# Meeting Higgs and EWPO with R-symmetric SUSY

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P. Dießner[†], J. Kalinowski[‡], **Wojciech Kotlarski**[†‡], D. Stöckinger[†]

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[†]Technische Universität Dresden, [‡]University of Warsaw

# Plan of the talk

- Motivation
- R-symmetric SUSY
  - what is an R-symmetry
  - different possible R-symmetric models ➜ **MRSSM**
- The electroweak sector
  - Lightest Higgs boson at 1-loop level and beyond
  - Constraints: *W* boson mass, *STU* parameters, Higgs searches and exclusions, vacuum stability, flavour physics
  - Glimpse of what we are working on now

# Motivation

- Supersymmetry is still one of the most promising candidates for physics beyond the SM although
  - no direct SUSY signal at Run I of the LHC
  - direct searches still allow for TeV SUSY but indirect ones push minimal SUSY into uncomfortable parameter region
    - 125 GeV Higgs requires $\gtrsim$ 700 GeV stops ($\gtrsim$ 5 TeV if we neglect mixing)
    - flavor physics suggests even larger SUSY scale (within the MSSM)
- If gluinos are found, important question: are they Dirac or Majorana particles?

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**Motivates us to go beyond the MSSM**

# Pros of the MRSSM

- it ameliorates the flavor problem of the MSSM — Kribs, Poppitz, Weiner (2008)
- Dirac gluinos relax experimental limits on squark masses
- Dirac gaugino masses are supersoft — Fox, Nelson, Weiner (2006)
- gives correct W and Higgs bosons masses at (possibly very) light stop masses — **this talk**
- interesting LHC phenomenology distinct from the MSSM
- Dirac type neutralino as a candidate for dark matter
  Belanger, Benakli, Goodsell, Moura, Pukhov (2009), Buckley, Hooper, Kumar (2013)

# R-symmetry

[Fayet; Salam & Strathdee, ...]

- additional symmetry of the SUSY algebra allowed by the Haag - Łopuszański - Sohnius theorem
- for N=1 it is a global $U_R(1)$ symmetry under which the SUSY generators are charged
- implies that the spinorial coordinates are also charged

$$Q_R(\theta) = 1, \; \theta \to e^{\imath\alpha}\theta$$

- Lagrangian invariance
  - Kähler potential invariant if R-charge of vector superfield is 0
  - R-charge of the superpotential must be 2
  - soft-breaking terms must have R-charge 0
- Here I'll not consider model building but focus on phenomenological analysis of low energy theory

# Low-energy R-symmetry realization

R charges of component fields

| | $Q_R$ | scalar | vector | fermionic |
|---|---|---|---|---|
| vector superfield | 0 | - | 0 | 1 |
| chiral superfield | $Q$ | $Q$ | - | $Q-1$ |

- freedom in the choice of chiral superfield charge
- we choose SM fields to have R=0 ➜ Higgs superfields $Q_R$=0, lepton and quark superfields have $Q_R$=+1
- with the above assignment R-symmetry forbids
  - $\mu \hat{H}_u \hat{H}_d$
  - $\lambda \hat{E}\hat{L}\hat{L}, \kappa \hat{U}\hat{D}\hat{D}, e\hat{H}\hat{L}$
  - soft SUSY breaking Majorana masses and trilinear scalar couplings
- flavor problem ameliorated but now gauginos and higgsinos are masses
  ➜ possible solution - Dirac gauginos

One way to fix it: Dirac masses
Minimal R-Symmetric Supersymmetric Standardmodel (MRSSM)
*Kribs et.al. arXiv:0712.2039*

| | | | $SU(3)_C$ | $SU(2)_L$ | $U(1)_Y$ | $U(1)_R$ |
|---|---|---|---|---|---|---|
| Additional fields: | Singlet | $\hat{S}$ | 1 | 1 | 0 | 0 |
| | Triplet | $\hat{T}$ | 1 | 3 | 0 | 0 |
| | Octet | $\hat{O}$ | 8 | 1 | 0 | 0 |
| | R-Higgses | $\hat{R}_u$ | 1 | 2 | $-1/2$ | 2 |
| | | $\hat{R}_d$ | 1 | 2 | $1/2$ | 2 |

other realizations:

…

Davies, March-Russell, McCullough (2011)
Lee, Raby, Ratz, Schieren, Schmidt-Hoberg, Vaudrevange (2011)
Frugiuele, Gregoire (2012)

…

# MRSSM lagrangian

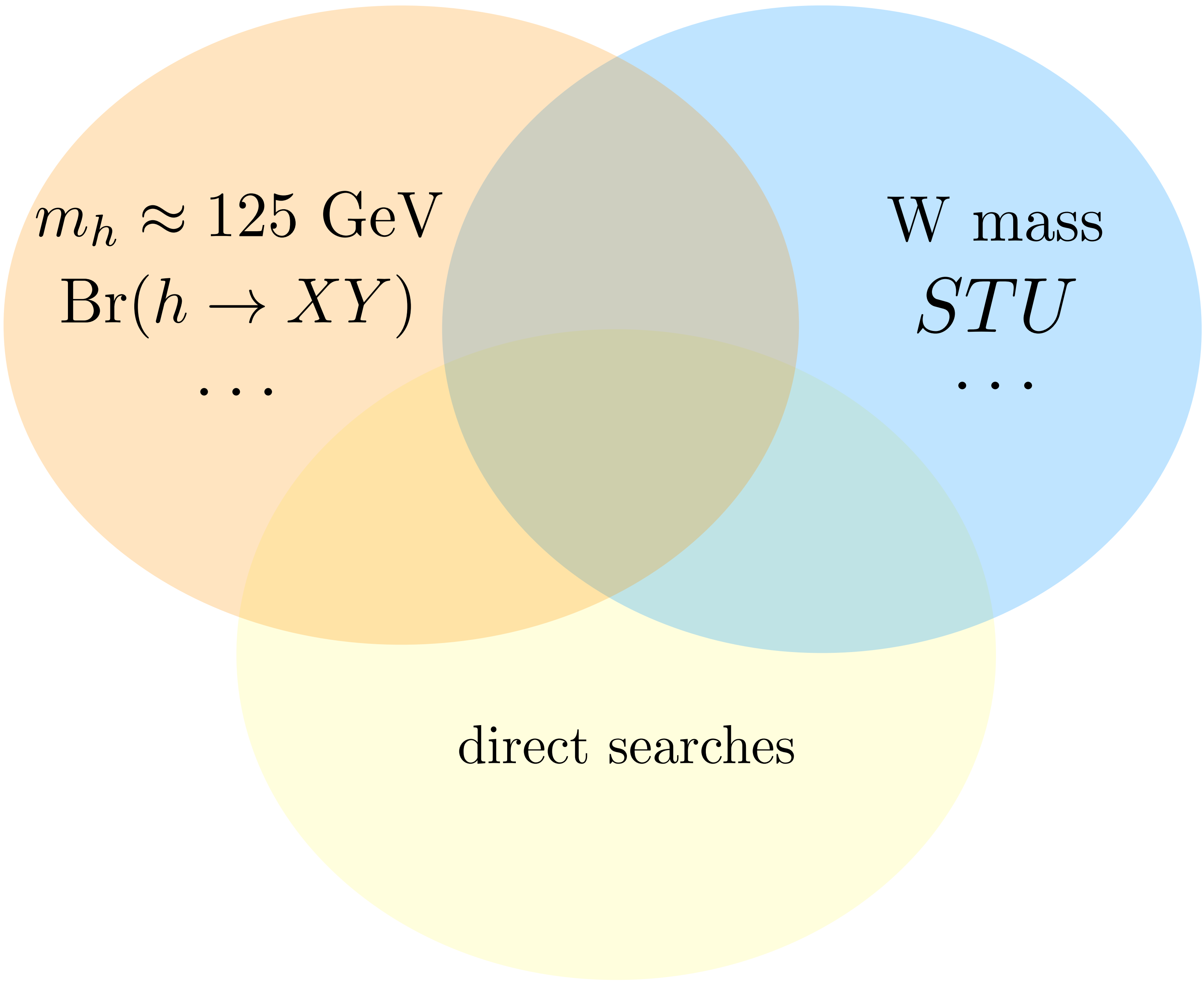
- Superpotential — Choi, Choudhury, Freitas, Kalinowski, Zerwas (2011)

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

  - μ-type terms
  - terms with $\lambda$, $\Lambda$ couplings generate quartic Higgs couplings in the potential
  - MSSM-like Yukawa terms

- Allowed soft SUSY-breaking terms
  - conventional MSSM $B_\mu$-term: $V \ni B_\mu (H_d^- H_u^+ - H_d^0 H_u^0) + \text{h.c.}$
  - Dirac mass terms for gauginos $M^D \tilde{g} \tilde{g}'$
  - scalar soft masses $m^2 |\Phi|^2$

# Can MRSSM accommodate both the Higgs and EWPO?



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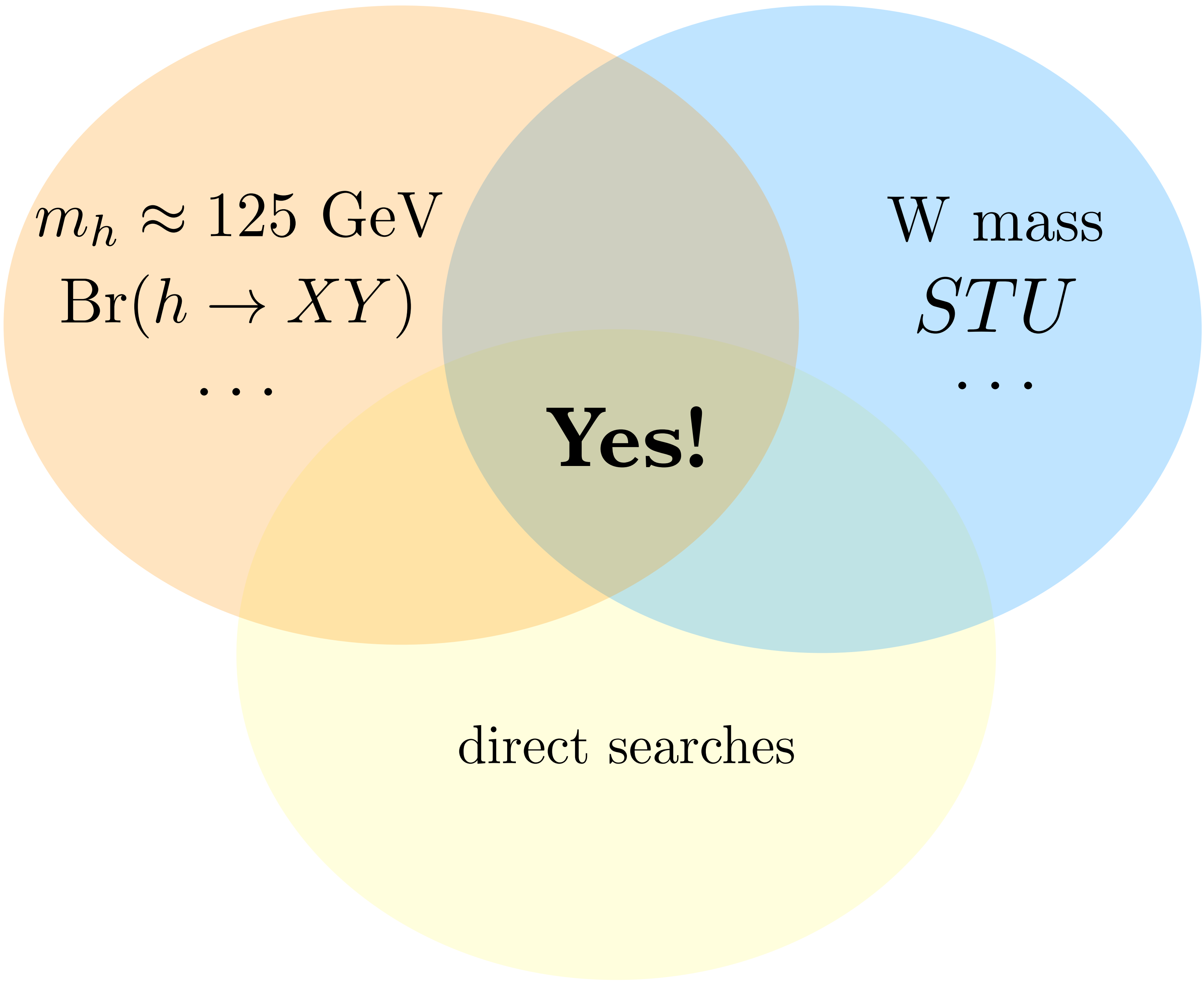


# Scalar Higgs sector and tree-level analysis

- 4 scalar degrees of freedom $\{\sigma_d, \sigma_u, \sigma_S, \sigma_T\}$ mix to form 4 physical Higgs bosons

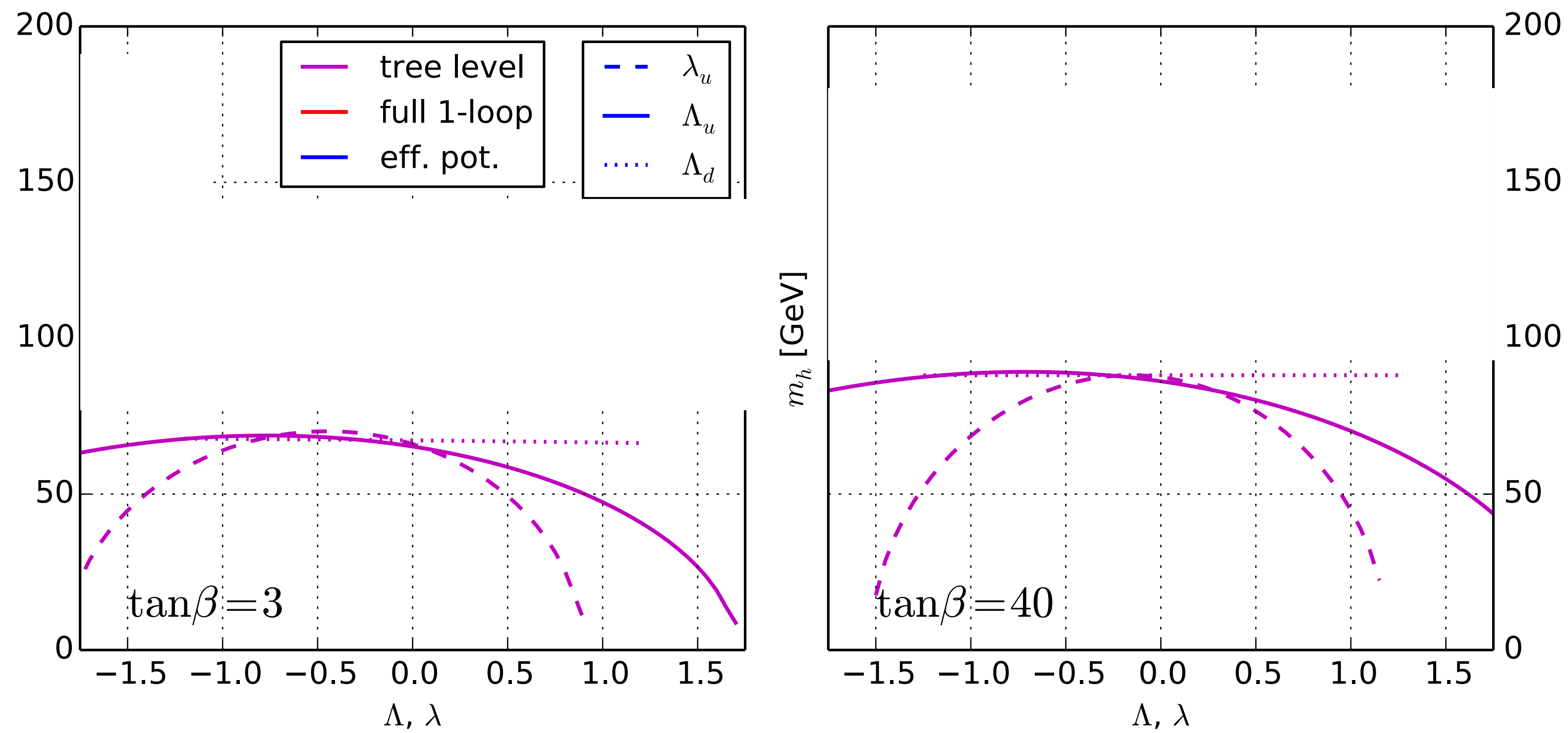
- Approximate formula for the lightest Higgs mass at the tree level

$$m^2_{h,\text{approx}} = M_Z^2 \cos^2 2\beta - v^2 \left( \frac{\left(g_1 M_D^B + \sqrt{2}\lambda\mu\right)^2}{4(M_D^B)^2 + m_S^2} + \frac{\left(g_2 M_D^W + \Lambda\mu\right)^2}{4(M_D^W)^2 + m_T^2} \right) \cos^2 2\beta$$

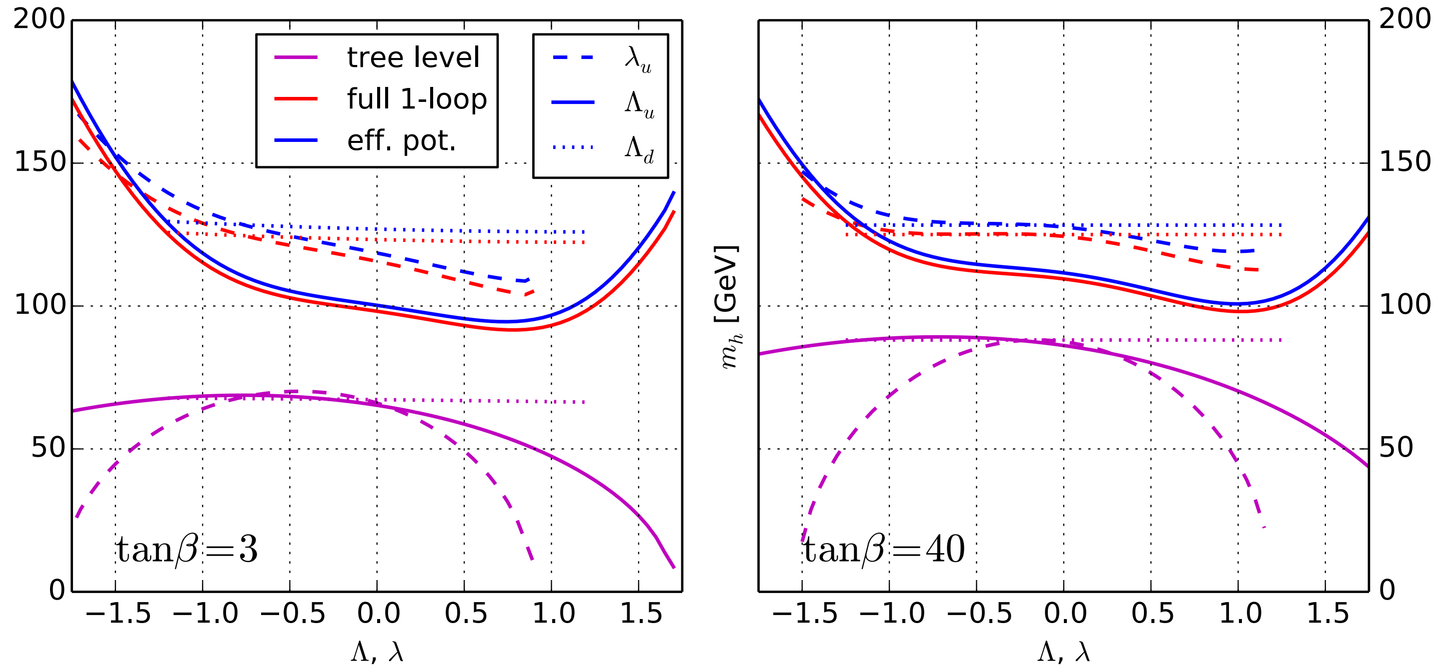
under simplifying assumptions: large $m_A^2$, $\lambda = \lambda_u = -\lambda_d \quad \Lambda = \Lambda_u = \Lambda_d$

$$\mu = \mu_u = \mu_d \qquad v_s \approx v_T \approx 0$$

- ❗ Tree-level mass of the lightest state always **lower** than in the MSSM due to the mixing with $\sigma_S$ and $\sigma_T$ fields.



# Lightest Higgs mass — full 1loop analysis

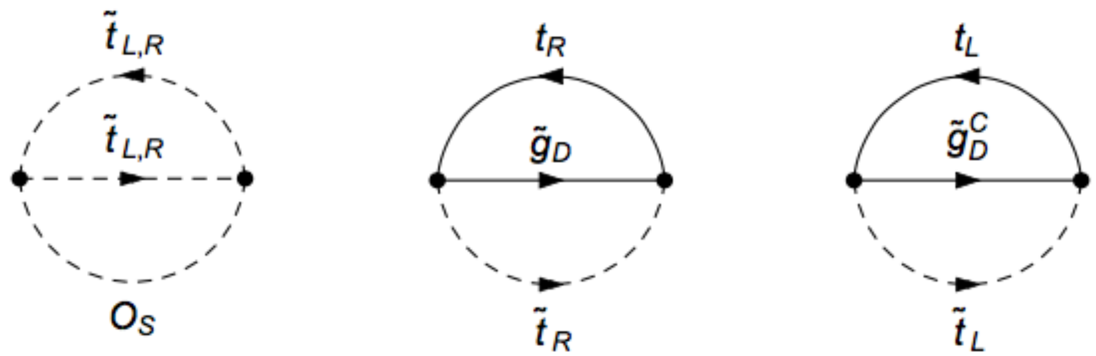



- large enhancement of tree-level Higgs mass
  - with ~1 TeV stops and no LR mixing lightest higgs mass too low
  - large contributions from new states, mainly Higgs and R-Higgs sectors

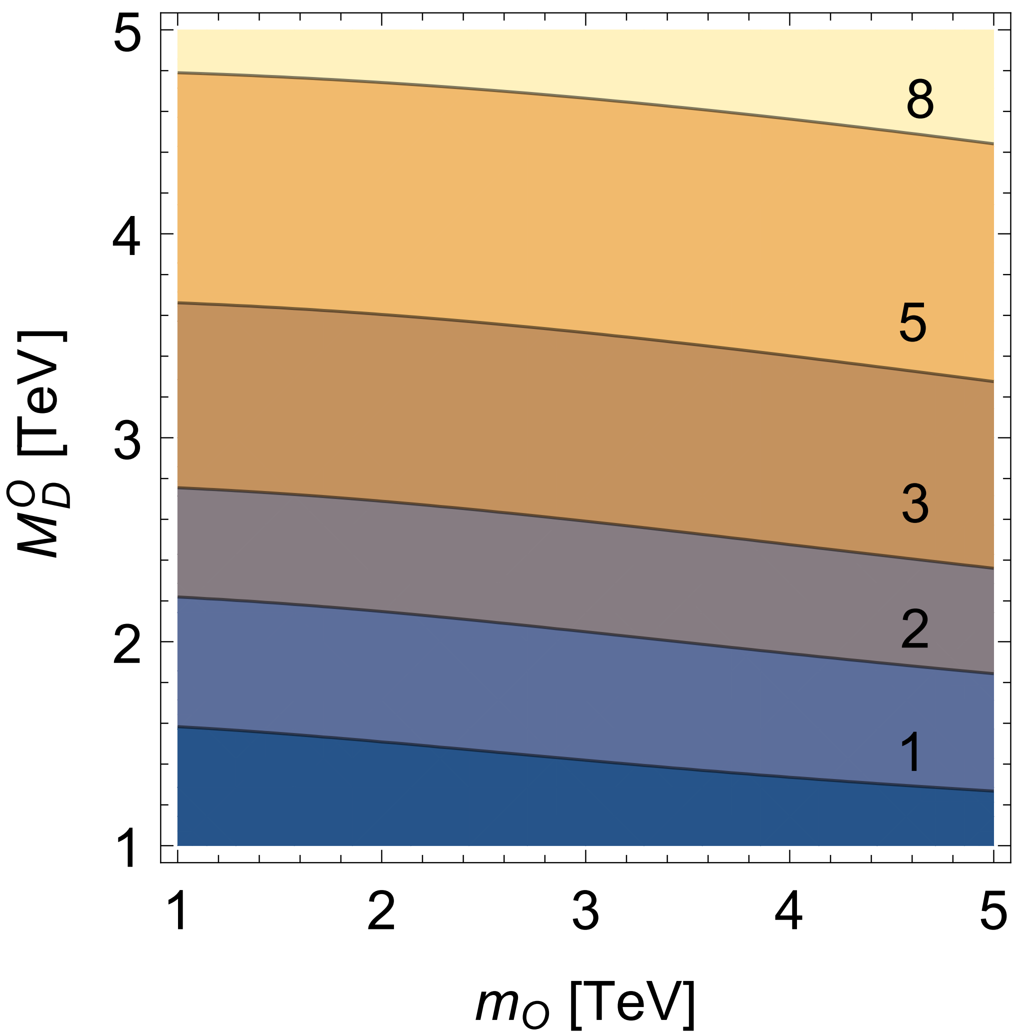
# Lightest Higgs mass — leading 2-loop corrections

- Effective potential approximation without contributions from broken gauge groups

- MRSSM specific contributions




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




S. P. Martin, Phys.Rev., vol. D65, p. 116003, 2002

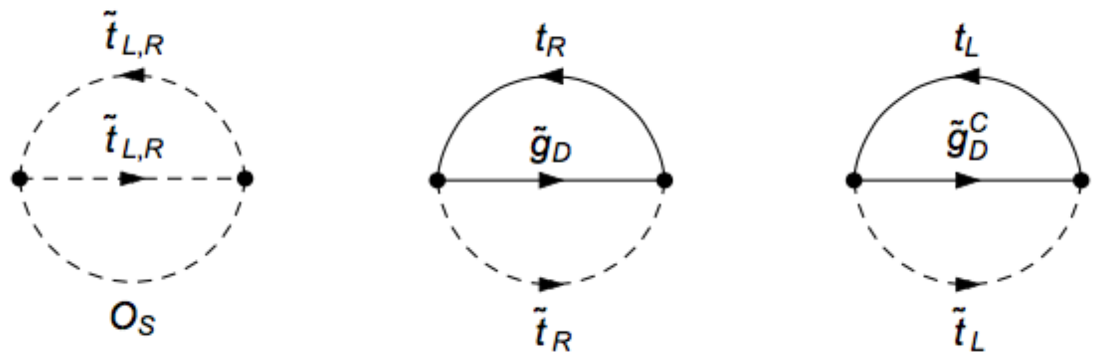
M. D. Goodsell, K. Nickel, and F. Staub, Eur.Phys.J., vol. C75, no. 1, p. 32, 2015

# Lightest Higgs mass — leading 2-loop corrections

- Effective potential approximation without contributions from broken gauge groups

- MRSSM specific contributions

only the scalar component of the (complex) sgluon filed contributes

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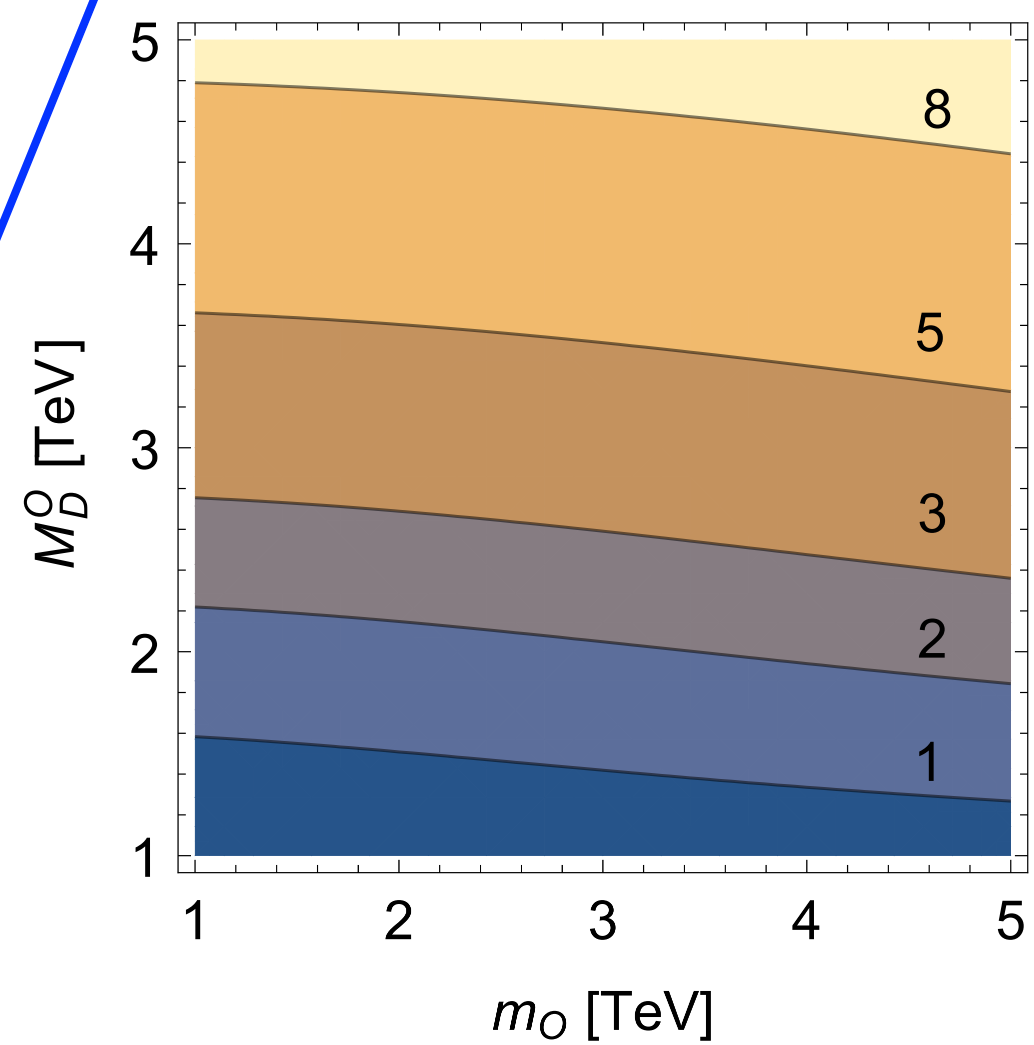


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# Impact of 2-loop corrections

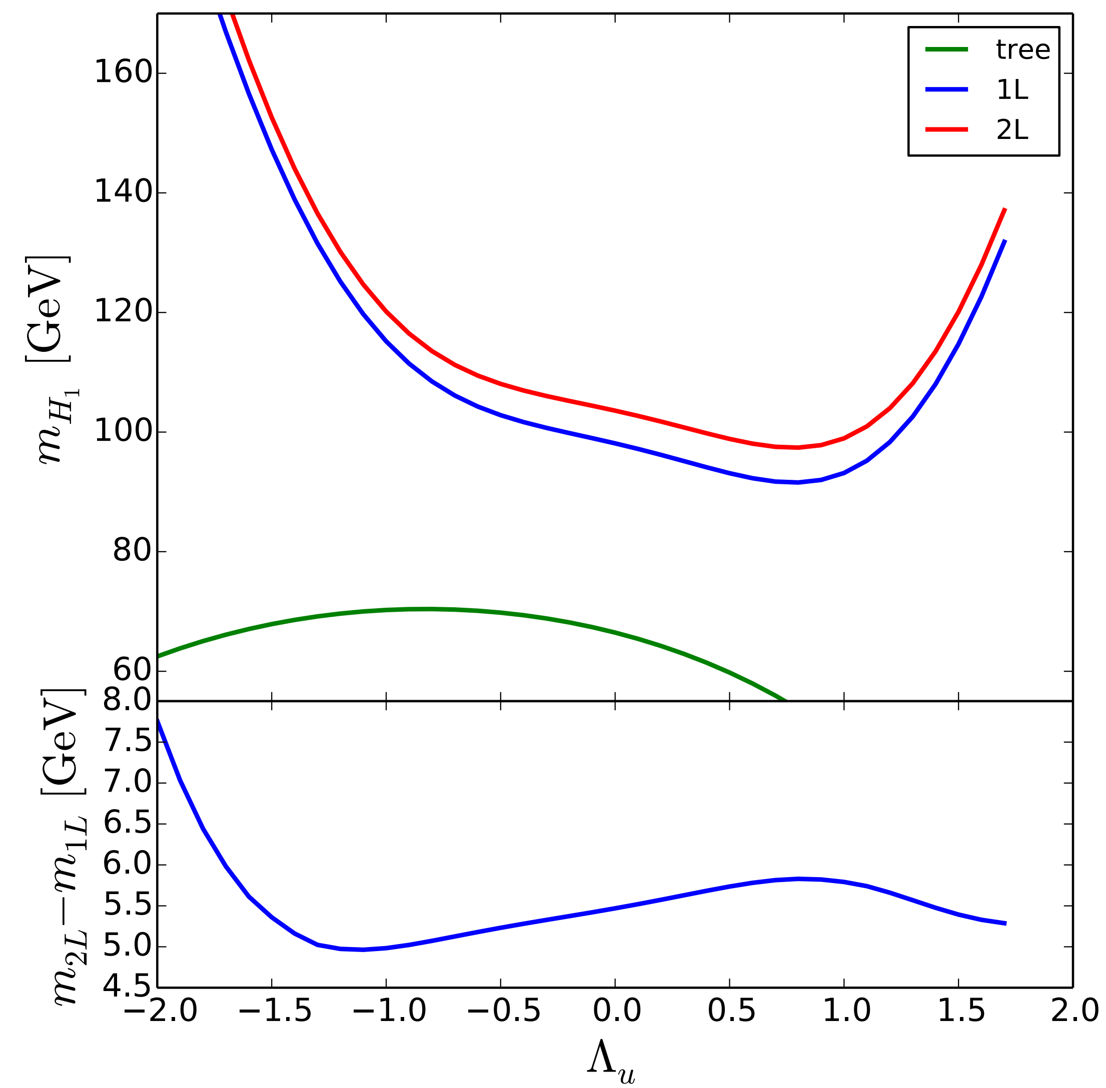
- MRSSM specific contributions
  Two loop corrections in the $\overline{\mathrm{DR}}$ scheme are generally positive and amount to approximately +5 GeV

- Updated BM points

| | A | B | C |
|---|---|---|---|
| $m_{H_1}$ | 125.3 GeV | 125.5 GeV | 125.4 GeV |
| $m_W$ | 80.397 GeV | 80.381 GeV | 80.386 GeV |
| HiggsBounds's obsratio | 0.61 | 0.65 | 0.87 |
| HiggsSignals's p-value | 0.72 | 0.66 | 0.72 |

with reduced values of superpotential parameters $\Lambda_u$

| A | B | C | | A | B | C |
|---|---|---|---|---|---|---|
| -1.2 | -1.0 | -1.15 | → | -1.11 | -0.85 | -1.03 |



# $m_W$ calculation setup

- MRSSM contains a Y=0 Higgs triplet with vev $v_T$ giving tree level contribution to $m_W$, which is measured with very high precision ($m_W = 80.385 \pm 0.015$)

- EW-gauge sector is described at tree-level in terms of 4 parameters

$$\{g_1, g_2, v, v_T\} \to \{\alpha_{EM}, G_\mu, m_Z, \hat{v}_T\}$$

Chankowski, Pokorski, Wagner (2007)

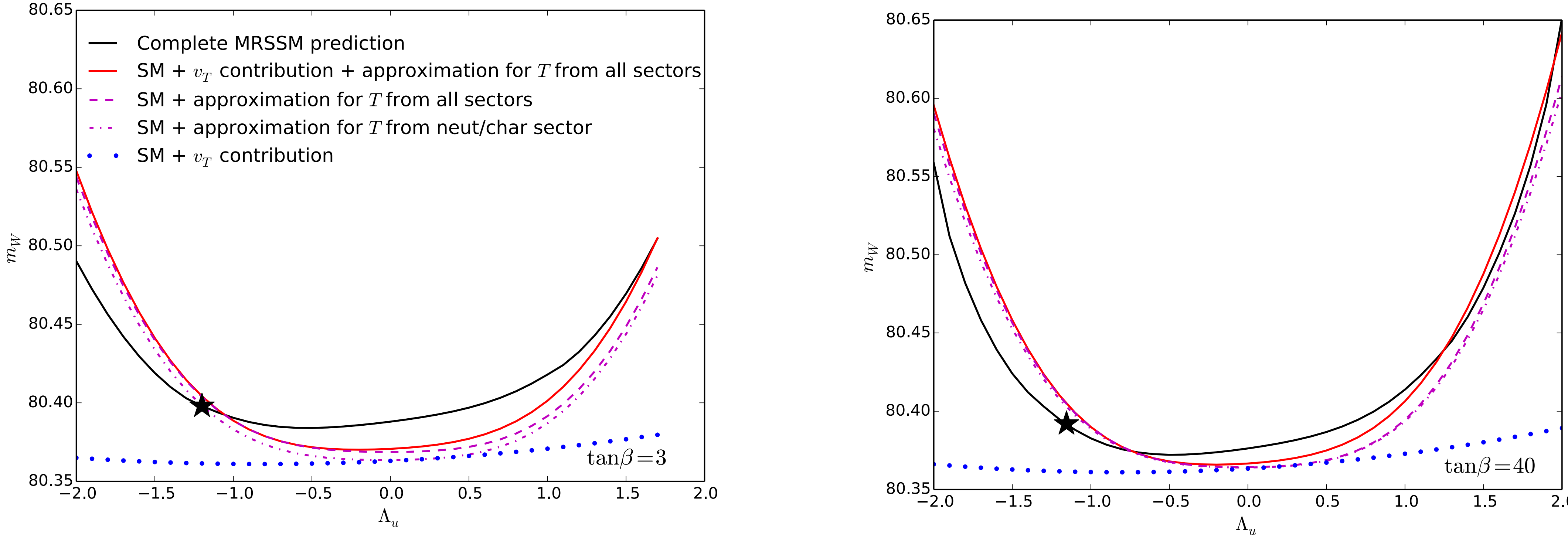
- Calculation based on Degrassi, Fanchiotti, Sirlin (1990) scheme modified to accommodate non vanishing $v_T$

$$m_W^2 = \frac{1}{2} m_Z^2 \hat{\rho} \left[ 1 + \sqrt{1 - \frac{4\pi\hat{\alpha}}{\sqrt{2} G_\mu m_Z^2 \hat{\rho} (1 - \Delta\hat{r}_W)}} \right] \qquad \hat{\rho} = \frac{m_W^2}{m_Z^2 \hat{c}_W^2} \qquad \hat{\rho}_0 = 1 + \frac{4 v_T^2}{v^2}$$

- $\Delta\hat{r}_W$ contains: „oblique" and vertex- and box-corrections as well as term that translates pole $m_W$ to the running one

- automatically recovers SM 2-loop reducible contributions

# Results for $m_W$




- built in large cancelations between $\Delta\alpha, \Delta\hat{r}_W, \hat{\rho}$

- to understand qualitatively the parameter dependence expand in STU

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

- additional benefit: $STU$ give also a handle on observables other than $m_W$

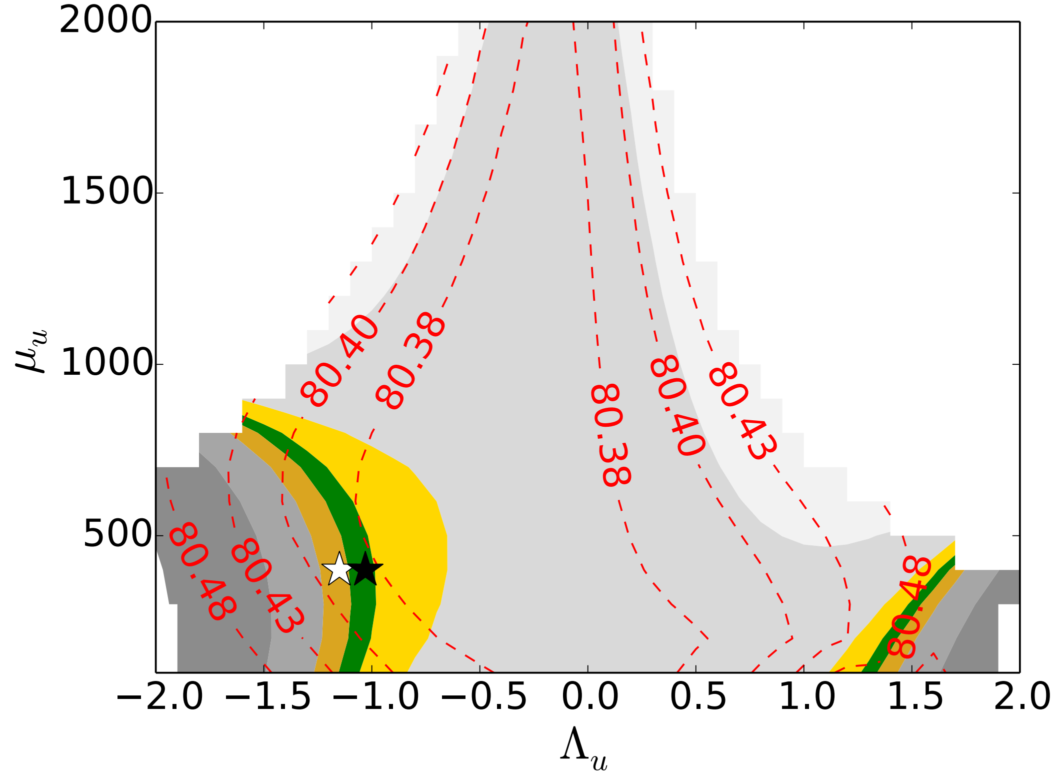
- for our benchmark points we find

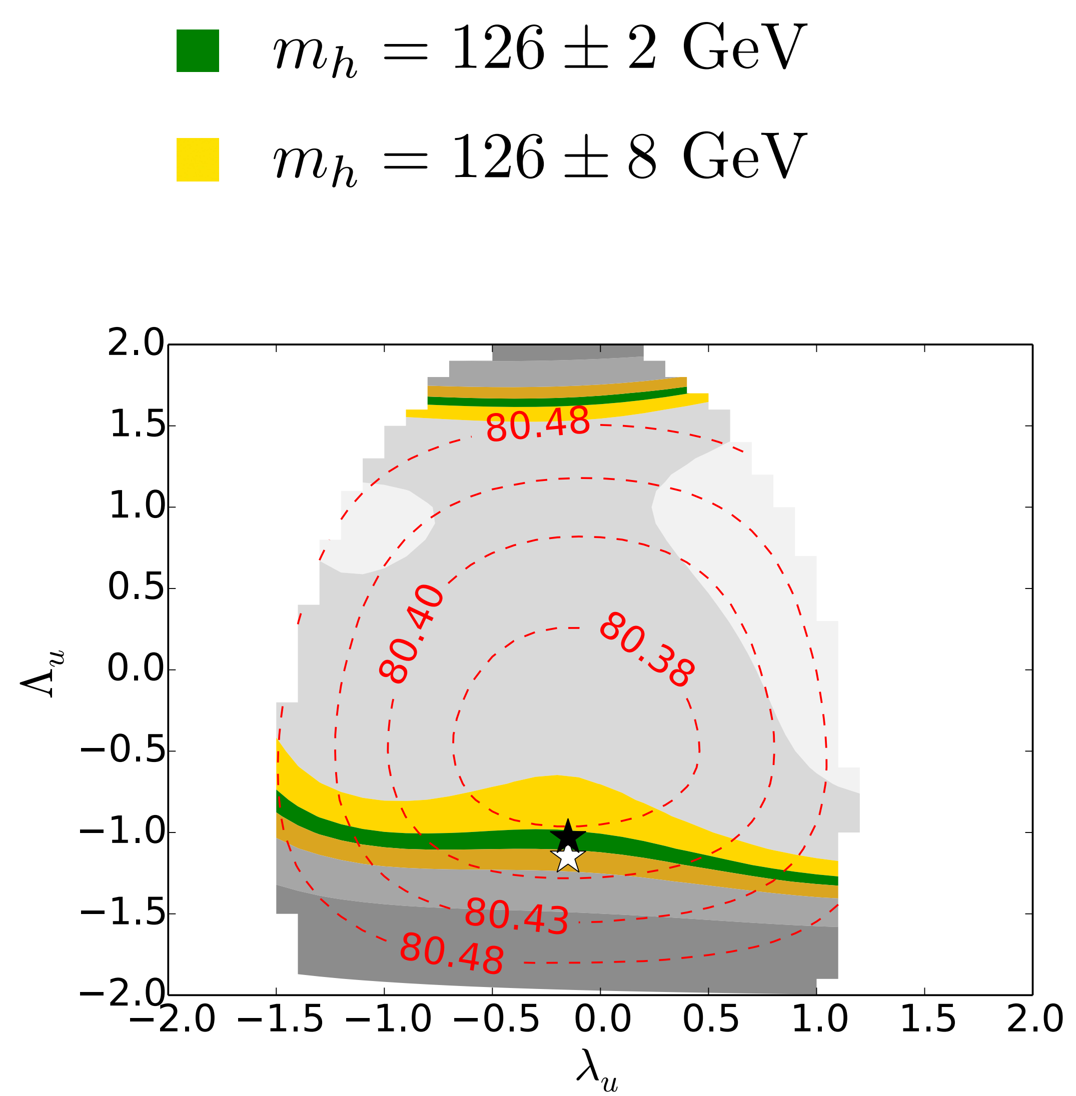
| | $\tan\beta = 3$ | $\tan\beta = 10$ | $\tan\beta = 40$ |
|---|---|---|---|
| $S$ | 0.0097 | 0.0092 | 0.0032 |
| $T$ | 0.090 | 0.091 | 0.085 |
| $U$ | 0.00067 | 0.00065 | 0.0010 |

# Properties of benchmark points

- 3 distinct parameter points with $\tan\beta = 3, 10, 40$
- W mass within 1σ from measured value $m_W^{\mathrm{exp}} = 80.385 \pm 0.015$ GeV
- lightest Higgs mass around 125 GeV
- Higgs sectors in agreement with direct measurements and exclusion limits **HiggsBounds** and **HiggsSignals**
- due to the lack of A-terms MRSSM is safe as far as colour- and charge-breaking minima are concerned — Casas, Lleyda, Muñoz (1996)
- absolute vacuum stability [disclaimer: within the scope of application of **Vevacious**]
- reasonable TeV range mass spectra

# $m_h - m_W$ interdependence for $\tan\beta = 40$

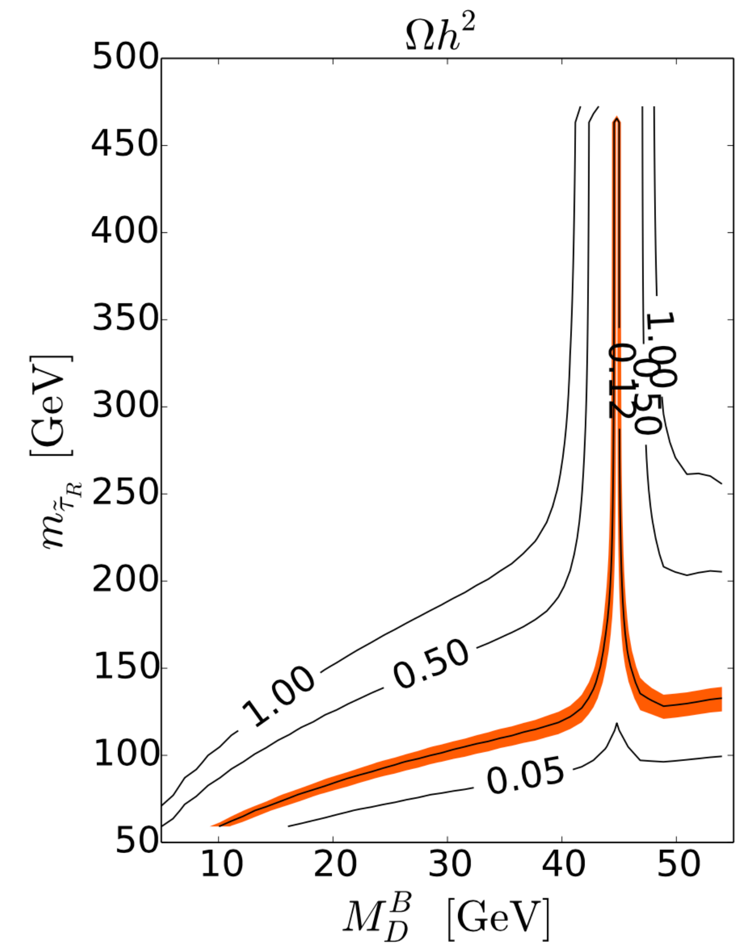



- contours for $m_W$
- color gradient for $m_h$
- ★ for benchmark point with 2-loop Higgs mass (☆ for 1-loop)

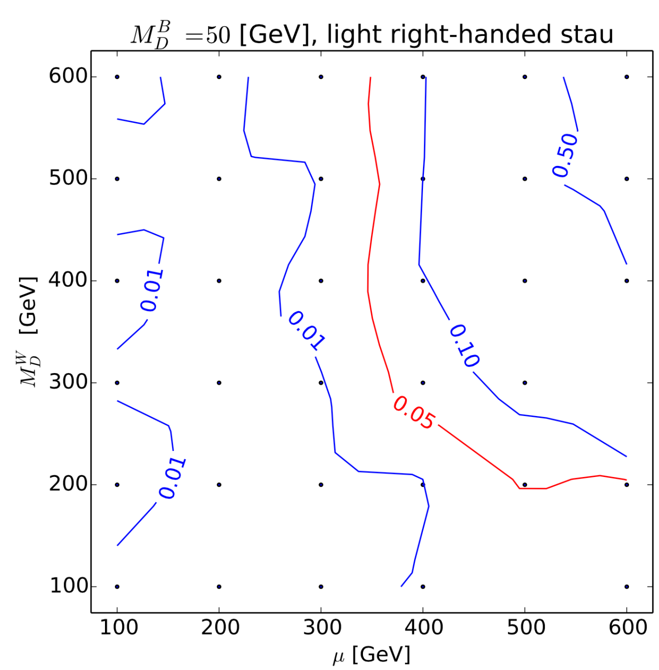
# Current research topic — "light singlet scenario"

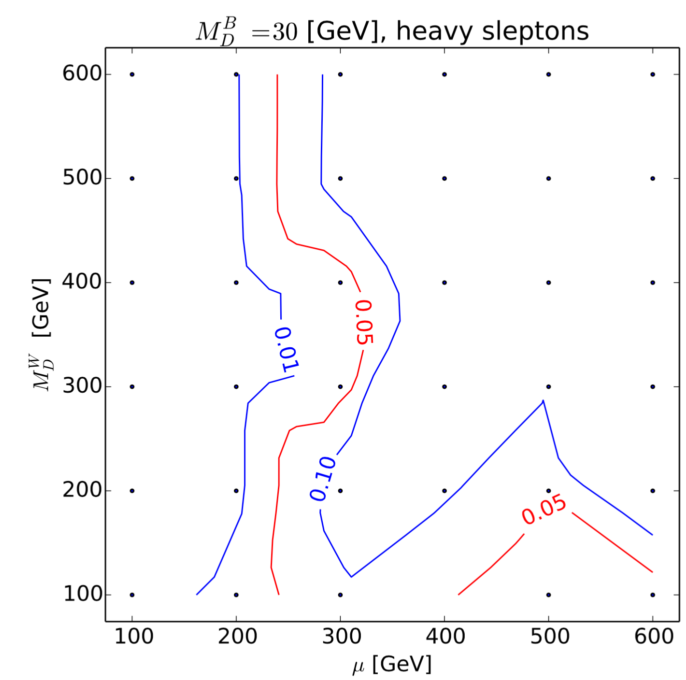
- 125 GeV Higgs as the second lightest Higgs




- "bino-singlino" (Dirac) dark matter candidate

- "collider-friendly" EW spectrum
crosschecked against 8 TeV LHC results using: `SARAH`'s generated `UFO` model + `Herwig++` + `CheckMate`



# Summary and outlook

- We took the low energy model without discussing its UV completion
- Viable realization of R-symmetric SUSY
  - ✓ ~125 GeV lightest Higgs mass
  - ✓ agreement with PEWO and flavor-physics
  - ✓ stable vacuum
  - ✓ LHC „friendly” particle spectra
- Future goals
  - ☐ R-symmetric SQCD at 14 TeV LHC

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Thank you for your attention!

# Back-up slides

# Particles content summary: MSSM vs. MRSSM

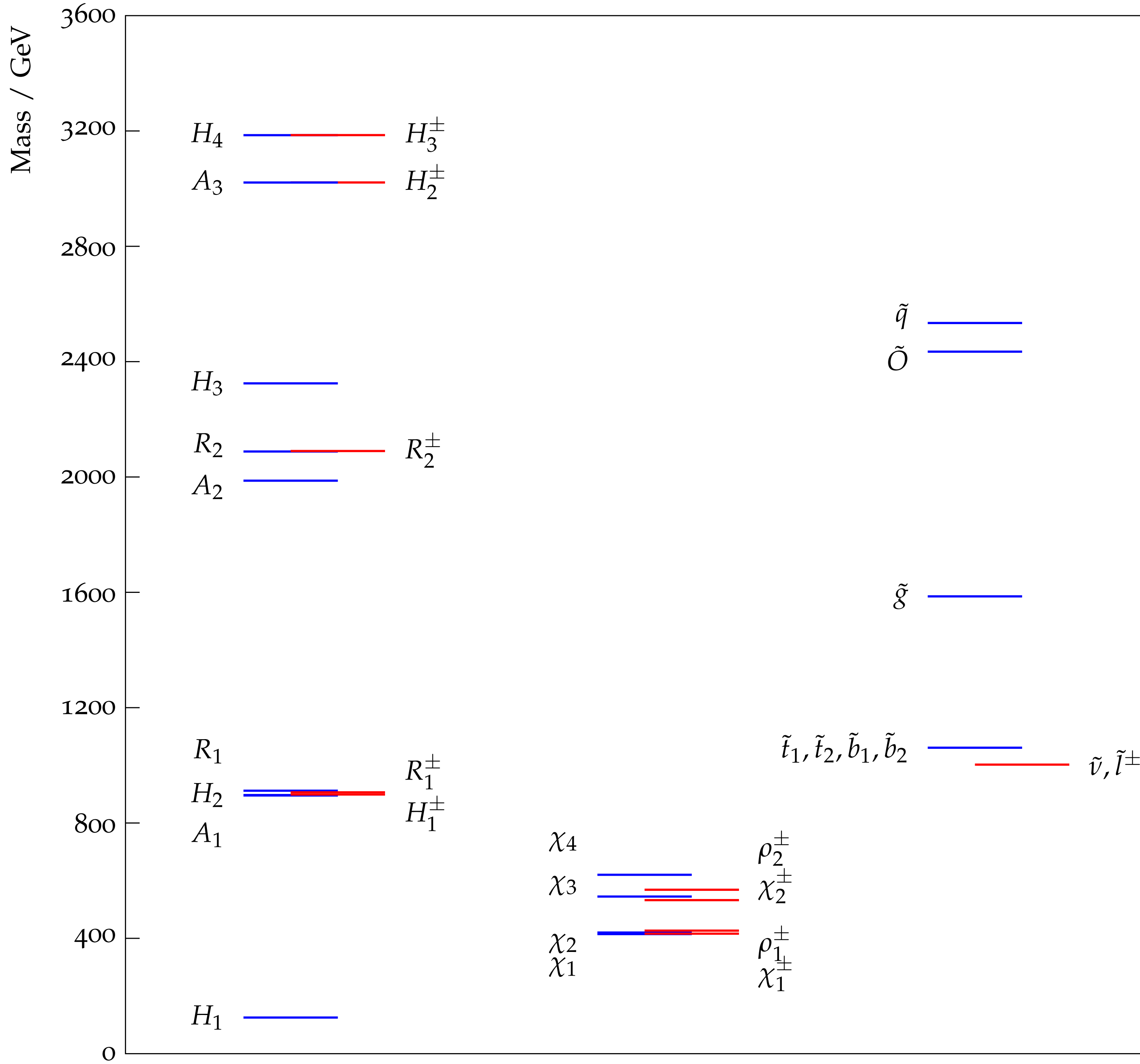
| | Higgs | | | | R-Higgs | | |
|---|---|---|---|---|---|---|---|
| | CP-even | CP-odd | charged | charginos | neutral | charged | sgluon |
| MSSM | 2 | 1 | 1 | 2 | 0 | 0 | 0 |
| MRSSM | 4 | 3 | 3 | 2+2 | 2 | 2 | 1 |

| | neutralino | gluino | |
|---|---|---|---|
| MSSM | 4 | 1 | Majorana fermions |
| MRSSM | 4 | 1 | Dirac fermions |

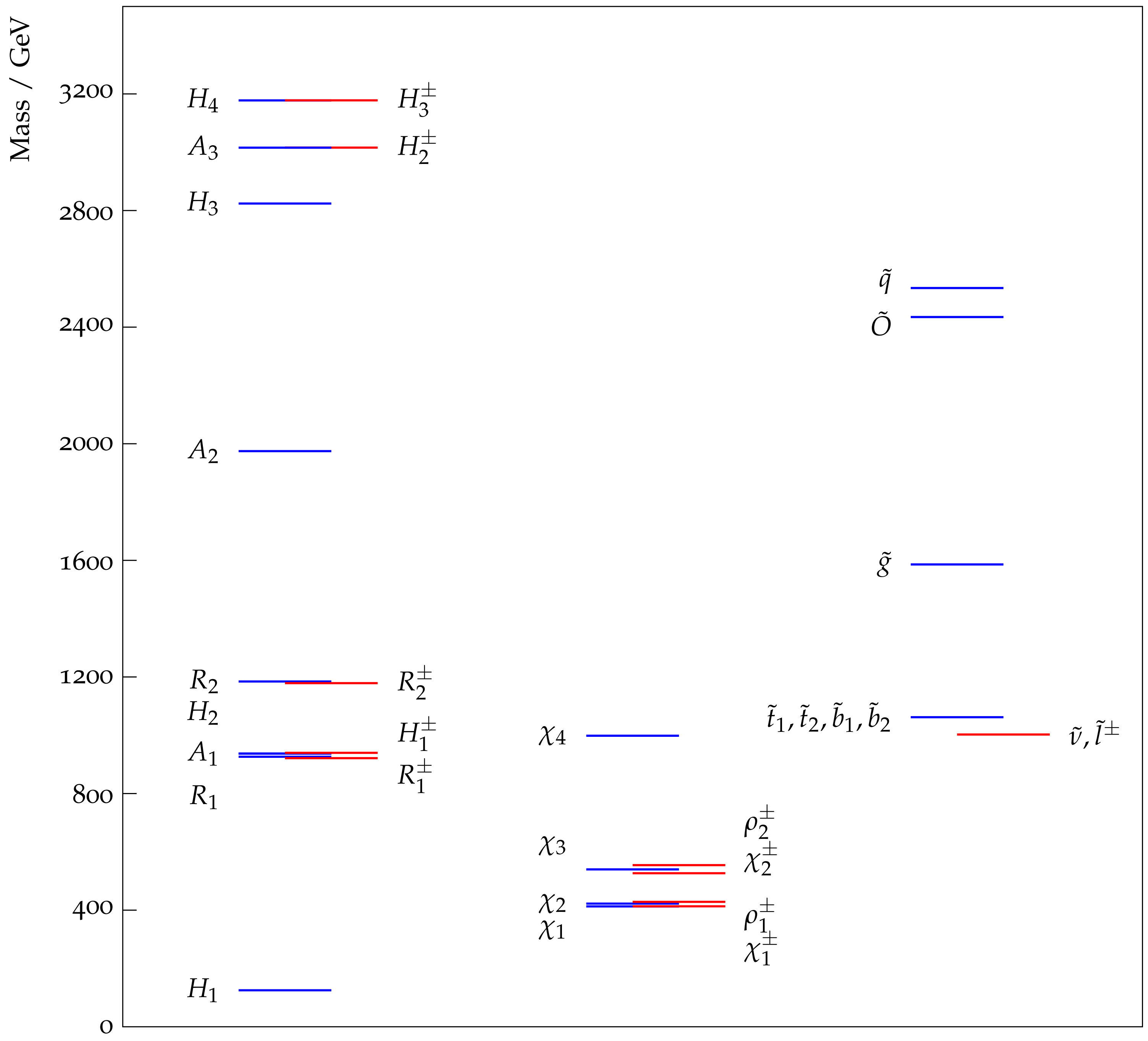
# Benchmark points

| | 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 | $-0.14$ |
| $v_T$ | $-0.33$ | $-0.19$ | $-0.34$ |
| $m_{H_d}^2$ | $671^2$ | $761^2$ | $1158^2$ |
| $m_{H_u}^2$ | $-532^2$ | $-544^2$ | $-543^2$ |

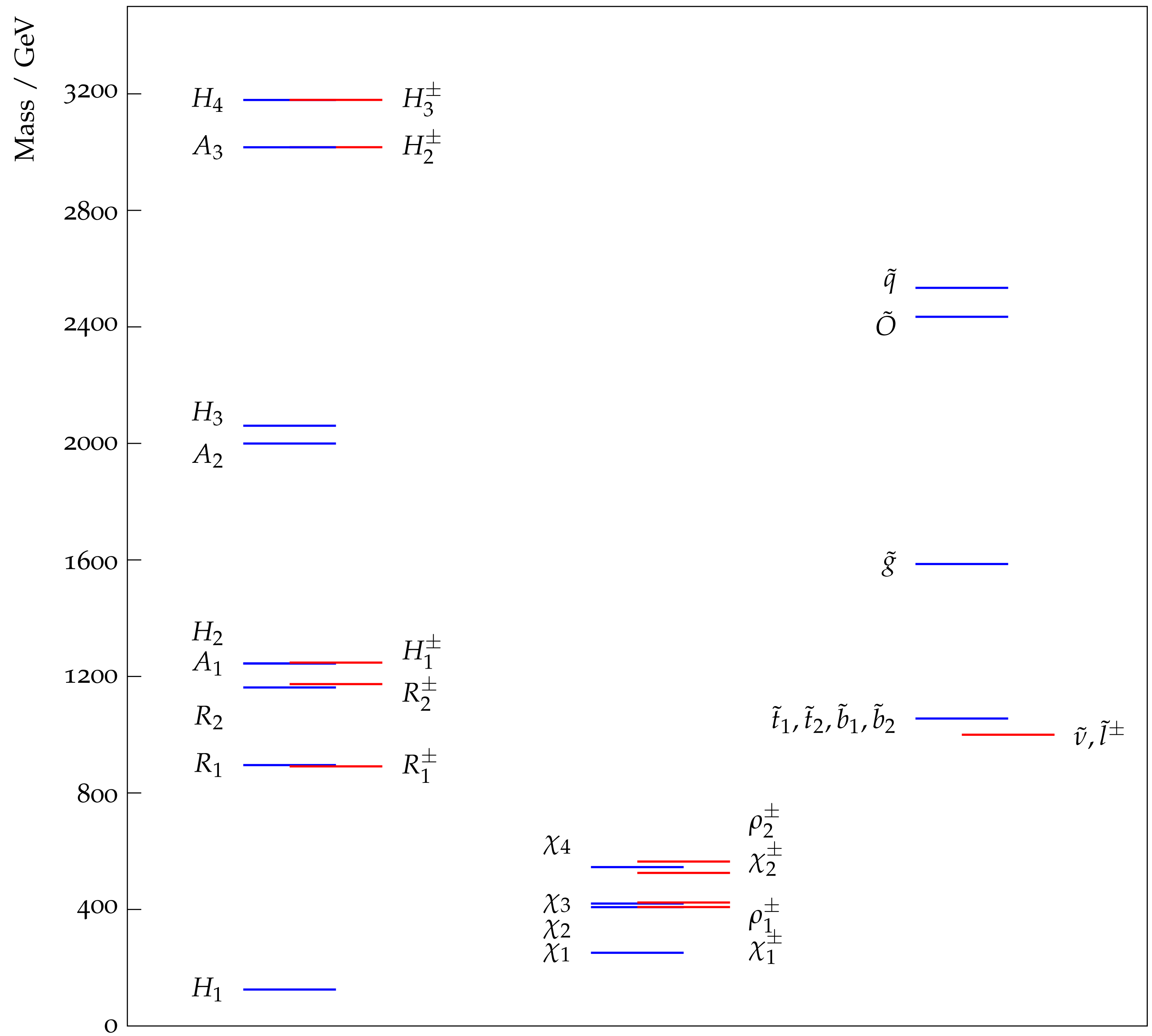
# Particle spectrum for tan β = 3



# Particle spectrum for tan β = 10



# Particle spectrum for tan β = 40



# Tools for numerical analysis

- Model implemented in **SARAH**
- Numerical analysis done within **SARAH**'s generated **SPheno**-like code
- Cross checked with analytic calculation with **FeynArts/FormCalc**
- Higgs sector checked with **HiggsBounds** and **HiggsSignals**
- Vacuum stability checked with **Vevacious**

# $SU(3)$ $\beta$ function

$$\beta_{g_3}^{(1)} = 0$$

$$\beta_{g_3}^{(2)} = \frac{1}{5} g_3^3 \Big(11 g_1^2 - 20 \mathrm{Tr}\Big(Y_d Y_d^\dagger\Big) - 20 \mathrm{Tr}\Big(Y_u Y_u^\dagger\Big) + 340 g_3^2 + 45 g_2^2\Big)$$