SUSY with R-symmetry: confronting EWPO and LHC constraints

arXiv:1410.4791

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Plan of the talk

- Motivation
- R-symmetric SUSY
  - what is an R-symmetry
  - different possible R-symmetric models ➜ **MRSSM**
- Strongly interacting sector of the MRSSM
- The electroweak sector
  - Higgs sector
  - Constraints: W boson mass, STU parameters, Higgs searches and exclusions, vacum stability, flavour physics
- Conclusion and outlook

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)
    - flavour 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 flavour 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 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)
- gauge sector has N=2 structure — 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 at the low scale

- Nelson-Seiberg theorem connects SUSY breaking with R-symmetry breaking
  Nelson, Seiberg (1994); Kang, Li, Sung (2013)

- but it does not state that there are no models with SUSY-breaking minima that preserve R-symmetry
  Intriligator, Seiberg, Shih (2007)

- Various phenomenologically viable models of this type have been constructed
  e.g. De Lope Amigo, Blechman, Fox, Poppitz (2009)

- Here we'll not consider model building but focus on focus on phenomenological analysis of low energy theory

Low-energy 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
- 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 realisations:

…

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 $m^2 \, |\Phi|^2$

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& - 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
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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
MRSSM	4	1

Particles content summary: MSSM vs. MRSSM

(scalar components of) H_u and H_d mix with S and T

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Particles content summary: MSSM vs. MRSSM

Winos and Higgsinos mix with R-Higgsinos and Triplinos

	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

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Particles content summary: MSSM vs. MRSSM

states not present in the MSSM

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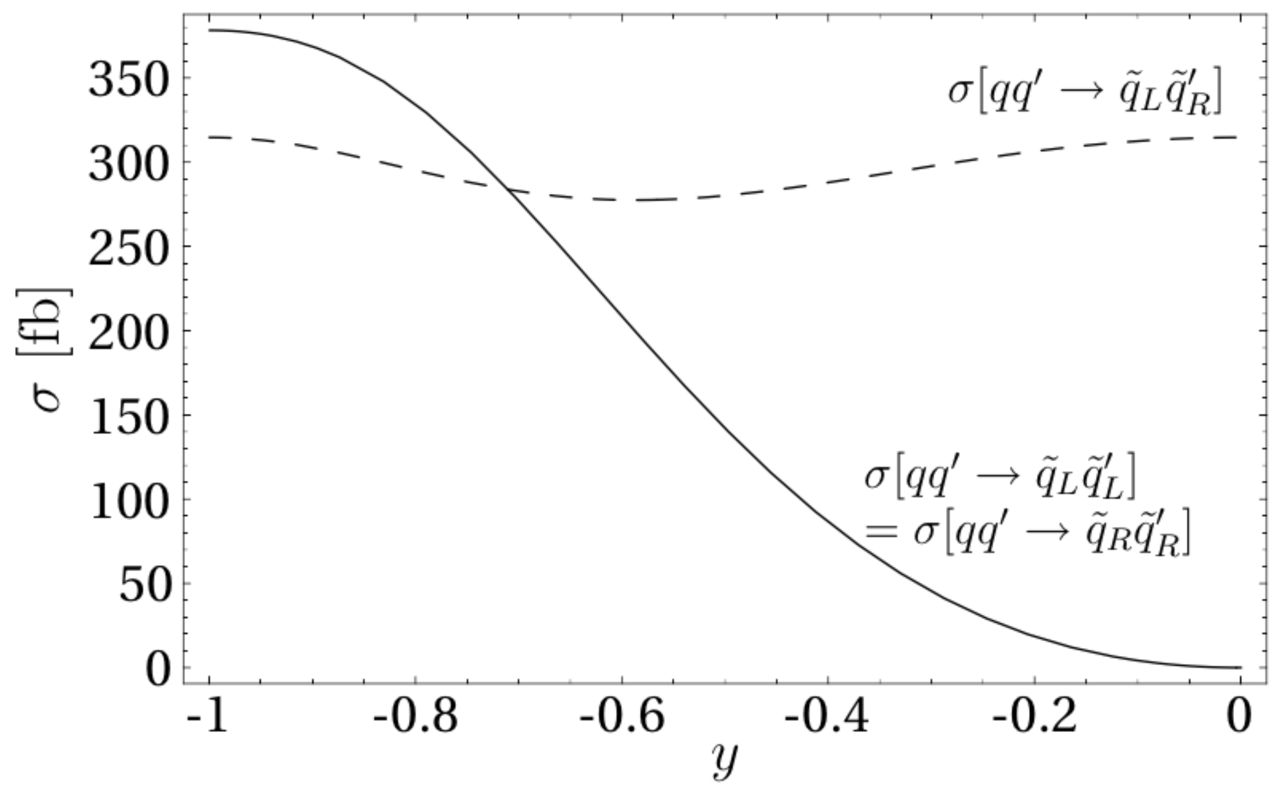
	neutralino	gluino	
MSSM	4	1	Majorana fermions
MRSSM	4	1	Dirac fermions

Strongly interacting sector

Squark and gluino production

- New states not present in the MSSM
  - Dirac gluino $\tilde{g}^D$
  - scalar companion - sgluon Θ
- Suppression of squark production



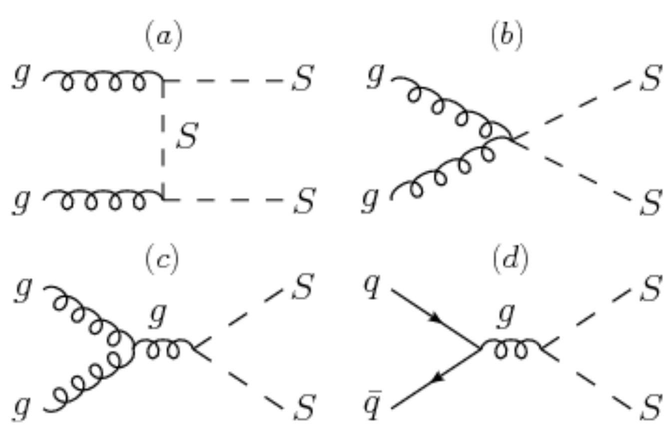
Choi, Drees, Freitas, Zerwas (2008)

- Enhancement of gluino pair production cross section — stronger exclusion bounds

Heikinheimo, Kellerstein and Sanz (2011)

Sgluons@LHC

- Sgluons have R-charge 0
  - can be produced singly and resonantly
  - however, they do not couple directly to SM particles ➜ single gluon production highly suppressed
  - pair production model independent



Netto, Lopez-Val, Mawatari, Plehn, Wigmore (2012)

	$\sqrt{S} = 8$ TeV			$\sqrt{S} = 14$ TeV		
m_G [GeV]	σ^{LO} [pb]	σ^{NLO} [pb]	K	σ^{LO} [pb]	σ^{NLO} [pb]	K
200	2.12×10^{2}	3.36×10^{2}	1.58	9.77×10^{2}	1.48×10^{3}	1.52
350	8.16×10^{0}	1.36×10^{1}	1.66	5.44×10^{1}	8.46×10^{1}	1.56
500	7.64×10^{-1}	1.34×10^{0}	1.75	7.14×10^{0}	1.14×10^{1}	1.60
750	3.40×10^{-2}	6.54×10^{-2}	1.93	5.56×10^{-1}	9.29×10^{-1}	1.67
1000	2.47×10^{-3}	5.29×10^{-3}	2.15	7.31×10^{-2}	1.28×10^{-1}	1.75

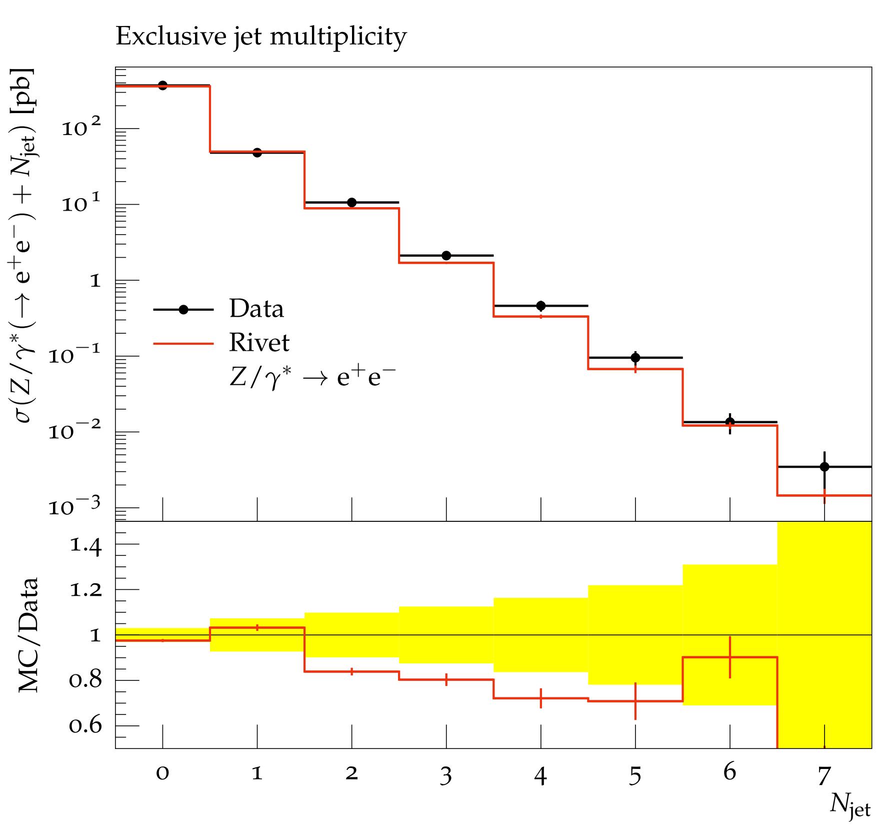
roughly 100 events/day

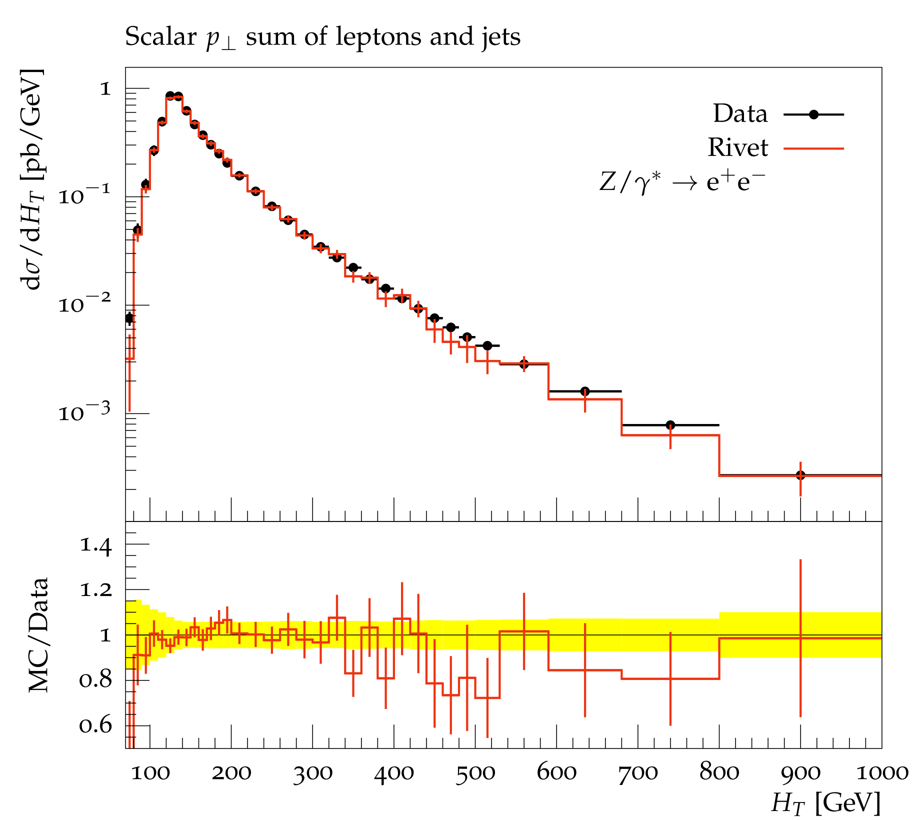
- 4-(gluon) jets or 4-top quarks as a possible experimental signature
- 4-jet searches exclude sgluons with mass lower than ~300 GeV [ATLAS]

Sgluons@LHC — $t\bar{t}t\bar{t}$ signature

- $t\bar{t}t\bar{t}$ production in the SM is quite rare
- we considered event with same-sign muon in association with large hadronic activity — main background coming from $t\bar{t}t\bar{t}, t\bar{t}W^{\pm}, t\bar{t}Z$
- we used novel Monte Carlo simulation technic — UNLOPS (Unitarized NLO+PS merging) Lönnblad, Prestel (2011, 2012)
- MC validation

$$pp \to e^+e^-@\sqrt{s} = 7 \text{ TeV LHC}$$





NLO:	$1j$
LO:	$4j$
$t_{\rm MS}$:	25 GeV
$\mu_R = \mu_F$:	m_Z
PDFs:	CT10

Sgluons@LHC — $t\bar{t}t\bar{t}$ signature (results)

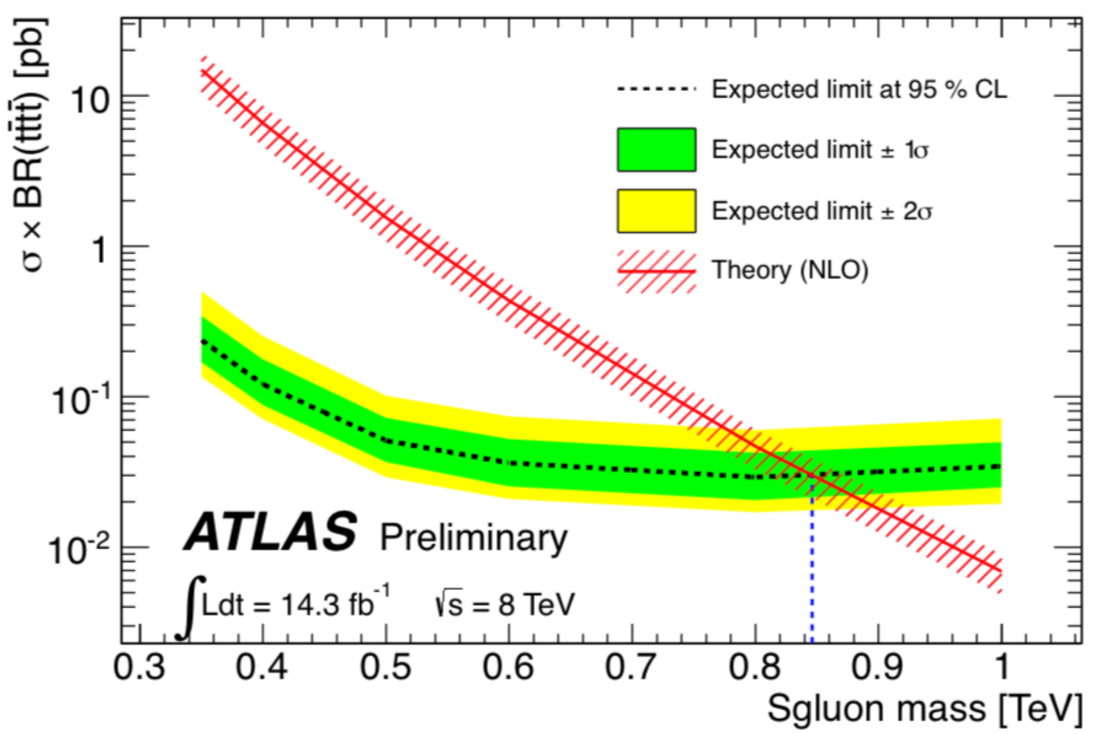
- cross-sections summary @14 TeV LHC

@14 TeV	$t\bar{t}t\bar{t}$	$t\bar{t}W^{\pm}$	$t\bar{t}Z$	1TeV sgluons
$\sigma \cdot br(fb)$	0.3	6+3	6	2.5

- result of our analysis: for 1 TeV sgluons and 300/fb we expect $S/\sqrt{B+1} > 5$

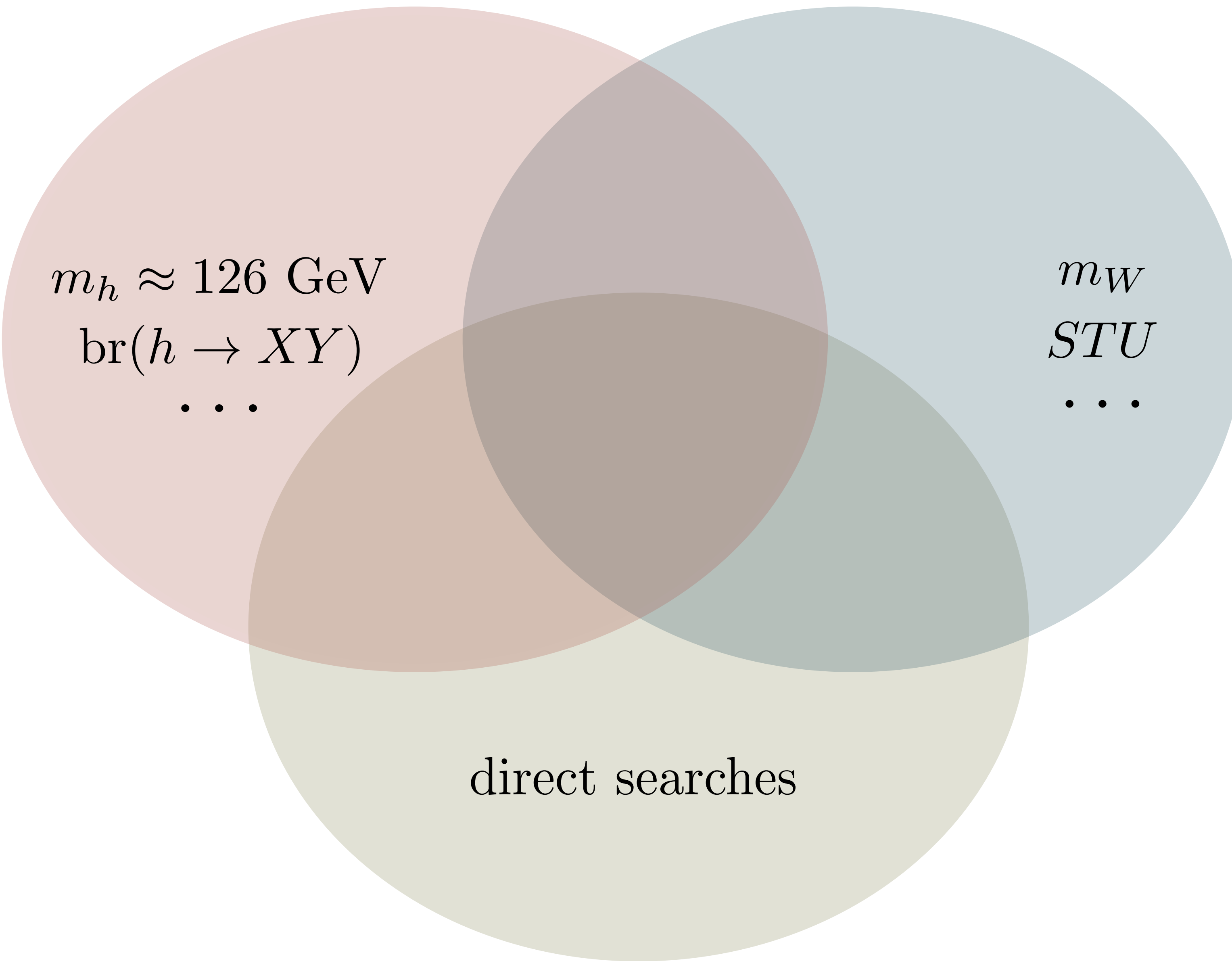
Kalinowski, Kalinowski, Kotlarski (2013)

- the same game was played for 8 TeV showing similar sensitivity as the ATLAS analysis



Electroweak sector

Can MRSSM accommodate both the Higgs and EWPO?



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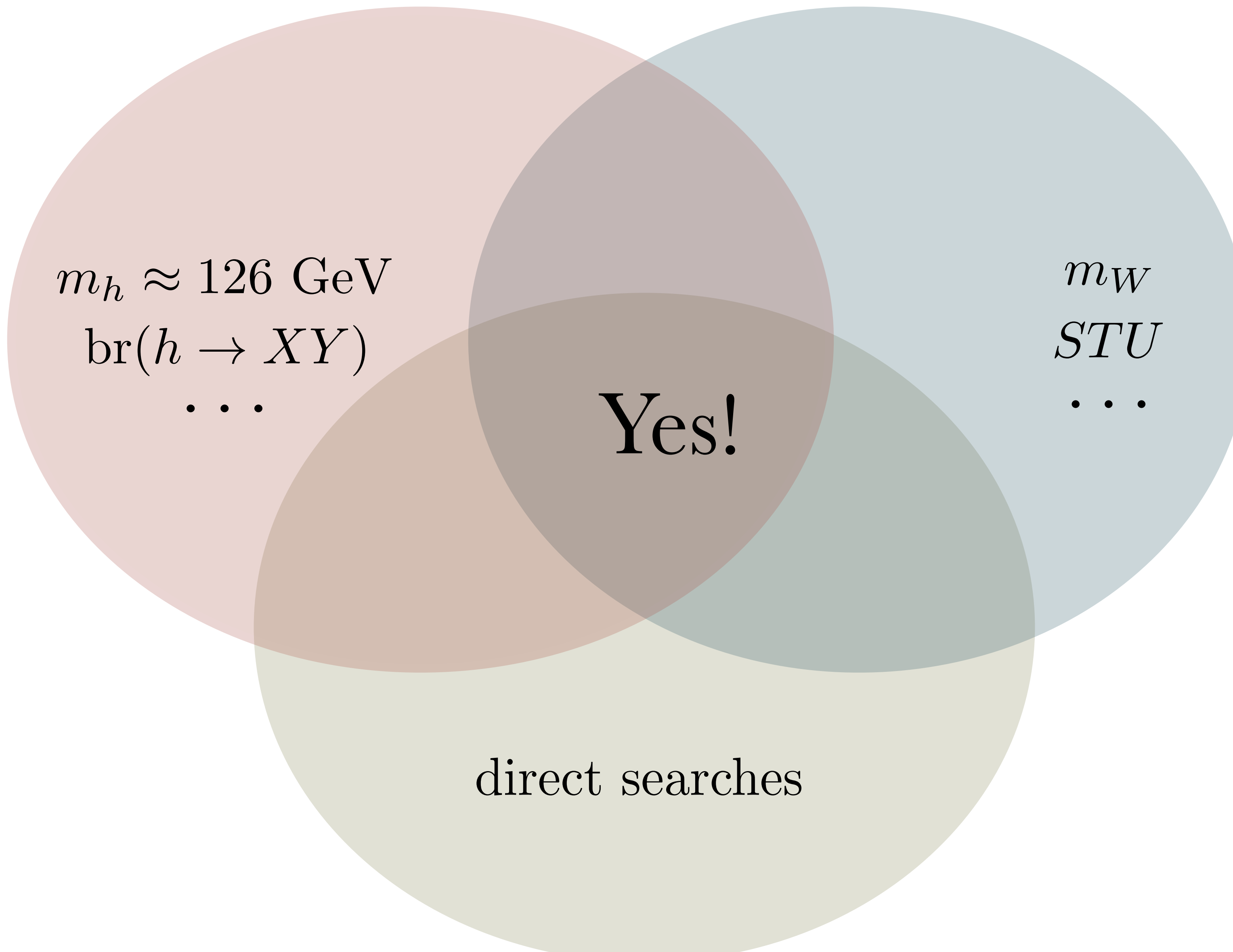


- We provide 3 typical benchmark points with $\tan\beta = 3, 10, 40$

Scalar Higgs sector and tree-level analysis

- 4 scalar degrees of freedom $\{h_d, h_u, \Re(S), \Re(T^0)\}$ mix to form 4 physical Higgs bosons

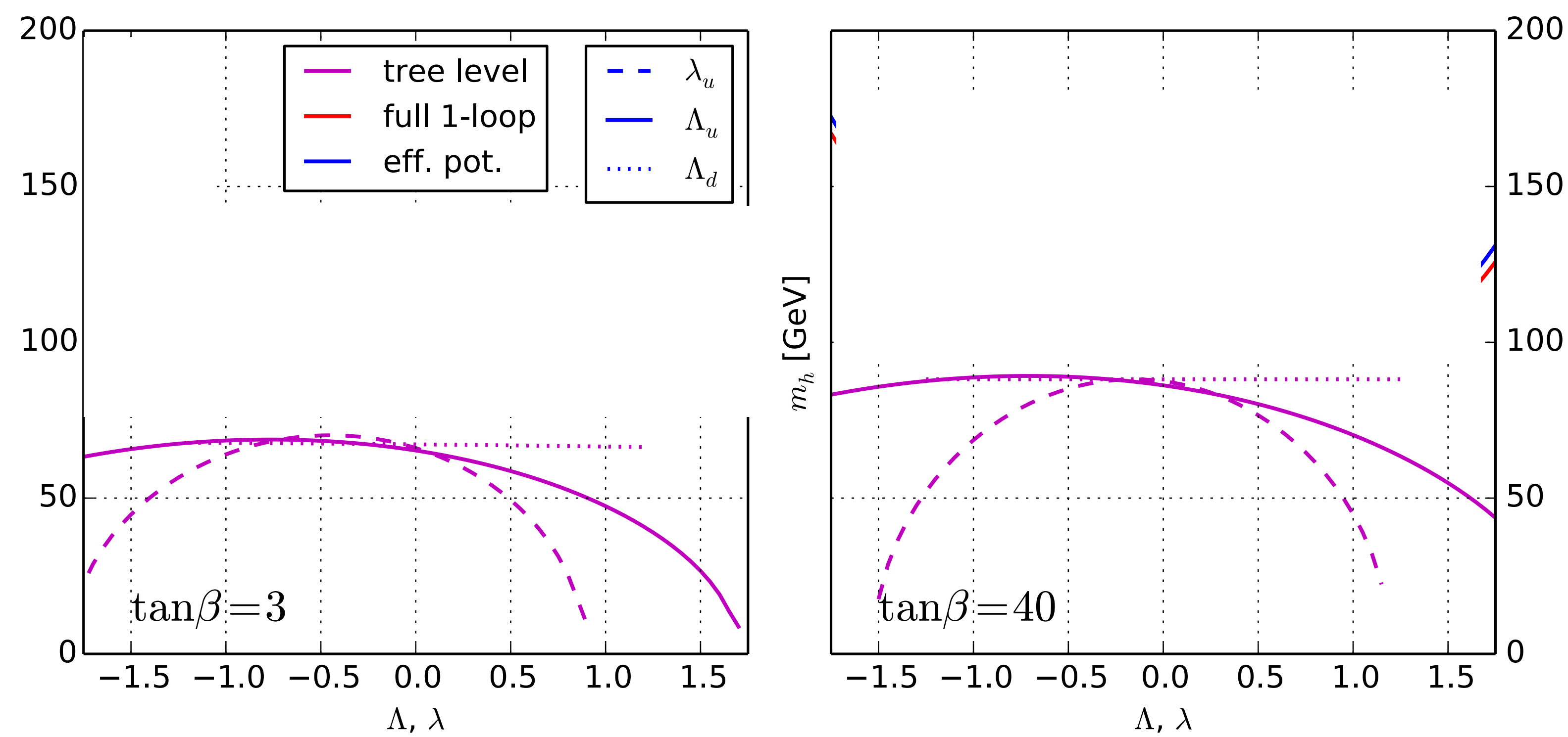
- Approximate formula for the lightest Higgs mass at the tree level

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

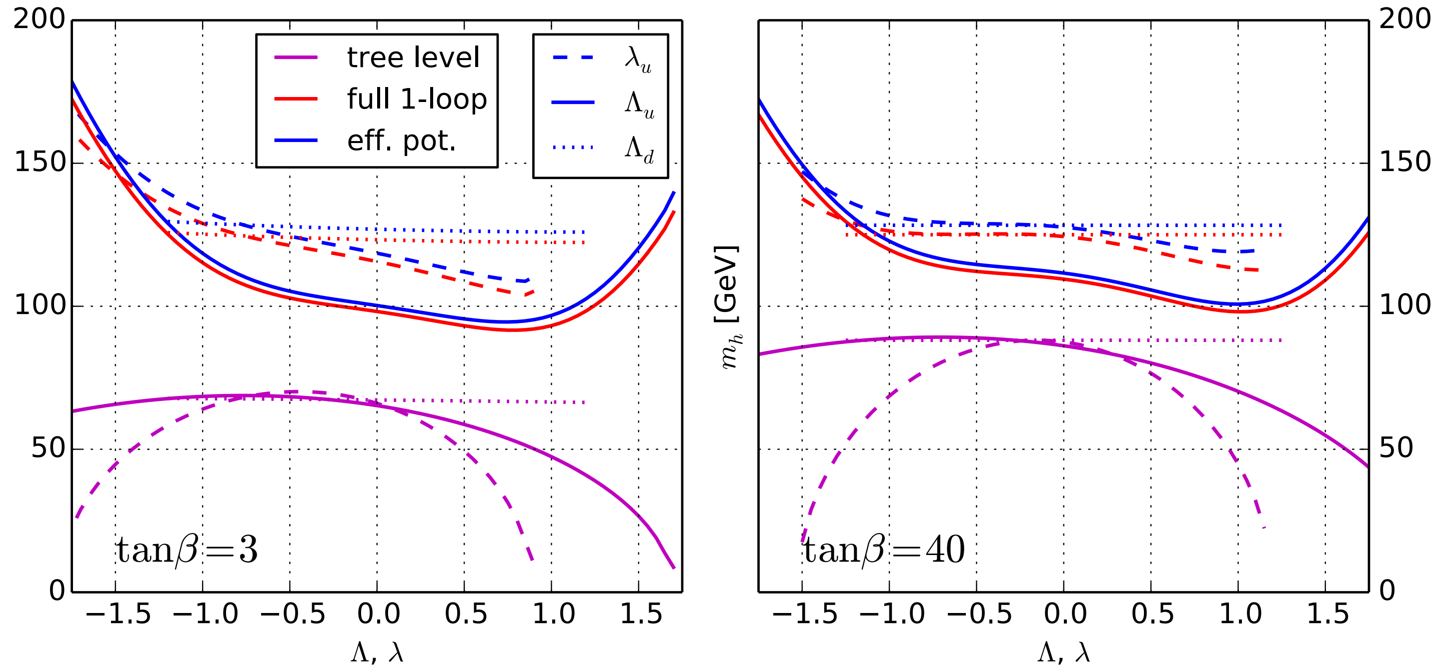
under simplifying assumptions: large m_A^2, $\lambda = \lambda_u = -\lambda_d \quad \Lambda = \Lambda_u = \Lambda_d$

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

- Tree-level mass of the lightest state always **lower** than in the MSSM due to the mixing with S and 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
- 0.5 TeV stops would work also fine
- effective potential approximation gives higher value

m_W calculation setup

- MRSSM contains a Y=0 Higgs triplet giving tree level contribution to m_W

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

- 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)

- Introduce quantity $\hat{\rho} = \frac{m_W^2}{m_Z^2 \hat{c}_W^2}$, which at tree-level equals $\hat{\rho}_0 = 1 + \frac{4v_T^2}{v^2}$

- Express muon decay constant at tree level as

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

m_W master formula at one-loop

- m_W measured with high precision $m_W = 80.385 \pm 0.015$ GeV

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

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

- solve for m_W

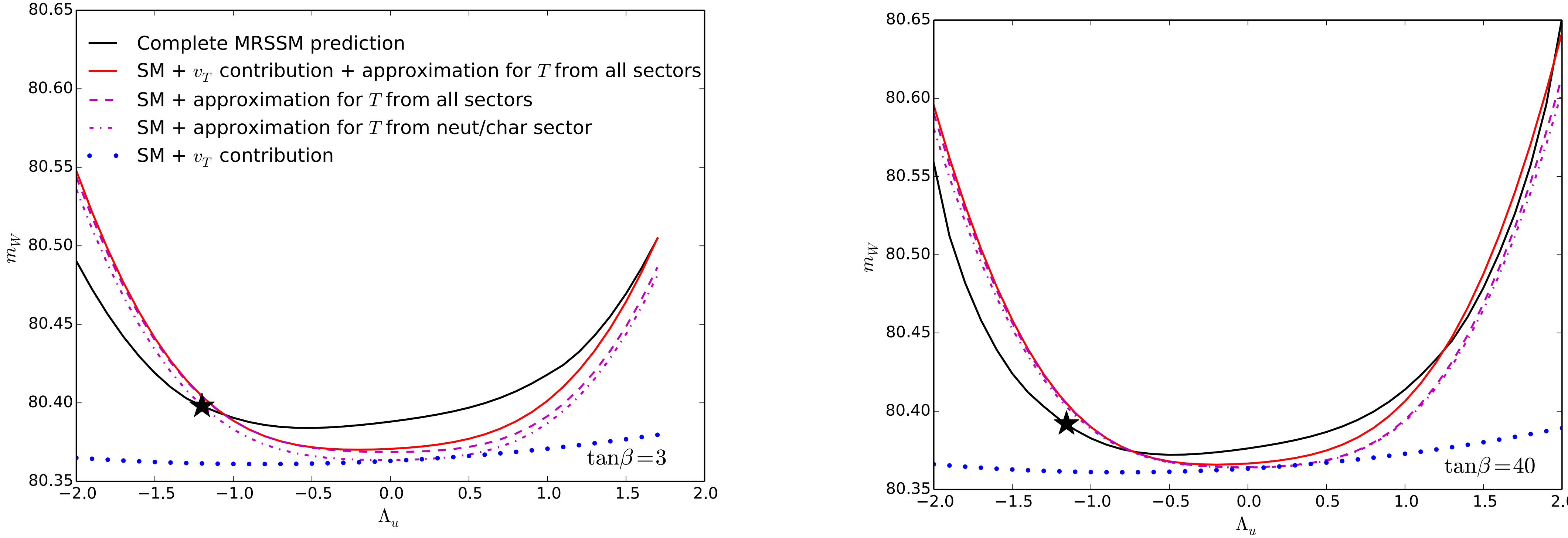
$$m_W^2 = \frac{1}{2}m_Z^2\hat{\rho}\left[1+\sqrt{1-\frac{4\pi\hat{\alpha}}{\sqrt{2}G_\mu m_Z^2\hat{\rho}(1-\Delta\hat{r}_W)}}\right]$$

master formula of Degrassi, Fanchiotti, Sirlin (1990)

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

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

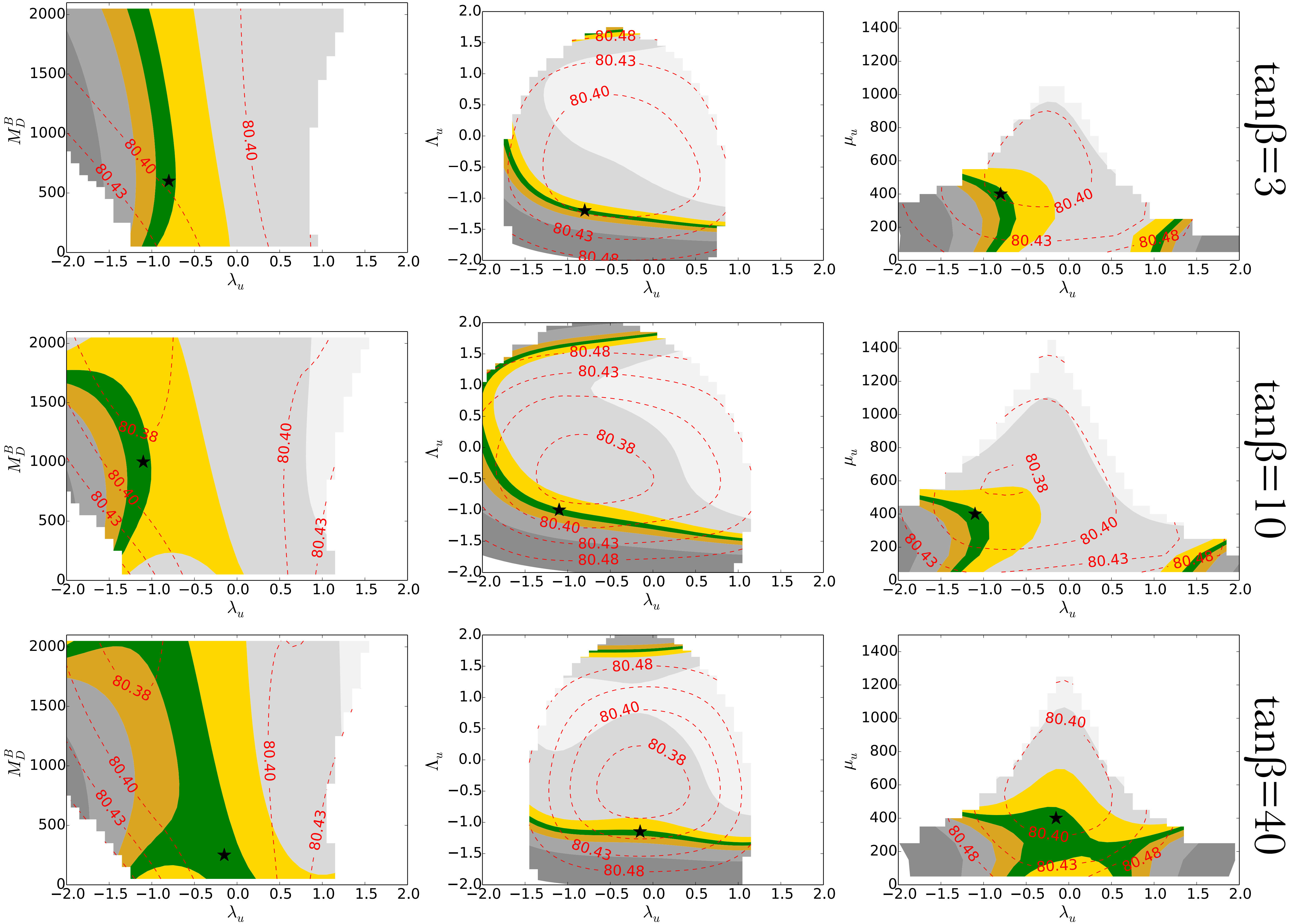
- additional benefit: STU give also a handle on observables other than mW

- for out 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

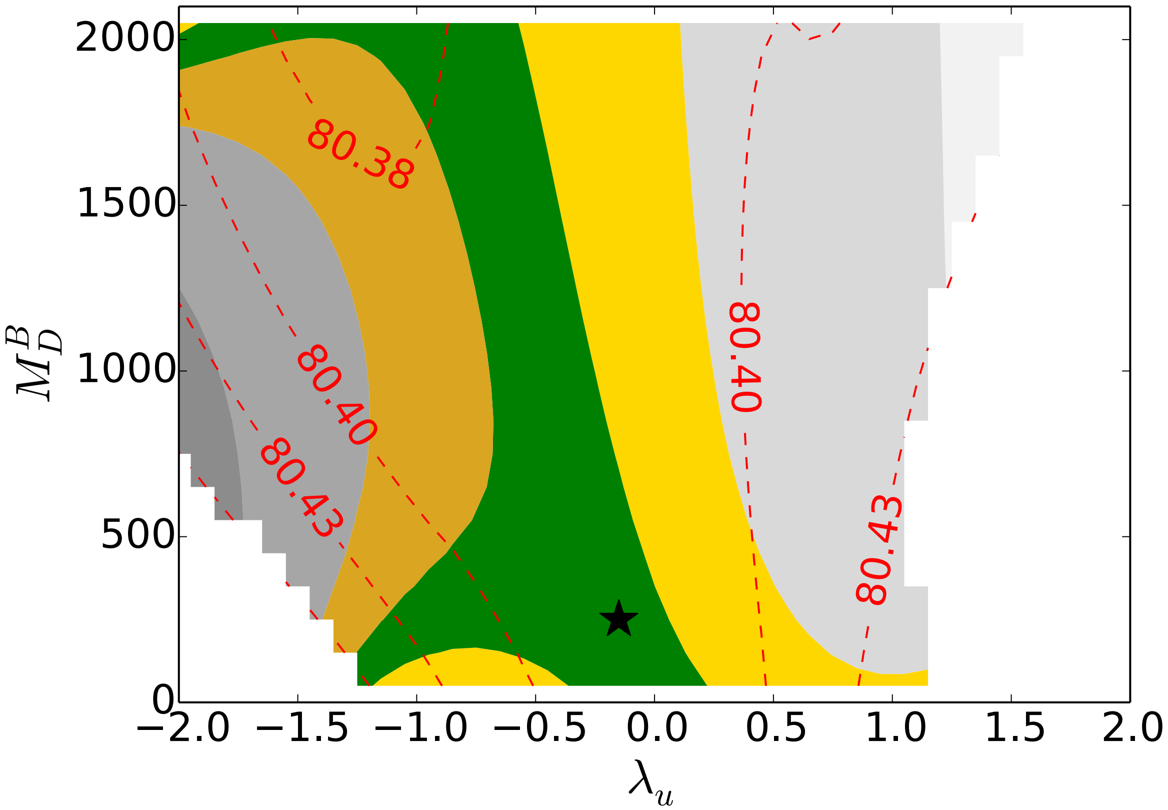
Properties of benchmark points

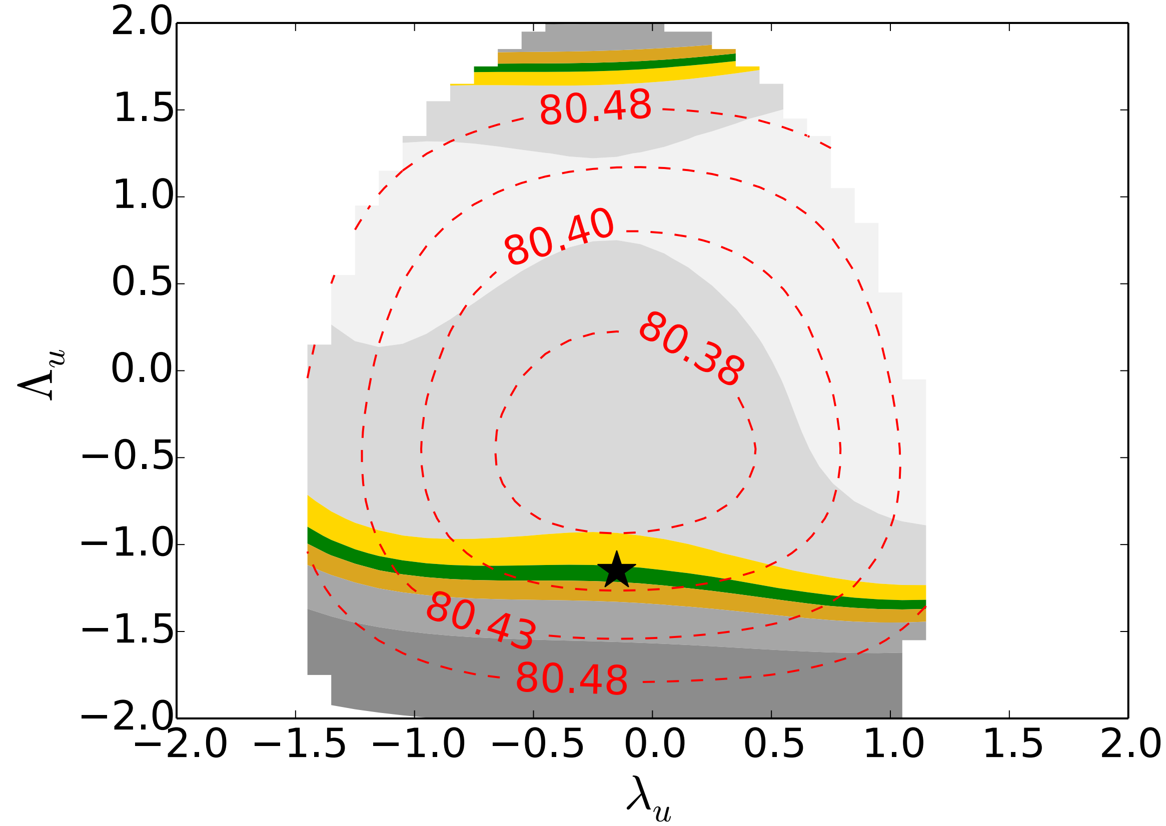
- 3 distinct parameter points with $\tan\beta = 3, 10, 40$
- W mass within 1σ from measured value $m_W^{\text{exp}} = 80.385 \pm 0.015$ GeV
- lightest Higgs mass around 125 GeV
- Higgs sectors in agreement with direct measurements and exclusion limits **HiggsBounds** and **HiggsSignals**
- due to the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



tanβ=3
tanβ=10
tanβ=40
M_D^B
Λ_u
μ_u
λ_u
80.38
80.40
80.43
80.48

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

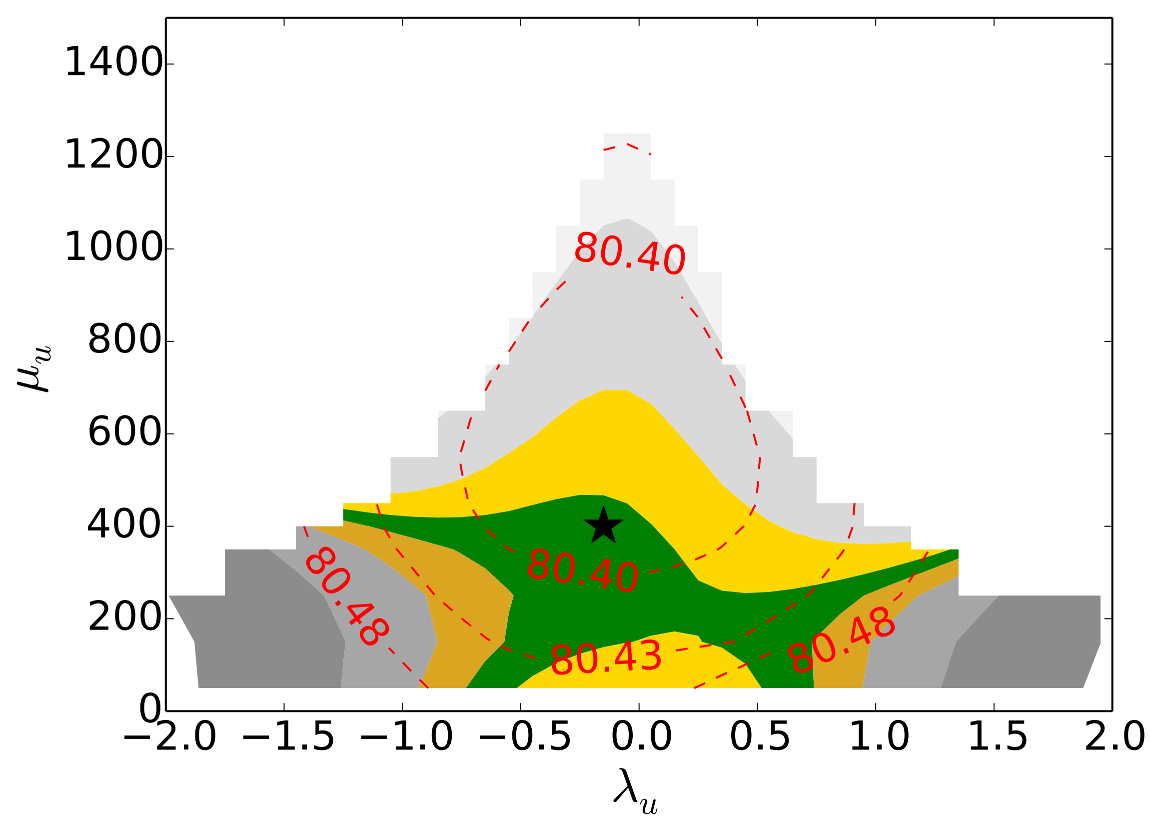




- contours for m_W
- colour gradient for m_h
- ✗ for benchmark point

$m_h = 126 \pm 2$ GeV

$m_h = 126 \pm 8$ GeV



Conclusions and outlook

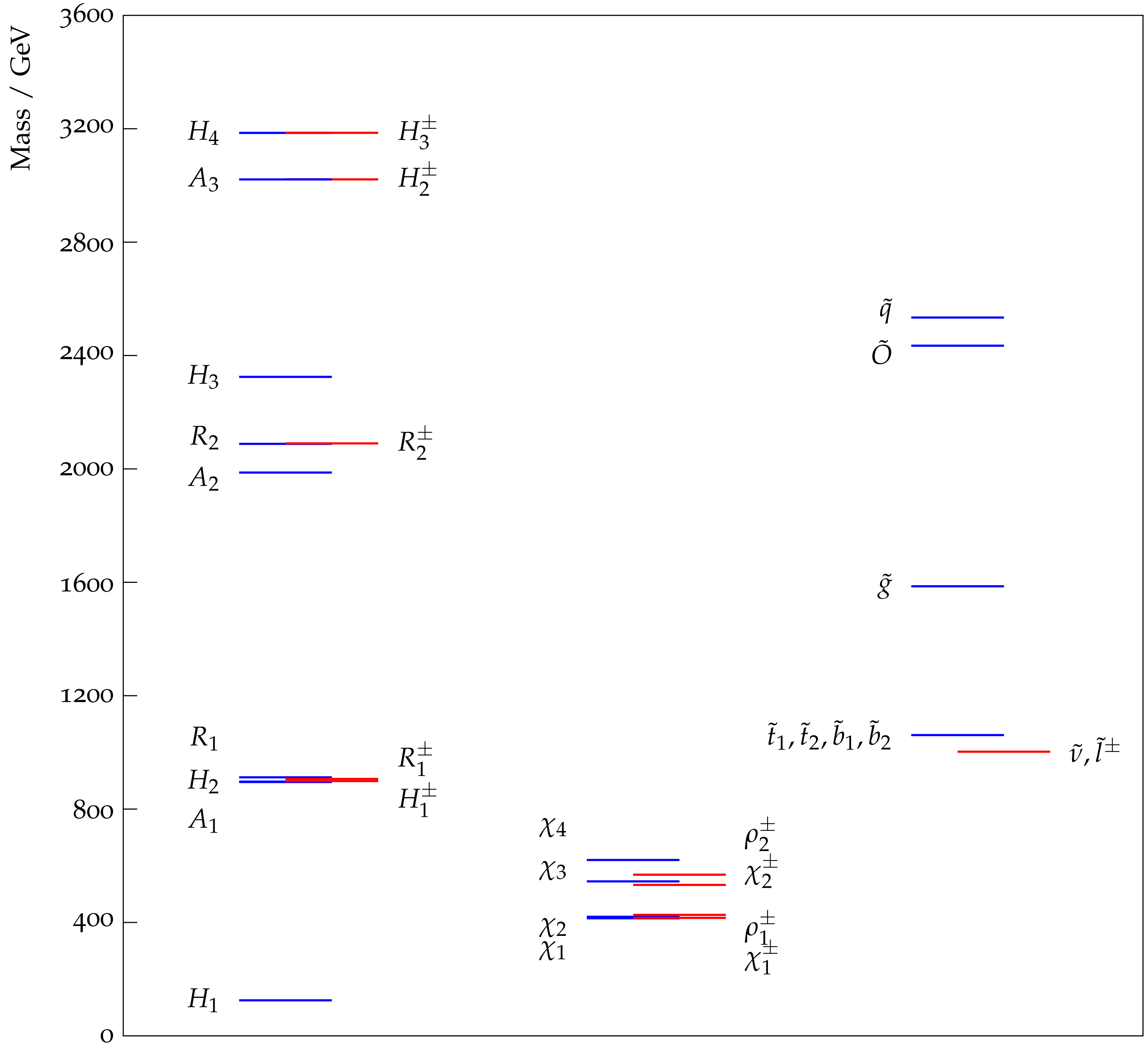
- We took the low energy model without discussing its UV completion
- Viable realisation of R-symmetric SUSY
  - ✓ ~125 GeV lightest Higgs mass
  - ✓ agreement with PEWO and flavour-physics
  - ✓ stable vacuum
  - ✓ LHC „friendly” particle spectra
- Still a lot to do
  - ☐ broader exploration of parameter space
  - ☐ consequences for 14 TeV LHC
  - ☐ dedicated study of Dark matter

Back-up slides

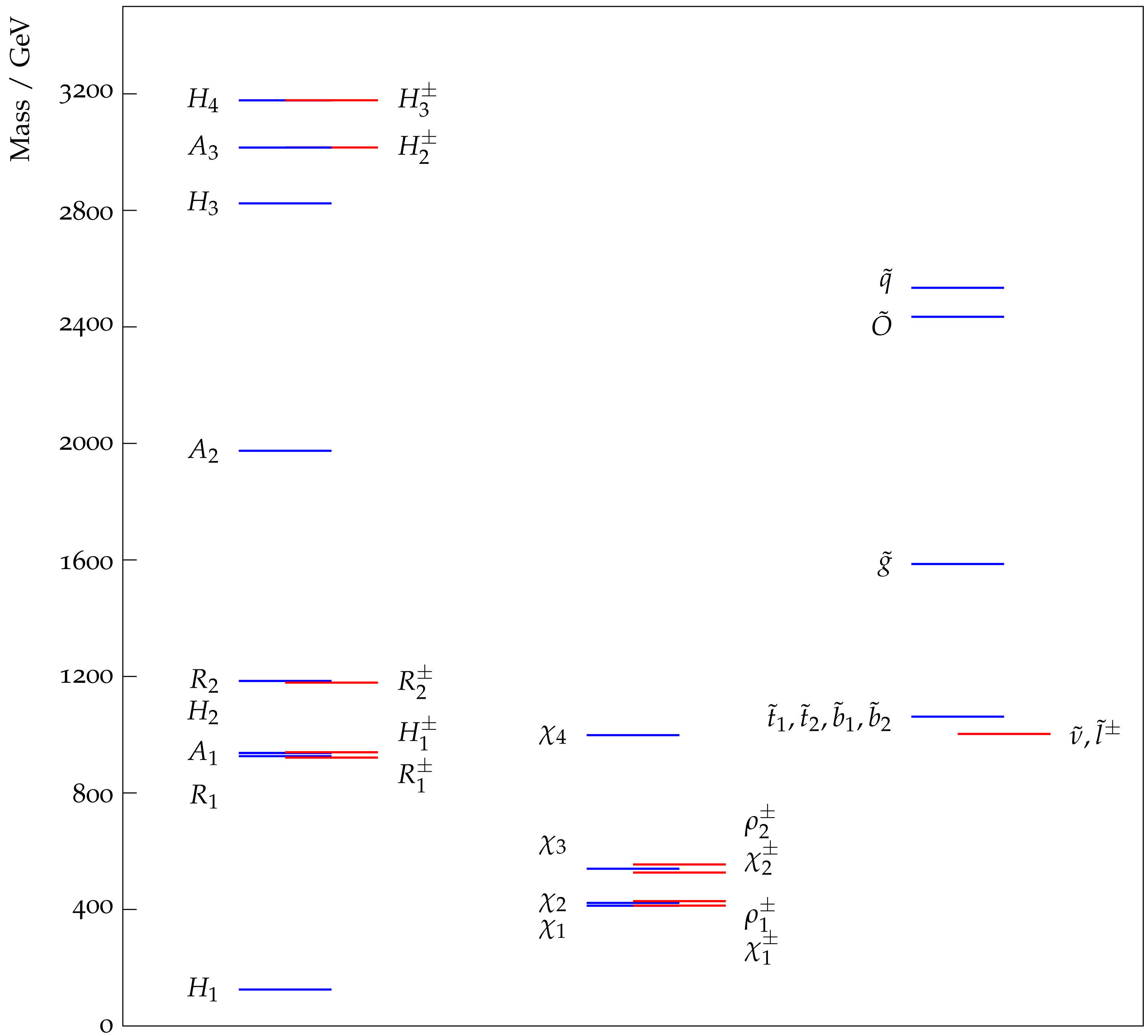
Benchmark points

	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

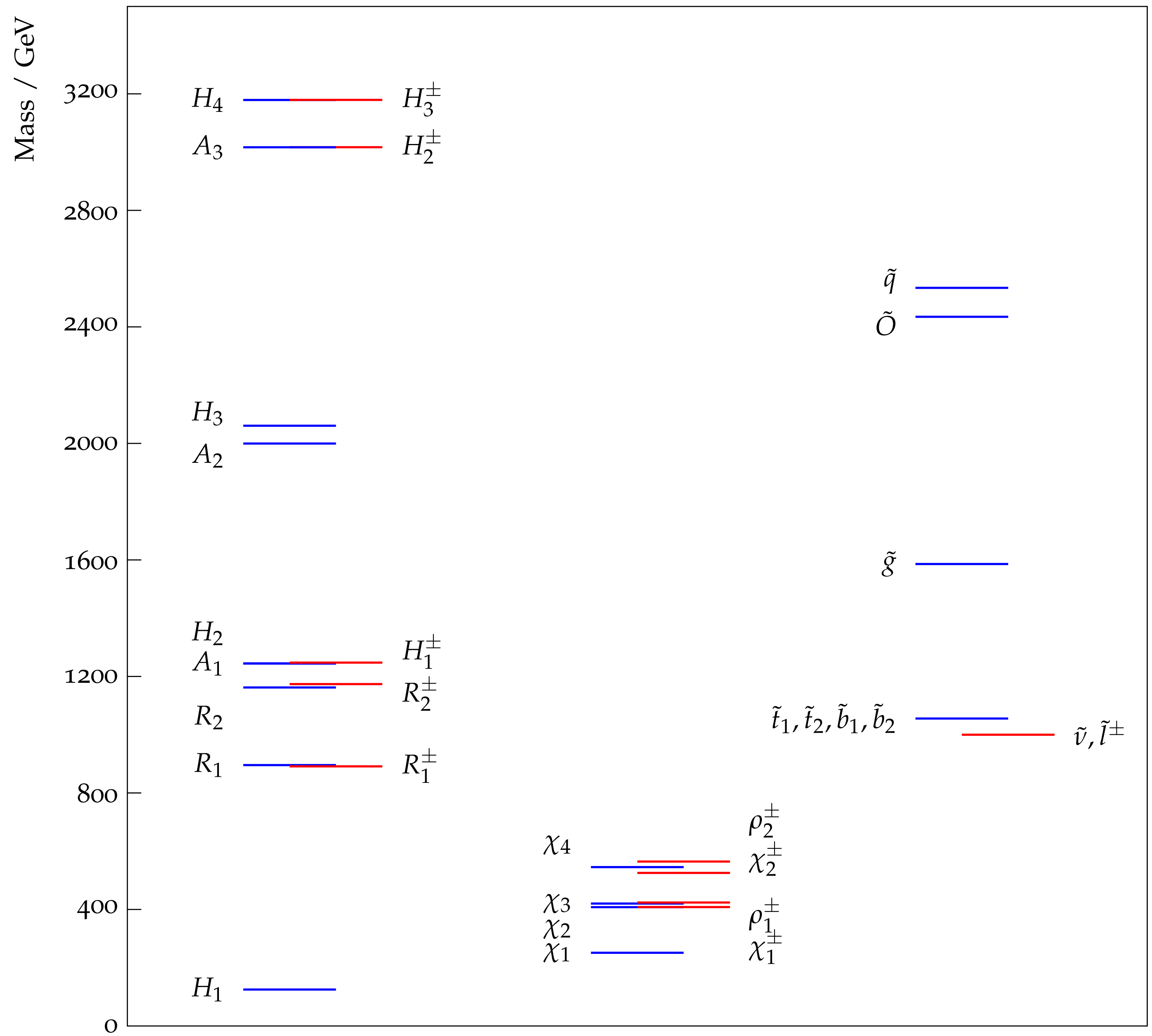
Particle spectrum for tan β = 3



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**

Effective potential approximation

- Serious problem — effective potential **is gauge dependent**
- Potential is gauge independent at the critical point (Nielsen's identity)
- Other quantities are not

Summary

		ξ-ind?		
$\mathcal{E}$	vacuum energy	✔	$\langle\Omega\|\hat{H}\|\Omega\rangle$	
δv	correction to VEV	✗	$\langle\Omega\|\hat{\Phi}\|\Omega\rangle$	matrix elements of non-gauge-invariant operators are not expected to be gauge-independent.
m_H^2	"Higgs mass" -square	✗	exact definition: $p^2 - m_r^2 - \Sigma(p^2)\big\|_{m^2_{\text{pole}}} = 0$	$\partial^2 V/\partial h^2$ is approximating $\Sigma(0)$, not m^2_{pole}. Further, $\Sigma(0)$ is gauge-dependent, and singular when $\xi = 0$.

Gauge-independent only following $\hbar$ -expansion.

Matches Feynman pert. th. only following $\hbar$-expansion.

Theoretical **abomination**.
Never use.

Hiren Patel, MPI-K Particle and Astroparticle Seminar (27.01.2014)

$SU(3)$ β function

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

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