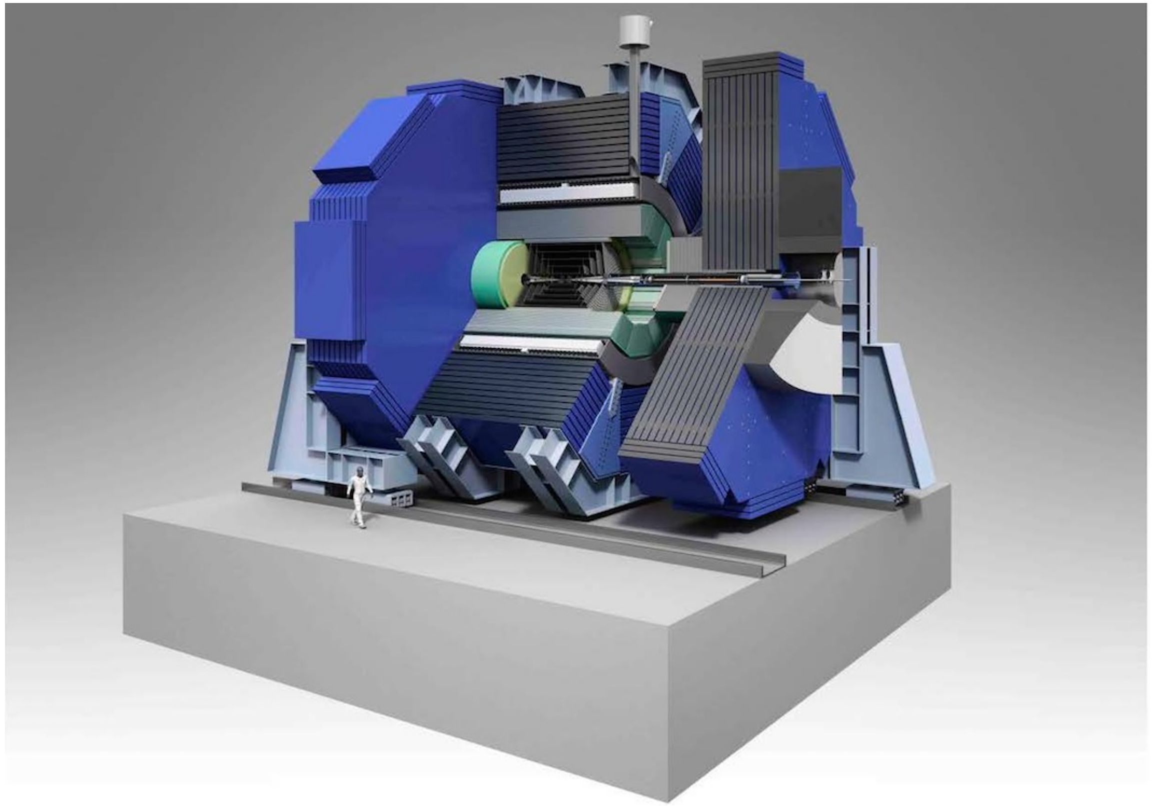
Higgs Physics and the ILC



Howard E. Haber

SID Workshop
January 12, 2015

Outline

I. Higgs physics after discovery
- What is the current data telling us?
- Toward the Standard Model (SM)-like Higgs boson

II. Implications for the dynamics of EWSB
- The principle of naturalness under tension
- Approaching the alignment limit
- Tree-level vs. loop level; weak coupling vs. strong coupling
- Motivations for a precision Higgs program

III. Expectations for precision of future Higgs measurements
- Precision Higgs programs at the LHC and ILC
- Limits due to theoretical systematic errors

IV. Case studies
- The wrong sign Higgs couplings to fermion pairs
- Complementarity between H(125) precision and the search for new scalar states of the Higgs sector

V. The bottom line

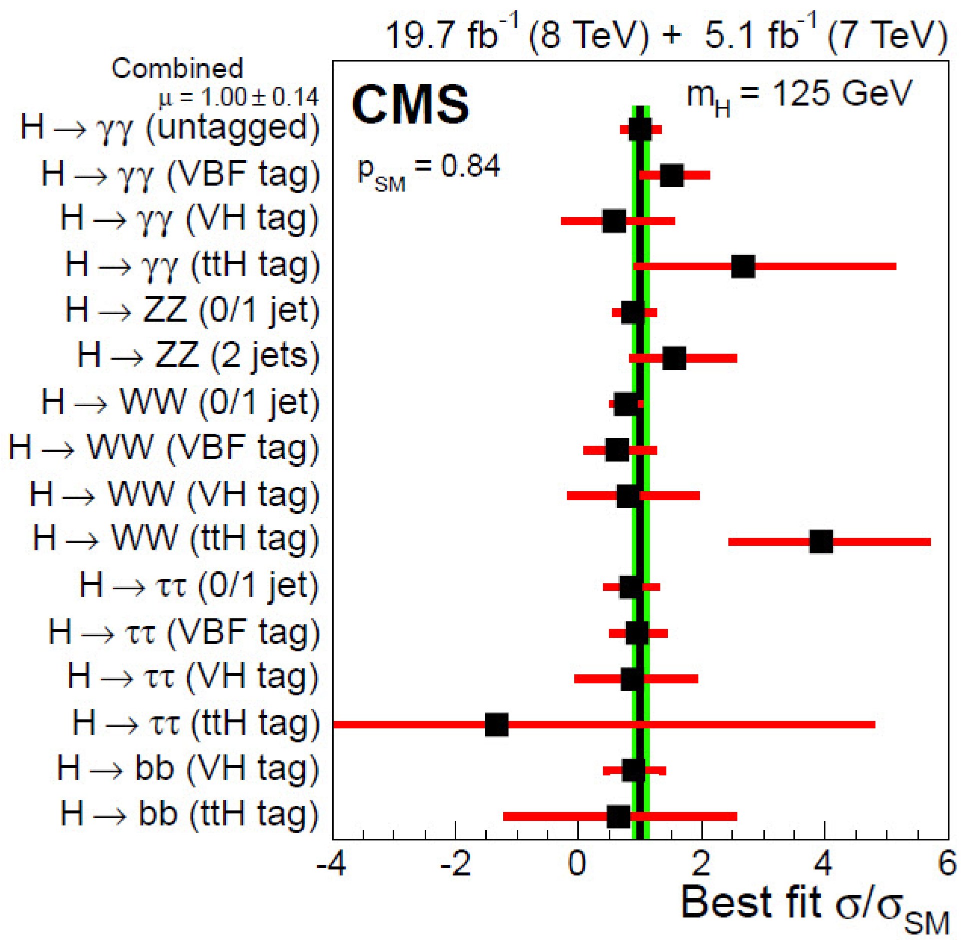
I. The Higgs boson discovered on the 4th of July 2012

- Is it the Higgs boson of the Standard Model?
- Is it the first scalar state of an enlarged Higgs sector?
- Is it a premonition for new physics beyond the Standard Model at the TeV scale?

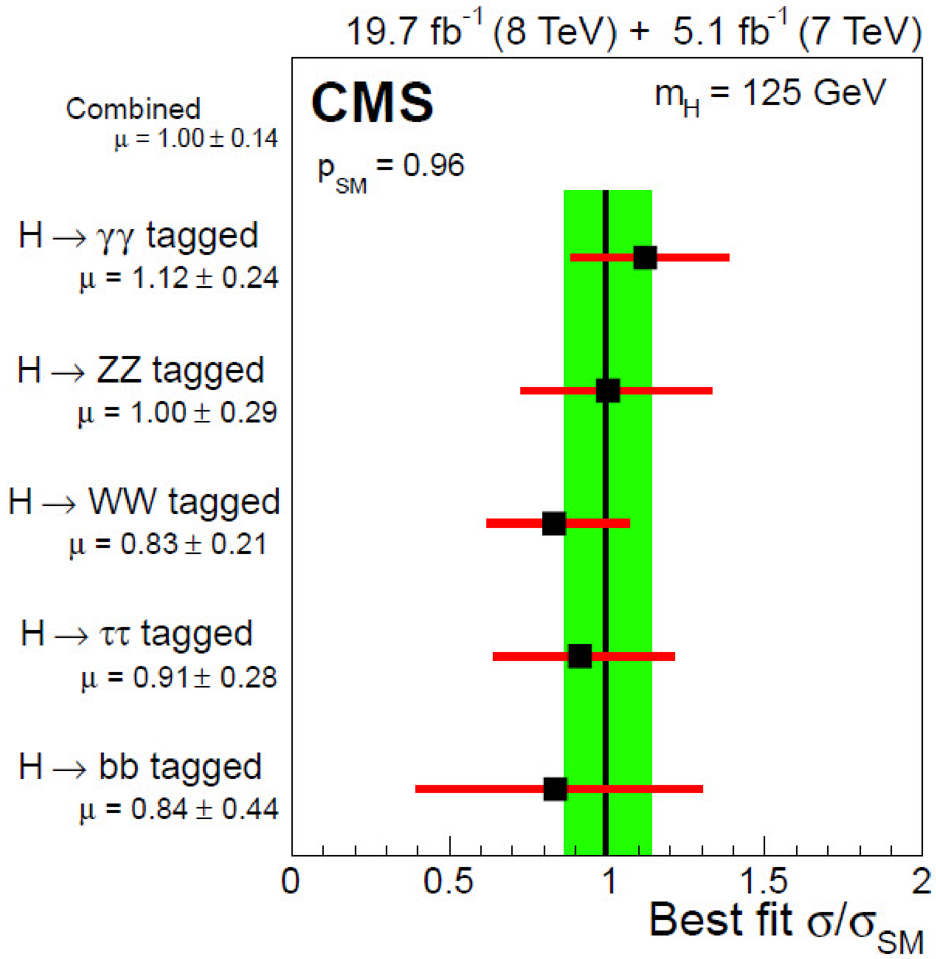
Let's look at a snapshop of the current LHC Higgs data.

$m_H = 125.2 \pm 0.4$ GeV

Evidence for a Standard Model (SM)—like Higgs boson



Values of the best-fit σ/σ_{SM} for the combination (solid vertical line) and for subcombinations by predominant decay mode and additional tags targeting a particular production mechanism. The vertical band shows the overall σ/σ_{SM} uncertainty. The σ/σ_{SM} ratio denotes the production cross section times the relevant branching fractions, relative to the SM expectation. The horizontal bars indicate the ±1 standard deviation uncertainties in the best-fit σ/σ_{SM} values for the individual modes; they include both statistical and systematic uncertainties. Taken from arXiv:1412.8662 (December, 2014).



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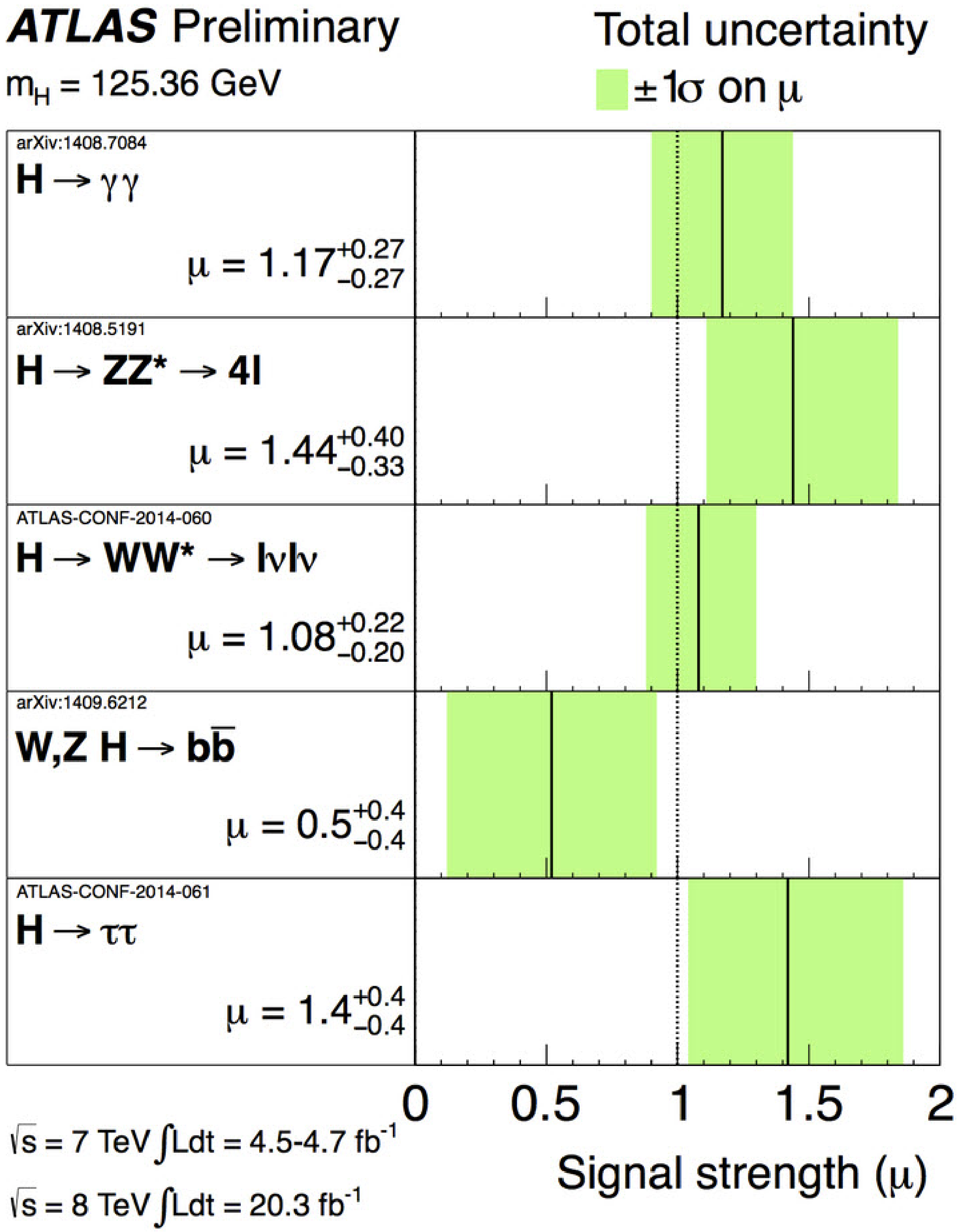
ATLAS evidence for a SM-like Higgs boson (from a CERN seminar October 7, 2014)



Any theory that introduces new physics beyond the Standard Model (SM) must contain a SM-like Higgs boson. This constrains all future model building.

Motivations for a precision Higgs program:

- Learn as much as possible about H(125)
- Probe the dynamics of electroweak symmetry breaking (EWSB)
- Discover deviations from SM predictions
    - evidence for physics beyond the SM
    - hints of a new mass scale

II. Possible implications of a SM-like Higgs boson

- Maybe there is no new physics beyond the SM (BSM) until energy scales >> 1 TeV, in which case H(125) *is* the SM Higgs boson (the nightmare scenario?).

- If additional scalars exist, then H(125) can mix with other scalar states. If this mixing is suppressed, then H(125) will be SM-like.

- Radiative corrections to the couplings of H(125) induced by new BSM physics could yield small but observable deviations.

- Since $H^\dagger H$ is a singlet with respect to the SM gauge group, it can couple to new physics that are neutral with respect to the SM (e.g. hidden valleys) . This is the Higgs portal. It can also yield deviations to H(125) couplings from SM predictions.

Implications for EWSB dynamics

- Tension with naturalness (Is the Higgs sector fine-tuned?)
  - The nightmare scenario: no new TeV-scale physics found; the SM survives to energies much larger than the TeV scale.

- New physics beyond the SM is present but not yet discovered. The Higgs sector is likely to be non-minimal.
  - In the *alignment limit*, the H(125) is approximately aligned in field space with the vacuum expectation value (vev), and thereby behaves like a SM-like Higgs boson
  - In the *decoupling limit*, all other scalar states are massive, in which case the H(125) is approximately aligned with the vev. The decoupling limit implies approximate alignment but not vice versa.

Implications for EWSB dynamics breaking (continued)

- Deviations of the H(125) couplings from the SM can be due to:
  - tree-level effects (e.g. mixing with other scalar states)
  - loop-level effects (e.g. virtual effects of new particles, which in some cases be parameterized by higher dimensional operators)

  Competition between tree-level and loop-level effects may be relevant (tree-level does not always win!).

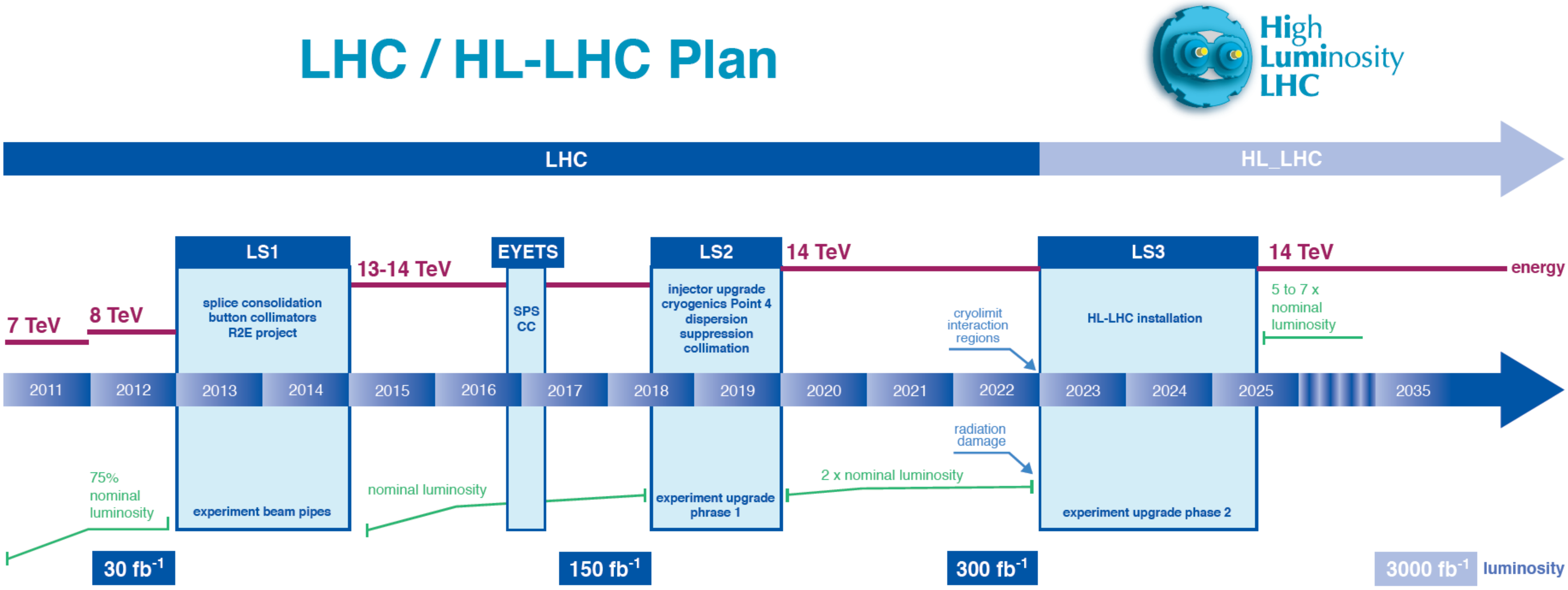
- The argument of weakly-coupled vs. strongly-coupled EWSB is not yet settled. Deviations of the H(125) couplings from the SM can inform this debate.

- Prior to the discovery of new states associated with physics beyond the Standard Model (BSM), the precision Higgs program, along with precision measurements in the gauge boson sector, will be essential for probing EWSB dynamics and deriving constraints on BSM physics.

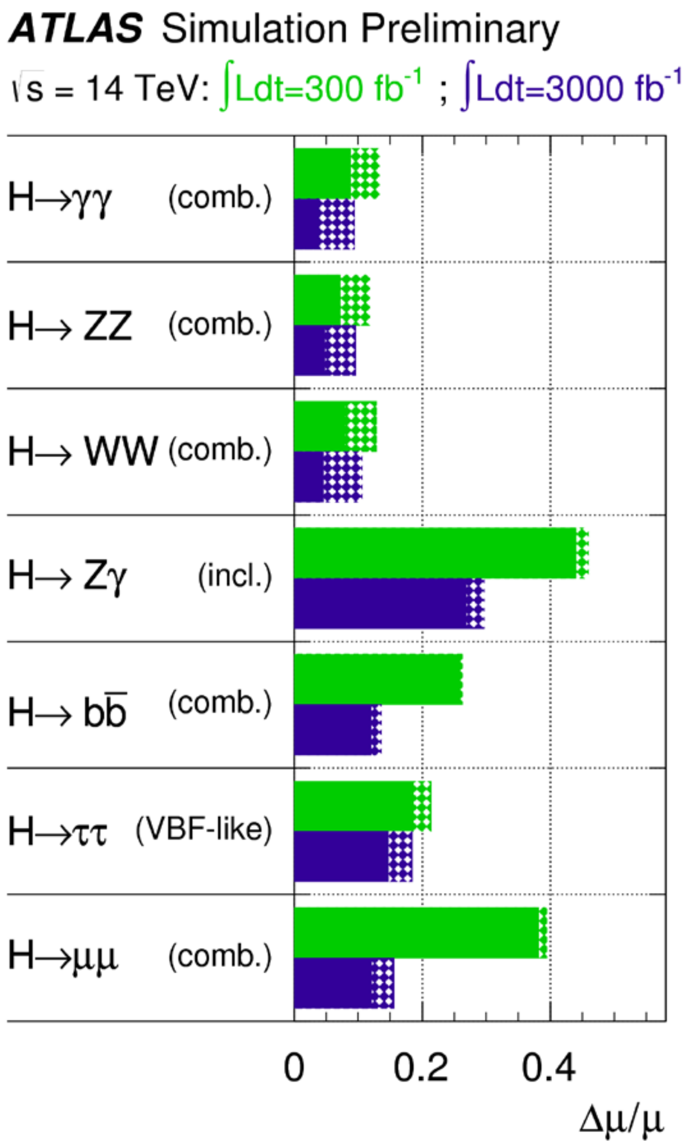
How much precision do we need?

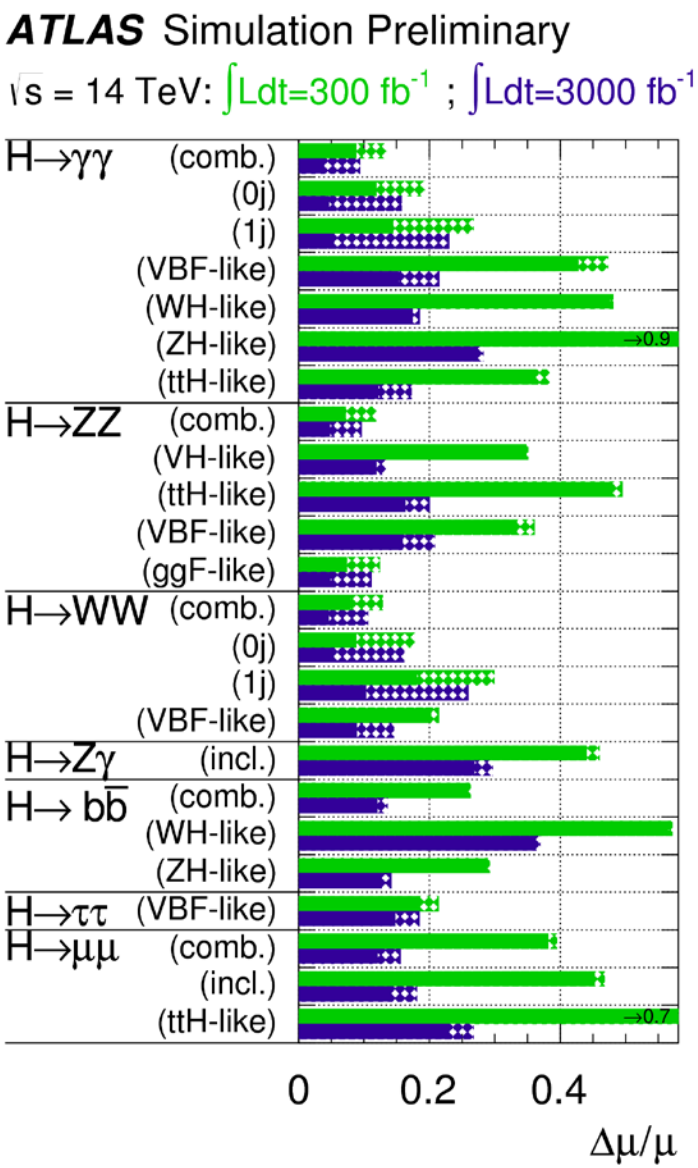
- Current LHC data already yields Higgs couplings (with some assumptions) of roughly 20%--30% in the main channels.
- It does not seem likely that large tree-level mixing effects are present.
- The absence of BSM physics below $\Lambda \approx 1$ TeV in LHC data may be suggesting that deviations of Higgs coupling from their SM values should be less than about $(2m_H/\Lambda)^2 \approx 6\%$. If no BSM physics is revealed in future LHC running, this estimate is likely to drop below 1%.
- We may very well require sensitivity to effects approaching those of electroweak radiative corrections, i.e. below 1%.

III. Expectations for future precision Higgs measurements

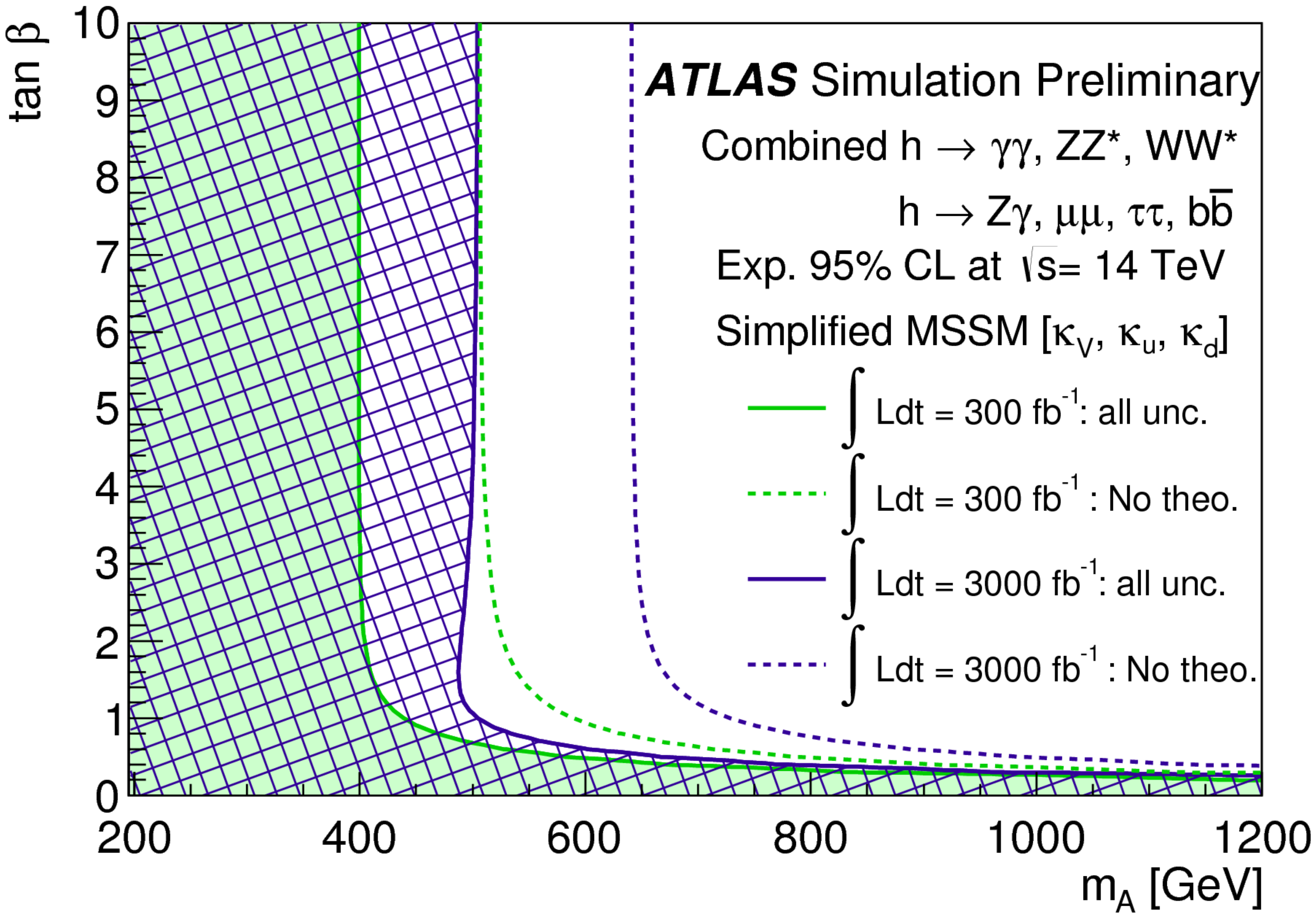


Latest HL-LHC plan announced by Lucio Rossi at the 4th Joint HiLumi LHC/ LARP Annual Meeting at KEK on 11 Nov 2014



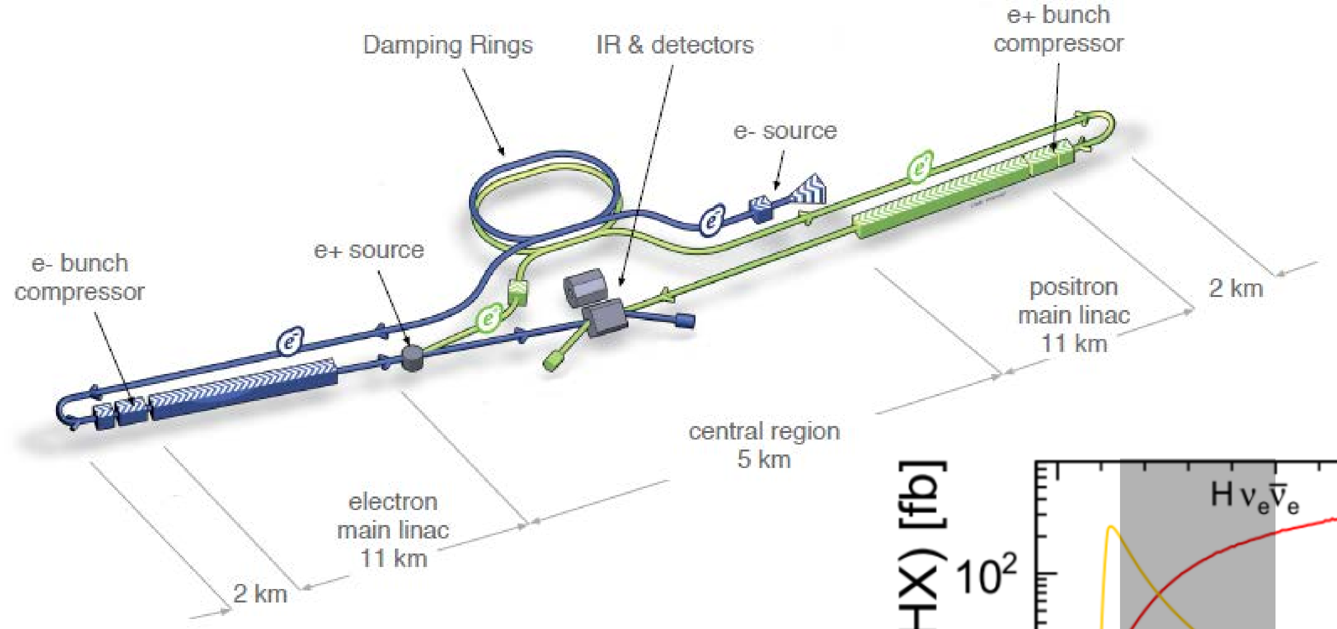


Relative uncertainty on the signal strength μ for all Higgs final states considered in this note in the different experimental categories used in the combination, assuming a SM Higgs boson with a mass of 125 GeV expected with 300/fb and 3000/fb of 14 TeV LHC data. The uncertainty pertains to the number of events passing the experimental selection, not to the particular Higgs boson process targeted. The hashed areas indicate the increase of the estimated error due to current theory systematic uncertainties. The abbreviation "(comb.)" indicates that the precision on μ is obtained from the combination of the measurements from the different experimental sub-categories for the same final state, while "(incl.)" indicates that the measurement from the inclusive analysis was used. The left side shows only the combined signal strength in the considered final states, while the right side also shows the signal strength in the main experimental sub-categories within each final state. Taken from ATL-PHYS-PUB-2014-016 (Oct. 2014).

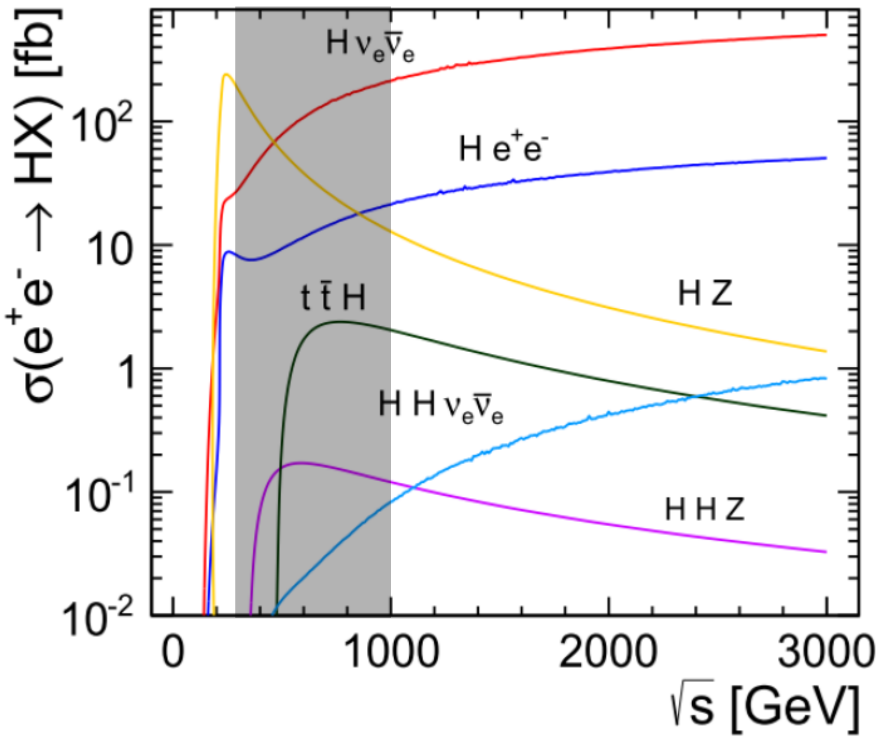


Regions of the (m_A, tanβ) plane expected to be excluded in a simplified MSSM model via fits to the measured rates of Higgs boson production and decays. The likelihood contours where -2ln Λ=6.0, corresponding approximately to 95% CL (2σ), are indicated assuming the SM Higgs sector. The light shaded and hashed regions indicate the expected exclusions, respectively. The SM decoupling limit is $m_A \rightarrow \infty$. Taken from ATL-PHYS-PUB-2014-017 (Oct. 2014).

A program of precision Higgs couplings at the
ILC : e^+e^- Linear Collider at 250 GeV < $\sqrt{s}$ < 1000 GeV



The ILC Higgs White paper (D.M. Asner, et al., arXiv:1310.0763 [hep-ph]), prepared for the 2013 Snowmass Community study, projected possible outcomes of a dedicated Higgs precision study at the ILC under various energy/luminosity scenarios.



Energy/Luminosity scenarios

Stage #	nickname	$E_{cm}(1)$ (GeV)	Lumi (1) (fb^{-1})	$E_{cm}(2)$ (GeV)	Lumi (2) (fb^{-1})	$E_{cm}(3)$ (GeV)	Lumi (3) (fb^{-1})	Runtime (years)
1	ILC (250)	250	250					1.1
2	ILC (500)	250	250	500	500			2.0
3	ILC (1000)	250	250	500	500	1000	1000	2.9
4	ILC(LumUp)	250	1150	500	1600	1000	2500	5.8

- At each stage, the *accumulated* luminosity of a given energy is listed. The runtimes listed consist of actual elapsed *cumulative* running time at the end of each stage. Assuming that the ILC runs for 1/3 of the time, then the actual time elapsed is equal to the runtime times 3.

- Assume that the ILC is run at its baseline luminosity at 250 GeV (stage 1), then at 500 GeV (stage 2), and finally at 1000 GeV (stage 3)

- Then, stage 4 repeats the successive stages 1, 2 and 3 at the upgraded luminosity.

In real time, this entire program would require 5.8 x 3 = 17.4 years.

Summary of expected accuracies $\Delta g_i/g_i$ and Γ_T for model independent determinations of the Higgs boson couplings

Mode	ILC(250)	ILC(500)	ILC(1000)	ILC(LumUp)
$\sqrt{s}$ (GeV)	250	250+500	250+500+1000	250+500+1000
L (fb^{-1})	250	250+500	250+500+1000	1150+1600+2500
$\gamma\gamma$	18 %	8.4 %	4.0 %	2.4 %
gg	6.4 %	2.3 %	1.6 %	0.9 %
WW	4.9 %	1.2 %	1.1 %	0.6 %
ZZ	1.3 %	1.0 %	1.0 %	0.5 %
$t\bar{t}$	–	14 %	3.2 %	2.0 %
$b\bar{b}$	5.3 %	1.7 %	1.3 %	0.8 %
$\tau^+\tau^-$	5.8 %	2.4 %	1.8 %	1.0 %
$c\bar{c}$	6.8 %	2.8 %	1.8 %	1.1 %
$\mu^+\mu^-$	91 %	91 %	16 %	10 %
Γ_T	12 %	5.0 %	4.6 %	2.5 %
hhh	–	83 %	21 %	13 %
BR(invis.)	< 0.9 %	< 0.9 %	< 0.9 %	< 0.4 %

The theory errors are $\Delta F_i/F_i$=0.5%. For the invisible branching ratio, the numbers quoted are 95% confidence upper limits.

Comparing the projected precision of the HL-LHC and ILC Higgs programs

M. Peskin used the ILC Higgs White paper analysis, and added the additional branching ratio constraint, $\sum_i BR_i = 1$, based on anticipated measured upper limits for BR's of exotic Higgs decay modes. Comparisons with CMS pessimistic and optimistic scenarios for 3000 fb^{-1} of data are provided:

CMS-1: current systematic and theoretical uncertainties are employed.

CMS-2: theoretical errors are reduced by a factor of two and systematic errors are assumed to decrease as the square root of the integrated luminosity.

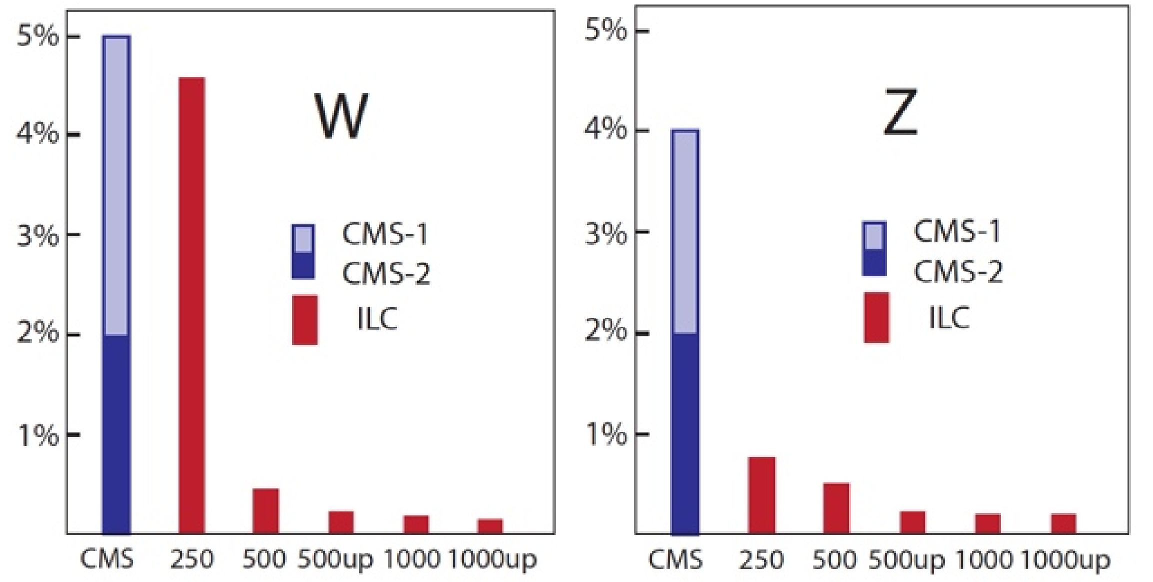


Figure 1: Estimates of the ILC measurement accuracies for the Higgs boson couplings to WW and ZZ. These estimates are based on the 10-parameter fit described in the text. The successive entries correspond to the stages of the ILC program shown in Table 4. The CMS Scenario 1 and Scenario 2 estimates for 3000 fb^{-1}, from [7], are shown on the left.

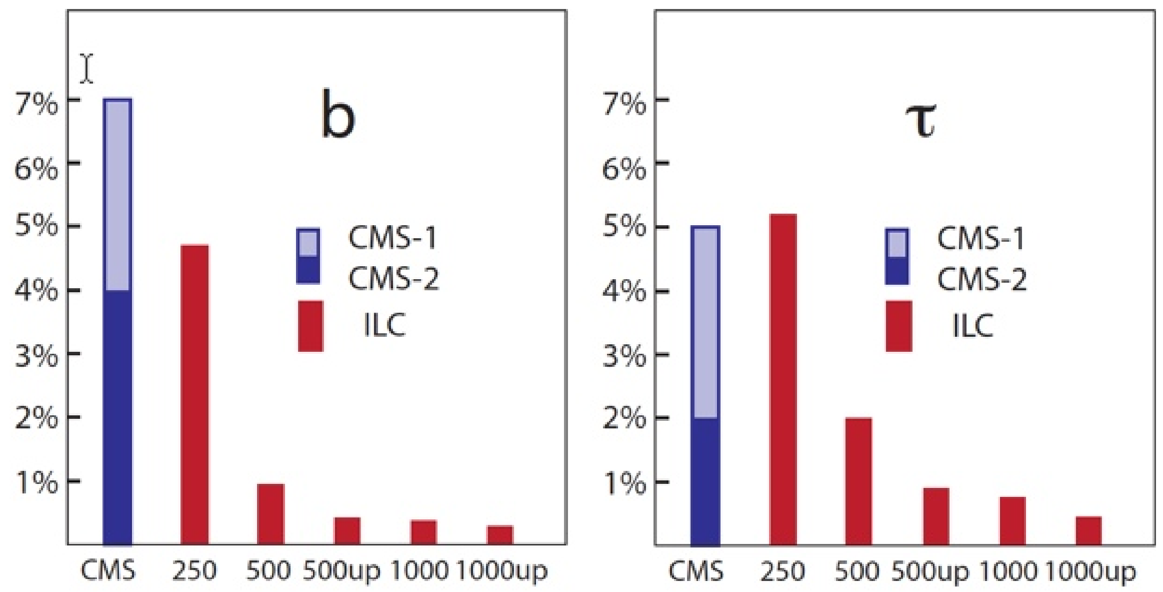


Figure 2: Estimates of the ILC measurement accuracies for the Higgs boson couplings to $b\bar{b}$ and $\tau^+\tau^-$. These estimates are based on the 10-parameter fit described in the text. The successive entries correspond to the stages of the ILC program shown in Table 4. The CMS Scenario 1 and Scenario 2 estimates for 3000 fb^{-1}, from [7], are shown on the left.

Reference: M.E. Peskin, *Estimation of LHC and ILC Capabilities for Precision Higgs Boson Coupling Measurements*, arXiv:1312.4974 [hep-ph].

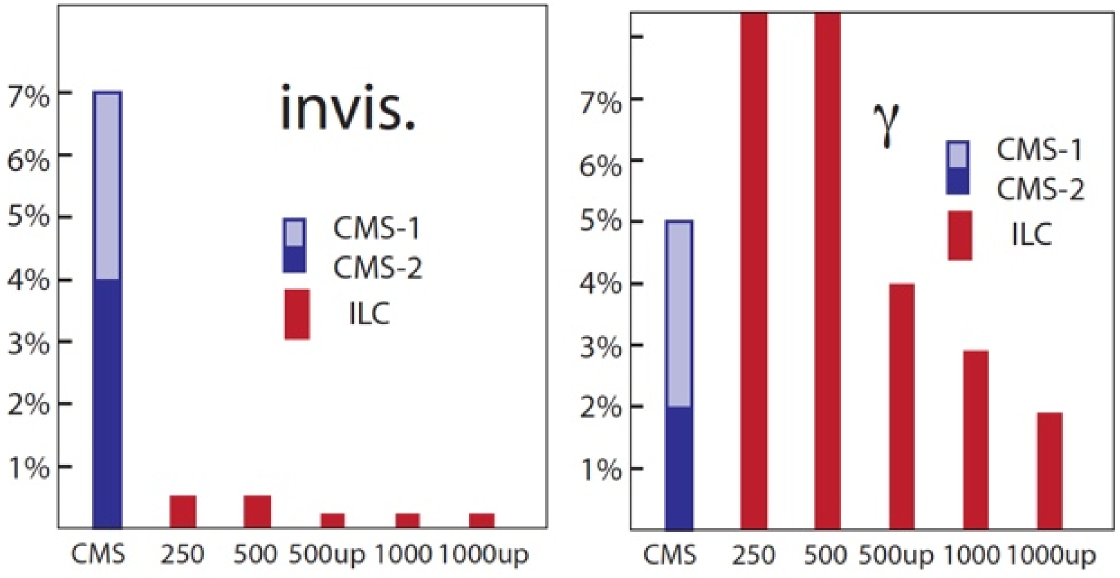


Figure 3: Estimates of the ILC measurement accuracies for the Higgs boson couplings to invisible modes and to $\gamma\gamma$. These estimates are based on the 10-parameter fit described in the text. The successive entries correspond to the stages of the ILC program shown in Table 4. The CMS Scenario 1 and Scenario 2 estimates for 3000 fb^{-1}, from [7], are shown on the left.

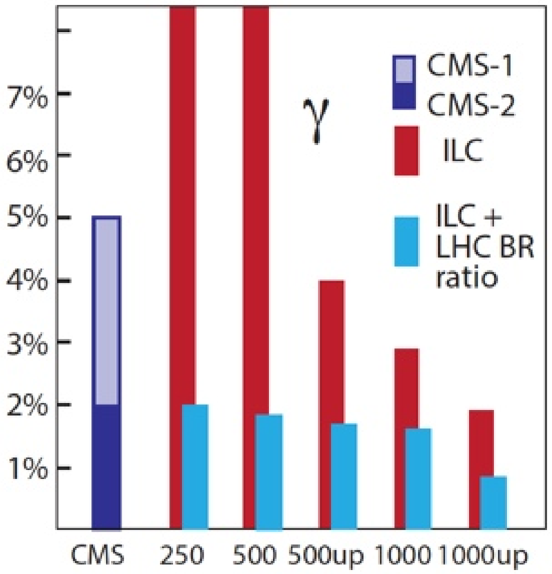


Figure 4: Estimates of the ILC measurement accuracies for the Higgs boson couplings to $\gamma\gamma$ when combined with the measurement of $BR(\gamma\gamma)/BR(ZZ^*)$ projected by ATLAS [6]. The successive entries correspond to the stages of the ILC program shown in Table 4. The CMS Scenario 1 and Scenario 2 estimates for 3000 fb^{-1}, from [7], are shown on the left.

Peskin notes that by combining one LHC observable, namely Δ[BR(H→γγ)/BR(H →ZZ*)]=3.6% as projected by ATLAS in their high luminosity LHC analysis, with the ILC precision measurement of the *ZZH* coupling, one is able to obtain a very precise determination of the *γγH* coupling.

Beating down the theory errors

Will the accuracy of the SM predictions for the Higgs couplings be better than the anticipated precision of the corresponding ILC measurements?

Two sources of theoretical uncertainty:

- Higher order perturbative corrections to Higgs partial widths not yet computed. In G.P. Lepage, P.B. Mackenzie and M.E. Peskin, *Expected Precision of Higgs Boson Partial Widths within the Standard Model,* arXiv:1404.0319 [hep-ph], these uncertainties are estimated to be of order 0.1%.
- Parametric uncertainty of the input parameters (primarily α_s, m_b, m_c).

Example: Baikov, Chetyrkin and Kühn (2006) have obtained:

$$\Gamma(H \to b\bar{b}) = \Gamma_0\big[1 + 5.667a + 29.15a^2 + 41.76a^3 - 825.7a^4\big]$$
$$= \Gamma_0\big[1 + 0.2037 + 0.0377 + 0.0019 + 0.0013\big]\,,$$

where $a \equiv \alpha_s(m_H)/\pi$.

IV. Case studies:

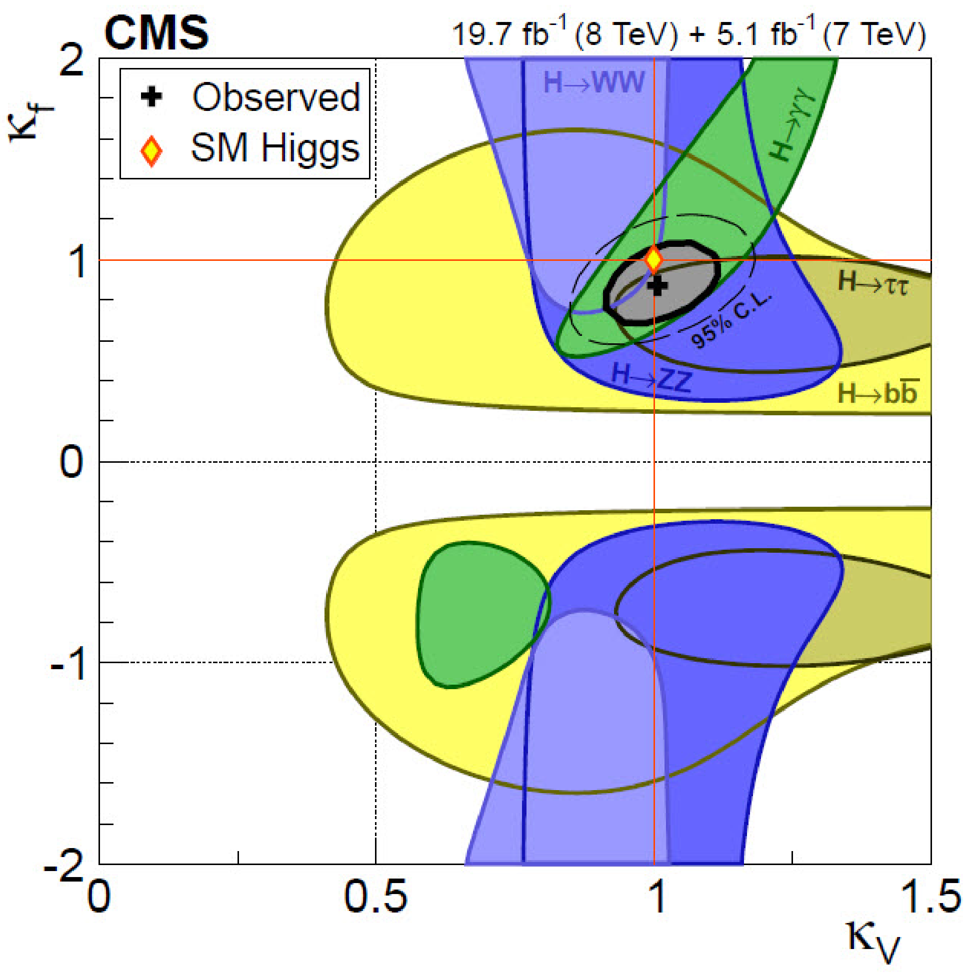
1. The wrong sign Higgs couplings to fermion pairs

P.M. Ferreira, J.F. Gunion, H.E. Haber and R. Santos, *Probing wrong-sign Yukawa couplings at the LHC and a future linear collider*, Phys. Rev. **D89**, 115003 (2014)

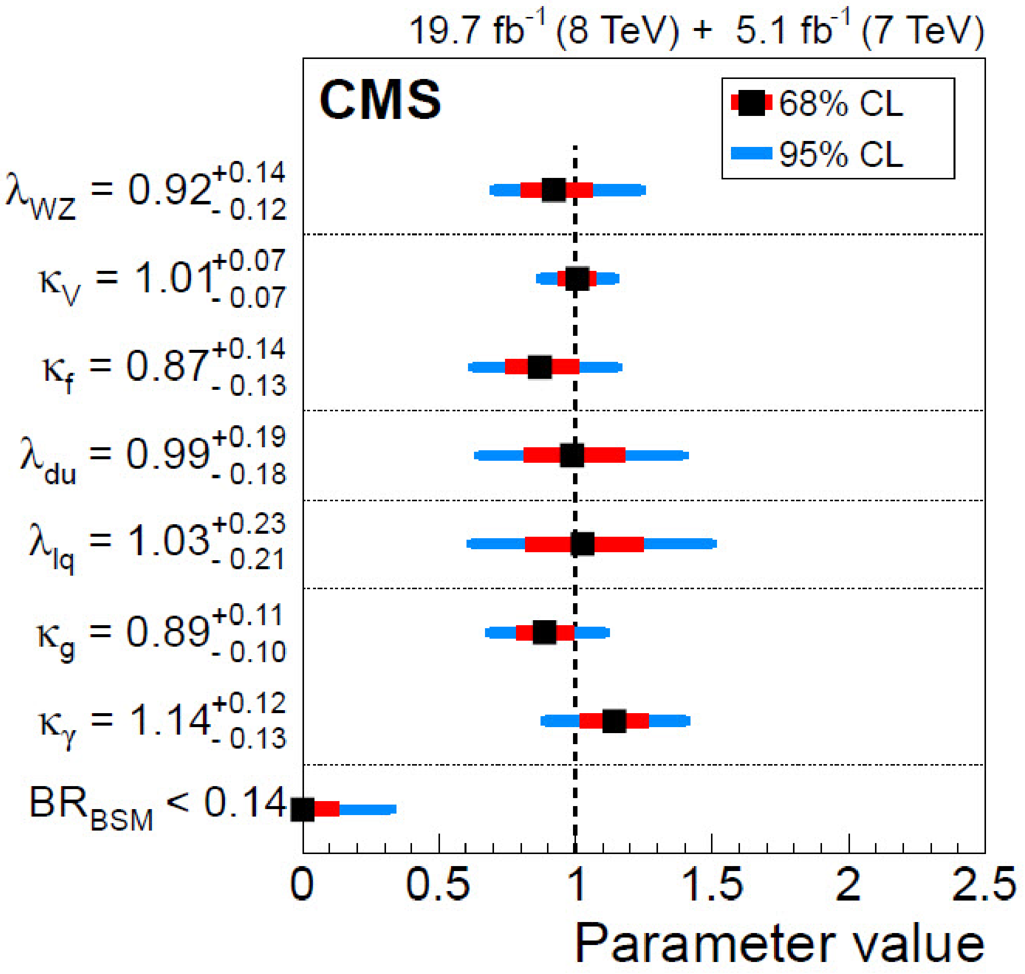
2. Complementarity between H(125) precision and the search for new scalar states of the Higgs sector

M. Carena, H.E. Haber, I. Low, N.R. Shah and C.E.M. Wagner, *Complementarity Between Non-Standard Higgs Searches and Precision Higgs Measurements in the MSSM*, arXiv:1410.4969 [hep-ph], Phys. Rev. **D91** (2015) in press.

CMS search for deviations from SM-Higgs couplings



2D test statistics q(κ$_V$, κ$_F$) scan for individual channels (colored swaths) and for the overall combination (thick curve). The cross indicates the global best-fit values. The dashed contour bounds the 95% CL region for the combination. The yellow diamond shows the SM point (κ_V, κ_f) = (1, 1). Two quadrants corresponding to (κ_V, κ_f) = (+,+) and (+,−) are physically distinct. Taken from arXiv:1412.8662 (December, 2014).



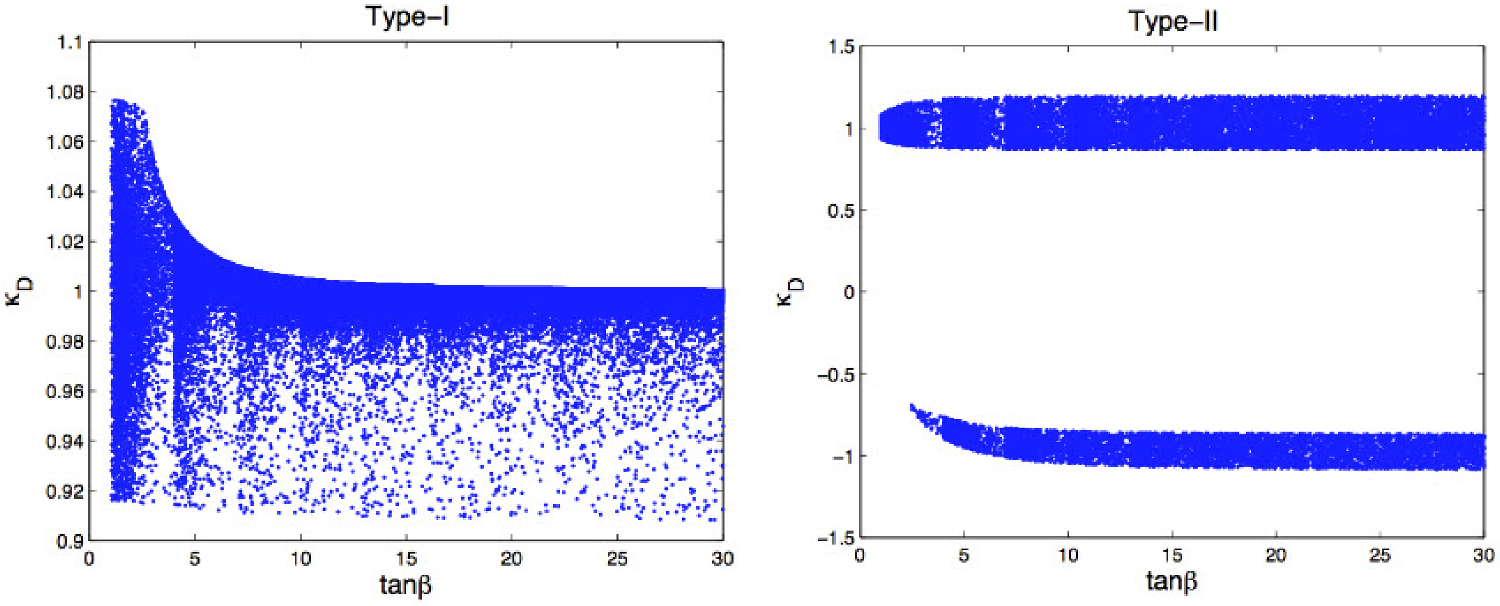
Summary plot of likelihood scan results for the different parameters of interest in benchmark models separated by dotted lines. The BR_{BSM} value at the bottom is obtained for the model with three parameters (κ_g, κ_γ, BR_{BSM}). The inner bars represent the 68% CL confidence intervals while the outer bars represent the 95% CL confidence intervals. Taken from arXiv:1412.8662 (December, 2014).

Is it possible that the Higgs coupling to down-type fermions, κ_D, has the expected magnitude but the opposite sign to their predicted SM values?

We have scanned the 2HDM parameter space, imposing theoretical constraints, direct LHC experimental constraints, and indirect constraints (from precision electroweak fits, B physics observables, and R_b). The latter requires that $m_{H^\pm} \gtrsim 340$ GeV in the Type-II 2HDM.

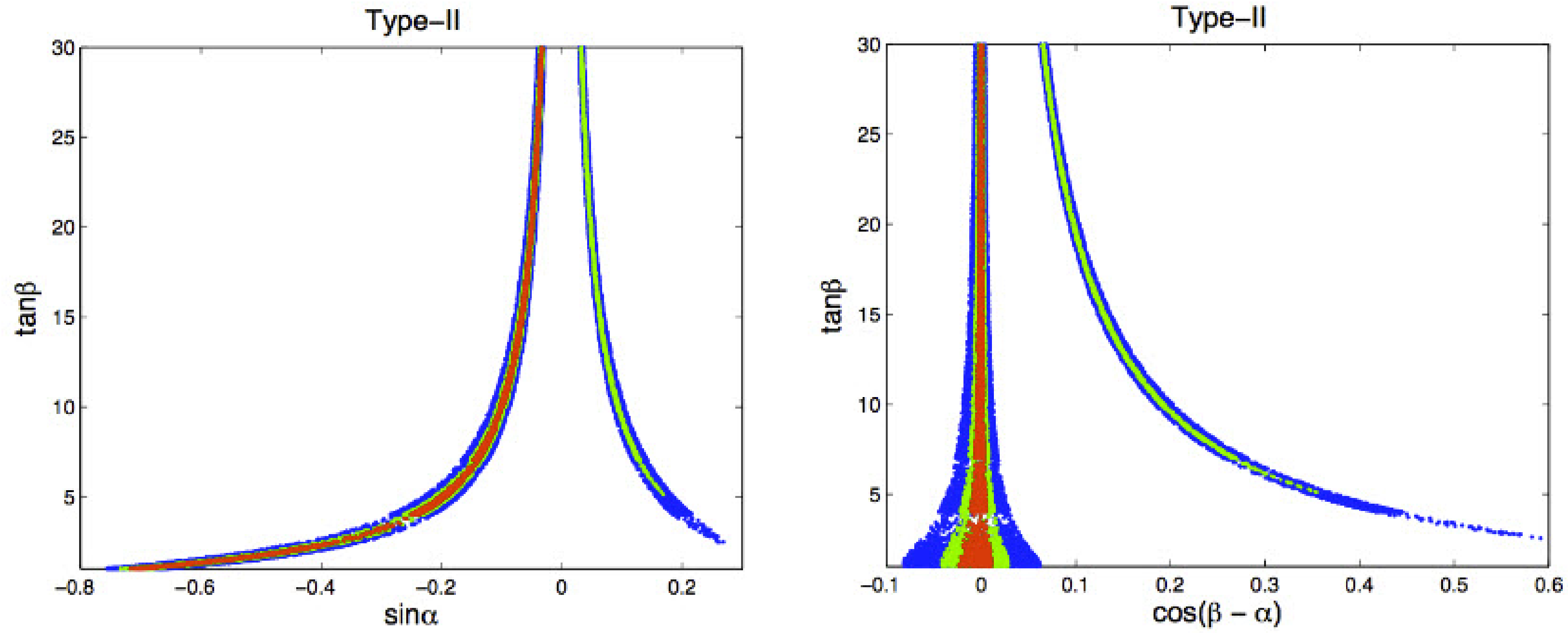
Given a final state f resulting from Higgs decay, we define

$$\mu_f^h(\text{LHC}) = \frac{\sigma^{\text{2HDM}}(pp \to h)\, BR^{\text{2HDM}}(h \to f)}{\sigma^{\text{SM}}(pp \to h_{\text{SM}})\, BR(h_{\text{SM}} \to f)}\,.$$

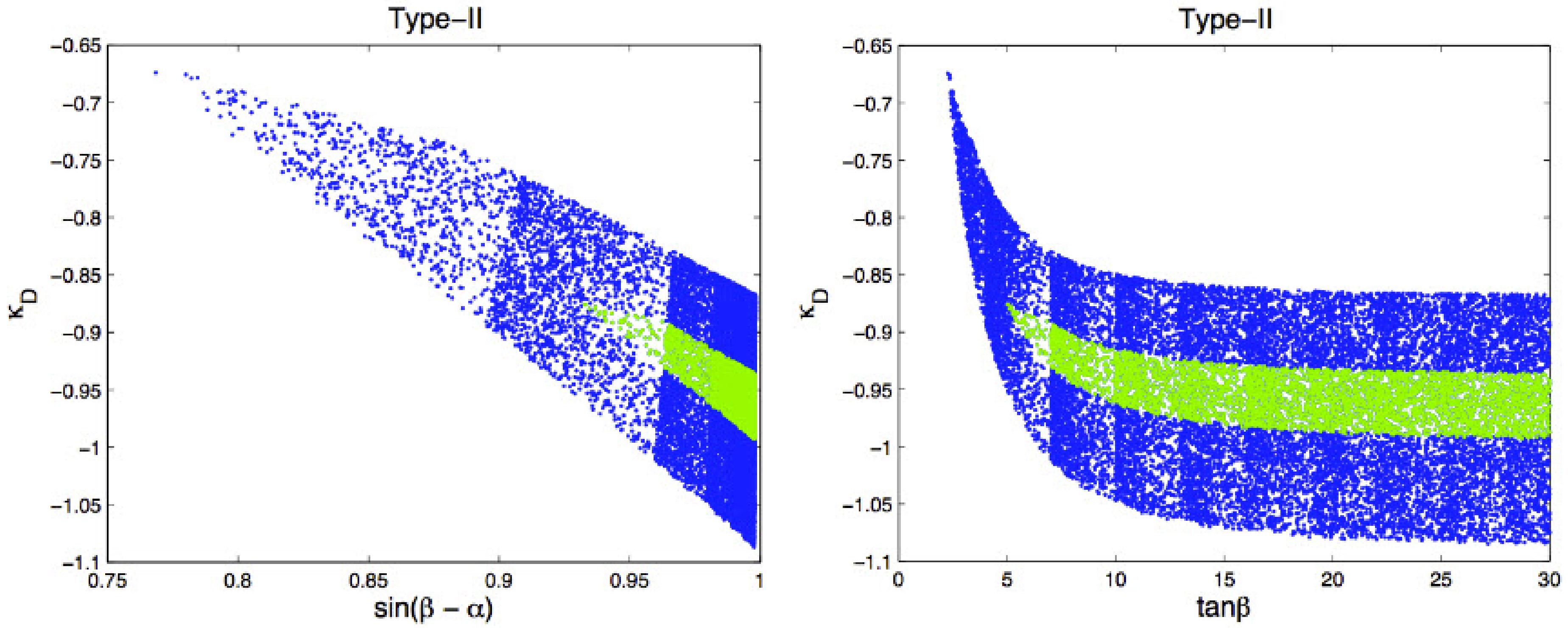


Ratio of the $h\overline{D}D$ coupling [κ_D] in the 2HDM relative to the SM vs. $\tan\beta$. All $\mu_f^h(\text{LHC})$ are within 20% of the SM value.

Our baseline will be to require that the $\mu_f^h(\mathrm{LHC})$ for final states $f = WW$, ZZ, $b\bar{b}$, $\gamma\gamma$ and $\tau^+\tau^-$ are each consistent with unity within 20% (blue), roughly the precision of the current data. We then examine the consequences of taking all the $\mu_f^h(\mathrm{LHC})$ be within 10% (green) or 5% (red) of the SM prediction.



Points in the left branch correspond to $s_{\beta-\alpha} \sim 1$ and $\kappa_D > 0$. Points in the right branch correspond to $s_{\beta+\alpha} \sim 1$ and $\kappa_D < 0$. The absence of a red region in the latter indicates that a precision in the Higgs data at the 5% level is sufficient to rule out the wrong-sign $h\overline{D}D$ Yukawa regime.



The Yukawa coupling ratio $\kappa_D = h_D^{2HDM}/h_D^{SM}$ with all $\mu_f^h(\mathrm{LHC})$ within 20% (blue) and 10% (green) of their SM values. If one demands consistency at the 5% level, no points survive.

As the Higgs data requires h to be more SM-like (and $s_{\beta-\alpha}$ is pushed closer to 1), the value of $\tan\beta$ required to achieve the wrong-sign $h\overline{D}D$ coupling becomes larger and larger, and $|\kappa_D|$ is forced to be closer to 1.

Is alignment without decoupling in the MSSM viable?

Analysis strategy:

- Make use of model-independent CMS search for $H, A \to \tau^+\tau^-$ in the regime $m_A > 200$ GeV. Both gg fusion and $b\bar{b}$ fusion production mechanisms are considered. CMS also considers specific MSSM Higgs scenarios. Recent ATLAS results are similar to those of CMS (although CMS limits are presently the most constraining).

- Analyze various benchmark MSSM Higgs scenarios and deduce limits on $\tan\beta$ as a function of m_A.

- Compare resulting limits to the constraints imposed by the properties of the observed Higgs boson with $m_h \simeq 125$ GeV.

- Extrapolate to future LHC runs. Determine what is needed to rule out alignment without decoupling in the MSSM.

MSSM Higgs scenarios[‡]

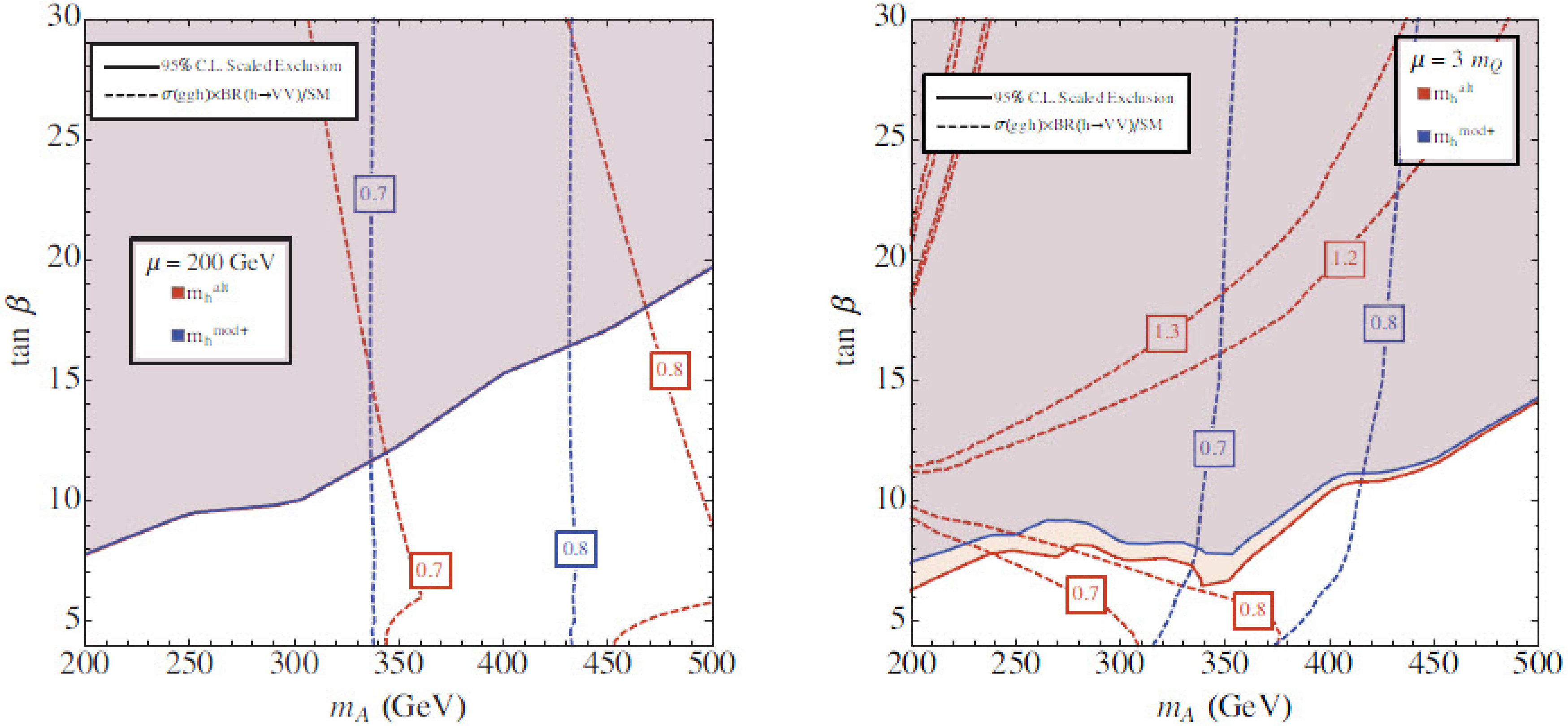
	$m_h^{\mathrm{mod}+}$	m_h^{alt}
A_t/m_Q	1.5	2.45
$M_2 = 2\ M_1$	200 GeV	200 GeV
M_3	1.5 TeV	1.5 TeV
$m_{\tilde{\ell}} = m_{\tilde{q}}$	m_Q	m_Q
$A_\ell = A_q$	A_t	A_t
μ	free	free

The m_h^{alt} scenario (for large μ) has been chosen to exhibit a region of the MSSM parameter space where the alignment limit is approximately realized.

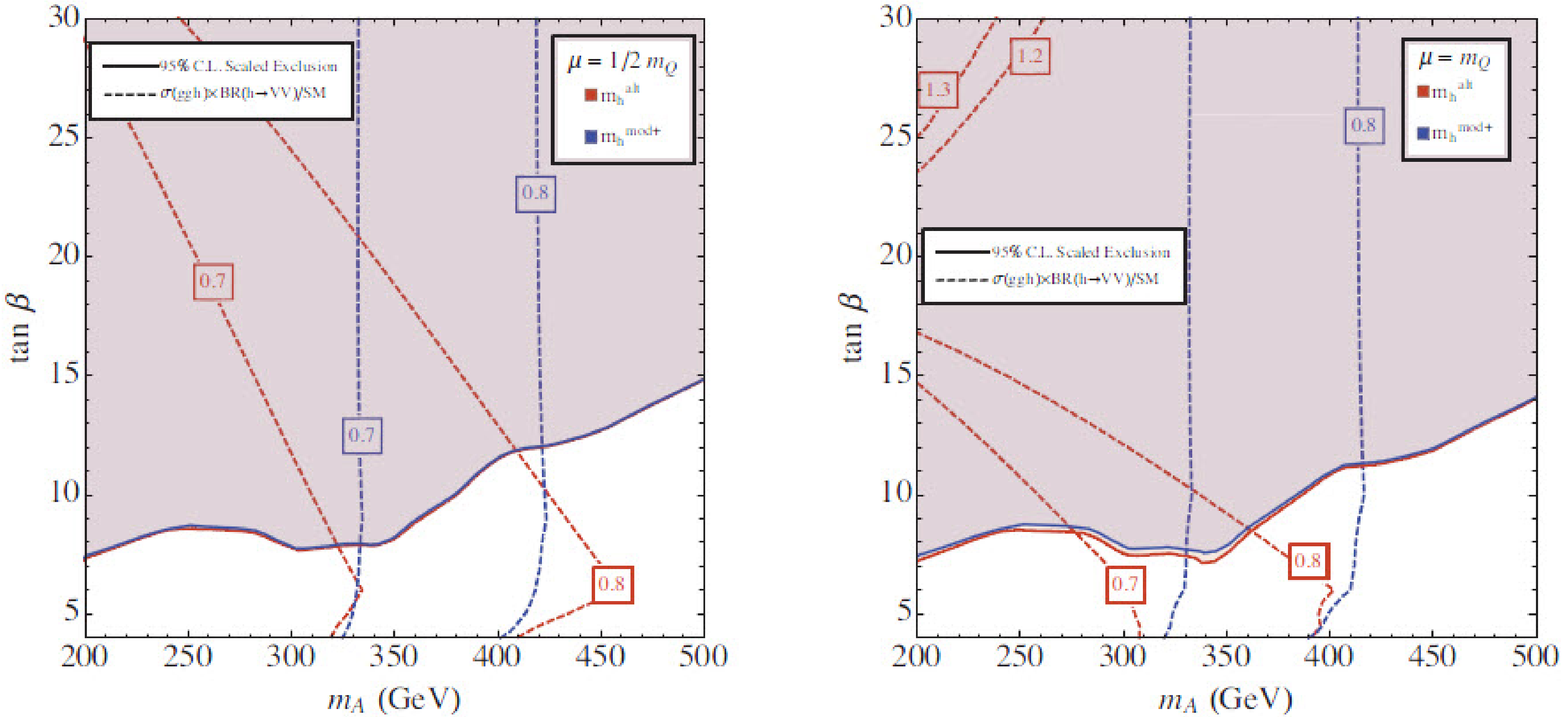
For $m_Q = 1$ TeV, $m_h = 125.5 \pm 3$ GeV for $\tan\beta > 6$ and $m_A > 200$ GeV. Here, we regard the ± 3 GeV as the theoretical error in the determination of m_h. Thus, for $\tan\beta < 6$, we increase m_Q such that m_h falls in the desired mass range for all $m_A > 200$ GeV.

[‡]Additional benchmark scenarios can be found in M. Carena, S. Heinemeyer, O. Stål, C.E.M. Wagner and G. Weiglein, "MSSM Higgs Boson Searches at the LHC: Benchmark Scenarios after the Discovery of a Higgs-like Particle," Eur. Phys. J. **C73**, 2552 (2013).

Complementarity of the H , A search and the h data



The alignment limit is most pronounced at large μ in the m_h^{alt} scenario. Taking values of μ much larger than $3M_Q$ would result in color and charge violating vacua, which suggests that alignment for $\tan\beta$ values below 10 is not viable in the MSSM.



As μ is reduced, the $\tan\beta$ value at which alignment is realized in the $m_h^{\rm alt}$ scenario increases.

Note that the observation of $\sigma \times {\rm BR}(h \to VV)$ close to its SM value implies that ${\rm BR}(h \to b\bar{b})$ must also be close to its SM value since $h \to b\bar{b}$ is the dominant decay mode of h. The latter implies that $c_{\beta-\alpha}\tan\beta \ll 1$, which accounts for the nearly vertical blue dashed lines above.

V. The Bottom Line

- The ILC will provide the next significant step in the precision study of Higgs boson properties. LHC precision measurements in the 5—10% range will be brought down to the 1% level.

- The ILC is able to provide a model-independent determination of Higgs couplings via the measurement of σ_{ZH}, in addition to measuring σ x Br in numerous channels. (In contrast, LHC only can directly measure σ x Br).

- Together with the LHC Higgs data, the ILC will provide critical measurements that can probe new physics beyond the Standard Model and provide important clues as to what may lie ahead.

Back-up slides

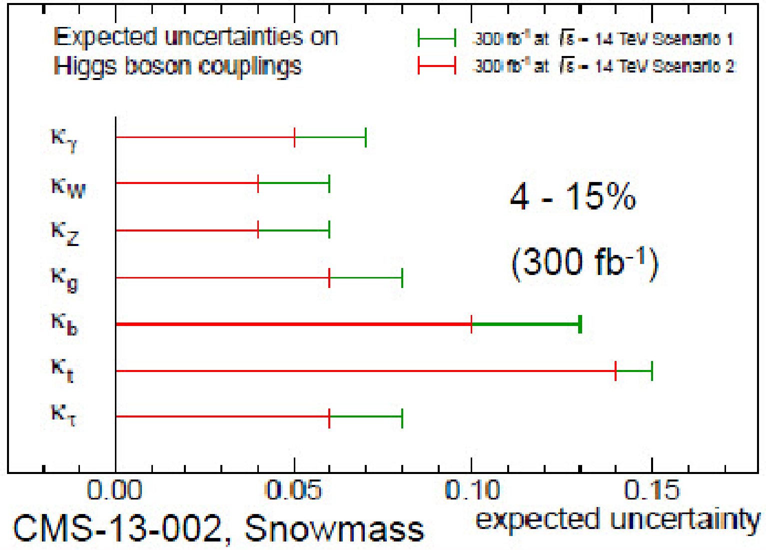
Higgs couplings

Combined fits of selected coupling scale factors κ_Y assuming the Standard Model.
Largest fit version:

$\Delta\kappa/\kappa$ [%] (300 fb^{-1})	$\gamma\gamma$	WW	ZZ	gg	$\tau\tau$	bb	tt	$\mu\mu$	$Z\gamma$
ATLAS	13 (8)	8 (7)	8 (7)	11 (9)	18 (13)	$\kappa_b = \kappa_\tau$	22 (20)	23 (21)	79 (78)
CMS	7 (5)	6 (4)	6 (4)	8 (6)	8 (6)	13 (10)	15 (14)	23 (23)	41 (41)

Rare decay modes

CMS Projection

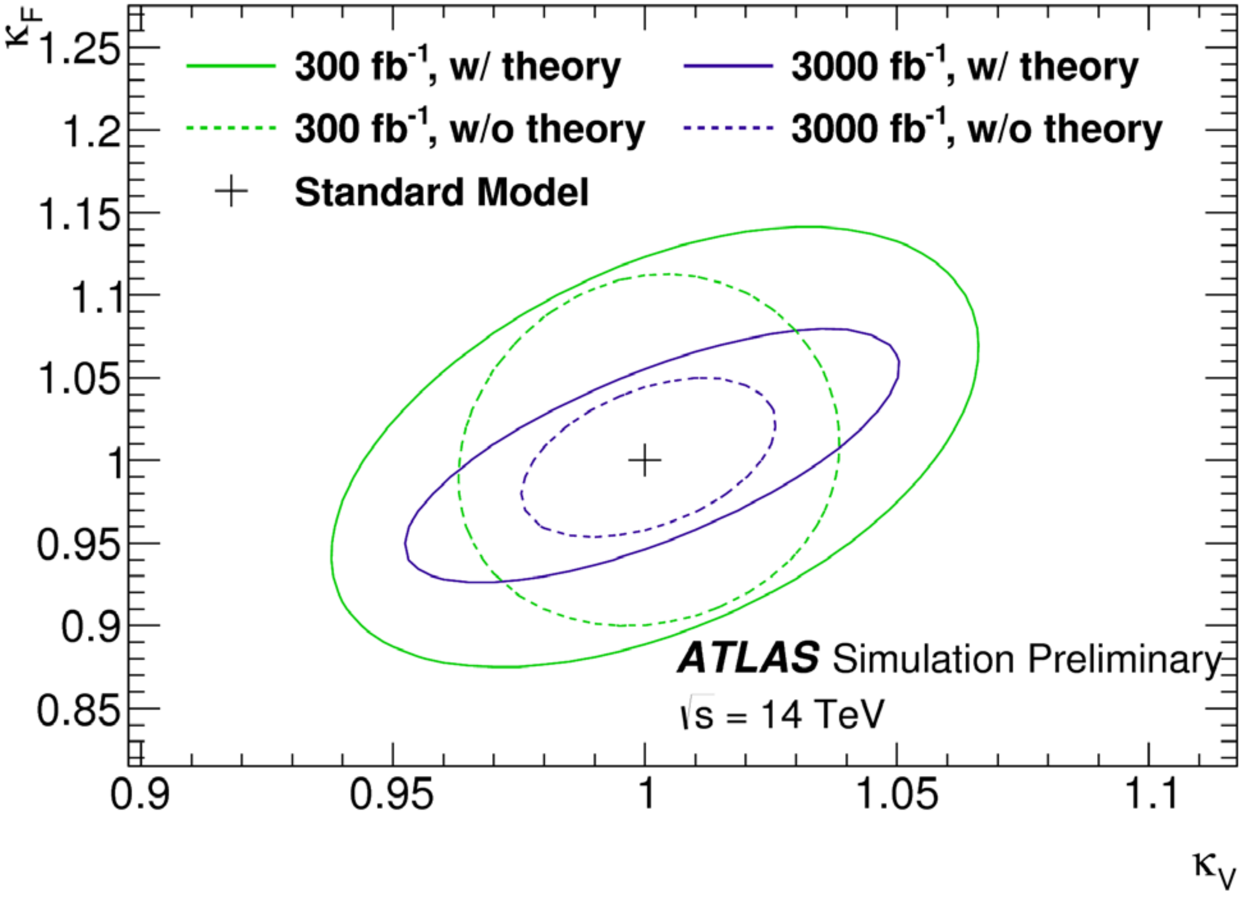


CMS-13-002, Snowmass

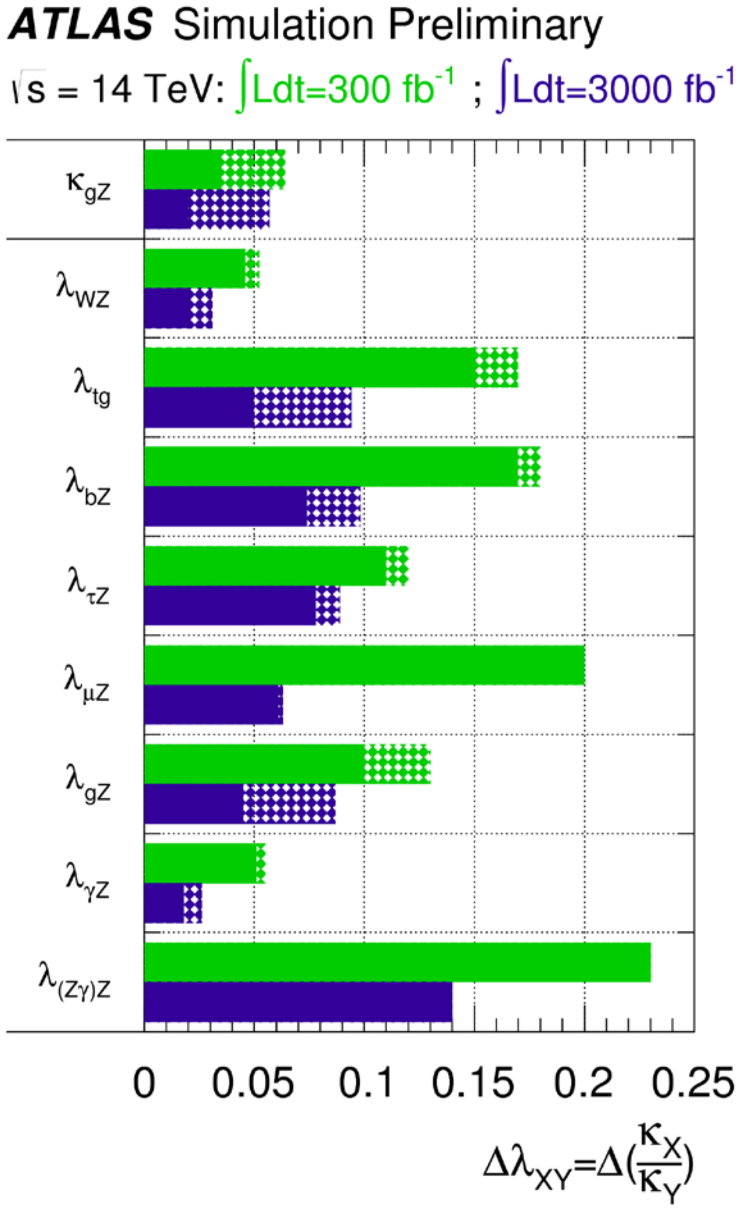
Other benchmark tests:

1) Universal couplings to fermions (F) and weak vector bosons (V) as in the Standard Model
2) Overall coupling scale factor κ_H (sensitive to new physics).
3) Branching fraction BR_{inv} to invisible, undetected final states (sensitive to new physics).

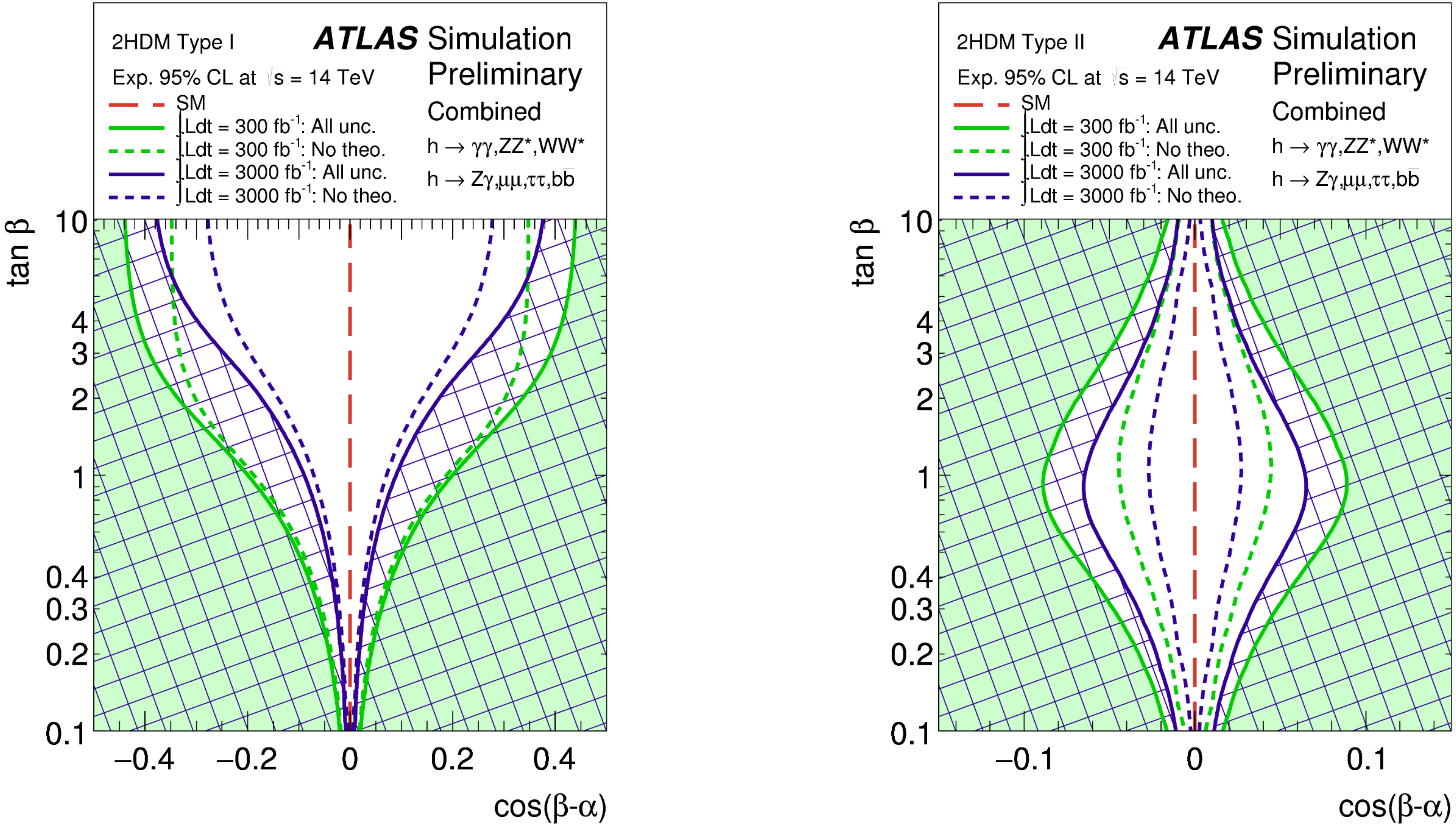
$\Delta\kappa/\kappa$ [%] (300 fb^{-1})	κ_H	κ_V	κ_F	BR_{inv} limit [%]
ATLAS	3.2 (2.5)	3.3 (2.7)	8.6 (7.1)	< 28 (<25)
CMS		6 (3)	9 (7)	< 28 (<17)



68% CL expected likelihood contours for κ_V and κ_F in a minimal coupling fit at 14 TeV for an assumed integrated luminosity of 300/fb and 3000/fb. Taken from ATL-PHYS-PUB-2014-016 (Oct. 2014).



Relative uncertainty expected for the determination of coupling scale factor ratios λ_{XY} in a generic fit without assumptions, assuming a SM Higgs boson with a mass of 125 GeV and with 300/fb or 3000/fb of 14 TeV LHC data. The hashed areas indicate the increase of the estimated error due to current theory systematic uncertainties. Taken from ATL-PHYS-PUB-2014-016 (Oct. 2014).



Regions of the (cos(β-α), tanβ) plane in the Type-I and Type-II 2HDMs expected to be excluded by fits to the measured rates of Higgs boson production and decays. The confidence intervals account for a possible relative sign between different couplings. The expected likelihood contours where -2lnΛ=6.0, corresponding approximately to 95% CL (2σ), are indicated assuming the SM Higgs sector. The light shaded and hashed regions indicate the expected exclusions. Taken from ATL-PHYS-PUB-2014-017 (Oct. 2014).

The ILC Higgs White paper (D.M. Asner, et al., arXiv:1310.0763 [hep-ph]), prepared for the Snowmass Community study.

Simulations: Full simulations performed with ILD and/or SiD dectector.

Systematic errors:

	Baseline	LumiUP
luminosity	0.1%	0.05%
polarization	0.1%	0.05%
b-tag efficiency	0.3%	0.15%