Non-minimal SUSY

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based on work with: [Peter Athron, Jaehyeon Park, Alexander Voigt; Tom Steudtner]

[Philip Diessner, Jan Kalinowski, Wojciech Kotlarski]

R-symmetry

[Philip Diessner, Jan Kalinowski, Wojciech Kotlarski]

Motivation,
Phenomenology

FlexibleSUSY

[Peter Athron, Jaehyeon Park, Alexander Voigt; Tom Steudtner]

M_h (preliminary, work in progress!!)

Outline

List of available spectrum generators

Model	Spectrum generator
MSSM	Softsusy, Spheno, Isasusy, SuseFlav, Suspect
NMSSM	NMSpec, Softsusy
CE_6SSM	$CE_6SSMSpec$
any SUSY model	Sarah [F. Staub], **FlexibleSUSY** [Athron, Park, DS, Voigt]

Current progress: resummation of $\geq$ 2-loop logs in m_h

[Steudtner, DS, Voigt]

Higgs mass is very important precision constraint on SUSY

- for heavy SUSY particles, loops dominated by $L \equiv \log \frac{M_{\text{SUSY}}}{M_{\text{weak}}}$

Two approaches

$$\text{fixed-order P.T.} = \text{tree} + \mathcal{O}(\alpha_i) + \mathcal{O}(\alpha_i^2) + \mathcal{O}(\alpha_i^3) + \ldots$$

$$\text{resummed logs} = \text{tree} + \mathcal{O}(\alpha_i^n L^n) + \mathcal{O}(\alpha_i^n L^{n-1}) + \ldots$$

MSSM programs: H3m, FeynHiggs, Softsusy, Spheno; SUSYHD ...

Standard FlexibleSUSY-MSSM = Softsusy

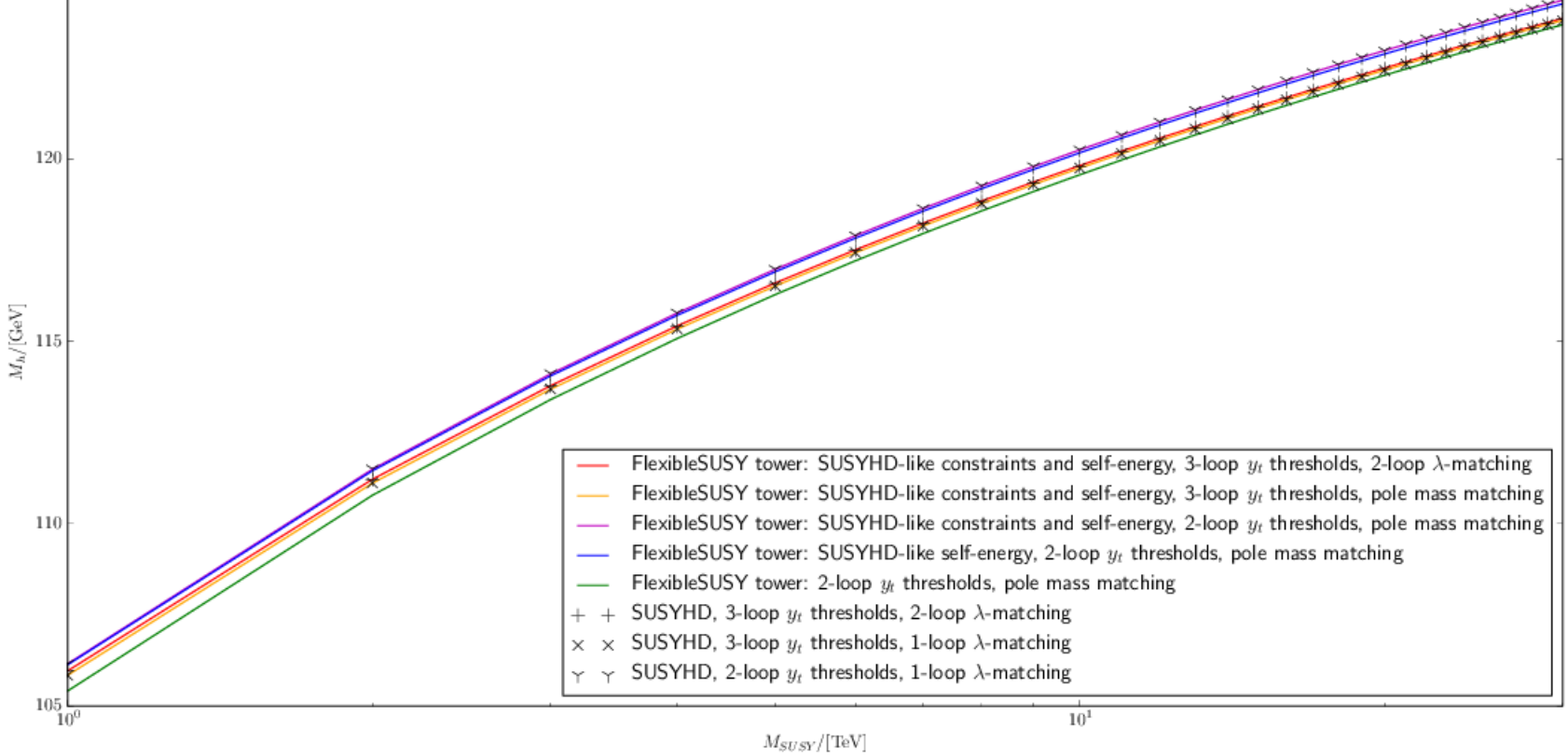
Aim: Implement resummation in FlexibleSUSY!

Current progress: resummation of $\geq$ 2-loop logs in m_h

[Steudtner, DS, Voigt]

Implement resummation in FlexibleSUSY using Tower of EFTs:

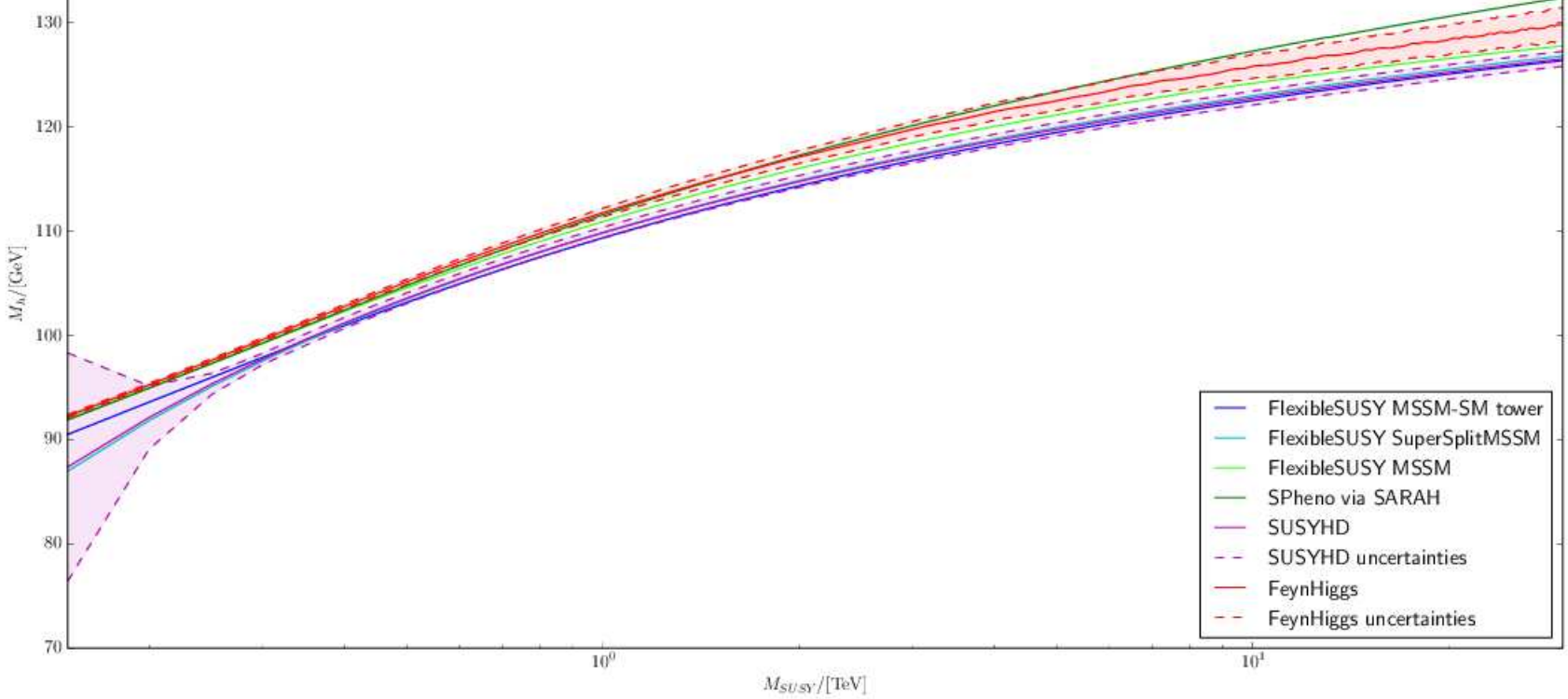
$\geq M_{\text{SUSY}}$:	SUSY model	
at M_{SUSY}:	match to SM	
	need 1-loop matching $(\lambda, y_t!)$	$\lambda^{\text{SM}}(M_{\text{SUSY}}) =\sim g^2 + \delta\lambda$
	$\updownarrow$	
$< M_{\text{SUSY}}$:	run in SM	
	need 2-loop SM β functions	$\frac{\mathrm{d}\lambda^{\text{SM}}(\mu)}{\mathrm{d}\ln\mu} = \beta_\lambda^{\text{SM}}(\mu)$
	$\updownarrow$	
at M_{weak}:	compute Higgs mass in SM	
	need 1-loop SM $\hat{\Sigma}_h$	$m_h^2 = \lambda^{\text{SM}}(M_{\text{weak}})v^2 + \hat{\Sigma}_h$
Then:	add non-log 1-loop terms	
	need full 1-loop SUSY $\hat{\Sigma}_h$	



- Validation: reproduce versions of SUSYHD [Vega, Villadoro '15] up to 2-loop matching and 3-loop running

  (here: 2-loop always without EW gauge couplings!)

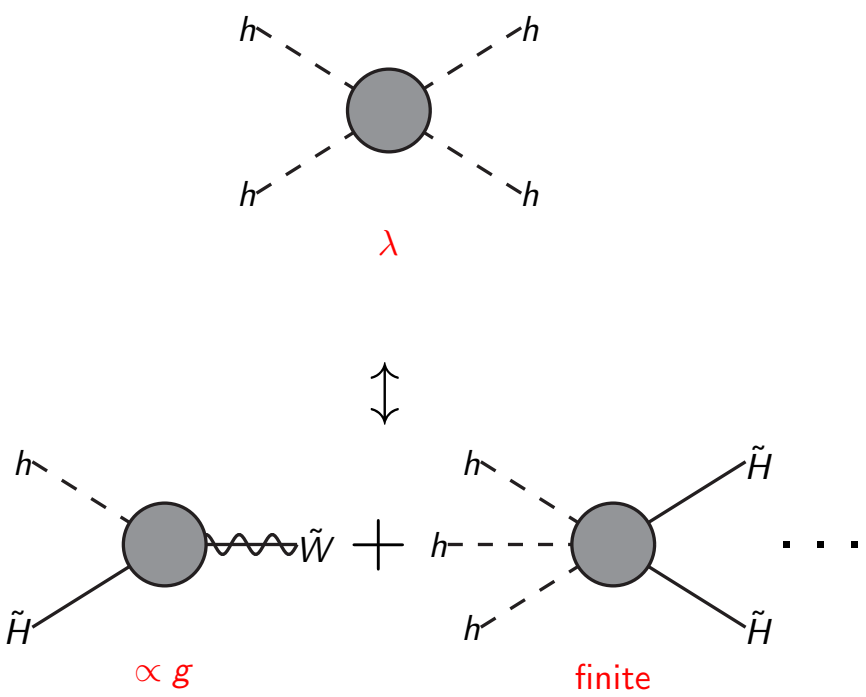
- remaining differences understood



Outlook:

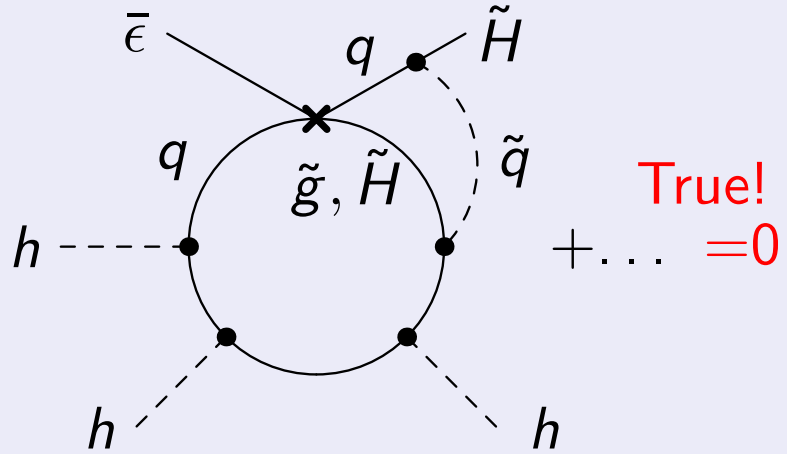
- MSSM: 2-loop matching + 3-loop running + explicit 2-loop result
  $\rightarrow$ help analyze/clarify differences between computations
- Other models: generate M_h calculation in NMSSM, R-symmetry, etc
  (first aim: 1-loop + $\geq$ 2-loop logs)
  $\rightarrow$ complementary to Sarah (fixed 2-loop) [Goodsell,Nickel,Staub'14]

Remark: Does dimensional reduction break SUSY? [DS'05;Hollik,DS'05]



Relevant STI valid at $\mathcal{O}(\alpha_{t,b}^2, \alpha_{t,b}\alpha_s)$

$\langle \Delta hhh\tilde{H} \rangle = 0 \Leftrightarrow$



At higher orders, the proof breaks down [Hollik, DS '05]

DRED might break SUSY

Relevant for non-gaugeless limit calculations...

Outline

1. FlexibleSUSY
2. R-Symmetry
   - Particularly interesting model
   - Compatible with M_h, EWPO?
   - Scenario with light singlet possible?
3. Summary

What is R-symmetry?

maximal possible symmetry of QFT =
SUSY + R-Symmetry (Haag, Lopuszanski, Sohnius)

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- $\theta^\alpha \to e^{i\varphi}\theta^\alpha$
- U(1) symmetry, conserved R-charge
- particle and SUSY partner have different R-charges
- distinct from MSSM with R-parity, distinct phenomenology

R-Symmetry needs Dirac gauginos

Gauginos always R-charged

- Majorana gaugino masses forbidden! $m_\lambda \lambda^{a\alpha} \lambda^a_\alpha$

Dirac gaugino masses possible, need additional d.o.f.

- new spinor in adjoint rep. $\rightsquigarrow$ $m_D \lambda^{a\alpha} \psi^a_\alpha$

New spinor must be part of chiral superfield!

- SU(3)×SU(2)×U(1) requires chiral superfields (adjoint) $\hat{O}$, $\hat{T}$, $\hat{S}$
- colour octet scalars (sgluons), SU(2) triplet scalar (Higgs Triplet!), Higgs singlet

Construct MRSSM: R(SM-fields)=0 [Fayet...Kribs,Poppitz,Weiner]

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MRSSM: R-symmetric model with new fields: $\hat{O}$, $\hat{T}$, $\hat{S}$; $\hat{R}_u$, $\hat{R}_d$.

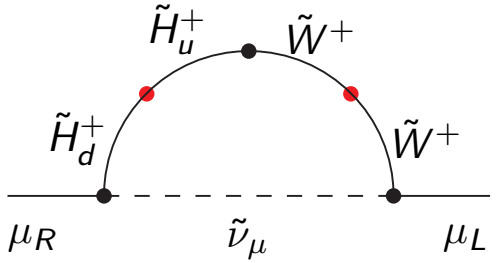
$\mu = A_i = m_\lambda = 0$; Yukawa-, $B\mu$-terms as in MSSM.

$$W_{\text{MRSSM}} = \ldots + \mu_u \hat{H}_u \hat{R}_u + \Lambda_u \hat{H}_u \hat{T} \hat{R}_u + \lambda_u \hat{H}_u \hat{S} \hat{R}_u + y_u \hat{Q} \hat{H}_u \hat{U}$$

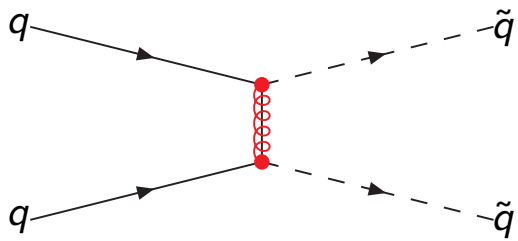
$$\mathcal{L}_{\text{Dirac-mass}} = -m_D \lambda^a \psi^a + \sqrt{2} m_D D^a \phi^a$$

R-Symmetry has phenomenologically distinct properties

- solves SUSY flavour problem with small M_{sfermion} [Kribs, Poppitz, Weiner]
  (however, also kills large $(g-2)_\mu$ contributions)
  (m_λ, μ, A_i forbidden by R-symmetry)



- sub-TeV squarks compatible with LHC
  (suppressed cross section) [Kribs, Martin]



Question: MRSSM compatible with Higgs, W mass measurements? [Diessner, Kalinowski, Kotlarski, DS '14, '15]

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Difficulties for M_h:

- more scalars S, T^0 mix, reduced tree-level mass (for $v_{S,T} \ll v$, $m_D^2 \ll m_{\text{soft}}^2$:)

$$m_{h,\text{tree}}^2 = M_Z^2 \cos^2 2\beta - v^2 \cos^2 2\beta \left(\frac{(g_1 m_D^B + \sqrt{2}\lambda\mu_u)^2}{8(m_D^B)^2 + 2m_S^2} + g_2\text{-term} \right)$$

  - off-diag. elements=Higgsino/gaugino masses shouldn't be too large, loop corrections very important

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- large loop contributions to M_h from y_u and $\Lambda_u \hat{H}_u \hat{T} \hat{R}_u, \ldots$

  (Implementation: MRSSM implemented in Sarah and FlexibleSUSY (cross-checks very important!), and one-loop and selected two-loop contributions cross-checked by hand)

$$(\Delta m_h)^2 \approx \frac{2v^2}{16\pi^2} \left(\frac{\Lambda^2 \lambda^2}{2} + \frac{4\lambda^4 + 4\lambda^2 \Lambda^2 + 5\Lambda^4}{4} \log \frac{m^2_{\text{soft}}}{m^2_D} \right)$$

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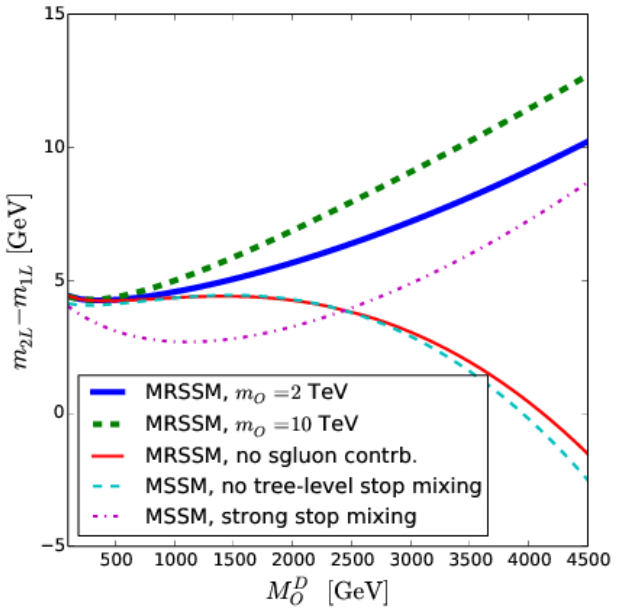
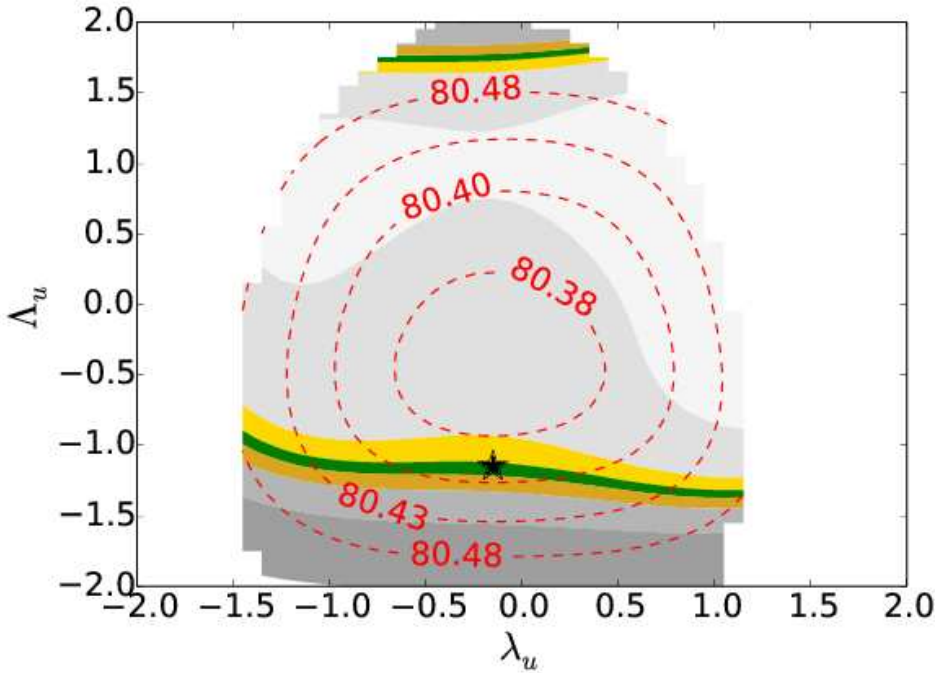
- two-loop corrections from sgluons also positive



Question: MRSSM compatible with Higgs, W mass measurements? Answer: YES!

- additional Yukawa-like couplings λ_u, Λ_u
- can increase M_h and M_W
- further positive two-loop corrections to M_h from sgluons
- very promising!

[Diessner,Kalinowski,Kotlarski,DS '14, '15]



- SUSY masses $\chi^{0,\pm} \sim 500$ GeV ... $m_T \sim 3$ TeV

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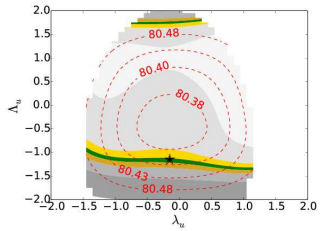

	BMP1	BMP2	BMP3
$\tan\beta$	3	10	40
B_μ	500^2	300^2	200^2
λ_d, λ_u	$1.0, -0.8$	$1.1, -1.1$	$0.15, -0.15$
Λ_d, Λ_u	$-1.0, -1.2$	$-1.0, -1.0$	$-1.0, -1.15$
M_B^D	600	1000	250
$m^2_{R_u}$	2000^2	1000^2	1000^2
μ_d, μ_u	$400, 400$		
M_W^D	500		
M_O^D	1500		
m^2_T, m^2_S, m^2_O	$3000^2, 2000^2, 1000^2$		
$m^2_{Q;1,2}$, $m^2_{Q;3}$	$2500^2, 1000^2$		
$m^2_{D;1,2}$, $m^2_{D;3}$	$2500^2, 1000^2$		
$m^2_{U;1,2}$, $m^2_{U;3}$	$2500^2, 1000^2$		
m^2_L, m^2_E	1000^2		
$m^2_{R_d}$	700^2		
v_S	5.9	1.3	-0.14
v_T	-0.33	-0.19	-0.34
$m^2_{H_d}$	671^2	761^2	1158^2
$m^2_{H_u}$	-532^2	-544^2	-543^2

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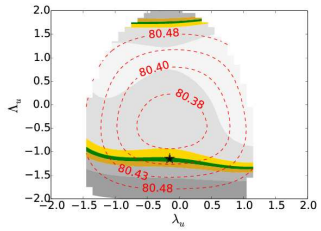

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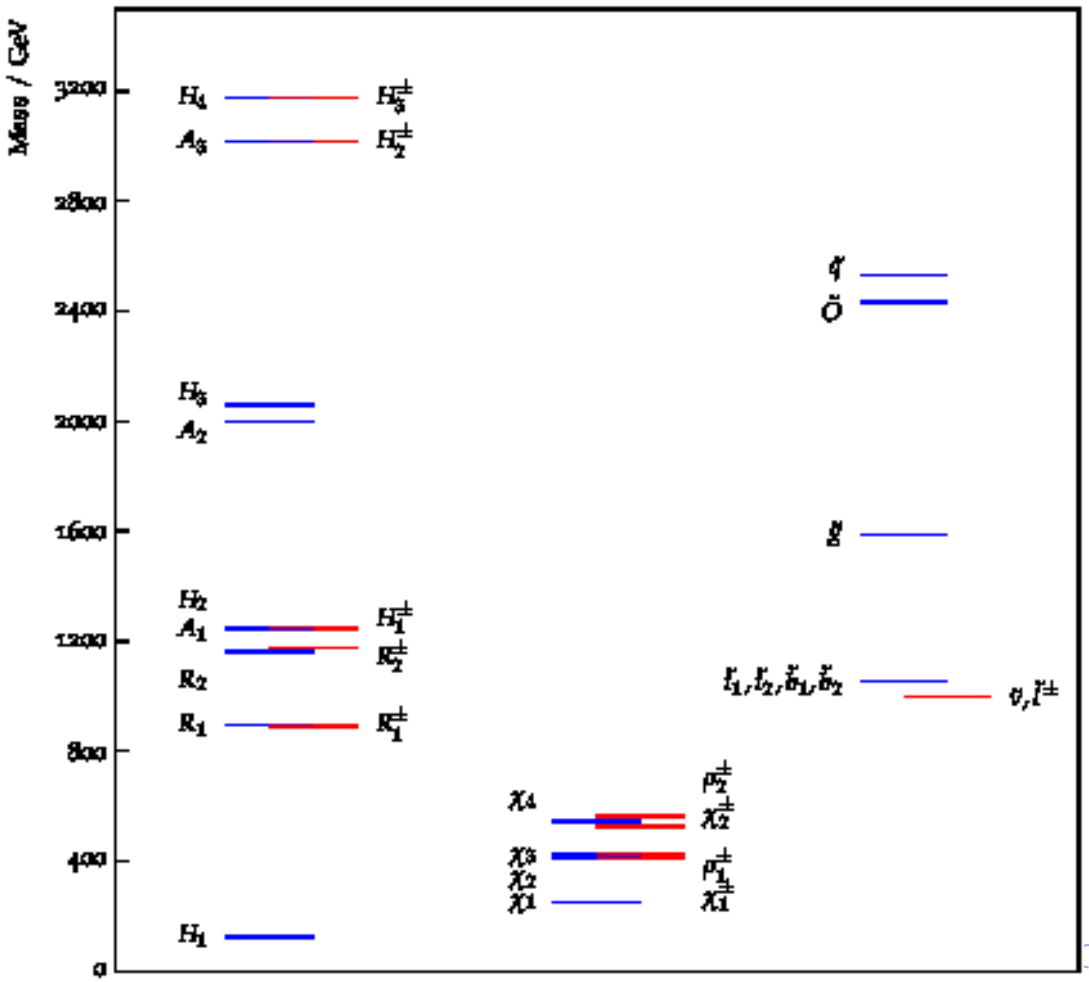


Question 2: light singlet possible/helpful? [preliminary]

- Should be an advantage:
- No tree-level reduction for SM-like Higgs
- relevant H_u–S mass matrix shows the requirements:

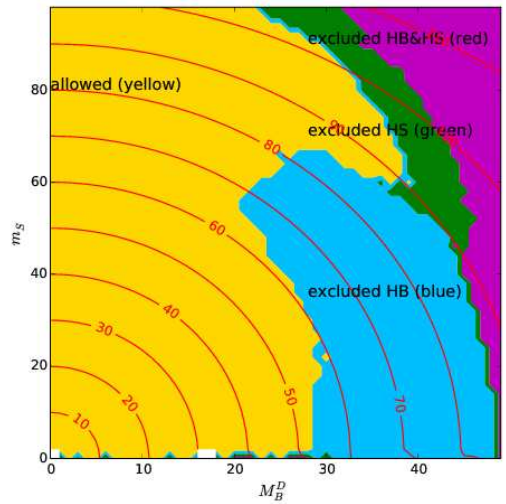
$$\mathcal{M}^{\text{limit}}_{\text{phi;2,3}} = \begin{pmatrix} m_Z^2 & v_u(\sqrt{2}\lambda_u \mu_u^{\text{eff-}} + g_1 m_D^B) \\ v_u(\sqrt{2}\lambda_u \mu_u^{\text{eff-}} + g_1 m_D^B) & 4(m_D^B)^2 + m_S^2 + \frac{\lambda_u^2 v_u^2}{2} \end{pmatrix} .$$

- small m_D^B, m_S, $\lambda_u v_u \rightarrow$ is this viable?

Question 2: light singlet possible/helpful? [preliminary]

- No tree-level reduction for SM-like Higgs
- allowed region for $\lambda_u = 0$:

  (used HiggsBounds/HiggsSignals)



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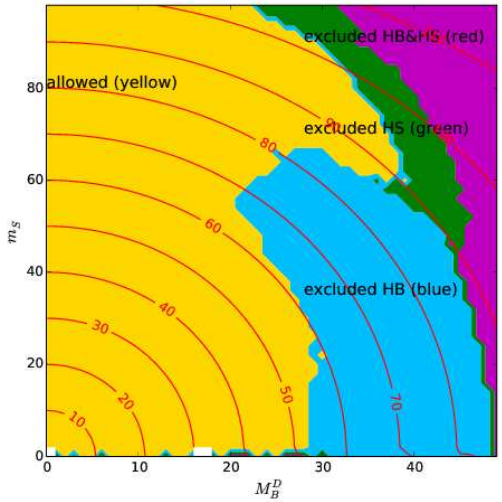
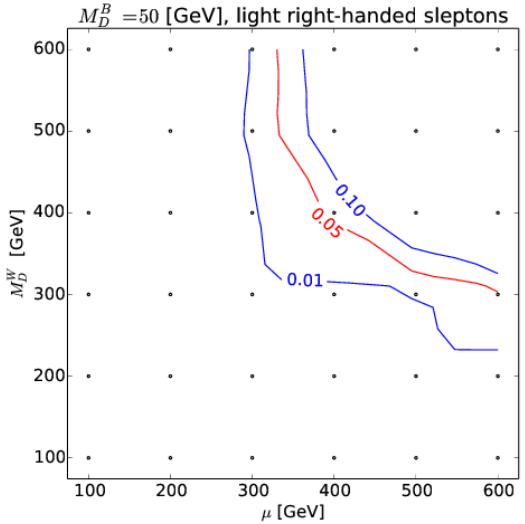


- light bino Dirac mass possible!

- Compatible with LHC for wino/slepton/Higgsino masses $\sim$ few 100 GeV (used CheckMate)



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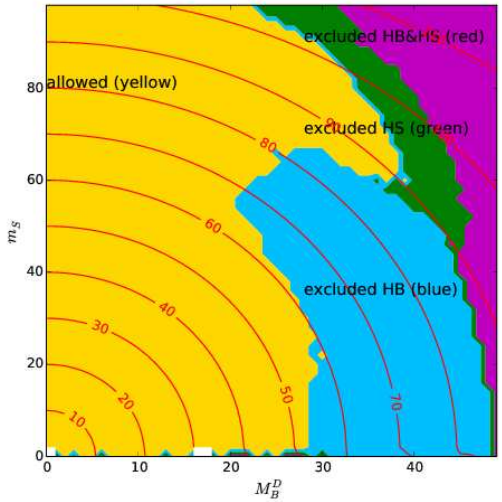

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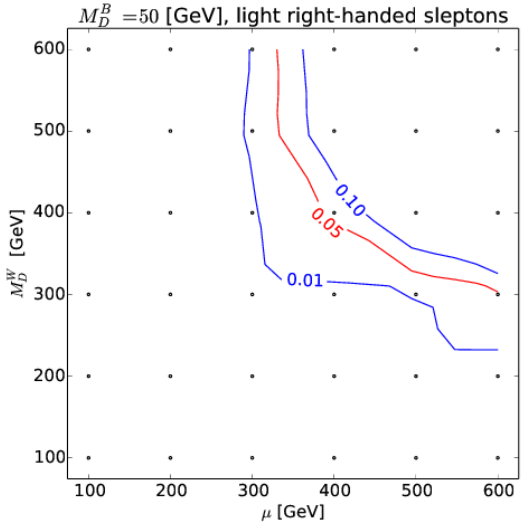

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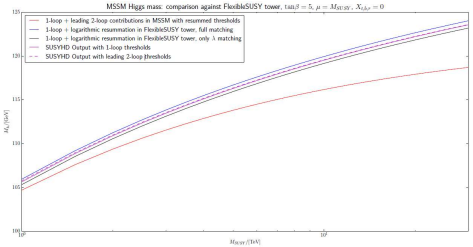
$\Rightarrow$ Light singlet viable in corner of parameter space [Diessner, Kalinowski, Kotlarski, DS]

Outline

Summary and Conclusions

- FlexibleSUSY: c++/Mathematica spectrum generator generator
  - many models predefined
  - easy to extend
  - precise m_h in progress



- R-Symmetry, MRSSM: distinct, motivated model
  - M_W, m_h can be explained
  - light singlet scenario viable
  - Outlook: squark LHC limits...