Precision Higgs Measurements and Searches for Non-Standard Higgs Bosons at the LHC

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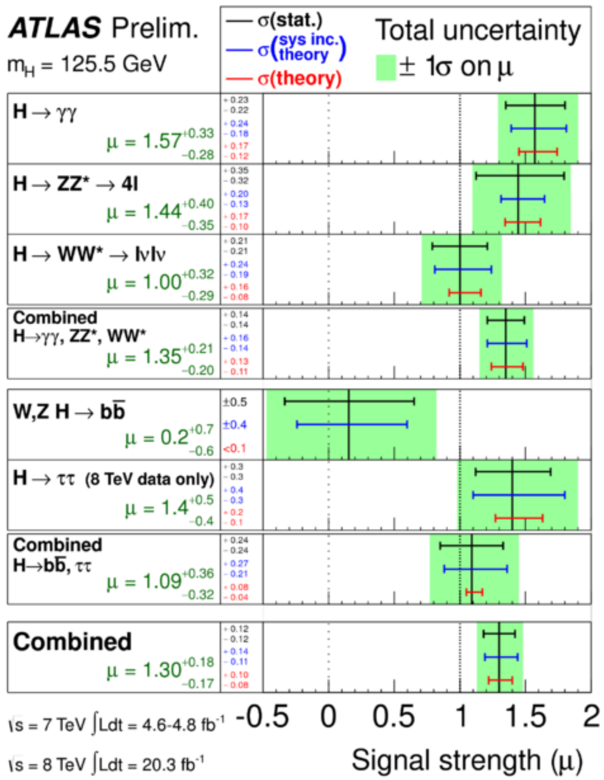
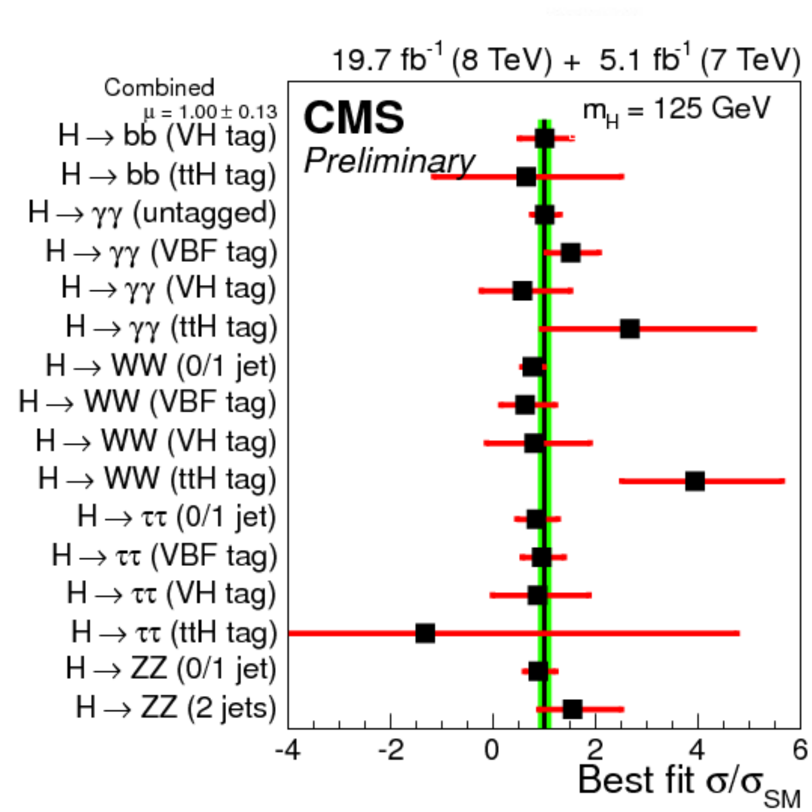
The properties of the recently discovered Higgs boson are close to the SM ones

Variations of Higgs couplings are still possible





As these measurements become more precise, they constrain possible extensions of the SM, and they could lead to the evidence of new physics.

It is worth studying what kind of effects one could obtain in well motivated extensions of the Standard Model, like SUSY.

(for an extensive review, see Christensen, Han and Su'13)

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

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

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

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

- 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

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

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

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

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

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

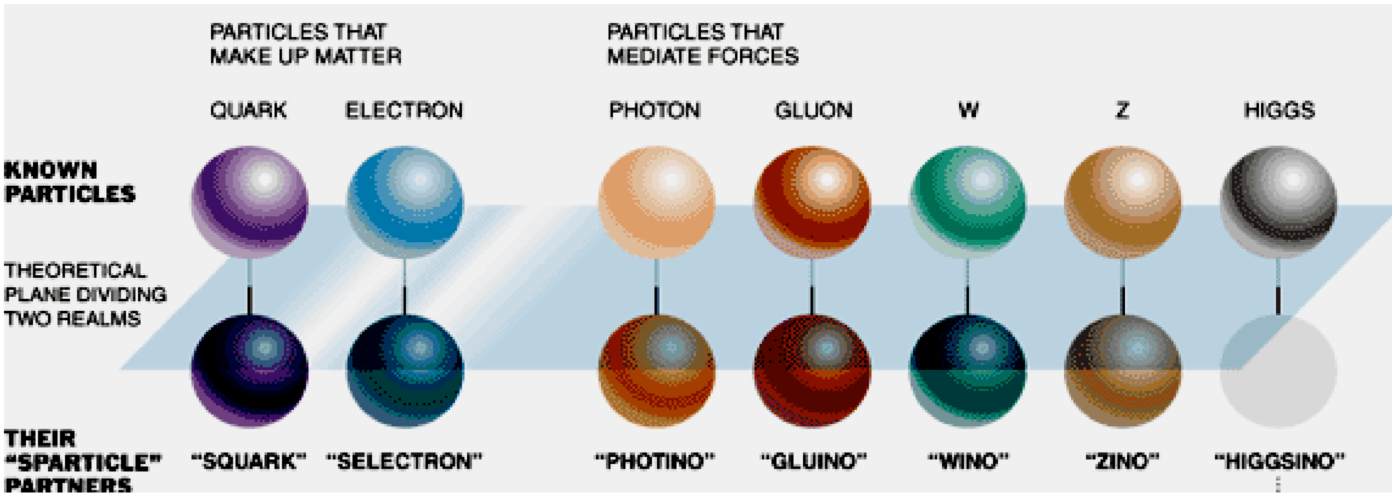
For small departures from alignment, the parameter η can be determined as a function of the quartic couplings and the Higgs masses

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

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

Supersymmetry

fermions **bosons**



Photino, Zino and Neutral Higgsino: Neutralinos

Charged Wino, charged Higgsino: Charginos

Particles and Sparticles share the same couplings to the Higgs. Two superpartners of the two quarks (one for each chirality) couple strongly to the Higgs with a Yukawa coupling of order one (same as the top-quark Yukawa coupling)

$$\text{Two Higgs doublets necessary} \rightarrow \tan\beta = \frac{v_2}{v_1}$$

Any evidence of SUSY ?

- Not any convincing hints.
- But imagine we go back in time and you only new about the electron, the positron and the photon.
- You design an electron-positron collider and you suddenly produce muons !

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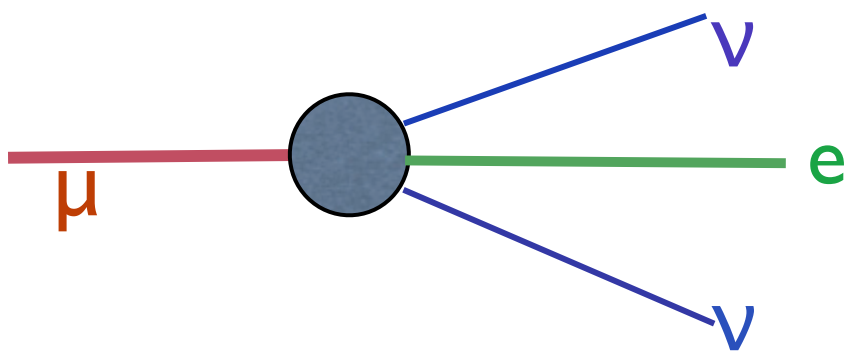

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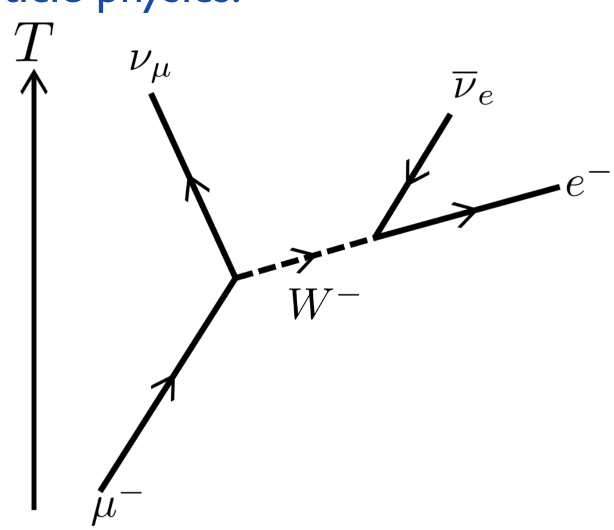
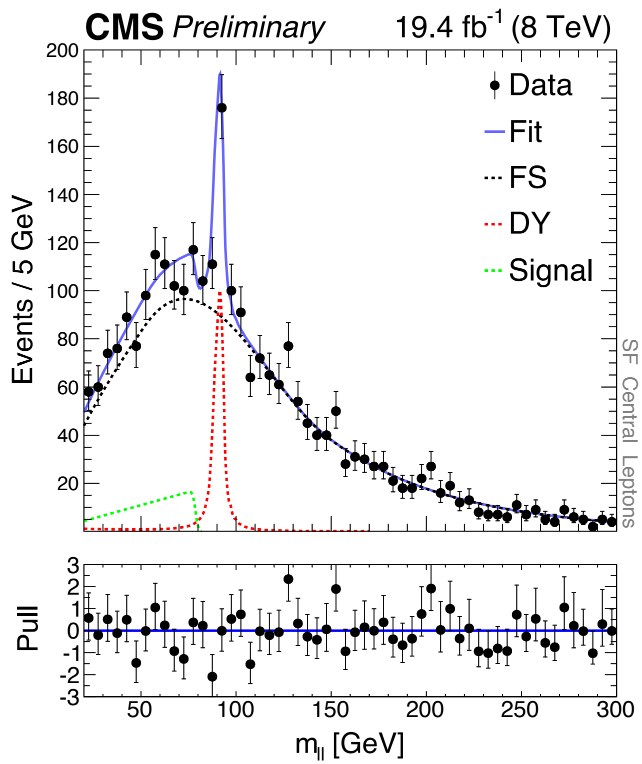
- You design a electron-positron collider and you suddenly produce muons !
- You observe that the muons decay into an electron and something invisible, which is not a particle. The invisible invariant mass distribution has an end point at the mass difference of the muon and the electron.
- You go back to your particle physics notes and you discovered that there must be two neutral particles (you call them neutrinos).
- You also realize that there must be some massive particle mediating the decay. If you are at Chicago, you call it W, after the last name of the guy who taught you particle physics.

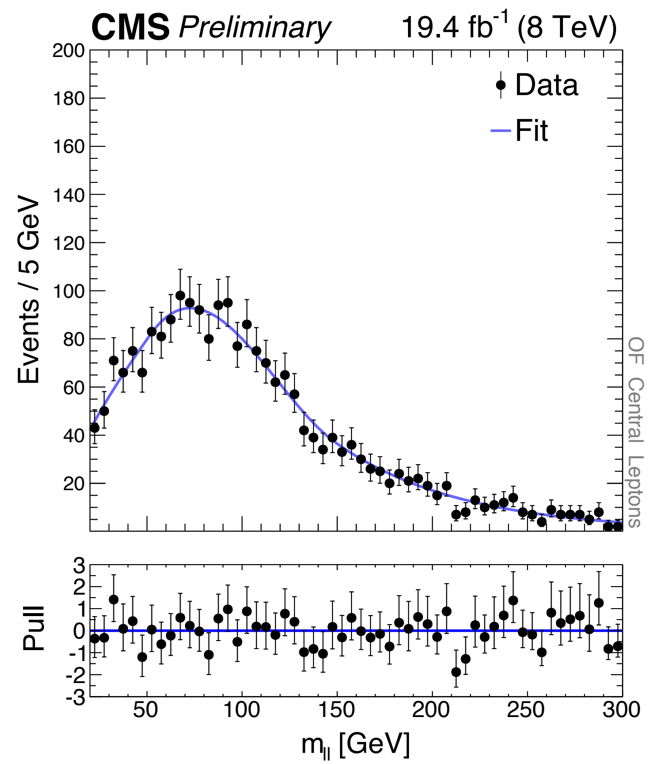


You discovered three particles at once ! (actually four)

Edge in the invariant mass distribution of leptons

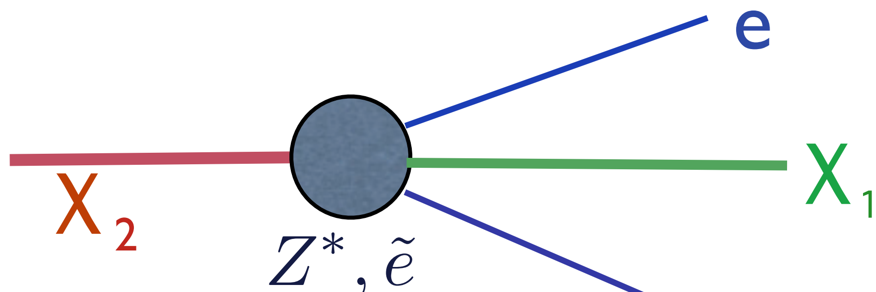
P. Huang, C.W., arXiv:1410.4998





$\tilde{b} \to b\ \chi_2^0$

$\tilde{b} \to b\ \chi_2^0 \to b\ e^+ e^- \chi_1^0$



$m_{\tilde{b}} \simeq 390\text{GeV}$

$m_{\tilde{\chi}_2^0} \simeq 340\text{GeV}$

$m_{\tilde{\chi}_1^0} \simeq 260\text{GeV}$

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

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

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

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

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

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

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

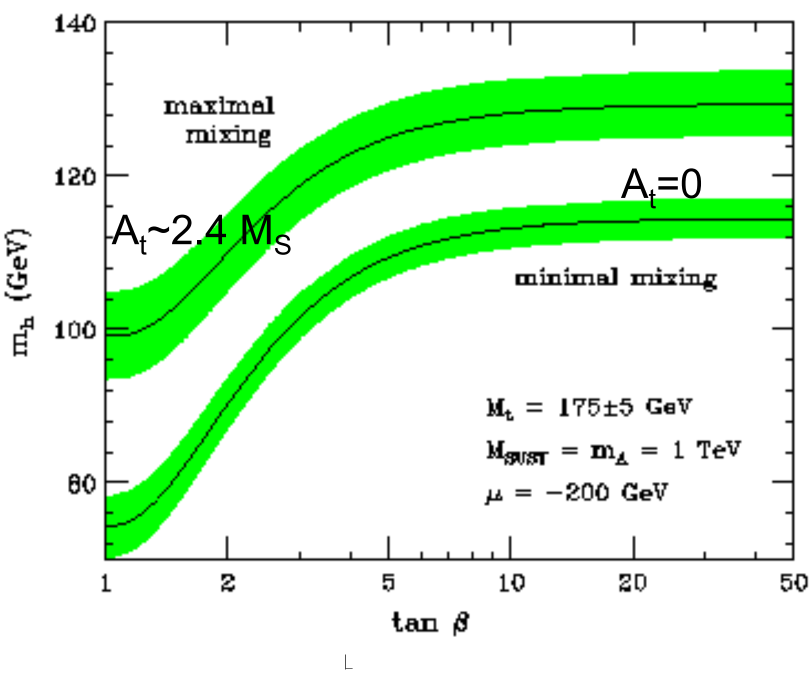
Analytic expression valid for $M_{SUSY} \sim m_Q \sim m_U$

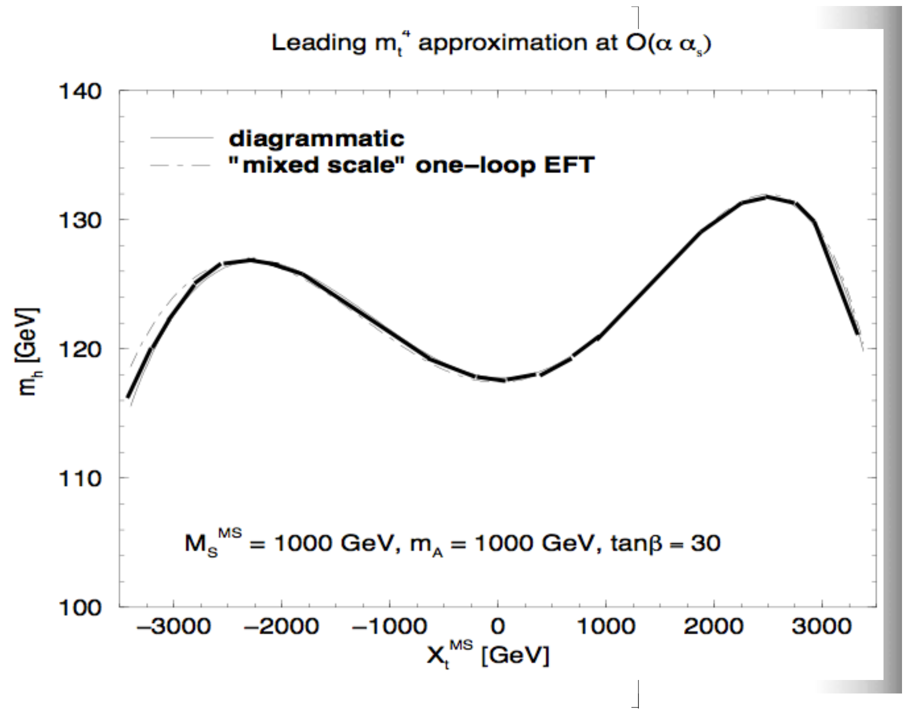
Standard Model-like Higgs Mass

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

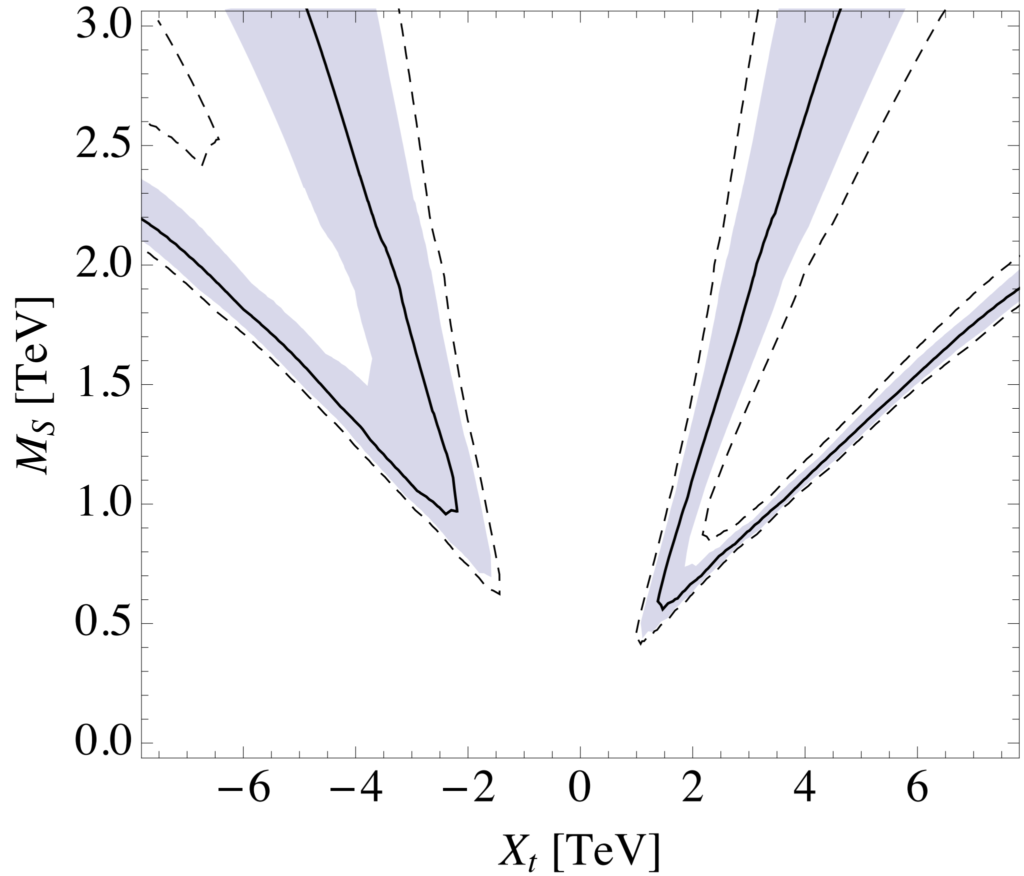
For masses of order 1 TeV, diagrammatic and EFT approach agree well, once the appropriate threshold corrections are included





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

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

Draper, Lee, C.W. '13

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

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

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

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

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

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

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

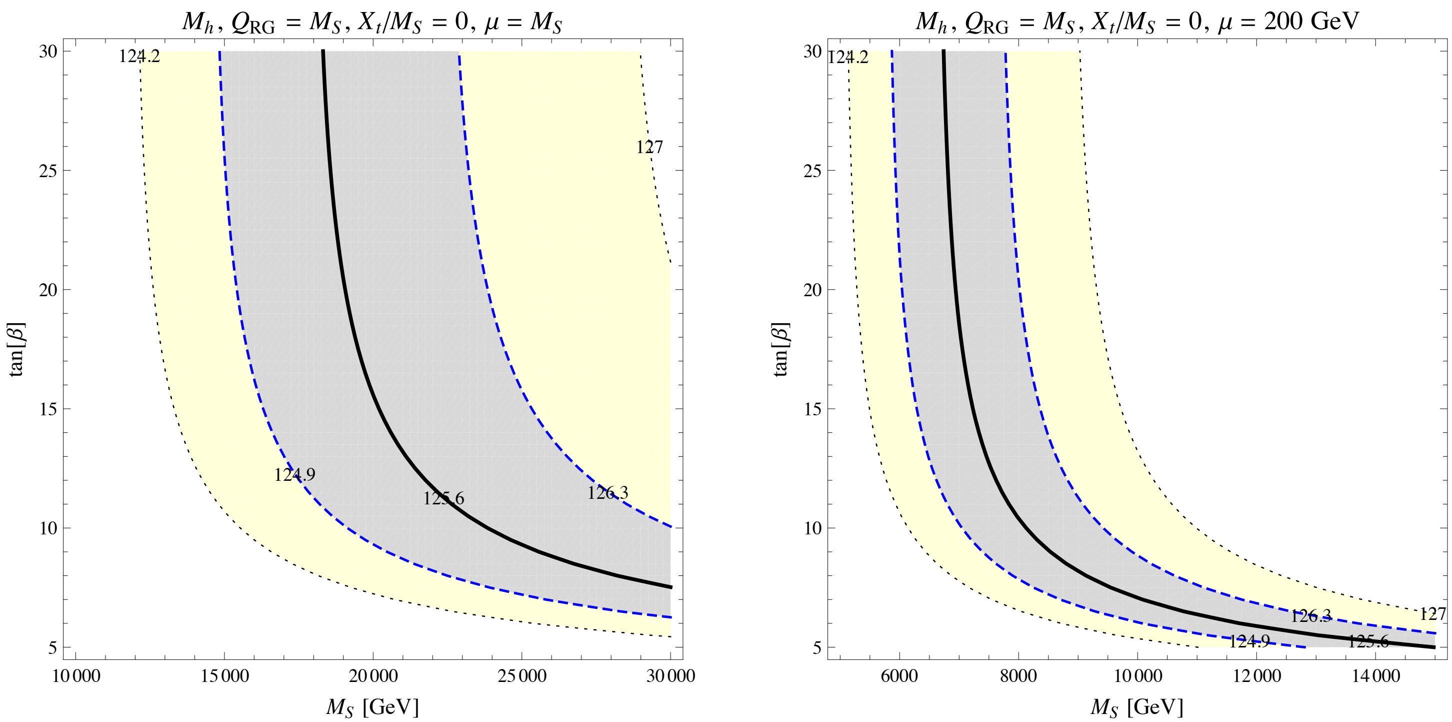
$$+ y_t^4(972.596 y_t^4 - 1001.98 y_t^2 g_3^2 + 200.804 g_3^4)\Bigg\} L,$$

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

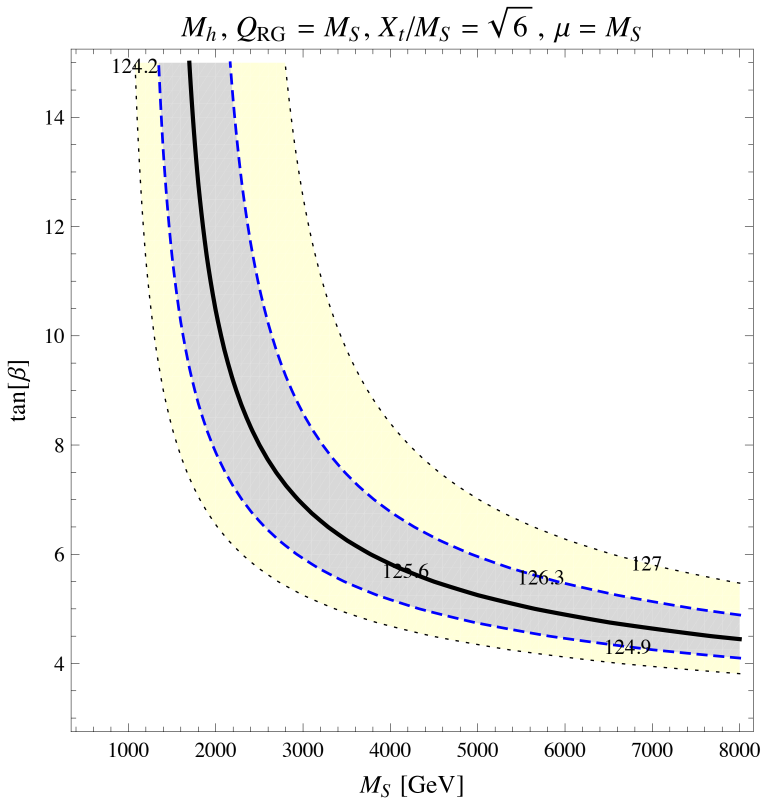
Necessary stop mass values to get the proper Higgs mass for Small mixing in the stop sector

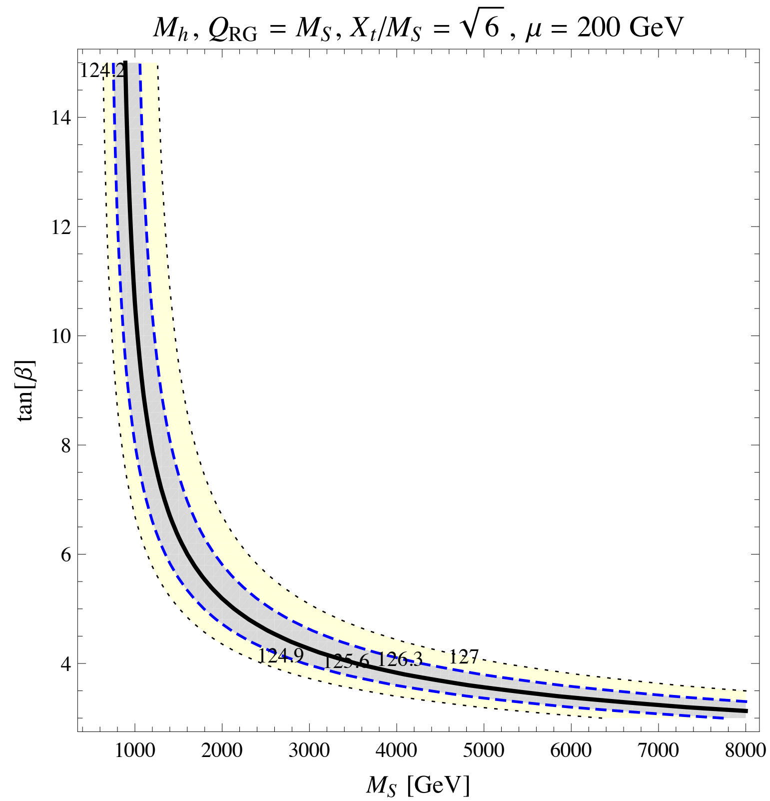


Such heavy stops would be out of the reach of the LHC
A higher energy collider necessary to investigate stop sector

Draper, Lee, C.W. '13

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





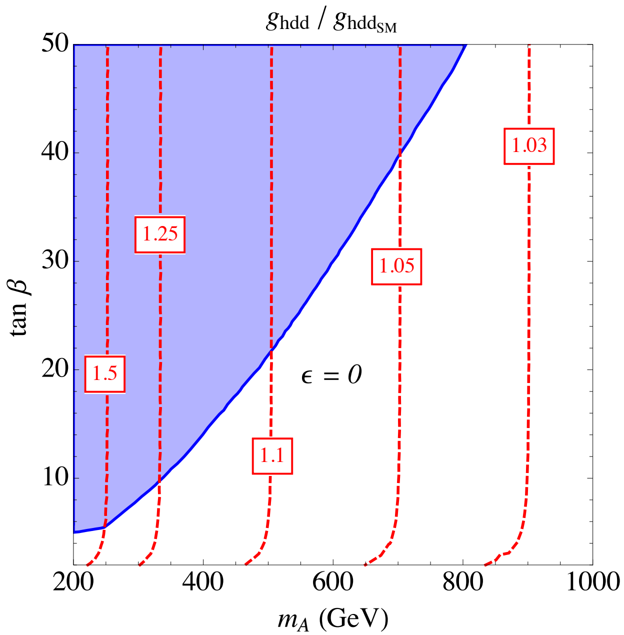
Light Stops at the reach of the LHC for large mixing in the Stop sector and moderate values of tanβ

Down Couplings in the MSSM for low values of μ

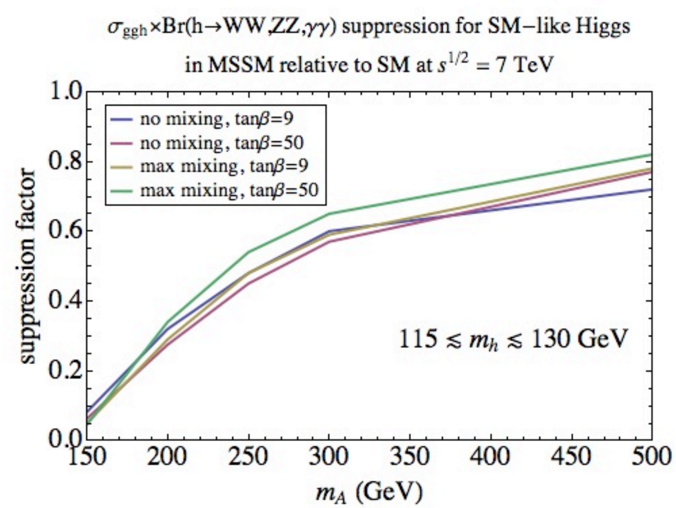
- In this regime, $\lambda_{6,7} \simeq 0$, and

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

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



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

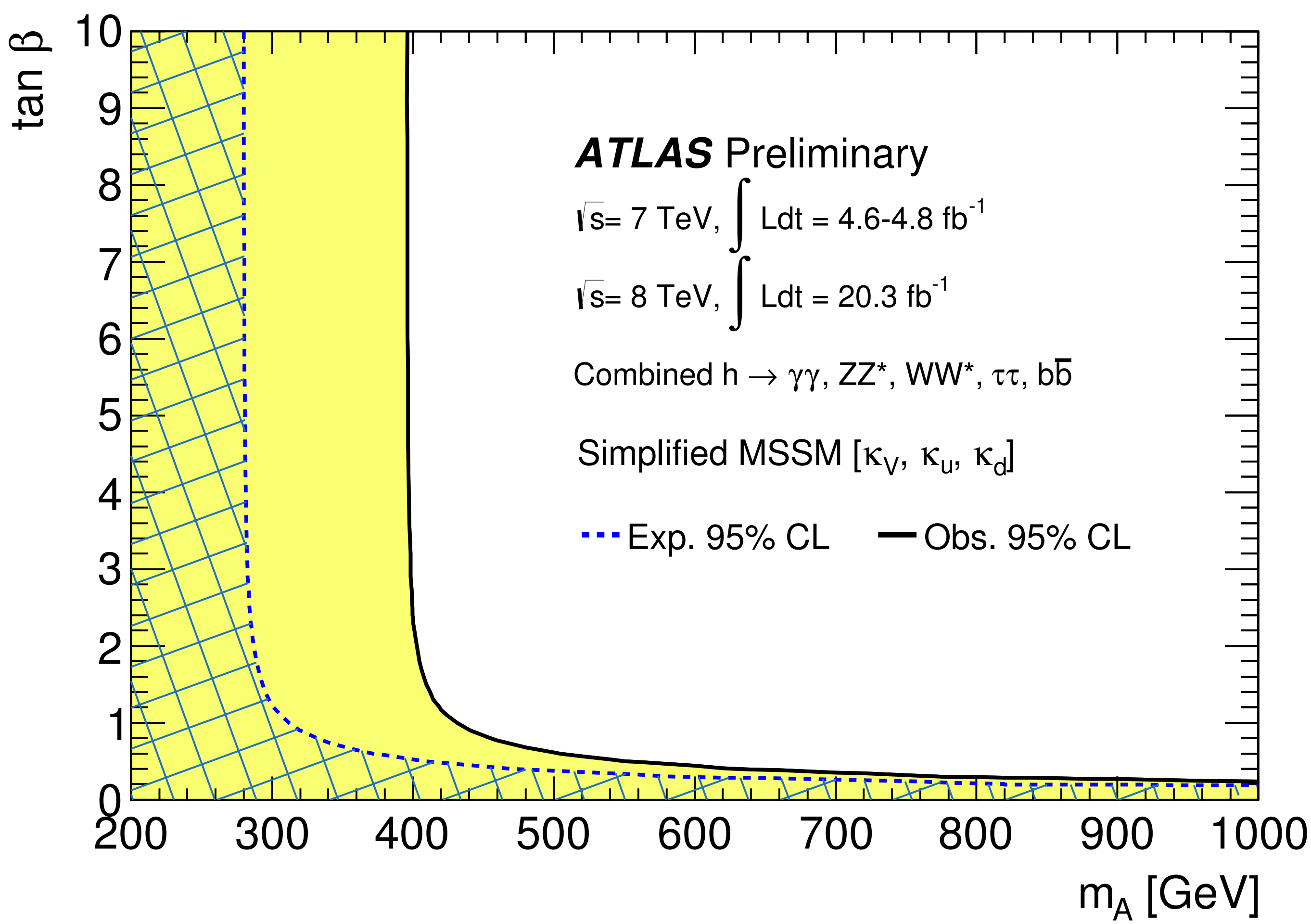


All vector boson branching ratios suppressed by enhancement of the bottom decay width

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

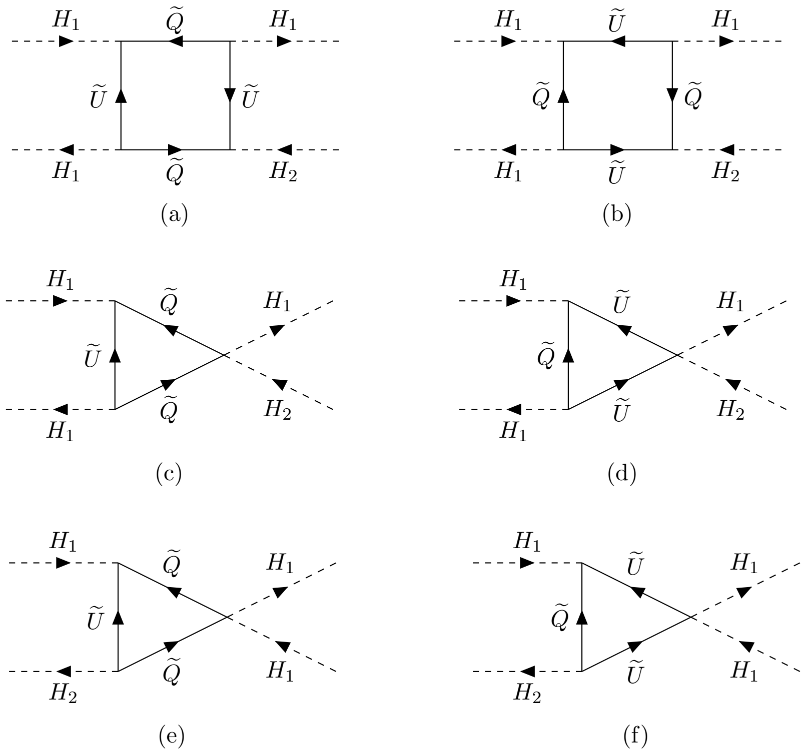
Low values of μ similar to the ones analyzed by ATLAS

ATLAS-CONF-2014-010



Bounds coming from precision h measurements

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

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

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

At moderate or large $\tan\beta$

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

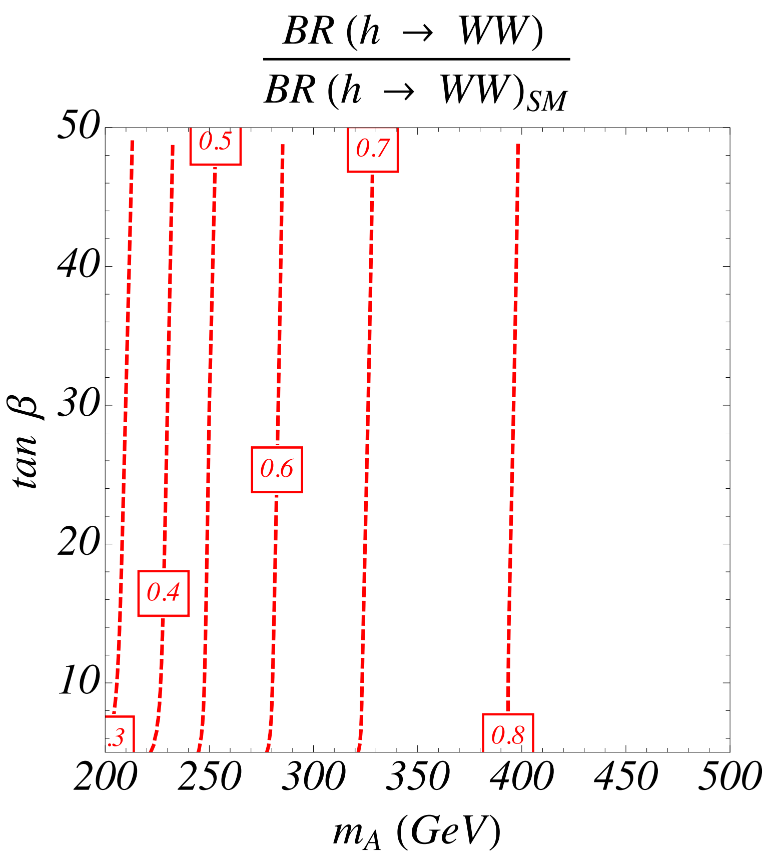
Carena, Haber, Low, Shah, C.W.' 14

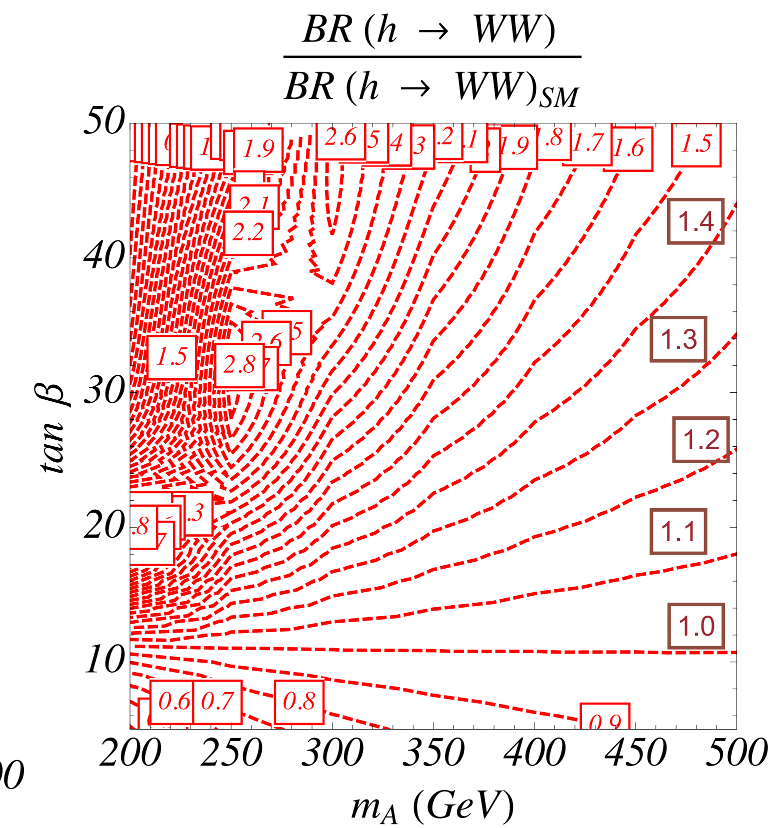
Higgs Decay into Gauge Bosons

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

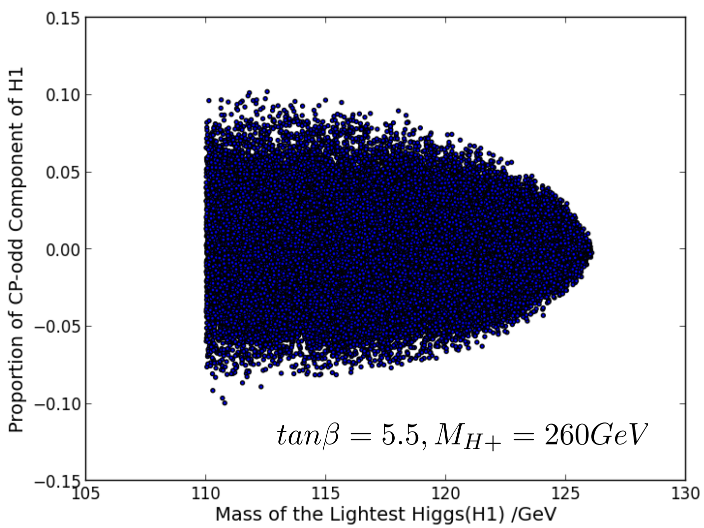
Comment on CP-violation

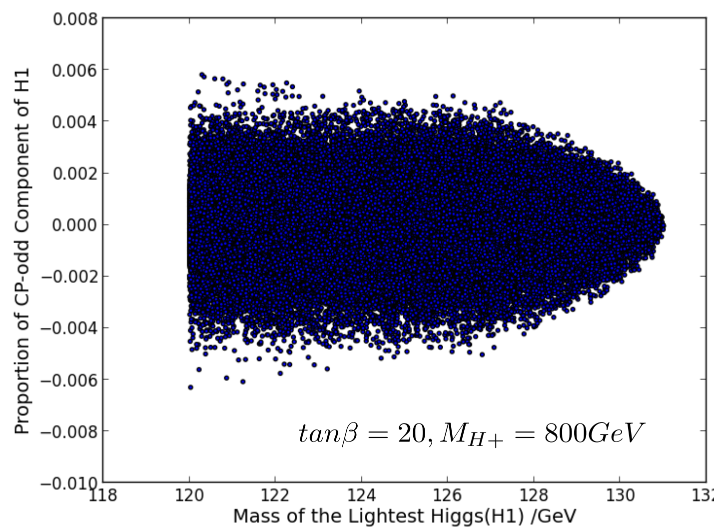
- In the presence of CP-violating phases in the soft SUSY parameters, the mass eigenstates are no longer CP-eigenstates
- Mixing between the would be CP-even and CP-odd Higgs bosons exist.

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 !

Bing Li, C.W.'15

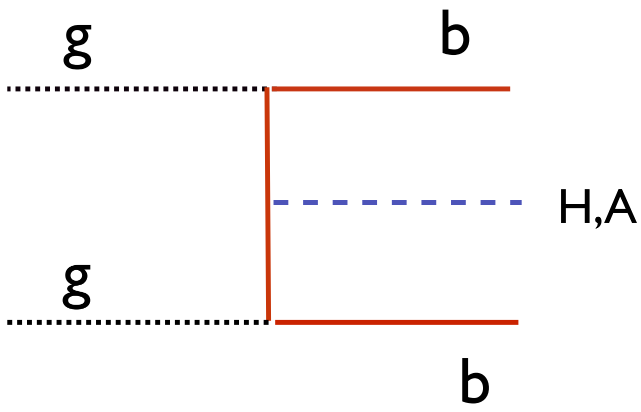




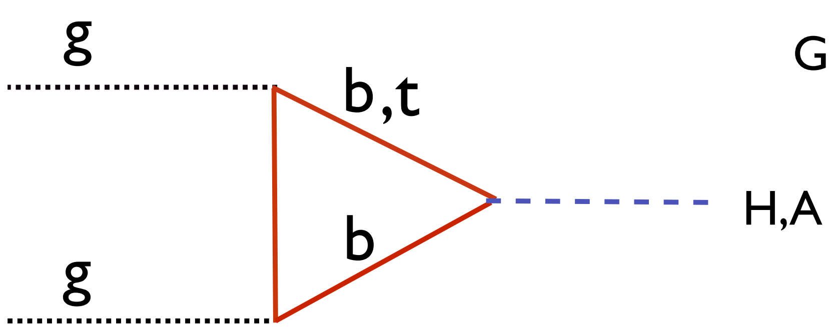
- It is further restricted by electric dipole moment constraints and Higgs couplings

Non-Standard Higgs Production

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



Associated Production



Gluon Fusion

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

Searches for non-standard Higgs bosons

M. Carena, S. Heinemeyer, G.Weiglein,C.W, EJPC'06

- Searches at the Tevatron and the LHC are induced by production channels associated with the large bottom Yukawa coupling.

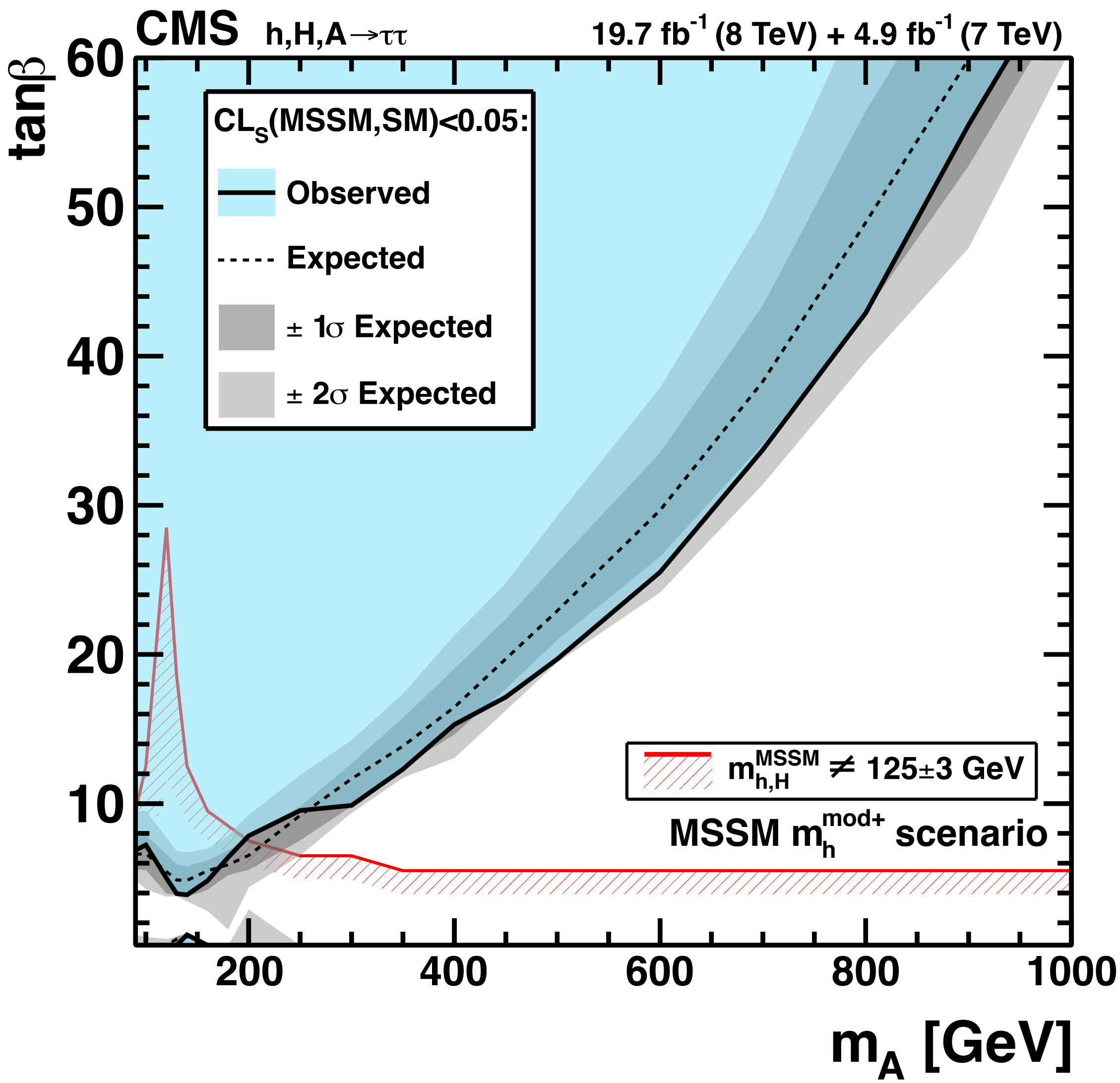
$$\sigma(b\bar{b}A) \times BR(A \to b\bar{b}) \simeq \sigma(b\bar{b}A)_{\rm SM} \frac{\tan^2\beta}{(1+\Delta_b)^2} \times \frac{9}{(1+\Delta_b)^2+9}$$

$$\sigma(b\bar{b}, gg \to A) \times BR(A \to \tau\tau) \simeq \sigma(b\bar{b}, gg \to A)_{\rm SM} \frac{\tan^2\beta}{(1+\Delta_b)^2+9}$$

- There may be a strong dependence on the parameters in the bb search channel, which is strongly reduced in the tau tau mode.

- If charginos are light, they contribute to the total with, suppressing the BR.

$$\sigma(pp \to H, A \to \tau\tau) \propto \frac{\tan^2\beta}{\left[\left(3\frac{m_b^2}{m_\tau^2} + \frac{(M_W^2+M_Z^2)(1+\Delta_b)^2}{m_\tau^2\tan^2\beta}\right)(1+\Delta_\tau)^2 + (1+\Delta_b)^2\right]}$$



How to test the region of low tanbeta and moderate mA ?

Decays of non-standard Higgs bosons into paris of standard ones, charginos and neutralinos may be a possibility.

Can change in couplings help there ?

It depends on radiative corrections

We shall assume light gauginos, $M_2 = 2\ M_1 \simeq 200$ GeV.

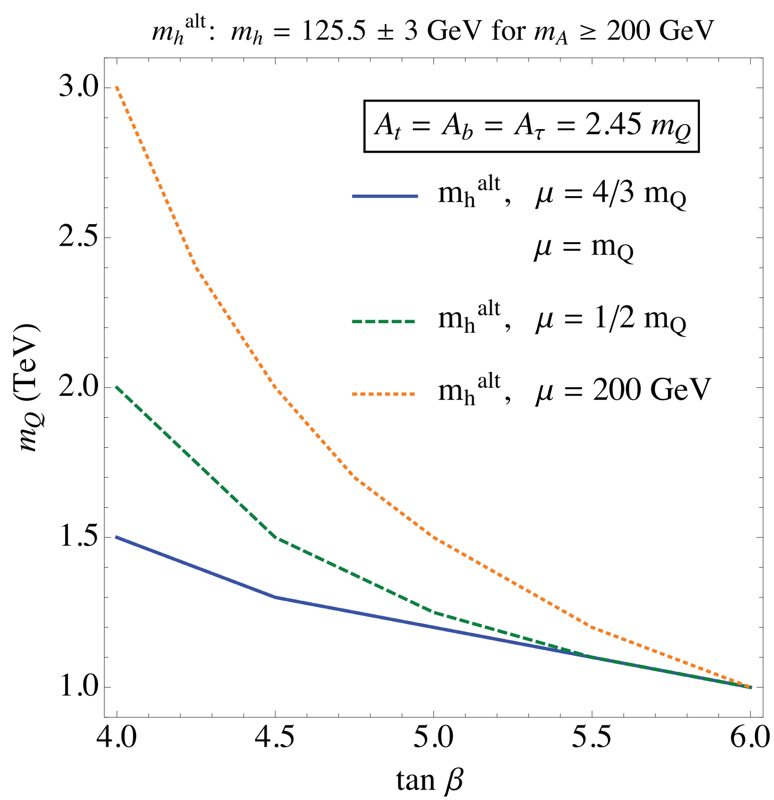
This is an example of a low μ scenario

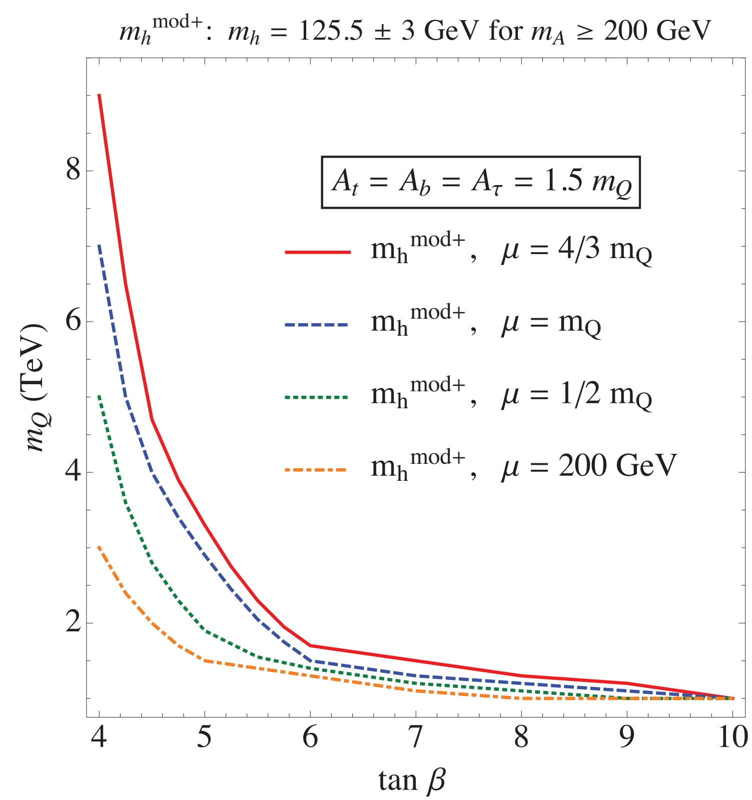
$$A_t \simeq 1.5\ M_{\rm SUSY}, \quad \mu = 200 \text{ GeV}$$

At low values of $\tan\beta$, the SUSY mass scale must be raised.

Variation of the SUSY scale

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





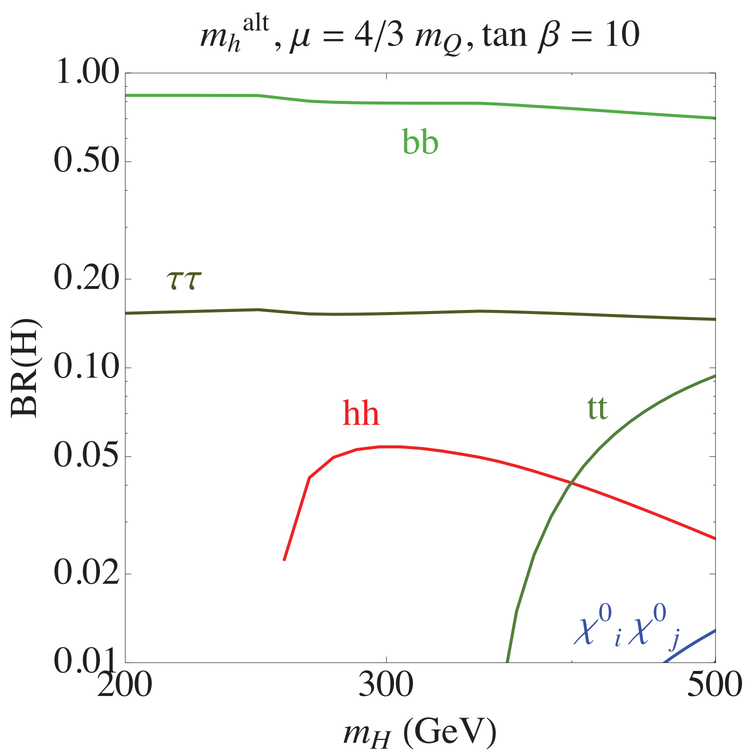
M. Carena, H. Haber, I. Low, N. Shah, C.W.'14

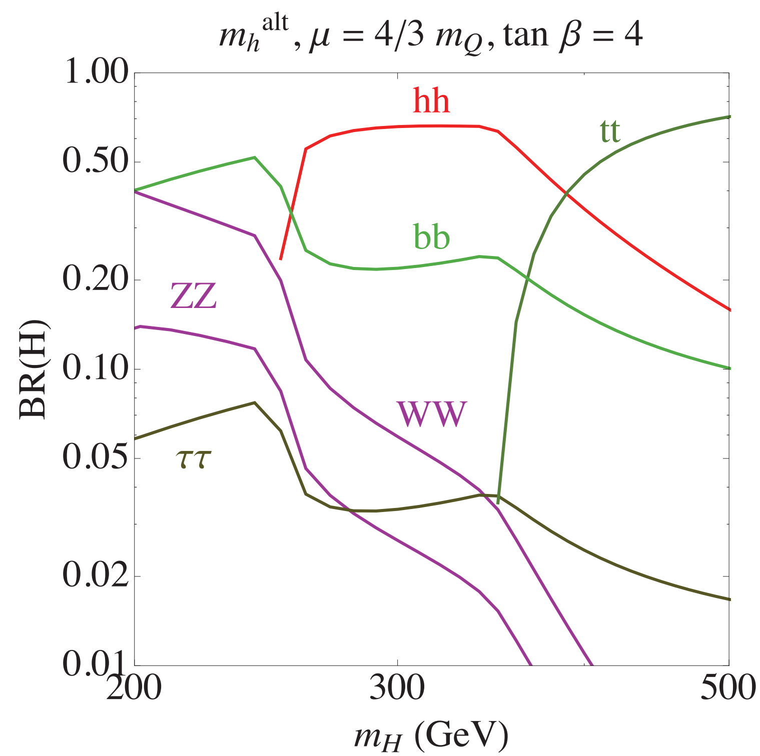
Heavy Supersymmetric Particles

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.

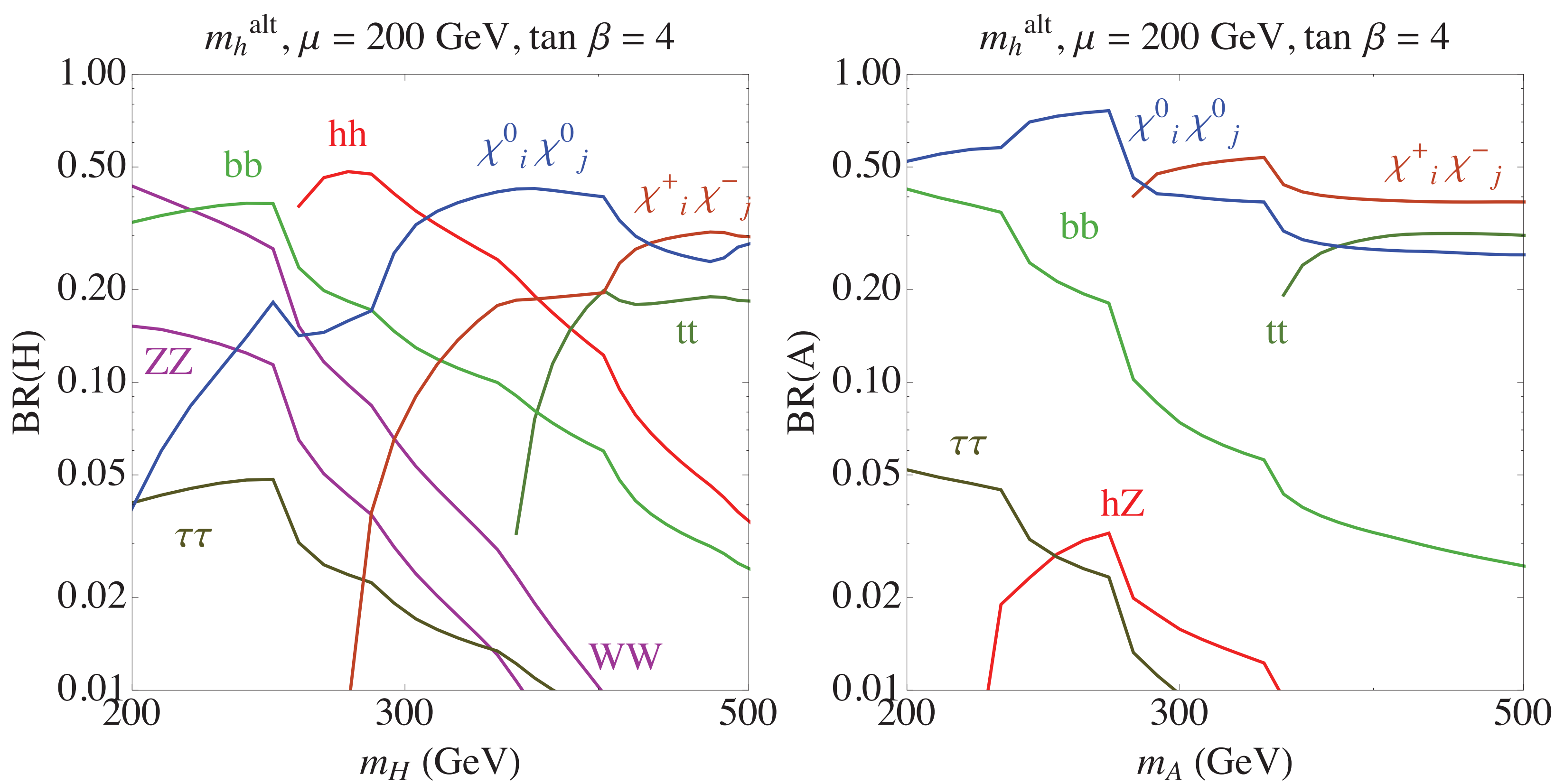




At large tanβ, bottom and tau decay modes dominant.
As tanβ decreases decays into SM-like Higgs and wek bosons become relevant

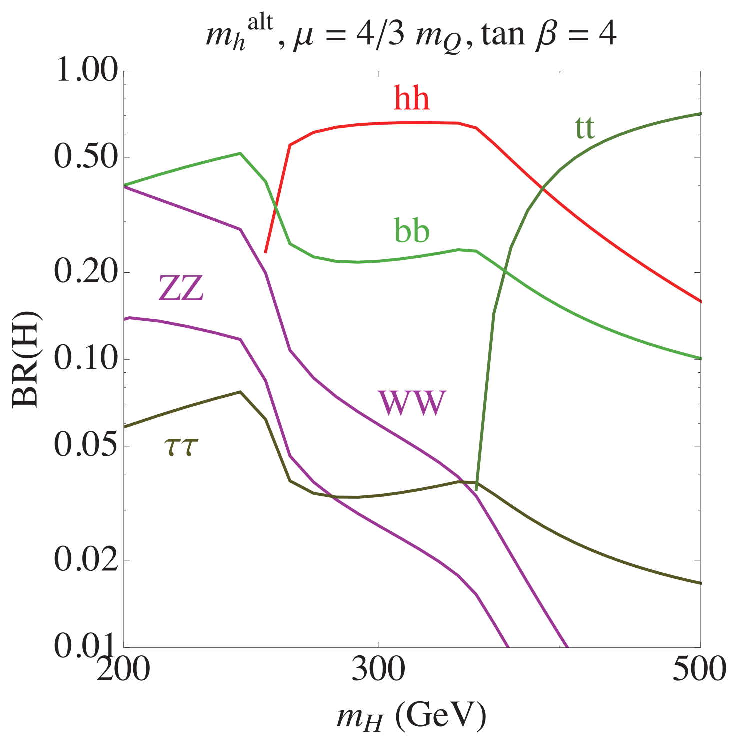
Light Charginos and Neutralinos can significantly modify M the CP-odd Higgs Decay Branching Ratios

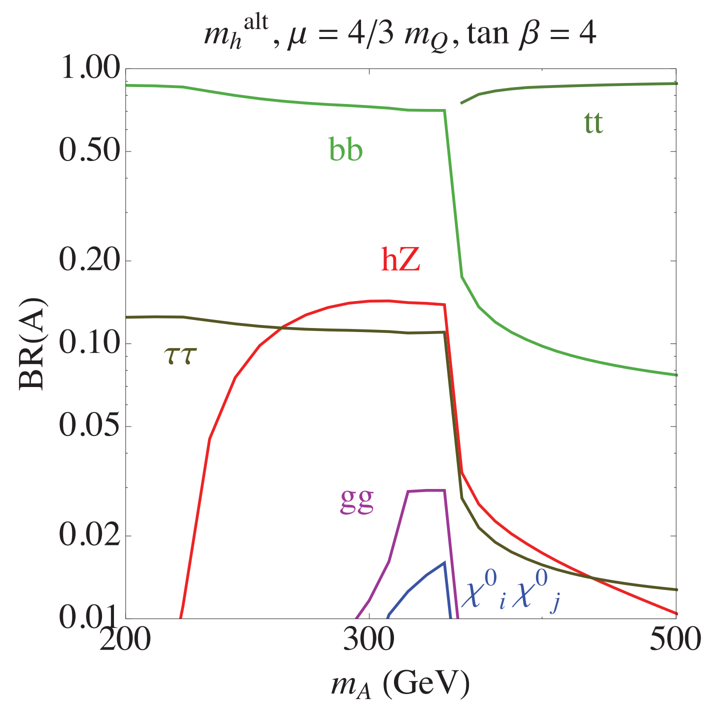
Carena, Haber, Low, Shah, C.W.'14



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

Large μ and small tanβ





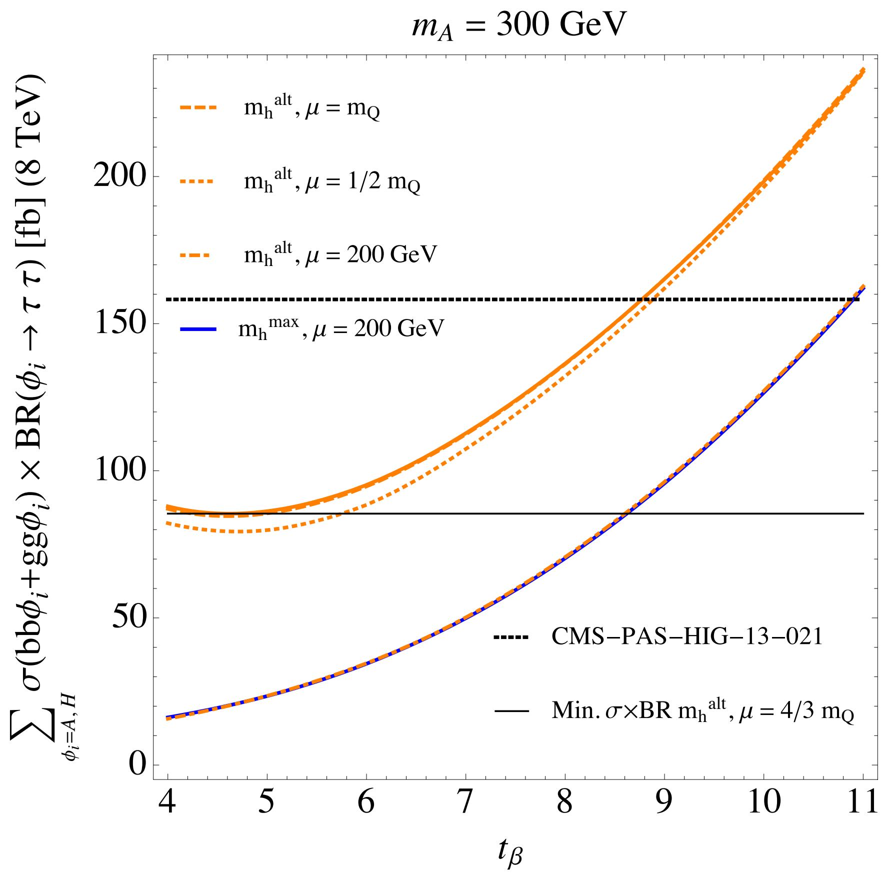
Decays into gauge and Higgs bosons become important. Observe, however that the BR(A to τ τ) remains large up to the top-quark threshold scale

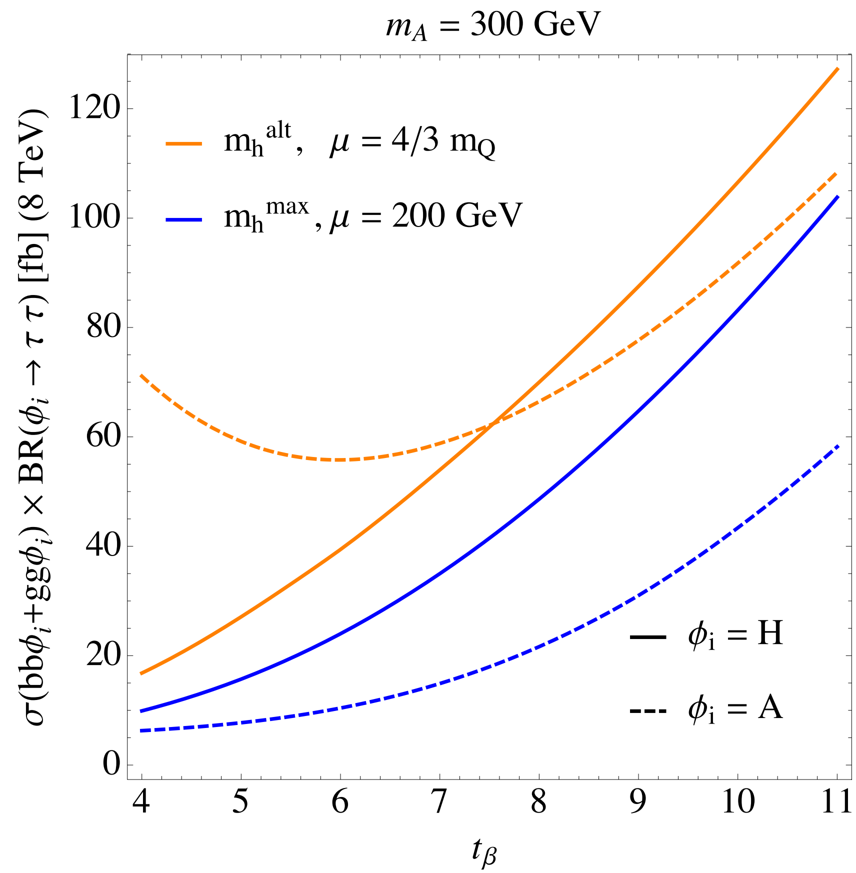
Comments on Production Cross Sections

- 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

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

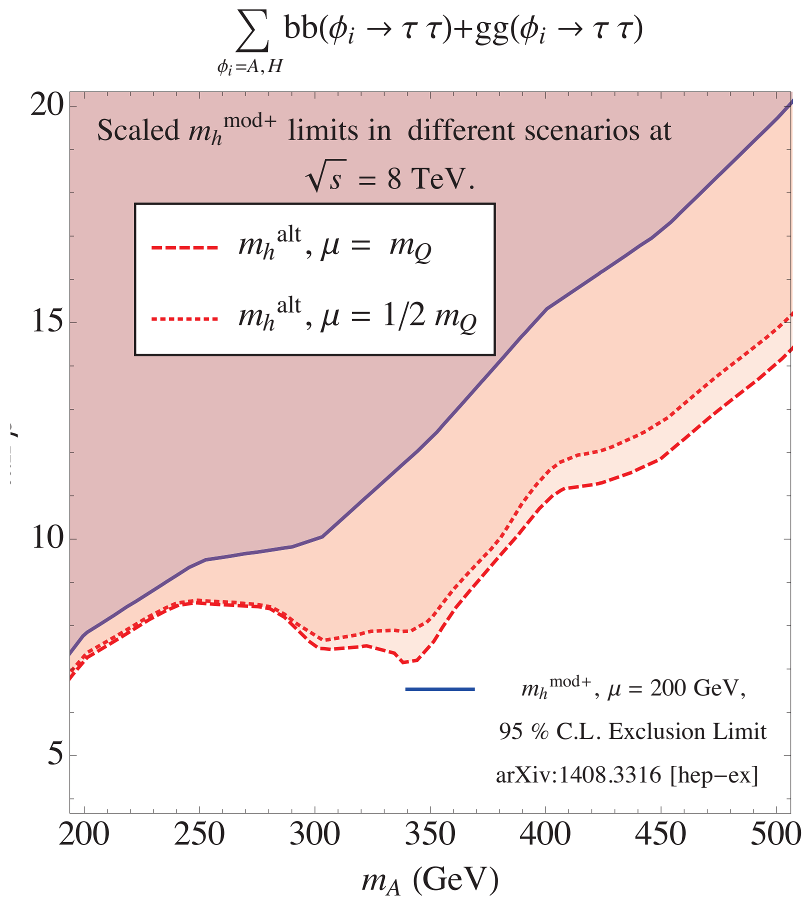




The CP-odd Higgs contribution is unsuppressed at low values of tanβ

Variation of the Experimental Bound with the value of μ

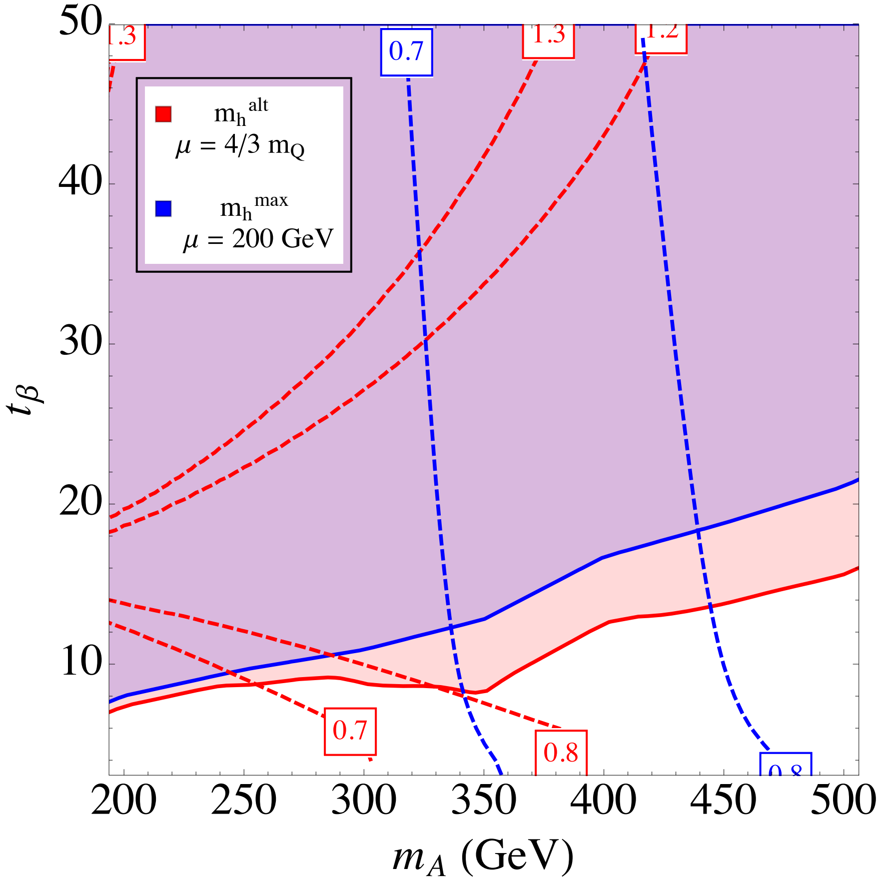
Carena, Haber, Low, Shah, C.W.'14



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)

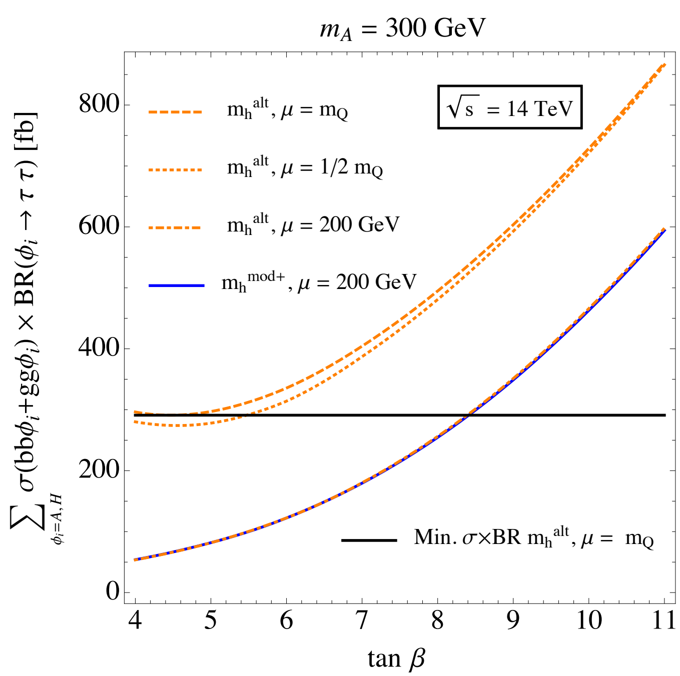
--- $\sigma(bbh+ggh) \times BR(h \to VV)/SM$

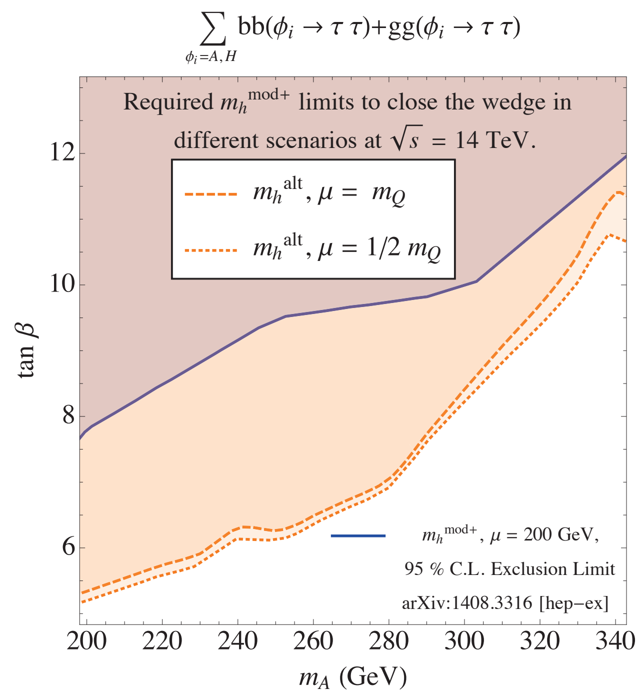
Limits coming from direct searches of $H, A \to \tau\tau$ become stronger for larger values of μ

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 that would close the wedge for masses below 350 GeV





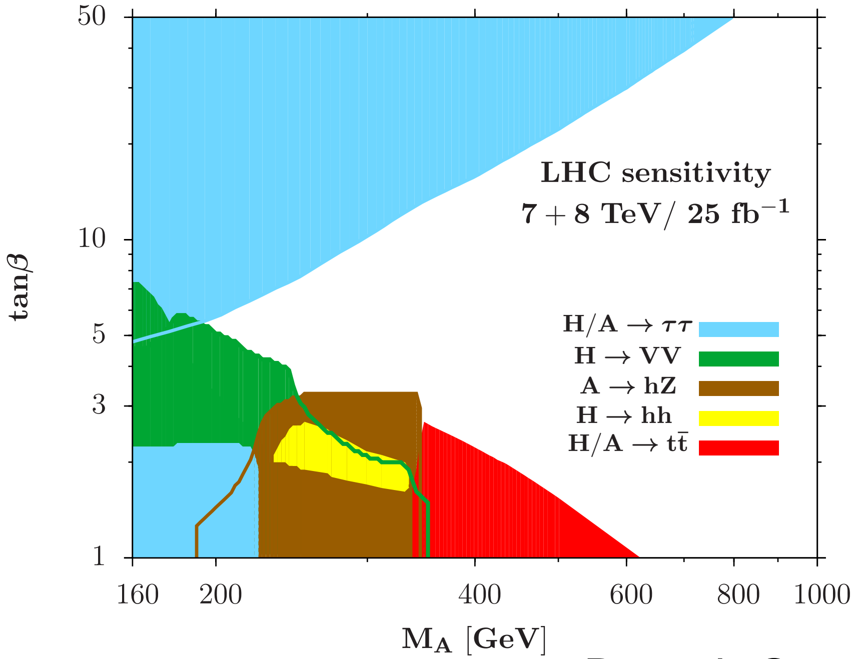
Comment on other direct search channels

- 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
- However, 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

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

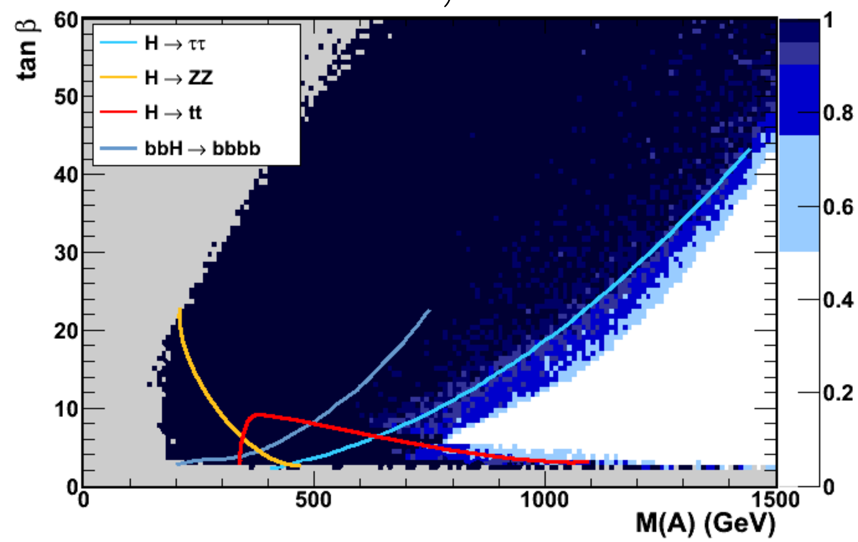
- Therefore, these channels cannot be efficiently used when the conditions of alignment are fulfilled
- Moreover, the reach of these channels should be revised in the presence of light charginos and neutralinos, which may provide alternative search channels.

Reach in different channels. Energy Dependence

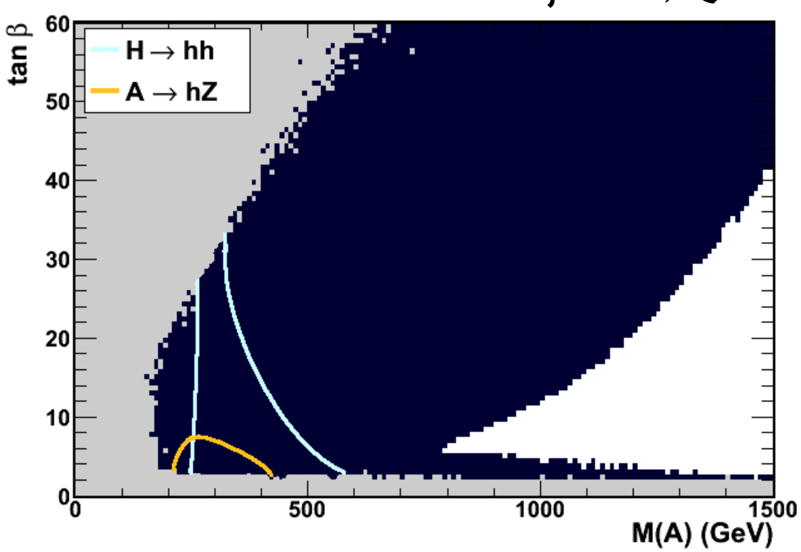


Djouadi, Quevillon'13

14 TeV, 150 fb^{-1}



Arbey, Battaglia, Mahmoudi'13



14 TeV, 150 fb^{-1}

These latest channels are only open away from the Alignment region. Here μ is mostly sizable, but sufficiently small so alignment not obtained

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,

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

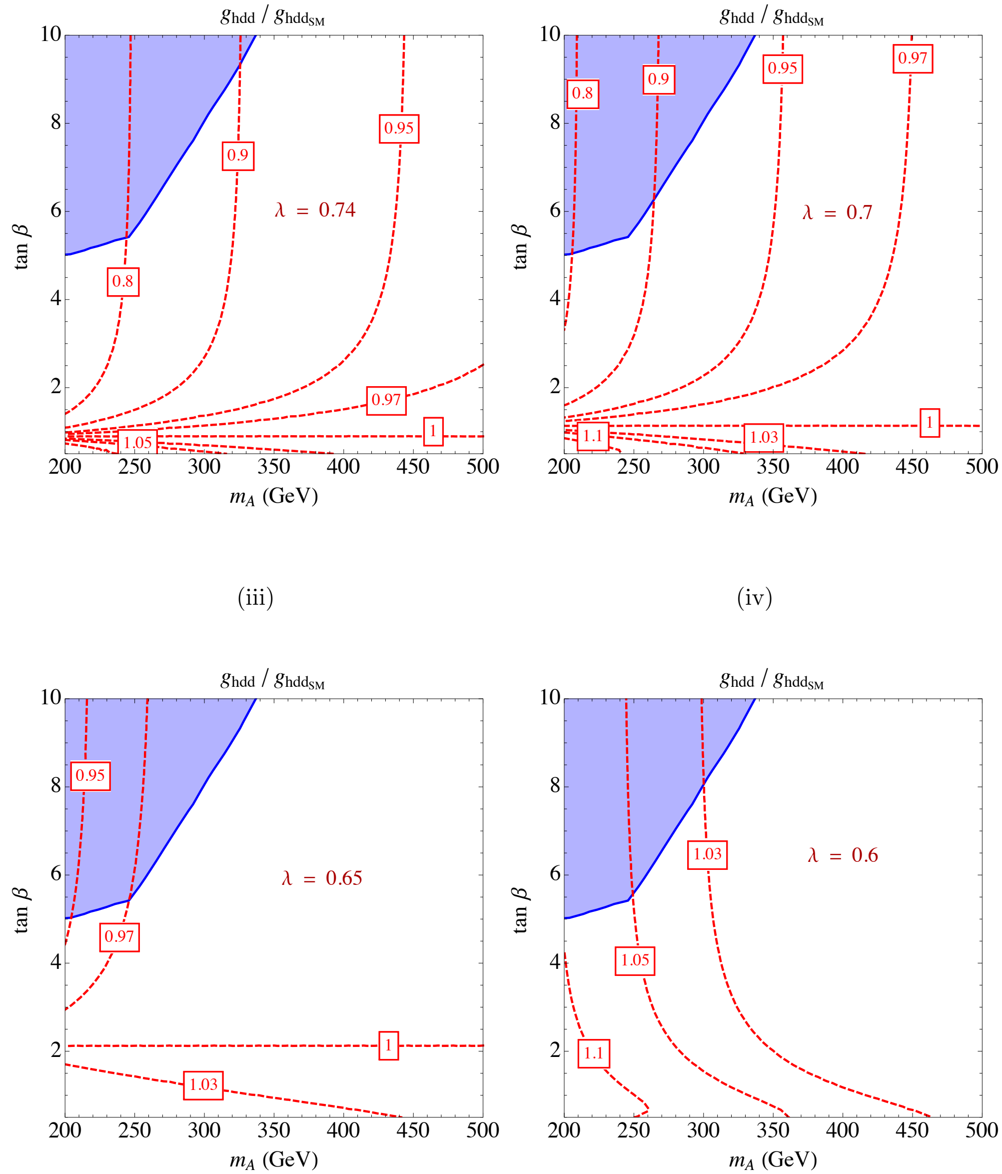
- The last term is the one appearing in the MSSM, that are small for moderate mixing and small values of $\tan\beta$

- 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

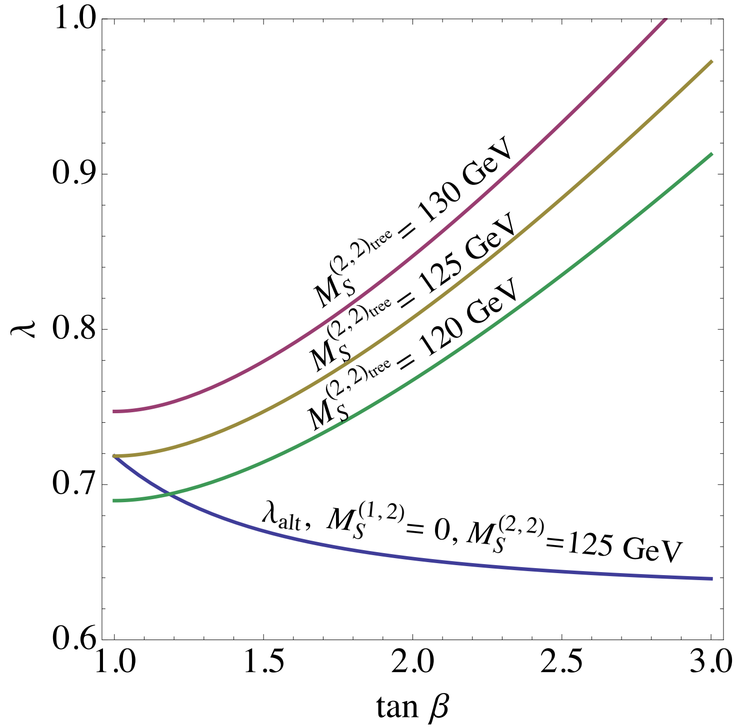
It is clear from these plots that the NMSSM does an amazing job in aligning the MSSM-like CP-even sector, provided lambda is of about 0.65

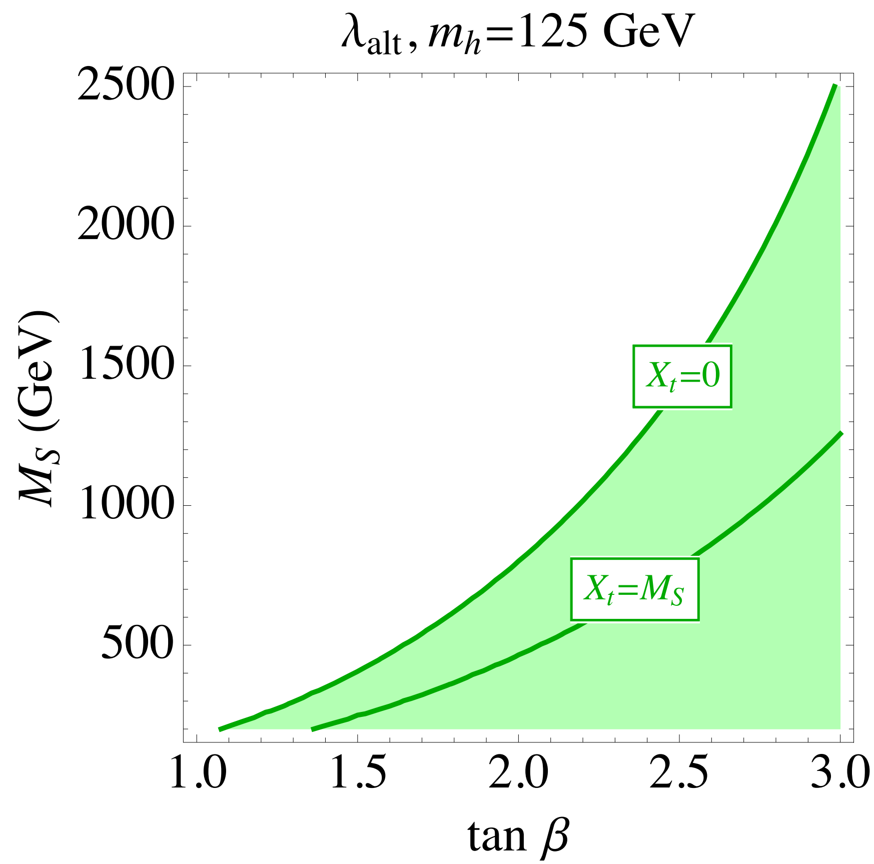
Stop Contribution at alignment

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

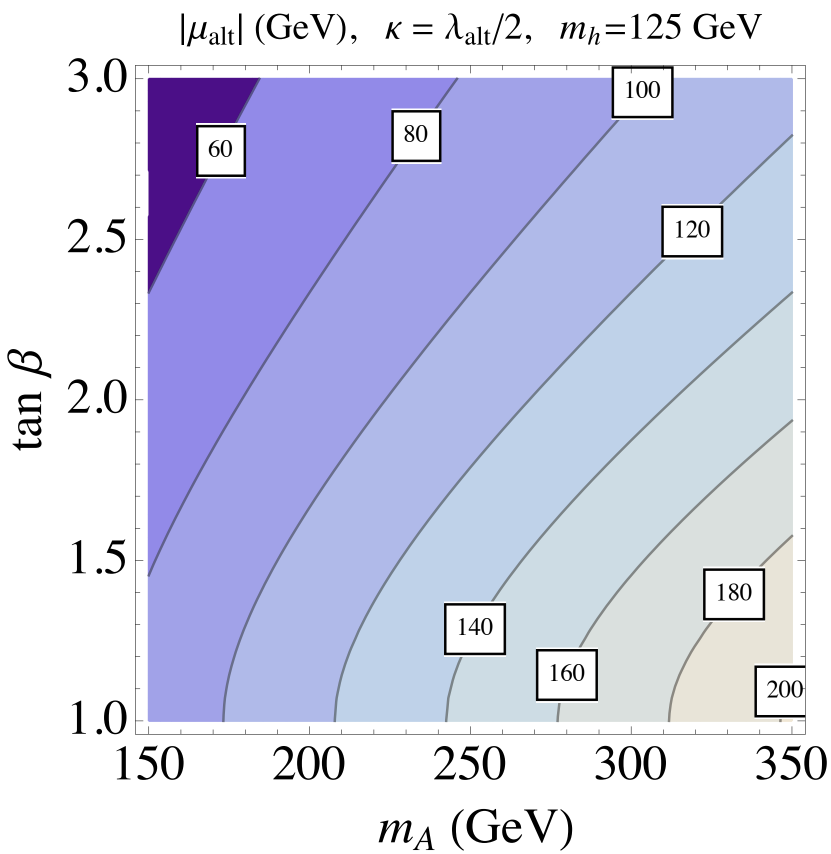
- If one assumes $\tan\beta < 3$ and lambda of order 0.65, and in addition one asks for kappa in the perturbative regime, one inmediately conclude that in order to get small mixing in the Higgs sector, the CP-odd Higgs is correlated in mass with the parameter mu, namely

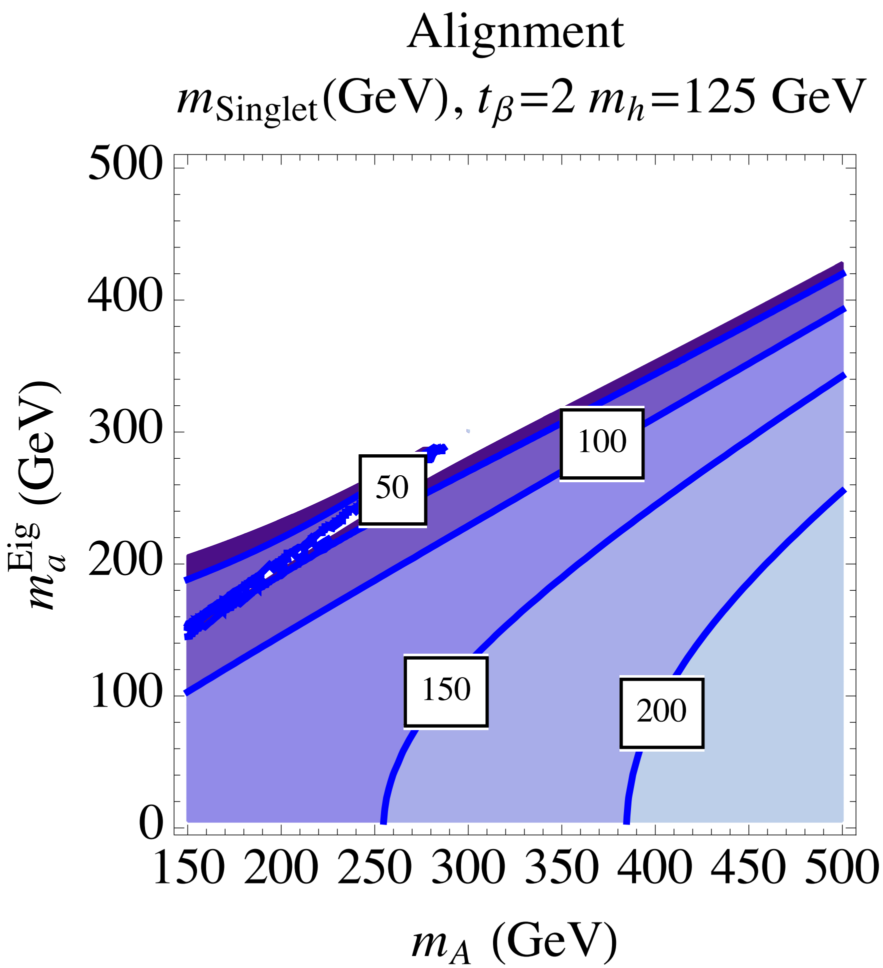
- Since both of them small is a measure of naturalness, we see again that alignment and naturalness come together in a beautiful way in the NMSSM

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

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

Phenomenological Consequences

- The (approximate) alignment and perturbativity conditions led to a light spectrum that is testable
- The loop-induced couplings of the SM-like Higgs can still be modified in a significant way, due to the presence of light stops and, if the gauginos are also light, light charginos
- The non-standard Higgs bosons may present decays into the lighter Higgs bosons as well as into the light electroweakinos. The gluon fusion production cross section of the would be heavy MSSM states is enhanced due to the top Yukawa contributions, and can be of the order of several pb.
- The decay of these non-standard Higgs bosons into taus and bottoms will be suppressed due to the small values of tanbeta and the presence of additional decays.
- In the case of thermal dark matter light gauginos are favored in order to evade the otherwise large direct dark matter detection cross sections.
- The natural NMSSM in the presence of alignment leads to a reach phenomenology at the LHC.

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.
- Bounds on the CP-odd Higgs mass are model dependent and should take into account this dependence.
- 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.
- These regions are associated with values of lambda of about 0.65 and light Higgs and Higgsino states, and therefore present a rich phenomenology for the LHC and also for direct and indirect Dark Matter detection.