Supersymmetry and Higgs Physics

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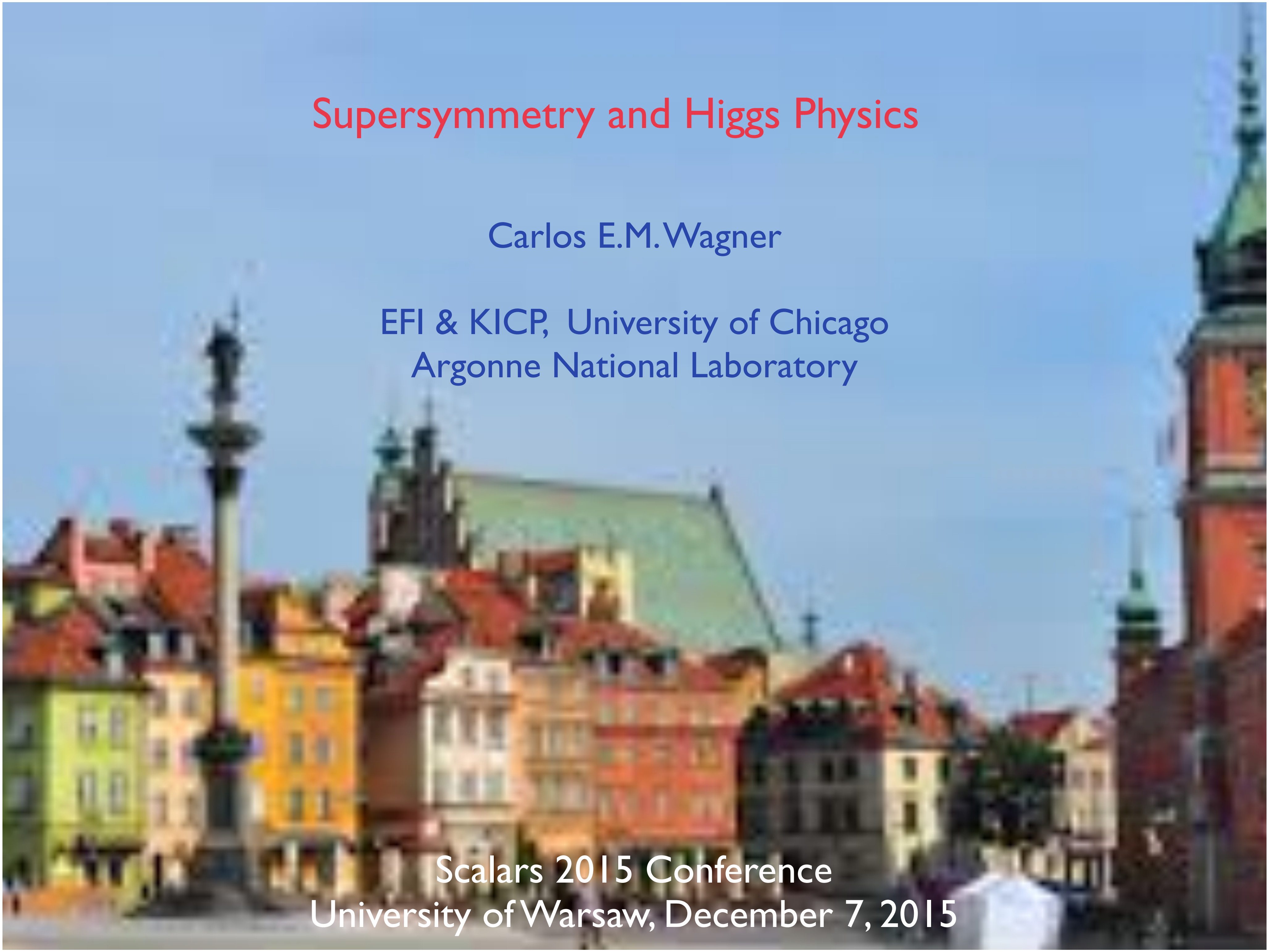
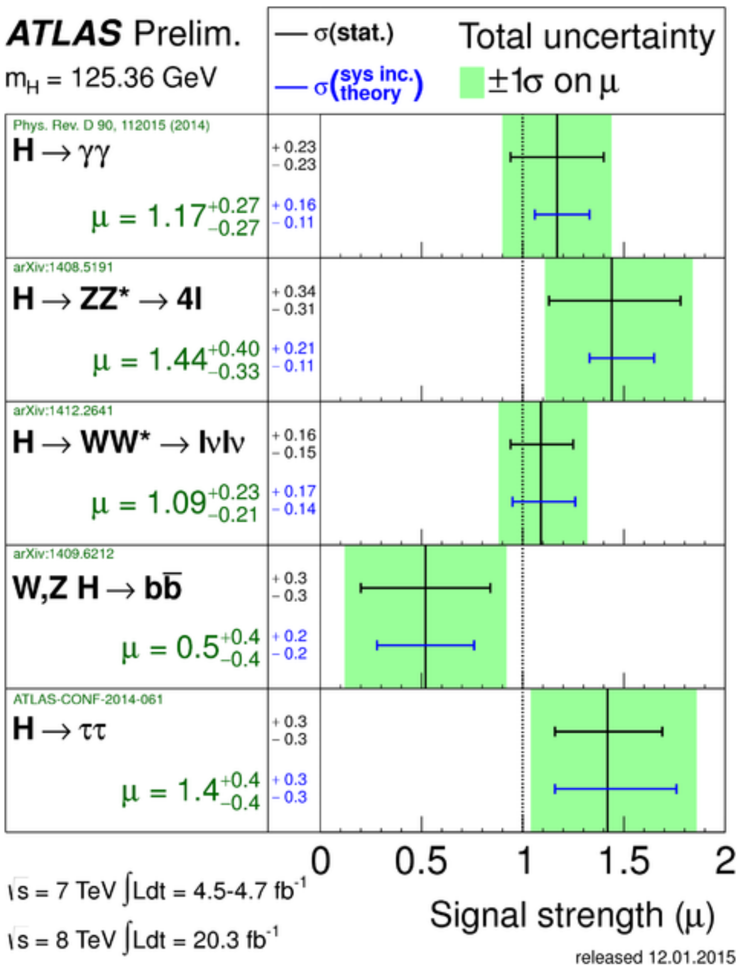
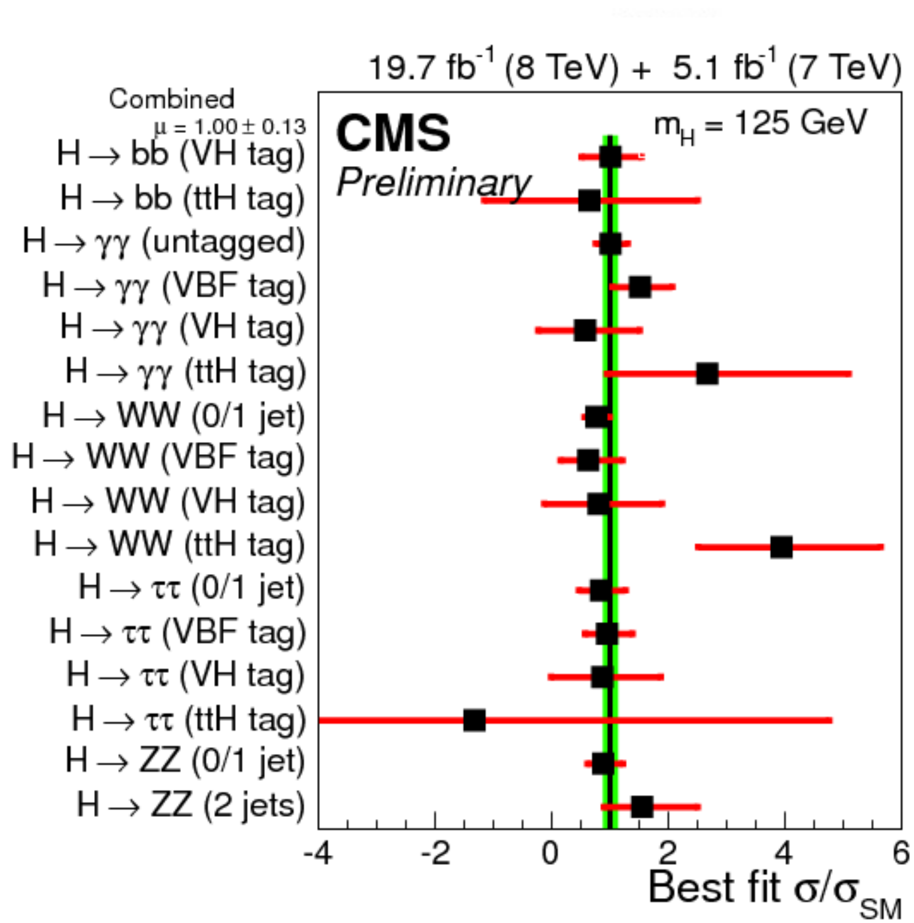


Higgs Boson Discovery at the LHC :

Very good agreement of Higgs Physics Results with SM Predictions





Going Beyond the SM :
Two Higgs Doublet Models

- The simplest extension of the SM is to add one Higgs doublet, with the same quantum numbers as the SM one.

- Now, we will have contributions to the gauge boson masses coming from the vacuum expectation value of both fields

$$(\mathcal{D}\phi_i)^\dagger \mathcal{D}\phi_i \rightarrow g^2 \phi_i^\dagger T^a T^b \phi_i A_\mu^a A^{\mu,b}$$

- Therefore, the gauge boson masses are obtained from the SM expressions by simply replacing

$$v^2 \rightarrow v_1^2 \; + \; v_2^2$$

- There is then a free parameter, that is the ratio of the two vacuum expectation values, and this is usually denoted by

$$\tan\beta = \frac{v_2}{v_1}$$

- The number of would-be Goldstone modes are the same as in the SM, namely 3. Therefore, there are still 5 physical degrees of freedom in the scalar sector which are a charged Higgs, a CP-odd Higgs and two CP-even Higgs bosons.

CP-even Higgs Bosons

- There is no symmetry argument and in general these two Higgs boson states will mix. The mass eigenvalues, in increasing order of mass, will be

$$\sqrt{2}\ h = -\sin\alpha\ \mathrm{Re}H_1^0 + \cos\alpha\ \mathrm{Re}H_2^0$$

$$\sqrt{2}\ H = \cos\alpha\ \mathrm{Re}H_1^0 + \sin\alpha\ \mathrm{Re}H_2^0$$

- From here one can easily obtain the coupling to the gauge bosons. This is simply given by replacing in the mass contributions

$$v_i \to v_i + ReH_i^0$$

- This leads to a coupling proportional to

$$v_i\ \mathrm{Re}H_i^0$$

- Hence, the effective coupling of h is given by

$$hVV = (hVV)^{\mathrm{SM}}(-\cos\beta\sin\alpha + \sin\beta\cos\alpha) = (hVV)^{\mathrm{SM}}\sin(\beta-\alpha)$$

$$HVV = (hVV)^{\mathrm{SM}}(\cos\beta\cos\alpha + \sin\beta\sin\alpha) = (hVV)^{\mathrm{SM}}\cos(\beta-\alpha)$$

- These proportionality factors are nothing but the projection of the Higgs mass eigenstates into the one acquiring a vacuum expectation value.

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,

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

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

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

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

$$\cos\alpha = \sin\beta$$

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

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

Alignment in General two Higgs Doublet Models

H. Haber and J. Gunion'03

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

- 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

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

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

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

CP-even Higgs Mixing Angle and Alignment

M. Carena, I. Low, N. Shah, C.W.', arXiv:1310.2248

$$\sin\alpha = \frac{\mathcal{M}_{12}^2}{\sqrt{\mathcal{M}_{12}^4 + (\mathcal{M}_{11}^2 - m_h^2)^2}}$$

$$-\tan\beta\ \mathcal{M}_{12}^2 = (\mathcal{M}_{11}^2 - m_h^2) \longrightarrow \sin\alpha = -\cos\beta$$

Condition independent of the CP-odd Higgs mass.

$$\begin{pmatrix} s_\beta^2 & -s_\beta c_\beta \\ -s_\beta c_\beta & c_\beta^2 \end{pmatrix} \begin{pmatrix} -s_\alpha \\ c_\alpha \end{pmatrix} = -\frac{v^2}{m_A^2} \begin{pmatrix} L_{11} & L_{12} \\ L_{12} & L_{22} \end{pmatrix} \begin{pmatrix} -s_\alpha \\ c_\alpha \end{pmatrix} + \frac{m_h^2}{m_A^2} \begin{pmatrix} -s_\alpha \\ c_\alpha \end{pmatrix}$$

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 $\lambda_1, \tilde{\lambda}_3 < \lambda_{\rm SM}$

Deviations from Alignment

Type II 2HDM

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

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

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

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

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

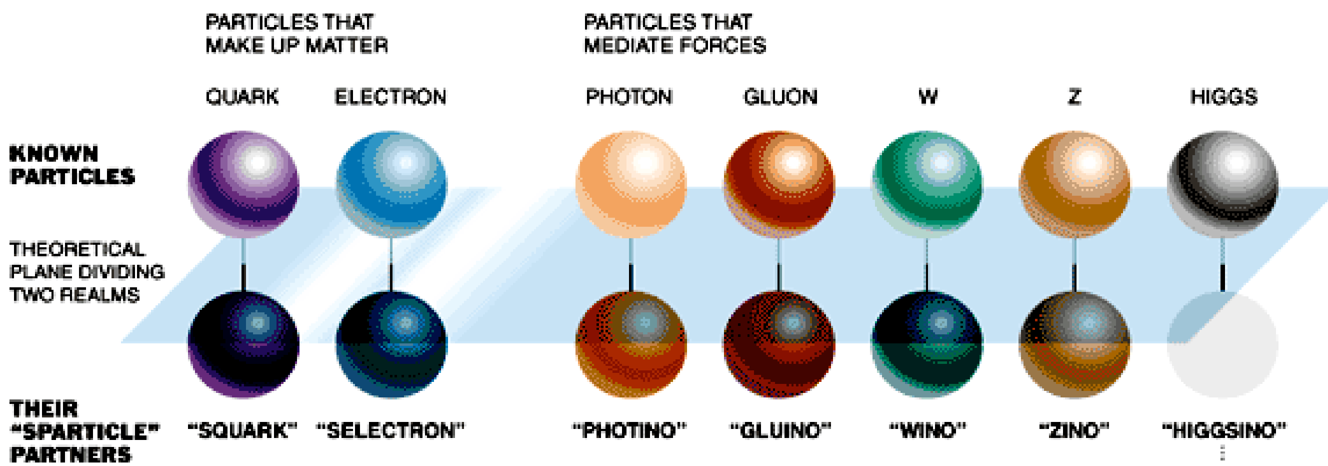
For small departures from alignment, the parameter η can be determined as a function of the quartic couplings and the Higgs masses

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

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

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

$$\mathbf{M}^2_{\tilde{t}} = \begin{pmatrix} \mathbf{m}^2_Q + \mathbf{m}^2_t + \mathbf{D}_L & \mathbf{m}_t \mathbf{X}_t \\ \mathbf{m}_t \mathbf{X}_t & \mathbf{m}^2_U + \mathbf{m}^2_t + \mathbf{D}_R \end{pmatrix}$$

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

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

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

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

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

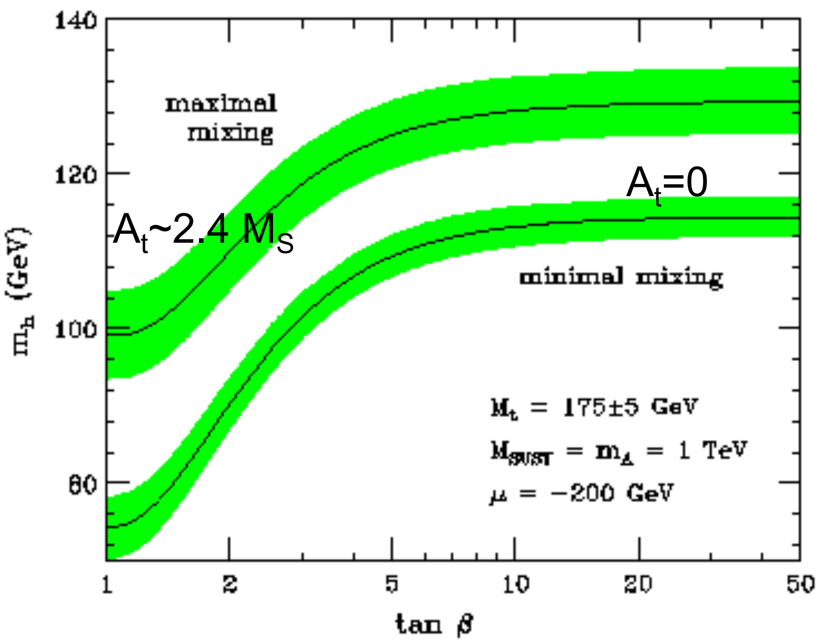
Analytic expression valid for $M_{SUSY} \sim m_Q \sim m_U$

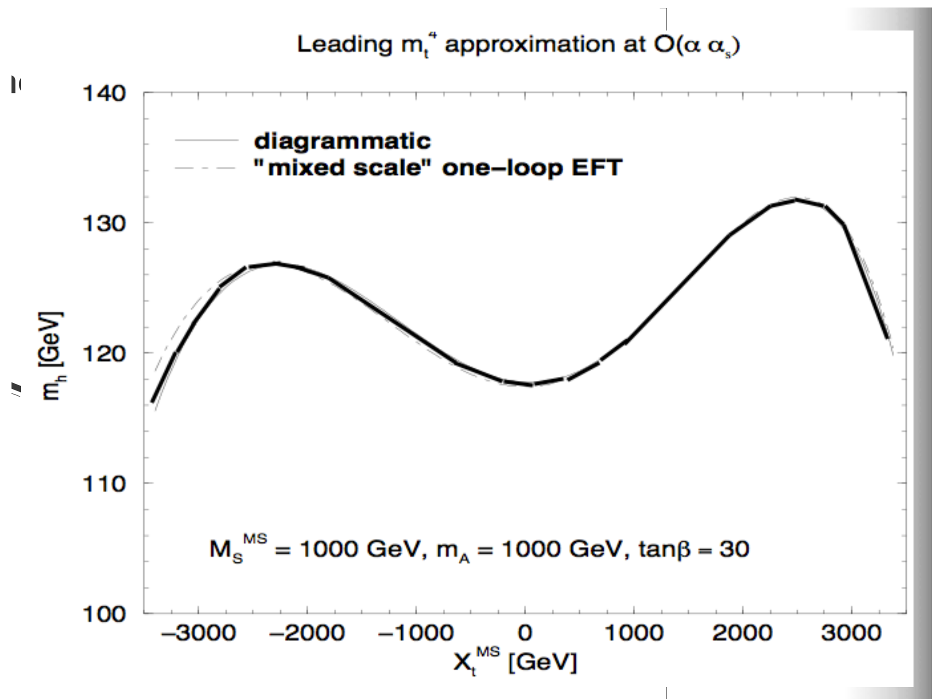
Standard Model-like Higgs Mass

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

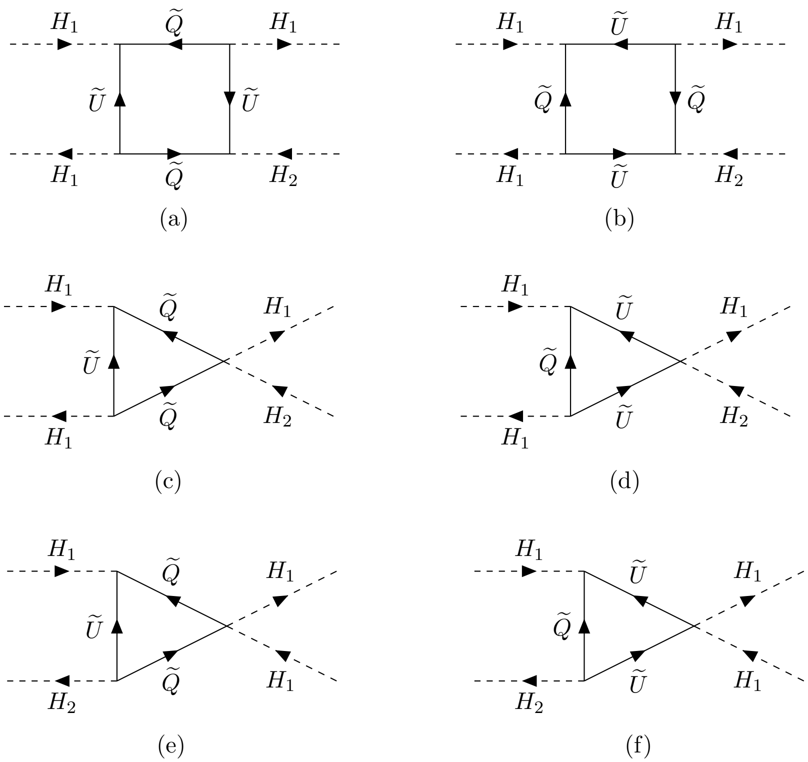
For masses of order 1 TeV, diagrammatic and EFT approach agree well, once the appropriate threshold corrections are included





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

Condition of Alignment : 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

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

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

At moderate or large $\tan\beta$

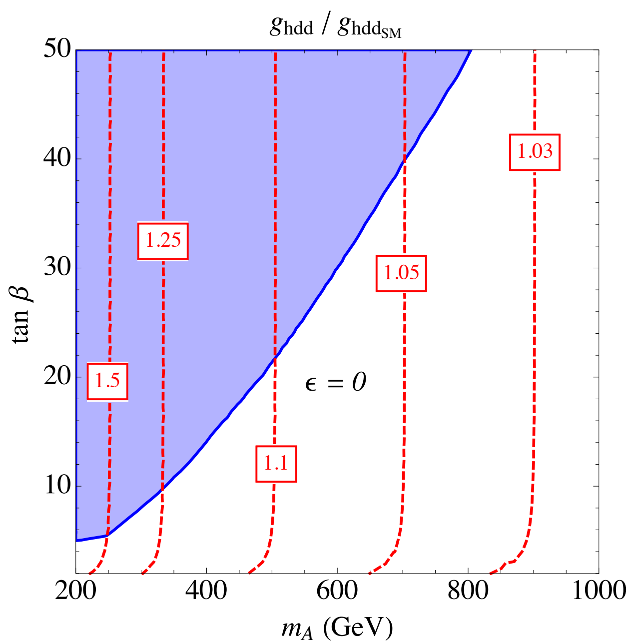
This expression may be given in terms of mh.
Alignment difficult close to maximal mixing.

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

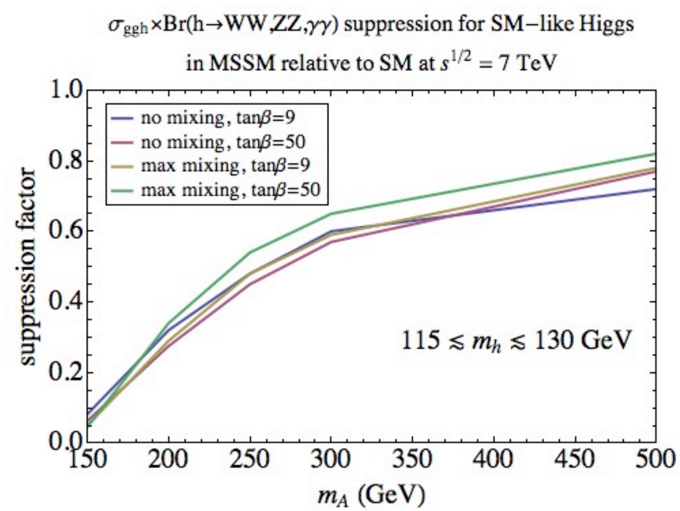
- In this regime, $\lambda_{6,7} \simeq 0$, and

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

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



Draper,Liu,C.W.'10



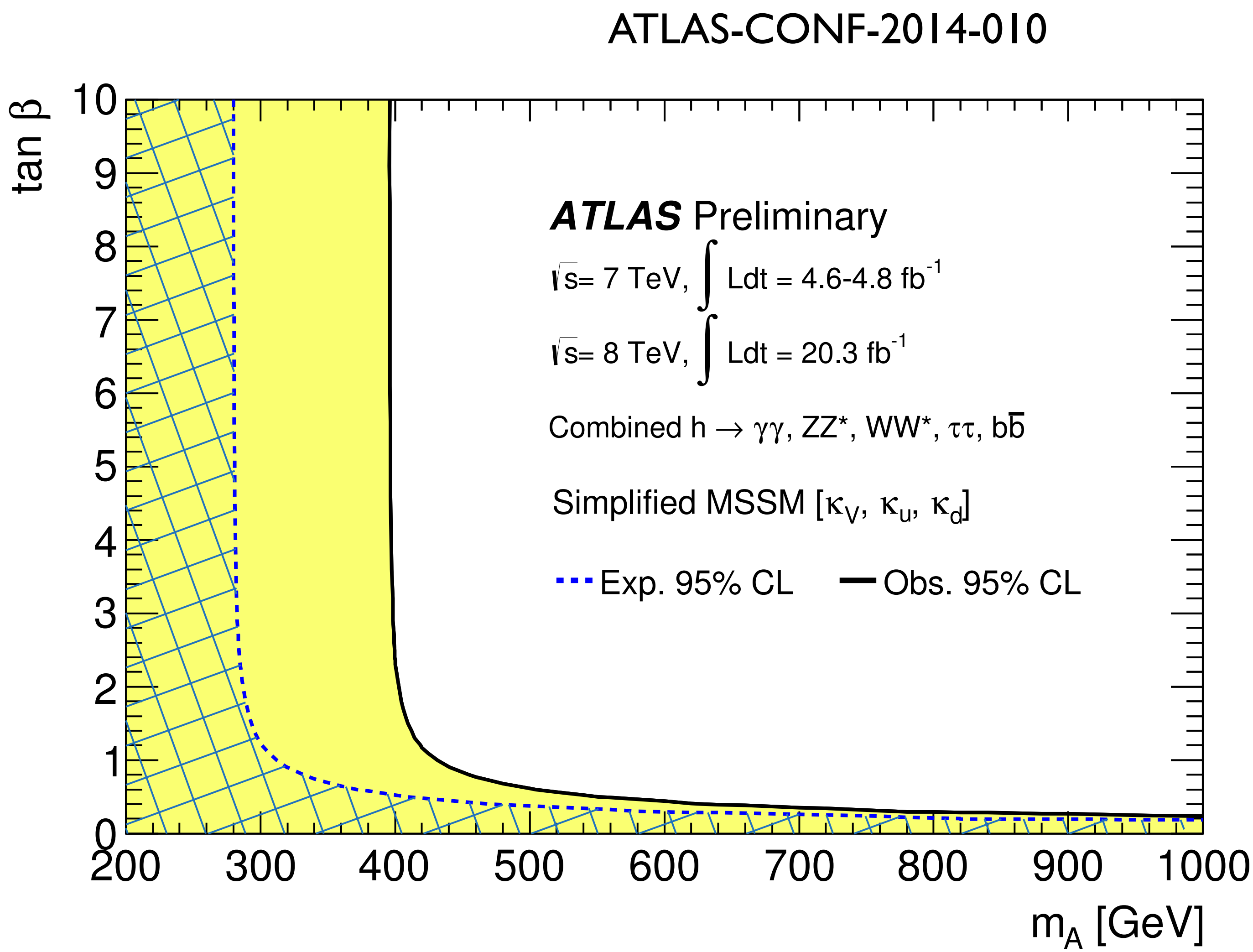
Carena, Low, Shah, C.W.'13

For moderate or large values of tanβ

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



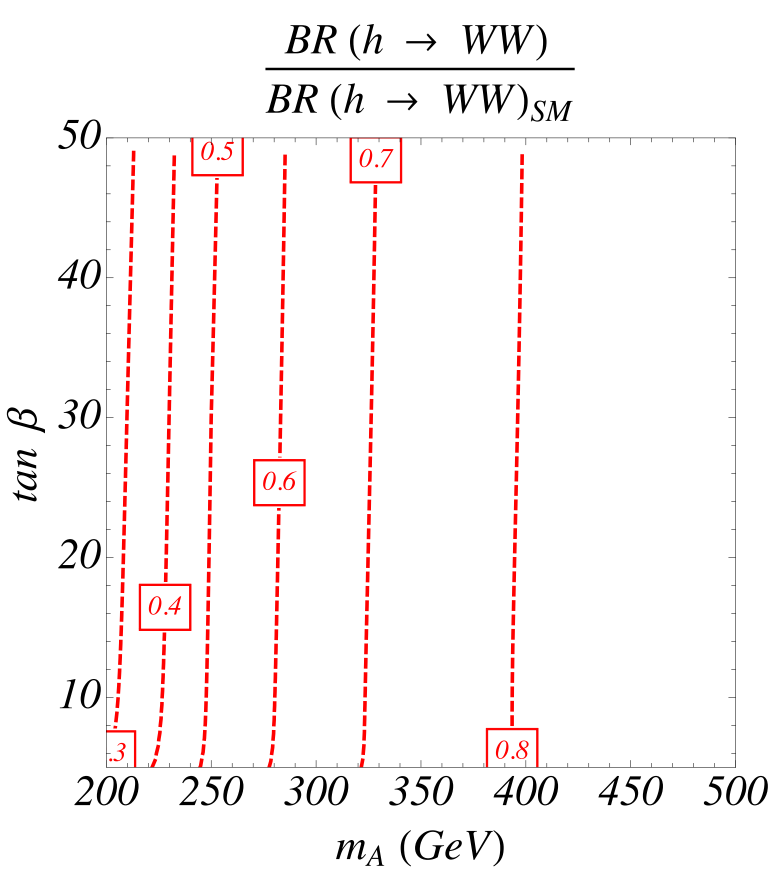
Bounds coming from precision h measurements

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

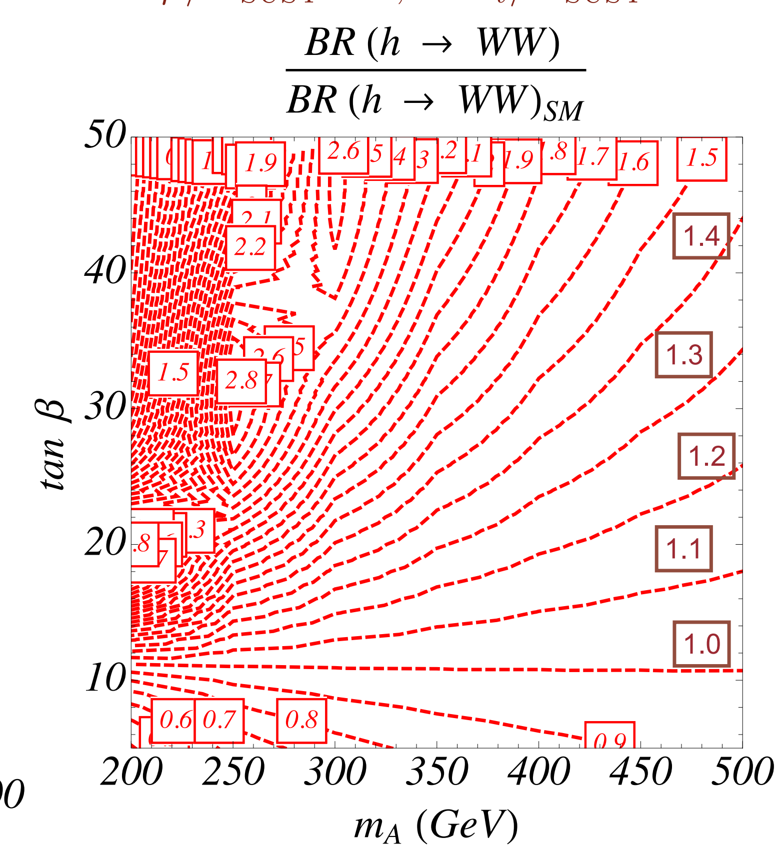
Higgs Decay into Gauge Bosons

Mostly determined by the change of width

Small μ



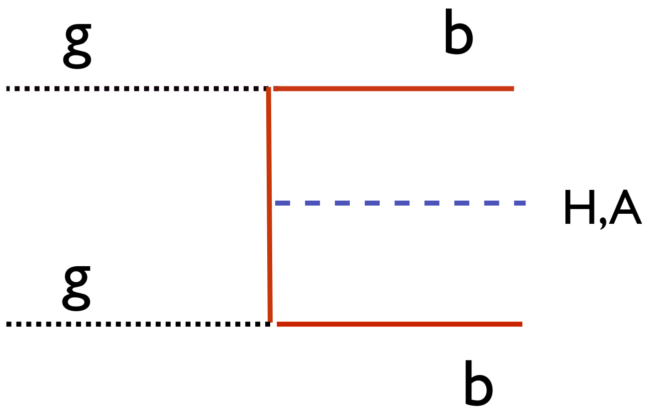
$\mu/M_{\rm SUSY} = 2, \quad A_t/M_{\rm SUSY} \simeq 3$



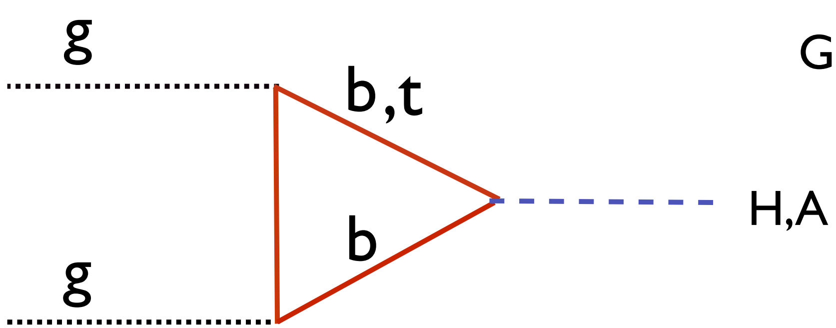
CP-odd Higgs masses of order 200 GeV and tanβ = 10 OK in the alignment case

Non-Standard Higgs Production

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



Associated Production

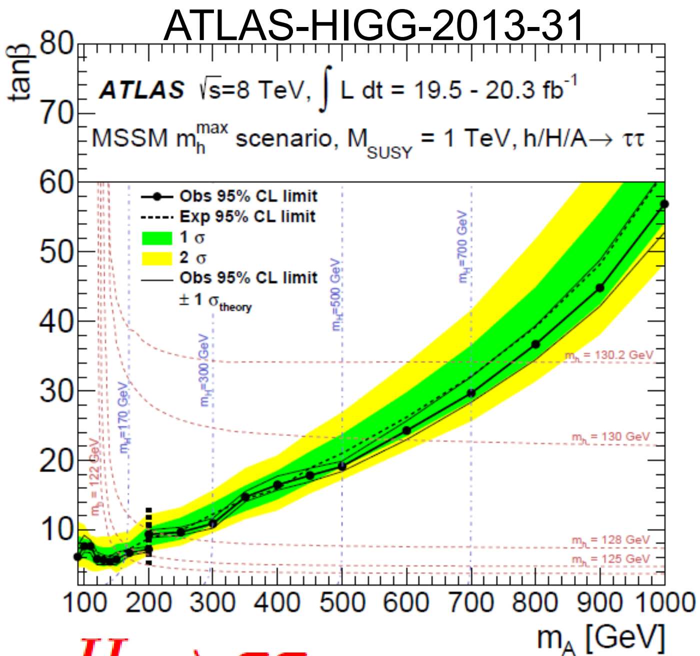


Gluon Fusion

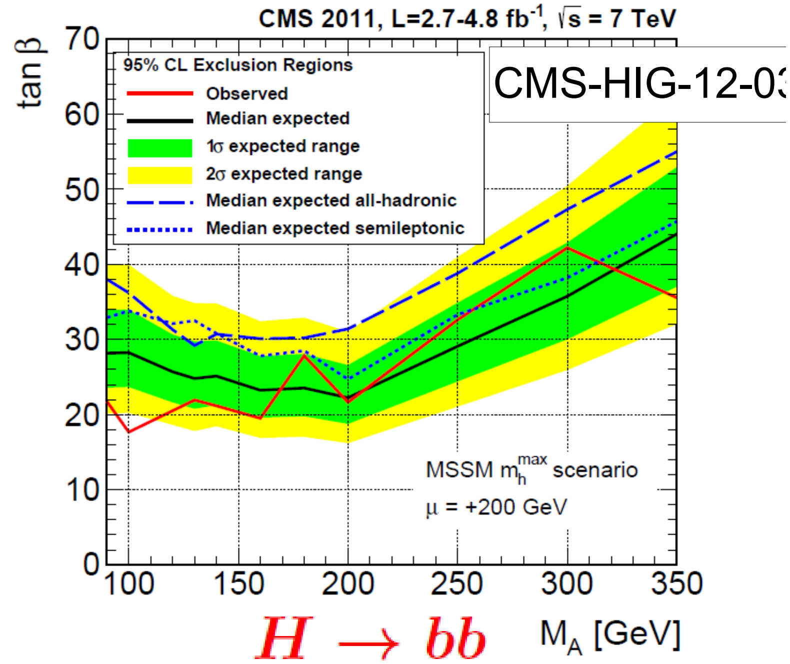
$$g_{Abb} \simeq g_{Hbb} \simeq \frac{m_b \tan\beta}{(1+\Delta_b)v}, \qquad g_{A\tau\tau} \simeq g_{H\tau\tau} \simeq \frac{m_\tau \tan\beta}{v}$$

Non-Standard Higgs Searches

Neutral Higgs bosons



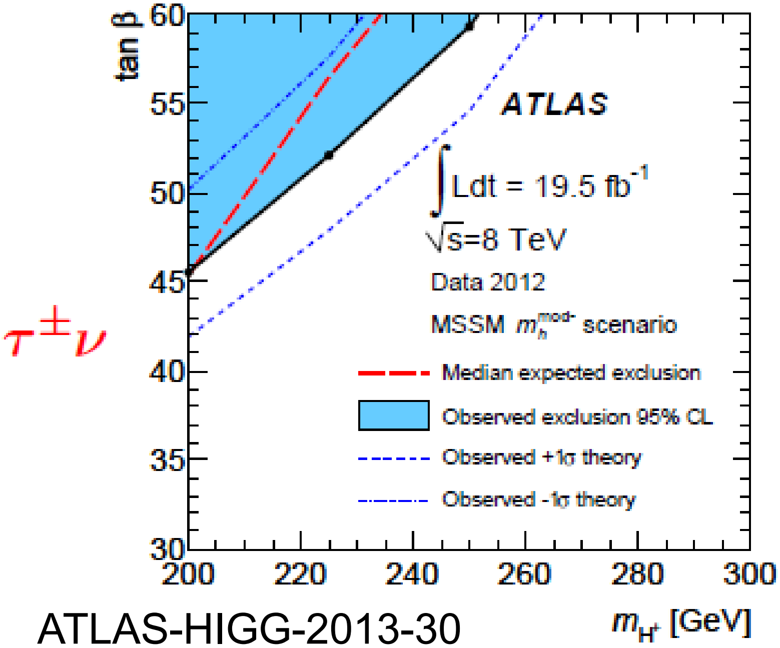
$H \to \tau\tau$



$H \to bb$

Charged Higgs bosons

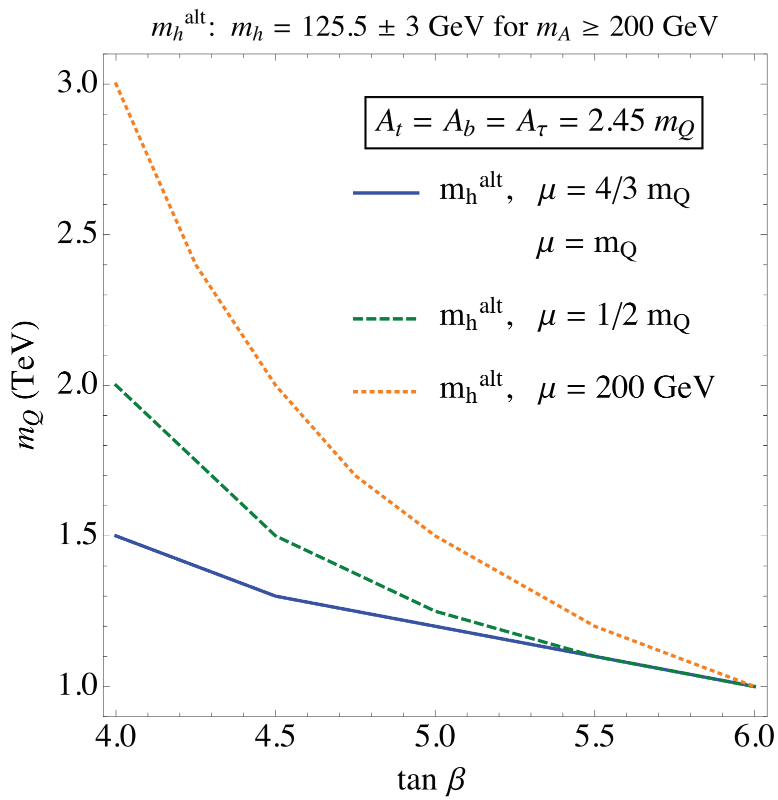
$H^\pm \to \tau^\pm \nu$

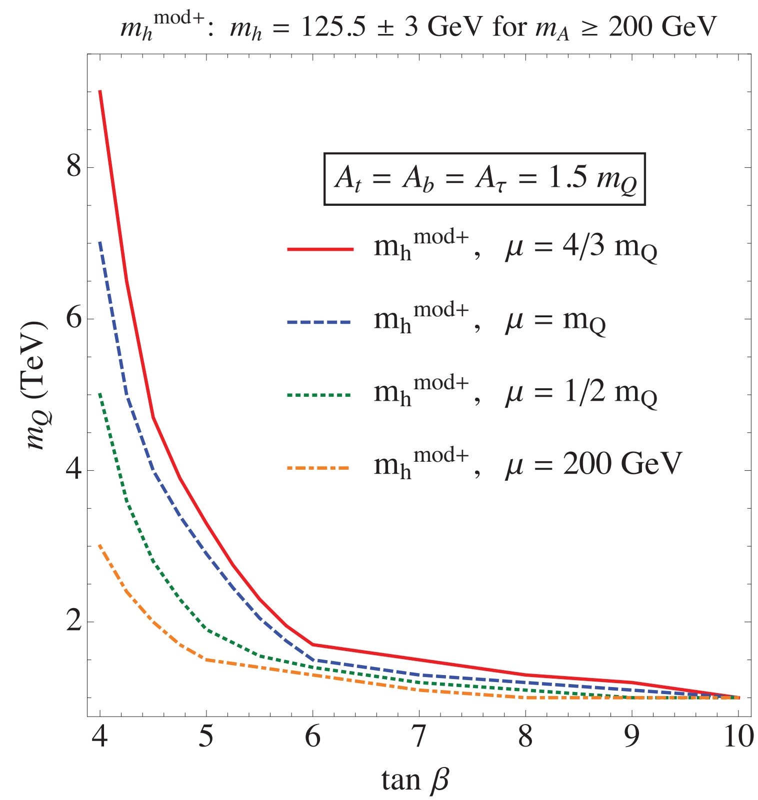


Variation of the SUSY scale (FeynHiggs)

P. Draper, G. Lee and C.W.'13; G. Lee, C.W.'15

At lower values of $\tan\beta$ the stop mass scale should be raised in order to recover the proper values of m_h





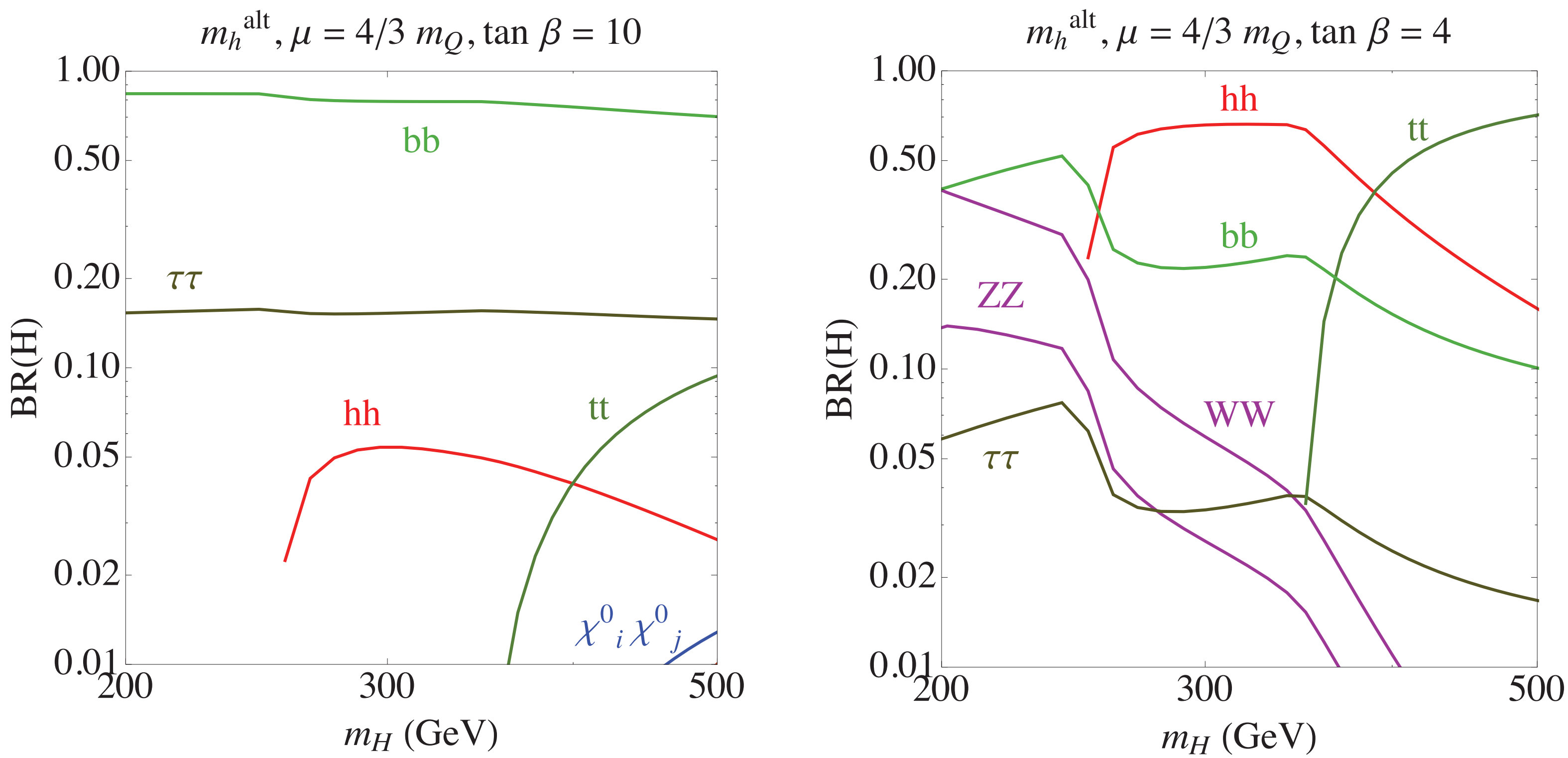
M. Carena, H. Haber, I. Low, N. Shah, C.W.'14

Heavy Supersymmetric Particles

Heavy Higgs Bosons : A variety of decay Branching Ratios

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

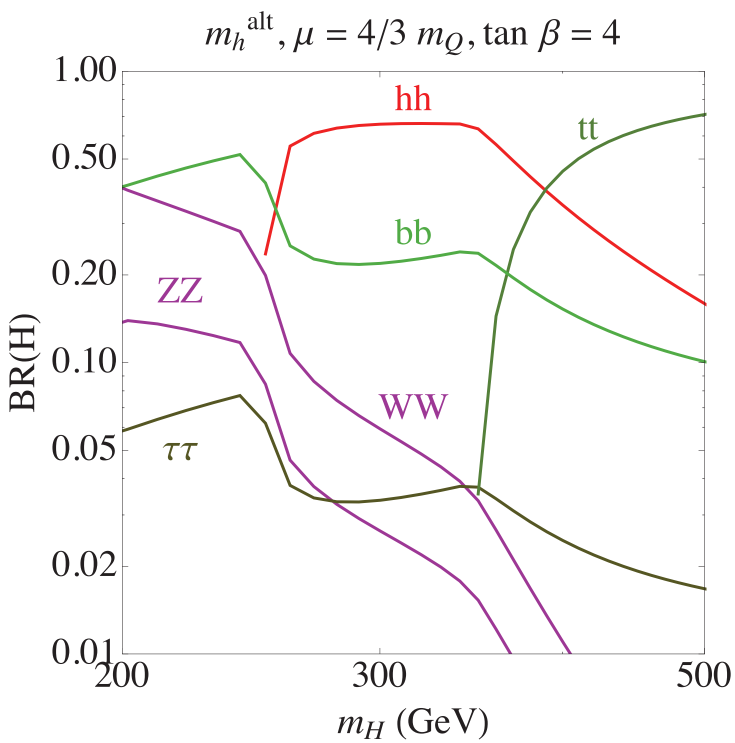
Depending on the values of μ and tanβ different search strategies must be applied.



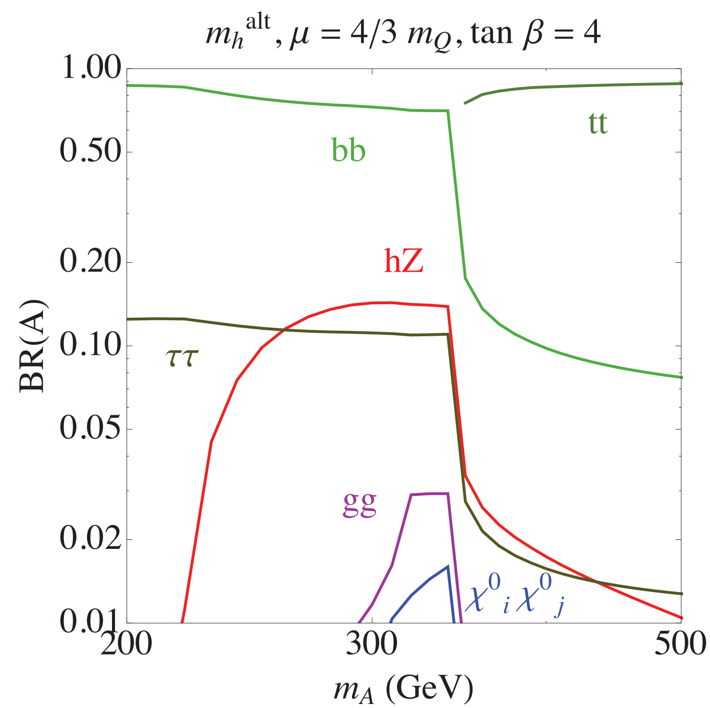
At large tanβ, bottom and tau decay modes dominant.
As tanβ decreases decays into SM-like Higgs and wek bosons become relevant

Large μ and small tanβ

hh dominant until top threshold



hZ relevant

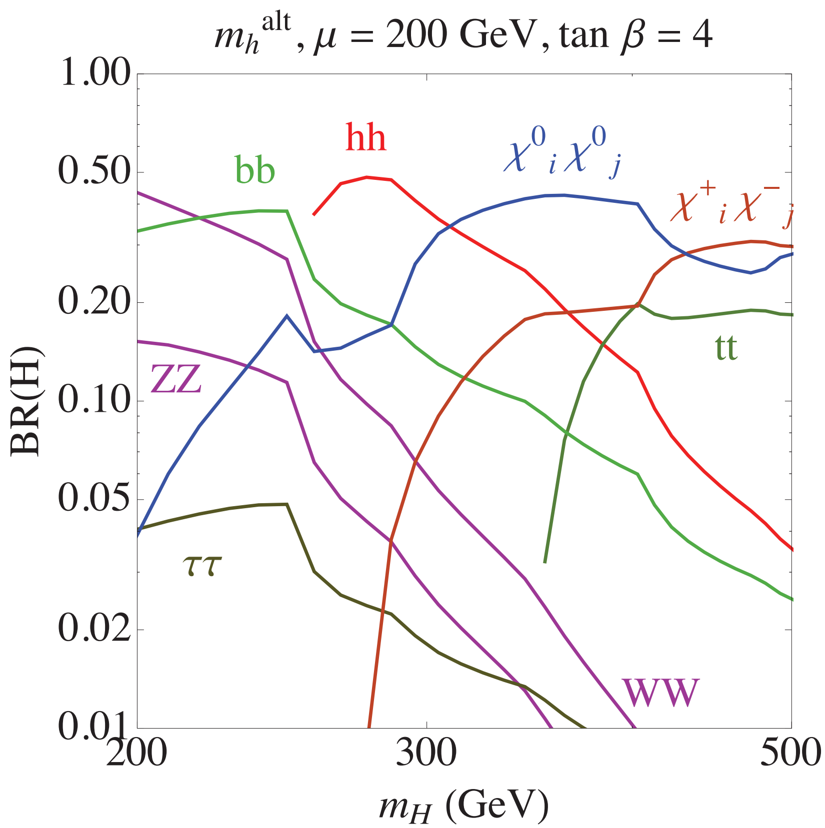


Decays into gauge and Higgs bosons become important. Observe, however that the BR(A to τ τ) remains large up to the top-quark threshold scale

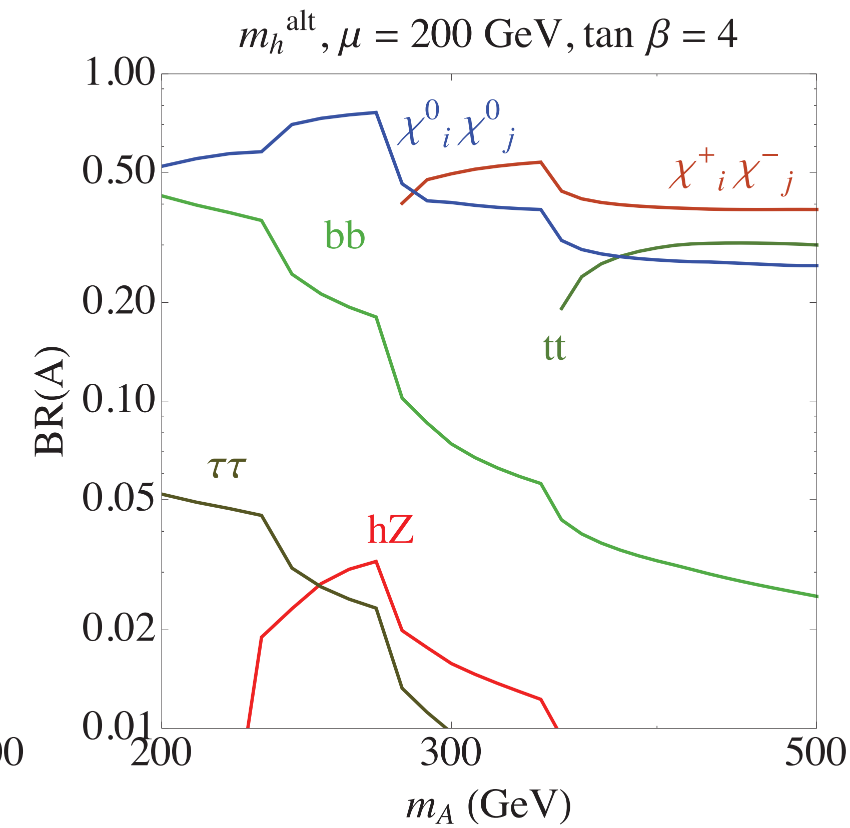
Light Charginos and Neutralinos can significantly modify M the CP-odd Higgs Decay Branching Ratios

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.

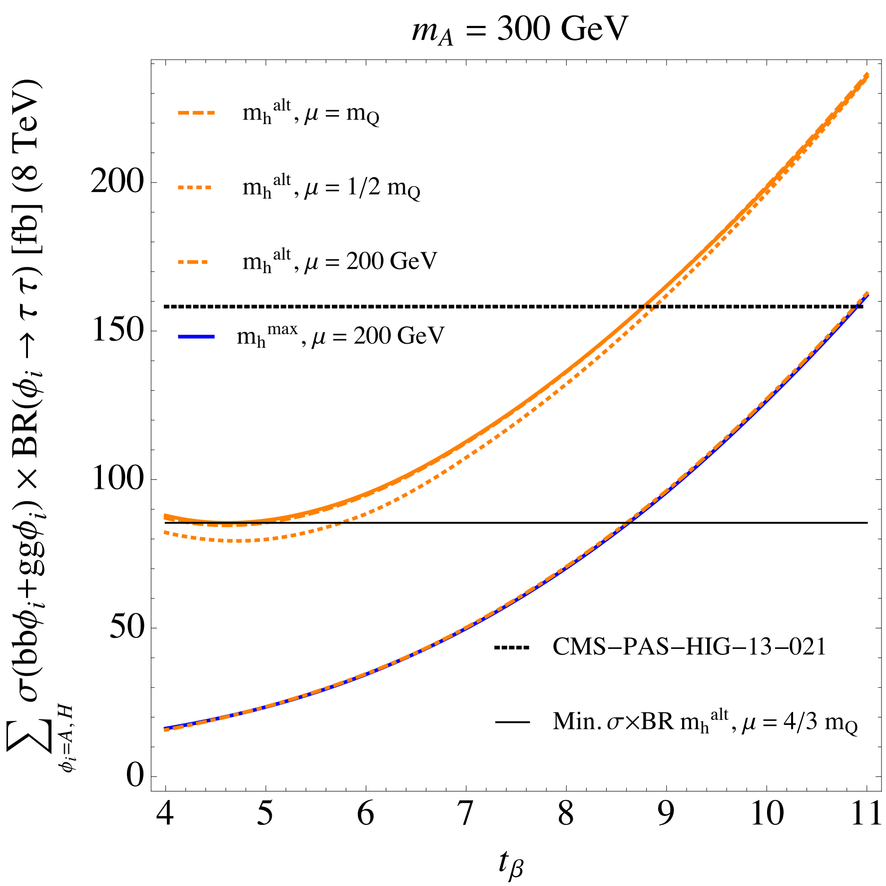
Comments on Production Cross Sections

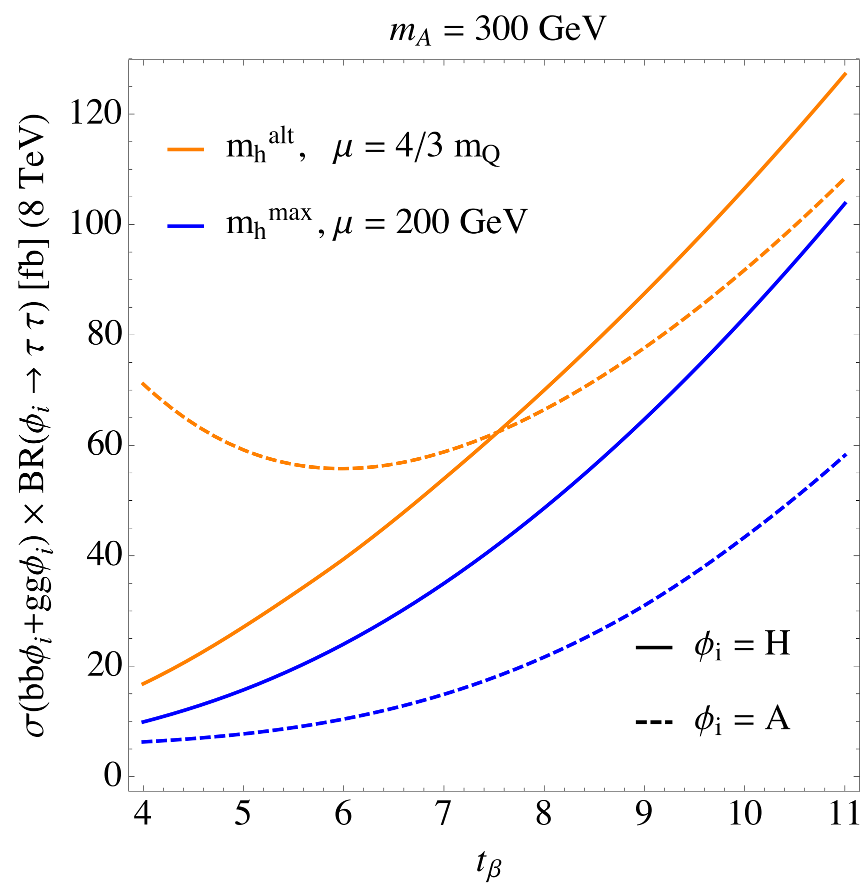
- At moderate or large values of tanβ, the production cross section is governed by the large coupling of bottom-quarks to non-standard Higgs bosons.
- At small values of tanβ, instead, the bottom coupling become small, while the top quark coupling becomes large. The main production cross section is induced by gluon fusion processes, mediated by the top-quark.
- There is a minimum of the production cross section of non-standard Higgs bosons in the region where neither the top, nor the bottom couplings are large. This occurs at values of tanβ about 6 or 7.
- At small values of tanβ, the heavy CP-even Higgs boson decay branching ratio into τ pairs is suppressed, while the CP-odd Higgs boson one is only suppressed if there are light neutralinos or charginos.
- If light neutralinos or charginos were observed at the LHC, these would provide alternative search channels for non-standard Higgs bosons.

Change in bound of $\tan\beta$ due to variation of μ

Inclusive $\Phi \to \tau\tau$

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

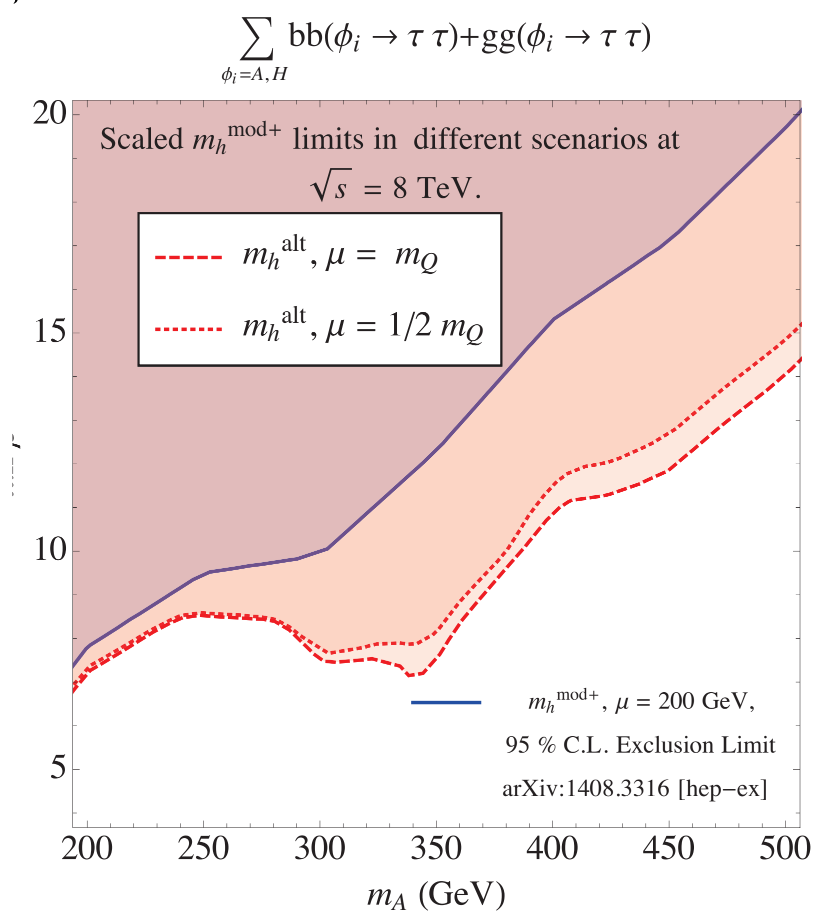




For large values of μ,
the CP-odd Higgs contribution is unsuppressed at low values of tanβ

Variation of the Experimental Bound with the value of μ

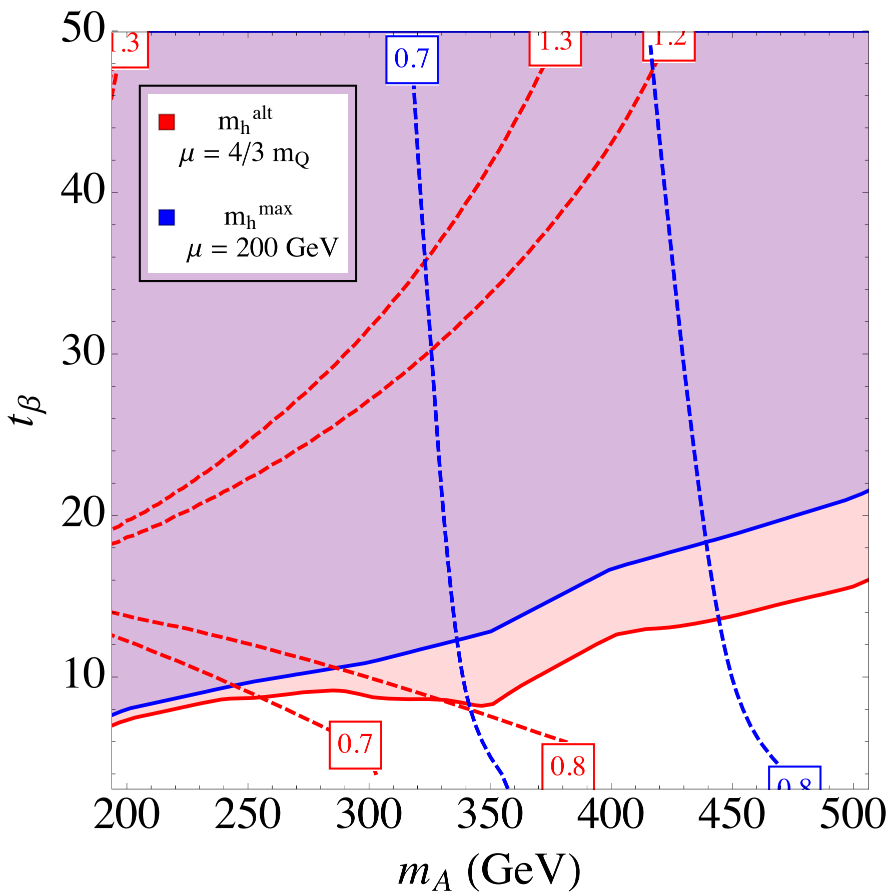
Carena, Haber, Low, Shah, C.W.'14



The bound becomes stronger at large values of μ,
due to the increase in the CP-odd Higgs τ decay branching ratio

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)

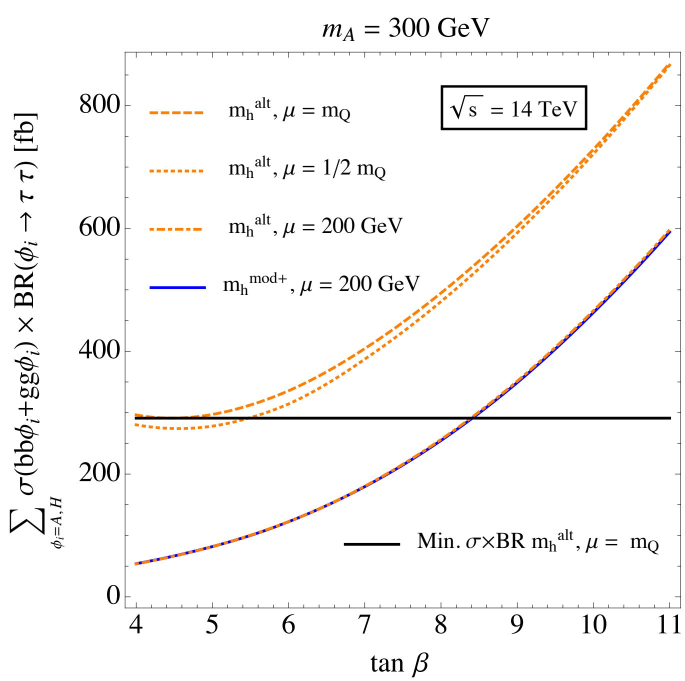
--- $\sigma(bbh+ggh)\times BR(h\to VV)/SM$

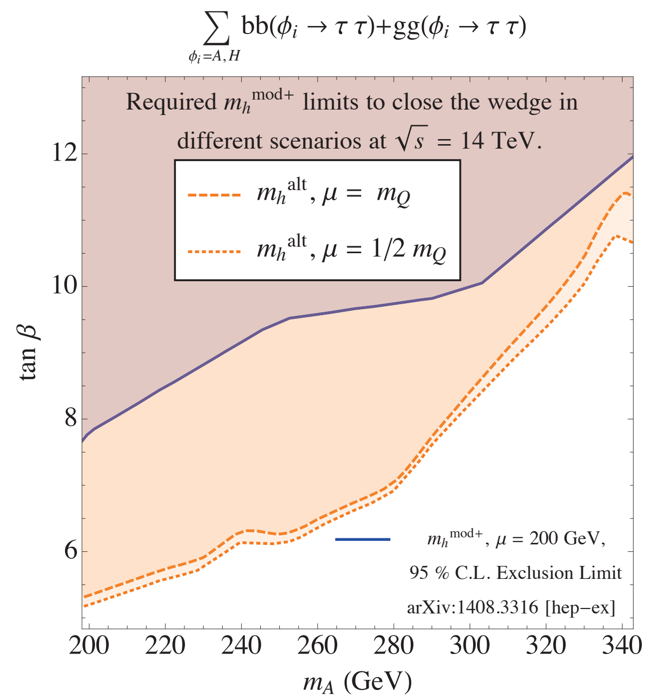
Limits coming from direct searches of $H, A \to \tau\tau$ become stronger for larger values of μ

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

Limit in the mhmax scenario (small μ) that would allow to close the wedge at large μ for masses below 350 GeV





At low values of μ, it is difficult to close the wedge by ττ modes

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.

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 $\tan\beta$

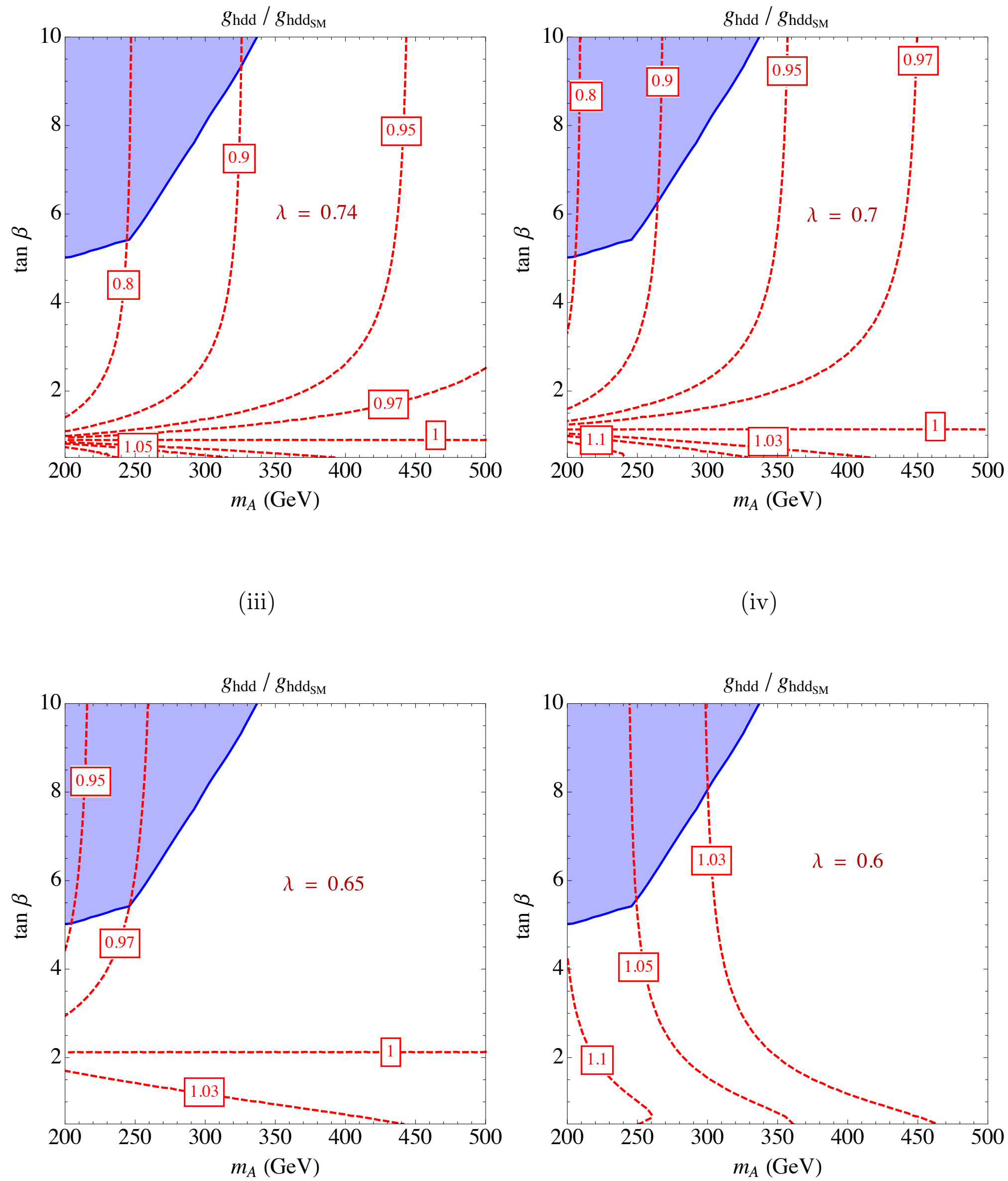
- So, alignment leads to a determination of lambda,

- 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



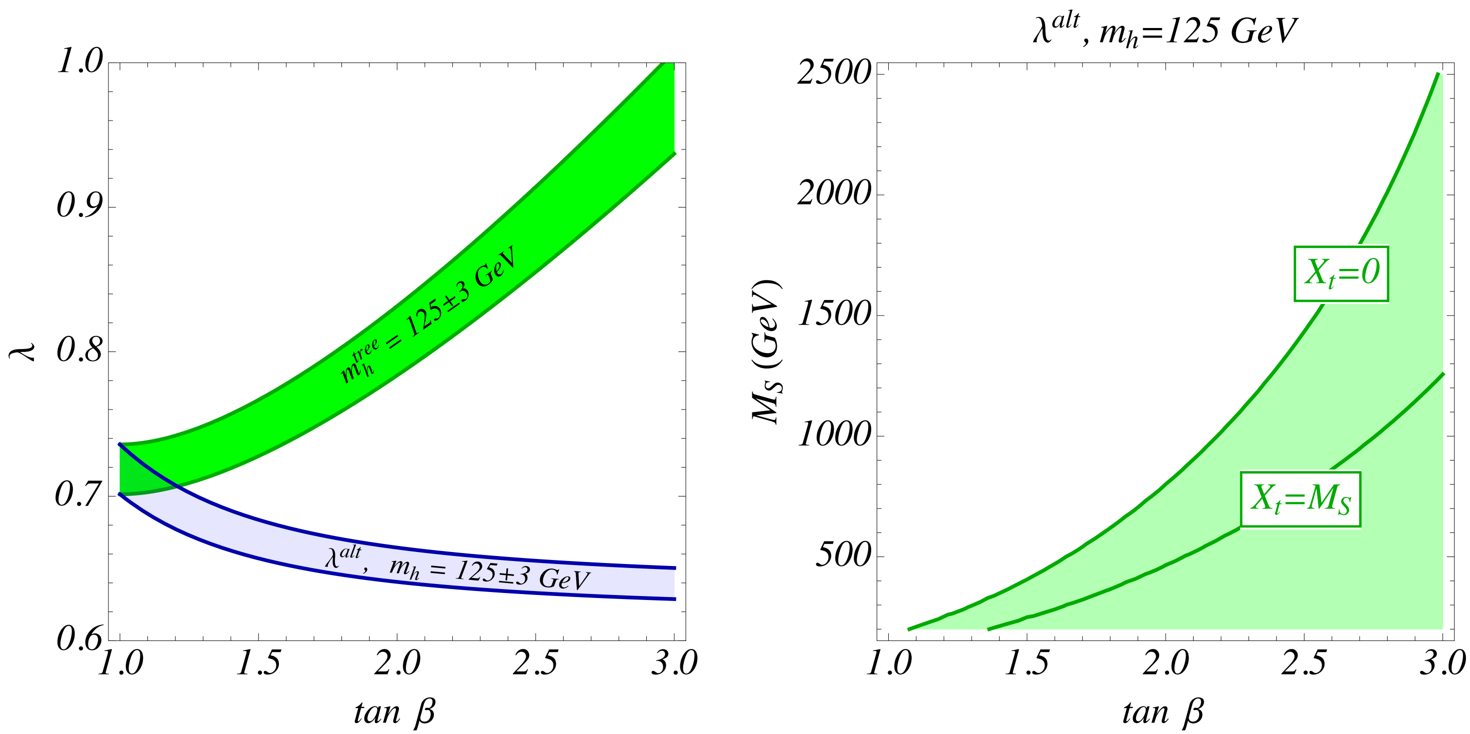
It is clear from these plots that the NMSSM does an amazing job in aligning the MSSM-like CP-even sector, provided lambda is of about 0.65

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

Aligning the 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

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

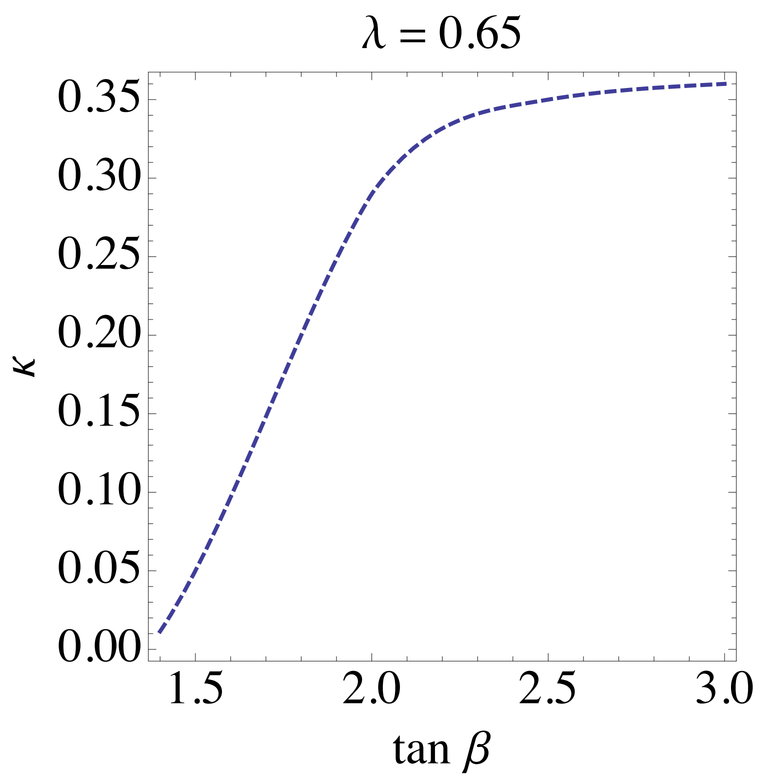
- If one assumes alignment, the expression inside the bracket must cancel

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

- 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

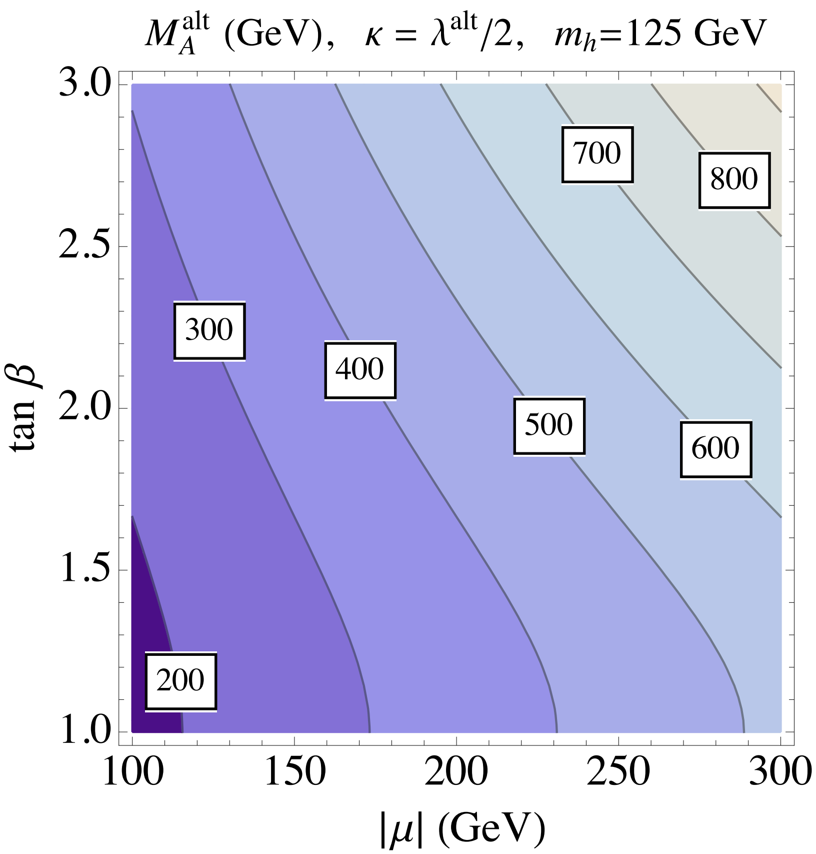
Perturbative Values of kappa

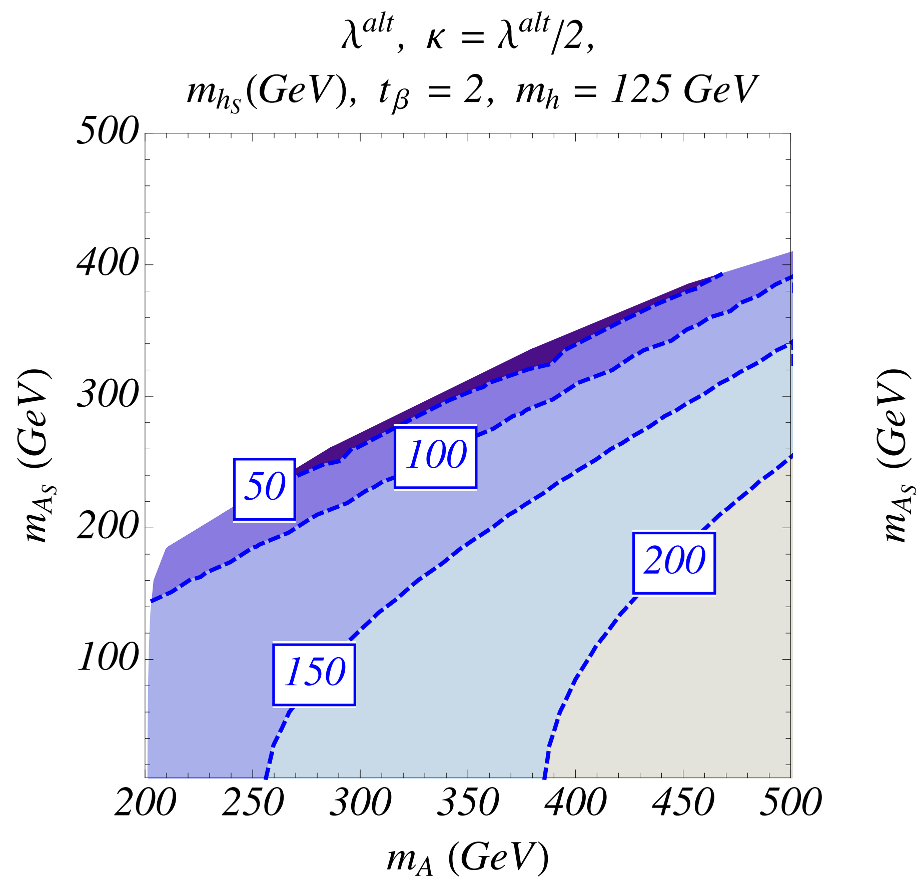


Top Yukawa Coupling becomes stronger for smaller values of $\tan\beta$

Values of the Singlet, Higgsino and Singlino Masses

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





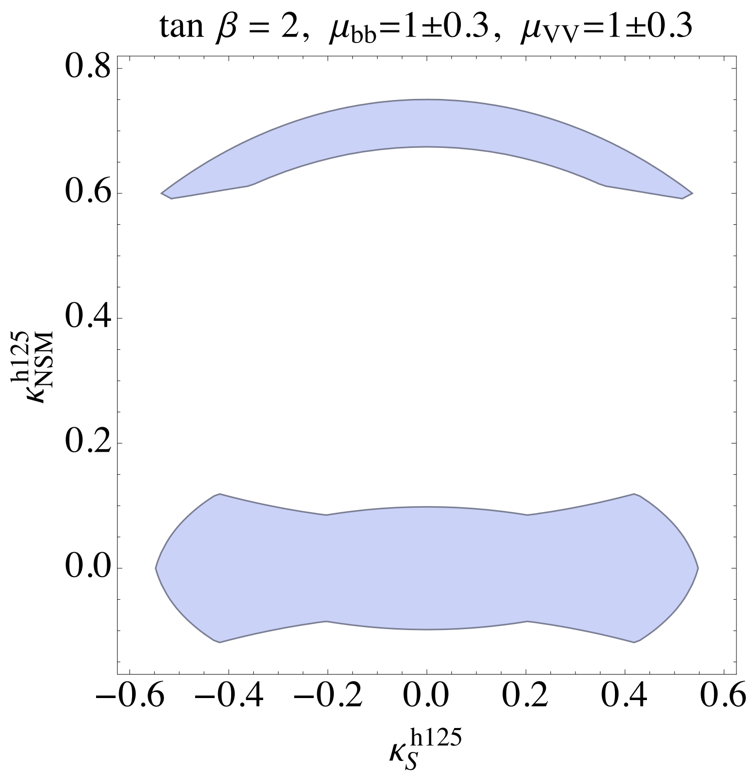
In this limit, the singlino mass is equal to the Higgsino mass.

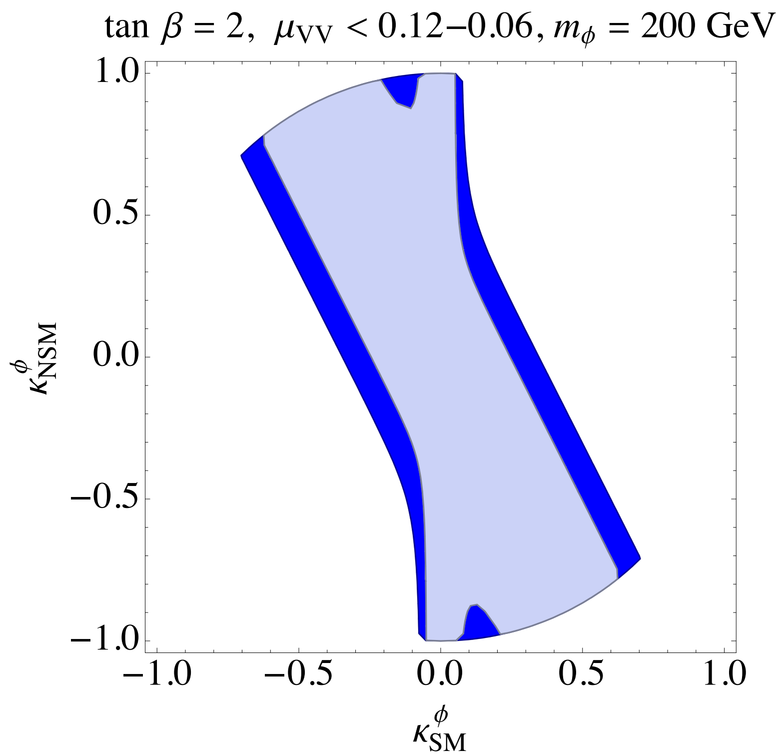
$$m_{\tilde{S}} = 2\mu\frac{\kappa}{\lambda}$$

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

Constraints on Higgs Components
Fairly weak bound on the Higgs singlet component

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





Precision Higgs Measurements
at the 8 TeV LHC

Searches for New States

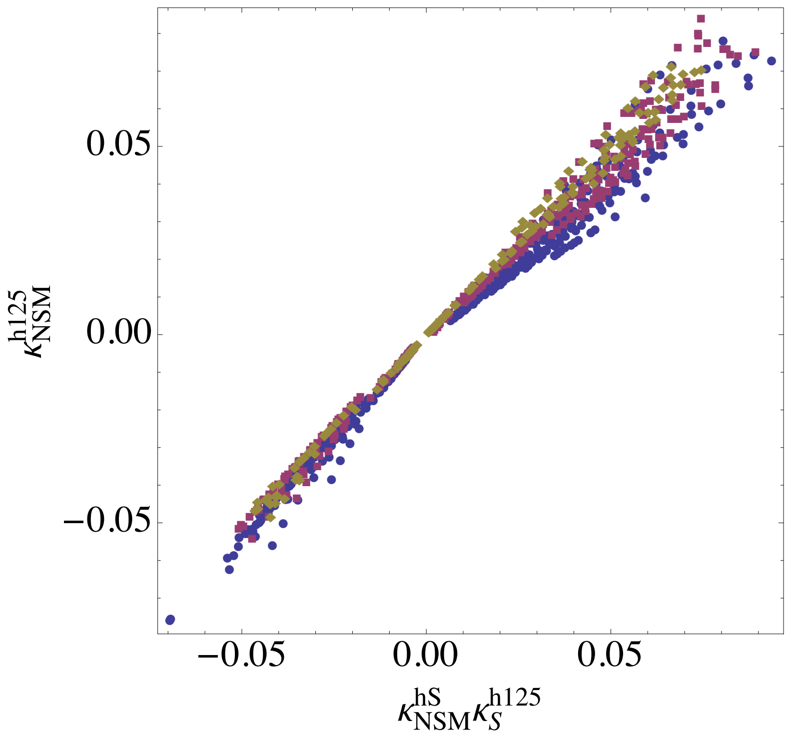
Φ decaying to VV at the LHC

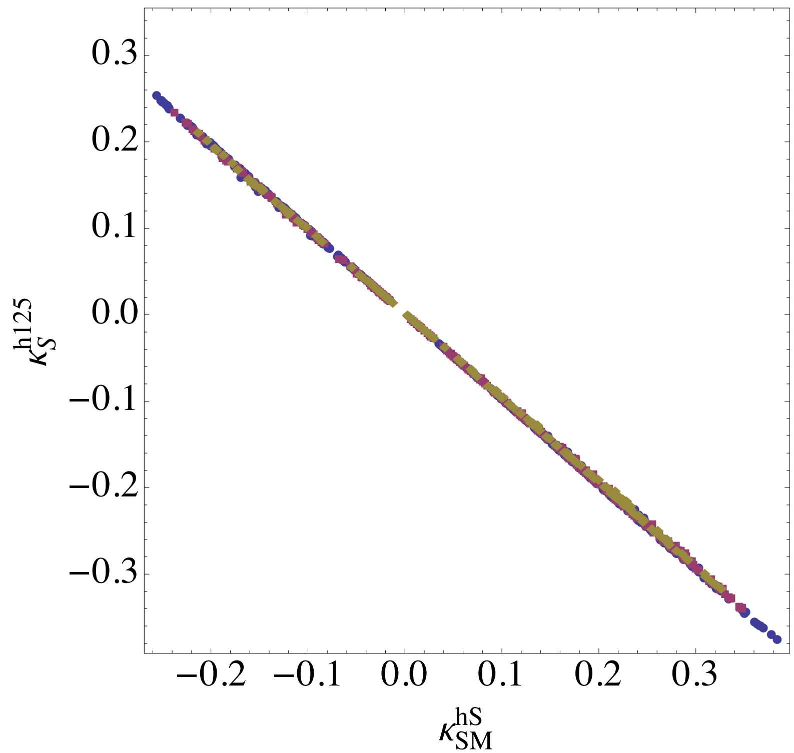
No large tuning necessary in this region of parameters

Components in the aligned NMSSM

Blue : tanβ = 2
Red : tanβ = 2.5
Yellow : tanβ = 3

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

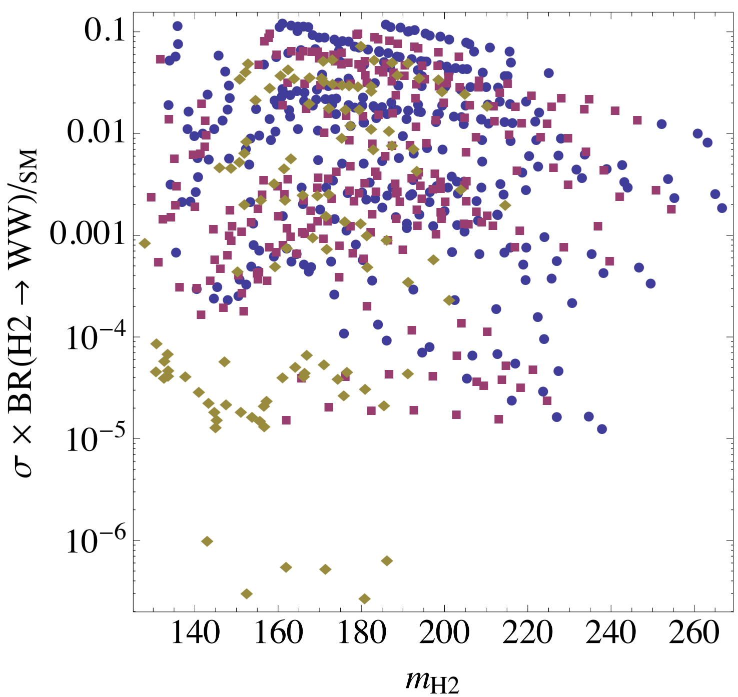




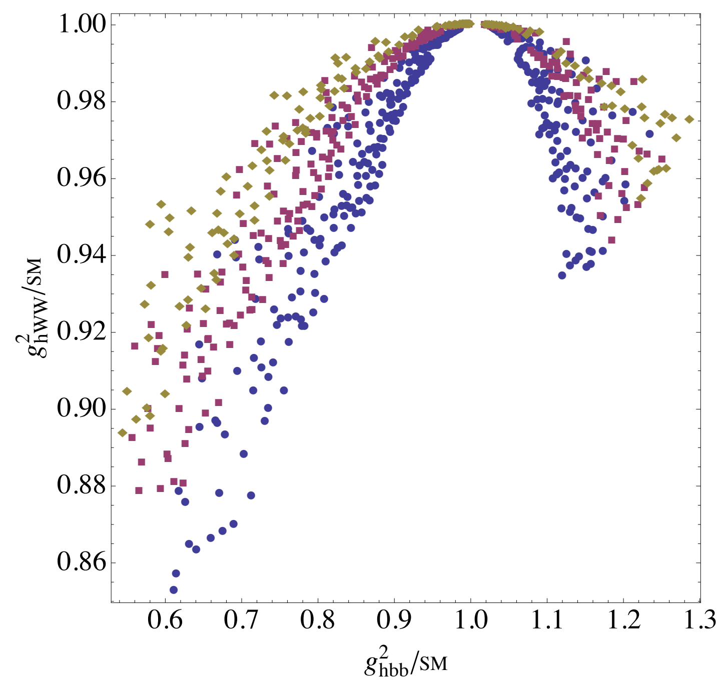
Mixing between the two MSSM CP-even like states induced mostly by the mixing with singlets

Allowed signals and Higgs couplings after incorporating constraints

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



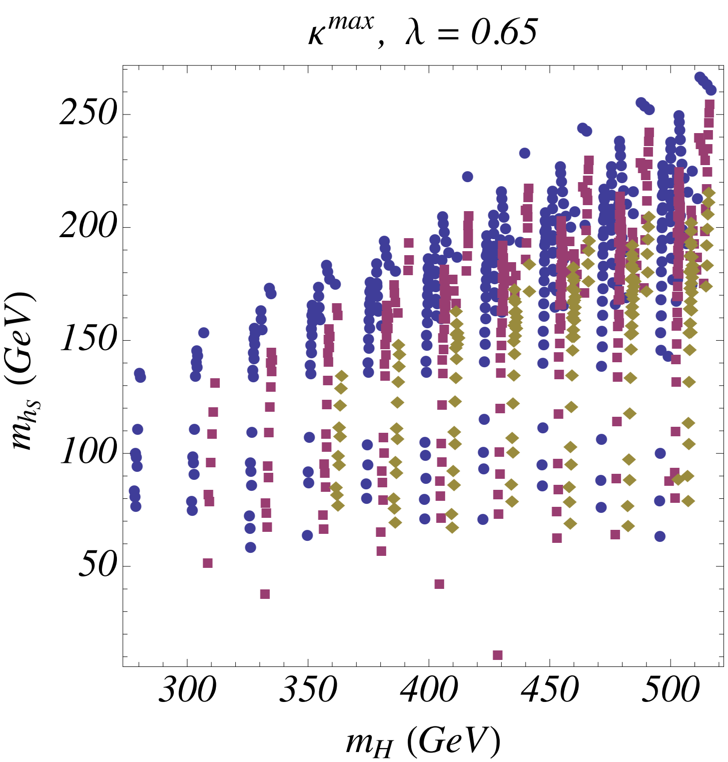
Relevant signal in wide regions of parameters

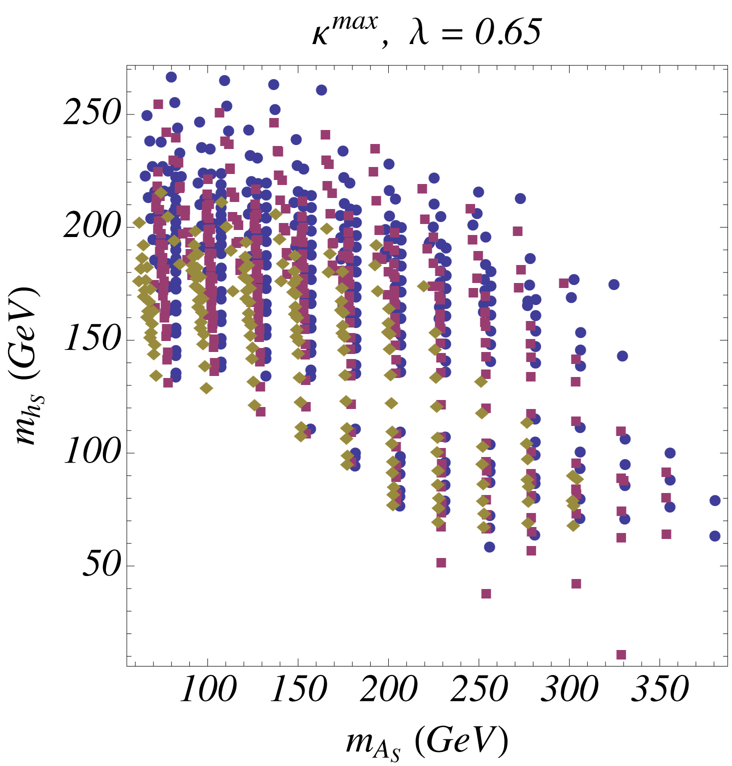


Couplings may present large deviations, if they are correlated

Allowed CP-even and CP-odd Masses

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





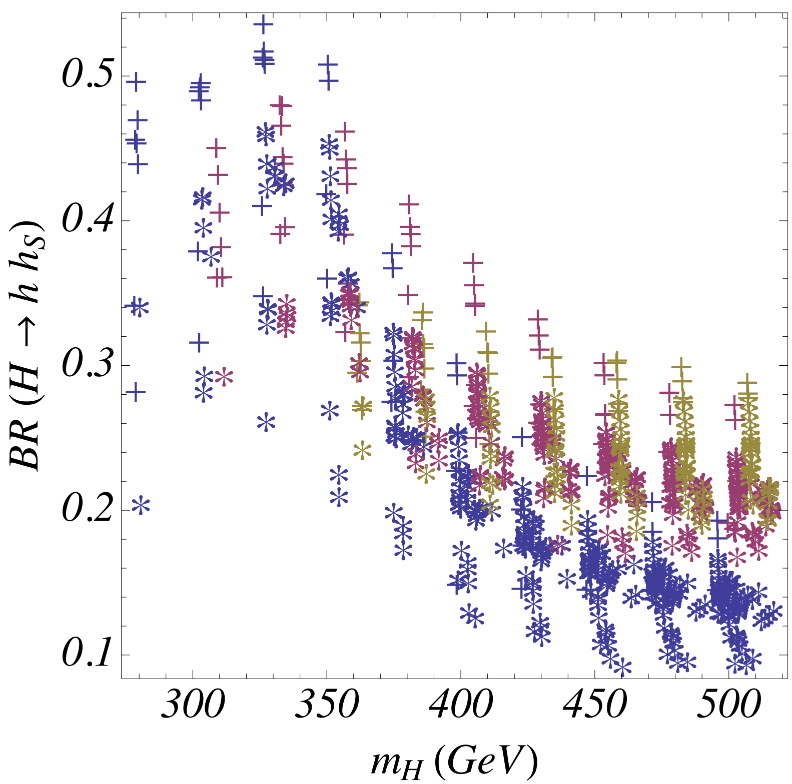
Heavier CP-even Higgs can decay to lighter ones

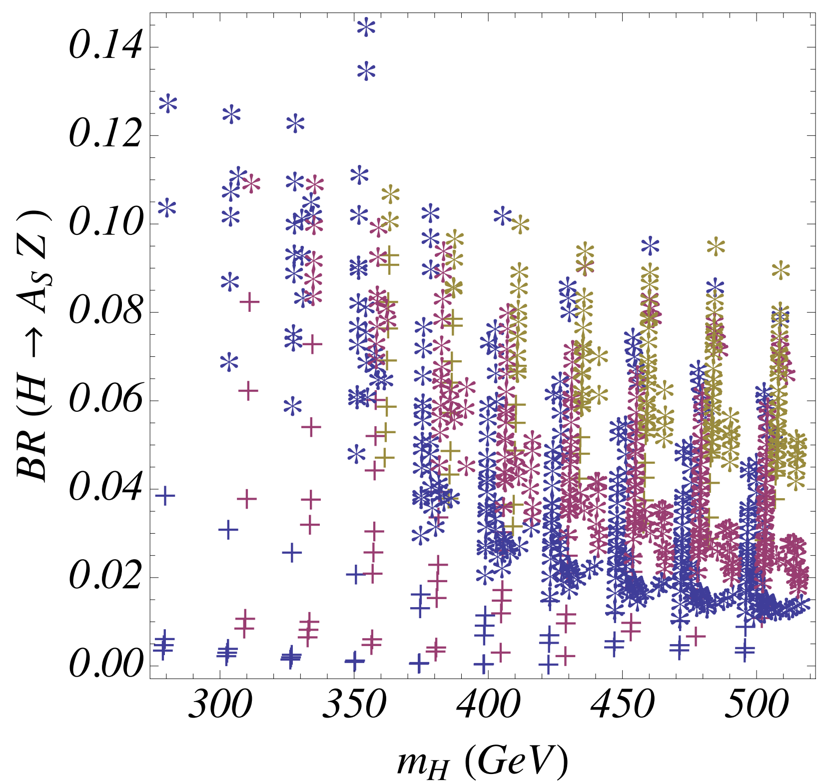
Anti-correlation between singlet-like CP-even and odd masses

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

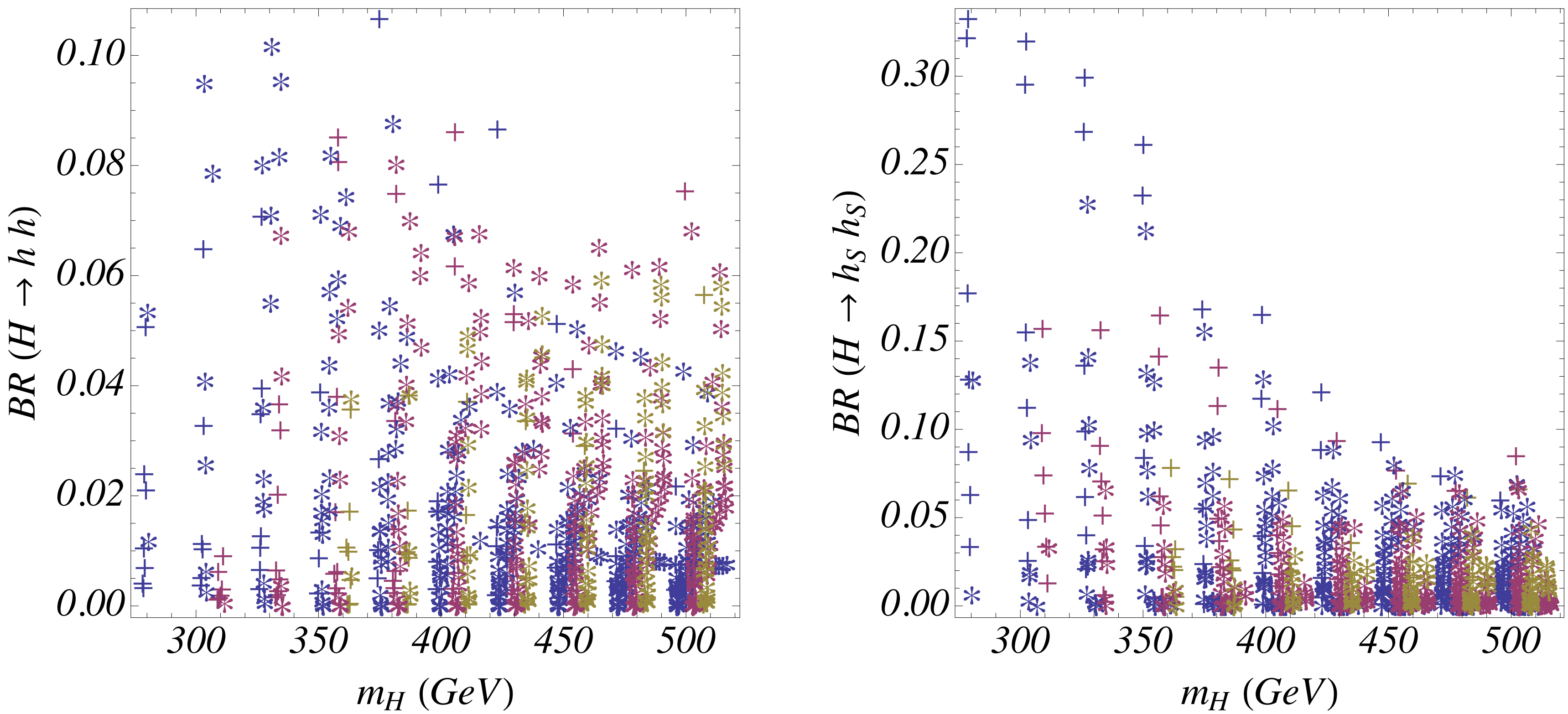




Decays into pairs of SM-like Higgs bosons suppressed by alignment

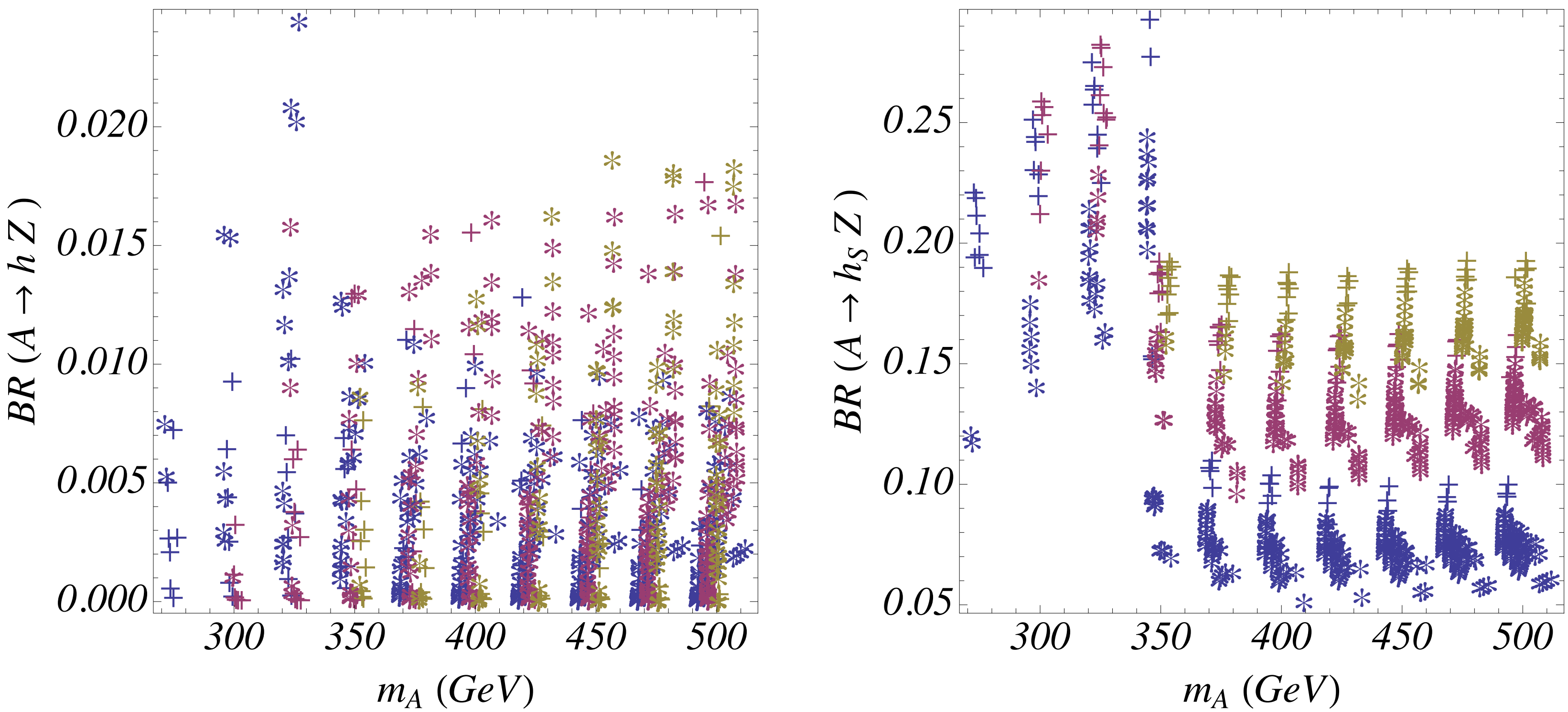
Carena, Haber, Low, Shah, C.W.'15

Crosses : H1 singlet like
Asterix : H2 singlet like



Heavy CP-odd Higgs Bosons have similar decay modes

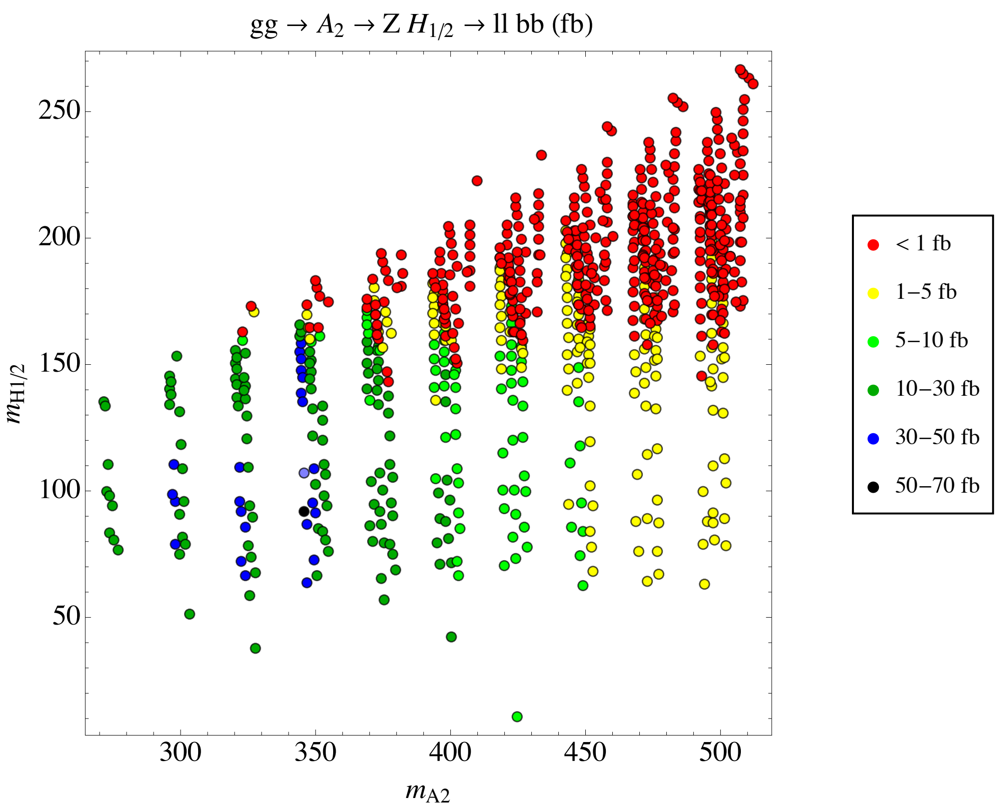
Carena, Haber, Low, Shah, C.W.'15

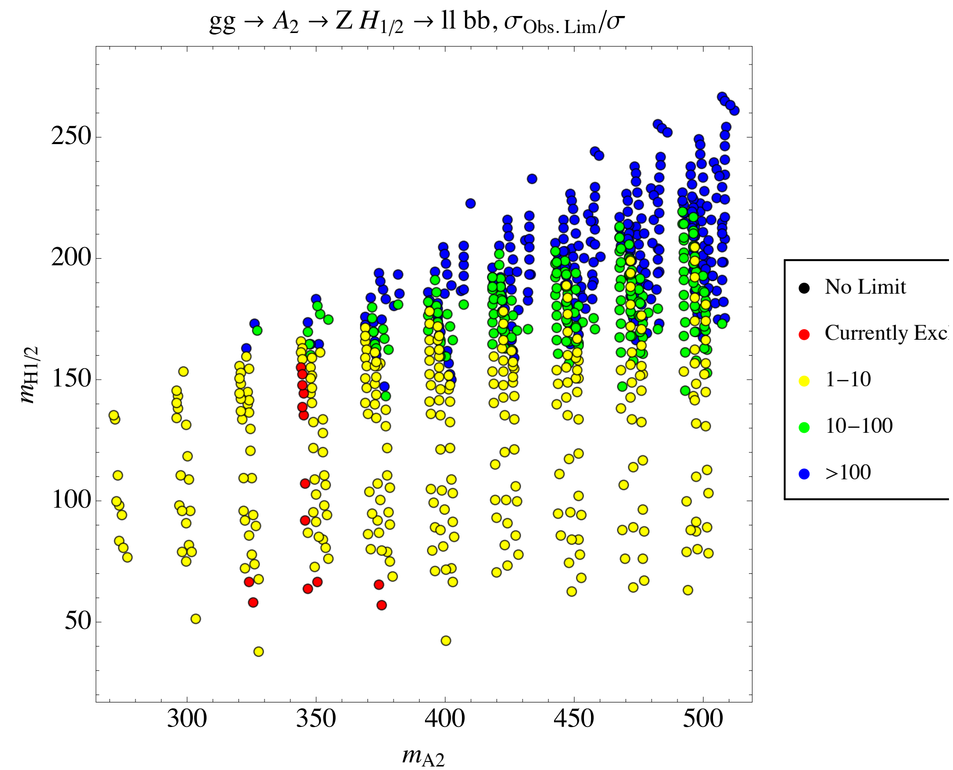


Significant decay of heavy CP-odd
Higgs bosons into singlet like states plus Z

Production Cross Sections quite significant, but yet unconstrained at the 8 TeV LHC

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



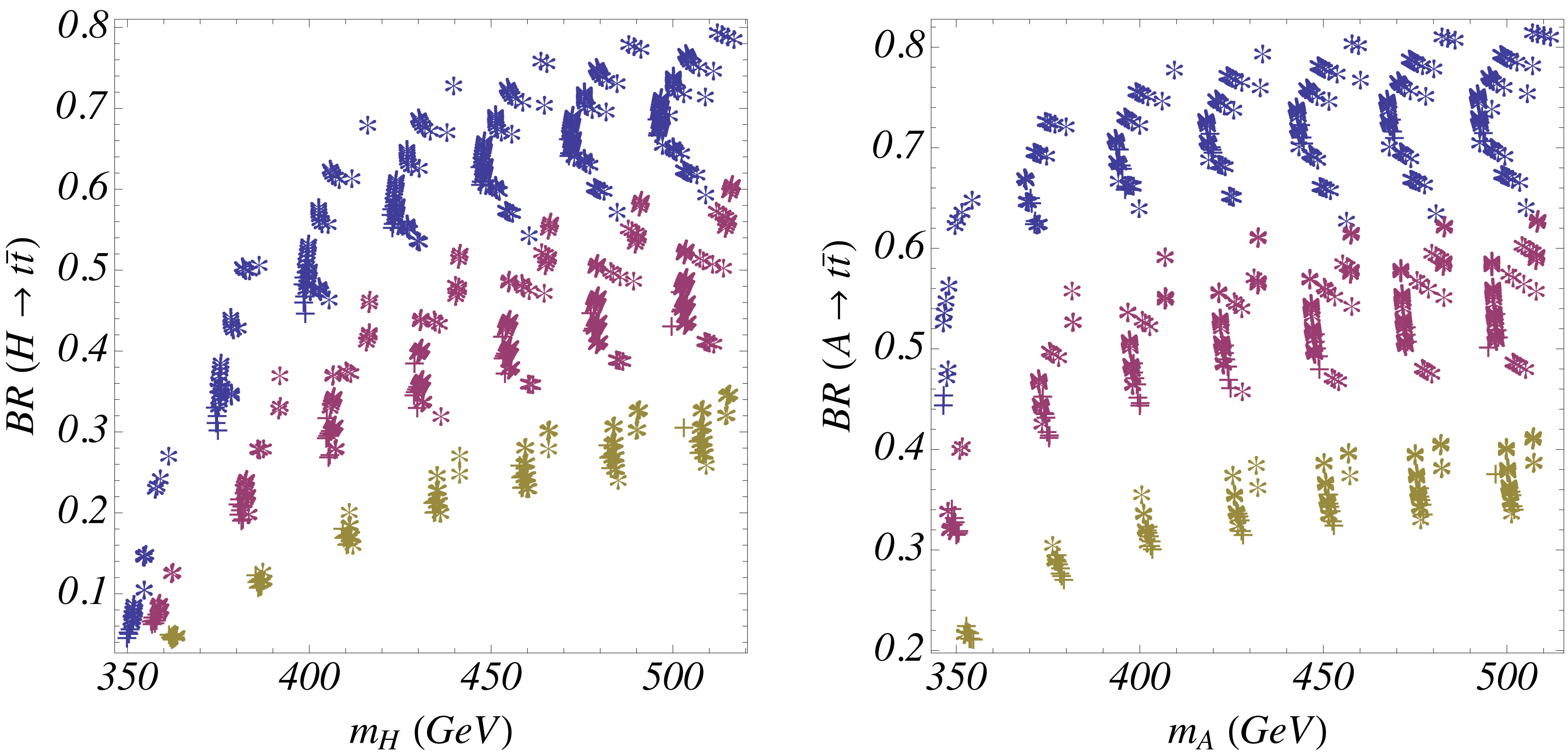


Searches must be done for arbitrary masses, not just 125 GeV

Discovery Mode at the 14 TeV LHC ?

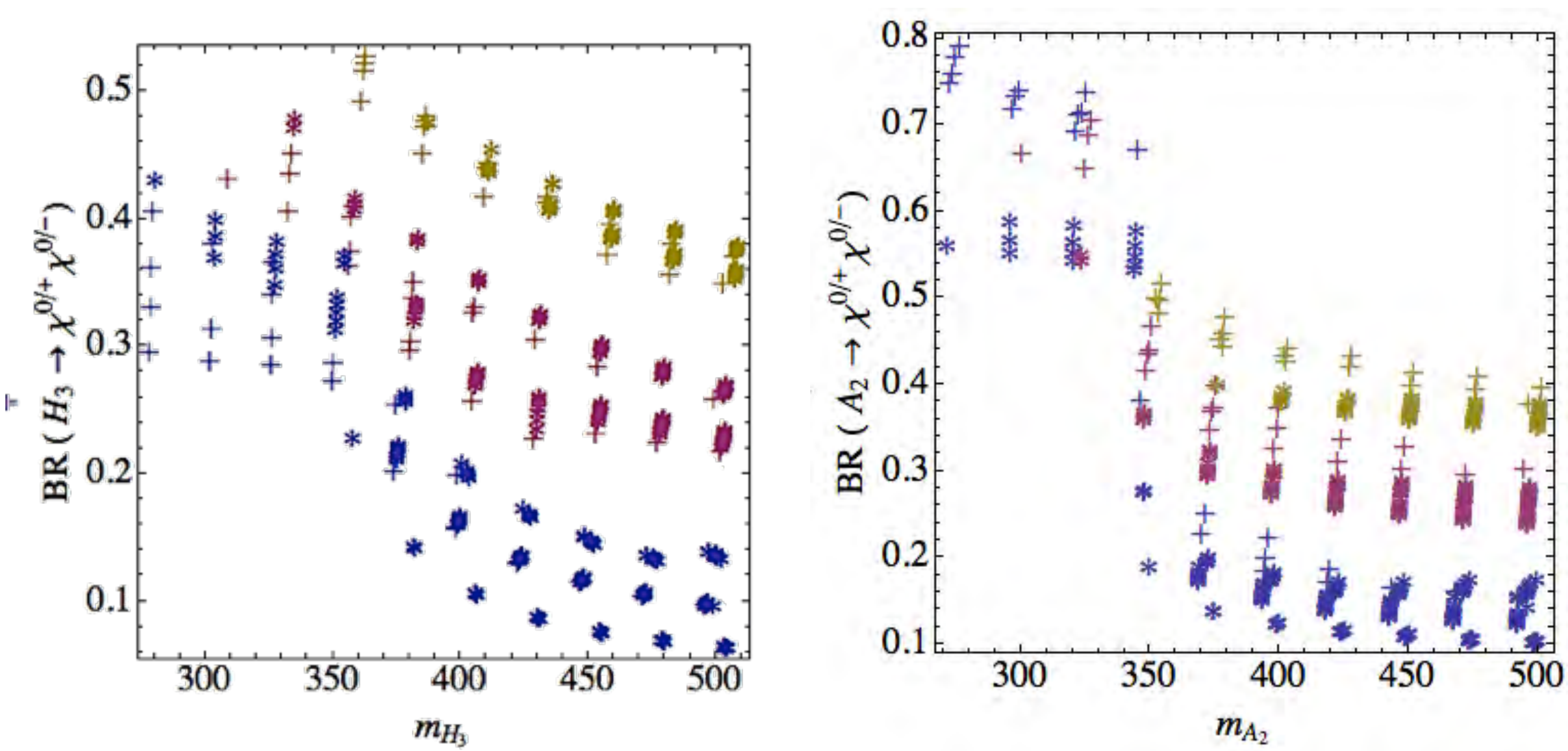
Decays into top significant but may be somewhat suppressed by decays into non-standard particles

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



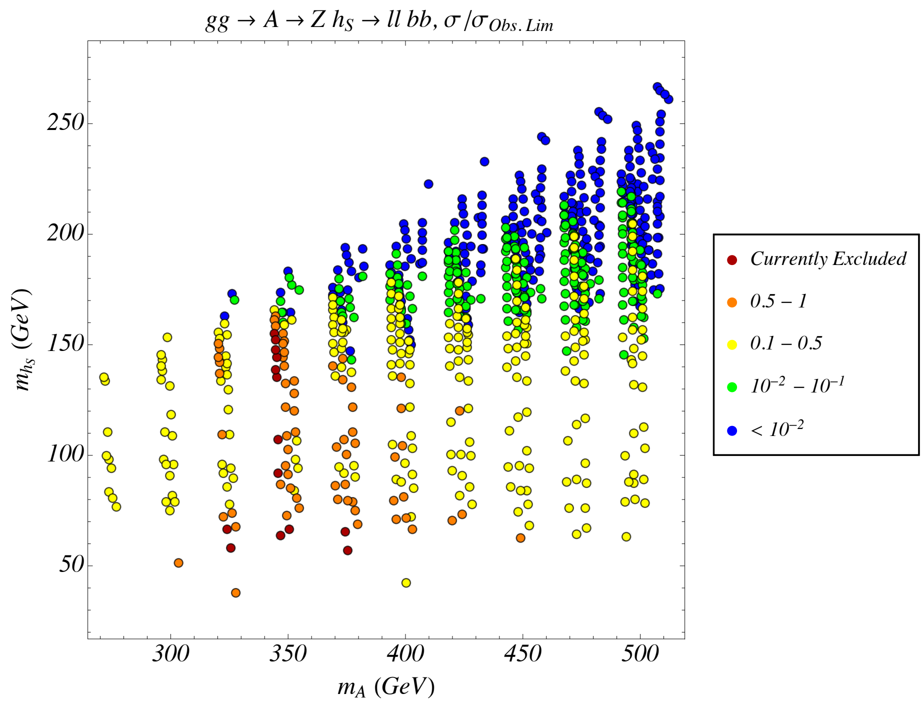
Decays into neutralinos
and charginos are relevant, also above the top threshold

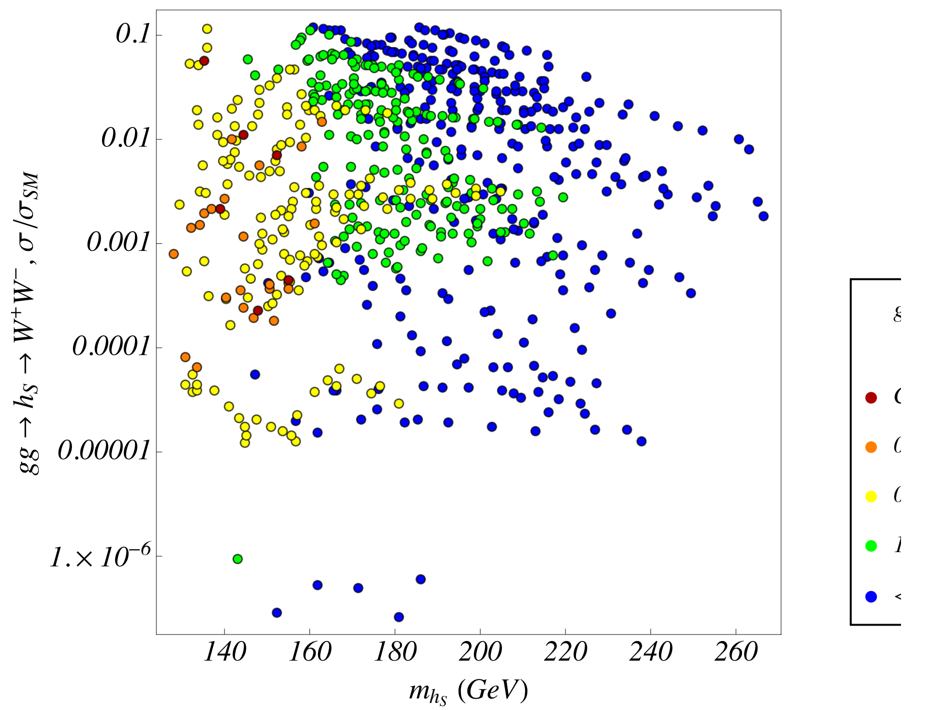
Carena, Haber, Low, Shah, C.W.'15



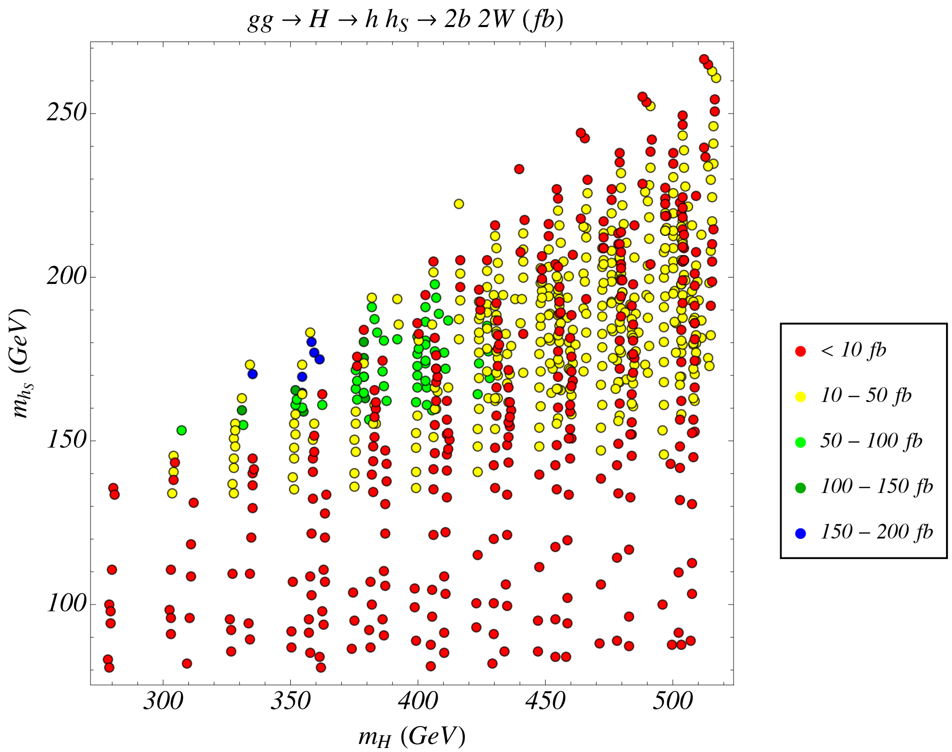
Complementarity between WW and ll bb modes

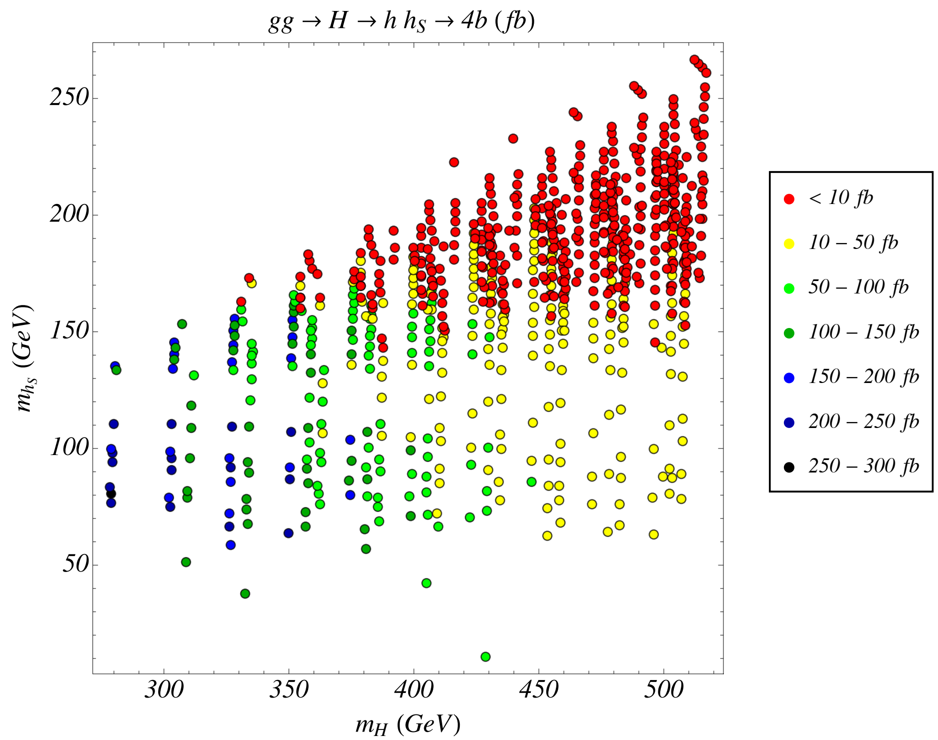
Carena, Haber, Low, Shah, C.W.'15





Promising H decay channel





(a)

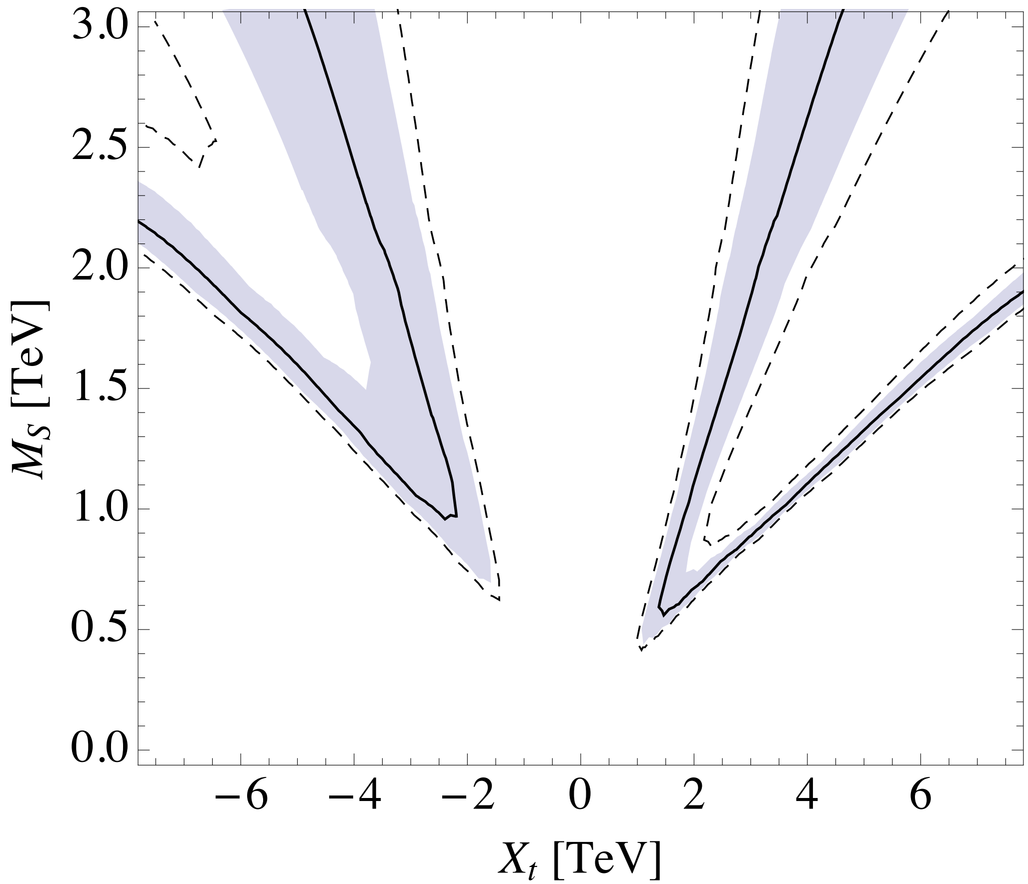
Complementarity between bbWW and 4b channels.

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
- 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

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

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

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

Cancellations still present at higher orders

$$\delta_4\lambda = \Big\{ 20736\lambda^5 + 51840\lambda^4 y_t^2 + \lambda^3 y_t^2(21600 y_t^2 - 23040 g_3^2)$$
$$+ \lambda^2 y_t^2(-30780 y_t^4 - 18720 g_3^2 y_t^2 + 14400 g_3^4)$$
$$+ \lambda y_t^2(-22059 y_t^6 + 28512 g_3^2 y_t^4 + 10560 g_3^4 y_t^2 - 10560 g_3^6)$$
$$+ y_t^4(-8208 y_t^6 + 56016 y_t^6 g_3^2 - 84576 y_t^2 g_3^4 + 44160 g_3^6) \Big\} L^4$$

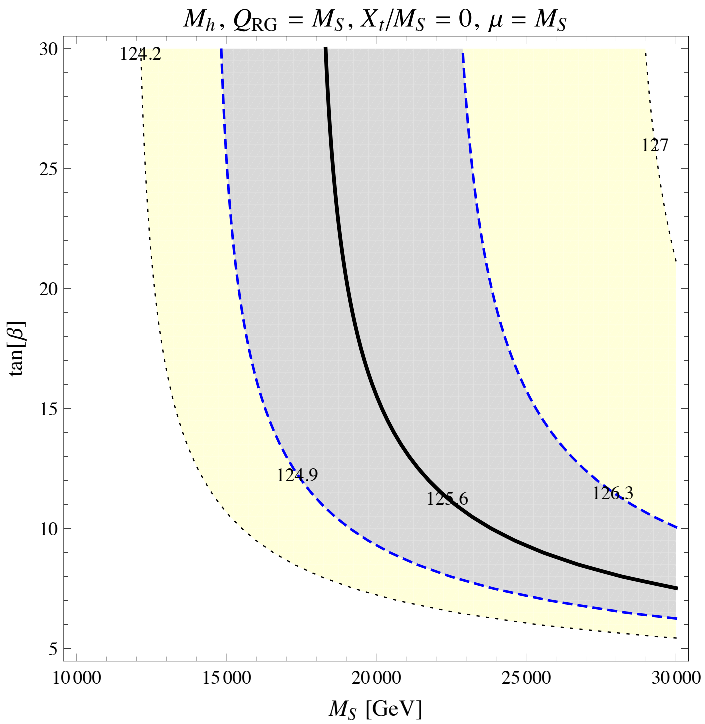
Draper, Lee, C.W. '13

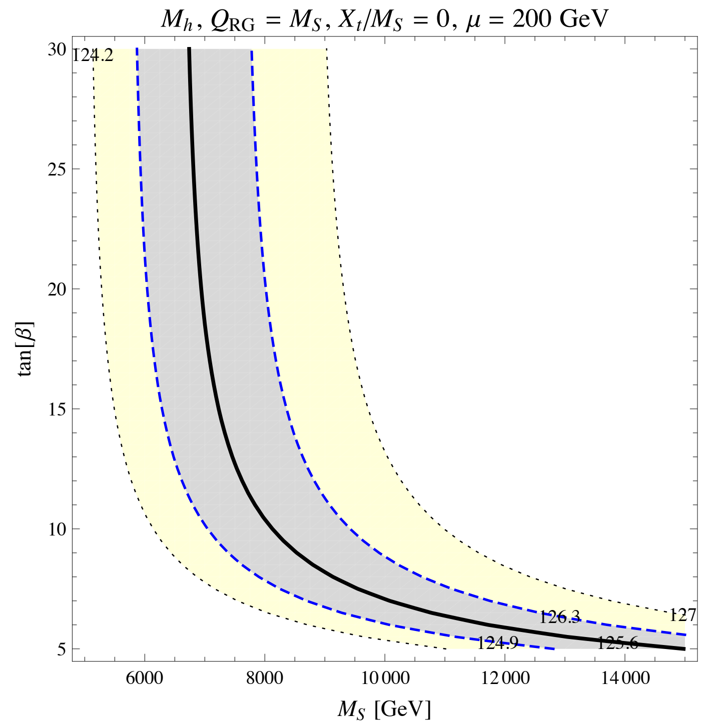
For values of the strong gauge coupling of the order of the Yukawa coupling, the corrections become significantly smaller than naively expected. Positive three-loop corrections small, implying the need for very heavy stops for small values of the stop mass mixing parameter Xt.

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

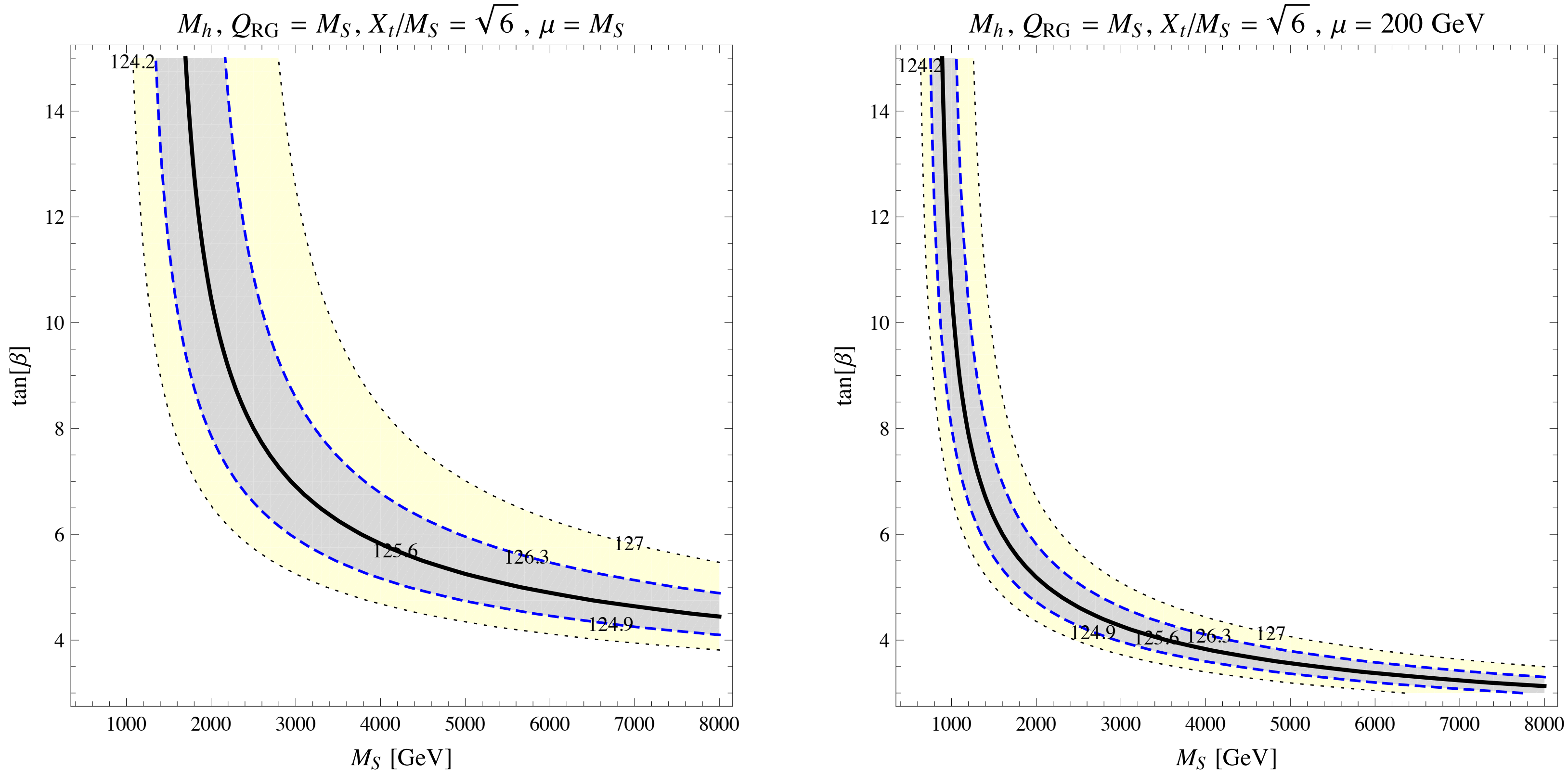




Such heavy stops would be out of the reach of the LHC
A higher energy collider necessary to investigate stop sector

Draper, Lee, C.W. '13

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

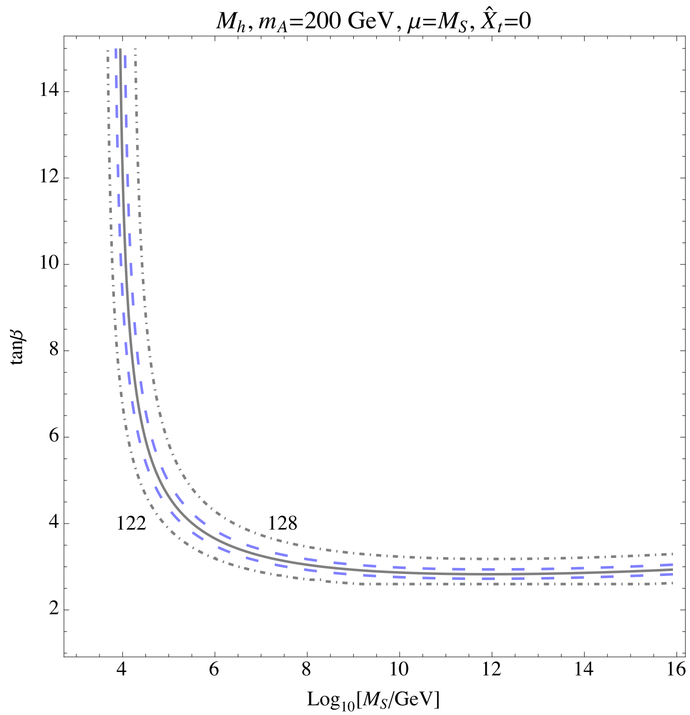


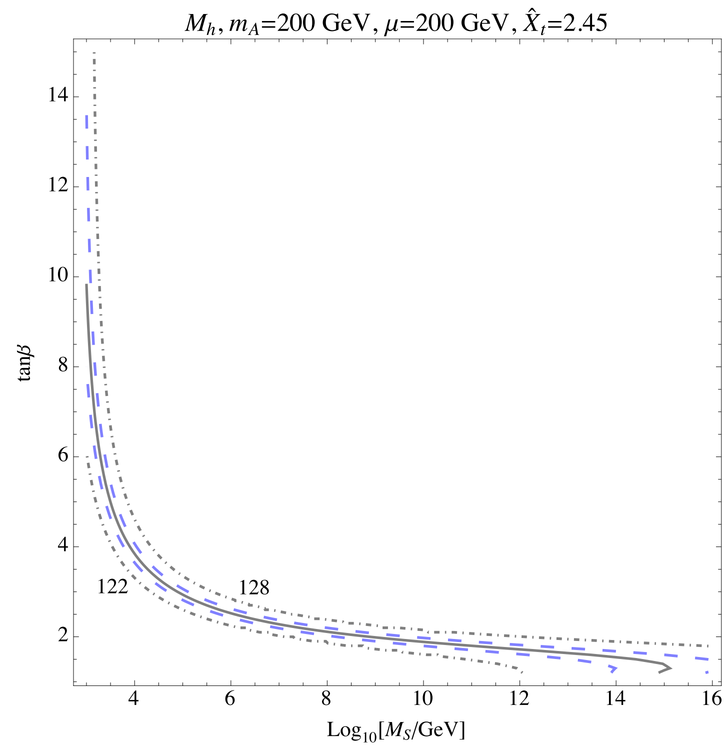
Light Stops at the reach of the LHC for large mixing in the Stop sector and moderate values of tanβ

Lower values of MA

Lee, C.W.'15

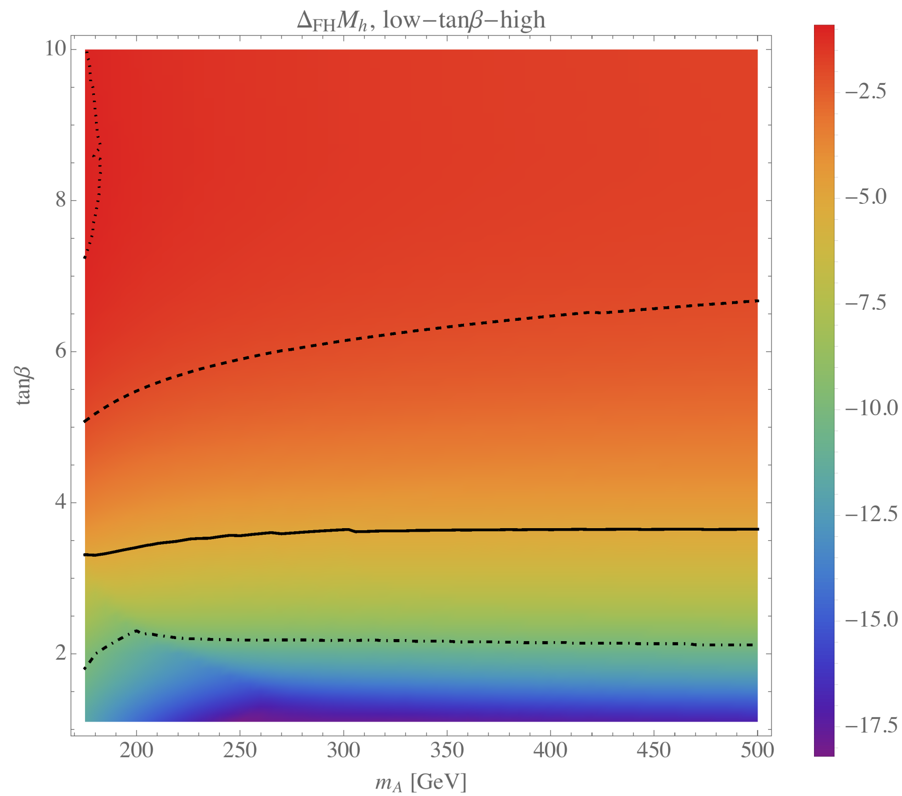
- Lower values of MA may have an important effect on the determination of Higgs masses and mixings. The mass of the lightest CP-even Higgs is lowered by these mixing effects.
- These effects may be reduced at alignment, which however may only be obtained for large values of μ and tanβ.
- This means that certain low values of MA and tanβ, it is not possible to obtain the right Higgs mass even if the stop spectrum is pushed all the way to the GUT scale.





Working on a program that allows to compute masses and mixings for arbitrary values of MA, tanβ and MS

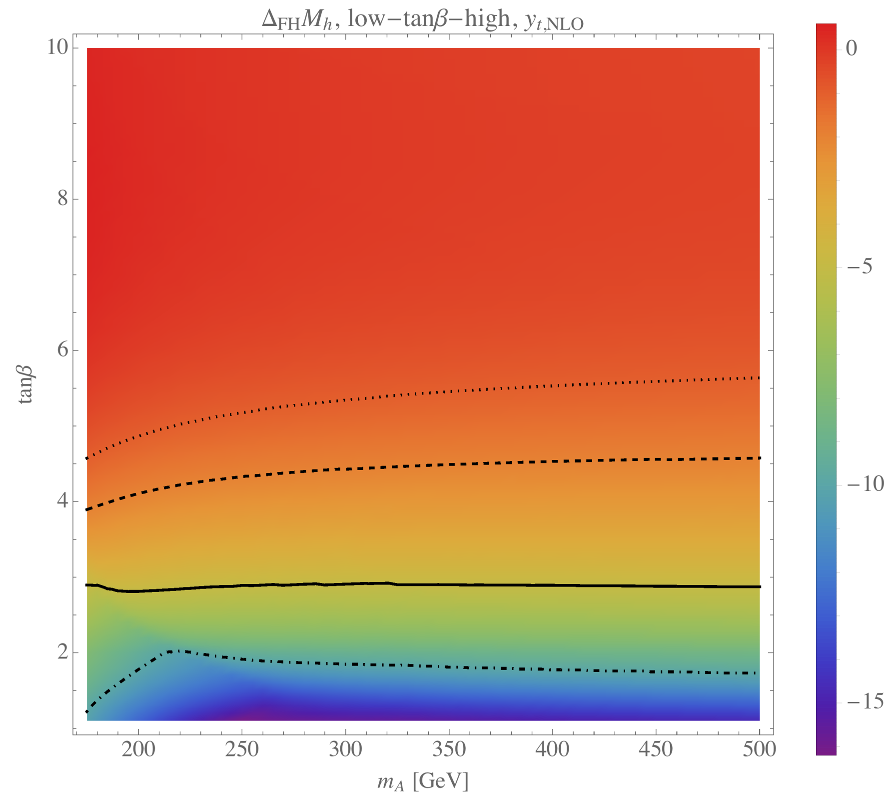
Comparison with FeynHiggs



Next to 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

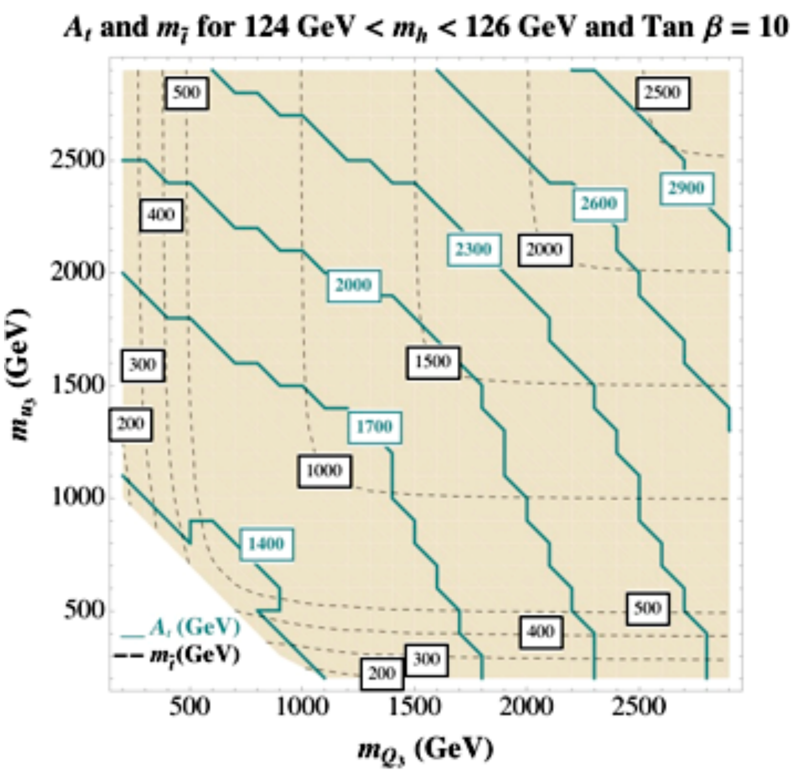


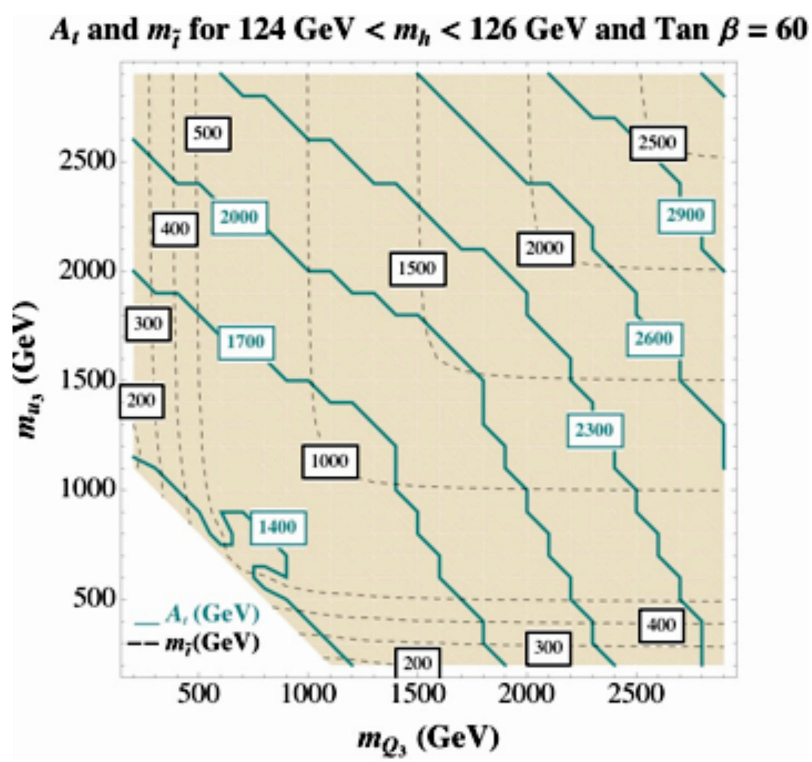
Leading order relation between M_t and running $m_t(M_t)$

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

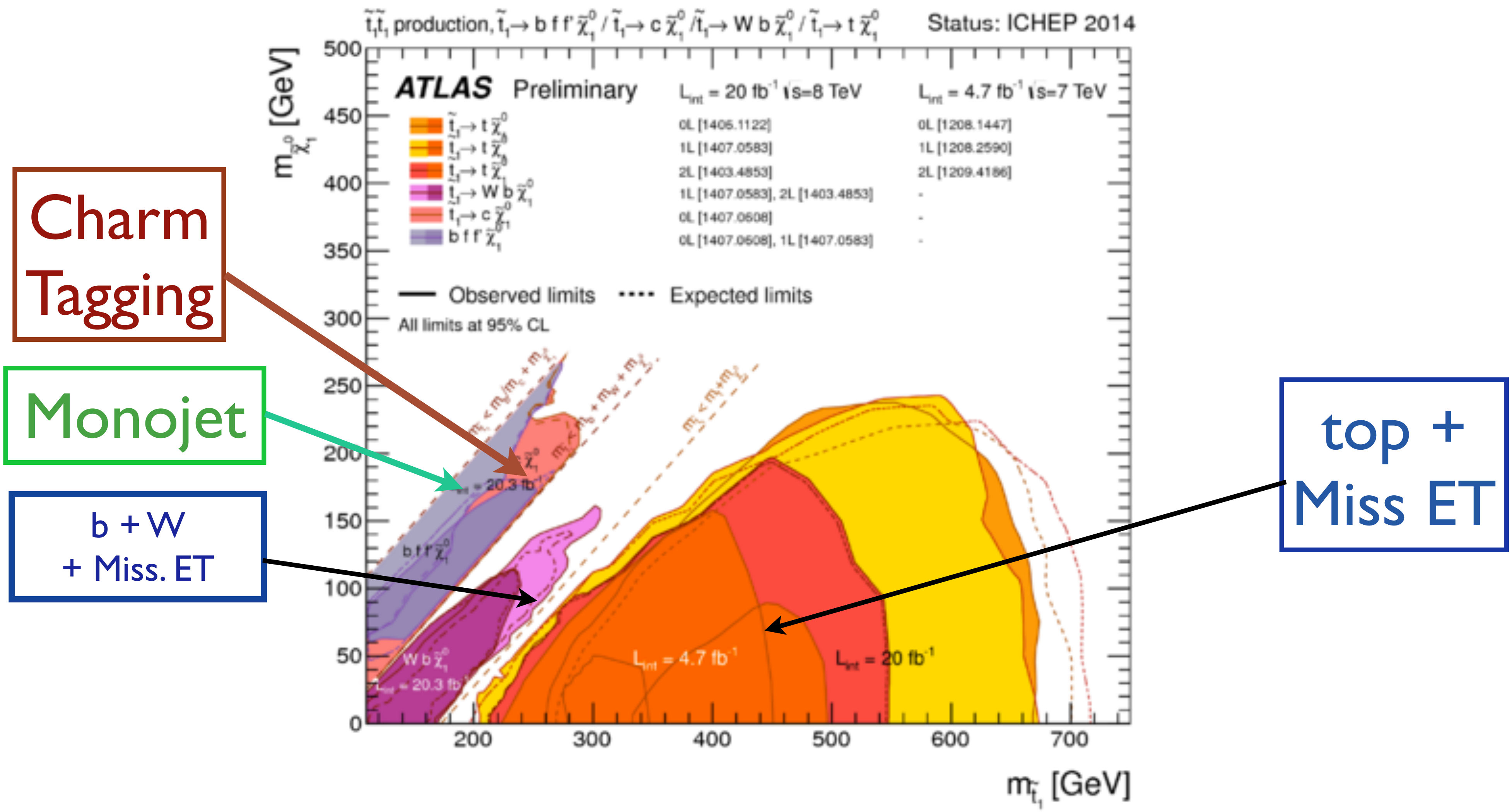
Light stop coupling to the Higgs

$$m_Q \gg m_U; \qquad m_{\tilde{t}_1}^2 \simeq m_U^2 + m_t^2 \left(1 - \frac{X_t^2}{m_Q^2}\right)$$

Lightest stop coupling to the Higgs approximately vanishes for $X_t \simeq m_Q$
Higgs mass pushes us in that direction
Modification of the gluon fusion rate milder due to this reason.

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.



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

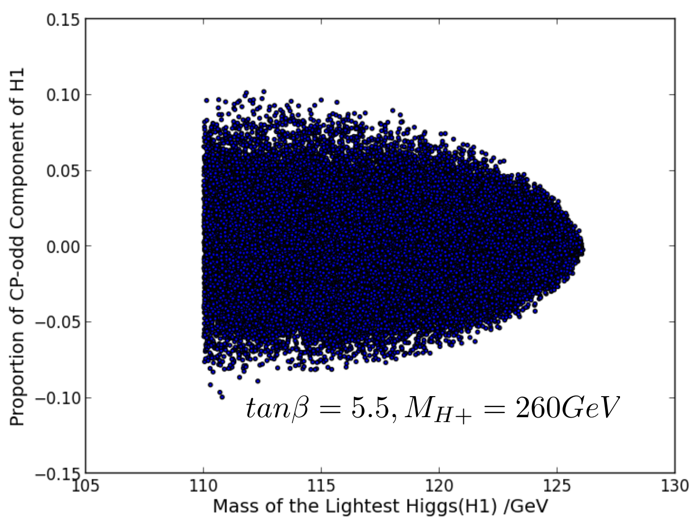
- How large could be the CP-odd component of the lightest neutral Higgs ?

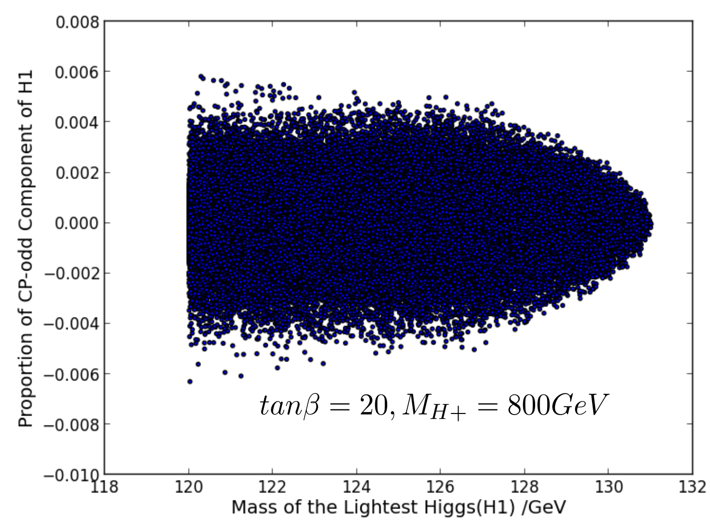
- It is proportional to $\mathrm{Im}\left(\frac{3h_t^4 v^2 \sin^2\beta \sin 2\beta}{8\pi^2}\left[\frac{X_t Y_t^*}{2M_{\mathrm{SUSY}}^2}\left(1-\frac{|X_t|^2}{6M_{\mathrm{SUSY}}^2}\right)\right]\right)$

- 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 couplings

Mixing mass matrix

Bing Li, C.W.'14

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

Higgs Basis.
Third component A

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

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

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

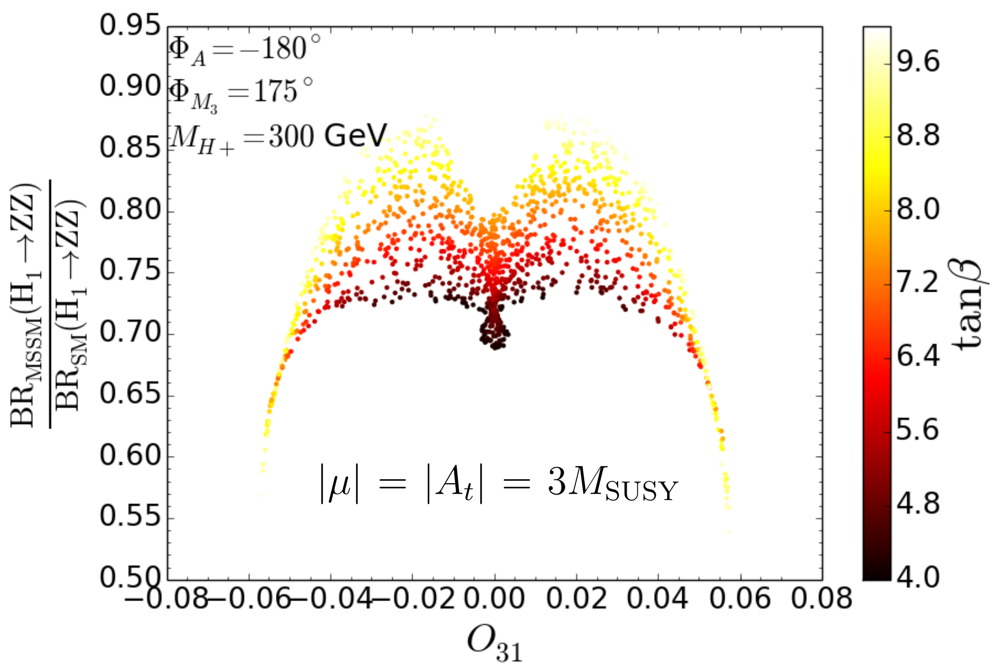
$$
O_{31} \propto -\frac{3h_t^4 v^2 \sin^4\beta}{16\pi^2 m^2_{H^+}}\frac{\mathrm{Im}(\mu A_t)}{M^2_{\rm SUSY}}\left(1 - \frac{|X_t|^2}{6M^2_{\rm SUSY}}\right)
$$

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)