Supersymmetry and Higgs Physics

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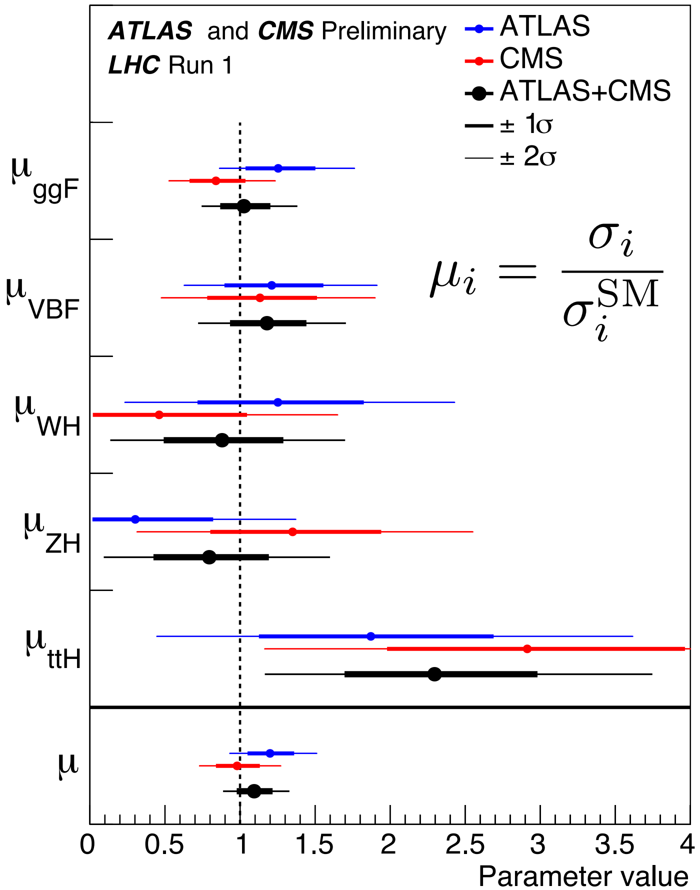
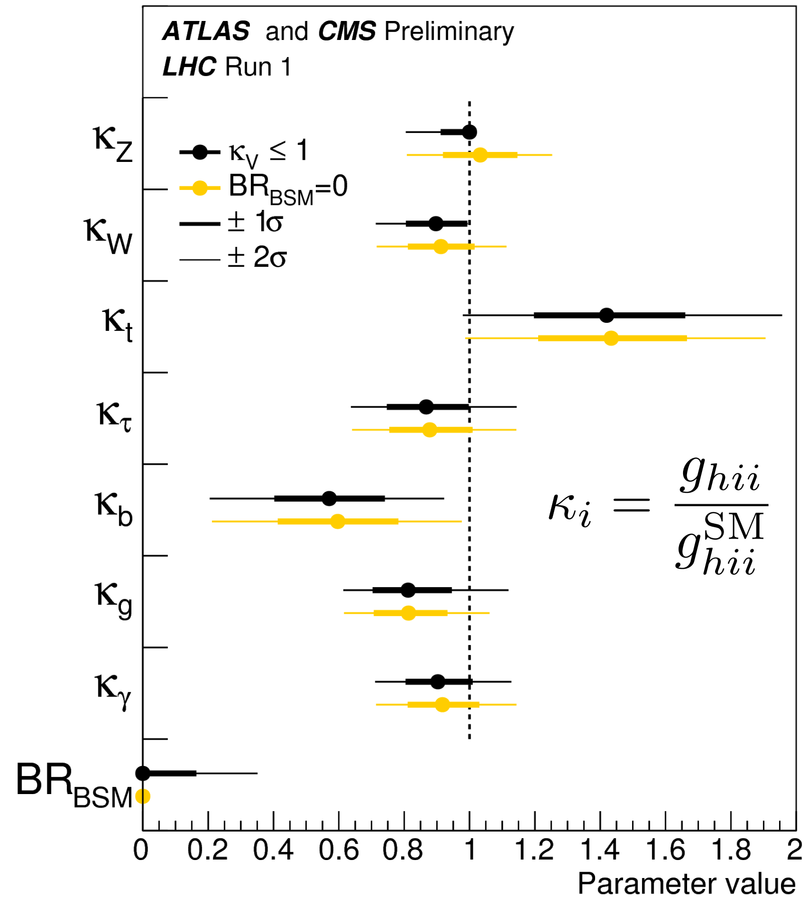
Based on the following works :

- 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); arXiv:1510.09137, PRD93 (2016)
- G. Lee, C.W., arXiv:1508.00576, PRD92 (2015)
- M. Badziak, C.W. , arXiv:1602.06198, JHEP 1605 (2016); arXiv: 1611.02353, JHEP 1702 (2017)
- A. Joglekar, M. Li, P. Huang, C.W., arXiv:1711.05743
- N. Coyle, B. Li, C.W., to appear

ATLAS and CMS Combination

Very good agreement of production rates with SM predictions





Assuming no strict correlation between gluon and top couplings

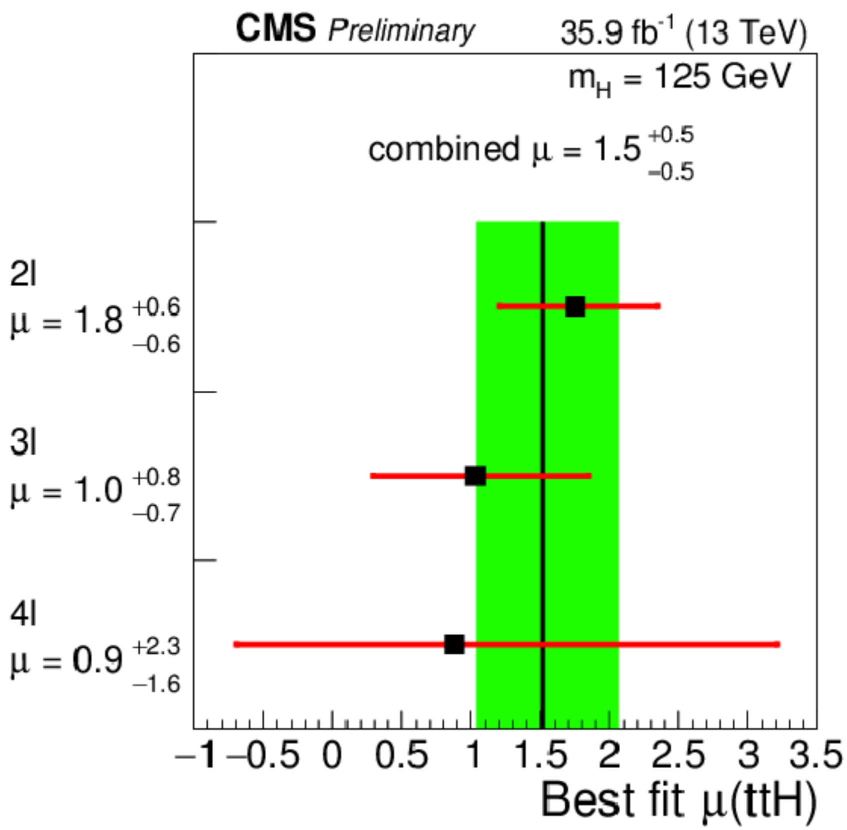
Direct Measurement of Bottom and Top Couplings subject to large uncertainties : 2σ deviations from SM predictions possible

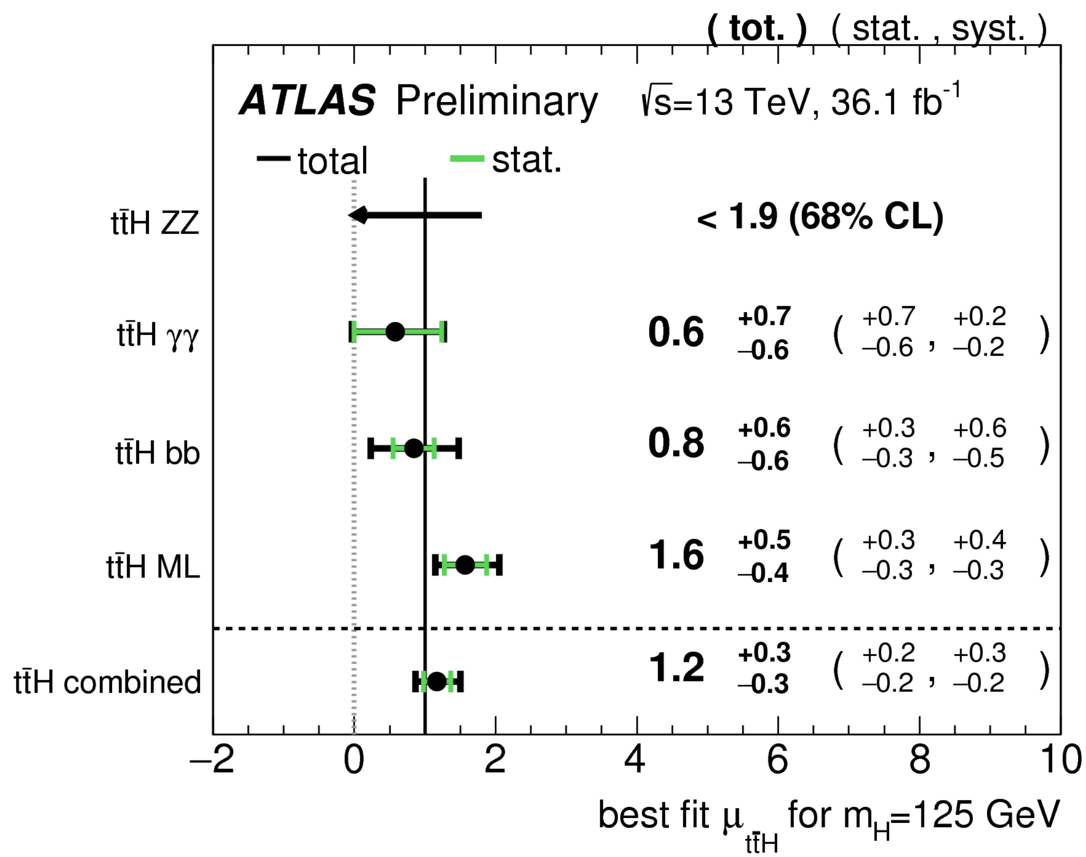
Badziak, C.W.'16

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

New tth results

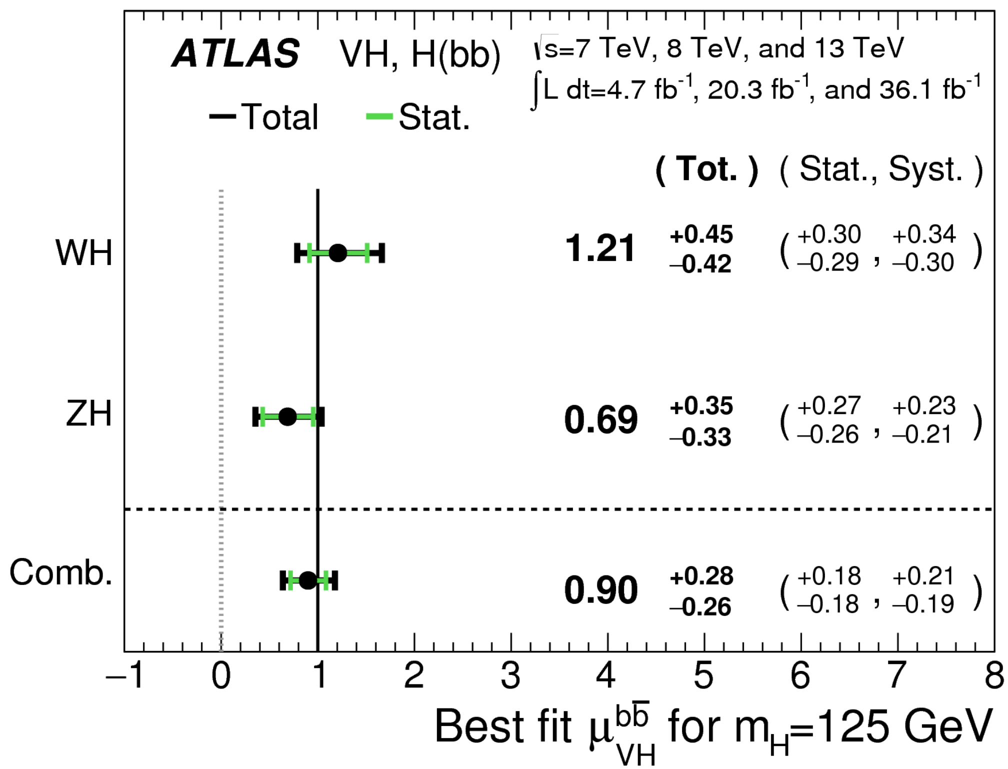
Values overall consistent with the SM, within a few tens of percent



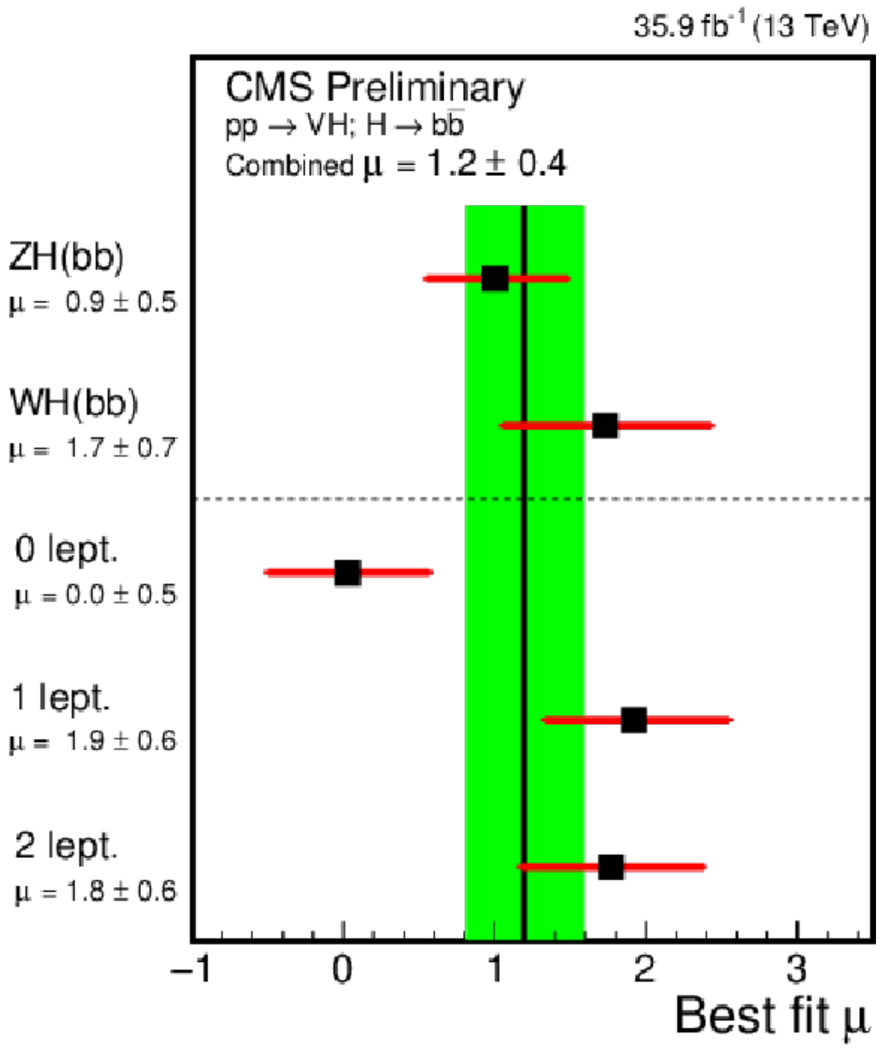


Things have changed in an interesting way :

There is today evidence of a Higgs decaying to bottom quarks



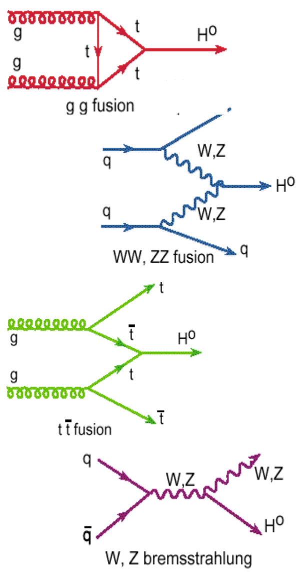
This evidence is present at both experiments

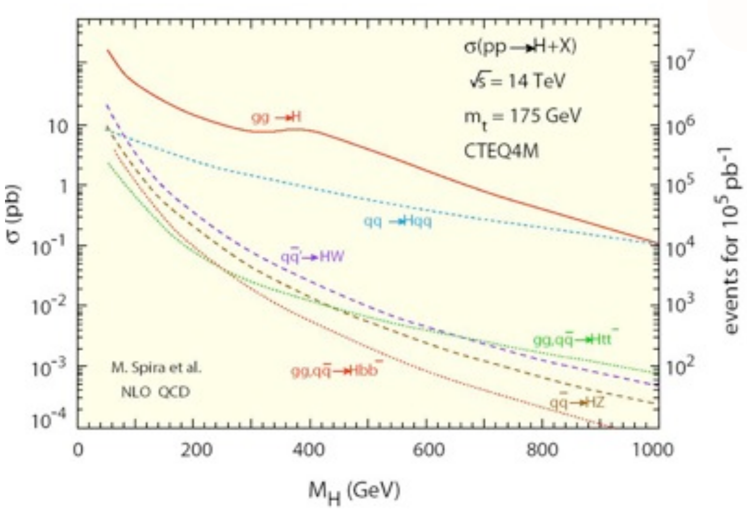


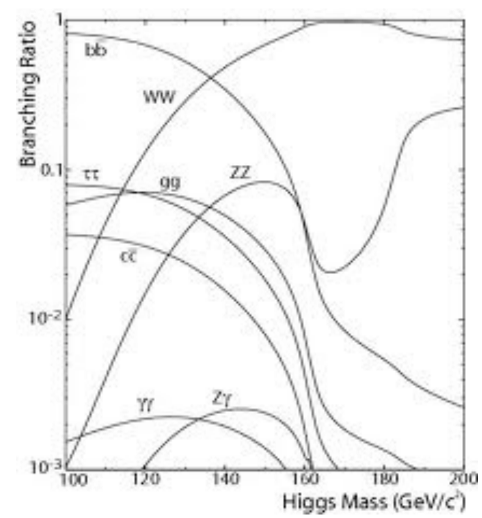
Consistency with SM results

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

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

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.

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,

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

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

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

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

$$\sin\alpha = -\cos\beta,$$
$$\cos\alpha = \sin\beta$$

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

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

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

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

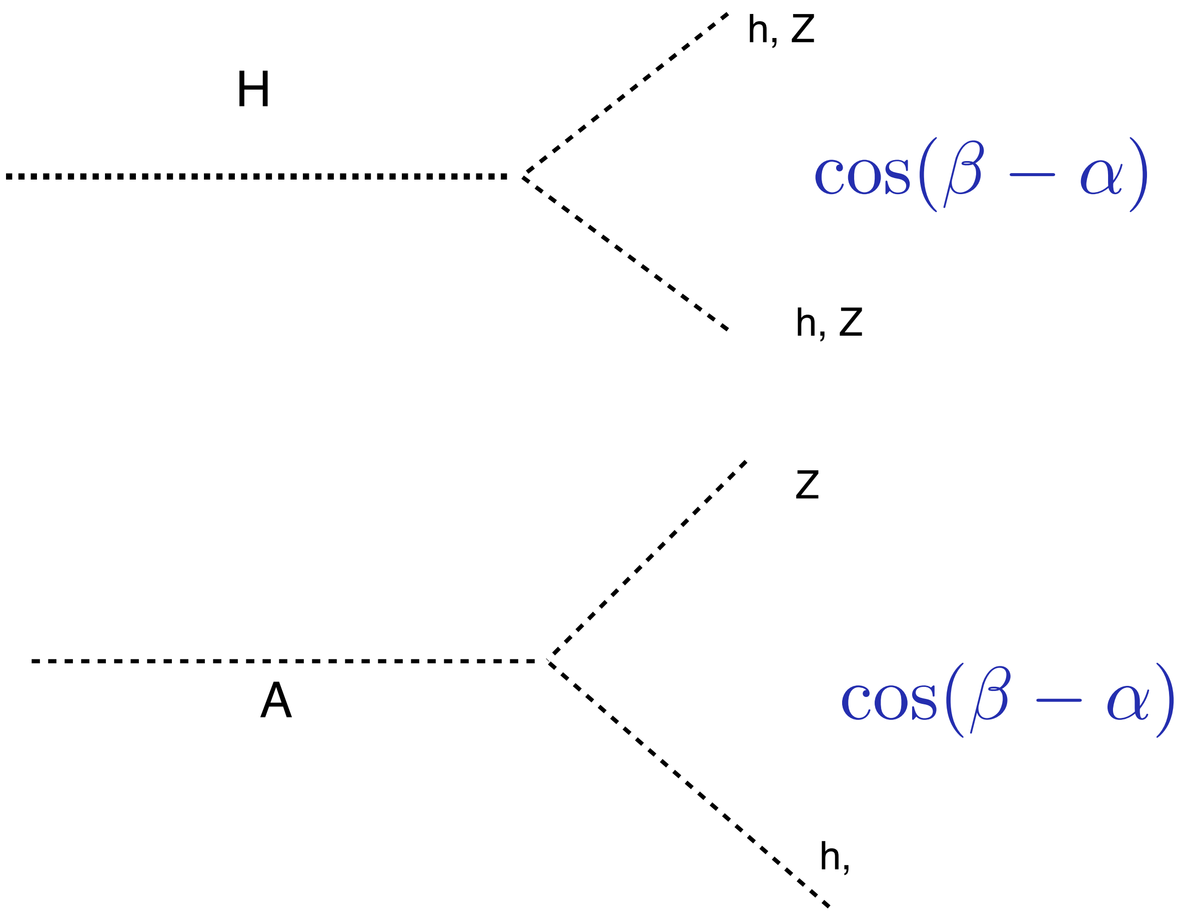
$$\eta = s_\beta^2\left(1 - \frac{\mathcal{A}}{\mathcal{B}}\right) = s_\beta^2 \frac{\mathcal{B} - \mathcal{A}}{\mathcal{B}} , \qquad \mathcal{B} - \mathcal{A} = \frac{1}{s_\beta}\left(-m_h^2 + \tilde{\lambda}_3 v^2 s_\beta^2 + \lambda_7 v^2 s_\beta^2 t_\beta + 3\lambda_6 v^2 s_\beta c_\beta + \lambda_1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

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

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

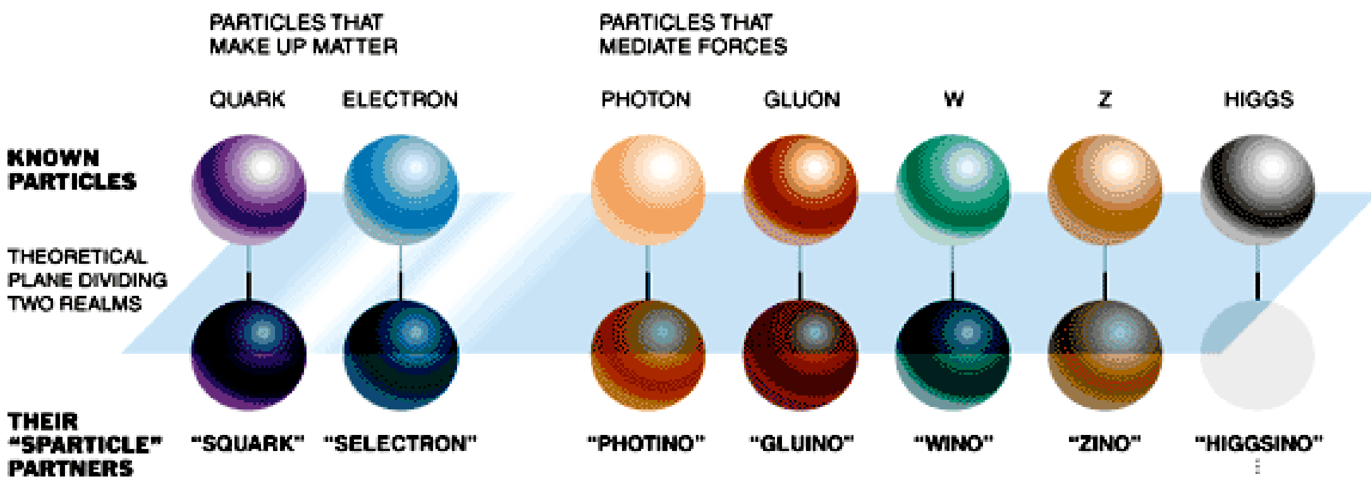
H and A Decay to Boson Pairs

Suppressed at Alignment



supersymmetry

fermions ⟷ **bosons**



Photino, Zino and Neutral Higgsino: Neutralinos

Charged Wino, charged Higgsino: Charginos

No new dimensionless couplings. Couplings of supersymmetric particles equal to couplings of Standard Model ones.
Two Higgs doublets necessary. Ratio of vacuum expectation values denoted by $\tan\beta$

Lightest SM-like Higgs mass strongly depends on:

* CP-odd Higgs mass m_A
* tan beta
* the top quark mass
* the stop masses and mixing

$$M^2_{\tilde{t}} = \begin{pmatrix} m_Q^2 + m_t^2 + D_L & m_t X_t \\ m_t X_t & m_U^2 + m_t^2 + D_R \end{pmatrix}$$

M_h depends logarithmically on the averaged stop mass scale M_{SUSY} and has a quadratic and quartic dep. on the stop mixing parameter X_t. [and on sbotton/stau sectors for large tanbeta]

For moderate to large values of tan beta and large non-standard Higgs masses

$$m_h^2 \cong M_Z^2 \cos^2 2\beta + \frac{3}{4\pi^2}\frac{m_t^4}{v^2}\left[\frac{1}{2}\tilde{X}_t + t + \frac{1}{16\pi^2}\left(\frac{3}{2}\frac{m_t^2}{v^2} - 32\pi\alpha_3\right)\left(\tilde{X}_t t + t^2\right)\right]$$

$$t = \log(M_{SUSY}^2/m_t^2) \qquad \tilde{X}_t = \frac{2X_t^2}{M_{SUSY}^2}\left(1 - \frac{X_t^2}{12M_{SUSY}^2}\right)$$

$X_t = A_t - \mu/\tan\beta \rightarrow$ LR stop mixing

M.Carena, J.R. Espinosa, M. Quiros, C.W.'95
M. Carena, M. Quiros, C.W.'95

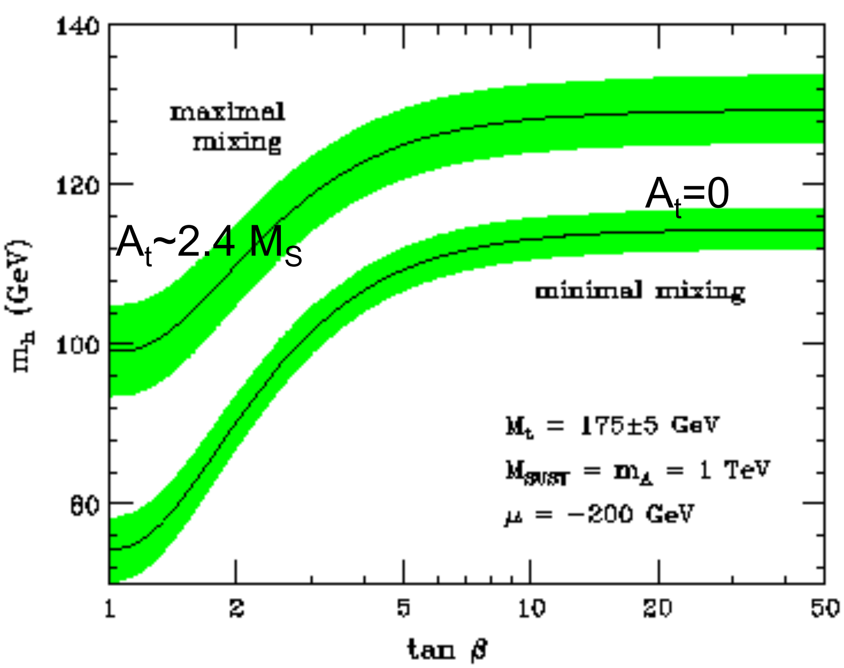
Analytic expression valid for $M_{SUSY} \sim m_Q \sim m_U$

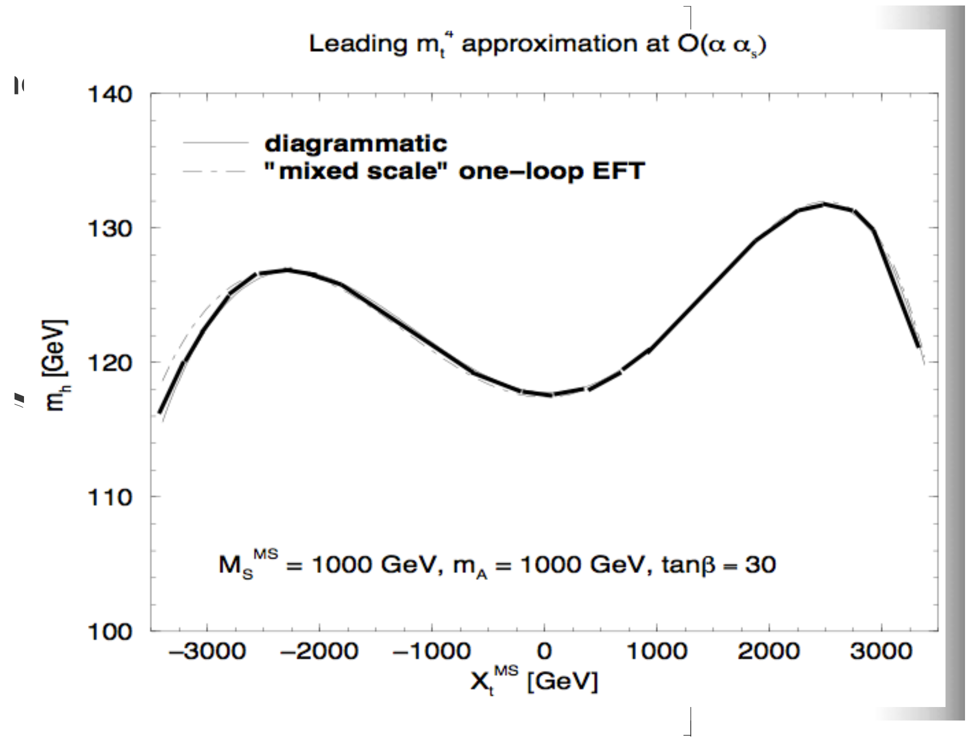
Standard Model-like Higgs Mass

Long list of two-loop computations: Carena, Degrassi, Ellis, Espinosa, Haber, Harlander, Heinemeyer, Hempfling, Hoang, Hollik, Hahn, Martin, Pilaftsis, Quiros, Ridolfi, Rzehak, Slavich, C.W., Weiglein, Zhang, Zwirner

Carena, Haber, Heinemeyer, Hollik, Weiglein, C.W.'00

For masses of order 1 TeV, diagrammatic and EFT approach agree well, once the appropriate threshold corrections are included

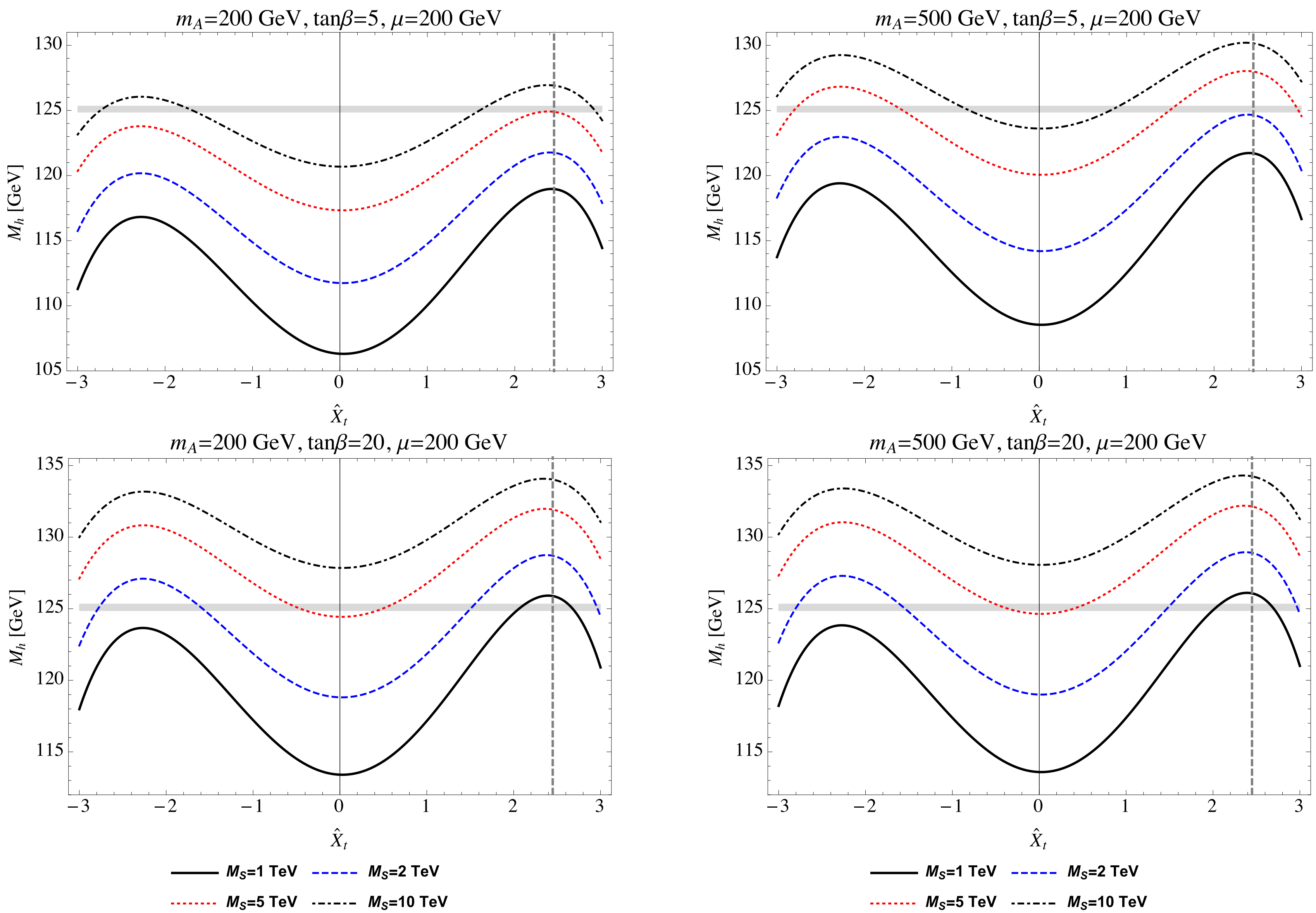




$$X_t = A_t - \mu/\tan\beta, \qquad X_t = 0 : \text{ No mixing}; \quad X_t = \sqrt{6} M_S : \text{ Max. Mixing}$$

Dependence on Stop Mixing

Vega and Villadoro '15, Wagner and Lee'15, FeynHiggs'17

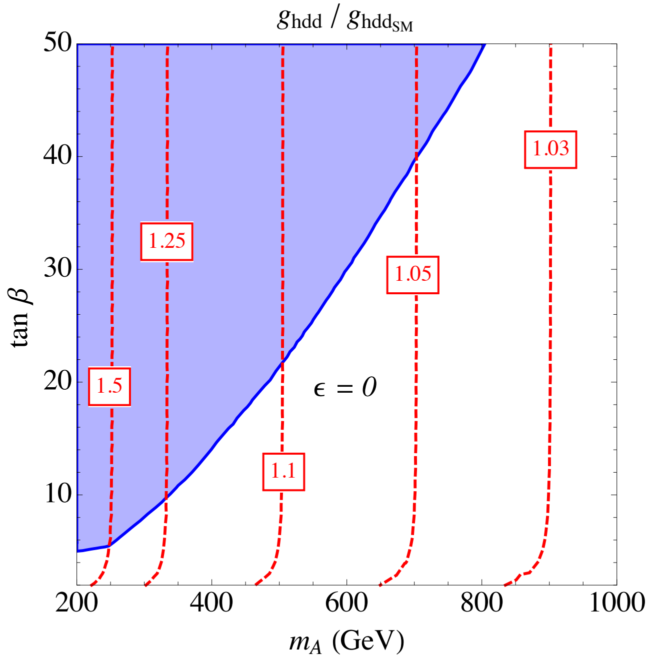


Down Couplings in the MSSM for low values of μ

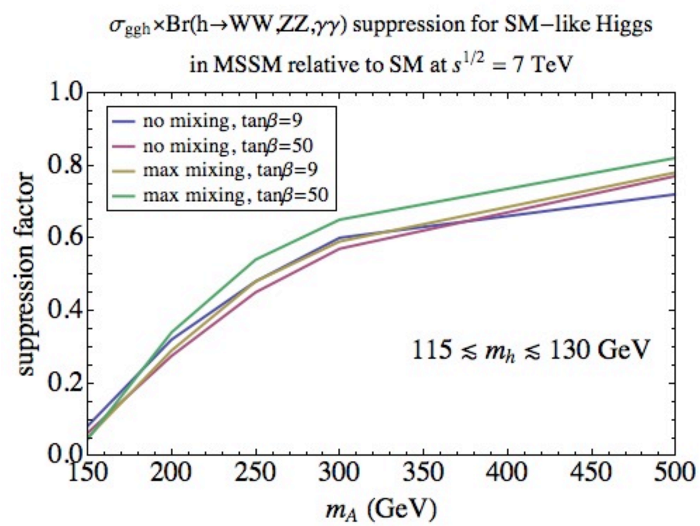
- In this regime, $\lambda_{6,7} \simeq 0$, and

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

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



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

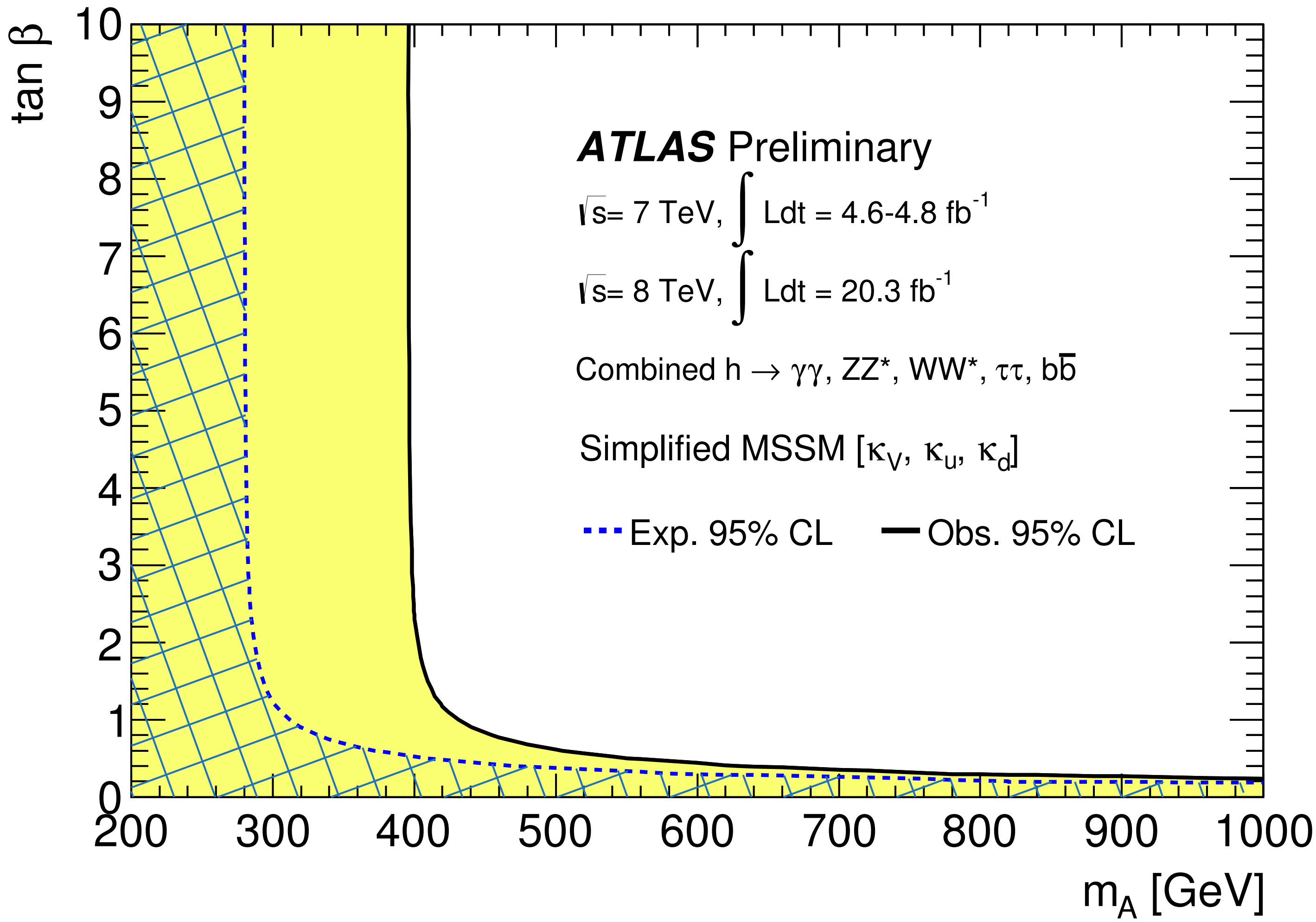


All vector boson branching ratios suppressed by enhancement of the bottom decay width

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

Low values of μ similar to the ones analyzed by ATLAS

ATLAS-CONF-2014-010



Bounds coming from precision h measurements

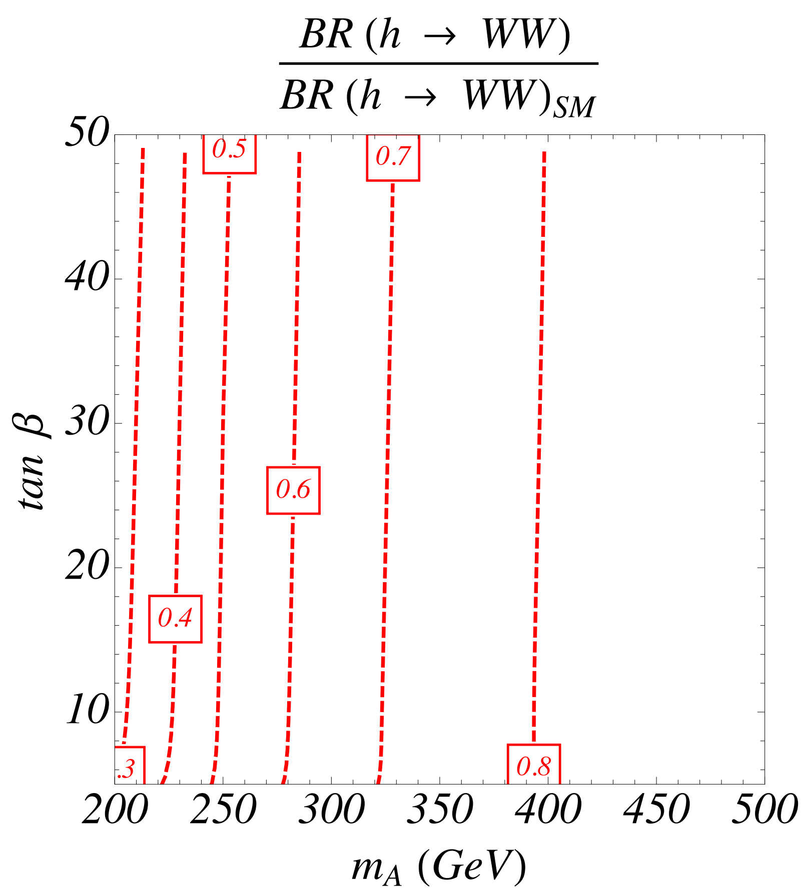
Carena, Haber, Low, Shah, C.W.'14

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

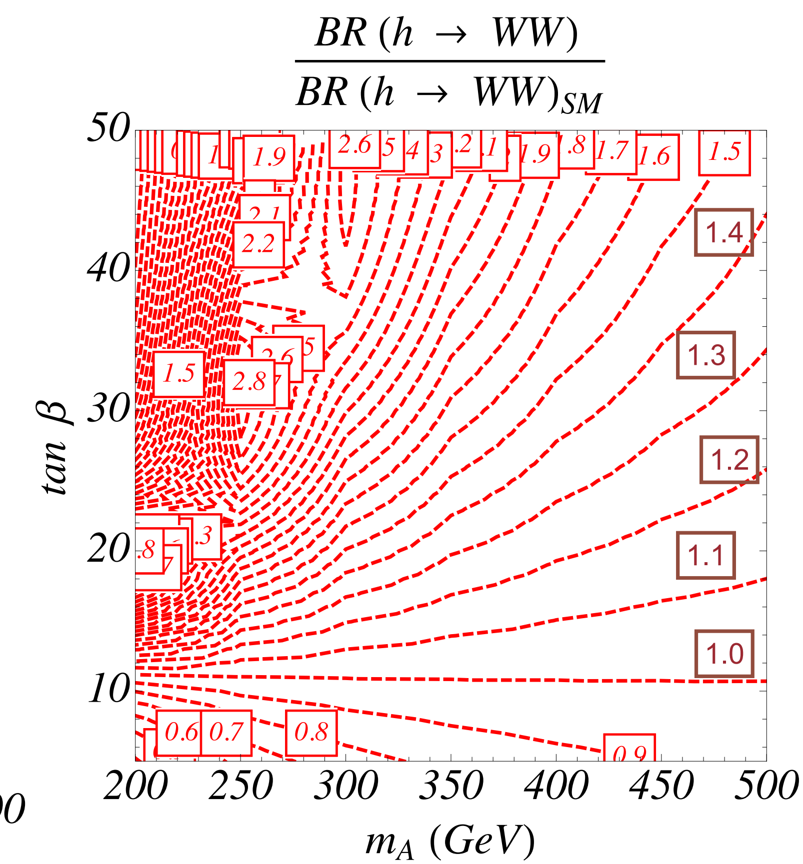
Higgs Decay into Gauge Bosons

Mostly determined by the change of width

Small μ



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



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

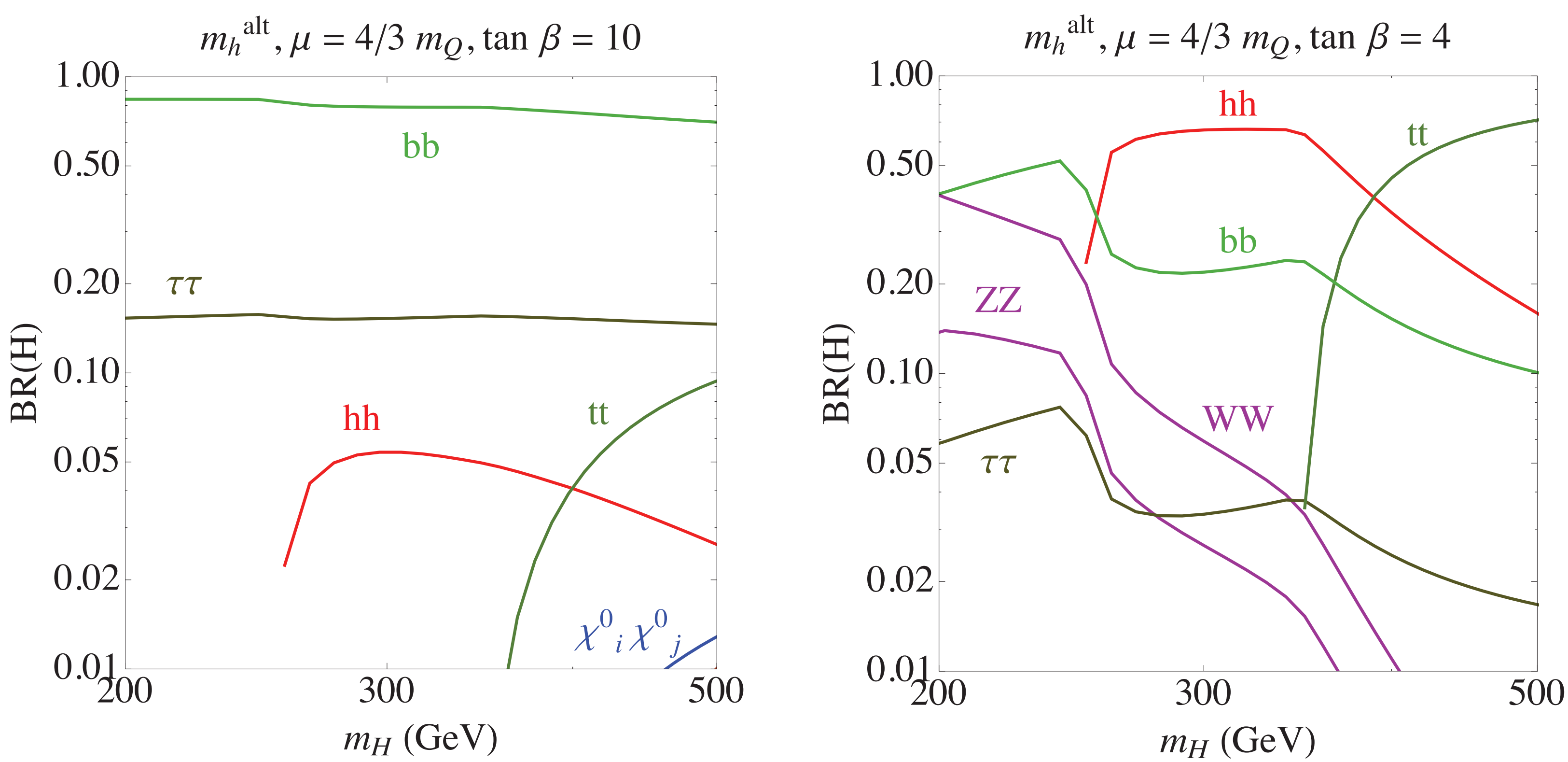
Heavy Supersymmetric Particles

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.

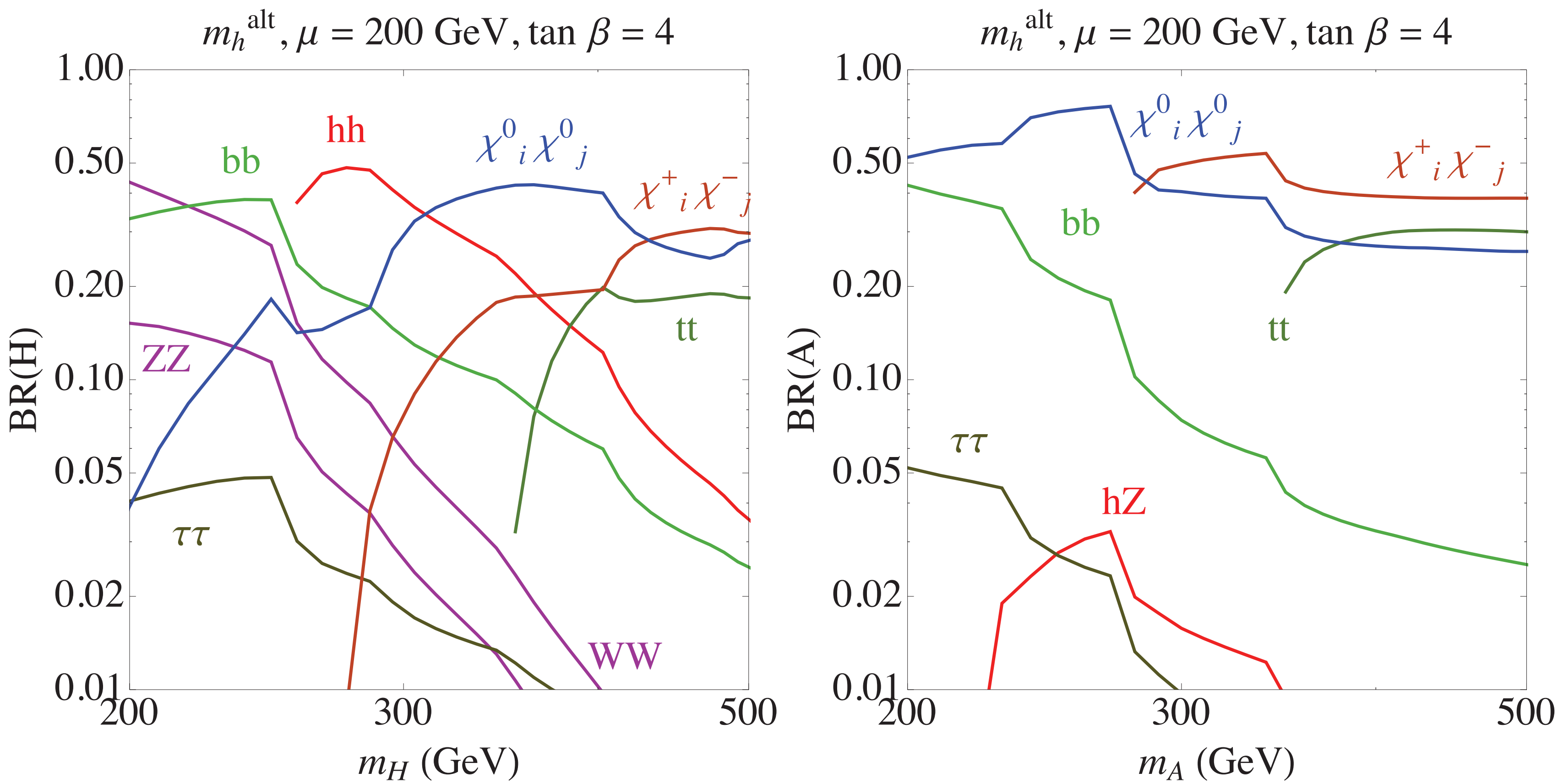


At large tanβ, bottom and tau decay modes dominant.

As tanβ decreases decays into SM-like Higgs and wek bosons become relevant

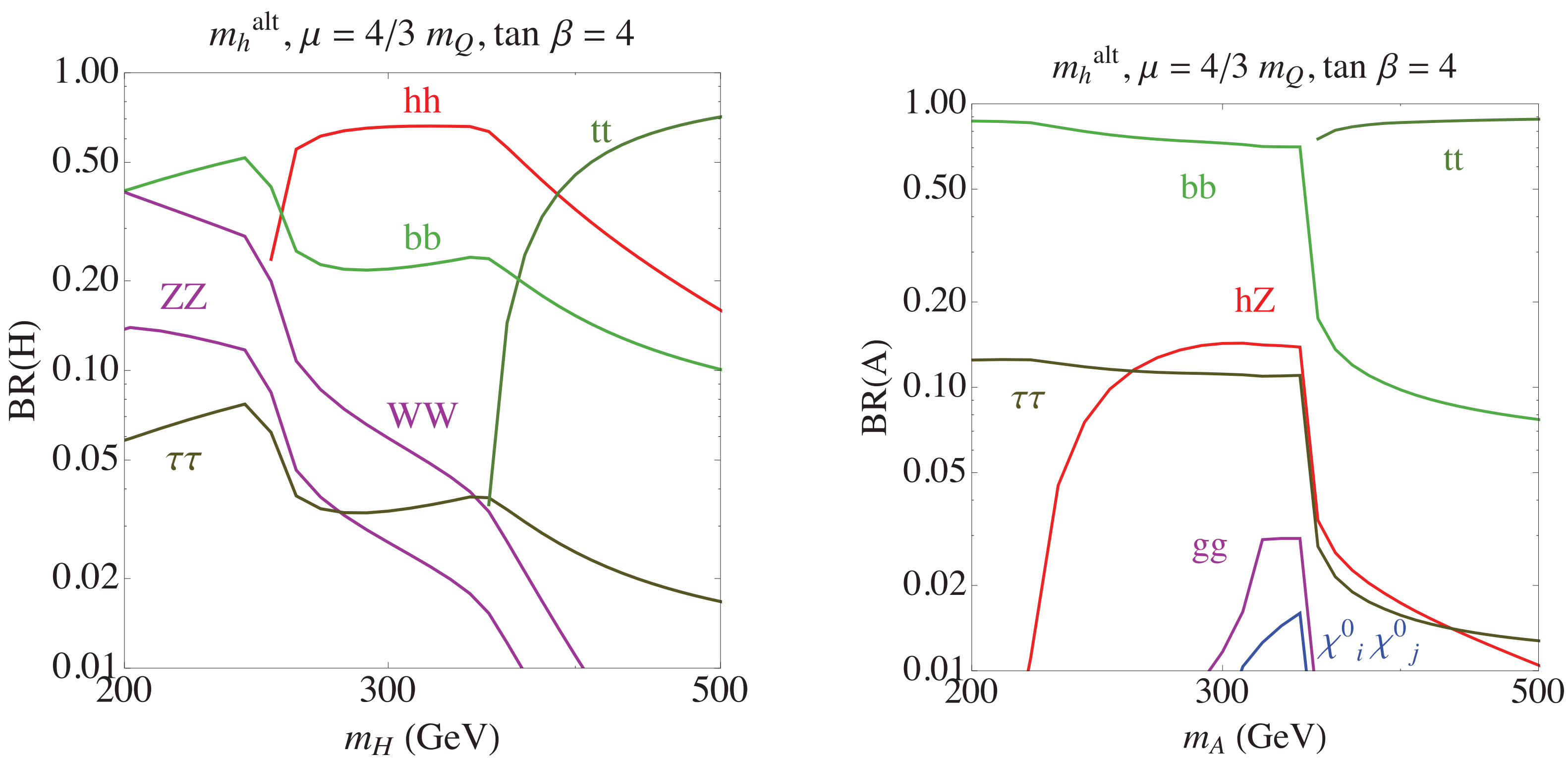
Light Charginos and Neutralinos can significantly modify M the CP-odd Higgs Decay Branching Ratios

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.

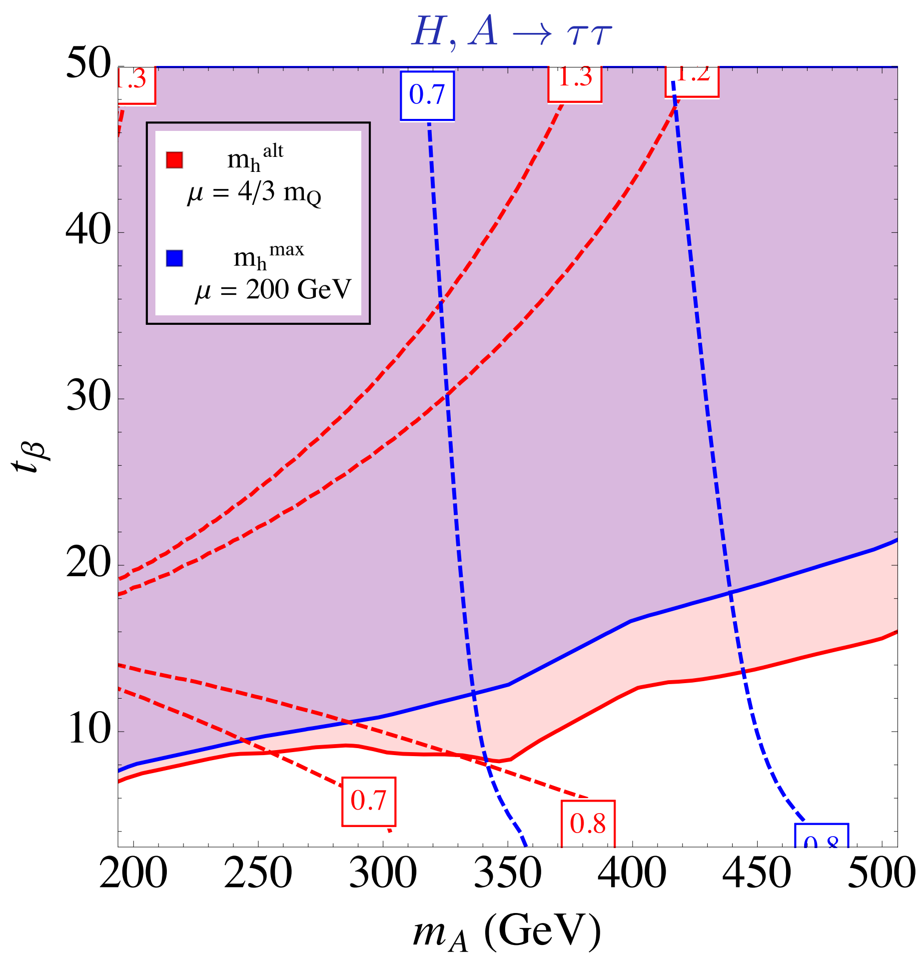
Large μ and small tanβ



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)

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

$$\delta\tilde{\lambda}_3 = \lambda^2 \qquad\qquad \cos(\beta - \alpha) \simeq -M_S^2(1,2)/(m_H^2 - m_h^2)$$

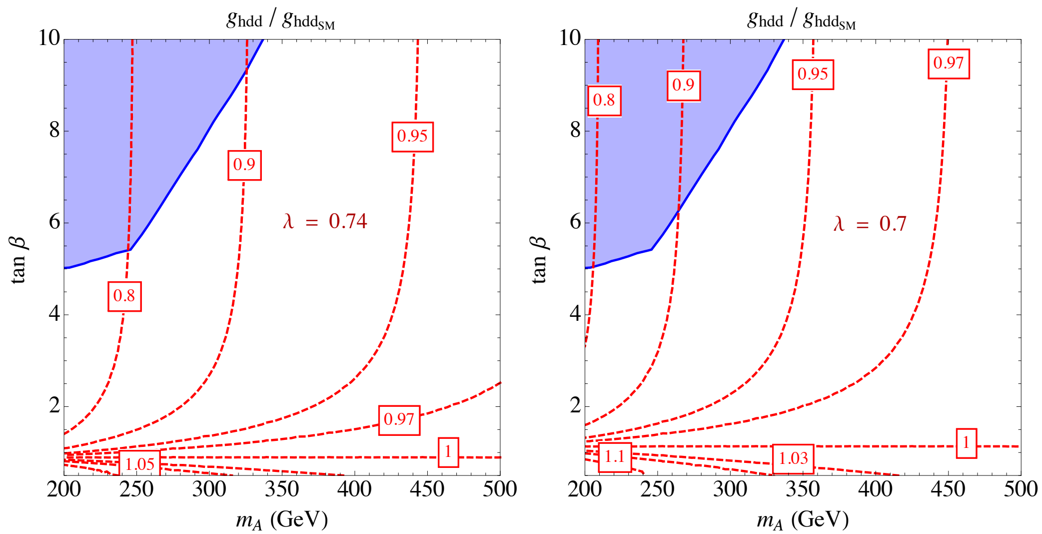
- The last term is the one appearing in the MSSM, that are small for moderate mixing and small values of $\tan\beta$

- 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

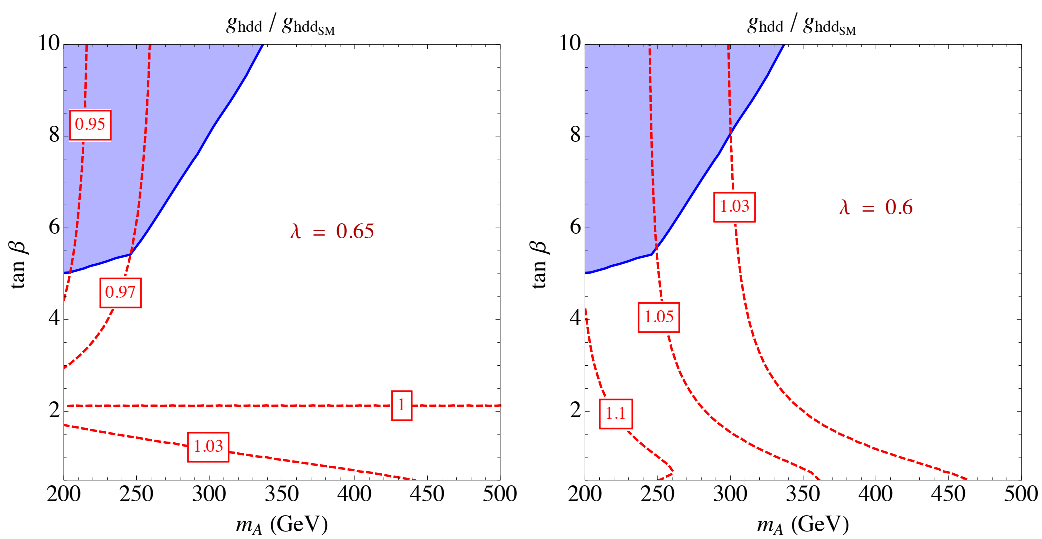
$$\lambda^2 = \frac{m_h^2 - M_Z^2 \cos 2\beta}{v^2 \sin^2\beta}$$

Alignment in the NMSSM (heavy or Aligned singlets)

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



(iii) (iv)



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

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

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

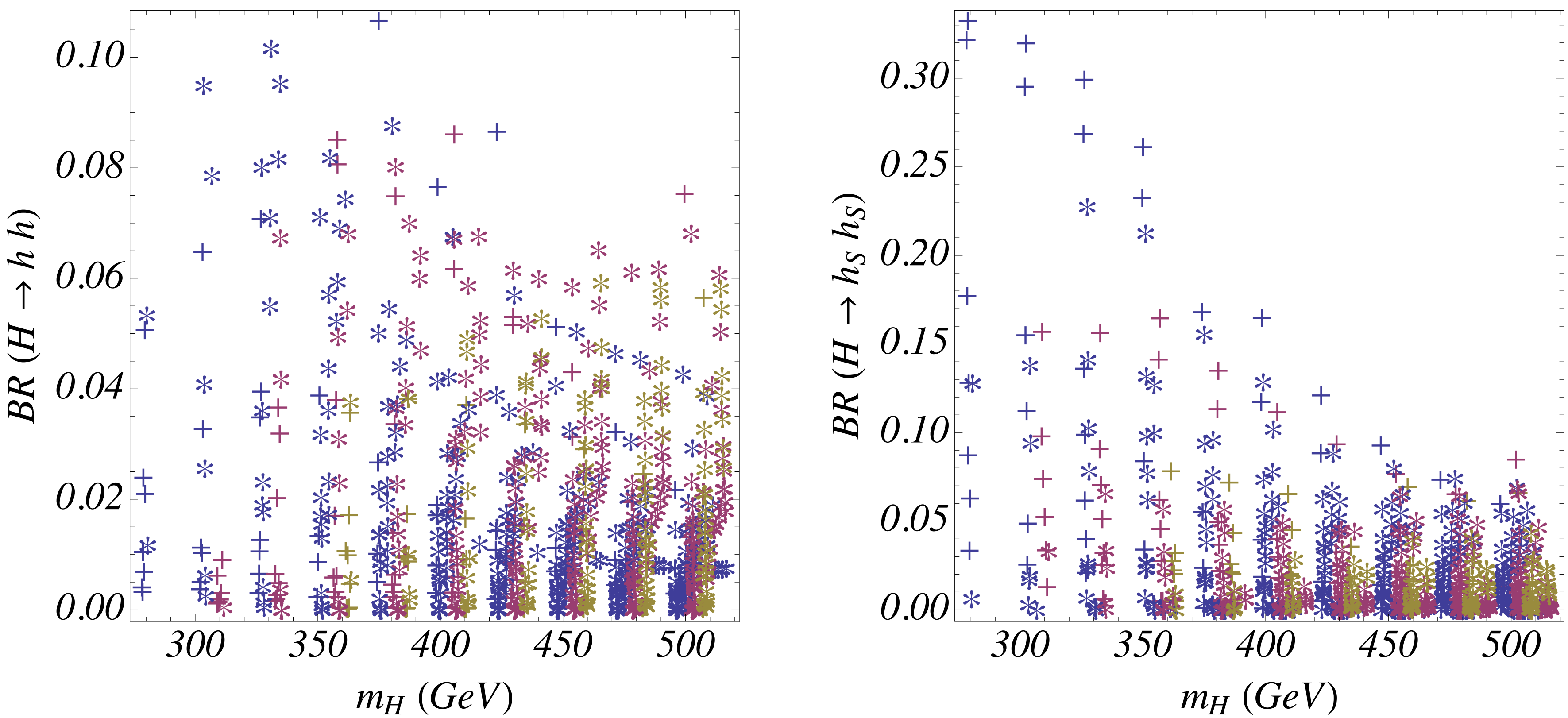
- If one assumes alignment, the expression inside the bracket must cancel
- If one assumes $\tan\beta < 3$ and lambda of order 0.65, and in addition one asks for kappa in the perturbative regime, one immediately conclude that in order to get small mixing in the Higgs sector, the CP-odd Higgs is correlated 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

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

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

Crosses : H1 singlet like
Asterix : H2 singlet like

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

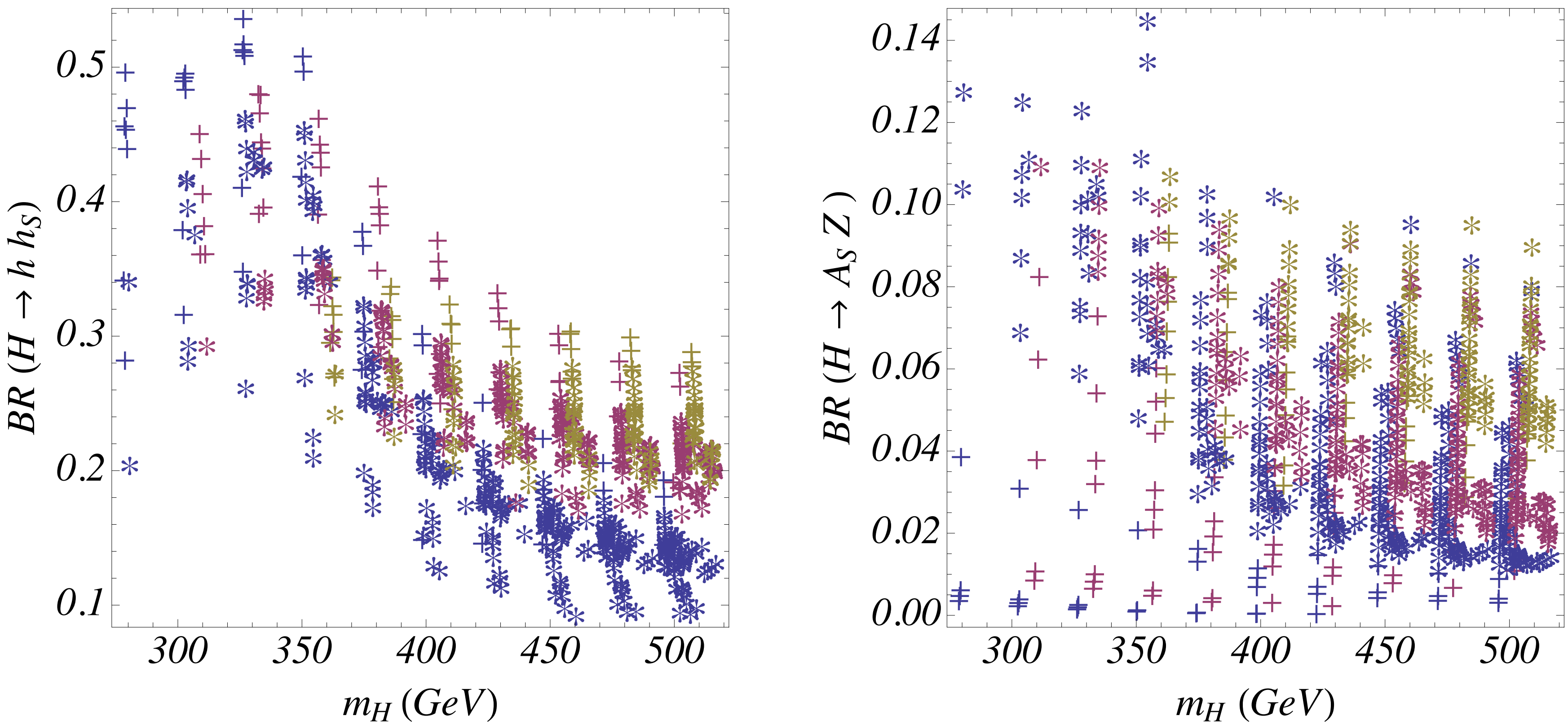


Significant decays of heavier Higgs Bosons into lighter ones and Z's

Crosses : H1 singlet like
Asterix : H2 singlet like

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

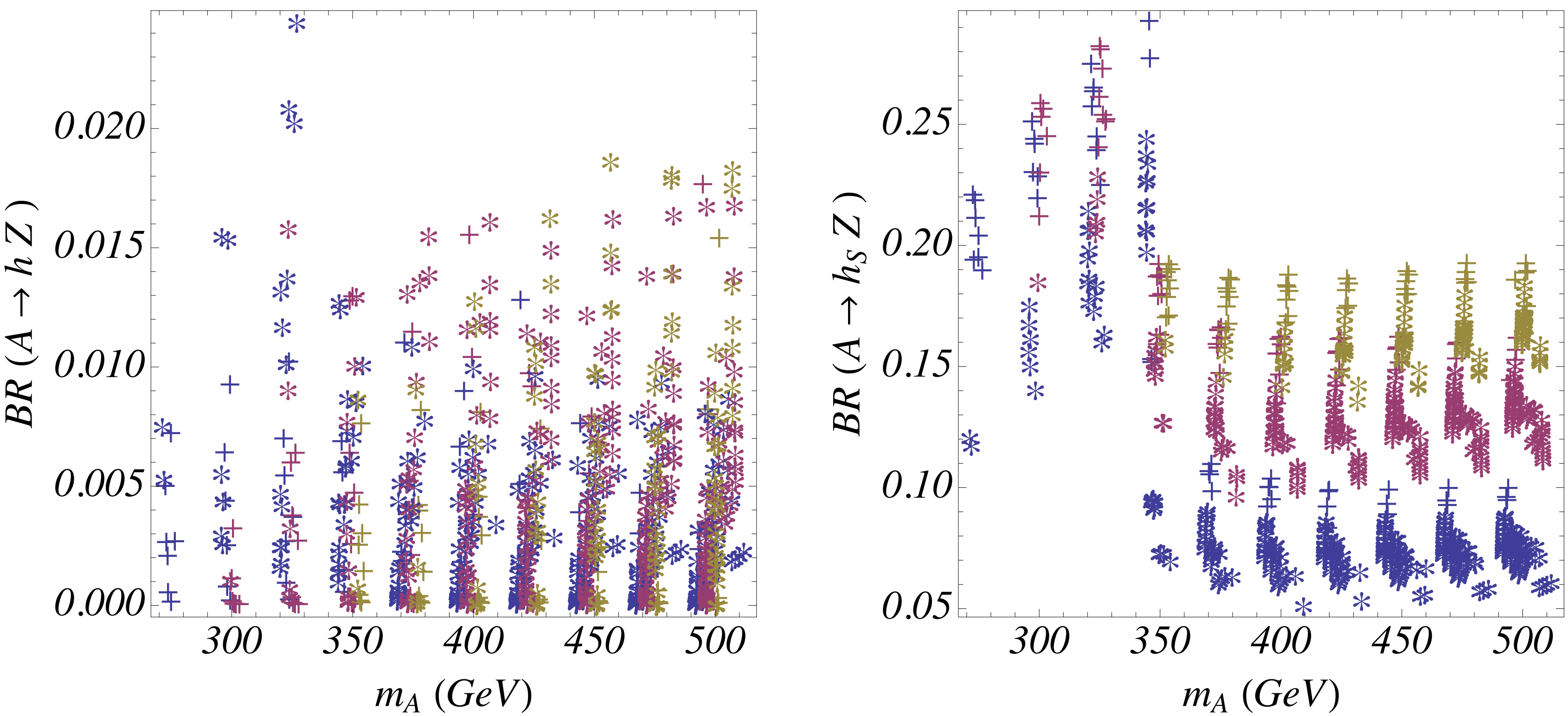
Carena, Haber, Low, Shah, C.W.'15



Heavy CP-odd Higgs Bosons have similar decay modes

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

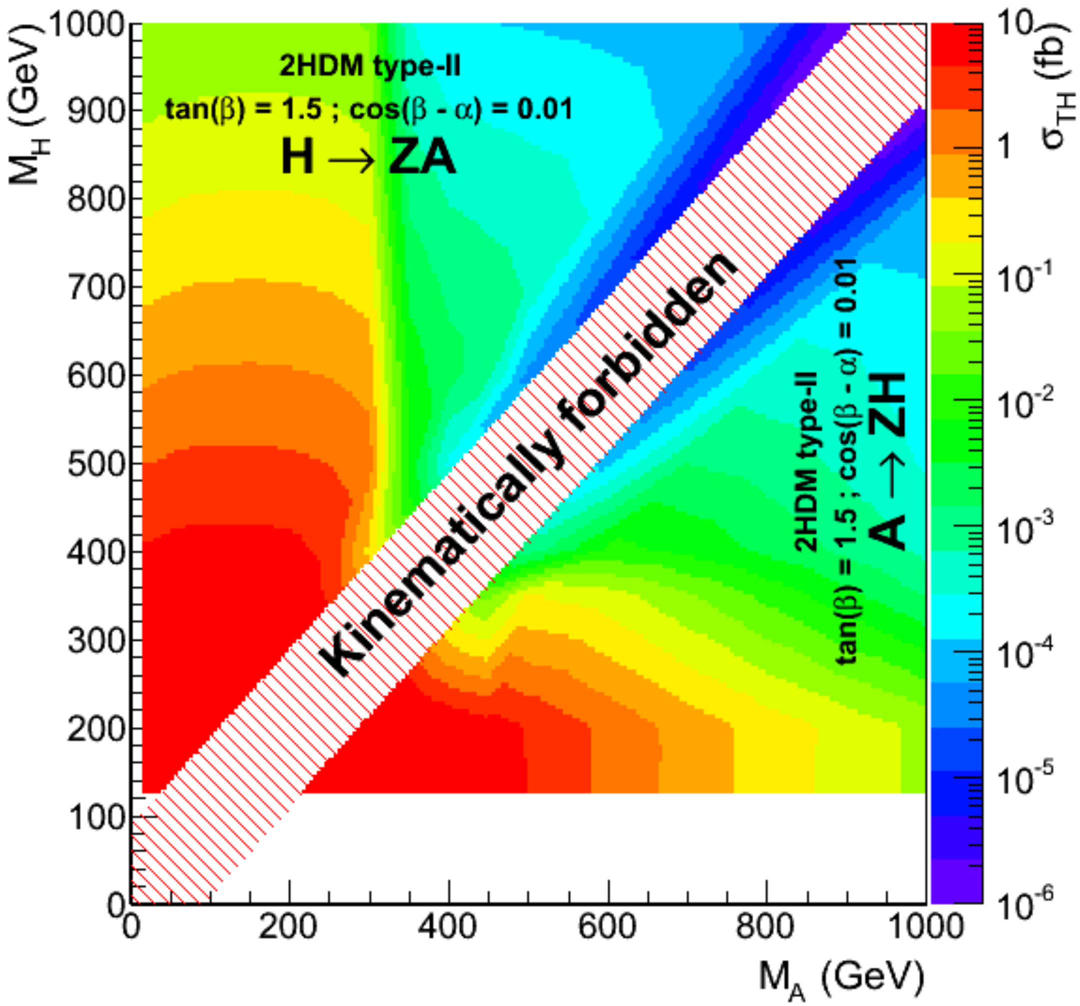
Blue : $\tan\beta = 2$
Red : $\tan\beta = 2.5$
Yellow: $\tan\beta = 3$



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

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 !

Top Quark and Bottom Quark Couplings Modifications

M. Badziak and C.W. '1602.06198

Modifying the top and bottom couplings in two Higgs Doublet Models

- Measurement of the top and bottom couplings still subject to large errors.
- The enhancement on the top coupling is somewhat weaker in the 13 TeV data. Modifications of a few tens of percent possible.
- Modifying the top-quark coupling is simple for small values of tanβ, but the bottom coupling is modified as well in an opposite direction

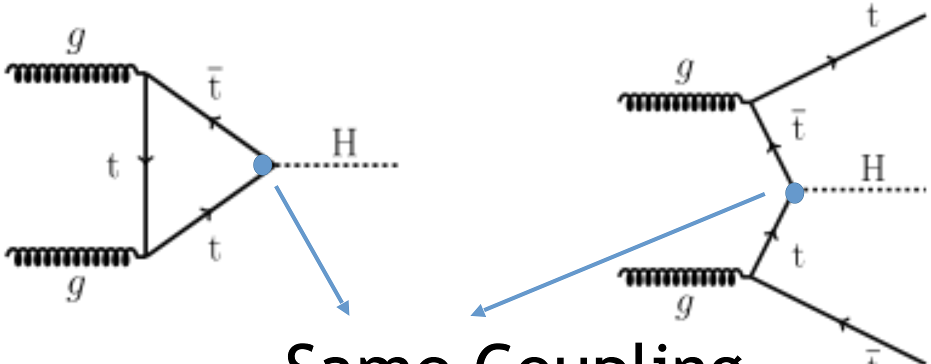
$$h = -\sin\alpha H_d^0 + \cos\alpha H_u^0$$
$$H = \quad \cos\alpha H_d^0 + \sin\alpha H_u^0$$

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

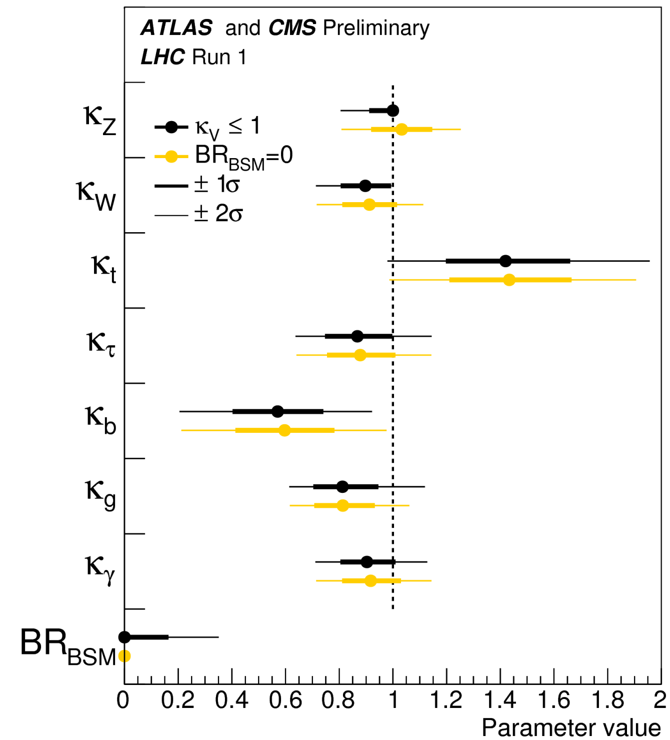
$$\tan\beta = \frac{v_u}{v_d}$$

What is the problem in 2HDM ?

Suppression of the gluon fusion rate ?



Same Coupling



Would expect top rate to be suppressed as well ! No evidence of that in data, although errors are too large to tell.

M. Badziak and C.W. ‘1602.06198, 1611.03253

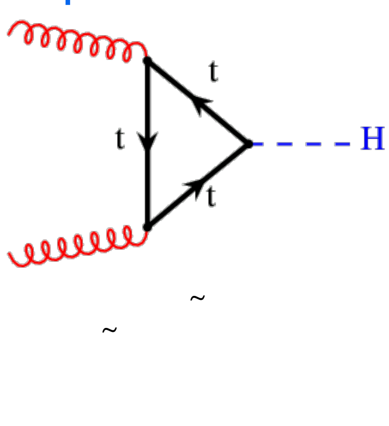
The Gluon Fusion Rate

- Suppression of the bottom coupling would demand some suppression of the gluon-Higgs coupling.

- Problem is even more severe when the top coupling is enhanced, since we have to compensate for this potential source of ggh enhancement

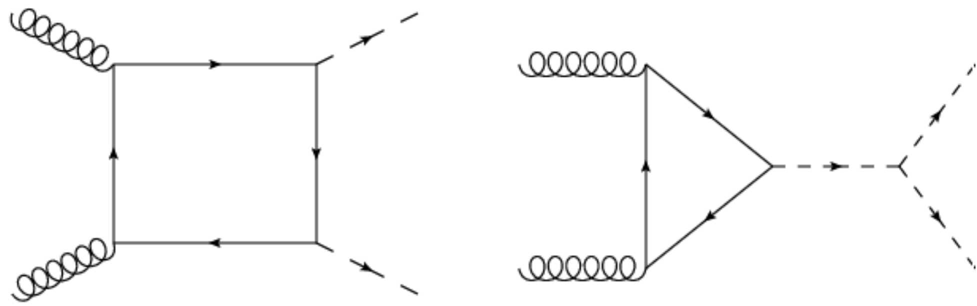
$$\kappa_t = \sin(\beta - \alpha) + \cot\beta \cos(\beta - \alpha)$$
$$\kappa_b = \sin(\beta - \alpha) - \tan\beta \cos(\beta - \alpha)$$
$$\kappa_V = \sin(\beta - \alpha) \simeq 1$$

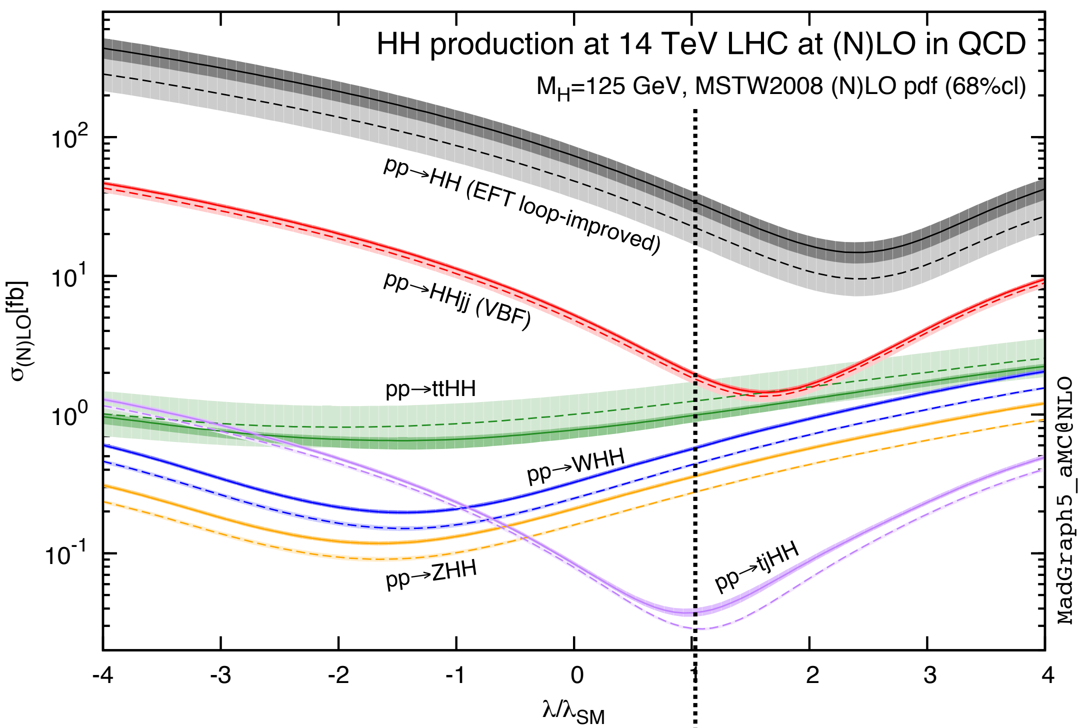
- However, the gluon fusion cross section could also be modified in the presence of extra color particles. For instance, for scalar tops,



$$\frac{\kappa_g}{\kappa_g^{\rm SM}} \simeq \kappa_t \left[1 + \frac{m_t^2}{4}\left(\frac{1}{m_{\tilde{t}_1}^2} + \frac{1}{m_{\tilde{t}_2}^2} - \frac{X_t^2}{m_{\tilde{t}_1}^2 m_{\tilde{t}_2}^2}\right)\right]$$

Connection with Di-Higgs Production





Frederix et al'14

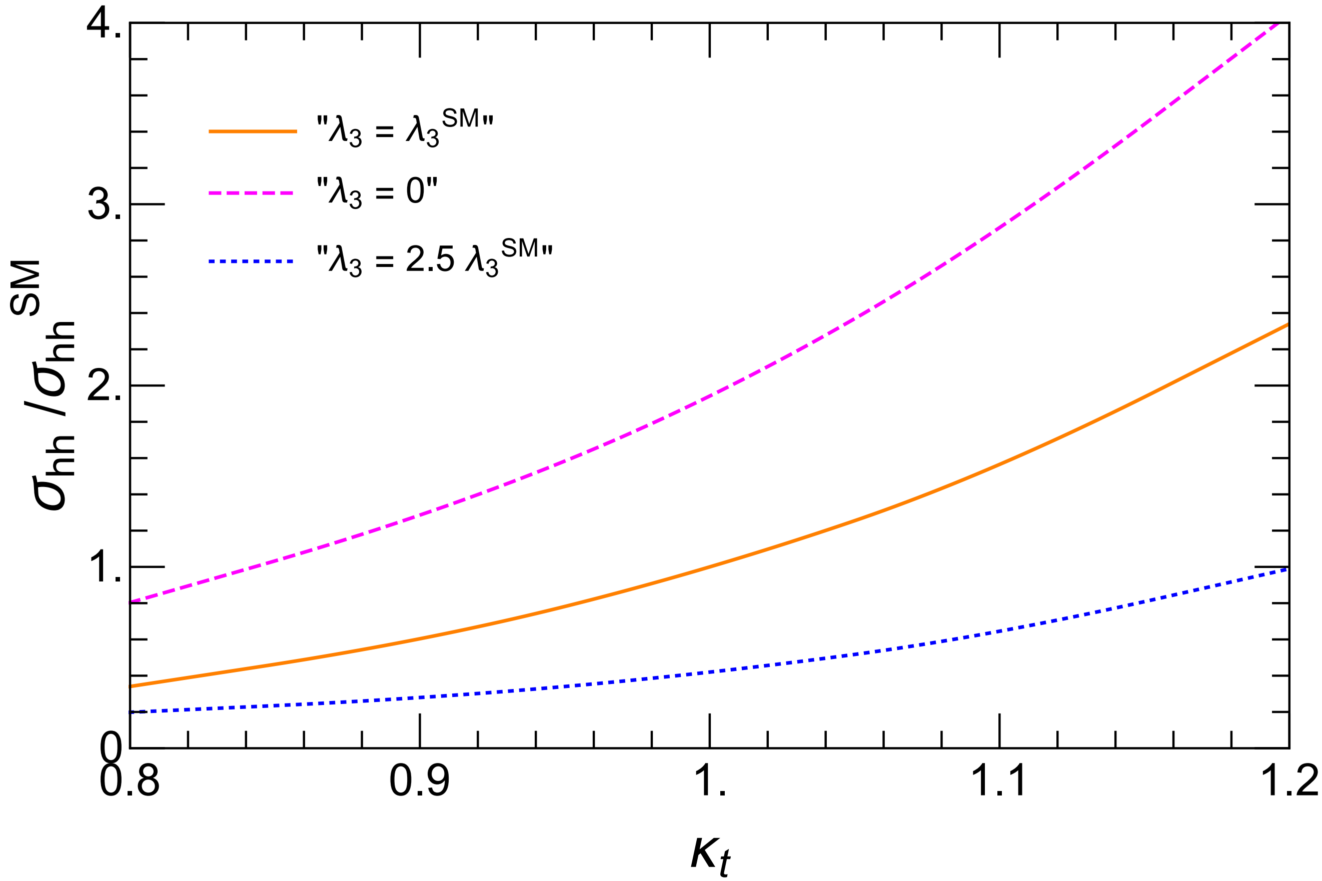
Very few events in the SM case after cuts are implemented.

Light Stops or small modifications of the top quark coupling (or both) can strongly enhance the di-Higgs production rate.

Joglekar, Huang, Li, C.W.'17

Variation of the Di-Higgs Cross Section with the Top Quark and Self Higgs Couplings

Huang, Joglekar, Li, C.W.'17

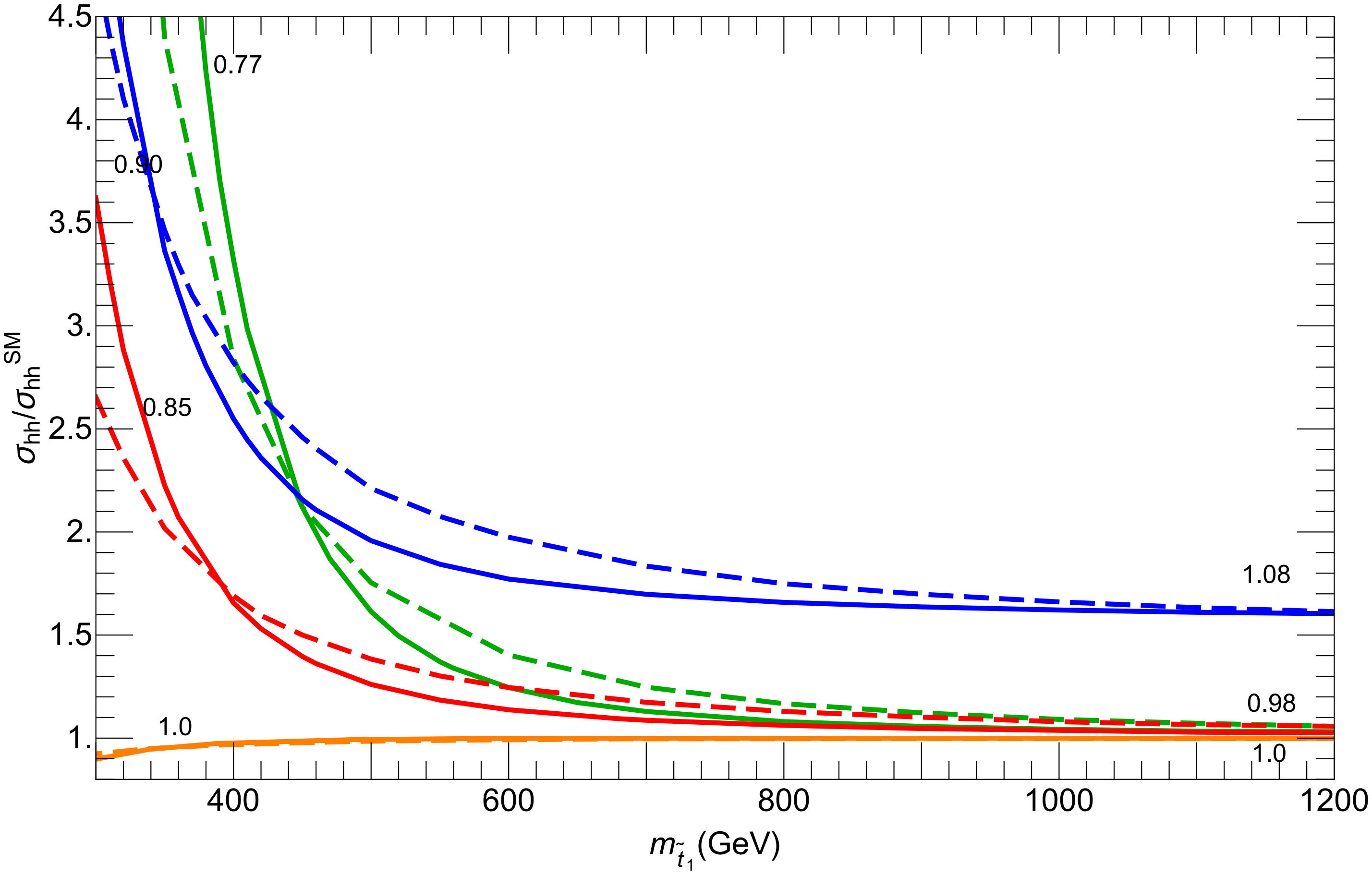


Strong dependence on the value of kt and λ3

Even small variations of kt can lead to 50 percent variations of the di-Higgs cross section

Stop Effects on Di-Higgs Production Cross Section

Huang, Joglekar, Li, C.W.'17



Orange : Stop corrections to kappa_g decoupled

Red : X_t fixed at color breaking vacuum boundary value, for light mA

Green : X_t fixed at color breaking boundary value, for mA = 1.5 TeV

Blue : Same as Red, but considering \kappa_t = 1.1

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 ?

- Easy to invert 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.

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

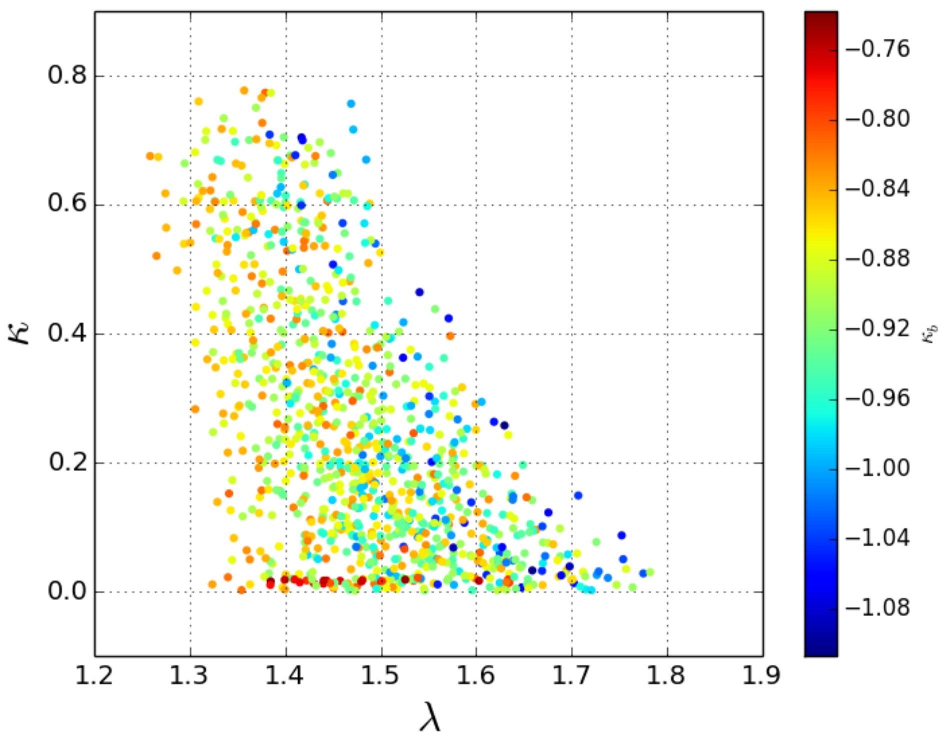
- This causes problems with the spectrum, since some scalars tend to become tachyonic in the relevant region of parameters. We cured this problem by adding a tadpole term

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

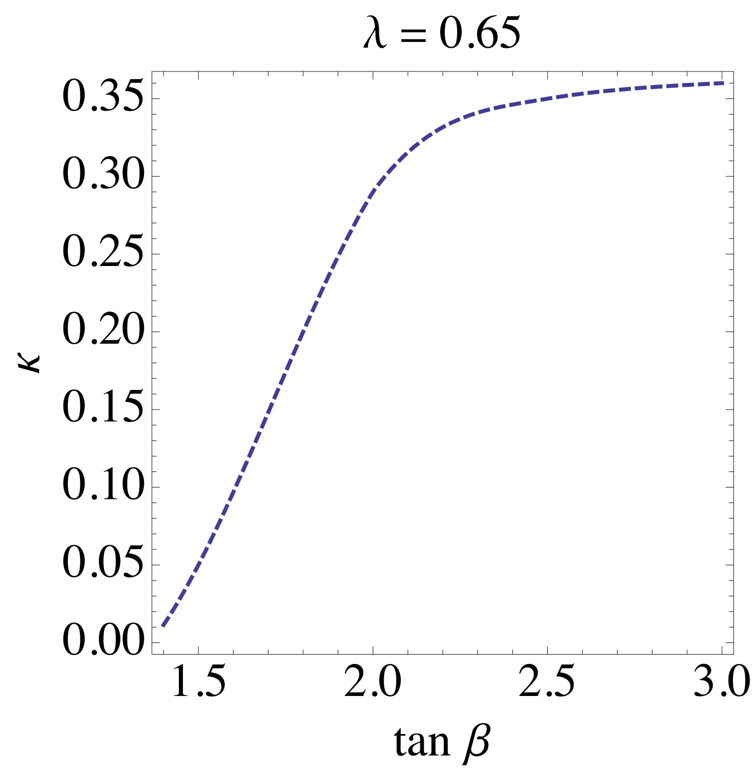
- Since the Higgs-gauge boson coupling with respect to the SM is $\sin(\beta - \alpha)$, one needs sizable values of $\tan\beta$, and moderate values of m_H , but still allowed by searches for non-standard Higgs bosons. Values of $\tan\beta \simeq 7 - 10$ are the most appropriate ones.

Values of the dimensionless couplings

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



Necessary values to invert the bottom coupling

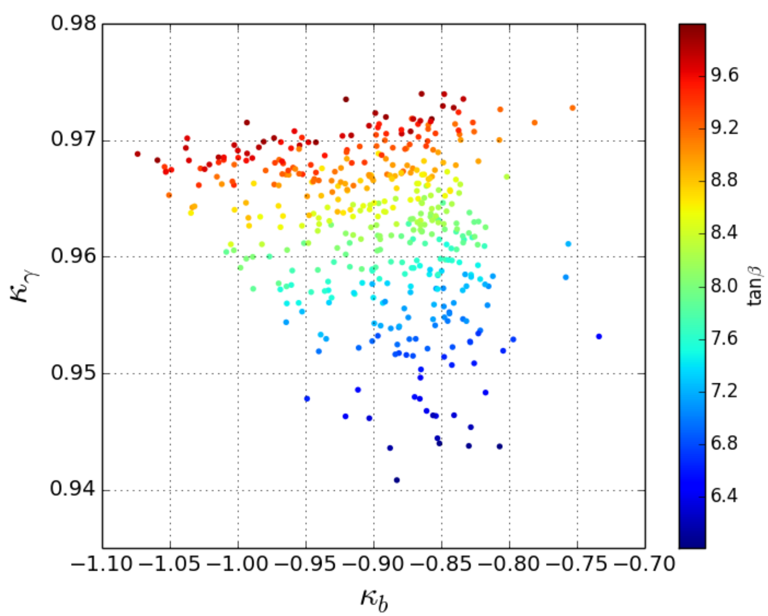


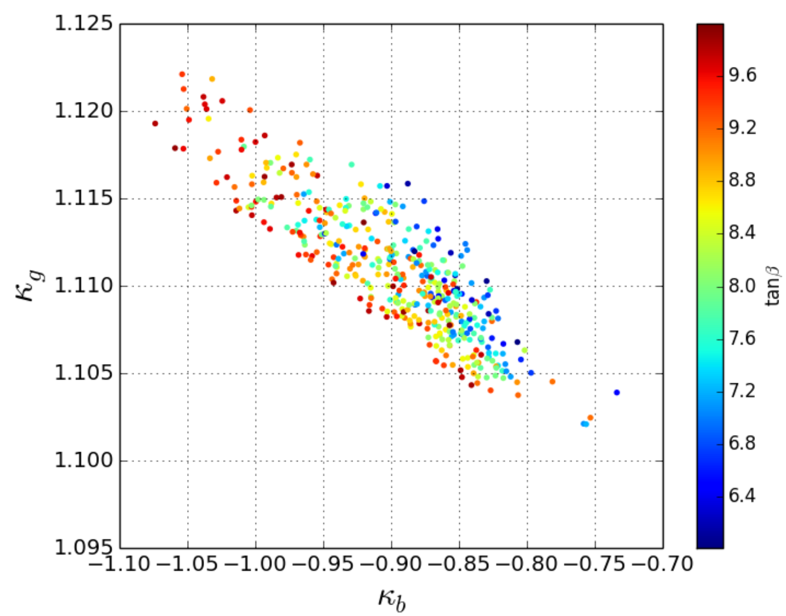
Upper bound on these parameters to preserve perturbative consistency up to the GUT scale

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.





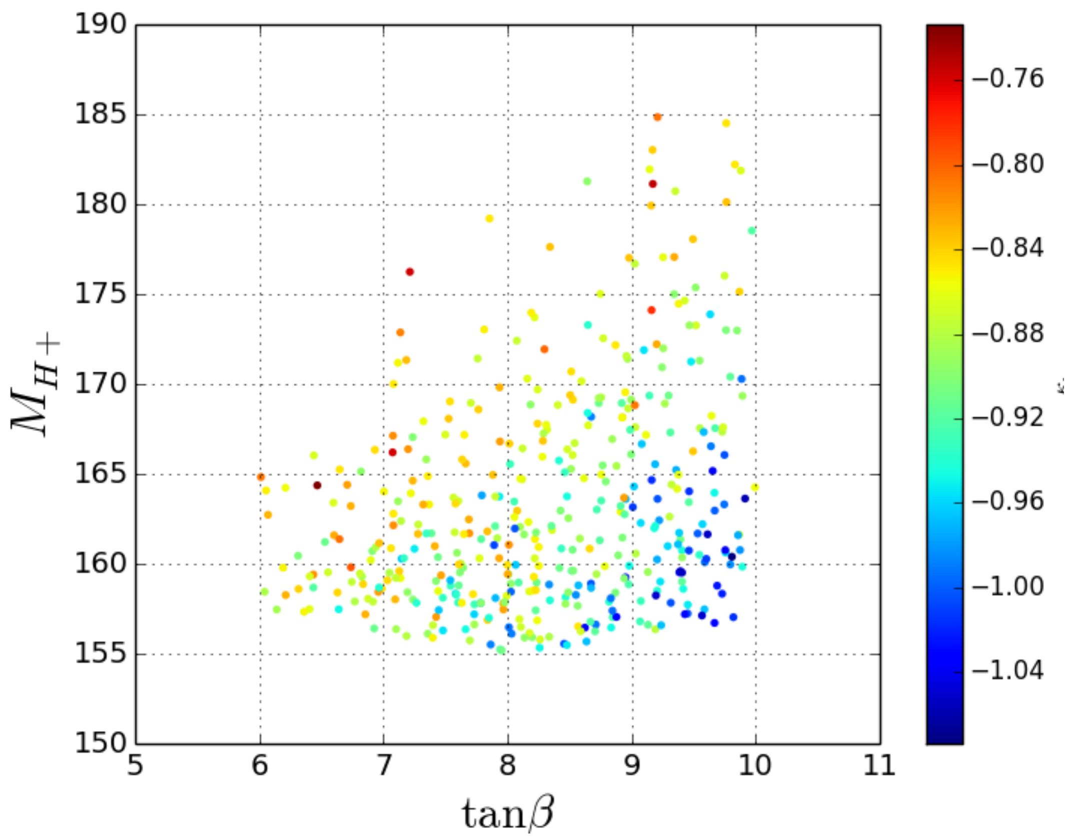
B. Li, N. Coyle, C.W. ’17 (to appear)

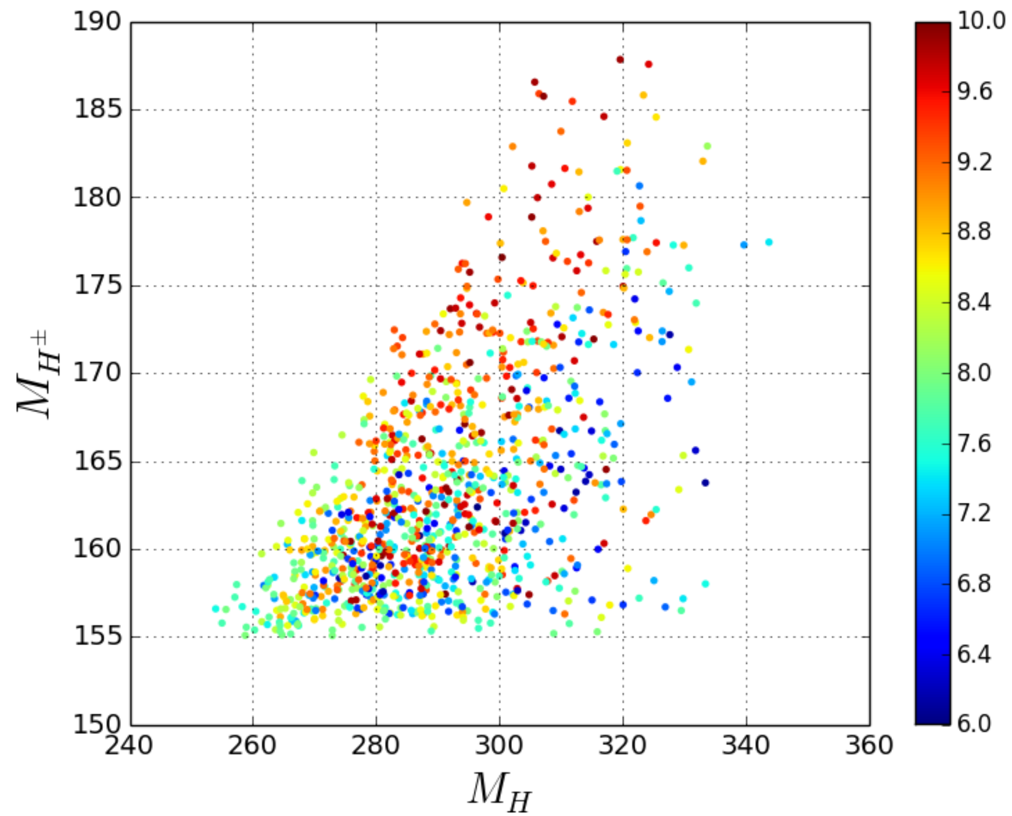
Low charged Higgs masses

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

$$m_{H^+}^2 \simeq m_A^2 - \lambda^2 v^2 \qquad v = 174\ GeV$$

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

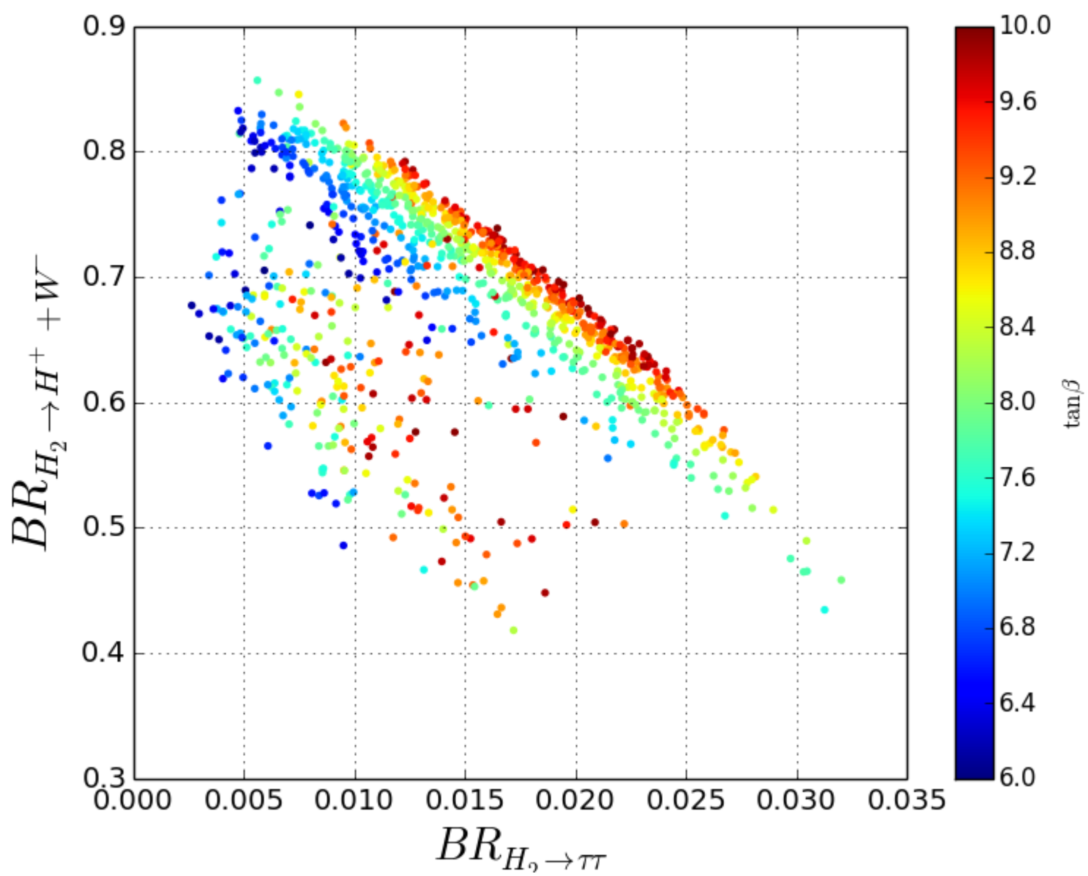




B. Li, N. Coyle, C.W. '17 (to appear)

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.



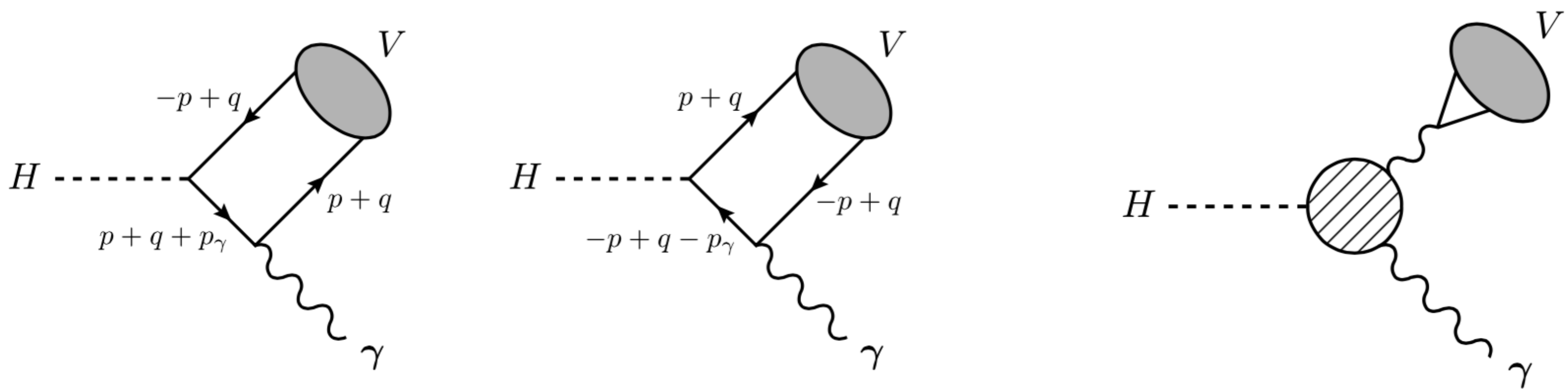
Additional tests of this idea ?

Radiative Higgs Decays

Bodwin et al'14, Neubert et al'15

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

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



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 $\kappa_b = -1$

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

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

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

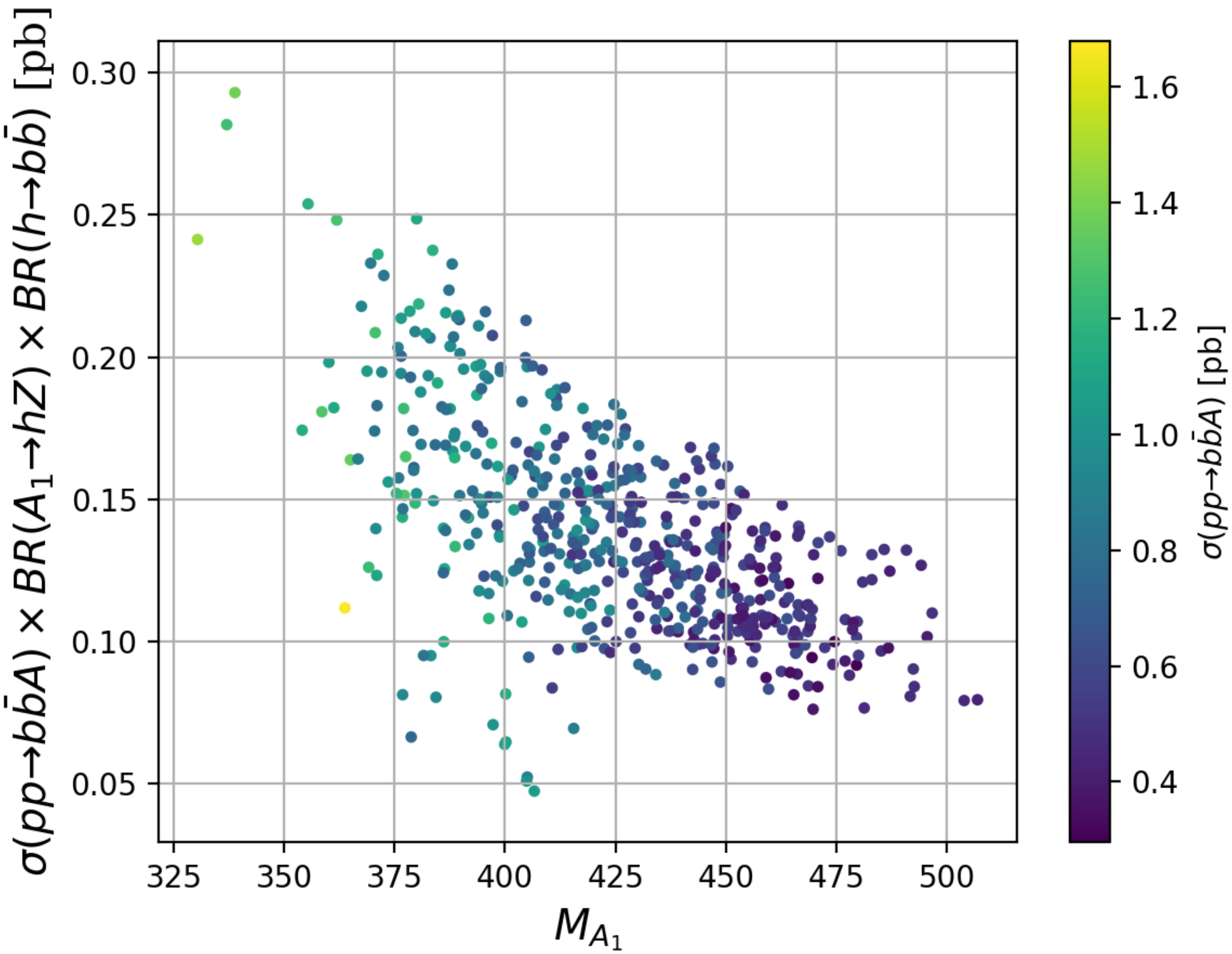
κ_b	$\Upsilon(1S)$	$\Upsilon(2S)$	$\Upsilon(3S)$
	Run 2 (130 fb^{-1})		
1	0.00442 ± 0.06214	0.0155 ± 0.0483	0.0178 ± 0.0414
-1	8.02 ± 0.32	3.75 ± 0.15	2.73 ± 0.11
	Run 3 (300 fb^{-1})		
1	0.0102 ± 0.1434	0.358 ± 0.1115	0.0408 ± 0.0956
-1	18.5 ± 0.7	8.65 ± 0.36	6.31 ± 0.26

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.

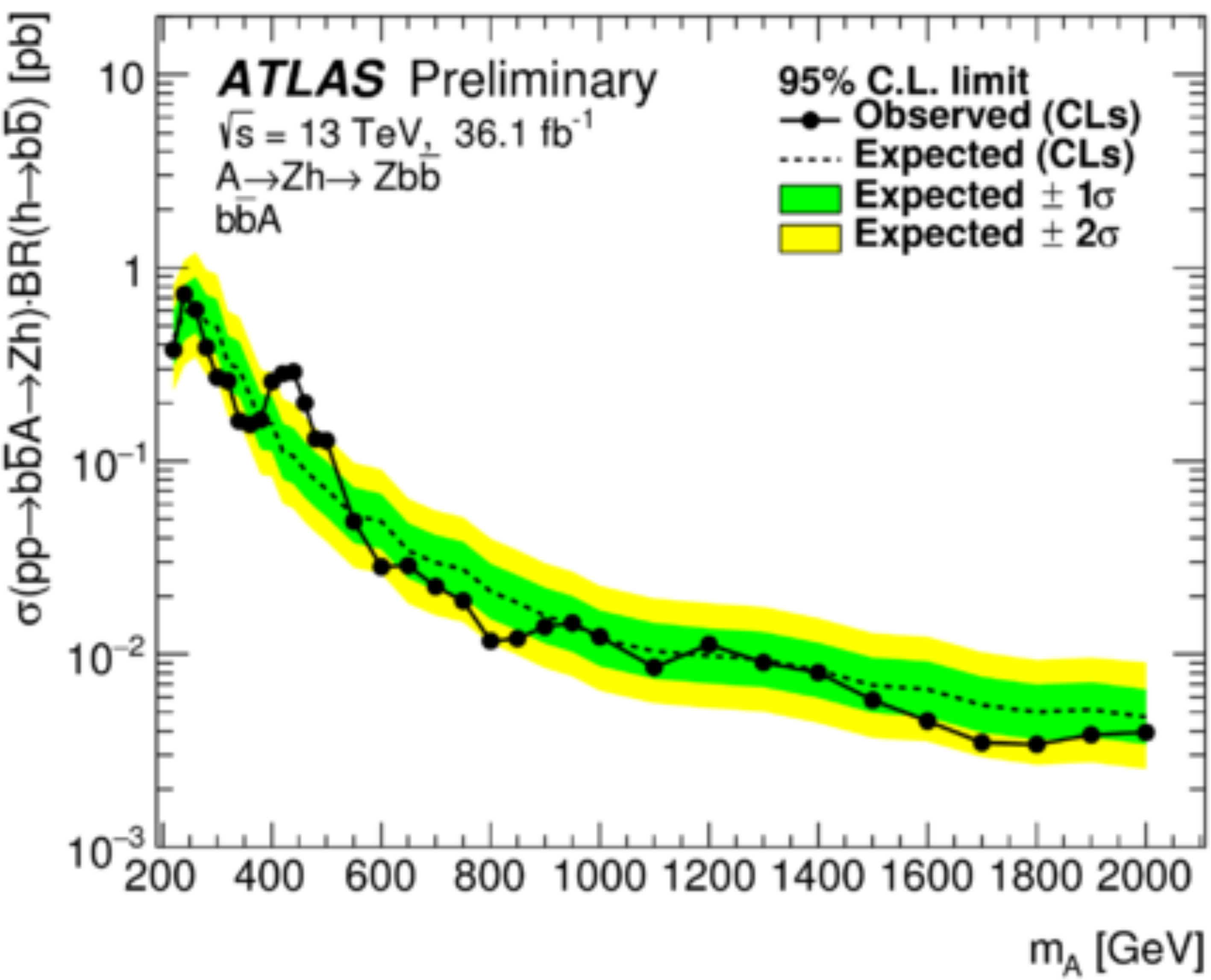
More general Parameters : Superpotential Tadpole

One may reduce the mass gap with the charged Higgs, and due to the large misalignment, decays into Higgs and gauge bosons open up.



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

Consistent with ATLAS Excess

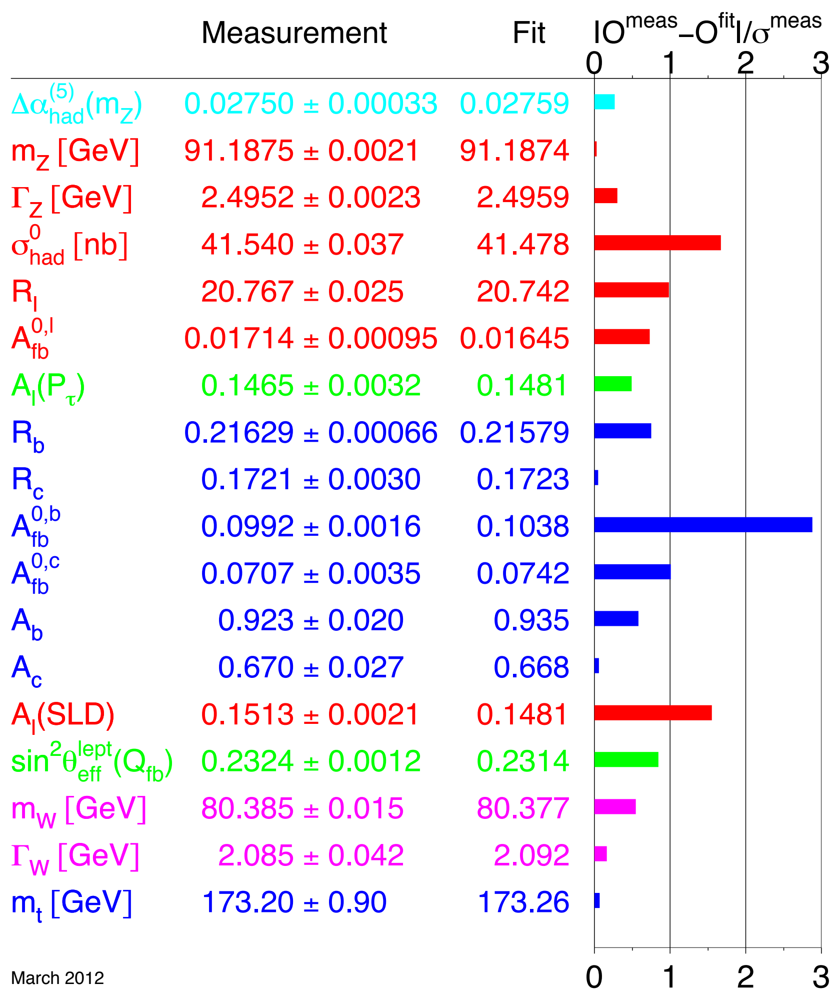


Conclusions

- 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, after discussing the alignment condition, we have also 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.

D. Liu, J. Liu, X. Wang, C.W. , to appear

Bottom AFB



- New gauge boson that couples to bottom quark.
- Could mimic the Higgs boson

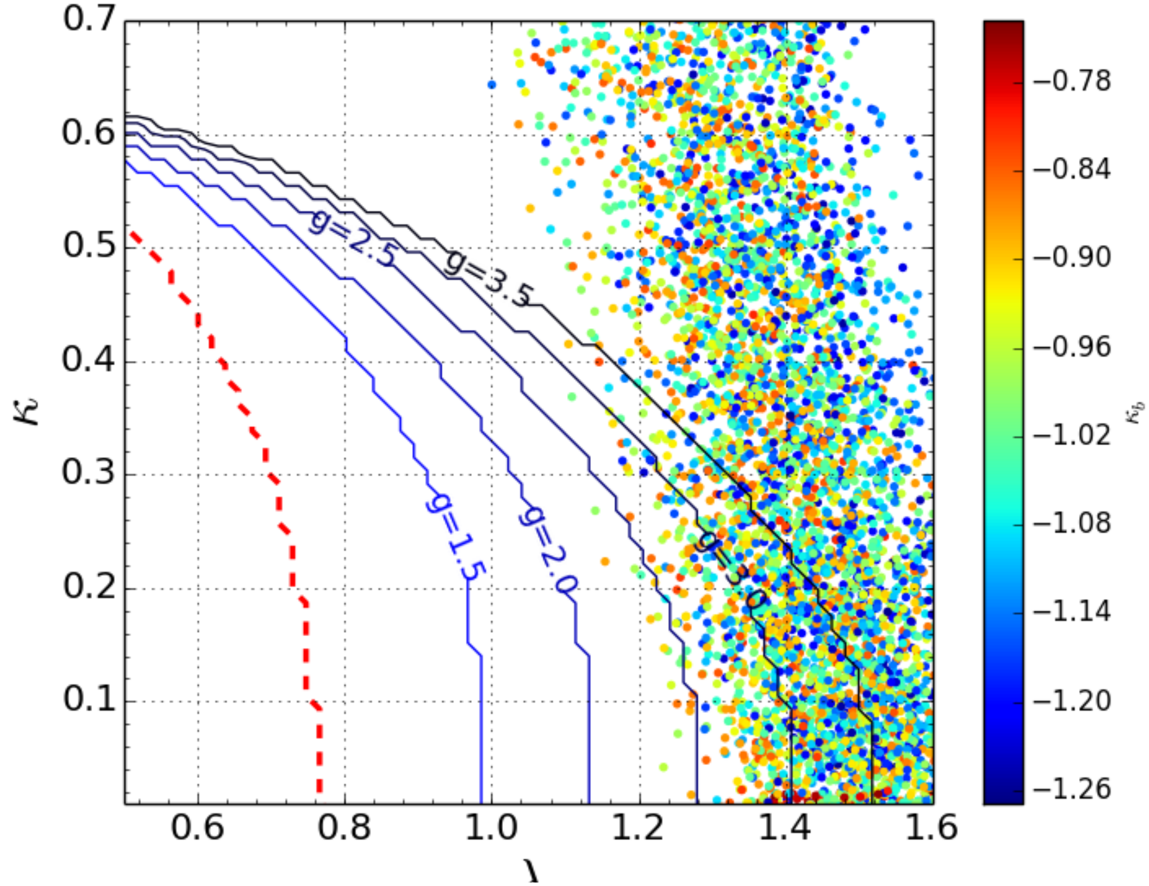
B. Li, N. Coyle, C.W. '17 (to appear)

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

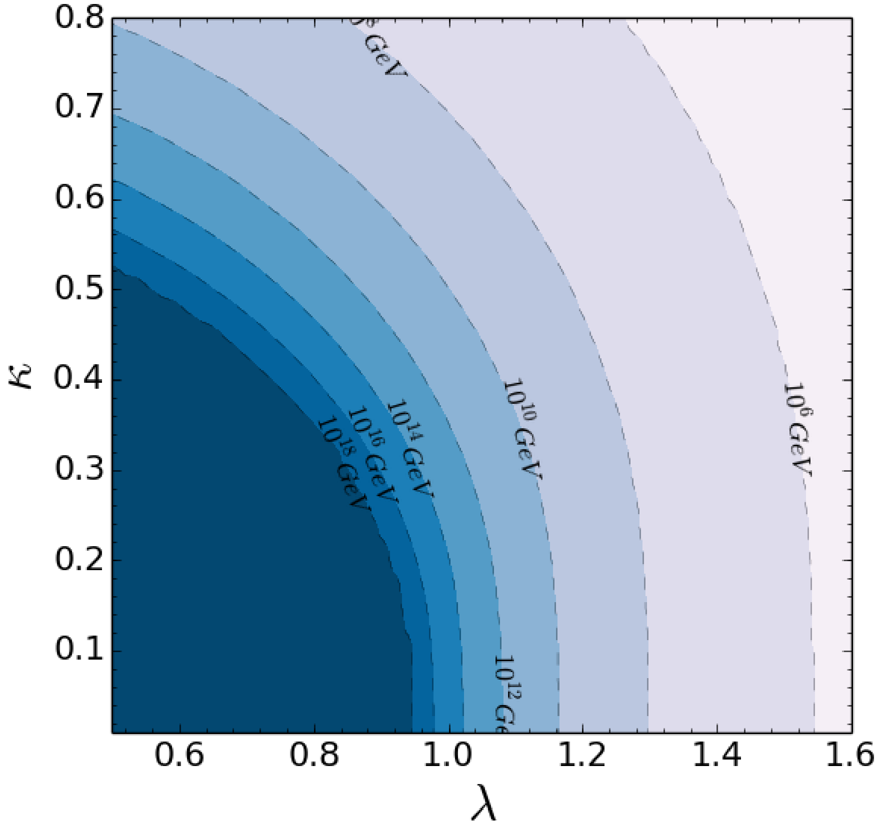
$$SU(3)_c \times SU(2)_1 \times SU(2)_2 \times U(1)_Y$$



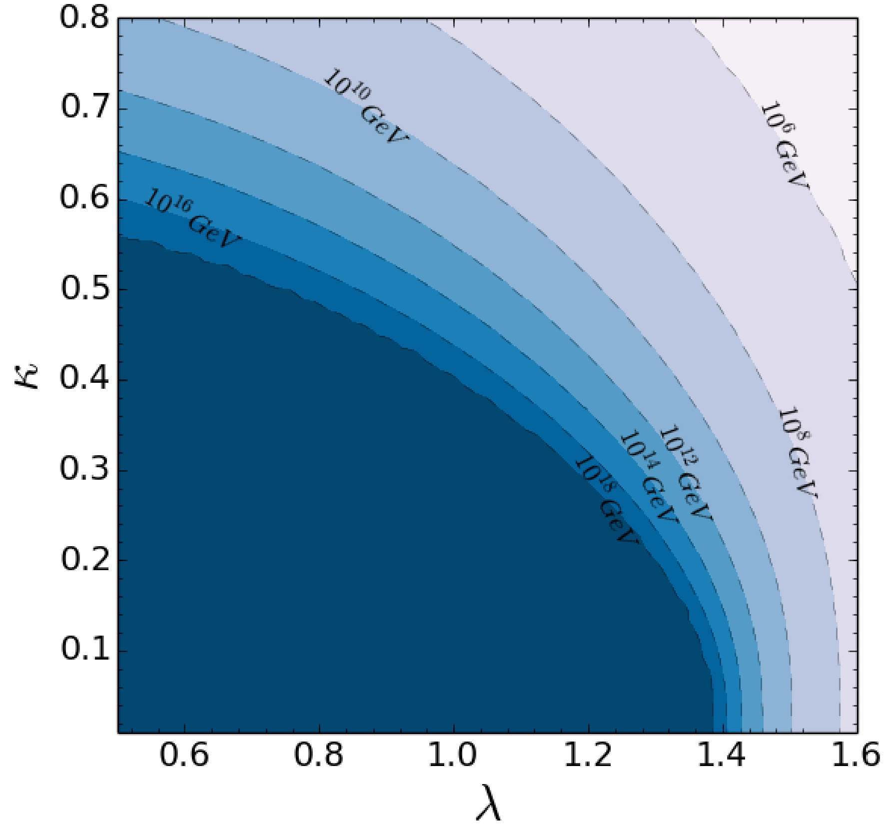
B. Li, N. Coyle, C.W. ’17 (to appear)

Loss of Perturbative Consistency for different values of g_1

$g_1 = 1.5$

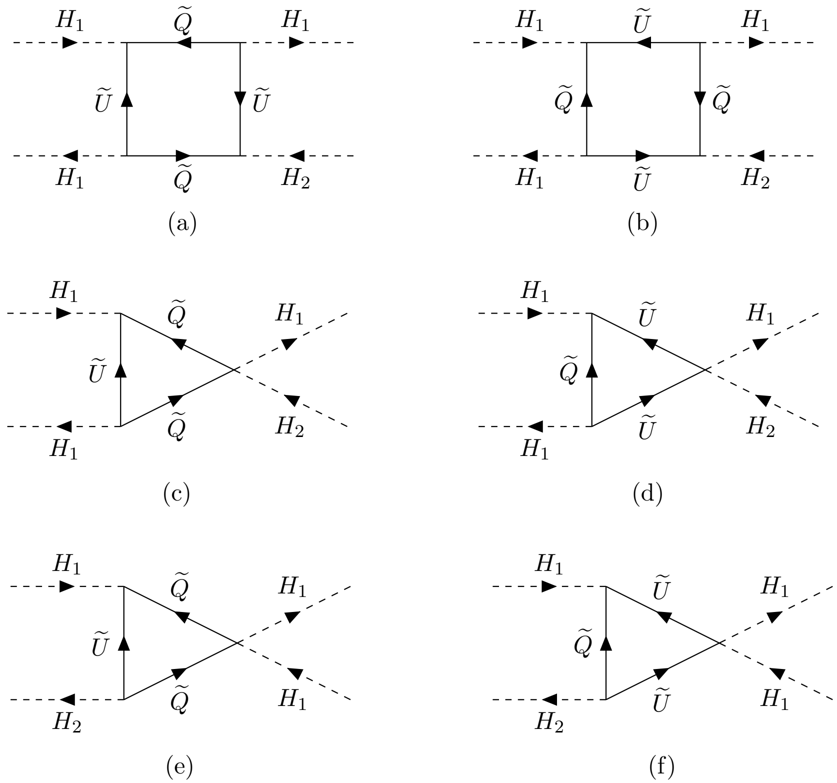


$g_1 = 3.$



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

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

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

At moderate or large $\tan\beta$

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

Quartic Couplings

Tree level :

$$\lambda_1 = \lambda_2 = \frac{1}{4}(g_2^2 + g_Y^2)\,,$$
$$\lambda_3 = \frac{1}{4}(g_2^2 - g_Y^2)\,,$$
$$\lambda_4 = -\frac{1}{2}g_2^2\,,$$
$$\lambda_5 = \lambda_6 = \lambda_7 = 0\,,$$

One-loop thresholds at the scale Ms

Haber & Hempgling'93

$$\Delta_{\rm th}^{(1)}\lambda_1 = -\frac{\kappa}{2}h_t^4\hat{\mu}^4 + 6\kappa h_b^4\widehat{A}_b^2\left(1-\frac{\widehat{A}_b^2}{12}\right) + 2\kappa h_\tau^4\widehat{A}_\tau^2\left(1-\frac{\widehat{A}_\tau^2}{12}\right) + \kappa\frac{g_2^2+g_Y^2}{4}\left[3h_t^2\hat{\mu}^2 - 3h_b^2\widehat{A}_b^2 - h_\tau^2\widehat{A}_\tau^2\right],$$

$$\Delta_{\rm th}^{(1)}\lambda_2 = 6\kappa h_t^4\widehat{A}_t^2\left(1-\frac{\widehat{A}_t^2}{12}\right) - \frac{\kappa}{2}h_b^4\hat{\mu}^4 - \frac{\kappa}{6}h_\tau^4\hat{\mu}^4 - \kappa\frac{g_2^2+g_Y^2}{4}\left[3h_t^2\widehat{A}_t^2 - 3h_b^2\hat{\mu}^2 - h_\tau^2\hat{\mu}^2\right],$$

$$\kappa = \frac{1}{16\pi^2}$$

Dominant Corrections for heavy Stops and Higgs Masses, $L = \log(M_S/M_t)$

Draper, Lee, C.W. '13, S. Martin'07

The analysis of the three-loop corrections show a high degree of cancellation between the dominant and subdominant contributions

Harlander, Kant, Mihaila, Steinhauser'08,'10

Feng, Kant, Profumo, Sanford'13

$$\delta_3\lambda = \Big\{ -1728\lambda^4 - 3456\lambda^3 y_t^2 + \lambda^2 y_t^2(-576 y_t^2 + 1536 g_3^2)$$
$$+ \lambda y_t^2(1908 y_t^4 + 480 y_t^2 g_3^2 - 960 g_3^4) + y_t^4(1548 y_t^4 - 4416 y_t^2 g_3^2 + 2944 g_3^4)\Big\} L^3$$
$$+ \Big\{ -2340\lambda^4 - 3582\lambda^3 y_t^2 + \lambda^2 y_t^2(-378 y_t^2 + 2016 g_3^2)$$
$$+ \lambda y_t^2(1521 y_t^4 + 1032 y_t^2 g_3^2 - 2496 g_3^4) + y_t^4(1476 y_t^4 - 3744 y_t^2 g_3^2 + 4064 g_3^4)\Big\} L^2$$
$$+ \Big\{ -1502.84\lambda^4 - 436.5\lambda^3 y_t^2 - \lambda^2 y_t^2(1768.26 y_t^2 + 160.77 g_3^2)$$
$$+ \lambda y_t^2(446.764\lambda y_t^4 + 1325.73 y_t^2 g_3^2 - 713.936 g_3^4)$$
$$+ y_t^4(972.596 y_t^4 - 1001.98 y_t^2 g_3^2 + 200.804 g_3^4)\Big\} L, \qquad ($$

This is a SM effect, since this is the effective theory we are considering.

This shows that a partial computation of three loop effects is not justified