Higgs couplings to b quarks

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Discussion based on work with L. Almeida, R.S. Gupta, S. Lee, A. Petrov, S. Pokorski, H. Rzehak, Z. Zhang & CLIC Higgs working group.

Planck 2017 :: Warsaw

Higgs Boson

We have found the Higgs boson.

It acts consistent with SM expectation so far.

However, high priority should be precision studies of Higgs.

1) How precise are the current LHC measurements?
2) How precise do we need the measurements to be?
3) How precise can the LHC measurements become?
4) Can future colliders do *substantively* better than the LHC?

Parameter	ATLAS+CMS Measured	ATLAS+CMS Expected uncertainty	ATLAS Measured	CMS Measured
Parameterisation assuming $B_{BSM} = 0$				
κ_Z	-0.98 $[-1.08, -0.88] \cup [0.94, 1.13]$	$[-1.01, -0.87] \cup [0.89, 1.11]$	1.01 $[-1.09, -0.85] \cup [0.87, 1.15]$	-0.99 $[-1.14, -0.84] \cup [0.94, 1.19]$
κ_W	0.87 $[0.78, 1.00]$	$[-1.08, -0.90] \cup [0.88, 1.11]$	0.92 $[-0.94, -0.85] \cup [0.78, 1.05]$	0.84 $[-0.99, -0.74] \cup [0.71, 1.01]$
κ_t	$1.40^{+0.24}_{-0.21}$	${}^{+0.26}_{-0.39}$	$1.32^{+0.31}_{-0.33}$	$1.51^{+0.33}_{-0.32}$
$\lvert\kappa_\tau\rvert$	$0.84^{+0.15}_{-0.11}$	${}^{+0.16}_{-0.15}$	$0.97^{+0.19}_{-0.19}$	$0.77^{+0.18}_{-0.15}$
$\lvert\kappa_b\rvert$	$0.49^{+0.27}_{-0.15}$	${}^{+0.25}_{-0.28}$	$0.61^{+0.26}_{-0.31}$	$0.47^{+0.34}_{-0.19}$
$\lvert\kappa_g\rvert$	$0.78^{+0.13}_{-0.10}$	${}^{+0.17}_{-0.14}$	$0.94^{+0.18}_{-0.17}$	$0.67^{+0.14}_{-0.12}$
$\lvert\kappa_\gamma\rvert$	$0.87^{+0.14}_{-0.09}$	${}^{+0.12}_{-0.13}$	$0.88^{+0.15}_{-0.15}$	$0.89^{+0.19}_{-0.13}$

where $\kappa_j^2 = \sigma_j/\sigma_j^{SM}$ or $\kappa_j^2 = \Gamma^j/\Gamma^j_{SM}$

Let’s focus on the Higgs couplings to b quarks.

Many BSM physics ideas → hbb deviations

Special SM challenges also to consider.

Future collider options relevant too.

Must note differences in uncertainties quoted for couplings -- after a fit to observable(s) − and uncertainty in observables (e.g., σ.B observable).

$$\frac{\Delta B_b}{(B_b)_{sm}} \quad \longrightarrow \quad \kappa_b \simeq \frac{5}{4}\Delta$$

$$\frac{\Delta\Gamma_b}{(\Gamma_b)_{sm}} \quad \longrightarrow \quad \kappa_b = \frac{1}{2}\Delta$$

$\sigma \cdot B_b$ measurement uncertainty scales like B_b.

$\frac{\sigma \cdot B_b}{\sigma \cdot B_Z}$ measurement uncertainty scales like Γ_b.

Current constraint on κ_b

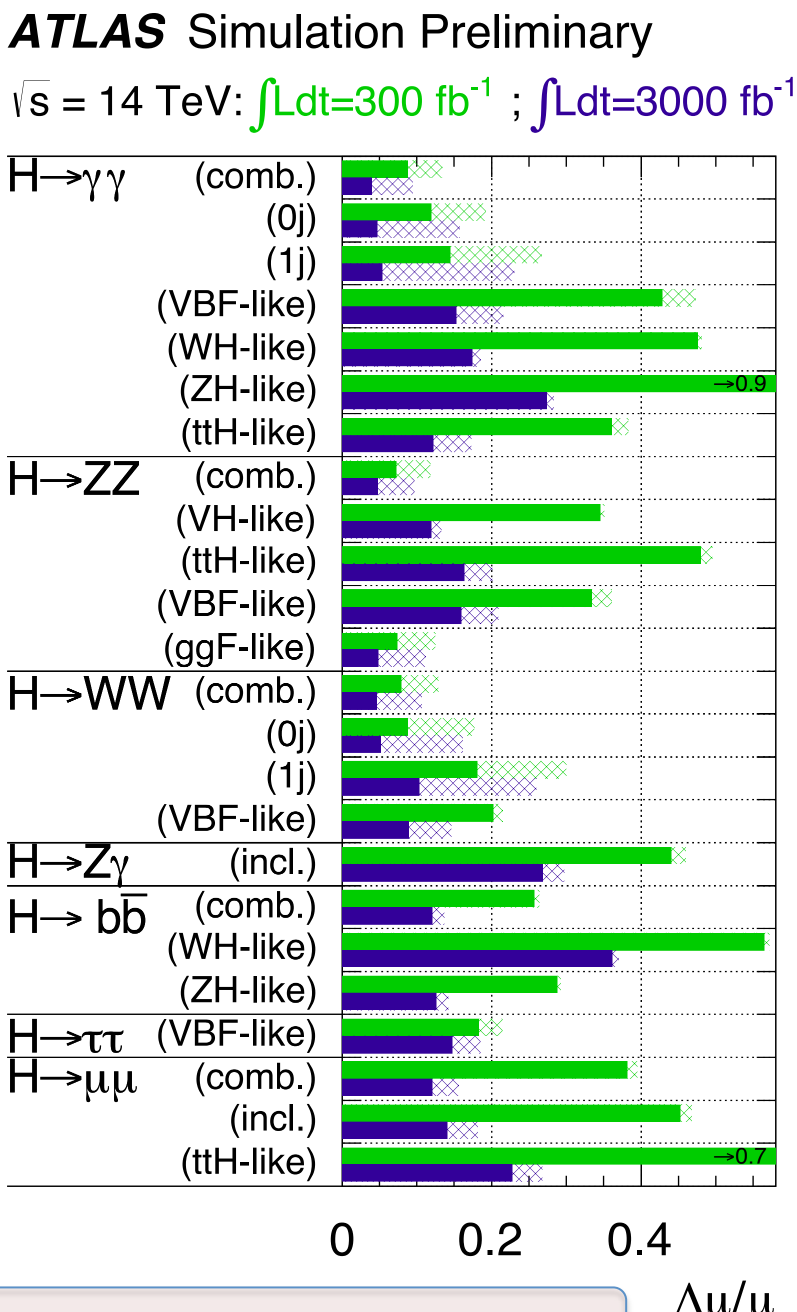
$$\kappa_b = 0.49^{+0.27}_{-0.15}$$

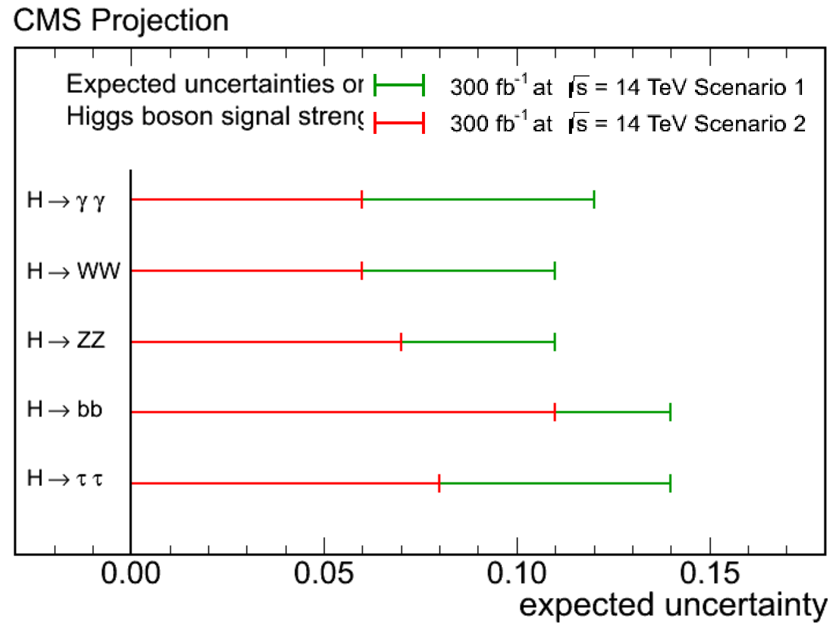
ATLAS & CMS
JHEP 8, 45 (2016).

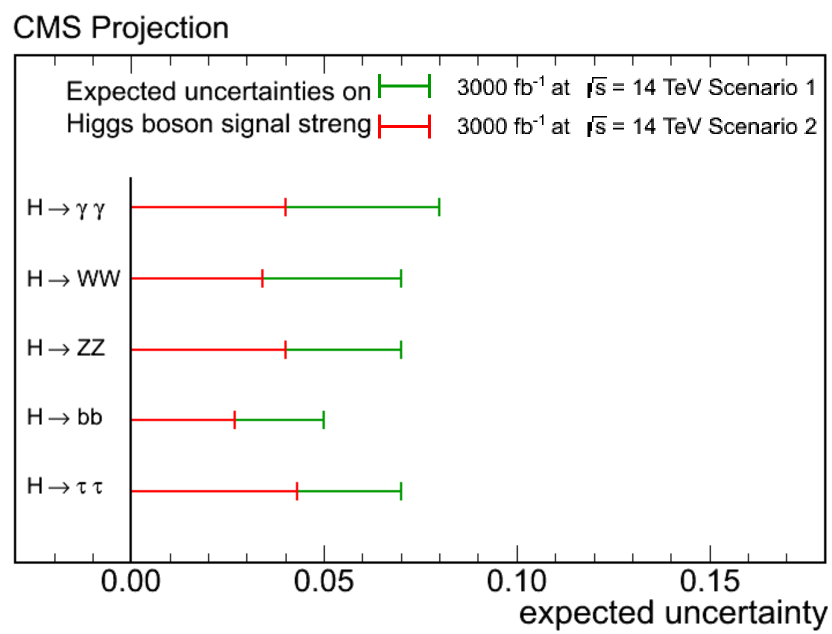
Super-naïve 2σ limit: $0.19 < \kappa_b < 1.03$

Super-naïve 3σ limit: $0.04 < \kappa_b < 1.30$

<u>Agreed</u>: measurements not currently in the precision realm.







HL-LHC typically in ~ 5 - 10% range.

Gadatsch, HL-LHC Workshop, `15

ILC σ x BR determinations

Table 2.4. Expected accuracies for cross section times branching ratio measurements for the $125\,\text{GeV}$ h boson.

	$\Delta(\sigma \cdot BR)/(\sigma \cdot BR)$				
$\sqrt{s}$ and $\mathcal{L}$ (P_{e^-}, P_{e^+})	250 fb^{-1} at 250 GeV (-0.8,+0.3)		500 fb^{-1} at 500 GeV (-0.8,+0.3)		1 ab^{-1} at 1 TeV (-0.8,+0.2)
mode	Zh	$\nu\bar{\nu}h$	Zh	$\nu\bar{\nu}h$	$\nu\bar{\nu}h$
$h \to b\bar{b}$	1.1%	10.5%	1.8%	0.66%	0.47%
$h \to c\bar{c}$	7.4%	-	12%	6.2%	7.6%
$h \to gg$	9.1%	-	14%	4.1%	3.1%
$h \to WW^*$	6.4%	-	9.2%	2.6%	3.3%
$h \to \tau^+\tau^-$	4.2%	-	5.4%	14%	3.5%
$h \to ZZ^*$	19%	-	25%	8.2%	4.4%
$h \to \gamma\gamma$	29-38%	-	29-38%	20-26%	7-10%
$h \to \mu^+\mu^-$	100%	-	-	-	32%

ILC TDR 2013

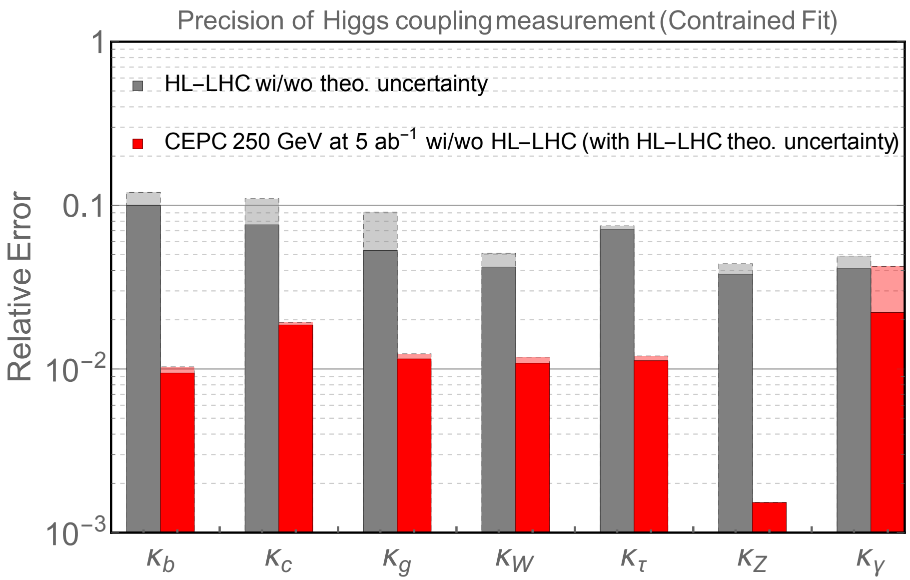
Typically in the neighborhood of a few percent.

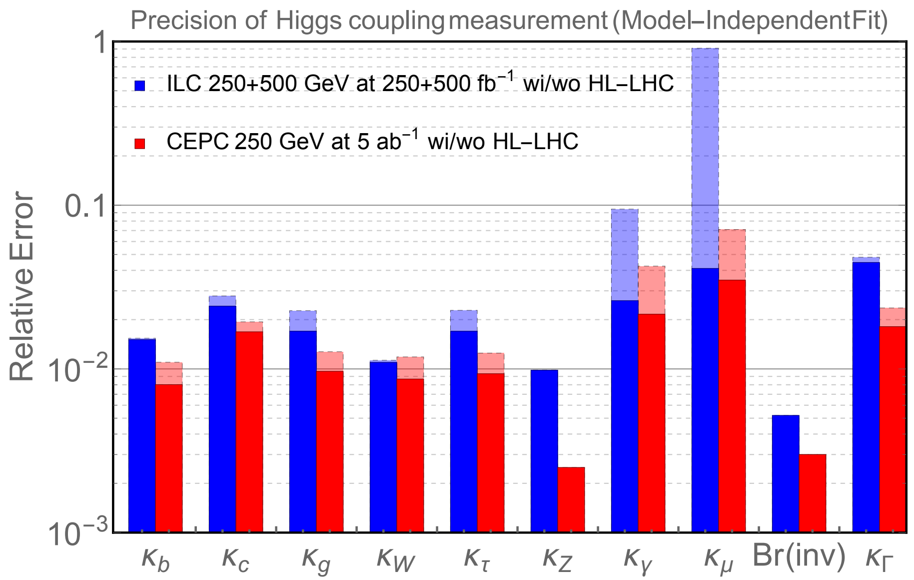
TLEP / FCC-ee Estimates

	TLEP 240 (10 ab^{-1})	ILC 250 (0.25 ab^{-1})
σ_{HZ}	**0.4%**	2.5%
$\sigma_{HZ} \times BR(H \to b\bar{b})$	**0.2%**	1.1%
$\sigma_{HZ} \times BR(H \to c\bar{c})$	**1.2%**	7.4%
$\sigma_{HZ} \times BR(H \to gg)$	**1.4%**	9.1%
$\sigma_{HZ} \times BR(H \to WW)$	**0.9%**	6.4%
$\sigma_{HZ} \times BR(H \to \tau\tau)$	**0.7%**	4.2%
$\sigma_{HZ} \times BR(H \to ZZ)$	**3.1%**	19%
$\sigma_{HZ} \times BR(H \to \gamma\gamma)$	**3.0%**	35%
$\sigma_{HZ} \times BR(H \to \mu\mu)$	**13%**	100%

Table 4: Statistical precision for Higgs measurements obtained from the proposed TLEP programme at $\sqrt{s} = 240$ GeV only (shown in Table 3). For illustration, the baseline ILC figures at $\sqrt{s} = 250$ GeV, taken from Ref. [6], are also given. The order-of-magnitude smaller accuracy expected at TLEP in the $H \to \gamma\gamma$ channel is the threefold consequence of the larger luminosity, the superior resolution of the CMS electromagnetic calorimeter, and the absence of background from Beamstrahlung photons.

Precision at Higgs factory

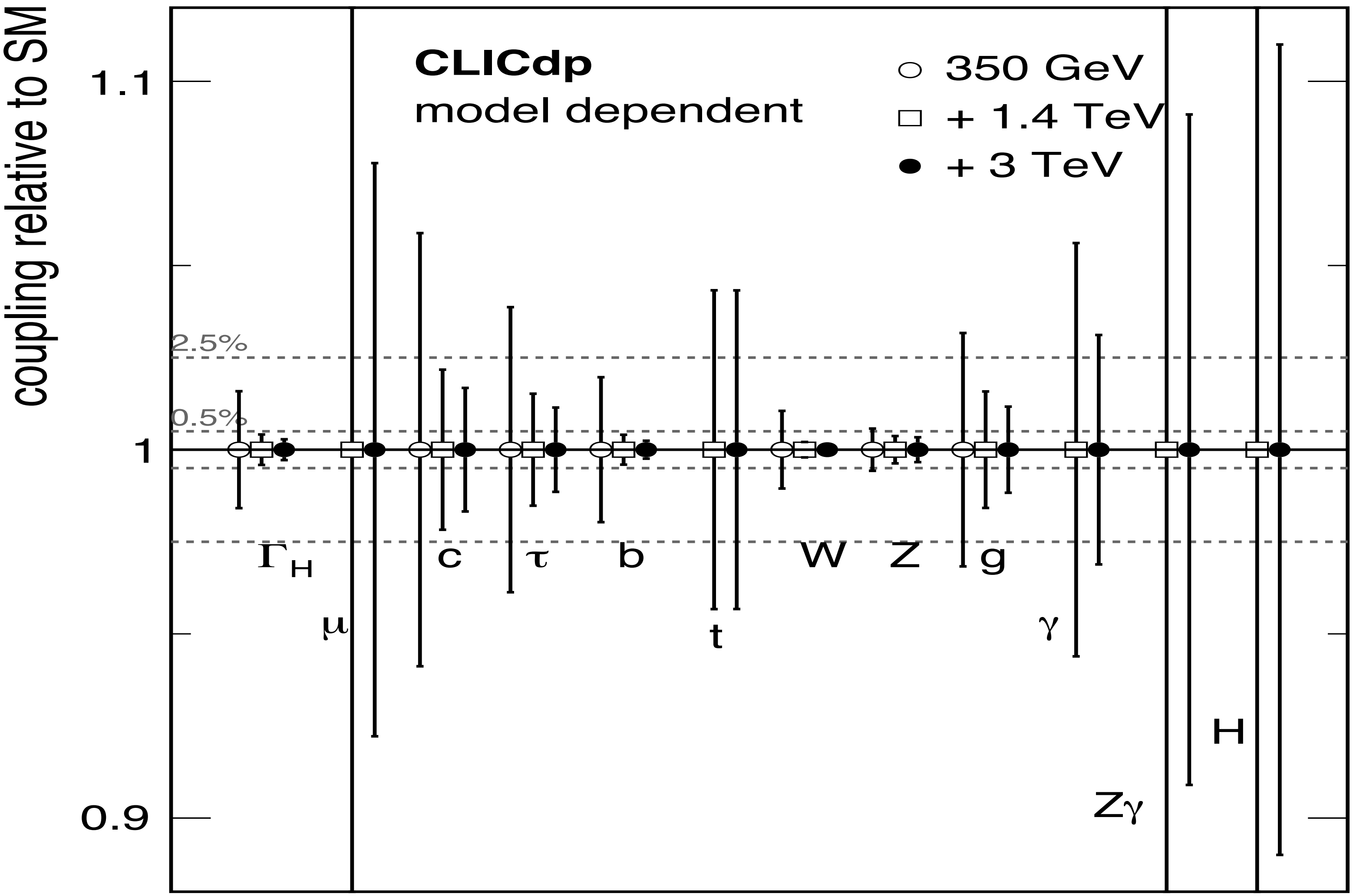




$$\kappa_X = \frac{\text{Measured Higgs-X coupling}}{\text{Standard Model Higgs-X coupling}}$$

CEPC CDR, `15

CLIC Projections



$350\,\text{GeV}$	$1.4\,\text{TeV}$	$3\,\text{TeV}$
$500\,\text{fb}^{-1}$	$1.5\,\text{ab}^{-1}$	$2\,\text{ab}^{-1}$

CLIC Higgs Study, 1608.07538

Calculating Higgs boson partial widths and branching fractions is an exercise in precision SM analysis.

Specifying the input observables and their uncertainties translates into central values and errors on Higgs partial widths and BRs.

m_H	$125.7(4)$	pole mass m_t	$173.07(89)$
$\overline{\text{MS}}$ mass m_c	$1.275(25)$	$\overline{\text{MS}}$ mass m_b	$4.18(3)$
pole mass m_τ	$1.77682(16)$	$\alpha_S(M_Z)$	$0.1184(7)$
$\alpha(M_Z)$	$1/128.96(2)$	$\Delta\alpha^{(5)}_{had}$	$0.0275(1)$

Almeida, Lee, Pokorski, JW 2013

	$P_\Gamma^{\pm}$(par.add.)	$P_\Gamma^{\pm}$(par.quad.)	$(P_\Gamma^{+}, P_\Gamma^{-})(\mu)$
total	2.82 (1.79)	1.71 (1.07)	(0.08,0.10)
gg	2.52 (1.83)	1.74 (1.49)	(0.05,0.03)
$\gamma\gamma$	1.45 (0.42)	1.38 (0.35)	(1.31,0.60)
$b\bar{b}$	2.62 (2.43)	1.84 (1.82)	(0.29,0.01)
$c\bar{c}$	7.34 (7.15)	5.55 (5.54)	(0.45,0.35)
$\tau^+\tau^-$	0.36 (0.12)	0.32 (0.08)	(0.01,0.01)
WW^*	4.41 (1.17)	4.97 (1.25)	(0.25,0.31)
ZZ^*	4.90 (1.25)	4.42 (1.11)	(0.,0.)
$Z\gamma$	3.56 (0.92)	3.52 (0.88)	(0.56,0.23)
$\mu^+\mu^-$	0.34 (0.11)	0.32 (0.08)	(0.03,0.03)

Almeida, Lee, Pokorski, JW 2013

Percent relative uncertainty on the partial widths from parametric and scale-dependence uncertainties. WW, ZZ uncertainties mainly due to Δm_H.

Note, uncertainty on bb final state affects all branching fractions.

Table 13: This table gives the estimates for percent relative uncertainty on the partial widths from parametric and scale-dependence uncertainties. Parametric uncertainties arise from incomplete knowledge of the input observables for the calculation (i.e., errors on m_c, α_s, etc.). For parametric uncertainties, we put an additional number in parentheses, which is the value it would have if the Higgs mass uncertainty were 0.1 GeV (instead of 0.4 GeV). Scale-dependence uncertainties are indicative of not knowing the higher order terms in a perturbative expansion of the observable. These uncertainties are estimated by varying μ from $m_H/2$ to $2m_H$. More details on the precise meaning of the entries of this table are found in the text of sec. 4. Errors below 0.01% are represented in this table as 0. These results were computed using $\overline{MS}$ m_b and m_c inputs (see Table 10) rather than their pole mass inputs (see Table 1). Compare results with the pole mass input results of Table 4.

Reducing Uncertainties in Γs and BRs

Reducing the uncertainties in extracted m_b and m_c MSbar masses (or the equivalent) are needed to reduce uncertainties in theory calculations.

Likewise for α_s and m_H.

The precision Higgs program is just as well stated as a precision m_b , m_c , α_s and m_H program.

α_s and m_H seem easier to improve than m_b and m_c.

Let's look at the role of light quark mass uncertainties…

$$\frac{\Delta\Gamma_{H\to c\bar{c}}}{\Gamma_{H\to c\bar{c}}} \simeq \frac{\Delta m_c(m_c)}{10\ \text{MeV}} \times 2.1\%, \quad \frac{\Delta\Gamma_{H\to b\bar{b}}}{\Gamma_{H\to b\bar{b}}} \simeq \frac{\Delta m_b(m_b)}{10\ \text{MeV}} \times 0.56\%.$$

[Denner et al, 1107.5909]

[Almeida, Lee, Pokorski, Wells, 1311.6721]

[Lepage, Mackenzie, Peskin, 1404.0319]

$m_Q(m_Q) \equiv m_Q^{\overline{\text{MS}}}(\mu = m_Q)$: inputs of the calculation.

From PDG particle listings:

$$m_c(m_c) = 1.275(25)\ \text{GeV}, \quad m_b(m_b) = 4.18(3)\ \text{GeV}.$$

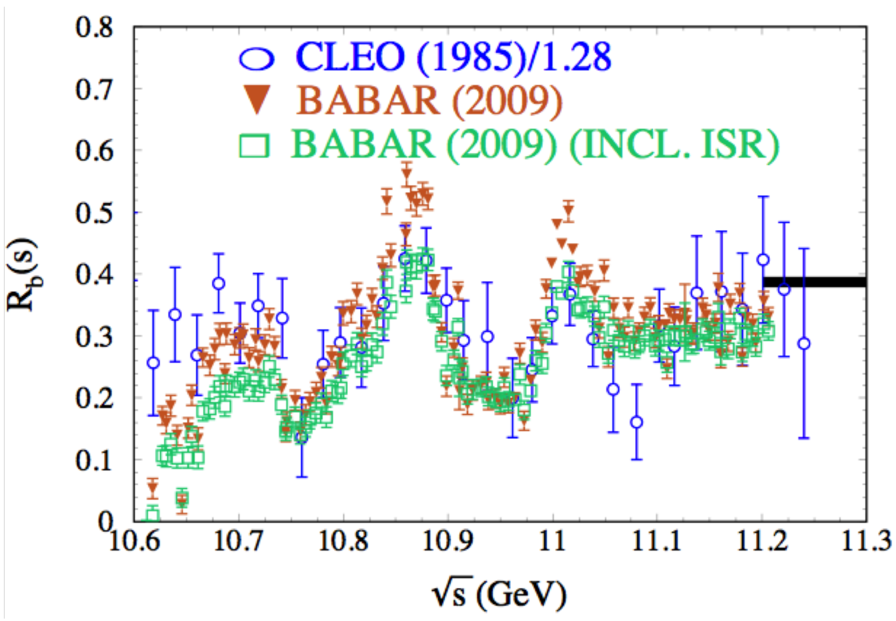
$\Rightarrow$ A few % theory uncertainty in $\Gamma_{H\to c\bar{c}}$, $\Gamma_{H\to b\bar{b}}$ – too large!

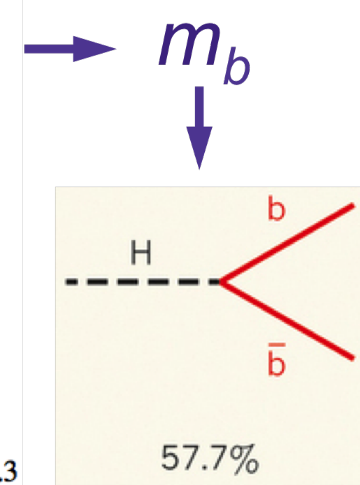
Zhang, Charm 2015

Uncertainty from m_Q? – Ultimately from low-energy observables from which m_Q are extracted!

- Example: nth moment of R_Q [Chetyrkin et al, 0907.2110]

$$\mathcal{M}_n^Q \equiv \int \frac{\mathrm{d}s}{s^{n+1}} R_Q(s), \quad \text{where } R_Q \equiv \frac{\sigma(e^+e^- \to Q\bar{Q}X)}{\sigma(e^+e^- \to \mu^+\mu^-)}.$$





We will recast $\Gamma_{H\to Q\bar{Q}}$ in terms of $\mathcal{M}_1^c, \mathcal{M}_2^b$.

Zhang, Charm 2015

$$\mathcal{M}_n^Q = \frac{(Q_Q/(2/3))^2}{(2m_Q(\mu_m))^{2n}} \sum_{i,a,b} C_{n,i}^{(a,b)}(n_f)\left(\frac{\alpha_s(\mu_\alpha)}{\pi}\right)^i \ln^a \frac{m_Q(\mu_m)^2}{{\mu_m}^2} \ln^b \frac{m_Q(\mu_m)^2}{{\mu_\alpha}^2} + \mathcal{M}_n^{Q,\mathrm{np}}.$$

$$\Rightarrow \begin{cases} m_c(m_c) = m_c(m_c)\left[\alpha_s, \mathcal{M}_1^c, \mu_m^c, \mu_\alpha^c, \mathcal{M}_1^{c,\mathrm{np}}\right], \\ m_b(m_b) = m_b(m_b)\left[\alpha_s, \mathcal{M}_2^b, \mu_m^b, \mu_\alpha^b\right]. \end{cases}$$

[Kuhn, Steinhauser, hep-ph/0109084]

[Kuhn, Steinhauser, Sturm, hep-ph/0702103]

[Chetyrkin, Kuhn, Maier, Maierhofer, Marquard, Steinhauser, Sturm, 0907.2110]

μ_m, μ_α: renormalization scales; need not be identical [Dehnadi, Hoang, Mateu, Zebarjad, 1102.2264]. (if forced equal uncertainty is underestimated)

$$\Rightarrow \begin{cases} m_c(m_c) = m_c(m_c)\left[\alpha_s, \mathcal{M}_1^c, \mu_m^c, \mu_\alpha^c, \mathcal{M}_1^{c,\mathrm{np}}\right], \\ m_b(m_b) = m_b(m_b)\left[\alpha_s, \mathcal{M}_2^b, \mu_m^b, \mu_\alpha^b\right]. \end{cases}$$

Current uncertainty from these methods is about 30 MeV on the b quark mass (PDG estimate).

We need to get down to below 10 MeV uncertainty to take full advantage of a precision Higgs program.

10 MeV m_b uncertainty → uncertainty in Γ_b = 0.5%.

How will this be solved?

Progress: Lepage et al (2014) pointed out that dedicated lattice program may be required. They estimate that Δm_b, Δm_c and $\Delta\alpha_s$ could be reduced by factors of 7, 3 and 6 respectively.

Now from BSM perspective…

… how large can these couplings be given current LHC constraints on BSM and possible later constraints (or discovery)?

Let us consider the largest coupling deviations away from the SM Higgs couplings that are possible if no other state directly related to EWSB (another Higgs, or "rho meson") is directly accessible at the LHC.

SUSY Case:

Two Higgs Doublets of Supersymmetry

Supersymmetry requires two Higgs doublets. One to give mass to up-like quarks (H_u), and one to give mass to down quarks and leptons (H_d).

8 degrees of freedom. 3 are eaten by longitudinal components of the W and Z bosons, leaving 5 physical degrees of freedom: $H^{\pm}$, A, H, and h.

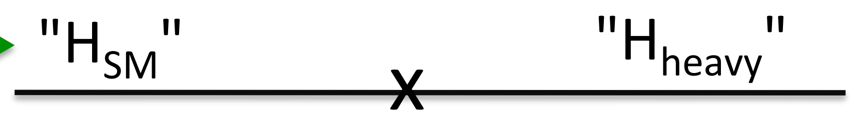
As supersymmetry gets heavier ($m_{3/2} >> M_Z$), a full doublet gets heavier together ($H^{\pm}$,A,H) while a solitary Higgs boson (h) stays light, and behaves just as the SM Higgs boson.

Corrections to Higgs Couplings in MSSM

Two leading corrections are

a) mixing of would-be SM Higgs with heavy Higgs

Not mass eigenstate

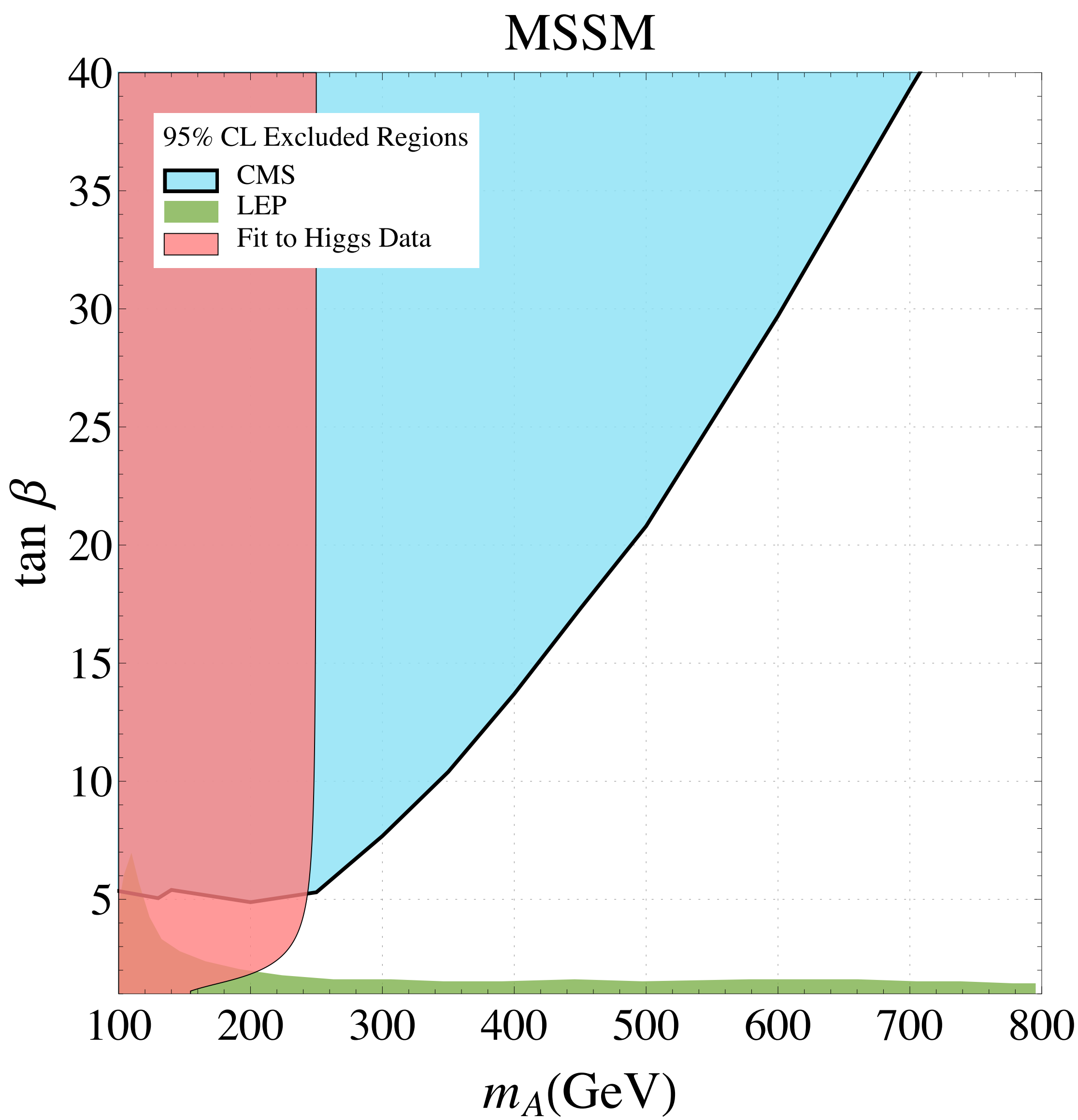


mixing angle is $\sim m_Z^2 / m_A^2$

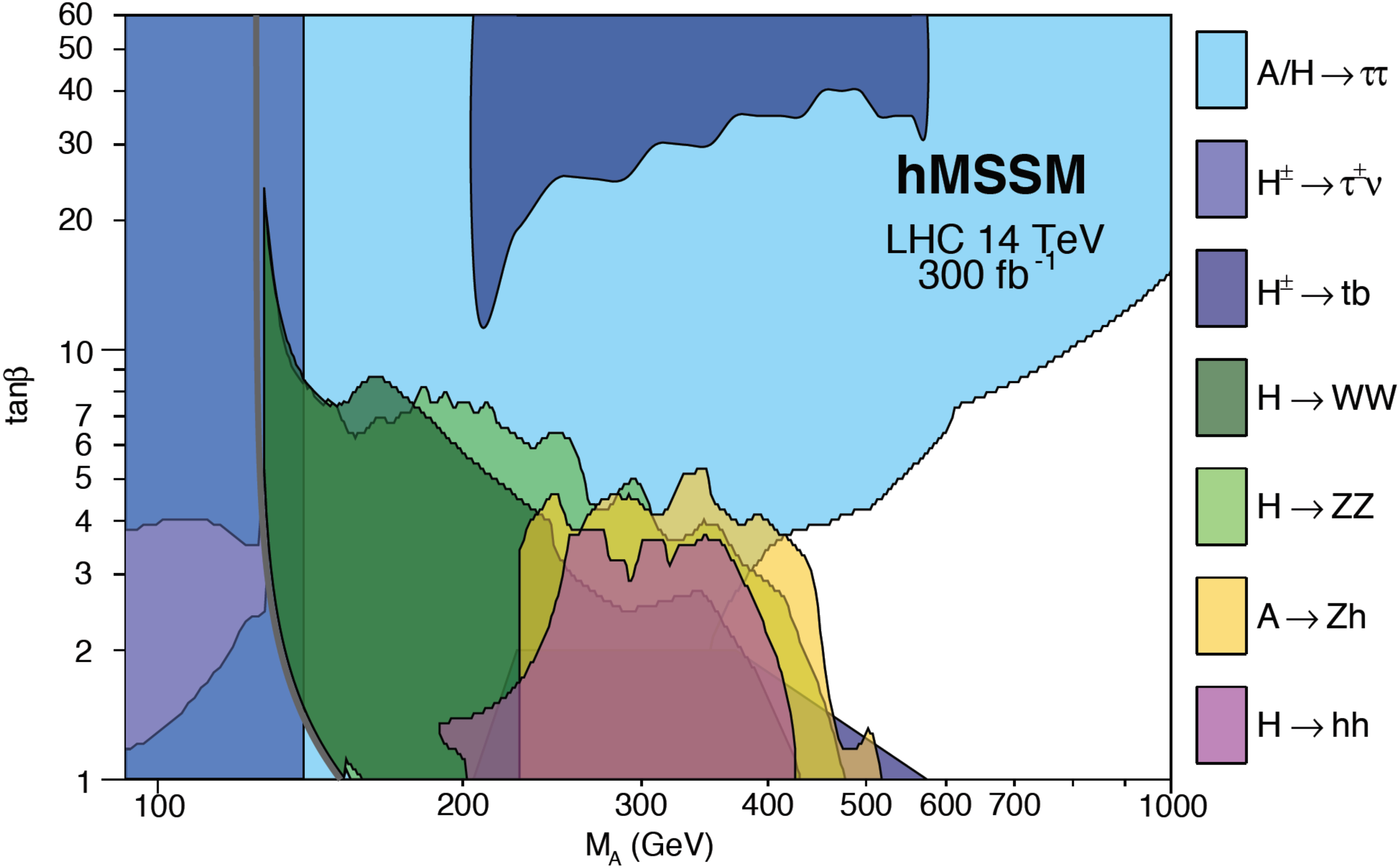
$$\frac{g_d}{g_d^{SM}} \approx 1 + \frac{2m_Z^2}{m_A^2} - \frac{\Delta_{12}}{m_A^2} \tan\beta$$

Δ_{ij} are radiative corrections to the CP Higgs mass matrix for eigenstates h,H.

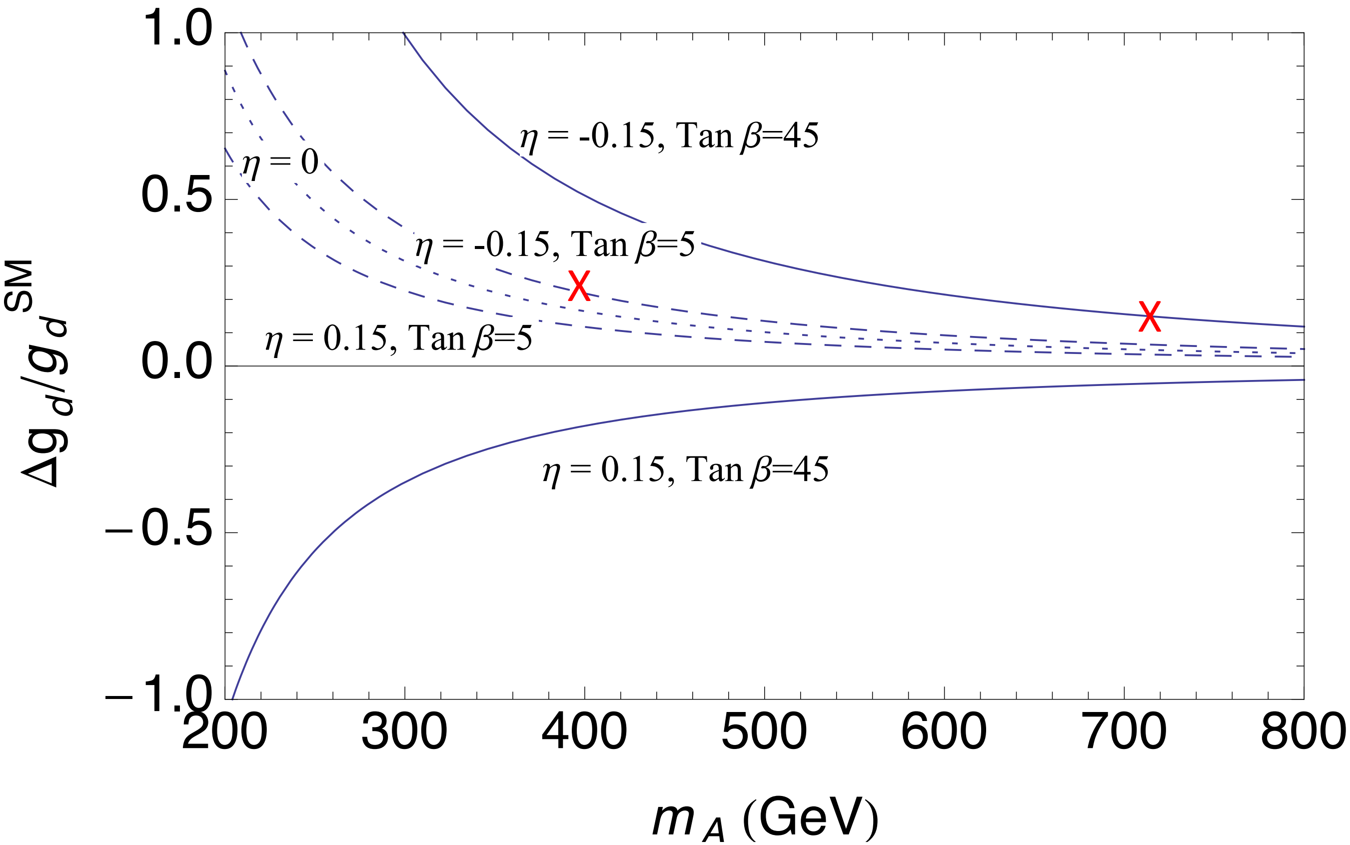
Key parameters are tanβ and m_A.



D'Agnolo, Kuflik, Zanetti, `13



Djouadi et al., ‘15

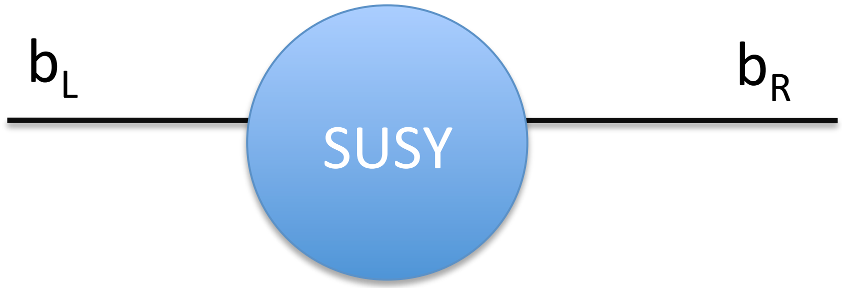


Deviations higher for smaller tanβ, typically, due to limits in the mA-tanβ plane.

FIG. 7: $\Delta g_d/g_d^{SM}$ as a function of m_A for $\Delta_{11} = 0$ and various values of η, where $\Delta_{12} = \eta\Delta_{22}$. The overall contribution due to radiative corrections has been chosen such that we get $m_h = 125\,\text{GeV}$.

Gupta, Rzehak, JW, ‘13

b) Finite b quark mass corrections, disrupting Yukawa – Mass relation



$$\delta_b^{\mathrm{finite}} \simeq -\frac{g_3^2}{12\pi^2}\frac{\mu M_{\tilde{g}}\tan\beta}{m_{\tilde{b}}^2} + \frac{y_t^2}{32\pi^2}\frac{\mu A_t \tan\beta}{m_{\tilde{t}}^2} + \ldots$$

Effective lagrangian: $\mathcal{L} = \mathbf{y_b}\, b_L^\dagger H^* b_R + \mathbf{C_b}\, |H|^2 b_L^\dagger H^* b_R + h.c.$

Leads to shift in higgs-b-b couplings $$\frac{h\bar{b}b}{(h\bar{b}b)_{\mathrm{sm}}} = 1 + \kappa_b$$

where
$$\kappa_b \simeq \frac{\alpha_s}{\pi}\frac{M_{\tilde{g}}\mu^3}{m_{\tilde{b}}^6}(m_b^2\tan^2\beta)\tan\beta$$
$$\simeq \frac{\alpha_s}{\pi}\left(\frac{m_b^2\tan^2\beta}{\tilde{m}^2}\right)\tan\beta$$

tanβ enhanced but decouples with large susy masses.

Easily obtain κ_b > 5% for all tanβ values.

Max deviation of ~1 for tanβ ~ 5 is possible, due to light m_A undetectable at LHC.

These results hold even after the LHC obtains 300 fb^{-1} of data, if no exotic discoveries made. Higher deviations possible otherwise.

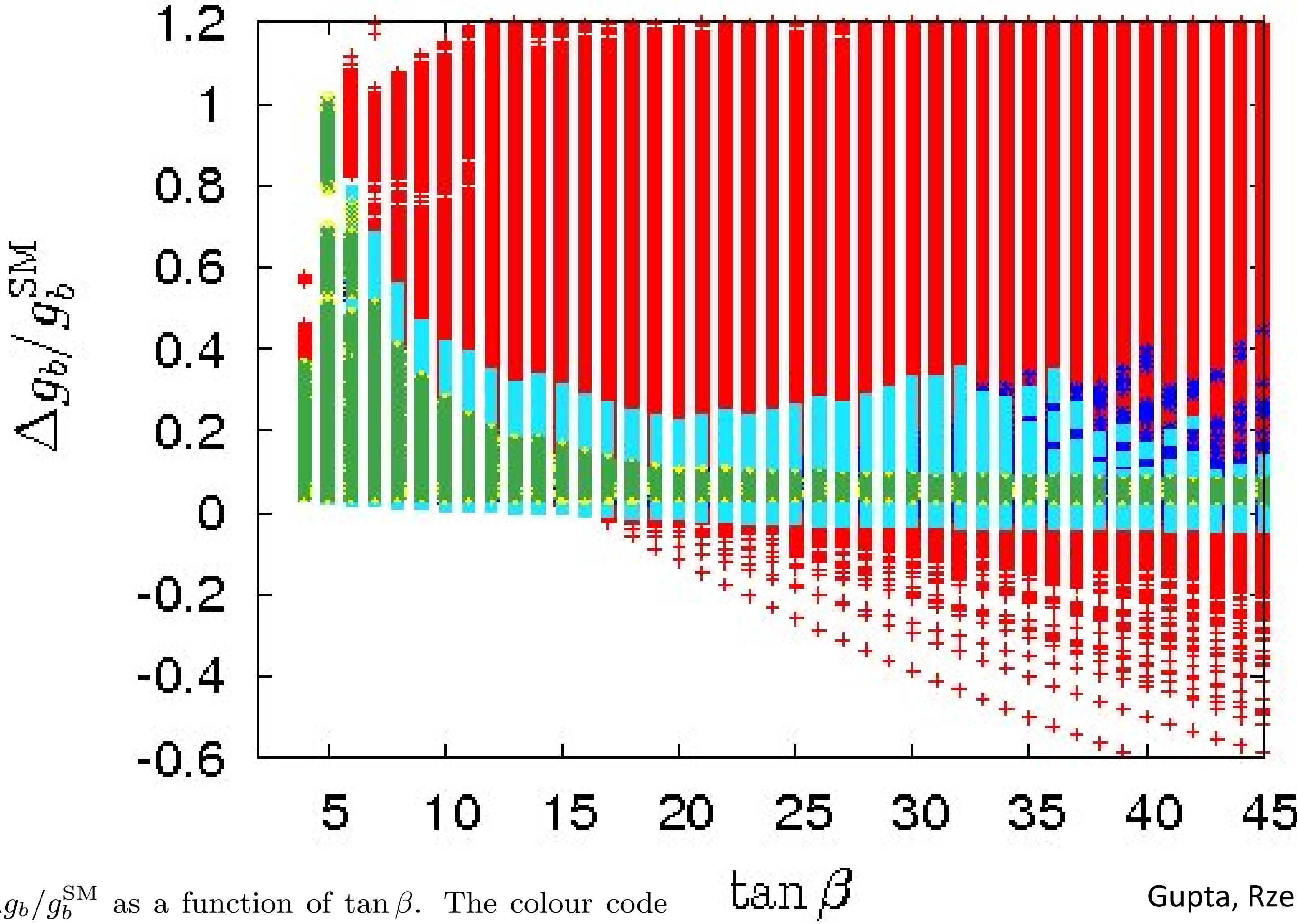


FIG. 9: $\Delta g_b/g_b^{\rm SM}$ as a function of $\tan\beta$. The colour code is the following: Red means several Higgs bosons can be discovered at the LHC - all the other points correspond to a single Higgs boson discovery at the LHC. Dark blue points are excluded by the $\Gamma(b \to s\gamma)$ constraint. Light blue, yellow and green correspond to at least one third generation squark has a mass less than 1.0 TeV, all third generation squarks are heavier than 1.0 TeV but at least one top squark is lighter than 1.5 TeV and both top squarks heavier than 1.5 TeV, respectively.

Gupta, Rzehak, JW

Smaller tanβ correlated with lower heavy Higgs masses going undetected.

Conclusions

Expt: Excellent prospects for precision study of Higgs boson (ILC, CLIC, FCC, etc.).

SM: SM prediction of H→bb is presently too uncertain and needs additional focus and work.

BSM: BSM prediction for H→bb can easily be well above 5% even after 300 fb^{-1} of LHC data. Even more otherwise.

In progress: Recast in EFT and connect predictions to unification ideas (e.g., b-tau-t).