Beyond-MSSM Higgs sectors

Florian Staub

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Outline

Introduction

The MSSM has been the top candidate for BSM physics for many years. However, there are good reasons to look beyond the MSSM.

- Higgs mass/Naturalness → F- or D-term enhanced mass?
- Missing signals for SUSY at LHC
  → non-SUSY BSM? compressed spectra? RpV? split-SUSY? ...
- Neutrino masses → R-parity violation? Seesaw mechanism?
- The μ problem → effective μ term?
- Strong CP problem → (gauged?) Peccei-Quinn symmetry?
- GUT/String model → extended gauge sector?
- ...

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- GUT/String model → extended gauge sector?
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Extended Higgs sectors

Many extensions of the MSSM come together with additional Higgs fields

What usually happens

Effects of an extended Higgs sector

1. Additional contributions to the Higgs mass can be present.
2. The MSSM doublets mix with other states
3. The couplings of *the* Higgs get modified and new couplings might arise
4. New, light scalars with suppressed couplings to SM states can show up
5. New charged and also double charged Higgs bosons can be present

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The extensions of the MSSM can be categorized as

1. Models with SM gauge sector
2. Models with extended gauge sector

Models with SM gauge sector

The easiest extensions of the MSSM are

- Singlet extensions (NMSSM, nMSSM, SMSSM, GNMSSM)
- Triplet extensions (TMSSM)

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- Singlet/Triplet extensions (TNMSSM)

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- Dirac gaugino models with broken R-symmetry in the Higgs sector (MDGSSM)
- R-symmetric models (MRSSM)

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Unfortunately, I have no time to speak about bilinear RpV, DiracNMSSM, PQ-models, Sister Higgs models, ...

Singlet extensions I

The most general (renormalizable) superpotential of models with one additional singlet is

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

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Different symmetries can be assumed to forbid some of these terms:

- Z_3: $t_S = \mu_S = \mu = 0$ (NMSSM)
- Z_5: $\mu_S = \mu = \kappa = 0$ (nMSSM)
- Z_8^R: $t_S = 0$ (GNMSSM)

Also other parameter combinations are considered sometimes (e.g. $t_s = \kappa = 0$) without referring to a fundamental symmetry.

Singlet extensions II

Singlet extensions give a push at tree-level to the Higgs mass

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

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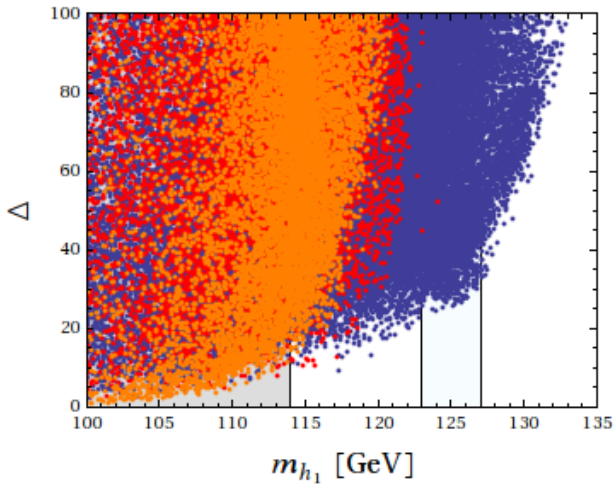
- improved fine-tuning



(blue: GNMSSM, orange: MSSM [Ross,Schmidt-Hoberg,FS,1205.1509])

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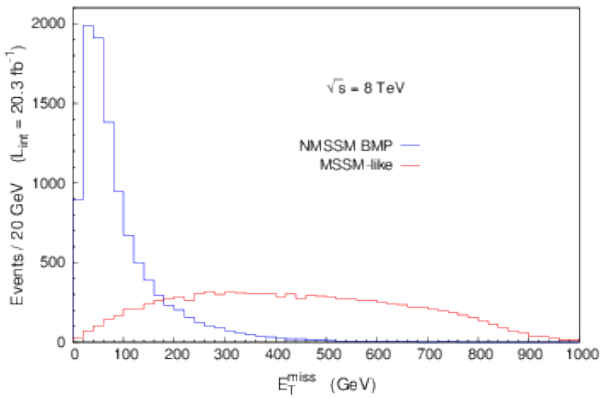
- New decay channels of Higgs fields

  $(h \to AA/HH \to 4b/2b2\tau/4\tau)$ [Stal, Weiglein,1108.0595]
- Light singlinos could significantly reduce $\not{E}_T$ and hide SUSY [Ellwanger,Teixeira,1406.7221]



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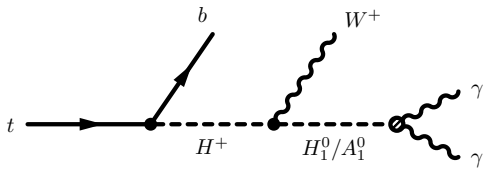
- Mixing with singlets or large λ can change BR (especially diphoton rate)

  [Ellwanger,1112.3548],[Schmidt-Hoberg,FS,1208.1683]
- New search strategies for H^+

  [Das,Mitzka,Porod,1408.1704]



Triplet extensions

One can consider either models with **one** triplet ($\hat{\mathbf{T}}$, $Y = 0$) or **two** triplets ($\hat{\mathbf{T}}_\mathbf{1}$, $\hat{\mathbf{T}}_\mathbf{2}$, $Y = \pm 1$)

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

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

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- Share many features with singlet extensions (F-term enhancement, changes in Higgs BR and possible cascade decays)
- Predict additional charged and double charged (for $Y = \pm 1$) Higgs particles
- Triplet extensions have in common that they can give large corrections to ρ parameter:

  $\rightarrow$ constraints on v_T and/or λ_T

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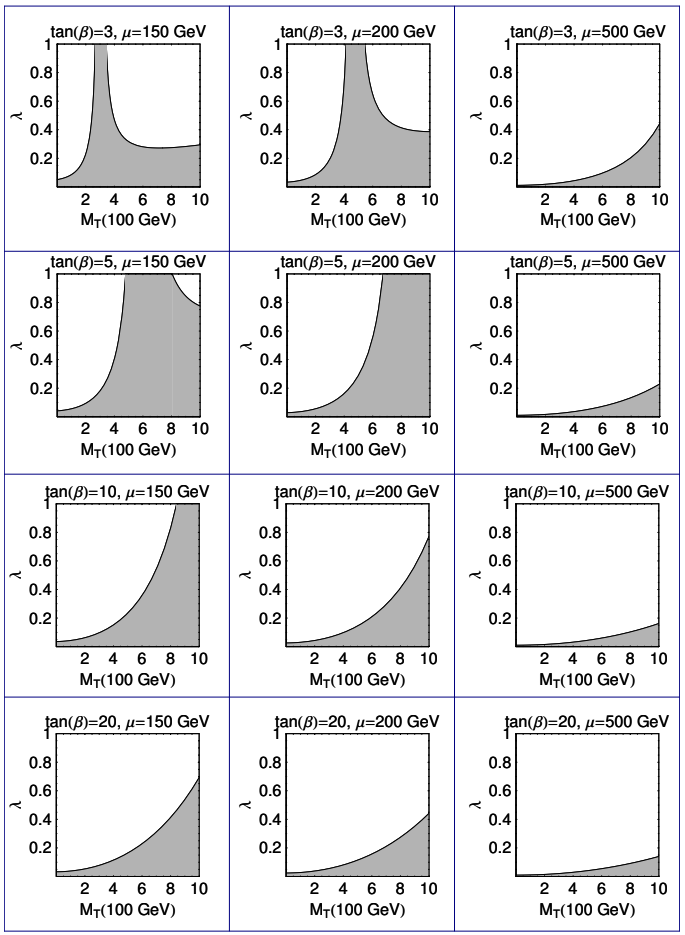

[Di Chiara, Hsieh,0805.2623]

Singlet/Triplet extensions

One can combine the ideas and consider [Agashe et al., 1109.2842]

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- Solves μ-problem of triplets
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In models with **Dirac gauginos**, the presence of singlets and triplets is well motivated...

Models with Dirac gauginos I

- Two possible mass terms for gauginos λ:

$$\text{Majorana: } M_M \lambda\lambda\,, \qquad \text{Dirac: } M_D \lambda\Psi$$

(Ψ superfield in adjoint representation)

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- Dirac mass terms are theoretical well motivated:

[Fayet; Hall&Randall; Polchinski&Susskind; Fox,Nelson&Weiner; Antoniadis,Benakli,Delgado&Quiros;...]

  - Consequence of $N = 2$ SUSY
  - Consistent with R-symmetry (in contrast to Majorana terms)
  - Predict singlet ($\hat{\mathbf{S}}$), triplet ($\hat{\mathbf{T}}$) and color octet ($\hat{\mathbf{O}}$)

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- Dirac masses have interesting phenomenological aspects
  - Suppressed cross section for colored SUSY particles

    [Heikinheimo,Kellerstein,Sanz,1111.4322], [Kribs,Martin,1203.4821]
  - Relaxed constraints from flavor physics [Kribs,Poppitz,Weiner,0712.2039]
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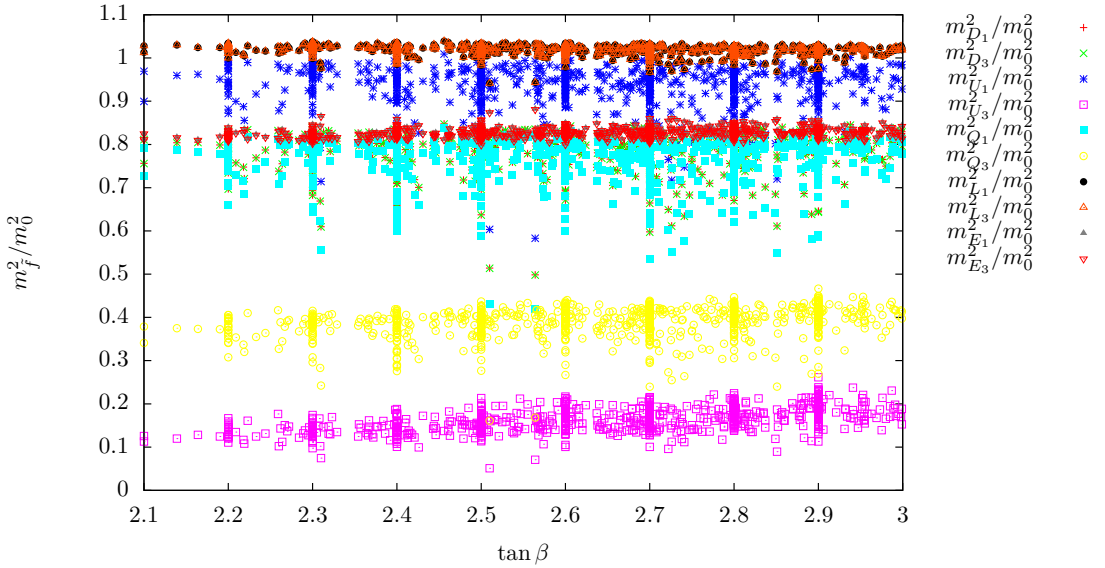

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Models with Dirac gauginos II

R-symmetry forbids many terms

- Majorana mass terms and trilinear soft-terms (A_t!)
- Bilinear terms in the superpotential ($\mu_S \hat{\mathbf{S}}^2, \mu_T \hat{\mathbf{T}}^2, \dots$)

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However, a consistent Higgs sector demands either additional superfields or R-symmetry breaking in Higgs sector, e.g.

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

- Majorana gaugino masses and trilinear soft-terms remain zero
  $\rightarrow$ Model still 'supersoft'
  $\rightarrow$ Stop corrections small and large λ & small $\tan\beta$ needed to explain Higgs mass
- Dirac mass terms give **negative** contributions to Higgs mass
  $\rightarrow$ can't be too large

Models with Dirac gauginos III

If R-symmetry should be unbroken, the Higgs sector has to be extended by two doublets $\mathbf{\hat{R}_u}$, $\mathbf{\hat{R}_d}$

$$\begin{aligned} W_R &= (\mu_u + \lambda \mathbf{\hat{S}})\, \mathbf{\hat{H}_u}\, \mathbf{\hat{R}_u} + (\mu_d + \lambda_d \mathbf{\hat{S}})\, \mathbf{\hat{H}_d}\, \mathbf{\hat{R}_d} \\ &\quad + \Lambda_d\, \mathbf{\hat{R}_d}\, \mathbf{\hat{T}}\, \mathbf{\hat{H}_d} + \Lambda_u\, \mathbf{\hat{R}_u}\, \mathbf{\hat{T}}\, \mathbf{\hat{H}_u} \end{aligned}$$

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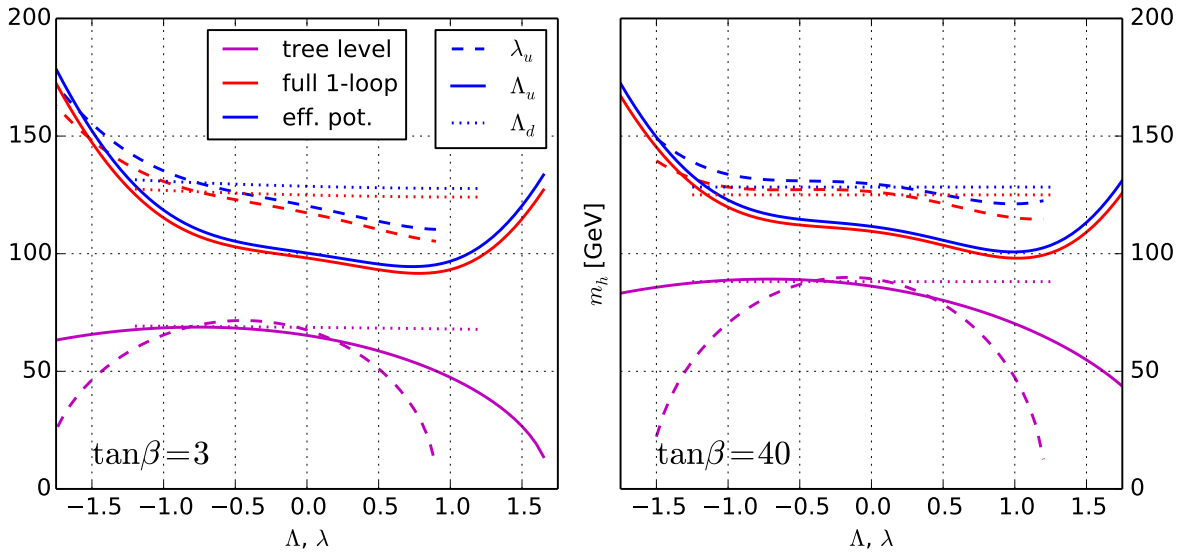

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- 3 charged Higgs and 2 charged R-Higgs

Models with extended gauge sector

Extending the SM gauge sector

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

introduces not only additional gauge bosons but also scalars to break the new gauge group.

- The easiest extensions come with one additional $U(1)$
- GUT theories predict often even more gauge groups and also $SU(N)$s

Additional gauge groups can arise at any scale

Phenomenological most interesting are those with new vector bosons in the TeV range

$U(1)$ extensions I

There are many different realizations for $G_{SM} \times U(1)_X$ with $X = \chi, R, B-L, N, \eta, Y, S, I, \not{\phi}, \ldots$. [Erler et al,1103.2659]

- consequences of many GUT or string models
- the kind of $U(1)$ does not only fix the couplings of the Z' but also the interactions of the new Higgs states

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A few aspects of $U(1)$ models

- Z' phenomenology — see e.g. works by Erler, Langacker, Munir,...
- Could explain origin of R-parity [Perez,Spinner,1005.4930]
- Absence of gauge anomalies demand often right neutrinos
- Many new DM candidates [Basso et al.,1207.0507]
- Changed cross-sections of SUSY states [Krauss et al.,1206.3513]
- Might help to resurrect GMSB [Mummidi,Vempati,1311.4280]

$U(1)$ extensions II

The new Higgs states ($\hat{\mathbf{\Phi}}$) are usually SM singlets, but

- many superpotential terms ($\hat{\mathbf{\Phi}}^3$, $\hat{\mathbf{\Phi}}\,\hat{\mathbf{H}}_\mathbf{d}\,\hat{\mathbf{H}}_\mathbf{u}$) are forbidden by gauge invariance $\rightarrow$ large differences to NMSSM!
- D-term interactions between $\hat{\mathbf{H}}_\mathbf{d}$, $\hat{\mathbf{H}}_\mathbf{u}$ and $\hat{\mathbf{\Phi}}$ always possible if $U(1)$s not orthogonal (gauge kinetic mixing)

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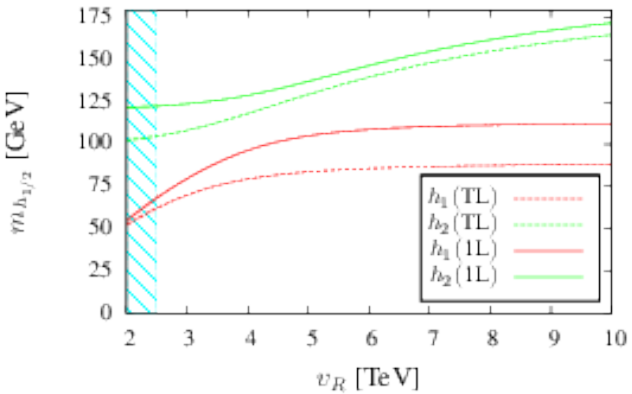
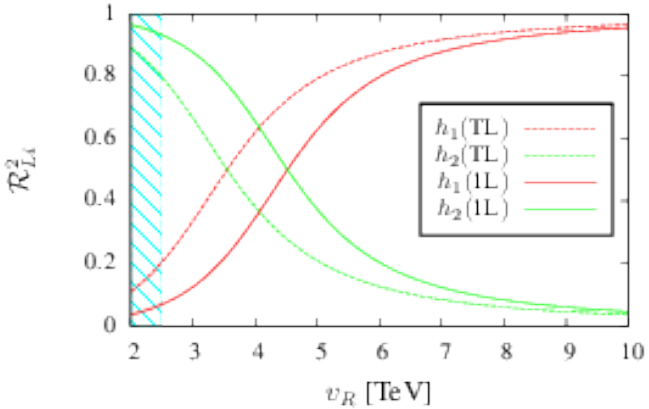
- D-term enhancement to tree-level Higgs mass possible
- Mixing with additional **light** scalars gives push to Higgs mass





[Hirsch et al, 1110.3037]

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- D-term enhancement to tree-level Higgs mass possible
- Mixing with additional **light** scalars gives push to Higgs mass
- Possible decays of Higgs in new states like sterile sneutrinos

$SU(N)$ extensions

Additional $SU(N)$ often motivated by $SO(10)$ GUTs

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SO(10) \quad & \to SU(4)_{PS} \times SU(2)_L \times SU(2)_R \\
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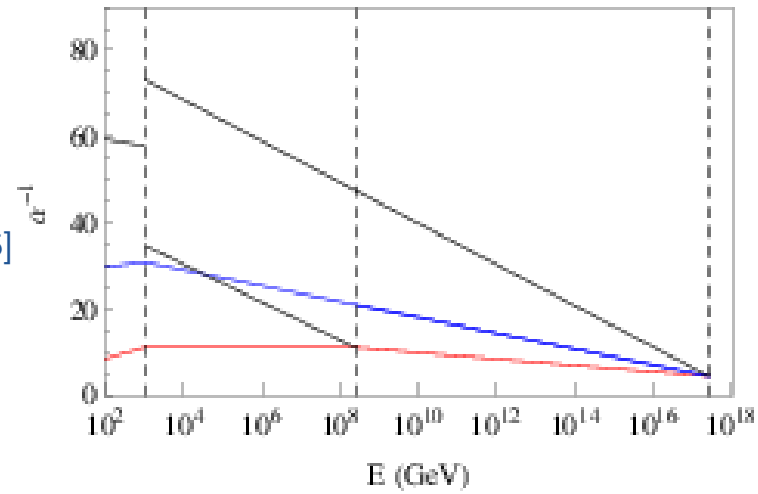
- Not always all intermediate steps are realized
- There are many models consistent with gauge coupling unification

[Arbelaez et al.,1301.6085]



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- Not always all intermediate steps are realized
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[Arbelaez et al.,1301.6085]

- Predict new charged and often double charged Higgs
- Rich phenomenology because of many new states together with Z' and W'

Superfield	$SU(3)_C \times SU(2)_L \times SU(2)_R \times U(1)$	S	M	H
$\psi = (\nu, e)$	$(1, 2, 1, -1/2)$	0	$-$	$+$
$\psi^c = (e^c, n^c)$	$(1, 1, 2, 1/2)$	$-1/2$	$-$	$+$
N	$(1, 1, 1, 0)$	0	$-$	$-$
n	$(1, 1, 1, 0)$	1	$-$	$+$
$Q = (u, d)$	$(3, 2, 1, 1/6)$	0	$-$	$+$
$Q^c = (h^c, u^c)$	$(3^*, 1, 2, -1/6)$	$1/2$	$-$	$+$
d^c	$(3^*, 1, 1, 1/3)$	0	$-$	$+$
h	$(3, 1, 1, -1/3)$	-1	$-$	$+$
Δ_1	$(1, 2, 2, 0)$	$1/2$	$+$	$+$
Δ_2	$(1, 2, 2, 0)$	$-1/2$	$+$	$+$
Φ_{L1}	$(1, 2, 1, -1/2)$	0	$+$	$+$
Φ_{L2}	$(1, 2, 1, 1/2)$	0	$+$	$+$
Φ_{R1}	$(1, 1, 2, -1/2)$	$-1/2$	$+$	$+$
Φ_{R2}	$(1, 1, 2, 1/2)$	$1/2$	$+$	$+$
η_{L1}	$(1, 2, 1, -1/2)$	0	$+$	$-$
η_{L2}	$(1, 2, 1, 1/2)$	0	$+$	$-$
η_{R1}	$(1, 1, 2, -1/2)$	$1/2$	$+$	$-$
η_{R2}	$(1, 1, 2, 1/2)$	$-1/2$	$+$	$-$
ζ_1	$(1, 1, 1, -1)$	0	$+$	$-$
ζ_2	$(1, 1, 1, 1)$	0	$+$	$-$
ζ_3	$(1, 1, 1, 0)$	0	$+$	$-$

[Bhattacharya et al.,1308.4177]

$SU(N)$ extensions II

Charged & double charged Higgs in SUSY LR

[Bambhaniya et al.,1311.4144,1408.0774]

- Limits of $M_{H^{++}} > 445\ (409)$ GeV CMS (ATLAS)

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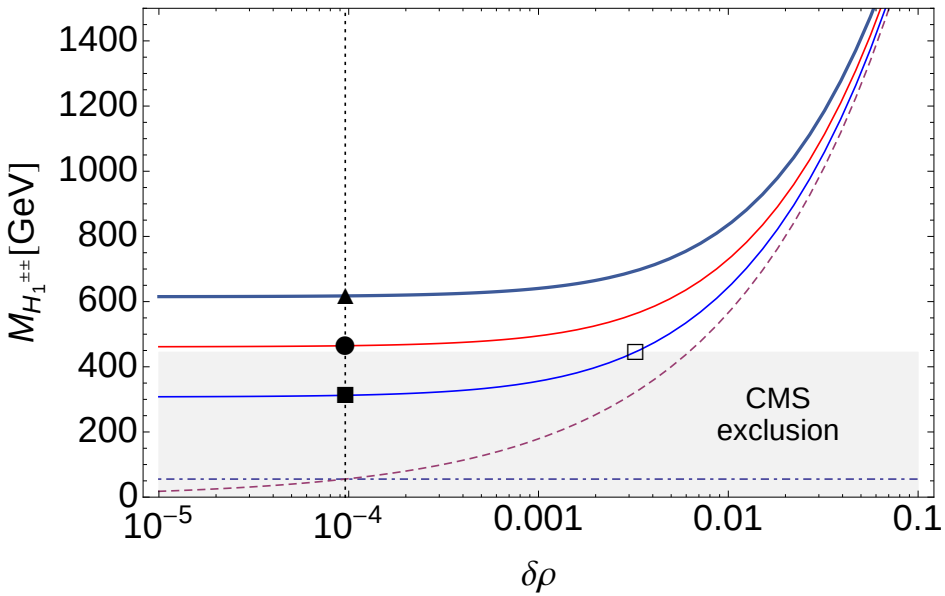

$M_A = 10, 15, 20$ TeV

$SU(N)$ extensions II

Charged & double charged Higgs in SUSY LR

[Bambhaniya et al.,1311.4144,1408.0774]

- Limits of $M_{H^{++}} > 445\ (409)$ GeV CMS (ATLAS)
- M_H^{++} often correlated with $\delta\rho$
- Often multi lepton processes with small SM background

Don'ts and Dos

Sometimes, BMSSM studies are done in a very simplistic way.

But ...

- **Tree-level Higgs masses in BMSSM models are not sufficient!** `FormCalc`, `SARAH`, `FlexibleSUSY` give loop masses
- **To get MC model files don't hack the MSSM one!** `LanHEP`, `FeynRules`, `SARAH` create model files for many tools
- `HiggsBounds`/`HiggsSignals` ~~**can**~~ **should always be used**
- **If you go to extreme parameter regions check the vacuum stability** You can use `Vevacious` for that
- **Don't forget about flavor physics: especially light, charged Higgs can be dangerous!** `FormCalc`/`FlavorKit`/`Peng4BSM` calculate flavor observables in BMSSM models

What you could do

BSM Toolbox . . . FS,Ohl,Porod,Speckner,1109.5147

. . . is a collection of scripts to create an environment including

- `SARAH` [FS,0806.0538,0909.2863,1002.0840,1207.0906,1309.7223]
- `SPheno` [Porod,hep-ph/0301101],[Porod,FS,1104.1573]
- `WHIZARD` [Kilian,Ohl,Reuter,0708.4233],[Moretti,Ohl,Reuter,0102195]
- `HiggsBounds/-Signals` [Bechtle et al.,1102.1898,1305.1933,1311.0055]
- `CalcHep` [Pukhov et al.,hep-ph/9908288,hep-ph/0412191,1207.6082]
- `MicrOmegas` [Belanger et al.,hep-ph/0405253,1004.1092,1305.0237,1407.6129]
- `MadGraph` [Alwall et al.,1106.0522,1405.0301]
- `SSP` [FS,Ohl,Porod,Speckner,1109.5147]

and to implement new models into the other tools based on the implementation in `SARAH`

What you could do

BSM Toolbox [FS,Ohl,Porod,Speckner,1109.5147]

The BSM toolbox is a collection of scripts to create an environment including SARAH, SPheno, WHIZARD, MadGraph HiggsBounds, CalcHep, MicrOmegas and SSP and to implement new models into the other tools based on the implementation in SARAH

- Many of the presented models are already implemented
- Provides two-loop running and one-loop corrections to all masses [1]
- Calculates many flavor observables via the FlavorKit

http://projects.hepforge.org/sarah/Toolbox.html

[1] soon even two-loop Higgs masses for BMSSM!

Conclusion

- There are many possibilities to extent the MSSM
- Many extensions come together with an extended Higgs sector
- A few extensions are already studied in great detail but others wait to be explored
- There exist nowadays the tools to study non-minimal models with a high precision