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# Higgs sector in the R-symmetric supersymmetric model


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# Motivation

- Supersymmetry: theoretically still most promising BSM path
- Exact: no new parameters, but inconsistent with experiment
- Must be broken: this is where many arbitrary parameters enter
- Once parameters fixed: completely computable, mathematically consistent theory up to $M_{GUT}$

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- No direct sign of SUSY at the LHC, unless 125 GeV Higgs
- But 125 GeV Higgs pushes the SUSY scale up

# Motivation

Even before the LHC the minimal SUSY was under severe pressure:

- dim-4 B- and L-violating operators → extra symmetry (e.g. R-parity)
- possible flavor and CPV → strong constraints on the parameter space
- already LEP2 limit on Higgs mass >114 GeV required fine tuning

with 125 GeV Higgs even more

Should we give up supersymmetry ?

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- N>1 ??

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- N>1 ??

## Supersymmetry with R-symmetry

Continuous R-symmetry can ameliorate the above problems by

- removing dim-4 B- and L-violating terms, and dim-5 in proton decay
- removing soft tri-linear scalar couplings
- removing some large contributions to flavor-violating observables
- additional scalar fields are not ad hoc but enforced by N=2 structure of the gauge/gaugino sector

# Outline

- R-symmetry
- Structure of the minimal SUSY with R-symmetry (MRSSM)
- Confronting the experiment
    - Higgs mass
    - electroweak precison observables
    - constraints from LHC
    - dark matter connection

    based on:

    Diessner, JK, Kotlarski, Stockinger,
    JHEP 1412 (2014) 124
    Adv. HEP (2015) 760729
    JHEP 1603 (2016) 007
- Summary

# Supersymmetry

Supersymmetry: superspace $\{x^\mu, \theta, \bar\theta\}$

superfields

matter and Higgs – chiral $\hat\Phi(x^\mu, \theta) = \{\varphi, \psi^\alpha\}$

gauge fields – vector $\hat G(x^\mu, \theta, \bar\theta) = \{\tilde G^\alpha, G^\mu\}$

Lagrangian

- kinetic terms $\int d^2\theta\, d^2\bar\theta\ \hat\Phi^\dagger\, e^{-2g\hat G}\hat\Phi + (\int d^2\theta\ \hat G^\alpha \hat G_\alpha + h.c.)$

where $\hat G^\alpha \ni \lambda^\alpha + \theta^\alpha D$ field-strength superfield

- potential $\int d^2\theta\ W$ where superpotential

$$W \sim \mu \hat H_d \hat H_u + y_d \hat H_d \hat Q \hat D^c + \ldots$$

- soft-SUSY breaking: tri-linear scalar couplings and soft masses

# R-symmetry

R-symmetry – a continuous U(1) global symmetry under $\theta \to e^{i\alpha}\theta$

[Fayet '76; Salam & Strathdee, ...]

Grassmann coordinates have non-trivial R-charge

$$R(\theta) = +1, \quad R(d\theta) = -1, \quad R(\bar\theta) = -1, \quad R(d\bar\theta) = +1$$

superfields $\hat{X}_i(x^\mu, \theta, \bar\theta) \to e^{i\xi_i\alpha}\, \hat{X}_i(x^\mu, e^{i\alpha}\theta, e^{-i\alpha}\bar\theta)$

➔ component fields have different R-charge

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➔ component fields have different R-charge

Consider kinetic terms $\int d^2\theta\, d^2\bar\theta\; \hat\Phi^\dagger\, e^{-2g\hat G}\hat\Phi + \left(\int d^2\theta\; \hat G^\alpha \hat G_\alpha + h.c.\right)$

$\hat G^\alpha \sim \bar D^2\, D^\alpha \hat G$

vector superfield $R(\hat G) = 0 \quad \Rightarrow \quad R(G^\mu) = 0, \quad R(\tilde G^\alpha) = 1$

➡ are automatically R-symmetric

# R-symmetry

- R-symmetry: exact or broken explicitly

  in the MSSM it is broken by soft gaugino masses $M_{\tilde{G}} \tilde{G}^{\alpha} \tilde{G}_{\alpha}$

- for exact we need

  R(superpotential)=2 $\int d^2\theta \, W$

  R(soft terms) =0

- freedom to assign the R-charges to chiral superfields

MRSSM: SM particles have R=0, superpartners R≠0

[Kribs Poppitz Weiner 2007]

matter $R(\hat{Q}) = 1 \quad \Rightarrow \quad R(\tilde{q}) = 1, \quad R(q) = 0$

Higgs $R(\hat{H}) = 0 \quad \Rightarrow \quad R(H) = 0, \quad R(\tilde{H}) = -1$

other choices:

Frugiuele, Gregoire
Frugiuele, Gregoire, Kumar, Ponton
Davies, March-Russell, McCullough
Riva, Biggio, Pomarol

# Constraints from R-symmetry

terms allowed:

- superpotential: Yukawa $y_d \hat{H}_d \hat{Q} \hat{D}^c$
- soft terms: scalar masses $M_{\tilde{q}}^2 |\tilde{q}|^2$

also ΔL=2 Majorana neutrino mass $\hat{H}_u \hat{L} \hat{H}_u \hat{L}$ allowed

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superpotential

- mu-term $\mu \hat{H}_d \hat{H}_u$
- L- and B-violation $\hat{L}\hat{Q}\hat{L}$ , $\hat{H}_u \hat{L}$

soft terms:

- tri-linear couplings $A_d H_d \tilde{Q} \tilde{d}^*$
- Majorana masses $M_{\tilde{G}} \tilde{G}^\alpha \tilde{G}_\alpha$

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- superpotential: Yukawa $y_d \hat{H}_d \hat{Q} \hat{D}^c$
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also $\Delta L=2$ Majorana neutrino mass $\hat{H}_u \hat{L} \hat{H}_u \hat{L}$ allowed

**terms forbidden:**

- superpotential
  - mu-term $\mu \hat{H}_d \hat{H}_u$
  - L- and B-violation $\hat{L}\hat{Q}\hat{L}$ , $\hat{H}_u \hat{L}$
- soft terms:
  - tri-linear couplings $A_d H_d \tilde{Q} \tilde{d}^*$
  - Majorana masses $M_{\tilde{G}} \tilde{G}^\alpha \tilde{G}_\alpha$

Since mu-term and Majorana masses are forbidden, need new means to give masses to gauginos/higgsinos

# Minimal R-symmetric SSM

[Kribs Poppitz Weiner 2007]

The field content of MRSSM: fields of the MSSM with addition of:

- chiral superfields in the adjoint representation

  e.g. SU(3) octet

$$\hat{O} = O + \sqrt{2}\tilde{O}\theta + \theta\theta F_O$$

$$R(\hat{O}) = 0 \Rightarrow R(O) = 0,\ R(\tilde{O}) = -1$$

  to build a Dirac gluino $\tilde{g}_D = \tilde{O}_L + \tilde{g}_R$

- similarly for the SU(2) triplet $\hat{T}$ and U(1) singlet $\hat{S}$ superfields
- new scalar fields in adjoint representations:
  octet of sgluons O,
  triplet of T
  and a singlet S
- super-soft Dirac mass generates sgluon coupling to squarks

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N=2 structure of gauge/gaugino sector

Del Aguila et al, '85

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- two chiral iso-dublets with R-charge 2

$$\hat{R}_u,\; \hat{R}_d$$

to build a mu-type term

$$W \ni \mu_d \hat{R}_d \cdot \hat{H}_d + \mu_u \hat{R}_u \cdot \hat{H}_u$$

- other couplings allowed

$$W \ni \Lambda_d \hat{R}_d \cdot \hat{T}\hat{H}_d + \lambda_d \hat{S}\hat{R}_d \cdot \hat{H}_d + (u \to d)$$

important to get Higgs boson mass

- new scalar R-Higgs bosons
- Dirac mass parameters enter scalar particle mass matrices

# MRSSM

R-charges of the superfields and their component fields

| Field | Superfield | | Boson | | Fermion | |
|---|---|---|---|---|---|---|
| Gauge Vector | $\hat{g}, \hat{W}, \hat{B}$ | 0 | $g, W, B$ | 0 | $\tilde{g}, \tilde{W} \tilde{B}$ | +1 |
| Matter | $\hat{l}, \hat{e}$ | +1 | $\tilde{l}, \tilde{e}_R^*$ | +1 | $l, e_R^*$ | 0 |
| | $\hat{q}, \hat{d}, \hat{u}$ | +1 | $\tilde{q}, \tilde{d}_R^*, \tilde{u}_R^*$ | +1 | $q, d_R^*, u_R^*$ | 0 |
| $H$-Higgs | $\hat{H}_{d,u}$ | 0 | $H_{d,u}$ | 0 | $\tilde{H}_{d,u}$ | −1 |
| R-Higgs | $\hat{R}_{d,u}$ | +2 | $R_{d,u}$ | +2 | $\tilde{R}_{d,u}$ | +1 |
| Adjoint Chiral | $\hat{O}, \hat{T}, \hat{S}$ | 0 | $O, T, S$ | 0 | $\tilde{O}, \tilde{T}, \tilde{S}$ | −1 |

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Physical fields: matter, gauge and Higgs as in MSSM

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Physical fields:

matter, gauge and Higgs as in MSSM

gluinos and neutralinos are Dirac
additional pair of charginos

gauge-adjoint scalars (e.g. sgluons)
and R-Higgs bosons

# MRSSM Lagrangian

Superpotential

$$
\begin{aligned}
W = &\mu_d \hat{R}_d \hat{H}_d + \mu_u \hat{R}_u \hat{H}_u \\
&+ \Lambda_d \hat{R}_d \hat{T} \hat{H}_d + \Lambda_u \hat{R}_u \hat{T} \hat{H}_u + \lambda_d \hat{S} \hat{R}_d \hat{H}_d + \lambda_u \hat{S} \hat{R}_u \hat{H}_u \\
&- Y_d \hat{d} \hat{q} \hat{H}_d - Y_e \hat{e} \hat{l} \hat{H}_d + Y_u \hat{u} \hat{q} \hat{H}_u
\end{aligned}
$$

soft SUSY breaking terms

$$
\begin{aligned}
V_{SB}^{EW} = &B_\mu (H_d^- H_u^+ - H_d^0 H_u^0) + \text{h.c.} \\
&+ m_{H_d}^2 (|H_d^0|^2 + |H_d^-|^2) + m_{H_u}^2 (|H_u^0|^2 + |H_u^+|^2) \\
&+ m_{R_d}^2 (|R_d^0|^2 + |R_d^+|^2) + m_{R_u}^2 |R_u^0|^2 + m_{R_u}^2 |R_d^-|^2 \\
&+ m_S^2 |S|^2 + m_T^2 |T^0|^2 + m_T^2 |T^-|^2 + m_T^2 |T^+|^2 + m_O^2 |O|^2 \\
&+ \tilde{d}_{L,i}^* m_{q,ij}^2 \tilde{d}_{L,j} + \tilde{d}_{R,i}^* m_{d,ij}^2 \tilde{d}_{R,j} + \tilde{u}_{L,i}^* m_{q,ij}^2 \tilde{u}_{L,j} + \tilde{u}_{R,i}^* m_{u,ij}^2 \tilde{u}_{R,j} \\
&+ \tilde{e}_{L,i}^* m_{l,ij}^2 \tilde{e}_{L,j} + \tilde{e}_{R,i}^* m_{e,ij}^2 \tilde{e}_{R,j} + \tilde{\nu}_{L,i}^* m_{l,ij}^2 \tilde{\nu}_{L,j} \,.
\end{aligned}
$$

# Higgs sector – tree level

- EW symmetry breaking triggered by vev's of neutral fields

$$H_d^0 = \frac{1}{\sqrt{2}}(v_d + \phi_d + i\sigma_d), \quad H_u^0 = \frac{1}{\sqrt{2}}(v_u + \phi_u + i\sigma_u) \ ,$$
$$T^0 = \frac{1}{\sqrt{2}}(v_T + \phi_T + i\sigma_T), \quad S = \frac{1}{\sqrt{2}}(v_S + \phi_S + i\sigma_S) \ ;$$

- 4 scalar neutral fields: $\{\phi_d,\ \phi_u,\ \phi_T,\ \phi_S\}$ mix to give physical Higgses

$$\mathcal{M}_{H^0} = \begin{pmatrix} \mathcal{M}_{\rm MSSM} & \mathcal{M}_{21}^T \\ \mathcal{M}_{21} & \mathcal{M}_{22} \end{pmatrix}$$

- 4 pseudo-scalar neutral fields: $\{\sigma_u, \sigma_d\}$ and $\{\sigma_T, \sigma_S\}$ do not mix

➡ $\tan\beta,\ M_A$ as in MSSM

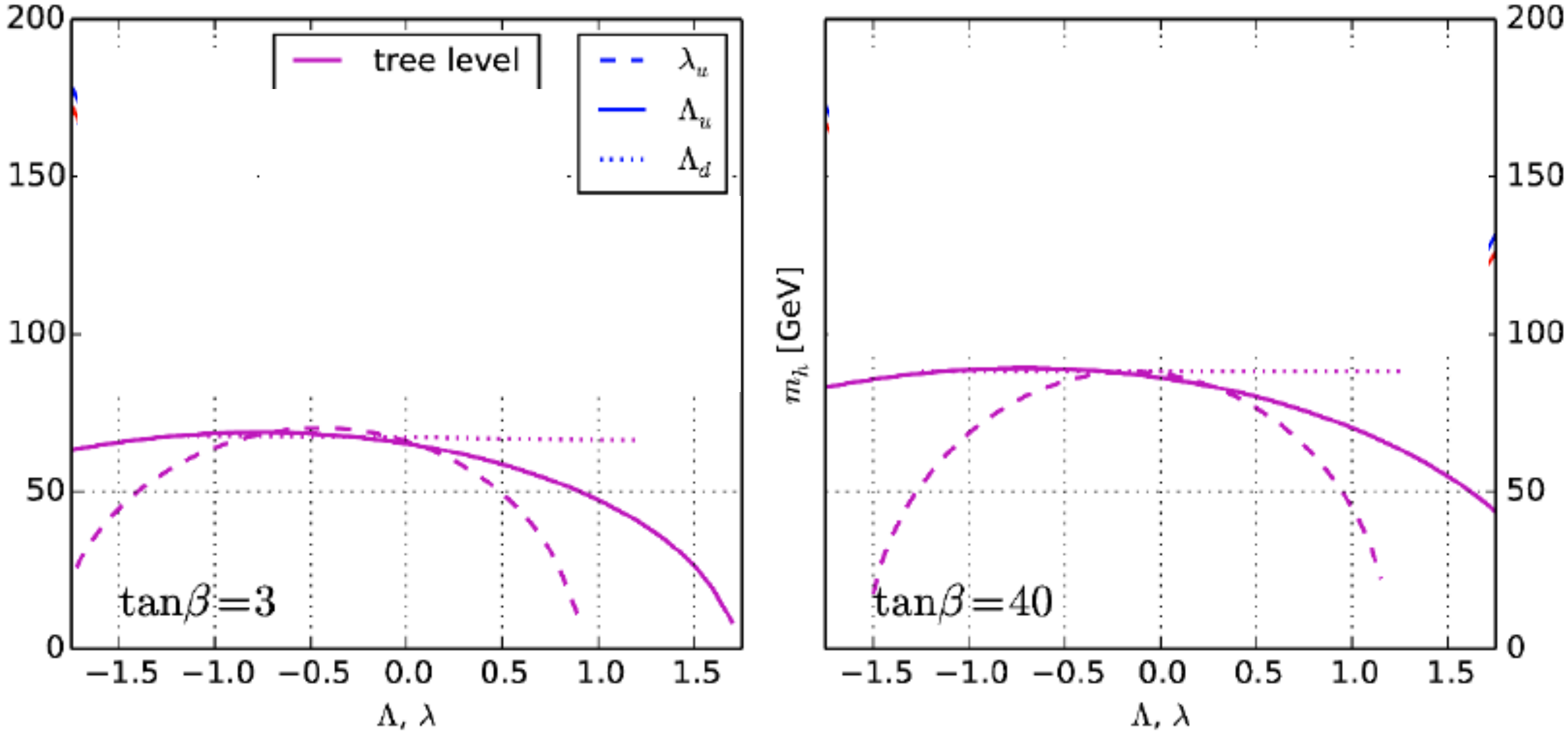
# MRSSM confronting experiment

Can the MRSSM accomodate the Higgs mass, EWPO and LHC constraints?

First option: 125 GeV Higgs – the lightest state

Diessner, JK, Kotlarski, Stockinger, JHEP 1412 (2014) 124

# lightest Higgs – tree level




- approximate formula for the lightest Higgs at tree level

$$m^2_{H_1,\text{approx}} = m_Z^2 \cos^2 2\beta - v^2 \left( \frac{\left(g_1 M_B^D + \sqrt{2}\lambda\mu\right)^2}{4(M_B^D)^2 + m_S^2} + \frac{\left(g_2 M_W^D + \Lambda\mu\right)^2}{4(M_W^D)^2 + m_T^2} \right) \cos^2 2\beta$$

under simplifying assumptions of large pseudoscalar A mass and

$$\lambda = \lambda_u = -\lambda_d,\ \Lambda = \Lambda_u = \Lambda_d,\ \mu_u = \mu_d = \mu \text{ and } v_S \approx v_T \approx 0:$$

➡ always lower than in the MSSM due to mixing with S and T

# Higgs sector at one-loop level and beyond

# lightest Higgs and PO observables

Getting 125 GeV Higgs and PO not obvious because:

- mixing with other states lowers the tree level mass
  needs even larger radiative corrections than in MSSM
- no LR stop mixing – an important MSSM mechanism to rise
  the Higgs mass is not present
- the vev of the EW triplet contributes to the rho parameter at tree-level

$$m_Z^2 = \frac{g_1^2 + g_2^2}{4} v^2 \,, \qquad m_W^2 = \frac{g_2^2}{4} v^2 + g_2^2 v_T^2 \,, \qquad \hat{\rho}_{\rm tree} = 1 + \frac{4 v_T^2}{v^2}$$

- the W mass (and other PO) affected by loops
- LHC and flavor constraints

# effective potential

In MSSM

$$\Delta m^2_{H_1,\mathrm{eff.pot},y_t} = \frac{6v^2}{16\pi^2}\left[Y_t^4 \log\left(\frac{m_{\tilde{t}_1} m_{\tilde{t}_2}}{m_t^2}\right)\right]$$

# effective potential

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In MRSSM

$$\begin{aligned}\Delta m^2_{H_1,\text{eff.pot},\lambda} = \frac{2v^2}{16\pi^2}\Bigg[ & \frac{\Lambda^2\lambda^2}{2} + \frac{4\lambda^4 + 4\lambda^2\Lambda^2 + 5\Lambda^4}{8}\log\frac{m^2_{R_u}}{Q^2} \\ & + \left(\frac{\lambda^4}{2} - \frac{\lambda^2\Lambda^2}{2}\frac{m_S^2}{m_T^2 - m_S^2}\right)\log\frac{m_S^2}{Q^2} \\ & + \left(\frac{5}{8}\Lambda^4 + \frac{\lambda^2\Lambda^2}{2}\frac{m_T^2}{m_T^2 - m_S^2}\right)\log\frac{m_T^2}{Q^2} \\ & - \left(\frac{5}{4}\Lambda^4 - \lambda^2\Lambda^2\frac{(M_W^D)^2}{(M_B^D)^2 - (M_W^D)^2}\right)\log\frac{(M_W^D)^2}{Q^2} \\ & - \left(\lambda^4 + \lambda^2\Lambda^2\frac{(M_B^D)^2}{(M_B^D)^2 - (M_W^D)^2}\right)\log\frac{(M_B^D)^2}{Q^2}\Bigg] .\end{aligned}$$

# lightest Higgs – full one-loop level

renormalize parameters in the DRbar scheme

solve tadpoles

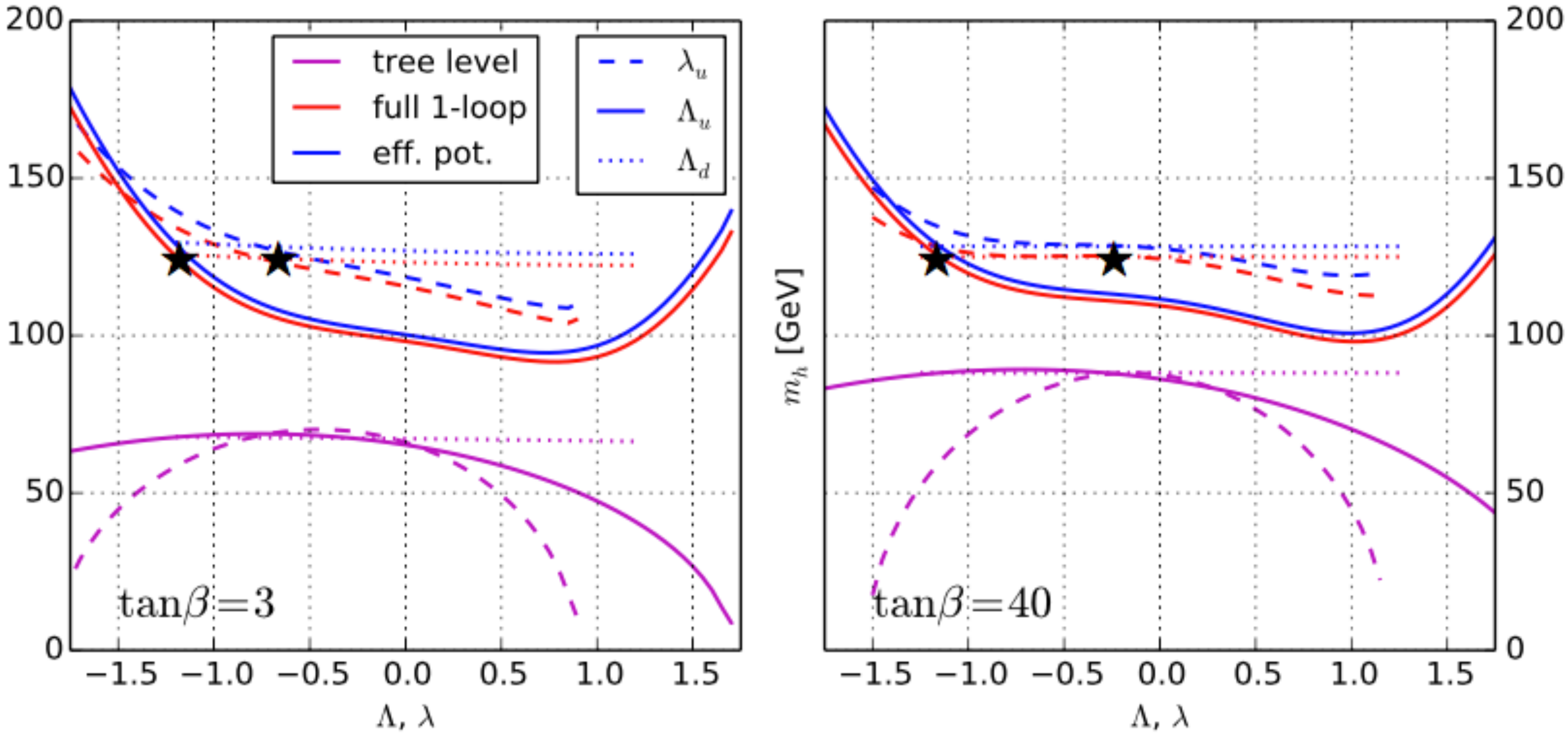
$$
\begin{aligned}
t_d &= v_d[\tfrac{1}{8}\left(g_1^2+g_2^2\right)\left(v_d^2-v_u^2\right) - g_1 M_B^D v_S + g_2 M_W^D v_T + m_{H_d}^2 + (\mu_d^{\text{eff},+})^2] - v_u B_\mu \\
t_u &= v_u[\tfrac{1}{8}\left(g_1^2+g_2^2\right)\left(v_u^2-v_d^2\right) + g_1 M_B^D v_S - g_2 M_W^D v_T + m_{H_u}^2 + (\mu_u^{\text{eff},-})^2] - v_d B_\mu \\
t_T &= \tfrac{1}{2} g_2 M_W^D \left(v_d^2-v_u^2\right) + \tfrac{1}{2}\Lambda_d v_d^2 \mu_d^{\text{eff},+} - \Lambda_u v_u^2 \mu_u^{\text{eff},-} + 4(M_W^D)^2 v_T + m_T^2 v_T \,, \\
t_S &= \tfrac{1}{2} g_1 M_B^D \left(v_u^2-v_d^2\right) + \tfrac{1}{\sqrt{2}}\lambda_d v_d^2 \mu_d^{\text{eff},+} + \lambda_u v_u^2 \mu_u^{\text{eff},-} + 4(M_B^D)^2 v_S + m_S^2 v_S \,.
\end{aligned}
$$

trade $v_S, v_T$ for $m_S, m_T$

calculate pole masses $\quad 0 \stackrel{!}{=} \det\left[p^2\delta_{ij} - \hat{m}_{ij}^2 + \Re(\hat{\Sigma}_{ij}(p^2))\right]_{p^2=m^2_{\text{pole}}}$

calculations done using SARAH, FeynArts, FormCalc and SPheno

# lightest Higgs – full one-loop level




- 125 GeV Higgs for $\Lambda, \lambda \sim -1$

even with top 1 TeV and no LR mixing

# W mass – full one-loop level

Beyond tree-level
$$\frac{G_\mu}{\sqrt{2}} = \frac{\pi\hat{\alpha}}{2\hat{s}_W^2 m_W^2}\frac{1}{1-\Delta\hat{r}_W}$$

we get the master formula of Degrassi, Franchiotti, Sirlin (1990)

$$m_W^2 = \frac{1}{2}m_Z^2\hat{\rho}\left[1+\sqrt{1-\frac{4\pi\hat{\alpha}}{\sqrt{2}G_\mu m_Z^2\hat{\rho}(1-\Delta\hat{r}_W)}}\right]$$

need to calculate $\hat{\alpha}$, $\hat{\rho}$, and $\Delta\hat{r}_W$ at one-loop level

# W mass – full one-loop level

Beyond tree-level
$$\frac{G_\mu}{\sqrt{2}} = \frac{\pi\hat{\alpha}}{2\hat{s}_W^2 m_W^2}\frac{1}{1-\Delta\hat{r}_W}$$

we get the master formula of Degrassi, Franchiotti, Stirlin (1990)

$$m_W^2 = \frac{1}{2}m_Z^2\hat{\rho}\left[1+\sqrt{1-\frac{4\pi\hat{\alpha}}{\sqrt{2}G_\mu m_Z^2\hat{\rho}(1-\Delta\hat{r}_W)}}\right]$$

need to calculate $\hat{\alpha}$, $\hat{\rho}$, and $\Delta\hat{r}_W$ at one-loop level

For qualitative discussion -- useful to use

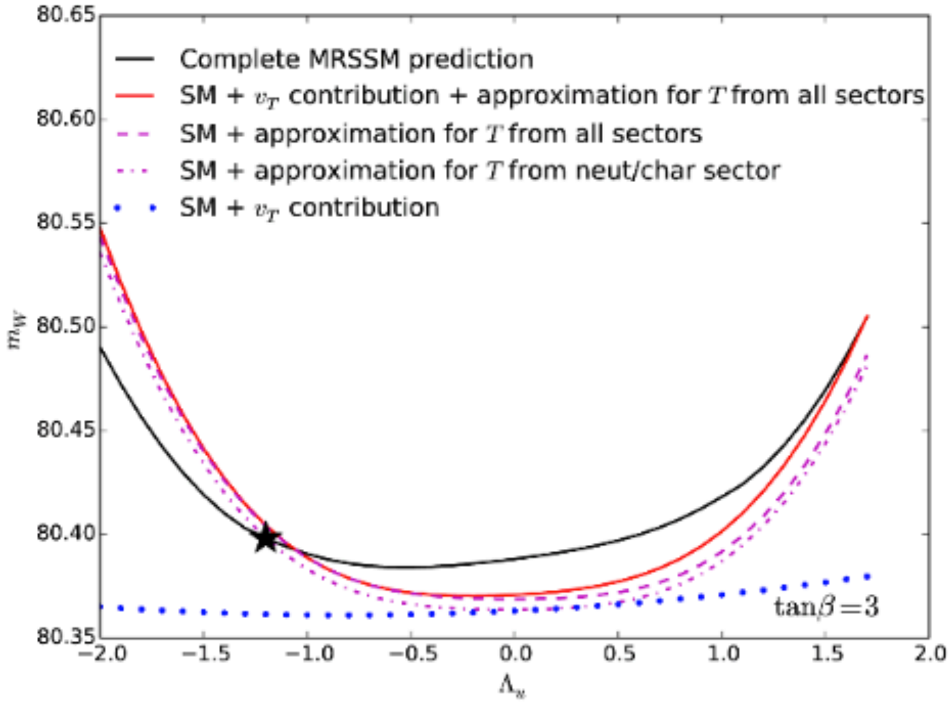
$$m_W = m_W^{\rm ref} + \frac{\hat{\alpha} m_Z \hat{c}_W}{2(\hat{c}_W^2-\hat{s}_W^2)}\left(-\frac{S}{2}+\hat{c}_W^2 T + \frac{\hat{c}_W^2-\hat{s}_W^2}{4\hat{s}_W^2}U\right)$$

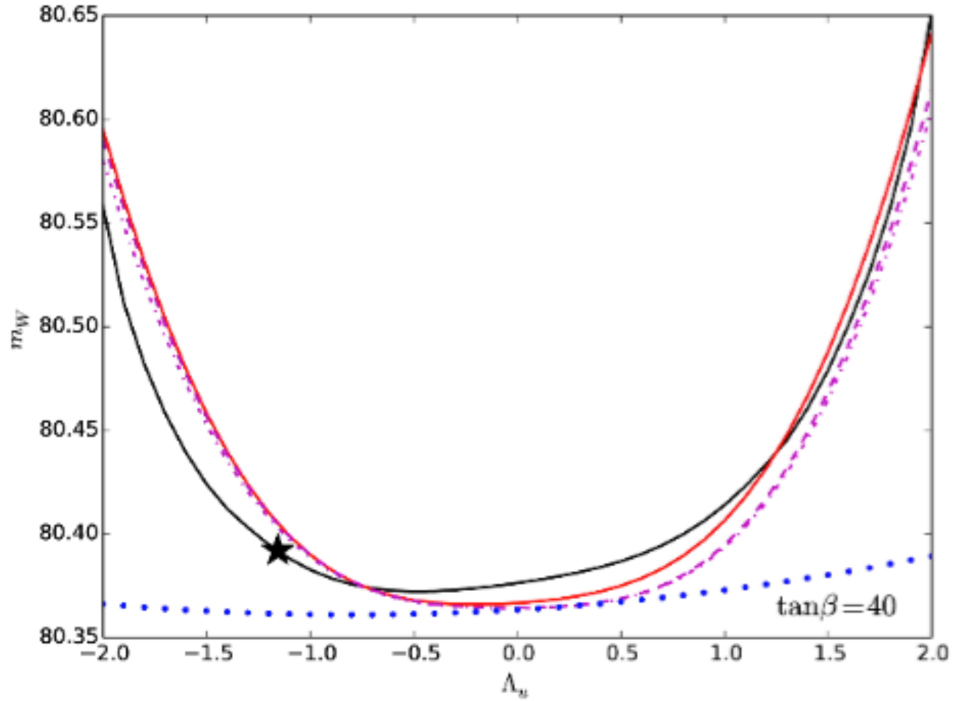
chargino/neutralino sector gives dominant contributions

$$T = \frac{1}{16\pi\hat{s}_W^2\hat{m}_W^2}\frac{v_u^4}{(M_W^D)^2}\left[\frac{13g_2^4+2g_2^3\Lambda_u+18g_2^2\Lambda_u^2+2g_2\Lambda_u^3+13\Lambda_u^4}{96}\right].$$

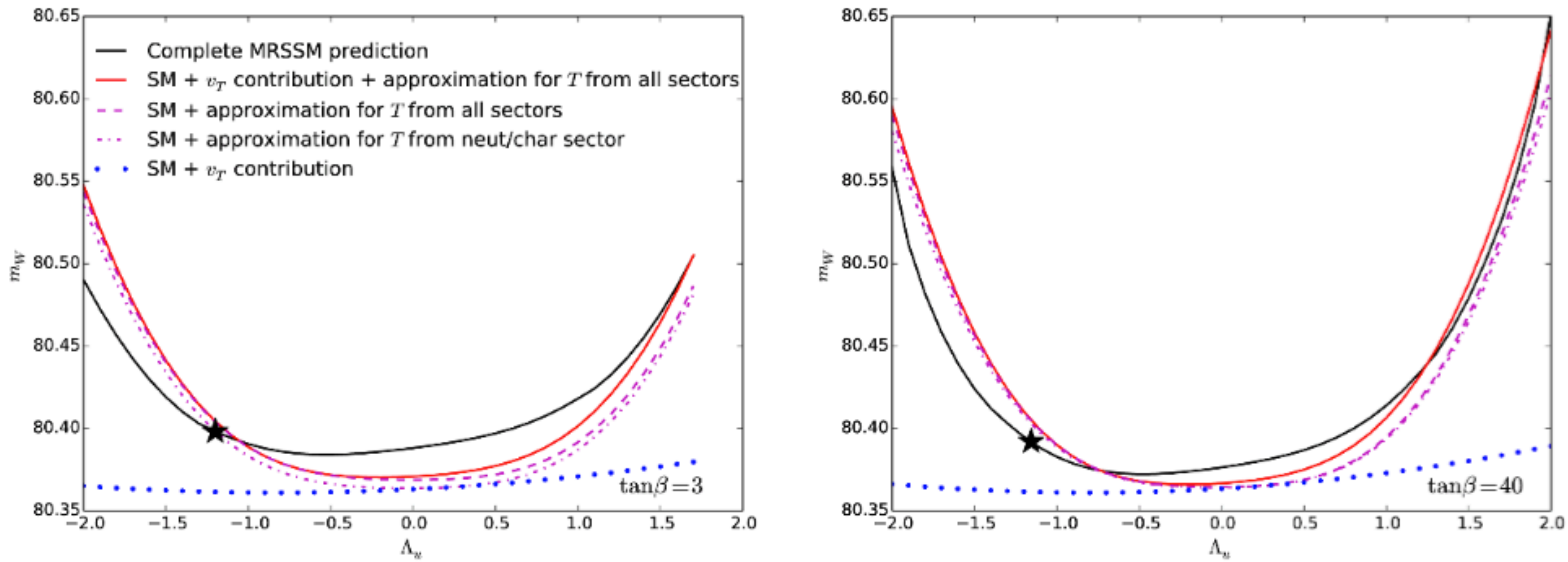
assuming
$\mu_u = M_W^D$
$\lambda_u = g_1 = 0$

# W mass – full one-loop level



# W mass – full one-loop level




Benchmarks:

$$\tan\beta = 3, 10, 40$$

| | BMP1 | BMP2 | BMP3 |
|---|---|---|---|
| $m_{H_1}$ | 125.3 GeV | 125.1 GeV | 125.1 GeV |
| $m_W$ | 80.399 GeV | 80.385 GeV | 80.393 GeV |
| HiggsBounds's obsratio | 0.61 | 0.61 | 0.63 |
| HiggsSignals's p-value | 0.42 | 0.40 | 0.40 |
| $S$ | 0.0097 | 0.0092 | 0.0032 |
| $T$ | 0.090 | 0.091 | 0.085 |
| $U$ | 0.00067 | 0.00065 | 0.0010 |
| Vevacious | ✓ | ✓ | ✓ |
| selected $b$ physics observables | ✓ | ✓ | ✓ |

# Higgs at two loops

Since full one-loop corrections large, check dominant two-loop from top/stop because of large top Yukawa

# Higgs - leading two-loop

Since full one-loop corrections large, check dominant
two-loop from top/stop because of large top Yukawa

In the MSSM the answer is well known

The MRSSM is distinctively different

- new large couplings $\Lambda, \lambda \sim -1$, is perturbativity still at work?
- new sectors enter the game: Dirac gluinos and scalar gluons

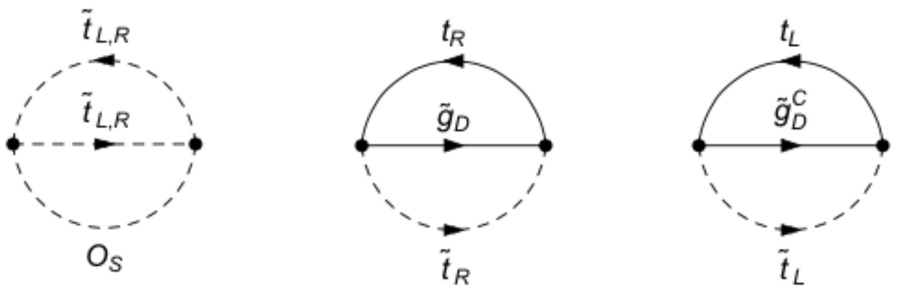
new release of SARAH provides tools to calculate in
effective potential approximation

Goodsell, Nickel, Staub EPJC75 (2015) 32

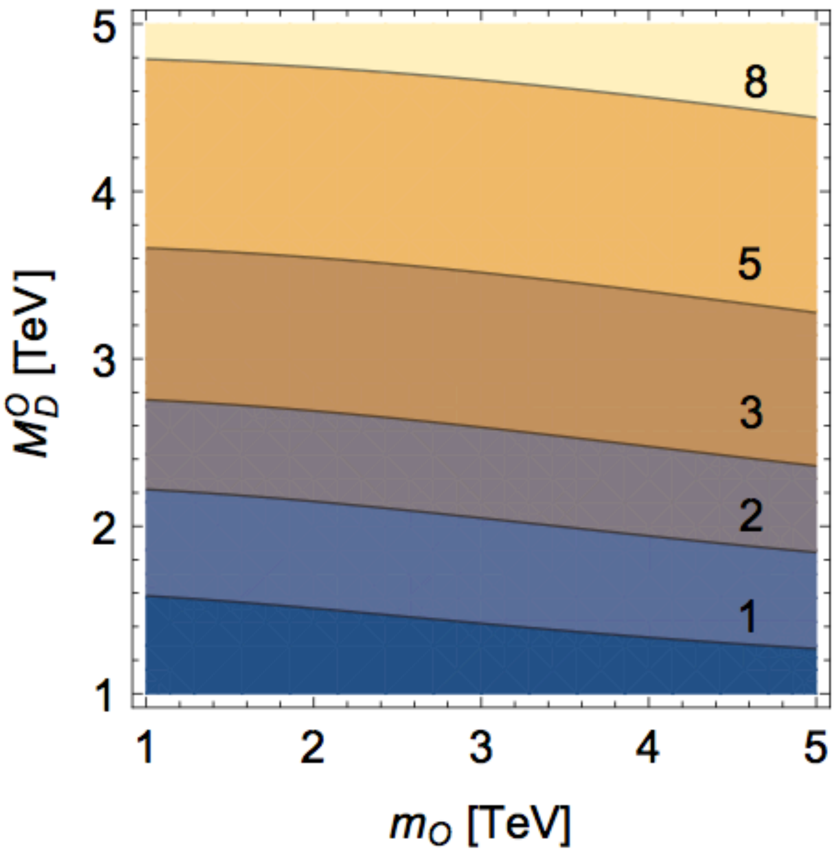
# Higgs - leading two-loop

Diessner, JK, Kotlarski, Stockinger, Adv. HEP (2015) 760729

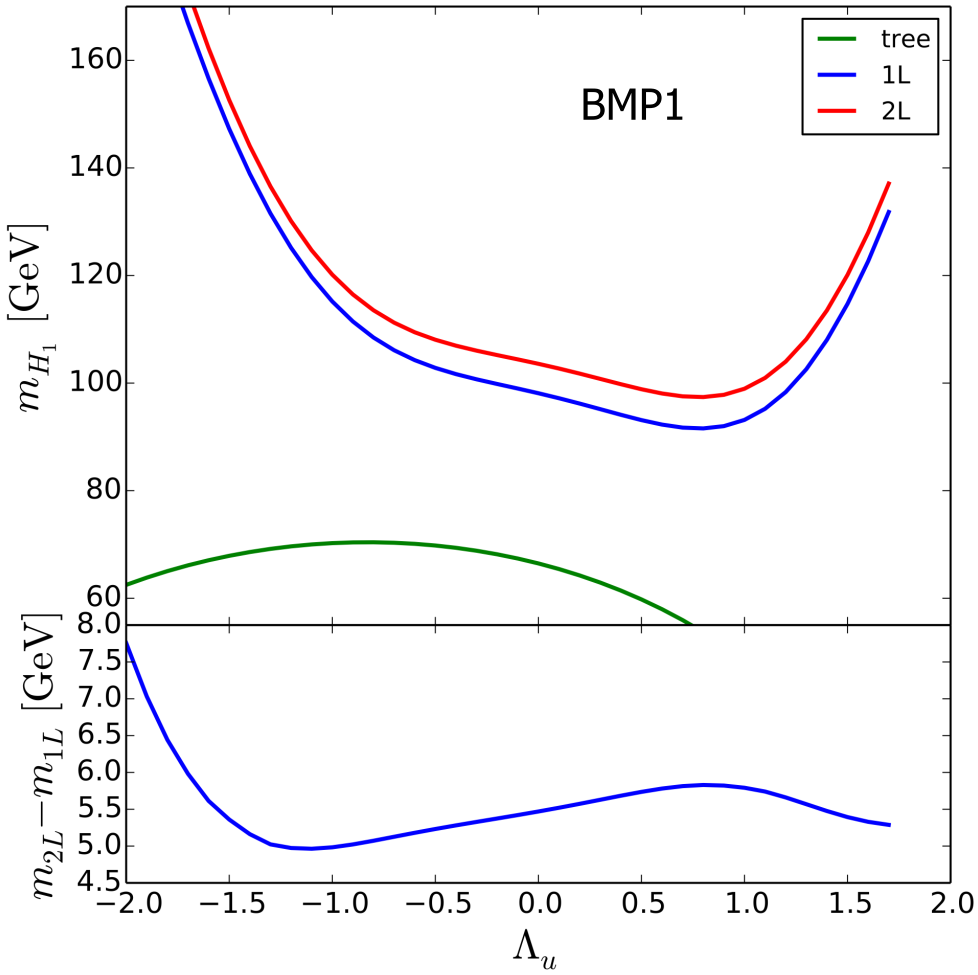
MRSSM specific contributions – from Dirac gluinos and sgluons




$$V_{eff}^{(2)} = \frac{8g_3^2}{(16\pi^2)^2}(M_O^D)^2 \sum_{i=L,R} f_{SSS}(m^2_{\tilde{t}_i}, m^2_{\tilde{t}_i}, m^2_{O_S}) + \frac{8g_3^2}{(16\pi^2)^2} \sum_{i=L,R} f_{FFS}(m^2_t, m^2_{\tilde{t}_i}, m^2_{\tilde{g}_D})$$



# Impact of leading two-loop correction



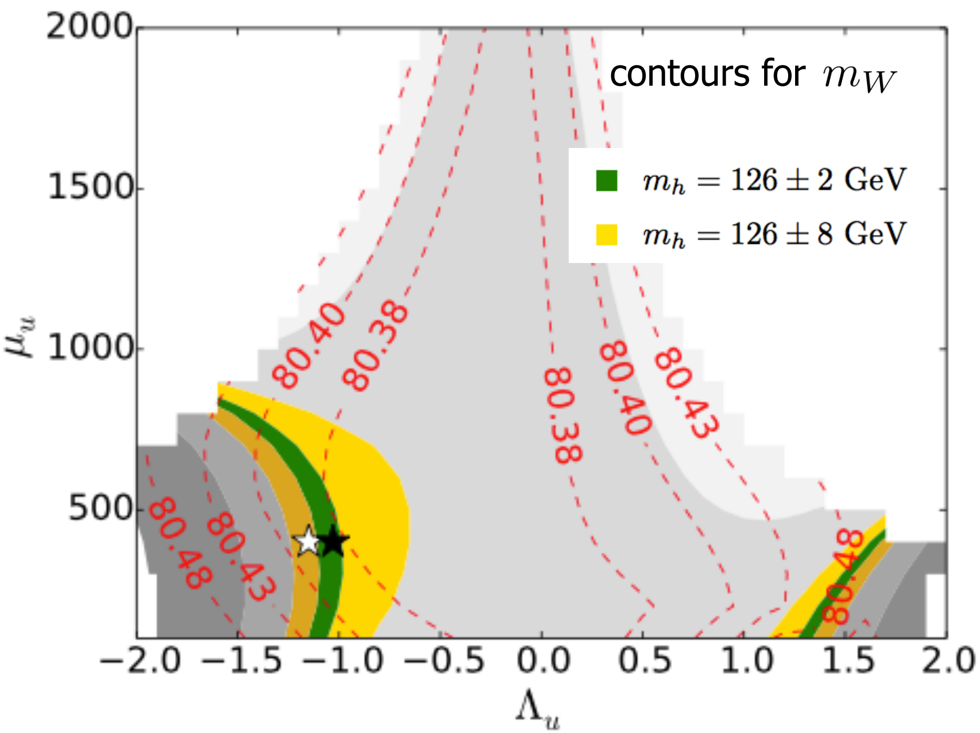

two-loop corrections:

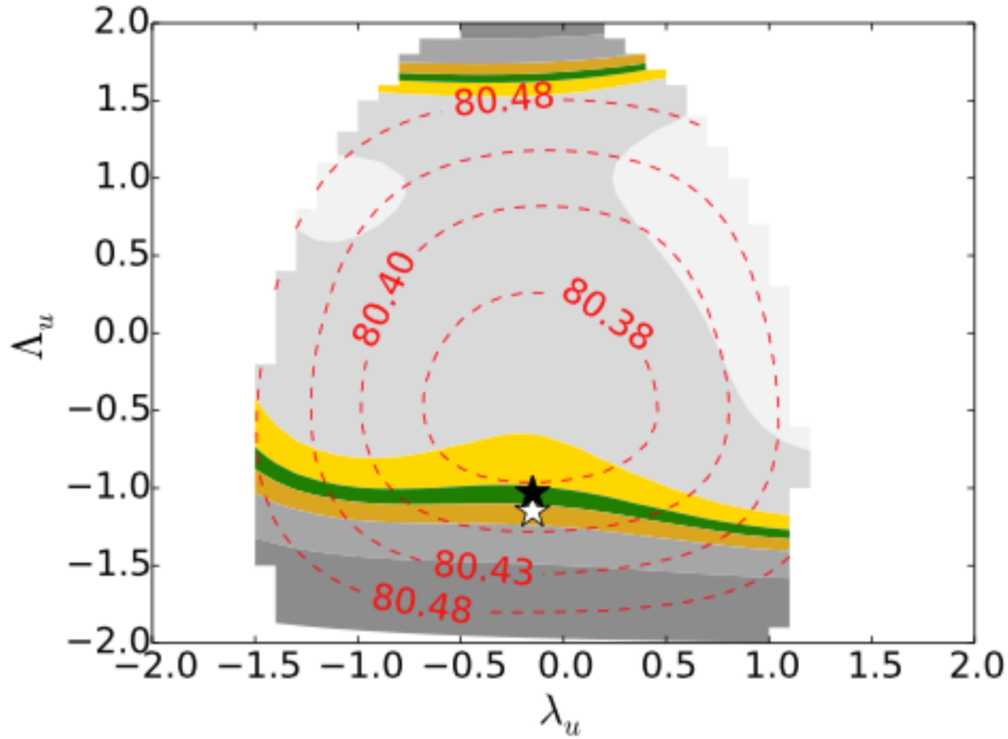
small, inspite large 1-loop

add ~5GeV to Higgs mass

allows to lower $\Lambda$ $\lambda$

# Impact of leading two-loop correction




★ for benchmark point with 2-loop Higgs mass (☆ for 1-loop)

two-loop corrections increase agreement between $m_h$ and $m_W$

# MRSSM confronting experiment

Can the MRSSM accomodate the Higgs mass, EWPO and LHC constraints?

First option: 125 GeV Higgs – the lightest state

Diessner, JK, Kotlarski, Stockinger, JHEP 1412 (2014) 124

Diessner, JK, Kotlarski, Stockinger, Adv. HEP (2015) 760729

Answer not obvious because:

- mixing with other states lowers the tree level mass

# MRSSM confronting experiment

Can the MRSSM accomodate the Higgs mass, EWPO and LHC constraints?

First option: 125 GeV Higgs – the lightest state

Diessner, JK, Kotlarski, Stockinger, JHEP 1412 (2014) 124

Diessner, JK, Kotlarski, Stockinger, Adv. HEP (2015) 760729

Second option: 125 GeV Higgs – the next-to-lightest state

Diessner, JK, Kotlarski, Stockinger, JHEP 1603 (2016) 007

mixing with other fields pushes the tree-level mass upwards

# Light singlet scenario

# MRSSM with a light singlet

- In large $\tan\beta,\ M_A$ limit, the $(\phi_u, \phi_S)$ mass submatrix

$$\mathcal{M}^{\phi}_{u,S} = \begin{pmatrix} m_Z^2 + \Delta m^2_{\rm rad} & v_u\left(\sqrt{2}\lambda_u \mu_u^{{\rm eff},-} + g_1 M_B^D\right) \\ v_u\left(\sqrt{2}\lambda_u \mu_u^{{\rm eff},-} + g_1 M_B^D\right) & 4(M_B^D)^2 + m_S^2 + \frac{\lambda_u^2 v_u^2}{2} \end{pmatrix}$$

$$\mu_i^{{\rm eff},\pm} = \mu_i + \frac{\lambda_i v_S}{\sqrt{2}} \pm \frac{\Lambda_i v_T}{2}, \qquad i = u, d.$$

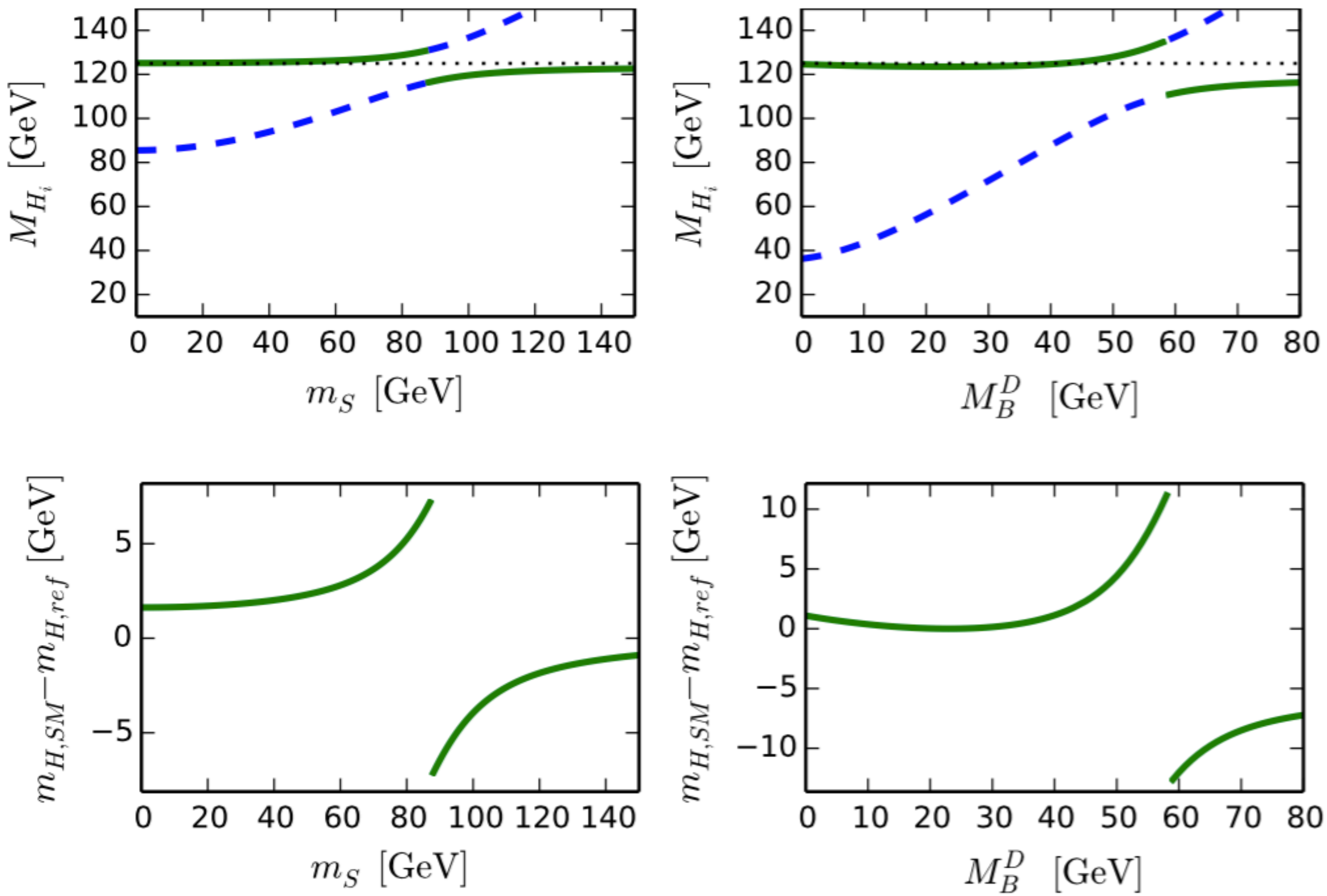
- to realise light singlet scenario

$$m_S, M_B^D < m_Z < \mu_u\,, \qquad |\lambda_u| \ll 1$$

- then the SM-like Higgs at tree level

$$m^2_{h,\rm tree} \approx m_Z^2 \cos^2 2\beta + v^2 \cos^2 2\beta \left( \frac{(g_1 M_B^D + \sqrt{2}\lambda\mu)^2}{|m_S^2 + 4(M_B^D)^2 - m_Z^2 \cos^2 2\beta|} \right)$$

# MRSSM with a light singlet – one loop

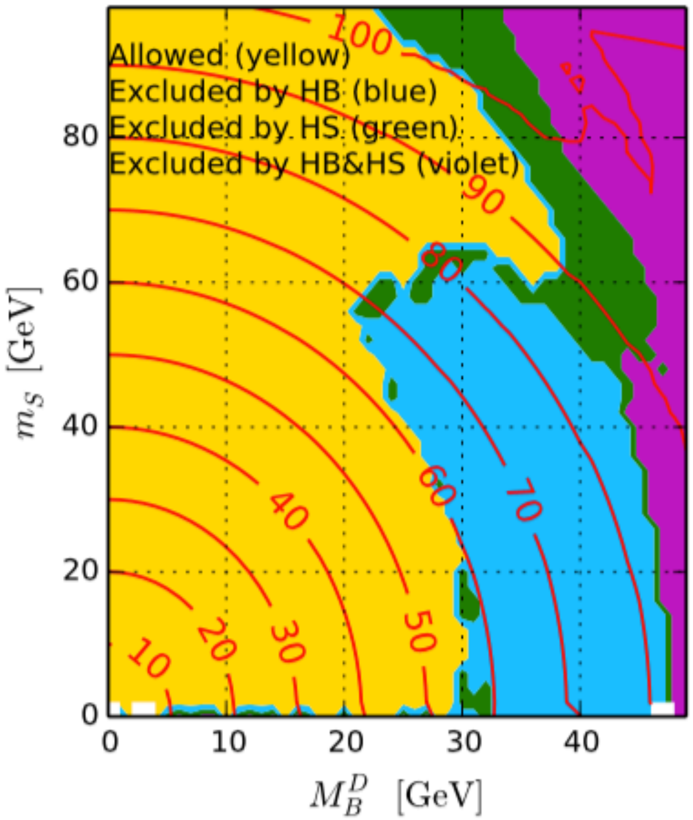


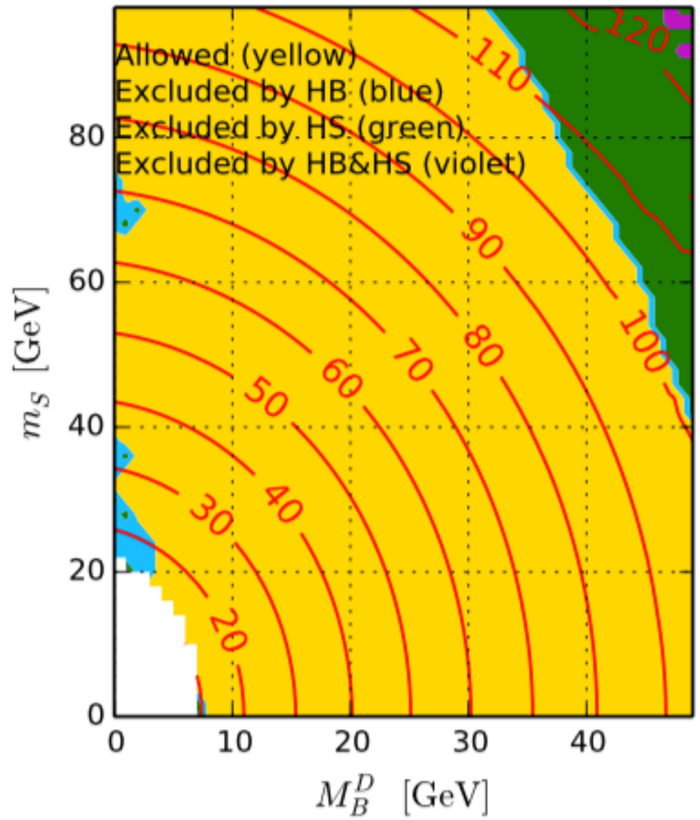

level crossing of two lightest Higgs bosons

relative mass shift due to mixing

# MRSSM with a light singlet – one loop

LHC and PO constraints



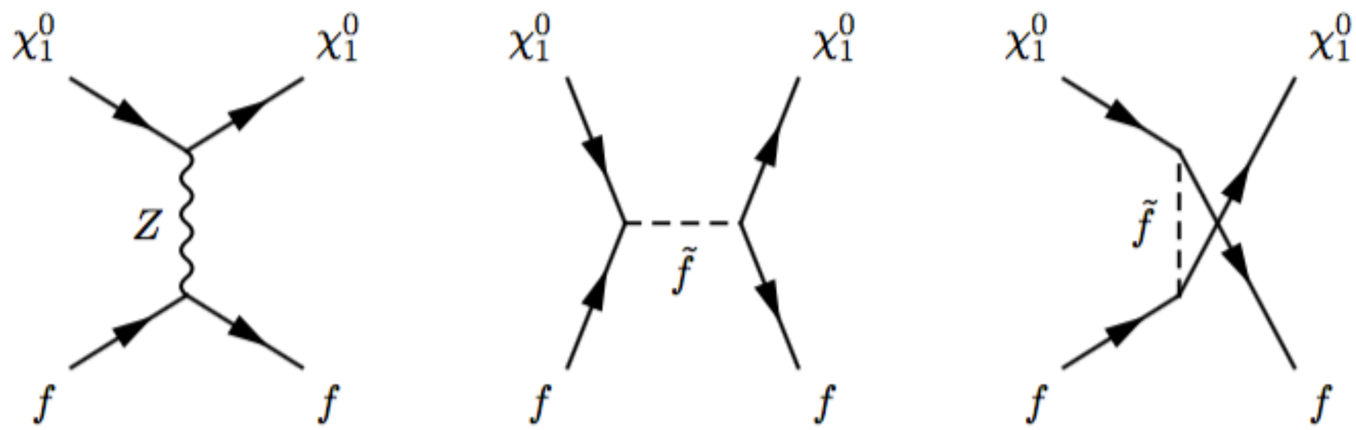




| | BMP4 | BMP5 | BMP6 |
|---|---|---|---|
| $m_{H_1}$ | 100 | 94 | 95 |
| $m_{H_2}$ | 125.8 | 125.5 | 125.8 |
| HiggsSignals p-value | 0.75 | 0.76 | 0.72 |
| Allowed by HiggsBounds | ✓ | ✓ | ✓ |
| $m_W$ | 80.384 | 80.392 | 80.404 |

# MRSSM with a light singlet – dark matter

light singlet requires low singlet and bino-singlino mass parameters

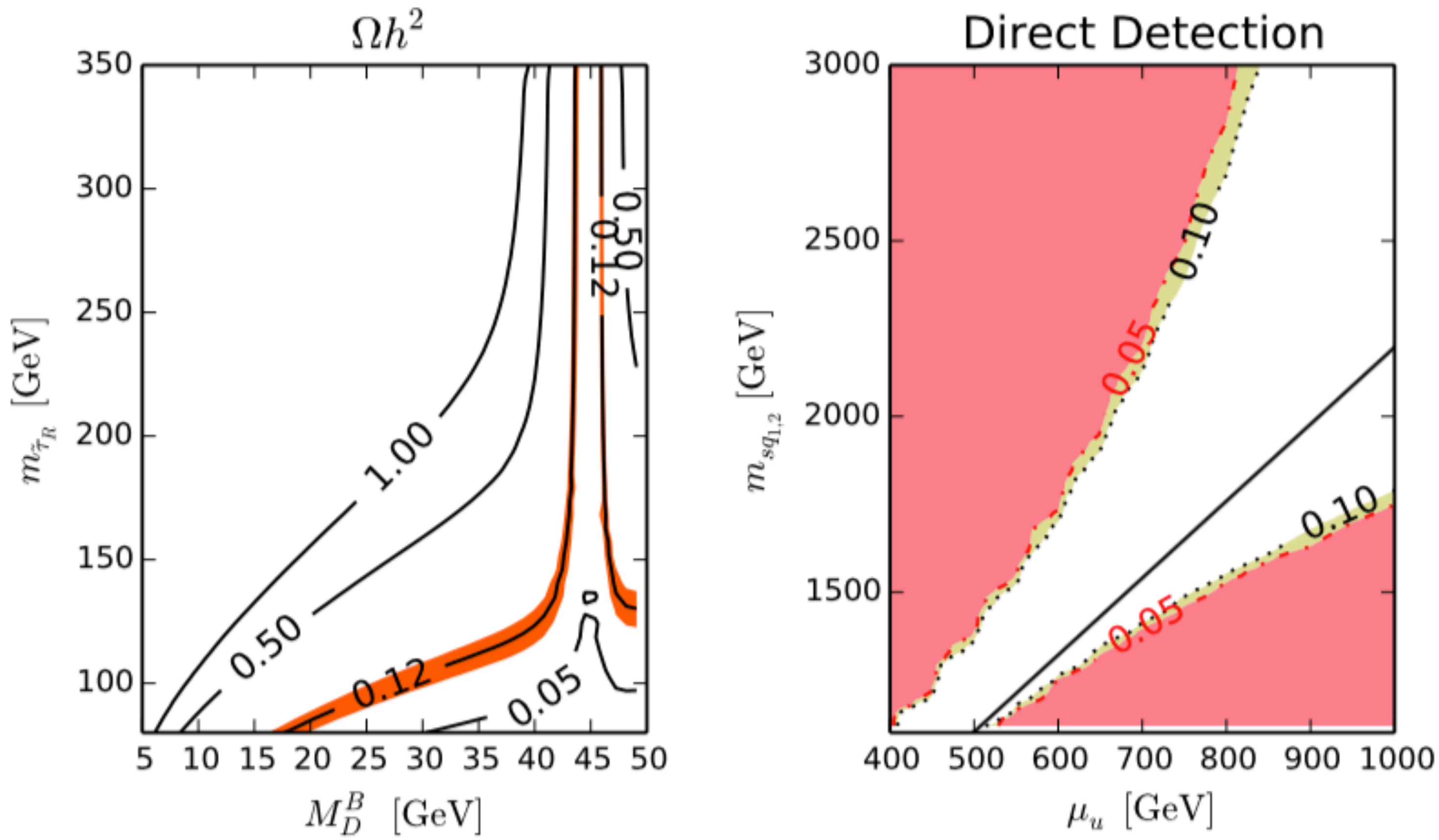
the lightest neutralino – a candidate for dark matter




relic density $f \to \tau$

direct detection $f \to u, d$

# MRSSM with a light singlet – dark matter




| | BMP4 | BMP5 | BMP6 |
|---|---|---|---|
| $m_{\chi^1}$ | 49.8 GeV | 43.9 GeV | 29.7 GeV |
| $m_{\tilde{\tau}_R}$ | 128.5 GeV | 1 TeV | 105.6 GeV |
| $\Omega h^2$ | 0.119 | 0.092 | 0.127 |
| direct detection p-value | 0.9 | 0.5 | 0.2 |

# MRSSM with a light singlet

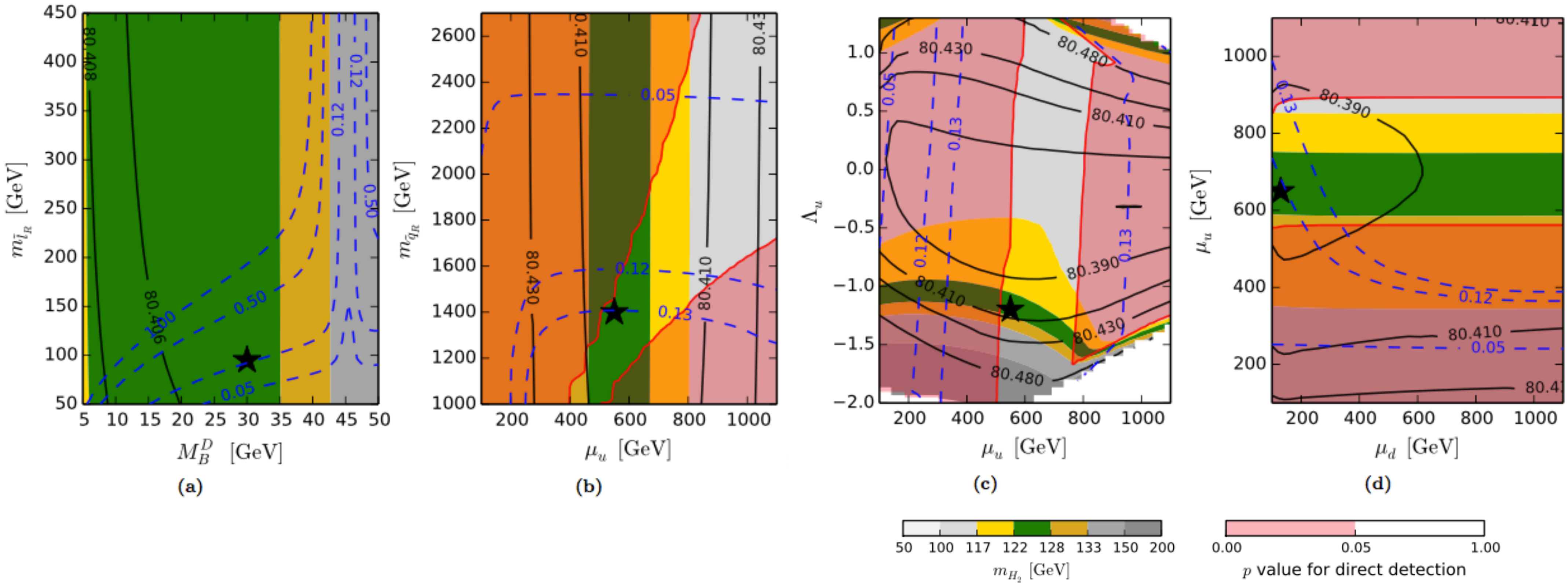



**Figure 8.** Shown are parameter regions and their agreement with experiment. Red overlaid areas are excluded with 95% CL by dark matter direct detection. Black full (blue dashed) lines show $m_W$ ($\Omega h^2$). The mass of the SM-like Higgs boson $m_{H_2}$ is given by the colour scale shown. All non-varied parameters are set to the values of BMP6, except for the bottom right plot, where BMP4 is used. BMPs are marked by stars. The white areas in (d) stem from tachyonic states appearing in the mass spectrum, at the borders to these areas the interpolation breaks down.

# Summary

- Well motivated R-symmetric SUSY model discussed
- Gauginos become Dirac particles, new scalar partners
- Full one-loop and dominant two-loop
- Viable benchmarks with
  - ~ 125 GeV Higgs boson mass
  - agreement with EWPO and flavor physics
  - stable vacuum
  - consistent with LHC constraints
  - in the light singlet scenario also a viable dark matter candidate
- Conserved R-charge restricts production channels and decay modes
  - distinct phenomenology at colliders
  - some states light and could be seen at the LHC

# Summary

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  - some states light and could be seen at the LHC

Many things to do: work on SQCD in progress

Backup

benchmarks:

| | BMP1 | BMP2 | BMP3 |
|---|---|---|---|
| $\tan\beta$ | 3 | 10 | 40 |
| $B_\mu$ | $500^2$ | $300^2$ | $200^2$ |
| $\lambda_d,\ \lambda_u$ | $1.0, -0.8$ | $1.1, -1.1$ | $0.15, -0.15$ |
| $\Lambda_d,\ \Lambda_u$ | $-1.0, -1.2$ | $-1.0, -1.0$ | $-1.0, -1.15$ |
| $M_B^D$ | 600 | 1000 | 250 |
| $m_{R_u}^2$ | $2000^2$ | $1000^2$ | $1000^2$ |
| $\mu_d,\ \mu_u$ | $400, 400$ | | |
| $M_W^D$ | 500 | | |
| $M_O^D$ | 1500 | | |
| $m_T^2,\ m_S^2,\ m_O^2$ | $3000^2, 2000^2, 1000^2$ | | |
| $m_{Q;1,2}^2,\ m_{Q;3}^2$ | $2500^2, 1000^2$ | | |
| $m_{D;1,2}^2,\ m_{D;3}^2$ | $2500^2, 1000^2$ | | |
| $m_{U;1,2}^2,\ m_{U;3}^2$ | $2500^2, 1000^2$ | | |
| $m_L^2,\ m_E^2$ | $1000^2$ | | |
| $m_{R_d}^2$ | $700^2$ | | |
| $v_S$ | 5.9 | 1.3 | $-0.14$ |
| $v_T$ | $-0.33$ | $-0.19$ | $-0.34$ |
| $m_{H_d}^2$ | $671^2$ | $761^2$ | $1158^2$ |
| $m_{H_u}^2$ | $-532^2$ | $-544^2$ | $-543^2$ |

one loop

| | | | |
|---|---|---|---|
| $m_{H_1}$ | 125.3 GeV | 125.1 GeV | 125.1 GeV |
| $m_W$ | 80.399 GeV | 80.385 GeV | 80.393 GeV |
| HiggsBounds's obsratio | 0.61 | 0.61 | 0.63 |
| HiggsSignals's p-value | 0.42 | 0.40 | 0.40 |

benchmarks:

including two-loop corr.

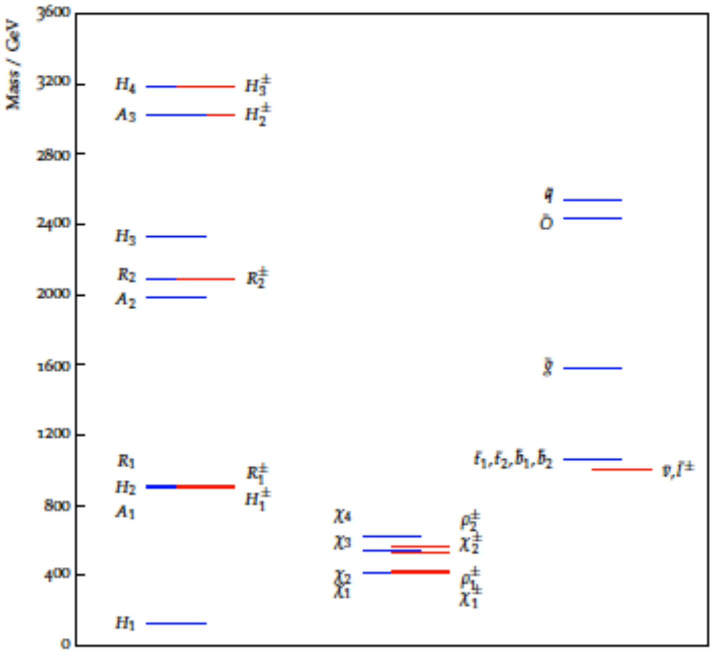
$\Lambda_u$ reduces to

| | BMP1 | BMP2 | BMP3 | BMP1 (two-loop) | BMP2 (two-loop) | BMP3 (two-loop) |
|---|---|---|---|---|---|---|
| $\tan\beta$ | 3 | 10 | 40 | | | |
| $B_\mu$ | $500^2$ | $300^2$ | $200^2$ | | | |
| $\lambda_d,\ \lambda_u$ | $1.0, -0.8$ | $1.1, -1.1$ | $0.15, -0.15$ | | | |
| $\Lambda_d,\ \Lambda_u$ | $-1.0, -1.2$ | $-1.0, -1.0$ | $-1.0, -1.15$ | $-1.11$ | $-0.85$ | $-1.03$ |
| $M_B^D$ | 600 | 1000 | 250 | | | |
| $m_{R_u}^2$ | $2000^2$ | $1000^2$ | $1000^2$ | | | |
| $\mu_d,\ \mu_u$ | $400, 400$ | | | | | |
| $M_W^D$ | 500 | | | | | |
| $M_O^D$ | 1500 | | | | | |
| $m_T^2,\ m_S^2,\ m_O^2$ | $3000^2, 2000^2, 1000^2$ | | | | | |
| $m_{Q;1,2}^2,\ m_{Q;3}^2$ | $2500^2, 1000^2$ | | | | | |
| $m_{D;1,2}^2,\ m_{D;3}^2$ | $2500^2, 1000^2$ | | | | | |
| $m_{U;1,2}^2,\ m_{U;3}^2$ | $2500^2, 1000^2$ | | | | | |
| $m_L^2,\ m_E^2$ | $1000^2$ | | | | | |
| $m_{R_d}^2$ | $700^2$ | | | | | |
| $v_S$ | 5.9 | 1.3 | $-0.14$ | 5.2 | 1.01 | $-0.22$ |
| $v_T$ | $-0.33$ | $-0.19$ | $-0.34$ | $-0.25$ | $-0.02$ | $-0.21$ |
| $m_{H_d}^2$ | $671^2$ | $761^2$ | $1158^2$ | $674^2$ | $764^2$ | $1160^2$ |
| $m_{H_u}^2$ | $-532^2$ | $-544^2$ | $-543^2$ | $-502^2$ | $-512^2$ | $-516^2$ |
| $m_{H_1}$ | 125.3 GeV | 125.1 GeV | 125.1 GeV | 125.3 GeV | 125.5 GeV | 125.4 GeV |
| $m_W$ | 80.399 GeV | 80.385 GeV | 80.393 GeV | 80.397 GeV | 80.381 GeV | 80.386 GeV |
| HiggsBounds's obsratio | 0.61 | 0.61 | 0.63 | 0.61 | 0.65 | 0.87 |
| HiggsSignals's p-value | 0.42 | 0.40 | 0.40 | 0.72 | 0.66 | 0.72 |

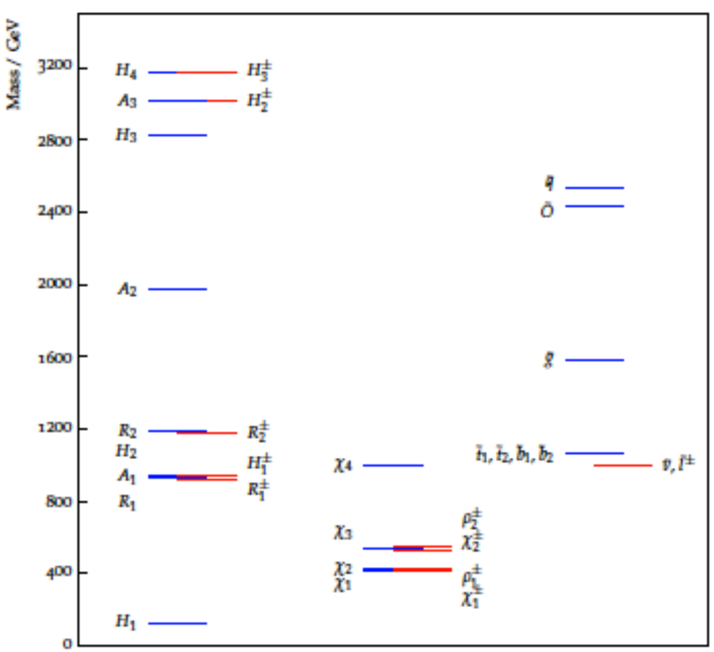
one loop

# benchmarks

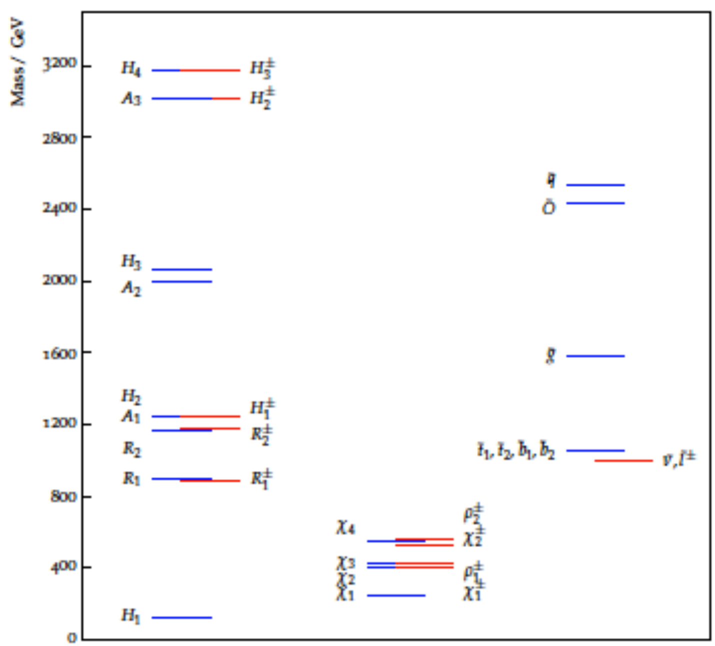
BMP1




BMP2




BMP3



benchmarks for light singlet scenario

| | BMP4 | BMP5 | BMP6 |
|---|---|---|---|
| $\tan\beta$ | 40 | 20 | 6 |
| $B_\mu$ | $200^2$ | $200^2$ | $500^2$ |
| $\lambda_d,\ \lambda_u$ | $0.01, -0.01$ | $0.0, -0.01$ | $0.0, 0.0$ |
| $\Lambda_d,\ \Lambda_u$ | $-1, -1.2$ | $-1, -1.15$ | $-1, -1.2$ |
| $M_B^D$ | 50 | 44 | 30 |
| $m_S^2$ | $30^2$ | $40^2$ | $80^2$ |
| $m_{R_u}^2,\ m_{R_d}^2$ | | $1000^2, 700^2$ | |
| $\mu_d,\ \mu_u$ | $130, 650$ | $400, 550$ | $550, 550$ |
| $M_W^D$ | 600 | 500 | 400 |
| $M_O^D$ | | 1500 | |
| $m_T^2,\ m_O^2$ | | $3000^2, 1000^2$ | |
| $m_{Q;1,2}^2,\ m_{Q;3}^2$ | $1500^2, 700^2$ | $1300^2, 700^2$ | $1400^2, 700^2$ |
| $m_{D;1,2}^2,\ m_{D;3}^2$ | $1500^2, 1000^2$ | $1300^2, 1000^2$ | $1400^2, 1000^2$ |
| $m_{U;1,2}^2,\ m_{U;3}^2$ | $1500^2, 700^2$ | $1300^2, 700^2$ | $1400^2, 700^2$ |
| $m_{L;1,2}^2,\ m_{E;1,2}^2$ | $800^2,\ 800^2$ | $1000^2,\ 1000^2$ | $500^2,\ 350^2$ |
| $m_{L;3,3}^2,\ m_{E;3,3}^2$ | $800^2,\ 136^2$ | $1000^2,\ 1000^2$ | $500^2,\ 95^2$ |
| $m_{H_d}$ | $1217^2$ | $211^2$ | $1042^2$ |
| $m_{H_u}$ | $-(767^2)$ | $-(207^2)$ | $-(201)^2$ |
| $v_S$ | $-64.9$ | $-42.5$ | $-56.1$ |
| $v_T$ | $-1.08$ | $-1.2$ | $-1.1$ |

| | $\chi_1^0$ | $\chi_2^0$ | $\chi_3^0$ | $\chi_4^0$ | $\chi_1^\pm$ | $\chi_2^\pm$ | $\rho_1^\pm$ | $\rho_2^\pm$ | $\tilde{\tau}_R$ | $\tilde{\mu}_R$ | $\tilde{e}_R$ | $\tilde{\ell}_L$ | $m_{H_1}$ |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 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 |

**Table 5.** Masses of the non-SM particles in the BMPs relevant for the LHC studies discussed here. All values given in GeV.