Higgs Precision Requirements

Heidi Rzehak

Albert-Ludwigs-Universität Freiburg

28th January 2015

Higgs precision requirements?

Several aspects:

- Experimental requirements (detectors, . . .)?
- Expected size of deviations?
- Theoretical requirements (precision predicitions, . . .)?

Expectations?

Based on assumptions e.g.:

- No beyond Standard Model physics related to electroweak symmetry breaking at the LHC
- Different Standard Model extensions

Constraints:

⋆ Discovery potential of the LHC

⋆ Electroweak precision tests

Expected maximal deviations

With assumptions from before:

	$\|\Delta hVV\|$	$\|\Delta h\bar{t}t\|$	$\|\Delta h\bar{b}b\|$	$\|\Delta hhh\|$
Mixed-in Singlet	6%	6%	6%	18%
Composite Higgs	8%	tens of %	tens of %	tens of %
MSSM	$< 1\%$	3%	10%, 100%	2%, 15%

(first values) $\tan\beta > 20$ no superpartners; (second values) all other cases

[Gupta, H.R., Wells, arXiv:1206.3560, arXiv:1305.6397]

Expected maximal deviations

Mixed-in Singlet = Standard Model (SM) + exotic Higgs boson singlet:

Higgs fields mix via operator $|H_{SM}|^2|S|^2$ [Schabinger, Wells, hep-ph/0509209; Bowen, Cui, Wells, hep-ph/0701035]

$\Rightarrow$ 2 CP-even mass eigenstates h, H
with couplings^2 to other particles

$$g_h^2 = \cos^2\theta_h \, g_{SM}^2 \qquad \theta_h = \text{mixing angle}$$
$$g_H^2 = \sin^2\theta_h \, g_{SM}^2$$

All couplings to other particles scaled with the same factor.

Expected maximal deviations

With assumptions from before:

	$\lvert\Delta hVV\rvert$	$\lvert\Delta h\bar{t}t\rvert$	$\lvert\Delta h\bar{b}b\rvert$	$\lvert\Delta hhh\rvert$
Mixed-in Singlet	6%	6%	6%	18%
Composite Higgs	8%	tens of %	tens of %	tens of %
MSSM	$< 1\%$	3%	10%, 100%	2%, 15%

(first values: $\tan\beta > 20$, no superpartners; second values: all other cases)

[Gupta, H.R., Wells, arXiv:1206.3560, arXiv:1305.6397]

Expected maximal deviations

Model where the SM Higgs like particle is a pseudo-Goldstone:

SM vector bosons and fermions + strong sector with Higgs multiplet

in terms of an effective field theory

for a strong interacting light Higgs (SILH) boson [Guidice, Grojean, Pomarol, Rattazzi, hep-ph/0703164]

Lagrangian:

$$\mathcal{L}_{\text{SILH}} = \left(\frac{c_y y_f}{f^2} H_{SM}^\dagger H_{SM} \bar{f}_L H_{SM} f_R + \frac{c_S g g'}{4 m_\rho^2} (H_{SM}^\dagger \sigma_I H_{SM}) B_{\mu\nu} W^{I\mu\nu} + h.c. \right)$$
$$+ \frac{c_H}{2f^2} \partial^\mu (H_{SM}^\dagger H_{SM}) \partial_\mu (H_{SM}^\dagger H_{SM}) + \frac{c_6 \lambda}{f^2} (H_{SM}^\dagger H_{SM})^3 + \ldots$$

New parameters: c_H, c_y, c_S, c_6:

Naive Dimensional Analysis: $\mathcal{O}(1)$ numbers

Expected maximal deviations

With assumptions from before:

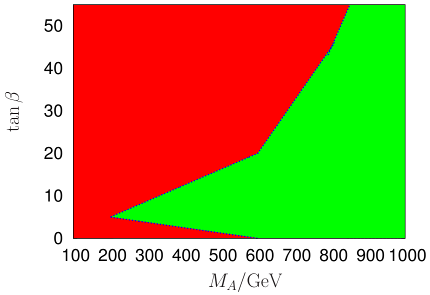
	$\lvert\Delta hVV\rvert$	$\lvert\Delta h\bar{t}t\rvert$	$\lvert\Delta h\bar{b}b\rvert$	$\lvert\Delta hhh\rvert$
Mixed-in Singlet	6%	6%	6%	18%
Composite Higgs	8%	tens of %	tens of %	tens of %
MSSM	$< 1\%$	3%	10%, 100%	2%, 15%

$\tan\beta > 20$ no superpartners (first values: 10%, 2%); all other cases (second values: 100%, 15%)

[Gupta, H.R., Wells, arXiv:1206.3560, arXiv:1305.6397]

Expected maximal deviations

h, H, A, $H^{\pm}$
discovery potential
for $\sqrt{s} = 14$ TeV, $L = 300$ fb^{-1}
(modeled after figure of
[CLIC Conceptual Design Report (2012);
ATLAS collaboration, CERN-LHCC-99-15])



red region: Several of h, H, A, $H^{\pm}$ can be discovered

green region: Only a single one, h, can be discovered

$\tan\beta$ = ratio of the Higgs vacuum expectation values
M_A = mass of the CP-odd Higgs boson

Expected maximal deviations

With assumptions from before:

	$\lvert\Delta hVV\rvert$	$\lvert\Delta h\bar{t}t\rvert$	$\lvert\Delta h\bar{b}b\rvert$	$\lvert\Delta hhh\rvert$
Mixed-in Singlet	6%	6%	6%	18%
Composite Higgs	8%	tens of %	tens of %	tens of %
MSSM	$< 1\%$	3%	10%, 100%	2%, 15%

tan $\beta > 20$
no superpartners

all other
cases

[Gupta, H.R., Wells, arXiv:1206.3560, arXiv:1305.6397]

Expected maximal deviations

Important:

For the triple Higgs coupling deviations in the MSSM:

Use same approximation for: Higgs mass and triple coupling

Standard Model coupling depends on the Higgs mass value,

for meaningful comparison, the same precision is needed.

Precision of Standard Model Higgs couplings

Is our knowledge of the Standard Model couplings precise enough?

Uncertainties:

- Missing higher-order corrections
- Uncertainties of input parameters

Higgs decay widths in the Standard Model ($M_H = 126$ GeV)

Channel	Γ [MeV]	$\Delta\alpha_s$	Δm_b	Δm_c	Δm_t	THU
$H \to b\bar{b}$	2.36	-2.3% $+2.3\%$	$+3.3\%$ -3.2%	$+0.0\%$ -0.0%	$+0.0\%$ -0.0%	$+2.0\%$ -2.0%
$H \to \tau^+\tau^-$	$2.59 \cdot 10^{-1}$	$+0.0\%$ -0.0%	$+0.0\%$ -0.0%	$+0.0\%$ -0.0%	$+0.1\%$ -0.1%	$+2.0\%$ -2.0%
$H \to \mu^+\mu^-$	$8.99 \cdot 10^{-4}$	$+0.0\%$ -0.0%	$+0.0\%$ -0.0%	-0.1% -0.0%	$+0.0\%$ -0.1%	$+2.0\%$ -2.0%
$H \to c\bar{c}$	$1.19 \cdot 10^{-1}$	-7.1% $+7.0\%$	-0.1% $+0.1\%$	$+6.2\%$ -6.1%	$+0.0\%$ -0.1%	$+2.0\%$ -2.0%
$H \to gg$	$3.57 \cdot 10^{-1}$	$+4.2\%$ -4.1%	-0.1% $+0.1\%$	$+0.0\%$ -0.0%	-0.2% $+0.2\%$	$+3.0\%$ -3.0%
$H \to \gamma\gamma$	$9.59 \cdot 10^{-3}$	$+0.0\%$ -0.0%	$+0.0\%$ -0.0%	$+0.0\%$ -0.0%	$+0.0\%$ -0.0%	$+1.0\%$ -1.0%
$H \to Z\gamma$	$6.84 \cdot 10^{-3}$	$+0.0\%$ -0.0%	$+0.0\%$ -0.0%	$+0.0\%$ -0.1%	$+0.0\%$ -0.1%	$+5.0\%$ -5.0%
$H \to WW$	$9.73 \cdot 10^{-1}$	$+0.0\%$ -0.0%	$+0.0\%$ -0.0%	$+0.0\%$ -0.0%	$+0.0\%$ -0.0%	$+0.5\%$ -0.5%
$H \to ZZ$	$1.22 \cdot 10^{-1}$	$+0.0\%$ -0.0%	$+0.0\%$ -0.0%	$+0.0\%$ -0.0%	$+0.0\%$ -0.0%	$+0.5\%$ -0.5%

[LHC Higgs Cross Section Working Group Collaboration, arXiv:1307.1347]

Higgs decay widths in the Standard Model ($M_H = 126$ GeV)

Calculation performed using

- HDecay [Djouadi, Kalinowski, Mühlleitner, Spira, hep-ph/9704448, arXiv:1003.1643]

- Prophecy4f for $H \to WW, ZZ \to 4$ fermions [Bredenstein, Denner, Dittmaier, Weber, hep-ph/0604011, 0611234]

Parametric uncertainties:

$$\Delta_+^p \Gamma = \max\{\Gamma(p+\Delta p), \Gamma(p), \Gamma(p-\Delta p)\} - \Gamma(p)$$
$$\Delta_-^p \Gamma = \Gamma(p) - \min\{\Gamma(p+\Delta p), \Gamma(p), \Gamma(p-\Delta p)\}$$

Theoretical uncertainties (THU) estimations based on:

- scale variation by factor of $2^{\pm 1}$ for QCD corrections

Higgs decay widths in the Standard Model ($M_H = 126$ GeV)

Included corrections:

- $\mathrm{H} \to \mathrm{b\bar{b}}, \mathrm{c\bar{c}}$:
  - ⋆ massless QCD up to $\mathrm{N^4LO}$ [Baikov, Chetyrkin, Kühn, hep-ph/0511063; . . .]
  - ⋆ approximation of electroweak corrections [Djouadi, Hollik 92; Kniehl 92; Djouadi, Haidt, Kniehl, Zerwas, Mele, 91; . . .]
- $\mathrm{H} \to \tau^+\tau^-, \mu^+\mu^-$: approximation of electroweak corrections (as above)
- $\mathrm{H} \to gg$:
  - ⋆ up to $\mathrm{N^3LO}$ in heavy top mass limit [Spira, Djouadi, Graudenz, Zerwas, hep-ph/9504378; Chetyrkin, Kniehl, Steinhauser, hep-ph/9705240; Baikov, Chetyrkin, hep-ph/0604194; . . .]
  - ⋆ grid for electroweak corrections [Actis, Passarino, Sturm, Uccirati, arXiv:0809.3667; arXiv:0809.1301]

Higgs decay widths in the Standard Model ($M_H = 126$ GeV)

- $\mathrm{H} \to \gamma\gamma$:
  - ⋆ full NLO QCD corrections [Dawson, Kauffman, 93; Djouadi, Spira, Zerwas, hep-ph/9305335; Melnikov, Yakovlev, hep-ph/9302281; Inoue, Najima, Oka, Saito, 94; . . .]
  - ⋆ grid for electroweak corrections [Actis, Passarino, Sturm, Uccirati, arXiv:0809.3667; arXiv:0809.1301]
- $\mathrm{H} \to \mathrm{Z}\gamma$: LO virtual W, top, bottom, τ loop contributions
- $\mathrm{H} \to \mathrm{ZZ}, \mathrm{WW} \to 4$ fermions:
  - ⋆ NLO QCD + NLO electroweak [Bredenstein, Denner, Dittmaier, Weber, hep-ph/0604011, 0611234]

For complete list of references,
see [LHC Higgs Cross Section Working Group Collaboration, arXiv:1201.3084]

Further parametric uncertainties

Similar analysis: Almeida, Lee, Pokorski, Wells, arXiv:1311.6721

Consideration of additional parametric uncertainties:

- Higgs mass
- $\alpha(M_Z)$
- Z boson mass
- τ lepton mass
- Fermi constant G_F

For $\mathrm{H} \to \mathrm{ZZ}, \mathrm{WW}, \mathrm{Z}\gamma$:

Higgs mass uncertainties are especially important

With all uncertainties:

Branching ratios theoretically determined only at a few percent level

To pessimistic for the future?

Further analysis: [Lepage, Mackenzie, Peskin, arXiv:1404.0319]

- Better precision:
  Use $\overline{\text{MS}}$ mass instead of the bottom/charm pole mass
- For projections into the future:
  take into account improvements from lattice QCD

Their conclusions:

⋆ Precision already below percent level

⋆ Will improve

Precision in extensions of the Standard Model

Many higher-order corrections are already known e.g. in the MSSM

Ongoing effort to improve the precision in other models:

- Two-Higgs doublet models, (N)MSSM, ...
- Effective theories

$\Rightarrow$ Uncertainties due to missing higher-order corrections will reduce.

$\Rightarrow$ Parametric uncertainties? (need input)

Conclusion

- Deviations of the Standard Model couplings might be at percent level.
- Theoretical precision of Standard Model couplings is at a similar level or below.
- Current and future work will improve the situation.

⇒ Precise measurement of Higgs couplings will be useful.

Higgs couplings in a mixed-in Singlet Model

Standard Model (SM) + exotic Higgs boson singlet:

Higgs fields mix via operator $|H_{SM}|^2 |S|^2$

[Schabinger, Wells, hep-ph/0509209; Bowen, Cui, Wells, hep-ph/0701035]

$\Rightarrow$ 2 CP-even mass eigenstates h, H

with couplings^2

$$g_h^2 = c_h^2 \, g_{SM}^2 \qquad c_h = \cos\theta_h \qquad \theta_h = \text{mixing angle}$$

$$g_H^2 = s_h^2 \, g_{SM}^2 \qquad s_h = \sin\theta_h$$

Here: h the SM like one

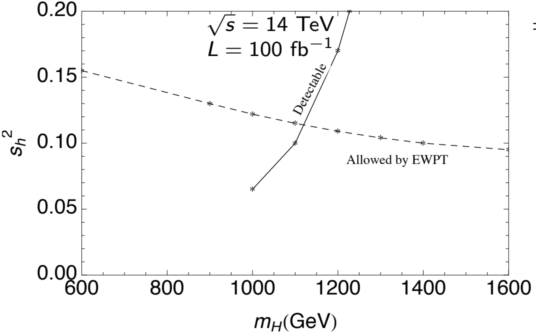
H the heavier Higgs boson – detectable at the LHC

if light enough

Higgs couplings in a mixed-in Singlet Model

[Gupta, H.R., Wells, arXiv:1206.3560]

Region of possible LHC detection of the heavy Higgs boson and region allowed by electroweak precision tests in the s_h^2-m_H plane:



$\Rightarrow$ max. deviation of Higgs couplings to other particles:

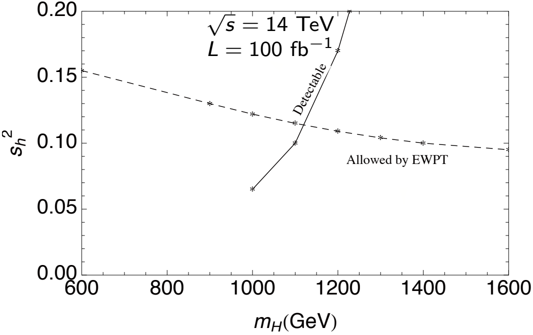
$$\frac{\Delta g_h}{g_{SM}} \approx -\frac{s_h^2}{2} \approx -6\%$$

detectability region based on: [Bowen, Cui, Wells, hep-ph/0701035; Iordanidis, Zeppenfeld, hep-ph/9709506]

Higgs couplings in a mixed-in Singlet Model

[Gupta, H.R., Wells, arXiv:1305.6397]

Region of possible LHC detection of the heavy Higgs boson and region allowed by electroweak precision tests in the s_h^2-m_H plane:



$\Rightarrow$ max. deviation of the triple Higgs coupling:

$$\frac{\Delta g_{hhh}}{g_{hhh}^{SM}} = (c_h^3 - 1) - s_h^3 \frac{v}{v'}$$

$$\approx -18\%$$

detectability region based on: [Bowen, Cui, Wells, hep-ph/0701035; Iordanidis, Zeppenfeld, hep-ph/9709506]

Higgs couplings in Composite Higgs Models

Model where the SM Higgs like particle is a pseudo-Goldstone:

SM vector bosons and fermions + strong sector with Higgs multiplet

in terms of an effective field theory

for a strong interacting light Higgs (SILH) boson

[Guidice, Grojean, Pomarol, Rattazzi, hep-ph/0703164]

two independent parameters: mass of new resonance m_ρ

decay constant f with $m_\rho = g_\rho f$

g_ρ = coupling of the new resonance

Lagrangian:

$$\mathcal{L}_{\mathrm{SILH}} = \left(\frac{c_y y_f}{f^2} H_{SM}^\dagger H_{SM} \bar{f}_L H_{SM} f_R + \frac{c_S g g'}{4 m_\rho^2} (H_{SM}^\dagger \sigma_I H_{SM}) B_{\mu\nu} W^{I\mu\nu} + h.c. \right)$$

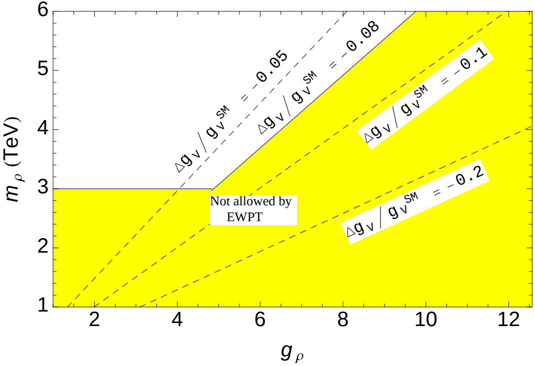
$$+ \frac{c_H}{2f^2} \partial^\mu (H_{SM}^\dagger H_{SM}) \partial_\mu (H_{SM}^\dagger H_{SM}) + \frac{c_6 \lambda}{f^2} (H_{SM}^\dagger H_{SM})^3 + \ldots$$

Naive Dimensional Analysis: c_H, c_y, c_S, c_6: $\mathcal{O}(1)$ numbers

Higgs couplings in Composite Higgs Models

[Gupta, H.R., Wells, arXiv:1206.3560]

region allowed by electroweak precision tests in the m_ρ-g_ρ plane:



max. deviation:

coupling to vector bosons:

$$\frac{\Delta g_V}{g_V^{SM}} = -\frac{c_H \xi}{2} + \dots$$
$$\approx -8\%$$

coupling to fermions:

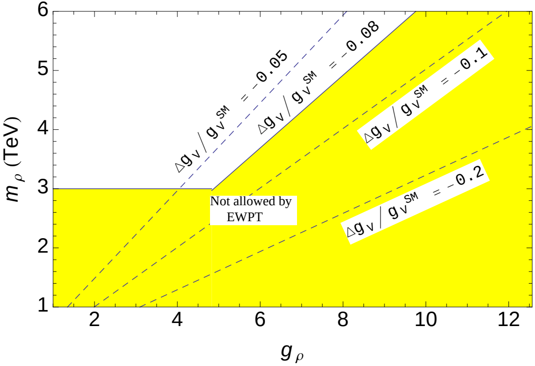
$$\frac{\Delta g_f}{g_f^{SM}} = -\frac{c_H \xi}{2} + c_y \xi + \dots$$
$$\approx -8\% - 15\% \frac{c_y}{c_H}$$

$\xi = \frac{v^2 g_\rho^2}{m_\rho^2}$, m_ρ and g_ρ mass and coupling of the new resonance

Higgs couplings in Composite Higgs Models

[Gupta, H.R., Wells, arXiv:1206.3560]

region allowed by electroweak precision tests in the m_ρ-g_ρ plane:



max. deviation:

coupling to gluons:

$$\frac{\Delta g_g}{g_g^{SM}} = -\frac{c_H \xi}{2} + c_y \xi + \ldots$$
$$\approx -8\% - 15\% \frac{c_y}{c_H}$$

coupling to photons:

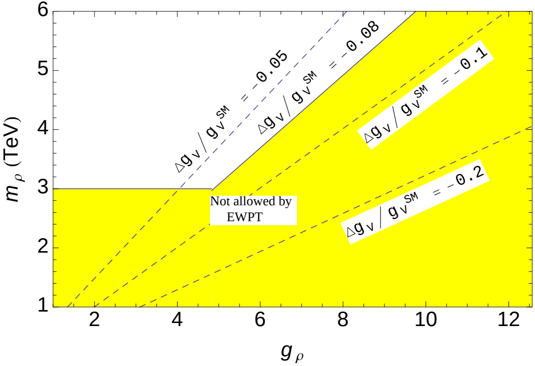
$$\frac{\Delta g_\gamma}{g_\gamma^{SM}} = -\frac{c_H \xi}{2} + 0.3 c_y \xi + \ldots$$
$$\approx -8\% - 5\% \frac{c_y}{c_H}$$

g_g^{SM}, g_γ^{SM}: loop-induced

Higgs couplings in Composite Higgs Models

[Gupta, H.R., Wells, arXiv:1305.6397]

region allowed by electroweak precision tests in the m_ρ-g_ρ plane:



max. deviation:

triple Higgs coupling:

$$\frac{\Delta g_{hhh}}{g_{hhh}^{\rm SM}} = -\frac{3}{2} c_H \xi + c_6 \xi + \ldots$$

$$\approx -23\% + 15\% \frac{c_6}{c_H}$$

Higgs couplings in the MSSM

MSSM Higgs potential: depends on gauge couplings

Particles to be fully identified or discovered:

- 2 CP-even h, H
- 1 CP-odd A
- 2 charged $H^\pm$

might be discovered at the LHC depending on parameters

- lots of superpartners

in our case: h is always the SM like Higgs boson

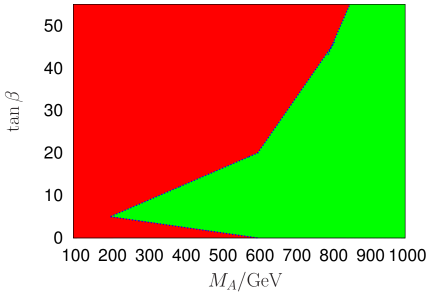
otherwise (i.e. $H =$ SM like Higgs boson):

h, A or $H^\pm$ should be discovered at the LHC

Higgs couplings in the MSSM

[Gupta, H.R., Wells, arXiv:1206.3560]

h, H, A, $H^{\pm}$
discovery potential
for $\sqrt{s} = 14$ TeV, $L = 300$ fb^{-1}
(modeled after figure of
[CLIC Conceptual Design Report (2012);
ATLAS collaboration, CERN-LHCC-99-15])



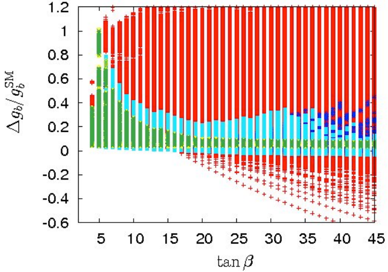
red region: Several of h, H, A, $H^{\pm}$ can be discovered

green region: Only a single one, h, can be discovered

$\tan\beta$ = ratio of the Higgs vacuum expectation values

Higgs couplings in the MSSM

[Gupta, H.R., Wells, arXiv:1206.3560]



Legend:

several h, H, A, $H^{\pm}$ discovered

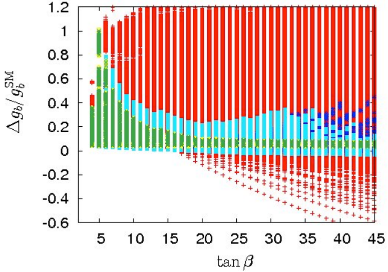
only h is discovered:

- exluded by $Br(b \to s\gamma)$
- also stop quarks lighter than a 1 TeV
- stops heavier 1 TeV, but not all heavier than 1.5 TeV
- stops heavier than 1.5 TeV

Scan done using FeynHiggs [Hahn, Heinemeyer, Hollik, H.R., Weiglein, Williams]

Higgs couplings in the MSSM

[Gupta, H.R., Wells, arXiv:1206.3560]



Legend:

several h, H, A, $H^{\pm}$ discovered

only h is discovered:

exluded by $Br(b \to s\gamma)$

also stop quarks lighter than a 1 TeV

stops heavier 1 TeV, but not all heavier than 1.5 TeV

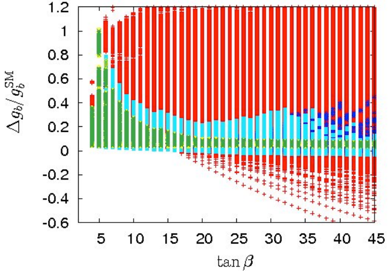
stops heavier than 1.5 TeV

- biggest deviation of the SM Higgs coupling to bottom quarks $\Delta g_b / g_b^{SM}$ with $\Delta g_b = g_b^{MSSM} - g_b^{SM}$ for $\tan\beta = 5$, up to a 100%.

  $M_A \gg M_Z$: $\frac{\Delta g_b}{g_b^{SM}} \propto \frac{M_Z^2}{M_A^2}$

Higgs couplings in the MSSM

[Gupta, H.R., Wells, arXiv:1206.3560]



Legend:

several h, H, A, $H^{\pm}$ discovered

only h is discovered:

exluded by $Br(b \to s\gamma)$

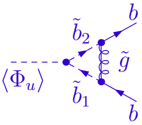
also stop quarks lighter than a 1 TeV

stops heavier 1 TeV, but not all heavier than 1.5 TeV

stops heavier than 1.5 TeV

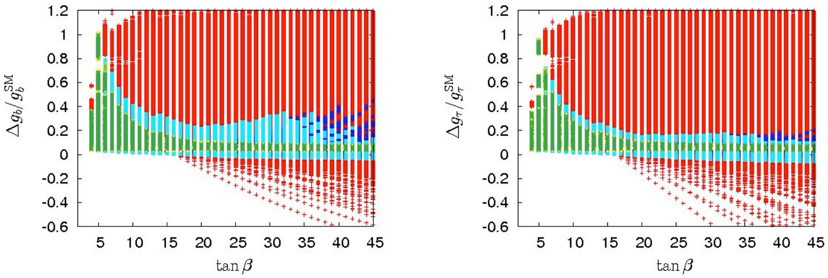
- for large $\tan\beta$ and light stops, enhancement by Δ_b contributions

  Δ_b: $\tan\beta$ enhanced contribution due to



[Carena, Garcia, Nierste,Wagner, hep-ph/9912516]

Higgs couplings in the MSSM



- overall behaviour similar for $\Delta g_\tau / g_\tau^{\text{SM}}$, no Δ_τ contributions included
- for $\tan\beta > 20$ and heavy stops: maximal deviation of ~ 10 %.
- Maximal deviations for coupling to Z or W: $\Delta g_V / g_V^{\text{SM}} < 1$ %
- Maximal deviations for coupling to top quarks: $\Delta g_t / g_t^{\text{SM}} \approx 3$ %

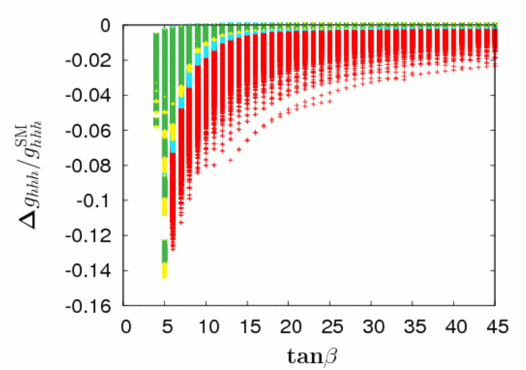
Higgs couplings in the MSSM

[Gupta, H.R., Wells, arXiv:1305.6397]

Devation of the triple Higgs coupling in the MSSM:

Use same approximation for Higgs boson mass and triple coupling!

Here: renormalization-group improved corrections of the eff. potential, incl. some 2-loop terms [Carena, Espinosa, Quiros, Wagner, hep-ph/9504316]



relaxed Higgs mass constraint:

$|\Delta g_{hhh}/g_{hhh}^{SM}| \lesssim 15\%$

strict Higgs mass constraint:

$|\Delta g_{hhh}/g_{hhh}^{SM}| \lesssim 4\%$

$m_{\tilde{t}_1} < 1.0$ TeV

1.0 TeV $\leq m_{\tilde{t}_1} < 2.5$ TeV

lighter stop mass $m_{\tilde{t}_1} \geq 2.5$ TeV