Targets for Higgs Couplings

James Wells
(Michigan, MCTP)

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Higgs Boson Observables

Our consideration is Higgs boson observables:

$\sigma(pp \to hX \to AB+X)$ subject to experimental cuts, which are unfolded to yield measurements.

Precise theory predictions include knowing precisely the theory predictions for

$\sigma(pp \to hX)$ and $BR(h \to AB)$

Measurement of Higgs Couplings

The proper way to test the SM is to compute SM observables and compare with data in a χ^2 type of analysis.

$$\theta_i^{expt} = \theta_i^{th}(g_1, g_2, g_3, y_b, y_t, \cdots)$$

$$\chi^2 = \sum_i \frac{\left(\theta_i^{expt} - \theta_i^{th}(g_1, g_2, g_3, y_b, y_t, \cdots)\right)^2}{\left(\Delta\theta_i^{expt}\right)^2} \Rightarrow y_b \pm \delta y_b$$

Is χ^2 at the minimum acceptable? Yes/No

(For presentation, ignoring correlation matrix among observables.)

"Measurement of hbb coupling"

You can, however, "measure hbb coupling" by deleting m_b observable and seeing how well y_b can be extracted by $h \rightarrow bb$ plus all the rest: y_b(higgs) and compare that to y_b extracted from m_b plus all the rest.

Global fit of $\sigma(h \rightarrow bb)$ + all other obs but without m_b

$\Rightarrow$ $y_{b,higgs}$ extracted

Global fit of all obs including m_b but without $\sigma(h \rightarrow bb)$

$\Rightarrow$ $y_{b,mb}$ extracted

Compare by renormalizing to common scale, say m_Z.

This ratio $y_{b,higgs}(m_Z) / y_{b,mb}(m_Z)$ should be 1.

$\theta_{\alpha,i}$ = sensitive to y_b but not involving direct Higgs production

$\theta_{\beta,i}$ = sensitive to y_b through direct Higgs boson production

$\theta_{\gamma,i}$ = all other observables

$$\chi^2_{\alpha\gamma} = \sum_{i\in\alpha,\gamma} \frac{\left(\theta_i^{expt} - \theta_i^{th}(\ldots, y_b, \ldots)\right)^2}{\left(\Delta\theta_i^{expt}\right)^2} \Longrightarrow (y_b)_{\alpha\gamma} \pm (\delta y_b)_{\alpha\gamma}$$

$$\chi^2_{\beta\gamma} = \sum_{i\in\beta,\gamma} \frac{\left(\theta_i^{expt} - \theta_i^{th}(\ldots, y_b, \ldots)\right)^2}{\left(\Delta\theta_i^{expt}\right)^2} \Longrightarrow (y_b)_{\beta\gamma} \pm (\delta y_b)_{\beta\gamma}$$

Test if $\xi_b = \frac{(y_b)_{\beta\gamma}}{(y_b)_{\alpha\gamma}} \simeq 1$

New Physics: HκSM

Harder to do the analogy with hVV couplings (V=γ, g, W, Z).

Instead a *new theory of physics beyond the SM* is considered:

Call this the "Higgs kappa Standard Model" (HκSM).

It is parametrized by κ's, which are defined by replacing

$g(hAA)_{SM}$ ➔ $\kappa_A\, g(hAA)_{SM}$; other interactions remain SM.

Attention must be given to clear definitions of κ_γ and κ_g.

Best way is through effective theory gauge invariant higher dimensional operators. Theory : SM-EFT. (e.g., Contino, Ghezzi, Grojean, Muhlleitner, Spira, ‘13,’14; Pomarol, ’14; etc.)

K_i - theory is a BSM theory!

$$\mathcal{L} = \cdots + \sum_{AB} \lambda_{AB}^{SM} h A B$$

replace $\lambda_{AB}^{SM} \to \kappa_{AB} \lambda_{AB}^{SM}$ and do fits to data

$$\chi^2 = \sum_{i=\text{all}} \frac{\left(\theta_i^{\text{expt}} - \theta_i^{\text{th}}(\ldots, \kappa_b, \ldots)\right)^2}{\left(\Delta\theta_i^{\text{expt}}\right)^2} \Longrightarrow \kappa_b \pm \delta\kappa_b$$

($\kappa_b \neq 1$ for BSM)

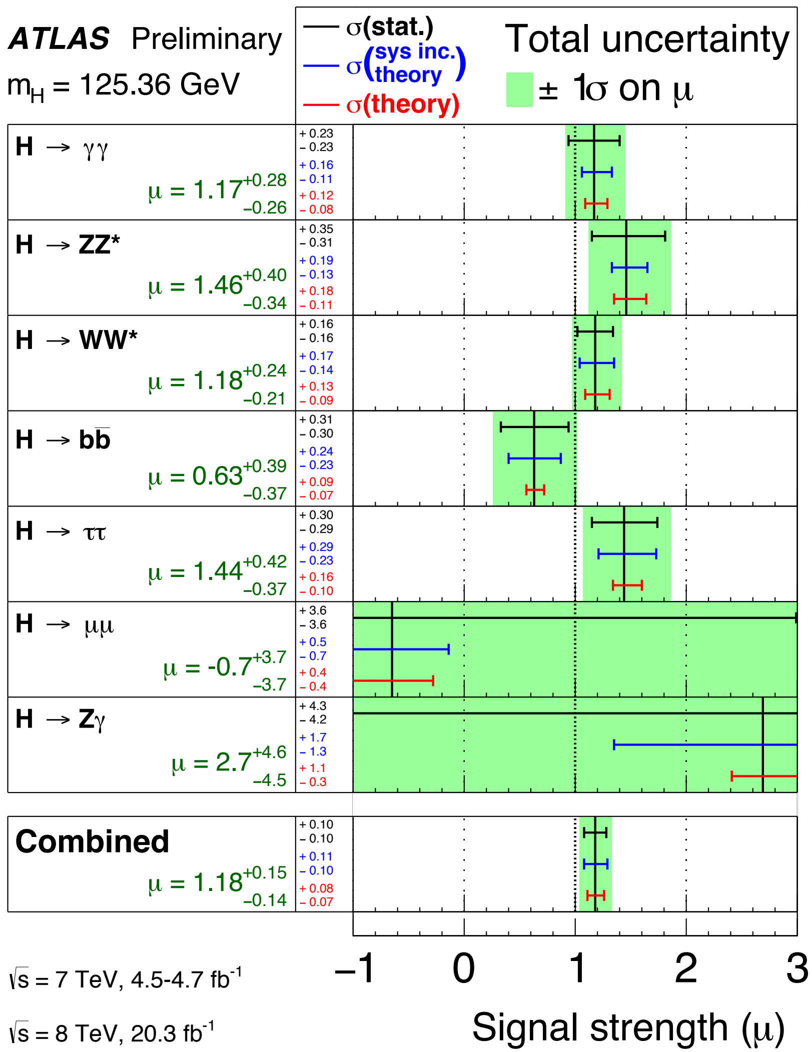
Safer (gauge invariant) approach to test is through EFT additions

$$\Delta\mathcal{L} = \mathcal{L}_{SM} + \sum_n c_n P_n^{(6)}$$

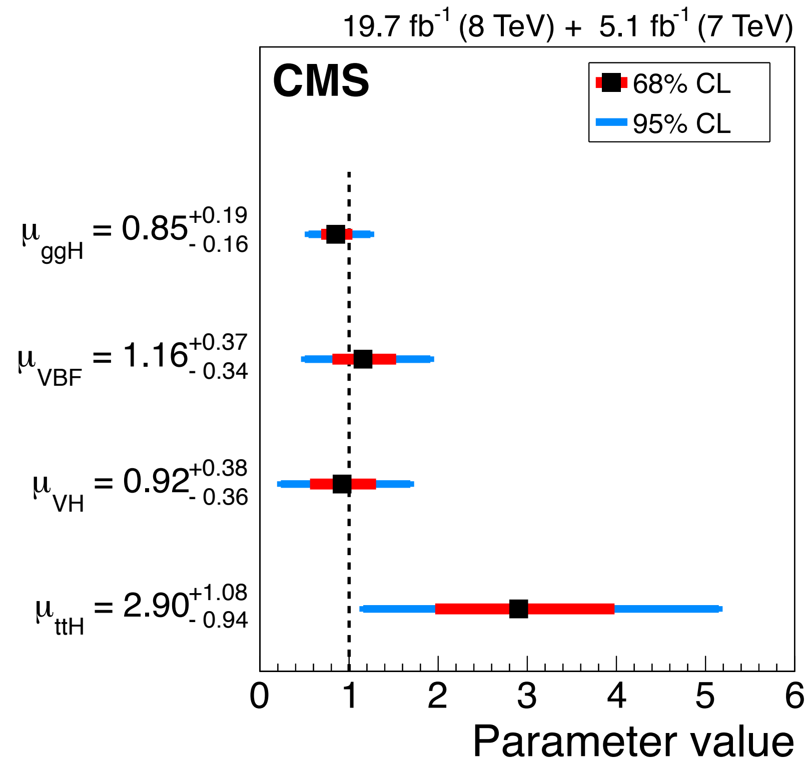
$$\chi^2 = \sum_{i=\text{all}} \frac{\left(\theta_i^{\text{expt}} - \theta_i^{\text{th}}(\ldots, c_k, \ldots)\right)^2}{\left(\Delta\theta_i^{\text{expt}}\right)^2} \Longrightarrow c_k \pm \delta c_k$$

($c_k \neq 0$ for BSM)

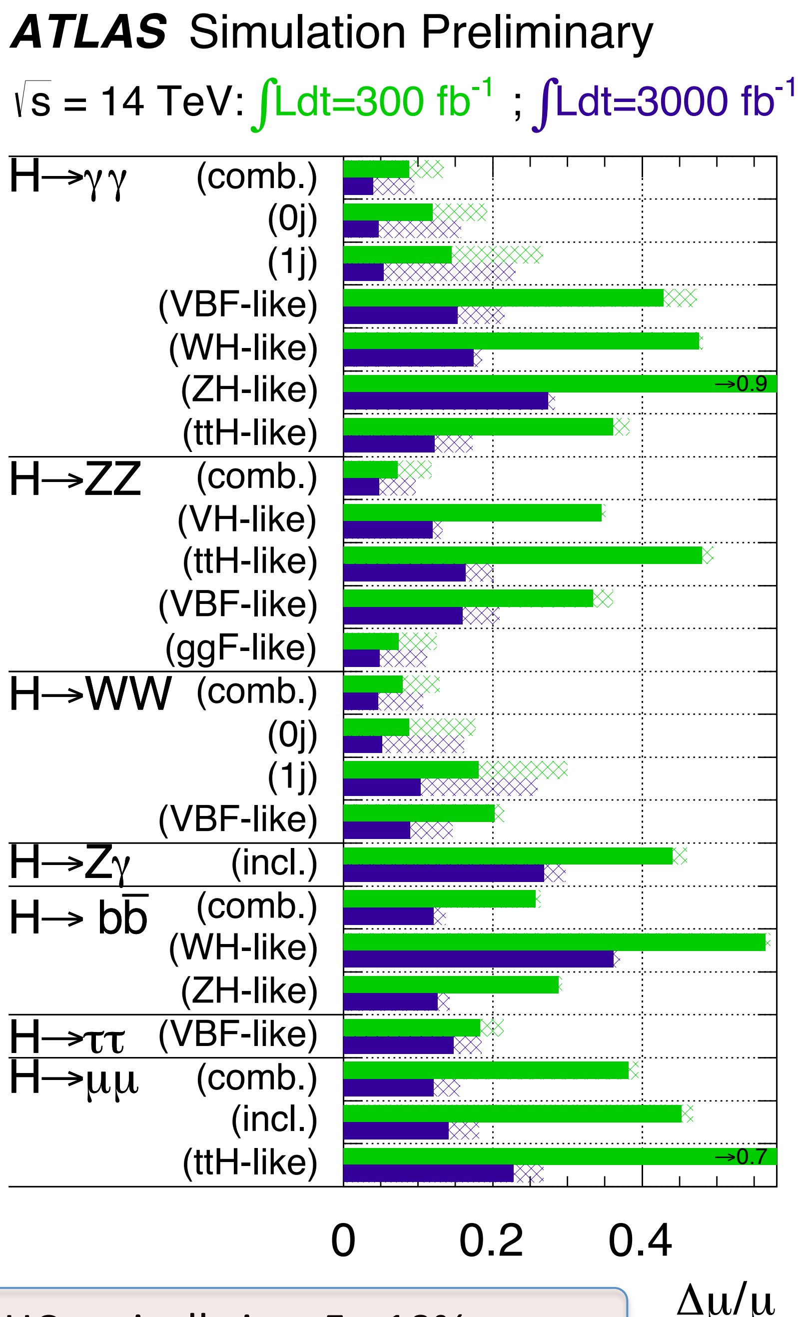
LHC Experiments

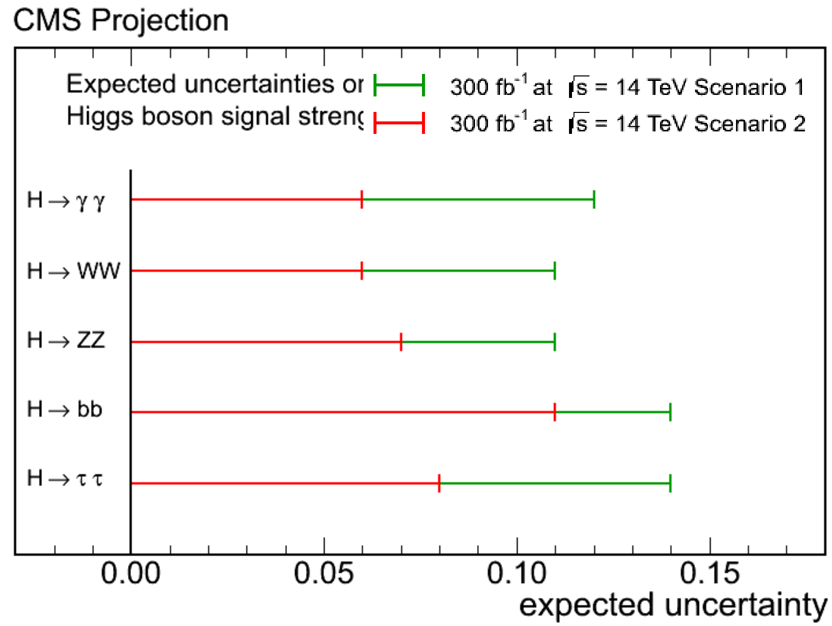


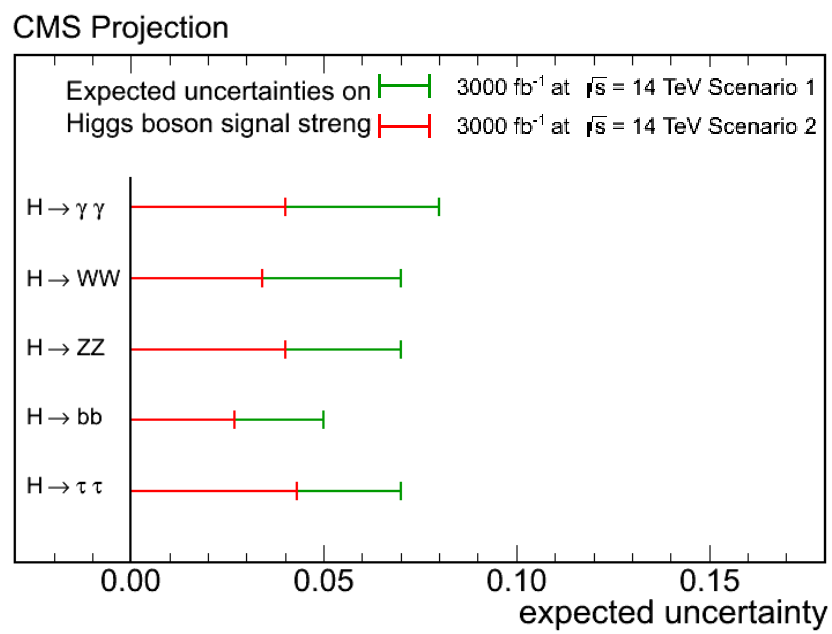
Gadatsch, HL-LHC Workshop, `15



- Precise measurements of diboson decay modes (theoretical uncertainties become relevant!)
- Some channels (e.g. $H \rightarrow b\bar{b}$) dominated by exp. uncertainties
- Rare decay modes statistics limited







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 GeV h boson.

	$\Delta(\sigma \cdot BR)/(\sigma \cdot BR)$				
$\sqrt{s}$ and $\mathcal{L}$	250 fb^{-1} at 250 GeV		500 fb^{-1} at 500 GeV		1 ab^{-1} at 1 TeV
(P_{e^-}, P_{e^+})	(-0.8,+0.3)		(-0.8,+0.3)		(-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%

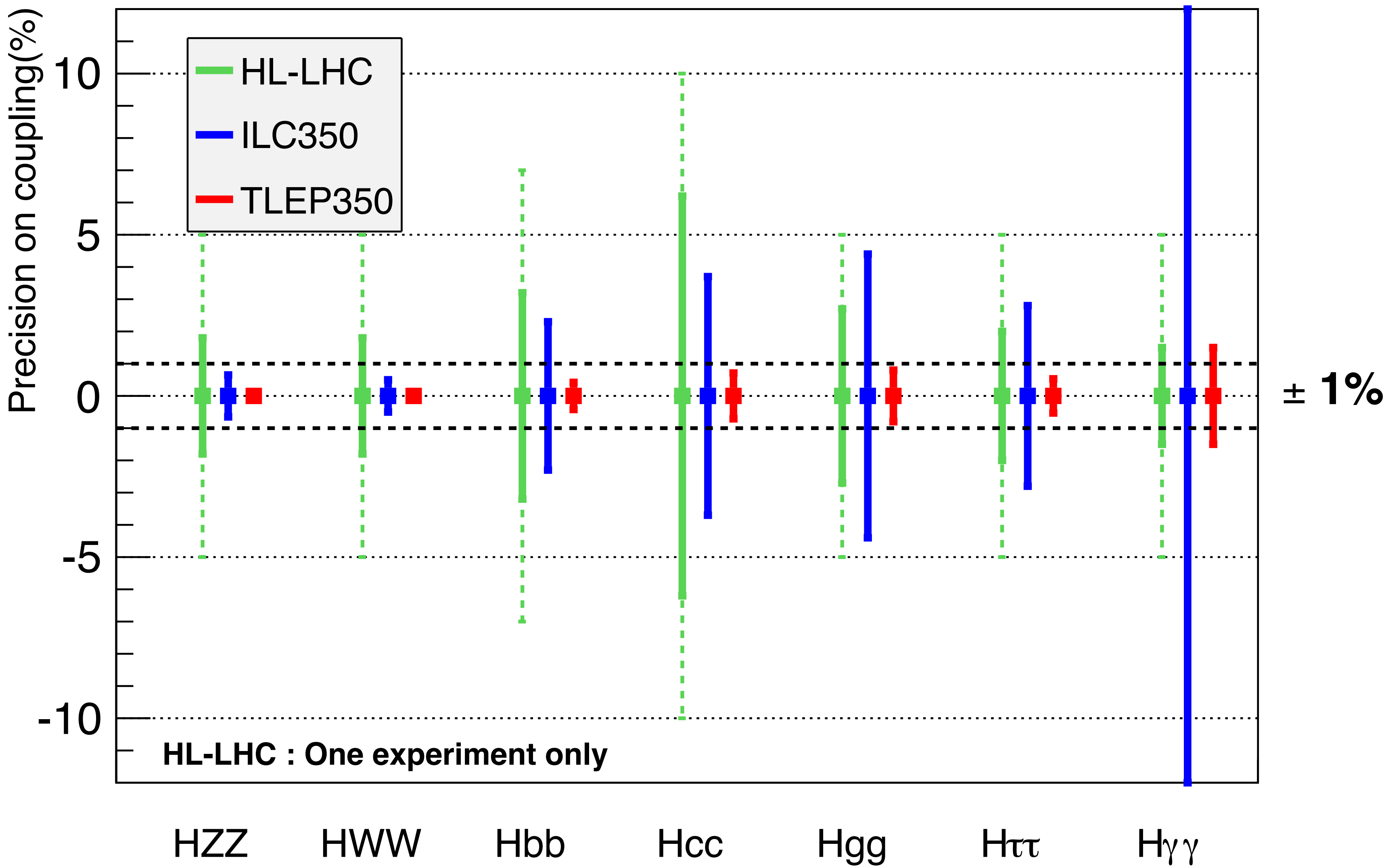
ILC TDR 2013

Typically in the neighborhood of a few percent.

TLEP / FCC-ee Estimates

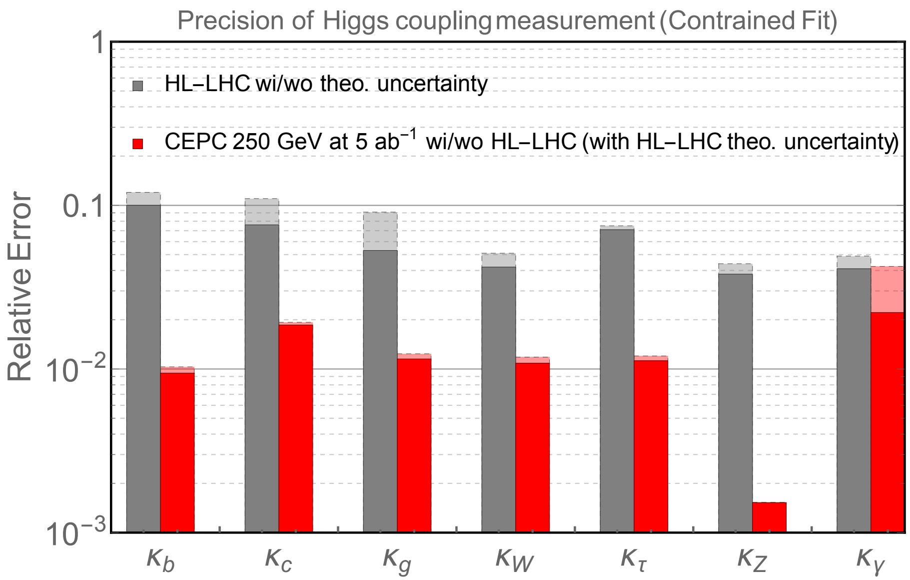
	TLEP 240	ILC 250
	10 ab^{-1}	0.25 ab^{-1}
σ_{HZ}	**0.4%**	2.5%
$\sigma_{HZ} \times BR(H \to b\bar{b})$	**0.2%**	1.1%
$\sigma_{HZ} \times BR(H \to c\bar{c})$	**1.2%**	7.4%
$\sigma_{HZ} \times BR(H \to gg)$	**1.4%**	9.1%
$\sigma_{HZ} \times BR(H \to WW)$	**0.9%**	6.4%
$\sigma_{HZ} \times BR(H \to \tau\tau)$	**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%

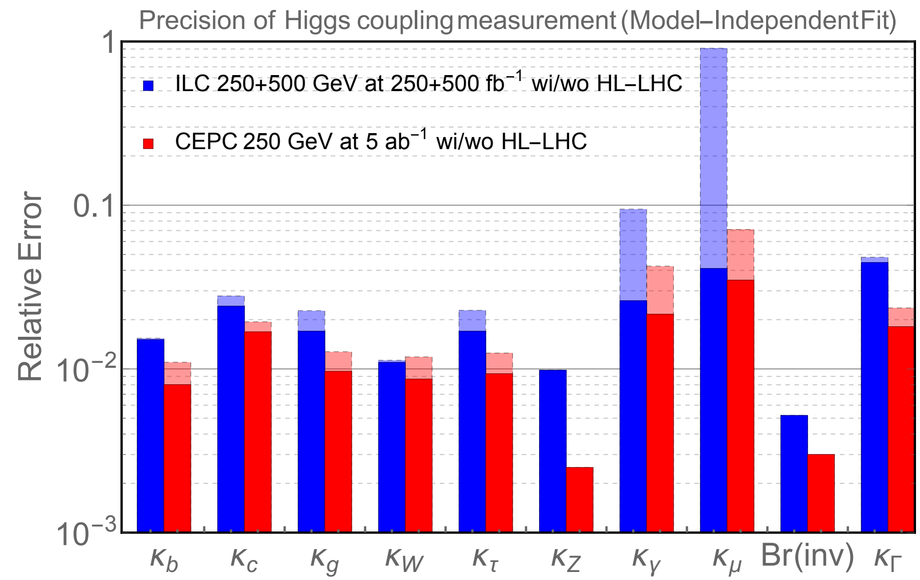
Table 4: Statistical precision for Higgs measurements obtained from the proposed TLEP programme at $\sqrt{s} = 240$ GeV only (shown in Table 3). For illustration, the baseline ILC figures at $\sqrt{s} = 250$ GeV, taken from Ref. [6], are also given. The order-of-magnitude smaller accuracy expected at 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.



From TLEP (FCC-ee) publication 1308.6176.

Precision at Higgs factory

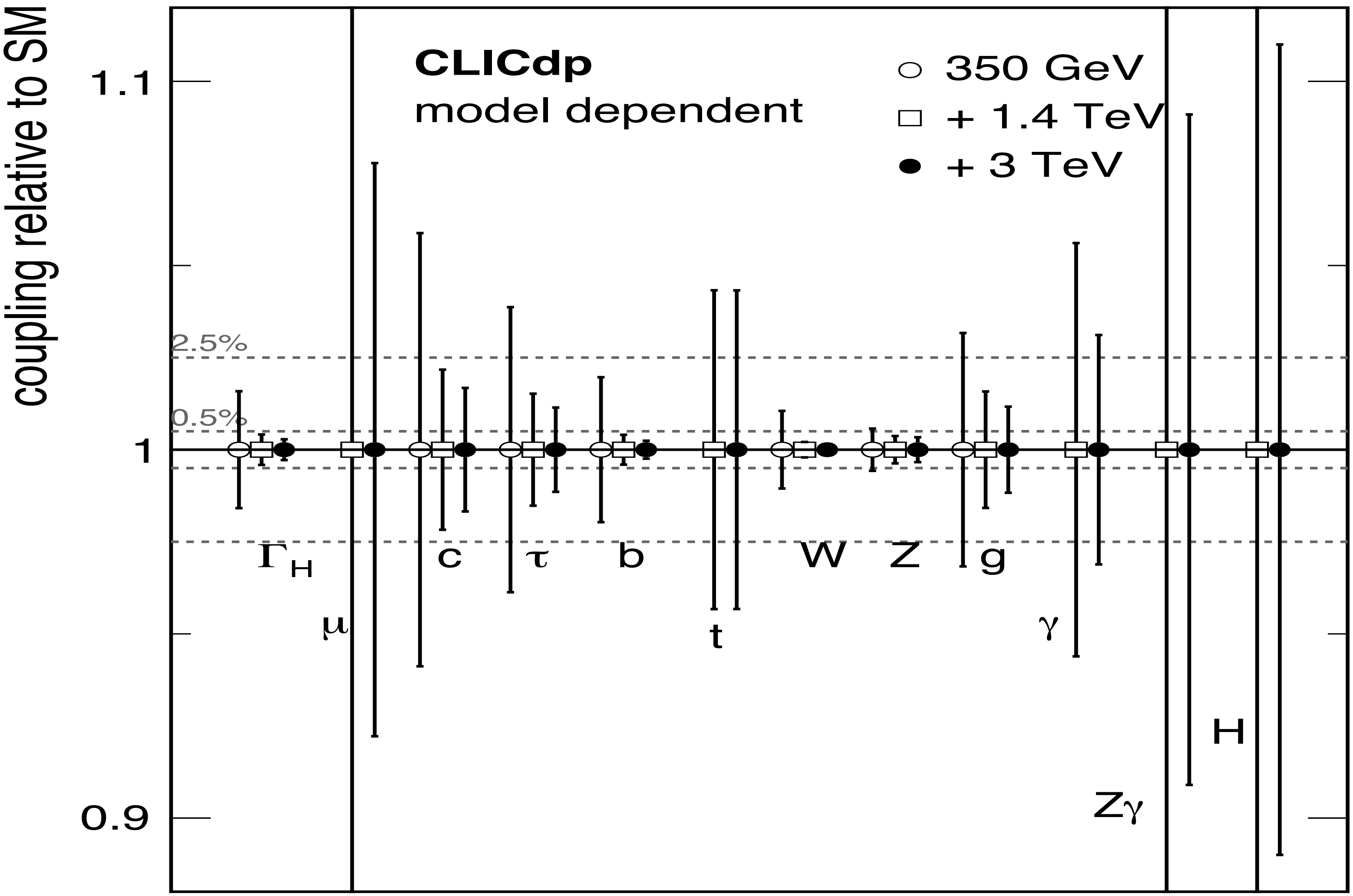




$$\kappa_X = \frac{\text{Measured Higgs-X coupling}}{\text{Standard Model Higgs-X coupling}}$$

Wang, MCTP Higgs Symposium, `15

CLIC Projections



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

CLIC Higgs Study, 1608.07538

Theory Issues

We shall come to new physics soon.

However, SM theory errors threaten the usefulness of percent-level Higgs measurements.

For example, measurements of σ x Br(bb) is at percent level or lower at ILC, FCC-ee and CLIC.

Errors at few percent level, relevant to LHC-HL, also need attention.

Tremendous work going into this.

Channel	M_H [GeV]	Γ [MeV]	$\Delta\alpha_s$	Δm_b	Δm_c	Δm_t	THU
$H \rightarrow bb$	122	2.30	−2.3% +2.3%	+3.2% −3.2%	+0.0% −0.0%	+0.0% −0.0%	+2.0% −2.0%
	126	2.36	−2.3% +2.3%	+3.3% −3.2%	+0.0% −0.0%	+0.0% −0.0%	+2.0% −2.0%
	130	2.42	−2.4% +2.3%	+3.2% −3.2%	+0.0% −0.0%	+0.0% −0.0%	+2.0% −2.0%
$H \rightarrow \mu^+\mu^-$	122	$8.71 \cdot 10^{-4}$	+0.0% +0.0%	+0.0% −0.0%	+0.0% −0.0%	+0.1% −0.1%	+2.0% −2.0%
	126	$8.99 \cdot 10^{-4}$	+0.0% +0.0%	+0.0% −0.0%	−0.1% −0.0%	+0.0% −0.1%	+2.0% −2.0%
	130	$9.27 \cdot 10^{-4}$	+0.1% +0.0%	+0.0% −0.0%	+0.0% −0.0%	+0.1% −0.0%	+2.0% −2.0%
$H \rightarrow c\bar{c}$	122	$1.16 \cdot 10^{-1}$	−7.1% +7.0%	−0.1% +0.1%	+6.2% −6.0%	+0.0% −0.1%	+2.0% −2.0%
	126	$1.19 \cdot 10^{-1}$	−7.1% +7.0%	−0.1% +0.1%	+6.2% −6.1%	+0.0% −0.1%	+2.0% −2.0%
	130	$1.22 \cdot 10^{-1}$	−7.1% +7.0%	−0.1% +0.1%	+6.3% −6.0%	+0.1% −0.1%	+2.0% −2.0%
$H \rightarrow \gamma\gamma$	122	$8.37 \cdot 10^{-3}$	+0.0% −0.0%	+0.0% −0.0%	+0.0% −0.0%	+0.0% −0.0%	+1.0% −1.0%
	126	$9.59 \cdot 10^{-3}$	+0.0% −0.0%	+0.0% −0.0%	+0.0% −0.0%	+0.0% −0.0%	+1.0% −1.0%
	130	$1.10 \cdot 10^{-2}$	+0.1% −0.0%	+0.0% −0.0%	+0.0% −0.0%	+0.0% −0.0%	+1.0% −1.0%

Table 1: SM Higgs partial widths and their relative parametric (PU) and theoretical (THU) uncertainties for a selection of Higgs masses. For PU, all the single contributions are shown. For these four columns, the upper percentage value (with its sign) refers to the positive variation of the parameter, while the lower one refers to the negative variation of the parameter.

Handbook of LHC Higgs Cross Sections. 3. Higgs Properties (2013)

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)

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

Almeida, Lee, Pokorski, JW 2013

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.

Compare this with LHC Cross Sections Handbook, which upon first look appears to have little uncertainty on H→WW.

		Γ [MeV]					
$H \to WW$	122	$6.25 \cdot 10^{-1}$	$^{+0.0\%}_{-0.0\%}$	$^{+0.0\%}_{-0.0\%}$	$^{+0.0\%}_{-0.0\%}$	$^{+0.0\%}_{-0.0\%}$	$^{+0.5\%}_{-0.5\%}$
	126	$9.73 \cdot 10^{-1}$	$^{+0.0\%}_{-0.0\%}$	$^{+0.0\%}_{-0.0\%}$	$^{+0.0\%}_{-0.0\%}$	$^{+0.0\%}_{-0.0\%}$	$^{+0.5\%}_{-0.5\%}$
	130	1.49	$^{+0.0\%}_{-0.0\%}$	$^{+0.0\%}_{-0.0\%}$	$^{+0.0\%}_{-0.0\%}$	$^{+0.0\%}_{-0.0\%}$	$^{+0.5\%}_{-0.5\%}$

There is no mistake in table. Each row is for fixed m_H. But notice how strongly the BR changes from 122 to 126 to 130 GeV.

	Δ_{m_t}	Δ_{m_H}	$\Delta_{\alpha(M_Z)}$	$\Delta_{\alpha_S(M_Z)}$	Δ_{m_b}	Δ_{M_Z}	Δ_{m_c}	Δ_{m_τ}	Δ_{G_F}
gg	0.07	0.46 (0.12)	0.01	1.77	1.00	0.01	0.15	-	-
$\gamma\gamma$	-	0.01 (-)	0.03	0.31	0.94	-	0.15	-	-
$b\bar{b}$	0.02	1.13 (0.28)	0.01	0.36	0.74	0.01	0.15	-	-
$c\bar{c}$	0.01	1.13 (0.28)	0.01	1.53	0.95	0.01	5.08	-	-
$\tau^+\tau^-$	0.04	1.07 (0.27)	0.01	0.30	0.95	0.01	0.15	0.02	-
WW^*	0.04	2.97 (0.74)	0.04	0.30	0.95	0.02	0.15	-	-
ZZ^*	0.03	3.48 (0.87)	0.02	0.30	0.95	0.02	0.15	-	-
$Z\gamma$	0.01	2.14 (0.53)	-	0.30	0.96	-	0.15	-	-
$\mu^+\mu^-$	0.04	1.07 (0.27)	0.01	0.30	0.95	0.01	0.15	-	-

Almeida, Lee, Pokorski, JW 2013

Uncertainties on the ***branching fractions*** due to uncertainties in the input observables.

Note, due to Γ(bb) in the denominator of all BRs, the uncertainties due to m_b and α_s propagate to all others.

In Higgs column, uncertainty is due to Δm_H=400 MeV (100 MeV)

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. However, Lepage et al (2014) have pointed out that lattice results can help. For example: estimates are that Δm_b, Δm_c and $\Delta\alpha_s$ could be reduced by more than a factor of 7, 3 and 6 respectively.

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

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

[Denner et al, 1107.5909]
[Almeida, Lee, Pokorski, Wells, 1311.6721]
[Lepage, Mackenzie, Peskin, 1404.0319]

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

From PDG particle listings:

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

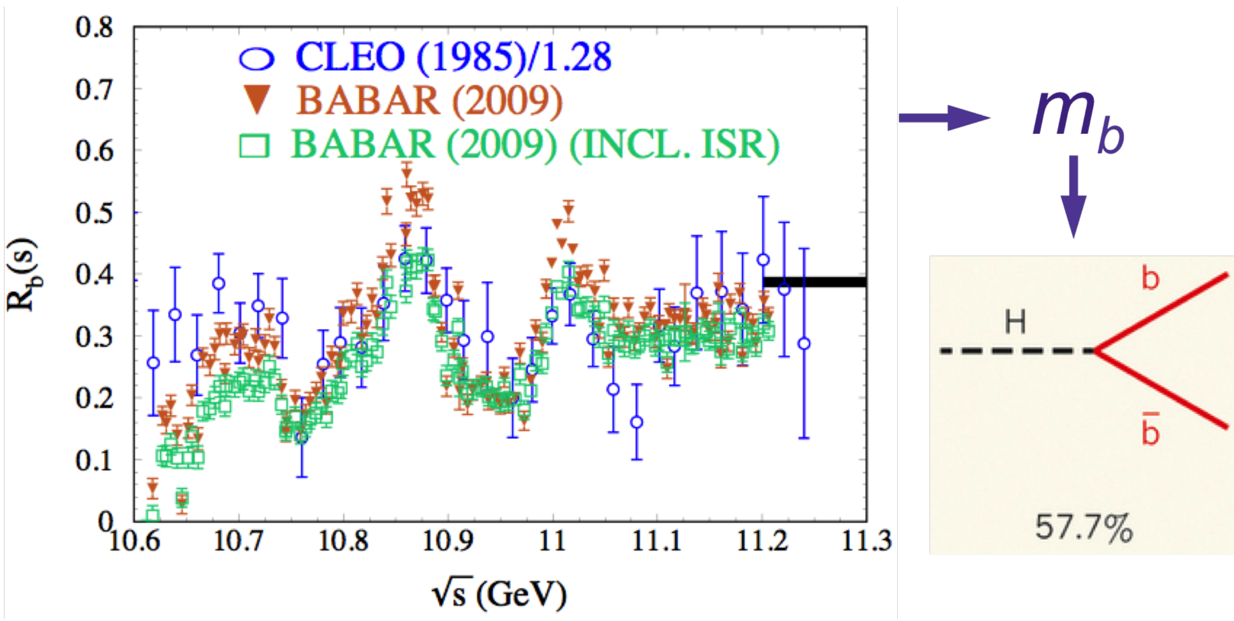
$\Rightarrow$ A few % theory uncertainty in $\Gamma_{H\to c\bar{c}}$, $\Gamma_{H\to b\bar{b}}$ – too large!

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

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

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

[Kuhn, Steinhauser, hep-ph/0109084]

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

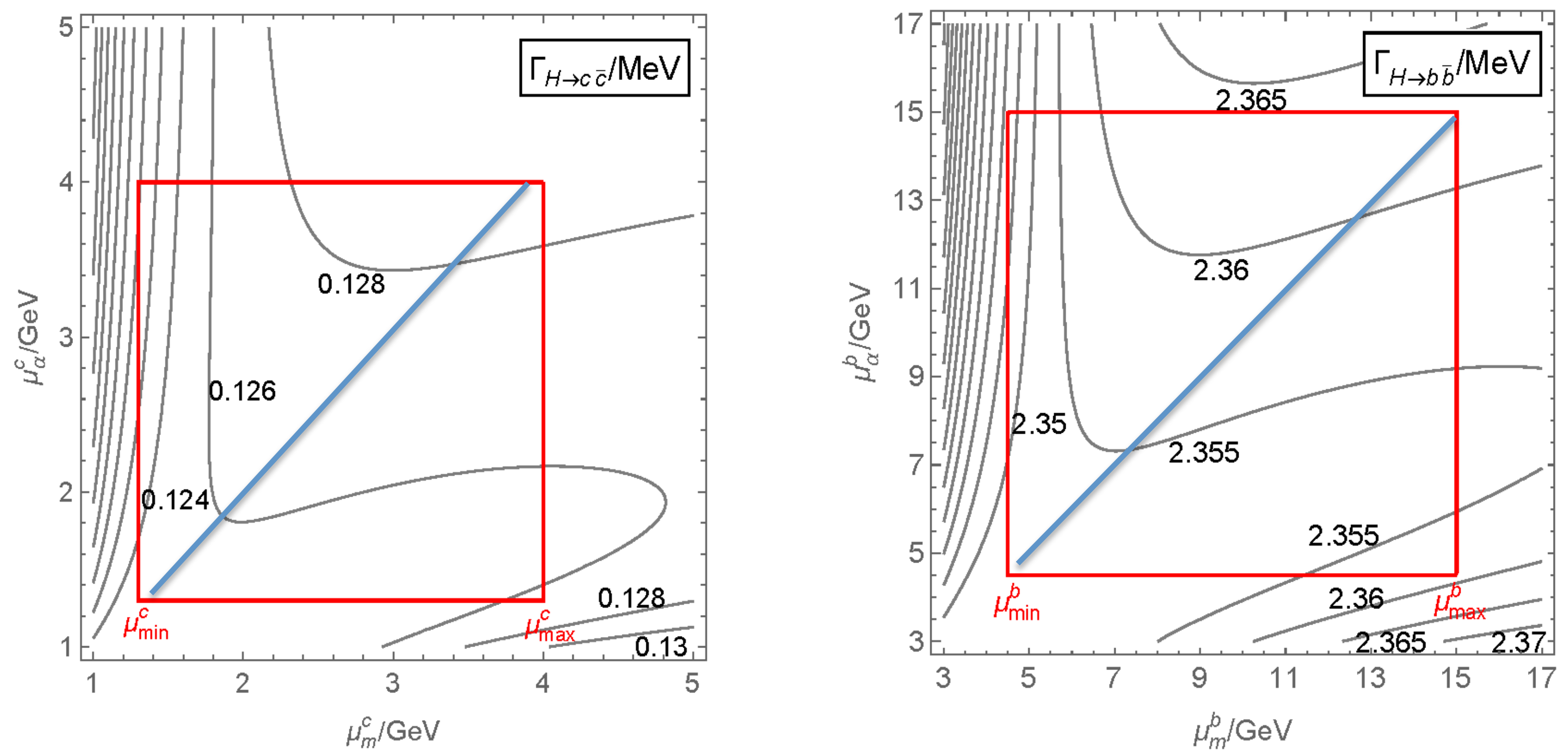
[Chetyrkin, Kuhn, Maier, Maierhofer, Marquard, Steinhauser, Sturm, 0907.2110]

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

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

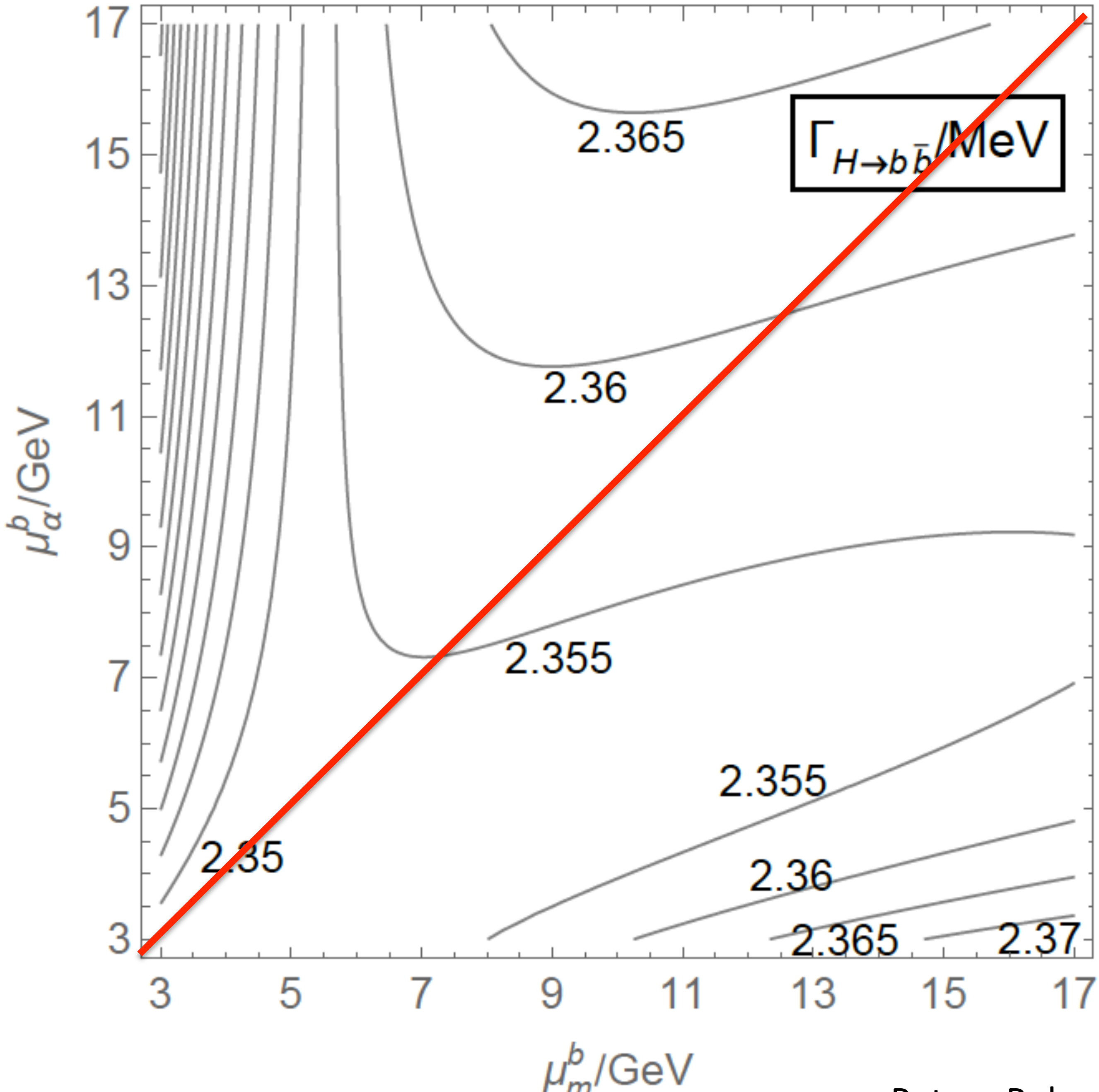
Perturbative part of $\mathcal{M}_n^Q$ is known only up to $\mathcal{O}\left(\alpha_s^3\right)$.

Uncertainty due to missing higher-order corrections is usually estimated from renormalization scale dependence.



Vary μ_m, μ_α within $[\mu_{\min}, \mu_{\max}]$ $\Rightarrow$ estimated perturbative uncertainty is very sensitive to $\mu_{\min}$.

Zhang, Charm '15



Petrov Pokorski, JW, Zhang

Low-energy observables play an important role in precision Higgs analysis due to their connection with m_c, m_b.

By directly working with low-energy observables $\mathcal{M}_1^c$, $\mathcal{M}_2^b$, we get a more detailed understanding of theory uncertainties in $\Gamma_{H\to c\bar{c}}$, $\Gamma_{H\to b\bar{b}}$.

What about *other* low-energy observables and Higgs observables?

$$\left\{\begin{matrix} \widehat{O}_1^{\rm low}(m_c, m_b, \alpha_s, \dots) \\ \widehat{O}_2^{\rm low}(m_c, m_b, \alpha_s, \dots) \\ \widehat{O}_3^{\rm low}(m_c, m_b, \alpha_s, \dots) \\ \vdots \end{matrix}\right\} \Leftarrow \left\{\begin{matrix} \underline{\text{Inputs}} \\ m_c \\ m_b \\ \alpha_s \\ \vdots \end{matrix}\right\} \Rightarrow \left\{\begin{matrix} \widehat{O}_1^{\rm Higgs}(m_c, m_b, \alpha_s, \dots) \\ \widehat{O}_2^{\rm Higgs}(m_c, m_b, \alpha_s, \dots) \\ \widehat{O}_3^{\rm Higgs}(m_c, m_b, \alpha_s, \dots) \\ \vdots \end{matrix}\right\}$$

A global fit ...

Zhang, Charm '15

Now that there is a theory setup and an experimental program to contemplate, let's ask an important question:

How well do we need to measure the couplings?

Fine to ask how well colliders can do, but important to ask:

How well do we need to measure the Higgs boson coupling?

<u>Criterion</u>: What are 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.

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.

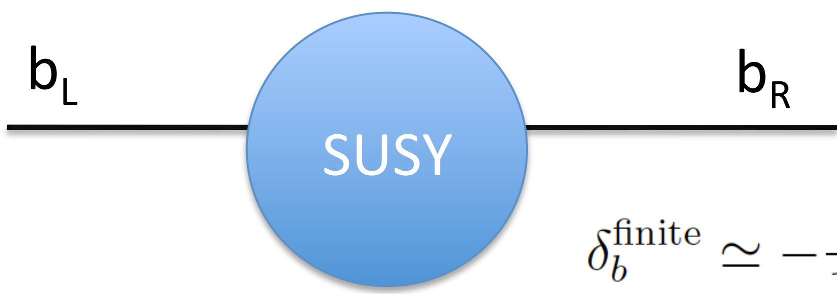
Corrections to Higgs Couplings in MSSM

Two leading corrections are

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

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

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



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

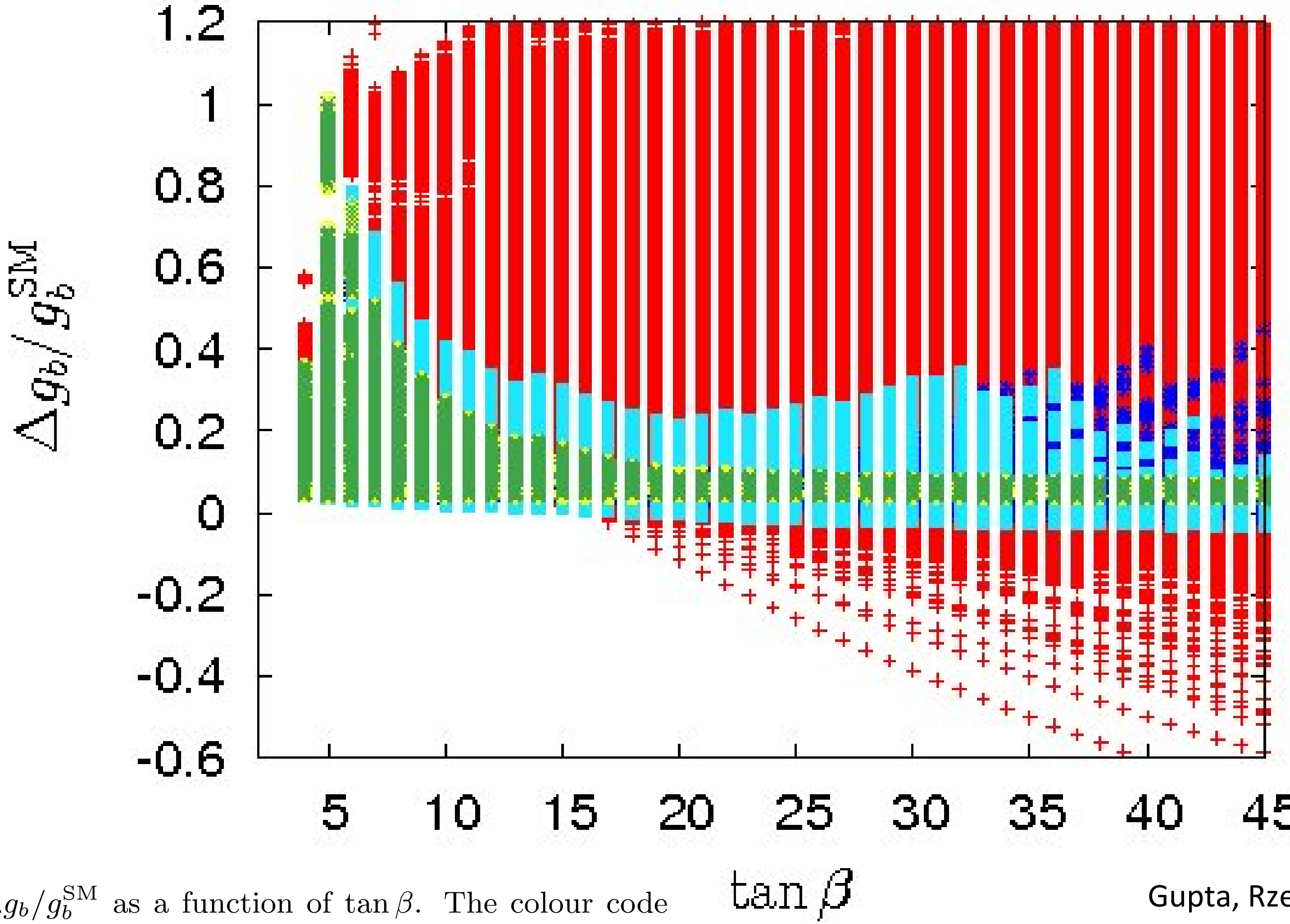


FIG. 9: $\Delta g_b/g_b^{\rm SM}$ as a function of $\tan\beta$. The colour code is the following: Red means several Higgs bosons can be discovered at the LHC - all the other points correspond to a single Higgs boson discovery at the LHC. Dark blue points are excluded by the $\Gamma(b \to s\gamma)$ constraint. 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.

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Smaller tanβ correlated with lower heavy Higgs masses going undetected.

Composite Higgs Theories

Several different ways composite Higgs can show up:

1. Precision Electroweak
2. **Higgs boson decay branching fraction deviations**
3. Higgs boson production cross-section deviations
4. Double Higgs production (key new enhanced observable)
5. Rho-meson resonance discovery and other dynamics

Different models have different priorities among these observables.

Even if rho-meson is found quickly at LHC, or other observable deviations come first, the precise study of all other observables is complementary and pins down the theory.

Hard to make definitive statement, but ~ 10% deviation possible.

Mixed-In Singlets

A word on the case of condensing singlet coupled to the Higgs.

Overall 6% deviations on Higgs couplings could be universally present with no other phenomena found (heavy Higgs) after 14 TeV LHC runs for 3 ab^{-1}.

Extra condensing Higgs boson – singlet under SM
- Constraints/searches: Precision EW, heavy Higgs search, and precision light Higgs alterations

Higgs Masses and Mixings

$$\begin{aligned} \mathcal{L}_\Phi &= |D_\mu \Phi_{SM}|^2 + |D_\mu \Phi_H|^2 + m^2_{\Phi_H}|\Phi_H|^2 + m^2_{\Phi_{SM}}|\Phi_{SM}|^2 \\ &\quad -\lambda|\Phi_{SM}|^4 - \rho|\Phi_H|^4 - \kappa|\Phi_{SM}|^2|\Phi_H|^2. \end{aligned} \tag{3}$$

$$\begin{pmatrix} \phi_{SM} \\ \phi_H \end{pmatrix} = \begin{pmatrix} c_h & s_h \\ -s_h & c_h \end{pmatrix} \begin{pmatrix} h \\ H \end{pmatrix}$$

The mixing angle and mass eigenvalues are

$$\tan(2\theta_h) = \frac{\kappa v \xi}{\rho\xi^2 - \lambda v^2}$$

$$M^2_{h,H} = (\lambda v^2 + \rho\xi^2) \mp \sqrt{(\lambda v^2 - \rho\xi^2)^2 + \kappa^2 v^2 \xi^2}$$

SUMMARY of “Higgs Targets”

	ΔhVV	$\Delta h\bar{t}t$	$\Delta h\bar{b}b$
Mixed-in Singlet	6%	6%	6%
Composite Higgs	8%	tens of %	tens of %
Minimal Supersymmetry	$< 1\%$	3%	$10\%^a$, $100\%^b$
LHC 14 TeV, $3\,\mathrm{ab}^{-1}$	8%	10%	15%

TABLE I: Summary of the physics-based targets for Higgs boson couplings to vector bosons, top quarks, and bottom quarks. The target is based on scenarios where no other exotic electroweak symmetry breaking state (e.g., new Higgs bosons or ρ particle) is found at the LHC except one: the $\sim 125\,\mathrm{GeV}$ SM-like Higgs boson. For the $\Delta h\bar{b}b$ values of supersymmetry, superscript a refers to the case of high $\tan\beta > 20$ and no superpartners are found at the LHC, and superscript b refers to all other cases, with the maximum 100% value reached for the special case of $\tan\beta \simeq 5$. The last row reports anticipated 1σ LHC sensitivities at 14 TeV with $3\,\mathrm{ab}^{-1}$ of accumulated luminosity [5].

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Conclusions

Higgs couplings measurements must be done in global fit to the data.

LHC will make helpful improvements.

Percent-level targets needed may require future facilities.

Extra connected Higgses and their associated observables can be challenging and require high luminosity to see.