Spontaneous CP violation, dark matter, and collider searches

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Based on JHEP11 (2012) 129 [arXiv: 1209.6302]
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Outline:

Motivation

Spontaneously CP violating NMSSM

Dark matter in SCPV NMSSM

- Candidates: neutralino, right-handed sneutrino
- Constraints
- Numerical results
- Direct searches of DM

Collider searches

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.

3) In supersymmetric models soft supersymmetry breaking terms can contain explicitly CP violating phases, or one can assume Lagrangian invariant under CP and the sources of CP violation to be vacuum phases. Then different observables are related, and there are only few new parameters.
Spontaneous breaking not possible in MSSM.
extensions needed

In supersymmetric models CP violation is typically too large.
EDMs can agree with experiments if there are cancellations, or phases are small, or masses are large.

MSSM has some tension with experimental results – one can question the naturality of the expected spectrum.

Look for extensions – the most minimal extension is NMSSM.

One can achieve spontaneous CP violation in a model with NMSSM+$N_{R,i}$.

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:

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

CP violating NMSSM+*N*

Superpotential:

Assume only 3rd gen

Assume only one *N*

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

Not all the parameters "natural":

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

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

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

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

The $\boldsymbol{Z_3}$ 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:

Imposing e.g. $\boldsymbol{Z_2}$ R-symmetry on all terms, including nonrenormalizable ones, generates radiatively $\xi^3 S$ term, with ξ at the ew-scale, thus explicitly breaking the $\boldsymbol{Z_3}$ symmetry .

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

The soft breaking terms then become:

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

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

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

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.

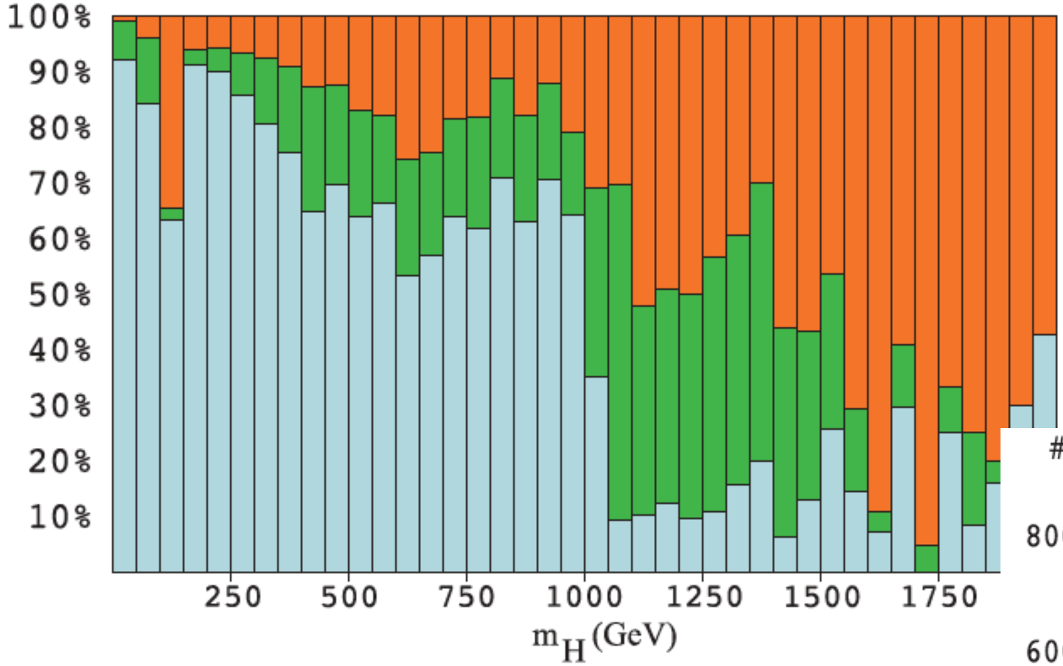
Also spontaneous R-parity breaking possible

$$\langle \tilde{L}_i \rangle = \begin{pmatrix} \sigma_{L_i} e^{i\theta_{L_i}} \\ 0 \end{pmatrix}, \ \langle \tilde{N}_i \rangle = \sigma_{R_i} e^{i\theta_{R_i}}$$

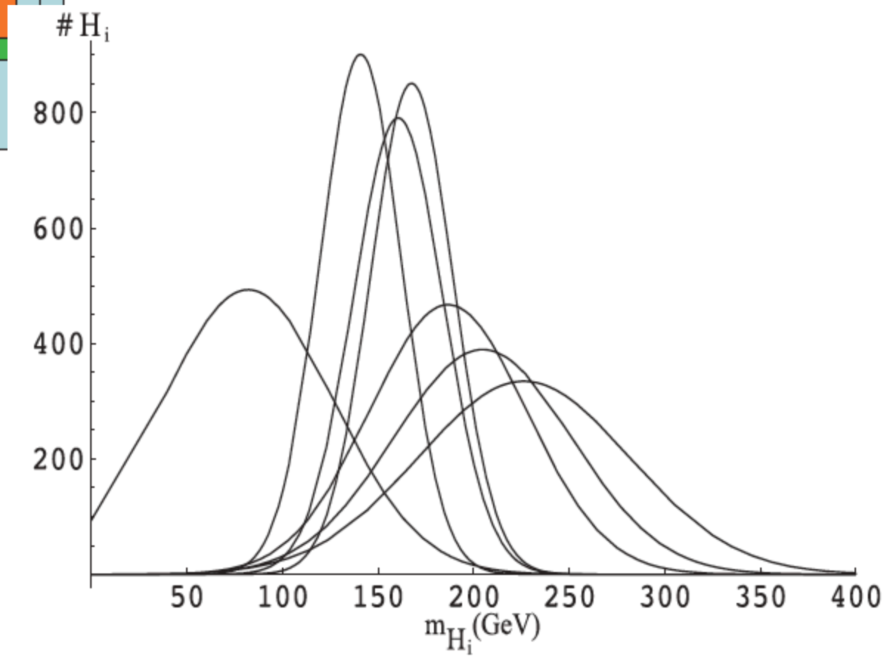
➡ 18x18 mass matrix, since sneutrinos mix with Higgses (neutrino mixing angles and mass spectrum can be satisfied).

All masses and minimization conditions have been calculated at one loop level including corrections from 3rd gen (s)quarks.

Composition of scalars (1000 parameter points):



Orange: doublet
Green: singlet
Blue: sneutrinos



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

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.

Note 3: intimate connections between Higgs sector, neutrino sector and spontaneous violation of CP and R-parity: experimental constraints can be satisfied, since certain parameters affect exclusively particular experimental quantities.

Dark matter candidates

Need to have R-parity conserved in order to preserve DM.

Neutralino

Mass matrix of the standard NMSSM form, except for the phases:

$$M_{\chi^0} = \begin{pmatrix} M_1 & 0 & -\frac{g_1 v_1}{\sqrt{2}} & \frac{g_1 v_2}{\sqrt{2}} e^{-i\delta_2} & 0 \\ 0 & M_2 & \frac{g_2 v_1}{\sqrt{2}} & -\frac{g_2 v_2}{\sqrt{2}} e^{-i\delta_2} & 0 \\ -\frac{g_1 v_1}{\sqrt{2}} & \frac{g_2 v_1}{\sqrt{2}} & 0 & -\lambda v_S e^{i\delta_S} & -\lambda v_2 e^{i\delta_2} \\ \frac{g_1 v_2}{\sqrt{2}} e^{-i\delta_2} & -\frac{g_2 v_2}{\sqrt{2}} e^{-i\delta_2} & -\lambda v_S e^{i\delta_S} & 0 & -\lambda v_1 \\ 0 & 0 & -\lambda v_2 e^{i\delta_2} & -\lambda v_1 & 2\kappa v_S e^{i\delta_S} \end{pmatrix}$$

Typically the LSP is dominantly bino or singlino.

Sneutrino

$$\begin{pmatrix} m_{ee}^2 & m_{eo}^2 \\ m_{oe}^2 & m_{oo}^2 \end{pmatrix} \qquad \begin{pmatrix} \mathrm{Re}\,\tilde{\nu}_L & \mathrm{Re}\,\tilde{N} & \mathrm{Im}\,\tilde{\nu}_L & \mathrm{Im}\,\tilde{N} \end{pmatrix}$$

$$\begin{pmatrix} m_L^2 & A^{+-} & 0 & B^{-+} \\ A^{+-} & m_R^2 + C^{+-} & -B^{++} & D^{-+} \\ 0 & -B^{++} & m_L^2 & A^{--} \\ B^{-+} & D^{-+} & A^{--} & m_R^2 - C^{+-} \end{pmatrix}$$

D^{-+} $\leftarrow$ $\propto \sin\delta_S, \sin 2\delta_S, \sin\delta_2$

$\Rightarrow$ suppression from small phases

$$A_i^{\pm\pm} = Y_N^i (A_N^i v_2 \cos\delta_2 \pm 2\lambda_N v_2 v_S \cos(\delta_2 - \delta_S) \pm \lambda v_1 v_2 \cos\delta_S),$$

$$B_i^{\pm\pm} = A_i^{\pm\pm}(\cos \to \sin),$$

$\leftarrow$ In addition to Y_N, small phases suppress.

$$C^{\pm\pm} = 2\lambda_N A_{\lambda_N} v_S \cos\delta_S \pm 2\kappa\lambda_N v_s^2 \cos 2\delta_S \pm 2\lambda\lambda_N v_1 v_2 \cos\delta_2,$$

$$D^{\pm\pm} = C^{\pm\pm}(\cos \to \sin),$$

$$m^2_{L,ij} = M^2_{L,ij} + Y^i_N Y^j_N (v_1^2 + v_2^2) + \frac{1}{2} m_Z^2 \cos 2\beta \delta_{ij},$$

→ $\tilde{\nu}_L$ mass degenerate, ~CP eigenstates

$$m^2_R = M^2_N + \sum_i {Y^i_N}^2 (v_1^2 + v_2^2) + 4\lambda_N^2 v_S^2.$$

→ $m^2_{\tilde{\nu}_{1,2}} \simeq m^2_R \mp \sqrt{C^{+-2} + D^{-+2}}$

No suppression from small phases in mixing

Constraints

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

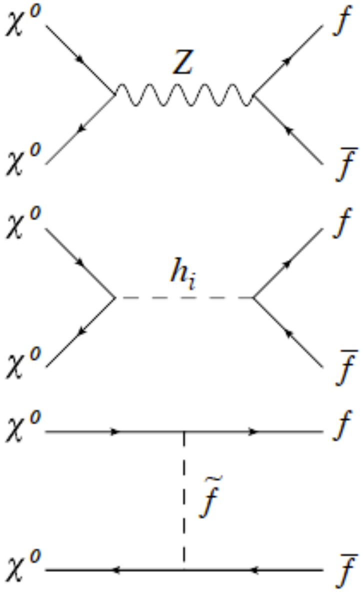
* $[0,0.3]$, $[\pi-0.3,\pi+0.1]$, $[2\pi-0.1,2\pi]$

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.



$\overset{d}{\sim} C^2$

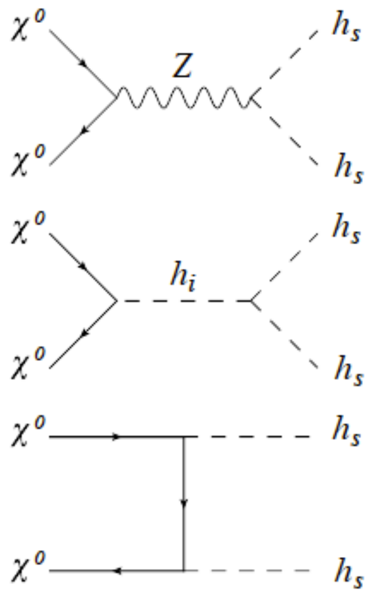
$\overset{s}{\sim} 0$

$\overset{d}{\sim} C \cdot (Y_f, \lambda_N \epsilon_{sd})$

$\overset{s}{\sim} \kappa \cdot (\lambda_N, Y_f \epsilon_{sd})$

$\overset{d}{\sim} (C, Y_f)^2$

$\overset{s}{\sim} \lambda_N^2$



$\overset{d}{\sim} C^2 \epsilon_{sd}^2$

$\overset{s}{\sim} 0$

$\overset{d}{\sim} C \epsilon_{sd} \kappa$

$\overset{s}{\sim} \kappa^2$

$\overset{d}{\sim} (\lambda, C\epsilon_{sd})^2$

$\overset{s}{\sim} (\kappa, \lambda\epsilon_{sd})^2$

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

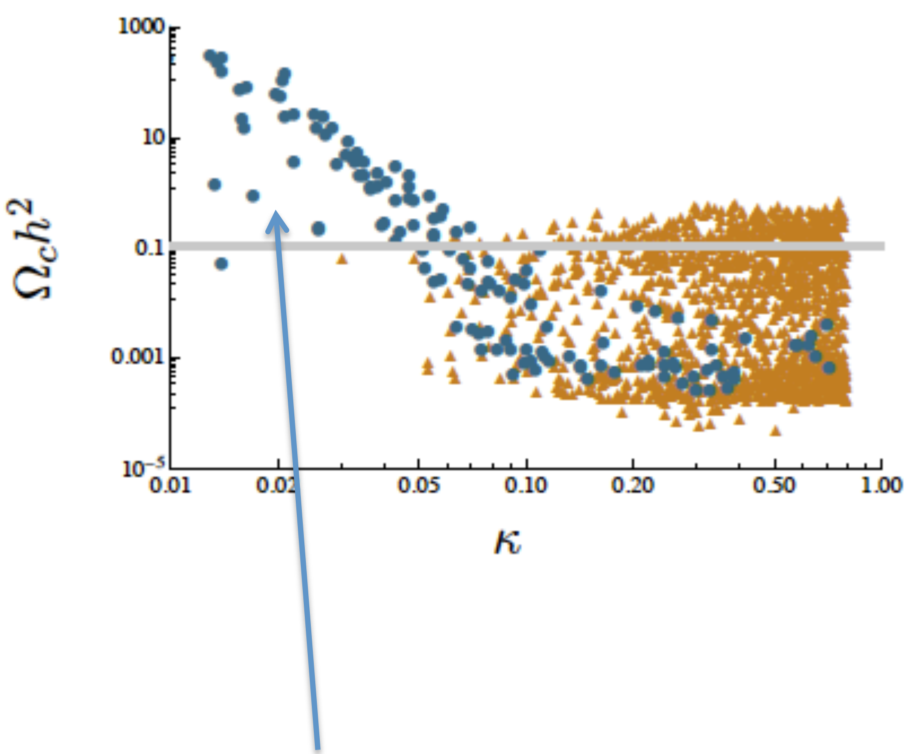
$\Rightarrow$

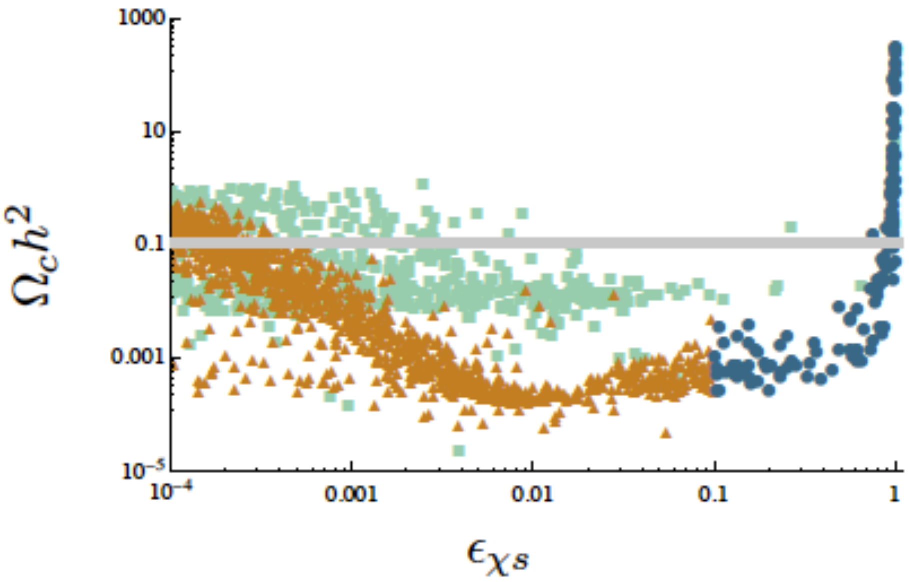
Dominant doublet channels C^2,

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

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

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





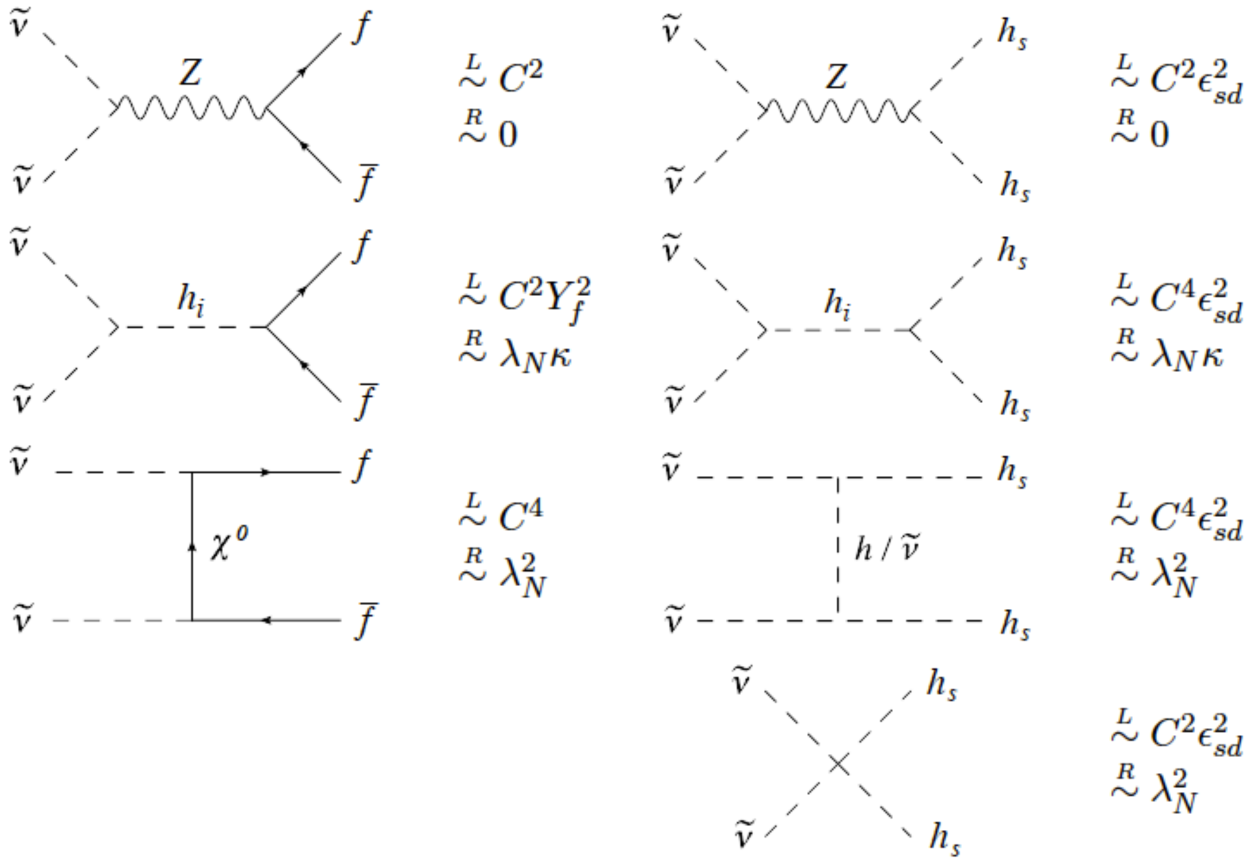
Small κ → large RD

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

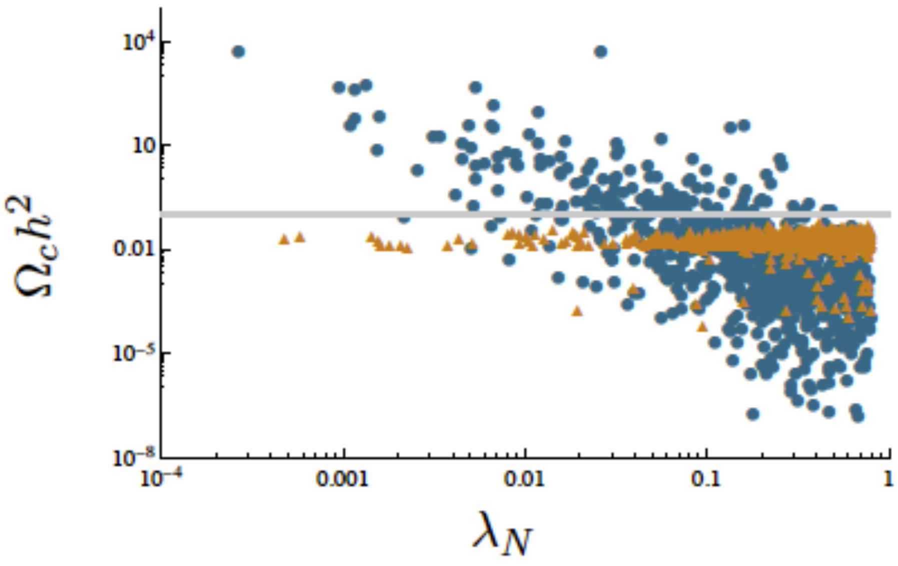
$\varepsilon_{\chi S} = |N_{51}|^2$ describes the singlino part in LSP.
With growing singlino part, new annihilation channels become important, but finally small κ suppresses the effect.

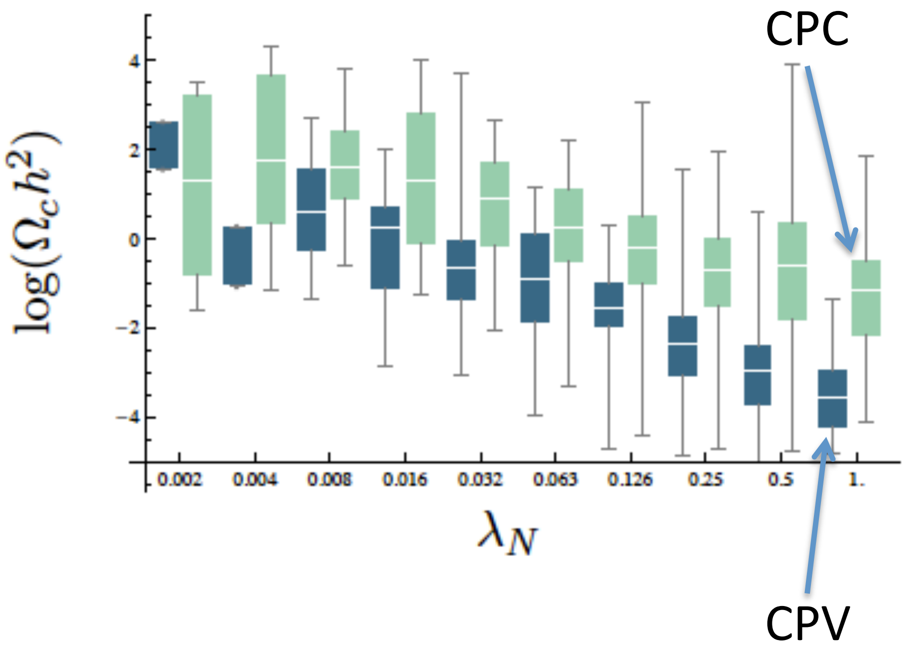
Sneutrino dark matter

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.



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



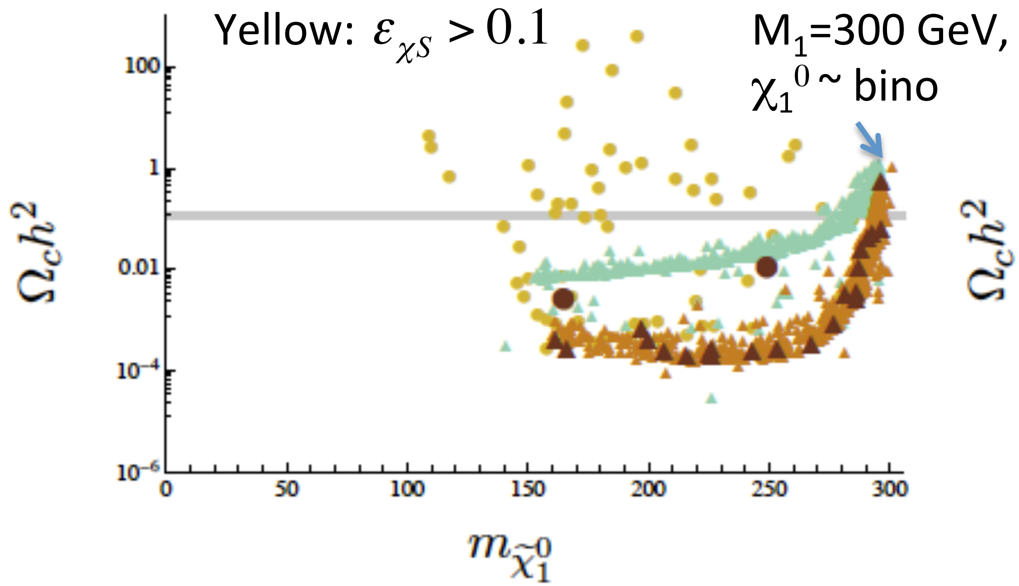


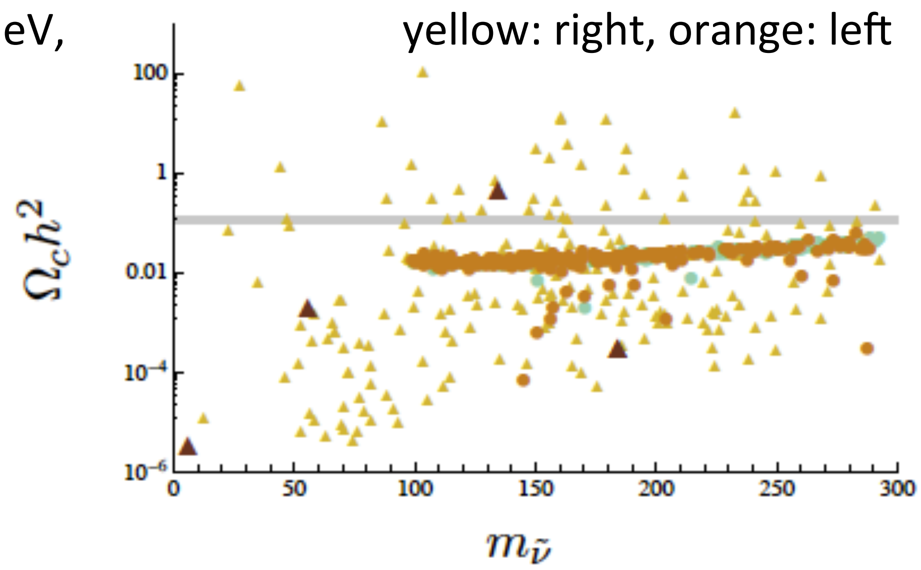
Because of the large λ_N, $h_S h_S$-channels decrease the RD

Boxes represent 25-75% of points.

Orange: L
Blue: R

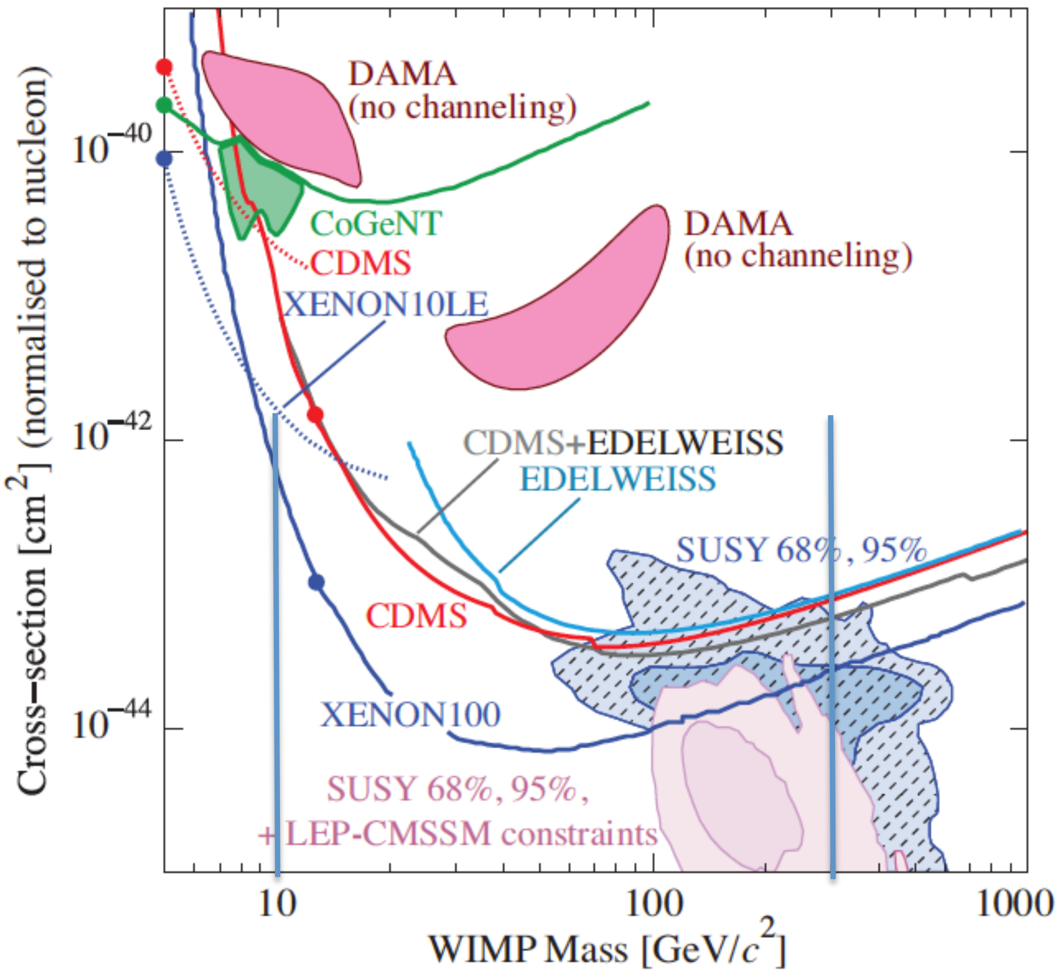
Comparison of CP conservation and violation

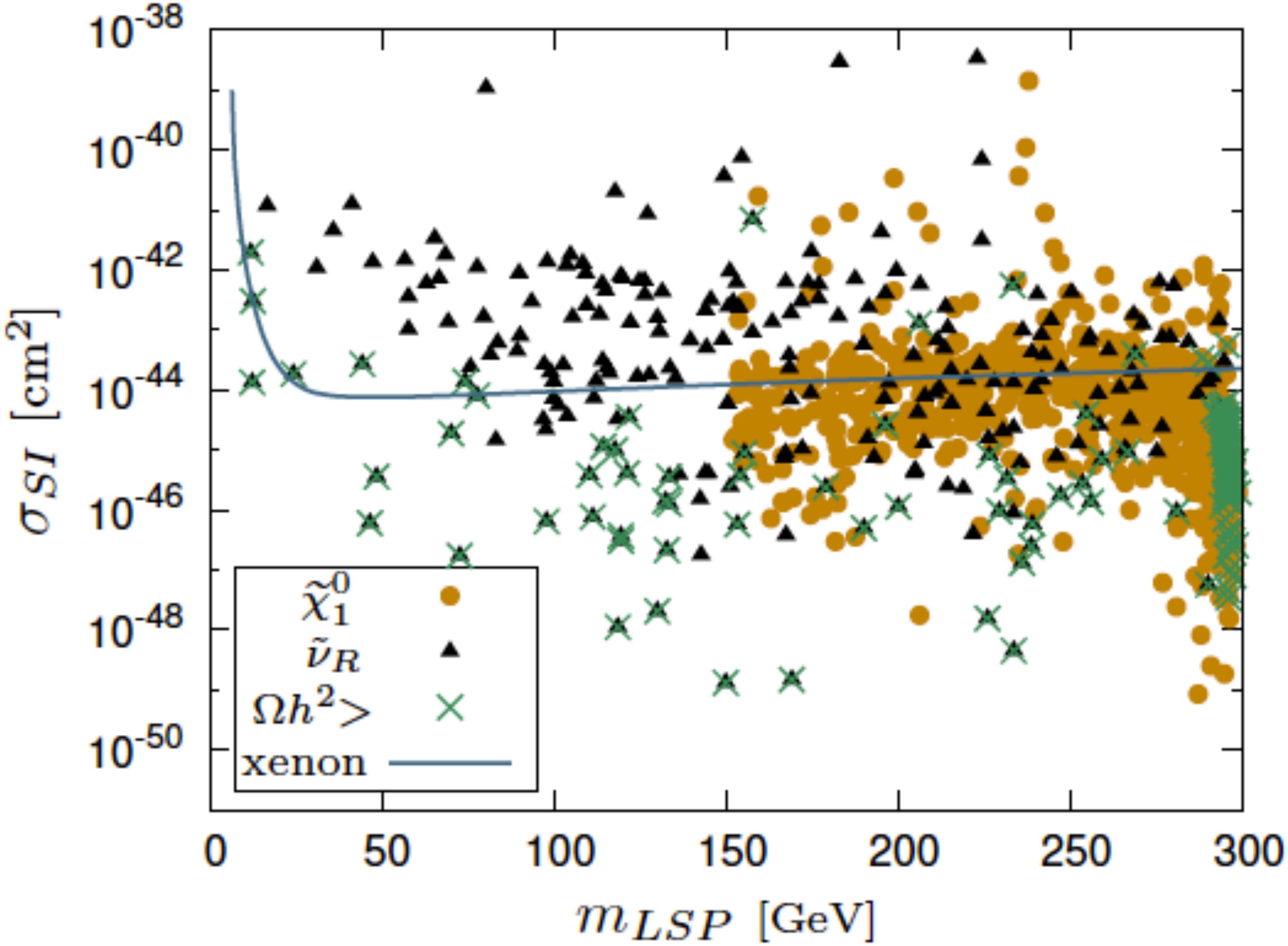




Green: CP conserving
Orange and yellow: CP violating
Big dots and triangles: satisfy all the constraints

Direct searches of dark matter




10^-38
10^-40
10^-42
10^-44
10^-46
10^-48
10^-50
σ_SI [cm^2]
0
50
100
150
200
250
300
m_LSP [GeV]
χ̃_1^0
ν̃_R
Ωh^2>
xenon

Collider searches

LHC-experiments: m_h ~ 125 GeV
A light scalar, h_S. If h_S heavier than $m_h/2$ ⇨ too much EDM!

Thus $h_2 \rightarrow h_S h_S$ an interesting possibility, but because of the large singlet content, h_S is invisible.

Determining invisible BR at LHC has been studied e.g. in Ghosh et al, 1211.7015.
Promising in *HV* and VBF channels:

14 TeV LHC, 30 fb^{-1}:

VBF	32%
$Z(\rightarrow l^+l^-)H$	32%

If the coupling between h_S and h_2 is small, the decay does not affect the collider searches:

$$C_{ijk}^{hhh} = i \sum_{r,s,t}^{6,6,6} \mathcal{O}_{ir}\mathcal{O}_{js}\mathcal{O}_{kt} \frac{\delta}{\delta\phi_r}\frac{\delta}{\delta\phi_s}\frac{\delta}{\delta\phi_t}\mathcal{L}_{\rm int}\,\big|_{\rm vev},$$

$$\phi \in \{\mathrm{Re}H_1^0, \mathrm{Re}H_2^0, \mathrm{Re}S, \mathrm{Im}H_1^0, \mathrm{Im}H_2^0, \mathrm{Im}S\}$$

Assume $C_{211}^{hhh} < 1\,\mathrm{GeV}$

Squarks and gluinos are heavy, and are not excluded by LHC.

→ The signal consists of sleptons, neutralinos, charginos, Higgs.

Find benchmark points satisfy Higgs constraints, EDM, B-physics, and RD.

	BP1	BP2	BP3	BP4	BP5	BP6	BP7
$\tan\beta$	45.7	12.4	33.9	26.9	30.1	43.5	44.9
λ	0.114	0.355	0.363	0.347	0.430	0.259	0.341
κ	0.038	0.63	0.231	0.294	0.357	0.174	0.292
v_S (GeV)	4277.2	1160.2	964.8	914.8	487.5	1881.9	816.7
λ_N	0.721	0.008	0.032	0.498	0.269	0.035	0.750
A_{λ_N} (GeV)	337.0	25.2	-668.9	319.7	365.3	-135.5	-975.5
M_N (GeV)	447.7	449.8	494.7	401.1	341.5	207.6	135.7
$M_{L,E}$ (GeV)	307.1	419.5	432.0	431.9	472.7	320.3	377.0
δ_S	3.228	0.156	3.142	3.203	3.213	3.199	3.173
δ_2	0.111	0.034	0.010	0.249	3.037	0.142	0.173
ξ (GeV)	118.1	-991.3	522.9	318.9	253.0	109.8	300.6
LSP-type	χ_0	χ_0	χ_0	χ_0	χ_0	$\tilde{\nu}_R$	$\tilde{\nu}_R$
m_{LSP} (GeV)	296.3	290.9	286.3	276.7	194.6	5.7	183.7
$\Omega_c h^2$	0.062	0.098	$8.3 \cdot 10^{-3}$	$8.3 \cdot 10^{-4}$	$6.5 \cdot 10^{-4}$	$3.3 \cdot 10^{-6}$	$2.9 \cdot 10^{-4}$

BP1: Δm_1=174 GeV

BP2: $\Delta m_{1,2}$~100 GeV, m_N~19 GeV

BP3: $\Delta m_{1,2}$~50 GeV, m_N~61 GeV

BP4: $\Delta m_{1,2}$~30 GeV

BP5: $\Delta m_{1,2}$<10 GeV, Light spectrum

BP6: m_N ~130 GeV

M_1=300 GeV,

$$\Delta m_{1,2} = \left| m_{\chi_1^\pm, \chi_2^0} - m_{\chi^0} \right|$$

The largest cross sections are typically:

$\chi_1^+ \chi_1^-$ (BP1 (8 fb), BP3 (23 fb), BP4 (40 fb), BP5 (74 fb @8 TeV),
BP6 (8 fb), BP7 (65 fb)) : 2 leptons large $\not{E}_T$

$\chi_1^+ \chi_1^0$ (BP5 (86 fb @8 TeV))

$\chi_1^+ \chi_2^0$ (BP2 (15 fb), BP5 (82 fb @8 TeV), *BP6 (8 fb)) :* 3 leptons large $\not{E}_T$

$\tilde{\nu}\tilde{\nu}$ (BP6, but not detected)

BP1: The signal ($\ell_i^- \ell_j^+ \not{E}_T$) drowned by the WW background
BP2: in $W^+ Z \not{E}_T$ requirement of large $\not{E}_T$ helps to suppress background
BP3, BP4, BP5: small transverse momenta
BP6: neutralino, chargino decays suppressed compared to BP2,
BP7: $\chi_1^+ \to \tau \tilde{\nu}_R (60\%), e/\mu \tilde{\nu}_R (20\%)$, signal $\ell_i^- \ell_j^+ \not{E}_T$

Need to be studied in detail:

- current experimental analysis done assuming 100% decays $\chi_1^+ \rightarrow W^+\chi_1^0$, $\chi_2^0 \rightarrow Z\chi_1^0$
- BR($\chi_2^0 \rightarrow h\chi_1^0$) can be large and phases affect the decays

CP asymmetries in $\chi_i^+\chi_j^0$ trilepton signal have been studied in MSSM context with explicit CP violation in Bornhauser et al, EPJC 72 (2012) 1887, arXiv:1110.6131

Conclusions:

EDM forces the CP violating phases small.

Variations in the spectrum give small effect.

Light singlet scalar important for RD, since it provides new annihilation channels.

Effects on collider signals under study: CP violating effects can affect observables reconstructed from the cascade decays of charginos, neutralinos, scalars.