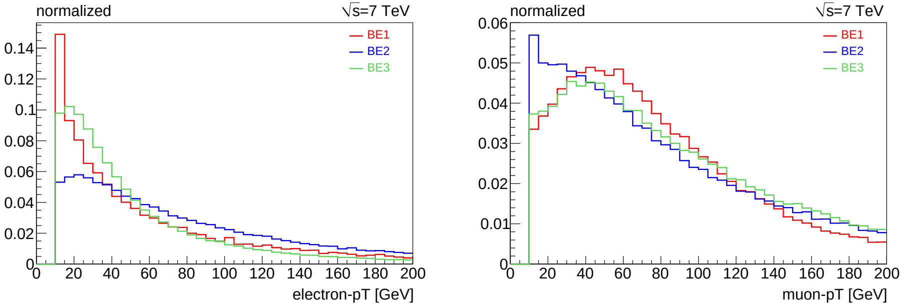
BE3:

$M_0 = 80$ GeV $\tan\beta = 4$
$M_{1/2} = 440$ GeV $\mu > 0$
$A_0 = -1200$ GeV $\lambda_{231}|_{\rm GUT} = 0.07$

$\sigma_{\rm LHC}$ @ 14 (7) TeV = 3.5 (0.24) pb

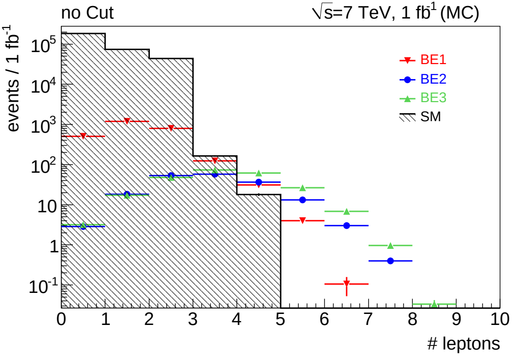
	mass [GeV]	channel	BR	channel	BR
$\tilde{e}_R^-$	154.3	$\mu^-\nu_\tau$	**50%**	$\tau^-\nu_\mu$	**50%**
$\tilde{\tau}_1^-$	179.5	$\tilde{e}_R^+\tau^- e^-$	51%	$\tilde{e}_R^+\tau^- e^-$	49%
$\tilde{\chi}_1^0$	180.4	$\tilde{e}_R^- e^+$	50%	$\tilde{e}_R^+ e^-$	50%
$\tilde{\mu}_R^-$	188.3	$\tilde{\chi}_1^0\mu^-$	100%		

Lepton-p_T-Distributions



- BE1: soft electrons due to low mass difference $|M_{\tilde{\chi}_1^0} - M_{\tilde{e}_R}| \approx 2$ GeV
- BE1: hard muons from LSP decay $\tilde{e}_R \to \mu\nu_\tau$
- BE2: hard electrons from RPV decay $\tilde{\tau}_1 \to e\bar{\nu}$
- BE2: soft muons from 3-body decay $\tilde{\mu}_R^\mp \to \tilde{e}_R^\mp e^\pm \mu^\mp$

Inclusive 3-lepton analysis



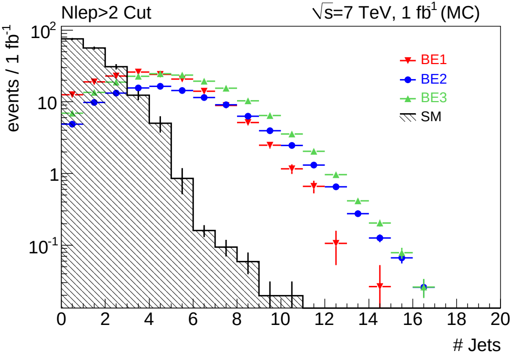
Analysis cuts:

1. $N^{lep} \geq 3$ $(leptons = e, \mu)$

lepton selection:

$p_T \geq 10$ GeV
$|\eta| \leq 2.5$
cone isolation w/ $R = 0.2$

Inclusive 3-lepton analysis



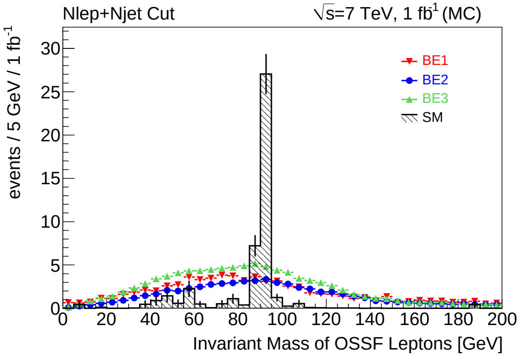
Analysis cuts:

1. $N^{lep} \geq 3$ $(leptons = e, \mu)$
2. $N^{jet} \geq 2$

jet selection: (FastJet)

$p_T \geq 10$ GeV
$|\eta| \leq 2.5$
kt algorithm w/ $R = 0.4$

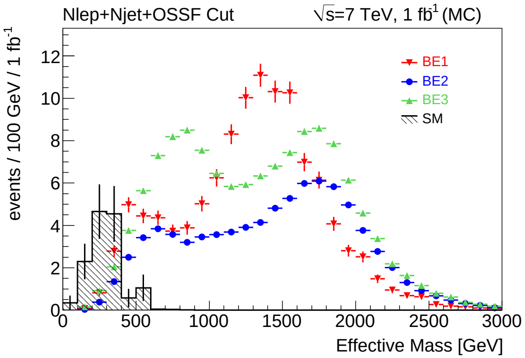
Inclusive 3-lepton analysis



Analysis cuts:

1. $N^{lep} \geq 3$ ($leptons = e, \mu$)
2. $N^{jet} \geq 2$
3. M_{OSSF} @ $M_Z \pm 10$ GeV $\rightarrow$ reject event

Inclusive 3-lepton analysis



Analysis cuts:

1. $N^{lep} \geq 3$ ($leptons = e, \mu$)
2. $N^{jet} \geq 2$
3. M_{OSSF} @ $M_Z \pm 10$ GeV → reject event
4. $M_{eff} \geq 300\,(800)$ GeV for $\sqrt{s} = 7\,(14)$ TeV

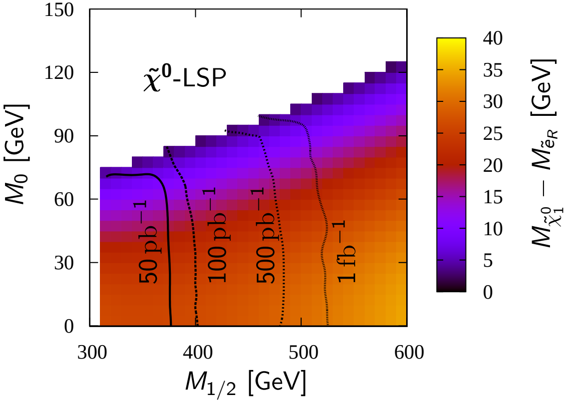
Effective Mass:

$$M_{\mathrm{eff}} = \sum_{\mathrm{all}} p_T^{\mathrm{jet}} + \sum_{\mathrm{all}} p_T^{\mathrm{lep}} + \not{E}_T$$

LHC discovery reach at $\sqrt{s} = 7$ TeV

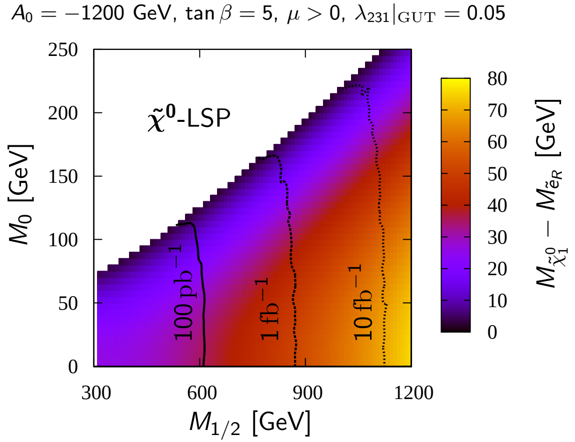
Minimal luminosity for 5σ excess:

$A_0 = -1200$ GeV, $\tan\beta = 5$, $\mu > 0$, $\lambda_{231}|_{\mathrm{GUT}} = 0.05$



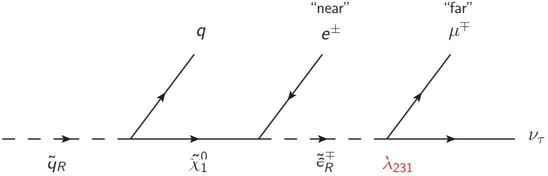
- Scenarios with $M_{\mathrm{squark}} \leq 1$ TeV can be tested with $500\,\mathrm{pb}^{-1}$.
- Smaller significances for $M_{\tilde{e}_R} \approx M_{\tilde{\chi}_1^0}$.

Minimal luminosity for 5σ excess:



- Scenarios with $M_{\mathrm{squark}} \leq 1.7$ TeV can be tested with $1\,\mathrm{fb}^{-1}$.

First steps towards a mass reconstruction



Kinematic edges:

for RPC SUSY: [B.C. Allanach, C.G. Lester, M.A. Parker, B.R. Webber, JHEP 0009:004 (2000)]

analytic expressions: [D.J. Miller, P. Osland, A.R. Raklev, JHEP 0603:034 (2006)]

- Same kinematics as in RPC SUSY cascade $\tilde{q}_L \to \tilde{\chi}_2^0 q \to \tilde{l}_R^{\pm} l^{\mp} q \to \tilde{\chi}_1^0 l^{\pm} l^{\mp} q$.
- Construct invariant masses M_{ll}, M_{llq} M_{lq}^{low}, M_{lq}^{high}.
- Fit kinematic edges and thresholds $\to$ determine $m_{\tilde{q}_R}$, $m_{\tilde{\chi}_1^0}$, $m_{\tilde{e}_R}$, $m_{invisible}$.

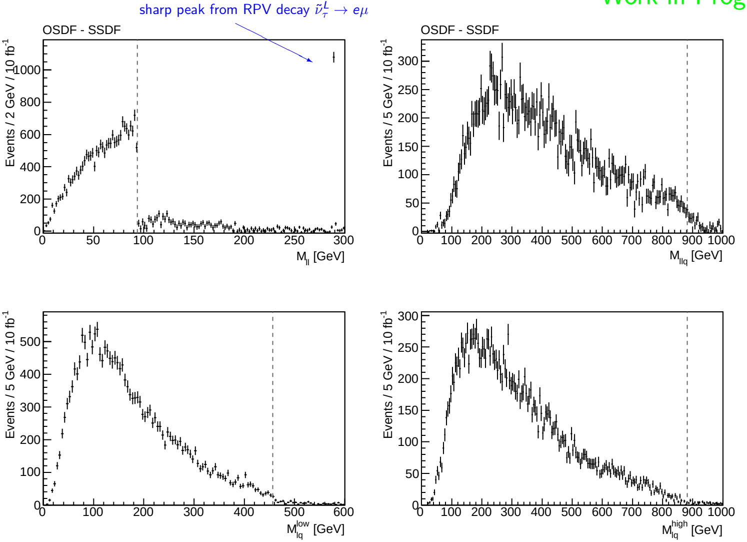
Main Differences:

- With λ_{231}: Can distinguish "near" and "far" lepton! ($\Rightarrow$ no combinatorial BG)
- Have two squark mass scales: $\tilde{t}_1$ and $\tilde{q}_R$

Work in progress!

Invariant mass distributions (BE3) at $\sqrt{s} = 14$ TeV

Work in Progress!



Summary

- SUSY with R-Parity Violation is **well motivated**!
  - Nature of the LSP is essential for collider physics
  - Additional contributions to RGEs $\rightarrow$ different LSP candidates
- The $\tilde{e}_R$ is a **viable LSP candidate** within RPV-mSUGRA model.
  - It is generated via a $LL\bar{E}$-coupling $\lambda \gtrsim \mathcal{O}(10^{-2})$.
  - We explored the possible $\tilde{e}_R$-LSP parameter space.
- $\tilde{e}_R$-LSP models at the LHC:
  - *Signatures*: We expect **multi-leptonic events** (with jets)!
  - Good prospects (with early data) at LHC with a **3-lepton analysis**!
  - **Masses reconstruction** with kinematic edges of invariant mass distributions **seems possible**. (Work in progress)

Summary

- SUSY with R-Parity Violation is **well motivated**!
  - Nature of the LSP is essential for collider physics
  - Additional contributions to RGEs $\rightarrow$ different LSP candidates
- The $\tilde{e}_R$ is a **viable LSP candidate** within RPV-mSUGRA model.
  - It is generated via a $LL\bar{E}$-coupling $\lambda \gtrsim \mathcal{O}(10^{-2})$.
  - We explored the possible $\tilde{e}_R$-LSP parameter space.
- $\tilde{e}_R$-LSP models at the LHC:
  - *Signatures*: We expect **multi-leptonic events** (with jets)!
  - Good prospects (with early data) at LHC with a **3-lepton analysis**!
  - **Masses reconstruction** with kinematic edges of invariant mass distributions **seems possible**. (Work in progress)

Thank you for your attention!

Backup Slides

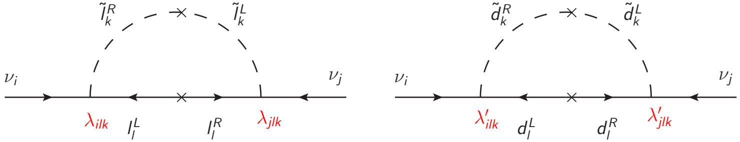
Backup: Neutrino Masses

- Recall $\kappa_i L_i H_2 \in W_{B_3}$ $\Rightarrow$ Mixing: $\nu_i \longleftrightarrow \tilde{H}^0$ (Neutralinos)

  $\Rightarrow$ one massive neutrino (at tree-level)

$$m_\nu < 1\,\mathrm{eV} \quad \text{for} \quad \kappa_i = \mathcal{O}(1\,\mathrm{MeV})$$

- Other neutrino masses generated at loop level:
  - fermion-sfermion loops (depend on RPV trilinear terms)



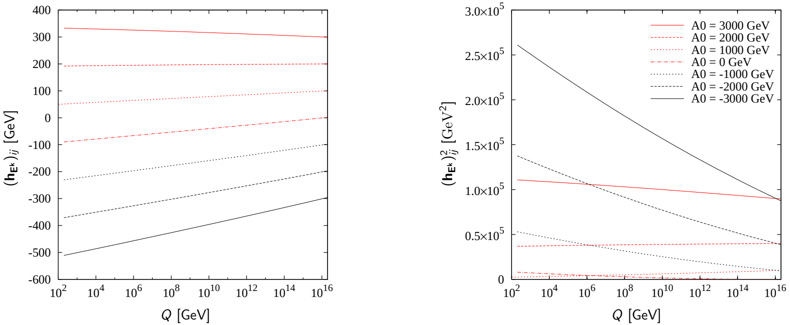
  - sneutrino-neutralino loops
    (depend on sneutrino-antisneutrino mass splitting)
    [Y. Grossman, H.E. Haber, SLAC-PUB-8173], [Y. Grossman, S. Rakshit, SLAC-PUB-10253]

Backup: RGE

A_0 dependence in running of soft-breaking trilinear scalar coupling $(\mathbf{h}_{\mathbf{E}^k})_{ij}$:

$$16\pi^2 \frac{d(\mathbf{h}_{\mathbf{E}^k})_{ij}}{d(\ln Q)} = -(\mathbf{h}_{\mathbf{E}^k})_{ij}\left[\frac{9}{5}g_1^2 + 3g_2^2\right] + \lambda_{ijk}\left[\frac{18}{5}g_1^2 M_1 + 6g_2^2 M_2\right]$$

with $(\mathbf{h}_{\mathbf{E}^k})_{ij} \equiv \lambda_{ijk} \times A_0$ at M_{GUT}.



Backup: $\tilde{e}_R$-LSP parameter space in B_3 mSUGRA

Typical B_3-mSUGRA parameter for $\tilde{e}_R$-LSP:

- small scalar mass M_0
- large gaugino mass $M_{1/2}$ (avoid $\tilde{\chi}_1^0$-LSP)
- small $\tan\beta$ (avoid $\tilde{\tau}_1$-LSP)
- large (negative) A_0 (see above)
- RPV-coupling $\lambda \gtrsim \mathcal{O}(10^{-2})$
  - 2σ bound: $\lambda_{231} \leq 0.05 \cdot \frac{M_{\tilde{e}_R}}{(100\,\mathrm{GeV})}$

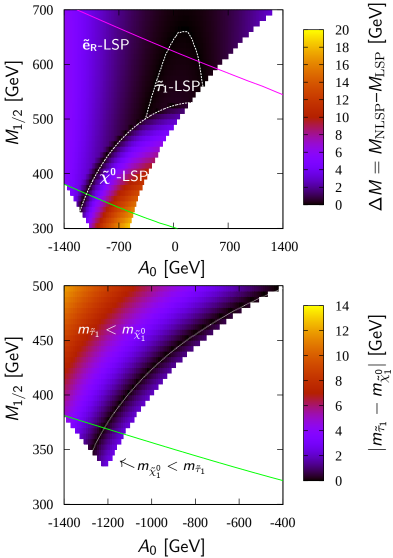
    [Y. Kao, T. Takeuchi: arXiv:0910.4980]

Two possible mass hierarchies:

- $M_{\tilde{e}_R} < M_{\tilde{\chi}_1^0} < M_{\tilde{\tau}_1}$
- $M_{\tilde{e}_R} < M_{\tilde{\tau}_1} < M_{\tilde{\chi}_1^0}$

$\Rightarrow$ these lead to different phenomenologies!

$M_0 = 80$ GeV, $\tan\beta = 5$, $\mu > 0$, $\lambda_{231}|_{\mathrm{GUT}} = 0.05$



— consistent with $\delta a_\mu^{\mathrm{SUSY}}$ within 2σ

— consistent with $\delta a_\mu^{\mathrm{SUSY}}$ within 3σ

Backup: Computing Tools

- SUSY spectrum calculated with SOFTSUSY 3.0.13

  [Comput. Phys. Commun. 143:305 (2002)]
- SUSY decays calculated with ISAJET 7.64 [arXiv:hep-ph/0312045]
  - We added the following three-body slepton decays
    - ★ $\tilde{\tau}_1^- \to \tilde{l}_R^\pm l^\mp \tau^-$
    - ★ $\tilde{l}_R^- \to \tilde{l}_R'^\pm l'^\mp l^-$
- MC event simulation:
  - Signal and Background: HERWIG 6.510

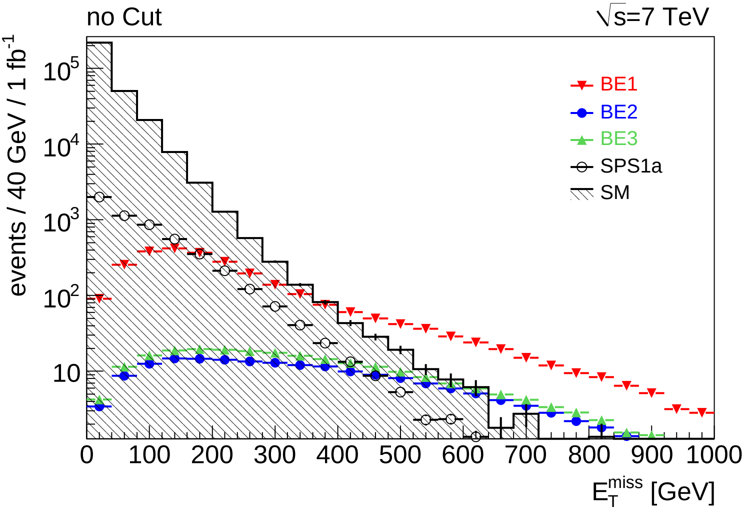
    [JHEP 0101:010 (2001)], [JHEP 0204:028 (2002)]
  - Parton level of some backgrounds: MadGraph 4.4.30 [JHEP 0709:028 (2007)]
  - Jet clustering: kt algorithm ($R = 0.4$) with FastJet 2.4.1

    http://www.lpthe.jussieu.fr/~salam/fastjet/
- Analysis: ROOT 5.26.00 [Nucl. Inst. & Meth. in Phys. Res. A 389 (1997) 81-86]

Backup: Cut flow for $\sqrt{s} = 7$ TeV and $1\,\mathrm{fb}^{-1}$

Sample	MC	no cut	$N_{lep} \geq 3$	$N_{jet} \geq 2$	M_{OSSF}	M_{eff}
BE1	HW	2643	158.0	126.4	113.5	112.6
BE2	HW	184.6	110.2	95.5	83.0	82.5
BE3	HW	237.1	169.2	148.7	129.5	128.4
tt	HW	86670	11.3	10.4	10.0	5.2
ZZ (lep)	MG+HW	29.9	16.4	2.8	0.4	0.1
WZ (lep)	MG+HW	197.4	83.5	11.1	1.0	0.1
ZZj	MG+HW	3162.3	14.8	6.0	0	0
Zj	MG+HW	59551	45.7	12.1	1.0	0
Ztt	HW	65.8	1.4	1.4	0.2	0.2
Zcc	HW	49480	0	0	0	0
Zbb	HW	44560	6.2	4.5	0	0
Wt	MG+HW	10234	0.8	0.7	0.7	0.3
Wjj	MG+HW	38219	0	0	0	0
WWj	MG+HW	10893	1.0	0.5	0	0.2
Σ bkg:		303062	181.1	49.5	13.6	6.3
$S/\sqrt{S+B}$:						
BE1		-	8.6	9.5	10.1	10.3
BE2		-	6.5	7.9	8.4	8.8
BE3		-	9.0	10.6	10.8	11.1

Backup: Missing E_T distribution



Backup: Invariant masses with kinematic edges

- Apply full 3-lepton inclusive analysis event selection
- Demand $N^{el} \geq 1$, $N^{\mu} \geq 1$
- M_{ll}:
  - Construct invariant mass distribution of OSDF leptons.
  - Subtract invariant mass distribution of SSDF leptons (reduce combinatorial background).
- M_{lq}:
  - Take only lepton combinations with $M_{ll} \leq M_{ll}^{\mathrm{edge}} + 1$ GeV (assume M_{ll} has already been fitted).
  - Construct invariant masses of one lepton with the first and the second hardest jet and take the lower value. Repeat with second lepton.
  - M_{lq}^{low} is the lower value, M_{lq}^{high} is the higher value. (Alternatively, $M_{lq}^{\mathrm{low}} = M_{eq}$ and $M_{lq}^{\mathrm{high}} = M_{\mu q}$).
- M_{llq}:
  - Construct invariant masses of OSDF leptons with the first and the second hardest jet and take the lower value.
  - Do the same for SSDF leptons and subtract it from the first distribution (reduce combinatorial background).