Beyond-MSSM Higgs sectors

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This is a compact overview of Higgs sectors in extensions of the MSSM. The focus is on the summary of the main features of models with additional singlets and triplets as well as of models with Dirac gauginos. In addition, also important aspects of models with an extended gauge sector are shown. Finally, I comment on available tools which can be used for an adequate study of non-minimal SUSY models.

Prospects for Charged Higgs Discovery at Colliders - CHARGED 2014,
16-18 September 2014
Uppsala University, Sweden

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1. Introduction

Supersymmetry (SUSY) has been the top candidate for beyond standard model (BSM) physics since many years. While in the past the focus has been on the minimal supersymmetric standard model (MSSM), the null results from LHC for SUSY searches [1] as well as the rather large Higgs mass [2, 3] have triggered more interest in SUSY models beyond the MSSM. The reason is that BMSSM model could not only address these problems but might answer also other questions which still remain open in the MSSM. An incomplete list of motivations to go beyond the MSSM is the following:

- **Naturalness**: the need to push the Higgs mass to the observed level by large loop corrections gets significantly softened if additional F- or D-term contributions to the tree-level mass are present [4–8].

- **Missing SUSY signals**: the unsuccessful searches for SUSY have put impressive limits on the SUSY masses in the simplest manifestation of SUSY. However, in the context of compressed spectra or R-parity violation these limits become much weaker [9–11].

- **Neutrino masses**: neutrinos would still be massless in the MSSM. To incorporate neutrino masses, either R-parity has to be violated to allow for a mixing of the neutrinos with SUSY states or additional particles are needed which contribute to the neutrino masses [12–20].

- **μ-problem**: the μ parameter in the superpotential from the MSSM must be of $O(EWSB)$ because of phenomenological reasons. However, since it is not protected by any symmetry its natural size would be $O(GUT)$. To relax this tensions, μ could be generated dynamically as a consequence of SUSY breaking like in singlet extensions [4, 21].

- **Strong CP-problem**: also the question about the strong CP problem remains open in the MSSM. To solve it, one can introduce a Peccei-Quinn symmetry [22]. The minimal, self-consistent SUSY model doing that needs three additional superfields whose scalar components can mix with the MSSM Higgs states [23].

- **UV-completion**: there are many SUSY scenarios motivated by GUT or string models where additional gauge groups are broken close to the TeV scale. These models predict usually plenty of additional states close to the SUSY scale beside Z' and W'.

Most extensions of the MSSM have in common that they come together with an extended Higgs sector. I'll give therefore an overview about the most popular extensions of the MSSM Higgs sector in the next section before I comment in sec. 3 on tools which can be used to study these and many other models.

2. Overview about non-minimal Higgs sectors

Extending the Higgs sector of the MSSM can have several consequences: (i) additional contributions to the Higgs mass can be present; (ii) the MSSM doublets mix with other states what will change the character of the 'SM-like' Higgs boson; (iii) as consequence of this mixing the

couplings of *the* Higgs can be modified compared to SM expectations; (iv) additional light scalars with a reduced couplings to SM particle can be present; (v) additional charged and also double charged bosons can appear.

What happens and how important an effect is, depends on the concrete model. Therefore, I'm going to discuss briefly the most important MSSM extensions in the following. I categorize the extension into two groups: (i) models with the SM gauge sector, (ii) models with an extended gauge sector, and start with the first one.

2.1 Models with SM gauge sector

I start with models which don't extend the gauge sector of the MSSM and consider in this case in particular singlet and triplet extensions as well as models with Dirac gauginos. Of course, there are many models which I'll have to skip, e.g. the DiracNMSSM [24, 25], models with a PQ-symmetry [23], models with bilinear R-parity violation [26, 27], sister Higgs models [28], models with a gauged R-symmetry [29] and many more. I'll always assume that the superpotential is decomposed as $W = W_Y + W_X$, where W_Y contains the Yukawa and W_X the Higgs part for a given model. In the MSSM W_X corresponds to

$$W_{MSSM} = \mu \, \hat{\mathbf{H}}_{\mathbf{d}} \, \hat{\mathbf{H}}_{\mathbf{u}} \,. \tag{2.1}$$

2.1.1 Singlet extensions

The simplest ansatz to go beyond the MSSM is to add a superfield which is a gauge singlet. The general superpotential for the Higgs sector with all renormalizable terms allowed by gauge invariance reads

$$W_S = t_S \hat{\mathbf{S}} + \mu_S \hat{\mathbf{S}}^2 + \kappa \hat{\mathbf{S}}^3 + \mu \, \hat{\mathbf{H}}_{\mathbf{d}} \, \hat{\mathbf{H}}_{\mathbf{u}} + \lambda \, \hat{\mathbf{S}} \hat{\mathbf{H}}_{\mathbf{d}} \, \hat{\mathbf{H}}_{\mathbf{u}} \,. \tag{2.2}$$

Usually, one proposes a discrete symmetry to forbid some of the these terms. The most studied assumption is the next-to-minimal supersymmetric standard model (NMSSM) with a Z_3 which forbids all dimension-full parameters: $t_S = \mu_S = \mu = 0$, see [4, 5] and references therein. Other possibilities are the near-to-minimal SSM (nMSSM) with a Z_5^R ($\mu_S = \mu = \kappa = 0$) [30, 31] and the general NMSSM (GNMSSM) with a Z_8^R ($t_S = 0$) [32–34]. All realizations have in common that they predict additional F-term contributions to the tree-level Higgs to evade the condition $m_h^{Tree} < m_Z$ known from the MSSM. The tree-level mass in singlet extensions can be approximated as

$$m_h^{2,Tree} = m_Z^2 \cos^2 2\beta + \frac{\lambda^2}{2} v^2 \sin^2 2\beta \,, \tag{2.3}$$

and in the limit of very small $\tan\beta < 3$ and large $\lambda > 0.5$ one finds that m_h^{Tree} can be easily above 100 GeV because of the second term. λ is usually assumed to be below 0.65 to have a theory which is perturbative up to the GUT scale. If this is given up, even larger λ couplings are possible [35]. The enhanced tree-level mass relaxes significantly the necessity of large loop corrections via (s)tops and renders such models a more natural candidate for BSM physics. One can quantify the naturalness of a model with respect to a set of independent parameters, p, by considering a fine-tuning (FT) measure like [36, 37]

$$\Delta \equiv \max \text{Abs}\left[\Delta_p\right], \qquad \Delta_p \equiv \frac{\partial \ln v^2}{\partial \ln p} = \frac{p}{v^2} \frac{\partial v^2}{\partial p} \,. \tag{2.4}$$
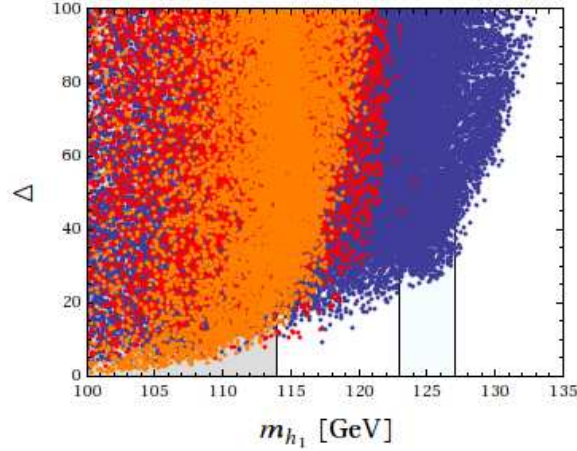
Figure 1: Fine-tuning Δ in the MSSM (orange) and GNMSSM (blue) in a fully constrained model. Plot taken from Ref. [38]

It has been shown that the NMSSM improves significantly the FT compared to the MSSM [39–43]. Moreover, going to the GNMSSM reduces the FT even further [34,38,44], see also Fig. 1 for a comparison of the FT in a constraint version of the MSSM and GNMSSM as function of m_h.

From a phenomenological point of view already the extension by just one singlet superfield can have profound consequences: new decay channels for the SM-like Higgs can appear (e.g. $h \to AA/HH \to 4b/4\tau/2b2\tau$) [45–47]. Also couplings to SM particles can be altered significantly: there is for instance the possibility to change the effective $h\gamma\gamma$ coupling either due to a mixing with the singlet or by chargino loops enhanced by large λ [48–51]. If the singlinos and the singlet have masses of only a few GeV, this can help to hide SUSY at the LHC because it reduces the missing transversal energy ($\not{E}_T$) to a level below the one needed for many SUSY searches [52]. On the other side new search strategies for charged Higgs fields are possible by considering the cascade $t \to bH^- \to bW^-H/A \to bW^-\gamma\gamma$ [53].

2.1.2 Triplet extensions

In the case of triplet extensions, one can consider either a model with only one triplet which doesn't carry hypercharge ($\hat{\mathbf{T}}$, $Y = 0$) or a model with two triplets with hypercharge ($\hat{\mathbf{T}}_1$, $\hat{\mathbf{T}}_2$, $Y = \pm 1$). The different terms in the superpotential of the two models read [54–57]

$$W_{T1} = \mu_T \text{Tr}(\hat{\mathbf{T}}^2) + \lambda_T \, \hat{\mathbf{H}}_\mathbf{d} \, \hat{\mathbf{T}} \, \hat{\mathbf{H}}_\mathbf{u} + \mu \, \hat{\mathbf{H}}_\mathbf{u} \, \hat{\mathbf{H}}_\mathbf{d} \,, \tag{2.5}$$

$$W_{T2} = \mu_T \text{Tr}(\hat{\mathbf{T}}_\mathbf{1} \hat{\mathbf{T}}_\mathbf{2}) + \lambda_u \, \hat{\mathbf{H}}_\mathbf{u} \, \hat{\mathbf{T}}_\mathbf{1} \, \hat{\mathbf{H}}_\mathbf{u} + \lambda_d \, \hat{\mathbf{H}}_\mathbf{d} \, \hat{\mathbf{T}}_\mathbf{2} \, \hat{\mathbf{H}}_\mathbf{d} + \mu \, \hat{\mathbf{H}}_\mathbf{u} \, \hat{\mathbf{H}}_\mathbf{d} \,. \tag{2.6}$$

In general, triplet extensions share many features with singlet extensions: there is a F-term enhancement to the Higgs mass, the Higgs branching ratios can be affected by the presence of the new particle(s) and new cascade decays compared to the MSSM can arise. A feature compared to singlet extensions is the presence of additional charged Higgs bosons. For the model with two triplets even double-charged Higgs bosons appear. Finally, triplet extensions affect the ρ parameter what constraints the parameter values in this kind models. If the triplets get non-vanishing vacuum expectation values (VEVs), ρ is already shifted at tree-level, i.e. triplet VEVs must be very small.

At one-loop one finds limits on combinations of (λ_T, μ_T) [58]. Unfortunately, both kinds of triplet extensions spoil the nice feature of gauge coupling unification.

2.1.3 Singlet/Triplet extensions

One can also combine the two ideas and consider a model with triplets and a singlet at the same time [59]:

$$W_{ST} = \lambda_T \hat{\mathbf{S}} \text{Tr}(\hat{\mathbf{T}}_{\mathbf{1}} \hat{\mathbf{T}}_{\mathbf{2}}) + \lambda_S \hat{\mathbf{S}} \hat{\mathbf{H}}_{\mathbf{u}} \hat{\mathbf{H}}_{\mathbf{d}} + \kappa \hat{\mathbf{S}}^3 + \lambda_u \hat{\mathbf{H}}_{\mathbf{u}} \hat{\mathbf{T}}_{\mathbf{1}} \hat{\mathbf{H}}_{\mathbf{u}} + \lambda_d \hat{\mathbf{H}}_{\mathbf{d}} \hat{\mathbf{T}}_{\mathbf{2}} \hat{\mathbf{H}}_{\mathbf{d}} . \tag{2.7}$$

The advantage of this setup is that the μ-problem for the triplets gets solved, too. In addition, one can easier keep $\delta\rho$ under control.

It's a matter of taste if this is enough motivation to assume the presence of both extensions. However, there is also a kind of models which *predicts* the presence of singlets and triplets instead of adding them ad-hoc: SUSY models with Dirac gauginos, which I'm going to discuss now.

2.1.4 Models with Dirac gauginos

In general, there are two possibilities to generate mass terms for gauginos λ:

$$M_M \lambda \lambda \qquad M_D \lambda \Psi \tag{2.8}$$

M_M is a Majorana mass term, while M_D is a Dirac mass term due to the interaction with a superfield Ψ in the adjoint representation [60–64]. Dirac mass terms are theoretical well motivated because they are a consequence of $N = 2$ SUSY. In contrast to Majorana masses Dirac masses are also consistent with an R-symmetry. Thus, if one assumes an underlying R-symmetry which forbids Majorana masses, singlet, triplet and octet superfields are needed to generate masses for all gauginos. Not only the Majorana masses are forbidden by the R-symmetry, but also trilinear soft-terms as well as bilinear terms in the superpotential. These constraints give this kind of models a new character compared to the extensions before because one adds not only new properties but also forbids feature of the MSSM. Therefore, models with Dirac gauginos can differ significantly from the MSSM: (i) the cross sections of colored SUSY states can be suppressed by the Dirac character of the gluino [65–68]; (ii) the constraints from flavor physics get relaxed [69, 70]; (iii) because of the supersoftness of the theory the RGEs especially for scalar soft masses change significantly and the mass pattern appearing in a constrained model are completely different to those in the CMSSM [71–73].

Broken R-Symmetry in Higgs sector If one just adds the superfields $\hat{\mathbf{S}}$, $\hat{\mathbf{T}}$ and $\hat{\mathbf{O}}$ which are necessary to generate Dirac gaugino masses, R-symmetry in the Higgs sector has to be broken. This happens by assuming that a subset of the following, R-symmetry violating terms is present [74]

$$W_{\not{R}} = (\lambda_S \hat{\mathbf{S}} + \mu) \hat{\mathbf{H}}_{\mathbf{u}} \hat{\mathbf{H}}_{\mathbf{d}} + \lambda_T \hat{\mathbf{H}}_{\mathbf{d}} \hat{\mathbf{T}} \hat{\mathbf{H}}_{\mathbf{u}} + \kappa \hat{\mathbf{S}}^3 . \tag{2.9}$$

Even if these terms violate R-symmetry they neither introduce Majorana masses nor trilinear soft-terms. Therefore, the radiative corrections of (s)tops to the Higgs are largely suppressed compared to the MSSM with large stop mixing. Thus, it is either necessary to have very heavy stops in the multi TeV range or to enhance the Higgs mass already at tree-level via the additional F-term

known from the NMSSM by choosing large λ and small $\tan\beta$. Another consequence of Dirac mass terms is the presence of new D-terms of the form $M_D\tilde{\Psi}^a\phi^*T^a\phi$ (T^a are the generators of the gauge groups). The corresponding $U(1)_Y$, $SU(2)$ terms give negative contributions to the tree-level Higgs mass. Thus, the bino and wino Dirac mass is usually assumed not to be too large.
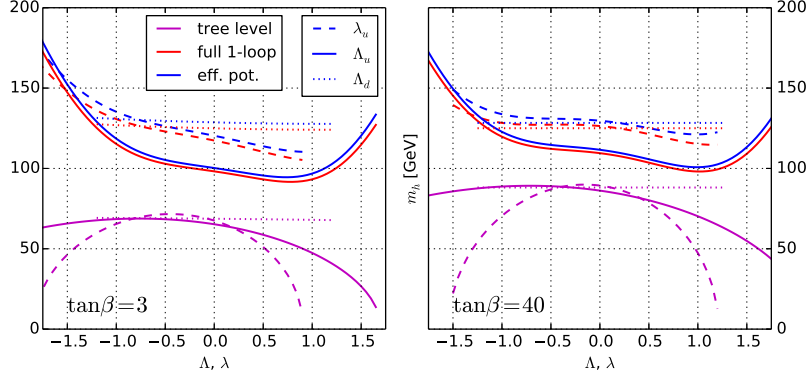
Figure 2: Lights Higgs mass in the MRSSM at tree-level and one-loop as function of the new λ/Λ couplings in the superpotential. Plots are an updated version of the ones of Ref. [76] and were kindly provided by Wojciech Kotlarski.

Unbroken R-Symmetry   If R-symmetry is taken to be unbroken, the Higgs sector has to be extended by two doublets $\hat{\mathbf{R}}_\mathbf{u}$ and $\hat{\mathbf{R}}_\mathbf{d}$ which allow to write down R-symmetric μ-terms [69].

$$W_R = (\mu_u + \lambda_u\hat{\mathbf{S}})\,\hat{\mathbf{H}}_\mathbf{u}\,\hat{\mathbf{R}}_\mathbf{u} + (\mu_d + \lambda_d\hat{\mathbf{S}})\,\hat{\mathbf{H}}_\mathbf{d}\,\hat{\mathbf{R}}_\mathbf{d} + \Lambda_d\,\hat{\mathbf{R}}_\mathbf{d}\,\hat{\mathbf{T}}\,\hat{\mathbf{H}}_\mathbf{d} + \Lambda_u\,\hat{\mathbf{R}}_\mathbf{u}\,\hat{\mathbf{T}}\,\hat{\mathbf{H}}_\mathbf{u}. \tag{2.10}$$

This is the minimal-R-symmetric SSM (MRSSM) and it has many additional differences compared to the MSSM. For instance, it predicts an asymmetric dark matter candidate because the neutralinos are also Dirac states. Since there is no λ-term to enhance the Higgs mass, the tree-level mass is usually lighter than in the MSSM [75]

$$m_h^2 \simeq M_Z^2\cos^2 2\beta - v^2\left(\frac{(g_1M_D^B + \sqrt{2}\lambda\mu)^2}{(4(M_D^B)^2 + m_s^2)} + \frac{(g_2M_D^W + \Lambda\mu)^2}{(4(M_D^W)^2 + m_T^2)}\right) \tag{2.11}$$

This effect together with the reduced (s)top corrections is not necessarily a big problem as one might think: loop corrections proportional to $\lambda_{d,u}$ or $\Lambda_{d,u}$ can be used to push the Higgs mass to 125 GeV as shown in Fig. 2. Also in the charged Higgs sector this model is very interesting: it predicts not only three charged Higgs particles but also two additional charged R-Higgs fields. The phenomenology of these new charged states is hardly explored at the moment.

2.2 Models with extended gauge sector

Extending the SM gauge sector

$$G_{SM} = SU(3)_c \times SU(2)_L \times U(1)_Y \tag{2.12}$$

introduces not only additional gauge bosons but also scalars to break the new gauge group. The easiest extensions are those with a single $U(1)$. However, GUT theories like $SO(10)$ predict often

6

also additional $SU(N)$ groups and in string models multiple $U(1)$'s can be present. These additional groups can be in principle be broken at any scale close to or significantly above the TeV range. I'm going to concentrate here on scenarios where this breaking happens at energies which can be probed in the near future directly at colliders. For higher breaking scales only indirect probes like from flavor observables are possible [77].

2.2.1 $U(1)$ extensions

There are many different realizations for $G_{SM} \times U(1)_X$ with $X = \chi, R, B-L, N, \eta, Y, S, I, \not{p}, \ldots$, see for instance Refs. [78] and references therein. The concrete gauge group is often fixed by the underlying string or GUT theory one has in mind. The kind of $U(1)$ does not only fix the couplings of the Z' but also the interactions of the new Higgs states. In general, $U(1)$ extensions have a very interesting phenomenology: (i) they predict a Z' boson which usually couples to SM fields; (ii) they could explain origin of R-parity and its spontaneous breaking [79, 80]; (iii) the absence of gauge anomalies predicts often right handed neutrinos and introduces therefore neutrino masses; (iv) many new dark matter candidates appear which not necessarily rely on the annihilation mechanisms known from the MSSM [81]; (v) the cross section of SUSY particles change compared to the MSSM [82]; (vi) $U(1)$ extensions might help to resurrect gauge mediated SUSY breaking (GMSB) [83, 84].

Even if the new scalars $\hat{\chi}$ to break the gauge additional gauge symmetries are gauge singlets under the SM gauge groups, the superpotential and the interactions with the MSSM doublets can be very different compared to the NMSSM because terms like $\hat{\chi}^3$, $\hat{\chi} \hat{\mathbf{H}}_{\mathbf{d}} \hat{\mathbf{H}}_{\mathbf{u}}$ are forbidden by the new gauge symmetry. However, D-term interactions between both sectors can even arise due to kinetic mixing even if the Higgs and $\hat{\chi}$ fields are not charged under the same gauge groups [85]. Kinetic mixing will always be generated by RGE running if the two $U(1)$s are not orthogonal [86], but it has only a moderate effect on the Higgs masses and couplings [87]. The effects are more pronounced if there are direct D-term interactions like in $U(1)_R \times U(1)_{B-L}$ models [8, 88]. In this case the additional D-terms as well as the mixing with additional light scalars can give a large push to the Higgs mass as shown in Fig. 3.
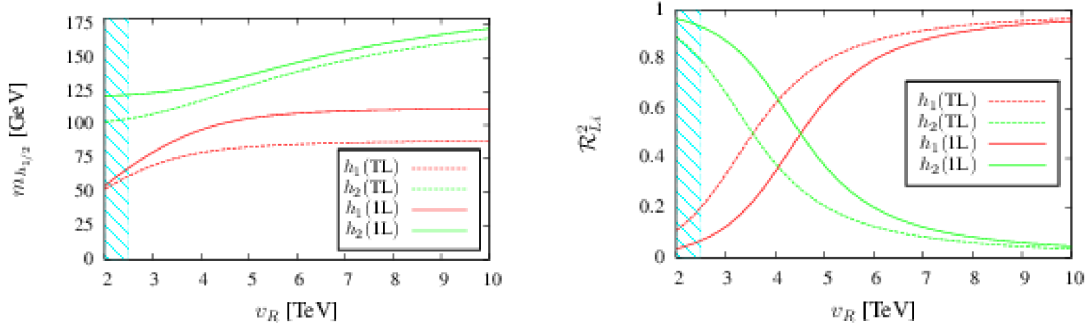
Figure 3: Masses (left) and doublet-fraction (right) of the two lightest scalars in a $U(1)_R \times U(1)_{B-L}$ model at tree-level and one-loop. Plots taken from Ref. [8]

2.2.2 $SU(N)$ extensions

Additional $SU(N)$ are often motivated by $SO(10)$ GUTs. The GUT groups gets broken down

to to the SM gauge sector via the cascade

$$
\begin{aligned}
SO(10) \quad &\to SU(4)_{PS} \times SU(2)_L \times SU(2)_R \\
&\to SU(3)_c \times SU(2)_L \times SU(2)_R \times U(1)_{B-L} \\
&\to SU(3)_c \times SU(2)_L \times U(1)_R \times U(1)_{B-L} \to G_{SM}
\end{aligned}
$$

Not always all intermediate steps are realized but it can be also be assumed that several steps happen at the same scale. This leads to three categories of models [89]: (i) Pati-Salam models, (ii) $SU(2)_L \times SU(2)_R$ models, (iii) $SU(2)_L \times U(1)_R$ models. Is has been shown that for each category many possible realizations exist which are consistent with gauge coupling unification, neutrino masses and a non-trivial CKM matrix [90]. See Fig. 4. All of these models have a very rich phenomenology because they predict many new states together with a Z' and W's. In particular, new charged or even double charged Higgs bosons are a widely spread feature in these models.
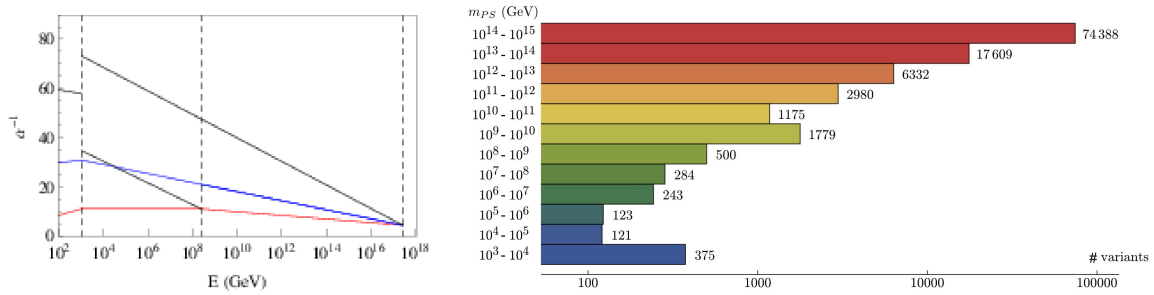
Figure 4: Left: Gauge coupling unification in $SO(10)$ models with an intermediate Pati-Salam scale. Plot taken Ref. [89]. Right: number of possible realization of such a model depending on the energy scale of the intermediate scale. Plot taken from [90].

The double charged Higgs bosons in left-right models have been studied to some extent and mass limits of $M_{H^{++}} > 445\,(409)$ GeV [CMS (ATLAS)] have been obtained [91,92]. Interestingly, there are also indirect constraints possible because M_H^{++} can be correlated with $\delta\rho$ [93]. For direct searches for double charged Higgs bosons multi-lepton channels are very promising [94].

3. Don'ts and Dos

There is sometimes a huge difference in the manner how a BMSSM study is performed compared to the MSSM. Therefore, I want to comment on some aspects of the analyses and list public computer tools which should be considered to be used to bring BMSSM studies to a level comparable with MSSM standards.

- **Tree-level Higgs masses in BMSSM models are not sufficient!** It is well known that the measured Higgs mass rules out large areas of the parameter space of the (natural) MSSM. Thus, also the Higgs sectors of BMSSM models have to be confronted with these limits. Thus, at least an one-loop calculation is mandatory to see if the Higgs mass is pushed into the correct direction. If the one-loop mass turns out to be well below 120 GeV, it makes no sense to further study that parameter point. One-loop calculations for a large range of BMSSM models can be either performed with `FeynArts`/`FormCalc` [95–97]. Also the

package `SARAH` [98] together with either `SPheno` [99, 100] or `FlexibleSUSY` [101] can be used what provides a highly automatized calculation of loop masses.

- **To get MC model files don't hack the MSSM one.** There are well established tools like `LanHEP` [102], `FeynRules` [103, 104], or `SARAH` to create model files for many Monte Carlo tools.

- `HiggsBounds`/`HiggsSignals` **[105–107] should always be used to check existing limits from Higgs searches and to give a quantative measure how good experimental data is reproduced.**. These codes are generic enough to deal with highly extended Higgs sectors if the user provides the necessary input.

- **Check the vacuum stability.** It has been shown that the MSSM with light stops but a large mixing to explain the Higgs mass suffers from an unstable, and often short-lived electroweak vacuum [108–112]. To check the stability of the desired vacuum, the tool `Vevacious` [113] was created.

- **Don't forget about flavor physics.** Especially light, charged Higgs particles can be dangerous because they can significantly enhance observables like $b \to s\gamma$. The `FlavorKit` interface [114] allows to calculate many flavor observables in BMSSM models via the combination `FeynArts`/`FormCalc`– `SARAH`– `SPheno`. Alternatively, one can also use `FeynArts` & `FormCalc` either stand-alone or coupled to `Peng4BSM` [115].

One easy possibility for a precise study of BMSSM models is to use the `SUSY` or `BSM Toolbox` [116]. This is a collection of scripts which creates an environment consisting of `SARAH`, `SPheno`, `WHIZARD` [117, 118], `MadGraph` [119, 120] `HiggsBounds`/`HiggsSignals`, `CalcHep` [121, 122], `MicrOmegas` [123] and `SSP` for the study of extended SUSY and non-SUSY models. Many of the models shown here are already delivered with `SARAH` and can be automatically implemented in all other tools via the `Toolbox` scripts. In this context the `SPheno` modules created for the new models provide a precise mass spectrum calculation based on two-loop RGE running and full one-loop corrections to all masses. An extensions for even a two-loop calculation in the Higgs sector is expected to appear soon [124]. `SPheno` does also calculate two and three body decays for the SUSY states present in the models and makes predictions for many flavor observables based on a full one-loop calculation. The scripts can be downloaded here

$$\texttt{http://sarah.hepforge.org/Toolbox.html}$$

4. Conclusion

I have briefly summarized the main aspects of SUSY models beyond the MSSM. One can see that there are many well motivated possibilities to go beyond the MSSM. Each of the presented model has its peculiarities. While some models are already studied in great detail, others lack from a deep exploration. However, there are nowadays the tools available to perform precise studies in all models and to confront these models with experimental and theoretical constraints.

Acknowledgments

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