Higgs and the electroweak precision observables in the MRSSM

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Plan of this talk

- Really short motivation
- How to build an R-symmetric SUSY
  1) what is an R-Symmetry
  2) what is allowed and what not
  3) different possible R-symmetric models
- The Higgs sector
- Prediction for the W-boson mass
- Some checks of our benchmark points

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 $\gtrsim$ 1 TeV stops ($\gtrsim$ 3 if we neglect mixing)
    - flavour physics suggests even larger SUSY scale (within the MSSM)

Motivation

- Supersymmetry is still one of the most promising candidates for physics beyond the SM although
  - no SUSY at Run I of the LHC
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Strong motivation to go beyond the MSSM!

- Here MRSSM **since**:
  - ☑ it ameliorates the flavour problem of the MSSM — Kribs, Poppitz, Weiner (2008)
  - ☑ gives correct W and Higgs mass at (possibly very) light stop masses — this talk
  - ☑ N=2 SUSY as possible UV completion (although might be hard to realise in practice)

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 super field is 0
  - R-charge of the superpotential must be 2
  - soft-breaking terms must have R-charge 0

R-symmetry realisation

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, choose SM fields with R=0
- Higgs superfields $Q=0$, lepton and quark superfields have $Q=1$
- R-symmetry forbids
  - $\mu \hat{H}_u \hat{H}_d$
  - $\lambda \hat{E}\hat{L}\hat{L}, \kappa \hat{U}\hat{D}\hat{D}, e\hat{H}\hat{L}$
  - Majorana masses and flavour changing A-terms

Flavour problem ameliorated but now gauginos are massless!

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

MRSSM in a nutshell

Additional fields:			$SU(3)_C$	$SU(2)_L$	$U(1)_Y$	$U(1)_R$
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- Superpotential — Choi, Choudhury, Freitas, Kalinowski, Zerwas (2011)

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

  - R-Higgses needed to construct mu-type terms and (Lagrangian) quartic-Higgs couplings

- Soft SUSY breaking terms
  - conventional MSSM $B_{\bar{\mu}}$ term allowed
  - Dirac mass terms for gauginos
- Pragmatic approach — study low energy phenomenology

Particles content of the MRSSM

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	$\hat{\mathcal{O}}, \hat{T}, \hat{S}$	0	O, T, S	0	$\tilde{O}, \tilde{T}, \tilde{S}$	−1

- real parts of the neutral, scalar, component of chiral multiplets $\hat{H}_d, \hat{H}_u, \hat{S}, \hat{T}$ mix to give 4 scalar Higgs bosons
- imaginary parts of the neutral, scalar, component of the same chiral multiplets mix to give 3 pseudo-scalar Higgs bosons and one Goldstone boson
- charged, scalar, component of the same chiral multiplets mix to give 3 charged Higgs bosons and one Goldstone boson
- 4 Dirac neutralinos, 4 Dirac charginos, 2 (complex) neutral and 2 charged R-Higgses

Scalar Higgs sector

- 4 scalar degrees of freedom $\{h_d, h_u, s, t\}$ mix to form 4 physical scalar Higgs bosons

- An approximate formula can be given for the lightest Higgs mass at the tree-level

  - one uses, as in the MSSM, mixing α angle to diagonalise the $\{h_d, h_u\}$ submatrix

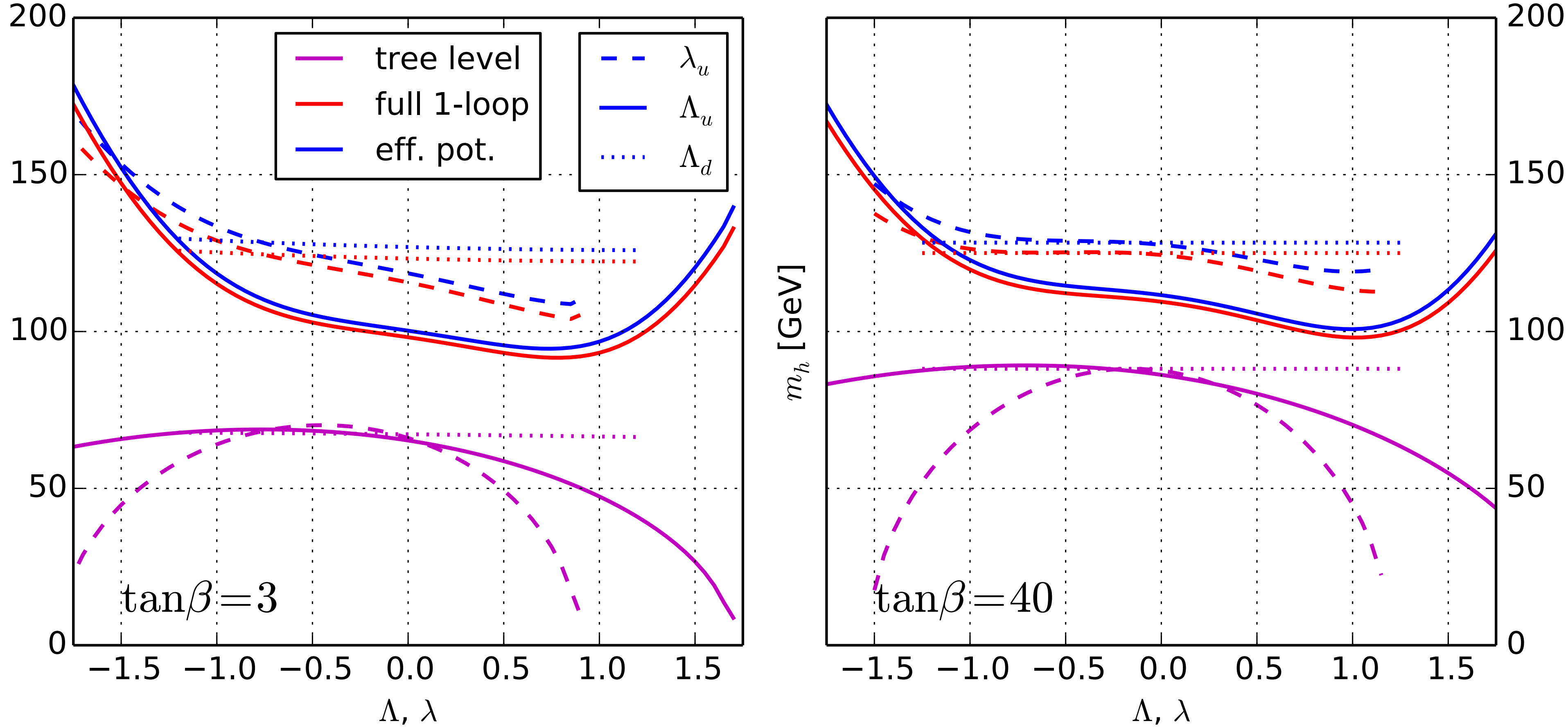
  - for large m_A^2 when $\alpha = \beta - \pi/2$

  - for simplicity $\lambda = \lambda_u = -\lambda_d, \Lambda = \Lambda_u = \Lambda_d, v_S \approx v_T \approx 0$

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

  - ➡ Tree-level mass of the lightest state always **lower** than in the MSSM

Lightest Higgs mass — tree level analysis



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

Lightest Higgs mass — effective potential approach

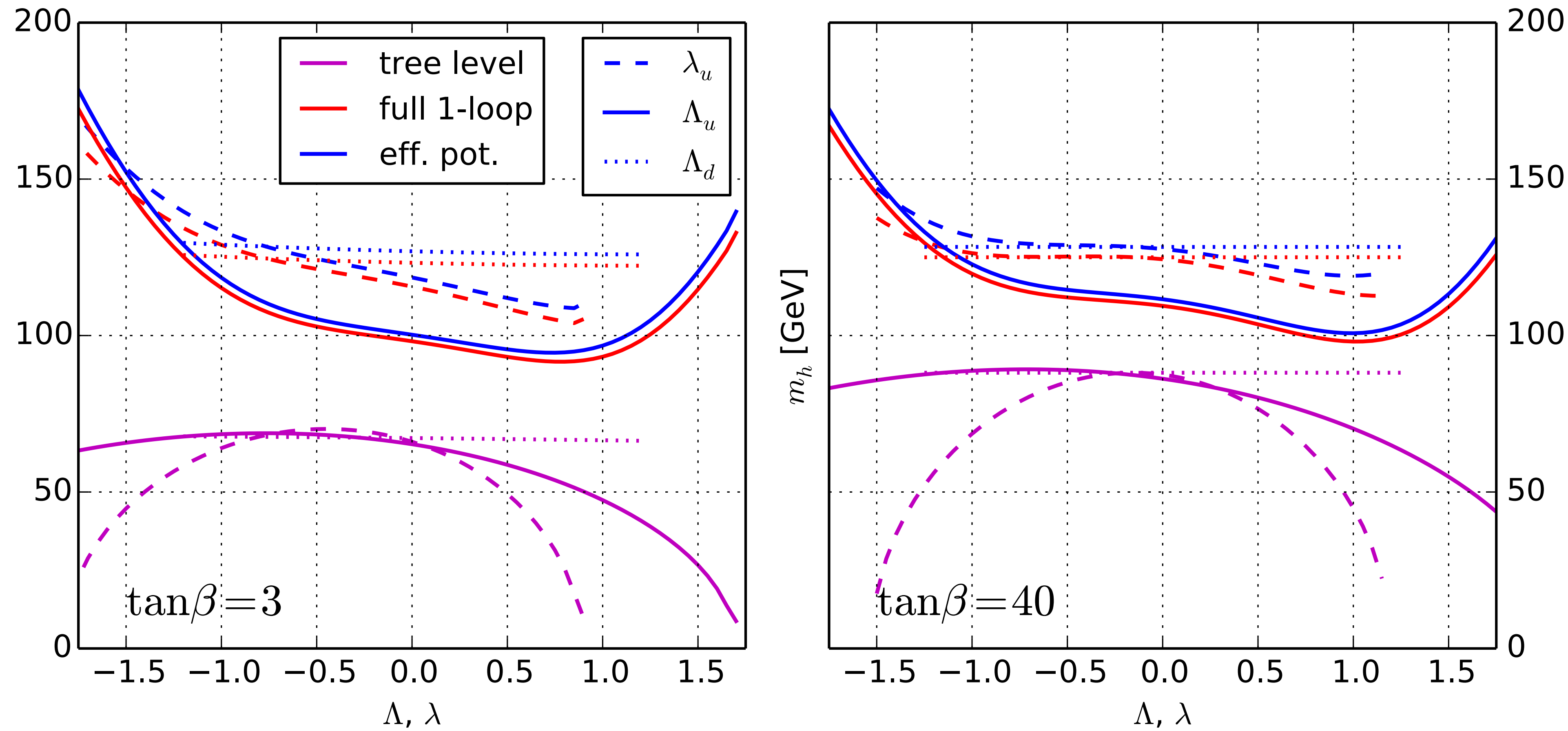
- Effective potential approximation (cf. approximate tree level result)

$$+\tan\beta \to \infty$$

$$\Delta m_h^2 = \frac{2v^2}{16\pi^2}\left[\frac{4\lambda^4+4\lambda^2\Lambda^2+5\Lambda^4}{8}\log\frac{m_{R_u}^2}{Q^2}\right.$$
$$+\left(\frac{\lambda^4}{2}-\frac{\lambda^2\Lambda^2}{2}\frac{m_S^2}{m_T^2-m_S^2}\right)\log\frac{m_S^2}{Q^2}$$
$$+\left(\frac{5}{8}\Lambda^4+\frac{\lambda^2\Lambda^2}{2}\frac{m_T^2}{m_T^2-m_S^2}\right)\log\frac{m_T^2}{Q^2}$$
$$-\left(\frac{5}{4}\Lambda^4-\lambda^2\Lambda^2\frac{(M_W^D)^2}{(M_B^D)^2-(M_W^D)^2}\right)\log\frac{(M_W^D)^2}{Q^2}$$
$$-\left(\lambda^4+\lambda^2\Lambda^2\frac{(M_B^D)^2}{(M_B^D)^2-(M_W^D)^2}\right)\log\frac{(M_B^D)^2}{Q^2}$$
$$\left.+\frac{\Lambda^2\lambda^2}{2}\right]$$

- Calculate also by **Bertuzzo, Frugiuele, Gregoire, Ponton (2014)**, although with somewhat different result (*under investigation*)

Lightest Higgs mass — full 1loop analysis



- large tree-level enhancement of Higgs mass, with ~1 TeV stops and no LR mixing (plots), from new states
- large contributions from Higgs and R-Higgs sectors
- 0.5 TeV stops would work also fine but hard to avoid direct detection limits
- few GeV downward difference compared to effective potential result

m_W at tree-level

[Degrassi, Fanchiotti, Sirlin (1990)]

- MRSSM contains a Y=0 Higgs triplet $\Rightarrow$ tree level contribution to m_W
- EW-gauge sector is described at tree-level in terms of 4 parameters

$$\{g_1, g_2, v, v_T\}$$

- Trade 3 of them for input, „low energy", observables

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

- Define quantity

$$\hat{\rho} = \frac{m_W^2}{m_Z^2 \hat{c}_W^2} \neq 1 \Rightarrow \hat{c}_W^2 = \frac{m_W^2}{\hat{\rho}\, m_Z^2}$$

- Calculate muon decay constant at the tree-level

$$\frac{G_\mu}{\sqrt{2}} = \frac{\pi \alpha_{EM}}{2 m_W^2 \hat{s}^2} = \frac{\pi \alpha_{EM}}{2 m_W^2 \left(1 - \frac{m_W^2}{\hat{\rho} m_Z^2}\right)}$$

m_W master formula at one-loop

- beyond the tree-level there are quantum corrections to the muon decay constant

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

- where

$$\hat{\rho} = \frac{c^2}{\hat{c}^2} = \hat{\rho}_0 \frac{1 + \frac{\hat{\Pi}^T_{ZZ}(m_Z^2)}{m_Z^2}}{1 + \frac{\hat{\Pi}^T_{WW}(m_W^2)}{m_W^2}}$$

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

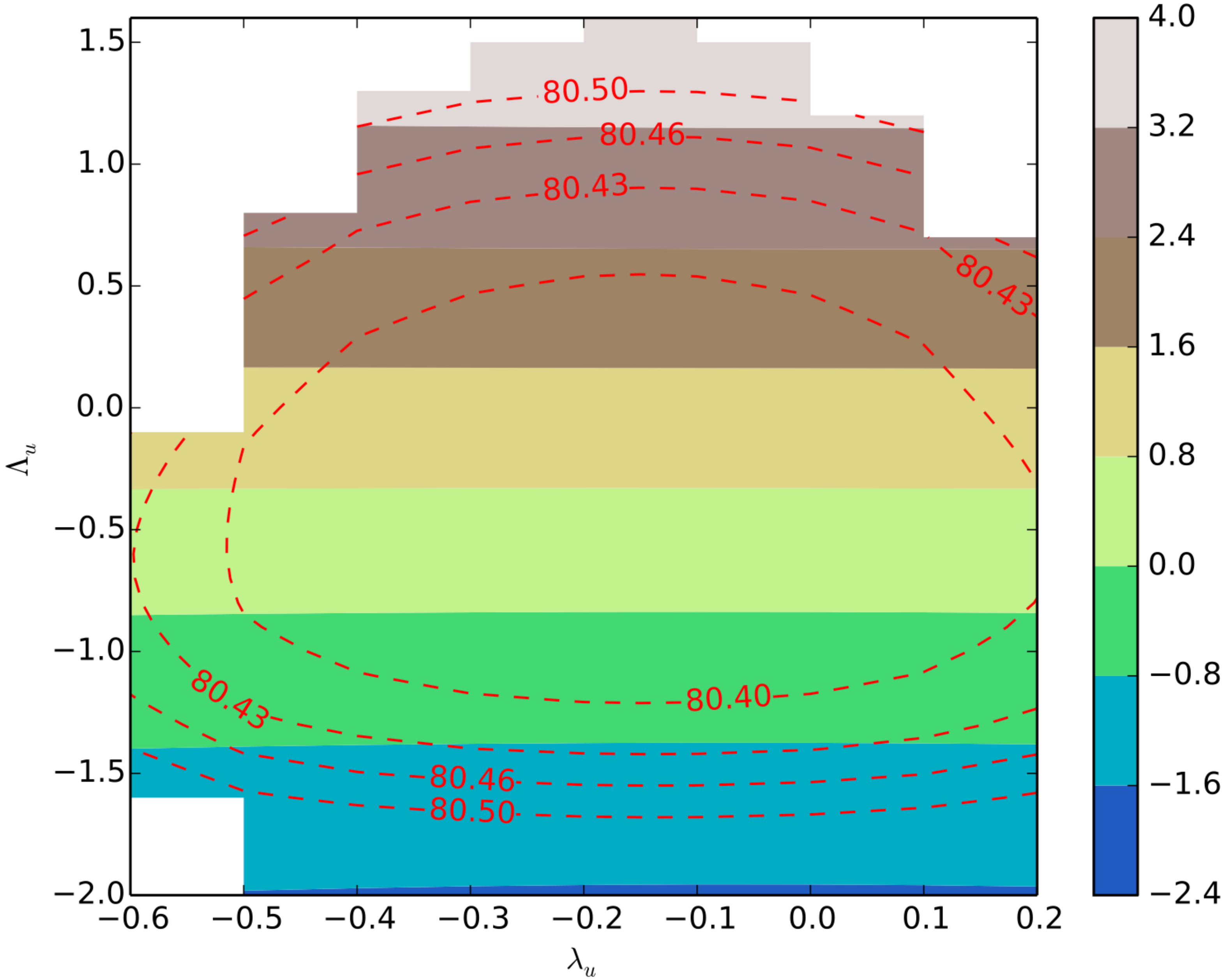
- solve for m_W

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

Two effects in m_W increase

$$m_W \; vs. \; v_T \;\; \text{for} \;\; \tan\beta = 50$$

enhancement of tree level v_T



v_T is the one-loop corrected solution of tadpole equation

loop corrections to Π_{WW}, Π_{ZZ}

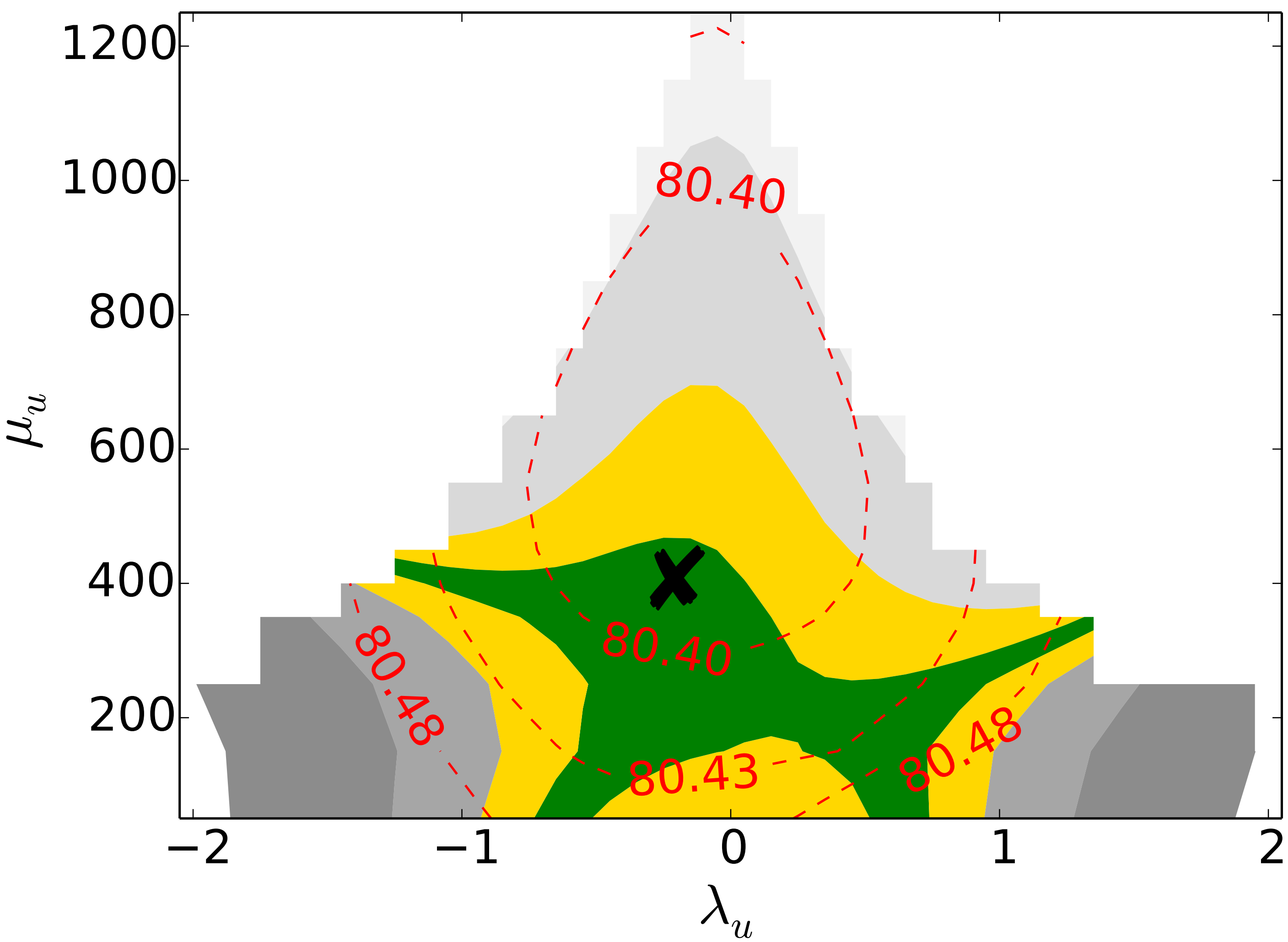
Benchmark points properties

- 3 distinct parameter points with $\tan\beta = 3, 10, 40$
- within $1-2\,\sigma$ from experimentally measured W-boson mass (less if you add theoretical uncertainty)

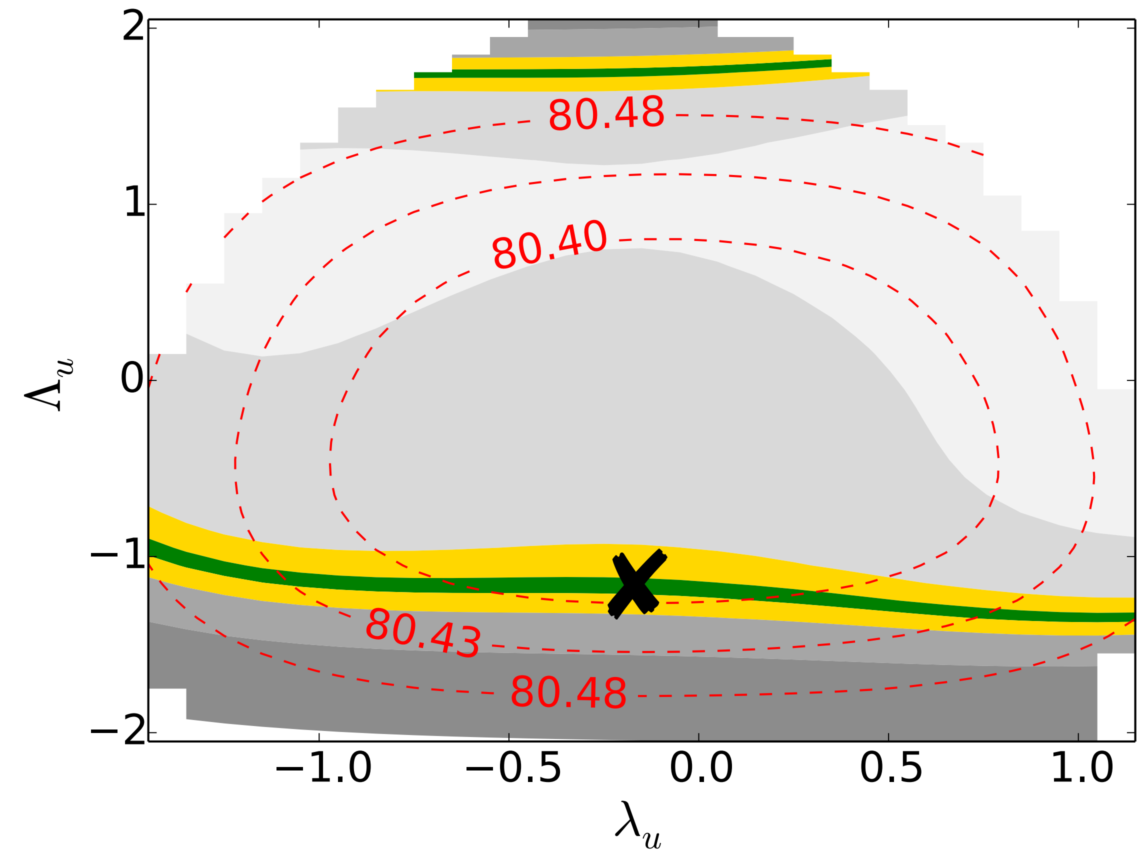
$$m_W^{\exp} = 80.385 \pm 0.015\ \text{GeV}$$

- lightest Higgs mass around 125 GeV
- points in agreement with direct Higgs measurements [**HiggsBounds,HiggsSignals**]
- Due to the lack of A-terms R-symmetric models are generally 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 $\tan\beta = 40$

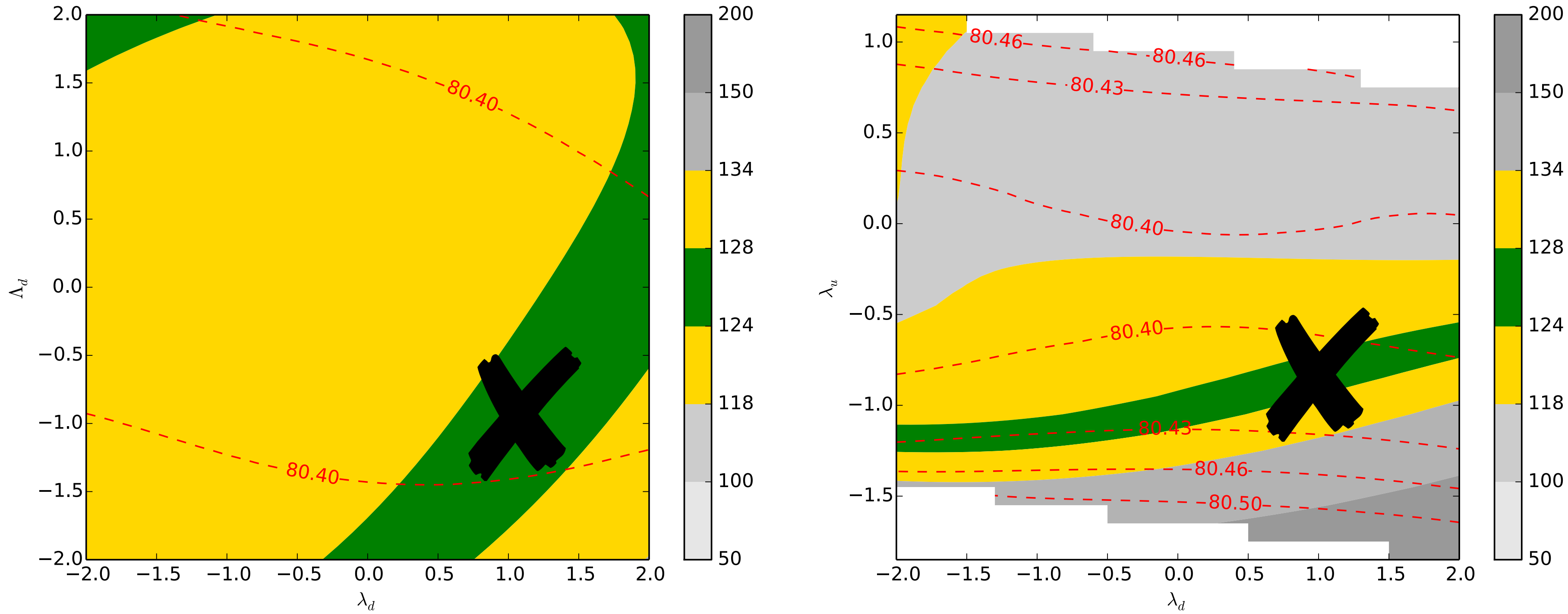


- contours for m_W
- colour gradient for m_h
- ✗ for benchmark point



- $m_h = 126 \pm 2\ \mathrm{GeV}$ (green)
- $m_h = 126 \pm 8\ \mathrm{GeV}$ (yellow)

$m_h - m_W$ interdependence for low $\tan\beta$



- to see dependence on down-type parameters one needs to reduce $\tan\beta$
- even for $\tan\beta = 3$ dependence in very mild

Conclusions and outlook

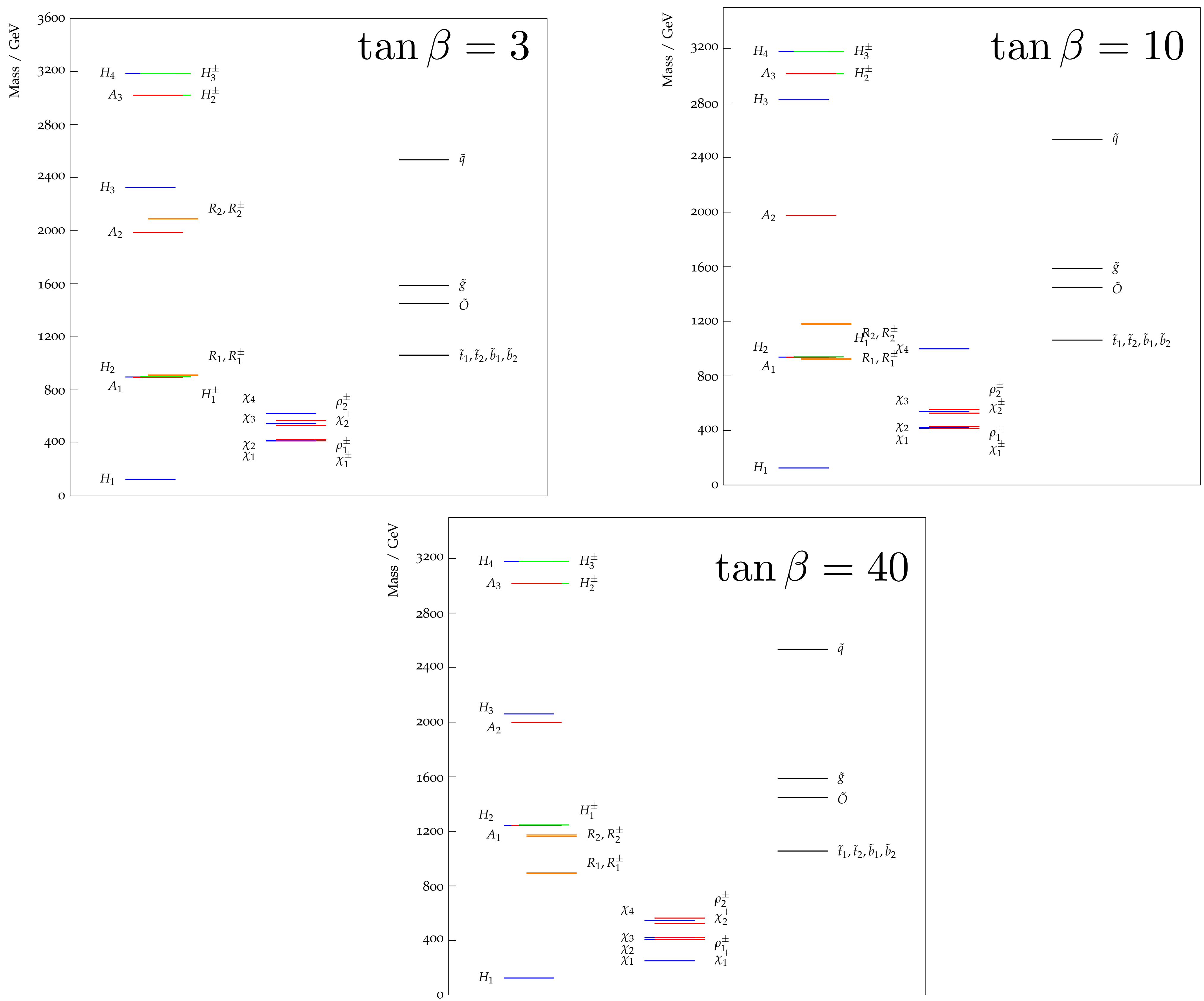
- I presented a viable R-symmetric realisation of SUSY which
  - is in agreement with PEWO and flavour-physics constrains
  - predicts stable vacuum
  - has interesting collider phenomenology to be explored
  - has Dirac type neutralino as a candidate for dark matter — **Buckley, Hooper, Kumar (2013)**
- We took the low energy model without discussing its UV completion
- Still a lot to do…. Consequences for 14 TeV LHC?

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_D^B	600	1000	250
$m_{R_u}^2$	2000^2	1000^2	1000^2
$(\mu_d,\ \mu_u)$		$(400, 400)$	
M_D^W		500	
M_D^O		1500	
(m_T^2, m_S^2)		$(3000^2, 2000^2)$	
$(m_{Q;1,2}^2, m_{Q;3}^2)$		$(2500^2, 1000^2)$	
$(m_{D;1,2}^2, m_{D;3}^2)$		$(2500^2, 1000^2)$	
$(m_{U;1,2}^2, m_{U;3}^2)$		$(2500^2, 1000^2)$	
$(m_L^2,\ m_E^2,\ m_O^2)$		1000^2	
$m_{R_d}^2$		700^2	

Particle spectra



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

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

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