How Difficult Is It To Conserve R-parity In The $B-L$-Extended MSSM?

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What can we say about supersymmetry and R-parity?

What question can we reasonably answer?

If we find SUSY, will we find R-parity?

- theoretically justified or just phenomenologically necessary?

$B - L$ symmetry $\Rightarrow$ R-parity

- $(-1)^{(3B+L+2s)} = (-1)^{(3(B-L)+2s)}$ for integer $2L$

Minimal $U(1)_{B-L}$ gauge extension?

- extra photon with $B - L$ coupling to SM

or

- sneutrino VEVs $\Rightarrow$ R-parity-violation...

The BLSSM

The Minimal R-parity-conserving $U(1)_{B-L}$-gauged Supersymmetric Standard Model

(Khalil, Masiero, arXiv:0710.3525, PLB; Perez, Spinner, arXiv:1005.4930, PRD)

- MSSM + $U(1)_{B-L} + 3 \times \hat{\nu}_R + \hat{\eta} + \hat{\bar{\eta}}$

$\hat{\eta}, \hat{\bar{\eta}}$:

- SM gauge singlets, $B - L = \pm 2 \times \nu_R \Rightarrow$ bileptons
- VEVs break $U(1)_{B-L} \Rightarrow Z'$ vector boson

$$\begin{aligned} \mathcal{W} &= Y_u^{ij} \hat{U}_i \hat{Q}_j \hat{H}_u - Y_d^{ij} \hat{D}_i \hat{Q}_j \hat{H}_d - Y_e^{ij} \hat{E}_i \hat{L}_j \hat{H}_d + \mu \hat{H}_u \hat{H}_d \\ &\quad + Y_\nu^{ij} \hat{L}_i \hat{H}_u \hat{\nu}_j - \mu' \hat{\eta} \hat{\bar{\eta}} + Y_x^{ij} \hat{\nu}_i \hat{\eta} \hat{\nu}_j \end{aligned}$$

$\eta, \bar{\eta}$ VEVs $\Rightarrow$ Majorana ν_R! (preserves R-parity: $\Delta L = 2$)

$M_0, M_{1/2}, A_0, \tan\beta, \tan\beta', m_{Z'}$, $\text{sgn}(\mu, \mu')$ constraints possible

Phenomenology of the BLSSM

- Massive Z' at LHC? Covered in talk by Manuel Krauß
  (Krauß, BOL, Porod, Staub, arXiv:1206.3513, PRD)
- Gauge kinetic mixing: large effects despite tiny Z-Z' mixing
  (BOL, Porod, Staub, arXiv:1112.4600, JHEP)
- Dark matter: $\tilde{\nu}$ (CP-even/-odd), $\tilde{Z}'/\tilde{\eta}/\tilde{\bar{\eta}} - \tilde{\chi}_1^0$
  (Basso, BOL, Porod, Staub, arXiv:1207.0507, JHEP)
- Less tuning for $m_h = 125$ GeV, large $h \to \gamma\gamma$
  (Basso, Staub, arXiv:1210:7946)

$\tilde{\nu}$ VEVs? Camargo, BOL, Porod, Staub arXiv:1212.????
(compared with Perez, Spinner, arXiv:1005.4930, PRD)

Why is it difficult to say whether the model conserves R-parity or not?

Even coupled polynomial equations are hard

Consider $V = x^4 - ax^2 + y^4 - by^2 + cxy$:

- $\partial V/\partial y = 0$ is a simple cubic in y
- $y = A + B\sqrt[3]{\left(C + x + D\sqrt[2]{[E + Fx + x^2]}\right)}$
- ...

So how about a set of ten complex tadpole equations in ten complex scalars?

The usual approach

- We know that we want $m_Z = 91$ GeV
- Tadpoles can be easy if VEVs are input and some Lagrangian parameters are output

$\Rightarrow$ engineer extremum at $m_Z = 91$ GeV

- Only know at best that it's a *local* minimum
- There could easily be deeper other minima
- Finding the others to check = back to the old problem

Are there methods to find all the minima?

Algorithms

Gröbner bases:

- Decomposition of system using fancy algebra
- Has been used to investigate NMSSM
  (Maniatis, von Manteuffel, Nachtmann, arXiv:hep-ph/0608314, EJPC)
- Computationally expensive, especially in terms of RAM

Homotopy continuation:

- Has been used to investigate SM with up to 5 extra scalars
  (Maniatis, Mehta, arXiv:1203.0409, EPJ+)
- Used public program `HOM4PS2`: fast enough for BLSSM
  - 20 minutes for tadpole equation system allowing 10 VEVs: $H_d, H_u, \eta, \bar{\eta}, 3 \times \tilde{\nu}_L, 3 \times \tilde{\nu}_R$

Homotopy continuation

Homotopy continuation:

- Gradual deformation of simple system of equations into target system
- Simple system chosen with n known roots, where n is maximum number of roots of target system
- Positions of roots updated iteratively from known values from last step

How often are there deeper other minima, and what are they like?

Result of scans

We performed two kinds of scan:

Parameter	Common to both
$M_{1/2}$/ GeV	100 – 1000
M_0/ GeV	100 – 3000
A_0/ GeV	-3000 – 3000
$\tan\beta$	3 – 45
$m_{Z'}$/ GeV	1500 – 3000
$\tan\beta'$	1.0 – 1.5

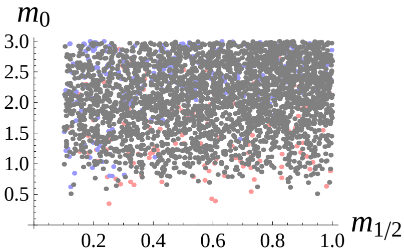
Fixed $Y_\nu^{ij} = 10^{-5}\delta^{ij}$

Parameter	Democratic	Hierarchical
Y_x^{11}	0.05–0.6	fixed 10^{-3}
Y_x^{22}	0.05–0.6	fixed 10^{-2}
Y_x^{33}	0.05–0.6	0.1 – 0.6

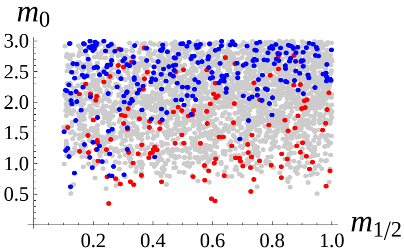
- ~3000 democratic scan points, 87% R-parity-conservation
- ~2000 hierarchical scan points, 45% R-parity-conservation

Is there a dependence on M_0 or $M_{1/2}$?

(masses in TeV)

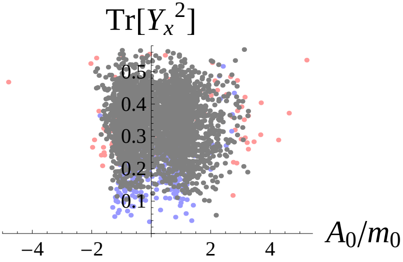


R-parity-conserving (grey)

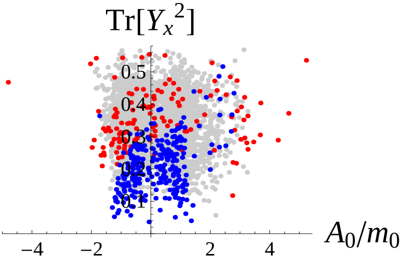


R-parity-violating (red) / $U(1)_{B-L}$ unbroken (blue)

Is there a dependence on the Yukawa couplings?



R-parity-conserving (grey)

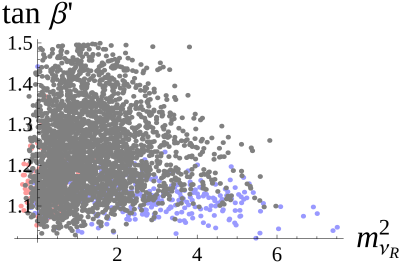


R-parity-violating (red) / $U(1)_{B-L}$ unbroken (blue)

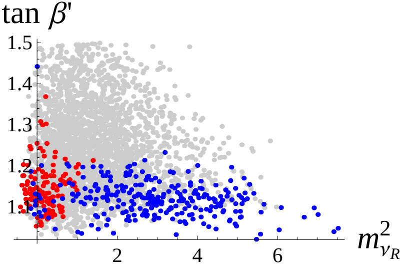
Trilinear bilepton-sneutrino terms can overcome sneutrino mass-squared terms.

Is the soft SUSY-breaking sneutrino mass-squared critical?

(masses-squared in TeV^2)



R-parity-conserving (grey)



R-parity-violating (red) / $U(1)_{B-L}$ unbroken (blue)

There are both R-parity-conserving *and* R-parity-violating parameters points for *both* signs of soft SUSY-breaking sneutrino mass-squared! (There are obvious trends, though.)

Things that I don't have time to get into

- We have checked full one-loop potential
  - some R-parity natures change, but not many
  - occasional problem: unbroken $U(1)_{B-L}$ due to breaking terms small compared to loop corrections
- We have estimated tunneling times
  - typically TeV-scale energy barriers, energy depth differences $\Rightarrow$ roughly tunneling times of (factors of $16\pi^2$ *etc.*)/TeV $\ll$ age of Universe

Summary and conclusions

Summary and outlook

Minimally extending MSSM by $U(1)_{B-L}$ has many interesting consequences:

- Theoretically motivated.
- Rich phenomenology.
- Natural explanation for R-parity, *but...*
- Existence of R-parity-conserving *local* minimum not sufficient to claim that parameter point has R-parity-conserving vacuum!
- There are parameter regions where R-parity is safe, regions where R-parity is rare.
- Process being automated in new version of `SARAH`– coming soon!

Well done, you survived to the end!

Thank you for your attention!

Backup slides

Scan results in detail

Categorization	Hierarchical scan		Democratic scan	
total	2302		3158	
	tree level	one-loop level	tree level	one-loop level
“RPC”	1981	1039	3008	2754
“RPV”	321	358	150	131
“unbroken”	0	898	0	267

Number of parameter points in the various categories. All of the parameter points from the hierarchical scan categorized as “unbroken” broke $SU(2)_L$ without breaking $U(1)_{B-L}$ or R-parity, while 250 of the 267 parameter points from the democratic scan did so, with the remaining 17 breaking $U(1)_{B-L}$ without breaking $SU(2)_L$. Not all parameter points that are “RPC” at the one-loop level were “RPC” at tree level, and likewise for the “RPV” category.

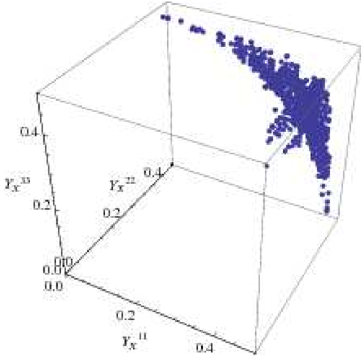
Agreement with literature

Filiviez Perez, Spinner, arXiv:1005.4930, PRD:

- more than one large $Y_x \Rightarrow m^2_\eta, m^2_{\bar{\eta}}$ driven negative faster than $m^2_{\tilde{\nu}}$

We agree:

- less difficult to find calculable points in democratic scan



Filiviez Perez, Spinner, arXiv:1005.4930, PRD:

- $m_{\tilde{\nu}}^2 > 0 = R$-parity-conservation
- $m_{\tilde{\nu}}^2 < 0 = R$-parity-violation
- Y_x hierarchical $\Rightarrow R$-parity-violation
- Y_x not hierarchical $\Rightarrow R$-parity-conservation

We disagree:

- $\tilde{\nu}$ masses-squared combination of $m_{\tilde{\nu}}^2 + \mu' \times$ bilepton VEV
- trilinear terms can overwhelm positive $m_{\tilde{\nu}}^2$
- Y_x not only parameters that drive $U(1)_{B-L}$-breaking

Loop corrections

- $V^{1\mathrm{L}} = V^{\mathrm{TL}} + \mathrm{STr}[m_i^4(\log(m_i^2/Q^2) - 3/2)]/(64\pi^2)$
- Different schemes checked

Tunneling times

- $\Gamma/$ volume $= Ae^{-B/\hbar}(1+\mathcal{O}(\hbar))$
- A is solitonic solution, should be $\sim$ energy scale of potential
- $B \sim$ ([surface tension]/[energy density difference]$)^3$