Higgs, neutrino sector, EDM and ϵ_K in a spontaneously CP and R-parity breaking supersymmetric model

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Spontaneous CP Violation

- SM CP violation is not sufficient to cause the observed baryon asymmetry of the universe. SUSY introduces a lot of new sources for CP violation.
- However SUSY phases easily lead to large EDMs.
- An elegant solution is to require CP invariance and break it via complex VEVs, $\langle \phi \rangle = \varphi e^{i\theta}$.
- Needs something beyond the MSSM (e.g. NMSSM + loop corrections).

R-parity

R-parity is defined as $(-1)^{2s+3(B-L)}$,
SM particles have parity 1 and SUSY particles have parity -1.

- Conservation of R-parity is imposed to prevent fast proton decay, which may happen if both B and L are broken. Breaking either on its own is OK, in particular $|\Delta L| = 2$ Majorana masses for ν can be accommodated without breaking R-parity.
- Experiments constrain tree level R-parity violation to be small.
- Both can be achieved by making R-parity a spontaneously broken symmetry.

Spontaneous R-parity Violation

- Needs nonzero VEV of scalar carrying lepton number.
- Using $\tilde{\nu}_L$ results in a Goldstone state (the Majoron) which has been excluded.
- Using $\tilde{\nu}_R$ allows for $h_\nu NLH_2 \rightarrow h_\nu \langle N \rangle LH_2$, which introduces bilinear R-parity violation.
- Inclusion of the right handed neutrinos N leads to the well known see-saw mechanism for ν_L masses.
- The presence of two separate mass generation mechanisms, bilinear R-parity violation and the left-right see-saw, makes it easy to accommodate the experimental bounds on ν_L masses.

Constructing Our Model

- Impose $\mathbf{Z}_3$ "like" R-symmetry to forbid explicit R-parity breaking and generate soft singlet tadpole.
- $h_\nu NLH_2$ for spontaneous R-parity violation. This introduces spontaneous lepton number violation $\longrightarrow$ Goldstone state.
- $\lambda_N N^2 S$ for explicitly breaking lepton number. R-parity is still OK since $|\Delta L| = 2$.
- $\lambda SH_1 H_2$ to generate $\mu H_1 H_2$ from the MSSM, with $\mu = \lambda\langle S\rangle$.
- $\kappa/3! S^3$ to avoid spontaneously breaking the Peccei-Quinn $U(1)$ symmetry introduced by the previous terms.

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The Superpotential and Soft Terms

$$
\begin{aligned}
W &= h_U Q H_2 U + h_D H_1 Q D + h_E H_1 L E + h_N L H_2 N \\
&\quad + \lambda_H H_1 H_2 S + \frac{\lambda_S}{3!} S^3 + \frac{\lambda_N}{2} N^2 S
\end{aligned}
$$

$$
\begin{aligned}
V_{soft} &= A_U \tilde{Q} \tilde{H}_2 \tilde{U} + A_D \tilde{H}_1 \tilde{Q} \tilde{D} + A_E \tilde{H}_1 \tilde{L} \tilde{E} + A_N \tilde{L} \tilde{H}_2 \tilde{N} \\
&\quad + A_H \tilde{H}_1 \tilde{H}_2 \tilde{S} + \frac{A_S}{3!} \tilde{S}^3 + \frac{A_{NS}}{2} \tilde{N}^2 \tilde{S} + \xi^3 \tilde{S} + M_\phi^2 \tilde{\Phi}^* \tilde{\Phi}
\end{aligned}
$$

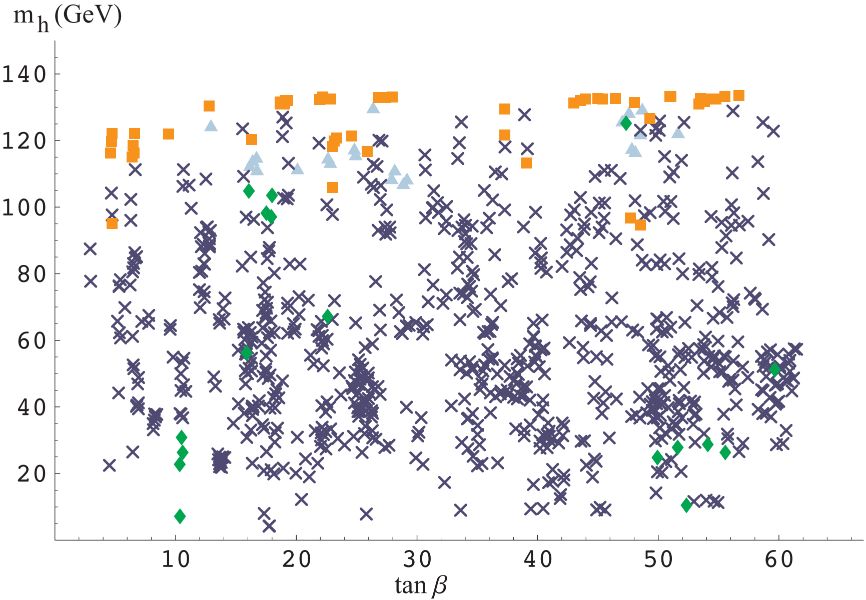
- Our model adds 51 parameters to the MSSM.
- Explicit R-parity breaking adds 48 parameters to the MSSM.

The Minimum of the Scalar Potential

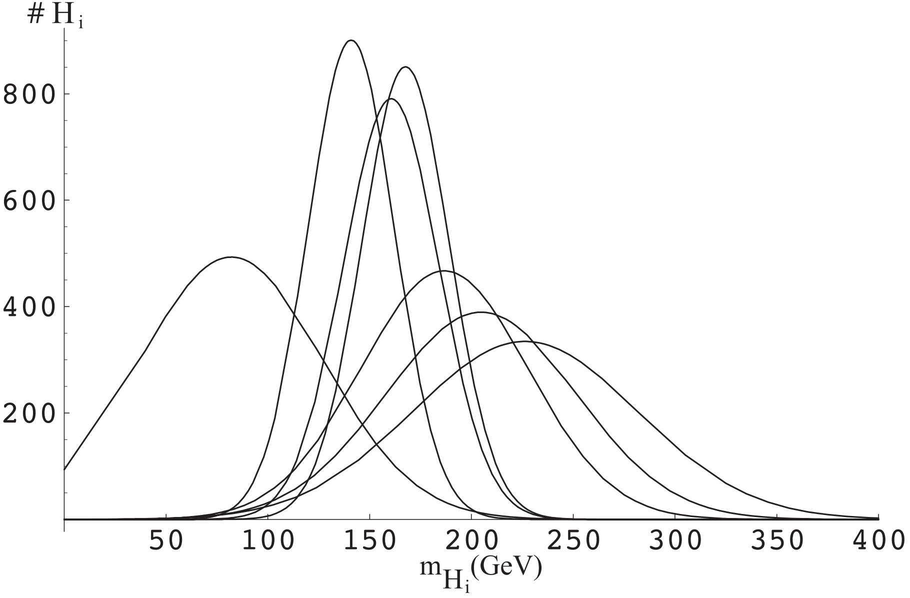
$$\left.\frac{\partial V_s}{\partial \varphi}\right|_{\tilde{\phi}=\langle\tilde{\phi}\rangle} = 0 \qquad \left.\frac{\partial V_s}{\partial \theta}\right|_{\tilde{\phi}=\langle\tilde{\phi}\rangle} = 0 \qquad M^2_{s\ ij} = \left.\frac{\partial^2 V_s}{\partial \tilde{\phi}_i \partial \tilde{\phi}_j}\right|_{\tilde{\phi}=\langle\tilde{\phi}\rangle}$$

- We use the extremum conditions to solve for the soft mass parameters and a subset of A-parameters ($A_,\ A_S,\ A^i_{NS},\ A^{i,3}_N$)
- Due to R-parity violation sneutrinos mix with the higgs sector and M^2_s is an 18×18 matrix.
- Numerical diagonalisation requires great precision.
- Sneutrino mixing can produce light Higgs states.
- Reduced ZZh and Zhh couplings relax the experimental bound of $m_H > 114$ GeV.

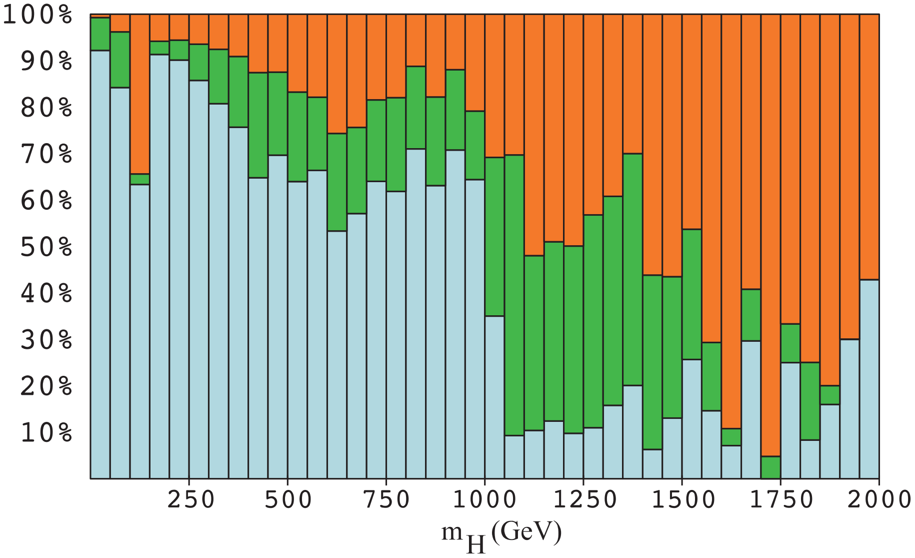
Lightest Neutral Higgs



The Next Few



Component Distribution



Two See-Saws

- Due to Rp violation gauginos, sneutrinos and higgsinos all mix together and in a field basis of $(\nu_{L_i}, \nu_R, \tilde{S}, \tilde{H}_1^0, \tilde{H}_2^0, \lambda_0, \lambda_3)$, M_χ is an 11×11 matrix.

$$\left(\begin{array}{c|cccccc}
\mathbf{0}_{3\times3} & \mathbf{h}_N^{3\times3}\langle H_2^0\rangle & \mathbf{0}_{3\times1} & \mathbf{0}_{3\times1} & h_N^{ij}\langle \tilde{N}_j^*\rangle & -\frac{g_1}{\sqrt{2}}\langle \tilde{\nu}_{L_i}^*\rangle & \frac{g_2}{\sqrt{2}}\langle \tilde{\nu}_{L_i}^*\rangle \\
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\end{array}\right)$$

- It has the general form

$$M_\nu = \begin{pmatrix} 0 & m_D \\ m_D & M_R \end{pmatrix}, \quad m_\nu = -m_D M_R^{-1} m_D^T.$$

- One can see that $M_R \sim M_{SUSY}$. Thus very small Yukawas h_N and small $\tilde{\nu}_L$ VEVs are needed to make m_D small enough for the see-saw mechanism to work properly.

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Neutrino Observables

- We diagonalise M_{χ^0} numerically. The diagonalising matrix $\mathcal{N}$, with $\mathcal{N}^* M_{\chi^0} \mathcal{N}^{-1} = \mathrm{diag}(m_{\chi^0_i}, m_{\nu_j})$, has the following general form

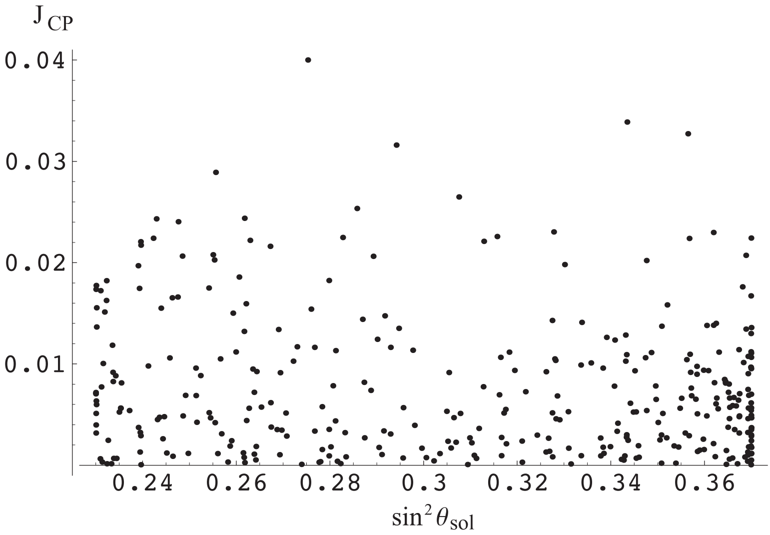
$$\mathcal{N} = \begin{pmatrix} \zeta & N_\chi \\ V_\nu^T & \bar{\zeta}^T \end{pmatrix}.$$

- From V_ν we can then extract the neutrino mixing angles and the Jarlskog invariant of the Neutrino sector.

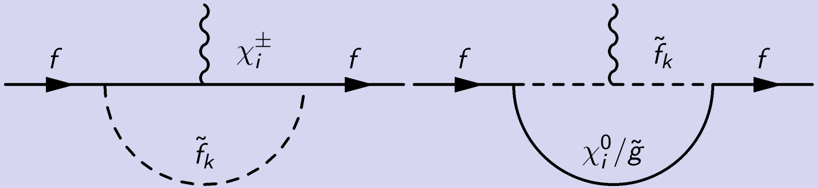
$$\sin\theta_{13} = \left|V_\nu^{13}\right| \qquad \tan\theta_{12} = \left|\frac{V_\nu^{12}}{V_\nu^{11}}\right| \qquad \tan\theta_{23} = \left|\frac{V_\nu^{23}}{V_\nu^{33}}\right|$$

$$J_{CP} = |Im(V_\nu^{*21} V_\nu^{*12} V_\nu^{11} V_\nu^{22})|$$

Jarlskog Invariant



EDMs



- The general $q\tilde{q}\chi$ interaction in the above diagrams is given by

$$-\mathcal{L}_{int} = \sum_{ik} \bar{\Psi}_f \left(K_{ik} \frac{1-\gamma_5}{2} + L_{ik} \frac{1+\gamma_5}{2} \right) \Psi_i \tilde{\phi}_k + \mathrm{h.c.}$$

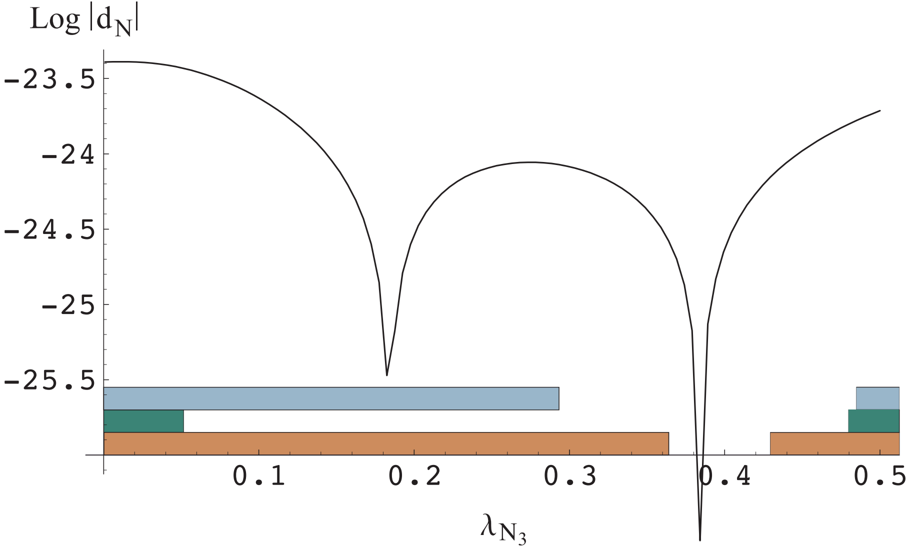
Cancellation and Suppression

- The contribution of these loops to the EDM of a fermion f is

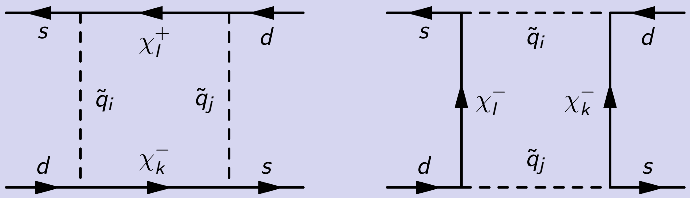
$$d_f = \sum_{ik} \frac{m_i}{(4\pi)^2 m_k^2} \mathrm{Im}(K_{ik} L_{ik}^*) \left[Q_i A\left(\frac{m_i^2}{m_k^2}\right) + Q_k B\left(\frac{m_i^2}{m_k^2}\right) \right].$$

- Tiny CP violating phases $\rightarrow\ \mathrm{Im}(K_{ik} L_{ik}^*) \simeq 0$.
- Heavy scalars, $m_k >> M_{SUSY}$.
- Cancellation between gluino, chargino and neutralino loop contributions.

Parameter Scan



ϵ_K



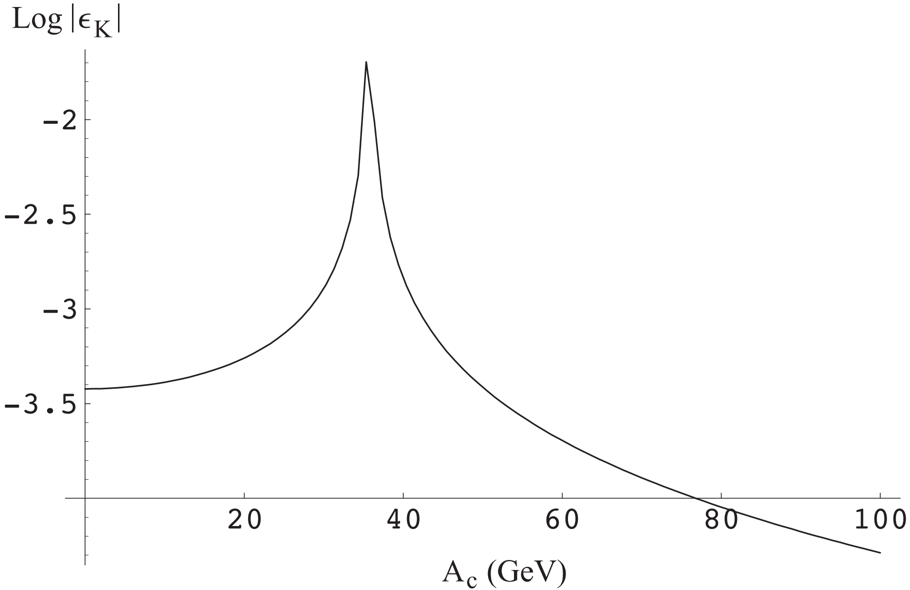
- The quark-squark-chargino interaction is

$$-\mathcal{L}_{q\tilde{q}\chi} = \bar{q}_i \left(V^L_{ijk} \gamma_L + V^R_{ijk} \gamma_R \right) \tilde{q}_j \chi_k + \text{h.c.}.$$

- $\epsilon_K = \mathrm{Im}(\mathcal{M}_{K\bar{K}} / \Delta m_K)$ with

$$\begin{aligned}\mathcal{M}_{K\bar{K}} &= \frac{i}{(2\pi)^4} \frac{1}{16\pi^2} \sum_{ijkl} \left\{ \frac{2}{m_i^2} \mathbf{I}^1_{ijkl} \left[W^1_{ijkl} \frac{2}{3} \mathbf{V}_2 + W^2_{ijkl} \left(\frac{1}{3} \mathbf{V}_1 - \frac{1}{2} \mathbf{V}_2 \right) \right] \right.\\ &+ \left. \frac{M_l M_k}{m_i}^4 \mathbf{I}^2_{ijkl} \left[W^3_{ijkl} \frac{5}{12} \mathbf{V}_1 + W^4_{ijkl} \left(-\frac{1}{2} \mathbf{V}_1 + \frac{1}{12} \mathbf{V}_2 \right) \right] \right\}.\end{aligned}$$

Parameter Scan



Conlusions

- We have a model with spontaneous CP and R-parity breaking that successfully produces a viable neutrino sector.
- Our model predicts reduced ZZh/Zhh couplings and several neutral Higgses within the reach of the LHC.
- We predict measurable CP violation in the leptonic sector with a Jarskog invariant below 0.04.
- We have shown that constraints for EDMs and ϵ_K can be easily achieved.