Lectures on Higgs Physics II

Two Higgs Doublet Models and Supersymmetry

Carlos E.M. Wagner

Argonne National Laboratory

EFI, KICP and Phys. Dept. University of Chicago

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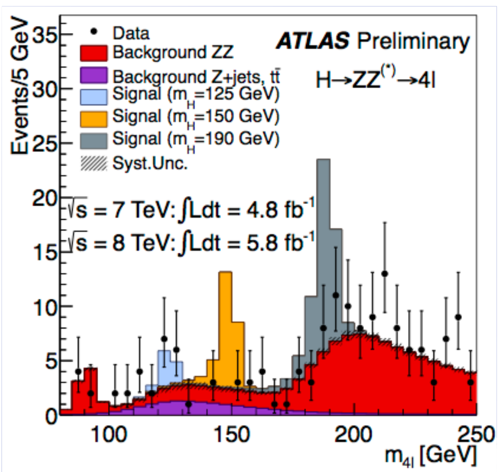
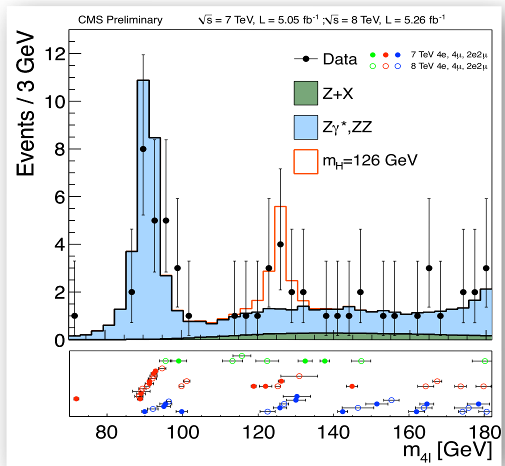
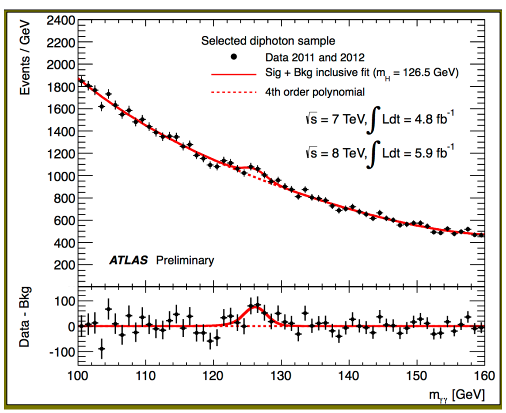
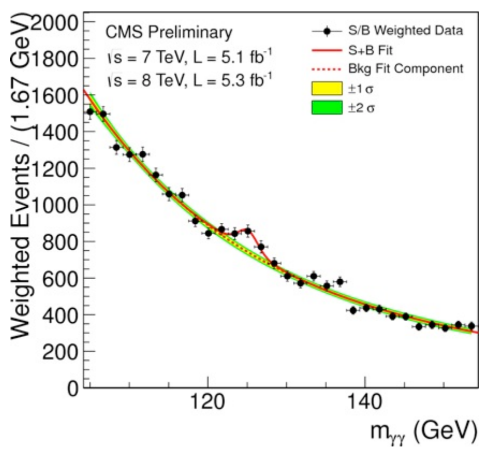
A Standard Model-like Higgs particle has been discovered by the ATLAS and CMS experiments at CERN









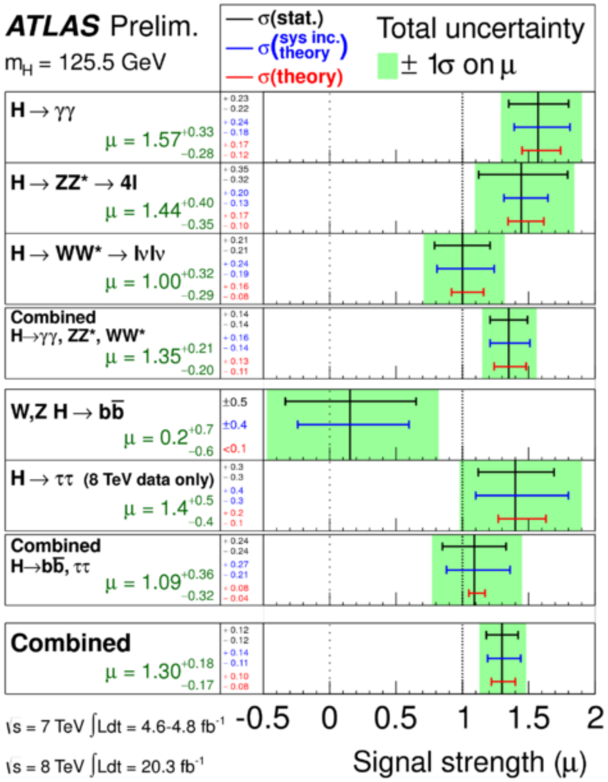
We see evidence of this particle in multiple channels.

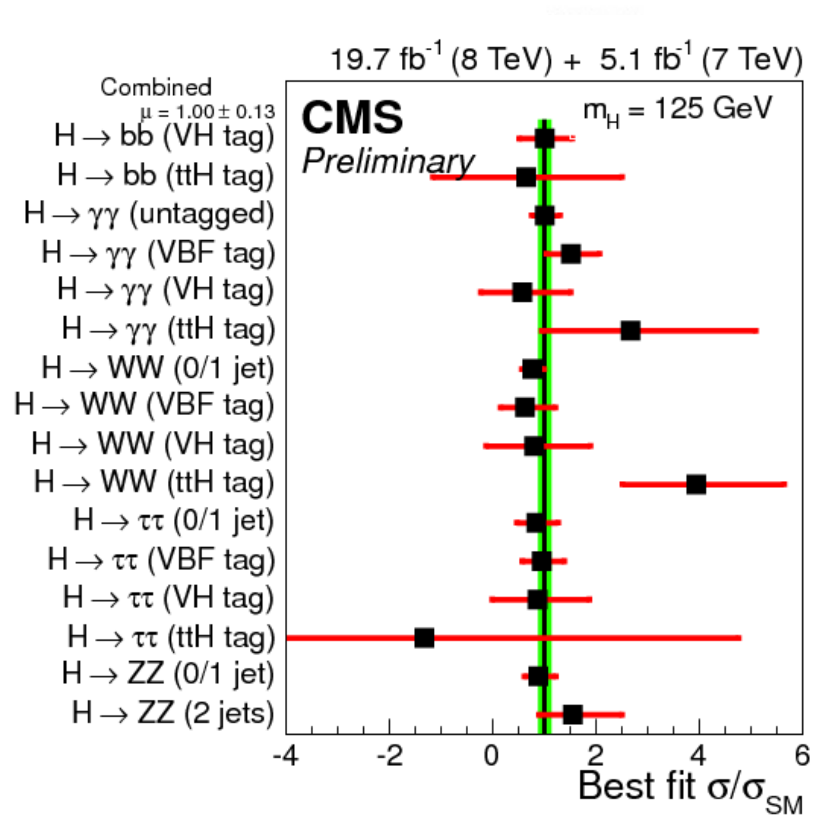
We can reconstruct its mass and we know that is about 125 GeV.

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

But we cannot determine the Higgs couplings very accurately

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.

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.

Goldstone Modes and Physical States

- Since both Higgs fields carry the same quantum numbers, one can always define the combinations

$$\frac{H_2 v_2 + H_1 v_1}{\sqrt{v_1^2 + v_2^2}} \equiv H_2 \sin\beta + H_1 \cos\beta = H_v$$

$$\frac{H_2 v_1 - H_1 v_2}{\sqrt{v_1^2 + v_2^2}} \equiv H_2 \cos\beta - H_1 \sin\beta = H_{NS}$$

- The first combination acquires vacuum expectation value v. The second does not acquire a vacuum expectation value.

- Then, it is clear that the Goldstone modes will be the charged and the imaginary part of the neutral components of H_v

- The charged and imaginary part of the neutral components of H_{NS} will be the physical charged and CP-odd Higgs bosons respectively.

$$G^{\pm} = H_2^{\pm} \sin\beta + H_1^{\pm} \cos\beta$$
$$H^{\pm} = -H_2^{\pm} \cos\beta + H_1^{\pm} \sin\beta$$

$$\sqrt{2}\ G^0 = \mathrm{Im} H_2^0 \sin\beta + \mathrm{Im} H_1^0 \cos\beta$$
$$\sqrt{2}\ A = -\mathrm{Im} H_2^0 \cos\beta + \mathrm{Im} H_1^0 \sin\beta$$

- What about the CP-even states ? There is no symmetry argument and in principle both states could mix.

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.

Comments

- The some of the square of the couplings of the trilinear couplings of the two CP-even Higgs bosons to the gauge bosons is equal to the square of the trilinear coupling in the SM.

- If the mixing angle is such that

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

  then the lightest Higgs behaves as the SM Higgs and acquires a vacuum expectation value equal to v. Only one of the two Higgs doublets is involved in electroweak symmetry breaking and contains all the Goldstone modes and the lightest Higgs state.

- The fields corresponding to the other Higgs boson do not present trilinear couplings to the gauge bosons.

- This limit is called the decoupling limit, and from an effective theory point of view it must be achieved when the masses of the non-standard Higgs bosons is large.

- Needless to say the quartic coupling of Higgs bosons with gauge bosons is governed by gauge interactions independent of the vacuum expectation values and it takes the SM value for both Higgs fields.

Fermion Masses and Flavor

- Similarly to the gauge boson masses, the fermion masses are obtain from the some of the contributions of both Higgs fields.

- For instance, the down-quark mass matrix is given by

$$M_d^{ij} = h_{d,1}^{ij} \frac{v_1}{\sqrt{2}} + h_{d,2}^{ij} \frac{v_2}{\sqrt{2}}$$

- The interaction of the two CP-even scalars with fermions is given, instead, by

$$g_{hd_id_j} \propto h_{d,1}^{ij}(-\sin\alpha) + h_{d,2}^{ij}(\cos\alpha)$$
$$g_{Hd_id_j} \propto h_{d,1}^{ij}(\cos\alpha) + h_{d,2}^{ij}(\sin\alpha)$$

- So, contrary to the SM, the rotation that diagonalizes the mass matrix does not diagonalize the couplings. This in general leads to large Higgs mediated Flavor changing processes, that are in conflict with experiment.

- One solution is to make the non-standard Higgs bosons very heavy, going close to the SM. Another natural solution is to restrict the couplings of each fermion sector to only one of the two Higgs doublets. This is what happens to a good approximation in supersymmetry.

Type II Higgs doublet models

- There are many possible choices one could make. For instance, we can add a symmetry transformation that prevents the coupling of one of the Higgs bosons to quarks and leptons. Let's say that such a Higgs boson is H1. Then, we regain alignment in flavor space.

- In principle such symmetry operator would also prevent the mixing of the two Higgs bosons, but let's assume that this symmetry is broken softly and allow scalar mixing. Then, the fermion couplings will be given by

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

- In Type II models, instead, the Higgs H1 would couple to down-quarks and charge leptons, while the Higgs H2 couples to up quarks and neutrinos. Therefore,

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

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

- 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.

Higgs Potential

- The most generic two Higgs doublet potential is given by

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

- As said before, we shall assume that

$$
\langle \Phi_i \rangle = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v_i \end{pmatrix}
$$

- One can minimize this potential, assuming real couplings, to get ($\tilde{\lambda}_3 = \lambda_3 + \lambda_4 + \lambda_5$)

$$
\boxed{
\begin{aligned}
& m_{11}^2 - t_\beta m_{12}^2 + \frac{1}{2} v^2 c_\beta^2 (\lambda_1 + 3\lambda_6 t_\beta + \tilde{\lambda}_3 t_\beta^2 + \lambda_7 t_\beta^3) = 0 \;, \\
& m_{22}^2 - t_\beta^{-1} m_{12}^2 + \frac{1}{2} v^2 s_\beta^2 (\lambda_2 + 3\lambda_7 t_\beta^{-1} + \tilde{\lambda}_3 t_\beta^{-2} + \lambda_6 t_\beta^{-3}) = 0
\end{aligned}
}
$$

- Now, since we know the exact components of the CP-odd Higgs and the charged Higgs one can use these minimization conditions to get their masses as a function of only one of the mass parameters and the quartic couplings. One obtains

$$
m_A^2 = \frac{2 m_{12}^2}{s_{2\beta}} - \frac{1}{2} v^2 (2\lambda_5 + \lambda_6 t_\beta^{-1} + \lambda_7 t_\beta) \qquad\qquad m_H^{\pm} = m_A^2 + \frac{v^2}{2} (\lambda_5 - \lambda_4)
$$

The CP-even sector

- The CP-even mass matrix may be computed by using the minimization condition and the value of the CP-odd Higgs mass. One obtains,

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

where

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

- Observe that for large values of the CP-odd Higgs mass, and perturbative couplings, one can ignore the second term compared to the first term, and then one obtains that the heavier CP-even Higgs is of order of the CP-odd Higgs mass, while the lightest Higgs remains of the order of an effective quartic coupling times the Higgs vacuum expectation value. Indeed, from our mixing angle definition, it must be fulfilled that

$$\begin{pmatrix} \mathcal{M}_{11}^2 & \mathcal{M}_{12}^2 \\ \mathcal{M}_{12}^2 & \mathcal{M}_{22}^2 \end{pmatrix} \begin{pmatrix} -s_\alpha \\ c_\alpha \end{pmatrix} = m_h^2 \begin{pmatrix} -s_\alpha \\ c_\alpha \end{pmatrix}$$

$$t_\alpha = \frac{\mathcal{M}_{12}^2}{\mathcal{M}_{11}^2 - m_h^2} = \frac{\mathcal{M}_{22}^2 - m_h^2}{\mathcal{M}_{12}^2}$$

Mixing Angle and Decoupling Limit

- From the expressions before, one obtains

$$s_\alpha \;=\; \frac{\mathcal{M}_{12}^2}{\sqrt{(\mathcal{M}_{12}^2)^2 + (\mathcal{M}_{11}^2 - m_h^2)^2}}\;, \qquad m_H^2 = \frac{\mathcal{M}_{11}^2(\mathcal{M}_{11}^2 - m_h^2) + (\mathcal{M}_{12}^2)^2}{\mathcal{M}_{11}^2 - m_h^2}$$

- Then, one can easily see that

$$s_\alpha \;\to -\cos\beta, \qquad m_H^2 \to m_A^2 \;\text{ when } m_A \to \infty$$

- The above expressions represent the decoupling limit advertised before.
- In the decoupling limit, the effective low energy theory is just the SM, and therefore the obtention of couplings of the lightest Higgs boson which approach the SM ones is not a surprise.
- Due to the results of the LHC, a relevant question is under which conditions I can keep a light non-standard Higgs spectrum while not deviating in a rough way from the SM couplings.

Alignment without Decoupling

- The eigenstate equation may be rewritten in the following way

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

- For large values of the CP-odd Higgs mass we obtain

$$\begin{pmatrix} s_\beta^2 & -s_\beta c_\beta \\ -s_\beta c_\beta & c_\beta^2 \end{pmatrix} \begin{pmatrix} -s_\alpha \\ c_\alpha \end{pmatrix} \approx 0 \qquad\qquad \cos(\beta - \alpha) = 0$$

- Now, the idea would be to obtain this condition for lower CP-odd Higgs masses, independently of m_A

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

$$m_h^2 = v^2 L_{11} + t_\beta v^2 L_{12} = v^2 \left(\lambda_1 c_\beta^2 + 3\lambda_6 s_\beta c_\beta + \tilde{\lambda}_3 s_\beta^2 + \lambda_7 t_\beta s_\beta^2\right) \; ,$$

$$m_h^2 = v^2 L_{22} + \frac{1}{t_\beta} v^2 L_{12} = v^2 \left(\lambda_2 s_\beta^2 + 3\lambda_7 s_\beta c_\beta + \tilde{\lambda}_3 c_\beta^2 + \lambda_6 t_\beta^{-1} c_\beta^2\right)$$

Case of $\lambda_{6,7} = 0$

- One of the conditions of alignment reduces to the obtention of the right Higgs mass

$$m_h^2 = (\lambda_2 \sin^4\beta + \tilde{\lambda}_3 \sin^2\beta \cos^2\beta + \lambda_1 \cos^4\beta) v^2$$

The additional condition is

$$\tan^2\beta = \frac{\lambda_1 - \lambda_{\rm SM}}{\lambda_{SM} - \tilde{\lambda}_3}$$

and should be positive. In the MSSM, this ratio tends to be negative, but tends to be positive in the NMSSM, as we will show tomorrow when we analyze this case

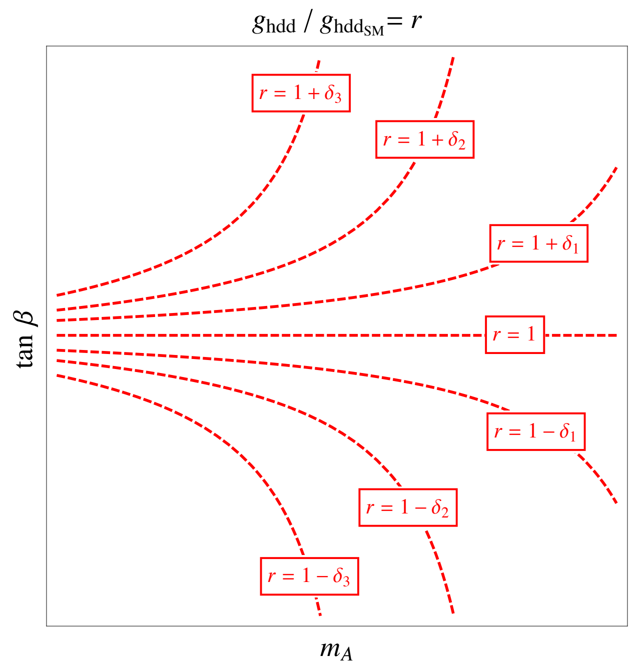
Case of $\lambda_{6,7} \neq 0$

Apart from the Higgs mass requirement, one obtains that at large tanbeta, alignment may occur without decoupling if

$$t_\beta^{(1)} = \frac{\lambda_{\rm SM} - \tilde{\lambda}_3}{\lambda_7}$$

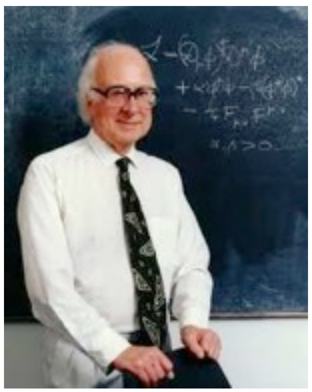
This may occur in the MSSM.

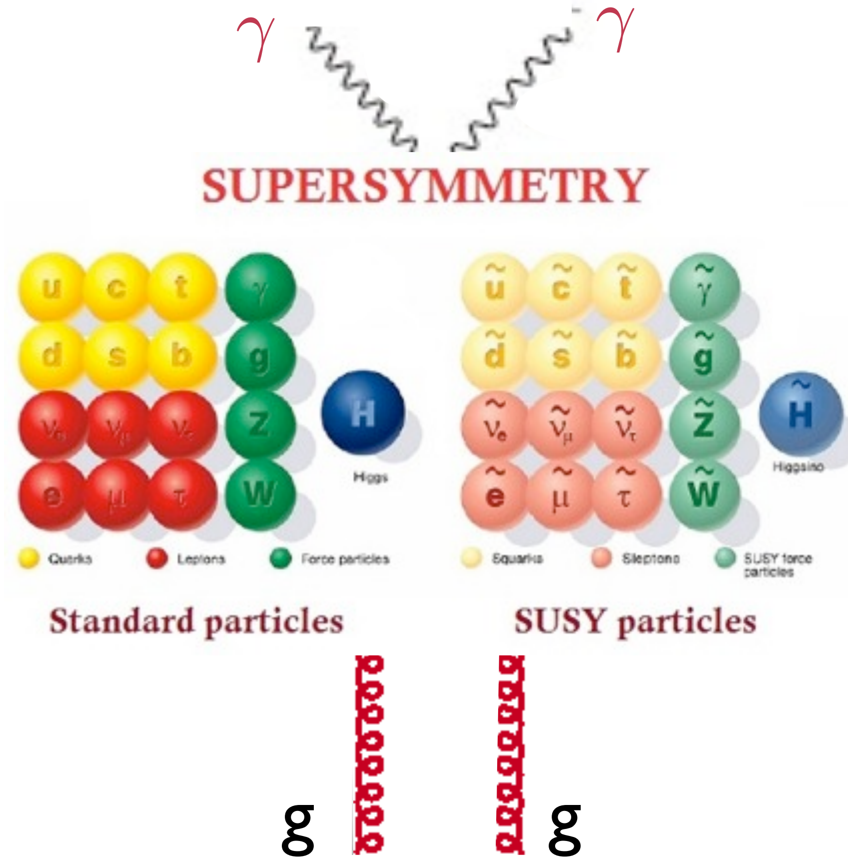
General behavior of the down-quark couplings to the lightest Higgs boson in the proximity of alignment



Behavior of the theory depends strongly on the value of the quartic couplings. We shall concentrate on the particular two Higgs doublet models associated with minimal supersymmetric extensions of the SM

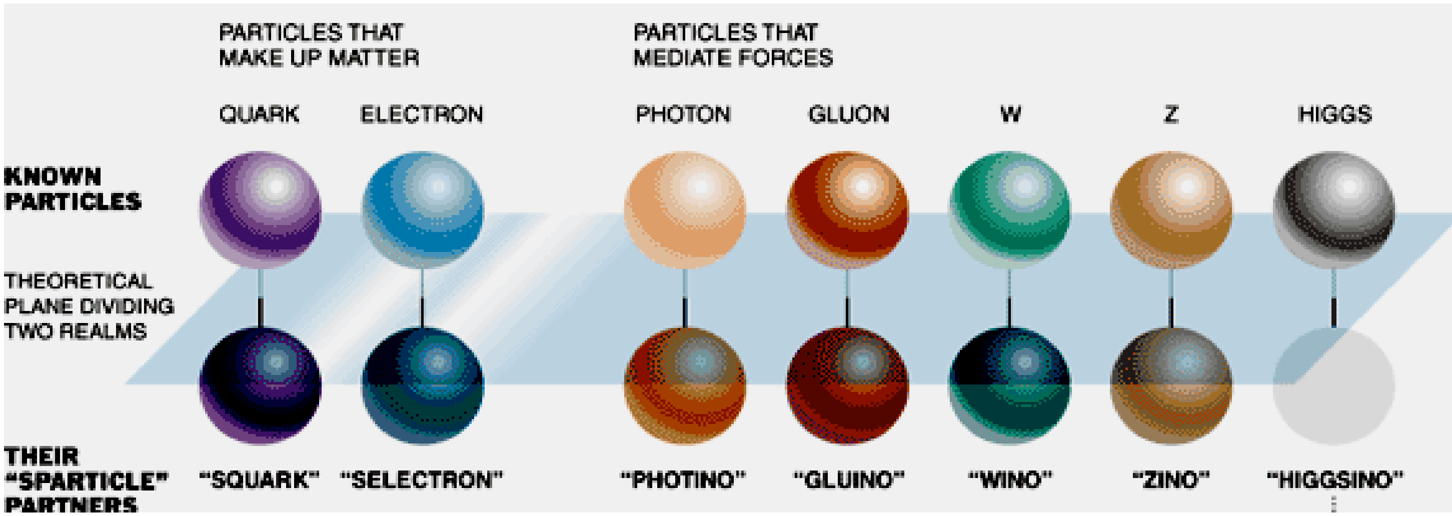
Supersymmetry and Higgs Physics





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)

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

Why Supersymmetry ?

- Helps to stabilize the weak scale—Planck scale hierarchy: $\delta\, m_H^2 \approx (-1)^{2\,S_i} \dfrac{n_i\, g_i^2}{16\pi^2} \Lambda^2$

- Supersymmetry algebra contains the generator of space-time translations.
  Possible ingredient of theory of quantum gravity.

- Minimal supersymmetric extension of the SM :
  Leads to Unification of gauge couplings.

- Starting from positive masses at high energies, electroweak symmetry breaking is induced radiatively.

- If discrete symmetry, P = $(-1)^{3B+L+2S}$ is imposed, lightest SUSY particle neutral and stable: Excellent candidate for cold Dark Matter.

Minimal Supersymmetric Standard Model

SM particle	SUSY partner	G_{SM}
(S = 1/2)	(S = 0)	
$Q = (t, b)_L$	$(\tilde{t}, \tilde{b})_L$	(3,2,1/6)
$L = (\nu, l)_L$	$(\tilde{\nu}, \tilde{l})_L$	(1,2,-1/2)
$U = \left(t^C\right)_L$	$\tilde{t}^*_R$	($\bar{3}$,1,-2/3)
$D = \left(b^C\right)_L$	$\tilde{b}^*_R$	($\bar{3}$,1,1/3)
$E = \left(l^C\right)_L$	$\tilde{l}^*_R$	(1,1,1)
(S = 1)	(S = 1/2)	
B_μ	$\tilde{B}$	(1,1,0)
W_μ	$\tilde{W}$	(1,3,0)
g_μ	$\tilde{g}$	(8,1,0)

Two Higgs Doublets

Higgs Doublets

- Two Higgs doublets with opposite hypercharge.

(S = 0)	(S = 1/2)	
H_1	$\tilde{H}_1$	(1,2,-1/2)
H_2	$\tilde{H}_2$	(1,2,1/2)

This is necessary in SUSY to

1) Cancel the gauge anoamlies

$$\sum_{quarks} Y_i = 0; \qquad \sum_{left} Y_i = 0;$$

$$\sum_i Y_i^3 = 0; \qquad \sum_i Y_i = 0$$

2) Generate Gauge invariant Yukawa couplings for all quarks and leptons

Effective Potential in SUSY

- In supersymmetry, one can derive the effective potential by introducing a quantity defined as the superpotential, which if one impose renormalizability is a generic analytic, gauge invariant polynomial of the chiral superfields (which include SM fermions and superpartners) of a degree lower and equal than 3

$$W[\Phi] \;=\; h_u^{ij} Q^i U^j H_2 + h_d^{ij} Q^i D^j H_1 + h_l^{ij} L^i E^j H_1 + \mu H_1 H_2$$

- Yukawa couplings are obtained by derivatives of the superpotential

$$-\frac{\partial W}{\partial \phi_i \partial \phi_j} \Psi_i \Psi_j + h.c.$$

- More important for our purposes, contributions to the scalar potential are obtained from

$$V = \sum_i \left| \frac{\partial W}{\partial \phi_i} \right|^2 + \frac{1}{2} \sum_a D^a D^a$$

$$D^a = -g_a \sum_i \phi_i^\dagger T^a \phi_i$$

- The potential is positive, what is not a surprise since in SUSY it is related to the square of the supersymmetric generators

Supersymmetry Breaking Parameters

Standard Model quark, lepton and gauge boson masses are protected by chiral and gauge symmetries.
Supersymmetric partners are not protected.
Explanation of absence of supersymmetric particles in ordinary experience/ high-energy physics colliders: Supersymmetric particles can acquire gauge invariant masses, as the one of the SM-Higgs.

Different kind of parameters:

Squark and slepton masses $m^2_{\tilde{q}}$, $m^2_{\tilde{l}}$
Gaugino (Majorana) masses M_i, $i = 1\text{-}3$
Trilinear scalar masses $(\tilde{f}^*_L \tilde{f}_R H_i)$ A_f, $-\mu^*$
Higgsino Mass μ Higgs Mass Parameters $|\mu|^2 + m^2_{H_i}$

Higgs Potential

- After supersymmetry breaking effects are considered, the Higgs potential reads

$$V(H_1, H_2) = m_1^2 H_1^\dagger H_1 + m_2^2 H_2^\dagger H_2 + m_3^2 (H_1^T i\tau_2 H_2 + h.c.) +$$

$$\frac{\lambda_1}{2}\left(H_1^\dagger H_1\right)^2 + \frac{\lambda_2}{2}\left(H_2^\dagger H_2\right)^2 + \lambda_3 \left(H_1^\dagger H_1\right)\left(H_2^\dagger H_2\right) + \lambda_4 \left|\left(H_1^T i\tau_2 H_2\right)\right|^2$$

  where

$$\lambda_1 = \lambda_2 = \frac{g_1^2 + g_2^2}{4}, \qquad \lambda_3 = \frac{g_2^2 - g_1^2}{4}, \qquad \lambda_4 = -\frac{g_2^2}{2}$$

- This effective potential is valid at the scale of the SUSY particle masses.

- The value of the effective potential at low energies may be obtained by evolving the quartic couplings with their renormalization group equations.

Lightest SM-like Higgs mass strongly depends on:

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

$$M^2_{\tilde{t}} = \begin{pmatrix} m^2_Q + m^2_t + D_L & m_t X_t \\ m_t X_t & m^2_U + m^2_t + D_R \end{pmatrix}$$

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

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

$$t = \log(M_{SUSY}^2 / m_t^2) \qquad \tilde{X}_t = \frac{2X_t^2}{M_{SUSY}^2}\left(1 - \frac{X_t^2}{12 M_{SUSY}^2}\right) \qquad \underline{X_t = A_t - \mu/\tan\beta} \rightarrow \text{LR stop mixing}$$

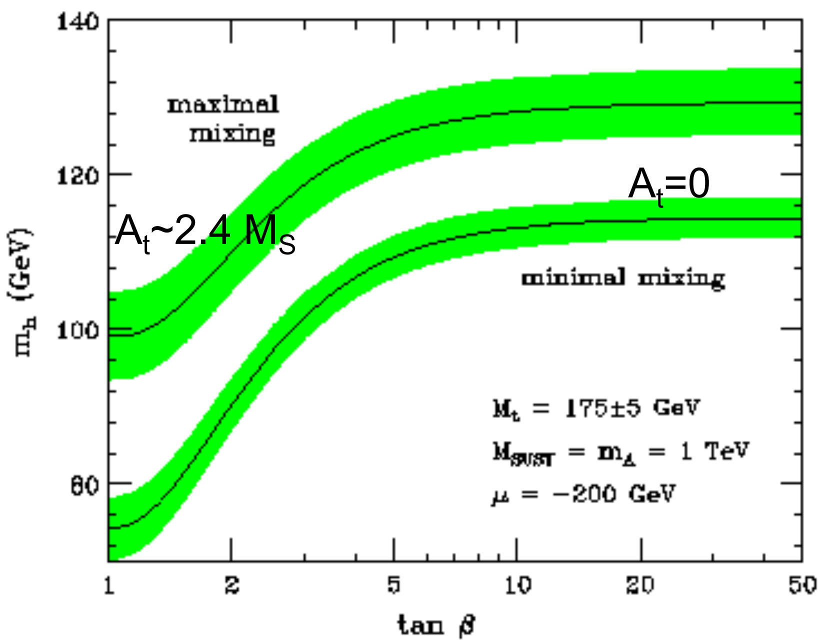
M.Carena, J.R. Espinosa, M. Quiros, C.W.'95
M. Carena, M. Quiros, C.W.'95

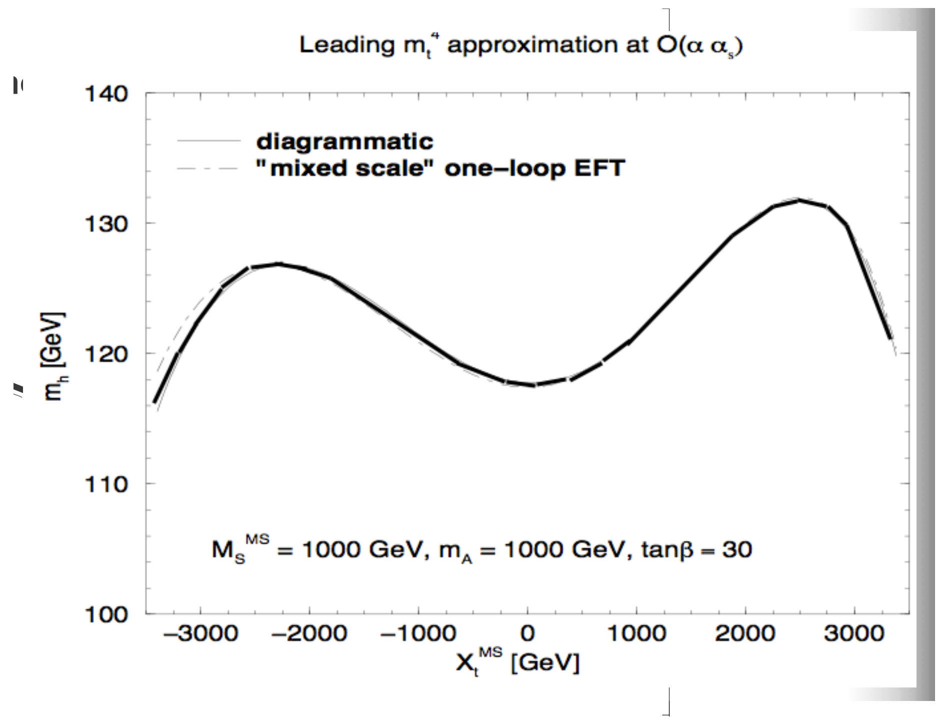
Analytic expression valid for $M_{SUSY} \sim m_Q \sim m_U$

Standard Model-like Higgs Mass

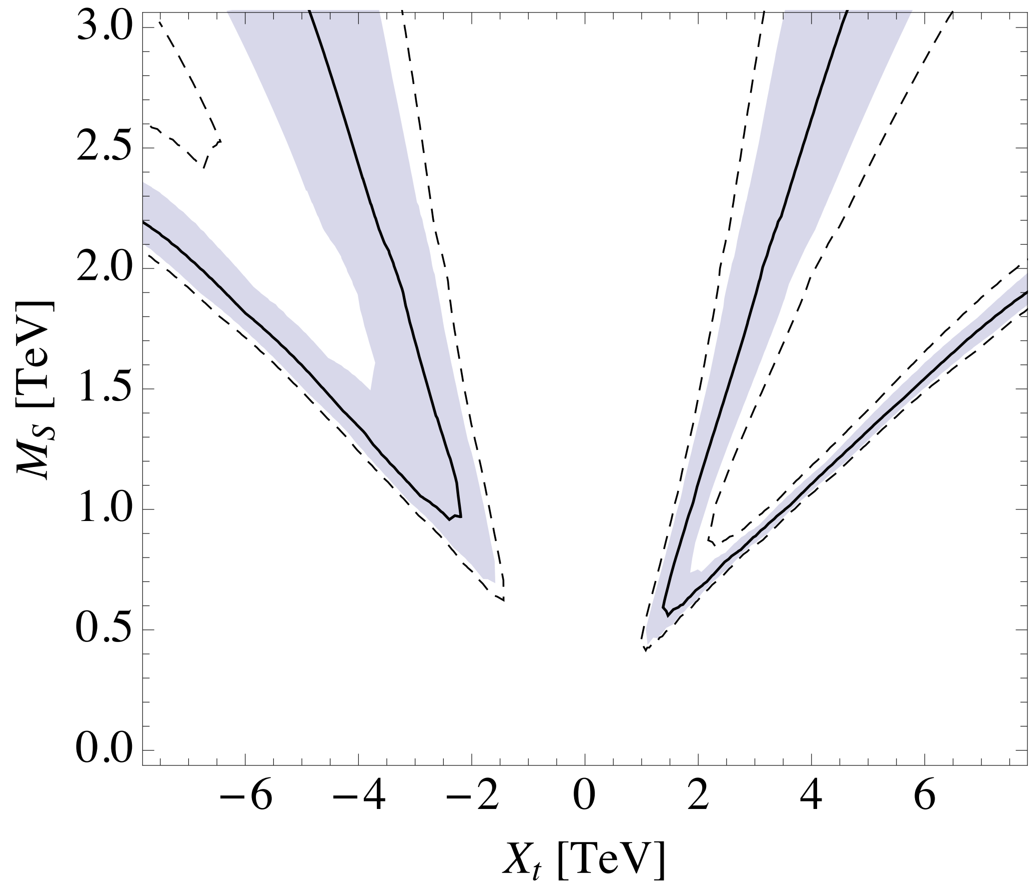
Long list of two-loop computations: Carena, Degrassi, Ellis, Espinosa, Haber, Harlander, Heinemeyer, Hempfling, Hoang, Hollik, Hahn, Martin, Pilaftsis, Quiros, Ridolfi, Rzehak, Slavich, C.W., Weiglein, Zhang, Zwirner

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





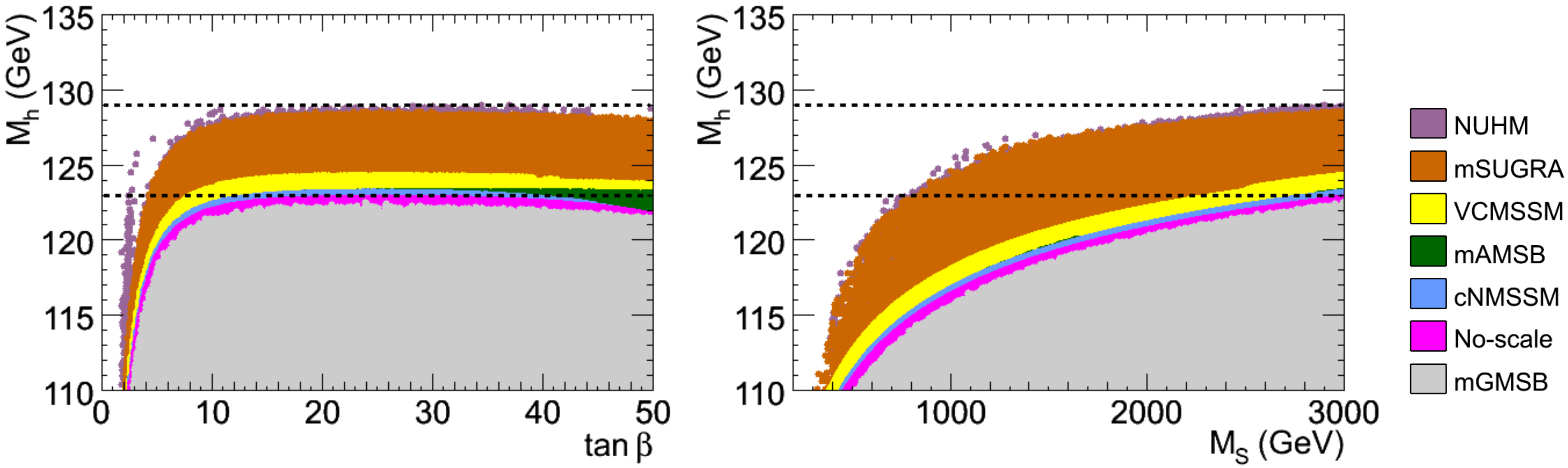
$$X_t = A_t - \mu/\tan\beta, \qquad X_t = 0 : \text{ No mixing}; \qquad X_t = \sqrt{6} M_S : \text{ Max. Mixing}$$



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. Elwanger'11

Constraints on Different Minimal Models

Maximal Higgs mass in constrained MSSM scenarios

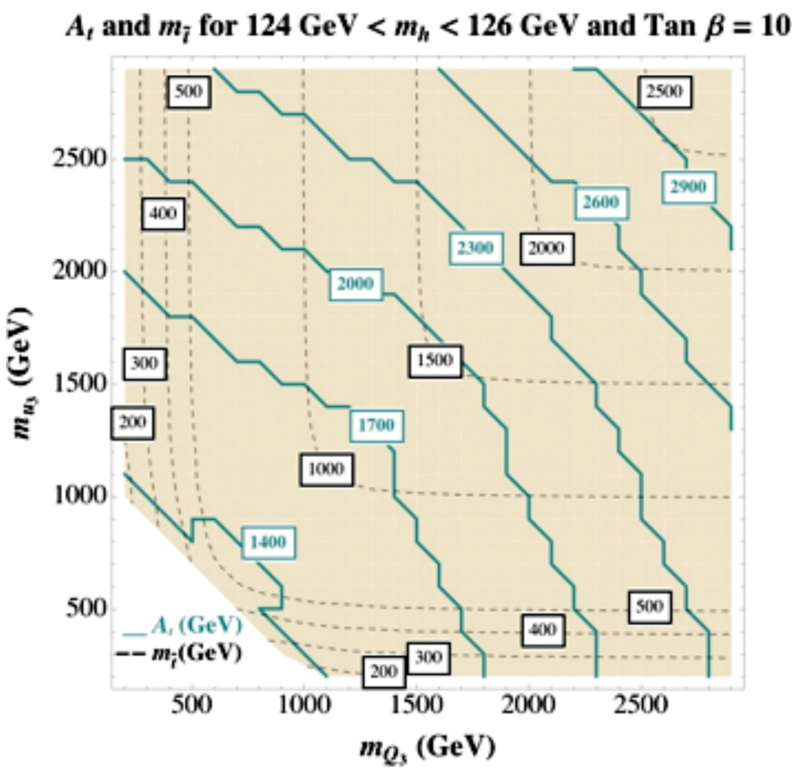


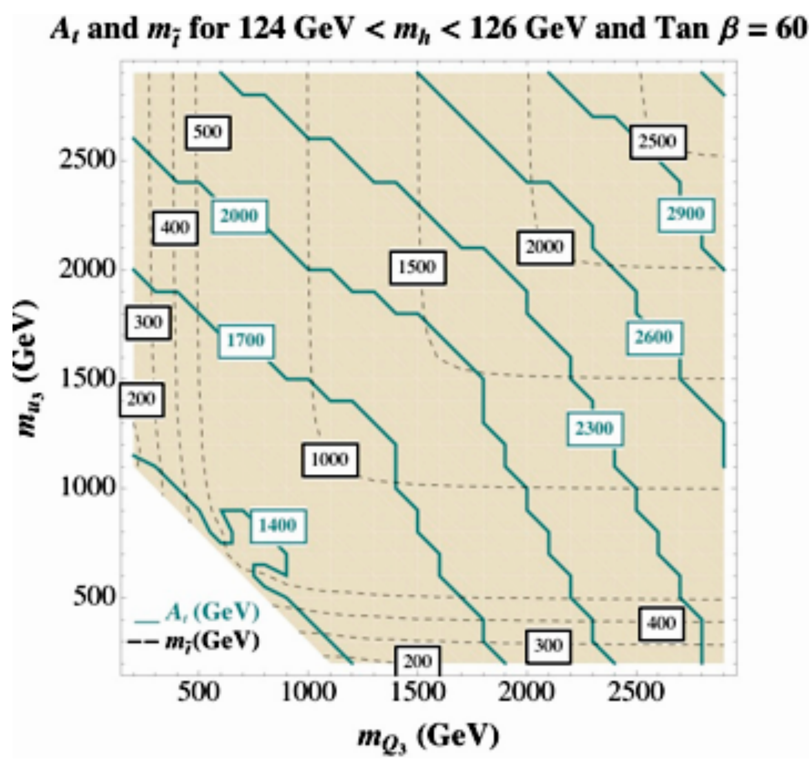
A. Arbey, M. Battaglia, A. Djouadi, F. Mahmoudi'12

Models which tend to predict small values of the stop mixing parameter are strongly constrained.

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
One stop can be light and the other heavy
or
in the case of similar stop soft masses.
both stops can be below 1TeV

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

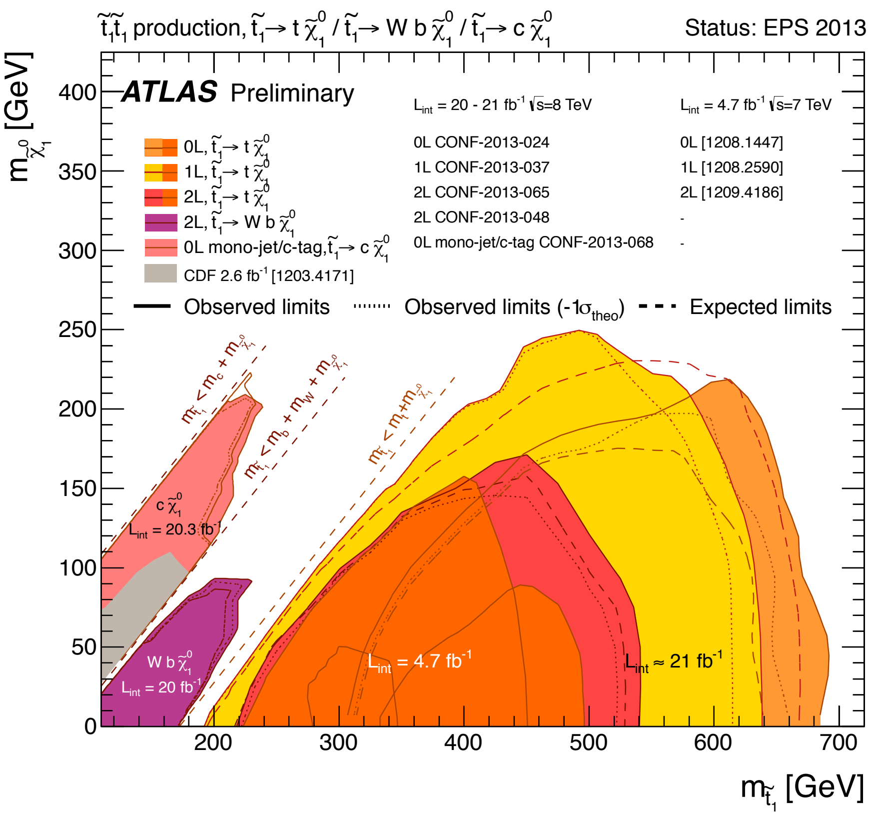
At large tan beta, light staus/sbottoms can decrease
mh by several GeV's via Higgs mixing effects
and compensate tan beta enhancement

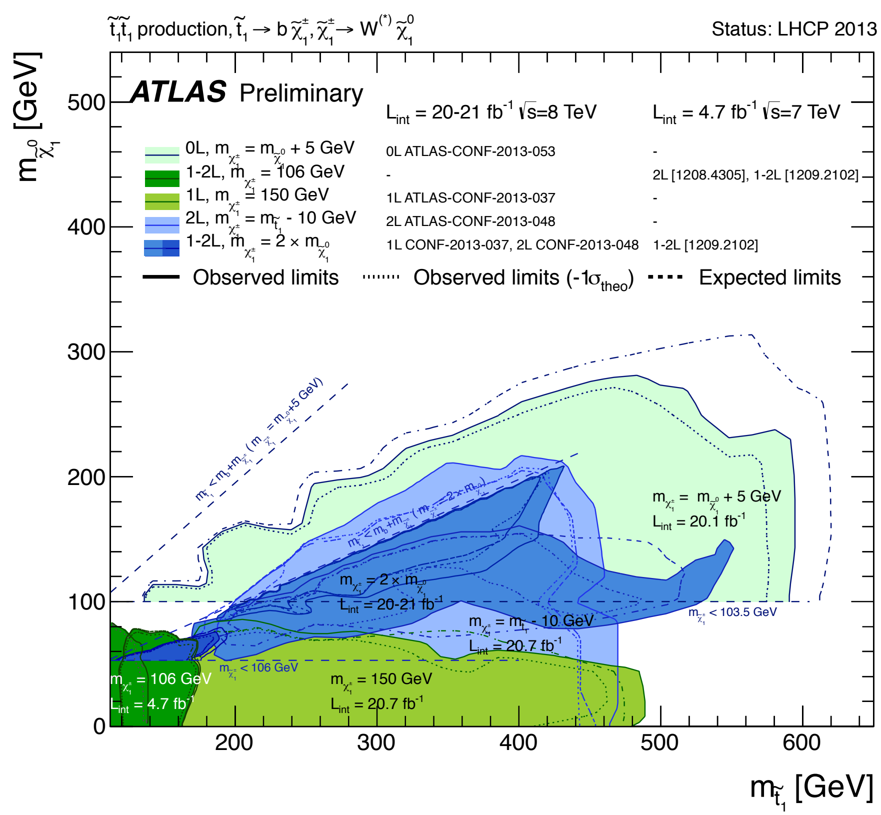
Light stop coupling to the Higgs

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

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.

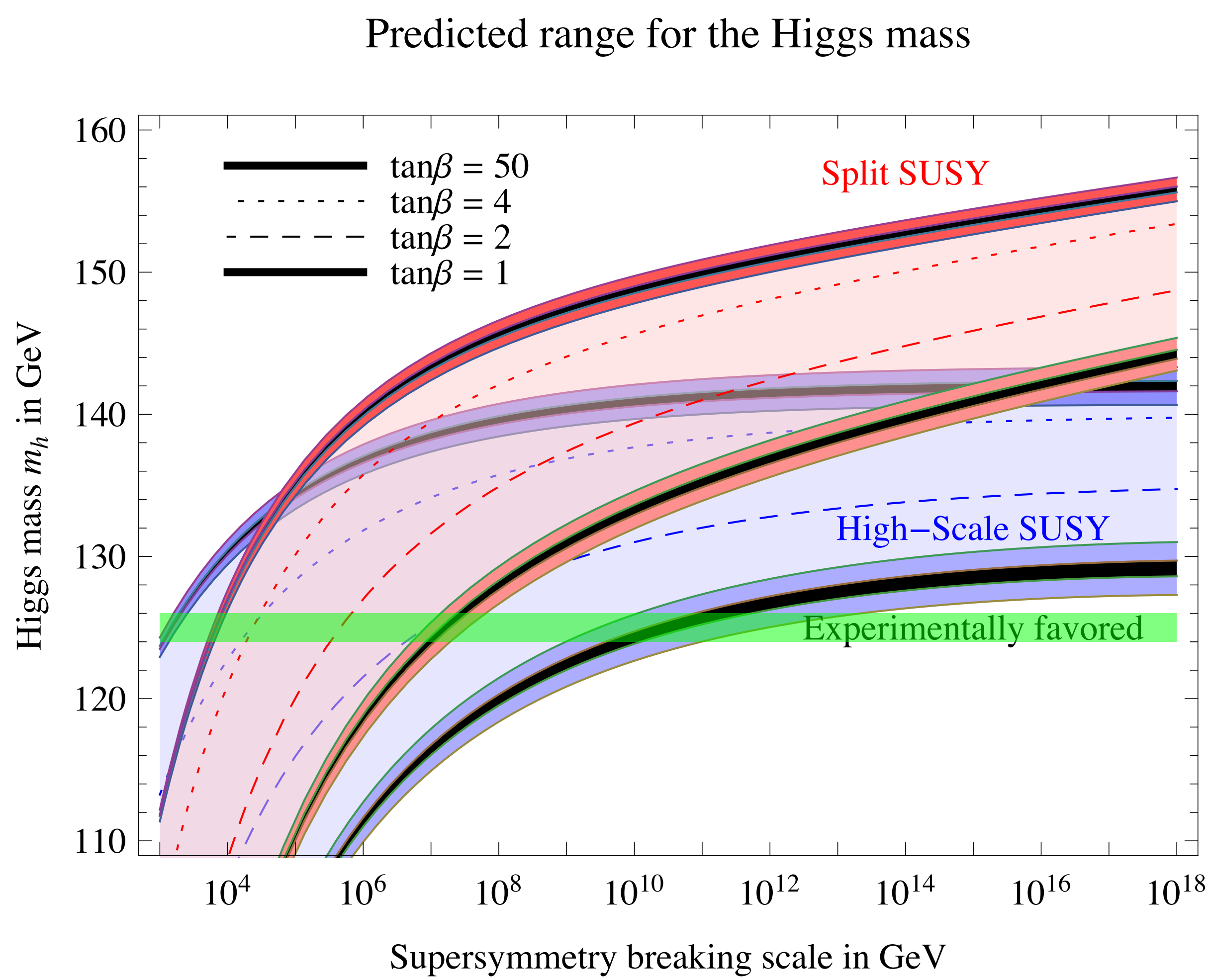
Limits on the Stop Mass



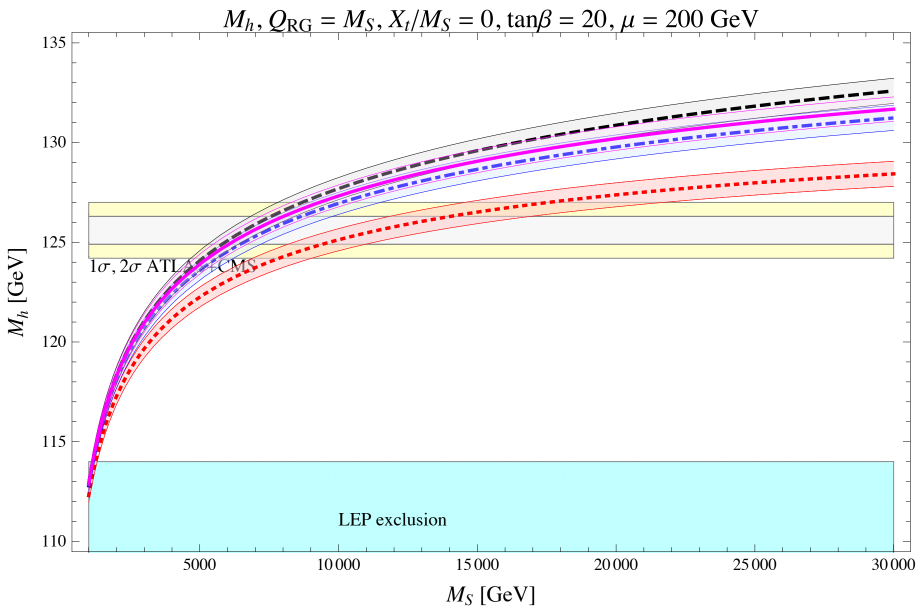


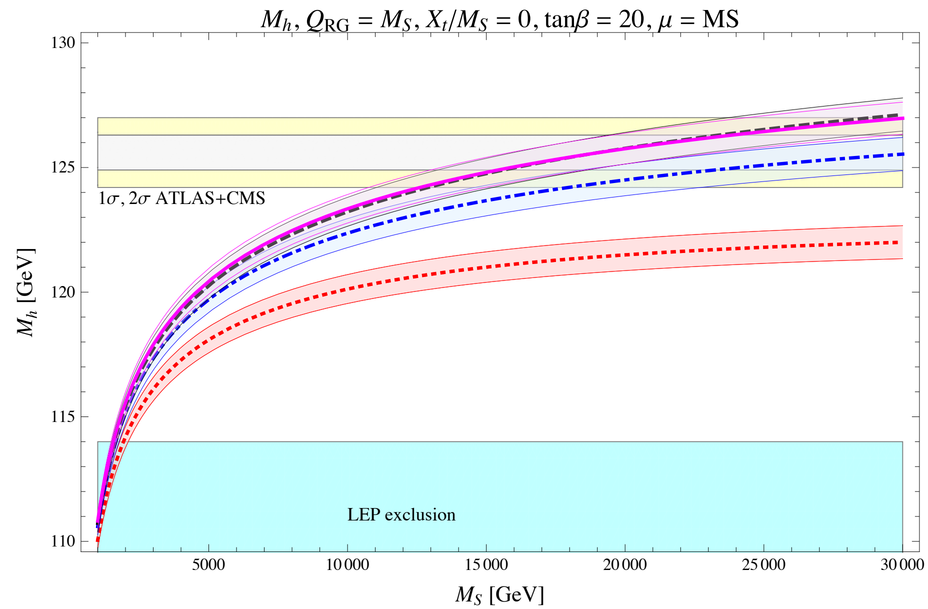
Large Stop Masses ?

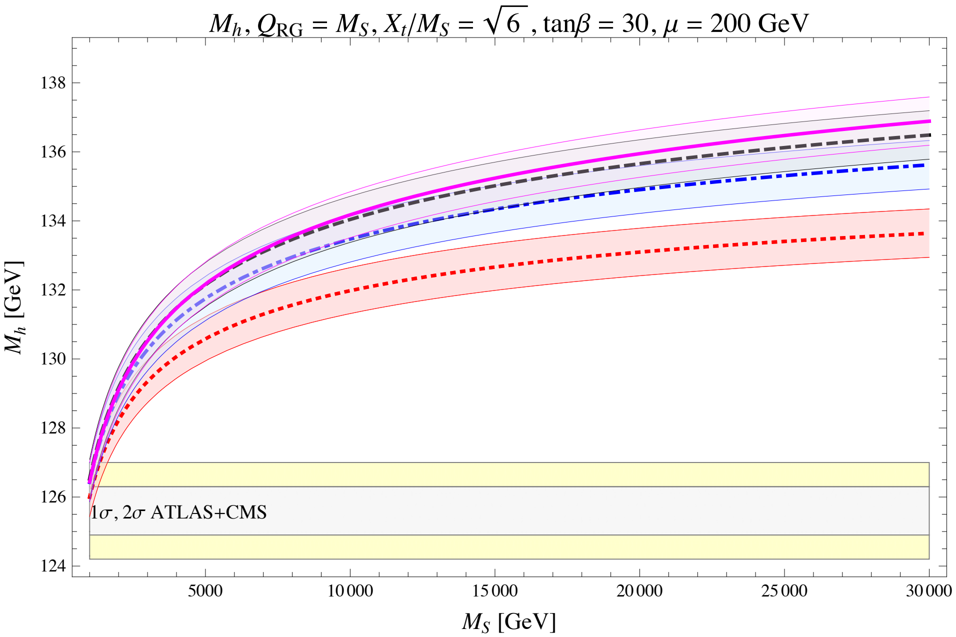
Giudice, Strumia'11

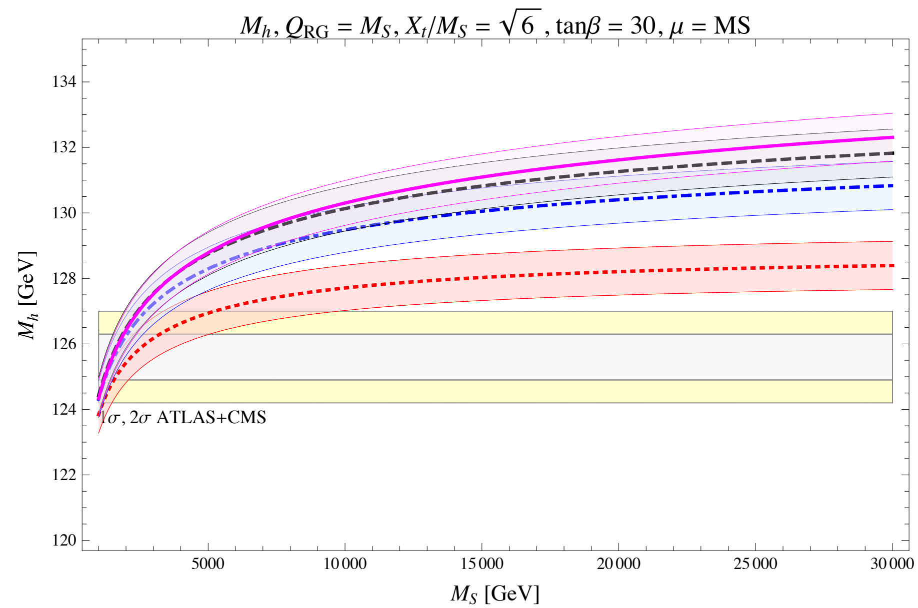


P. Draper, G. Lee, C.W.'13









Higgs Boson Properties

The gauge boson masses still proceed from the kinetic terms

$$\mathcal{L} = (\mathcal{D}^\mu H_u)^\dagger \mathcal{D}_\mu H_u + (\mathcal{D}^\mu H_d)^\dagger \mathcal{D}_\mu H_d + \to g^2 (H_u^\dagger W_\mu W^\mu H_u + H_d^\dagger W_\mu W^\mu H_d)$$

Therefore, the order parameter is $v = \sqrt{v_u^2 + v_d^2}$.

The fermion mass terms proceed from the Yukawa interactions

$$\mathcal{L} = -h_d \bar{D}_L H_d d_R - h_u \bar{U}_L H_u u_R + h.c.$$

Therefore, $m_d = h_d \, v \cos\beta$, and

$$\mathcal{L} \to -\frac{m_d}{v}(h + \tan\beta H)$$

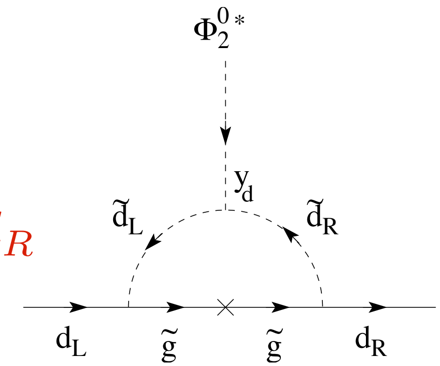
and the down sector has $\tan\beta$ enhanced couplings to the non-standard Higgs bosons.

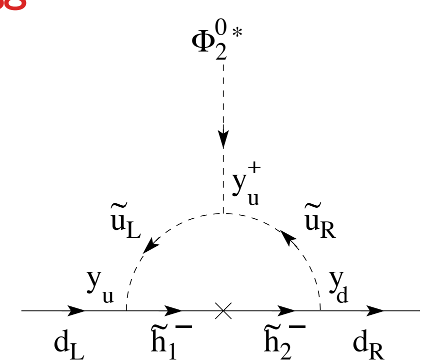
Hempfling '93
Hall, Rattazzi, Sarid'93
Carena, Olechowski, Pokorski, C.W.'93

Radiative Corrections to Flavor Conserving Higgs Couplings

- Couplings of down and up quark fermions to both Higgs fields arise after radiative corrections.

$$\mathcal{L} = \bar{d}_L (h_d H_1^0 + \Delta h_d H_2^0) d_R$$





- The radiatively induced coupling depends on ratios of supersymmetry breaking parameters

$$m_b = h_b v_1 \left(1 + \frac{\Delta h_b}{h_b} \tan\beta\right)$$

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

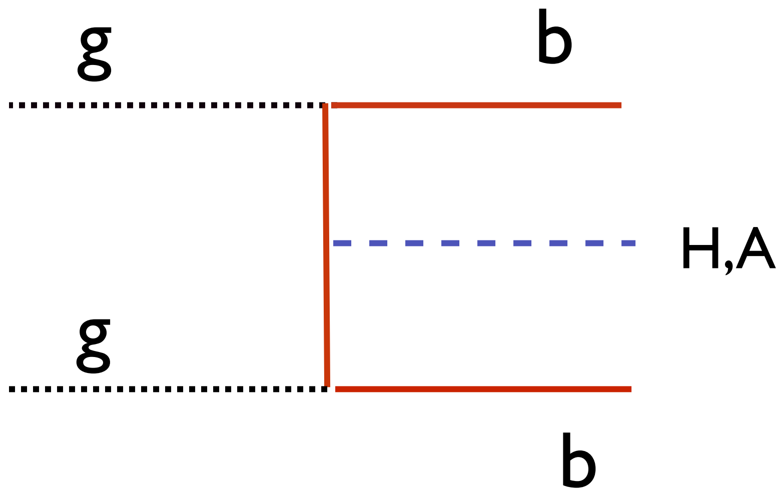
$$\frac{\Delta_b}{\tan\beta} = \frac{\Delta h_b}{h_b} \simeq \frac{2\alpha_s}{3\pi} \frac{\mu M_{\tilde{g}}}{\max(m_{\tilde{b}_i}^2, M_{\tilde{g}}^2)} + \frac{h_t^2}{16\pi^2} \frac{\mu A_t}{\max(m_{\tilde{t}_i}^2, \mu^2)}$$

$$X_t = A_t - \mu/\tan\beta \simeq A_t \qquad \Delta_b = (E_g + E_t h_t^2) \tan\beta$$

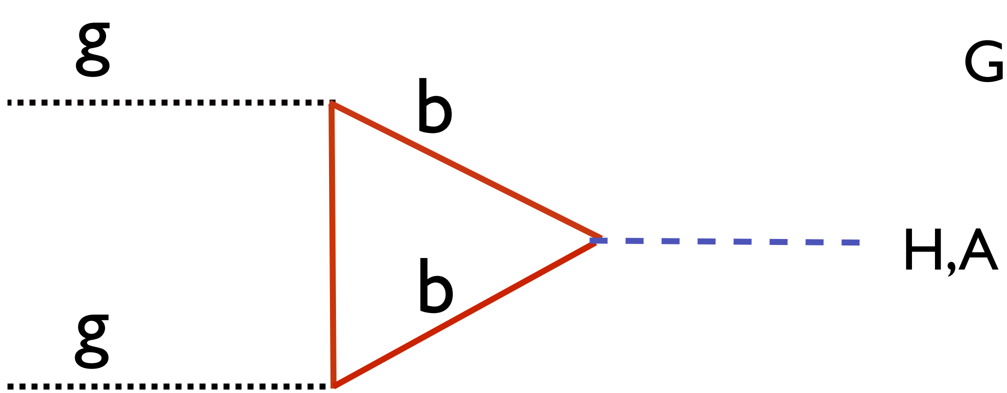
Resummation : Carena, Garcia, Nierste, C.W.'00

Non-Standard Higgs Production

QCD: S. Dawson, C.B. Jackson, L. Reina, D. Wackeroth, hep-ph/0603112



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.

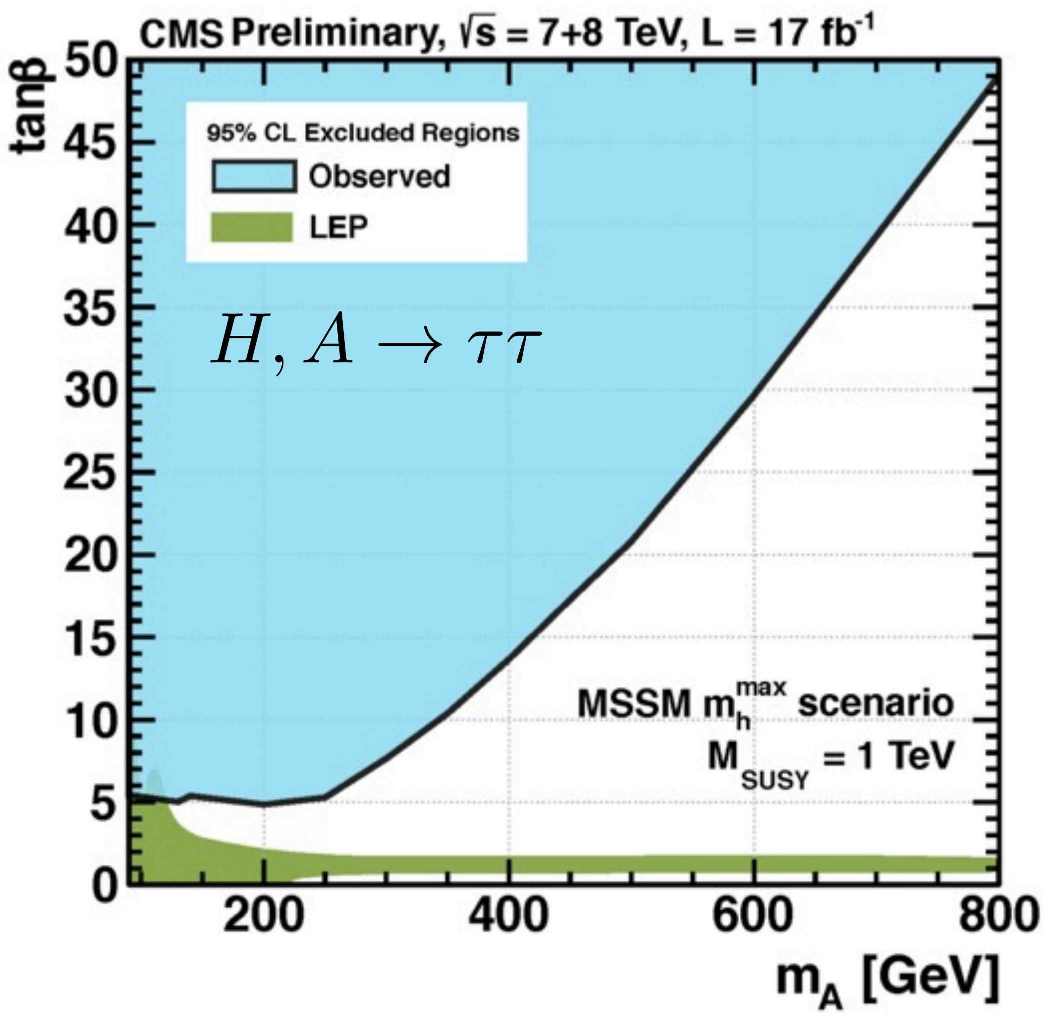
$$\sigma(b\bar{b}A) \times BR(A \to b\bar{b}) \simeq \sigma(b\bar{b}A)_{\rm SM} \frac{\tan^2\beta}{(1+\Delta_b)^2} \times \frac{9}{(1+\Delta_b)^2+9}$$

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

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

Validity of this approximation confirmed by NLO computation by D. North and M. Spira, arXiv:0808.0087
Further work by Mhulleitner, Rzehak and Spira, 0812.3815

In the MSSM, non-standard Higgs may be produced
via its large couplings to the bottom quark, and
searched for in its decays into bottom quarks and tau leptons



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 ?

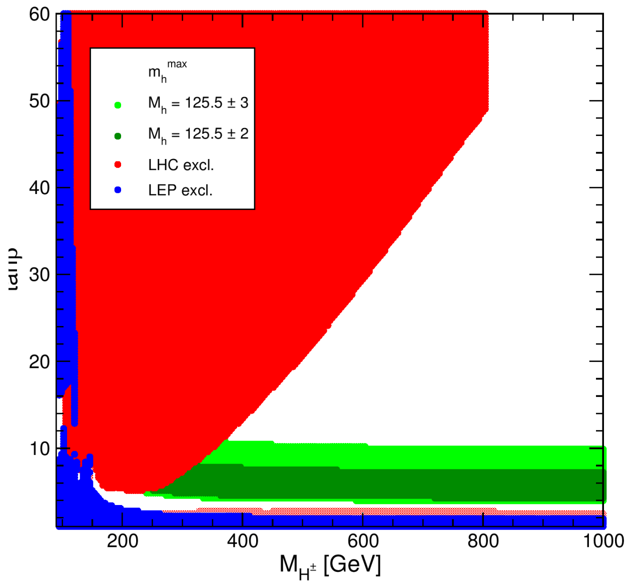
It depends on radiative corrections

See
Carena, Haber, Logan, Mrenna '01

M. Carena, S. Heinemeyer, O. Stål, C.E.M. Wagner, G. Weiglein, arXiv:1302.7033

The $m_h^{\max}$ scenario

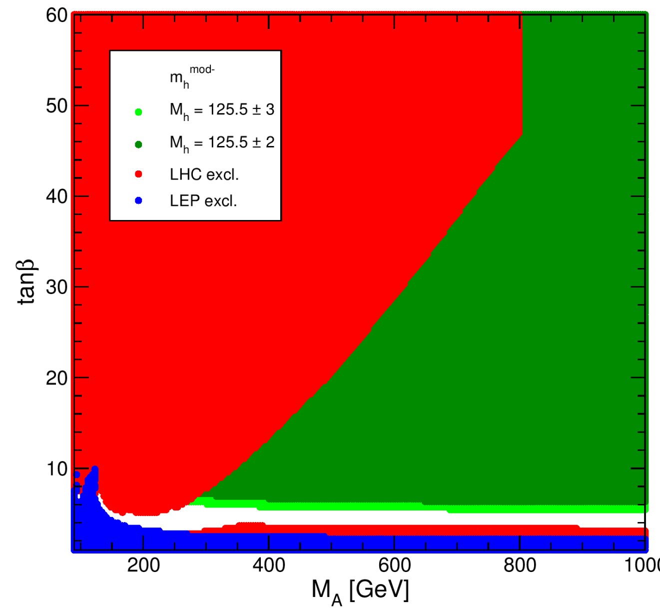
Gives the lowest value of tan(beta) consistent with the measured Higgs mass



$$
\begin{aligned}
M_{\mathrm{SUSY}} &= 1000 \text{ GeV}, \\
\mu &= 200 \text{ GeV}, \\
M_2 &= 200 \text{ GeV}, \\
X_t^{\mathrm{OS}} &= 2\, M_{\mathrm{SUSY}} \text{ (FD calculation)}, \\
X_t^{\overline{\mathrm{MS}}} &= \sqrt{6}\, M_{\mathrm{SUSY}} \text{ (RG calculation)}, \\
A_b &= A_\tau = A_t, \\
m_{\tilde{g}} &= 1500 \text{ GeV},
\end{aligned}
$$

The m_h^{mod} scenario

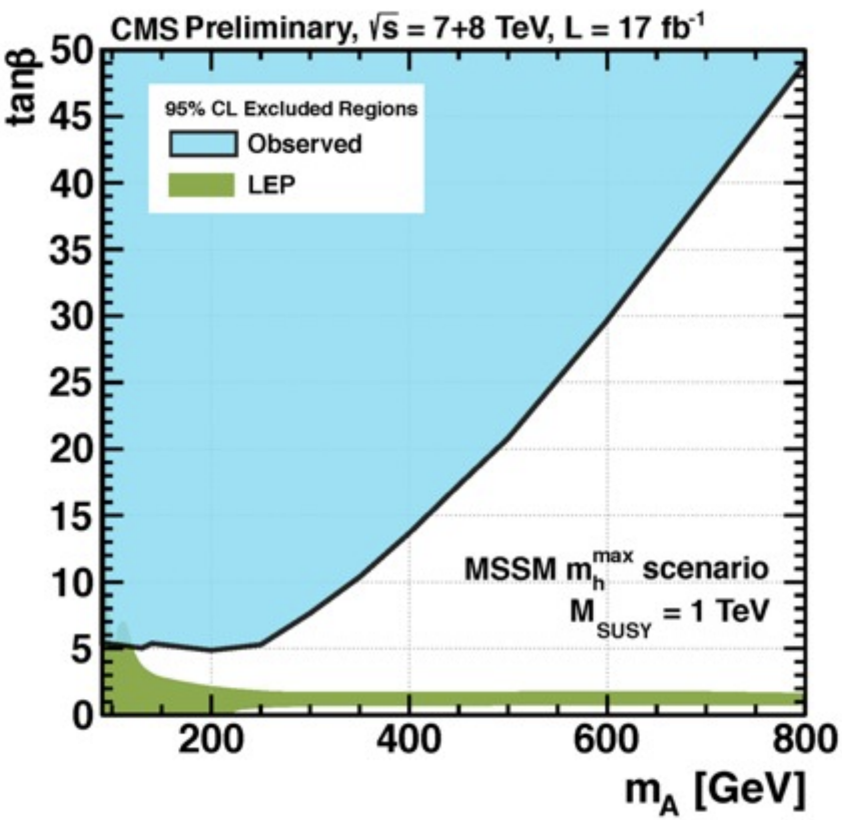
Moderate values of the stop mixing allow for consistency with the Higgs mass value in a broad region of the m_A-tan(beta) plane



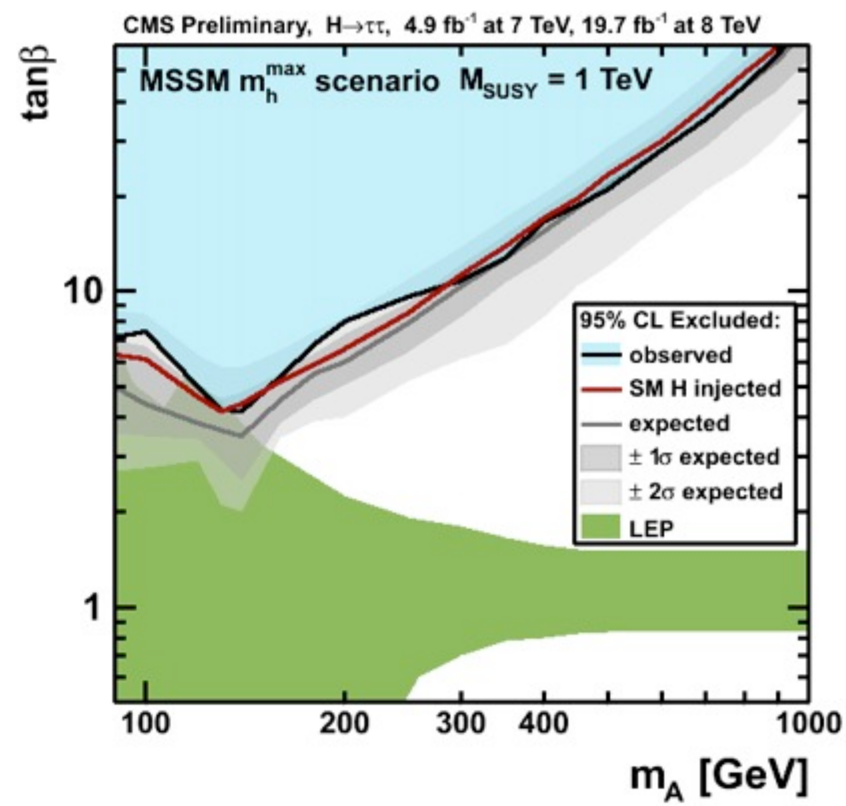
$$
\begin{aligned}
M_{\mathrm{SUSY}} &= 1000 \text{ GeV}, \\
\mu &= 200 \text{ GeV}, \\
M_2 &= 200 \text{ GeV}, \\
X_t^{\mathrm{OS}} &= 1.5\, M_{\mathrm{SUSY}} \text{ (FD calculation)}, \\
X_t^{\overline{\mathrm{MS}}} &= 1.6\, M_{\mathrm{SUSY}} \text{ (RG calculation)}, \\
A_b &= A_\tau = A_t, \\
m_{\tilde{g}} &= 1500 \text{ GeV},
\end{aligned}
$$

Small differences in final analysis... Small excess at 200 GeV and tanβ of order 10 ?

Need to control the SM-like Higgs behavior !



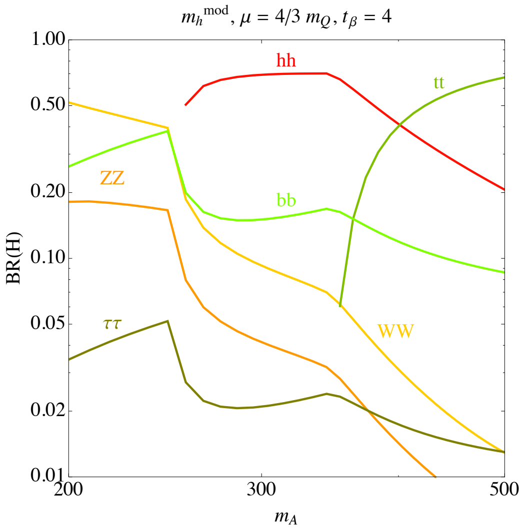
Bounds used

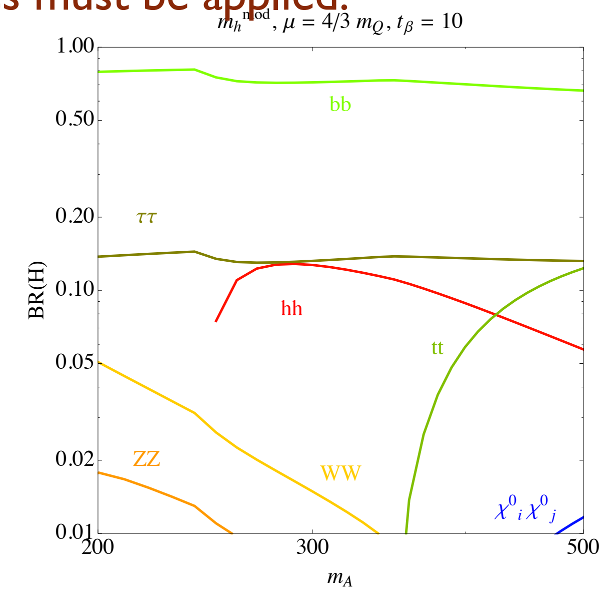


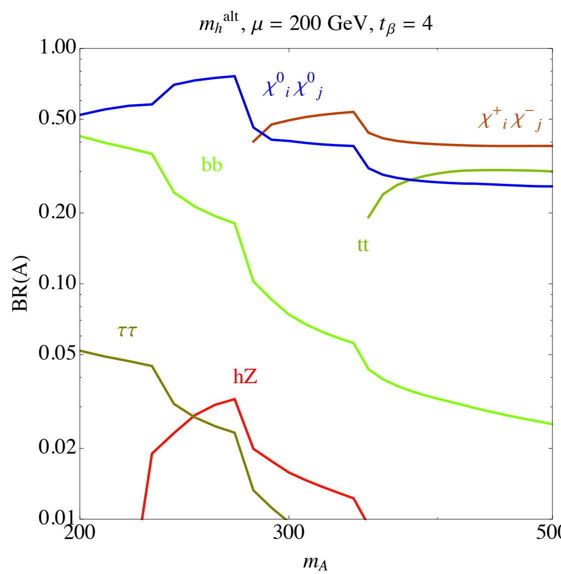
Final results

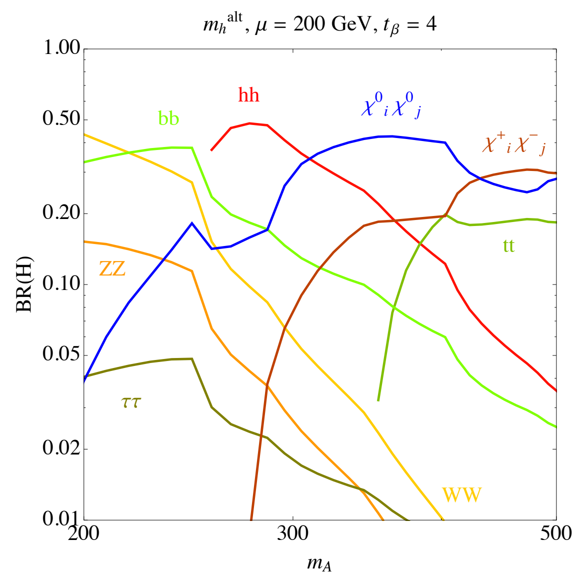
Depending on the values of mu and tanbeta different search strategies must be applied.

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









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

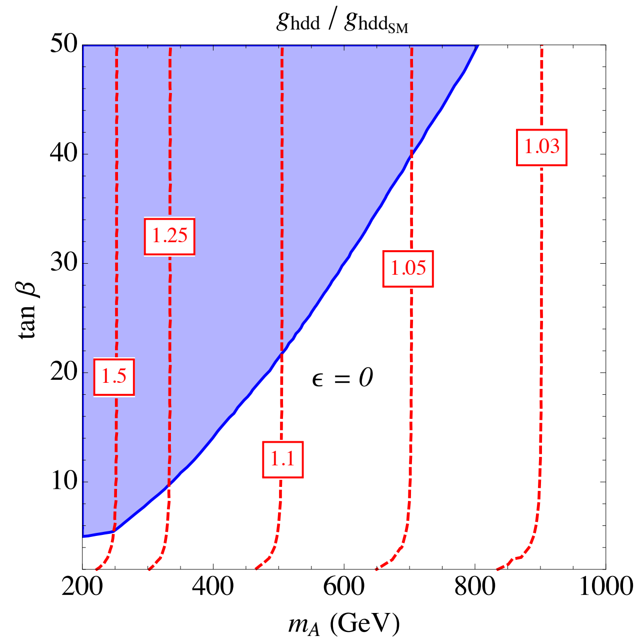
$$\lambda_1 \ \leq \ \lambda_{\rm SM} \ \leq \ \tilde{\lambda}_3 \quad \text{and} \quad \lambda_2 \ \leq \ \lambda_{\rm SM} \ \leq \ \tilde{\lambda}_3$$

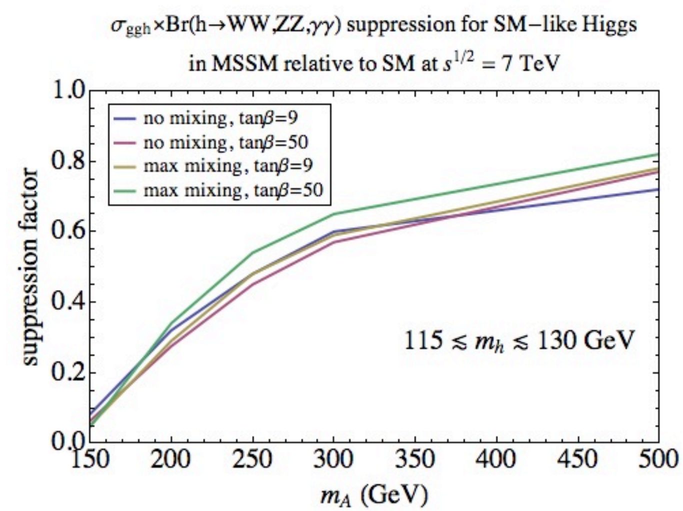
- Conditions not fulfilled in the MSSM, where both $\lambda_1, \tilde{\lambda}_3 < \lambda_{\rm SM}$

- In this regime,

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

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





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

Enhancement of bottom quark and tau couplings independent of $\tan\beta$

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

Impact and Size of Loop Corrections

Considering

$$\Delta L_{12} = \lambda_7, \qquad \Delta \tilde{L}_{12} = \Delta\left(\lambda_3 + \lambda_4\right), \qquad \Delta L_{11} = \lambda_5, \qquad \Delta L_{22} = \lambda_2.$$

The condition of alignment reads

$$\tan\beta \simeq \frac{\lambda_{\rm SM} - \tilde{\lambda}_3^{\rm tree} - \Delta\tilde{\lambda}_3}{\lambda_7} = \frac{120 - 32\pi^2\left(\Delta L_{11} + \Delta\tilde{L}_{12}\right)}{32\pi^2 \Delta L_{12}}$$

where the loop corrections are approximately given by

$$v^2 \Delta L_{12} \simeq \frac{v^2}{32\pi^2}\left[h_t^4 \frac{\mu \tilde{A}_t}{M_{\rm SUSY}^2}\left(\frac{A_t \tilde{A}_t}{M_{\rm SUSY}^2} - 6\right) + h_b^4 \frac{\mu^3 A_b}{M_{\rm SUSY}^4} + \frac{h_\tau^4}{3}\frac{\mu^3 A_\tau}{M_{\tilde{\tau}}^4}\right],$$

$$v^2 \Delta\tilde{L}_{12} \simeq \frac{v^2}{16\pi^2}\left[h_t^4 \frac{\mu^2}{M_{\rm SUSY}^2}\left(3 - \frac{A_t^2}{M_{\rm SUSY}^2}\right) + h_b^4 \frac{\mu^2}{M_{\rm SUSY}^2}\left(3 - \frac{A_b^2}{M_{\rm SUSY}^2}\right) + h_\tau^4 \frac{\mu^2}{3M_{\tilde{\tau}}^2}\left(3 - \frac{A_\tau^2}{M_{\tilde{\tau}}^2}\right)\right].$$

$$v^2 \Delta L_{11} \simeq -\frac{v^2}{32\pi^2}\left(\frac{h_t^4 \mu^2 A_t^2}{M_{\rm SUSY}^4} + \frac{h_b^4 \mu^2 A_b^2}{M_{\rm SUSY}^4} + \frac{h_\tau^4 \mu^2 A_\tau^2}{3M_{\tilde{\tau}}^4}\right)$$

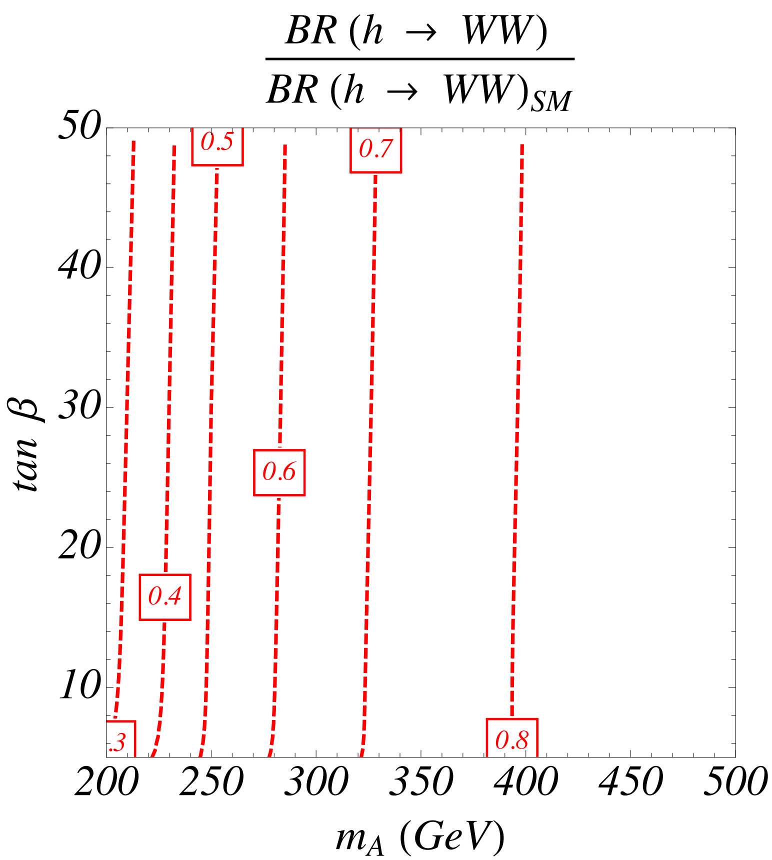
M. Carena, I. Low, N. Shah, C.W.'13

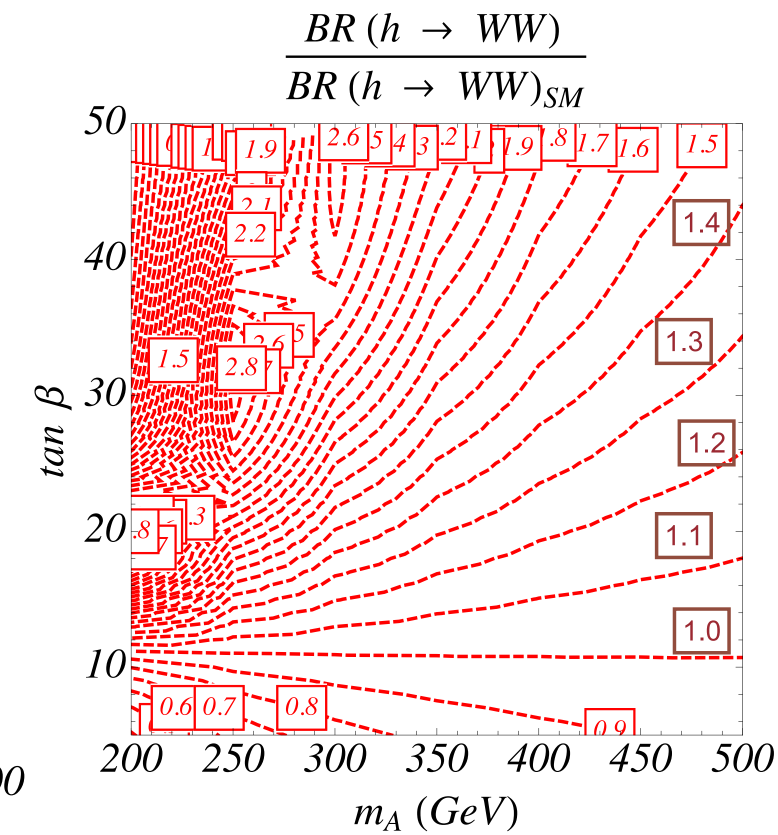
Higgs Decay into Gauge Bosons

Mostly determined by the change of width

Small μ

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

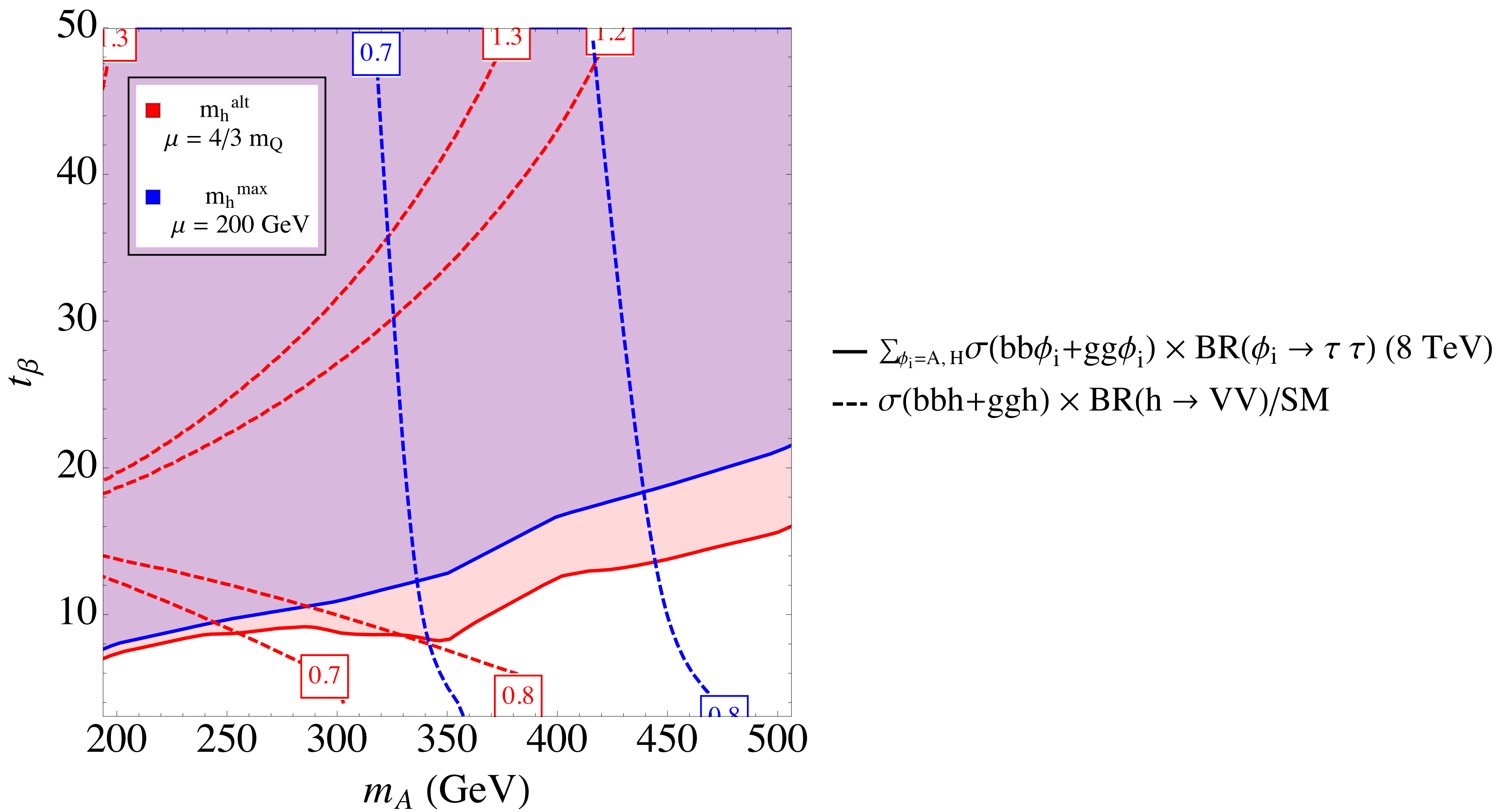




CP-odd Higgs masses of order 200 GeV and tanβ = 10 OK in the alignment case

Complementarity between different search channels

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



Loop Induced Couplings

$$\mathcal{L}_{h\gamma\gamma} = -\frac{\alpha}{16\pi}\frac{h}{v}\left[\sum_i 2b_i \frac{\partial}{\partial \log v}\log m_i(v)\right] F_{\mu\nu}F^{\mu\nu}$$

$$\left\{ \begin{array}{lll} b &=& \frac{4}{3}N_c Q^2 \quad \text{for a Dirac fermion ,} \\ b &=& -7 \qquad\ \ \text{for the } W \text{ boson ,} \\ b &=& \frac{1}{3}N_c Q_S^2 \quad \text{for a charged scalar .} \end{array} \right.$$

where in the Standard Model

$$\frac{g_{hWW}}{m_W^2} = \frac{\partial}{\partial v}\log m_W^2(v) \ , \qquad \frac{2g_{ht\bar{t}}}{m_t} = \frac{\partial}{\partial v}\log m_t^2(v)$$

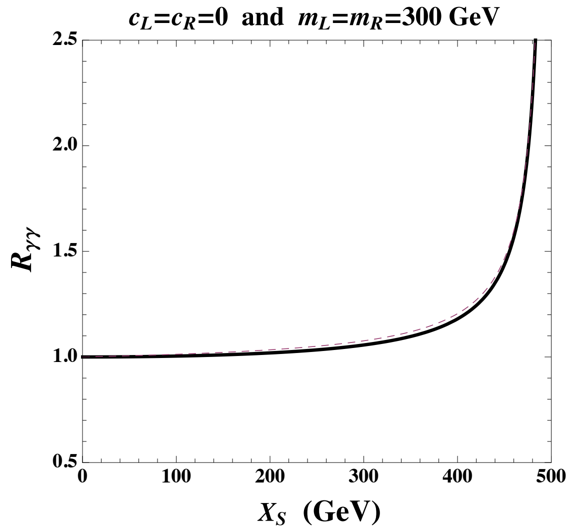
This generalizes for the case of fermions with contributions to their masses independent of the Higgs field. The couplings come from the vertex and the inverse dependence on the masses from the necessary chirality flip (for fermions) and the integral functions.

$$\mathcal{L}_{h\gamma\gamma} = \frac{\alpha}{16\pi}\frac{h}{v}\left[\sum_i b_i \frac{\partial}{\partial \log v}\log\left(\det \mathcal{M}_{F,i}^\dagger \mathcal{M}_{F,i}\right) + \sum_i b_i \frac{\partial}{\partial \log v}\log\left(\det \mathcal{M}_{B,i}^2\right)\right] F_{\mu\nu}F^{\mu\nu}$$

M. Carena, I. Low, C.W., arXiv:1206.1082, Ellis, Gaillard, Nanopoulos'76, Shifman, Vainshtein, Voloshin, Zakharov'79

Similar considerations apply to the Higgs gluon coupling

Two Scalars with Mixing



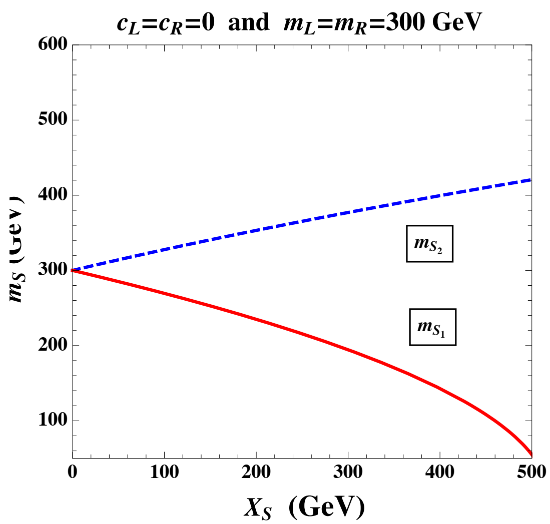
Similar to light stau scenario,
M. Carena, S. Gori, N. Shah, C.W., arXiv: 1112.3336,
M. Carena, S. Gori, N. Shah, C.W., L.T. Wang, arXiv:1205.5842

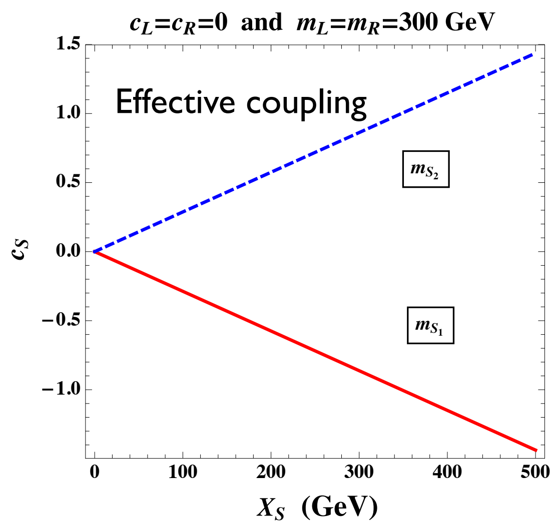
$$\mathcal{M}_S^2 = \begin{pmatrix} \tilde{m}_L(v)^2 & \frac{1}{\sqrt{2}} v X_S \\ \frac{1}{\sqrt{2}} v X_S & \tilde{m}_R(v)^2 \end{pmatrix}$$

$$\frac{\partial \log(\mathrm{Det} M_S^2)}{\partial v} \simeq -\frac{X_S^2 v}{m_{S_1}^2 m_{S_2}^2}$$

Negative Effective Coupling of lightest scalar

Large mixing and small value of the lightest scalar mass leads to enhancement of the diphoton amplitude



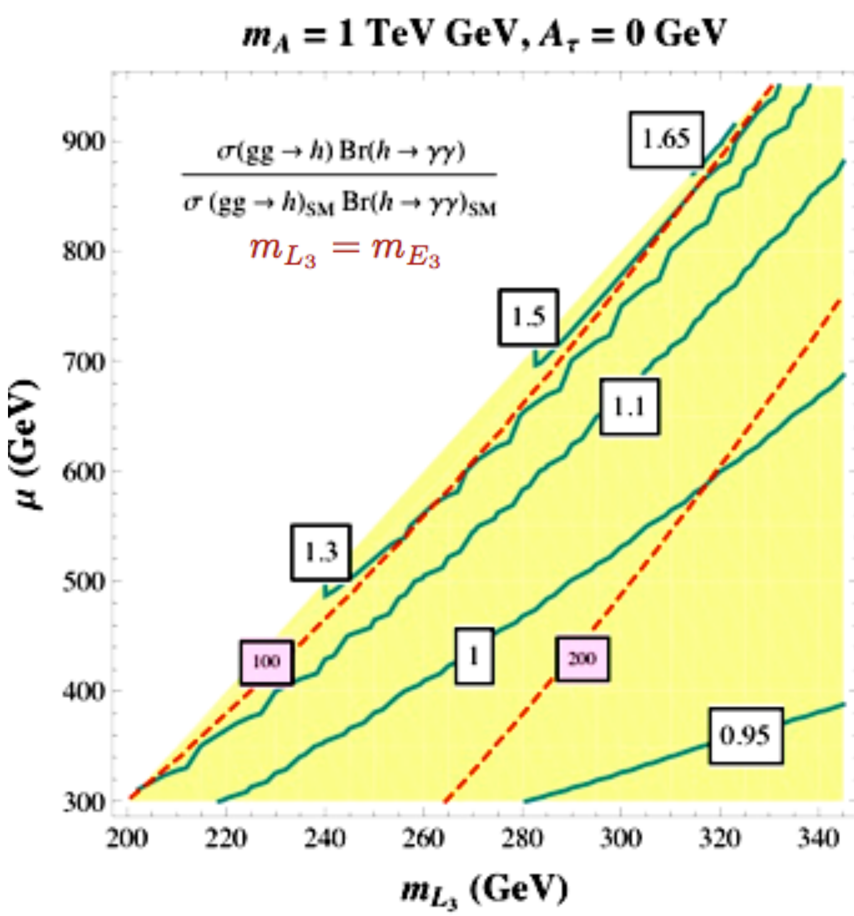


Lightest scalar, with mass below 200 GeV gives the dominant contribution in this case.

M. Carena, I. Low, C.W., arXiv:1206.1082

Higgs Decay into two Photons in the MSSM

Charged scalar particles with no color charge can change di-photon rate without modification of the gluon production process



$$\mathcal{M}^2_{\tilde{\tau}} \simeq \begin{bmatrix} m^2_{L_3} + m^2_\tau + D_L & h_\tau v(A_\tau \cos\beta - \mu \sin\beta) \\ h_\tau v(A_\tau \cos\beta - \mu \sin\beta) & m^2_{E_3} + m^2_\tau + D_R \end{bmatrix}$$

Light staus with large mixing

[sizeable μ and tan beta]:

➔ **enhancement of the**

Higgs to di-photon decay rate

$$\delta\mathcal{A}_{h\gamma\gamma}/\mathcal{A}^{\mathrm{SM}}_{h\gamma\gamma} \simeq -\frac{2\,m_\tau^2}{39\,m^2_{\tilde{\tau}_1} m^2_{\tilde{\tau}_2}}\left(m^2_{\tilde{\tau}_1} + m^2_{\tilde{\tau}_2} - X_\tau^2\right)$$

$$X_\tau = A_\tau - \mu\tan\beta$$

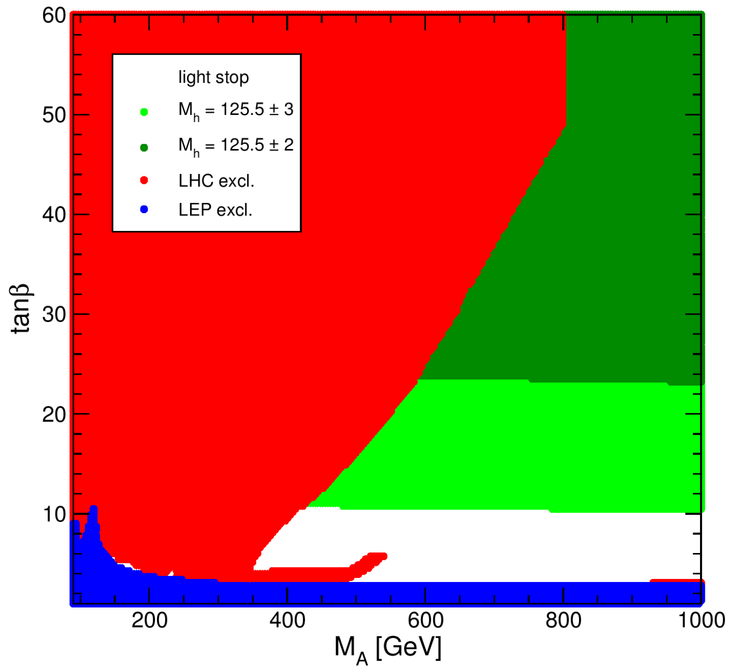
M. Carena, S. Gori, N. Shah, C.Wagner, arXiv:1112.336, +L.T.Wang, arXiv:1205.5842

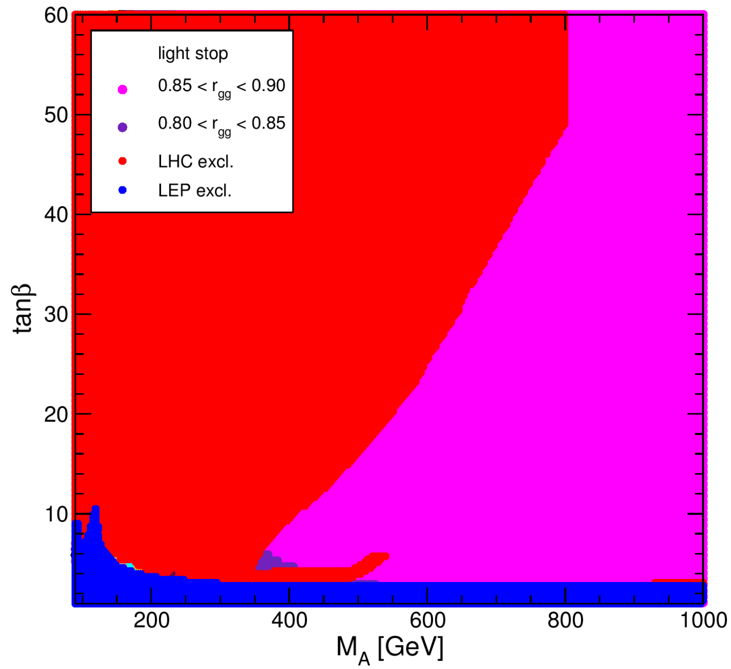
M. Carena, S. Heinemeyer, O. Stål,
C.E.M. Wagner, G. Weiglein,
arXiv:1302.7033

The Light Stop Scenario

Stop mixing large, lightest stop mass of order 320 GeV.
Heaviest stop mass of order 650 GeV.
Reduction of the gluon fusion process rate.

$$\delta\mathcal{A}_{hgg}/\mathcal{A}_{hgg}^{\rm SM} \simeq \frac{m_t^2}{4m_{\tilde t_1}^2 m_{\tilde t_2}^2}\left(m_{\tilde t_1}^2 + m_{\tilde t_2}^2 - X_t^2\right)$$





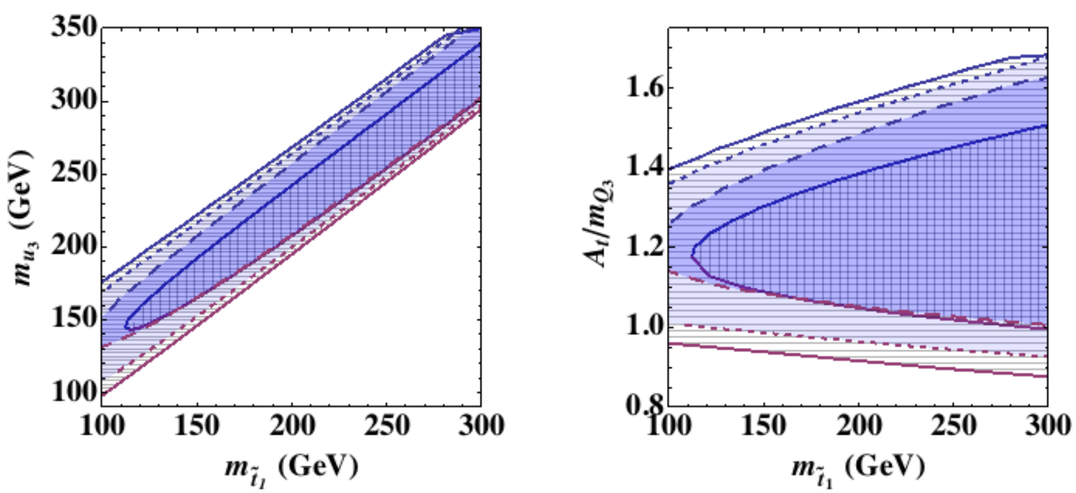
$$M_{\rm SUSY} = 500 \text{ GeV},$$
$$\mu = 350 \text{ GeV},$$
$$M_2 = 350 \text{ GeV},$$

$$X_t^{\rm OS} = 2.0\, M_{\rm SUSY} \text{ (FD calculation)},$$
$$X_t^{\overline{\rm MS}} = 2.2\, M_{\rm SUSY} \text{ (RG calculation)},$$
$$A_b = A_t = A_\tau,$$
$$m_{\tilde g} = 1500 \text{ GeV},$$

M. Carena, S. Gori, N. Shah, C. W. and L.T. Wang, arXiv:1303.4414

Light Stops, Light Staus and the 125 GeV Higgs

Cases	$\tan\beta$	$m_{\tilde{\tau}_1}$ (GeV)	m_{e_3} (GeV)	μ (GeV)	m_{Q_3} (TeV)	A_τ (TeV)	m_A (TeV)
(a) Shaded dashed	70	95	250	380	2	0	2
(b) Shaded dotted	70	95	230	320	2	1	1
(c) Horizontal hatch	105	95	240	225	2	1	1
(d) Vertical hatch	70	100	300	575	3	1.5	1

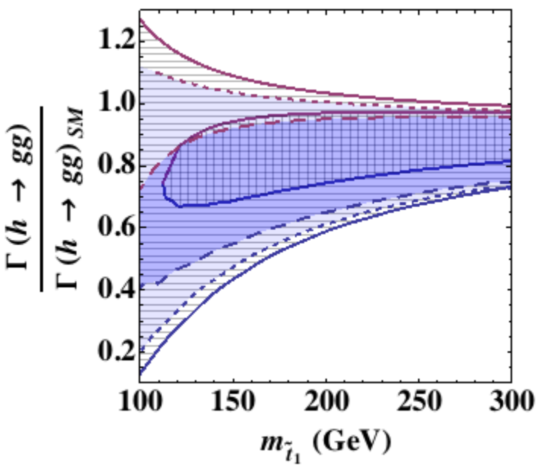


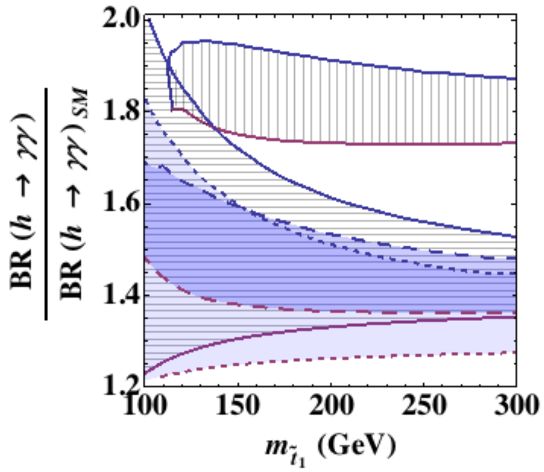
(a) to (c) : Consistent with vacuum stability constraints

M. Carena, S. Gori, I. Low, N. Shah, C.W., arXiv:1211.6136

Variation of Production Cross sections and Decay Rates

M. Carena, S. Gori, N. Shah, C.W. and L.T.Wang, arXiv:1303.4414

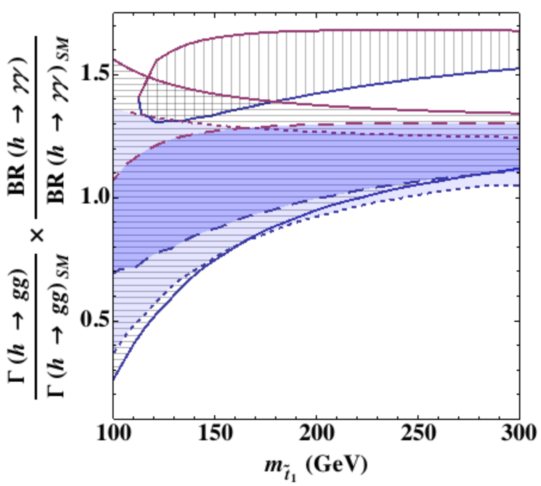




$$\delta\mathcal{A}_{hgg}/\mathcal{A}^{\rm SM}_{hgg} \simeq \frac{m_t^2}{4m_{\tilde t_1}^2 m_{\tilde t_2}^2}\left(m_{\tilde t_1}^2 + m_{\tilde t_2}^2 - X_t^2\right)$$

$$\delta\mathcal{A}_{h\gamma\gamma}/\mathcal{A}^{\rm SM}_{h\gamma\gamma} \simeq -\frac{2\, m_\tau^2}{39\, m_{\tilde\tau_1}^2 m_{\tilde\tau_2}^2}\left(m_{\tilde\tau_1}^2 + m_{\tilde\tau_2}^2 - X_\tau^2\right)$$

m_τ = 95 GeV



Light Staus can enhance the diphoton decay width
Light stops can either enhance or suppress gluon copling
Combination can lead to large variations of production in both gluon fusion and weak boson fusion (ratios of branching ratios)