Exploring neutrino physics at LHC via R-parity violating SUSY

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Supersymmetry & R-parity

- SUSY = global symmetry between fermions & bosons

\[ W_{Rp} = \lambda_{ijk} \hat{L}_i \hat{L}_j \hat{E}_k^C + \chi'_{ijk} \hat{L}_i \hat{Q}_j \hat{D}_k^C + \epsilon_i \hat{L}_i \hat{H}_u + \chi''_{ijk} \hat{U}_i^C \hat{D}_j^C \hat{D}_k^C \]

- R-parity conservation hinted but *not* required by proton stability
- Phenomenological consequences:
  - LSP may be charged and/or carry color (e.g. sleptons, squarks)
  - LSP is not stable
    - potentially long LSP lifetime
    - transverse missing energy (MET) in colliders may or may not be large

With no evidence for “standard” Rp conserving SUSY seen at LHC so far, RPV becomes a very attractive alternative
Outline

• Bilinear RPV (bRPV)
  ▫ connection with neutrino physics
  ▫ bRPV phenomenology @ LHC
  ▫ constraints on bRPV from ATLAS

• μνSSM *
  ▫ v-masses & μ-problem
  ▫ signatures at LHC

• Implications for dark matter

• Summary

* With many thanks to Pradipta Ghosh
Bilinear RPV and neutrino sector

- **Model parameters**
  - three parameters $\varepsilon_i$ in bilinear terms
  - three soft SUSY-breaking parameters $B_i$ expressed through sneutrino vev’s $v_i$ or “alignment” parameters $\Lambda_i = \varepsilon_i v_d + \mu v_i$

- **Bilinear RPV introduces neutrino masses** in an intrinsically supersymmetric way
  - EW symmetry is broken by Higgs and sneutrino VEVs
  - neutrinos mix with neutralinos $\rightarrow 7 \times 7$ mixing matrix
  - a “low-scale” seesaw mechanism renders neutrinos massive
    - tree level $\rightarrow$ atmospheric scale
    - 1-loop $\rightarrow$ solar scale

- **Direct connection between model phenomenology and neutrino parameters**

\[
W_{bRPV} = W_{\text{MSSM}} + \varepsilon_i \hat{L}_i \hat{H}_u
\]
\[
V_{\text{soft}} = V_{\text{MSSM}} - B_i \varepsilon_i \tilde{L}_i H_u
\]
bRPV searches with ATLAS

- bRPV couplings can be embedded in various SUSY models
  - practically same event as in RPC
    - but LSP decays at the end of SUSY cascade
  - bRPV parameters constrained by neutrino measurements:
    \[ \Delta m_{\text{atm}}^2, \Delta m_{\text{sol}}^2, \tan^2 \theta_{\text{atm}}, \tan^2 \theta_{\text{sol}}, \ldots \]
  - if tree-level dominance is assumed
    - only remaining free parameters those of the model
    - LSP decay modes fully defined
- Moderately large MET due to copious \textit{neutrino} production
- LSP may have long lifetime
bRPV @ ATLAS: first exclusion limits set

- Exactly 1 isolated muon + 3 or 4 jets + MET
- Analysis motivated and optimised for R-parity conserving models
- Neutralino LSP decays to muon+X are preferred w.r.t. electron → muon channel
- Prompt decays tested only (cτ < 5 mm)
- No excess of events observed → exclusion limits on bRPV-mSUGRA are set

<table>
<thead>
<tr>
<th>Selection</th>
<th>Observed</th>
<th>Fitted background</th>
</tr>
</thead>
<tbody>
<tr>
<td>3JL</td>
<td>58</td>
<td>64 ± 19</td>
</tr>
<tr>
<td>3JT</td>
<td>11</td>
<td>13.9 ± 4.3</td>
</tr>
<tr>
<td>4JL</td>
<td>50</td>
<td>53 ± 16</td>
</tr>
<tr>
<td>4JT</td>
<td>7</td>
<td>6.0 ± 2.7</td>
</tr>
</tbody>
</table>

1.04 fb⁻¹ @ √s = 7 TeV

• Production of all SUSY strong and EW processes
• All LSP decays taken into account

Muon channel

PRD 85 (2012) 012006
bRPV @ ATLAS: “multijets” channel

- Exactly one isolated electron or muon + ≥ 7 jets + MET

<table>
<thead>
<tr>
<th>Number of events</th>
<th>Electron</th>
<th>Muon</th>
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<tr>
<td>Observed</td>
<td>7</td>
<td>7</td>
</tr>
<tr>
<td>Fitted bkg</td>
<td>4.3 ± 1.2</td>
<td>2.2 ± 1.1</td>
</tr>
<tr>
<td>MC exp. SM</td>
<td>6.0 ± 2.4</td>
<td>3.7 ± 2.4</td>
</tr>
</tbody>
</table>

- Observed events compatible with SM expectation within ~2σ
- Updated exclusion limits obtained for bRPV-mSUGRA

<table>
<thead>
<tr>
<th></th>
<th>p₀ value</th>
<th>Significance</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electron</td>
<td>0.123</td>
<td>1.12σ</td>
</tr>
<tr>
<td>Muon</td>
<td>0.0186</td>
<td>2.083σ</td>
</tr>
<tr>
<td>Combined</td>
<td>0.0189</td>
<td>2.077σ</td>
</tr>
</tbody>
</table>

4.7 fb⁻¹ @ √s = 7 TeV

ATLAS-CONF-2012-140
Most recent results on mSUGRA-bRPV

mSUGRA parameters chosen to be compatible with measured Higgs mass

(2 same-sign leptons OR 3 leptons) + 3 bjets + $M_{\text{eff}}$

$1 \tau, \geq 2 \tau, \tau+\ell + E_{\text{miss}}$

Ongoing work on 2 same-sign leptons + MET for natural pMSSM with bRPV

$20.3 \text{ fb}^{-1} @ \sqrt{s} = 8 \text{ TeV}$

JHEP06(2014)035

JHEP09(2014)103
mSUGRA versus mAMSB

- Similarities:
  - same $\tilde{\chi}_1^0$ LSP decay modes

- Differences: in mAMSB
  - wino-like neutralino LSP $\rightarrow$ its interactions are stronger hence easier to be produced at LHC
  - $m(\tilde{\chi}_1^0) \approx m(\tilde{\chi}_1^\pm)$ $\rightarrow$ (long-lived) $\tilde{\chi}_1^\pm$ decays dominantly through RPV couplings to $\ell\ell\ell$, $\tau\ell\ell$, $\ell bb$, $\tau bb$, ... $\rightarrow$ displaced vertices
    - wider spectrum of final states
    - enhanced cross sections
Bilinear RPV and displaced vertices

LSP lifetime may be long ($c\tau \sim 1–100$ mm)

→ search for displaced vertices
Beyond bilinear RPV: $\mu\nu$SSM

- **$\mu$-from-$\nu$ Supersymmetric Standard Model**: introduces three singlet right-handed neutrino superfields to solve the $\mu$ problem and can generate three Majorana neutrino masses through the seesaw mechanism
  - (bilinear) RPV terms are generated after EWSB
  - combines bRPV & NMSSM features

\[ W = W^{\text{MSSM}} - \epsilon_{ab}\mu \hat{H}_d^a \hat{H}_u^b + \epsilon_{ab} \left( Y_{ij} \langle H_u^0 \rangle \hat{H}_u^b \hat{L}_i^a \hat{\nu}_j^c - \lambda_i \hat{\nu}_i^c \hat{H}_d^a \hat{H}_u^b \right) + \frac{1}{3} \kappa_{ijk} \hat{\nu}_i^c \hat{\nu}_j^c \hat{\nu}_k^c \]

- **Very rich phenomenology**
  - many Higgs bosons and gauginos
  - enlarged Higgs sector can easily accommodate a 125-GeV Higgs boson
  - long neutralino lifetimes $\rightarrow$ (extremely) displaced vertices
  - multileptons / multitaus

Muñoz, López-Fogliani, Ruiz de Austri, Fidalgo, Roy, Ghosh, Dey, Escudero *et al.*
μνSSM phenomenology

- Particle spectrum
  - 2 from MSSM + 3 \( \tilde{\nu}_i^c \) + 3 \( \tilde{\nu}_L^i \) \( \rightarrow \) 8 CP-even states \( S_\alpha^0 \)
    - \( S_4^0 \) lightest doublet-like Higgs; \( m(S_4^0) \sim 125 \text{ GeV} \)
  - 1 from MSSM + 3 \( \tilde{\nu}_i^c \) + 3 \( \tilde{\nu}_L^i \) \( \rightarrow \) 7 CP-odd states \( P_\alpha^0 \)
  - 1 from MSSM + 3 \( \tilde{e}_L^i \) + 3 \( \tilde{e}_R^i \) \( \rightarrow \) 7 charged states \( S_\alpha^\pm \)
  - 4 from MSSM + 3 \( \nu_i^c \) + 3 \( \nu_L^i \) \( \rightarrow \) 10 neutralinos \( \tilde{\chi}_\alpha^0 \)
    - \( \tilde{\chi}_1^0, \tilde{\chi}_2^0, \tilde{\chi}_3^0 \) \( \rightarrow \) neutrinos
    - \( \tilde{\chi}_4^0 \) \( \rightarrow \) “true” lightest neutralino
  - 2 from MSSM + 3 \( e_i^L,R \) \( \rightarrow \) 5 charginos \( \tilde{\chi}_\alpha^\pm \)
    - \( \tilde{\chi}_1^\pm, \tilde{\chi}_2^\pm, \tilde{\chi}_3^\pm \) \( \rightarrow \) e, \( \mu, \tau \)
    - \( \tilde{\chi}_4^\pm \) \( \rightarrow \) “true” lightest chargino

- Phenomenology largely defined by: \( \lambda, \kappa, \mu, \tan\beta, M_1, A_\lambda, A_\kappa \)
  - \( \lambda \equiv \sqrt{3\lambda} \), singlet-doublet mixing parameter (universal \( \lambda_i \) assumed)
  - \( \kappa \): common \( \kappa_{ijk} \) assumed
  - \( A_\lambda, A_\kappa \): soft SUSY-breaking parameters
With small doublet-singlet mixing $\lambda_i$
$\rightarrow h_i, P_i, \tilde{\chi}_{i+3}^0$ (i = 1, 2, 3) mostly $\tilde{\nu}_i^C$

- $h_4$ plays the role of the observed Higgs with $m(h_4) \approx 125$ GeV, while $\tilde{\chi}_4^0$ is the lightest neutralino with a mass of ~10 GeV

- $h/P \rightarrow bb$ dominant over a broad range of parameters
- $2m_\tau \lesssim h_i, P_i$ mass $\lesssim 2m_b$
- Small RPV $\rightarrow$ long-lived LSP $\rightarrow$ displaced yet detectable multi-leptons at LHC
- Multiple hadronically decaying $\tau$’s provide signature with low SM bkg
  - $\tau$ identification efficiency relatively low and varies with $p_T$

- The signal: $gg \rightarrow h_4 \rightarrow \tilde{\chi}_4^0 \tilde{\chi}_4^0 \rightarrow 2 h_i/P_i + 2\nu \rightarrow 2\tau^+2\tau^-2\nu$

Ghosh, López-Fogliani, VAM, Muñoz, Ruiz de Austri, PRD88 (2013) 015009
Lepton multiplicity

- e, µ from τ decay; \( h_i/P_i \rightarrow \mu\mu \) also possible
- (4e, 4µ from τ) \( \sim 0.1\% \); 4τ\(_{\text{had}}\) \( \sim 18\% \)
- hadronic τ’s most promising; µ+e workable, too

Ghosh, López-Fogliani, VAM, Muñoz, Ruiz de Austri, PRD88 (2013) 015009
Decay length, MET, $H_T^\ell$

6 neutrinos from $\tilde{\chi}_4^0$ and tau decays $\Rightarrow$ moderately large MET

$C_T(\tilde{\chi}_4^0) \approx 30$ cm $\Rightarrow$ large number of tracks initiate within the inner tracker $\rightarrow$ displaced vertices (DV)

$\sqrt{s} = 8$ TeV
$L = 20$ fb$^{-1}$

Ghosh, López-Fogliani, VAM, Muñoz, Ruiz de Austri, PRD88 (2013) 015009

$H_T^\ell = \sum_i p_T^\ell,i$

- $H_T^\ell$ moderately high for large lepton multiplicity
- $H_T^\ell +$ MET may be used as discriminating variable
$\tilde{\chi}_4^0$ decay kinematics

- Single $h_4$ production at the LHC → low momentum in central region
- High boost leads to collimated tracks → hard to disentangle from primary vertex

- Large fraction of DVs occur within $|z_{DV}| \lesssim 2.5$ m and $\rho_{DV} \lesssim 1$ m → in the volume of ATLAS and CMS inner trackers
- Possible to detect this signal

$\sqrt{s} = 8$ TeV, $L = 20$ fb$^{-1}$

Ghosh, López-Fogliani, VAM, Muñoz, Ruiz de Austri, PRD88 (2013) 015009
Probing displaced vertices

- Low DV mass and $n_{\text{trk}}$ make delayed-tau detection challenging yet...
- ... similar analysis with (b-)jets seems promising
  - large track multiplicity
  - already considered in ATLAS for Run-I analysis (to be published soon)

\[ \sqrt{s} = 8 \text{ TeV} \]
\[ L = 20 \text{ fb}^{-1} \]
More on Higgs decays

- A 125-GeV Higgs boson, $S_4^0$, can be accommodated within a wide range of $\tan\beta$ and $\lambda$ values
- $S_4^0$ decays to $S_i^0 S_j^0$, $P_i^0 P_j^0$, $\tilde{\chi}_{i+3}^0 \tilde{\chi}_{j+3}^0$ compatible with measured Higgs signal strengths $\mu_{XX}$
  - $0.01 < \lambda < 0.1$: All $\mu_{XX}$ remain within 2σ of CMS measurements for $2.5 < \tan\beta < 3.9$
  - $0.1 < \lambda < 0.7$: only (invisible) $S_4^0$ decays to $\tilde{\chi}_{i+3}^0 \tilde{\chi}_{j+3}^0$ remain viable in whole range of $\lambda$
  - $\lambda > 0.1$: for decays to pair of binos, all $\mu_{XX}$ are within 2σ for $2.4 < \tan\beta < 3.8$
- The final states are dominated by a combination of prompt or displaced leptons, taus, jets, photons plus MET due to neutrinos

Ghosh, López-Fogliani, VAM, Muñoz, Ruiz de Austri, JHEP 11(2014)102
Unusual Z and W decays

- New Z/W decays predicted leading to final states with **prompt** (P) or **displaced** (D) particles
- Partial widths respect current Z and W total and invisible widths
- Signatures with *taus* and *b-jets* preferred
- \( W^\pm \rightarrow \tilde{\chi}^\pm_i \tilde{\chi}_{j+3}^0 \)
  - \( \text{BR} < O(10^{-13}) \rightarrow \text{e.g. } 0.05 \text{ events with } \sqrt{s} = 14 \text{ TeV with } 3000 \text{ fb}^{-1} \)
  - very difficult at LHC; maybe possible at LC-MegaW and TLEP-OkuW
- \( Z^0 \rightarrow \tilde{\chi}_{i+3}^0 \tilde{\chi}_{i+3}^0 \) and \( Z^0 \rightarrow S_i^0 P_j^0 \)
  - \( \text{BR} \sim O(10^{-5}) \rightarrow \text{detection may be possible at HL-LHC, LC-GigaZ, TLEP-TeraZ} \)

\[ \begin{array}{ll}
\text{Z-decay} & \text{W}^\pm\text{-decay} \\
2x^D 2\bar{x}^D + E_T (\tilde{\chi}_{i+3}^0 \tilde{\chi}_{j+3}^0) & 1\ell^P + x^D \bar{x}^D + E_T (\tilde{\chi}_i^\pm \tilde{\chi}_{j+3}^0) \\
2x^P 2\bar{x}^P (S_i^0 P_j^0) & \\
\end{array} \]

\( x : e, \mu, \tau, \gamma, q \)
\( P : \text{prompt (short-lived)} \)
\( D : \text{delayed (long-lived)} \)

Prompt +Displaced yet detectable multi-leptons/taus/jets/photons (x) at LHC
What about dark matter?

- Gravitino LSP with cosmologically-long lifetime
  - signal: monochromatic gamma-rays
  - constrained by
    - $\nu$-oscillations
    - DM relic density $\Omega_\chi h^2$
    - $\gamma$-ray line searches
- If lightest neutralino is the NLSP
  \[ \tilde{\chi}_1^0 \rightarrow h^0 \nu_i, \quad \tilde{\chi}_1^0 \rightarrow W^\pm l^\mp_i, \quad \tilde{\chi}_1^0 \rightarrow \gamma \nu_i, \quad \tilde{\chi}_1^0 \rightarrow Z^0 \nu_i. \]
- (Long-lived) neutralino can also decay to 3 fermions
Monochromatic photons & (b)RPV SUSY

- Photon emission lines have been observed in the past
  - 130-GeV $\gamma$-line in Fermi-LAT data from galactic centre (2012)
  - 3.5 keV X-ray line observed in galaxy clusters (2014)
- Both can be explained by RPV SUSY
  - decaying axino with bRPV [Endo et al, PLB 721 (2013) 111; Choi & Seto, PLB 735 (2014) 92; Park$^2$, Kong, PLB 733 (2014) 217]
  - also... gravitino, bino, or hidden sector photino in RPV [Kolda & Unwin, PRD 90 (2014) 023535; Bomark & Roszkowski, PRD 90 (2014) 011701; Liew, JCAP 1405 (2014) 044]
Summary & outlook

- **R-parity violating supersymmetry** may reproduce correctly neutrino physics
- Enriched mass spectrum and R-parity breaking decays lead to **novel signals at colliders**
  - very few possibilities have been explored so far
- Searches for **displaced objects** at the LHC
  - less SM background
  - more sophisticated searches expected in near future
- **Looking forward to Run II probing higher energies**
Thank you for your attention!
Backup
Bilinear RPV phenomenology

- bRPV parameters constrained by neutrino measurements: $\Delta m_{\text{atm}}^2$, $\Delta m_{\text{sol}}^2$, $\tan^2\theta_{\text{atm}}$, $\tan^2\theta_{\text{sol}}$, ...
- If tree-level dominance is assumed...

Underlying SUSY model parameters (MSSM, mSUGRA, AMSB, ...) + Fitting to neutrino physics data = bRPV parameters determined unambiguously

\[ \Rightarrow \] Phenomenology is completely defined for specific SUSY-model point

- Spararticle mass spectra
- Spararticle decay modes
- LSP lifetime