Is a light singlet viable in an R-symmetric supersymmetric model?

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DESY Theory Workshop
01.10.2015

Motivation - Theory

$$m_{h,\text{tree}}^2 \approx m_Z^2 \cos^2 2\beta - v^2 \cos^2 2\beta \left(\frac{\left(g_1 M_B^D + \sqrt{2}\lambda\mu\right)^2}{|m_S^2 + 4(M_B^D)^2 - m_Z^2 \cos^2 2\beta|} \right)$$

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- Boson lighter than SM-like Higgs boson possible in MSSM, NMSSM
- As in NMSSM singlet natural candiate

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- Boson lighter than SM-like Higgs boson possible in MSSM, NMSSM
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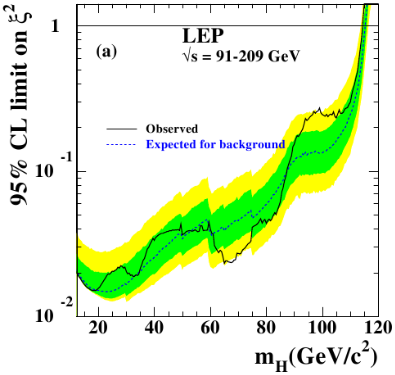
- Here, connection between scalar and fermionic sector via SUSY breaking, Dirac masses are relevant for both

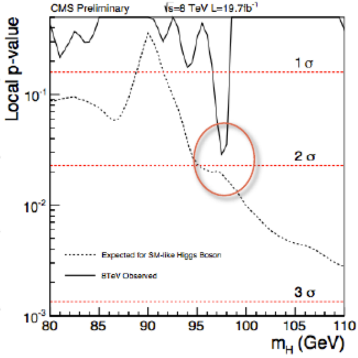
$$\mathcal{L}_{\text{dirac}} = -M_B^D \tilde{\lambda}_B \psi_S^a + \sqrt{2} M_B^D D_B^a \phi_S^a$$

Consequences not only for Higgs sector

Motivation - Experiment



LEP Higgs Working Group



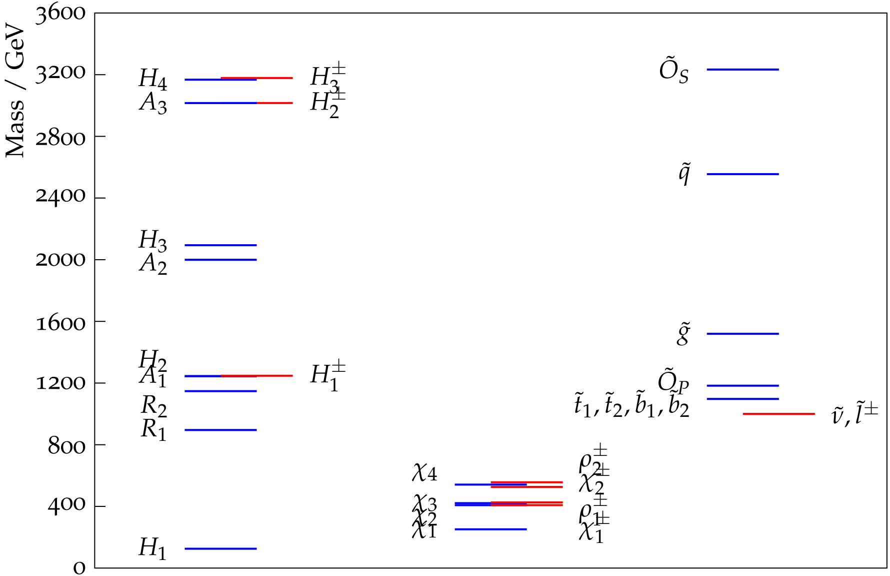
CMS HIG-14-037, taken from Tristan du Pree's talk at SUSY

Taken with a grain of salt!

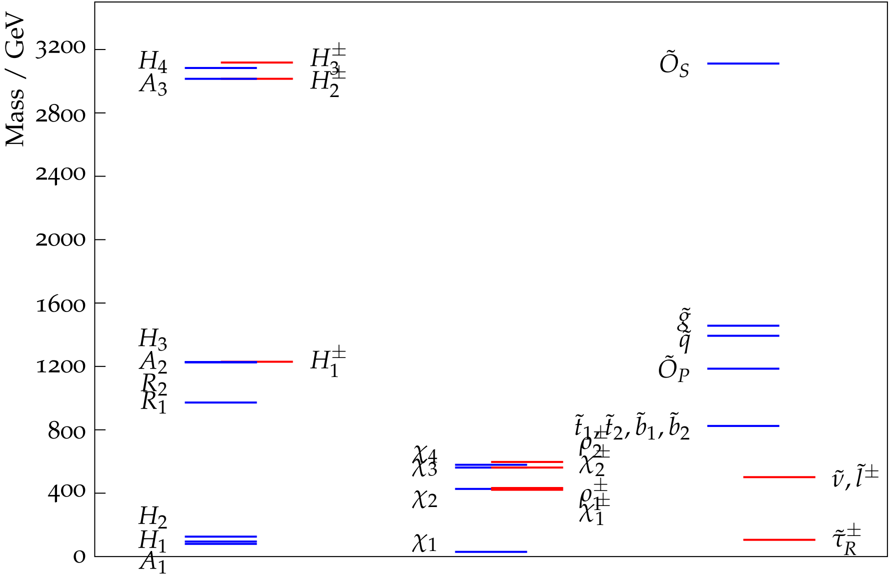
- only 2σ, nothing seen at ATLAS; Most likely fluctuation
- Still shows: A new low-mass signal possible; Another light Higgs boson might be out there

Outline

General mass spectrum - as in previous talk



Light-singlet mass spectrum

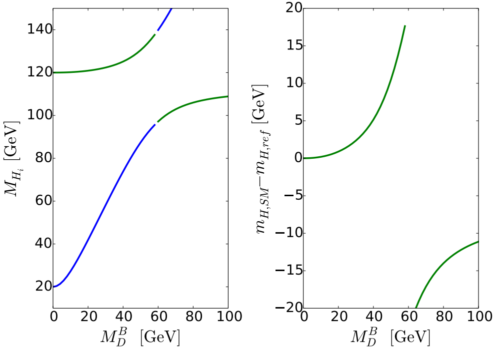


Singlet as lightest state

$$m^2_{H_2,\text{tree}} \approx m_Z^2 \cos^2 2\beta + v^2 \cos^2 2\beta \left(\frac{\left(g_1 M_B^D + \sqrt{2}\lambda\mu\right)^2}{|m_S^2 + 4(M_B^D)^2 - m_Z^2 \cos^2 2\beta|} \right)$$

$$m^2_{H_1} \approx m_S^2 + 4(M_B^D)^2 - \dots$$

Level crossing of Higgs states:
Upper limit on $M_B^D < 60$ GeV
($m_S < 110$ GeV)
(mass spectra calculated using
SARAH/SPheno)



Detailed check of coupling strengths using HiggsBounds/HiggsSignals

LHC searches

Electroweak production

- Upper limit on $M_B^D \Rightarrow$ Clear LSP candidate in χ_1^0
- LHC searches studied using `Herwig++` for event generation
- Detector simulation and analysis done with `CheckMATE`
- Experimental analyses used: 2 or 3 lepton + E_{miss}^T from ATLAS
  [ATLAS, JHEP05(2014)071; JHEP04(2014)169]

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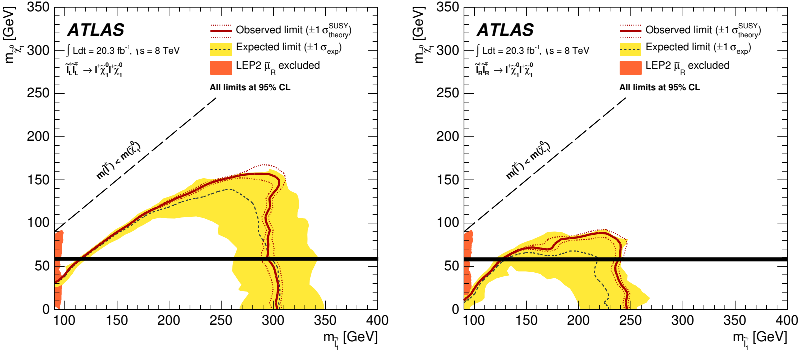
$$m_\chi = \begin{pmatrix} M_B^D & 0 & -\frac{1}{2}g_1 v_d & \frac{1}{2}g_1 v_u \\ 0 & M_W^D & \frac{1}{2}g_2 v_d & -\frac{1}{2}g_2 v_u \\ -\frac{1}{\sqrt{2}}\lambda_d v_d & -\frac{1}{2}\Lambda_d v_d & -\mu_d & 0 \\ \frac{1}{\sqrt{2}}\lambda_u v_u & -\frac{1}{2}\Lambda_u v_u & 0 & \mu_u \end{pmatrix}; \quad \begin{array}{c} \text{Gauge eigenstates:} \\ \xi_i = (\tilde{B}, \tilde{W}^0, \tilde{R}_d^0, \tilde{R}_u^0), \\ \zeta_i = (\tilde{S}, \tilde{T}^0, \tilde{H}_d^0, \tilde{H}_u^0) \end{array}$$

Doubled number of states compared to MSSM also for charginos

Sleptons

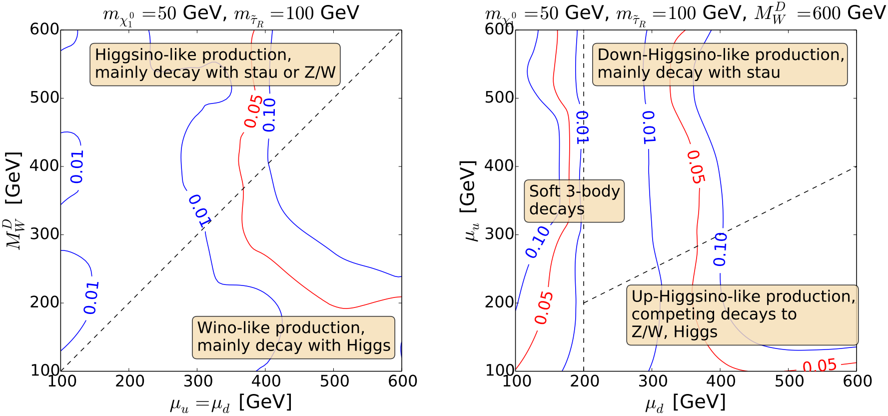
Direct production of Sleptons similar to MSSM/simplified model:



Taken from *ATLAS, JHEP05(2014)071; 2l+ETmiss*

- For LSP masses here, low mass region very constrained
- Limits for selectrons and smuons
- No limits on direct stau production

EWKinos



- Down- and up-Higgsino don't mix as strongly as in MSSM
- Decay to LSP and SM particles also different because of composition with new states
- Competing decay chains don't allow for universal limit

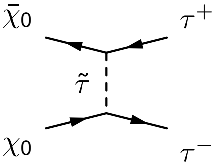
1. MRSSM and the extended Higgs Sector
2. LHC Bounds recasted
3. Dark Matter in the MRSSM
4. Conclusions

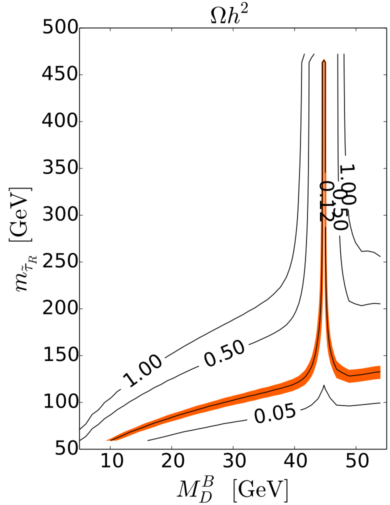
Relic density

R-Symmetric dark matter first studied in *Buckley, Hooper, Kumar '13*
Here using `micrOMEGAs`

Dark matter candidate

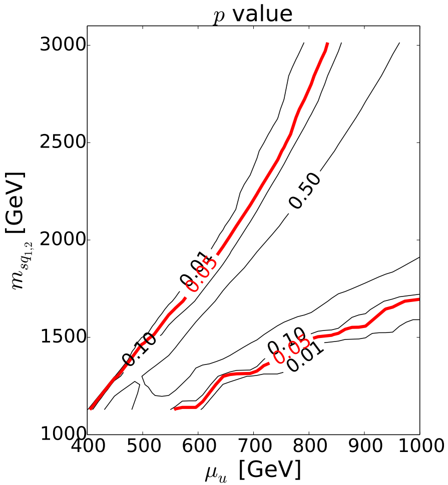
- Bino-Singlino is LSP
- Dirac fermion
- Annihilation using right-handed staus favoured



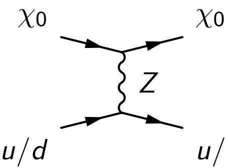


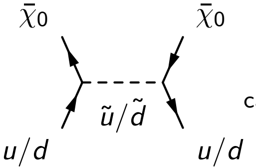
Direct Detection

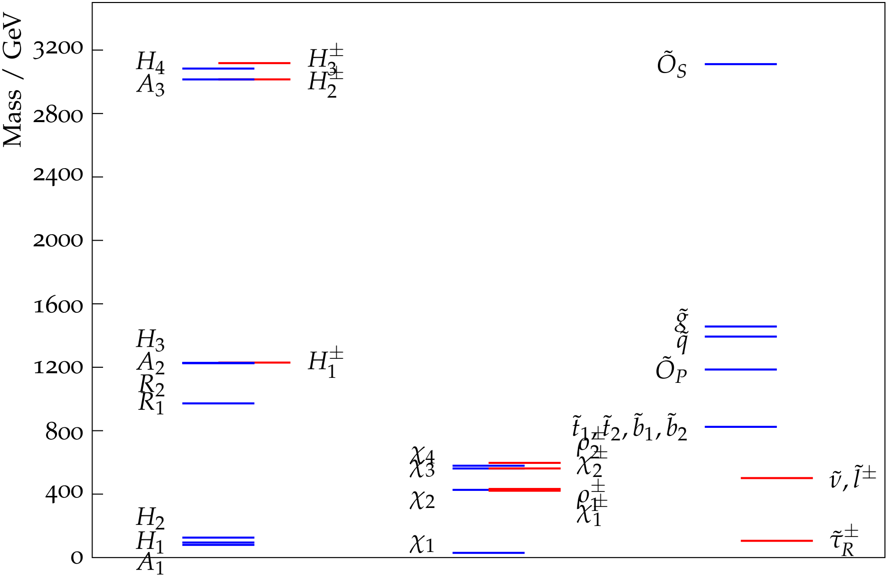
- Dirac LSP ⇒ Z-exchange contributes spin-independent (via Higgsino components)
- Also squark exchange
- Studied in *Buckley, Hooper, Kumar '13* with strong TeV-scale limits
- But neglecting interference, Here taken into account, **very important!**



calculate using `micrOMEGAs` and `LUXcalc`







Mass / GeV
3200
2800
2400
2000
1600
1200
800
400
0
H_4
A_3
$H_3^\pm$
$H_2^\pm$
H_3
A_2
R_2
R_1
$H_1^\pm$
H_2
H_1
A_1
χ_4
χ_3
χ_2
χ_1
$\rho_2^\pm$
$\chi_2^\pm$
$\rho_1^\pm$
$\chi_1^\pm$
$\tilde{O}_S$
$\tilde{g}$
$\tilde{q}$
$\tilde{O}_P$
$\tilde{t}_1, \tilde{t}_2, \tilde{b}_1, \tilde{b}_2$
$\tilde{\nu}, \tilde{l}^\pm$
$\tilde{\tau}_R^\pm$

Conclusions

- Singlet-like state lighter than SM-Higgs possible in MRSSM
- Strong ties between scalar and fermionic sector
- One requirement leads to constraints from many observables
- Studied using Higgs observables, LHC searches and dark matter
- Dark matter and LHC results also relevant
  for non-light singlet scenario
- Outlook: MRSSM NLO-SQCD@LHC

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Thanks for your attention!

References

- MRSSM G. D. Kribs, E. Poppitz and N. Weiner, “Flavor in supersymmetry with an extended R-symmetry,” Phys. Rev. D **78** (2008) 055010 [arXiv:0712.2039 [hep-ph]].
- P. Dießner, J. Kalinowski, W. Kotlarski and D. Stöckinger, JHEP **1412** (2014) 124 [arXiv:1410.4791 [hep-ph]].
- M. Badziak, M. Olechowski and S. Pokorski, JHEP **1306** (2013) 043 [arXiv:1304.5437 [hep-ph]].
- G. Aad *et al.* [ATLAS Collaboration], JHEP **1405** (2014) 071 [arXiv:1403.5294 [hep-ex]].
- G. Aad *et al.* [ATLAS Collaboration], JHEP **1404** (2014) 169 [arXiv:1402.7029 [hep-ex]].
- M. R. Buckley, D. Hooper and J. Kumar, Phys. Rev. D **88** (2013) 063532 [arXiv:1307.3561].

Backup

SUSY and R-Symmetry

usual: $\{Q, Q\} = \{\bar{Q}, \bar{Q}\} = 0$
in "Haag-Łopuszański-Sohnius-Theorem": $\{Q^L_\alpha, Q^M_\beta\} = \epsilon_{\alpha\beta} \sum_l (a^l)^{LM} R^l$
$[R, Q] = -Q, \quad [R, \bar{Q}] = \bar{Q},$
$\rightarrow$ in $\mathcal{N} = 1$ is $U(1)_R$

Dirac masses for soft breaking

$$\mathcal{L}_{\text{dirac}} = \int \mathrm{d}\theta^2 \hat{S} \hat{W}'^{\alpha} \hat{W}_{B\alpha} = -M^D \tilde{\lambda}_B \psi_S^a + \sqrt{2} M^D D_B^a \phi_S^a$$

using Spurion: $\hat{W}'^{\alpha} = \sqrt{2} M^D \theta^{\alpha}$

MRSSM Lagrangian

Superpotential

$$\mathcal{W} = y_e \hat{H}_d \hat{L} \hat{E} + y_d \hat{H}_d \hat{Q} \hat{d} - y_u \hat{H}_u \hat{Q} \hat{U} + \\ \mu_d \hat{H}_d \hat{R}_d + \mu_u \hat{H}_u \hat{R}_u + \\ \lambda_d \hat{H}_d \hat{R}_d \hat{S} + \lambda_u \hat{H}_u \hat{R}_u \hat{S} + \Lambda_d \hat{H}_d \hat{T} \hat{R}_d + \Lambda_u \hat{H}_u \hat{T} \hat{R}_u$$

MRSSM Lagrangian

Superpotential

$$\begin{aligned}\mathcal{W} =& y_e \hat{H}_d \hat{L} \hat{E} + y_d \hat{H}_d \hat{Q} \hat{d} - y_u \hat{H}_u \hat{Q} \hat{U} + \\ & \mu_d \hat{H}_d \hat{R}_d + \mu_u \hat{H}_u \hat{R}_u + \\ & \lambda_d \hat{H}_d \hat{R}_d \hat{S} + \lambda_u \hat{H}_u \hat{R}_u \hat{S} + \Lambda_d \hat{H}_d \hat{T} \hat{R}_d + \Lambda_u \hat{H}_u \hat{T} \hat{R}_u\end{aligned}$$

Soft SUSY Breaking

$$\begin{aligned}-\mathcal{L}_{\text{soft}} =& M_i^D \tilde{\lambda}_i^a \psi_j^a - \sqrt{2} M_i^D D_j^a \phi_i^a + m_k^2 \phi_k \phi_k^* + B\mu h_u h_d \\ & + h.c. \\ \{i, j\} \in& \{\{G, O\}, \{W, T\}, \{B, S\}\}; \\ k \in& \{q, u, d, l, e, H_d, H_u, R_d, R_u, S, T, O\}\end{aligned}$$

Other soft breaking terms related to S, T, O possible but for simplicity excluded here

MRSSM CP-odd Higgs mass matrix

$$\mathcal{M}_A = \begin{pmatrix} B_\mu \frac{v_u}{v_d} & B_\mu & 0 & 0 \\ B_\mu & B_\mu \frac{v_d}{v_u} & 0 & 0 \\ 0 & 0 & m_S^2 + \frac{\lambda_d^2 v_d^2 + \lambda_u^2 v_u^2}{2} & \frac{\lambda_d \Lambda_d v_d^2 - \lambda_u \Lambda_u v_u^2}{2\sqrt{2}} \\ 0 & 0 & \frac{\lambda_d \Lambda_d v_d^2 - \lambda_u \Lambda_u v_u^2}{2\sqrt{2}} & m_T^2 + \frac{\Lambda_d^2 v_d^2 + \Lambda_u^2 v_u^2}{4} \end{pmatrix}$$

MRSSM CP-even Higgs mass matrix

$$\mathcal{M}_{H^0} = \begin{pmatrix} \mathcal{M}_{\text{MSSM}} & \mathcal{M}_{21}^T \\ \mathcal{M}_{21} & \mathcal{M}_{22} \end{pmatrix}$$

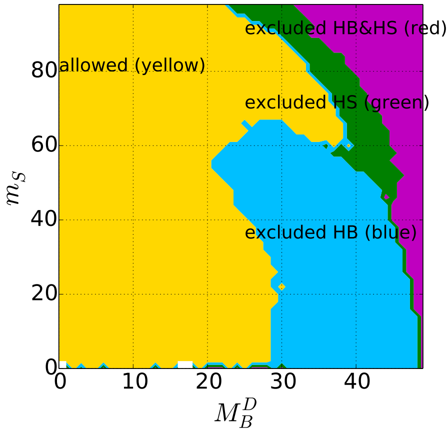
$$\mathcal{M}_{\text{MSSM}} = \begin{pmatrix} m_Z^2 c_\beta^2 + m_A^2 s_\beta^2 & -(m_Z^2 + m_A^2) s_\beta c_\beta \\ -(m_Z^2 + m_A^2) s_\beta c_\beta & m_Z^2 s_\beta^2 + m_A^2 c_\beta^2 \end{pmatrix},$$

$$\mathcal{M}_{22} = \begin{pmatrix} 4(M_B^D)^2 + m_S^2 + \frac{\lambda_d^2 v_d^2 + \lambda_u^2 v_u^2}{2} & \frac{\lambda_d \Lambda_d v_d^2 - \lambda_u \Lambda_u v_u^2}{2\sqrt{2}} \\ \frac{\lambda_d \Lambda_d v_d^2 - \lambda_u \Lambda_u v_u^2}{2\sqrt{2}} & 4(M_W^D)^2 + m_T^2 + \frac{\Lambda_d^2 v_d^2 + \Lambda_u^2 v_u^2}{4} \end{pmatrix},$$

$$\mathcal{M}_{21} = \begin{pmatrix} v_d(\sqrt{2}\lambda_d \mu_d^{\text{eff},+} - g_1 M_B^D) & v_u(\sqrt{2}\lambda_u \mu_u^{\text{eff},-} + g_1 M_B^D) \\ v_d(\Lambda_d \mu_d^{\text{eff},+} + g_2 M_W^D) & -v_u(\Lambda_u \mu_u^{\text{eff},-} + g_2 M_W^D) \end{pmatrix}.$$

Limits using Higgs observables

- Detailed check using `HiggsBounds`/`HiggsSignals`
- Constraining signal strengths of lightest and second lightest Higgs
- Enforcing that SM-like Higgs mass at 125 GeV by varying Λ_u/Λ_d



Here, $\lambda_u = 0$; for other values yellow region can shifts