Higgs mass in R-symmetric SUSY at one-loop level and beyond

JHEP 1412 (2014) 124, arXiv:1504.05386 (accepted for Advances in High Energy Physics)

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Physics at the LHC and beyond, September 29th-October 2nd 2015, Hamburg, Germany

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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

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 - next talk by P. Dießner
  Belanger, Benakli, Goodsell, Moura, Pukhov (2009), Buckley, Hooper, Kumar (2013)

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It's a must-see!!

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 λ, Λ couplings generate quartic Higgs couplings in the potential
  - MSSM-like Yukawa terms

- Allowed soft SUSY-breaking terms
  - conventional MSSM B_μ-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 $m^2 |\Phi|^2$

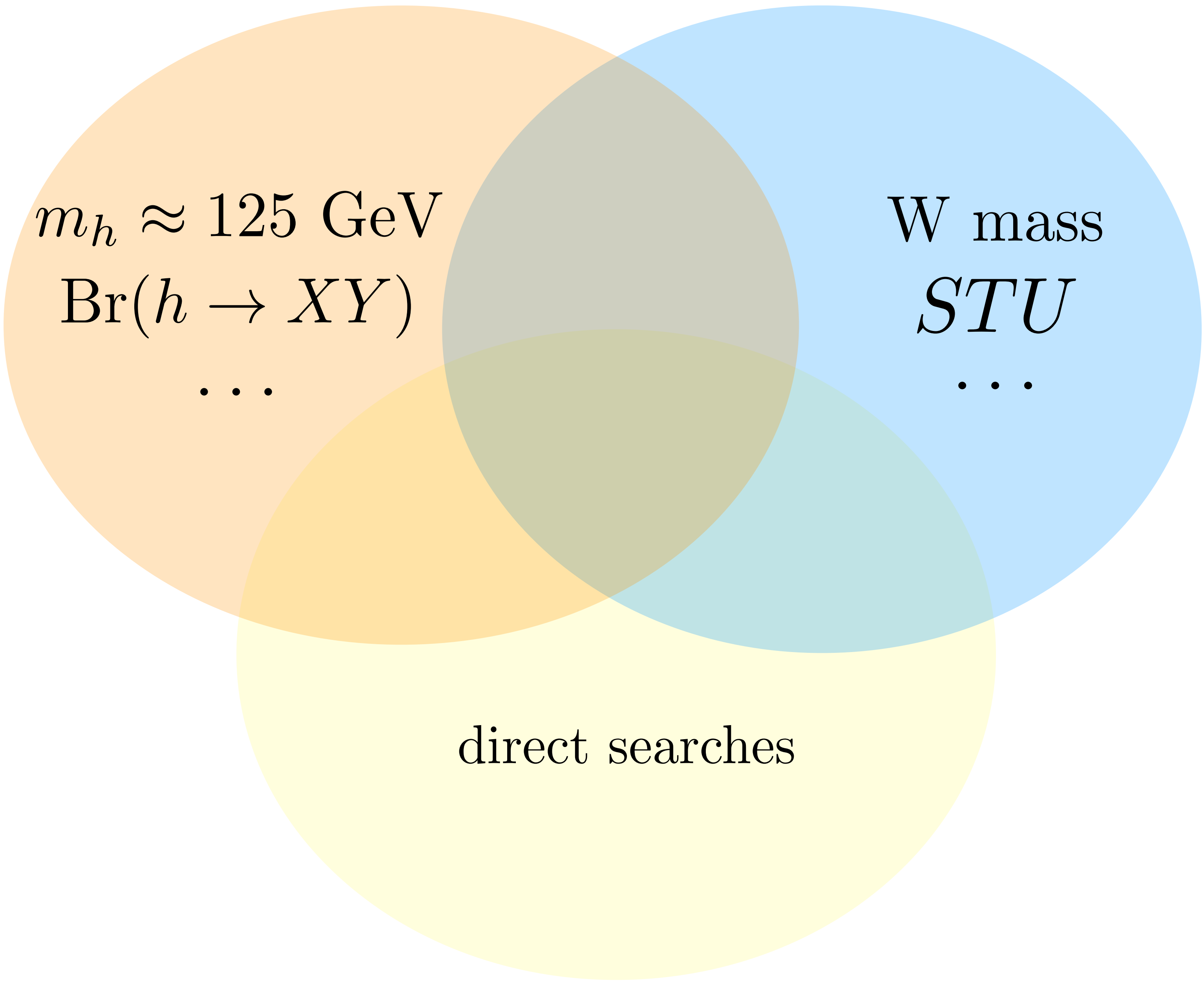
Particles content summary: MSSM vs. MRSSM

different number of physical states | completely new states

	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

Can MRSSM accommodate both the Higgs and EWPO?



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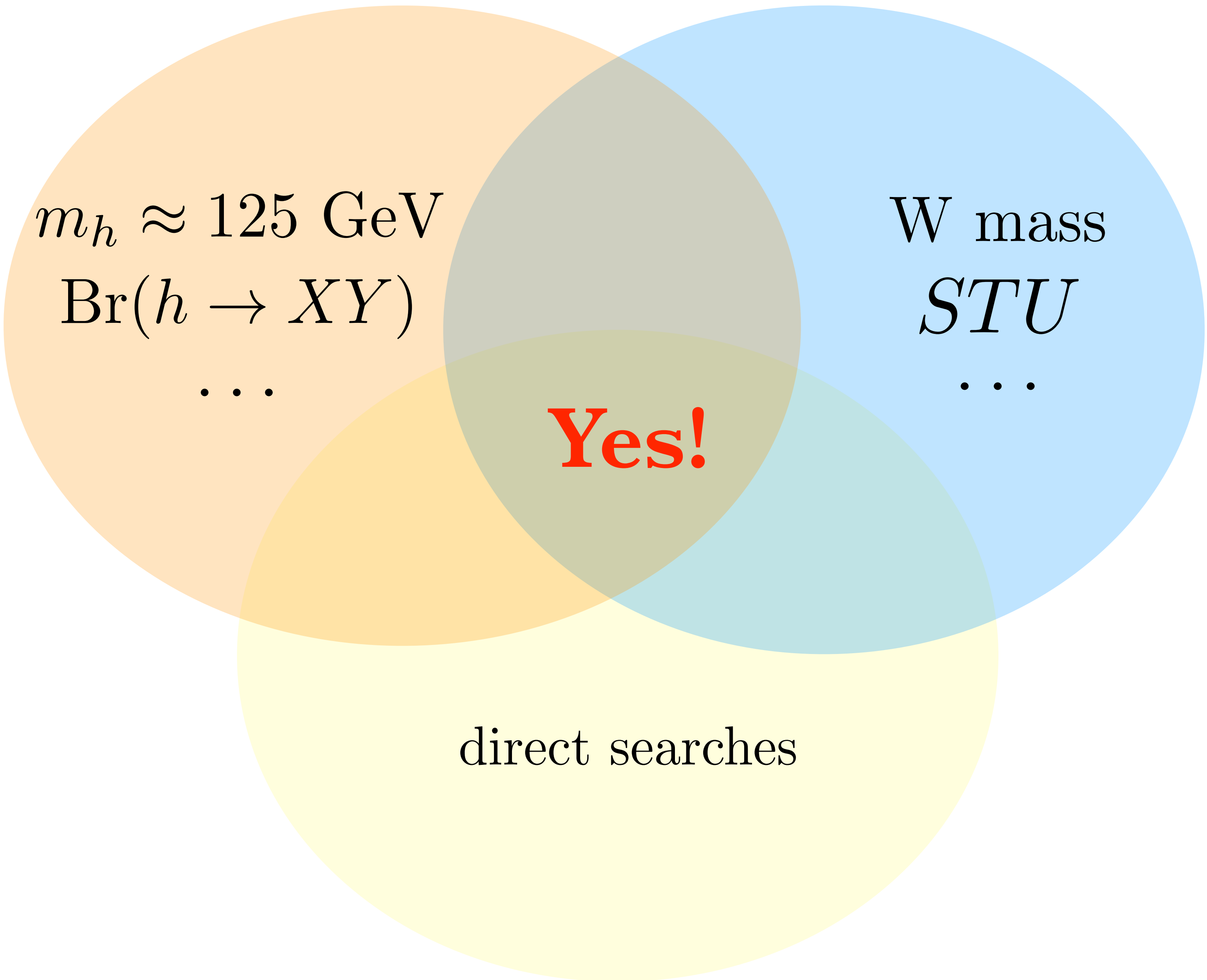


Scalar Higgs sector and tree-level analysis

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

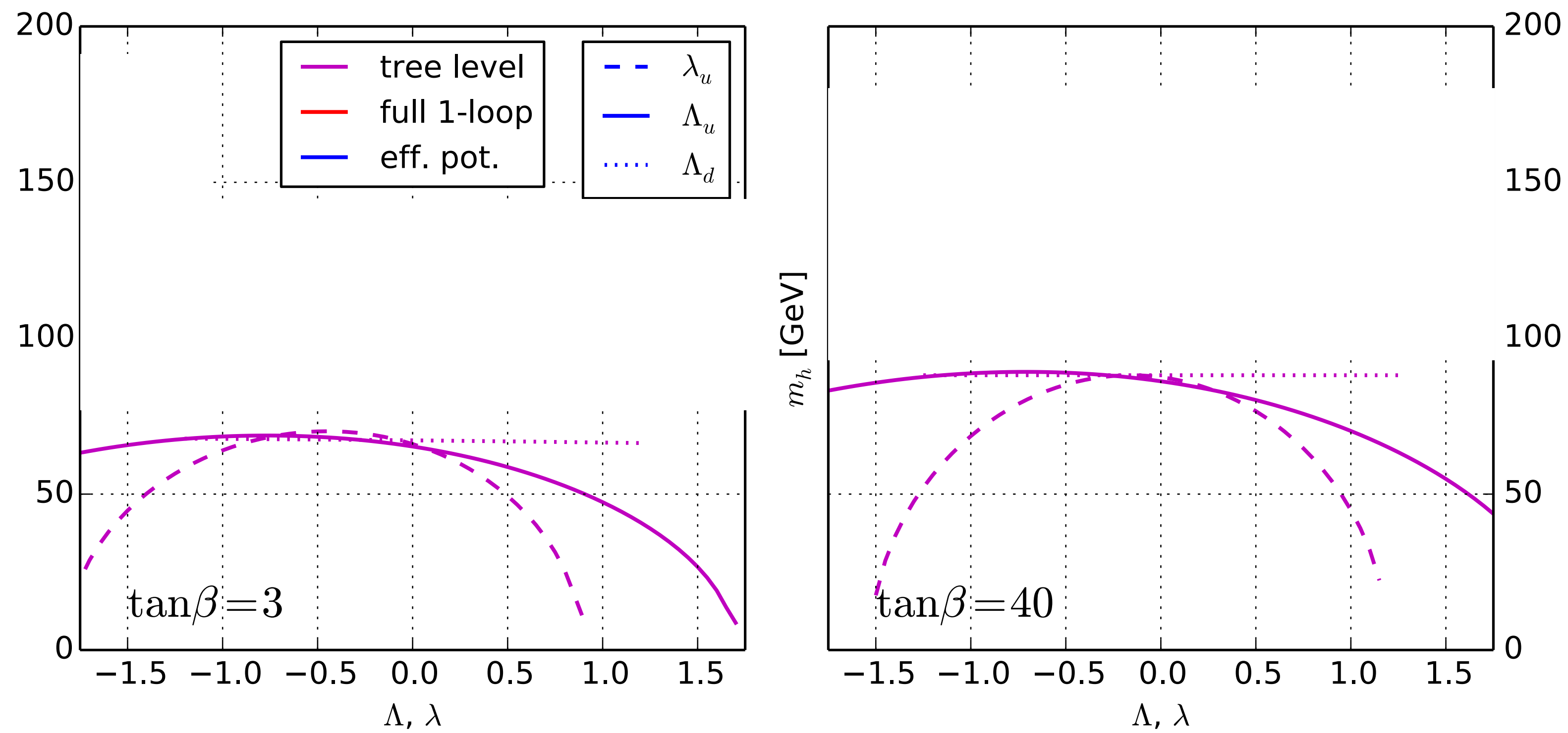
- Approximate formula for the lightest Higgs mass (**here**† composed of $\{\sigma_d,\sigma_u\}$) at the tree level

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

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

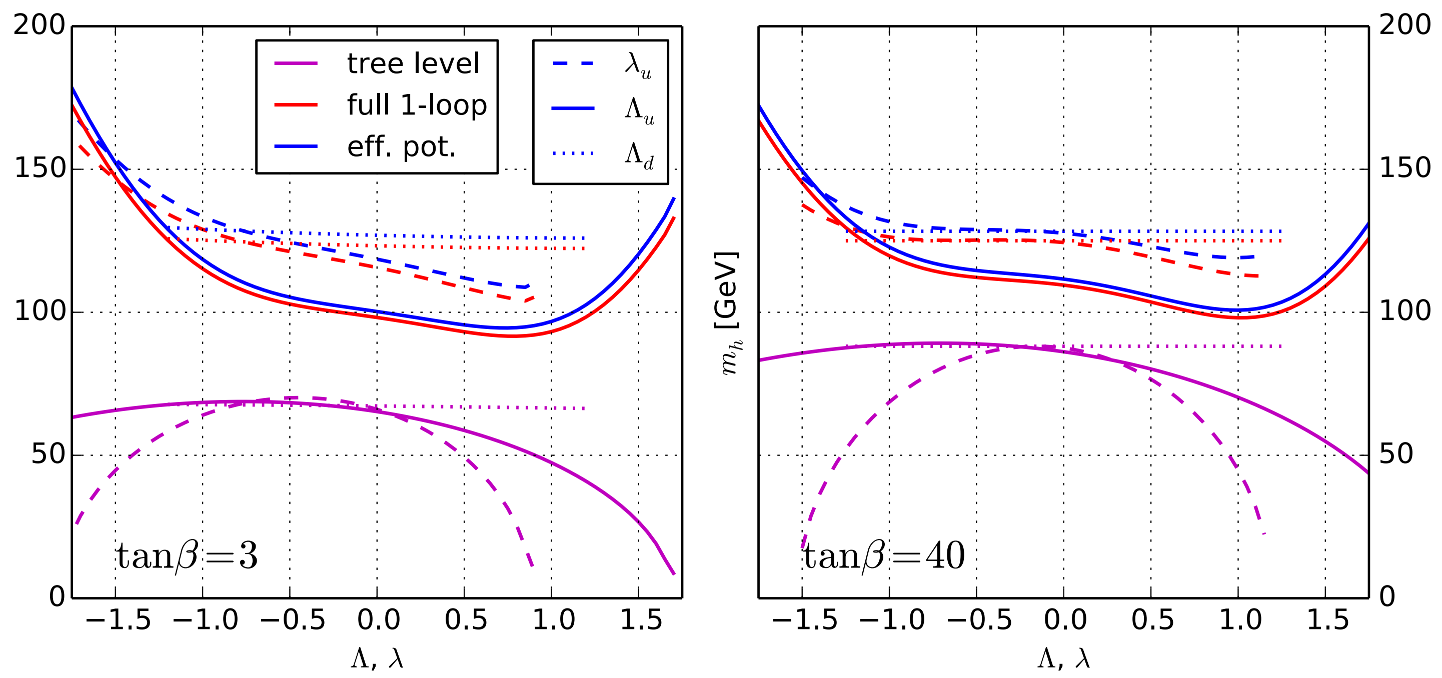
$\mu = \mu_u = \mu_d \quad v_s \approx v_T \approx 0$

- Tree-level mass of the lightest state in this setup **lower** than in the MSSM due to the mixing with σ_S and σ_T fields.



†other solutions possible

Lightest Higgs mass — full 1loop analysis

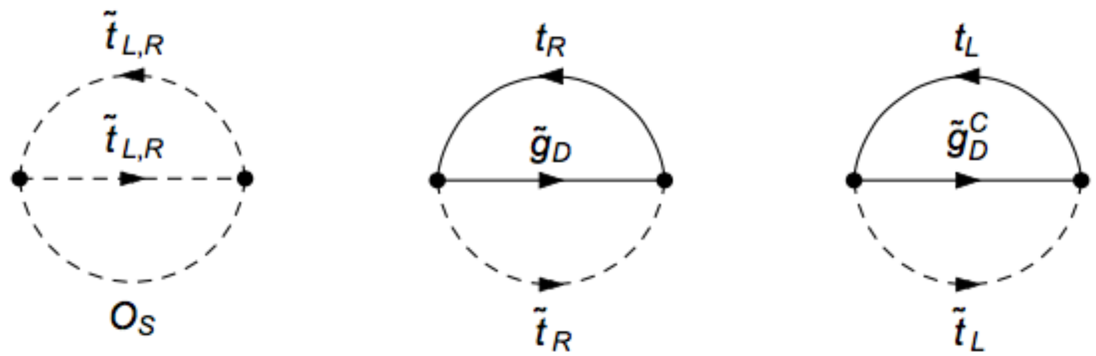


- large enhancement of tree-level Higgs mass
    - with ~1 TeV stops and no LR mixing lightest higgs mass too low
    - large contributions from new states, mainly Higgs and R-Higgs sectors

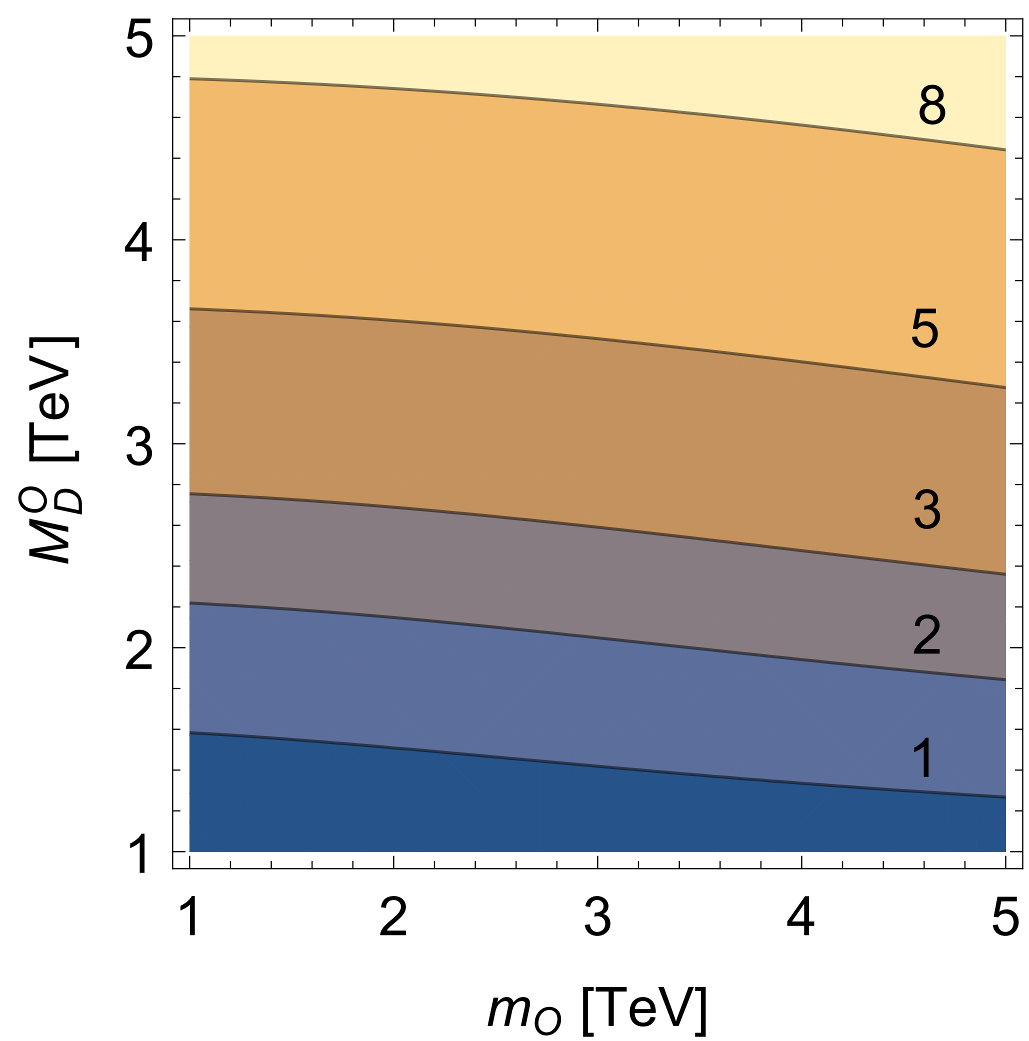
Lightest Higgs mass — leading 2-loop corrections

- 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

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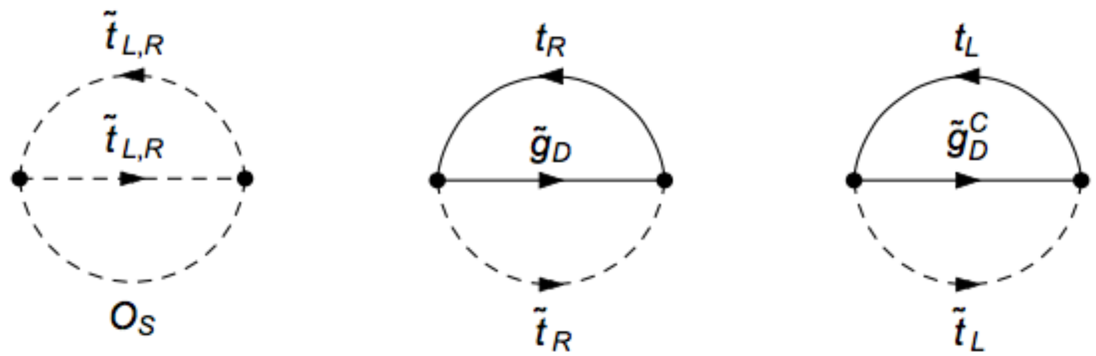
- MRSSM specific contributions

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



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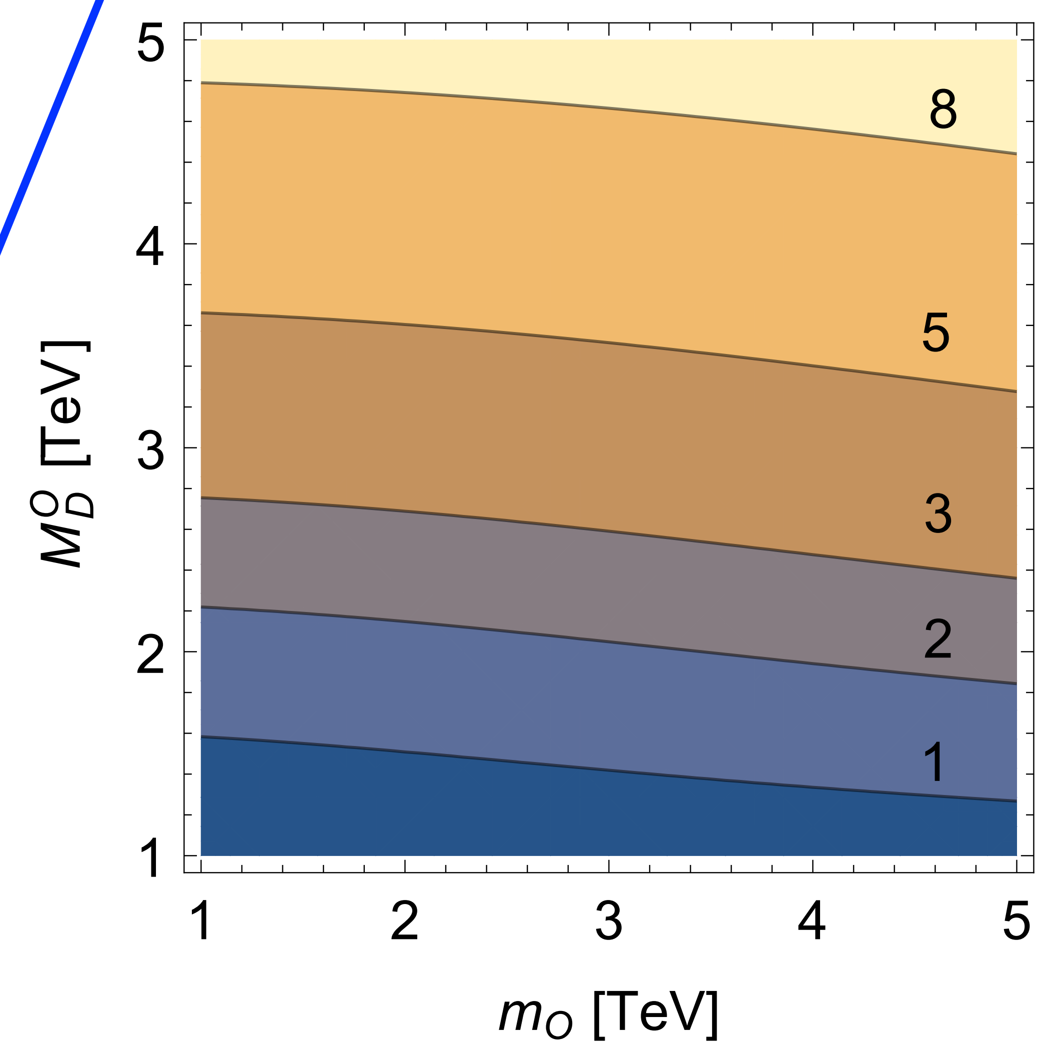

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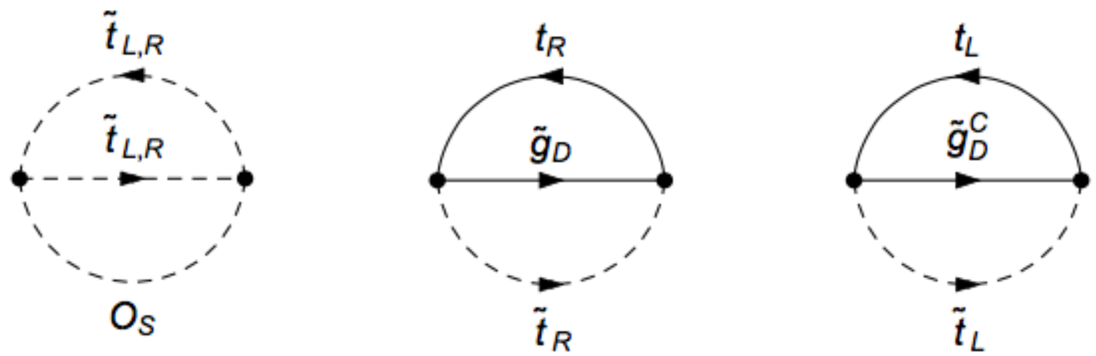

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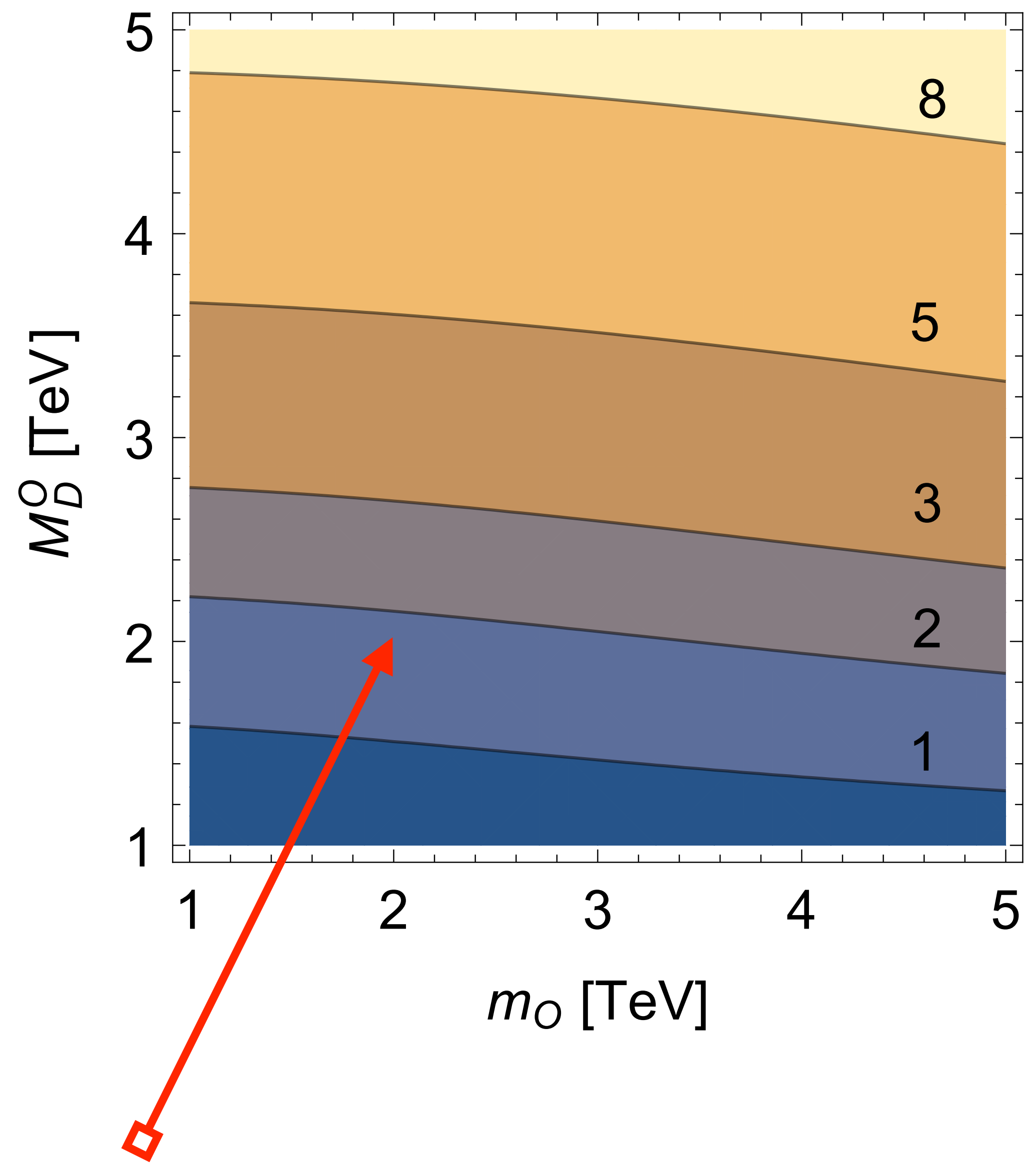

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Impact of 2-loop corrections

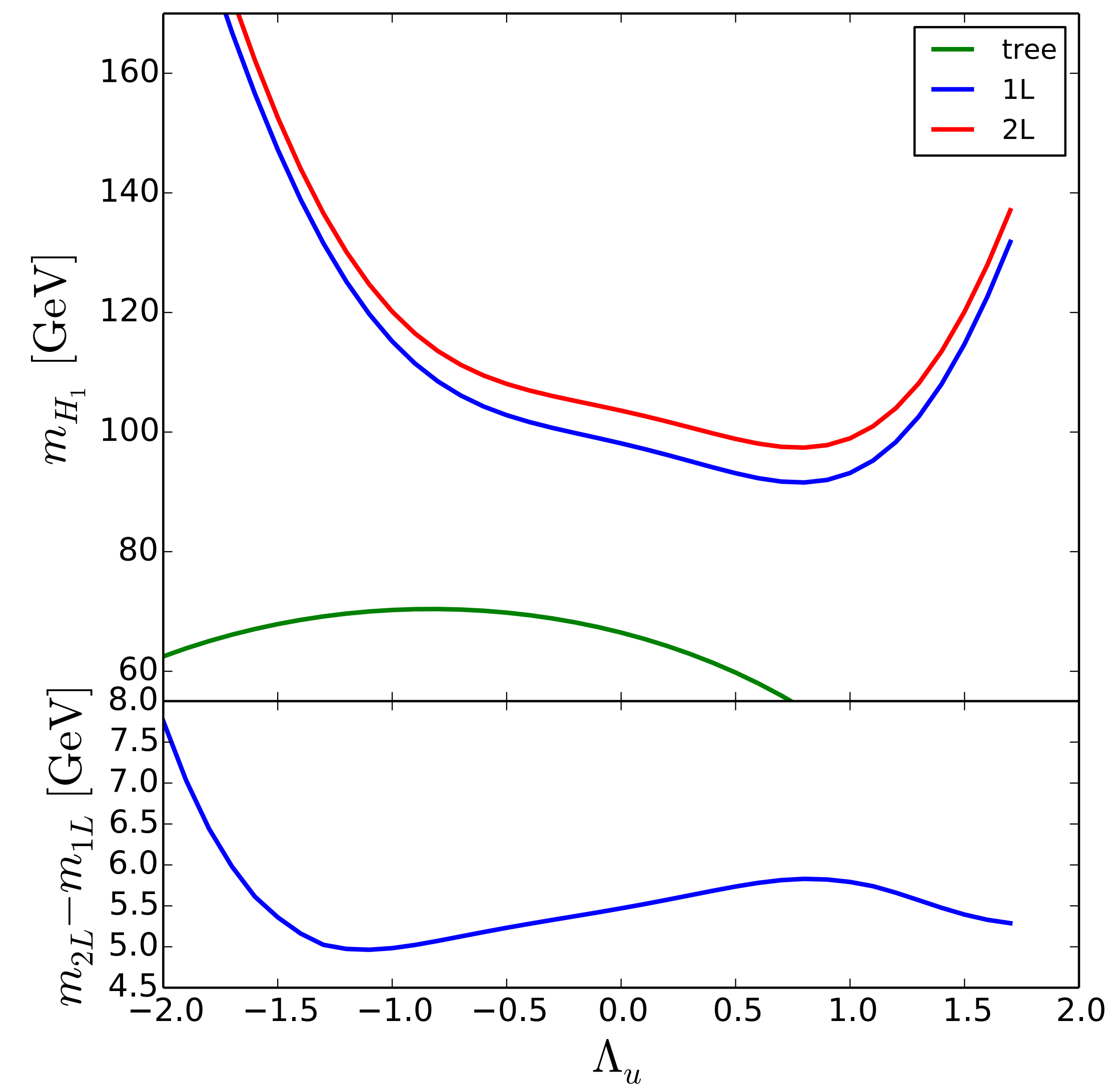
- MRSSM specific contributions
  Two loop corrections in the $\overline{\text{DR}}$ scheme are generally positive and amount to approximately +5 GeV

- 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 Λ_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)

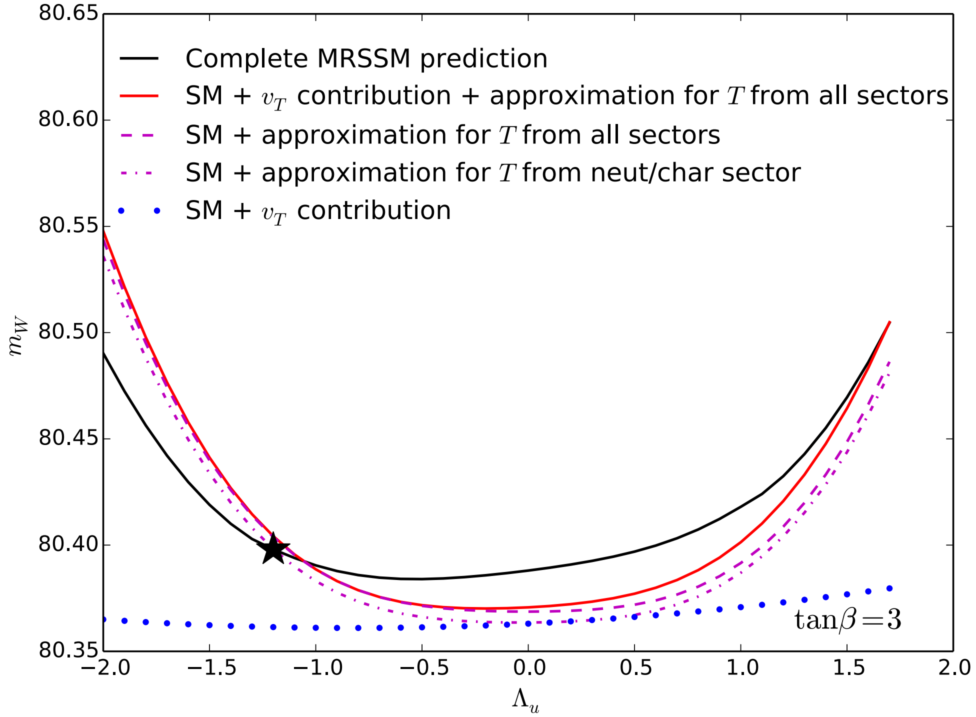
- Calculation based on Degrassi, Fanchiotti, Sirlin (1990) scheme modified to accommodate non vanishing v_T

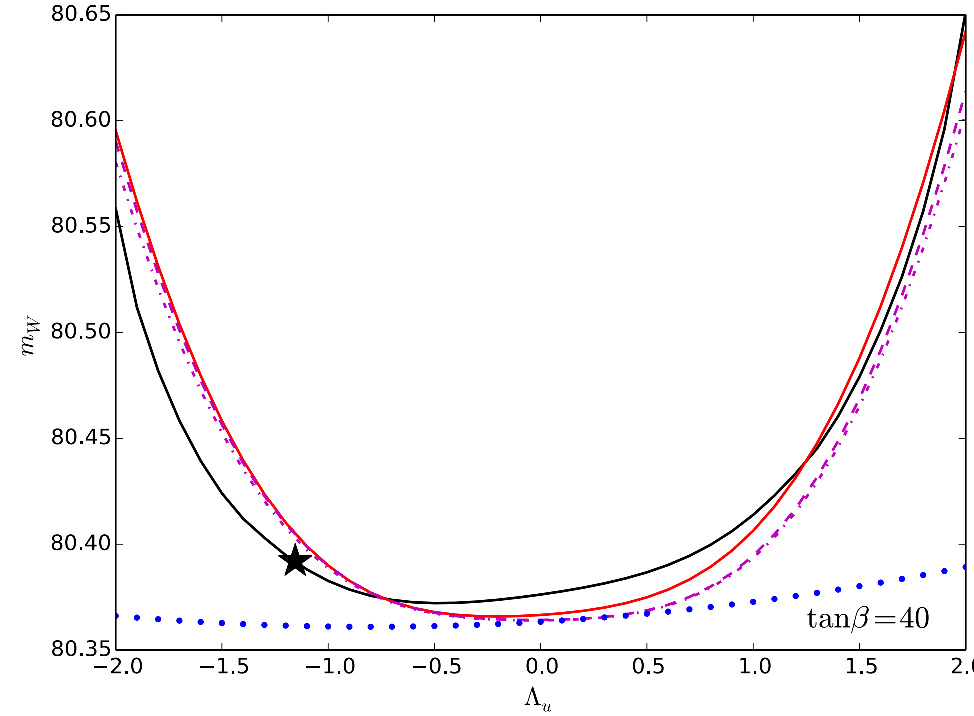
$$m_W^2 = \frac{1}{2} m_Z^2 \hat{\rho} \left[1 + \sqrt{1 - \frac{4\pi\hat{\alpha}}{\sqrt{2} G_\mu m_Z^2 \hat{\rho} (1 - \Delta\hat{r}_W)}} \right] \qquad \hat{\rho} = \frac{m_W^2}{m_Z^2 \hat{c}_W^2} \qquad \hat{\rho}_0 = 1 + \frac{4 v_T^2}{v^2}$$

- $\Delta\hat{r}_W$ 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

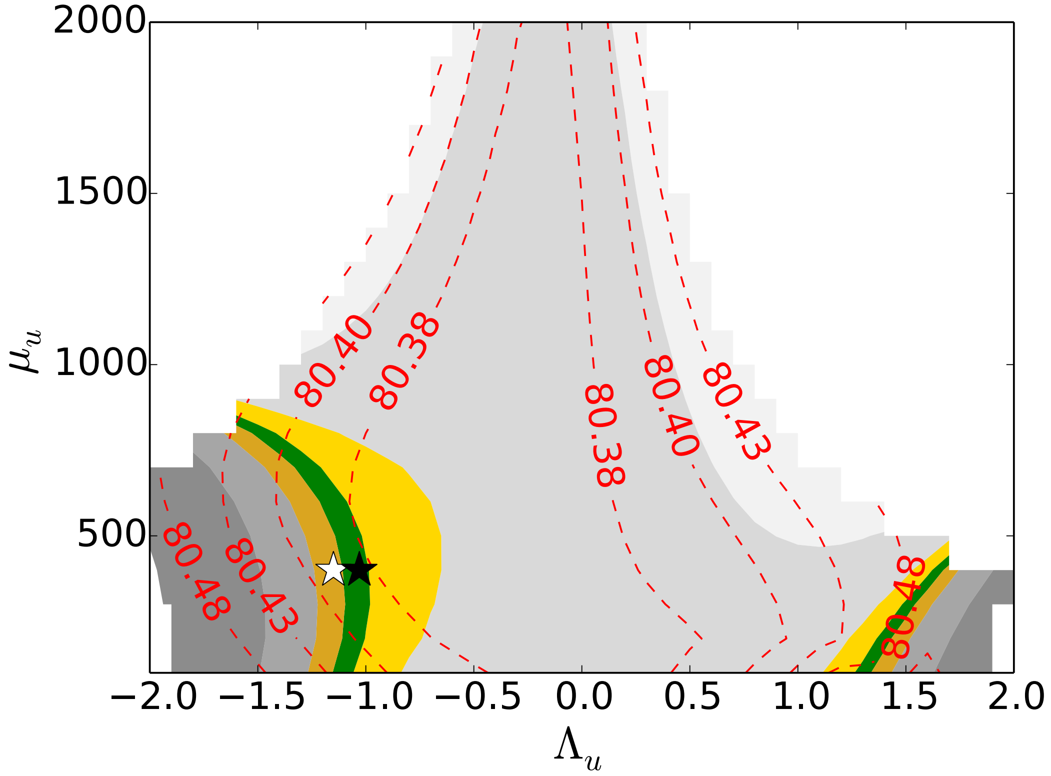
- for our benchmark points we find

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

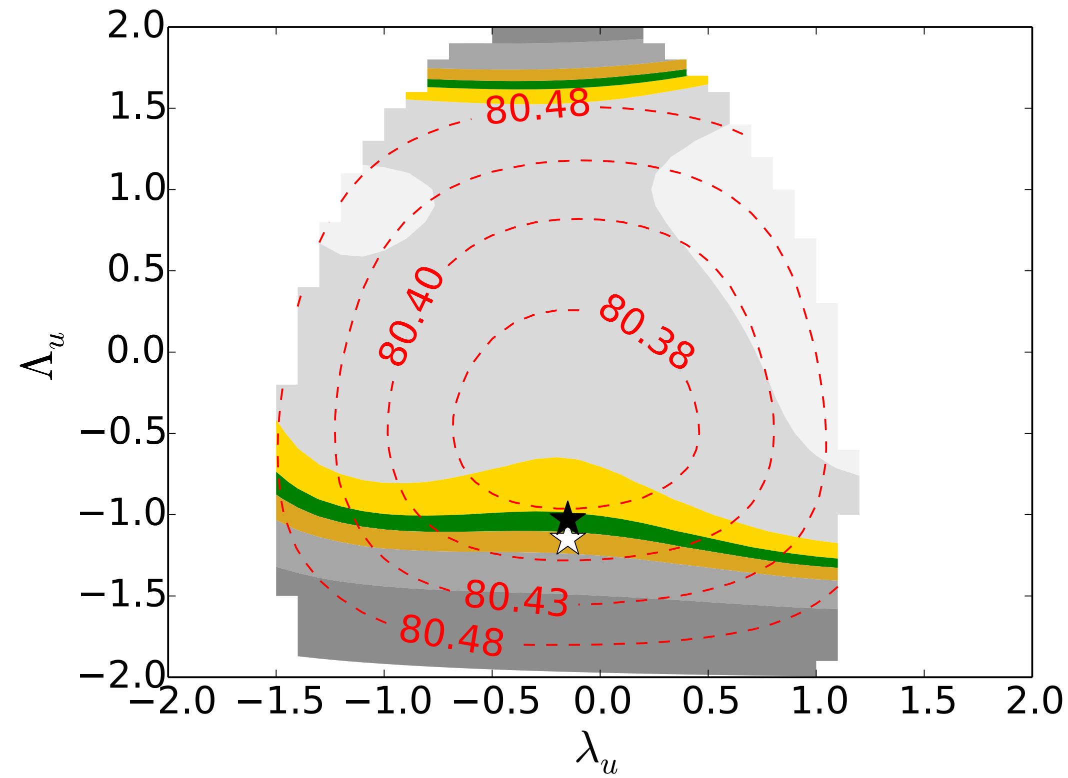
- 3 distinct parameter points with $\tan\beta = 3, 10, 40$
- W mass within 1σ from measured value $m_W^{\text{exp}} = 80.385 \pm 0.015$ GeV
- lightest Higgs mass around 125 GeV
- Higgs sectors in agreement with direct measurements and exclusion limits **HiggsBounds** and **HiggsSignals**
- due to the 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 $\tan\beta = 40$



■ $m_h = 126 \pm 2$ GeV

■ $m_h = 126 \pm 8$ GeV



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

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
  - "Light single scenario" almost analyzed (see next talk)
  - R-symmetric SQCD at 14 TeV LHC

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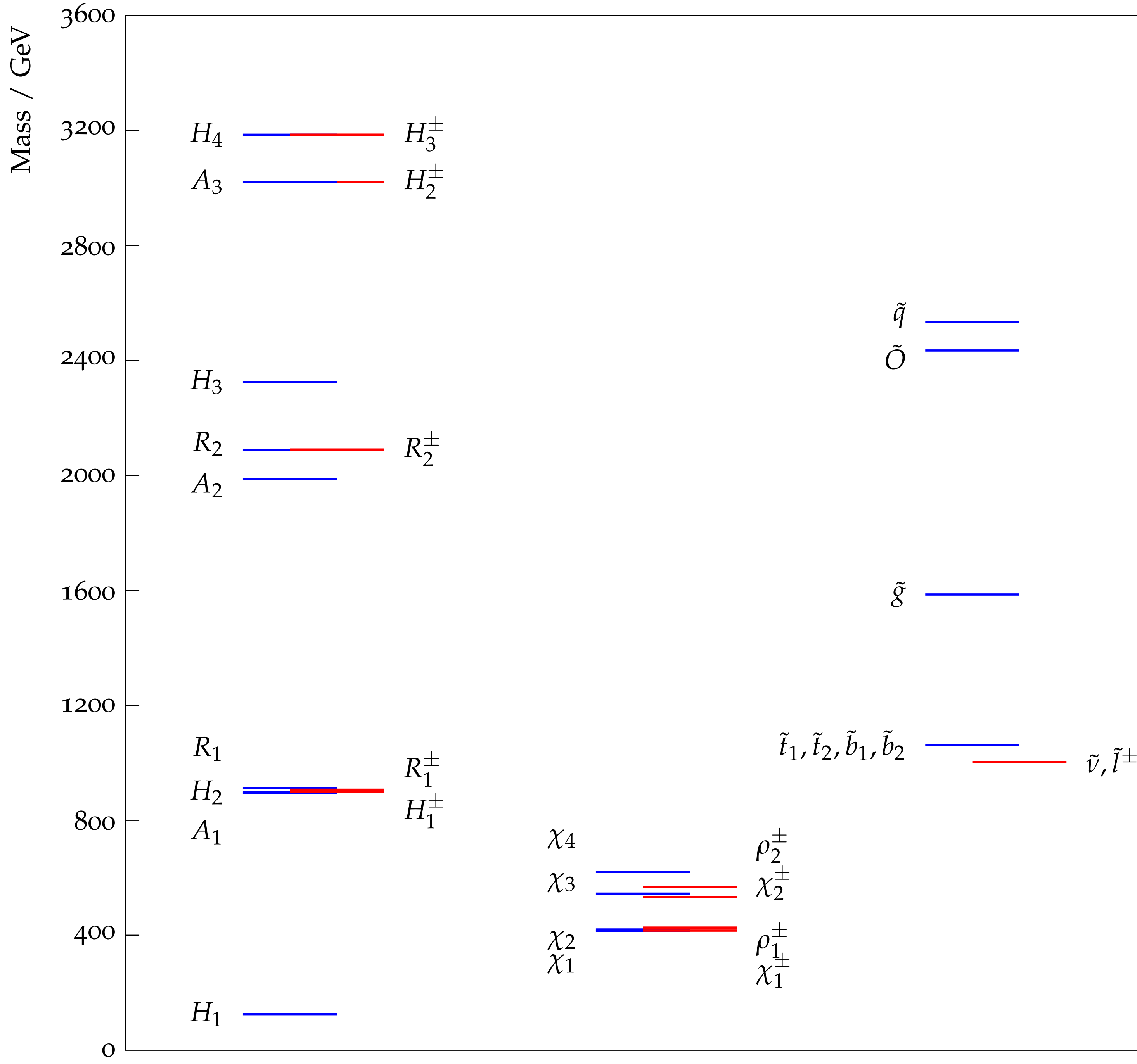
Thank you for your attention!

Back-up slides

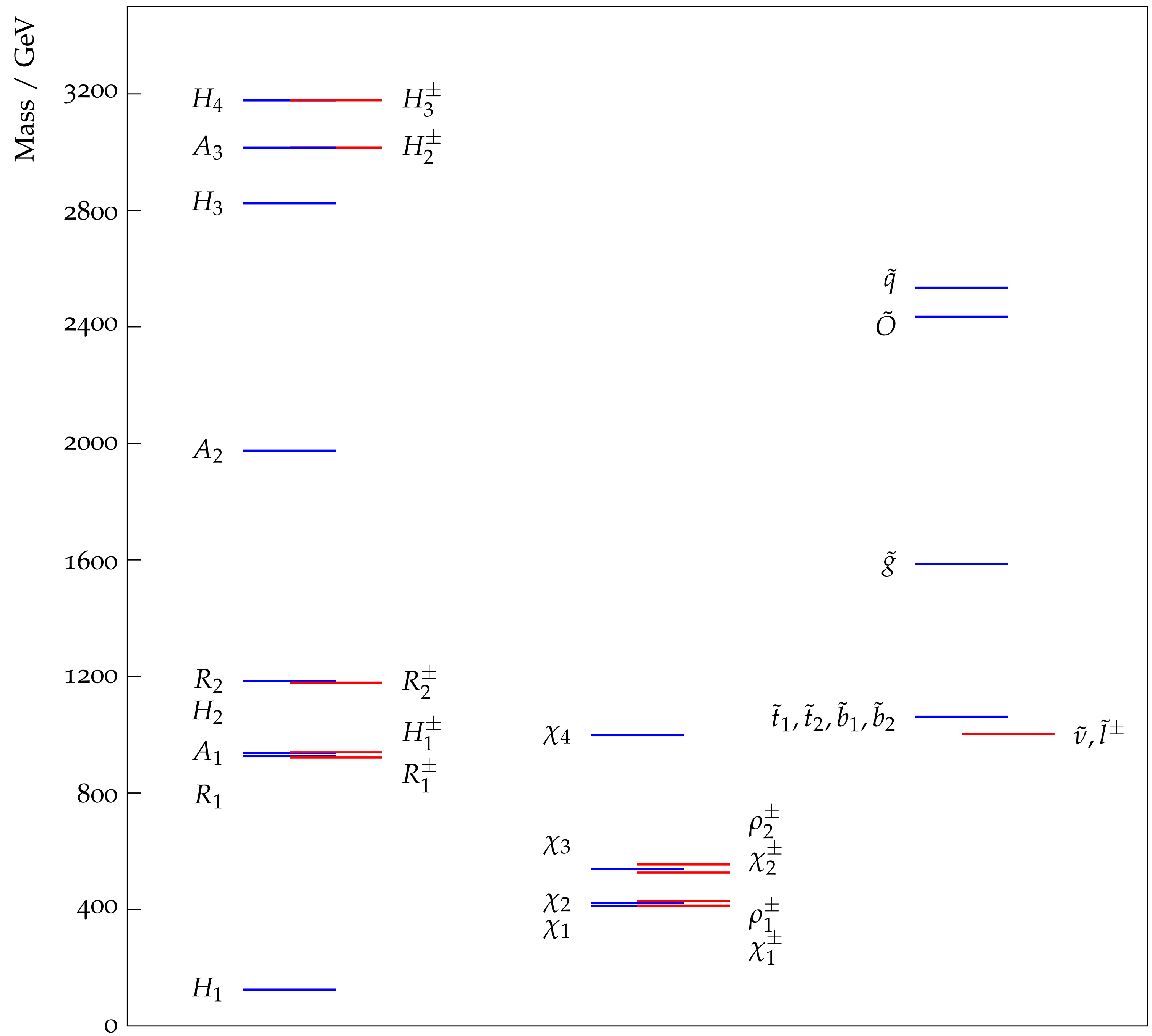
Benchmark points

	BMP1	BMP2	BMP3
$\tan\beta$	3	10	40
B_μ	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

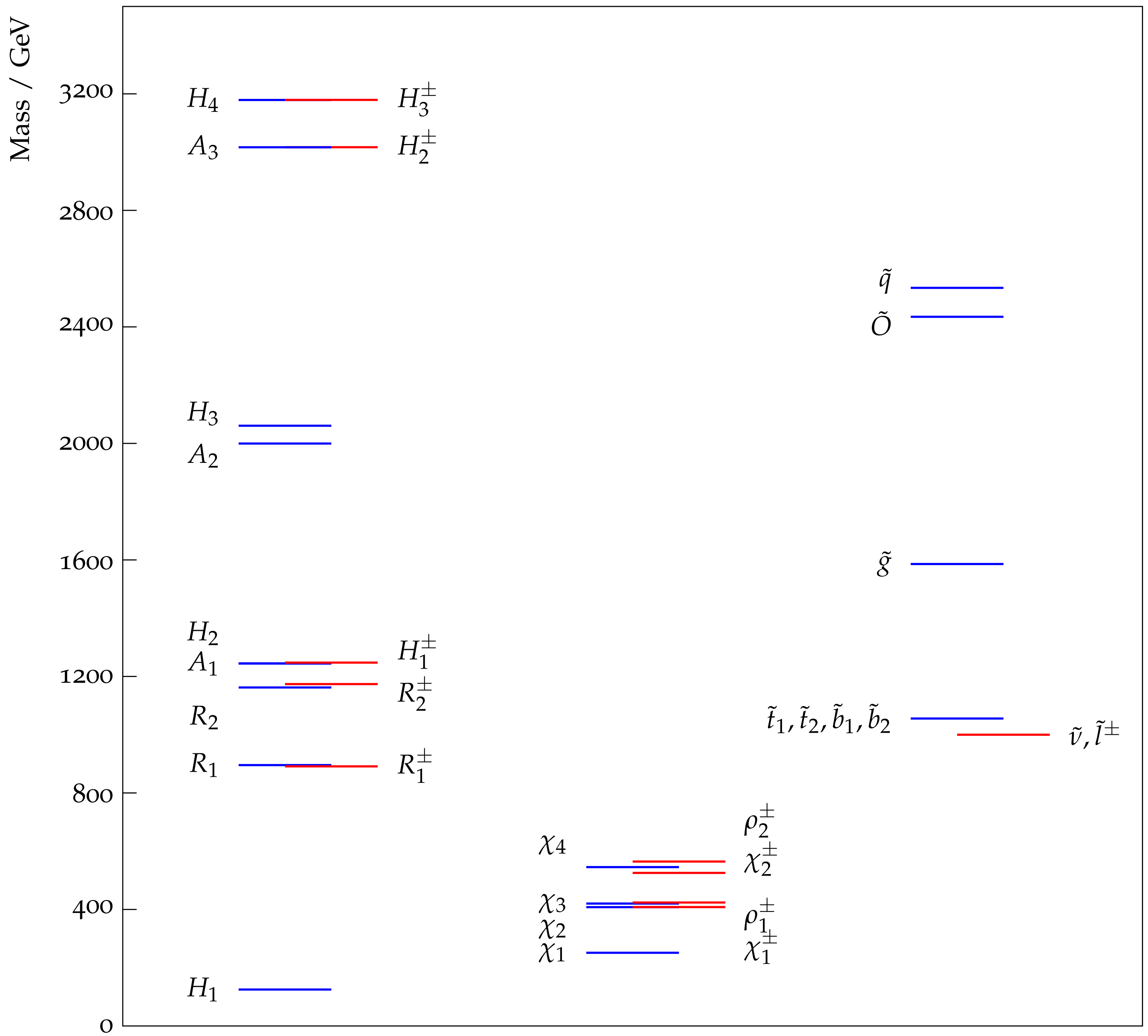
Particle spectrum for tan β = 3



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**

$SU(3)$ β function

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

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