Implications of spontaneous R-parity or CP violation in NMSSM with right-handed neutrinos

Katri Huitu

Based on:

KH, H. Waltari, 1405.5330;
KH, J. Laamanen, L. Leinonen, S.K.Rai, T. Rüppell, JHEP 1211 (2012) 129

Outline:

Motivation

Spontaneously R-parity violating NMSSM

Higgs sector and decays in SRPV NMSSM

Spontaneously CP violating NMSSM

Dark matter in SCPV NMSSM

Conclusions

Motivation

A Higgs boson has been found → scalars exist → supersymmetry?

1) neutrino masses,
2) dark matter,
3) amount of matter in the universe,
4) gravity, …

➡ physics beyond the SM is needed.

1) Neutrino masses by
- seesaw mechanism
- a small violation of R-parity, $(-1)^{3(B-L+2s)}$

If the R-parity breaking is spontaneous, it will appear only in the lepton sector and there is no problem with proton stability.

2) Supersymmetry has good candidates for DM:
lightest neutralino, sneutrino, gravitino…
Existence of dark matter suggests that R-parity is conserved, or dark matter is gravitino, or something quite different.

3) In supersymmetric models CP violation is typically too large, when soft susy breaking parameters can contain explicitly CP violating phases. For Lagrangian invariant under CP, the sources of CP violation can be phases in VEVs.
- EDMs can agree with experiments if there are cancellations, or phases are small, or masses are large.

With spontaneous breakings only a few new parameters, which appear in many observables constraining the model.

Spontaneous breaking of R-parity or CP not possible at tree-level in MSSM.

→ extensions needed

The most minimal extension is NMSSM.

One can achieve spontaneous R-parity or CP violation or both at tree-level in a model with NMSSM+$N_{R,l}$;
Extension with right-handed neutrinos can give masses also to left-handed neutrinos.

Higgs mass in NMSSM at tree-level reduces need for large radiative corrections:

$$m_h^2 \leq m_Z^2 \cos^2 2\beta + \lambda^2 \mathrm{v}^2 \sin^2 2\beta$$

NMSSM+*N*

Superpotential (R. Kitano, K.Y. Oda, PRD 61 (2000) 113001):

Assume only 3rd gen — Assume only one *N*

$$W = \epsilon_{\alpha\beta}\left(Y_E^{ij}\hat{H}_1^\alpha \hat{L}_i^\beta \hat{E}_j + Y_D^{ij}\hat{H}_1^\alpha \hat{Q}_i^\beta \hat{D}_j + Y_U^{ij}\hat{Q}_i^\alpha \hat{H}_2^\beta \hat{U}_j + Y_N^i \hat{L}_i^\alpha \hat{H}_2^\beta \hat{N} + \lambda \hat{S}\hat{H}_2^\alpha \hat{H}_1^\beta\right) + \lambda_N \hat{N}\hat{N}\hat{S} + \frac{\kappa}{3}\hat{S}\hat{S}\hat{S},$$

If $\langle \tilde{N} \rangle \neq 0$, similar than in bilinear RPV — Gives μ-term

Not all the parameters "natural":

$$\lambda \hat{S}\hat{H}_2\hat{H}_1 \rightarrow \text{ gives } \mu\text{-term} \rightarrow \text{if } \lambda \approx 1 \Rightarrow \langle S \rangle \approx \text{ew-scale}$$

$$\lambda_N \hat{N}\hat{N}\hat{S} \Rightarrow M_N \approx \lambda_N \langle S \rangle \rightarrow \text{if } \lambda_N \approx 1 \Rightarrow M_N \approx \langle S \rangle \approx \text{ew-scale}$$

$$Y_N \hat{L}\hat{H}_2\hat{N} \Rightarrow m_D \approx Y_N \cdot \text{ew-scale}$$

$$m_{\nu_L} \approx -m_D M_N^{-1} m_D^T = Y_N^2 \frac{(\text{ew-scale})^2}{M_N} \Rightarrow Y_N \approx 10^{-6} \text{ for } m_{\nu_L} \approx 0.1\,\text{eV}$$

The Z_3 symmetry of the superpotential could lead to cosmological domain wall problem, when symmetry is spontaneously broken

→ We include in the soft terms an S-tadpole:

add non-Z_3 symmetric nonrenormalizable operators, generate radiatively $\xi^3 S$ term, with ξ at the ew-scale, thus explicitly breaking the Z_3 symmetry .

C. Panagiotakopoulos, K. Tamvakis, PLB 446 (1999) 224.

The soft breaking terms for scalars then become:

$$V_{\rm soft} = \Big\{\epsilon_{\alpha\beta}\Big(A_E^{ij}Y_E^{ij}H_1^\alpha\widetilde{L}_i^\beta\widetilde{E}_j + A_D^{ij}Y_D^{ij}H_1^\alpha\widetilde{Q}_i^\beta\widetilde{D}_j + A_U^{ij}Y_U^{ij}\widetilde{Q}_i^\alpha H_2^\beta\widetilde{U}_j + A_N^iY_N^i\widetilde{L}_i^\alpha H_2^\beta\widetilde{N}$$
$$+ A_\lambda\lambda SH_2^\alpha H_1^\beta\Big) + A_{\lambda_N}\lambda_N\widetilde{N}\widetilde{N}S + \frac{A_\kappa\kappa}{3}SSS + \xi^3 S\Big\} + \text{h.c.}$$
$$+ M_{\Phi,ij}^2\Phi_i^\dagger\Phi_j + M_{\Theta,ij}^2\Theta_i\Theta_j^* + m_{H_1}^2H_1^\dagger H_1 + m_{H_2}^2H_2^\dagger H_2 + m_S^2SS^*, \qquad (\text{:}$$

where $\Phi = \{\widetilde{L},\widetilde{Q}\}, \Theta = \{\widetilde{E},\widetilde{N},\widetilde{U},\widetilde{D}\}$

$$M_{ij}^2 = M^2\delta_{ij}, M_U = M_D = M_Q, M_E = M_L$$

R-parity violating NMSSM+N

KH, H. Waltari, 1405.5330

Sneutrino develops a VEV: $\langle \tilde{N} \rangle = v_N \neq 0$

⇒ also left-handed sneutrino develops a VEV

Consider 5x5 mass matrix $\left(H_1, H_2, \tilde{L}, \tilde{N}, S\right)$

From potential using minimization conditions:

$$\Rightarrow \frac{1}{2}\lambda_N^2 v_N^2 + \left(\kappa\lambda_N + 2\lambda_N^2\right)v_S^2 + \frac{1}{2}\lambda\ \lambda_N v^2 \sin 2\beta + \frac{1}{\sqrt{2}} A_{\lambda_N} v_S > 0$$

valid for large part of the parameter space (even for A<0);

From mass matrix:

$Det\left(M^2\right)$, $Det\left(M^2 - m_Z^2\right)$ cannot both be positive.

⇒ $m_{h_1} = m_Z$ can be achieved with large $\tan\beta$;

$m_{h_1} > m_Z$ leads to R-parity conserving vacuum

Ranges for scanning:

Parameter	Minimum value	Maximum value
$\tan\beta$	1	30
λ_N	0.1	0.8
κ	0.05	0.25
λ	0.1	0.6
Y_N	10^{-8}	10^{-6}
A	-6000	-1000
ξ	-3500	-500
v_S	600	2500
v_N	50	4000
v_ν	10^{-6}	$5\cdot 10^{-4}$
$m_{\tilde{Q}_L,\tilde{t}_R,\tilde{b}_R}$	700	1700

Fixed:
M_1=300 GeV
M_2=600 GeV
M_3=1.5 TeV

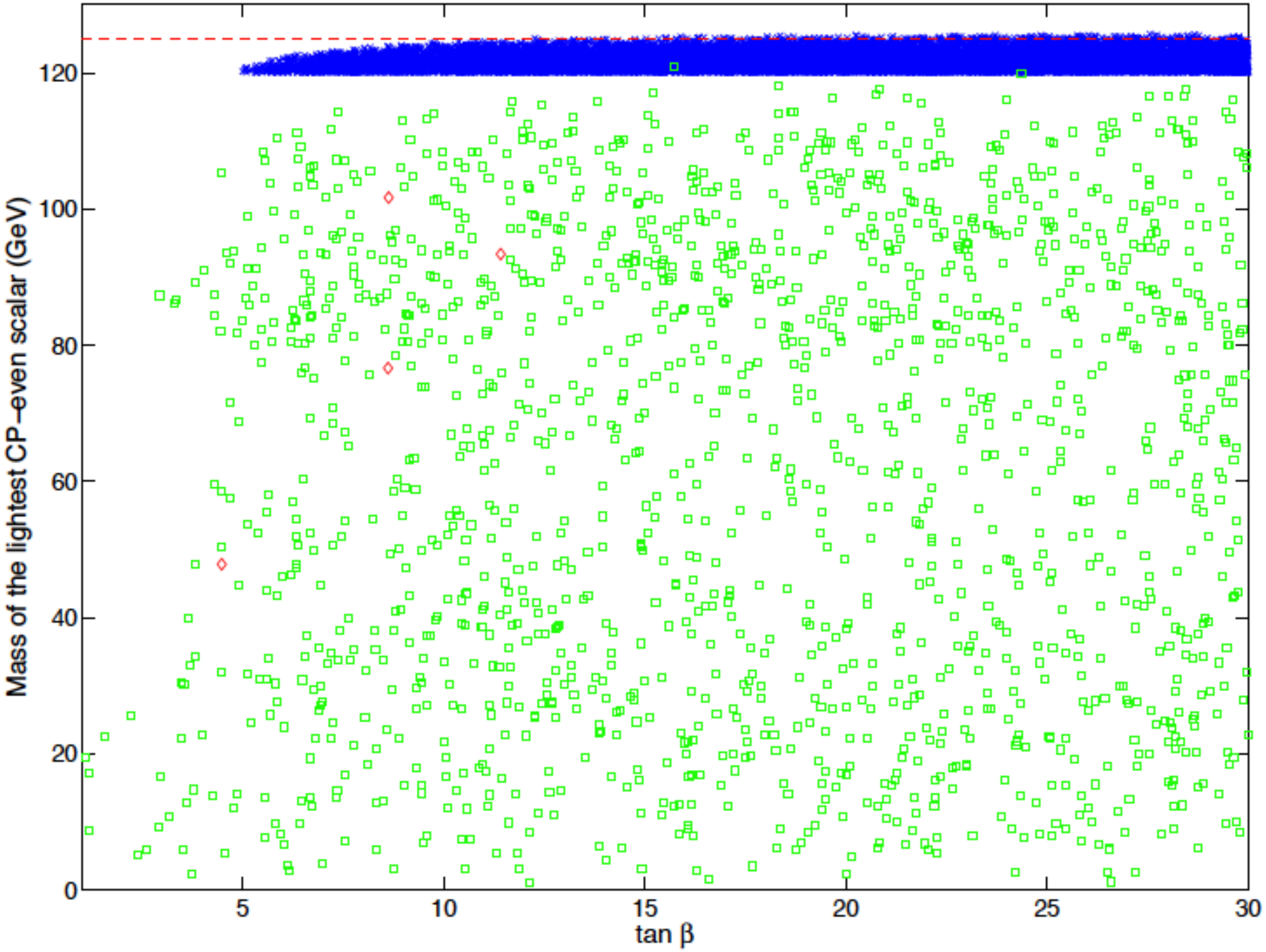
Total number of points	500 000
Mu-term generated ($v_S \neq 0$)	484 397
EW symmetry broken (v_u, $v_d \neq 0$)	457 508
R-parity broken (v_N, $v_\nu \neq 0$)	438 802
Neutrino mass within limits	90 303
A CP-even scalar within LHC mass limits and LEP limits for the lightest Higgs	13 750

$0.05\ \text{eV} < m_\nu < 0.5\ \text{eV}$
$m_H = 125$ GeV,
limits on ZZH_1 coupling

The lightest CP-even neutral scalar

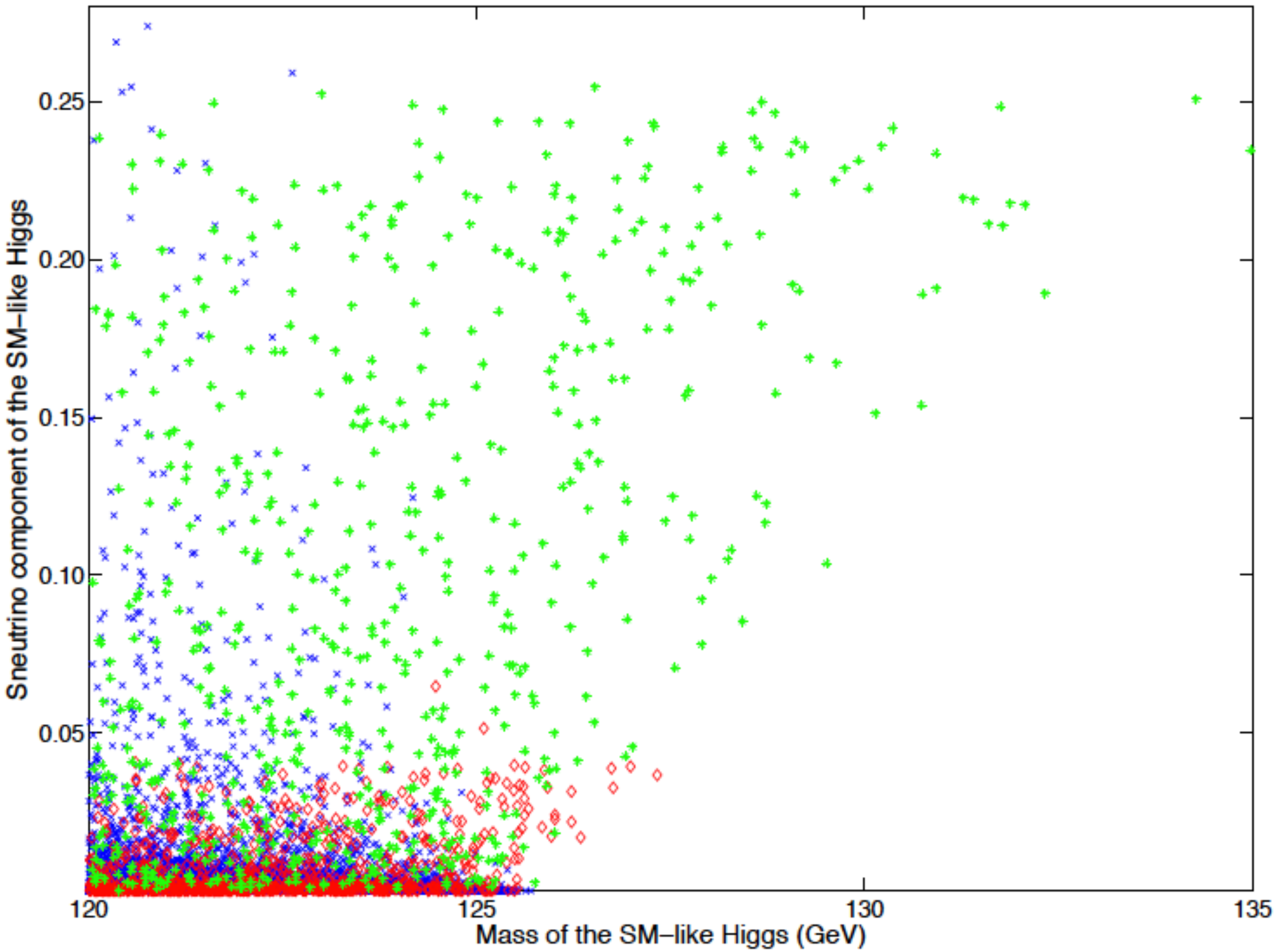
Blue: $h_1=H_2$,
Red: $h_1=H_1$,
Green: h_1=right-handed sneutrino,
Magenta: $h_1=S$;

Vacuum ok,
120-130 GeV H ok,
ZZh_1 ok,
Neutrino mass ok



With large sneutrino-doublet mixing easy to achieve 125 GeV.

Blue: lightest scalar SM-like Higgs,
Red: lightest scalar lighter than 80 GeV,
Green: lightest scalar between 80-120 GeV



Constraints: flavour violation possible

Lepton-chargino mixing suppressed by Y_N or $\frac{\langle \tilde{\nu}_L \rangle}{v}$

$BR(\mu \to e\gamma) << 5.7 \times 10^{-13}$ =current limit

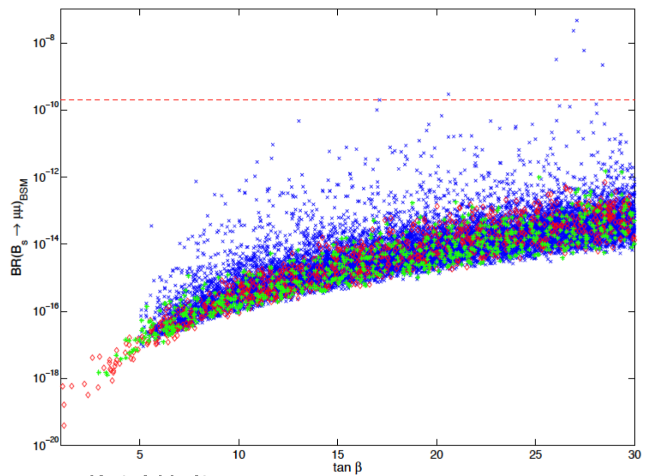
$\ell / \tilde{W}$ mixing

$$BR(\mu \to eee) = 3 \cdot 10^{-30} \times \left(\frac{\langle \tilde{\nu}_L \rangle}{1\ \text{MeV}} \right)^2 \left(\frac{\sin\gamma}{10^{-4}} \right)^2 \times \left(\frac{100\ \text{GeV}}{m_{\tilde{\nu}}} \right)^4 \tan^4 \beta$$

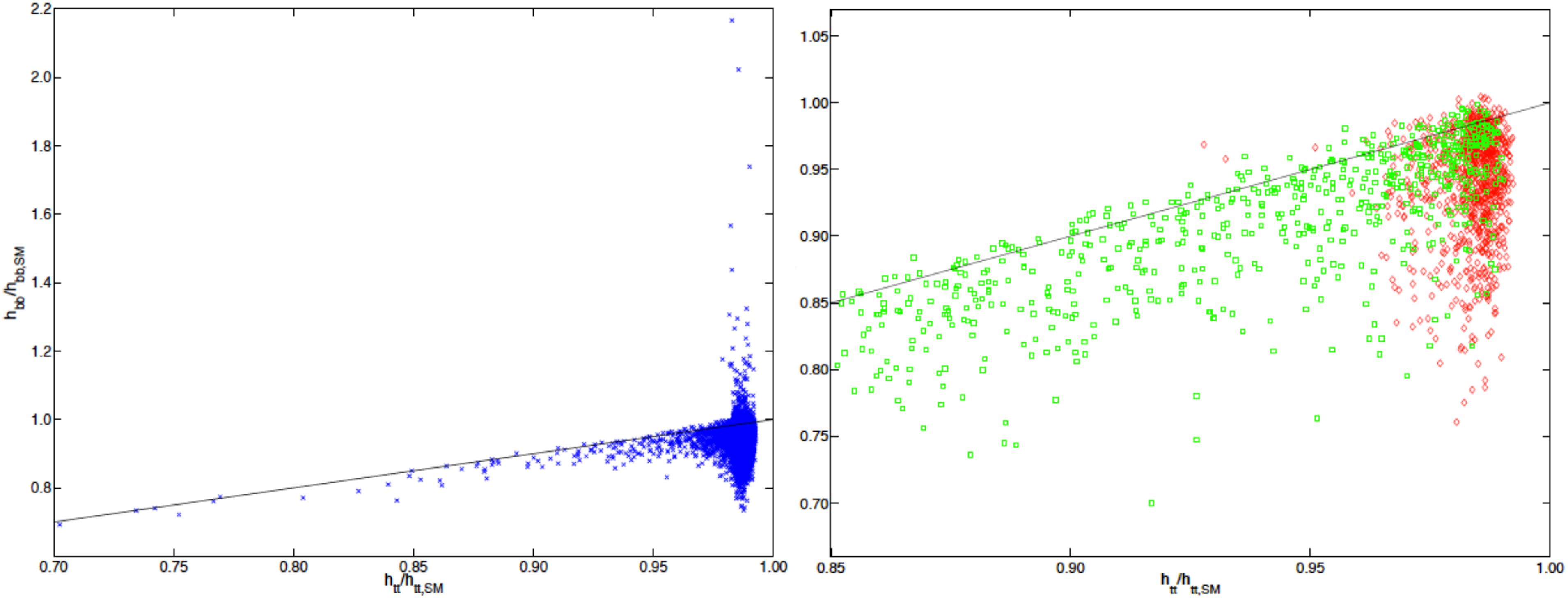
$<< 10^{-16}$ = current plan

$BR(b \to s\gamma)$; $m_{H^+} > 1$ TeV

$BR(B_s \to \mu^+ \mu^-)$: →



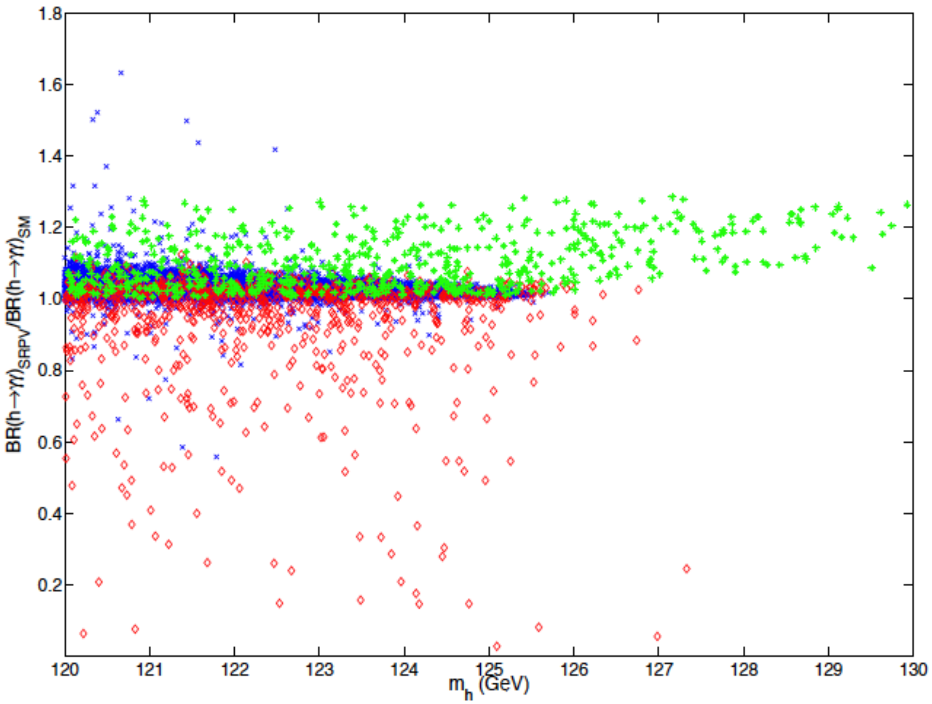
$$\frac{Y_{bb}}{Y_{bb,SM}} \text{ vs. } \frac{Y_{tt}}{Y_{tt,SM}}$$

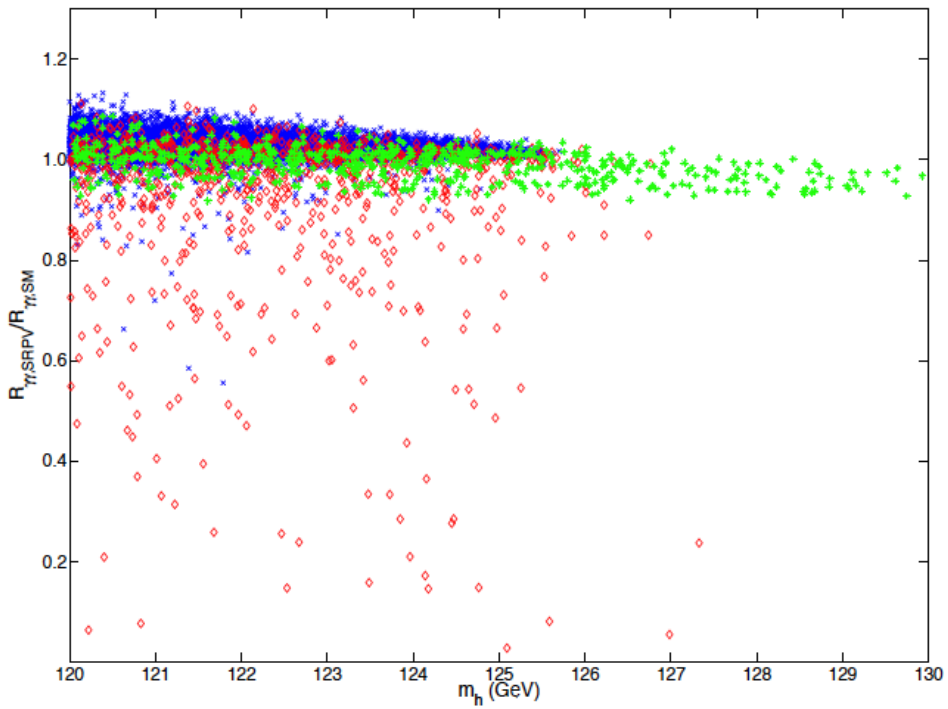


If the lightest scalar SM-like Higgs, large enhancement in b-coupling possible.
Red: lightest scalar lighter than 80 GeV,
Green: lightest scalar between 80-120 GeV

BR(h→γγ)

Cross section x BR(h→γγ)





Other effects affecting the rate:

-Higgs can have a large sneutrino component, which decays via H+ loop – effect always less than 1%

-Higgs can decay to two light sneutrinos, which decay to photons – tan β > 3 if sneutrino mass < $m_h/2$

CP violating NMSSM+*N*

KH, J. Laamanen, L. Leinonen, S.K.Rai, T. Rüppell, JHEP 1211 (2012) 129

$$W = \epsilon_{\alpha\beta}\left(Y_E^{ij}\hat{H}_1^\alpha\hat{L}_i^\beta\hat{E}_j + Y_D^{ij}\hat{H}_1^\alpha\hat{Q}_i^\beta\hat{D}_j + Y_U^{ij}\hat{Q}_i^\alpha\hat{H}_2^\beta\hat{U}_j + Y_N^i\hat{L}_i^\alpha\hat{H}_2^\beta\hat{N} + \lambda\hat{S}\hat{H}_2^\alpha\hat{H}_1^\beta\right) + \lambda_N\hat{N}\hat{N}\hat{S} + \frac{\kappa}{3}\hat{S}\hat{S}\hat{S},$$

SCPV due to the VEVs (assume R_P conservation):

$$\langle H_2\rangle = \begin{pmatrix} 0 \\ v_2 e^{i\delta_2}\end{pmatrix}, \qquad \langle S\rangle = v_S e^{i\delta_S}$$

→ Minimization conditions: solve for $m_{H_1}, m_{H_2}, m_S, A_\lambda, A_\kappa$

Even and odd parts in the 6x6 Higgs mass matrix mix.

New conditions from the minimization of the potential with respect to the phases → non-continuous effects.

Note 1: in spontaneous breaking parameter count remains the same: minimizing the potential with respect to the phases, one can solve for the same amount of soft parameters.

Note 2: only certain combinations of phases are physical: individual phases can be large. We assume here small physical phases.

Note 3: there is always a light (pseudo)scalar in the spectrum when phases are small Davies, Froggatt, Usai, PLB 517 (2001) 375-382.

Dark matter candidates:

neutralinos: phases in the mass matrix compared to NMSSM

right-handed sneutrino: phases + even and odd parts mix in the mass matrix

Constraints

Possible because of CP violation

Check: all the scalar masses positive.

LEP constraints for the scalar couplings to Z: h_iZZ, h_ih_jZ

m_h=125 GeV and other collider mass constraints

Dark matter (10% theoretical uncertainty added):

$$0.0941 < \Omega_{CDM} h^2 < 0.1311$$

Electric dipole moment: $d_e < 1.05 \cdot 10^{-27}$ ecm (ok for small phases)

B-meson decays: $BR(B \to X_S \gamma)$, $BR(B^+ \to \tau^+ \nu_\tau)$, $BR(B_S \to \mu^+ \mu^-)$
(for small phases spectrum almost same as in CP concerving case, except for the light h_S)

Parameters and tools

Fixed parameters:

M_1	300 GeV
M_2	600 GeV
M_3	1800 GeV
M_Q	1000 GeV
A_t	1500 GeV
A_b	1500 GeV
A_τ	-2500 GeV
Y_{N_i}	10^{-6}
A_{N_i}	0 GeV

Parameter values in scanning:

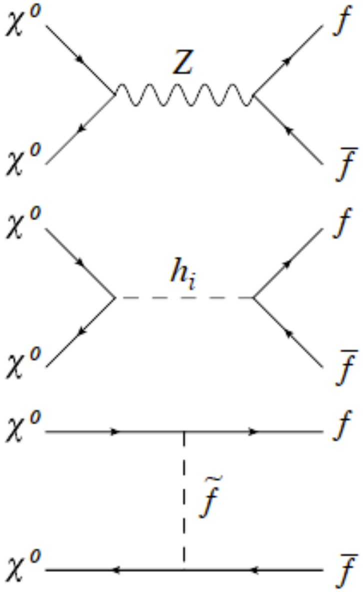
$\tan\beta$	2–50
μ	0–500 GeV
λ	0–0.8
κ	0–0.8
A_λ	-1000 GeV–1000 GeV
A_κ	-1000 GeV–1000 GeV
v_S	μ/λ
λ_N	0–0.8
A_{λ_N}	-1000 GeV–1000 GeV
M_N	0–500 GeV
$M_{L,E}$	0–500 GeV
δ_S	$0 - 2\pi^*$
δ_2	$0 - 2\pi^*$
ξ	-1000 GeV–1000 GeV

* $[0, 0.3]$, $[\pi - 0.3, \pi + 0.1]$, $[2\pi - 0.1, 2\pi]$

Tools:
LanHEP: model files for micrOMEGAs
micrOMEGAs: relic density, direct detection
NMSSMtools: *B*-constraints
Mathematica code: EDMs, mass matrices.

Neutralino dark matter

Difference to the MSSM neutralino DM mainly from singlino component.
CPV important because of possible new annihilation channels due to h_S.

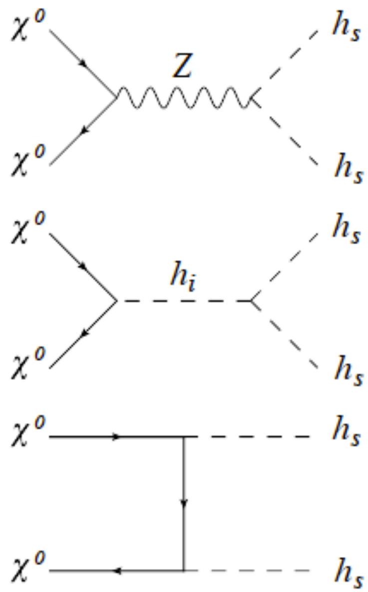


$\stackrel{d}{\sim} C^2$
$\stackrel{s}{\sim} 0$

$\stackrel{d}{\sim} C \cdot (Y_f, \lambda_N \epsilon_{sd})$
$\stackrel{s}{\sim} \kappa \cdot (\lambda_N, Y_f \epsilon_{sd})$

$\stackrel{d}{\sim} (C, Y_f)^2$
$\stackrel{s}{\sim} \lambda_N^2$

Singlet $\lambda_N{}^2$ channels open only if N_R lighter than neutralino



$\stackrel{d}{\sim} C^2 \epsilon_{sd}^2$
$\stackrel{s}{\sim} 0$

$\stackrel{d}{\sim} C \epsilon_{sd} \kappa$
$\stackrel{s}{\sim} \kappa^2$

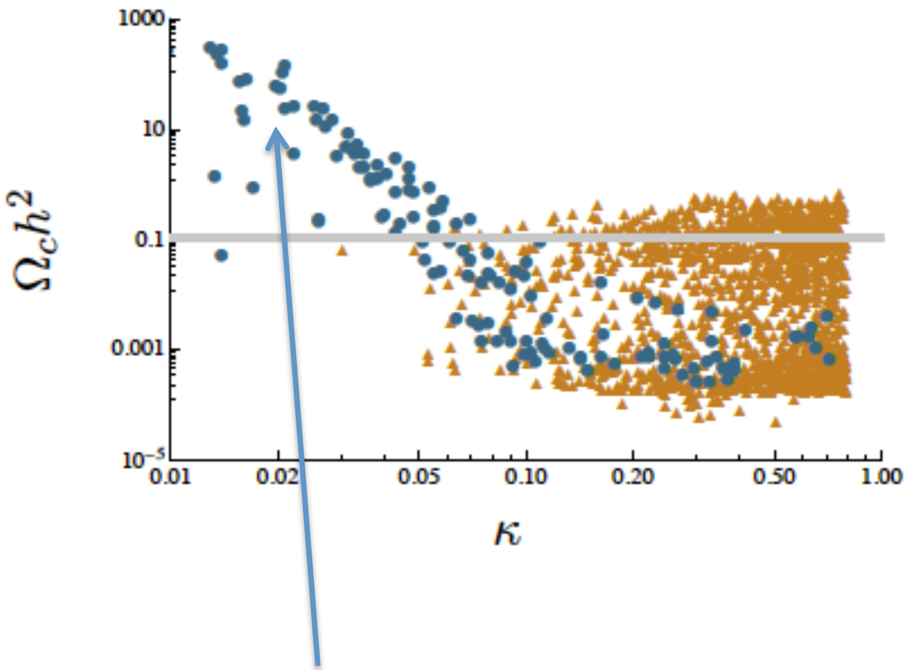
$\stackrel{d}{\sim} (\lambda, C\epsilon_{sd})^2$
$\stackrel{s}{\sim} (\kappa, \lambda\epsilon_{sd})^2$

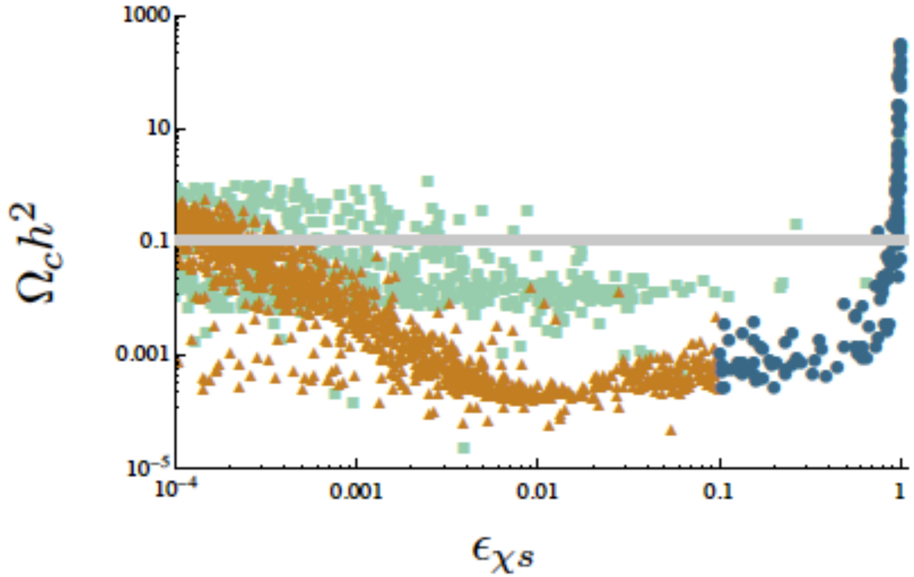
Singlet κ^2 unsuppressed.
Small κ → LSP mostly singlino, κ suppresses annihilation → large RD

$\varepsilon_{sd} \in [10^{-5}, 0.1]$
$\Rightarrow$
Dominant doublet channels C^2,

$$C = \frac{e}{2 s_W c_W} \approx 0.37$$

Neutralino dark matter: singlino a new component, new annihilation channels due to h_S.





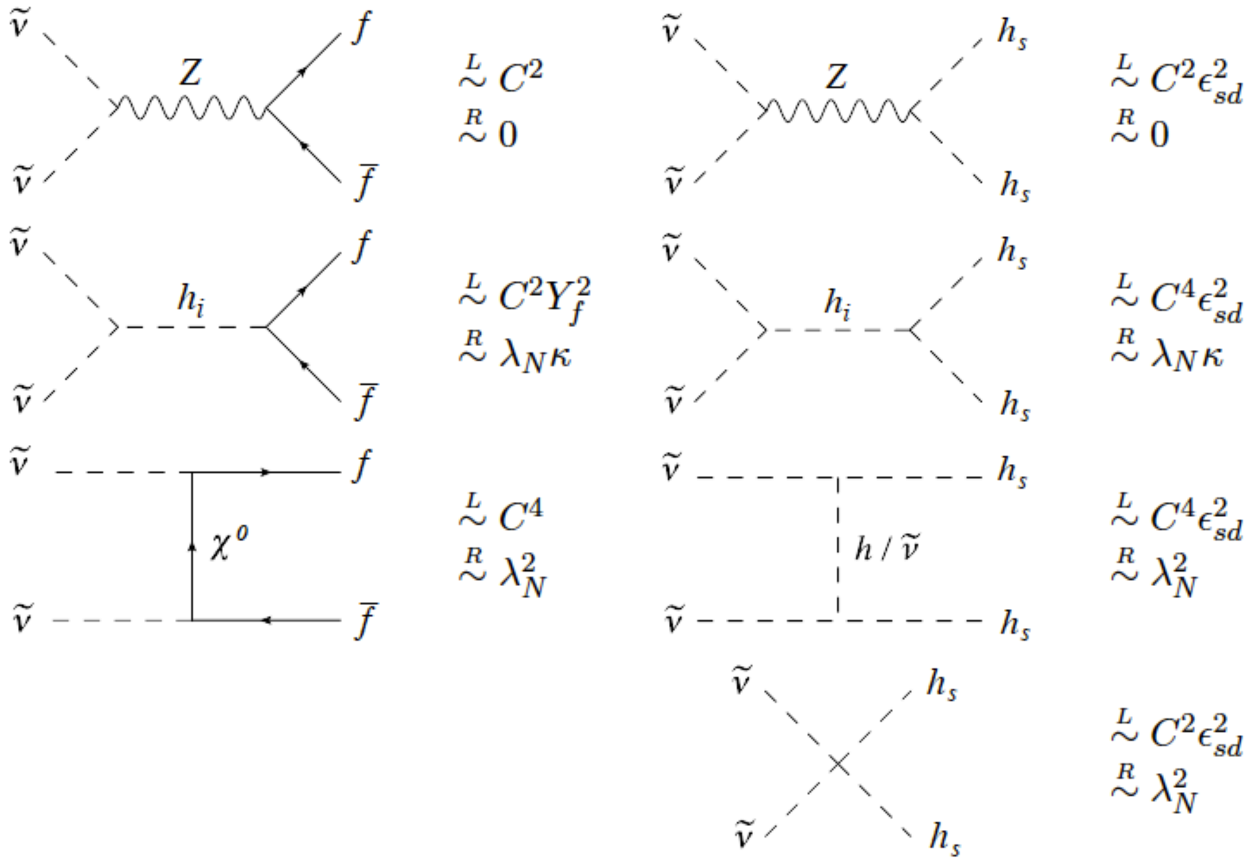
Small κ → LSP singlino dominated → large RD

Blue: singlino dominated LSP
Orange: doublino dominated LSP
Green: CPC neutralino case

$\varepsilon_{\chi S} = |N_{51}|^2$ describes the singlino part in LSP.
With growing singlino part, new annihilation channels become important, but finally small κ suppresses the effect.

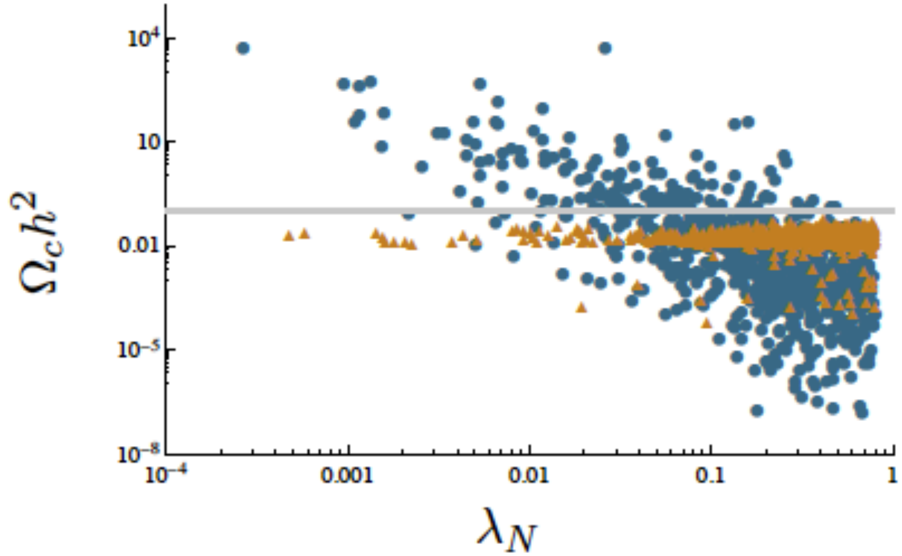
Sneutrino dark matter

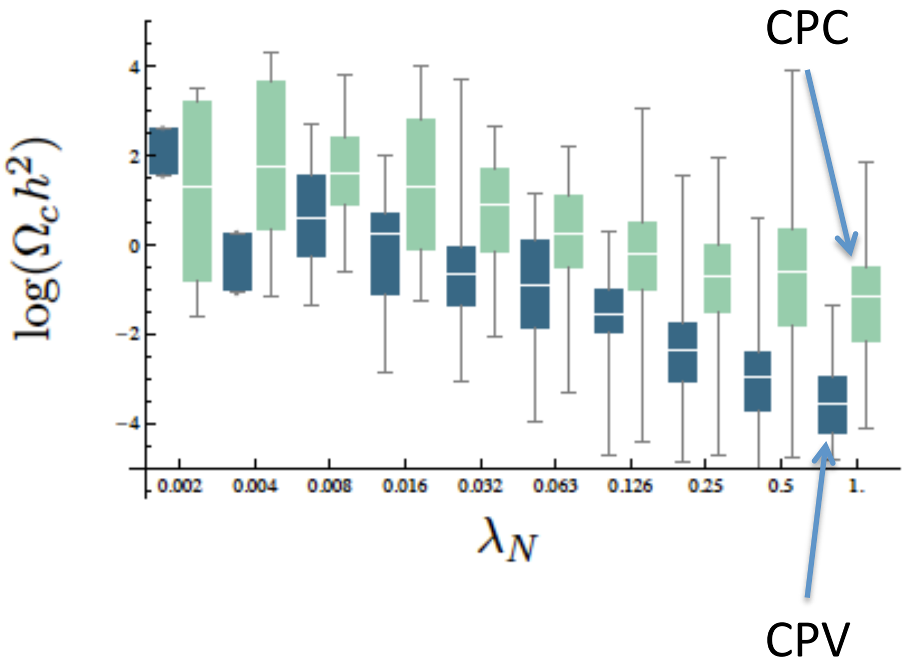
For the $\tilde{\nu}_L$ C^2-channel dominant.
For the $\tilde{\nu}_R$, the $h_S h_S$ channels are of the same order than the fermionic ones ⇨ lower RD than in the CP conserving case.



$$\varepsilon_{sd} \in \left[10^{-5}, 0.1\right]$$

Sneutrino dark matter: For the $\tilde{\nu}_R$, the $h_S h_S$ channels are of the same order than the fermionic ones ⇨ lower RD than in the CP conserving case.



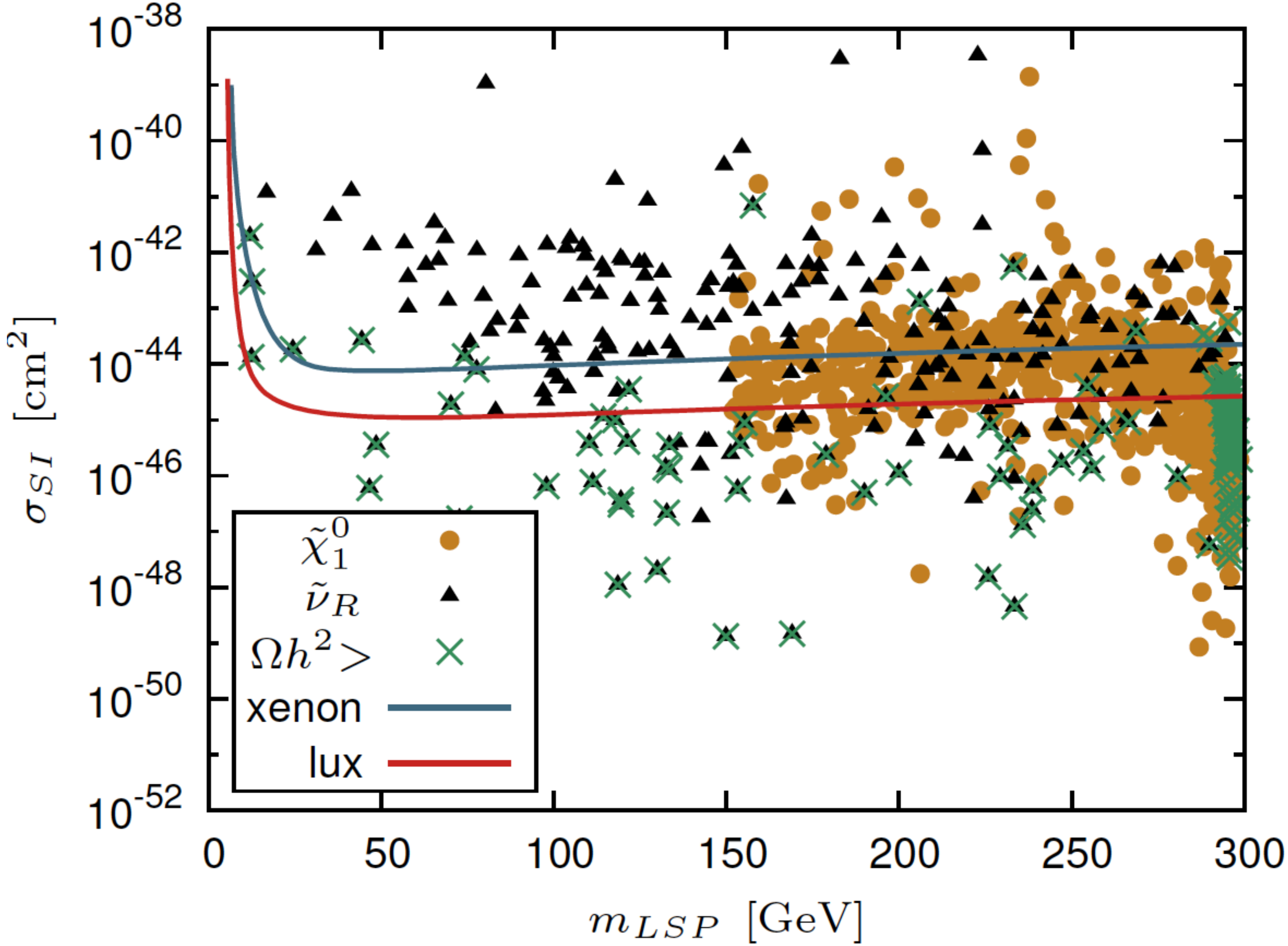


Because of the large λ_N, $h_S h_S$-channels decrease the RD

Boxes represent 25-75% of points.

Orange: L
Blue: R

Direct searches of dark matter



Conclusions:

-SRPV: mixing with sneutrinos helps to increase Higgs mass;
lighter stop can be light compared to MSSM

-SCPV: if EDM forces the CP violating phases small (unless cancellations) → always a light scalar;
light singlet scalar important for RD, since it provides new annihilation channels.

-If both R-parity and CP are simultaneously spontaneously broken, the effects are intertwined and parameter space very nontrivial – one can satisfy neutrino masses and mixing angles, EDM, kaon sector (depend on different model parameters)
M. Frank, K. H. and T. Rüppell, Eur.Phys.J. C52 (2007) 413-423

-However, with both spontaneous R-parity and CP violation, the number of new parameters is 51 (including 3 generations of right-handed neutrinos), compared to 48 of MSSM with explicit R-parity violation

-Effects on collider signals under study in SCPV case, observables reconstructed from the cascade decays of charginos, neutralinos, scalars;

LHC-experiments: $m_h \sim 125$ GeV

If h_S heavier than $m_h/2$, too much EDM!

⇨ $h_2 \rightarrow h_S h_S$ an interesting possibility;

Benchmark points satisfying Higgs constraints, EDM, B-physics, and RD exist.

A. Chatterjee, KH, J. Laamanen, L. Leinonen, S.K.Rai, T. Rüppell, in progress