Precision Higgs Analysis

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Lecture 3, CERN May 29, 2015

Higgs Boson Observables

Our consideration is Higgs boson observables:

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

Precise theory predictions include knowing precisely the theory predictions for

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

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.

In this approach, you are primarily limited to listing experimental measurements and their errors, and compare with SM calculations – using tables, plots, χ^2 analysis, etc.

For example, with the SM you cannot talk about measuring the Higgs coupling to bottom quarks. All you can talk about is extracting the Yukawa coupling y_b, and its uncertainties, through observables via a global fit of 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.

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:

I will call this the "Higgs kappa Standard Model" (HκSM).

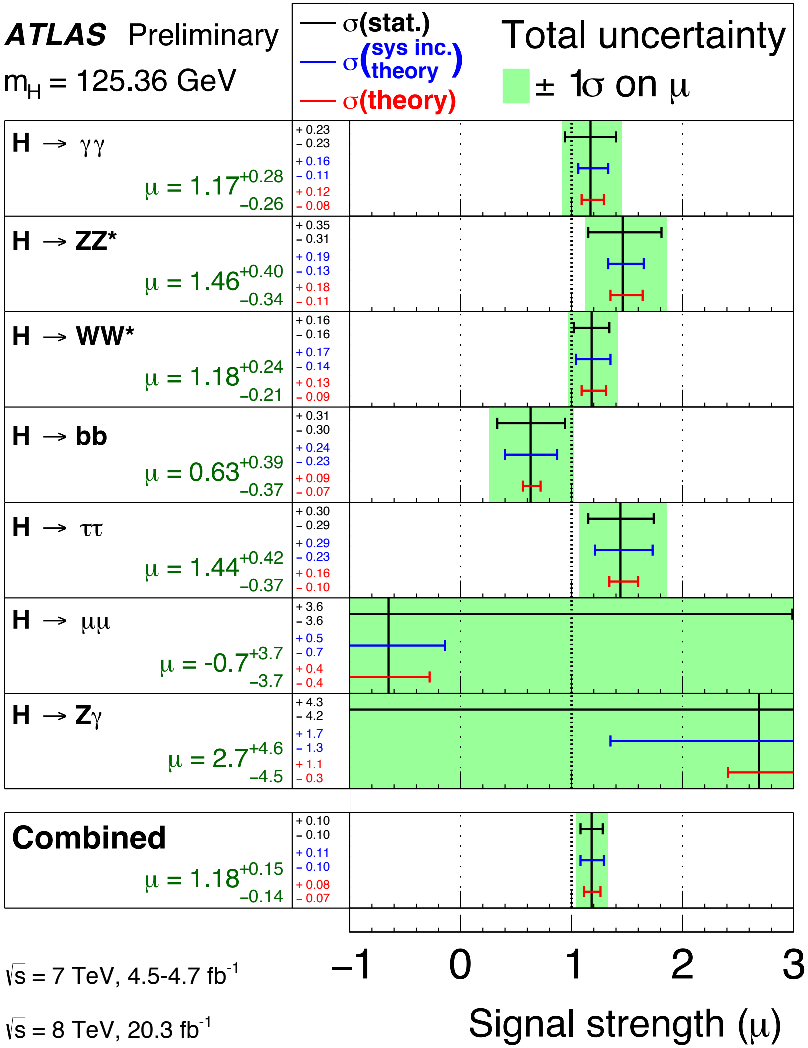
It is parametrized by κ's, which are defined by replacing

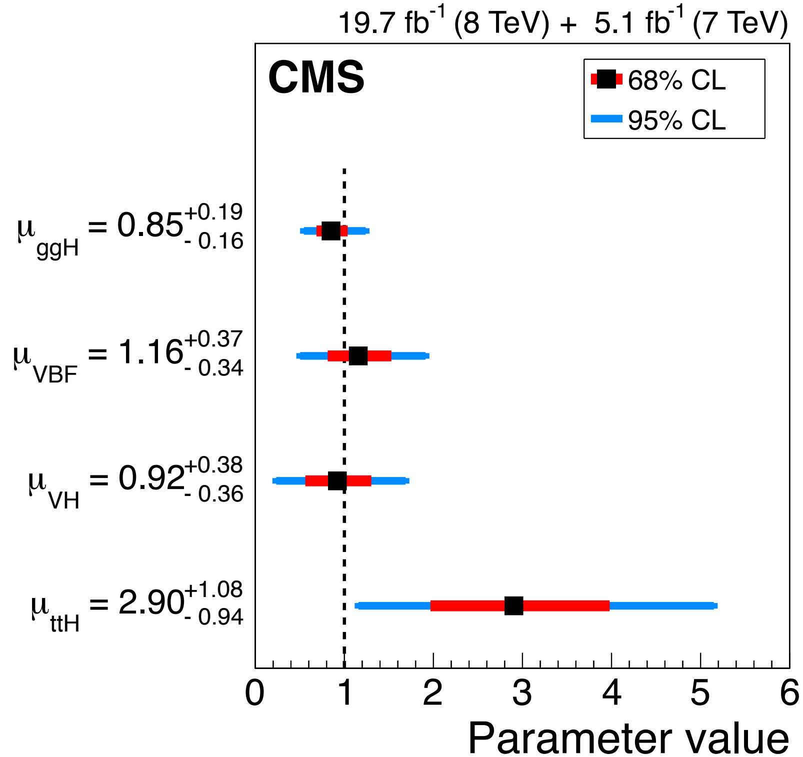
$g(hAA)_{SM} \rightarrow \kappa_A\, g(hAA)_{SM}$; other interactions remain SM.

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.)

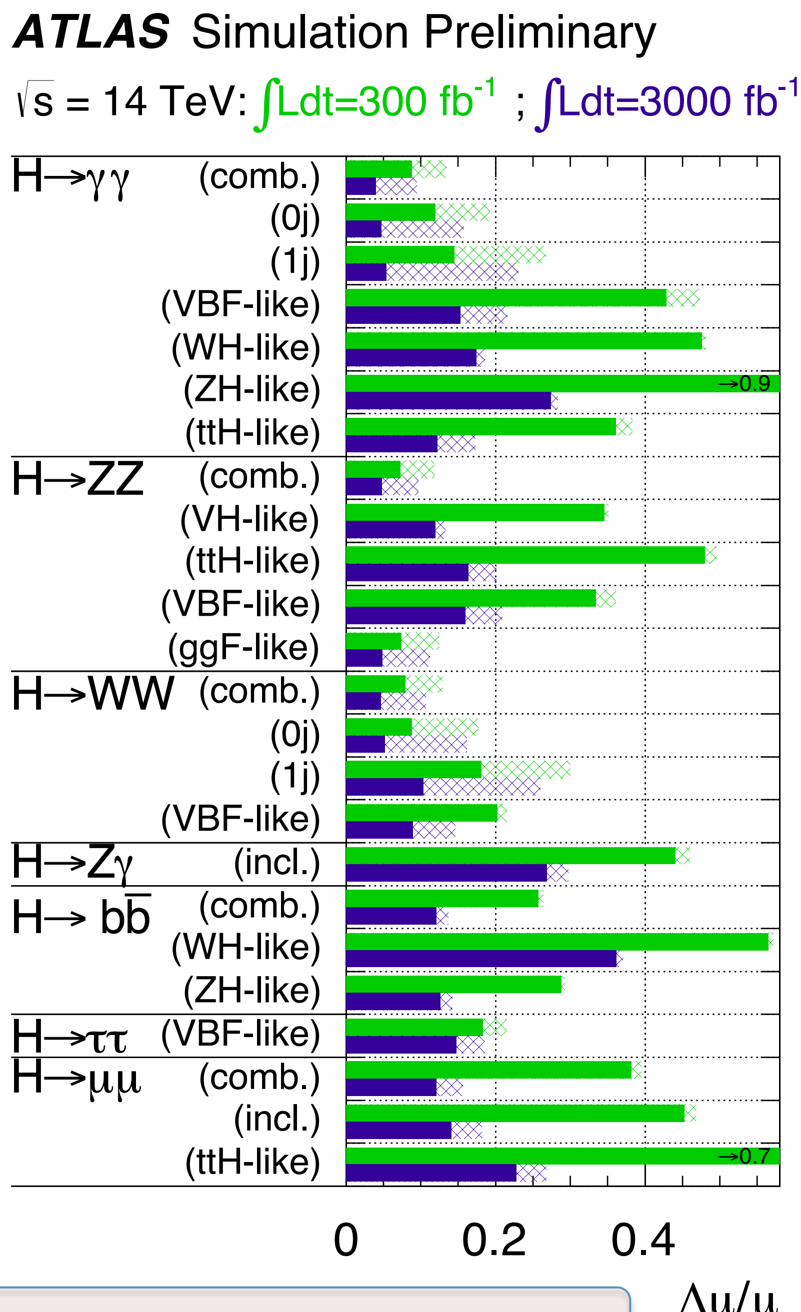
Current Status



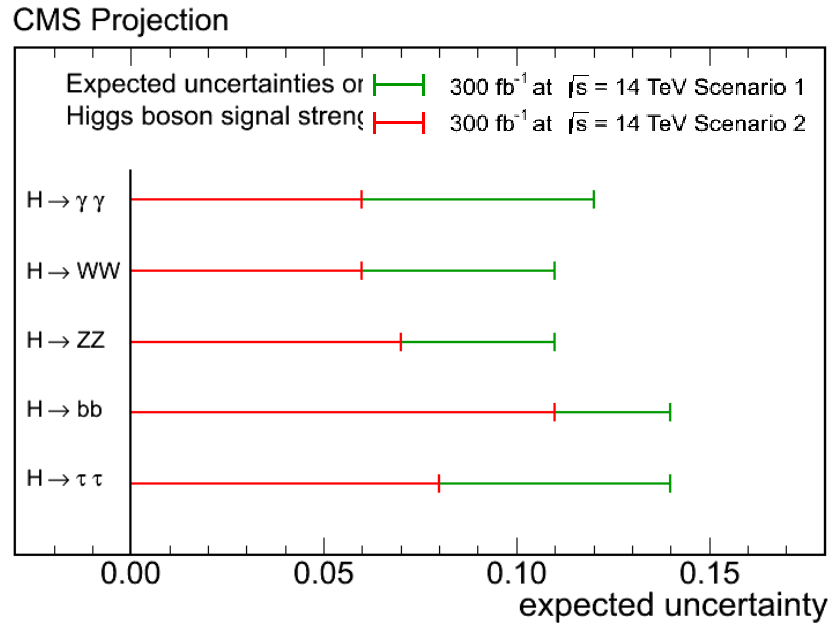


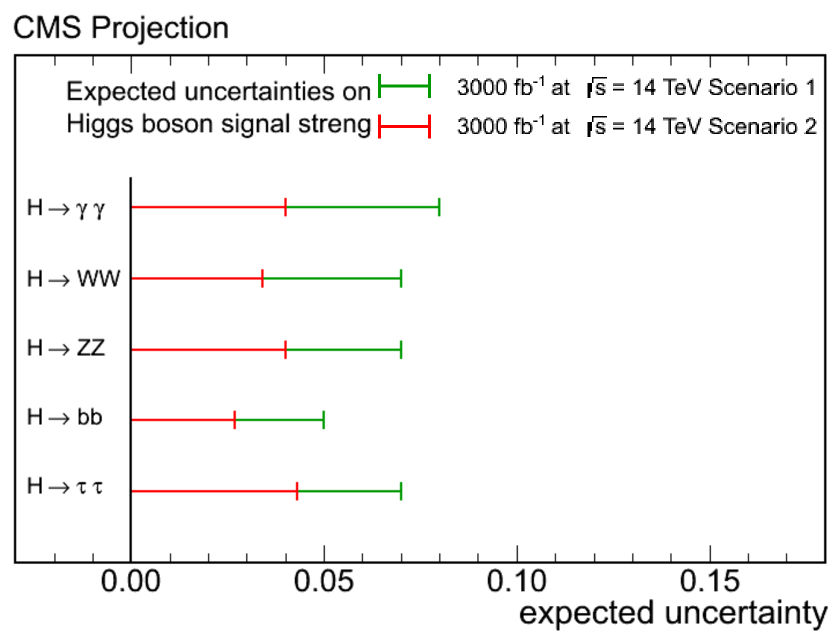
- Precise measurements of diboson decay modes (theoretical uncertainties become relevant!)
- Some channels (e.g. $H \to b\bar{b}$) dominated by exp. uncertainties
- Rare decay modes statistics limited

Gadatsch, HL-LHC Workshop, `15



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

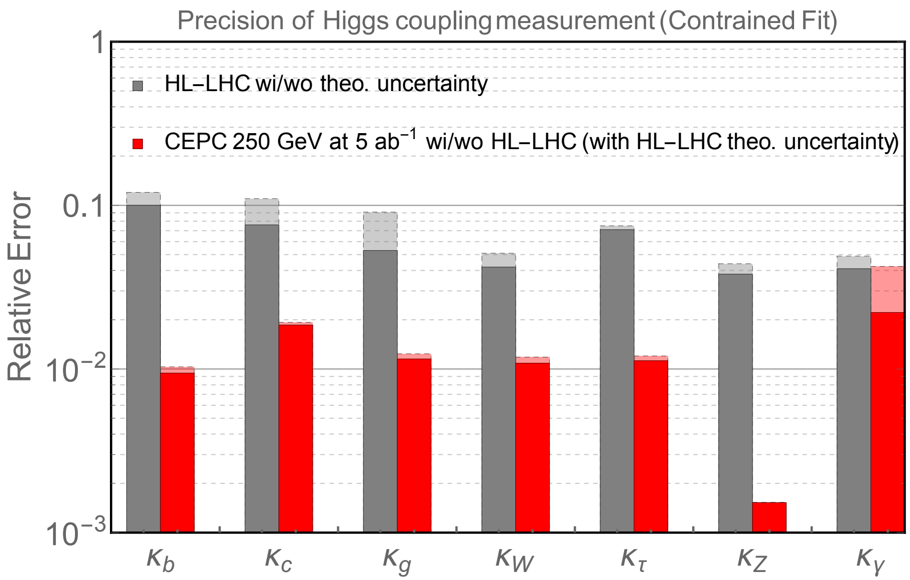
Typically in the neighborhood of a few percent.

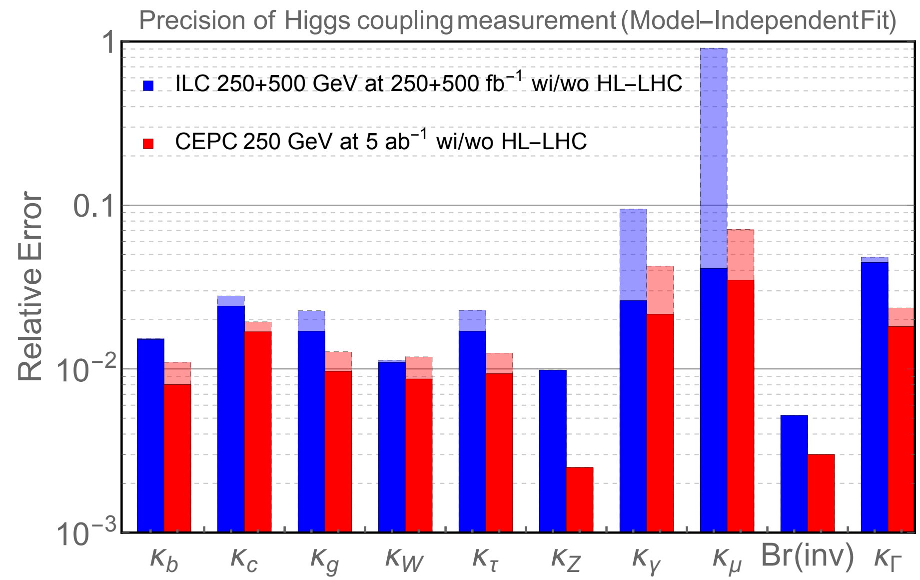
TLEP / FCC-ee Estimates

	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





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

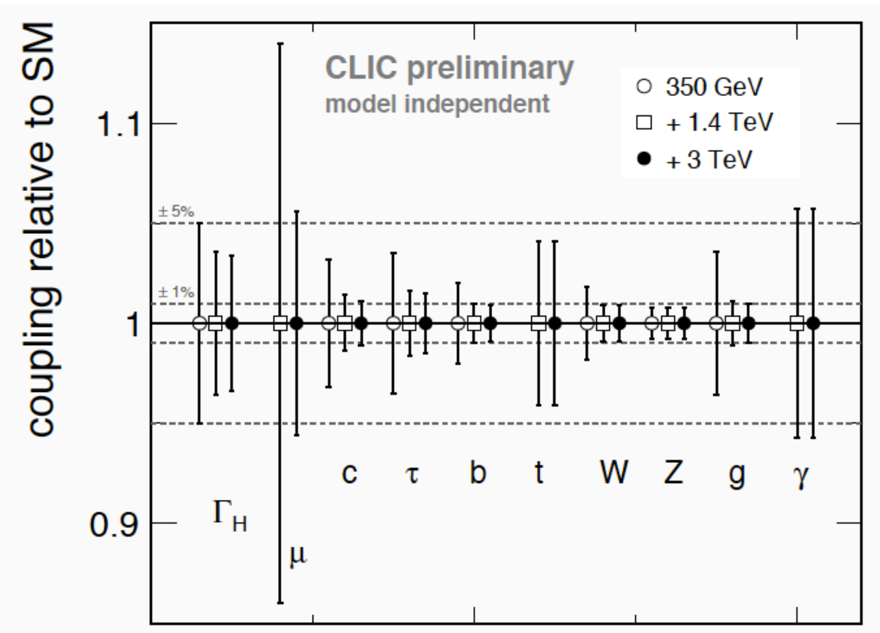
Wang, MCTP Higgs Symposium, `15

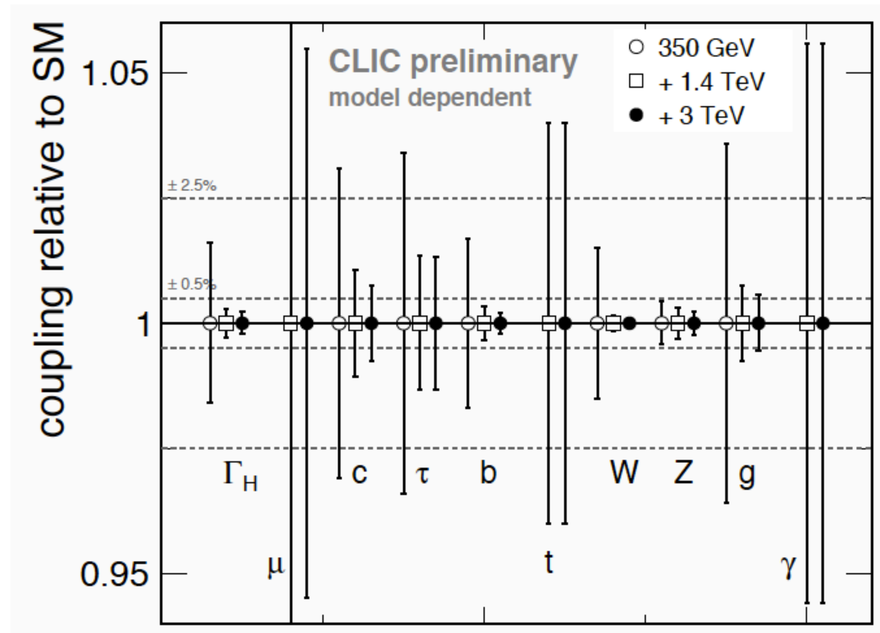
Global fits

CLIC

Eva Sicking, ICHEP 2014

- Fit of presented statistical precisions → extract couplings and Higgs width
- Fit results at higher energy include measurements from lower energies





- Fully model independent approach, unique for lepton colliders
- All results are limited by 0.9 % from $\sigma(HZ)$ measurement
- Higgs width extraction with 5-4 % precision

- LHC-like constraints: no invisible decays, fixed total width
- Sub-percent precision at high energies
- Higgs width extraction with 1.7-0.2 % precision

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, TLEP 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
$\mathrm{H} \to \mathrm{bb}$	122	2.30	−2.3%	+3.2%	+0.0%	+0.0%	+2.0%
			+2.3%	−3.2%	−0.0%	−0.0%	−2.0%
	126	2.36	−2.3%	+3.3%	+0.0%	+0.0%	+2.0%
			+2.3%	−3.2%	−0.0%	−0.0%	−2.0%
	130	2.42	−2.4%	+3.2%	+0.0%	+0.0%	+2.0%
			+2.3%	−3.2%	−0.0%	−0.0%	−2.0%
$\mathrm{H} \to \mu^+\mu^-$	122	$8.71\cdot10^{-4}$	+0.0%	+0.0%	+0.0%	+0.1%	+2.0%
			+0.0%	−0.0%	−0.0%	−0.1%	−2.0%
	126	$8.99\cdot10^{-4}$	+0.0%	+0.0%	−0.1%	+0.0%	+2.0%
			+0.0%	−0.0%	−0.0%	−0.1%	−2.0%
	130	$9.27\cdot10^{-4}$	+0.1%	+0.0%	+0.0%	+0.1%	+2.0%
			+0.0%	−0.0%	−0.0%	−0.0%	−2.0%
$\mathrm{H} \to \mathrm{c}\bar{\mathrm{c}}$	122	$1.16\cdot10^{-1}$	−7.1%	−0.1%	+6.2%	+0.0%	+2.0%
			+7.0%	+0.1%	−6.0%	−0.1%	−2.0%
	126	$1.19\cdot10^{-1}$	−7.1%	−0.1%	+6.2%	+0.0%	+2.0%
			+7.0%	+0.1%	−6.1%	−0.1%	−2.0%
	130	$1.22\cdot10^{-1}$	−7.1%	−0.1%	+6.3%	+0.1%	+2.0%
			+7.0%	+0.1%	−6.0%	−0.1%	−2.0%
$\mathrm{H} \to \gamma\gamma$	122	$8.37\cdot10^{-3}$	+0.0%	+0.0%	+0.0%	+0.0%	+1.0%
			−0.0%	−0.0%	−0.0%	−0.0%	−1.0%
	126	$9.59\cdot10^{-3}$	+0.0%	+0.0%	+0.0%	+0.0%	+1.0%
			−0.0%	−0.0%	−0.0%	−0.0%	−1.0%
	130	$1.10\cdot10^{-2}$	+0.1%	+0.0%	+0.0%	+0.0%	+1.0%
			−0.0%	−0.0%	−0.0%	−0.0%	−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	$173.07(89)$
$\overline{\mathrm{MS}}$ mass m_c	$1.275(25)$	$\overline{\mathrm{MS}}$ 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.

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.

		BR					
$H \to WW$	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:

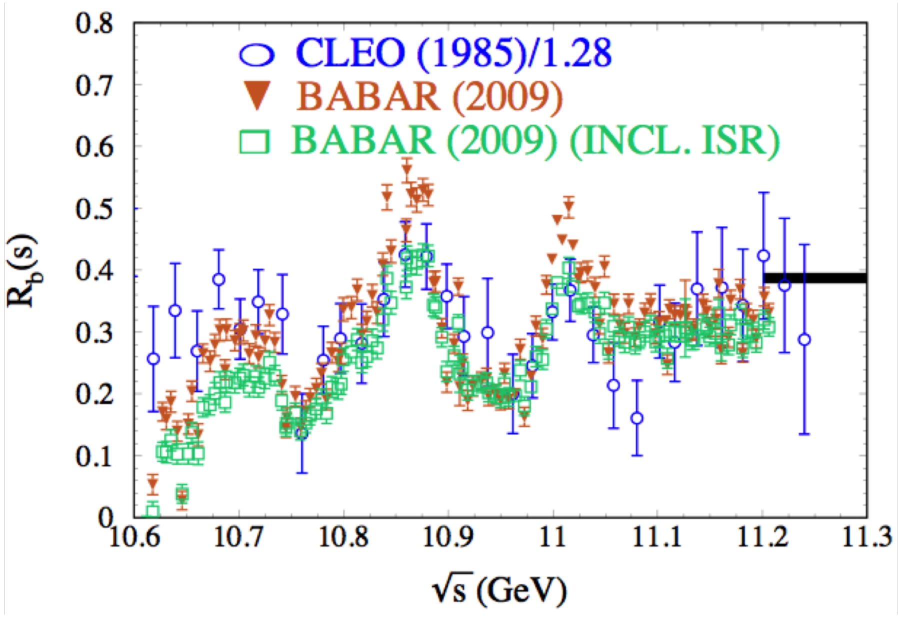
$$m_c(m_c) = 1.275(25)\ \mathrm{GeV}, \quad m_b(m_b) = 4.18(3)\ \mathrm{GeV}.$$

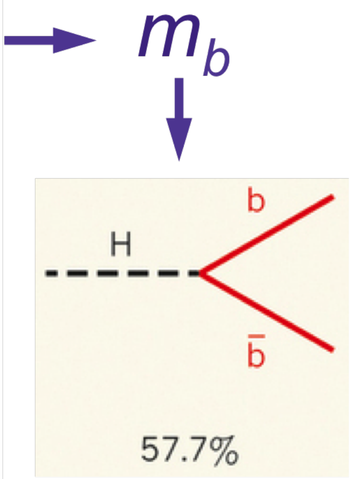
$\Rightarrow$ A few % theory uncertainty in $\Gamma_{H\to c\bar{c}}$, $\Gamma_{H\to b\bar{b}}$ – too large!

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

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

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

[Kuhn, Steinhauser, hep-ph/0109084]

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

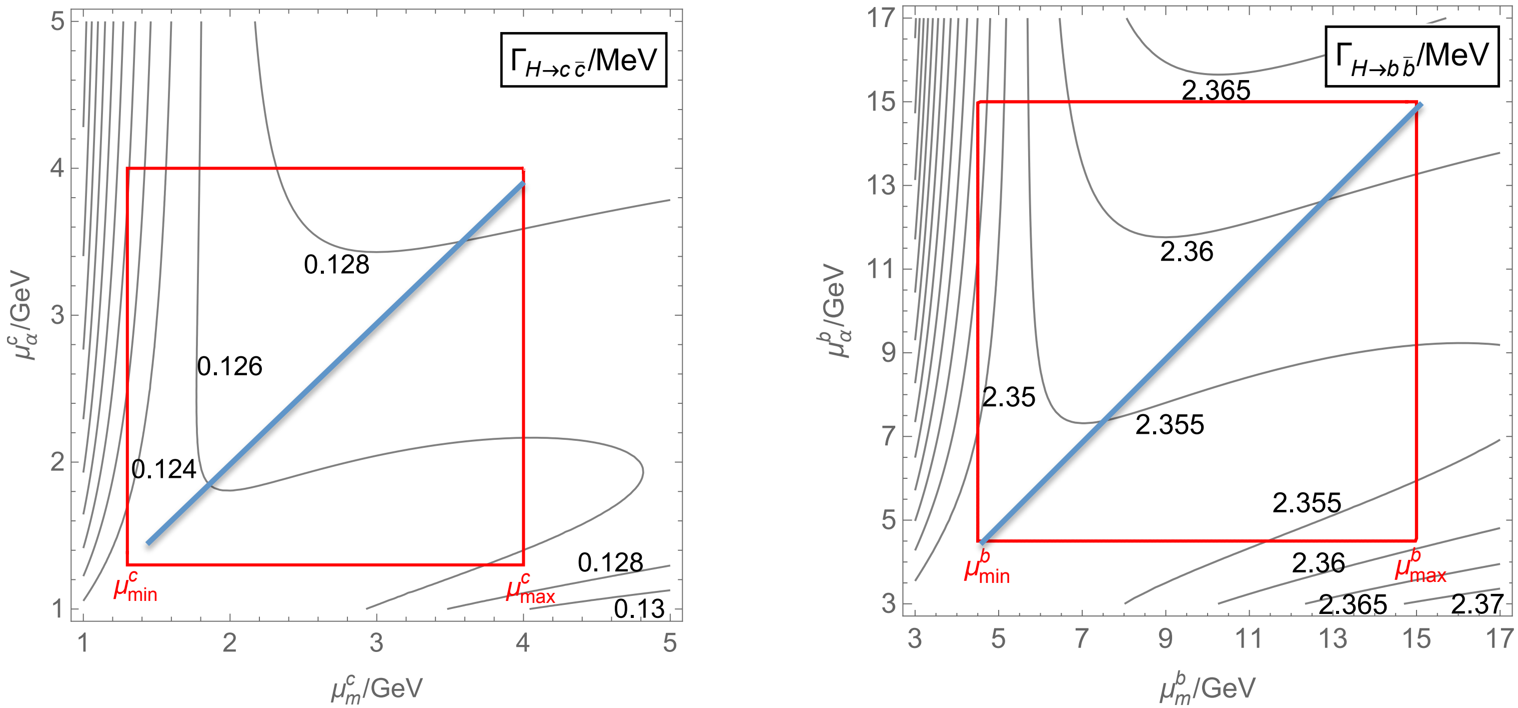
[Chetyrkin, Kuhn, Maier, Maierhofer, Marquard, Steinhauser, Sturm, 0907.2110]

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

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

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

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?

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

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.

Recall from Lecture 2:

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.

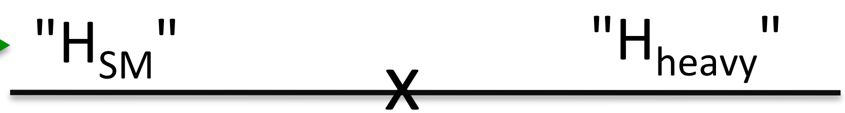
As supersymmetry gets heavier ($m_{3/2} >> M_Z$), a full doublet gets heavier together ($H^{\pm}$,A,H) while a solitary Higgs boson (h) stays light, and behaves just as the SM Higgs boson.

Corrections to Higgs Couplings in MSSM

Two leading corrections are

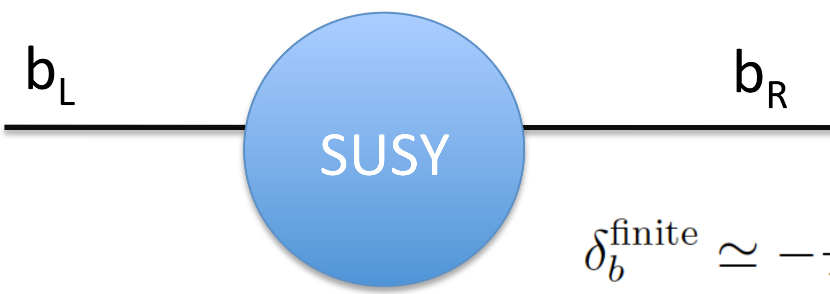
a) mixing of would-be SM Higgs with heavy Higgs

Not mass eigenstate



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

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



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

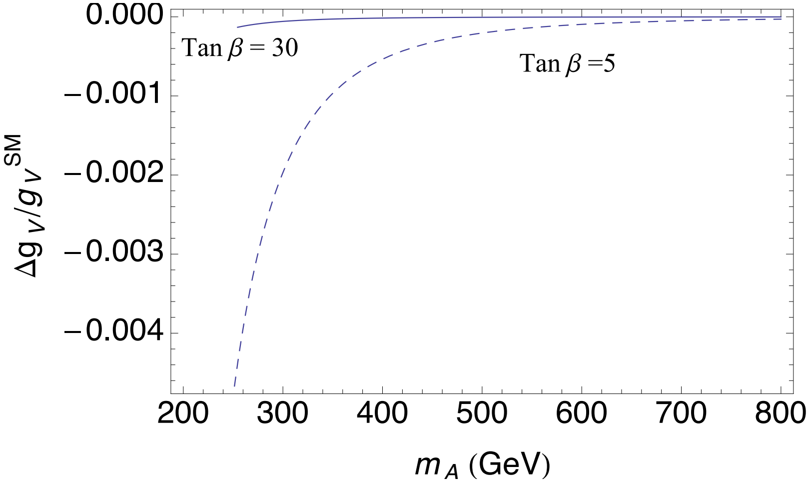


FIG. 3: $\Delta g_V / g_V^{SM}$ as a function of m_A with Δ_{22}, the radiative correction to the $\mathcal{M}_{22}^2$ entry of the Higgs mass matrix, chosen to obtain $m_h = 125\,\mathrm{GeV}$. Other values of $\Delta_{ij} = 0$. For the solid line we have taken $\tan\beta = 30$ and for the dashed line $\tan\beta = 5$.

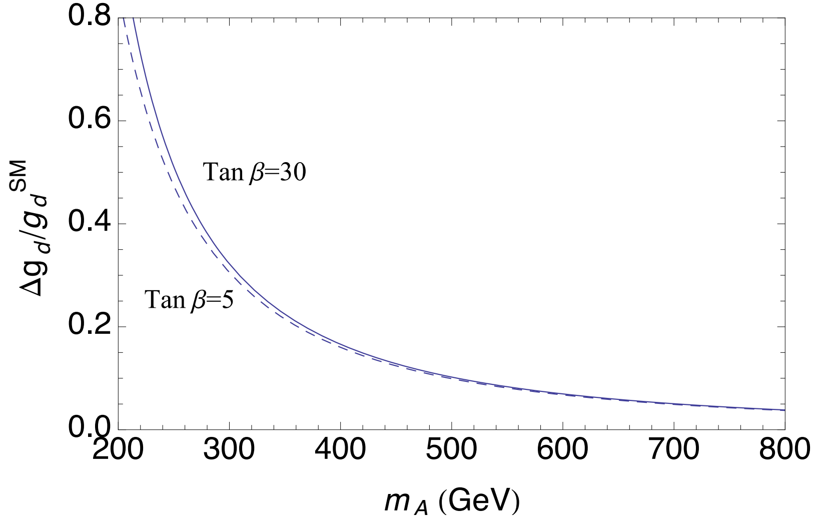


FIG. 5: We plot $\Delta g_d / g_d^{SM}$ as a function of m_A with Δ_{22}, the radiative correction to the $\mathcal{M}_{22}^2$ entry of the Higgs mass matrix, chosen to obtain $m_h = 125\,\mathrm{GeV}$. Other values of $\Delta_{ij} = 0$. For the solid line we have taken $\tan\beta = 30$ and for the dashed line $\tan\beta = 5$.

Gupta, Rzehak, JW, `13

These are baseline prediction that do not doesn't even include yet the delta m_b corrections.

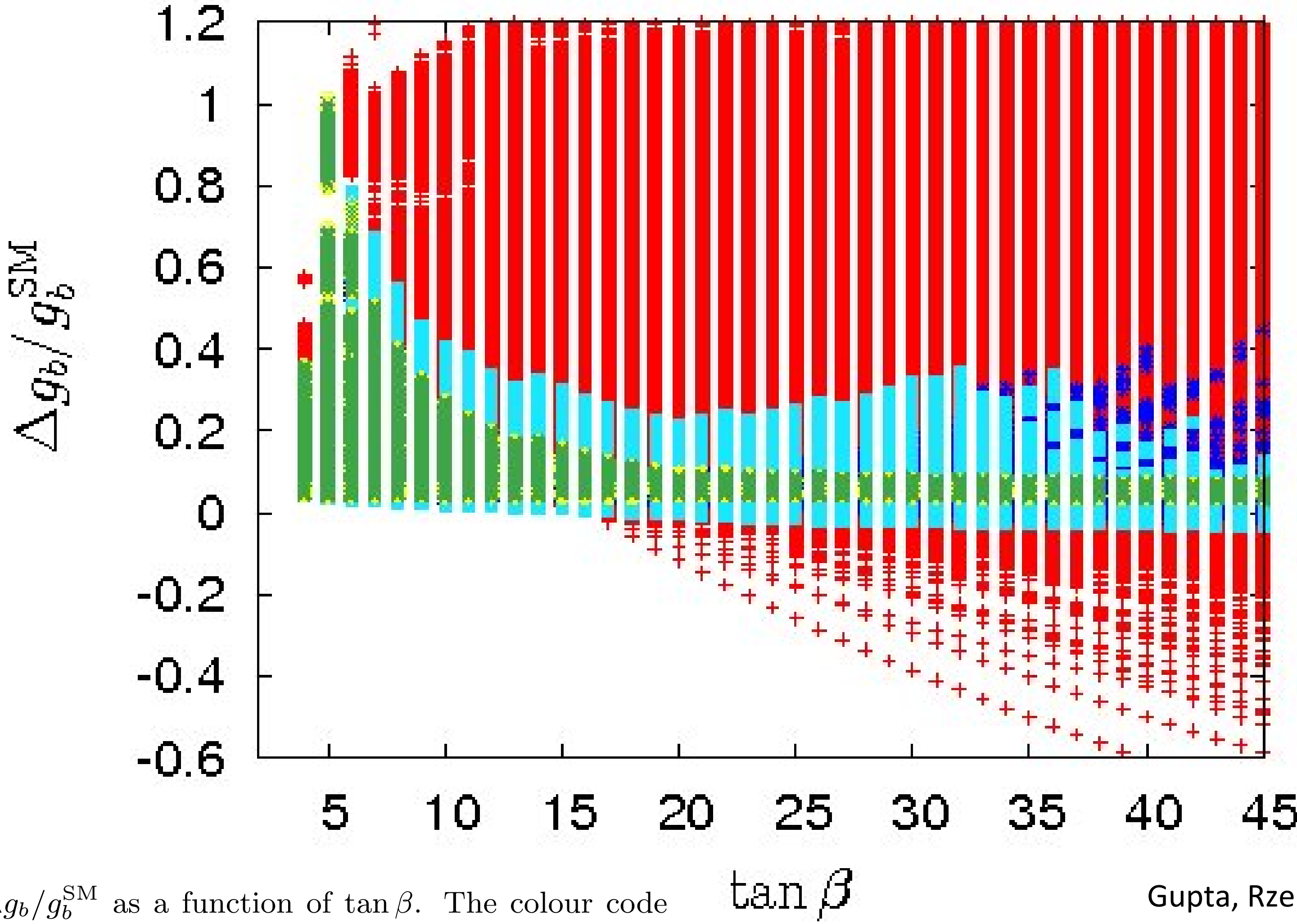


FIG. 9: $\Delta g_b/g_b^{\mathrm{SM}}$ as a function of $\tan\beta$. The colour code is the following: Red means several Higgs bosons can be discovered at the LHC - all the other points correspond to a single Higgs boson discovery at the LHC. Dark blue points are excluded by the $\Gamma(b \to s\gamma)$ 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, `13

Smaller tanβ correlated with lower heavy Higgs masses going undetected.

Composite Higgs Theory

$$
\begin{aligned}
\mathcal{L}_h = \xi \Bigg\{ & \frac{c_H}{2}\left(1+\frac{h}{v}\right)^2 \partial^\mu h \partial_\mu h - c_6 \frac{m_H^2}{2v^2}\left(v h^3 + \frac{3h^4}{2} + \ldots\right) + c_y \frac{m_f}{v} \bar{f} f \left(h + \frac{3h^2}{2v} + \ldots\right) \\
& + \left(\frac{h}{v} + \frac{h^2}{2v^2}\right)\left[\frac{g^2}{2g_\rho^2}\left(\hat{c}_W W_\mu^- \mathcal{D}^{\mu\nu} W_\nu^+ + \text{h.c.}\right) + \frac{g^2}{2g_\rho^2} Z_\mu \mathcal{D}^{\mu\nu}\left[\hat{c}_Z Z_\nu + \left(\frac{2\hat{c}_W}{\sin 2\theta_W} - \frac{\hat{c}_Z}{\tan\theta_W}\right) A_\nu\right]\right. \\
& - \frac{g^2}{(4\pi)^2}\left(\frac{c_{HW}}{2} W^{+\mu\nu} W^-_{\mu\nu} + \frac{c_{HW} + \tan^2\theta_W c_{HB}}{4} Z^{\mu\nu} Z_{\mu\nu} - 2\sin^2\theta_W c_{\gamma Z} F^{\mu\nu} Z_{\mu\nu}\right) + \ldots \\
& \left. + \frac{\alpha g^2 c_\gamma}{4\pi g_\rho^2} F^{\mu\nu} F_{\mu\nu} + \frac{\alpha_s y_t^2 c_g}{4\pi g_\rho^2} G^{a\mu\nu} G^a_{\mu\nu}\right]\Bigg\}
\end{aligned}
\tag{71}
$$

$$\hat{c}_W = c_W + \left(\frac{g_\rho}{4\pi}\right)^2 c_{HW} \tag{72}$$

$$\hat{c}_Z = \hat{c}_W + \tan^2\theta_W \left[c_B + \left(\frac{g_\rho}{4\pi}\right)^2 c_{HB}\right] \tag{73}$$

$$c_{\gamma Z} = \frac{c_{HB} - c_{HW}}{4\sin 2\theta_W} \tag{74}$$

$$
\begin{aligned}
\mathcal{L}_V \quad = \quad & -\frac{\tan\theta_W}{2} \widehat{S}\, W^{(3)}_{\mu\nu} B^{\mu\nu} - ig\cos\theta_W g_1^Z Z^\mu \left(W^{+\nu} W^-_{\mu\nu} - W^{-\nu} W^+_{\mu\nu}\right) \\
& - ig\left(\cos\theta_W \kappa_Z Z^{\mu\nu} + \sin\theta_W \kappa_\gamma A^{\mu\nu}\right) W_\mu^+ W_\nu^-
\end{aligned}
\tag{75}
$$

$$\widehat{S} = \frac{m_W^2}{m_\rho^2}\left(c_W + c_B\right), \qquad g_1^Z = \frac{m_Z^2}{m_\rho^2}\ \hat{c}_W \tag{76}$$

$$\kappa_\gamma = \frac{m_W^2}{m_\rho^2}\left(\frac{g_\rho}{4\pi}\right)^2 \left(c_{HW} + c_{HB}\right), \qquad \kappa_Z = g_1^Z - \tan^2\theta_W \kappa_\gamma. \tag{77}$$

Georgi, Kaplan, mid 80's; Modern incarnation: GGPR, hep-ph/0703164

$$\Gamma\left(h\to f\bar{f}\right)_{\rm SILH}=\Gamma\left(h\to f\bar{f}\right)_{\rm SM}\left[1-\xi\left(2c_y+c_H\right)\right]$$

$$\Gamma\left(h\to W^+W^-\right)_{\rm SILH}=\Gamma\left(h\to W^+W^{(*)-}\right)_{\rm SM}\left[1-\xi\left(c_H-\frac{g^2}{g_\rho^2}\hat{c}_W\right)\right]$$

$$\Gamma\left(h\to ZZ\right)_{\rm SILH}=\Gamma\left(h\to ZZ^{(*)}\right)_{\rm SM}\left[1-\xi\left(c_H-\frac{g^2}{g_\rho^2}\hat{c}_Z\right)\right]$$

$$\Gamma\left(h\to gg\right)_{\rm SILH}=\Gamma\left(h\to gg\right)_{\rm SM}\left[1-\xi\ {\rm Re}\left(2c_y+c_H+\frac{4y_t^2c_g}{g_\rho^2 I_g}\right)\right]$$

$$\Gamma\left(h\to\gamma\gamma\right)_{\rm SILH}=\Gamma\left(h\to\gamma\gamma\right)_{\rm SM}\left[1-\xi\ {\rm Re}\left(\frac{2c_y+c_H}{1+J_\gamma/I_\gamma}+\frac{c_H-\frac{g^2}{g_\rho^2}\hat{c}_W}{1+I_\gamma/J_\gamma}+\frac{\frac{4g^2}{g_\rho^2}c_\gamma}{I_\gamma+J_\gamma}\right)\right]$$

$$\Gamma\left(h\to\gamma Z\right)_{\rm SILH}=\Gamma\left(h\to\gamma Z\right)_{\rm SM}\left[1-\xi\ {\rm Re}\left(\frac{2c_y+c_H}{1+J_Z/I_Z}+\frac{c_H-\frac{g^2}{g_\rho^2}\hat{c}_W}{1+I_Z/J_Z}+\frac{4c_{\gamma Z}}{I_Z+J_Z}\right)\right]$$

Giudice et al., ‘07

Model Dependencies

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.

SUMMARY

	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].

Details in Gupta, Rzehak, JW, arXiv:1206.3560.

Let’s now discuss the “mixed in singlet case”

Overall 6% deviations on Higgs couplings could be universally present. But also careful high luminosity studies of vector boson production in order.

Higgs Masses and Mixings

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

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

The mixing angle and mass eigenvalues are

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

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

Two Paths to LHC Discovery

Within this framework, we studied two ways to find Higgs boson at the LHC:

1) Narrow Trans-TeV Higgs boson signal

2) Heavy Higgs to light Higgs decays

Bowen, Cui, JW

Narrow Trans-TeV Higgs Boson

When the mixing is small, the heavy Higgs has smaller cross-section (bad), but more narrow (good).

	Point A	Point B	Point C
s_ω^2	0.40	0.31	0.1
m_h (GeV)	143	115	120
m_H (GeV)	1100	1140	1100
$\Gamma(H \to hh)$ (GeV)	14.6	4.9	10
$BR(H \to hh)$	0.036	0.015	0.095

Investigate Point C example

Two Signals

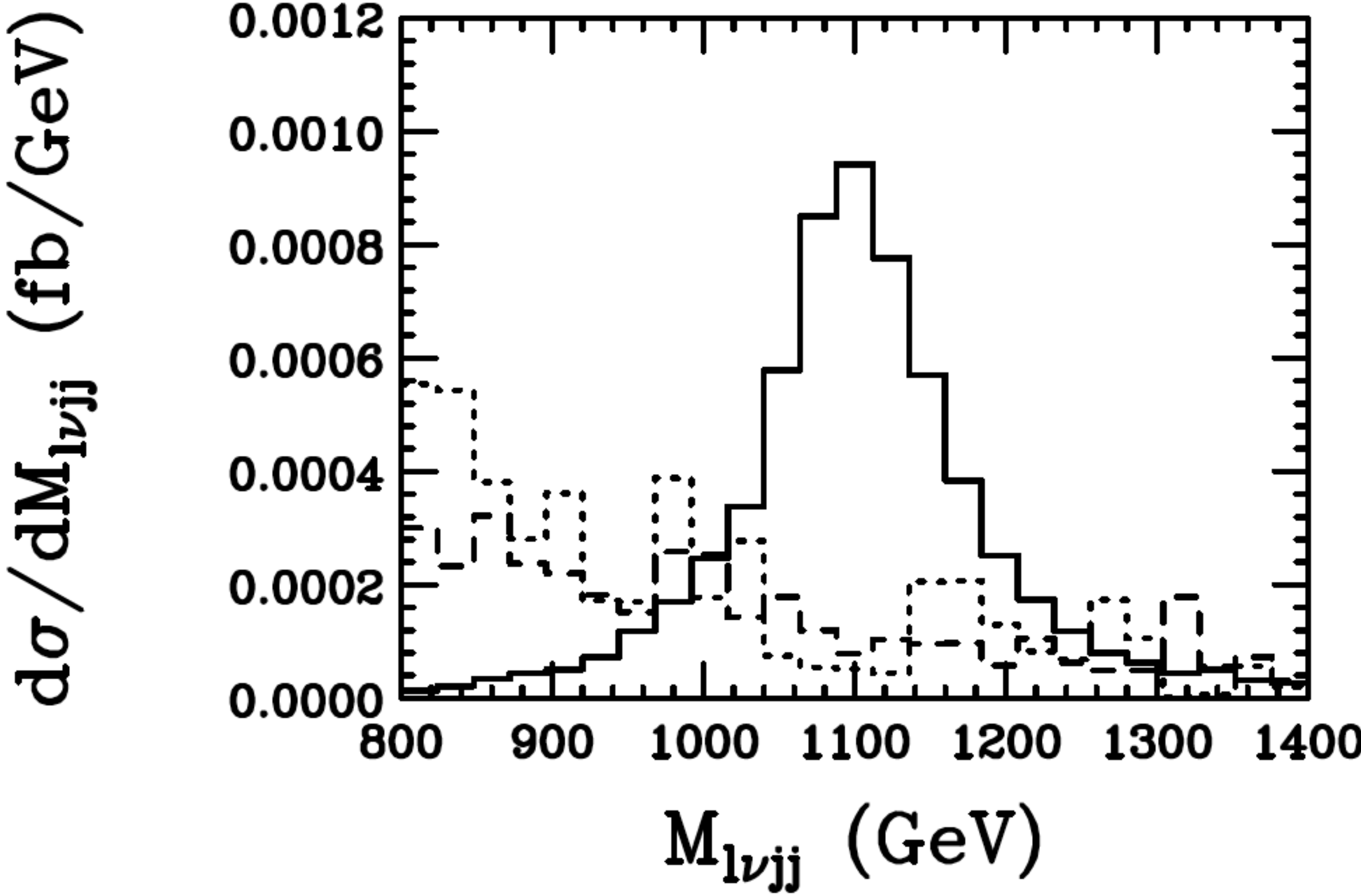
1) $$H \to WW \to l\nu jj$$

$$p_T(e,\mu) > 100\,\mathrm{GeV} \quad \text{and} \quad |\eta(e,\mu)| < 2.0$$
$$\text{Missing } E_T > 100\,\mathrm{GeV}$$
$$p_T(j,j) > 100\,\mathrm{GeV} \quad \text{and} \quad m_{jj} = m_W \pm 20\,\mathrm{GeV}$$
$$\text{“Tagging jets” with } |\eta| > 2.0$$

H->WW->jjlν

Techniques: Atlas & CMS TDRs and Iordanidis, Zeppenfeld, '97

Between 1.0 & 1.3 TeV 13 signal events in 100 fb^{-1} vs. 7.7 bkgd



H->WW (solid)

WWjj (dashed)

ttjj (dotted)

Difference from SUSY heavy Higgs boson

SUSY heavy Higgs has qualitatively different behavior:

ϕ		$g_{\phi\bar{t}t}$	$g_{\phi\bar{b}b}$	$g_{\phi VV}$
SM	H	1	1	1
MSSM	h^o	$\cos\alpha/\sin\beta$	$-\sin\alpha/\cos\beta$	$\sin(\beta-\alpha)$
	H^o	$\sin\alpha/\sin\beta$	$\cos\alpha/\cos\beta$	$\cos(\beta-\alpha)$
	A^o	$1/\tan\beta$	$\tan\beta$	0

Haber et al. '01

$$HVV: \quad \cos(\beta-\alpha) \to \boxed{0} + \mathcal{O}(m_Z^4/m_A^4)$$

$$H\bar{t}t: \quad \frac{\sin\alpha}{\sin\beta} \to \boxed{\frac{1}{\tan\beta}} + \mathcal{O}(m_Z^2/m_A^2)$$

$$H\bar{b}b: \quad \frac{\cos\alpha}{\cos\beta} \to \boxed{\tan\beta} + \mathcal{O}(m_Z^2/m_A^2)$$

Heavy Higgs decays mostly into tops or bottoms (or susy partners) depending on $\tan\beta$.

H decays to lighter Higgses

We can also have a heavier Higgs boson decaying into two lighter ones in this scenario.

	Point 1	Point 2	Point 3
s_ω^2	0.5	0.5	0.5
m_h (GeV)	115	175	225
m_H (GeV)	300	500	500
$\Gamma(H \to hh)$ (GeV)	2.1	17	17
$BR(H \to hh)$	0.33	0.33	0.33

Both Higgses suppressed with respect to SM Higgs.

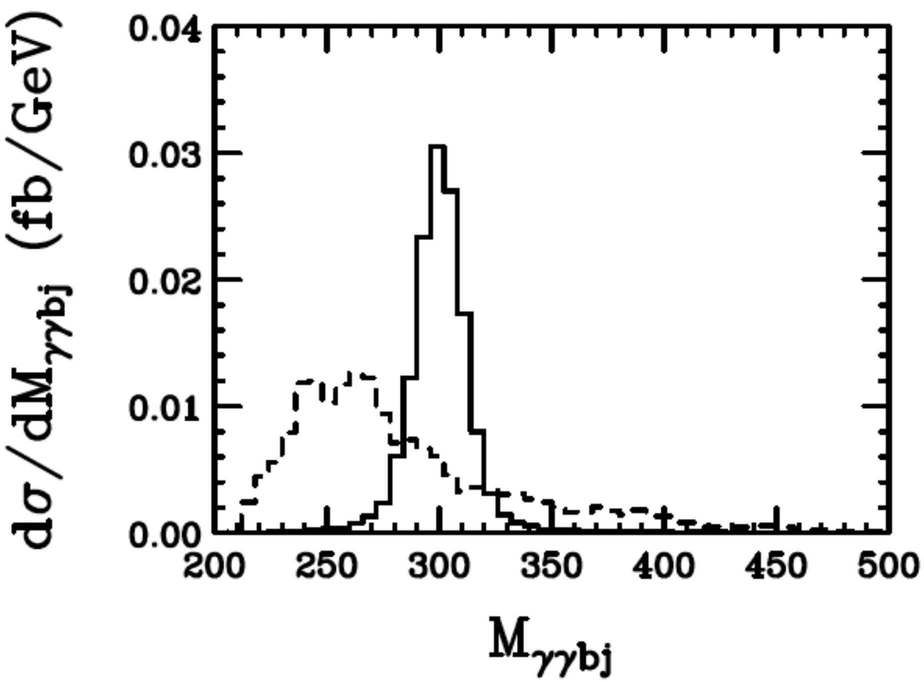
Standard Higgs search channels are reduced by 50% -- takes even longer to find….

Search through H->hh decays.

Heavy to Light Higgs rate

Considered discovery mode (Richter-Was et al.):

$$gg \to H \to hh \to \gamma\gamma\bar{b}b$$

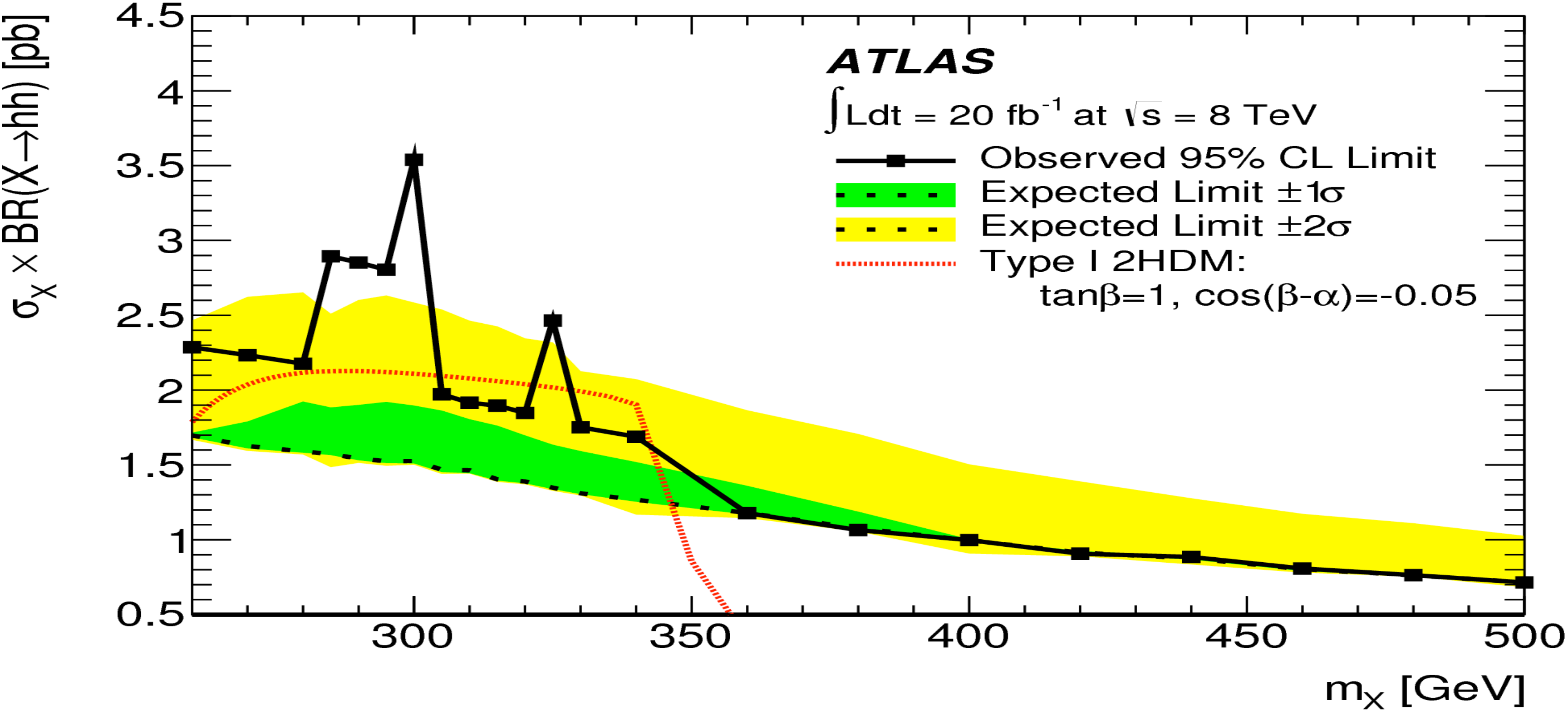


Channel	1 tag	2 tags
$H \to hh$	24	12
$\gamma\gamma bb$	0.4	0.2
$\gamma\gamma bc$	0.15	0.01
$\gamma\gamma bj$	1	0.009
$\gamma\gamma cc$	1.2	0.069
$\gamma\gamma cj$	3.6	0.042
$\gamma\gamma jj$	1.8	0.007
Total background	8.2	0.34

30 fb^{-1} bkgd estimates

Bowen, Cui, JW

(H →) hh → γγbb

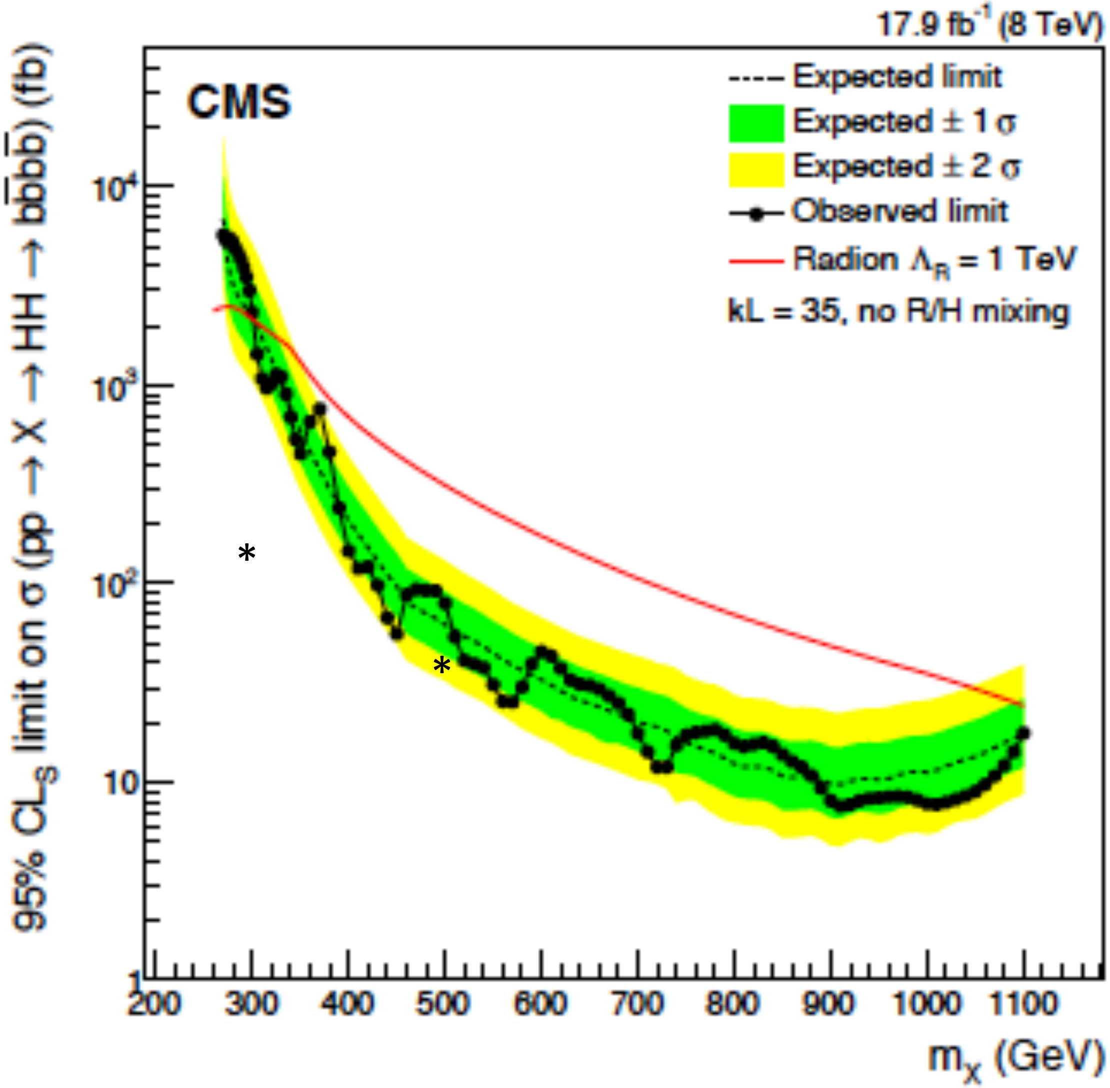


- σ x BR (pp → H → hh) between 0.7-3.5pb as a function of m_X
- Local excess of 3σ around m_X = 300 GeV
  - After LEE, global significance of 2.1σ

Theory much below:
For m_H = 300 (500) GeV, expect ~1.3 (0.5) fb

Assamagan, MCTP Higgs, `15

CMS (H →) hh →bbbb



Theory :
For mH = 300 (500) GeV
expect < 130 (50) fb,
assuming $\sin^2\theta < 0.1$

Assamagan, MCTP Higgs, `15

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.