A light singlet at the LHC and DM

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An interesting scenario of an R-symmetric supersymmetric model with a light singlet is discussed. Since a light scalar in this model necessarily implies a light Dirac neutralino, its viability as a dark matter candidate is addressed.

[*]Dedicated to the memory of Maria Krawczyk

1. Motivation

The N=1 supersymmetry algebra contains a single global $U(1)_R$ symmetry, called R-symmetry [1, 2], with $[R, Q_\alpha] = -Q_\alpha$, which implies that component fields of a superfield have R-charges differing by one unit. R-symmetry is stronger than R-parity: since gauge vector fields carry no R-charge ($R = 0$), gauginos have R-charge= 1 and therefore, unlike in the Minimal Supersymmetric Standard Model (MSSM), Majorana gaugino mass terms in the soft SUSY breaking potential have $R = 2$ and thus are inconsistent with R-symmetry. Gaugino mass terms of Dirac type can be introduced by enforcing an N=2 supersymmetric structure of the gauge/gaugino sector, i.e. adding for each gauge group factor a chiral superfield in the adjoint representation. An exciting implication of R-symmetry is that such a construction necessarily introduces additional scalar fields. This is an interesting option since after the discovery of a Standard Model (SM)-like Higgs boson at the LHC [3, 4, 5], it remains an open question whether there are additional scalar particles, possibly even with smaller mass. Moreover, since R-symmetry forbids also Higgsino mass parameter μ and all left-right sfermion mixings, alleviating some CP- and flavour-violating constraints [6] and reducing production cross section for squarks making squarks below the TeV scale generically compatible with LHC data, such a scenario is worth exploring.

2. Introduction

Supersymmetric extensions of the SM always predict additional scalars and scenarios with light scalars have been explored both in the minimal supersymmetric standard model (MSSM) and in its extensions, such as the NMSSM which contains a gauge singlet field. While in the MSSM a light scalar is not particularly motivated, in the NMSSM a light singlet-like scalar pushes the tree-level value of the SM-like Higgs boson mass up towards reducing fine-tuning (see e.g. [7] and [8] and references therein for the MSSM and NMSSM, respectively). It turns out that in the minimal R-symmetric supersymmetric model (MRSSM) a scenario with a light scalar is even more motivated since it is necessarily connected with a very light neutralino [9] which can play a role of a dark matter particle.

The MRSSM is defined by the superpotential [10]

$$W = \mu_d \hat{R}_d \cdot \hat{H}_d + \mu_u \hat{R}_u \cdot \hat{H}_u + \Lambda_d \hat{R}_d \cdot \hat{T} \hat{H}_d + \Lambda_u \hat{R}_u \cdot \hat{T} \hat{H}_u$$
$$+ \lambda_d \hat{S} \hat{R}_d \cdot \hat{H}_d + \lambda_u \hat{S} \hat{R}_u \cdot \hat{H}_u - Y_d \hat{d} \hat{q} \cdot \hat{H}_d - Y_e \hat{e} \hat{l} \cdot \hat{H}_d + Y_u \hat{u} \hat{q} \cdot \hat{H}_u, \quad (2.1)$$

where the MSSM-like fields are the Higgs doublet superfields $\hat{H}_{d,u}$ and the quark and lepton superfields $\hat{q}$, $\hat{u}$, $\hat{d}$, $\hat{l}$, $\hat{e}$. The new fields are the singlet, the SU(2)-triplet and the color-octet chiral superfields, $\hat{S}$, $\hat{T}$ and $\hat{O}$, which contain the Dirac-mass partners of the usual gauginos. Since the MSSM-like Higgs $\hat{H}_{d,u}$ are assumed to have $R = 0$ in the MRSSM, new doublets $\hat{R}_{d,u}$ with $R = 2$ are introduced (so called R-Higgs), which contain the Dirac-mass partners of the higgsinos, and the corresponding Dirac-higgsino mass parameters $\mu_{d,u}$. In addition to the standard Yukawa couplings the superpotential contains also Yukawa-like trilinear terms involving the new fields with $\lambda_{d,u}$ parameters for the terms involving the singlet $\hat{S}$ and $\Lambda_{d,u}$ for the terms involving the triplet $\hat{T}$; terms involving the octet $\hat{O}$ are forbidden by R-symmetry. Other parameters of the MRSSM are the Dirac mass parameters $M_{B,W,O}^D$ for the U(1), $SU(2)_L$ and $SU(3)_c$ MSSM-like gauginos $\tilde{B}$, $\tilde{W}^a$

and $\tilde{g}^a$, which are paired with fermionic components of $\hat{S}$, $\hat{T}$ and $\hat{O}$ respectively, the soft scalar mass parameters $m^2_{S,T,O}$ and $m^2_{H_d,H_u,R_d,R_u}$ for the singlet, triplet, octet and for the Higgs and R-Higgs states, and the standard B_μ parameter and sfermion mass parameters, while the trilinear sfermion couplings are forbidden by R-symmetry. For the explicit form of the soft SUSY breaking potential see e.g. Ref. [11], and for the detailed discussion of numerical tools used for results presented in this report we refer to [9].

3. The MRSSM with a light singlet

In the MRSSM the lightest Higgs boson tree-level mass is typically reduced compared to the MSSM due to mixing with the additional scalars and the loop corrections cannot be enhanced by stop mixing. However, the new fields and couplings give rise to the necessary large loop contributions to the Higgs mass without generating too large a contribution to the W-boson mass, as shown in Refs. [11, 12] where the lightest (SM-like) Higgs boson mass has been computed at the one-loop and leading two-loop level. If on the other hand the SM-like Higgs is assumed to be the second-lightest, the mixing with additional scalars rises its tree-level mass and thus lowers the necessary loop corrections, similarly to what occurs in the NMSSM.

However, unlike in the NMSSM, requiring the second-lightest scalar to be the SM-like imposes constraints on bino-singlino and higgsino masses and couplings. To see this qualitatively, let us consider the neutral Higgs sector of the MRSSM. The real components of neutral scalar fields $\phi_d, \phi_u, \phi_S, \phi_T$ of the two MSSM-like Higgs doublets $H_{d,u}$ and the $N = 2$ scalar superpartners of the singlet-triplet gauge fields S and T do not mix with the corresponding imaginary components for real vacuum expectation values $v_{d,u,S,T}$. Therefore the full 8x8 mass-squared matrix breaks into two 4x4 sub-matrices. In the imaginary component sector the MSSM-like states do not mix with the singlet-triplet states and the mass-squared matrix breaks further into two 2x2 sub-matrices. Thus the neutral Goldstone boson and one of the pseudo-scalar Higgs bosons A with $m^2_A = 2B_\mu/\sin 2\beta$ appear as in the MSSM. In the real component sector all four states mix. However, the SM-like Higgs boson is dominantly given by the up-type field ϕ_u for high m_A and $\tan\beta = v_u/v_d$. In this limit it is enough to consider the 2x2 sub-matrix of the neutral scalar mass matrix corresponding to the (ϕ_u, ϕ_S) fields only, which reads

$$\mathscr{M}^\phi_{u,S} = \begin{pmatrix} m^2_Z + \Delta m^2_{rad} & v_u \left(\sqrt{2}\lambda_u \mu^{\text{eff},-}_u + g_1 M^D_B \right) \\ v_u \left(\sqrt{2}\lambda_u \mu^{\text{eff},-}_u + g_1 M^D_B \right) & 4(M^D_B)^2 + m^2_S + \frac{\lambda^2_u v^2_u}{2} \end{pmatrix}, \tag{3.1}$$

where the dominant radiative correction to the diagonal component ϕ_u is denoted by Δm^2_{rad}, g_1 is the U(1) gauge coupling and $\mu^{\text{eff},-}_u$ stands for

$$\mu^{\text{eff},-}_u = \mu_u + \frac{\lambda_u v_S}{\sqrt{2}} - \frac{\Lambda_u v_T}{2}. \tag{3.2}$$

The parameters M^D_B, μ_u and λ_u appear in the scalar potential due to the usual D-term generation of Dirac mass terms for the MRSSM.

From this approximation it is evident that the light-singlet scenario, in which $m_{H_1} < m_{H_2} \approx 125$ GeV, can be achieved if the singlet-diagonal element in Eq. (3.1) is smaller than the doublet-
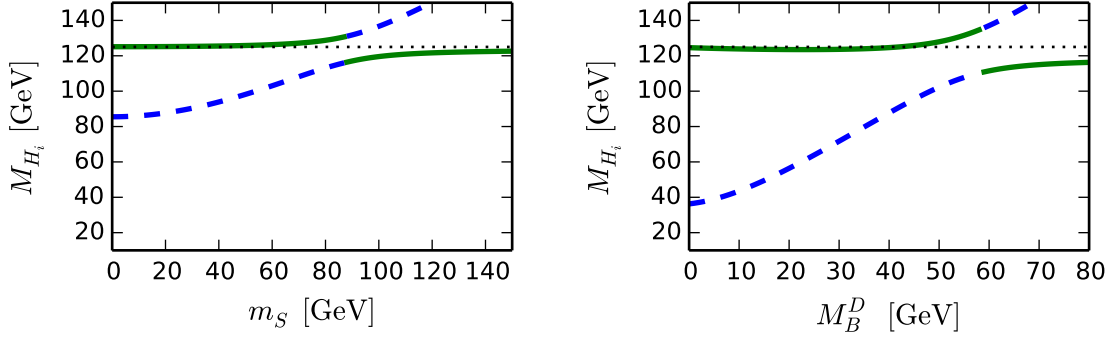
Figure 1: Lightest and second-lightest CP-even Higgs states as functions of the dimensionful parameter m_S (M_B^D) on the left (right); other parameters are as for BMP5 of Ref. [9]. The green full line indicates that the given state is more SM-like, while the blue dashed line when it is singlet-like.

diagonal one, and off-diagonal elements small enough to avoid tachyonic states. From this requirement one can draw the following hierarchy

$$m_S, M_B^D < m_Z < \mu_u, \qquad |\lambda_u| \ll 1. \tag{3.3}$$

It implies that not only m_S but also the bino-singlino mass parameter M_B^D must be of order tens GeV, a feature which is unique to the MRSSM.

A quantitative analysis of the masses of the two lightest Higgs states computed to two-loops are shown in Fig. 1 as a function of the two relevant parameters m_S (left panel) and M_B^D (right panel). The non-varying parameters are fixed to the benchmark point BMP5 of Ref. [9], see Appendix for masses of some SUSY particles. If the approximate inequality Eq. (3.3) is satisfied, the lightest state is significantly lighter than m_Z and has a high singlet component. When m_S or M_B^D become heavier, the lightest state becomes mainly a doublet-like and hence SM-like. In the light-singlet case, the upward shift of the SM-like Higgs can amount to more than 10 GeV, particularly due to the non-vanishing bino-singlino Dirac mass M_B^D, since this parameter also appears in the off-diagonal element of the mass matrix Eq. (3.1).

The novel feature of the light-singlet scenario in the MRSSM is the upper bound on the Dirac bino-singlino mass M_B^D, which has no counterpart e.g. in the NMSSM. Obviously this bound affects the neutralino sector and with LEP bounds on chargino and neutralino production it suggests that the LSP is a Dirac bino-singlino neutralino with mass related to M_B^D and thus limited from above.

4. Light-singlet scenario at the LHC

Experimental data impose direct constraints on the two lightest scalars and their mixing. First, there must be a SM-like state observed at the LHC, with mass and couplings to agree with the observed Higgs signal strengths and branching ratios. Second, the state lighter than the SM-like one has to be mostly singlet-like to pass limits from direct searches for light scalars, especially the LEP searches. Both constraints have been analyzed with `HiggsBounds`-4.2 and `HiggsSignals`-1.4 [13] and the resulting excluded and allowed regions in the plane of m_S and M_B^D are shown in
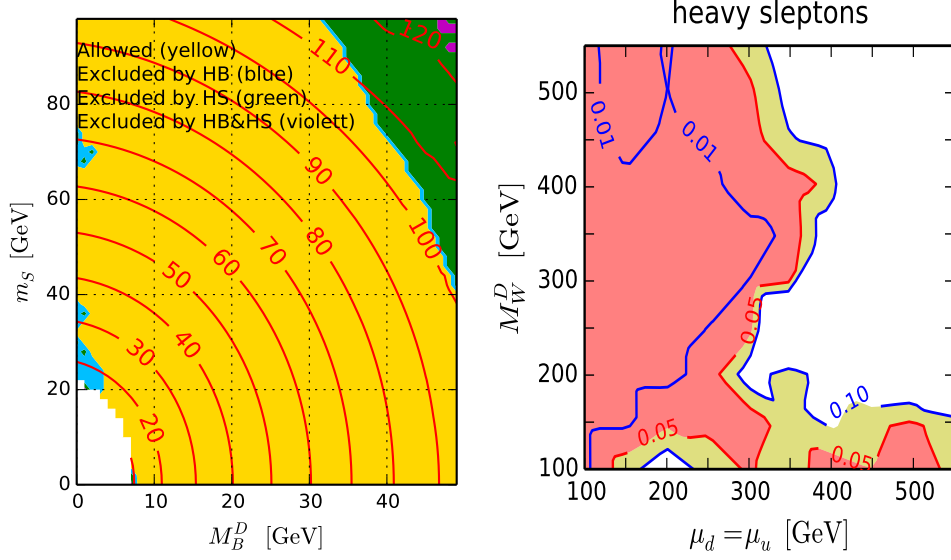
Figure 2: Left: exclusion plot using `HiggsSignals-1.3` and `HiggsBounds-4.2` with Λ_u scanned within the range $-1.5 < \Lambda_u < 0$. Red contours show the lightest scalar mass calculated at two loops. Right: exclusion limits for for heavy sleptons as a function of the two higgsino mass parameters $\mu_d = \mu_u$ and wino-triplino mass M_W^D. The red (yellow) region marks the 95% (90%) excluded parameter. All other parameters are fixed to the values of BMP5.

the left panel of Fig. 2. The parameter Λ_u is adjusted to ensure the correct mass of the observed Higgs boson; the remaining parameters are fixed as in BMP5 with $\lambda_u = -0.01$. We find that the light-singlet scenario can be realized in the MRSSM for $m_S < 100$ GeV and $M_B^D < 55$ GeV.

A light bino-like neutralino, and more generally light weakly interacting particles, are interesting since they might lead to observable signals at the LHC and explain the observed dark matter relic density. On the other hand, reinterpreting the LHC bounds in the context of the MRSSM has to be done with care, since the MRSSM differs from the MSSM in the number of degrees of freedom, different mixing patterns, Dirac-versus-Majorana nature of neutralinos, constraints due to the conserved R-charge etc.

In the slepton sector the left-right mixing vanishes in the MRSSM. This is not an essential difference to the MSSM, where typically the mixing is assumed to be small. Since in both models light sleptons decay to leptons and bino-like neutralino LSP, the Dirac or Majorana nature of the LSP is inessential and the MSSM exclusion bounds for light sleptons can be applied to the MRSSM case as well. The chargino and neutralino sectors are quite different. In the MRSSM, the four neutralinos are Dirac fermions composed of eight Weyl spinors $(\tilde{B}, \tilde{W}^0, \tilde{R}_d^0, \tilde{R}_u^0)$ and $(\tilde{S}, \tilde{T}^0, \tilde{H}_d^0, \tilde{H}_u^0)$ with mass eigenvalues dominantly given by the four independent mass parameters $(M_B^D, M_W^D, \mu_d, \mu_u)$. There are also four different charginos, with masses determined by the wino and the two higgsino mass parameters. In the MSSM there are only two charginos and the neutralinos are Majorana with only a single higgsino mass parameter μ, so that two neutralino masses are approximately degenerate. Further differences between MRSSM and MSSM exist in the couplings of charginos and neutralinos and therefore in the decay branching ratios. Fixing the bino-singlino to be very
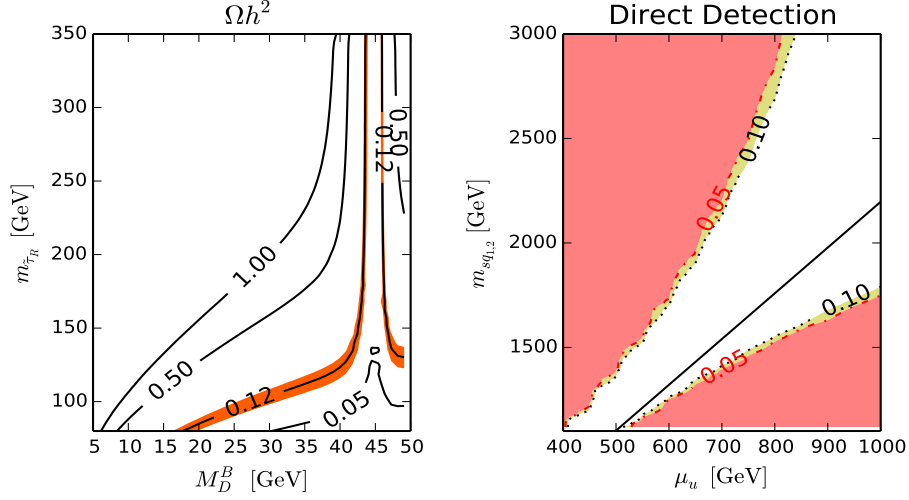
Figure 3: Left panel: dark matter relic density as a function of M_D^B and $m_{\tilde{\tau}_R}$. Right panel: exclusion limits from direct detection dending on μ_u and equal first and second generation squark masses; the straight line shows the relation for the full destructive interference in Eq. (5.2).

light, ~ 50 GeV, there are three relevant mass parameters: the Dirac wino-triplino mass M_W^D and the two higgsino masses $\mu_{d,u}$. Further, the exclusion limits depend on the slepton masses; for the electroweak and dark matter phenomenology all strongly interacting particles are not relevant and are assumed to be heavy enough to evade limits.

As an illustration we consider a specific case with heavy sleptons which is of interest for dark matter in the light-singlet scenario; for other parameter choices we refer to [9]. Right panel of Fig. 2 shows the exclusion regions in the $\mu_d = \mu_u - M_W^D$ plane. Once both higgsinos are heavier than around 300 GeV there is a region with $M_W^D \geq 200$ GeV that is not excluded. The benchmark point MBP5 lies in this viable parameter range.

5. Light-singlet scenario and dark matter

Demanding a light singlet Higgs state leads to an upper bound on the bino-singlino mass parameter $M_B^D < 55$ GeV. In this case the lightest neutralino is bino-singlino dominated, becomes the LSP and it is the dark matter candidate of our model.

For the DM relic density the crucial requirement, as in the MSSM, is to achieve sufficiently effective LSP pair annihilation processes. It turns out that two cases are promising: (a) $m_{\chi_1} \approx M_Z/2$ and S-channel resonant LSP pair annihilation into Z bosons is possible, or (b) right-handed staus are light and annihilation via t-channel stau exchange into tau leptons dominates.

Left panel of Fig. 3 shows the allowed contour in the M_B^D–$m_{\tilde{\tau}_R}$ parameter space. It clearly shows that the measured value of the relic density can be met in two different ways mentioned above: at the Z resonance or away from it. A sharp resonance-like peak is around $M_B^D \approx M_Z/2$ which results from the S-channel annihilation process, where the required stau mass has to be rather high. This is realized in the benchmark point BMP5. For M_B^D away from the resonance the required stau mass is below 150 GeV, as in benchmark points BMP4 and BMP6 of [9].

For the direct DM searches, the spin-independent DM–nucleon scattering cross section at zero momentum transfer can be written in terms of two scattering amplitudes f_p, f_n as

$$\sigma_{DM-N} = \frac{4\mu_{Z_A}^2}{\pi} \left(Zf_p + (A-Z)f_n\right)^2 . \tag{5.1}$$

Here $\mu_{Z_A}^2$ is the dark matter–nucleon reduced mass, and A and Z are atomic mass and number, respectively. It has been noted in Ref. [14] that the spin-independent cross-section for Dirac neutralinos is dominated by the vector part of the Z boson-exchange and squark-exchange contributions which can lead to large scattering rates and thus to strong bounds on the parameter space.

Since the Z boson only couples to the (R-)higgsino content of the LSP the corresponding amplitude can be suppressed if the higgsino mass parameters μ_u and μ_d are sufficiently large. Similarly, for the squark-mediated amplitudes squarks need to be also sufficiently heavy.

The right panel of Fig. 3 shows the 95 % and 90 % exclusion bounds (violet (dark) and yellow (light dark) regions) derived using the log likelihood for the direct detection by LUX depending on μ_u and the first/second generation squark masses. The derived limits are quite sensitive to the combination of both parameters. The funnel-shaped allowed region can be qualitatively explained by noting a complete destructive interference between the Z- and squark-exchange contributions in the limit of degenerate heavy squarks and heavy higgsinos, i.e. $\sigma_{DM-N} = 0$, when

$$m_{\tilde{q}}^2 = \frac{1}{3}\left(7 + 11\frac{A}{Z-A}\right)\mu_u^2 \overset{\text{Xe}}{\approx} 4.8\mu_u^2 , \tag{5.2}$$

where the numerical value is for Xenon with $A = 54$ and $Z = 131.3$. The straight line in Fig. 3 (right) corresponds to Eq. (5.2). Away from the line either the squark-mediated or the Z-mediated amplitude becomes small, the destructive interference does not work and experimental limit is not met. Note that the result for the exclusion bounds is calculated using the complete information of microOMEGAs [15] and LUXCalc [16], while Eq. (5.2) is only approximated. As the squark masses of the first two generations are limited by LHC searches, the direct detection non-discovery provides a lower limit on μ_u.
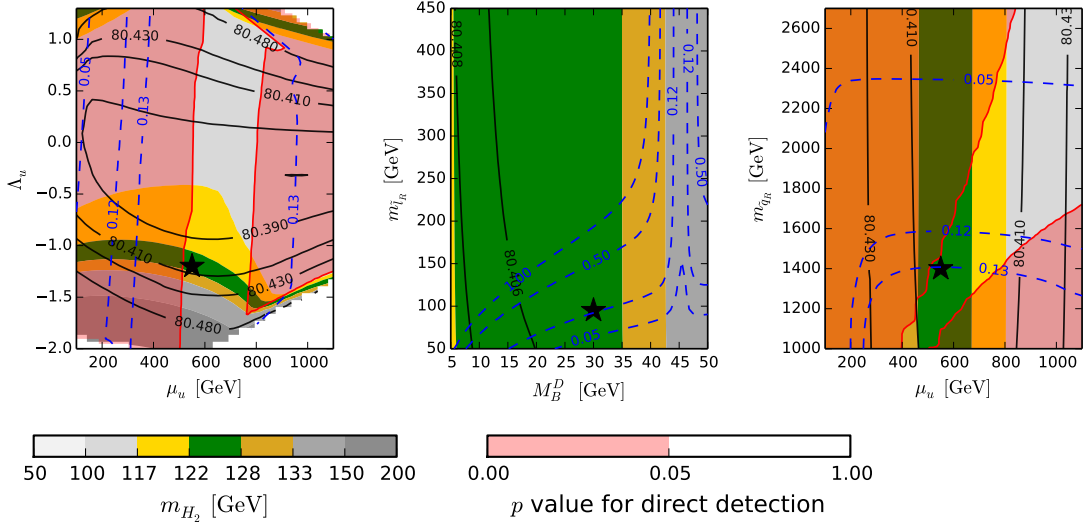
Figure 4: Parameter regions contrasted with experimental constraints. Red areas are excluded with 95% CL by dark matter direct detection, black full (blue dashed) lines show m_W (Ωh^2). The mass of the SM-like Higgs boson m_{H_2} is given by the colour scale shown. All non-varied parameters are set to the values of BMP6 and BMP6 position is shown by stars.

6. Summary and outlook

The minimal R-symmetric model MRSSM is a promising alternative to the MSSM. In particular, the light-singlet scenario is very attractive since it provides an increased tree-level SM-like Higgs boson mass and many light weakly interacting particles which could be discovered at the next LHC run as well as the possibility to explain dark matter. It is also very predictive as can be inferred from Fig. 4. If a light singlet-like Higgs boson is found, not only the parameter m_S but also M_B^D and λ_u must be very small. Then, the requirement of the 125 GeV Higgs mass essentially fixes Λ_u and constrains M_B^D and μ_u (left panel), implying that the fermionic partner is the LSP. On the other hand dark matter data constrain slepton and squark masses (middle and right panels) and other electroweak parameters pointing to interesting mass hierarchies of SUSY particles to be searched at the LHC. It would also be interesting to explore the ILC discovery potential at its initial 250 GeV phase [17] for the benchmark points discussed here.

Acknowledgments

Appendix

Masses of some SUSY particles relevant for the discussion in this report. All values are given in GeV. The four charginos appearing in the MRSSM are denoted as $\chi_1^\pm, \chi_2^\pm, \rho_1^\pm, \rho_2^\pm$.

	χ_1^0	χ_2^0	χ_3^0	χ_4^0	$\chi_1^\pm$	$\chi_2^\pm$	$\rho_1^\pm$	$\rho_2^\pm$	$\tilde{\tau}_R$	$\tilde{\mu}_R$	$\tilde{e}_R$	$\tilde{\ell}_L$	m_{H_1}
BMP4	49.8	132	617	691	131	625	614	713	128	802	802	808	100
BMP5	43.9	401	519	589	409	524	519	610	1000	1001	1001	1005	94
BMP6	29.7	427	562	579	422	562	433	587	106	353	353	508	95

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