Modification of the Higgs Coupling to Bottom Quarks

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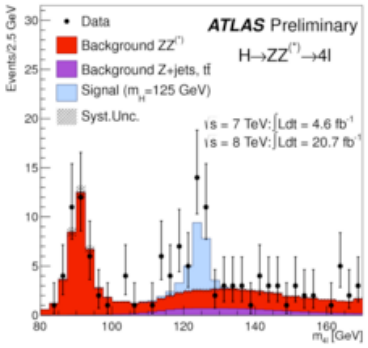
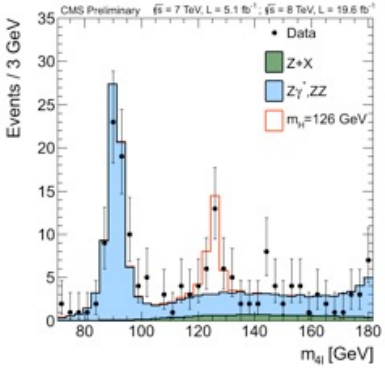
ATLAS Higgs to bb/Flavor Tagging Workshop
Simmons Center, Stony Brook, September 5, 2017

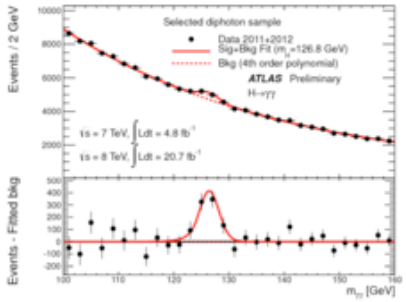
Based on the following works :

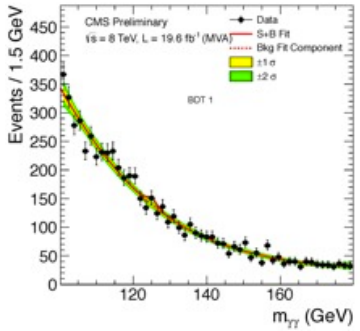
- M. Carena, I. Low, N. Shah, C.W., arXiv:1310.2248, JHEP 1404 (2014)
- M. Carena, H. Haber, I. Low, N. Shah, C.W., arXiv:1410.4969, PRD91 (2015)
- M. Carena, H. Haber, I. Low, N. Shah, C.W., arXiv:1510.09137, PRD93 (2016)
- M. Badziak, C.W. , arXiv:1602.06198, JHEP 1605 (2016)
- M. Badziak, C.W. , arXiv: 1611.02353, JHEP 1702 (2017)
- N. Coyle, B. Li, C.W., to appear

A Standard Model-like Higgs particle has been discovered by the ATLAS and CMS experiments at CERN







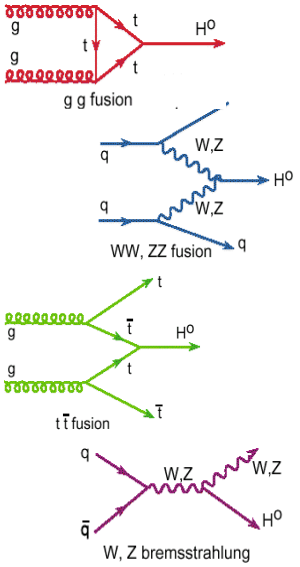


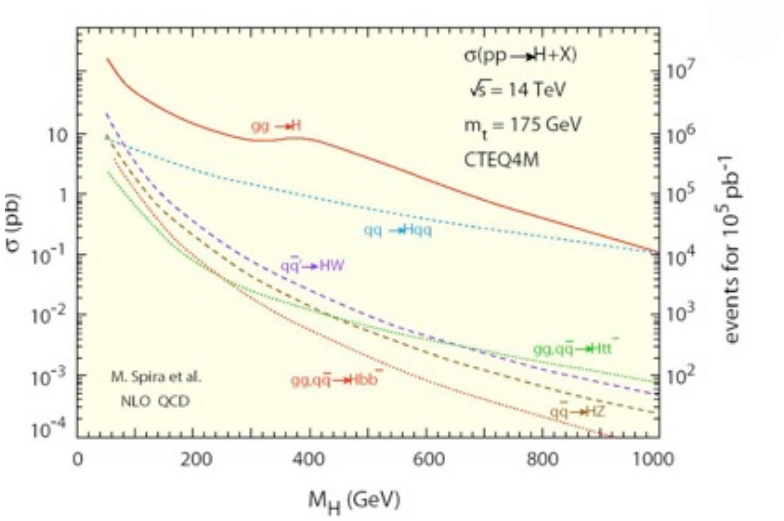
We see evidence of this particle in multiple channels.

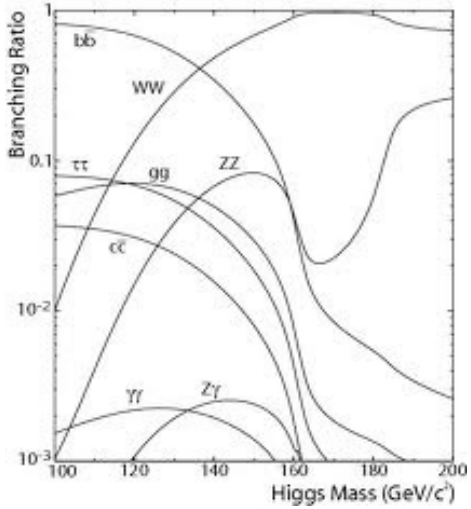
We can reconstruct its mass and we know that is about 125 GeV.

The rates are consistent with those expected in the Standard Model.

Standard Model Higgs Production Channels and Branching Ratios





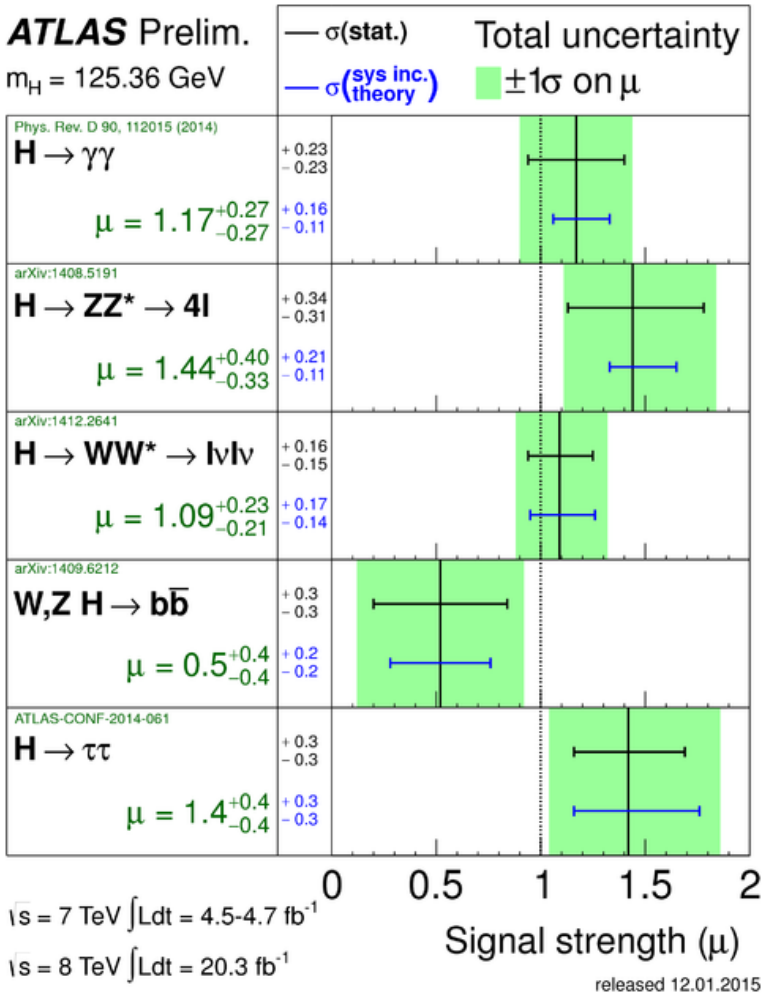


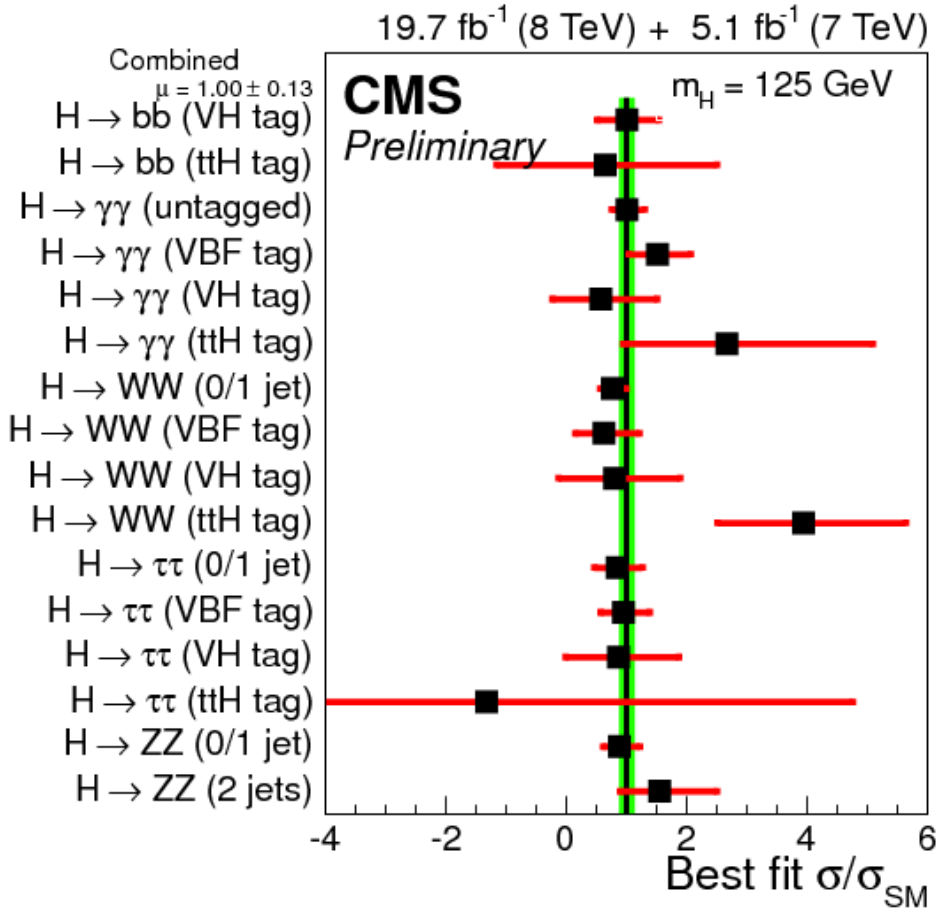
Higgs tends to decay into heavier SM particle kinematically available

A Higgs with a mass of about 125 GeV allows to study many decay channels

Higgs Boson Discovery at the LHC :

Very good agreement of Higgs Physics Results with SM Predictions





Relevant Higgs Decay Branching Ratios

$$BR(h \to b\bar{b})^{\rm SM} = 0.575$$
$$BR(h \to WW^*)^{\rm SM} = 0.216$$
$$BR(h \to gg)^{\rm SM} = 0.086$$
$$BR(h \to \tau^+\tau^-)^{\rm SM} = 0.063$$
$$BR(h \to c\bar{c})^{\rm SM} = 0.029$$
$$BR(h \to ZZ^*)^{\rm SM} = 0.027$$
$$BR(h \to \gamma\gamma)^{\rm SM} = 0.0023$$
$$BR(h \to \mu^+\mu^-)^{\rm SM} = 0.0022$$

The bottom decay is dominant. This, in spite of the fact that the relevant Yukawa coupling h_b is only about 1/60 !

The smallness of h_b is the only reason why off-shell and loop induced decays are sizable, and makes other possible rare decays relevant.

Impact of Modified Couplings

- In general, assuming modified couplings, and no new light particle the Higgs can decay into, the new decay branching ratios are given by

$$BR(h \to XX) = \frac{\kappa_X^2 \; BR(h \to XX)^{\rm SM}}{\sum_i \kappa_i^2 \; BR(h \to ii)^{\rm SM}}$$

- For small variations of (only) the bottom coupling, and $X \neq b$

$$BR(h \to b\bar{b}) \simeq BR(h \to b\bar{b})^{\rm SM}(1 + 0.4(\kappa_b^2 - 1))$$

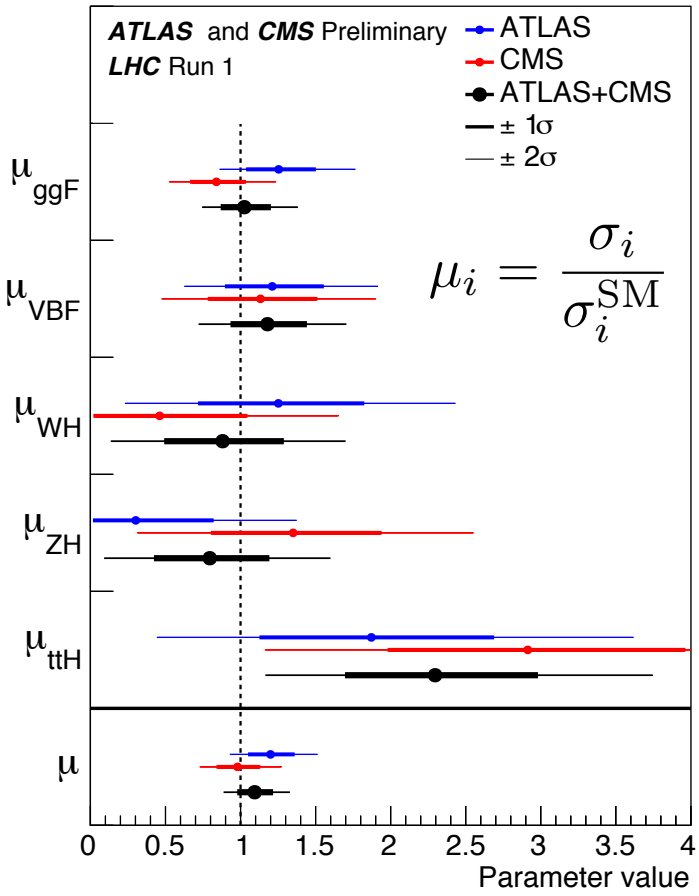
$$BR(h \to XX) \simeq BR(h \to XX)^{\rm SM}(1 - 0.6(\kappa_b^2 - 1))$$

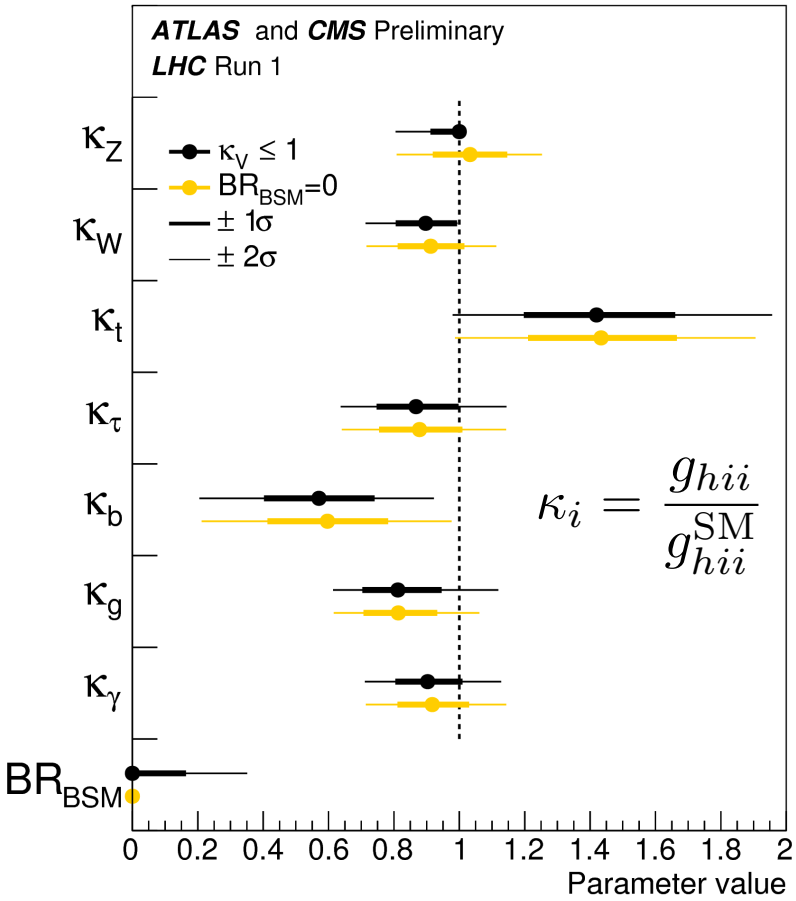
$$\frac{BR(h \to b\bar{b})}{BR(h \to XX)} = \frac{BR(h \to b\bar{b})^{\rm SM}}{BR(h \to XX)^{\rm SM}}(1 + (\kappa_b^2 - 1))$$

- So, due to the its large contribution to the Higgs decay width, a modification of a bottom coupling leads to a large modification of all other decay branching ratios (larger than the one into bottoms !)
- Observe that the coefficients are just given by the SM bottom decay branching ratio and its departure from one.

ATLAS and CMS Combination

Very good agreement of production rates with SM predictions





Assuming no strict correlation between gluon and top couplings

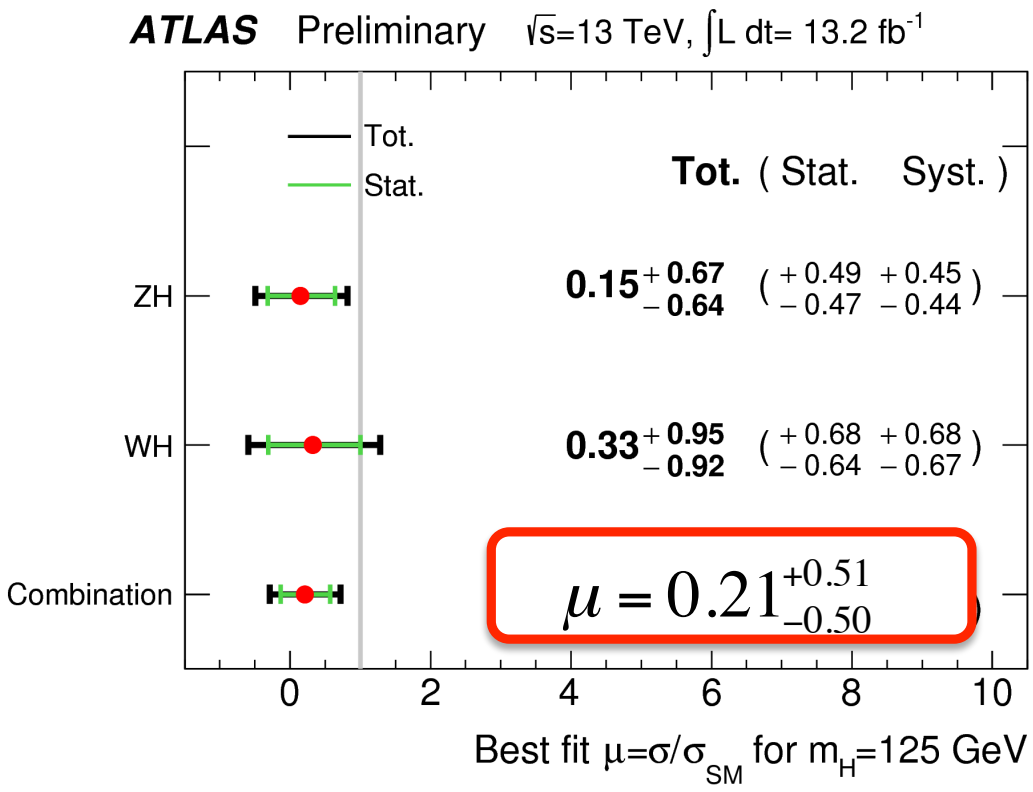
Direct Measurement of Bottom and Top Couplings subject to large uncertainties : 2σ deviations from SM predictions possible

Badziak, C.W.'16

Low bottom coupling had a major impact on the fit to the rest of the couplings.

A few months ago, at the Planck Conference
Bottom Coupling Suppression ?

ATLAS-CONF-2016-091



	Significance (expected)
ATLAS (13 TeV)	0.4σ (1.94σ)
ATLAS+CMS (8 TeV)	2.6σ (3.7σ)
Tevatron	2.8σ
	W(Z)Z(→bb)
Observed μ	$0.91 \pm 0.17(\text{stat})\ ^{+0.32}_{-0.27}(\text{syst})$
Significance	3.0σ (expected 3.2σ)

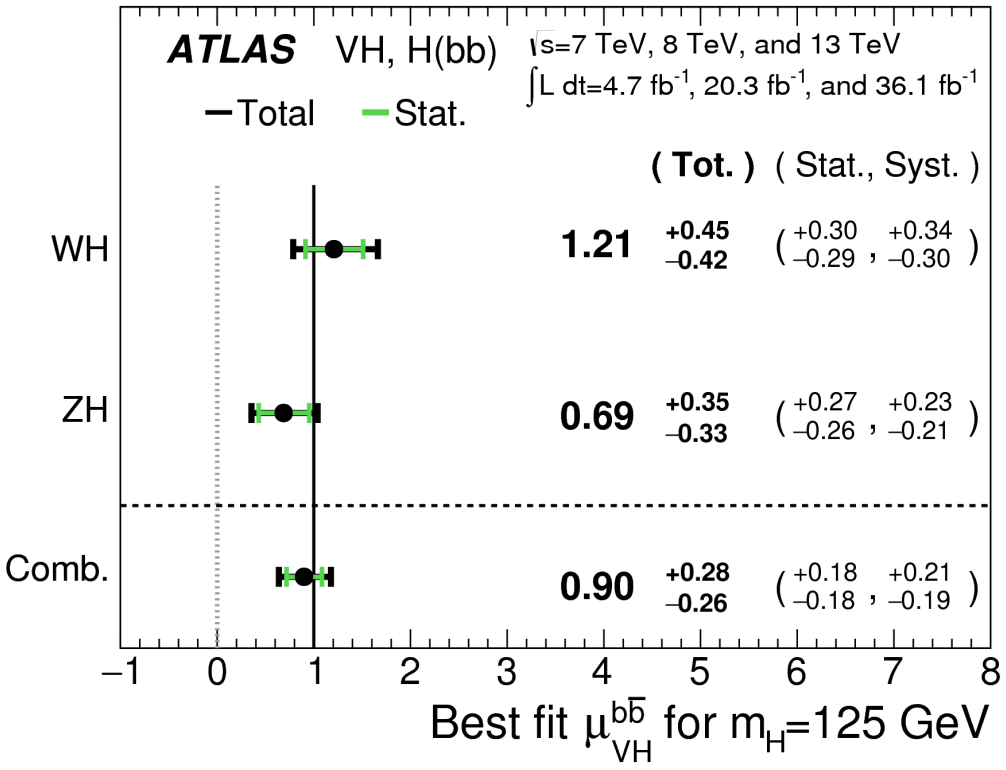
Fit tested on SM

The tendency still persists in recent data,

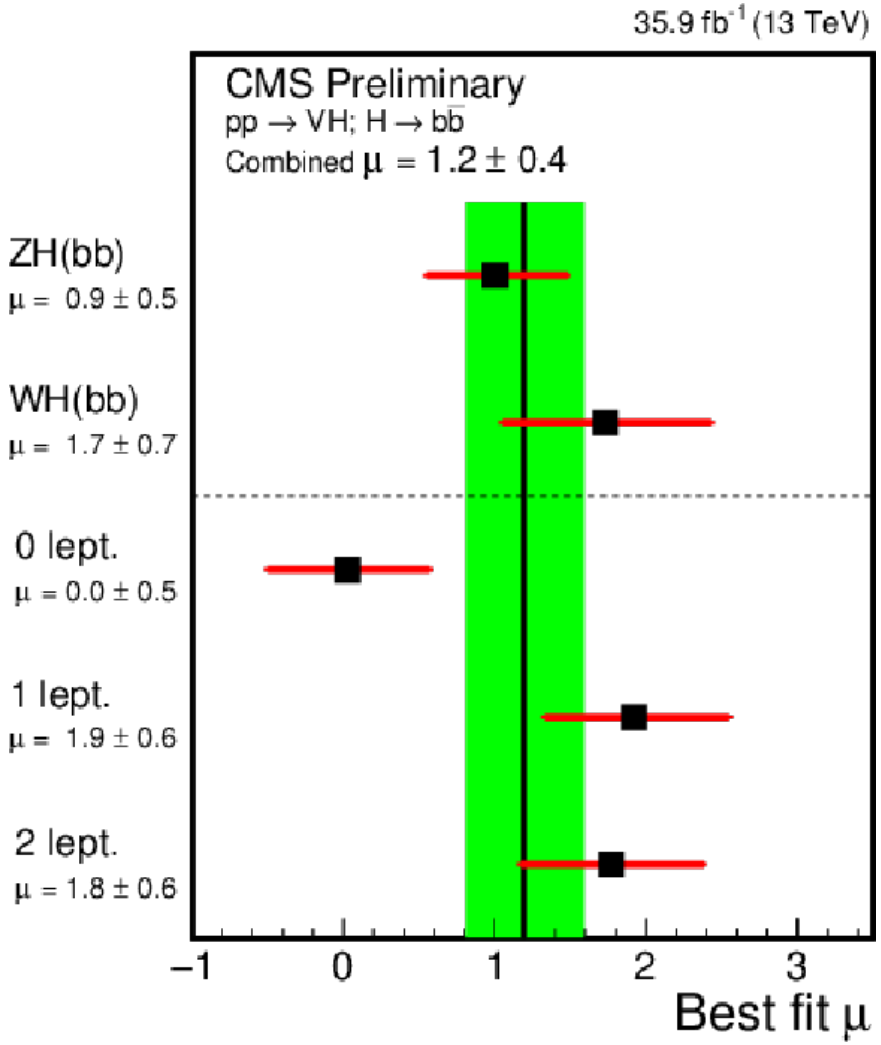
It is important to stress that a suppression of the bottom coupling would affect all Higgs BRs in a relevant way. Persistence of signal strengths would demand suppression of gluon fusion rate

Things have changed in an interesting way :

There is today evidence of a Higgs decaying to bottom quarks



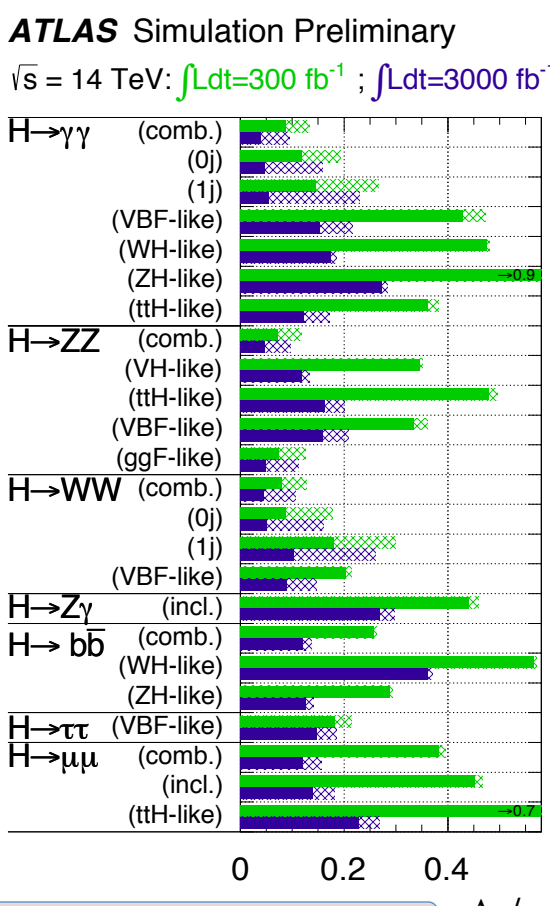
This evidence is present at both experiments

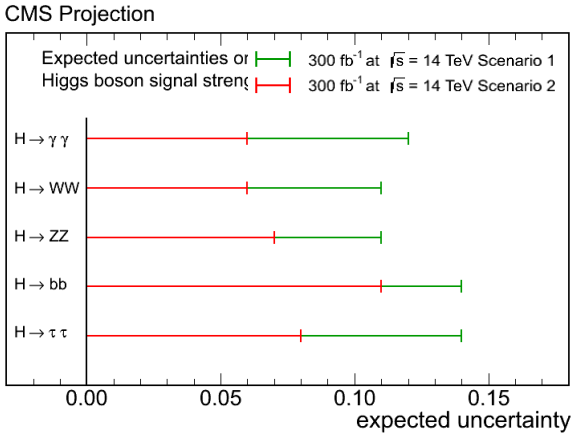


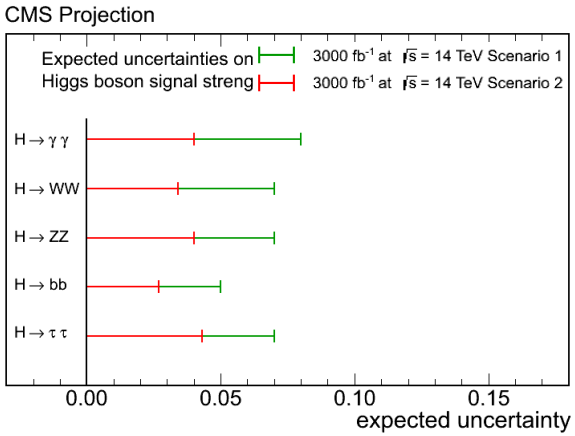
Consistency with SM results

Errors are still large an admit deviations of a few tens of percent from the SM results

Projected sensitivities



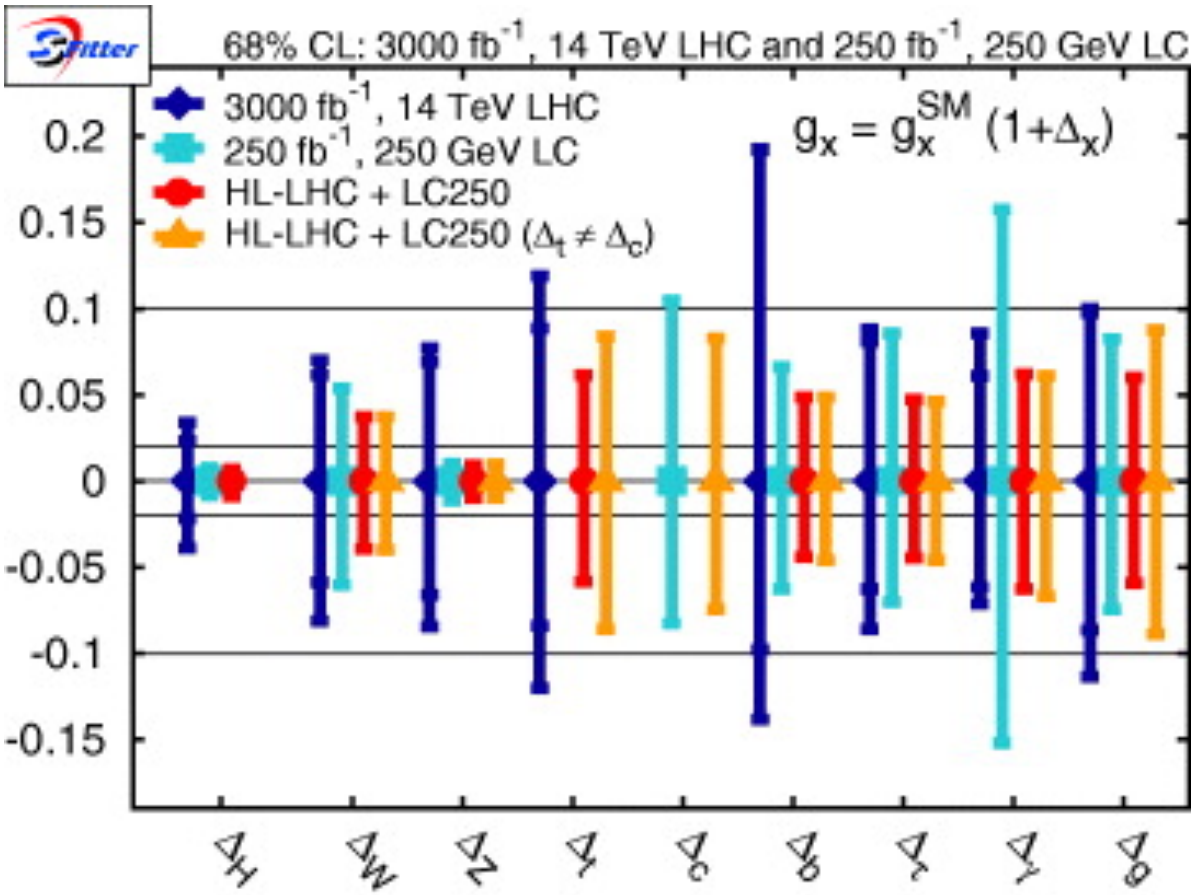




High Luminosity LHC will lead to precision determination of couplings, below 10 percent in many channels. Ten percent precision in bottom couplings may be obtained at the HL-LHC by combining all channels.

The LHC sensitivity is, I believe, better than expected from previous estimates

M. Klute et al, arXiv:1301.1322



Deviations with respect to the SM depend on precision of running mass determination

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

[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:

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

Present accuracy of 30 MeV is sufficient for LHC physics. Improvements necessary to compete with eventual lepton collider precision.

Modified couplings in 2HDMs

Low Energy Supersymmetry : Type II Higgs doublet models

- In Type II models, the Higgs Hd would couple to down-quarks and charge leptons, while the Higgs Hu couples to up quarks and neutrinos. Therefore,

$$g^{dd,ll}_{hff} = \frac{\mathcal{M}^{\rm diag}_{dd,ll}}{v}\frac{(-\sin\alpha)}{\cos\beta}, \qquad g^{dd,ll}_{Hff} = \frac{\mathcal{M}^{\rm diag}_{dd,ll}}{v}\frac{\cos\alpha}{\cos\beta}$$

$$g^{uu}_{hff} = \frac{\mathcal{M}^{\rm diag}_{uu}}{v}\frac{(\cos\alpha)}{\sin\beta}, \qquad g^{uu}_{Hff} = \frac{\mathcal{M}^{\rm diag}_{uu}}{v}\frac{\sin\alpha}{\sin\beta}$$

- If the mixing is such that $\cos(\beta-\alpha)=0$

$$h = -\sin\alpha H^0_d + \cos\alpha H^0_u \qquad \sin\alpha = -\cos\beta, \qquad \tan\beta = \frac{v_u}{v_d}$$
$$H = \cos\alpha H^0_d + \sin\alpha H^0_u \qquad \cos\alpha = \sin\beta$$

then the coupling of the lightest Higgs to fermions and gauge bosons is SM-like. We shall call this situation ALIGNMENT

- Observe that close to the alignment limit, the heavy Higgs couplings to down quarks and up quarks are enhanced (suppressed) by a $\tan\beta$ factor. We shall concentrate on this case.

- It is important to stress that the couplings of the CP-odd Higgs boson are

$$g^{dd,ll}_{Aff} = \frac{\mathcal{M}^{\rm dd}_{\rm diag}}{v}\tan\beta, \qquad g^{uu}_{Aff} = \frac{\mathcal{M}^{\rm uu}_{\rm diag}}{v\tan\beta}$$

General two Higgs Doublet Model

H. Haber and J. Gunion'03

$$
\begin{aligned}
V \;=\; & m_{11}^2\Phi_1^\dagger\Phi_1 + m_{22}^2\Phi_2^\dagger\Phi_2 - m_{12}^2(\Phi_1^\dagger\Phi_2 + \text{h.c.}) + \frac{1}{2}\lambda_1(\Phi_1^\dagger\Phi_1)^2 + \frac{1}{2}\lambda_2(\Phi_2^\dagger\Phi_2)^2 \\
& + \lambda_3(\Phi_1^\dagger\Phi_1)(\Phi_2^\dagger\Phi_2) + \lambda_4(\Phi_1^\dagger\Phi_2)(\Phi_2^\dagger\Phi_1) \\
& + \left\{\frac{1}{2}\lambda_5(\Phi_1^\dagger\Phi_2)^2 + [\lambda_6(\Phi_1^\dagger\Phi_1) + \lambda_7(\Phi_2^\dagger\Phi_2)]\Phi_1^\dagger\Phi_2 + \text{h.c.}\right\} \;,
\end{aligned}
$$

- From here, one can minimize the effective potential and derive the expression for the CP-even Higgs mass matrix in terms of a reference mass, that we will take to be mA

$$
\mathcal{M}^2 = \begin{pmatrix} \mathcal{M}_{11}^2 & \mathcal{M}_{12}^2 \\ \mathcal{M}_{12}^2 & \mathcal{M}_{22}^2 \end{pmatrix} \equiv m_A^2 \begin{pmatrix} s_\beta^2 & -s_\beta c_\beta \\ -s_\beta c_\beta & c_\beta^2 \end{pmatrix} + v^2 \begin{pmatrix} L_{11} & L_{12} \\ L_{12} & L_{22} \end{pmatrix}
$$

$$
\begin{aligned}
L_{11} &= \lambda_1 c_\beta^2 + 2\lambda_6 s_\beta c_\beta + \lambda_5 s_\beta^2 \;, \\
L_{12} &= (\lambda_3 + \lambda_4) s_\beta c_\beta + \lambda_6 c_\beta^2 + \lambda_7 s_\beta^2 \;, \\
L_{22} &= \lambda_2 s_\beta^2 + 2\lambda_7 s_\beta c_\beta + \lambda_5 c_\beta^2 \;.
\end{aligned}
$$

Carena, Low, Shah, C.W.'13

Deviations from Alignment

$$c_{\beta-\alpha} = t_\beta^{-1}\eta \ , \qquad s_{\beta-\alpha} = \sqrt{1 - t_\beta^{-2}\eta^2}$$

The couplings of down fermions are not only the ones that dominate the Higgs width but also tend to be the ones which differ at most from the SM ones

$$g_{hVV} \approx \left(1 - \frac{1}{2}t_\beta^{-2}\eta^2\right) g_V \ , \qquad g_{HVV} \approx t_\beta^{-1}\eta \ g_V \ ,$$

$$g_{hdd} \approx (1-\eta)\, g_f \ , \qquad g_{Hdd} \approx t_\beta(1 + t_\beta^{-2}\eta) g_f$$

$$g_{huu} \approx (1 + t_\beta^{-2}\eta)\, g_f \ , \qquad g_{Huu} \approx -t_\beta^{-1}(1-\eta) g_f$$

For small departures from alignment, the parameter η can be determined as a function of the quartic couplings and the Higgs masses

$$\eta = s_\beta^2\left(1 - \frac{\mathcal{A}}{\mathcal{B}}\right) = s_\beta^2 \frac{\mathcal{B}-\mathcal{A}}{\mathcal{B}} \ , \qquad \mathcal{B} - \mathcal{A} = \frac{1}{s_\beta}\left(-m_h^2 + \tilde{\lambda}_3 v^2 s_\beta^2 + \lambda_7 v^2 s_\beta^2 t_\beta + 3\lambda_6 v^2 s_\beta c_\beta + \lambda_1 v^2 c_\beta^2\right)$$

$$\tilde{\lambda}_3 = \lambda_3 + \lambda_4 + \lambda_5$$

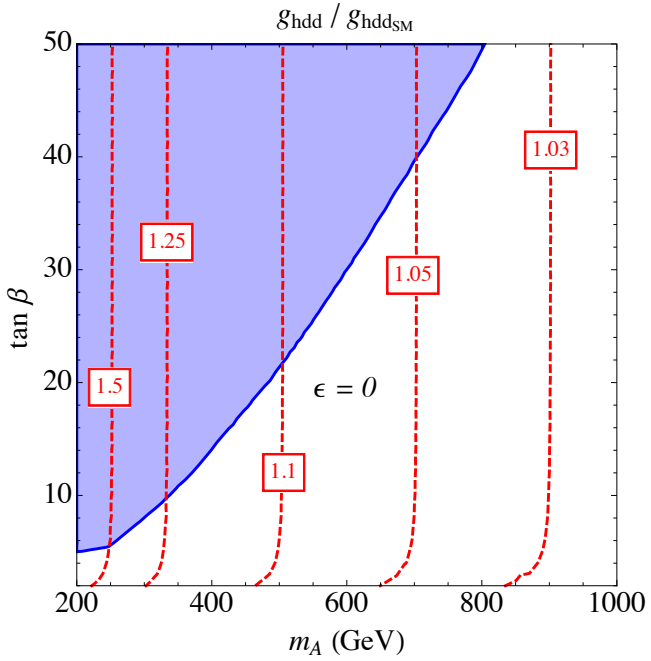
$$\mathcal{B} = \frac{\mathcal{M}_{11}^2 - m_h^2}{s_\beta} = \left(m_A^2 + \lambda_5 v^2\right) s_\beta + \lambda_1 v^2 \frac{c_\beta}{t_\beta} + 2\lambda_6 v^2 c_\beta - \frac{m_h^2}{s_\beta}$$

Down Couplings in the MSSM for low values of μ

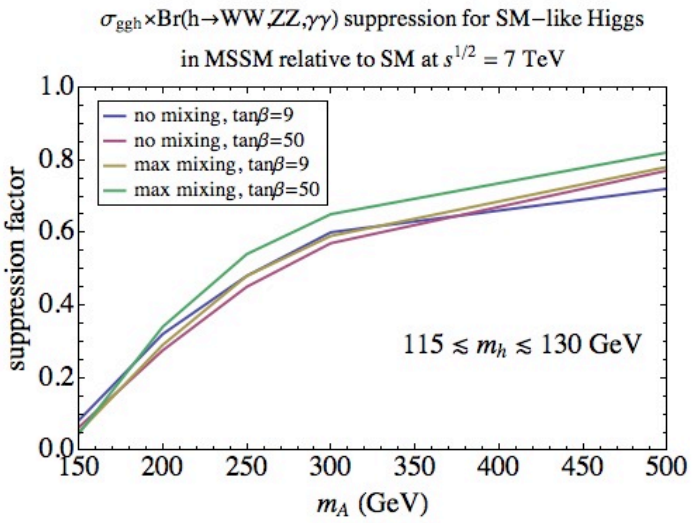
- In this regime, $\lambda_{6,7} \simeq 0$, and

$$\lambda_1 \simeq -\tilde{\lambda}_3 = \frac{g_1^2 + g_2^2}{4} = \frac{M_Z^2}{v^2} \simeq 0.125 \qquad \lambda^{\rm SM} \simeq 0.26 \qquad \lambda_7 \propto \frac{A_t \mu}{M_S^2}\left(1 - \frac{A_t^2}{6M_S^2}\right)$$

$$\lambda_2 \simeq \frac{M_Z^2}{v^2} + \frac{3}{8\pi^2} h_t^4 \left[\log\left(\frac{M_{\rm SUSY}^2}{m_t^2}\right) + \frac{A_t^2}{M_{\rm SUSY}^2}\left(1 - \frac{A_t^2}{12 M_{\rm SUSY}^2}\right)\right]$$



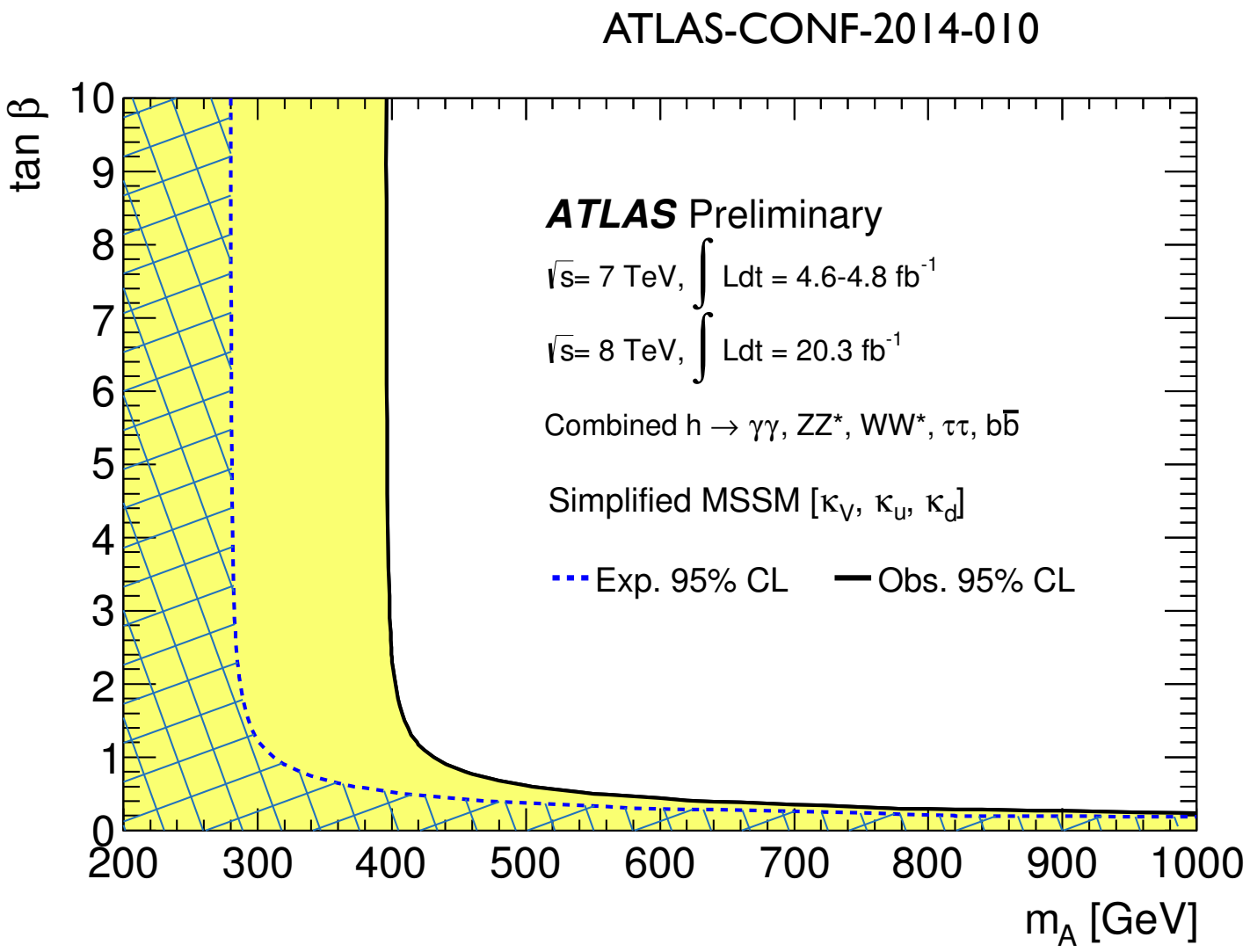
Carena, Low, Shah, C.W.'13



All vector boson branching ratios suppressed by enhancement of the bottom decay width

$$t_\beta\, c_{\beta-\alpha} \simeq \frac{-1}{m_H^2 - m_h^2}\left[m_h^2 + m_Z^2 + \frac{3m_t^4}{4\pi^2 v^2 M_S^2}\left\{A_t \mu t_\beta\left(1 - \frac{A_t^2}{6M_S^2}\right) - \mu^2\left(1 - \frac{A_t^2}{2M_S^2}\right)\right\}\right]$$

Low values of μ similar to the ones analyzed by ATLAS



Bounds coming from precision h measurements

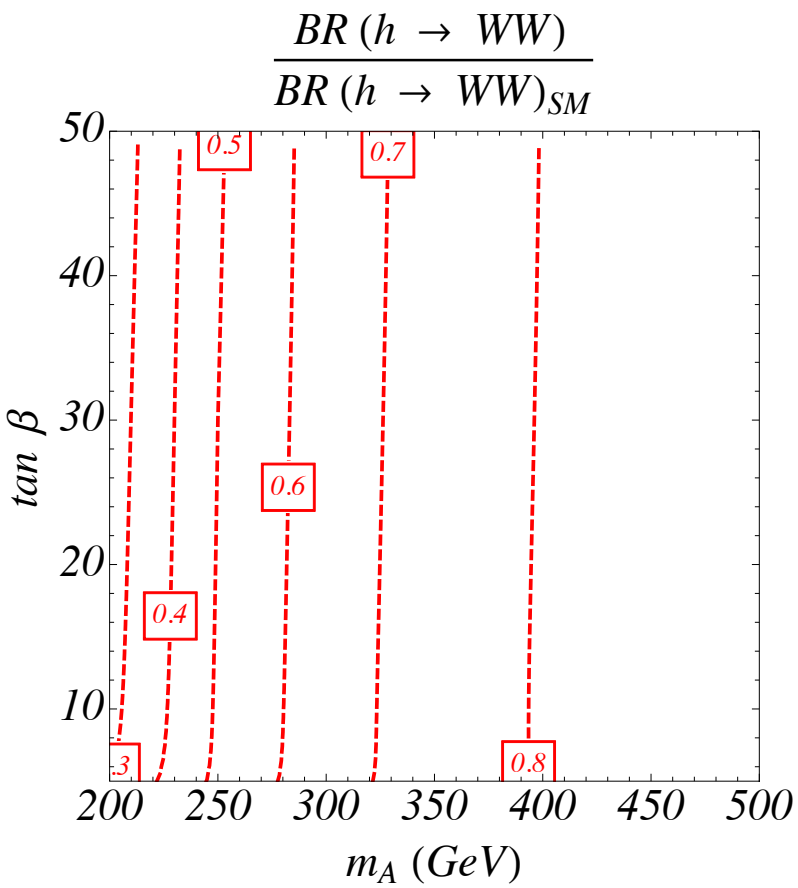
Carena, Haber, Low, Shah, C.W.'14

M. Carena, I. Low, N. Shah, C.W.'13

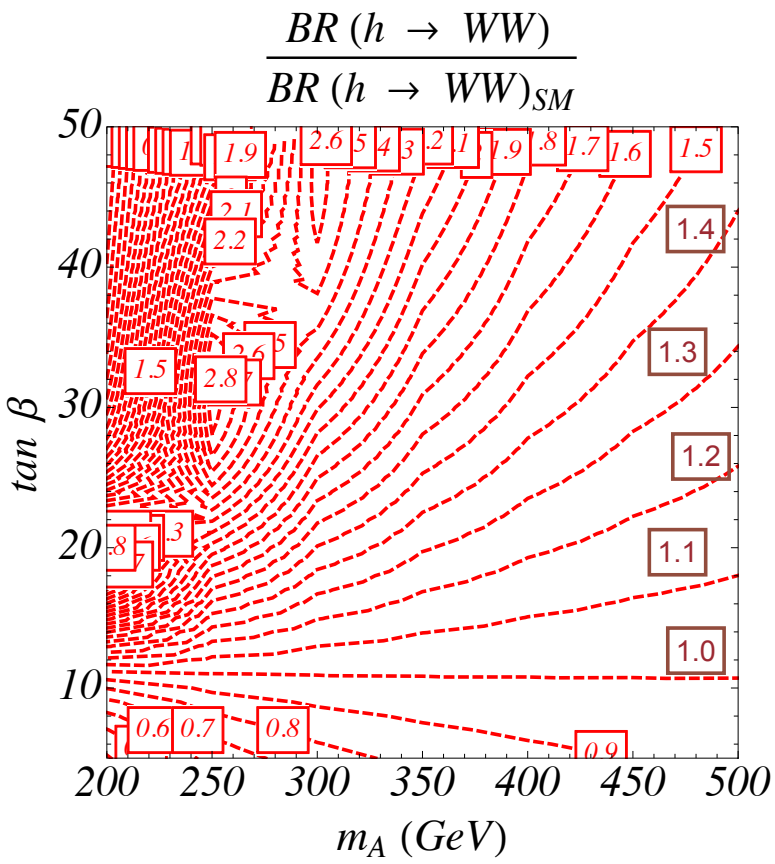
Higgs Decay into Gauge Bosons

Mostly determined by the change of width

Small μ



$\mu/M_{\rm SUSY} = 2, \quad A_t/M_{\rm SUSY} \simeq 3$



CP-odd Higgs masses of order 200 GeV and tanβ = 10 OK in the alignment case

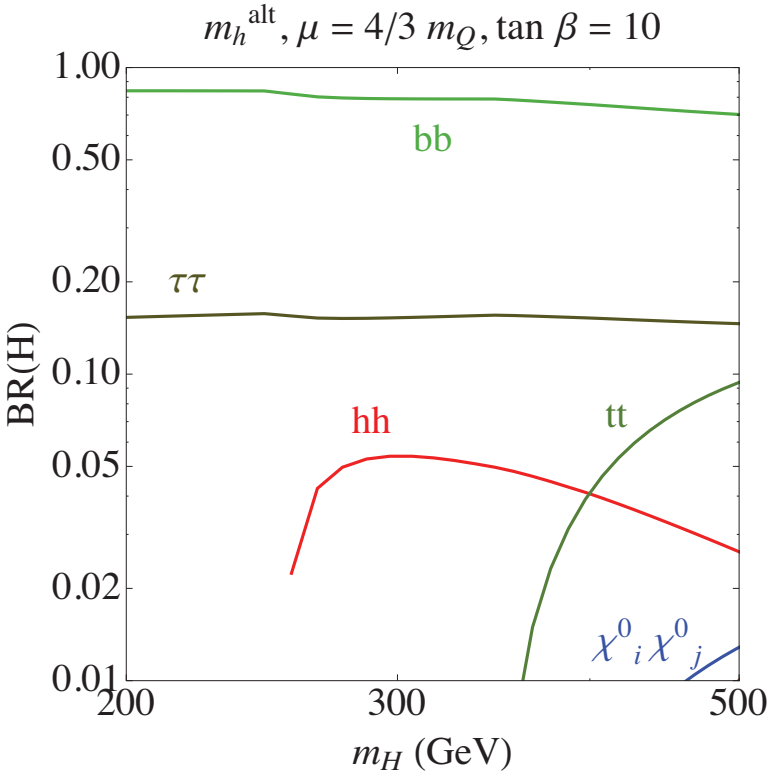
Heavy Supersymmetric Particles

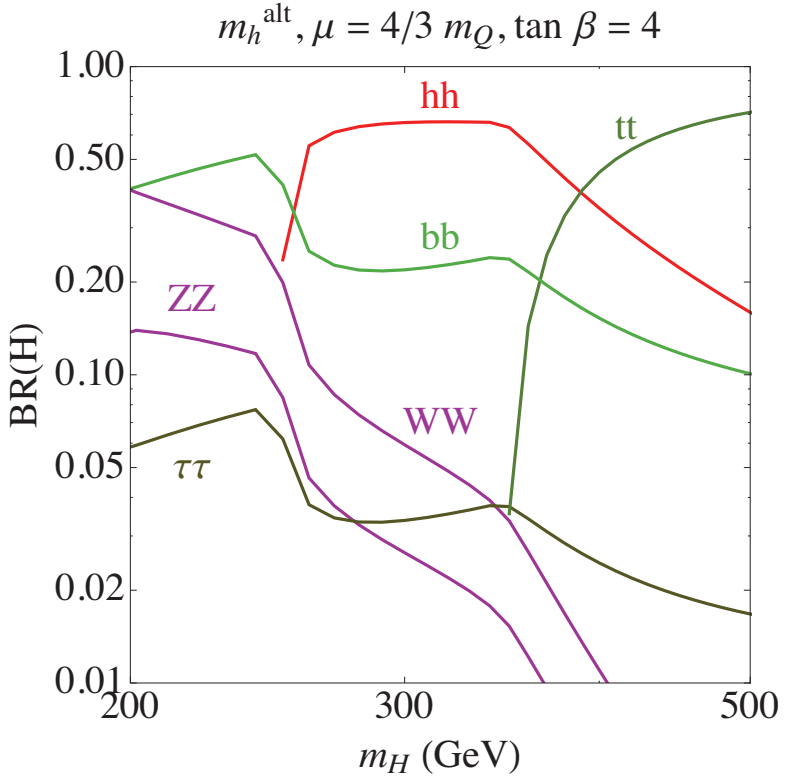
Heavy Higgs Bosons : A variety of decay Branching Ratios

Carena, Haber, Low, Shah, C.W.'14

$m_h^{\rm alt}$: Large μ. Alignment at values of $\tan\beta \simeq 12$

Depending on the values of μ and tanβ different search strategies must be applied.

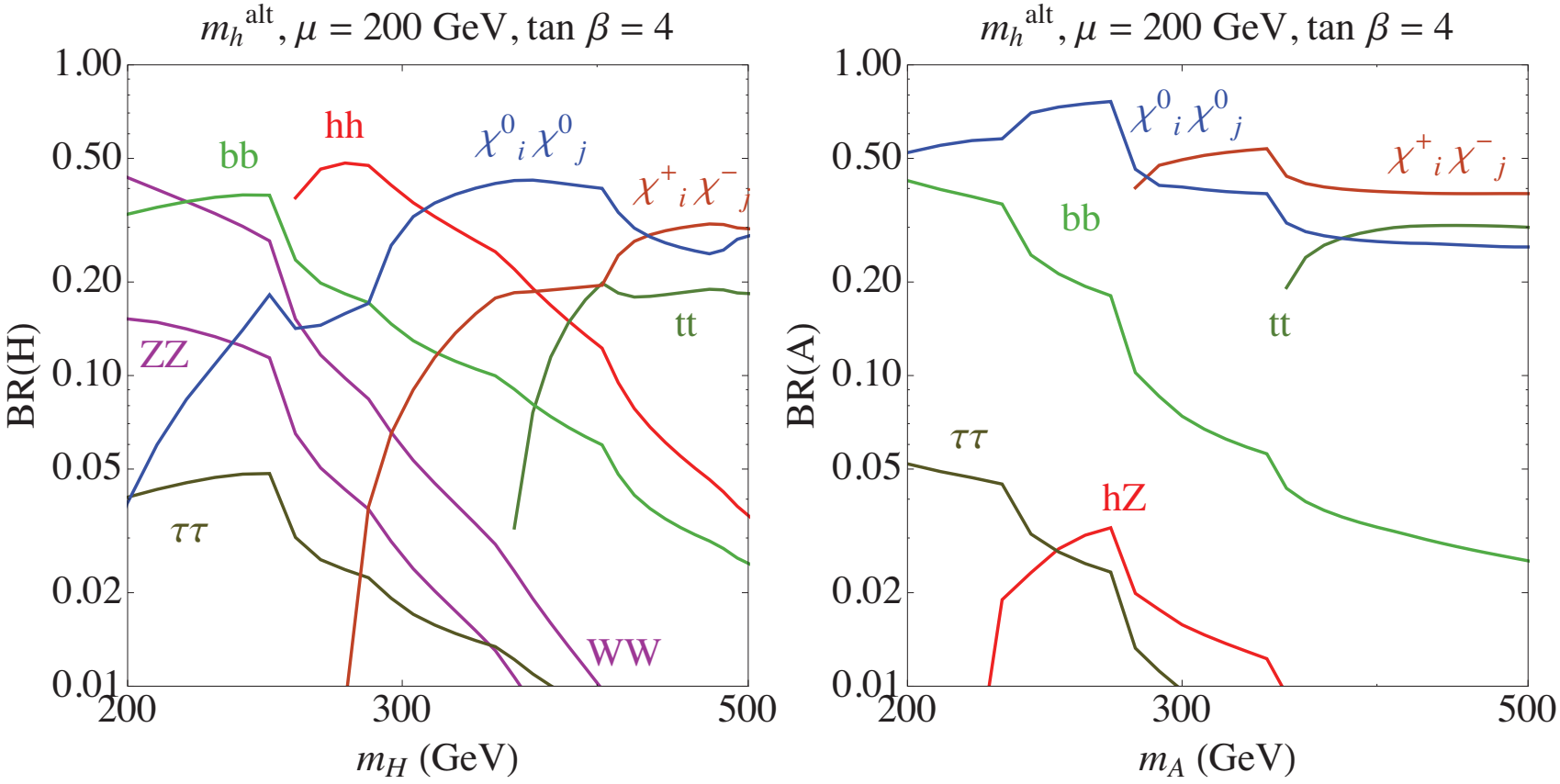




At large tanβ, bottom and tau decay modes dominant.
As tanβ decreases decays into SM-like Higgs and wek bosons become relevant

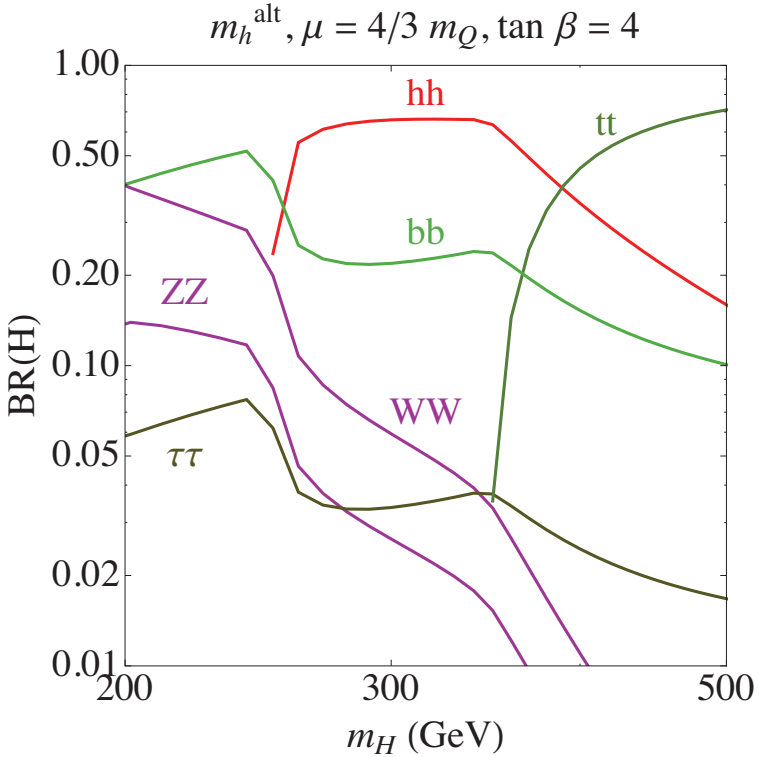
Light Charginos and Neutralinos can significantly modify M the CP-odd Higgs Decay Branching Ratios

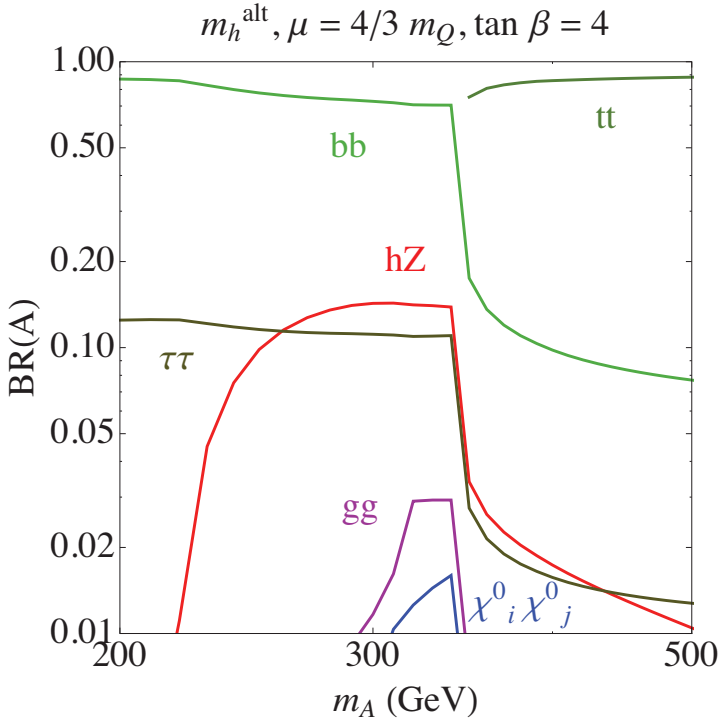
Carena, Haber, Low, Shah, C.W.'14



At small values of μ ($M_2 \simeq 200$ GeV here), chargino and neutralino decays prominent. Possibility constrained by direct searches.

Large μ and small tanβ

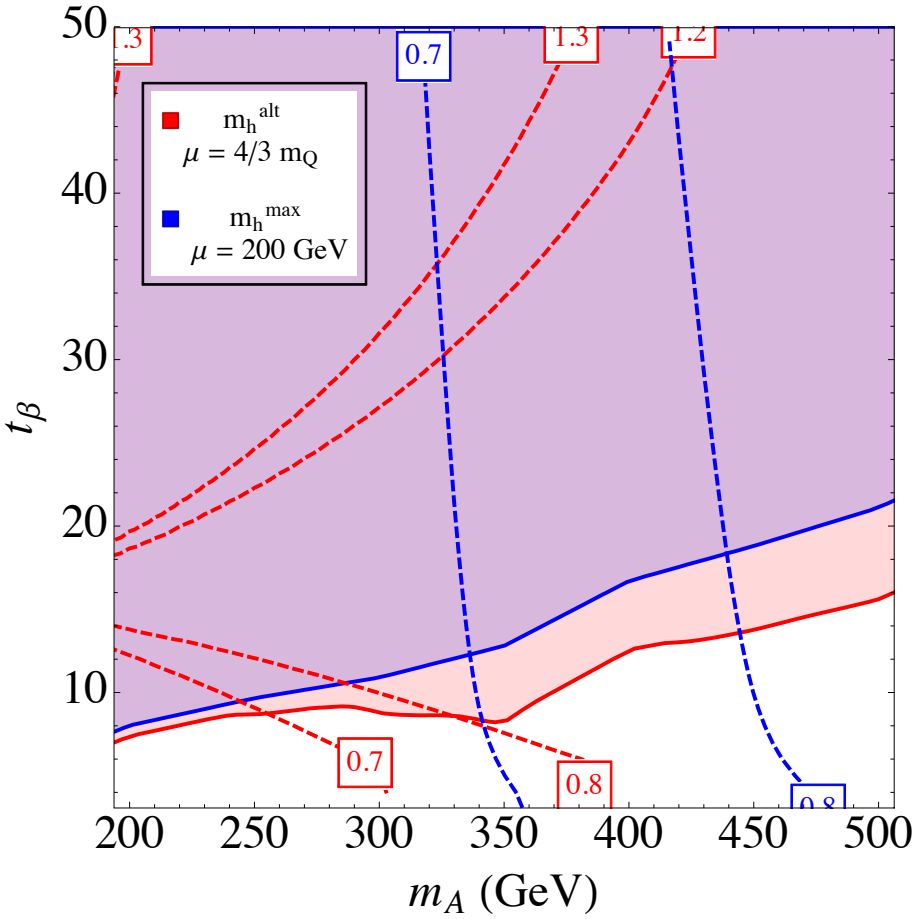




Decays into gauge and Higgs bosons become important. Observe, however that the BR(A to τ τ) remains large up to the top-quark threshold scale

Complementarity between precision measurements and search for new Higgs going to τ pairs

Carena, Haber, Low, Shah, C.W.'14



Limits coming from measurements of h couplings become weaker for larger values of μ

— $\sum_{\phi_i=A,H}\sigma(bb\phi_i+gg\phi_i) \times BR(\phi_i \to \tau\,\tau)$ (8 TeV)

--- $\sigma(bbh+ggh) \times BR(h \to VV)/SM$

Limits coming from direct searches of $H, A \to \tau\tau$ become stronger for larger values of μ

Bounds on m_A are therefore dependent on the scenario and at present become weaker for larger μ

With a modest improvement of direct search limit one would be able to close the wedge, below top pair decay threshold

Carena, Haber, Low, Shah, C.W.'15

Naturalness and Alignment in the NMSSM

see also Kang, Li, Li,Liu, Shu'13, Agashe,Cui,Franceschini'13

- It is well known that in the NMSSM there are new contributions to the lightest CP-even Higgs mass,

$$W = \lambda S H_u H_d + \frac{\kappa}{3} S^3$$

$$m_h^2 \simeq \lambda^2 \frac{v^2}{2} \sin^2 2\beta + M_Z^2 \cos^2 2\beta + \Delta_{\tilde{t}}$$

- It is perhaps less known that it leads to sizable corrections to the mixing between the MSSM like CP-even states. In the Higgs basis, (correction to λ_4)

$$M_S^2(1,2) \simeq \frac{1}{\tan\beta} \left(m_h^2 - M_Z^2 \cos 2\beta - \lambda^2 v^2 \sin^2 \beta + \delta_{\tilde{t}} \right)$$

$$\delta\tilde{\lambda}_3 = \lambda^2$$

- The last term is the one appearing in the MSSM, that are small for moderate mixing and small values of $\tan\beta$

- The values of λ end up in a very narrow range, between 0.65 and 0.7 for all values of tan(beta), that are the values that lead to naturalness with perturbativity up to the GUT scale

$$\lambda^2 = \frac{m_h^2 - M_Z^2 \cos 2\beta}{v^2 \sin^2 \beta}$$

Carena, Haber, Low, Shah, C.W.'15

Coupling of the Higgs to vector bosons and quarks within type II Higgs doublet models.

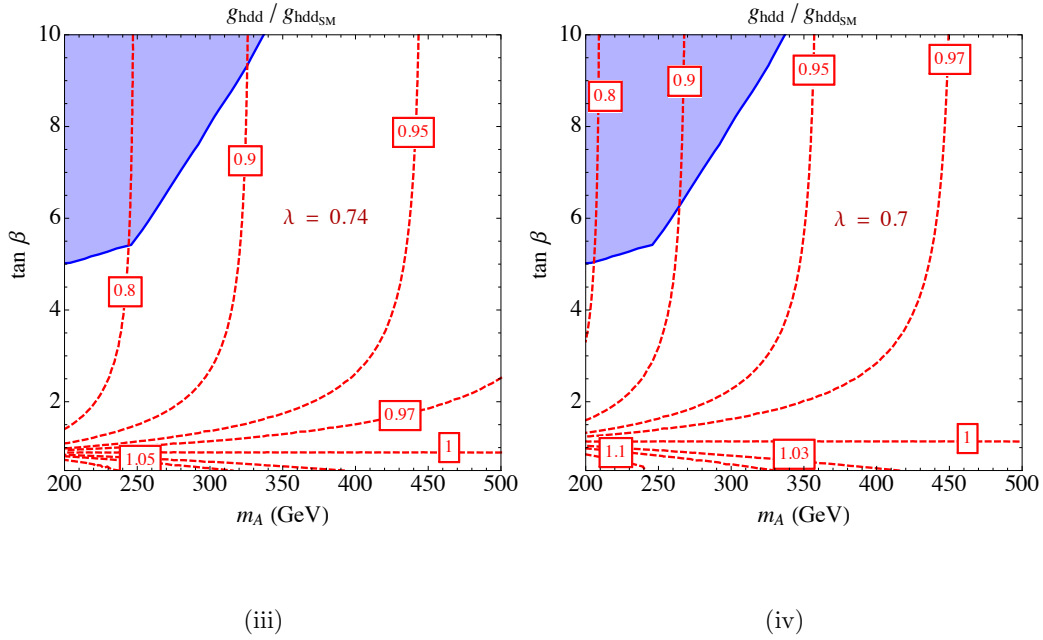
$$h = -\sin\alpha H_d^0 + \cos\alpha H_u^0$$
$$H = \cos\alpha H_d^0 + \sin\alpha H_u^0$$

$$\tan\beta = \frac{v_u}{v_d}$$

$$\kappa_t = \sin(\beta-\alpha) + \cot\beta\cos(\beta-\alpha)$$
$$\kappa_b = \sin(\beta-\alpha) - \tan\beta\cos(\beta-\alpha)$$
$$\kappa_V = \sin(\beta-\alpha) \simeq 1$$

At large $\tan\beta$: $$t_\beta\, c_{\beta-\alpha} \approx \frac{-1}{m_H^2 - m_h^2}\left[(m_h^2 + m_Z^2 - \lambda^2 v^2) + \frac{3m_t^4 A_t \mu t_\beta}{4\pi^2 v^2 M_S^2}\left(1 - \frac{A_t^2}{6M_S^2}\right)\right]$$

Alignment in the NMSSM (heavy or Aligned singlets)



Carena, Low, Shah, C.W.'13

It is clear from these plots that the NMSSM does an amazing job in aligning the MSSM-like CP-even sector, provided λ is about 0.65

Inverting the sign of the bottom coupling

B. Li, N. Coyle, C.W. '17 (to appear)

What about inverting the sign of the third generation couplings ?

- It turns out that is easy to achieve the inversion of the bottom coupling in type II Higgs doublet models
- In the NMSSM, in particular, this implies to go to larger values of lambda, since this is the parameter that allows to control this coupling.

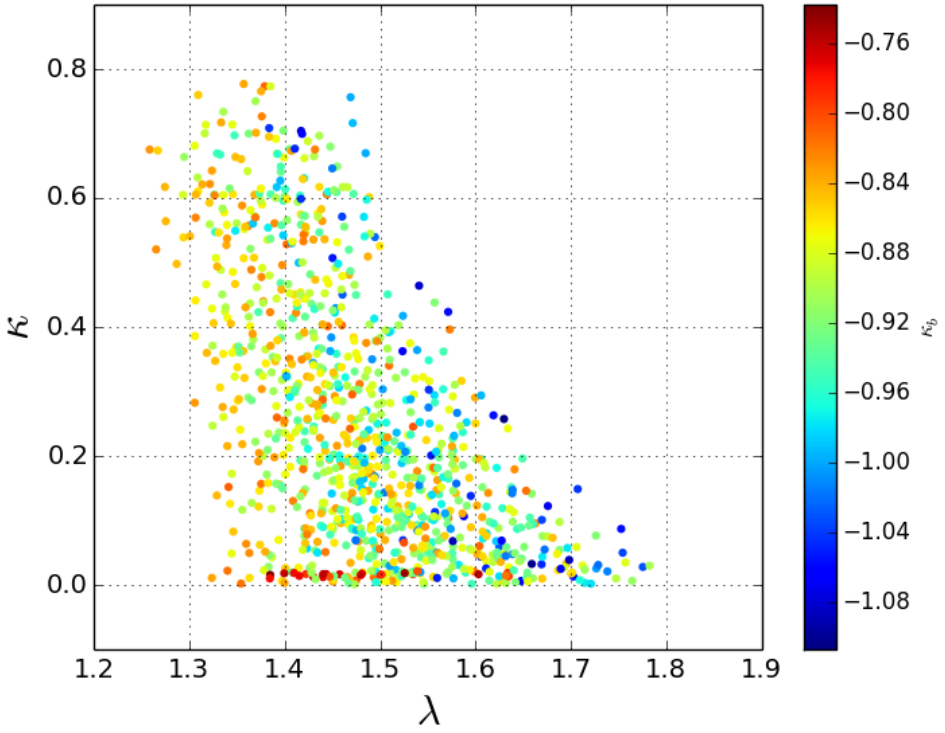
$$t_\beta \; c_{\beta-\alpha} \approx \frac{-1}{m_H^2 - m_h^2}\left[\left(m_h^2 + m_Z^2 - \lambda^2 v^2\right) + \frac{3 m_t^4 A_t \mu t_\beta}{4\pi^2 v^2 M_S^2}\left(1 - \frac{A_t^2}{6 M_S^2}\right)\right]$$

- This causes problems with the perturbative extrapolation of the theory to large scales, and also with the spectrum, since some scalars tend to become tachyonic in the relevant region of parameters
- We cured this problem by adding a tadpole term

$$\Delta V = \; \xi_S \; S + h.c.$$

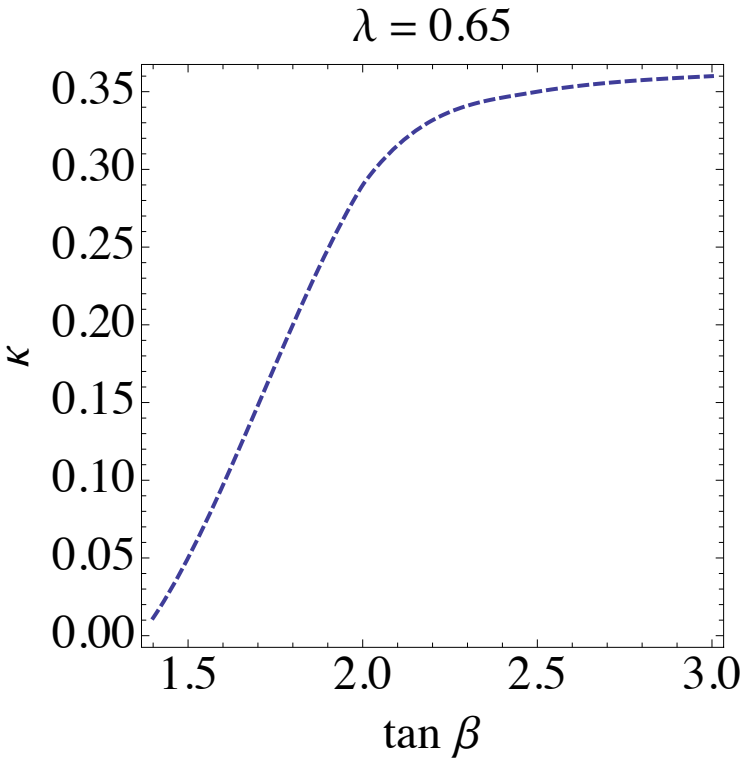
Values of the dimensionless couplings

B. Li, N. Coyle, C.W. '17 (to appear)



Necessary values to invert the bottom coupling

Carena, Haber, Low, Shah, C.W.'15

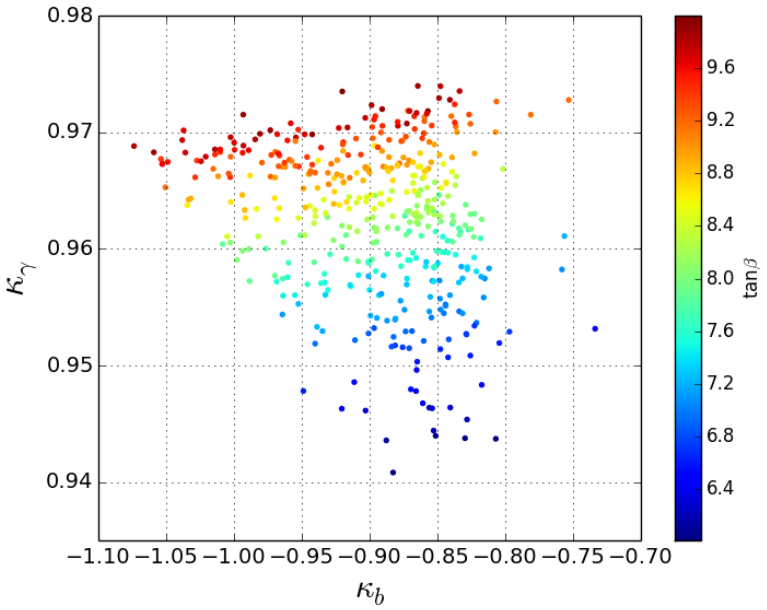


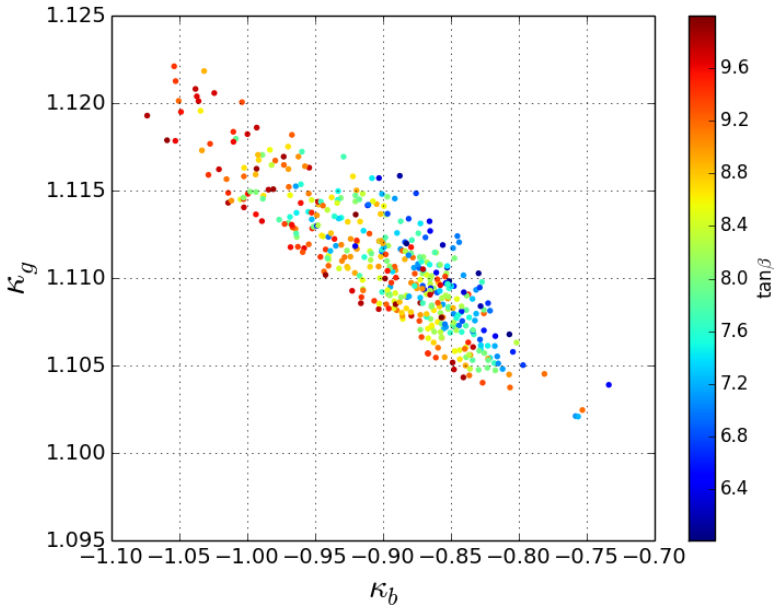
Upper bound on these parameters to preserve perturbative consistency up to the GUT scale

B. Li, N. Coyle, C.W. '17 (to appear)

Effects on gluon Fusion

- Changing the sign of the bottom coupling changes the gluon fusion rate by about 12 percent !
- Assuming that no other effect is present, the LHC collaborations announce a precision of about 5 percent for the gluon coupling by the end of the LHC run. So, under this assumption this effect may be tested.





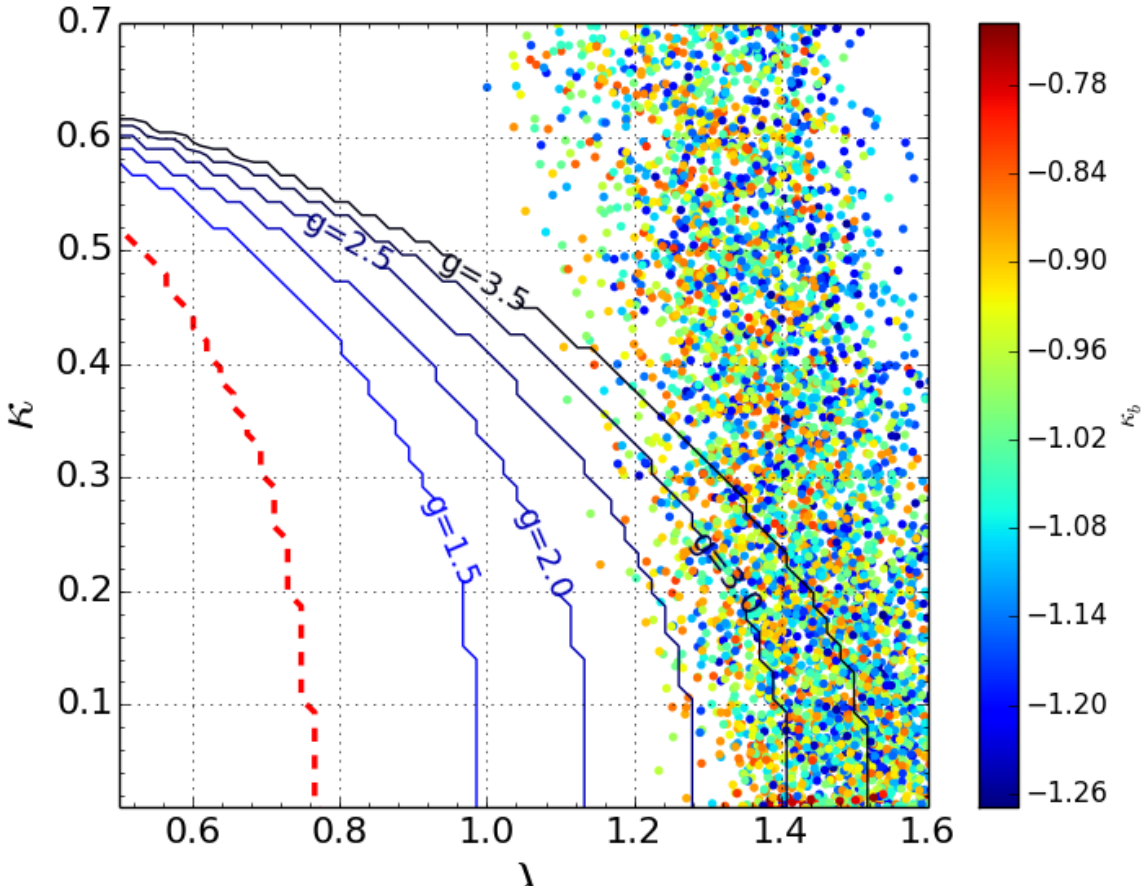
B. Li, N. Coyle, C.W. ’17 (to appear)

Fixing the perturbativity problem ?

It is known that one can add two SU(2)’s at higher energies, one that couples to the Higgs bosons and the third generation, and the other the first generation. This would break to the SM SU(2) at energies of a few TeV.

Batra et al’04

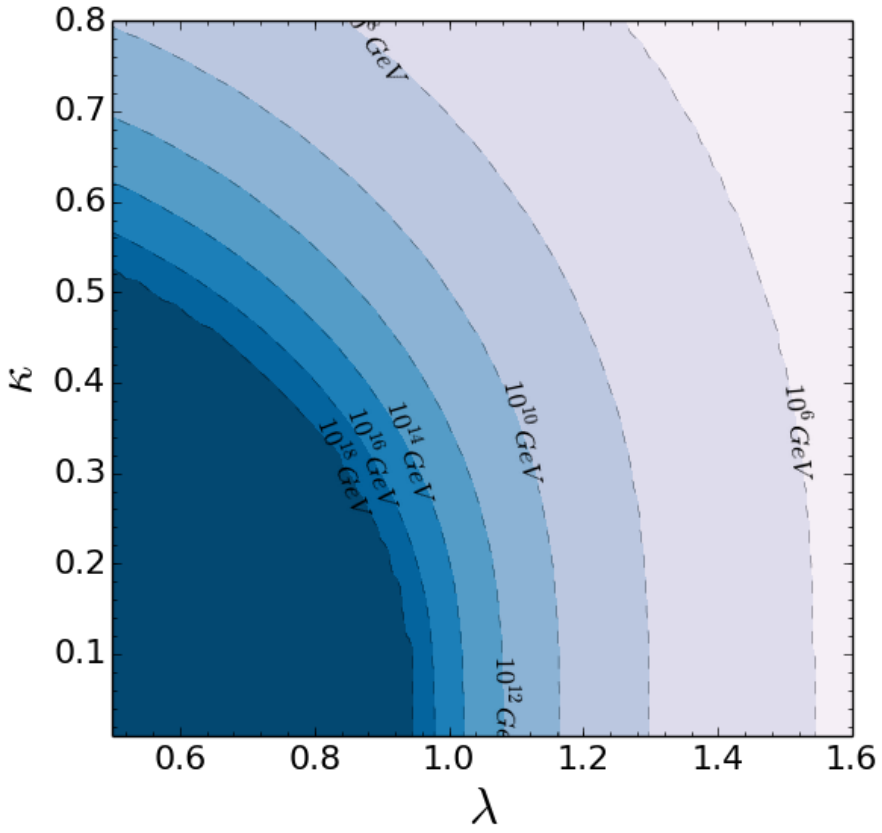
$$SU(3)_c \times SU(2)_1 \times SU(2)_2 \times U(1)_Y$$



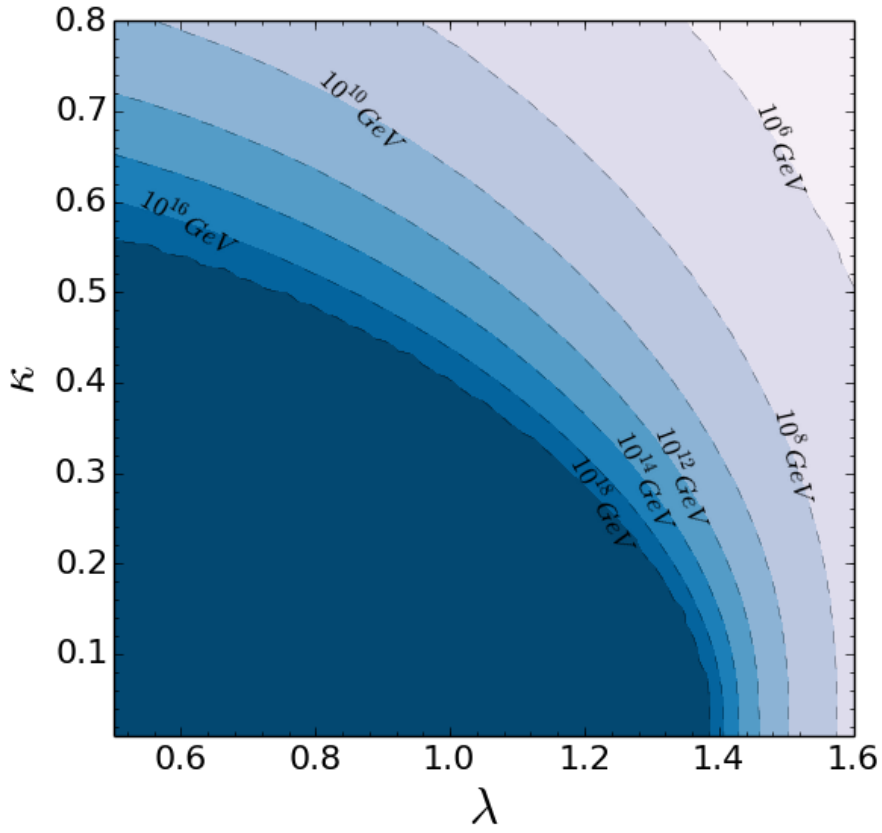
B. Li, N. Coyle, C.W. '17 (to appear)

Loss of Perturbative Consistency for different values of g_1

$g_1 = 1.5$



$g_1 = 3.$



Contours denote the value of the cutoff at which the perturbative consistency of the theory is lost.

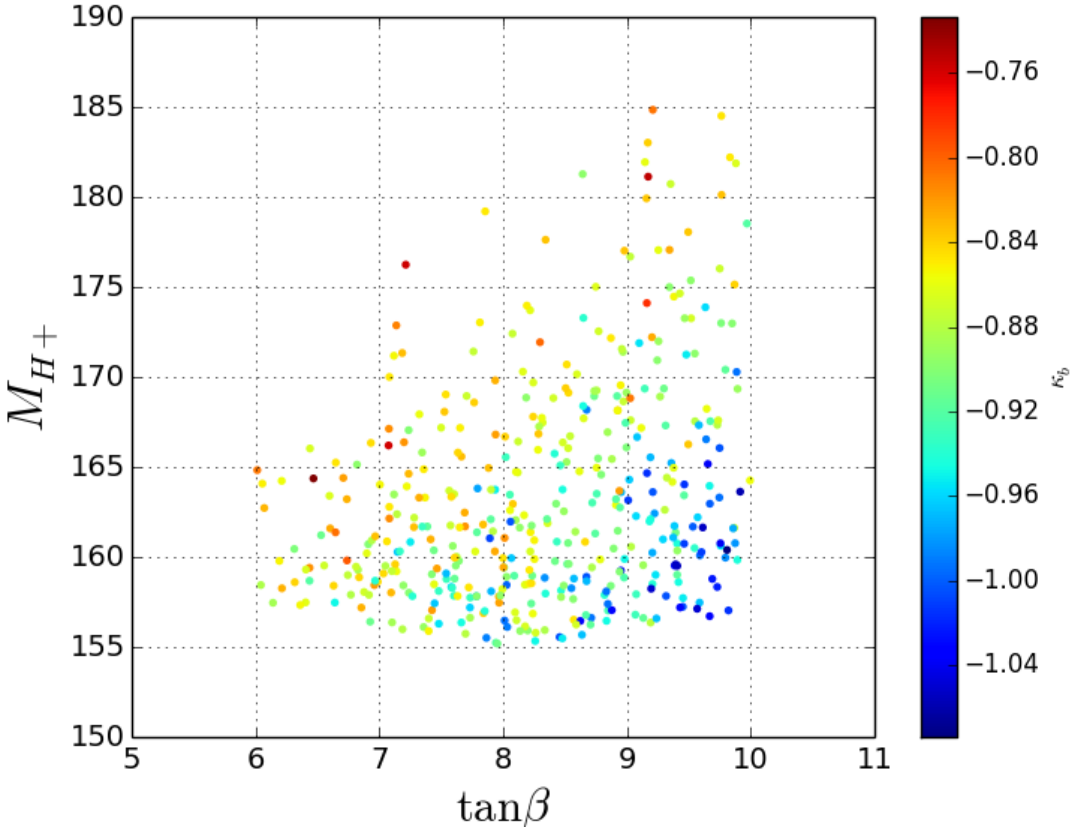
B. Li, N. Coyle, C.W. '17 (to appear)

Low charged Higgs masses

Part of the reason for large value of λ is the relation between the CP-odd and charged Higgs masses in these theories, namely

$$m_{H^+}^2 \simeq m_A^2 - \lambda^2 v^2$$

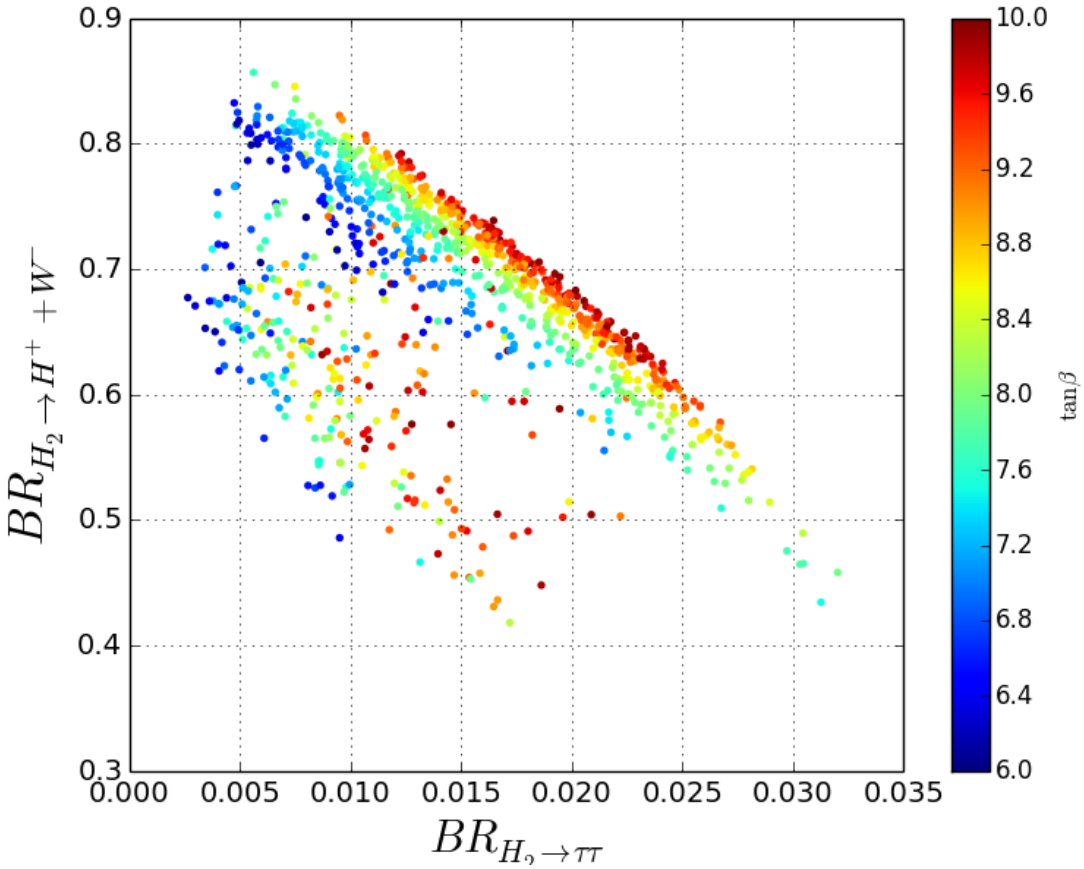
Constraints on Charged Higgs Mass coming from $t \to bH^+$ considered



B. Li, N. Coyle, C.W. ’17 (to appear)

Novelty : Decay into charged Higgs Bosons

Large values of λ imply that the charged Higgs mass becomes significantly lower than the neutral MSSM-like Higgs masses.



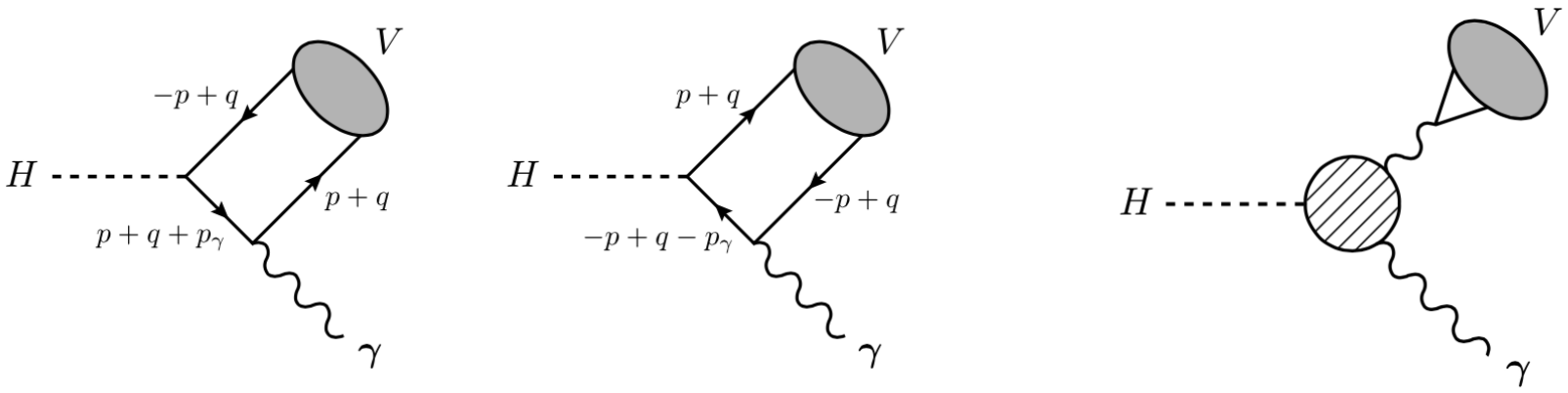
Additional tests of this idea ?

Radiative Higgs Decays

Bodwin et al'14, Neubert et al'15

$$\Gamma[H \to \Upsilon(1S) + \gamma] = |(3.33 \pm 0.03) - (3.49 \pm 0.15)\kappa_b|^2 \times 10^{-10}\ \text{GeV}$$

$$\Gamma[H \to \Upsilon(2S) + \gamma] = |(2.18 \pm 0.03) - (2.48 \pm 0.11)\kappa_b|^2 \times 10^{-10}\ \text{GeV}$$



Accidental cancellation present in the SM would lead to a large enhancement in the case of a change in sign of the bottom coupling to Higgs bosons.

B. Li, N. Coyle, C.W. '17 (to appear)

LHC Sensitivity

Branching ratios are small and therefore the number of events become only sizable at high luminosities. The approximate number of events are

For $\kappa_b = -1$

$$BR(H \to \Upsilon(1S) + \gamma) \simeq 1.1 \times 10^{-6}$$
$$BR(H \to \Upsilon(2S) + \gamma) \simeq 0.5 \times 10^{-6}$$
$$BR(H \to \Upsilon(3S) + \gamma) \simeq 0.4 \times 10^{-6}$$

κ_b	$\Upsilon(1S)$	$\Upsilon(2S)$	$\Upsilon(3S)$
	Run 2 (130 fb^{-1})		
1	0.00442 ± 0.06214	0.0155 ± 0.0483	0.0178 ± 0.0414
-1	8.02 ± 0.32	3.75 ± 0.15	2.73 ± 0.11
	Run 3 (300 fb^{-1})		
1	0.0102 ± 0.1434	0.358 ± 0.1115	0.0408 ± 0.0956
-1	18.5 ± 0.7	8.65 ± 0.36	6.31 ± 0.26

Therefore, at most a few hundred of events available in these channels.

Run I bound on the Branching ratios of order of a few 10^{-3}. Improvement in search sensitivity will be required to reach the required sensitivity at the HL-LHC.

Conclusions

- Current Higgs measurements are in agreement with the values predicted in the SM.
- Determination of bottom and top couplings still lacks precision, with a few tens of percent errors. Therefore, relevant modifications of these couplings may be present.
- Bottom coupling governs the width and therefore its departure from SM values leads to a relevant modification of all decay widths.
- An interesting, even if unlikely, possibility is that the sign of this coupling is inverted.
- In this talk we have explored scenarios in which relevant modifications of the bottom coupling may be present, in well motivated low energy supersymmetry extensions of the SM
- Relevant implications for Higgs phenomenology, that go beyond the modifications of the decay widths, and may allow to test these scenarios.

Run I Combined Best Fit

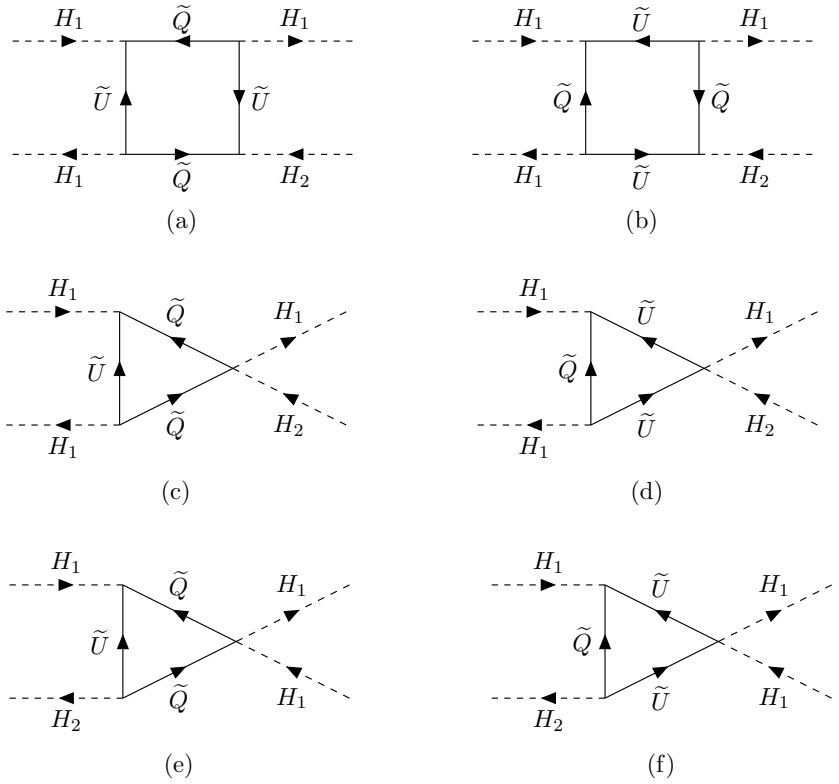
CERN-EP-2016-100 (16 Sep 2016)

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	$1.40^{+0.24}_{-0.21}$	$^{+0.26}_{-0.39}$	$1.32^{+0.31}_{-0.33}$	$1.51^{+0.33}_{-0.32}$
$\lvert\kappa_\tau\rvert$	$0.84^{+0.15}_{-0.11}$	$^{+0.16}_{-0.15}$	$0.97^{+0.19}_{-0.19}$	$0.77^{+0.18}_{-0.15}$
$\lvert\kappa_b\rvert$	$0.49^{+0.27}_{-0.15}$	$^{+0.25}_{-0.28}$	$0.61^{+0.26}_{-0.31}$	$0.47^{+0.34}_{-0.19}$
$\lvert\kappa_g\rvert$	$0.78^{+0.13}_{-0.10}$	$^{+0.17}_{-0.14}$	$0.94^{+0.18}_{-0.17}$	$0.67^{+0.14}_{-0.12}$
$\lvert\kappa_\gamma\rvert$	$0.87^{+0.14}_{-0.09}$	$^{+0.12}_{-0.13}$	$0.88^{+0.15}_{-0.15}$	$0.89^{+0.19}_{-0.13}$

Apparent suppression of the bottom coupling, associated with low precision, leads to a suppression of all other relevant couplings, with the exception of the top. Current best fit, if performed, would lead to values closer to the SM values.

Errors are still large and precision measurements are certainly a way of testing a modified value of the bottom coupling.

Higgs Basis



Haber and Gunion'02

$$H_1 = H_u \sin\beta + H_d \cos\beta$$
$$H_2 = H_u \cos\beta - H_d \sin\beta$$

In this basis, H_1 acquires a v.e.v., while H_2 does not. Alignment is obtained when quartic coupling $Z_6 H_1^3 H_2$ vanishes. H_1 and H_2 couple to stops with couplings

$$g_{H_1\tilde{t}\tilde{t}} = h_t \sin\beta X_t, \text{ with } X_t = A_t - \mu^*/\tan\beta$$
$$g_{H_2\tilde{t}\tilde{t}} = h_t \cos\beta Y_t, \text{ with } Y_t = A_t - \mu^* \tan\beta$$

Carena, Haber, Low, Shah, C.W.'14

$$m_Z^2 c_{2\beta} = \frac{3v^2 s_\beta^2 h_t^4}{16\pi^2}\left[\ln\left(\frac{M_S^2}{m_t^2}\right) + \frac{X_t(X_t+Y_t)}{2M_S^2} - \frac{X_t^3 Y_t}{12M_S^4}\right]$$

At moderate or large $\tan\beta$

$$t_\beta = \frac{m_Z^2 + \frac{3v^2 h_t^4}{16\pi^2}\left[\ln\left(\frac{M_S^2}{m_t^2}\right) + \frac{2A_t^2-\mu^2}{2M_S^2} - \frac{A_t^2(A_t^2-3\mu^2)}{12M_S^4}\right]}{\frac{3v^2 h_t^4 \mu A_t}{32\pi^2 M_S^2}\left(\frac{A_t^2}{6M_S^2} - 1\right)}$$

M. Badziak and C.W. '1602.06198

Away from Alignment : Enhancing tth Production

- The combination of Run I data has shown a somewhat large value of the production of Higgs bosons in association with top quarks

- Enhancing the top coupling is simple in type II 2HDM, but the bottom quark coupling is modified as well in an opposite direction

$$\kappa_t = \sin(\beta-\alpha) + \cot\beta\cos(\beta-\alpha)$$
$$\kappa_b = \sin(\beta-\alpha) - \tan\beta\cos(\beta-\alpha)$$
$$\kappa_V = \sin(\beta-\alpha) \simeq 1$$

- This tendency is in agreement with the one present in the current data

Alignment in General two Higgs Doublet Models

H. Haber and J. Gunion'03

$$
\begin{aligned}
V \;=\; & m_{11}^2\Phi_1^\dagger\Phi_1 + m_{22}^2\Phi_2^\dagger\Phi_2 - m_{12}^2(\Phi_1^\dagger\Phi_2 + \text{h.c.}) + \frac{1}{2}\lambda_1(\Phi_1^\dagger\Phi_1)^2 + \frac{1}{2}\lambda_2(\Phi_2^\dagger\Phi_2)^2 \\
& + \lambda_3(\Phi_1^\dagger\Phi_1)(\Phi_2^\dagger\Phi_2) + \lambda_4(\Phi_1^\dagger\Phi_2)(\Phi_2^\dagger\Phi_1) \\
& + \left\{\frac{1}{2}\lambda_5(\Phi_1^\dagger\Phi_2)^2 + [\lambda_6(\Phi_1^\dagger\Phi_1) + \lambda_7(\Phi_2^\dagger\Phi_2)]\Phi_1^\dagger\Phi_2 + \text{h.c.}\right\} \;,
\end{aligned}
$$

Symmetry arguments (not general) : Bhupal Dev, Pilaftsis'14

- From here, one can minimize the effective potential and derive the expression for the CP-even Higgs mass matrix in terms of a reference mass, that we will take to be mA

Carena, Low, Shah, C.W. '13

$$
\mathcal{M}^2 = \begin{pmatrix} \mathcal{M}_{11}^2 & \mathcal{M}_{12}^2 \\ \mathcal{M}_{12}^2 & \mathcal{M}_{22}^2 \end{pmatrix} \equiv m_A^2 \begin{pmatrix} s_\beta^2 & -s_\beta c_\beta \\ -s_\beta c_\beta & c_\beta^2 \end{pmatrix} + v^2 \begin{pmatrix} L_{11} & L_{12} \\ L_{12} & L_{22} \end{pmatrix}
$$

$$
\begin{aligned}
L_{11} &= \lambda_1 c_\beta^2 + 2\lambda_6 s_\beta c_\beta + \lambda_5 s_\beta^2 \;, \\
L_{12} &= (\lambda_3 + \lambda_4) s_\beta c_\beta + \lambda_6 c_\beta^2 + \lambda_7 s_\beta^2 \;, \\
L_{22} &= \lambda_2 s_\beta^2 + 2\lambda_7 s_\beta c_\beta + \lambda_5 c_\beta^2 \;.
\end{aligned}
$$

M. Carena, I. Low, N. Shah, C.W.'13

Alignment Conditions

$$(m_h^2 - \lambda_1 v^2) + (m_h^2 - \tilde{\lambda}_3 v^2) t_\beta^2 = v^2 (3\lambda_6 t_\beta + \lambda_7 t_\beta^3) \ ,$$

$$(m_h^2 - \lambda_2 v^2) + (m_h^2 - \tilde{\lambda}_3 v^2) t_\beta^{-2} = v^2 (3\lambda_7 t_\beta^{-1} + \lambda_6 t_\beta^{-3})$$

- If fulfilled not only alignment is obtained, but also the right Higgs mass, $m_h^2 = \lambda_{\rm SM} v^2$, with $\lambda_{\rm SM} \simeq 0.26$ and $\lambda_3 + \lambda_4 + \lambda_5 = \tilde{\lambda}_3$

$$\lambda_{\rm SM} = \lambda_1 \cos^4\beta + 4\lambda_6 \cos^3\beta \sin\beta + 2\tilde{\lambda}_3 \sin^2\beta \cos^2\beta + 4\lambda_7 \sin^3\beta \cos\beta + \lambda_2 \sin^4\beta$$

- For $\lambda_6 = \lambda_7 = 0$ the conditions simplify, but can only be fulfilled if

$$\lambda_1 \geq \lambda_{\rm SM} \geq \tilde{\lambda}_3 \quad \text{and} \quad \lambda_2 \geq \lambda_{\rm SM} \geq \tilde{\lambda}_3 \ ,$$

or

$$\lambda_1 \leq \lambda_{\rm SM} \leq \tilde{\lambda}_3 \quad \text{and} \quad \lambda_2 \leq \lambda_{\rm SM} \leq \tilde{\lambda}_3$$

- Conditions not fulfilled in the MSSM, where both $\lambda_1, \tilde{\lambda}_3 < \lambda_{\rm SM}$

Aligning the CP-even Singlets

Carena, Haber, Low, Shah, C.W.'15

- The previous formulae assumed implicitly that the singlets are either decoupled, or not significantly mixed with the MSSM CP-even states

- The mixing mass matrix element between the singlets and the SM-like Higgs is approximately given by

$$M_S^2(1,3) \simeq 2\lambda v \mu \left(1 - \frac{m_A^2 \sin^2 2\beta}{4\mu^2} - \frac{\kappa \sin 2\beta}{2\lambda}\right)$$

- If one assumes alignment, the expression inside the bracket must cancel

- If one assumes $\tan\beta < 3$ and lambda of order 0.65, and in addition one asks for kappa in the perturbative regime, one immediately conclude that in order to get small mixing in the Higgs sector, the CP-odd Higgs is correlated in mass with the parameter μ

- Since both of them small is a measure of naturalness, we see again that alignment and naturalness come together in a beautiful way in the NMSSM

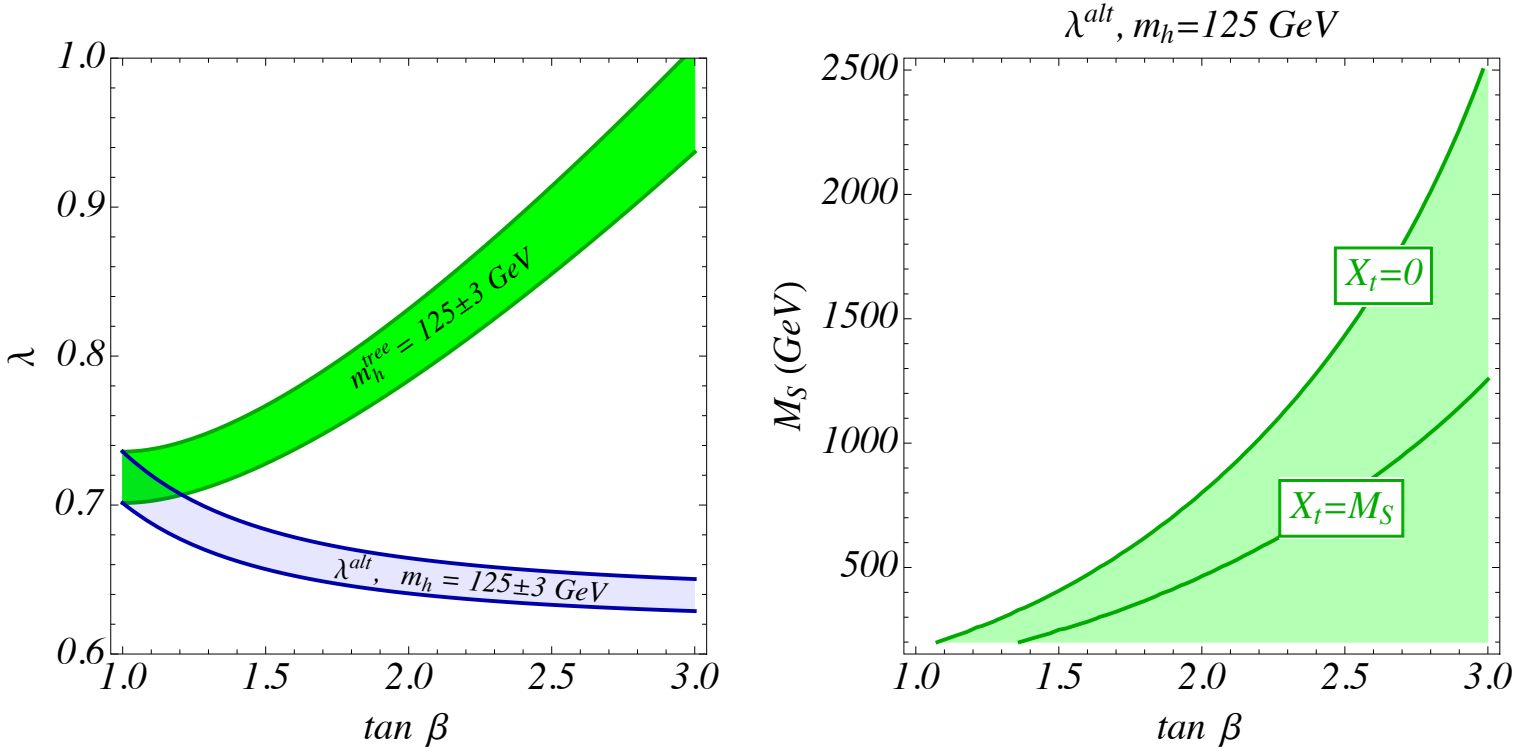
- Moreover, this ensures also that all parameters are small and the CP-even and CP-odd singlets (and singlino) become self consistently light

Stop Contribution at alignment

Carena, Haber, Low, Shah, C.W.'15

Interesting, after some simple algebra, one can show that

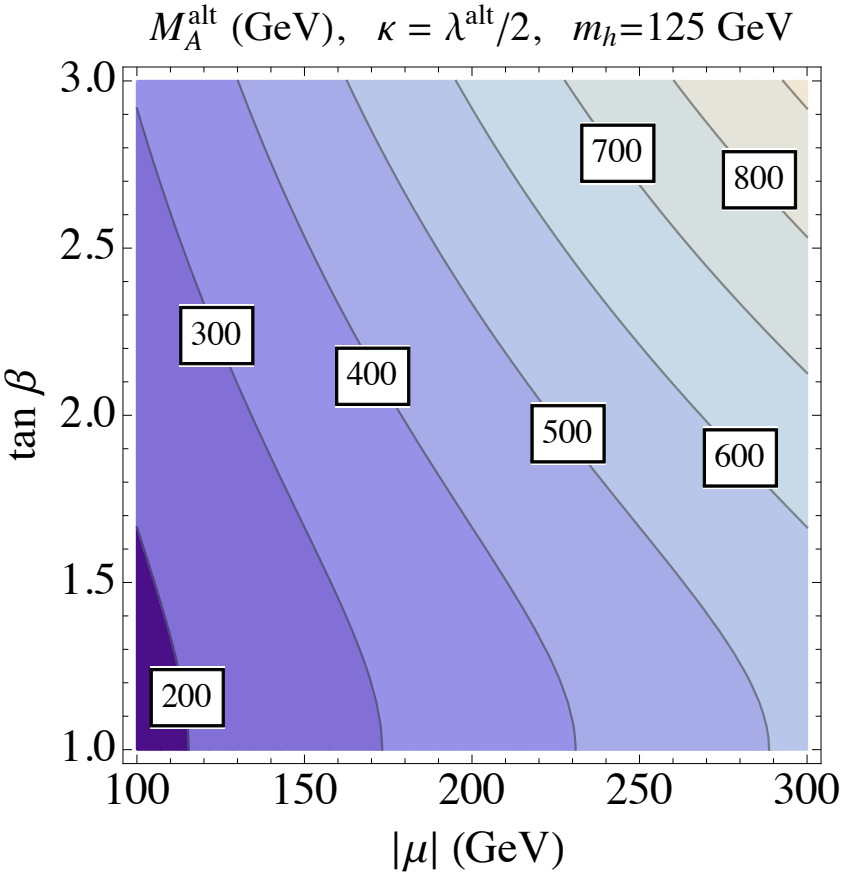
$$\Delta_{\tilde{t}} = -\cos 2\beta (m_h^2 - M_Z^2)$$

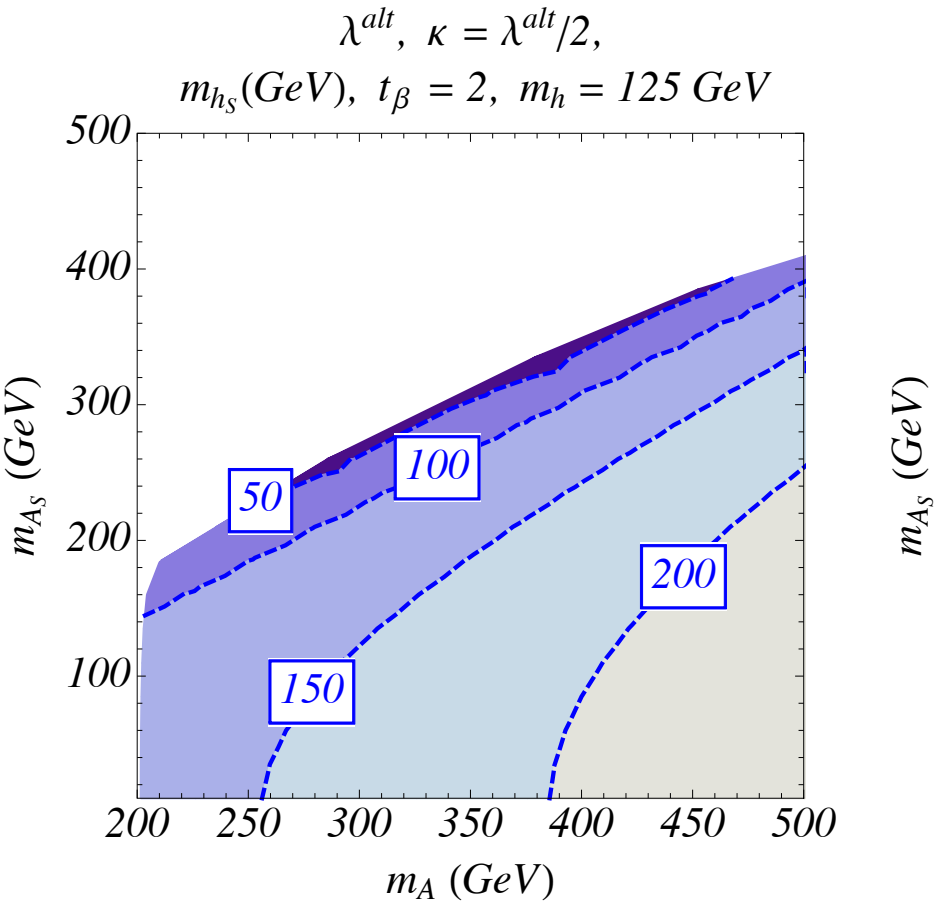


For moderate mixing, It is clear that low values of $\tan\beta < 3$
lead to lower corrections to the Higgs mass parameter at the alignment values

Values of the Singlet, Higgsino and Singlino Masses

Carena, Haber, Low, Shah, C.W.'15





In this limit, the singlino mass is equal to the Higgsino mass.

$$m_{\tilde{S}} = 2\mu\frac{\kappa}{\lambda}$$

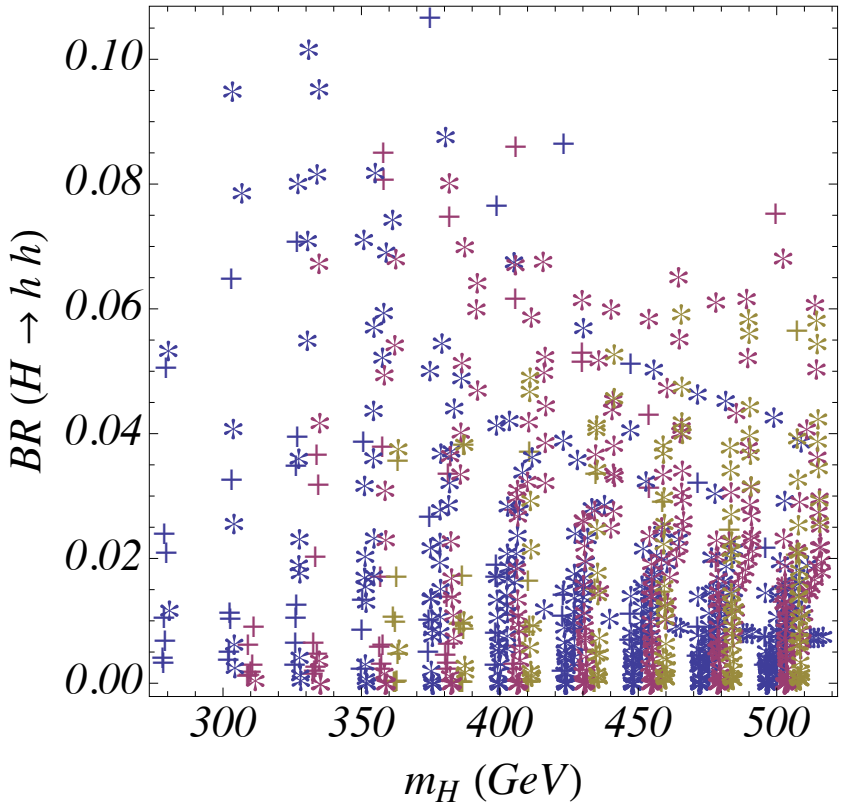
So, the whole Higgs and Higgsino spectrum remains light, as anticipated

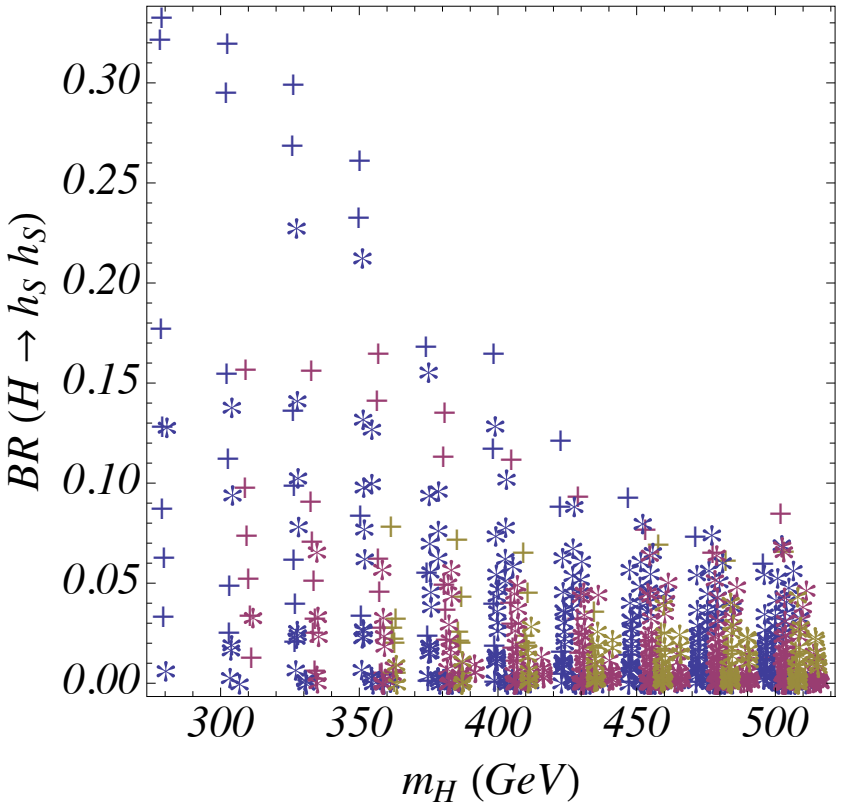
Carena, Haber, Low, Shah, C.W.'15

Decays into pairs of SM-like Higgs bosons suppressed by alignment

Crosses: H_1 singlet like
Stars : H_2 singlet like

Blue : $\tan\beta = 2$
Red : $\tan\beta = 2.5$
Yellow : $\tan\beta = 3$



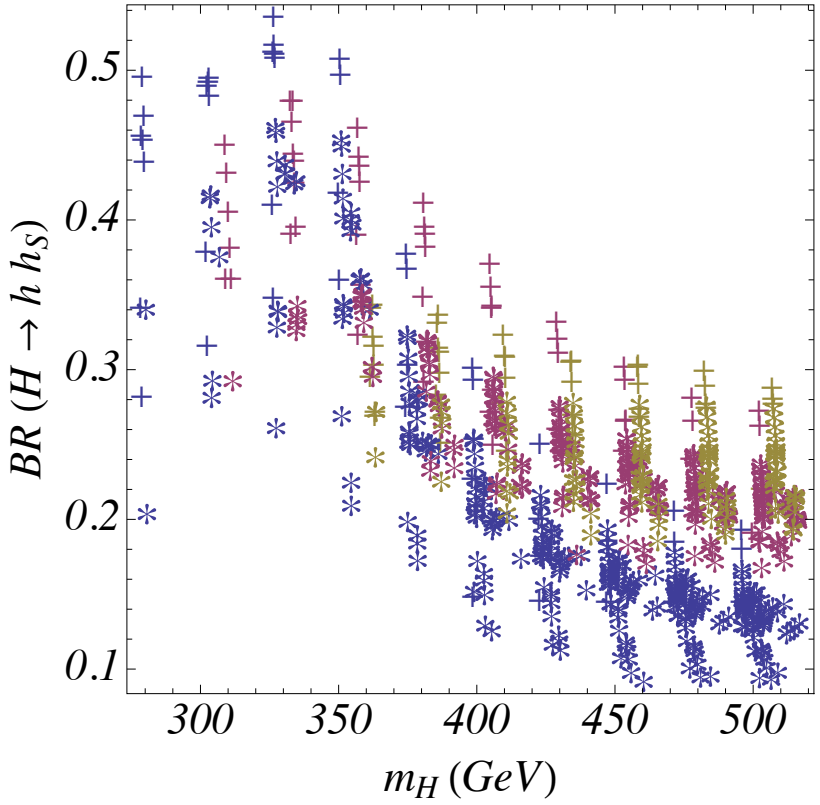


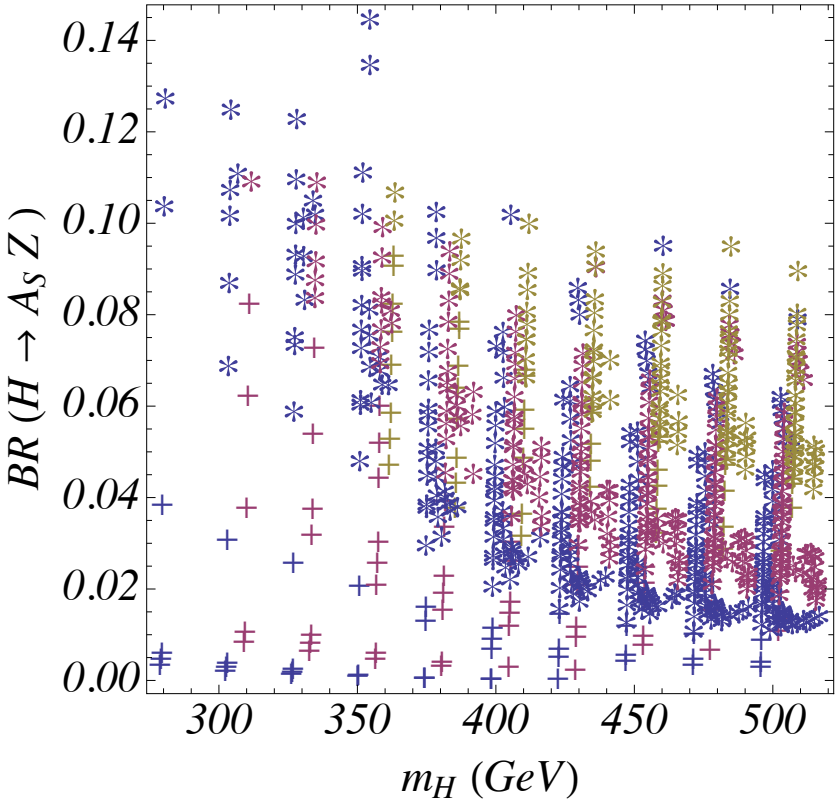
Carena, Haber, Low, Shah, C.W.'15

Significant decays of heavier Higgs Bosons into lighter ones and Z's

Crosses: H_1 singlet like
Stars : H_2 singlet like

Blue : $\tan\beta = 2$
Red : $\tan\beta = 2.5$
Yellow : $\tan\beta = 3$



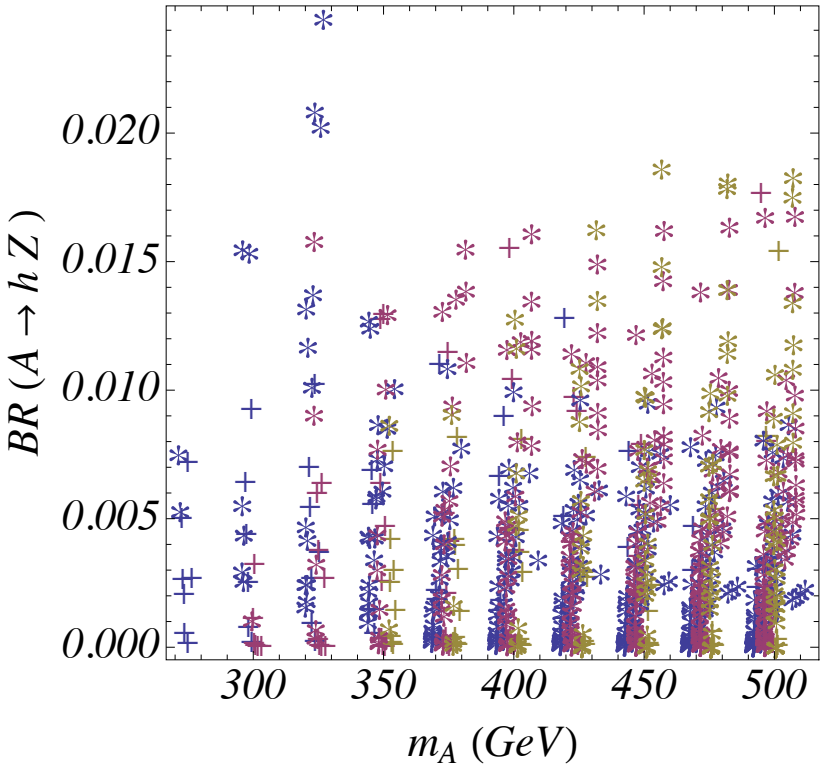


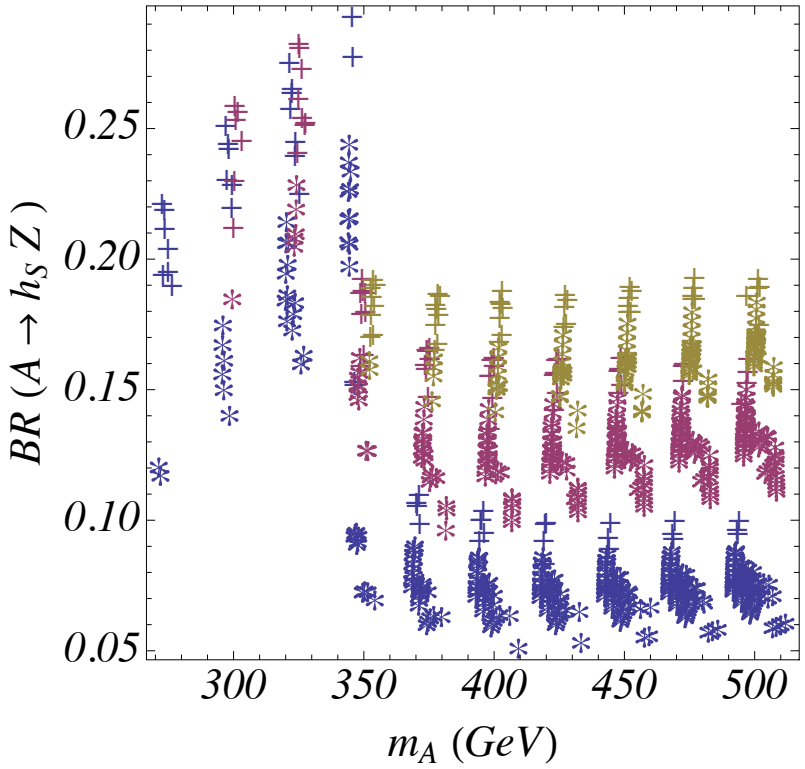
Carena, Haber, Low, Shah, C.W.'15

Heavy CP-odd Higgs Bosons have similar decay modes

Crosses: H_1 singlet like
Stars : H_2 singlet like

Blue : $\tan\beta = 2$
Red : $\tan\beta = 2.5$
Yellow : $\tan\beta = 3$





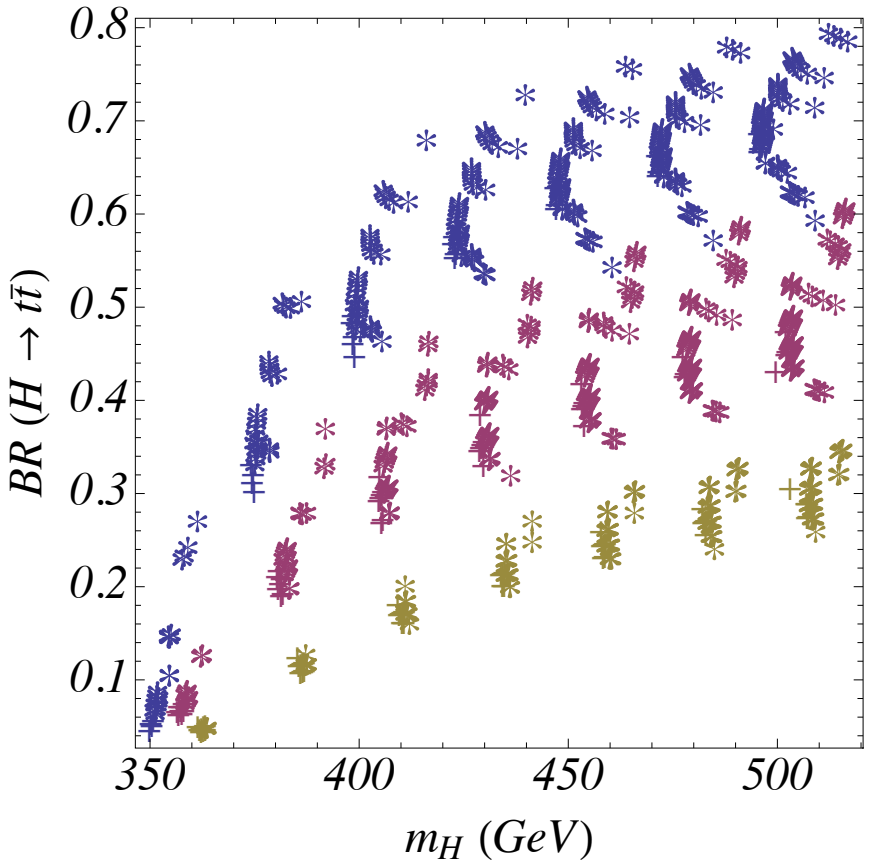
Significant decay of heavy CP-odd
Higgs bosons into singlet like states plus Z

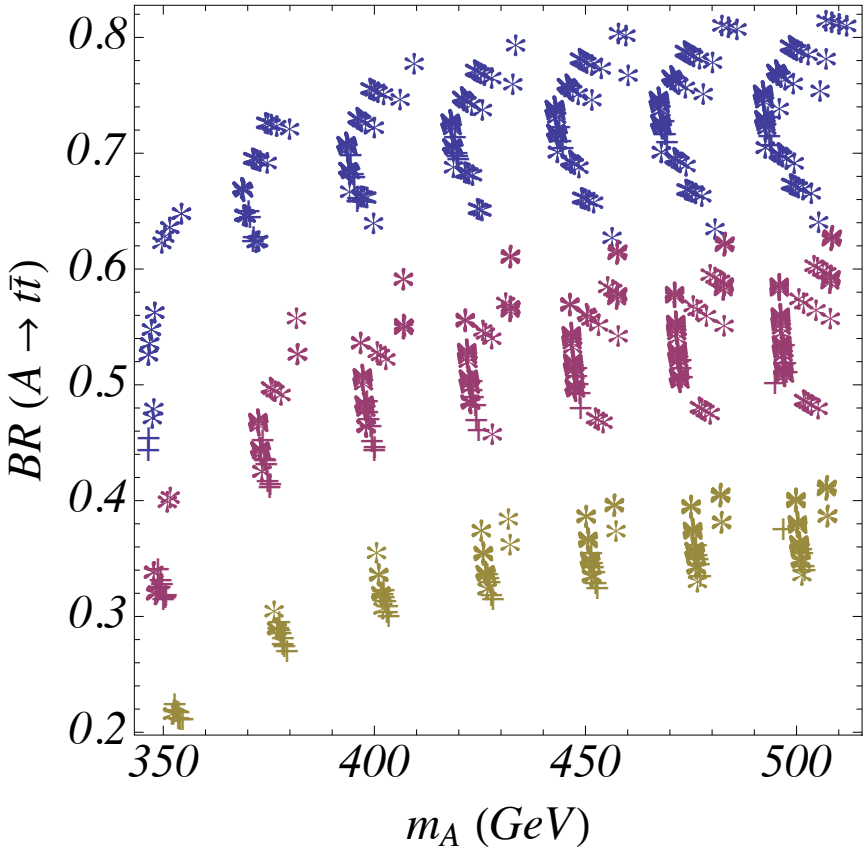
Carena, Haber, Low, Shah, C.W.'15

Decays into top significant but may be somewhat suppressed by decays into non-standard particles

Crosses: H_1 singlet like
Stars : H_2 singlet like

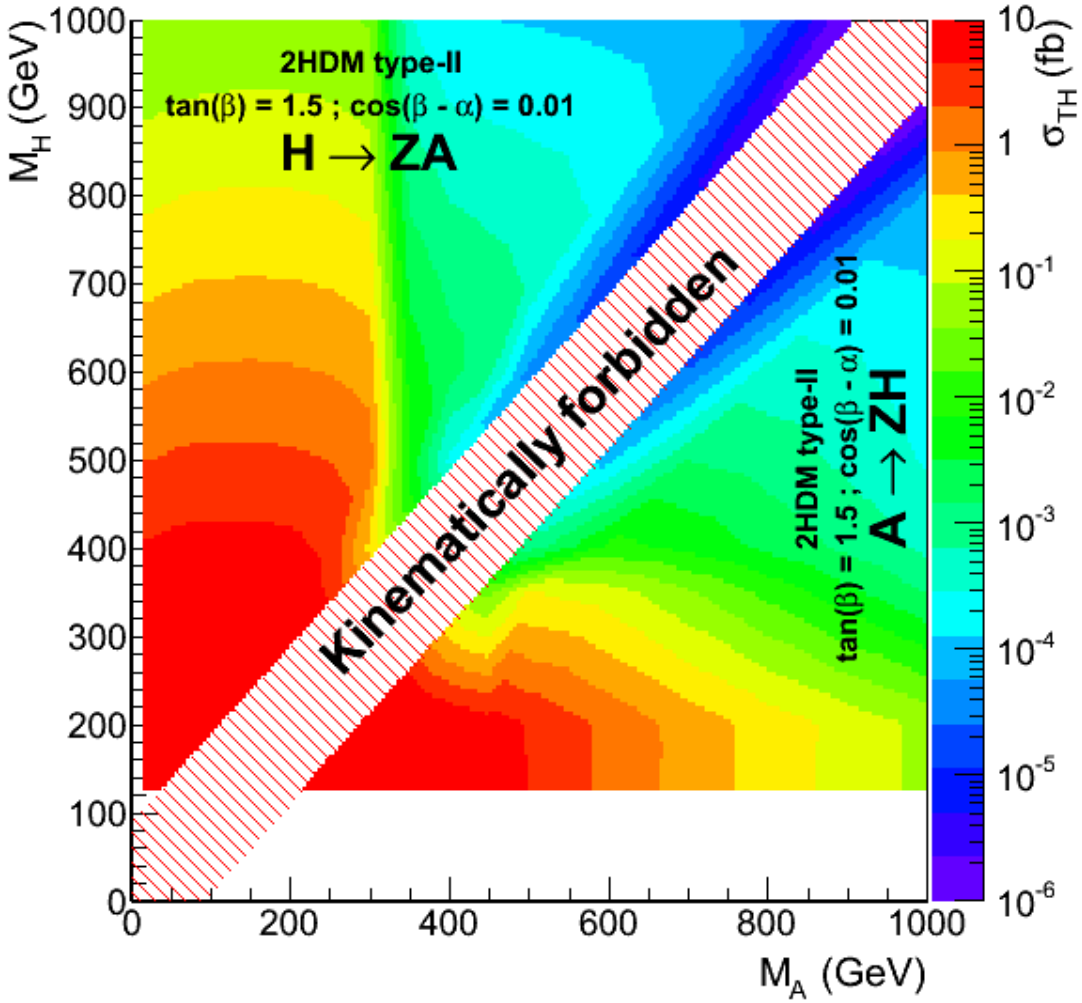
Blue : $\tan\beta = 2$
Red : $\tan\beta = 2.5$
Yellow : $\tan\beta = 3$





Search for (psudo-)scalars decaying into lighter ones

CMS-PAS-HIG-15-001



It is relevant to perform similar analyses replacing the Z by a SM Higgs (and interchanging CP properties) !