Weakly Coupled BSM Higgs Physics

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KITP Higgs Weeks
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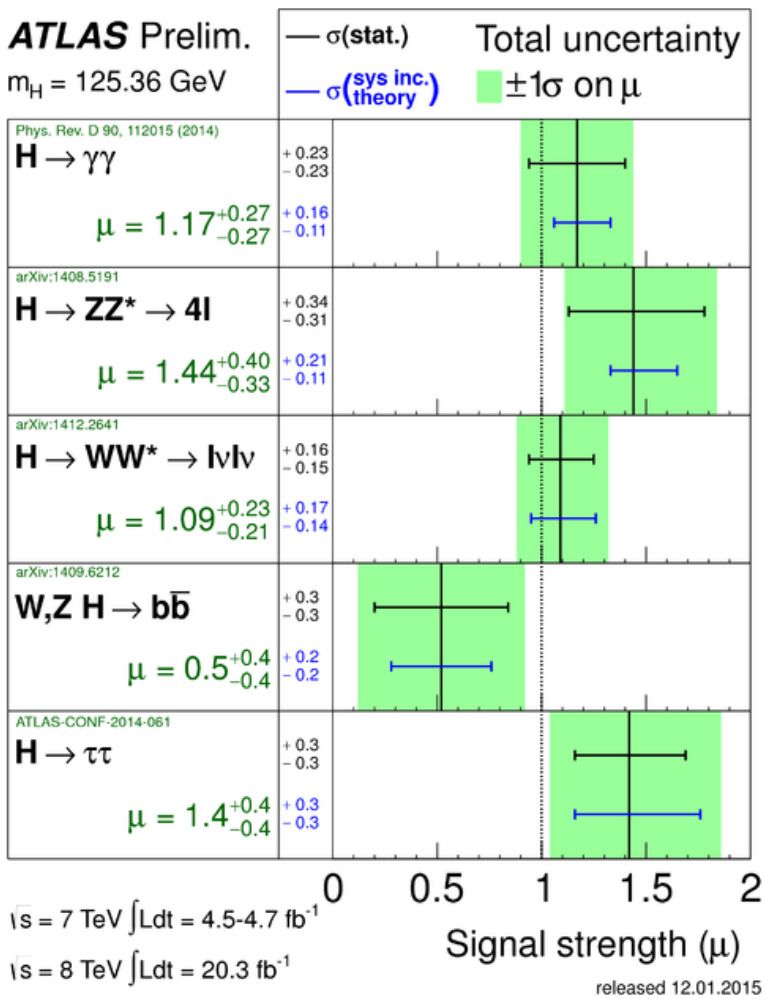
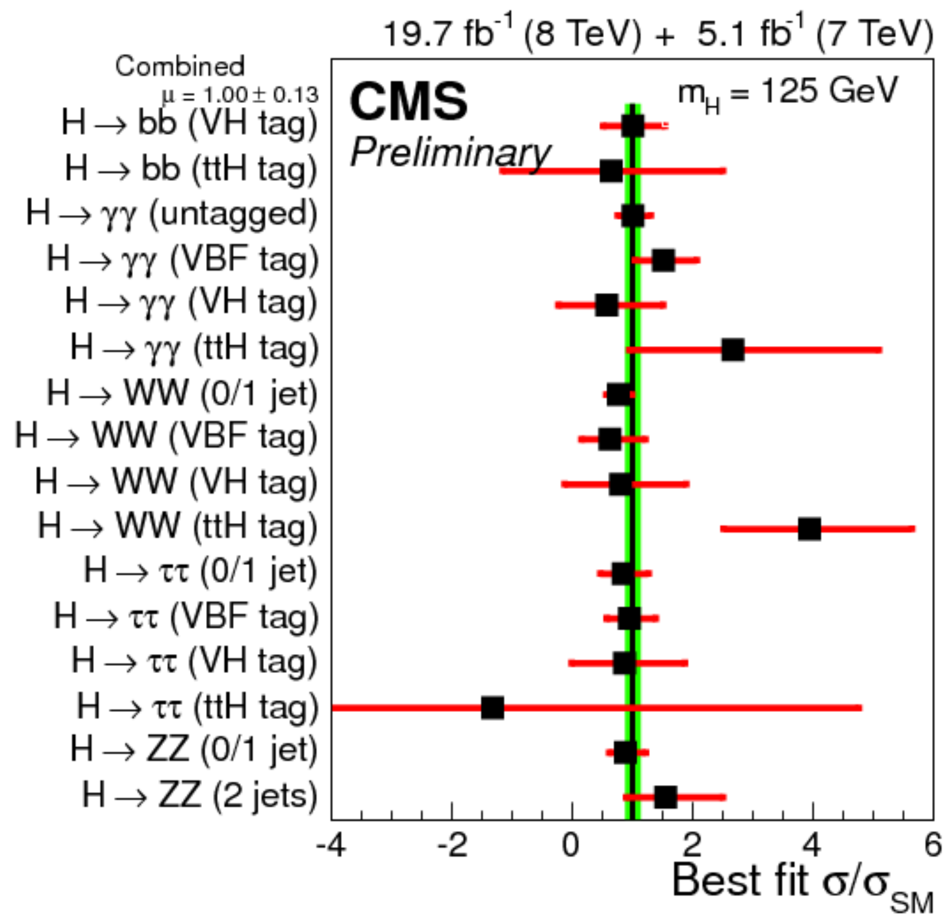
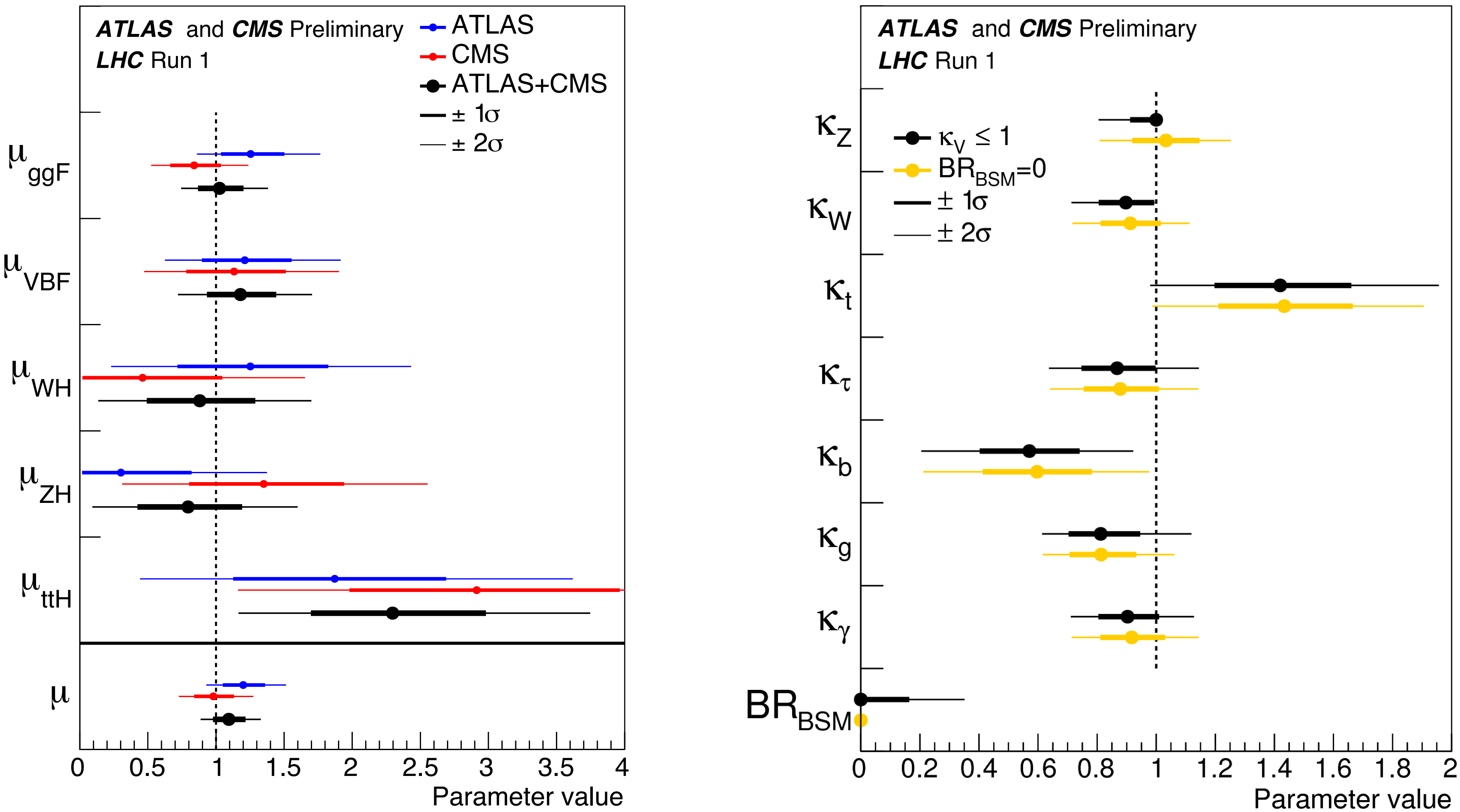
Higgs Boson Discovery at the LHC :

Very good agreement of Higgs Physics Results with SM Predictions





ATLAS and CMS Combination



Although the agreement with the SM is overall quite good, there are still relevant uncertainties in the Higgs couplings, which will be resolve with higher statistics and the analysis of new channels. Particularly interesting are the couplings to third generation quarks and leptons.

Topics

- Enhancement of the top coupling / suppression of the bottom coupling
- Lepton flavor violating decays of the Higgs
- Double Higgs Production / Modified trilinear couplings…
- Higgs Alignment in the MSSM and NMSSM
- MSSM Higgs Mass
- Searches for new Higgs Bosons in different channels

Enhancing (Suppressing) the tth (bbh) Coupling

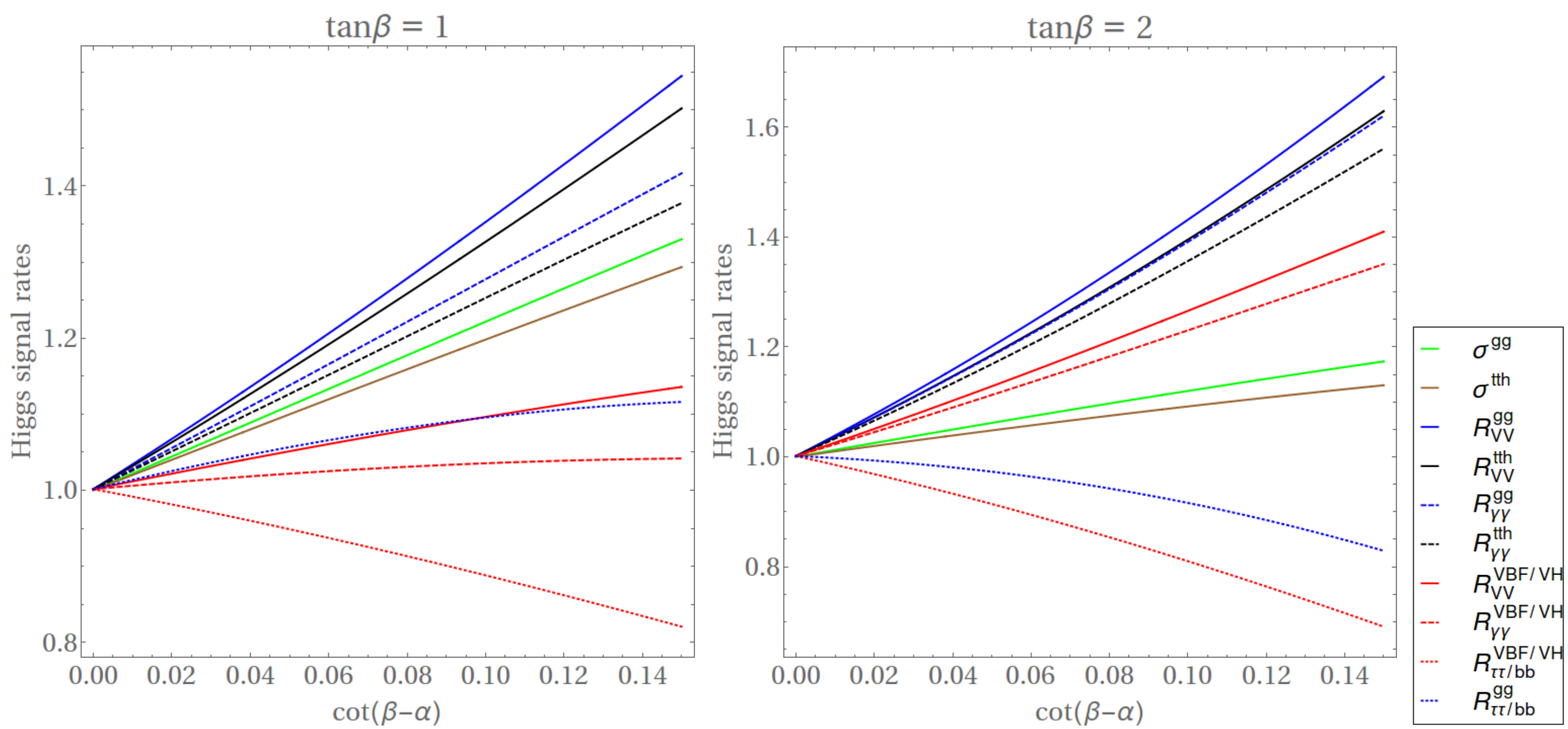
Type II
Two Higgs Doublet Models

$$c_t = \frac{\cos\alpha}{\sin\beta} = \sin(\beta-\alpha) + \cot\beta\cos(\beta-\alpha)\ ,$$

$$c_b = -\frac{\sin\alpha}{\cos\beta} = \sin(\beta-\alpha) - \tan\beta\cos(\beta-\alpha)\ ,$$

$$c_V = \sin(\beta-\alpha)\ ,$$

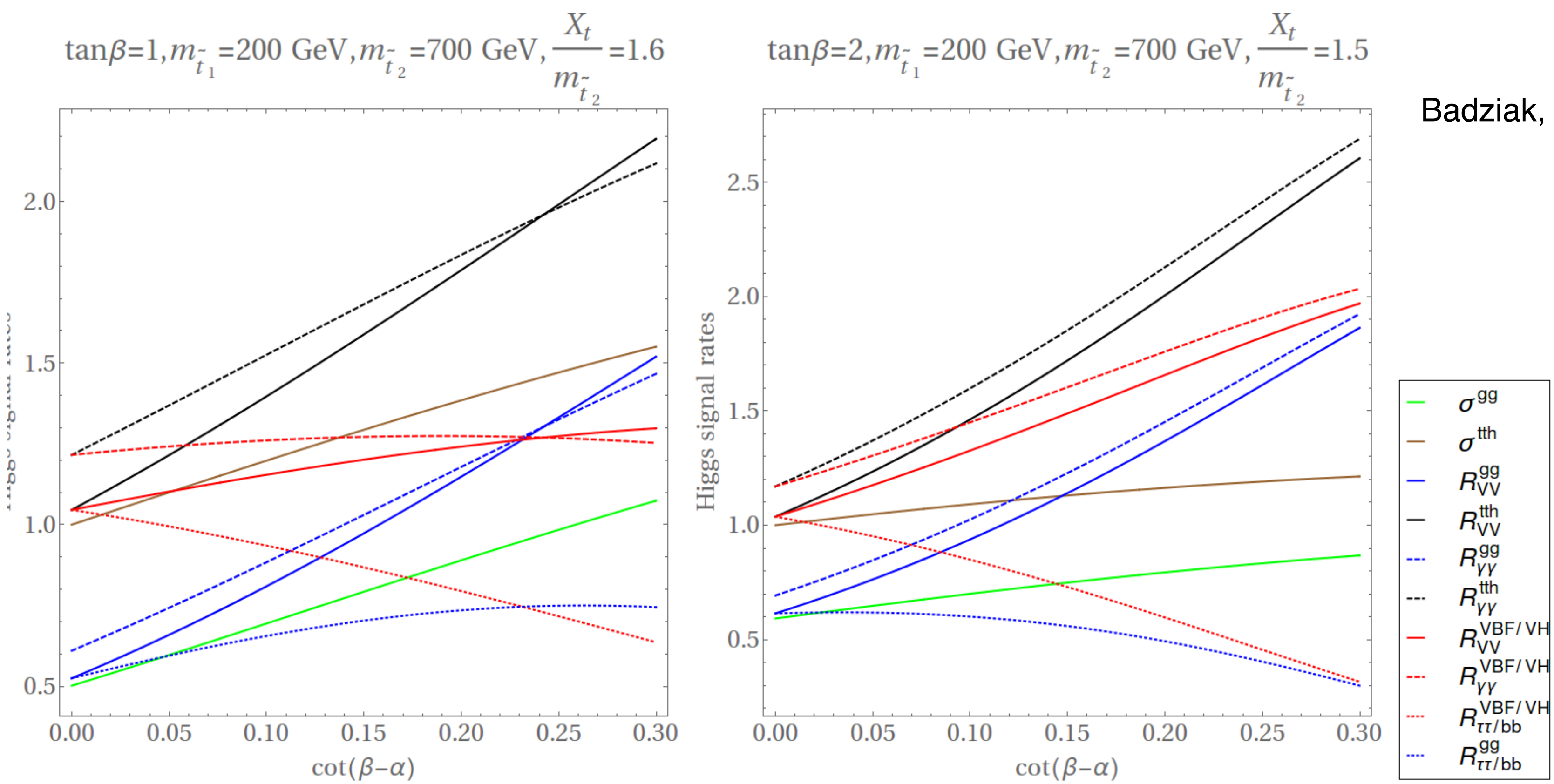
Badziak, C.W. '16



Strong Correlation between Different Channels
Relevant enhancement (suppression) of tth (bbh) not possible

Additional Loop Effects
(Example : Stop Effects)

$$\frac{c_g}{c_g^{\rm SM}} = \qquad c_t + \frac{m_t^2}{4}\left[c_t\left(\frac{1}{m_{\tilde{t}_1}^2}+\frac{1}{m_{\tilde{t}_2}^2}\right) - \frac{\tilde{X}_t^2}{m_{\tilde{t}_1}^2 m_{\tilde{t}_2}^2}\right]$$

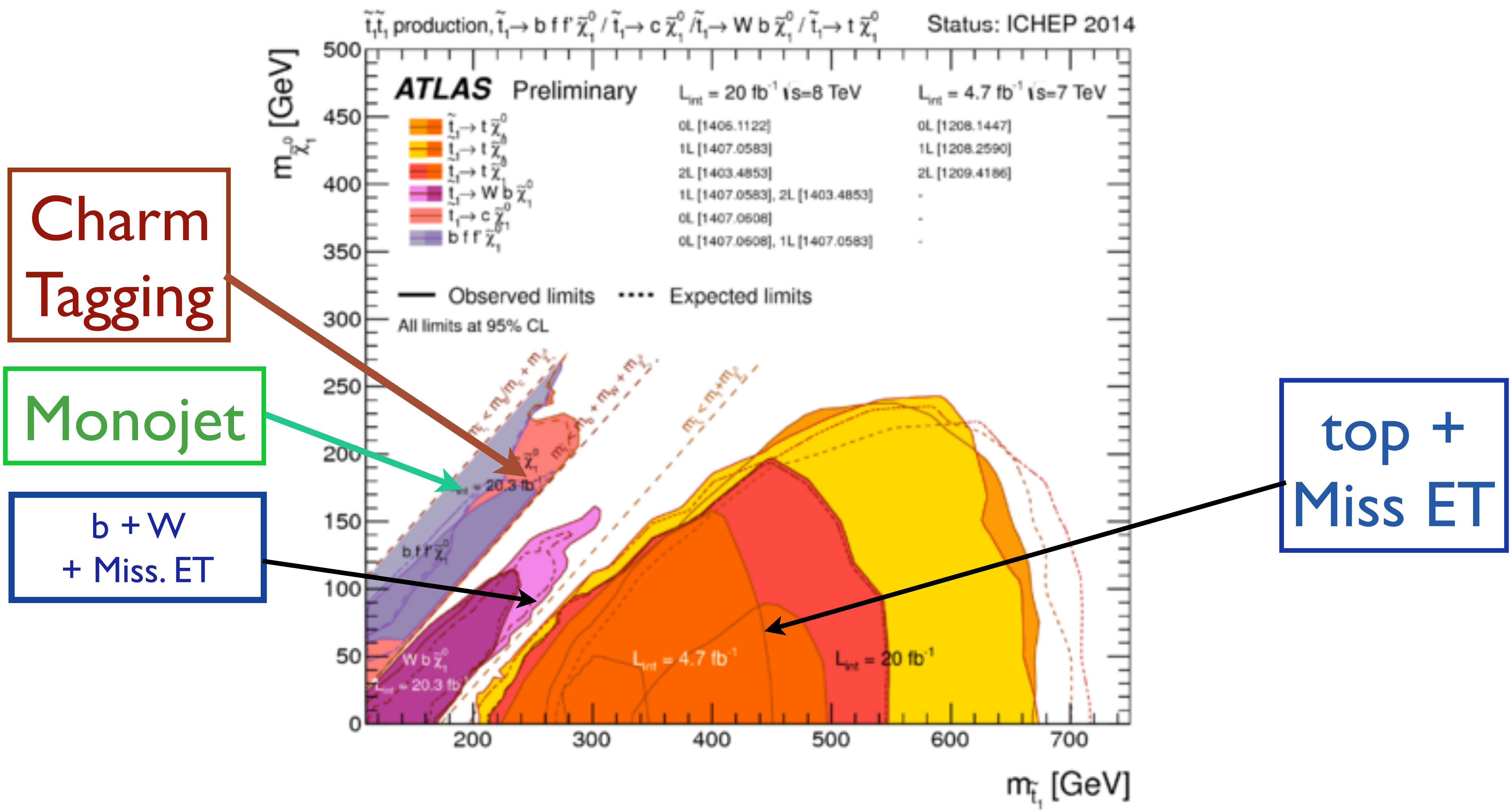


Badziak, C.W. '16

Loop Effects in the couplings of Higgs to gluons may dramatically affect the previous conclusions.

Stop Searches

Provided the lightest neutralino (DM) is heavier than about 250 GeV, there are no limits on stops. Even for lighter neutralinos, there are big holes.



Some Benchmarks

Badziak, C.W. '16

	B1	B2	B3
$\tan\beta$	1	1.5	2
$\cot(\beta-\alpha)$	0.25	0.22	0.18
$m_{\tilde{t}_1}$	200	200	210
$m_{\tilde{t}_2}$	700	700	700
$\tilde{X}_t/m_{\tilde{t}_2}$	1.7	1.6	1.6
$R_{VV}^{\rm tth}$	2.02	1.96	1.90
$R_{\gamma\gamma}^{\rm tth}$	2.09	2.09	2.07
$R_{VV}^{\rm gg}$	1.18	1.21	1.19
$R_{\gamma\gamma}^{\rm gg}$	1.22	1.29	1.29
$R_{VV}^{\rm VBF/VH}$	1.29	1.49	1.60
$R_{\gamma\gamma}^{\rm VBF/VH}$	1.33	1.59	1.74
$R_{\tau\tau}^{\rm VBF/VH}$	0.73	0.67	0.66

This provides a rather good agreement with the run I data analysis from the ATLAS/CMS combination

This cannot be achieved in the MSSM

Reasons :

a) Obtaining the Right Higgs mass is a problem.

b) Bottom coupling suppression only possible in regions forbidden by searches for heavy Higgs bosons.

Possible in the NMSSM, for SHuHd couplings lambda > 0.7, although this case is more restrictive then these benchmark scenarios.

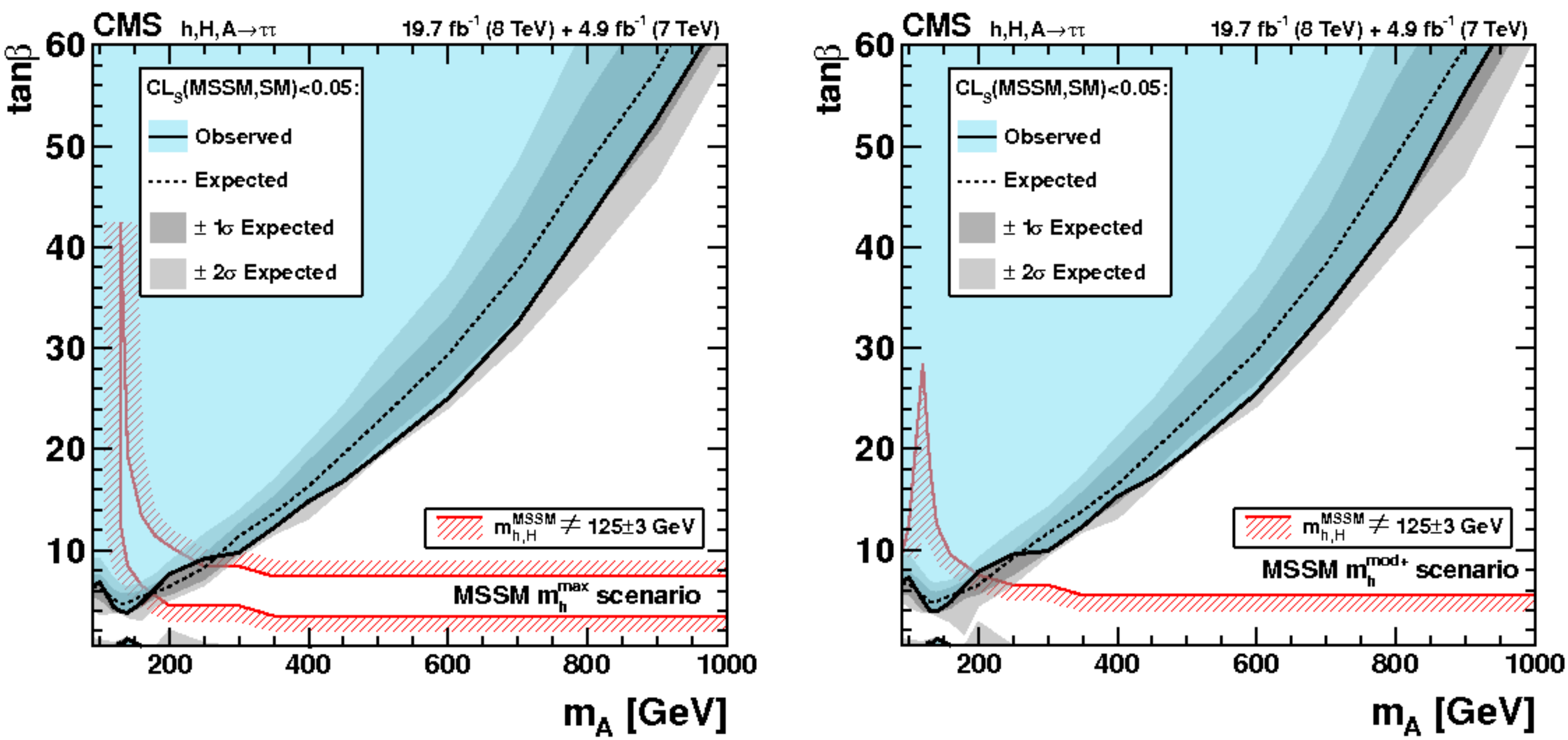
$$t_\beta\, c_{\beta-\alpha} \simeq \frac{-1}{m_H^2 - m_h^2}\left[m_h^2 + m_Z^2 + \frac{3m_t^4}{4\pi^2 v^2 M_S^2}\left\{A_t \mu t_\beta \left(1 - \frac{A_t^2}{6M_S^2}\right) - \mu^2\left(1 - \frac{A_t^2}{2M_S^2}\right)\right\}\right]$$

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

Lange

heavy neutral Higgs: ϕ→ττ

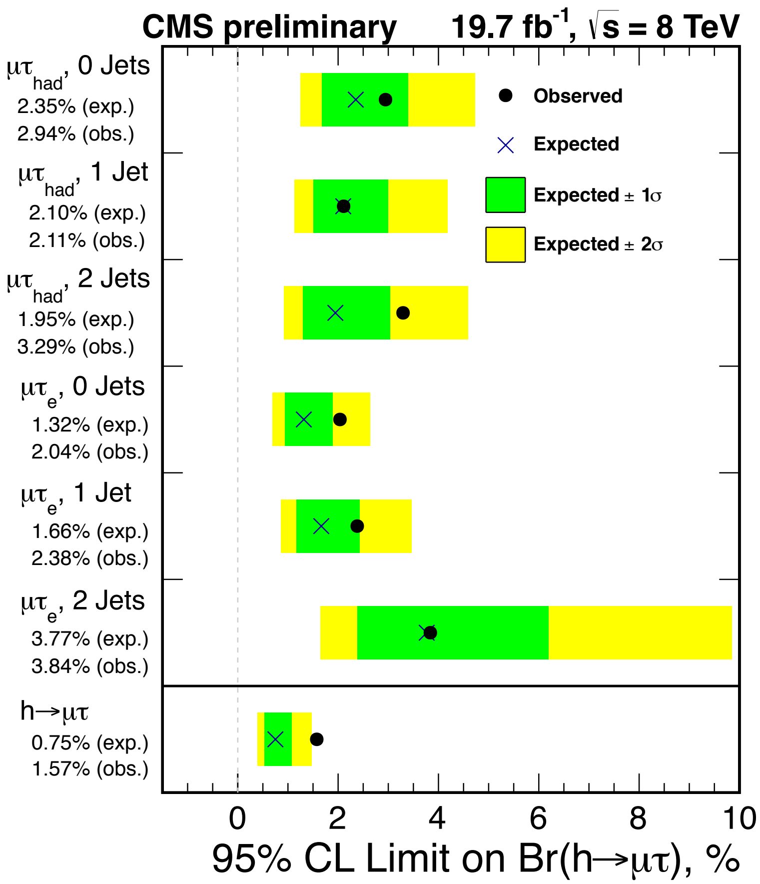
Submitted to JHEP (arXiv:1408.3316)
ATLAS-CONF-2014-049

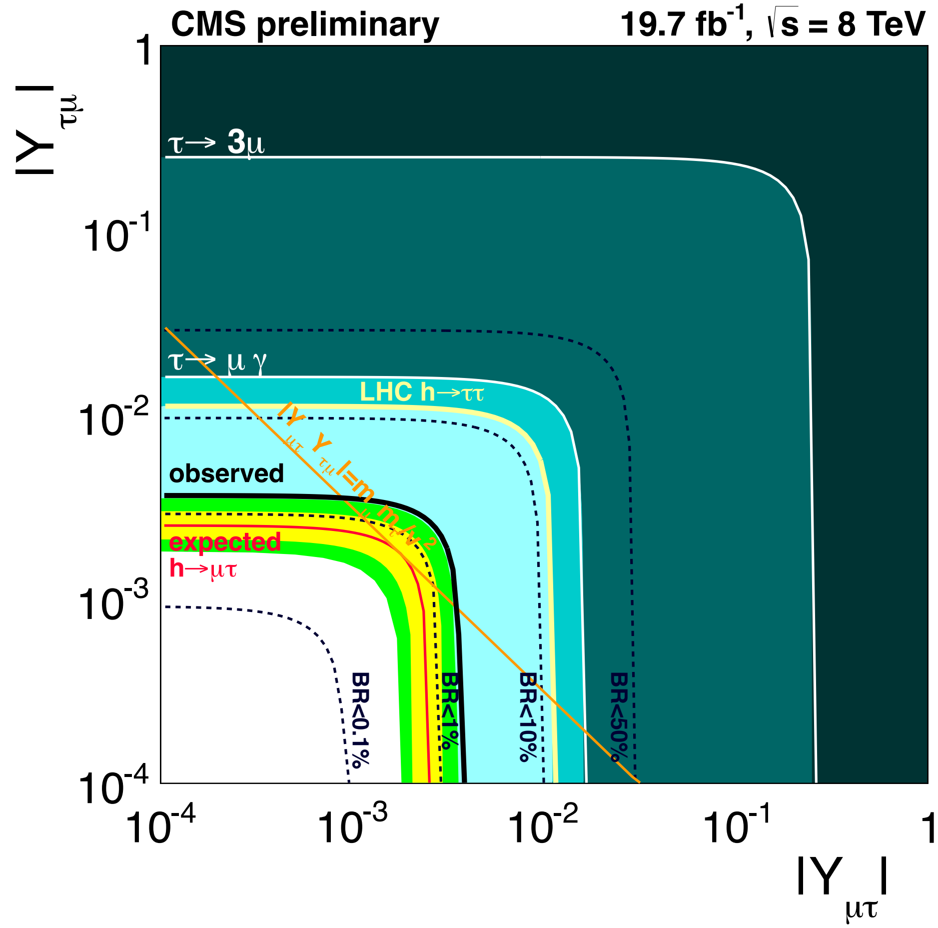


> interpretation in several scenarios taking Higgs @ 125 GeV into account

lepton flavour violating Higgs

CMS-PAS-HIG-14-005





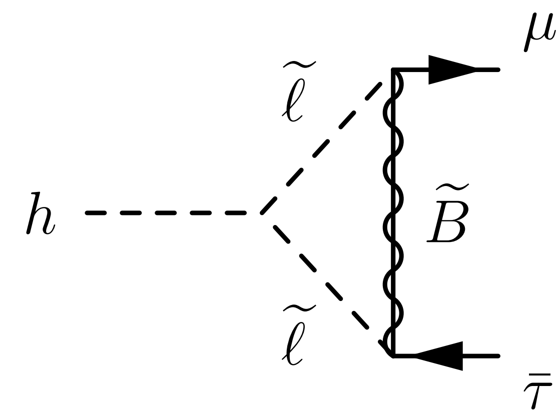
Models with more than one Higgs ?
Misalignment is required

$$\mathrm{BR}(h\to\tau\mu) = \begin{cases} (8.4^{+3.9}_{-3.7})\times 10^{-3} & \text{CMS}, \\ (7.7\pm 6.2)\times 10^{-3} & \text{ATLAS}. \end{cases}$$

MSSM Realization ?

Aloni, Nir and Stamou'15

$$\tilde{\mathcal{M}}^2 = \begin{pmatrix} (\tilde{m}_L^2)_{\mu\mu} & (\tilde{m}_L^2)_{\mu\tau} & 0 \\ (\tilde{m}_L^2)^*_{\mu\tau} & (\tilde{m}_L^2)_{\tau\tau} & -m_\tau \mu t_\beta \\ 0 & -m_\tau \mu t_\beta & (\tilde{m}_R^2)_{\tau\tau} \end{pmatrix}$$



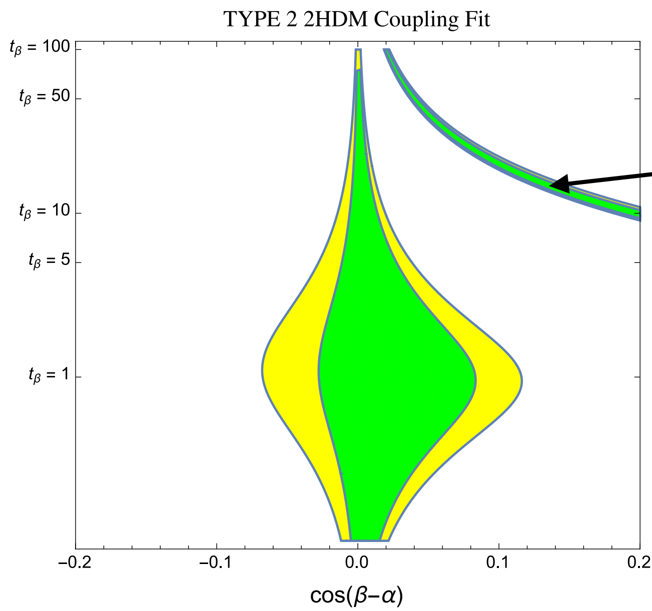
Assume contribution comes from flavor misalignment in the slepton sector

$$R^{\max}_{\tau\mu/\tau\tau} = \left\{ \frac{\alpha v}{\sqrt{2} m_\tau c_W^2} \sqrt{x_3} I_3(1, x_3, x_3) \left[\frac{c_{\beta-\alpha} t_\beta}{s_{\beta-\alpha}(s_{\beta-\alpha} - c_{\beta-\alpha} t_\beta)} \right] \right\}^2$$

Superpotential trilinear coupling still used, so some Higgs misalignment is necessary

$$R_{\tau\mu/\tau\tau} \lesssim 0.035 \qquad \text{for } |c_{\beta-\alpha} t_\beta| \ll 1$$

$$R_{\tau\mu/\tau\tau} \lesssim 0.31 \qquad \text{for } c_{\beta-\alpha} t_\beta \simeq 2$$



$$\tan\beta\cos(\beta-\alpha) = 2$$

Craig, Draper, Erasmo, Thomas, Zhang ‘15

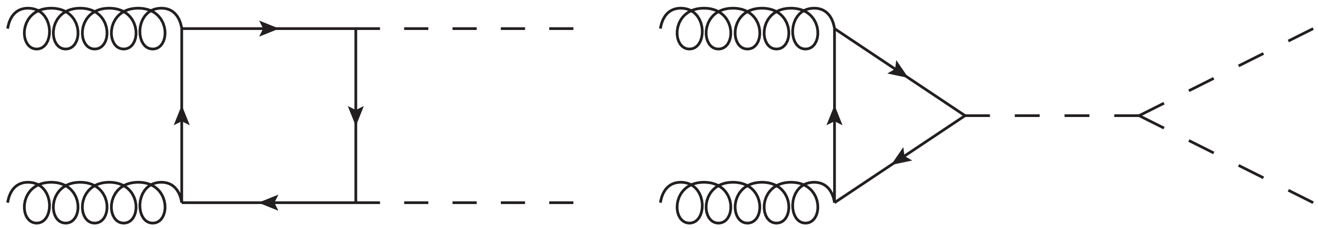
This condition is just associated with the change of sign of the bottom and tau Yukawa coupling

Previously we argue that it is hard to obtain suppression of the bottom coupling in the MSSM

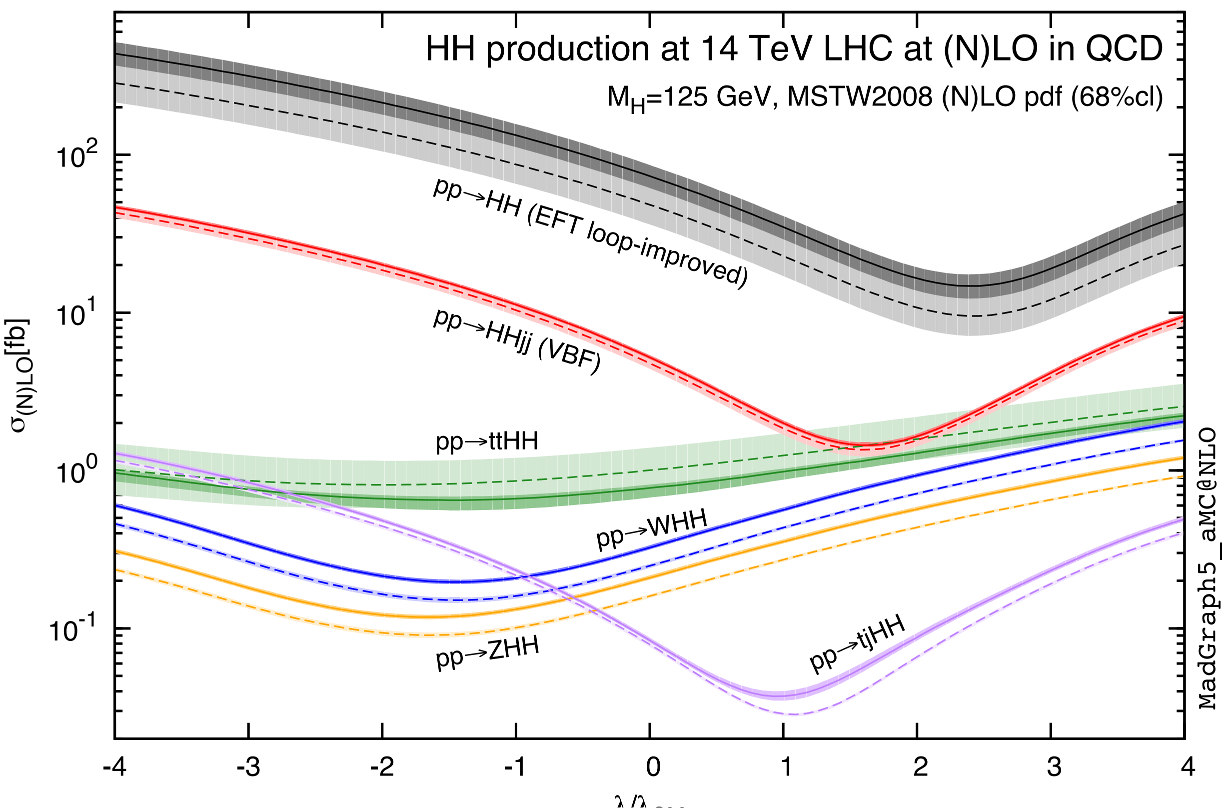
It is even harder to invert the sign of the bottom Yukawa coupling. This simply cannot be done within the MSSM

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

Double Higgs production



Frederix, Frixione, Hirschi, Maltoni, Mattelaier, Torrelli,Vryonidou,Zaro



Effective Theory Approach and its realization

$$V(\phi,T)=\frac{m^2+a_0T^2}{2}\left(\phi^\dagger\phi\right)+\frac{\lambda}{4}\left(\phi^\dagger\phi\right)^2+\frac{c_6}{8\Lambda^2}\left(\phi^\dagger\phi\right)^3$$

$$\frac{c_H}{8\Lambda^2}\partial_\mu(\phi^\dagger\phi)\partial^\mu(\phi^\dagger\phi)$$

Grojean, Servant, Wells '04
Noble, Perelstein '08
Gupta, Rhezak, Wells '13

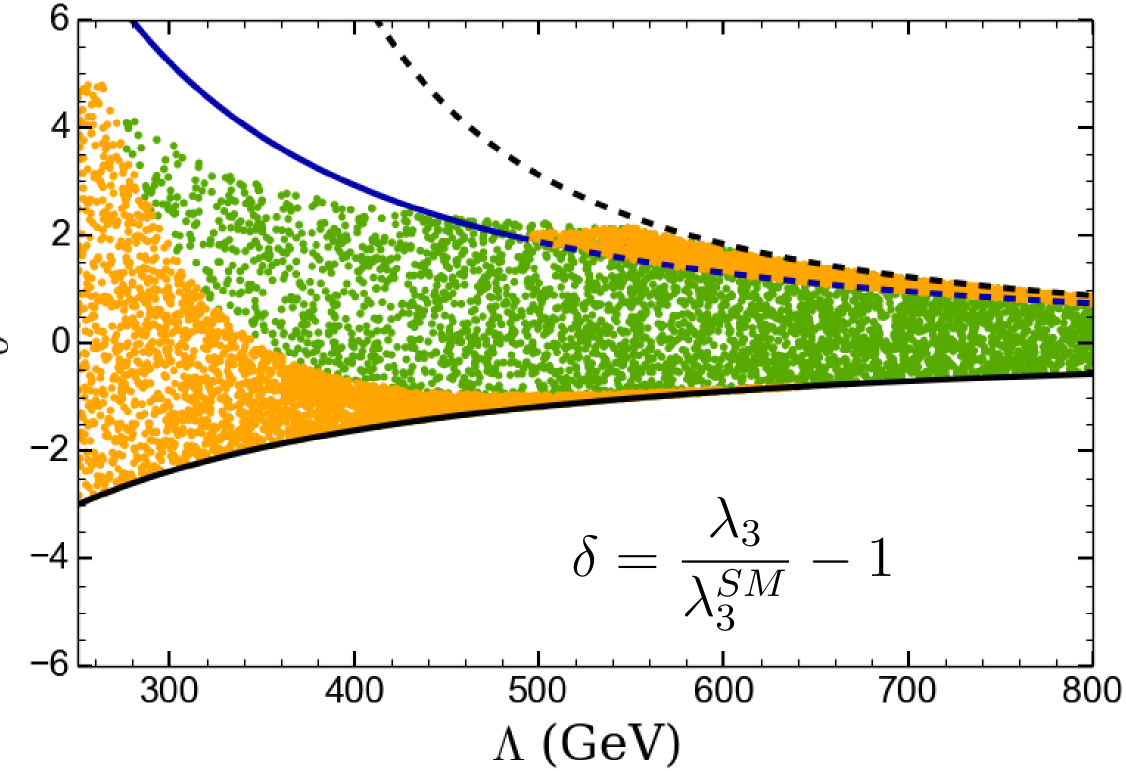
$$\lambda_3=\frac{3m_H^2}{v}\left(1+c_6\frac{2v^4}{m_h^2\Lambda^2}-\frac{3}{2}c_H\frac{v^2}{\Lambda^2}\right)$$

$$V(\phi_h,\phi_s,T)=\frac{m_0^2+a_0T^2}{2}\phi_h^2+\frac{\lambda_h}{4}\phi_h^4+a_{hs}\phi_s\phi_h^2+\frac{\lambda_{hs}}{2}\phi_s^2\phi_h^2+t_s\phi_s+\frac{m_s^2}{2}\phi_s^2+\frac{a_s}{3}\phi_s^3+\frac{\lambda_s}{4}\phi_s^4$$

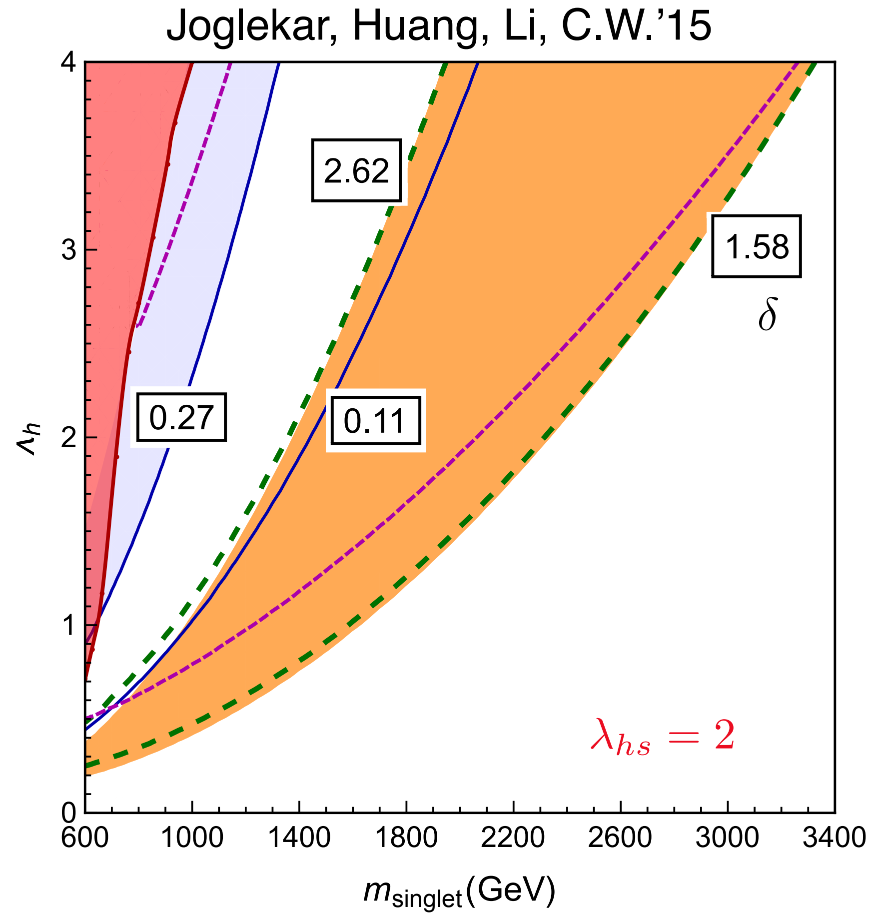
$$a_s=\lambda_s=0$$

$$\lambda_3=\frac{3m_h^2}{v}\left[\cos^3\theta+\left(\frac{2\lambda_{hs}v^2}{m_h^2}\right)\sin^2\theta\cos\theta\right]\longrightarrow\lambda_3=\frac{3m_h^2}{v}\left[1+\left(\frac{2\lambda_{hs}v^2}{m_h^2}-\frac{3}{2}\right)\tan^2\theta\right]$$

Values of a_s and λ_s different from zero
may lead to negative values of δ



(a)



$$\Lambda^2 = \frac{m_s^8}{4\lambda_{hs}(am_s^2 - t_s\lambda_{hs})^2}$$

Contours of variations of the trilinear coupling and of the square of the mixing angle

$$\tan\, 2\theta = \frac{4v(a_{hs} + \lambda_{hs} v_s)}{2\lambda_h v^2 - m_s^2 - \lambda_{hs} v^2} = \frac{4v(a_{hs} m_s^2 - t_s \lambda_{hs})}{(2\lambda_h v^2 - m_s^2 - \lambda_{hs} v^2)(m_s^2 + \lambda_{hs} v^2)}$$

Large Deviations of the trilinear coupling may be obtained in this model

Low Energy Supersymmetry : Type II Higgs doublet models

- In Type II models, the Higgs H1 would couple to down-quarks and charge leptons, while the Higgs H2 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 $\cos(\beta-\alpha) = 0$

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

then the coupling of the lightest Higgs to fermions and gauge bosons is SM-like. This limit is called decoupling limit. Is it possible to obtain similar relations for lower values of the CP-odd Higgs mass ? We shall call this situation ALIGNMENT

- Observe that close to the decoupling limit, the lightest Higgs couplings are SM-like, while 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 coupling of the CP-odd Higgs boson

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

Alignment in General two Higgs Doublet Models

H. Haber and J. Gunion'03

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

Symmetry arguments : 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

Craig, Galloway and Thomas'13

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

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

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

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

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

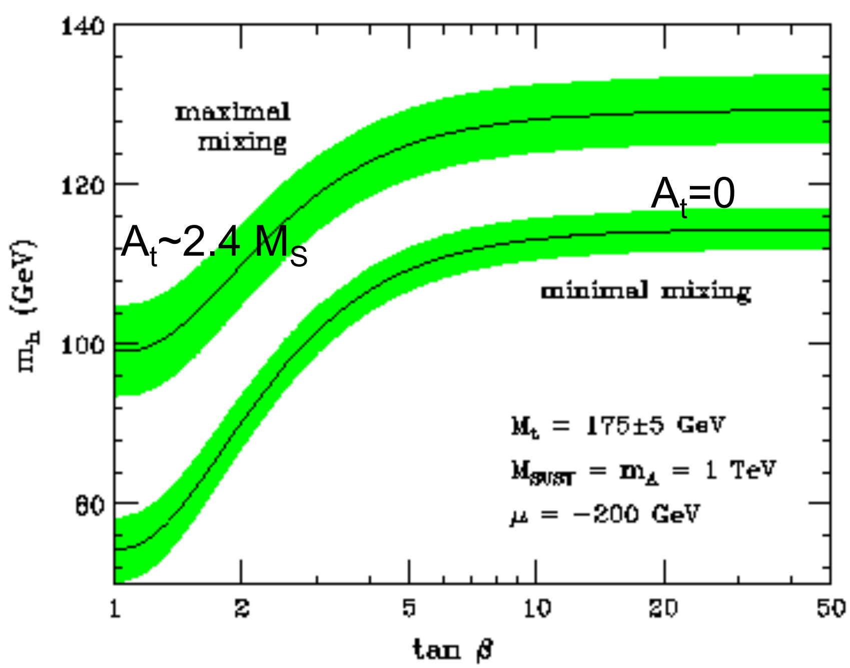
- Conditions not fulfilled in the MSSM, where both $\lambda_1, \tilde{\lambda}_3 < \lambda_{\rm SM}$

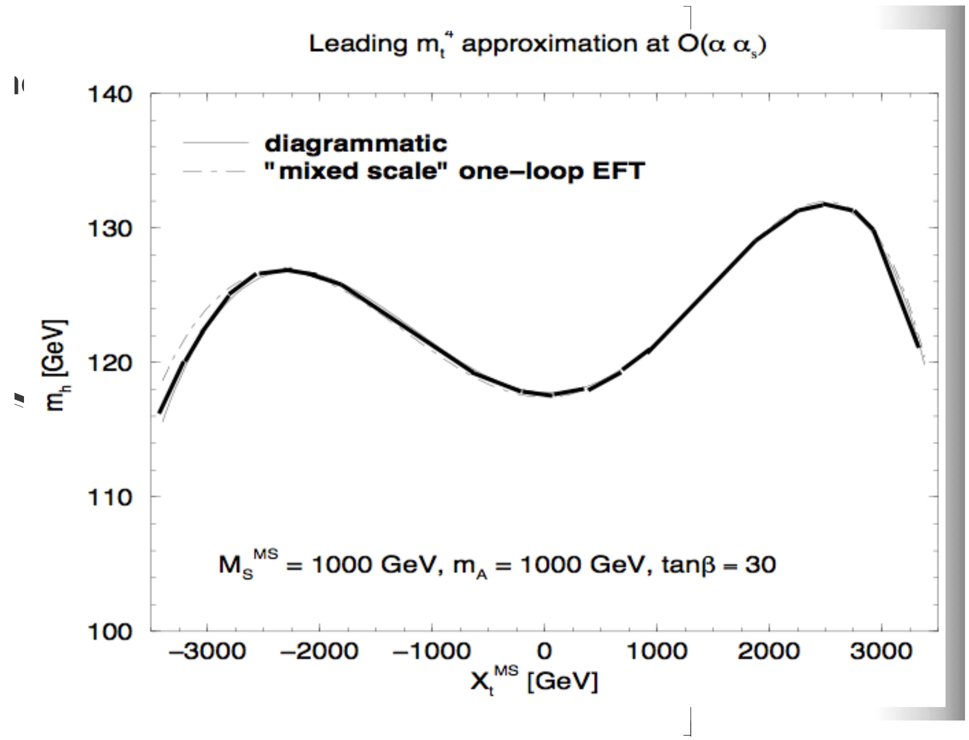
Standard Model-like Higgs Mass

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





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

Stop Mixing and the Stop Mass Scale

- For smaller values of the mixing parameter, the Stop Mass Scale must be pushed to values (far) above the TeV scale
- The same is true for smaller values of $\tan\beta$, for which the tree-level contribution is reduced
- In these cases, the RG approach allows to resum the large logarithmic corrections and leads to a more precise determination of the Higgs mass than the fixed order computations.
- The level of accuracy may be increased by including weak coupling corrections to both the RG running of the quartic coupling, as well as threshold corrections that depend on these couplings
- One can also use the RG approach to obtain partial results at a given fixed order by the methods we shall describe below

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

$$\delta_3\lambda = \Big\{ -1728\lambda^4 - 3456\lambda^3 y_t^2 + \lambda^2 y_t^2(-576 y_t^2 + 1536 g_3^2)$$

$$+ \lambda y_t^2(1908 y_t^4 + 480 y_t^2 g_3^2 - 960 g_3^4) + y_t^4(1548 y_t^4 - 4416 y_t^2 g_3^2 + 2944 g_3^4)\Big\} L^3$$

$$+ \Big\{ -2340\lambda^4 - 3582\lambda^3 y_t^2 + \lambda^2 y_t^2(-378 y_t^2 + 2016 g_3^2)$$

$$+ \lambda y_t^2(1521 y_t^4 + 1032 y_t^2 g_3^2 - 2496 g_3^4) + y_t^4(1476 y_t^4 - 3744 y_t^2 g_3^2 + 4064 g_3^4)\Big\} L^2$$

$$+ \Big\{ -1502.84\lambda^4 - 436.5\lambda^3 y_t^2 - \lambda^2 y_t^2(1768.26 y_t^2 + 160.77 g_3^2)$$

$$+ \lambda y_t^2(446.764\lambda y_t^4 + 1325.73 y_t^2 g_3^2 - 713.936 g_3^4)$$

$$+ y_t^4(972.596 y_t^4 - 1001.98 y_t^2 g_3^2 + 200.804 g_3^4)\Big\} L, \qquad ($$

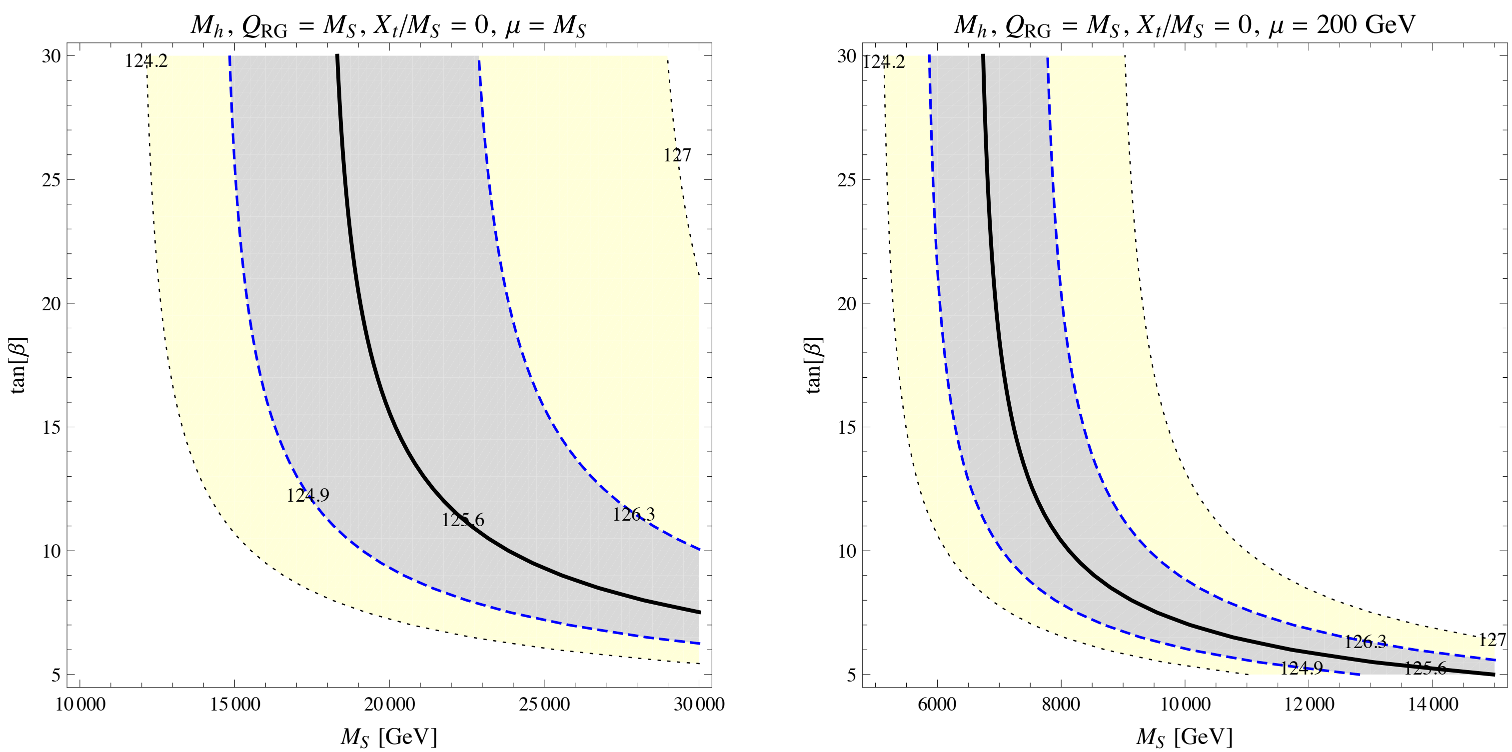
This is a SM effect, since this is the effective theory we are considering.

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

Draper, Lee, C.W. '13

Necessary stop mass values to get the proper Higgs mass for Small mixing in the stop sector

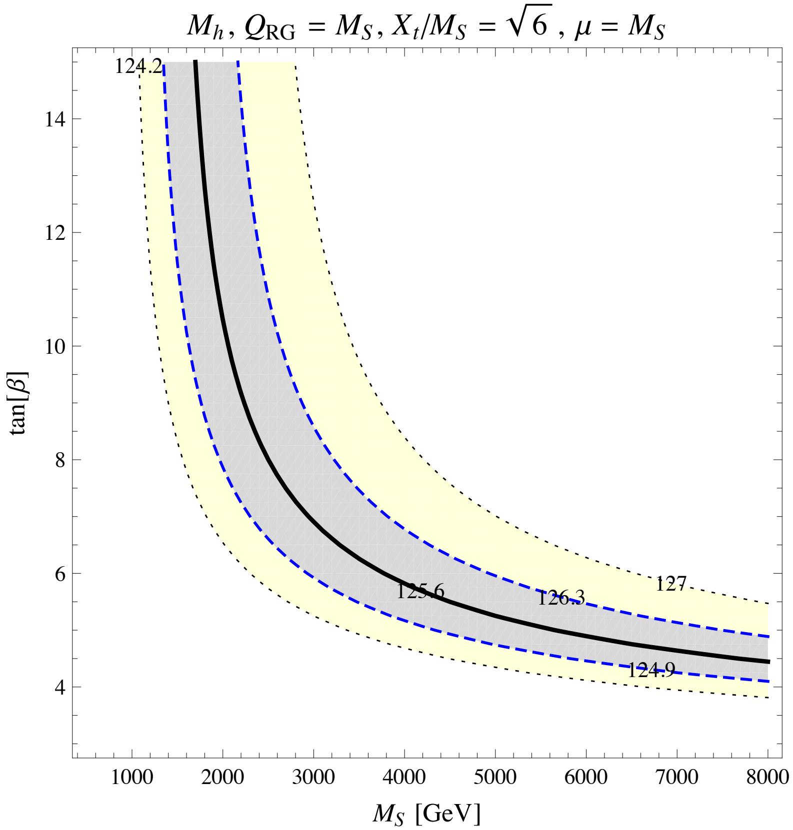
Here we kept the gaugino mass M2 = 200 GeV and M1 = 100 GeV
The effect at low values of mu is due to chargino and neutralino loops

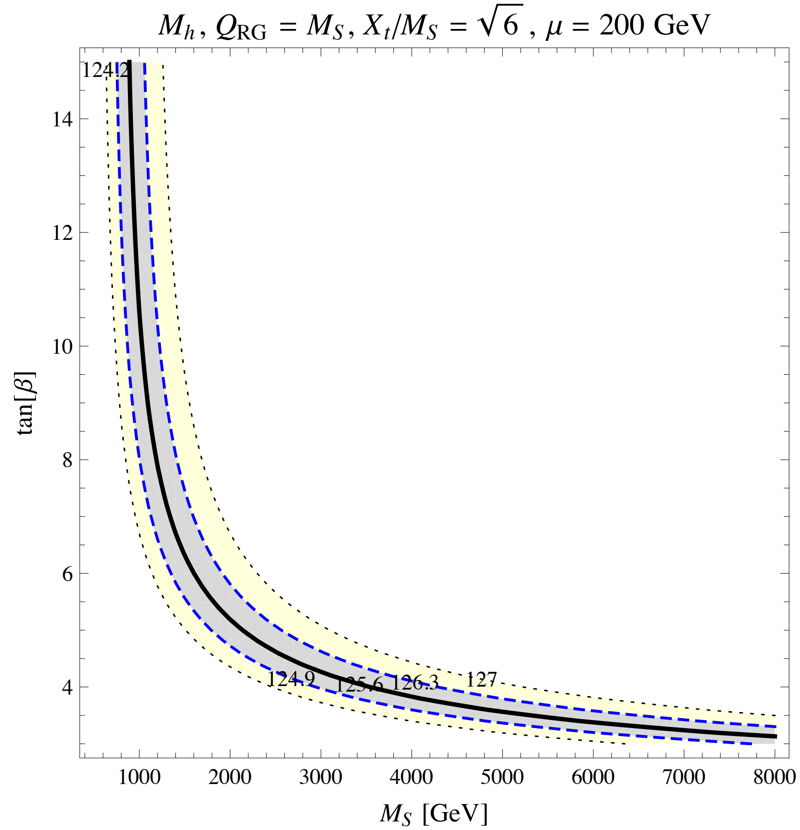


Such heavy stops would be out of the reach of the LHC
A higher energy collider necessary to investigate stop sector

Draper, Lee, C.W. '13

Necessary stop mass values to get the proper Higgs mass for Maximal mixing in the stop sector





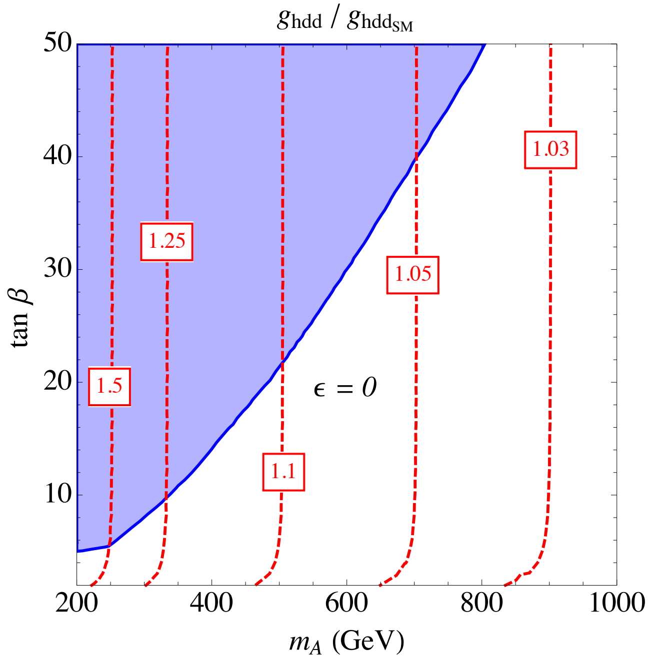
Light Stops at the reach of the LHC for large mixing in the Stop sector and moderate values of tanβ

Down Couplings in the MSSM for low values of μ
(no Alignment)

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

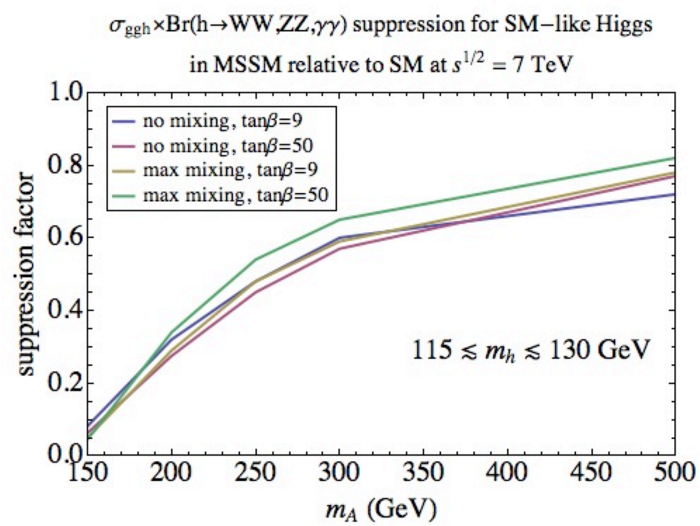
$$\lambda_1 \simeq -\tilde{\lambda}_3 = \frac{g_1^2 + g_2^2}{4} = \frac{M_Z^2}{v^2} \simeq 0.125 \qquad \lambda^{\rm SM} \simeq 0.26$$

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



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

Draper,Liu,C.W.'10



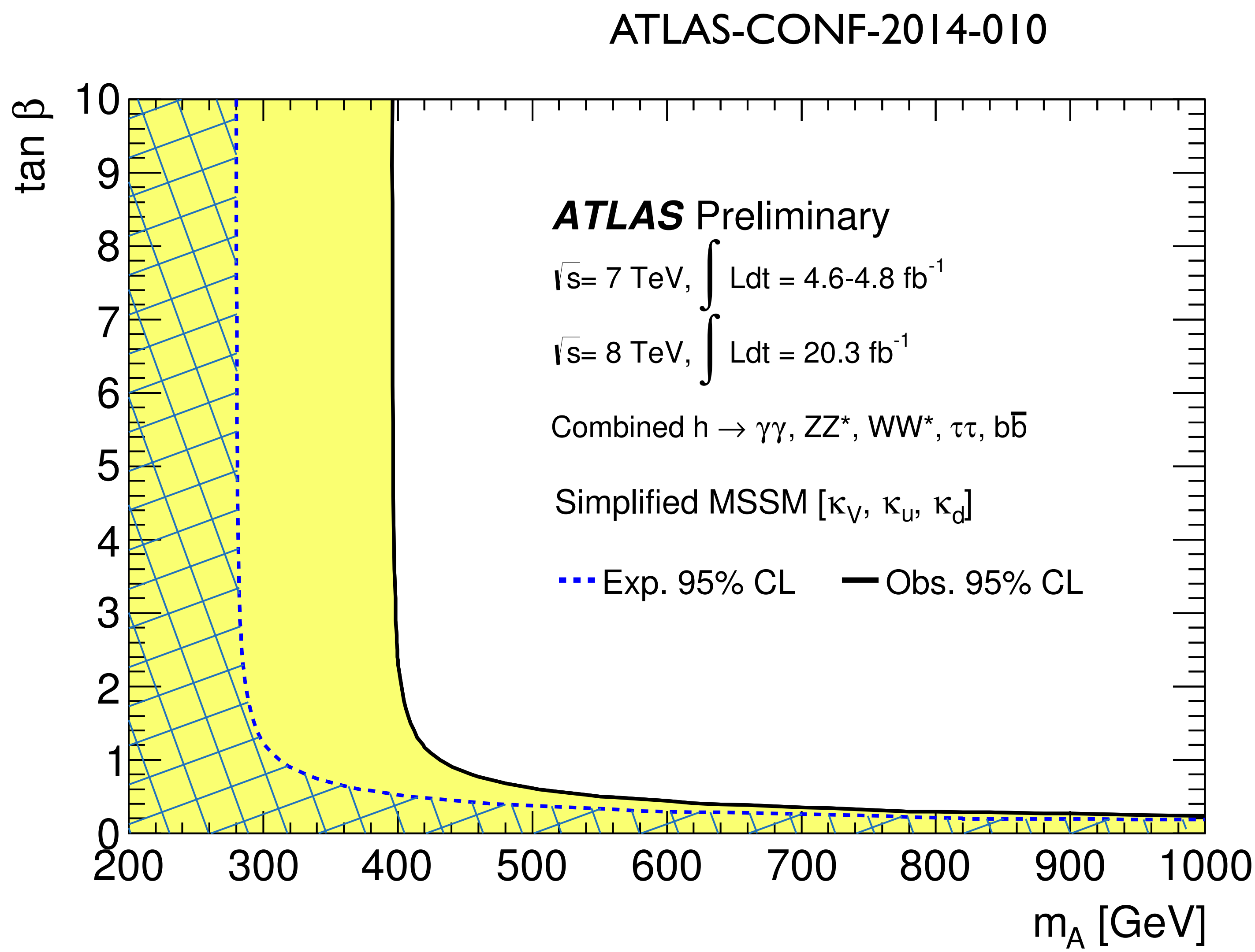
All vector boson branching ratios suppressed by enhancement of the bottom decay width

For moderate or large values of tanβ

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

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

Low values of μ similar to the ones analyzed by ATLAS



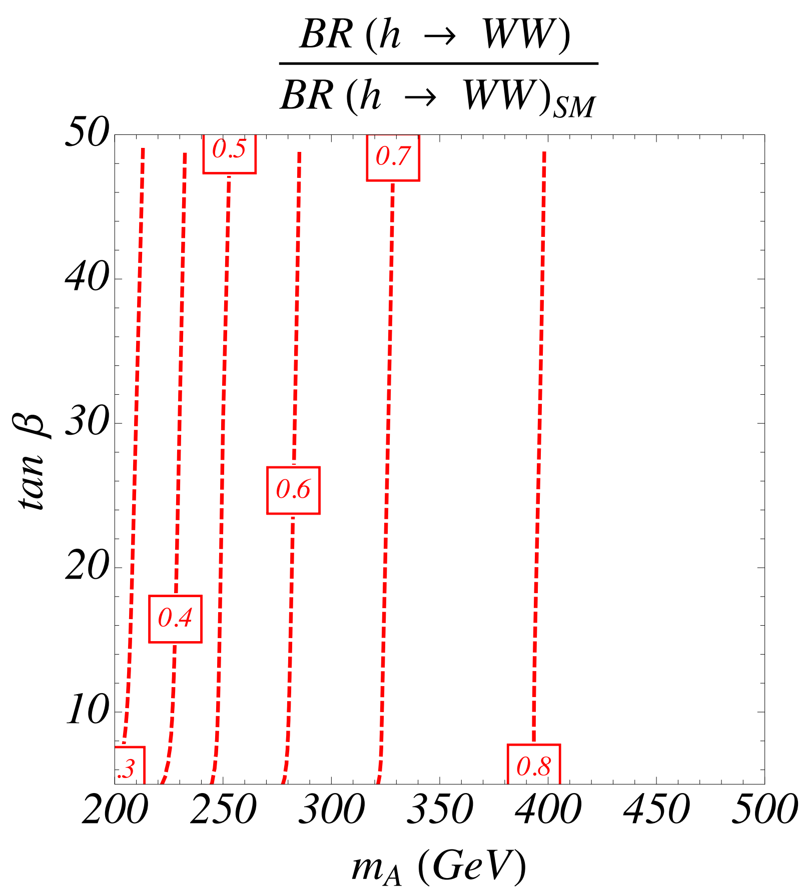
Bounds coming from precision h measurements

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

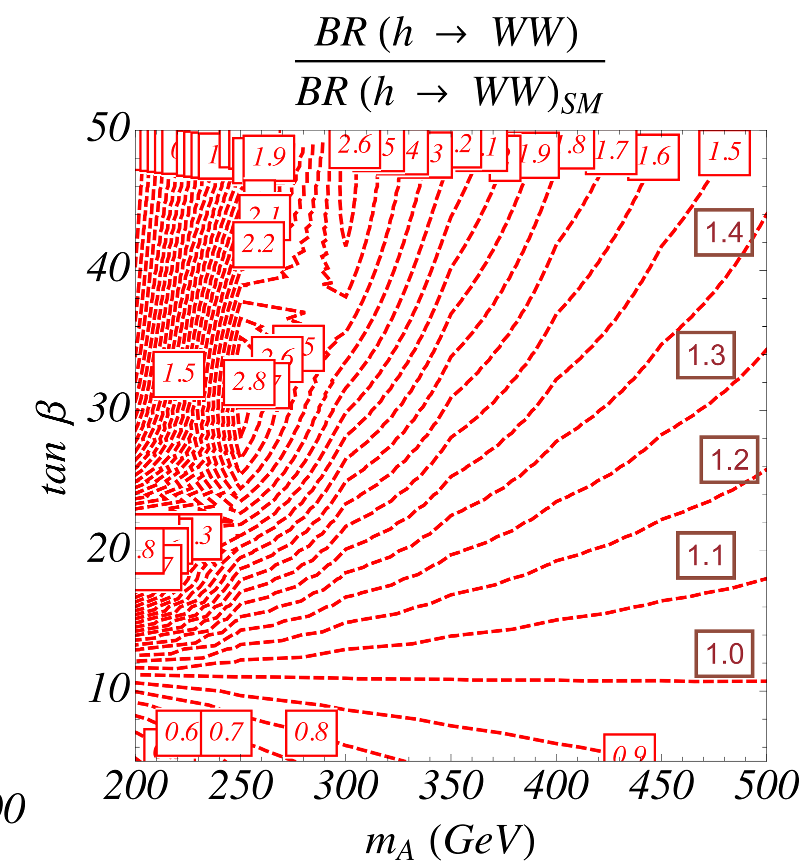
Higgs Decay into Gauge Bosons

Mostly determined by the change of width

Small μ



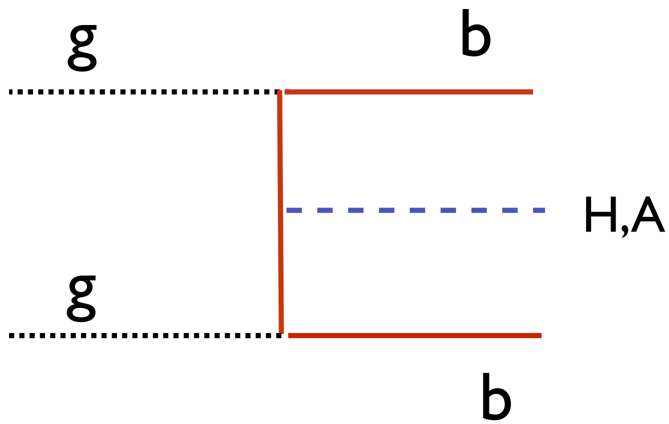
$\mu/M_{\rm SUSY} = 2, \qquad A_t/M_{\rm SUSY} \simeq 3$



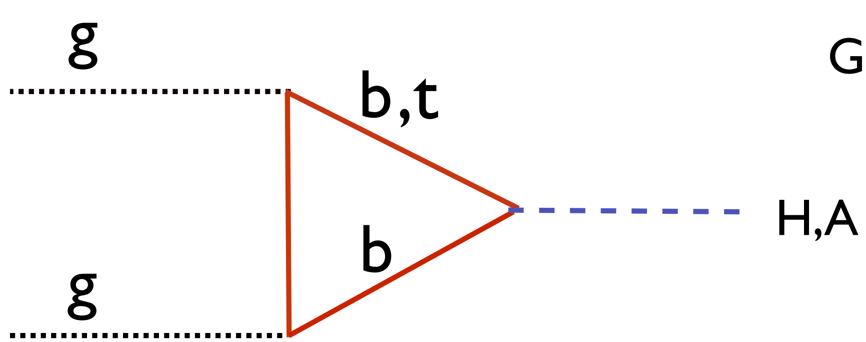
CP-odd Higgs masses of order 200 GeV and tanβ = 10 OK in the alignment case

Non-Standard Higgs Production

QCD: S. Dawson, C.B. Jackson, L. Reina, D.Wackeroth, hep-ph/06031



Associated Production



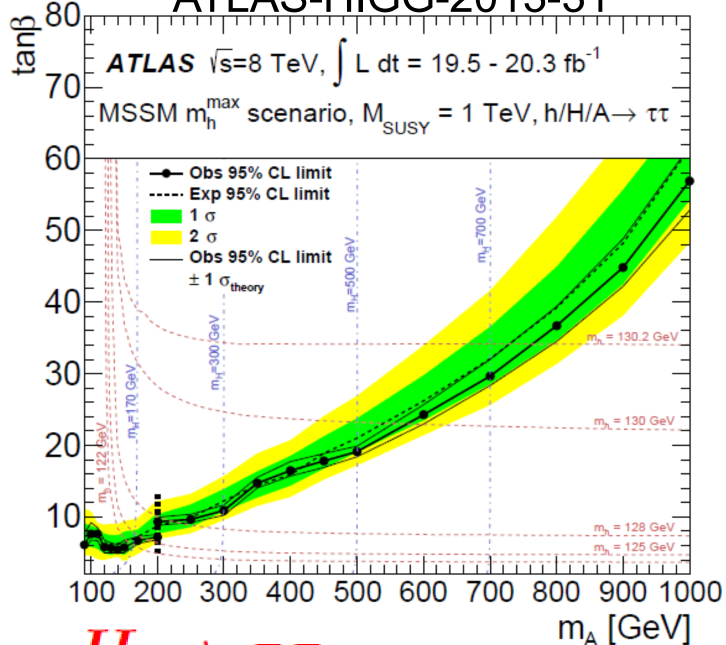
Gluon Fusion

$$g_{Abb} \simeq g_{Hbb} \simeq \frac{m_b \tan\beta}{(1+\Delta_b)v}, \qquad g_{A\tau\tau} \simeq g_{H\tau\tau} \simeq \frac{m_\tau \tan\beta}{v}$$

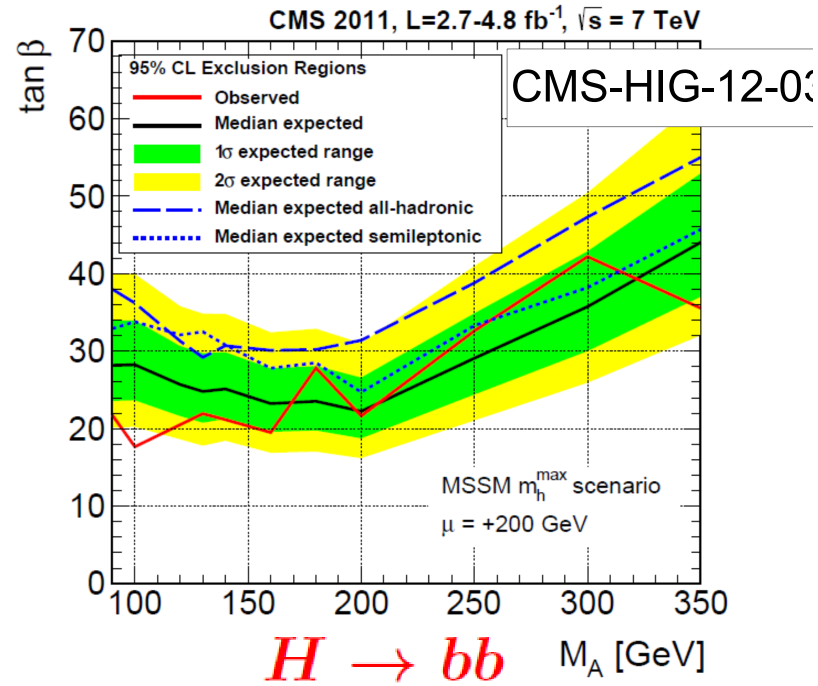
Non-Standard Higgs Searches

Neutral Higgs bosons

ATLAS-HIGG-2013-31



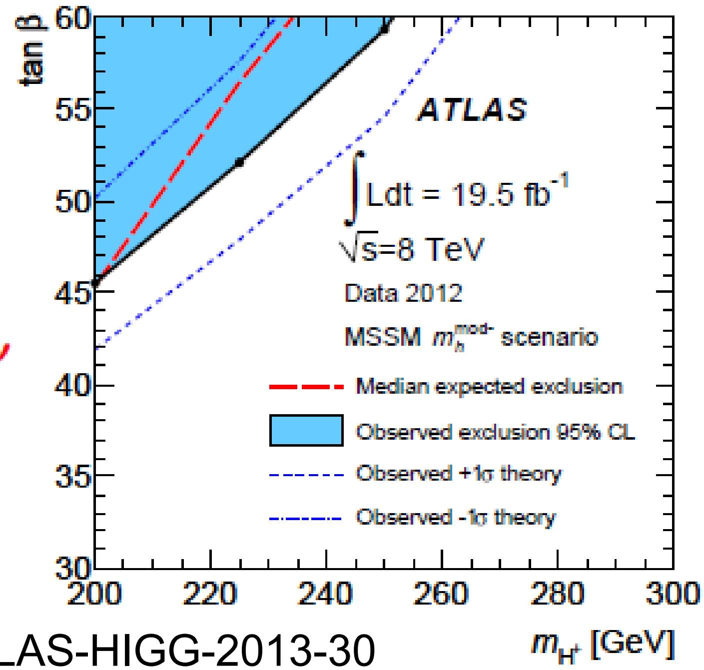
$H \to \tau\tau$



$H \to bb$

Charged Higgs bosons

$H^{\pm} \to \tau^{\pm}\nu$



ATLAS-HIGG-2013-30

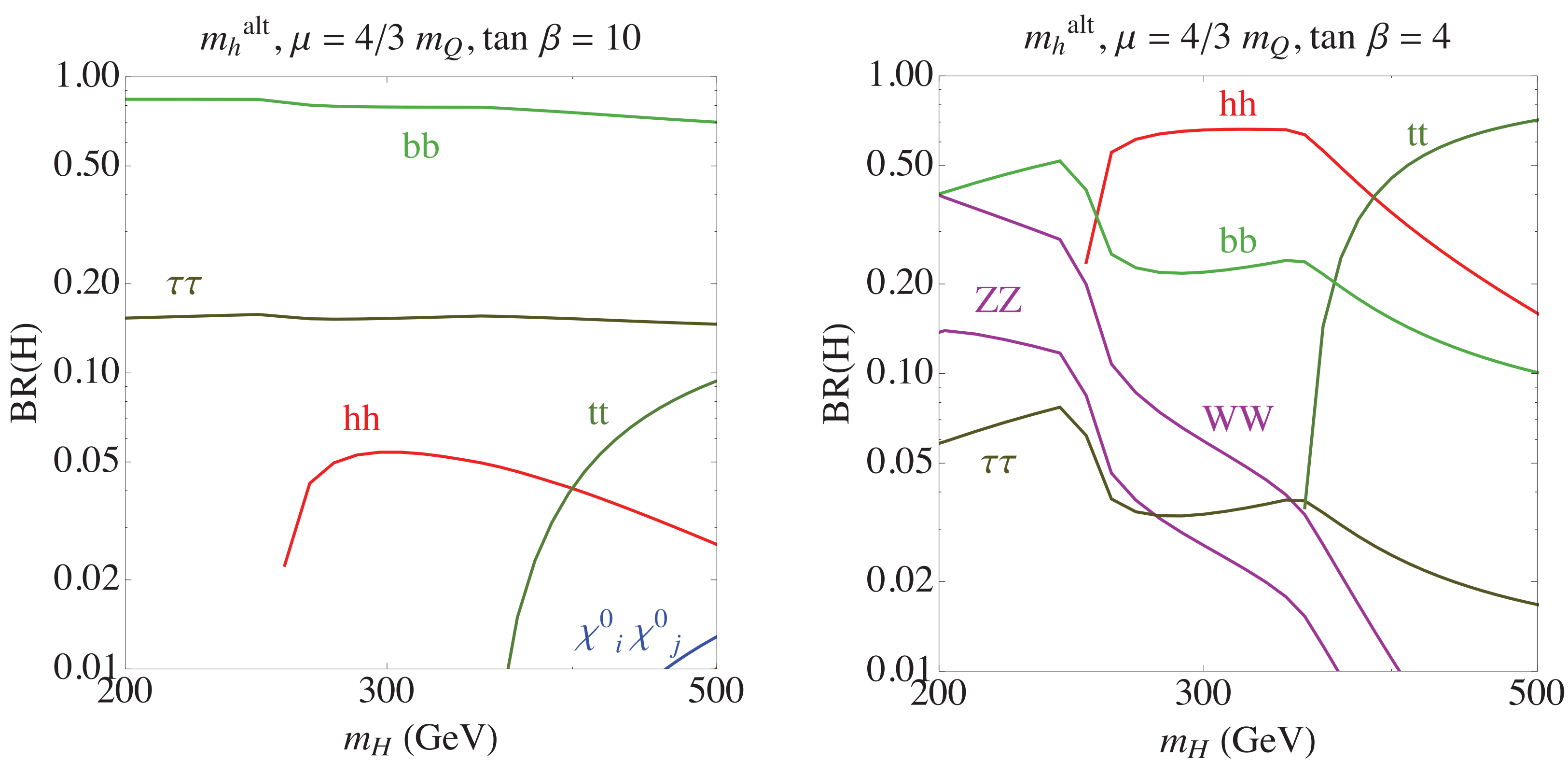
Heavy Supersymmetric Particles

Heavy Higgs Bosons : A variety of decay Branching Ratios

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

Craig, Galloway, Thomas'13

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

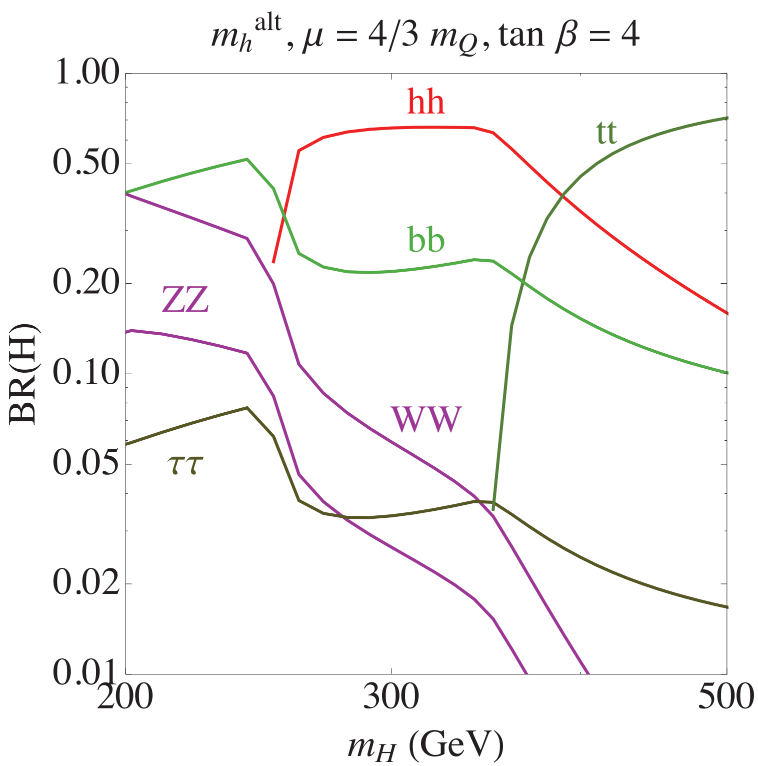


At large tanβ, bottom and tau decay modes dominant.

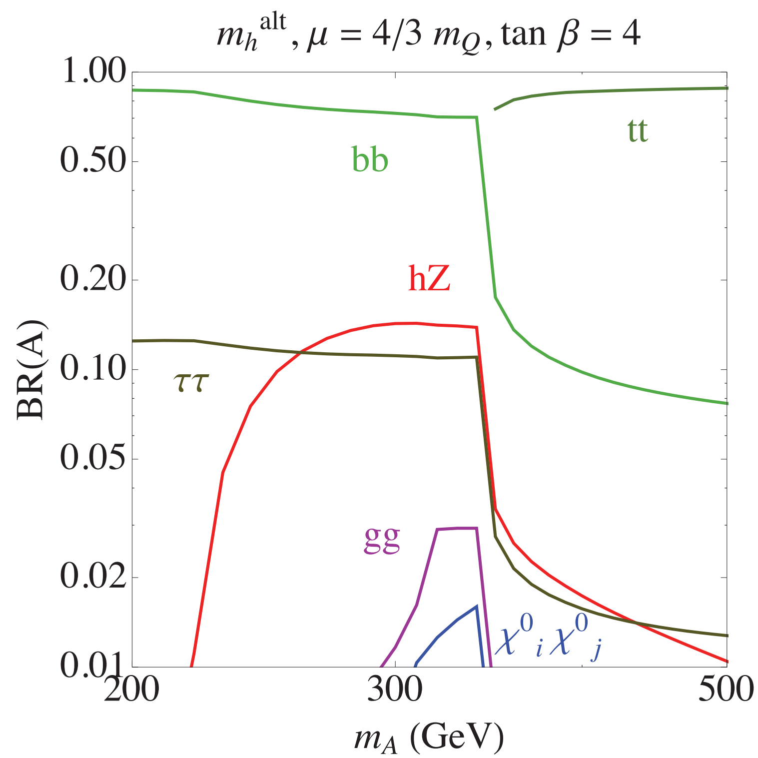
As tanβ decreases decays into SM-like Higgs and wek bosons become relevant

Large μ and small tanβ

hh dominant until top threshold



hZ relevant

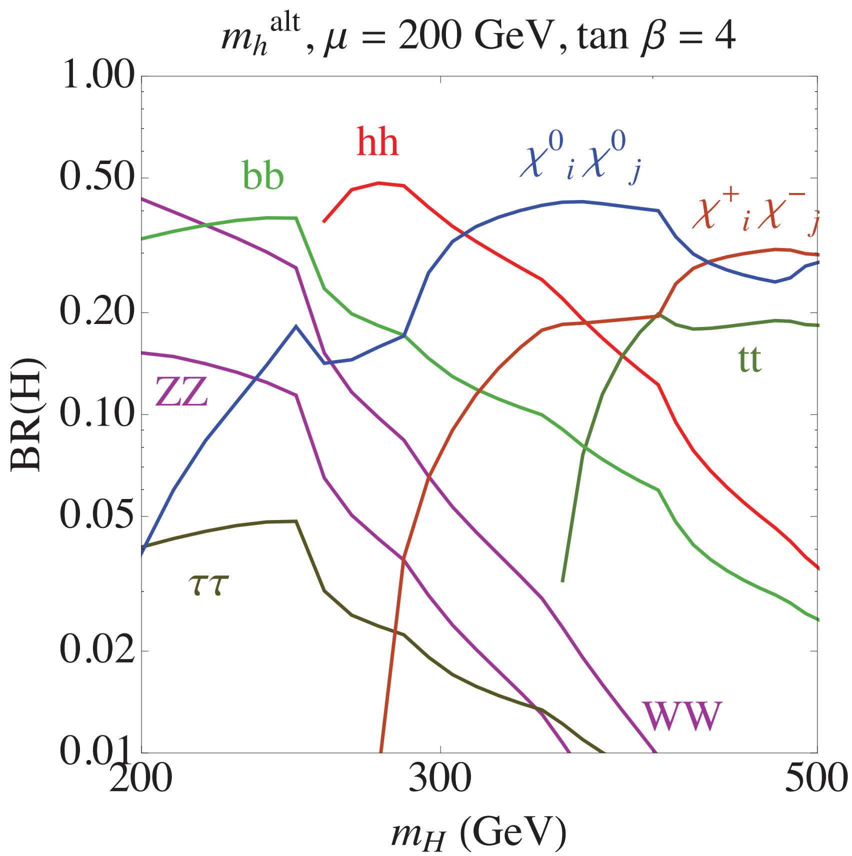


Decays into gauge and Higgs bosons become important. Observe, however that the BR(A to τ τ) remains large up to the top-quark threshold scale

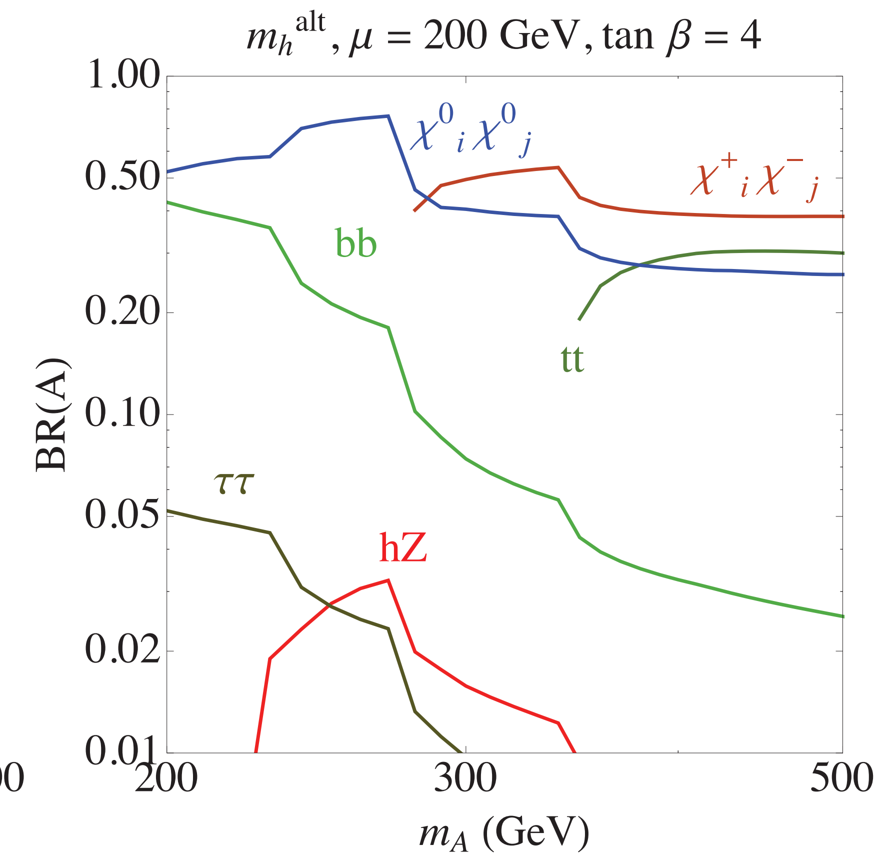
Light Charginos and Neutralinos can significantly modify M the CP-odd Higgs Decay Branching Ratios

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

hh still relevant, SUSY decays



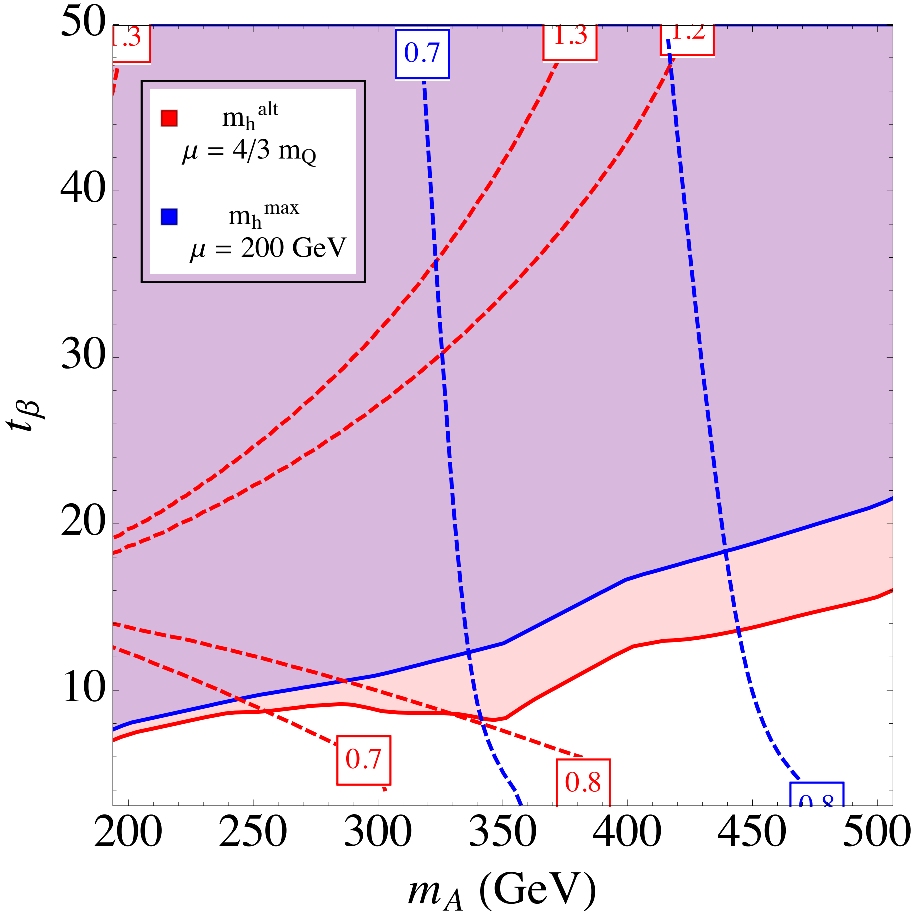
SUSY decays dominant, hZ suppressed



At small values of tanβ, and small μ, heavy Higgs decay into top quarks and electroweakinos become dominant. Still, decays into pairs of Higgs very relevant.

Complementarity between different search channels

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

Comment on other direct search channels

- There are other channels that can complement the search for the non-standard Higgs bosons
- Some powerful ones are the decay of the heavy CP-even Higgs boson into pairs of neutral gauge bosons, Z, or into pairs of lightest CP-even Higgs bosons
- Other channels involve the decay of the CP-odd Higgs boson into a Z and a lightest Higgs boson

S. Su et al.

- The decays into gauge bosons vanish in the alignment limit and, as emphasized by N. Craig et al '13, also the decay of H into hh vanishes in the same limit

$$g_{Hhh} \simeq g_{HZZ} \simeq g_{AhZ} \simeq 0$$

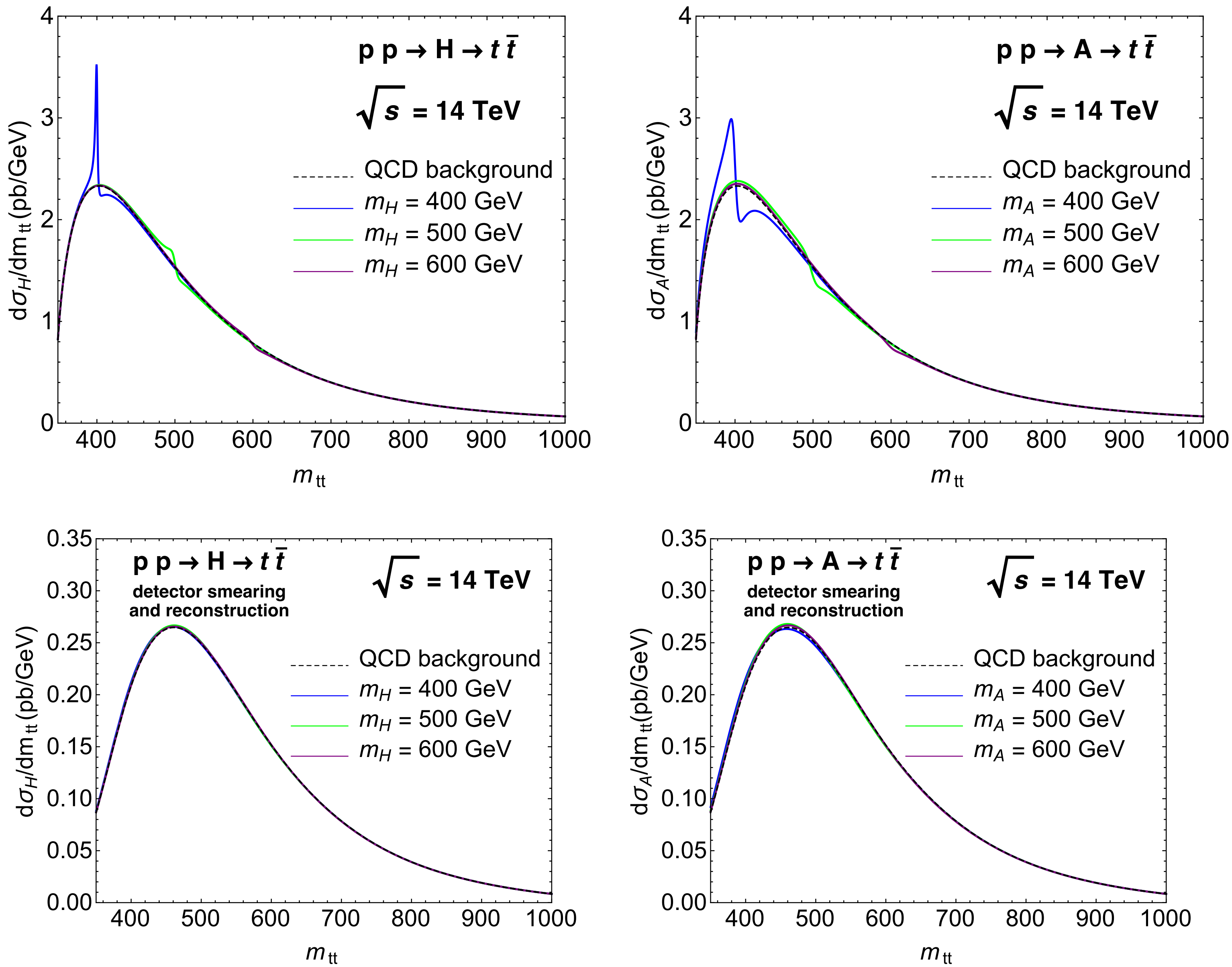
- Therefore, these channels cannot be efficiently used when the conditions of alignment are fulfilled. Decays into tops can be used at MH > 350 GeV.

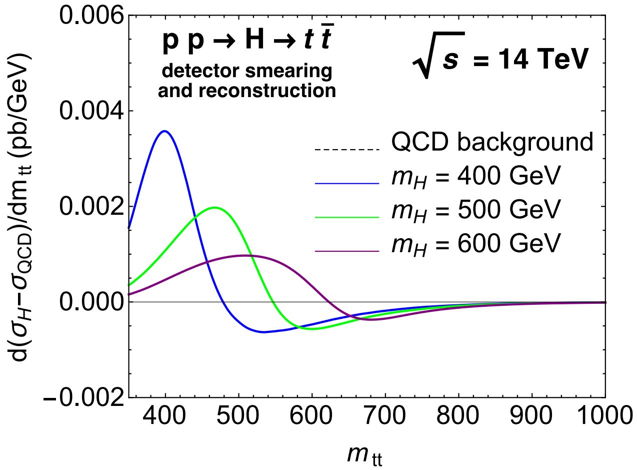
N. Craig et al'15 , Liu et al.'15

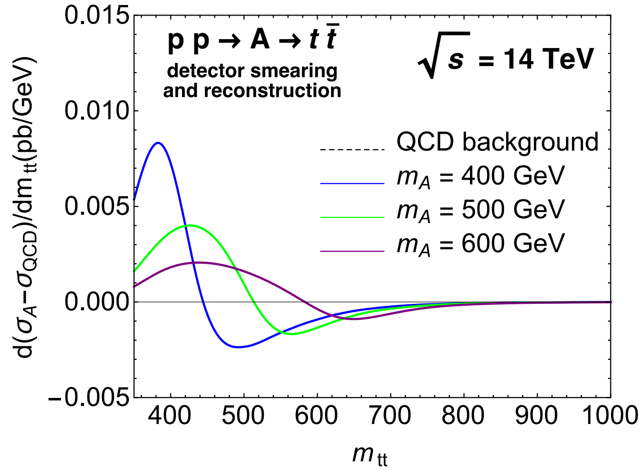
- Moreover, the reach of these channels should be revised in the presence of light charginos and neutralinos, which may provide alternative search channels.

Interference effects : The tt channel

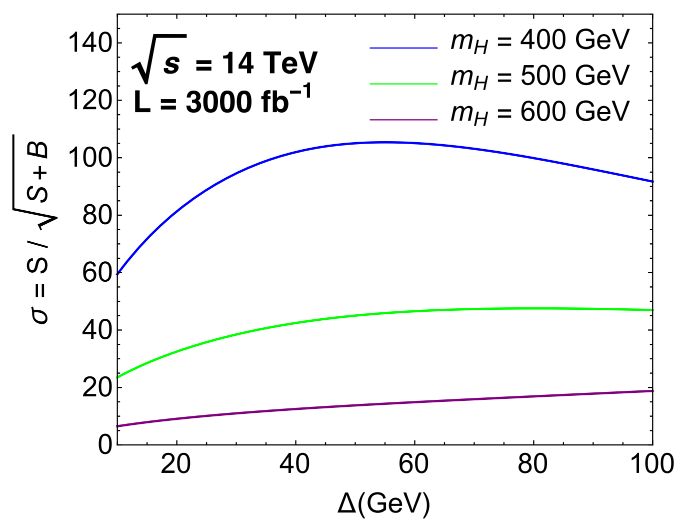
Craig, Draper, Erasmo, Thomas, Zhang '15

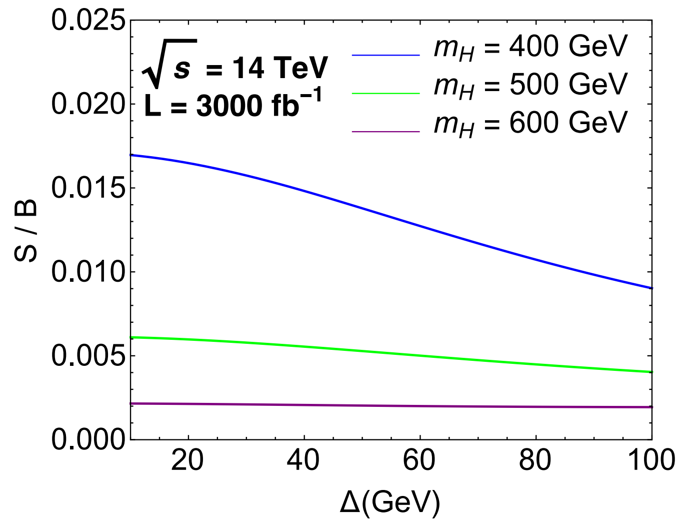






Craig, Draper, Erasmo, Thomas, Zhang '15





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,

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

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

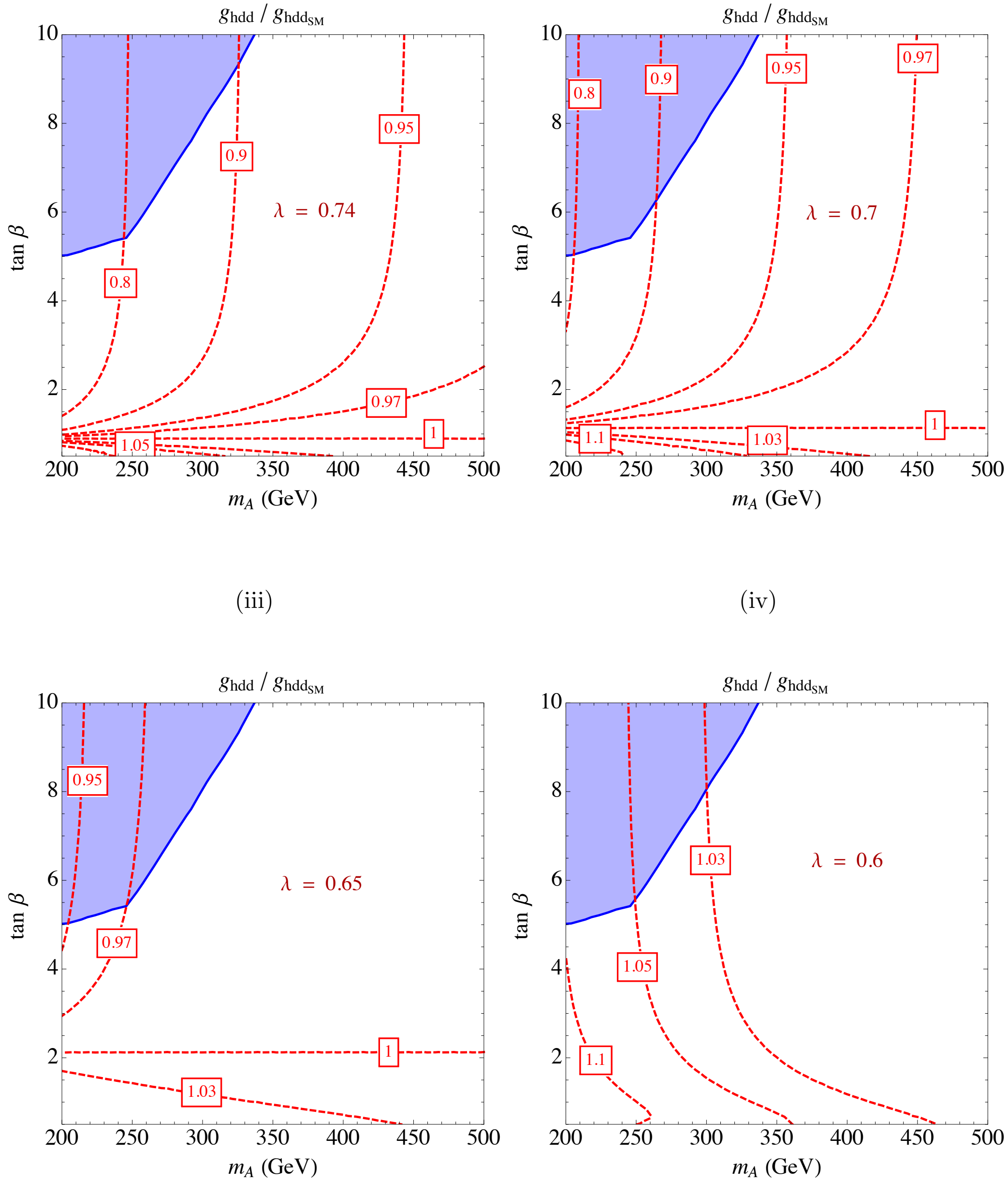
- It is perhaps less known that it leads to sizable corrections to the mixing between the MSSM like CP-even states. In the Higgs basis,

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

- The last term is the one appearing in the MSSM, that are small for moderate mixing and small values of $\tan\beta$
- So, alignment leads to a determination of lambda,
- The values of lambda end up in a very narrow range, between 0.65 and 0.7 for allvalues of tanbeta, 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

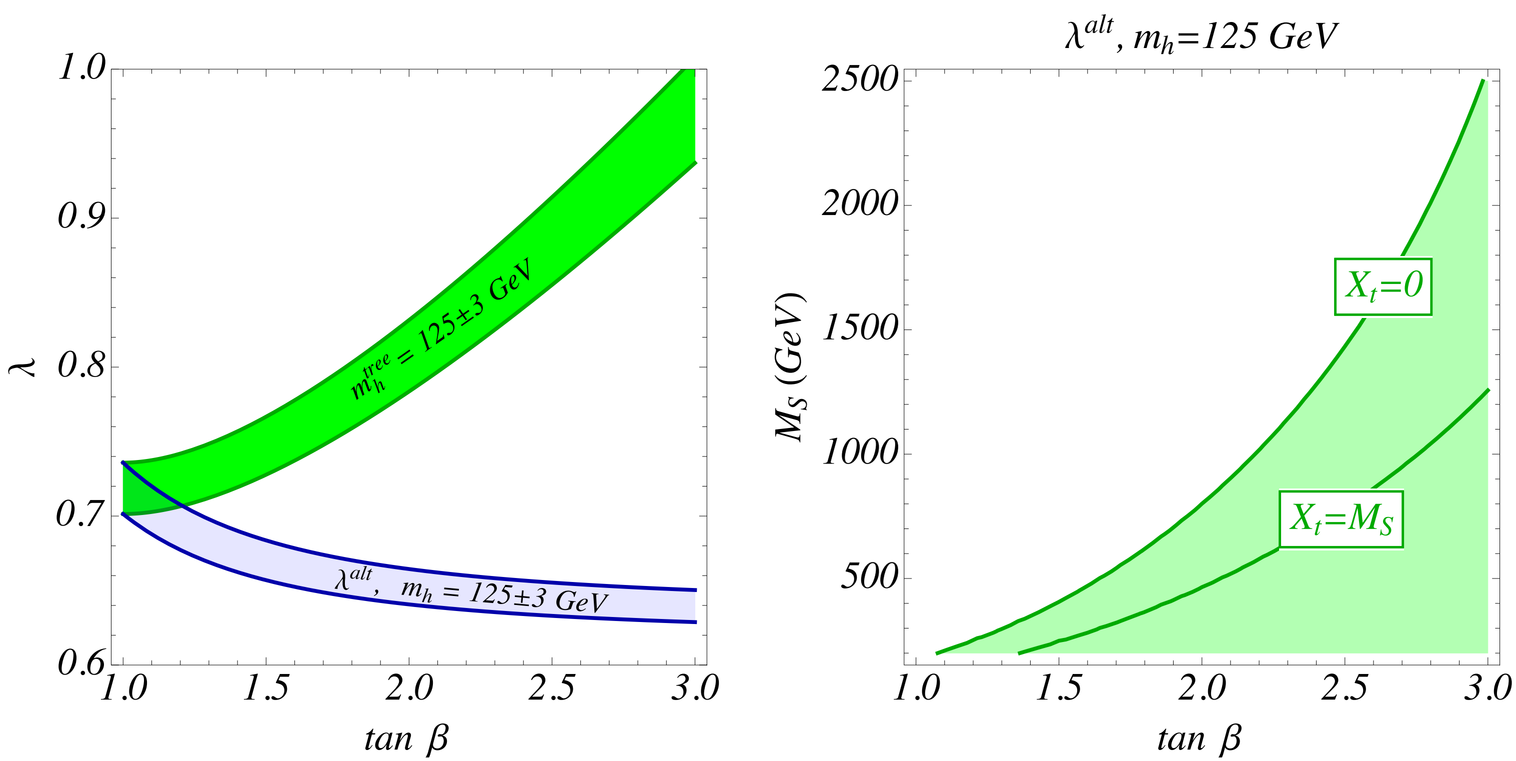
It is clear from these plots that the NMSSM does an amazing job in aligning the MSSM-like CP-even sector, provided lambda is of about 0.65

Stop Contribution at alignment

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

Interesting, after some simple algebra, one can show that

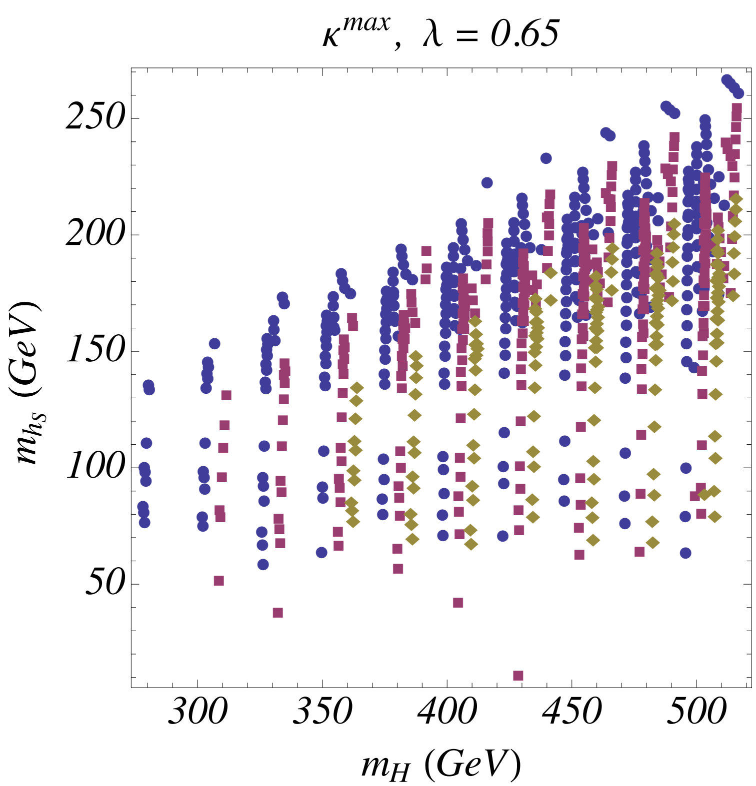
$$\Delta_{\tilde{t}} = -\cos 2\beta (m_h^2 - M_Z^2)$$

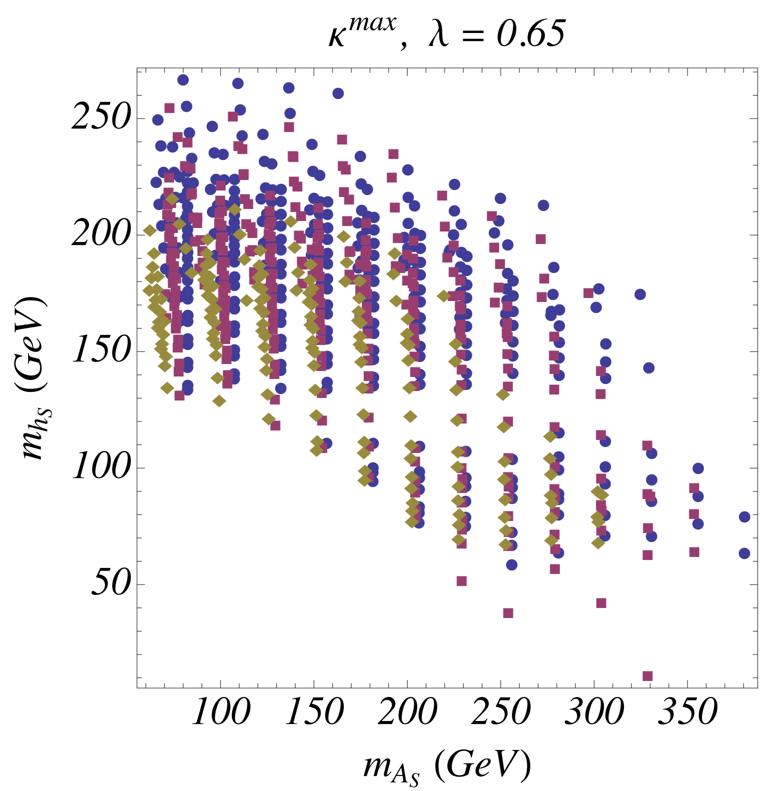


For moderate mixing, It is clear that low values of $\tan\beta < 3$ lead to lower corrections to the Higgs mass parameter at the alignment values

Allowed CP-even and CP-odd Masses

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





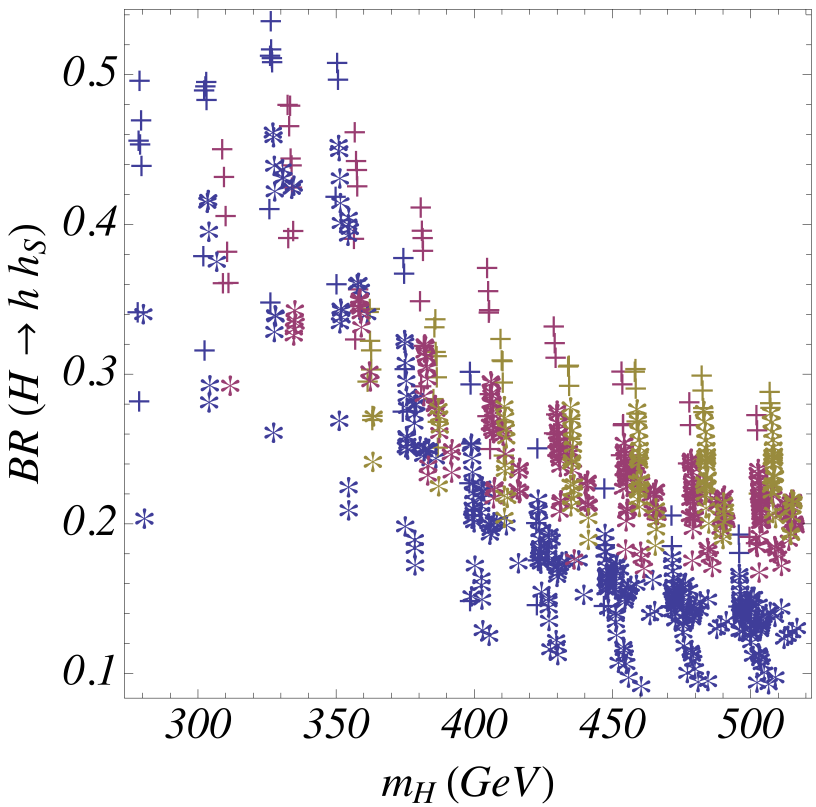
Heavier CP-even Higgs
can decay to lighter ones

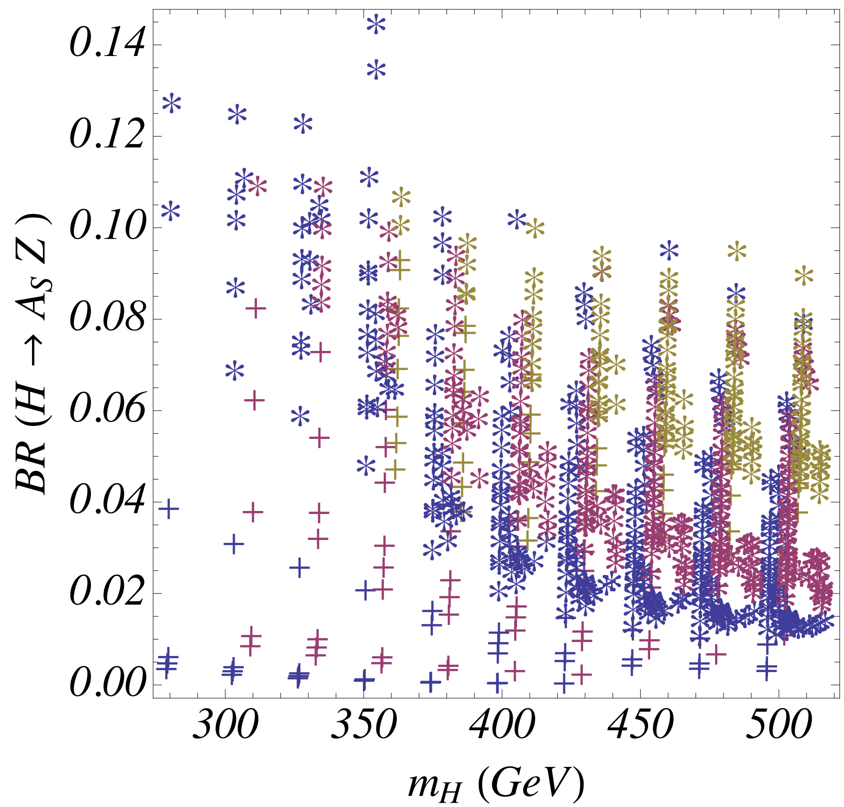
Anti-correlation between
singlet-like CP-even and odd masses

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

Crosses : H1 singlet like
Asterix : H2 singlet like

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

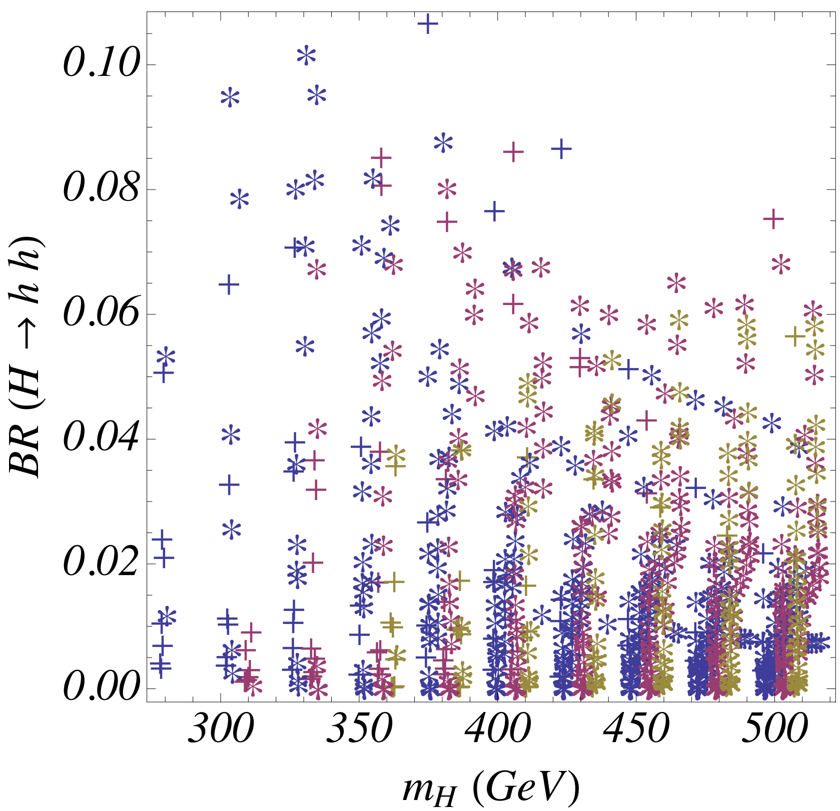


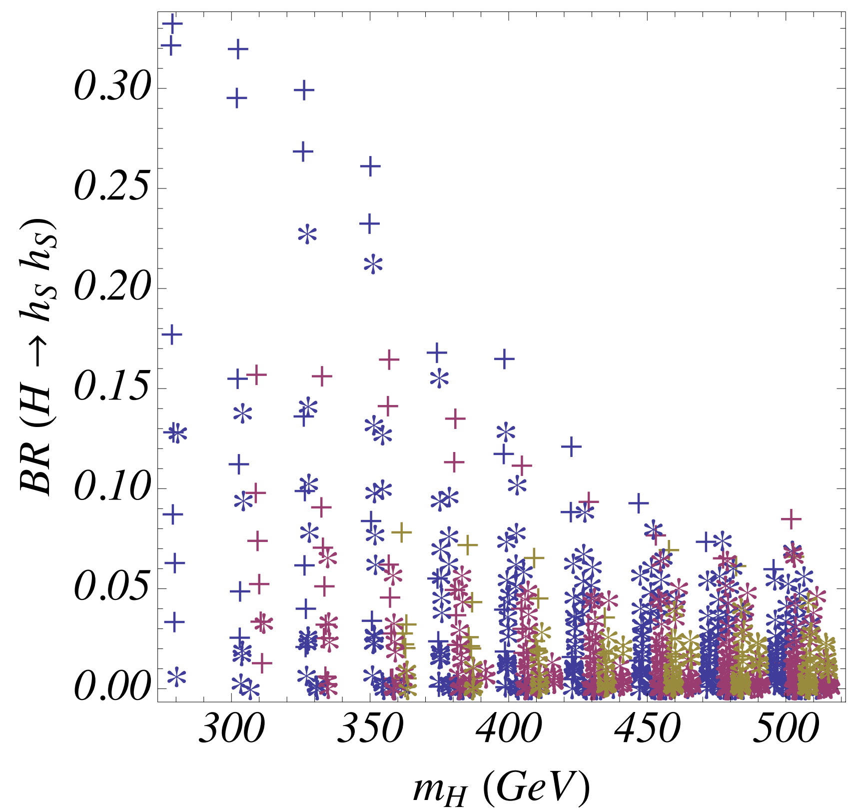


Decays into pairs of SM-like Higgs bosons suppressed by alignment

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

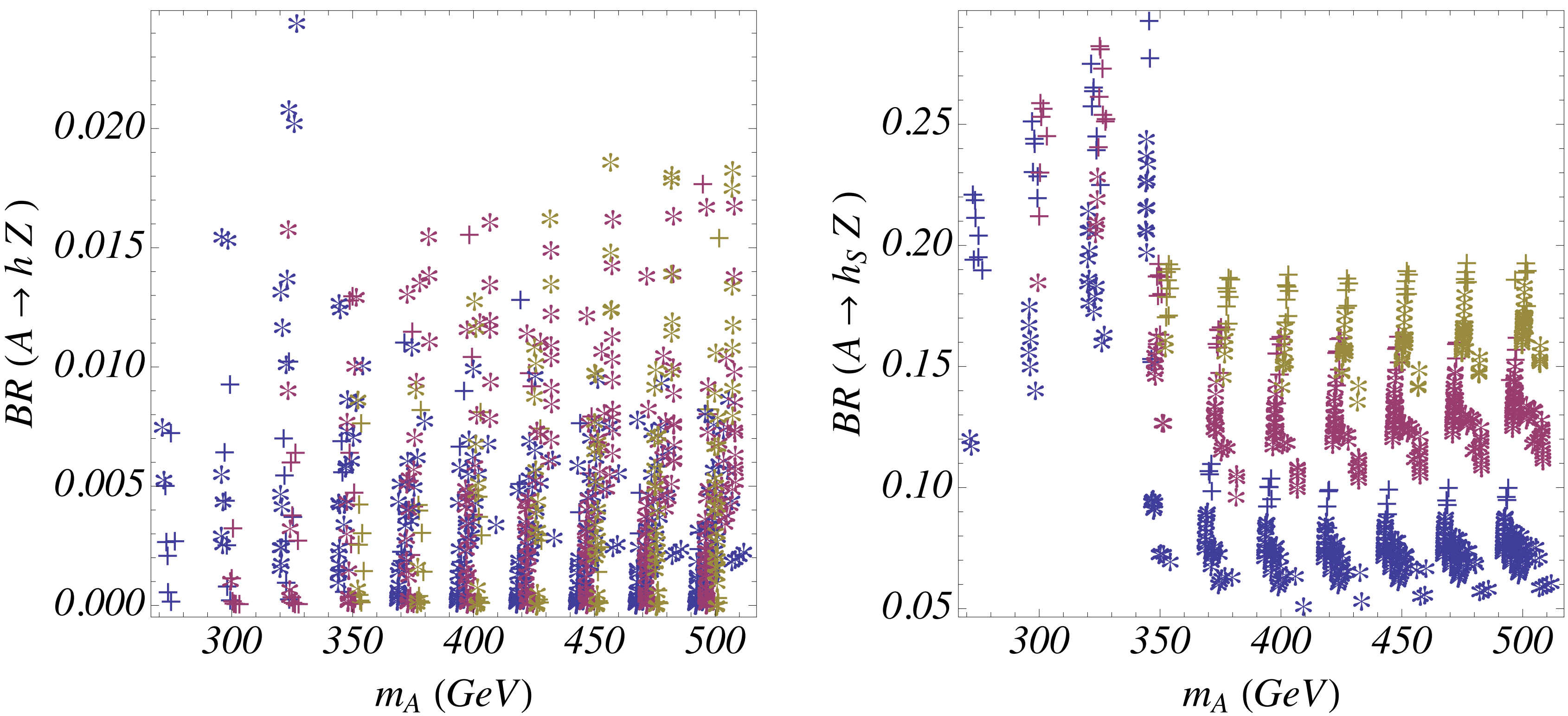
Crosses : H1 singlet like
Asterix : H2 singlet like





Heavy CP-odd Higgs Bosons have similar decay modes

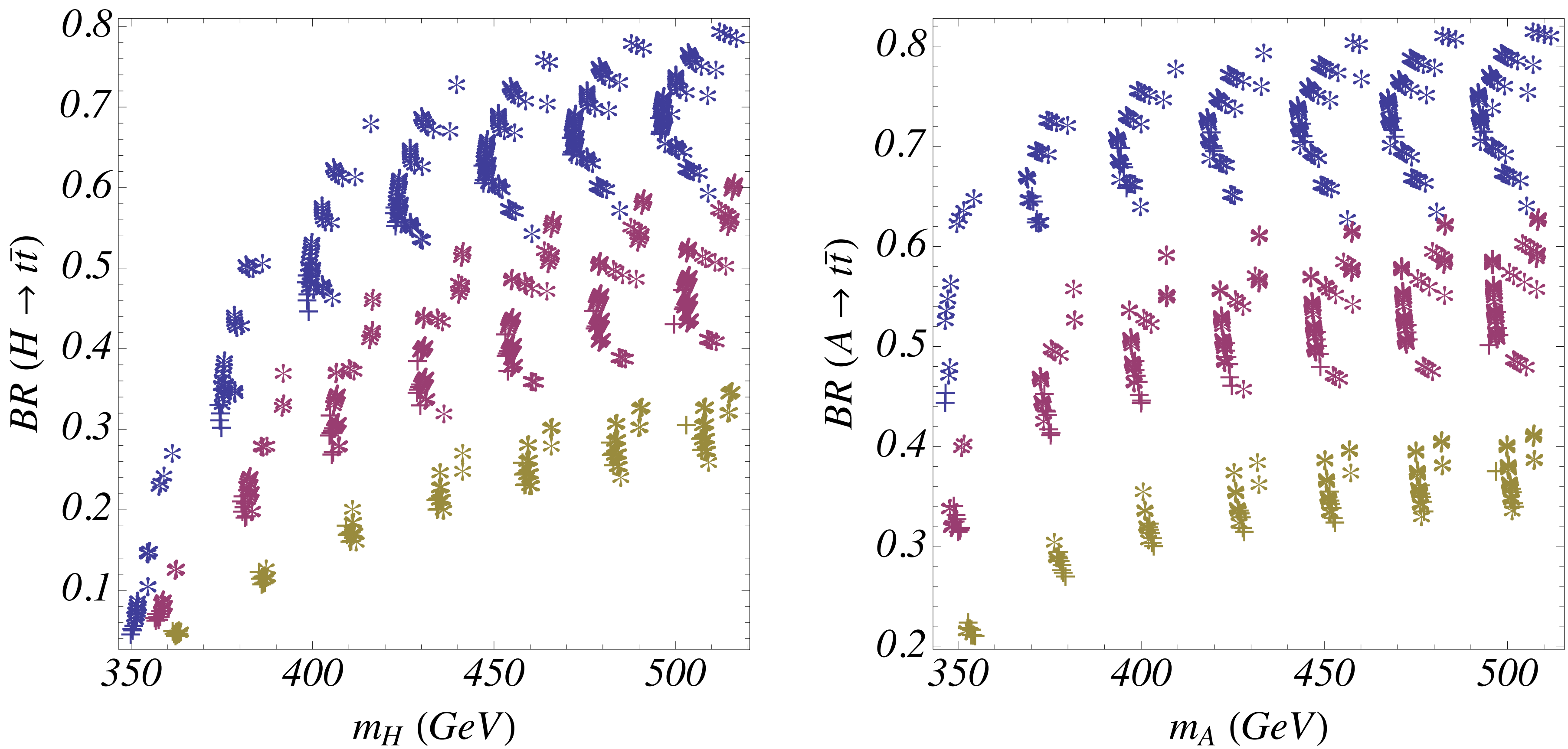
Carena, Haber, Low, Shah, C.W.'15



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

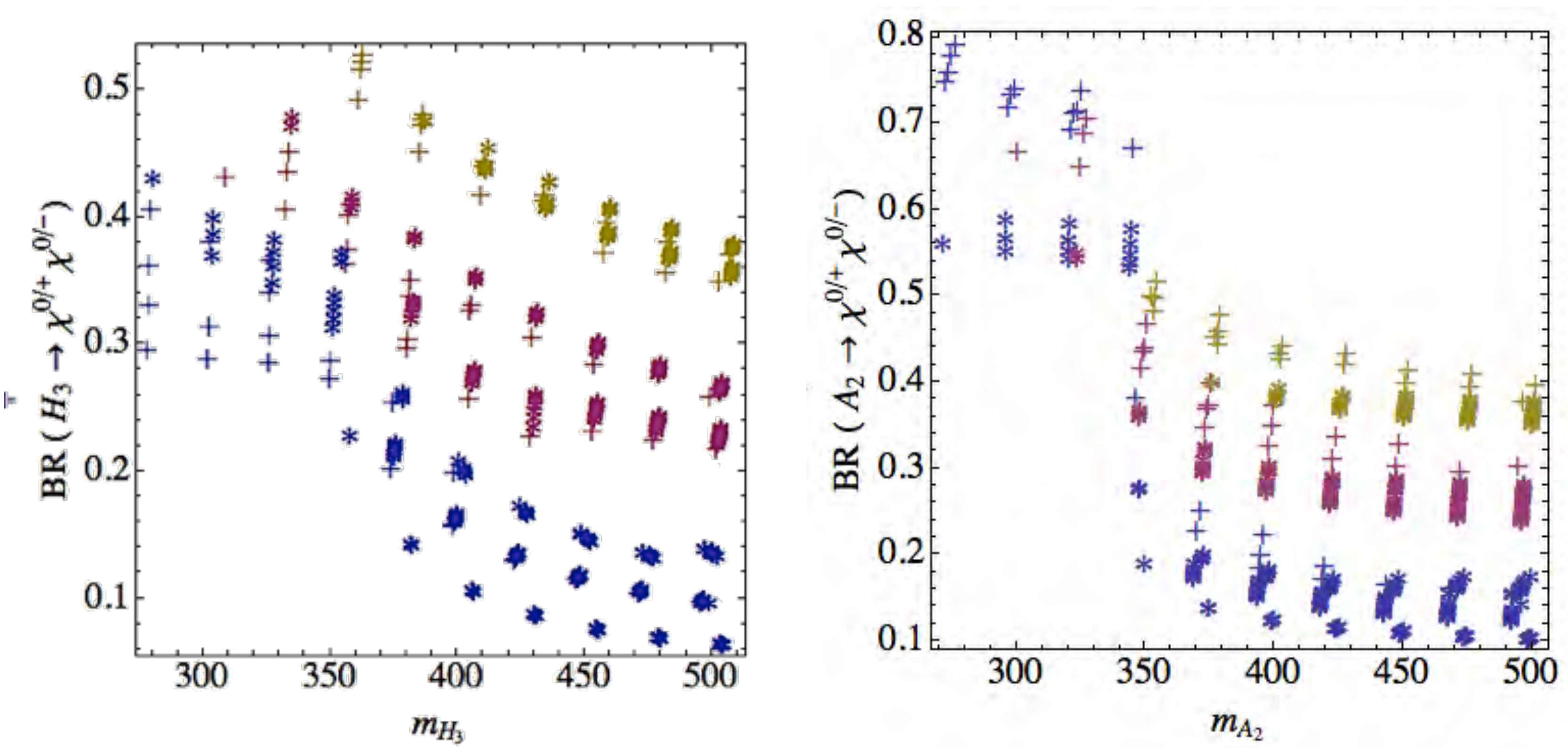
Decays into top significant but may be somewhat suppressed by decays into non-standard particles

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



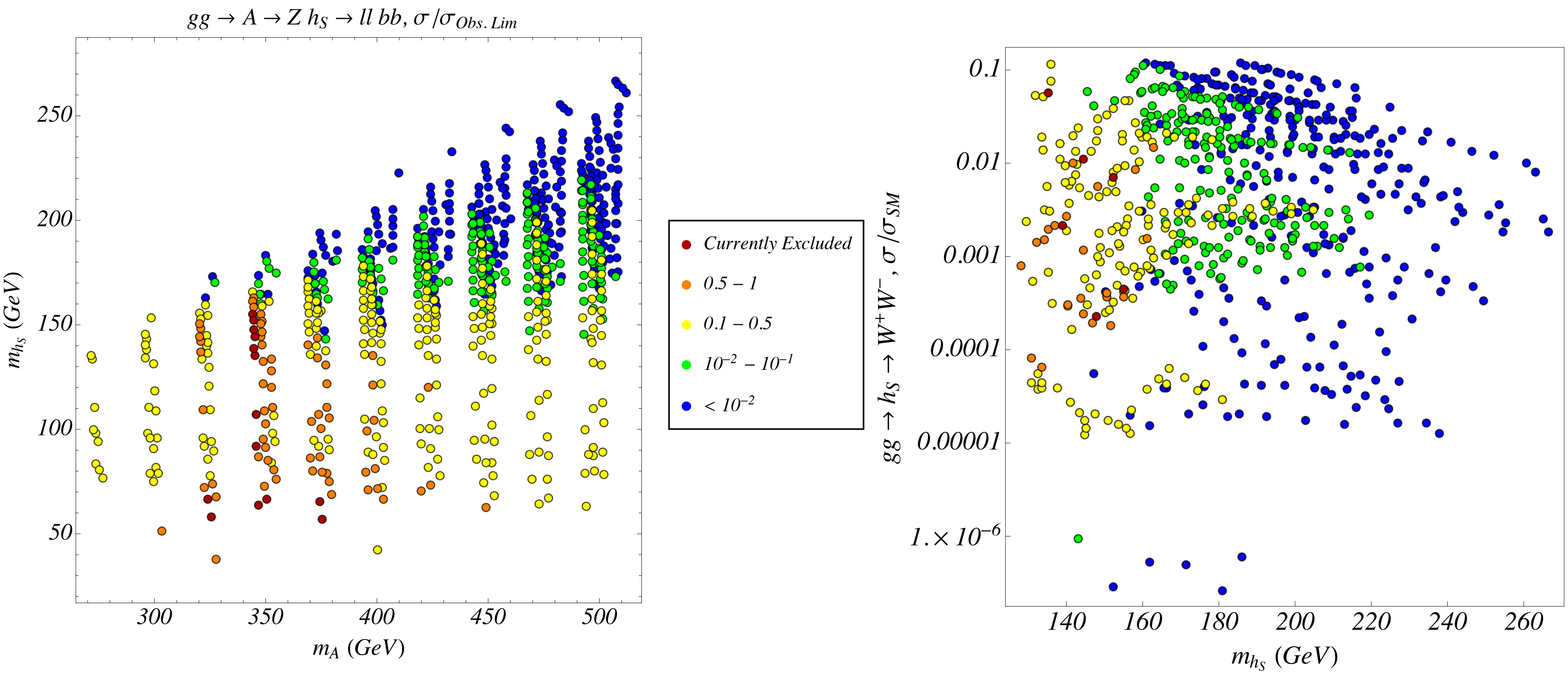
Decays into neutralinos and charginos are relevant, also above the top threshold

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



Complementarity between WW and ll bb modes

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



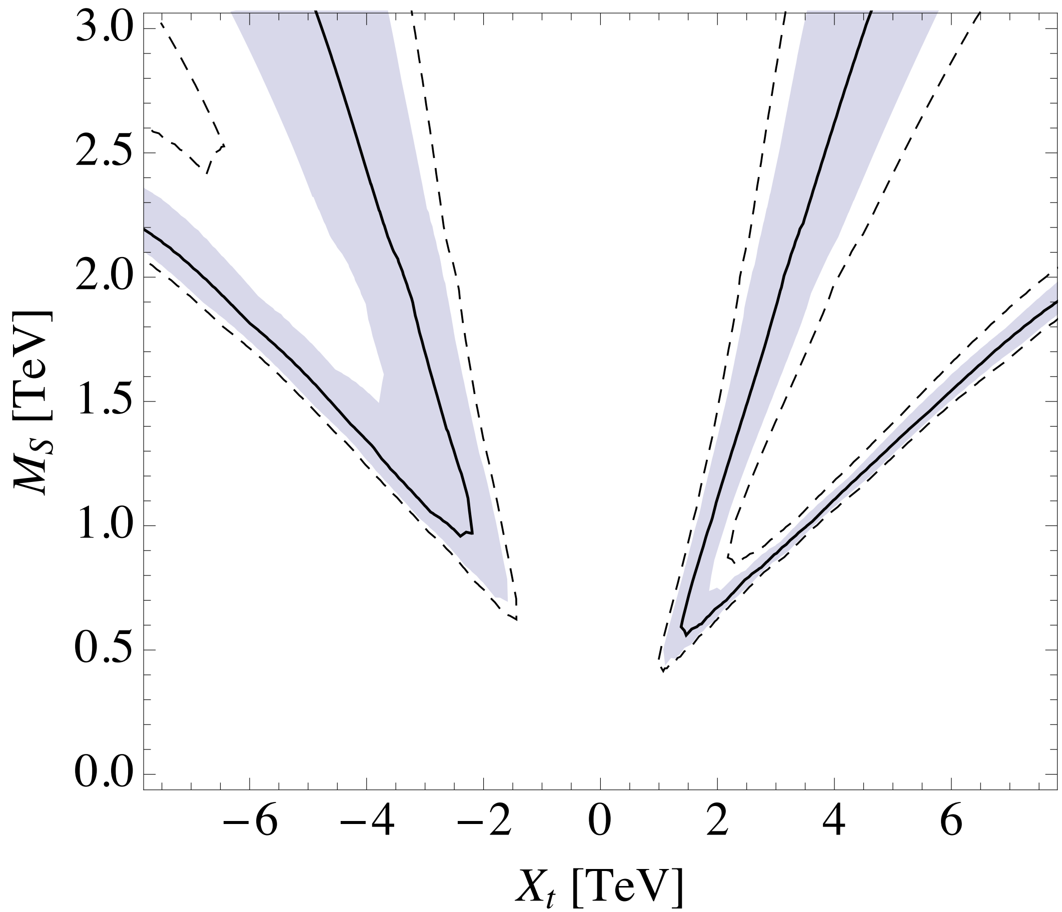
Due to behavior of the singlet decay branching ratio,
WW production enhanced in regions where bbll signal small

Conclusions

- Low energy supersymmetry provides a very predictive framework for the computation of the Higgs phenomenology.
- The properties of the lightest and heavy Higgs bosons depend strongly on radiative corrections mediated by the stops and on lambda.
- Alignment in the MSSM appears for large values of mu, for which decays into electroweakinos are suppressed, making the bounds coming from decays into SM particles stronger
- Complementarity between precision measurements and direct searches will allow to probe efficiently the MSSM Higgs sector
- In the NMSSM, alignment occurs in regions of parameter space in which the naturalness conditions are fulfilled, with lambda of order 0.65. Stops can be light, since their relation with the Higgs mass is different from the MSSM one
- Light Higgs, chargino and neutralino spectrum is a prediction of this model in this region of parameters.
- Searches for heavy Higgs bosons decaying into non-standard light Higgs and vector bosons is prominent and should be emphasized at LHC 14.

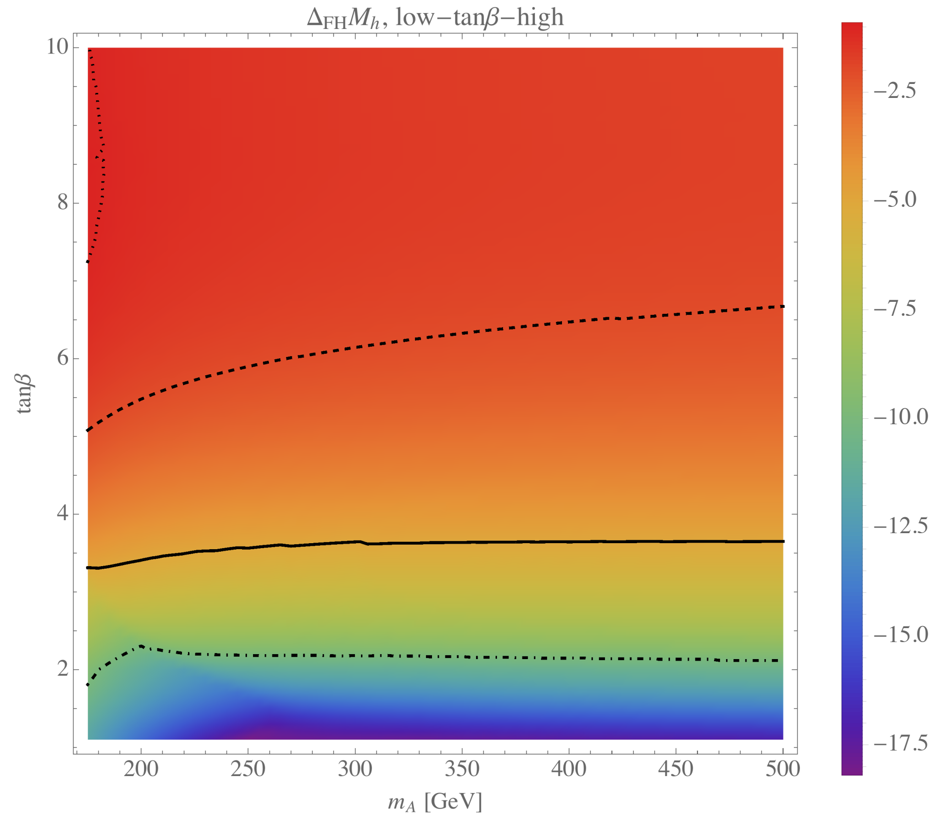
Backup Slides

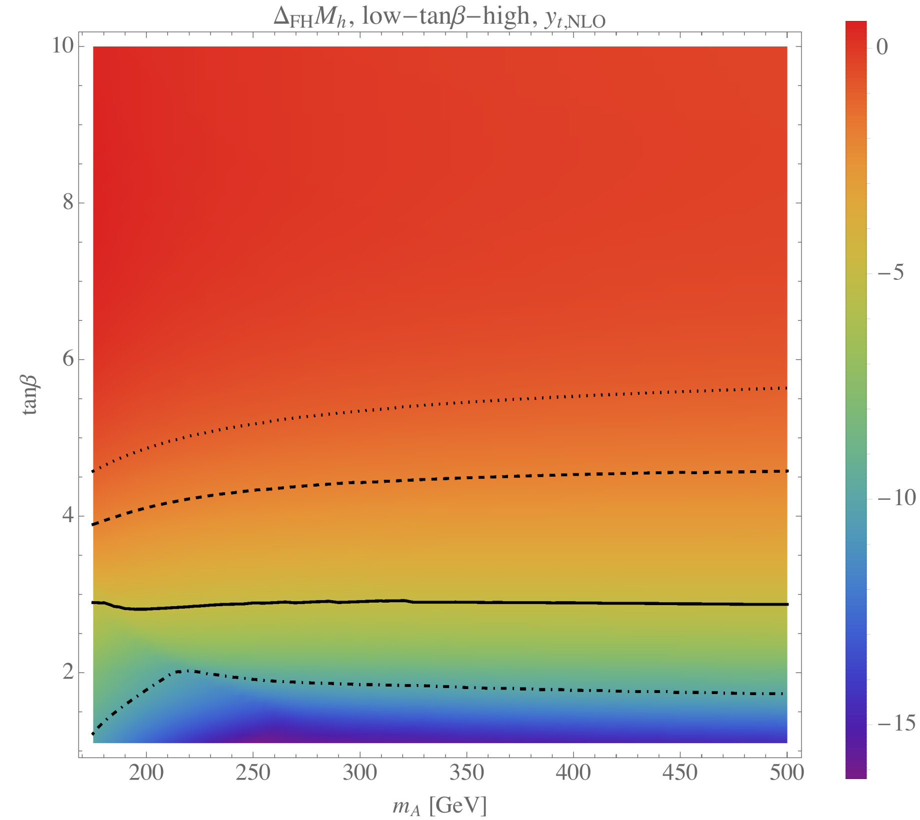
Large Mixing in the Stop Sector Necessary



P. Draper, P. Meade, M. Reece, D. Shih'11
L. Hall, D. Pinner, J. Ruderman'11
M. Carena, S. Gori, N. Shah, C. Wagner'11
A. Arbey, M. Battaglia, A. Djouadi, F. Mahmoudi, J. Quevillon'11
S. Heinemeyer, O. Stal, G. Weiglein'11
U. Ellwanger'11

Comparison with FeynHiggs





Next to leading order relation between M_t and running $m_t(M_t)$

Leading order relation between M_t and running $m_t(M_t)$

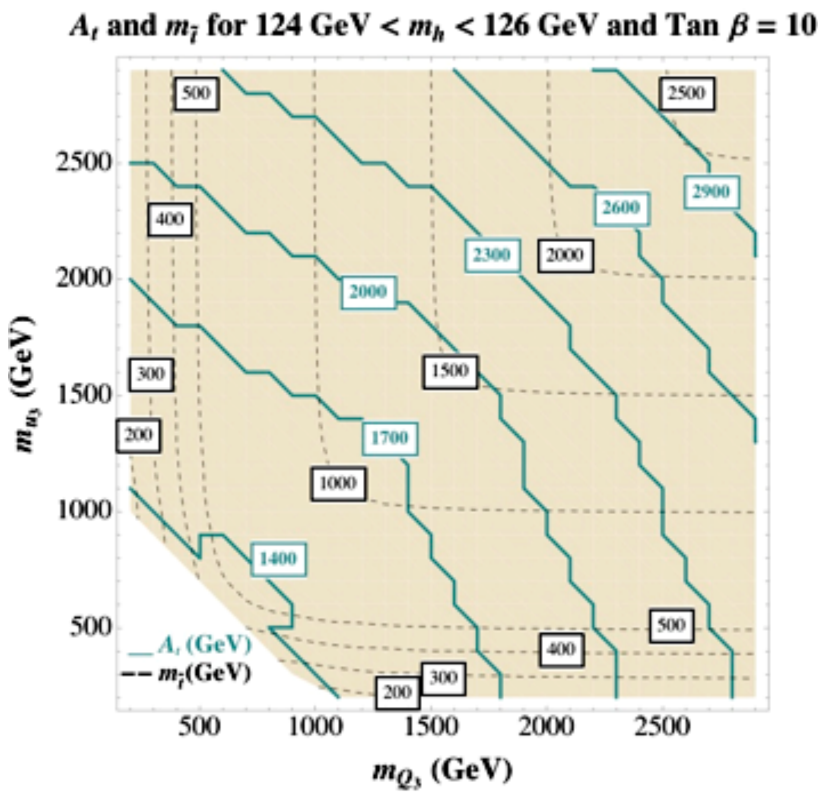
Somewhat less extreme differences than the ones presented in SUSYHD article

Vega and Villadoro'15

Good agreement for large $\tan\beta$ and LO relation between M_t and $m_t(M_t)$

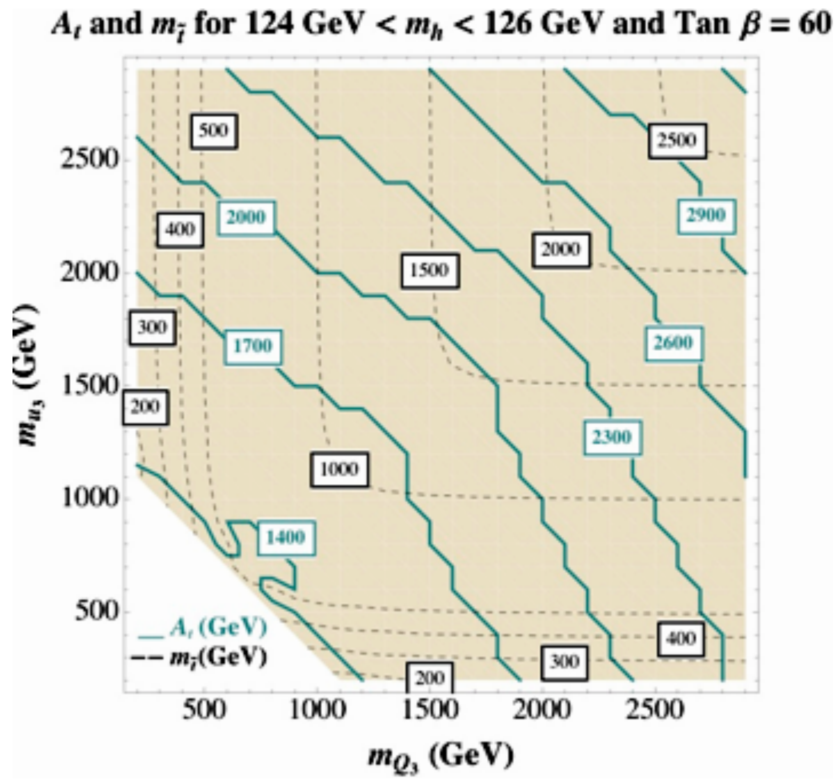
Splitting the Two Stop Masses
Soft supersymmetry Breaking Parameters

M. Carena, S. Gori, N. Shah, C. Wagner, arXiv:1112.336, +L.T. Wang, arXiv:1205.5842



Large stop sector mixing
A_t > 1 TeV

No lower bound on the lightest stop



Intermediate values of tan beta lead to the largest values of m_h for the same values of stop mass parameters

Comment on CP-violation

- In the presence of CP-violating phases in the soft SUSY parameters, the mass eigenstates are no longer CP-eigenstates

- Mixing between the would be CP-even and CP-odd Higgs bosons exist.

Pilaftsis'98, Pilaftsis, C.W.'99

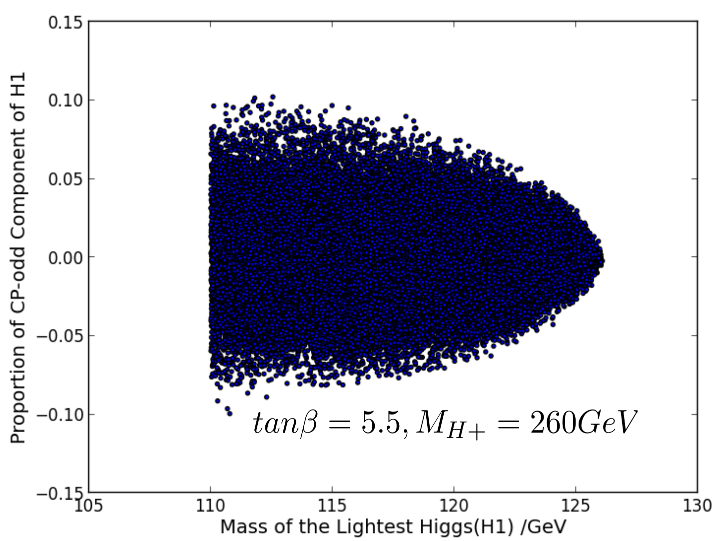
- How large could be the CP-odd component of the lightest neutral Higgs ?

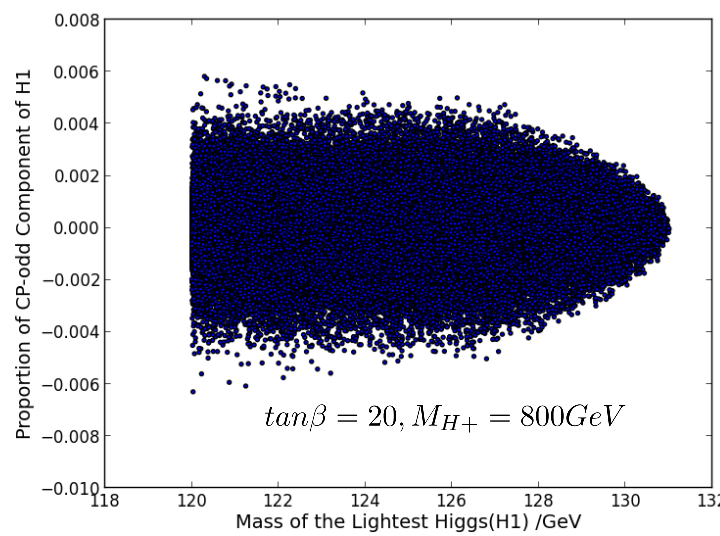
- It is proportional to $\mathrm{Im}\left(\frac{3h_t^4 v^2 \sin^2\beta \sin 2\beta}{8\pi^2}\left[\frac{X_t Y_t^*}{2M_{\mathrm{SUSY}}^2}\left(1-\frac{|X_t|^2}{6M_{\mathrm{SUSY}}^2}\right)\right]\right)$

- So, it goes to zero for maximal mixing ! For stop masses of the order of the TeV scale it is difficult to obtain the right Higgs mass and a relevant CP-odd component

MS = 2 TeV

Bing Li, C.W.'15





- A CP-odd component is further restricted by electric dipole moments and Higgs

Mixing mass matrix

Bing Li, C.W.'14

$$O M^2_{\rm diag} O^T = \begin{pmatrix} M_Z^2\cos^2 2\beta + \eta & \theta & \xi_2 \\ \theta & m_a^2 + M_Z^2 \sin^2 2\beta + \rho & \xi_1 \\ \xi_2 & \xi_1 & m_a^2 \end{pmatrix}$$

Higgs Basis.
Third component A

$$\eta = \frac{3h_t^4 v^2 \sin^4\beta}{8\pi^2}\left[\log\left(\frac{M^2_{\rm SUSY}}{m_t^2}\right) + \frac{|X_t|^2}{M^2_{\rm SUSY}}\left(1 - \frac{|X_t|^2}{12\; M^2_{\rm SUSY}}\right)\right]$$

$$\theta = -M_Z^2 \cos 2\beta \sin 2\beta + \frac{3h_t^4 v^2 \sin^2\beta \sin 2\beta}{16\pi^2}\left[\log\left(\frac{M^2_{\rm SUSY}}{m_t^2}\right) + \frac{|X_t|^2}{2M^2_{\rm SUSY}} + {\rm Re}\left(\frac{X_t Y_t^*}{2M^2_{\rm SUSY}}\left(1 - \frac{|X_t|^2}{6M^2_{\rm SUSY}}\right)\right)\right]$$

$$\xi_2 = {\rm Im}\left(\frac{3h_t^4 v^2 \sin^2\beta \sin 2\beta}{32\pi^2}\left[\frac{X_t Y_t^*}{M^2_{\rm SUSY}}\left(1 - \frac{|X_t|^2}{6M^2_{\rm SUSY}}\right)\right]\right)$$

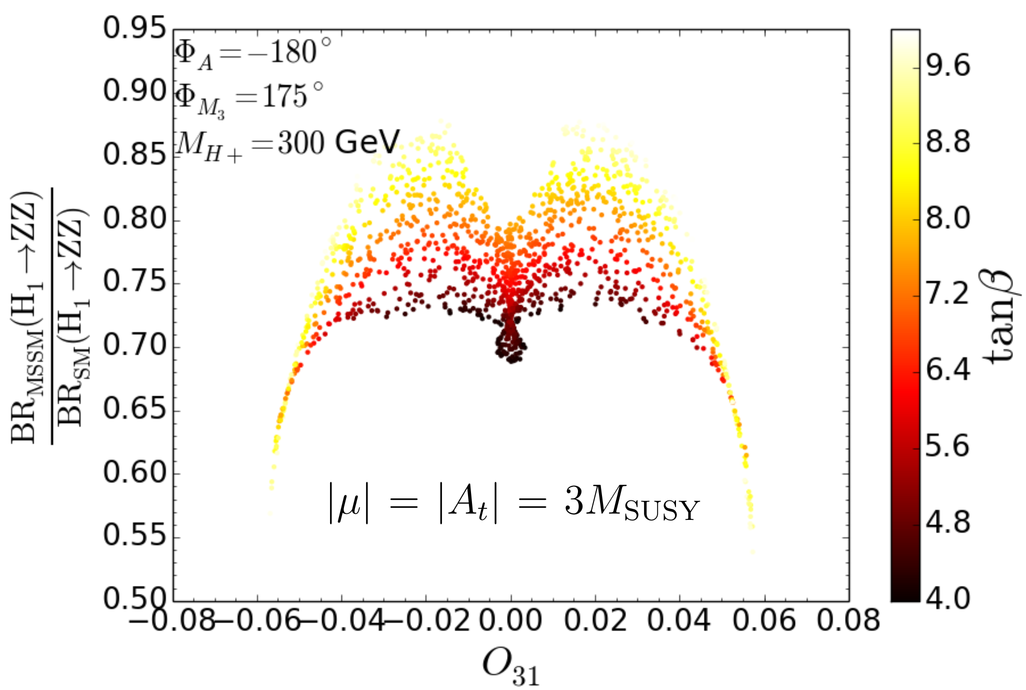
$$O_{31} \propto -\frac{3h_t^4 v^2 \sin^4\beta}{16\pi^2 m^2_{H^+}}\frac{{\rm Im}(\mu A_t)}{M^2_{\rm SUSY}}\left(1 - \frac{|X_t|^2}{6M^2_{\rm SUSY}}\right)$$

Observe that a large CP-odd component means that the alignment condition, already hard to achieve in the MSSM, becomes even harder to achieve.

CP-violation only possible for relatively small values of the non-standard Higgs masses, and hence significant deviations of the bottom coupling are expected.

Deviation of Higgs Branching Ratios compared to the SM

Bing Li, C.W.'15



Values of the CP-odd component of H1 of a few percent are obtained for these sizable values of At and μ and small values of the charged Higgs mass.

A sizable deviation of the Higgs branching ratios is observed, what constrains the CP-odd component.

Larger charged Higgs mass leads to branching ratios closer to the SM, but smaller CP-odd components, too.

Putting all constrains together, CP-odd components larger than a 3 percent are difficult to achieve in the MSSM for stops at the TeV scale. Larger values may be obtained for very heavy stops

CP-Violation in the tau lepton sector

The resulting values of the CP-odd component are very small and difficult to measure.

Observe, however that if one defines

$$\tan\phi_\tau = \frac{g^P_{h\tau\tau}}{g^S_{h\tau\tau}}$$

The axial coupling of the tau to H1, which is due to the mixing with the would be CP-odd scalar, is enhanced by tanβ.

$$\tan\phi_\tau \simeq \frac{O_{31}\tan\beta}{O_{11} - O_{21}\tan\beta}$$

Measurement at a high luminosity LHC may be possible

(Berge et al'14, Harnik et al)