Higgs mass calculations in minimal and non-minimal SUSY models

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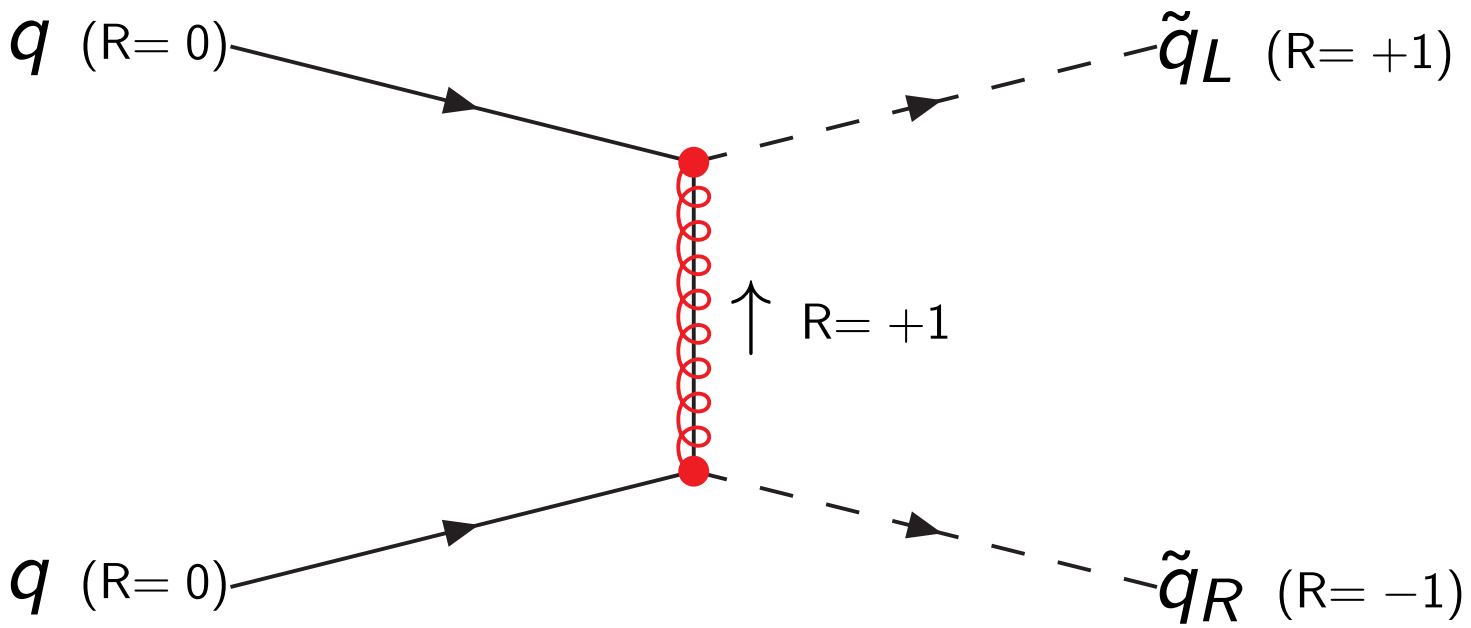
1. Higgs mass in Minimal R-symmetric SSM [Diessner, Kalinowski, Kotlarski, DS]
2. EFT-calculation of Higgs masses in FlexibleSUSY [Kwasnitza, Steudtner, DS, Voigt]
3. Does DRED preserve SUSY for Higgs mass calculations? [DS, Unger]

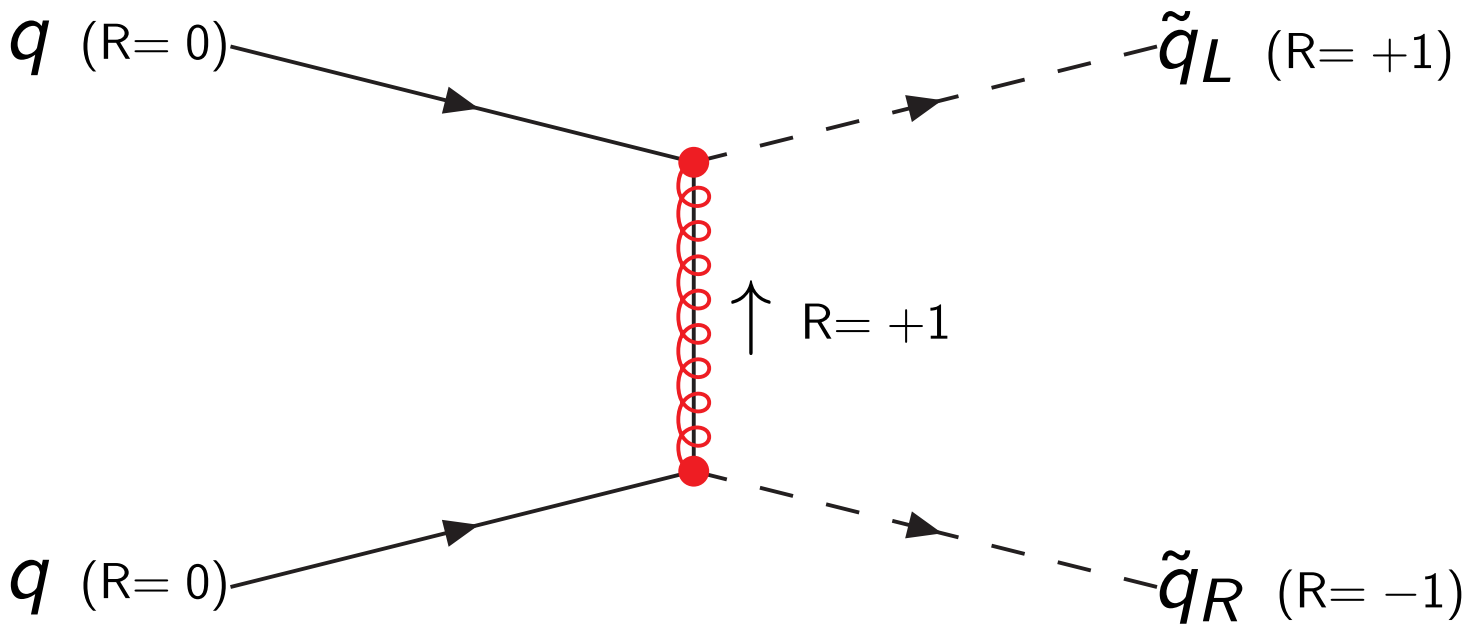
Outline

R-Symmetric model MRSSM [Kribs, Poppitz, Weiner]



- Continuous, conserved R-charge. R-charges fixed by SUSY-algebra

R-Symmetric model MRSSM [Kribs, Poppitz, Weiner]



- some MSSM-processes forbidden
- surviving ones have stronger m_{gluino}-suppression

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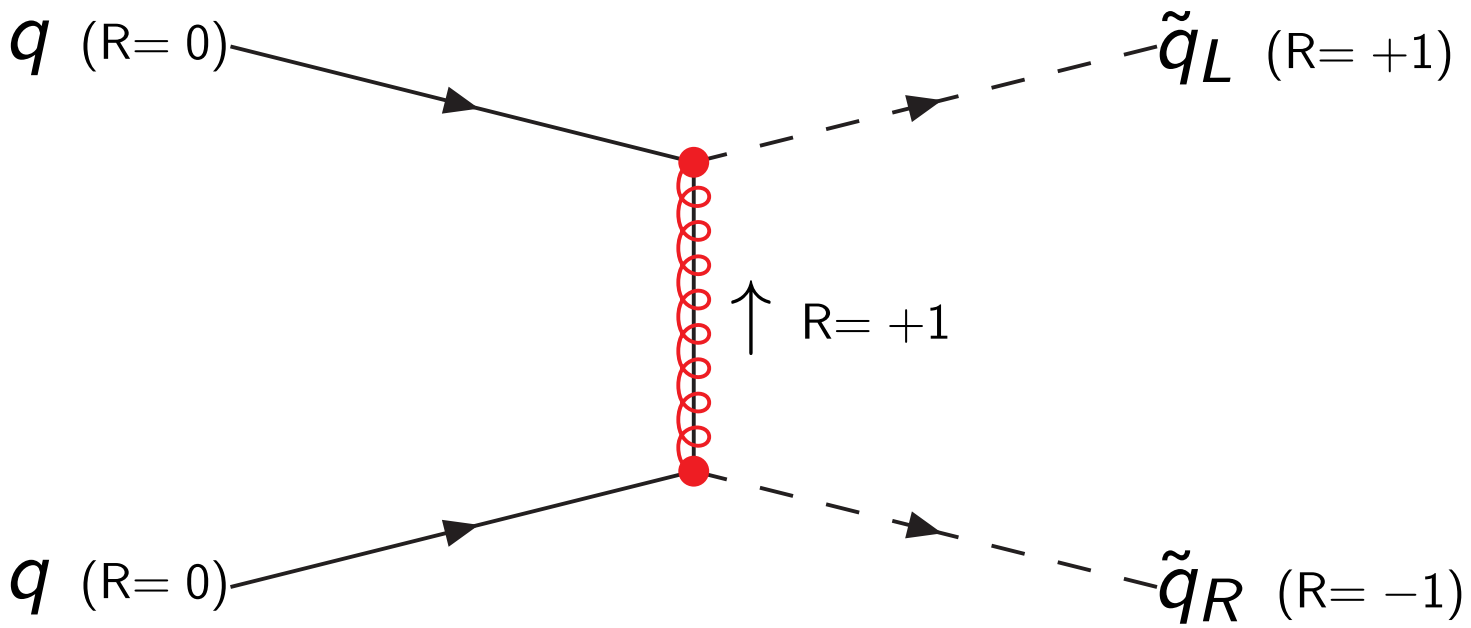

- gluino (and other gauginos/Higgsinos) = Dirac-fermion
- New scalar superpartners: sgluons, Higgs-triplet, Higgs-singlet; R-Higgs

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

Tree-level: difficulty: additional mixing with S, T^0!

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Tree-level: difficulty: additional mixing with S, T^0!

- reduced tree-level mass
- simple case: only H_u–S mass matrix relevant (for $v_{S,T} \ll v$, $m_D^2 \ll m_{\text{soft}}^2$:)

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

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

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One-loop level: difficulty: no stop mixing allowed!

However:

- large contributions from $y_u \hat{H}_u \hat{Q} \hat{U}$ and $\Lambda_u \hat{H}_u \hat{R}_u \hat{S}$, $\Lambda_u \hat{H}_u \hat{R}_u \hat{T}$

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

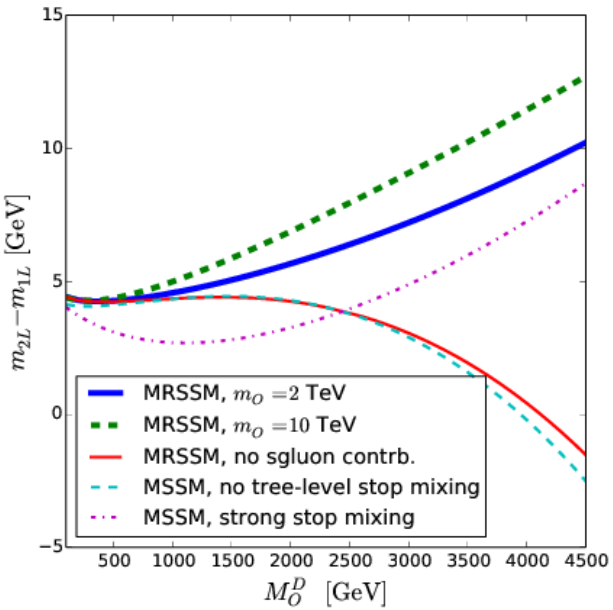
  - sufficient corrections for $\Lambda = \mathcal{O}(1)$

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

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

Two-loop level:

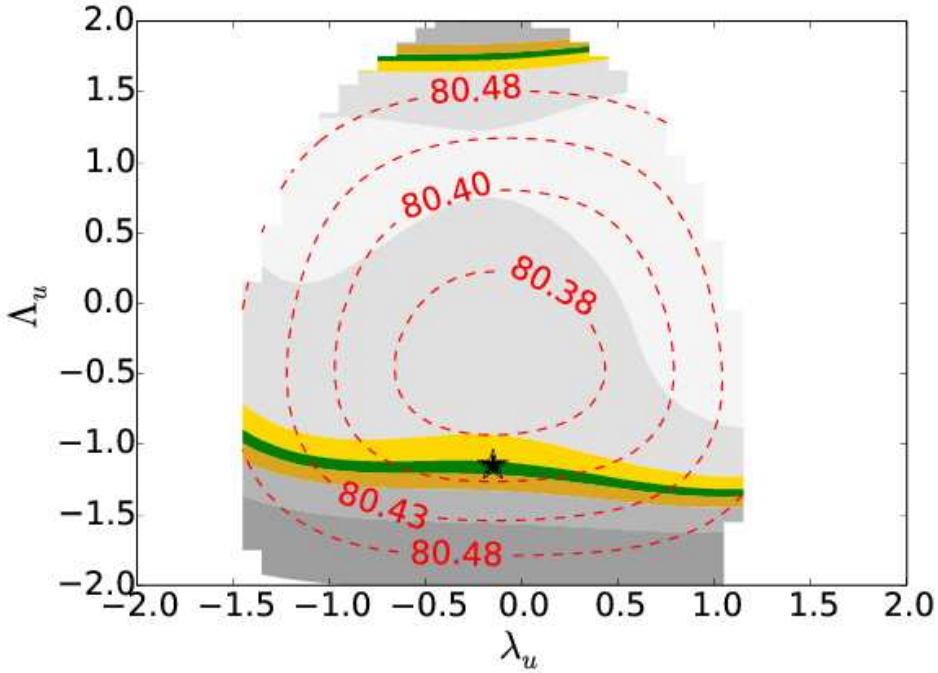
- two-loop corrections from sgluons also positive



Question: MRSSM compatible with Higgs mass? 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
- can also explain dark matter
- and accommodate very light singlet/singlino

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



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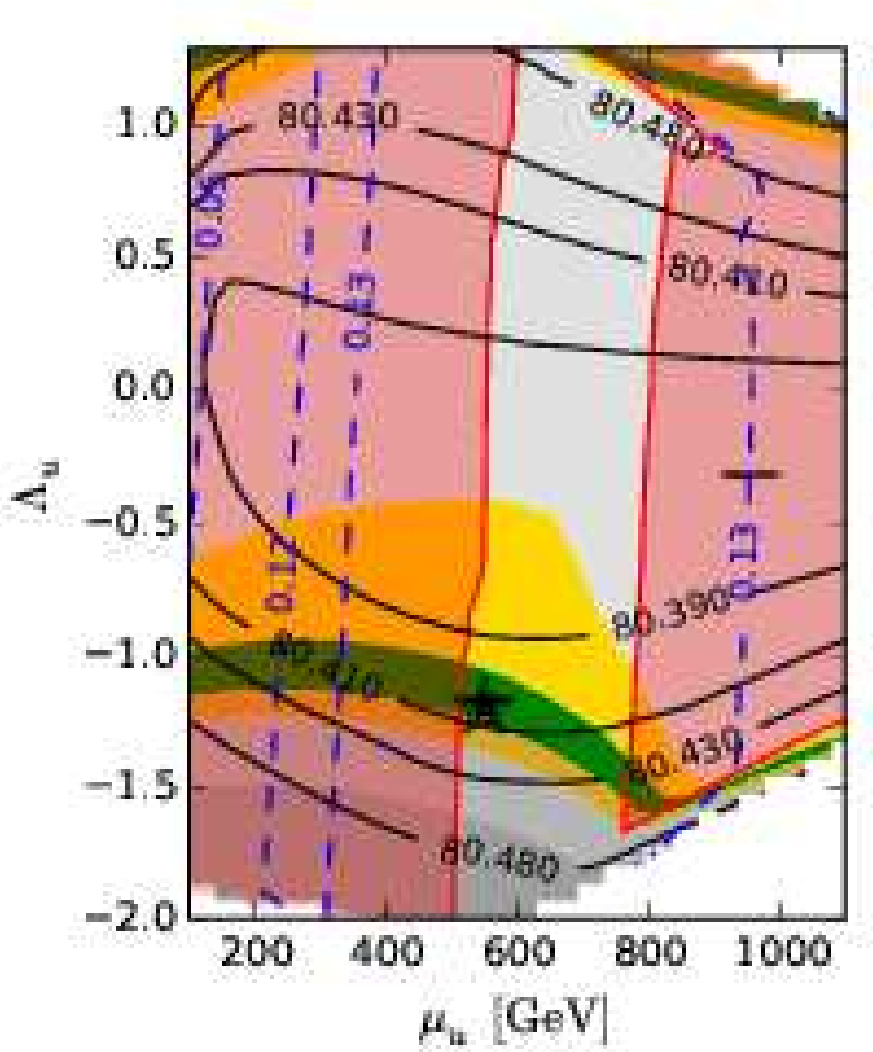

Outline

Spectrum generators and Higgs mass calculators

Higgs mass calculations in MSSM:

- MSSM, fixed order: H3m, FeynHiggs, Softsusy, Spheno,...
- MSSM, EFT: FeynHiggs, SUSYHD [Vega, Villadoro '15]

General SUSY model spectrum generators:

- Sarah-Spheno [Staub] for 2-loop Higgs mass: [Goodsell, Nickel, Staub '14]
- FlexibleSUSY [Athron, Park, DS, Voigt]

Aim: Implement resummation in FlexibleSUSY! [Steudtner, DS, Voigt; Kwasnitza, Steudtner, DS, Voigt]

Spectrum generators and Higgs mass calculators

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Status of FlexibleSUSY Higgs mass calculations:

MSSM FS-versions of:		non-MSSM, generated
FS-original ($\approx$ Softsusy)	fixed 2L	FS-original fixed 1L
Spheno	"	
SUSYHD	EFT, 2L matching+3L running	
FS-Tower	EFT, 1L matching+3L running	FS-Tower

$\Rightarrow$ many verifications; can study differences in detail. Note: $\geq$2-loop only in gaugeless limit!

Sketch of fixed-order and EFT calculations in FlexibleSUSY/Spheno/SUSYHD

Fixed-order (FlexibleSUSY/Softsusy/Spheno):

$$M_h^2 = (m_h^{\overline{DR}})^2 - \Sigma_h^{\overline{DR}}(M_h^2)$$

EFT/resummation in FS-Tower/SUSYHD using Tower of EFTs:

at M_{SUSY}: integrate out SUSY, match to SM $p_i = \lambda, y_t, \alpha_s, \ldots$

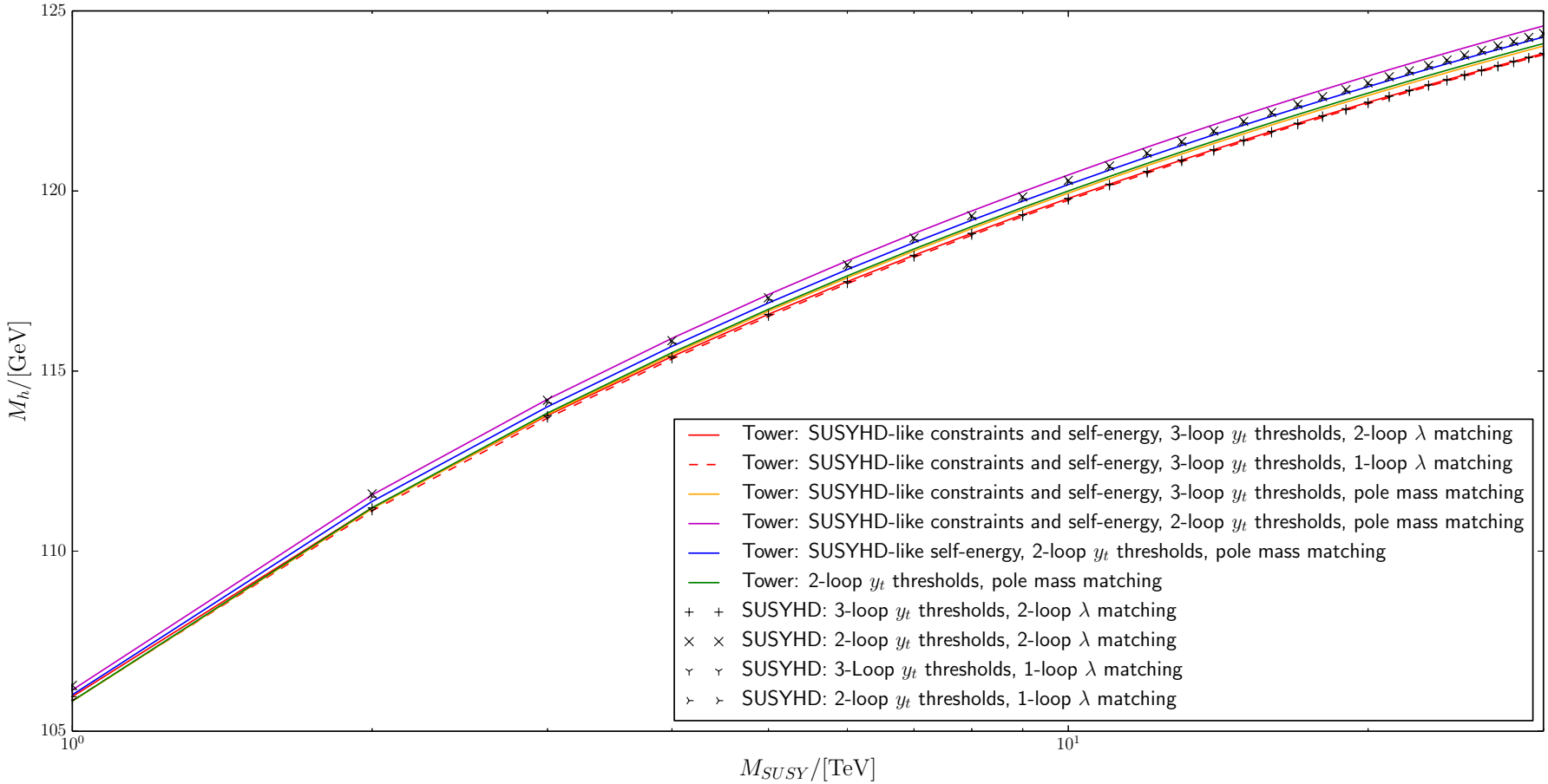
$$p_i^{\text{SM}}(M_{\text{SUSY}}) = p_i^{\text{SUSY}}(M_{\text{SUSY}}) + \delta p_i$$

$< M_{\text{SUSY}}$: run in SM

$$\frac{\mathrm{d}p_i^{\text{SM}}(\mu)}{\mathrm{d}\ln\mu} = \beta_{p_i}^{\text{SM}}(\mu)$$

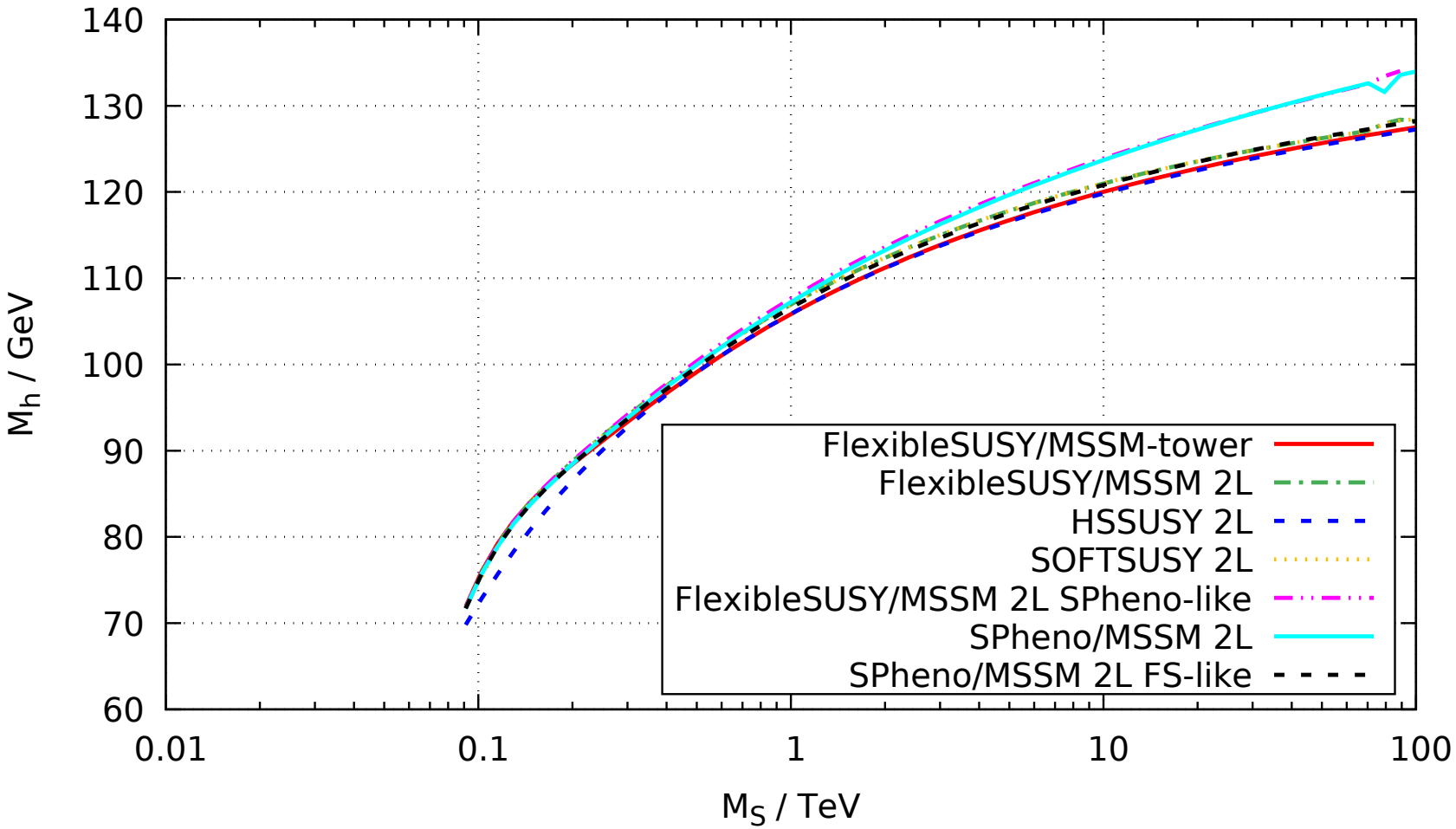
at M_{weak}: compute Higgs mass in SM, match to M_t, α_s^{Exp}...

$$m_h^2 = \lambda^{\text{SM}}(M_{\text{weak}})v^2 - \hat{\Sigma}_h$$



- Verify FS-Tower: reproduce SUSYHD, understand differences
- Choice: SUSYHD matches $\Gamma_{\phi\phi\phi\phi}(0)$, FS-tower matches $\Gamma_{hh}(M_h)$

FS-Tower vs SUSYHD and Spheno, FS-original



- FS-Tower reproduces HSSUSY (=SUSYHD-Clone) for large masses
- and agrees with fixed-order calculations for small masses
- Fixed-order FS and Spheno agree surprisingly well with FS-Tower

Analytical results in terms of M_t and $\alpha_s(M_Z)$

(Differences between Spheno, FS, and FS-tower: leading 3-L α_s^2 logs, $L = \log(M_{\text{SUSY}}/M_t)$)

Fixed-order FlexibleSUSY/Spheno: fixed-2-loop LL Higgs self energy

$$\Delta M_h^2 = -\frac{\beta_\lambda(m_t^{\overline{DR}}(M_S))^4 \left(L - 2\alpha_s^{\text{MSSM}}(M_S)\beta_y L^2\right)}{4\pi v^2}$$

Plug in running MSSM-parameters, obtained from e.g.

$$m_t^{\overline{DR}} = M_t + \Sigma_t^{\text{MSSM}} \begin{pmatrix} M_t & \text{(FS)} \\ m_t^{\overline{DR}} & \text{(Spheno)} \end{pmatrix}$$

Note: this is not fixed-order in $\alpha_s^{\text{SM}}(M_Z)$, M_t

Analytical results in terms of M_t and $\alpha_s(M_Z)$

(Differences between Spheno, FS, and FS-tower: leading 3-L α_s^2 logs, $L = \log(M_{\text{SUSY}}/M_t)$)

FS-Tower: integrate SM-RGE for λ, using RGEs for y and α_s

$$\frac{\mathrm{d}\lambda}{\mathrm{d}\ln\mu} = \beta_\lambda y^4, \qquad \frac{\mathrm{d}y}{\mathrm{d}\ln\mu} = \beta_y y \alpha_s, \qquad \frac{\mathrm{d}\alpha_s}{\mathrm{d}\ln\mu} = \beta_s \alpha_s^2$$

$$\Delta M_h^2 = -\frac{\beta_\lambda M_t^4 \left((1 - \alpha_s(M_Z)\beta_s L)^{1 - \frac{4\beta_y}{\beta_s}} - 1 \right)}{4\pi\alpha_s(M_Z) v^2 (4\beta_y - \beta_s)}$$

Different results at 3LL:

$$\Delta M_h^2 = \frac{3M_t^4}{v^2\pi^2}\left(L - 16\left(\frac{\alpha_s}{4\pi}\right)L^2 + \left\{ \frac{736}{9}_{\text{FS}}, \frac{992}{9}_{\text{Sph}}, \frac{736}{3}_{\text{Tower}} \right\} \left(\frac{\alpha_s}{4\pi}\right)^2 L^3 \right)$$

Interpretation

Interpretation:

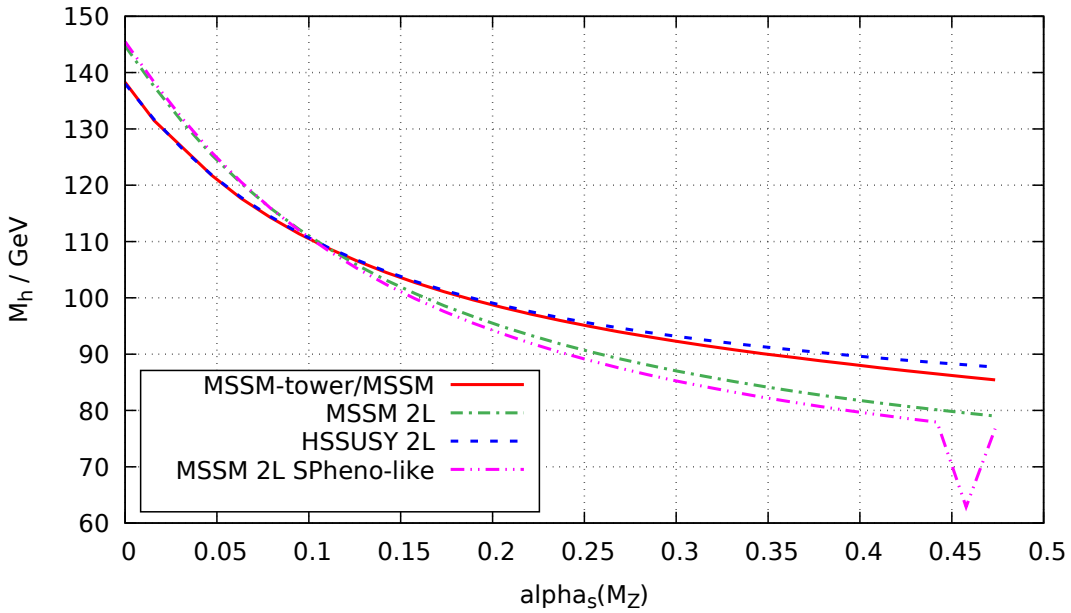
- "Fixed-order" FS and Spheno are not fixed order in $\alpha_s(M_Z)$ and M_t, partially resum logs
- better than expected
- difference between FS and Spheno is part of their theory uncertainty
- FS-Tower resums all leading/subleading logs correctly

Interpretation

Prove accidentality:

Change numerical value of α_s

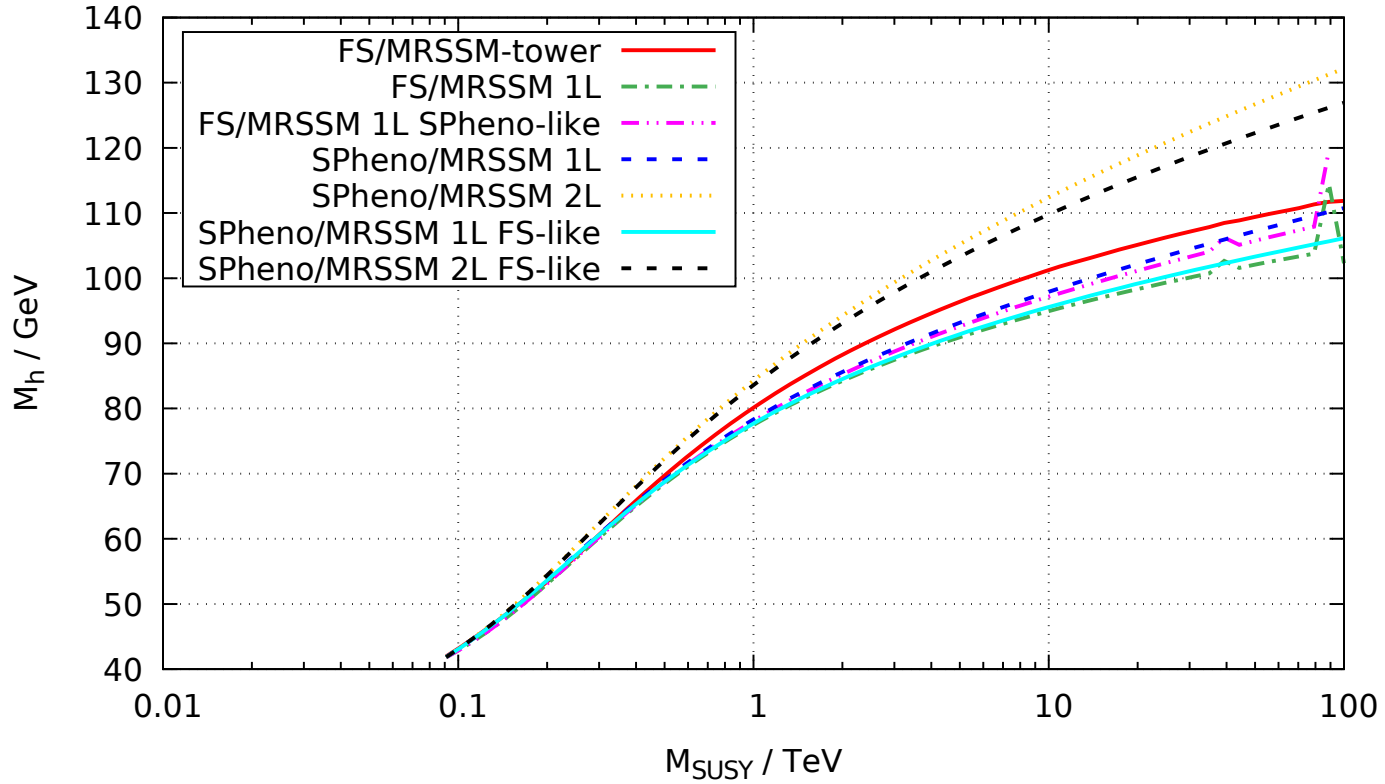
(for decreased EW gauge couplings)



Interpretation:

- "Fixed-order" FS and Spheno are not fixed order in $\alpha_s(M_Z)$ and M_t, partially resum logs
- better than expected
- difference between FS and Spheno is part of their theory uncertainty
- FS-Tower resums all leading/subleading logs correctly
- good agreement between FS and FS-Tower is accidental

Results in MRSSM

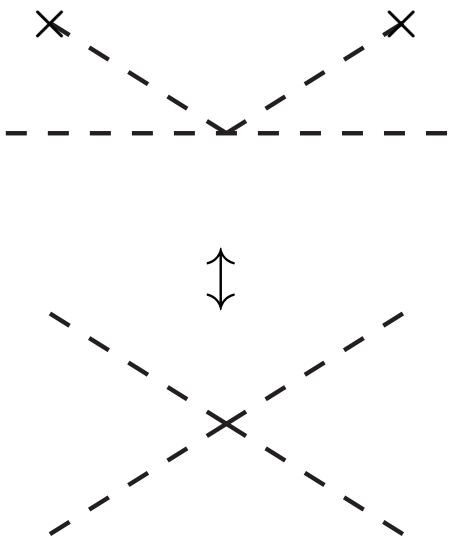


- 2-L Spheno/FS: wrong 3LL terms: theory uncertainty $>$ difference
- FS-Tower: only 1-loop matching, hence: non-log 2-Loop terms missing
- similar in other models (E6SSM, NMSSM)
- outlook: 2-loop matching, estimate of theory uncertainty

Outline

3. Does DRED preserve SUSY for Higgs mass calculations?

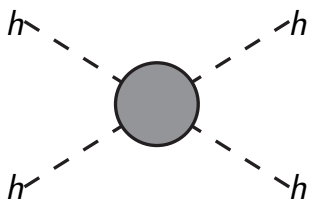
Higgs boson mass and quartic coupling



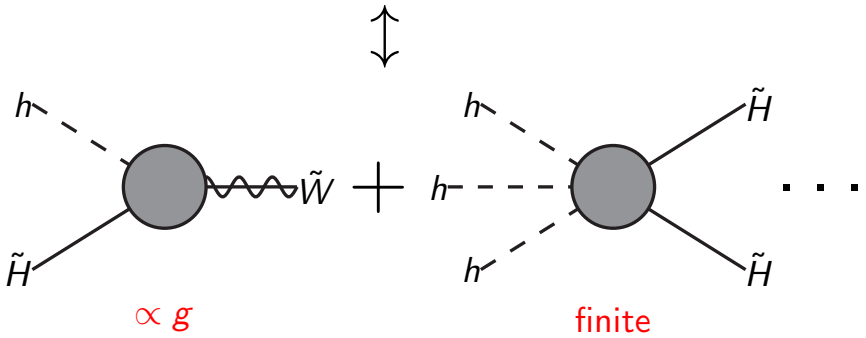
Higgs mass

- M_h governed by quartic Higgs self coupling λ
- $\lambda \propto g^2$ in MSSM

Quartic coupling and SUSY



λ



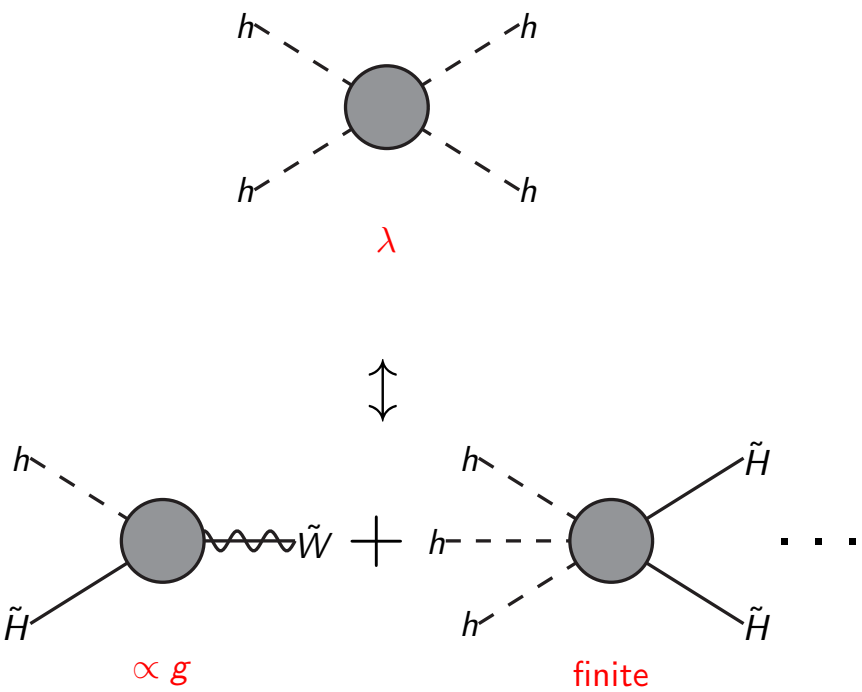
$\propto g$ finite

Slavnov-Taylor identity

- expresses $\lambda \propto g^2$
- Needs to be verified

$$0 \stackrel{?}{=} \delta_{\mathrm{SUSY}} \langle hhh\tilde{H} \rangle$$

Quartic coupling and SUSY



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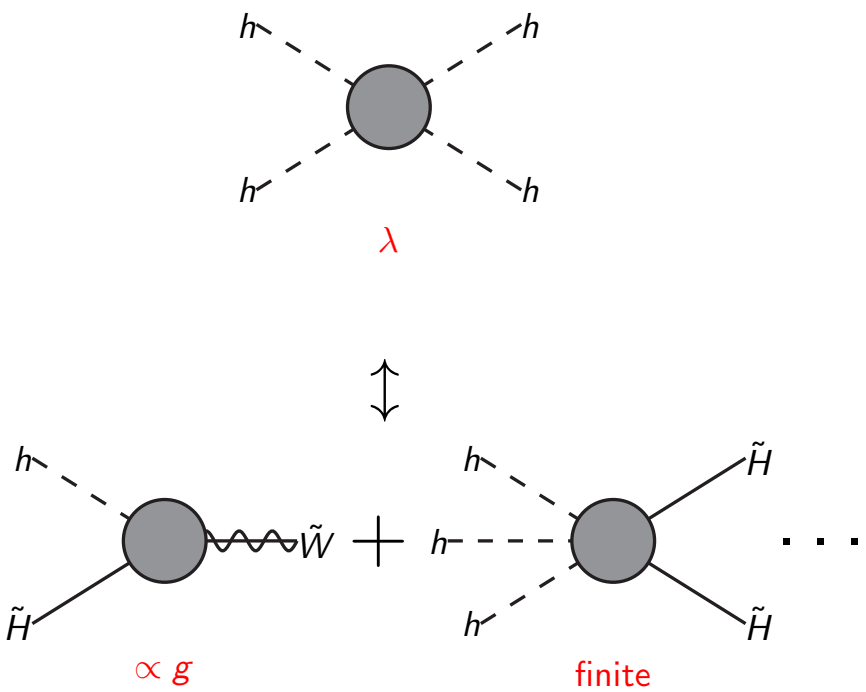
$$\text{explicit: } 0 = \frac{\delta^5 S(\Gamma)}{\delta\phi_a \delta\phi_b \delta\phi_c \delta\tilde{H} \delta\bar{\epsilon}} = \Gamma_{\tilde{H} Y_{\phi_i} \bar{\epsilon}} \Gamma_{\phi_a \phi_b \phi_c \phi_i} + \Gamma_{\phi_a \phi_b Y_\lambda \epsilon} \Gamma_{\phi_c \tilde{H} \lambda} + \dots$$

Quartic coupling and SUSY



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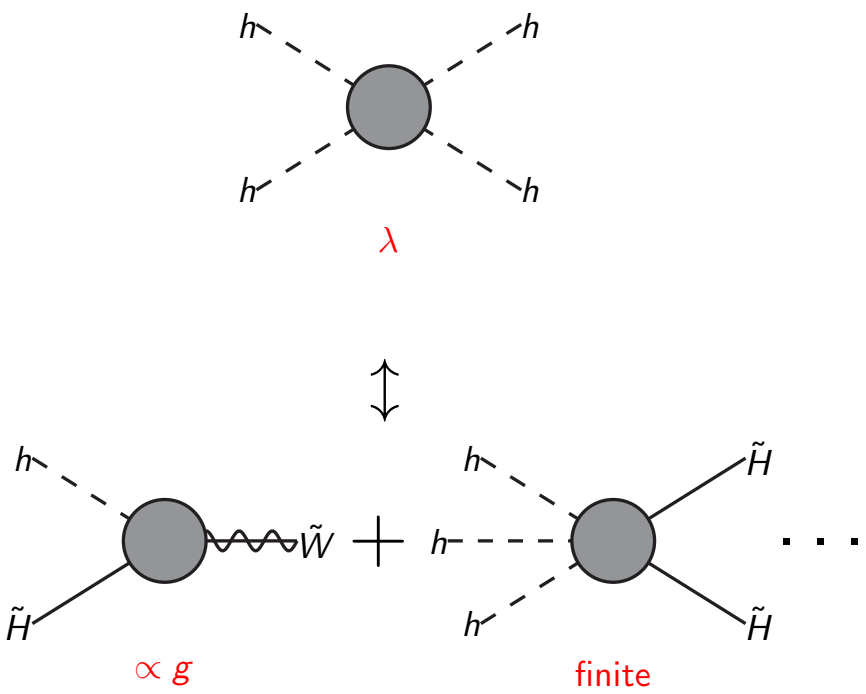
If verified:

- Usual, multiplicative renormalization o.k.
- otherwise, SUSY-restoring counterterms would have to be added

Quartic coupling and SUSY



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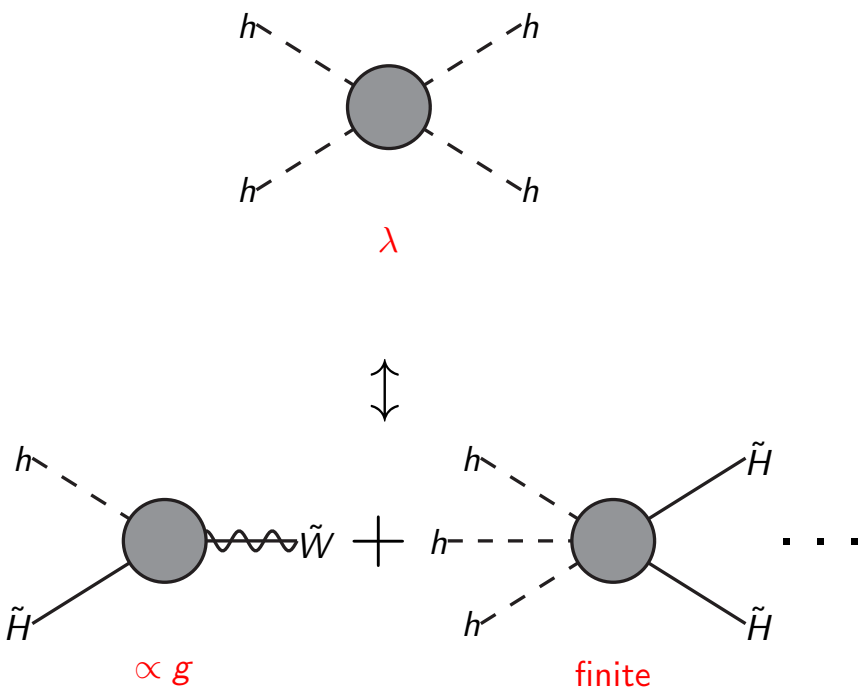
Strategy:

- Use quantum action principle in DRED [DS '05]

$$0 \stackrel{?}{=} \delta_{\mathrm{SUSY}} \langle hhh\tilde{H} \rangle \equiv \langle \Delta hhh\tilde{H} \rangle$$

Quartic coupling and SUSY



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Strategy:

- Use quantum action principle in DRED [DS '05]
- $\delta_{\mathrm{SUSY}} \langle hhh\tilde{H} \rangle = \langle \Delta hhh\tilde{H} \rangle$ where $\Delta = \delta_{\mathrm{SUSY}} \int d^D x \mathcal{L}$

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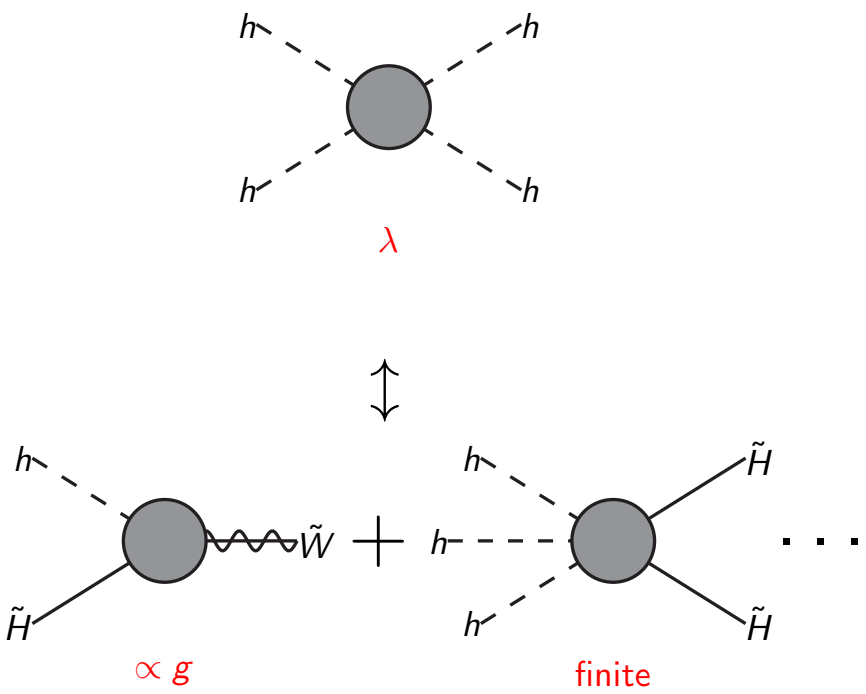
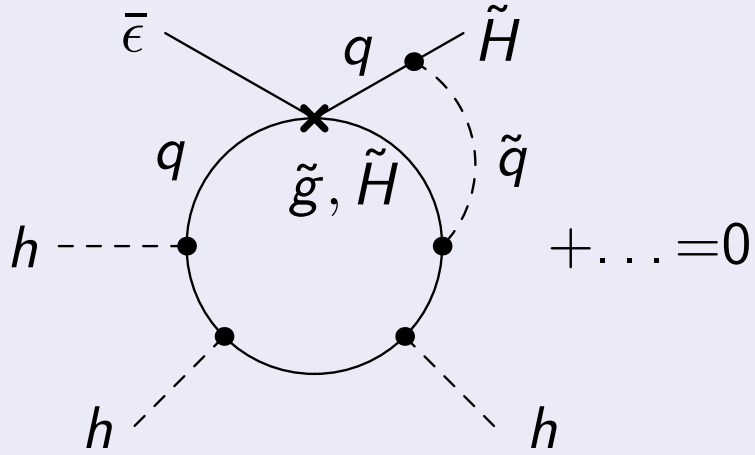
Quartic coupling and SUSY



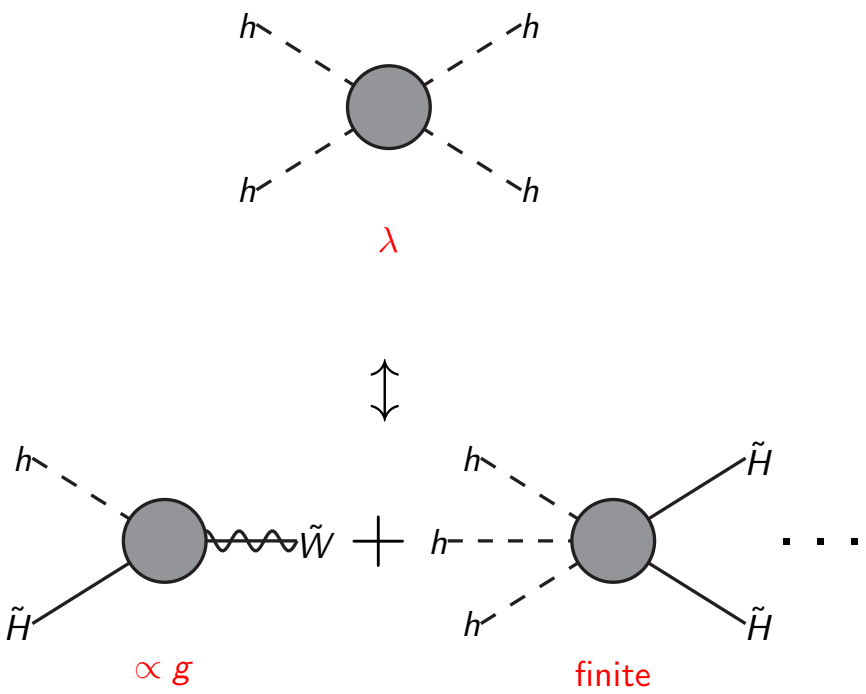
Old check: STI at 2-loop

$\mathcal{O}(\alpha_{t,b}^2, \alpha_{t,b}\alpha_s)$ [Hollik, DS '05]

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

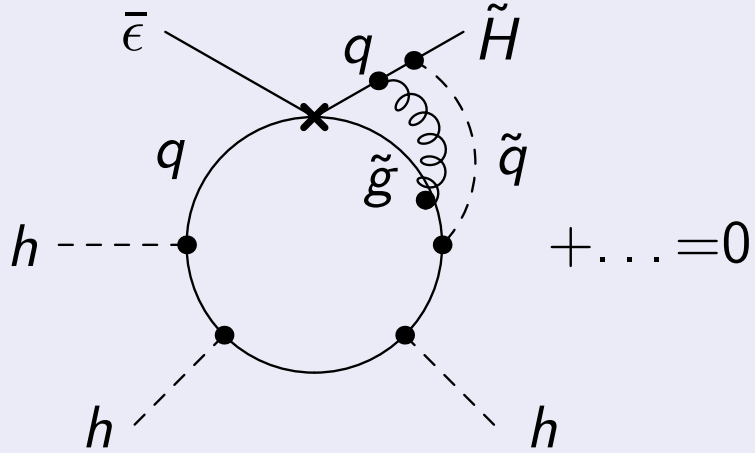


Quartic coupling and SUSY



New check: 3-loop STI at $\mathcal{O}(\alpha_t \alpha_s^2)$ [DS, Unger, preliminary]

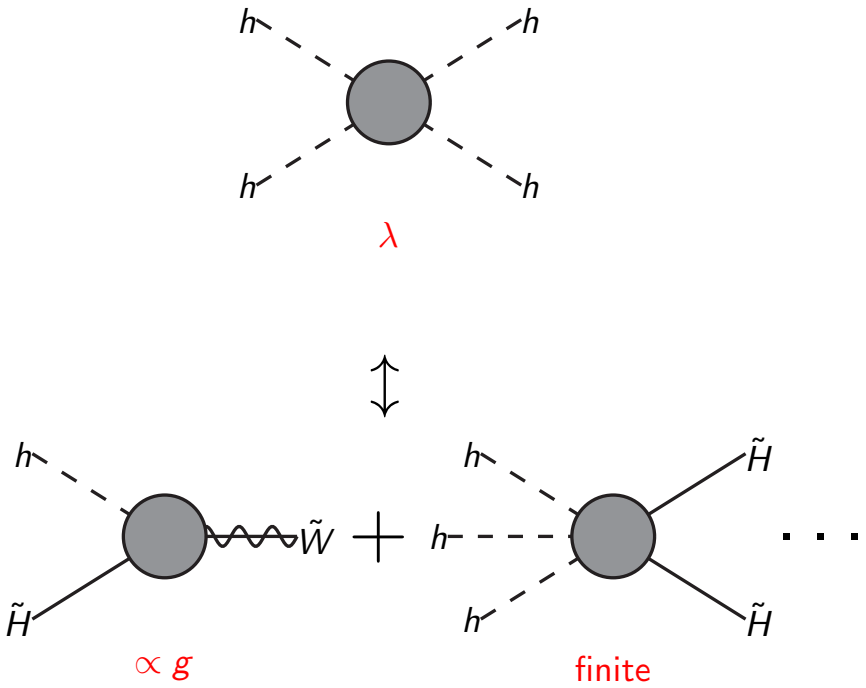
$\langle \Delta hhh\tilde{H} \rangle = 0 \Leftrightarrow$



Ingredients:

- structure of possible SUSY-restoring c.t. $\Rightarrow$ can set $p_{h_i} = 0$
- can simplify closed fermion loop to at most three γ-matrices
- recipe of [DS '05] then proves result

Quartic coupling and SUSY



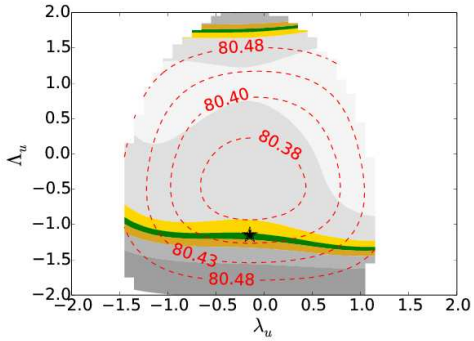
Outlook:

- check complete two-loop, three-loop (?)
- check further, relevant STIs

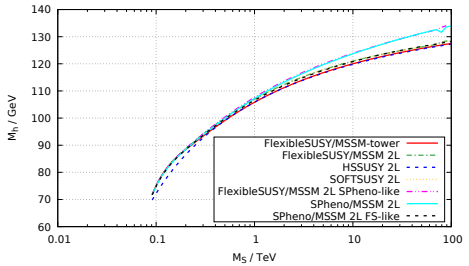
Outline

Summary and Conclusions

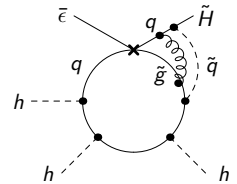
- R-Symmetry, MRSSM: distinct, motivated model
  - m_h, M_W, dark matter can be explained
  - light singlet scenario viable
  - Outlook: squark LHC limits...

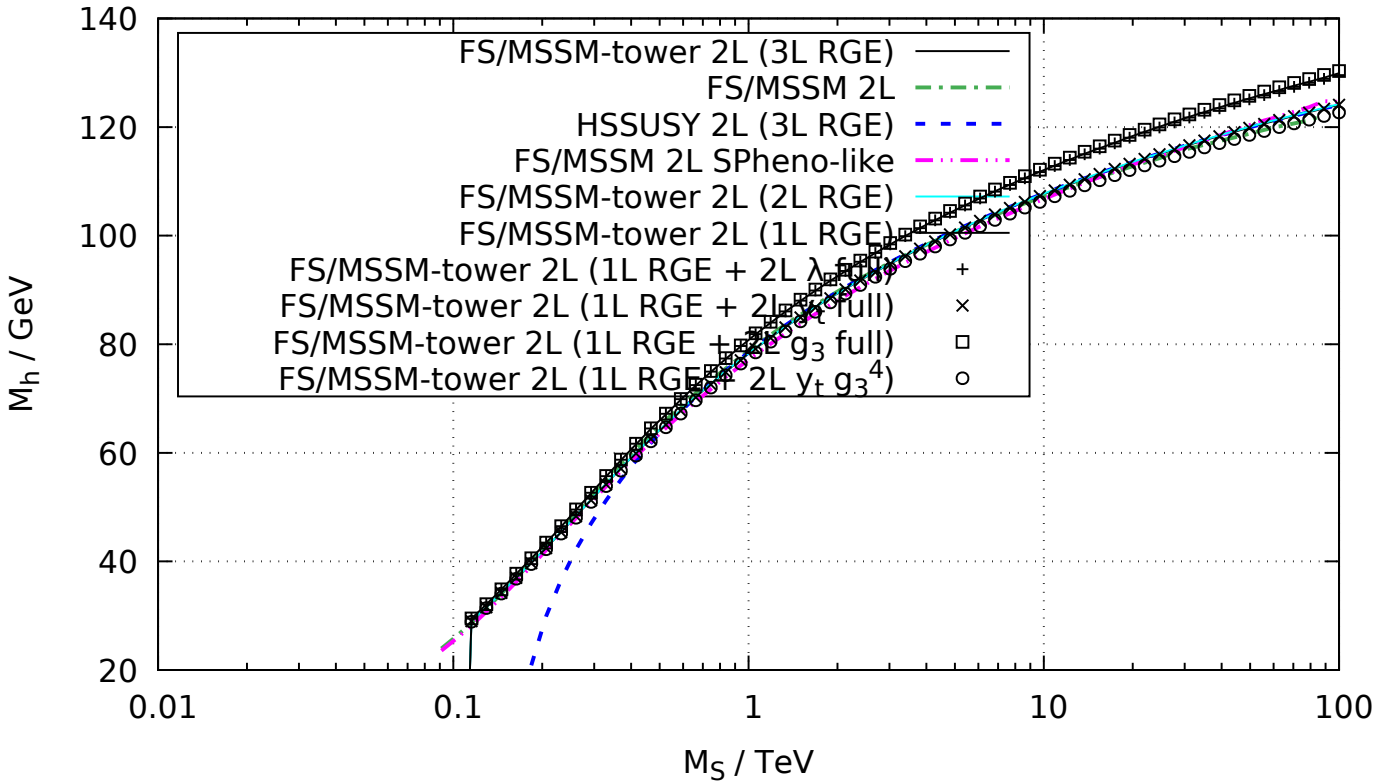


- FlexibleSUSY Higgs mass calculations
  - MSSM: reproduce fixed-order/EFT calculations
  - MRSSM, NMSSM, ... tested
  - Outlook: 2-loop matching



- DRED preserves relevant SUSY-STI at 3-loop QCD
  - Outlook: full 2-loop, further STIs




FS/MSSM-tower 2L (3L RGE)
FS/MSSM 2L
HSSUSY 2L (3L RGE)
FS/MSSM 2L SPheno-like
FS/MSSM-tower 2L (2L RGE)
FS/MSSM-tower 2L (1L RGE)
FS/MSSM-tower 2L (1L RGE + 2L λ full)
FS/MSSM-tower 2L (1L RGE + 2L y_t full)
FS/MSSM-tower 2L (1L RGE + 2L g_3 full)
FS/MSSM-tower 2L (1L RGE + 2L y_t g_3^4)
M_h / GeV
M_S / TeV
140
120
100
80
60
40
20
0.01
0.1
1
10
100

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

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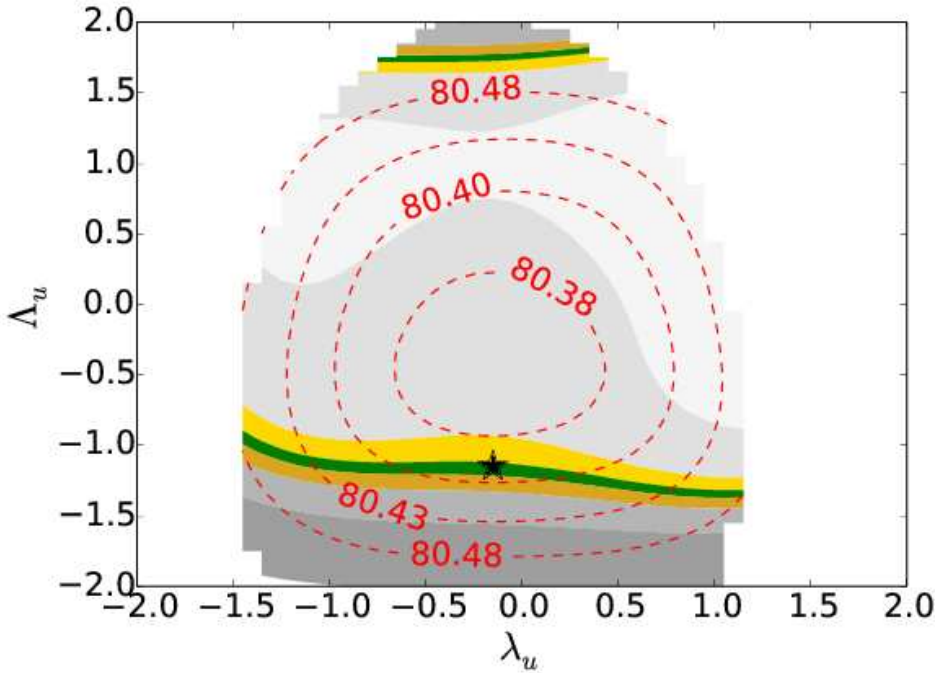
- further positive two-loop corrections to M_h from sgluons
- very promising!

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



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

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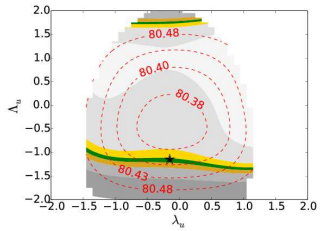
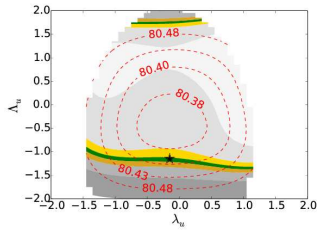


	BMP1	BMP2	BMP3
$\tan\beta$	3	10	40
B_μ	500^2	300^2	200^2
λ_d, λ_u	$1.0, -0.8$	$1.1, -1.1$	$0.15, -0.15$
Λ_d, Λ_u	$-1.0, -1.2$	$-1.0, -1.0$	$-1.0, -1.15$
M_B^D	600	1000	250
$m^2_{R_u}$	2000^2	1000^2	1000^2
μ_d, μ_u	$400, 400$		
M_W^D	500		
M_O^D	1500		
m^2_T, m^2_S, m^2_O	$3000^2, 2000^2, 1000^2$		
$m^2_{Q;1,2}$, $m^2_{Q;3}$	$2500^2, 1000^2$		
$m^2_{D;1,2}$, $m^2_{D;3}$	$2500^2, 1000^2$		
$m^2_{U;1,2}$, $m^2_{U;3}$	$2500^2, 1000^2$		
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

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]