Higgs Physics in the LHC Era

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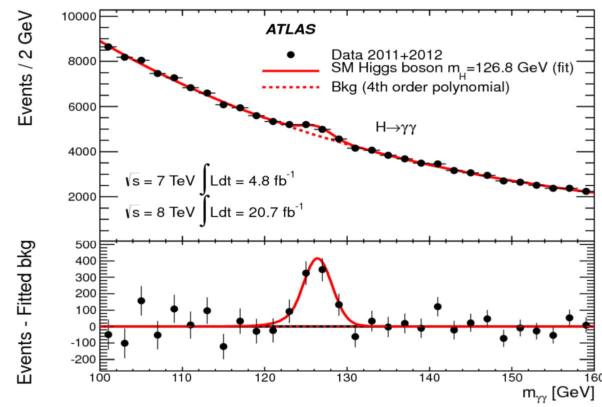
The Higgs Discovery in July 2012 has established the Standard Model (SM) as the proper low energy theory describing all known particle interactions



Amazing Properties of the SM Higgs sector

- The Higgs self interactions are described by a simple potential

$$V = -m_H^2 H^\dagger H + \frac{\lambda}{2}\left(H^\dagger H\right)^2$$

- This leads to the breakdown of the electroweak symmetry

$$H = \begin{pmatrix} G^+ \\ (v + h + iG^0)/\sqrt{2} \end{pmatrix}, \qquad v^2 = 2\frac{m_H^2}{\lambda}$$

- The interactions with gauge bosons are related to the mass generation mechanism

$$\frac{g^2}{2} H^\dagger H V_\mu V^\mu$$

- The linear interactions are therefore related to the insertion of a Higgs v.e.v. and if we add new doublets will be related to the projection of the particular Higgs field in the direction that acquires v.e.v.

$$g_{hVV} = \frac{m_V^2}{v}$$

Amazing Properties of the SM Higgs sector

- The interactions with fermions an even more amazing story. We start with a completely arbitrary 3x3 Yukawa matrix interactions, where this three is related to generations

$$y_{ij}\bar{\psi}^i_L H \psi^j_R + h.c.$$

- Now, when you give the Higgs a v.e.v. this becomes a mass matrix that you must diagonalize when going to the physical states.

- But, due to the fact that mass and Yukawa matrices are proportional to each other, the interactions become flavor diagonal

$$y_{hnm} = \frac{m_f}{v}\delta_{nm}$$

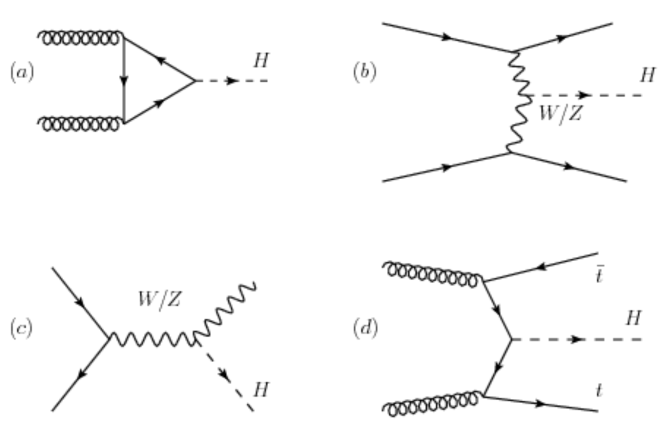
- In general, there are no tree-level Flavor Changing Neutral Currents ! No tree-level CP violation. All these effects occur at the loop-level, via the charged weak interactions, and are proportional to CKM matrix elements.

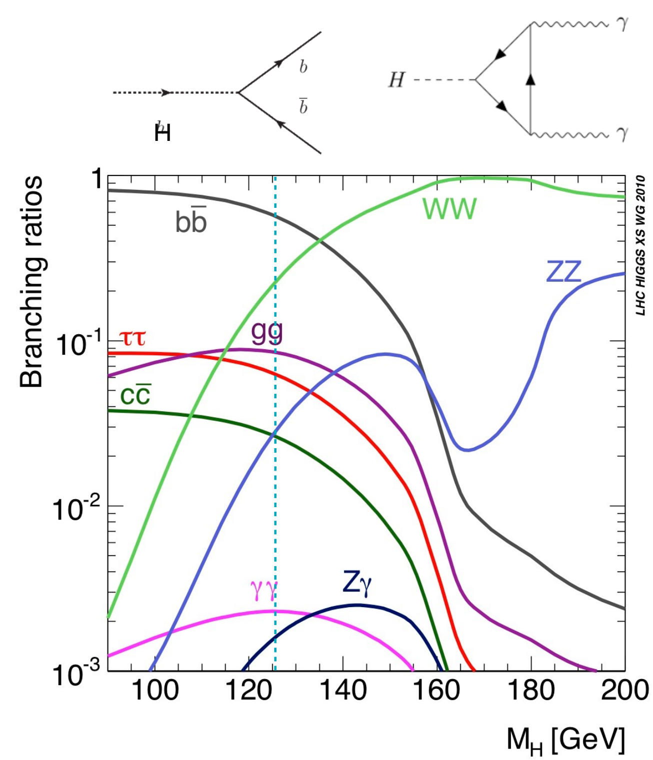
- I don't need to tell you how amazing this is ! Moreover, all available data is consistent with these predictions.

Testing the Higgs Properties at the LHC

We collide two protons (quarks and gluons) at high energies :

LHC Higgs Production Channels and Decay Branching Ratios

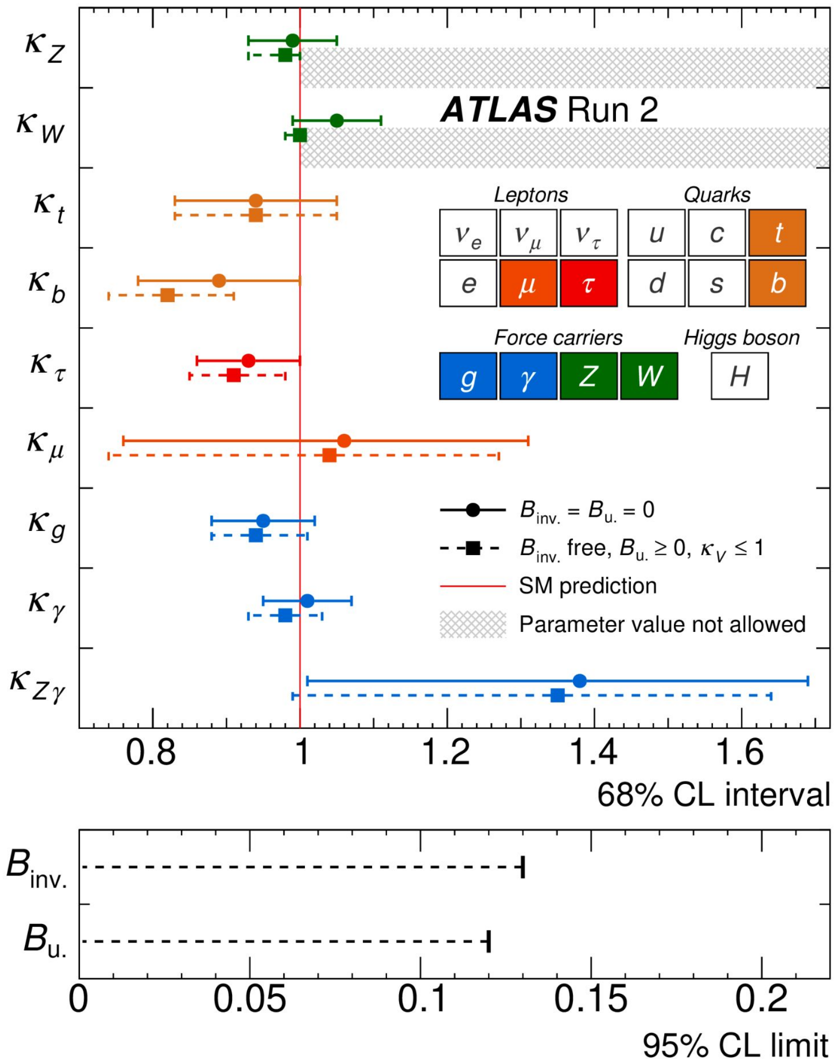


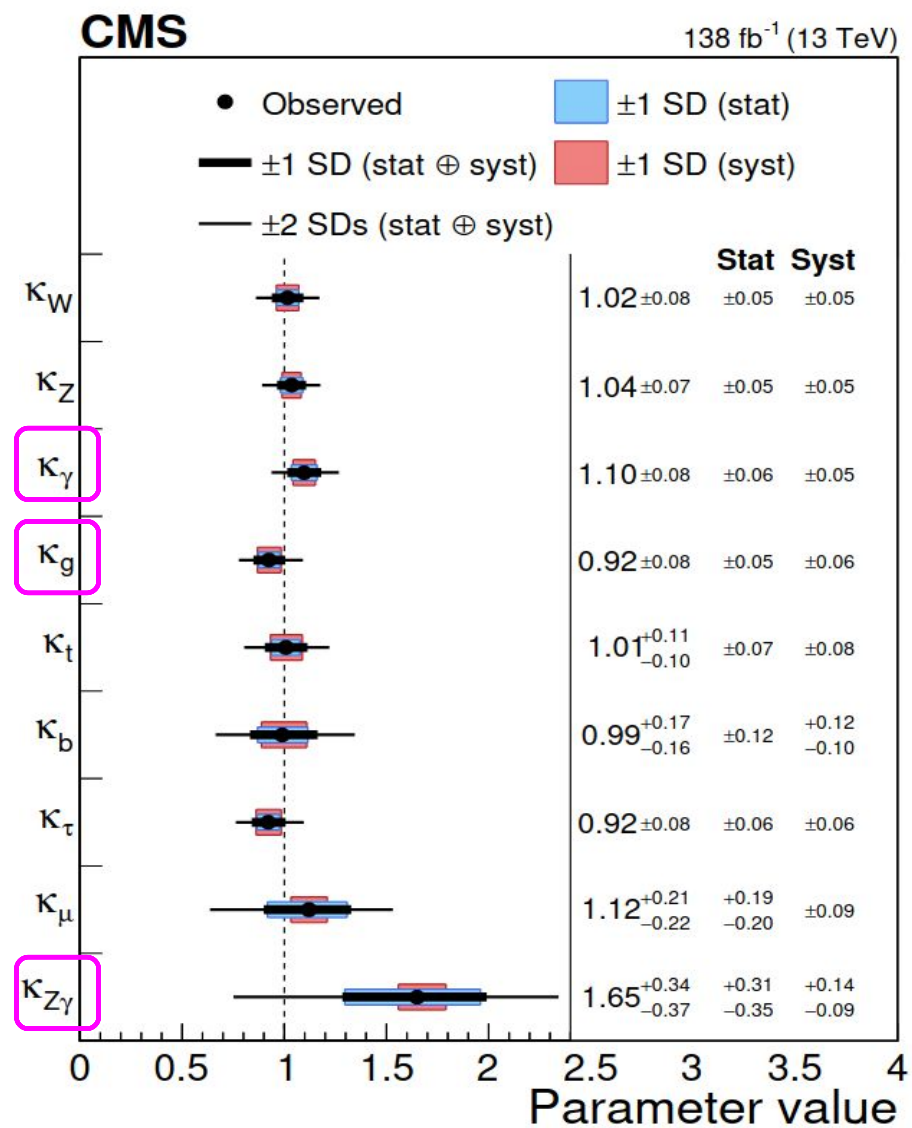


A Higgs with a mass of about 125 GeV allows to study many decay channels

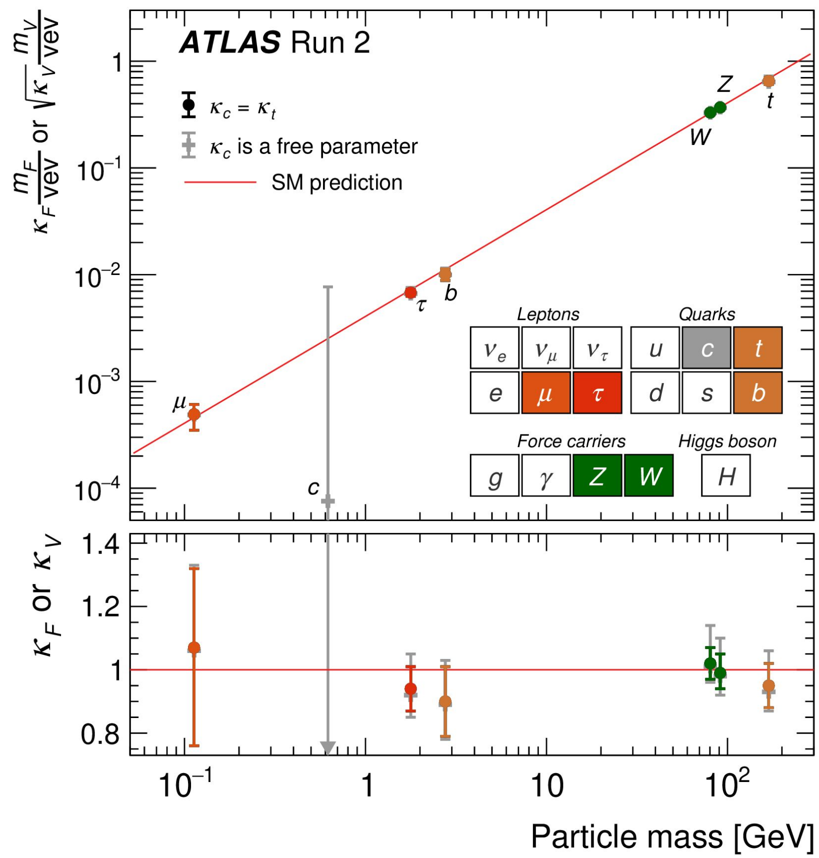
ATLAS and CMS Fit to Higgs Couplings

Departure from SM predictions of the order of few tens of percent allowed at this point.

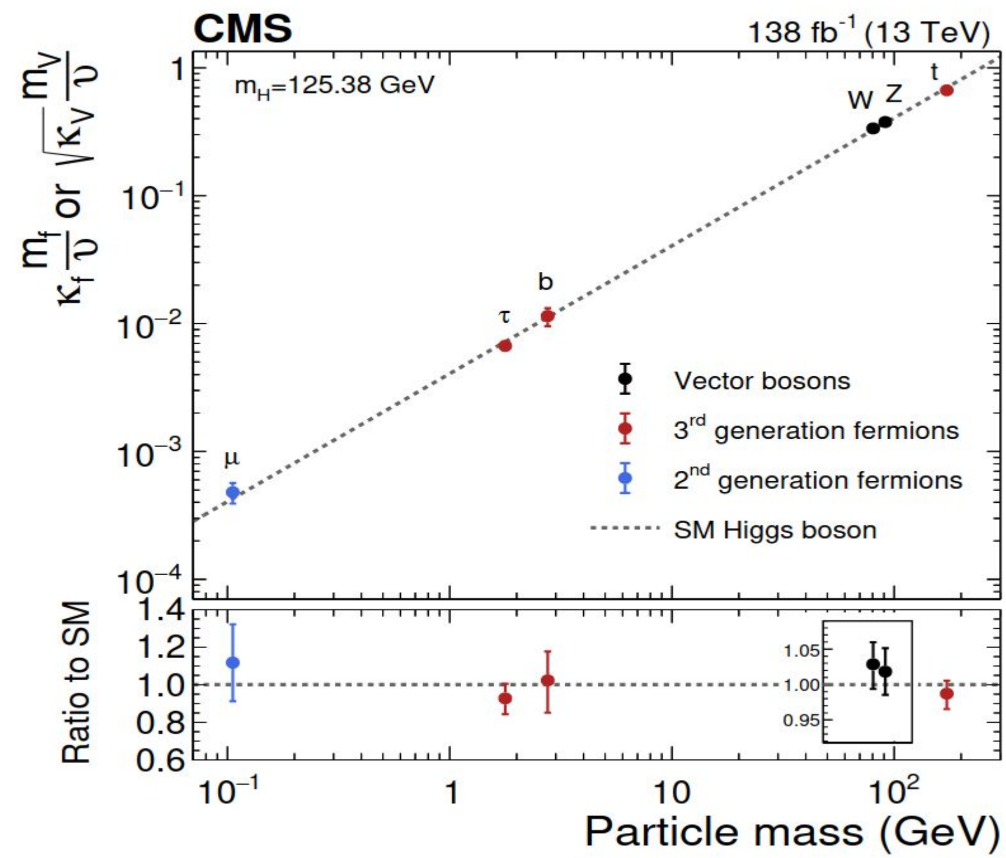




Correlation between masses and couplings consistent with the Standard Model expectations



H couplings vs particle mass



Why we should not be surprised

- There is another amazing property of the SM as an effective field theory
- Take any sector with gauge invariant mass terms, which do not involve the Higgs v.e.v.

$$\mathcal{L} = -m_\phi^2 \phi^\dagger \phi - M_\Psi \bar{\Psi}\Psi + \mathcal{L}_{\rm int}(\phi, \Psi, SM)$$

- The Appelquist-Carrazonne decoupling theorem says that as we push these gauge invariant masses up, the low energy effective theory will reduce to the Standard Model !
- The speed of decoupling depends on how these sector couple to the SM. In general, for a coupling κ, decoupling occurs when

$$\frac{k^2}{m_{\rm new}^2} \ll \frac{1}{v^2}$$

- Obviously decoupling doesn't occur if the masses are proportional to the v.e.v.
- These properties are behind the Effective Field Theory program.

Why we should be surprised

- The Higgs potential suffers from a problem of stability under ultraviolet corrections, namely, given any sector that couples to the Higgs sector with gauge invariant masses, the Higgs mass parameter will be affected

$$\Delta m_H^2 \propto (-1)^{2S} \frac{k^2 N_g}{16\pi^2} \; m_{\rm new}^2$$

- These are physical corrections, regularization independent and shows that unless the new physics is lighter than the few TeV scale of very weakly coupled to the Higgs sector, the presence of a Higgs weak scale mass parameter is hard to understand.

- This is particularly true in models that try to connect the Higgs with the ultraviolet physics, like Grand Unified Theories.

- In such a case, we need a delicate cancellation of corrections, that only an extension like supersymmetry can provide.

See-saw Mechanism

- The basic Lagrangian is

$$y\bar{L}_L H \nu_R + \frac{M}{2}\nu_R\nu_R + h.c.$$

- This leads to neutrino masses

$$m_\nu = \frac{m_D^2}{M} \equiv \frac{y^2 v^2}{M}$$

Slowest decoupling, dimension 5 operator

- Corrections to the Higgs mass parameter

$$\Delta m_H^2 \propto \frac{y^2}{16\pi^2} M^2 \equiv \frac{m_\nu M^3}{16\pi^2 v^2}$$

- Demanding this to be parametrically small compared to the SM Higgs mass parameter

$$M^3 < \frac{16\pi^2 v^4}{m_\nu} \Rightarrow M < 10^7 \text{ GeV}$$

- Minimal leptogenesis models demand larger values of M than this bound, and therefore generically imply a large fine tuning, unless you add supersymmetry.

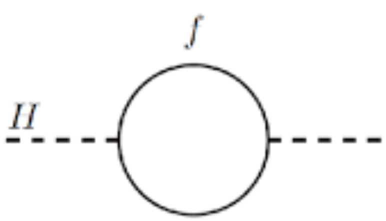
What sets the Higgs scale ?

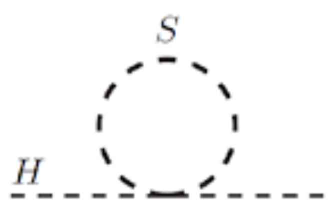
We don't understand why the Higgs mass parameter, which controls all elementary particle masses is so much smaller than the Planck scale.

$$G_N \frac{m_1 m_2}{r^2} \ll e^2/r^2$$

$$m_i \ll M_{\rm Pl}, \quad \text{where } M_{\rm Pl} = \sqrt{\frac{1}{G_N}} \simeq 10^{19}\ \text{GeV}$$

This in spite of the fact that quantum corrections should bring this parameter to be of the order of any heavy particle that couples to the Higgs !

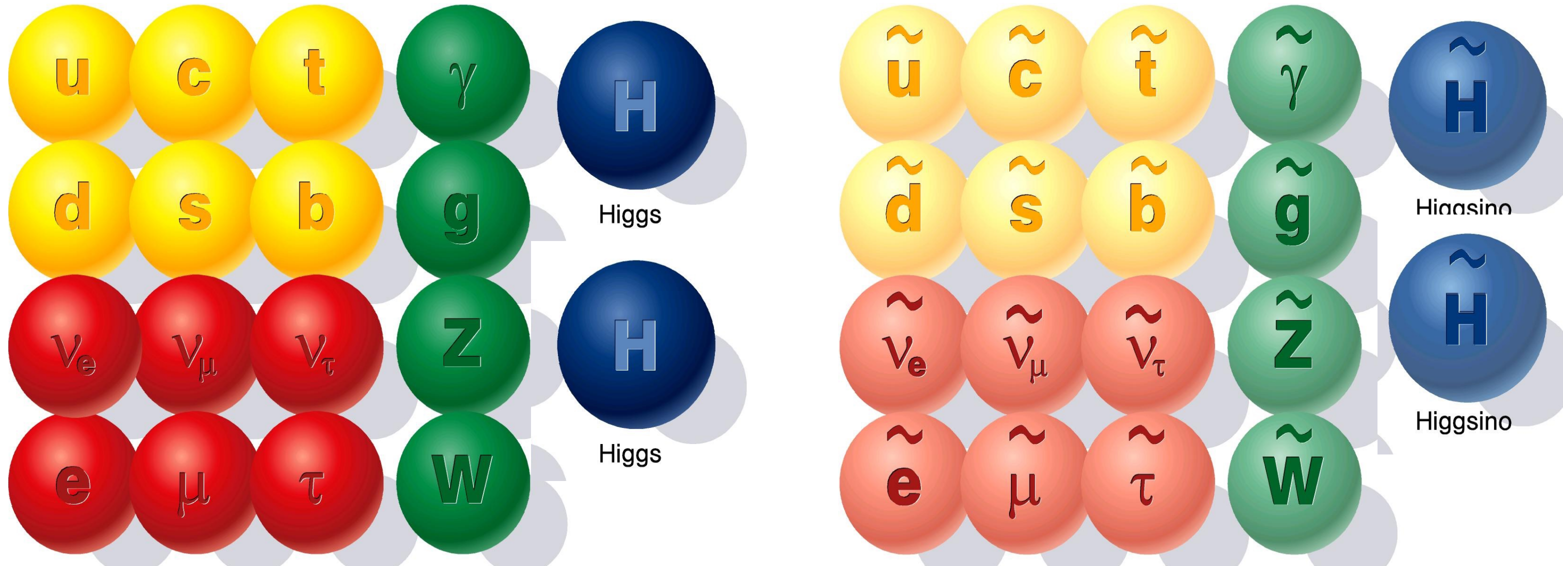




$$\Delta m_H^2 \simeq \lambda_f^2 \frac{M_f^2}{16\pi^2} - \lambda_S \frac{M_S^2}{16\pi^2}$$

In order to explain the weak scale, one would expect new physics at that scale.

Notorious Example : Supersymmetry



Relates particles of different spin :

For every SM fermion (boson) there is a
supersymmetric boson (fermion).
New Higgs bosons necessary in this model

SUSY is broken by mass terms.

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

Couplings are related in such a way that corrections to the Higgs mass parameter cancel

Simple Framework for analysis of coupling deviations
2HDM : General Potential

- General, renormalizable potential has seven quartic couplings, with three of them, given in the last line, may be complex.

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

- In general, it is assumed that lambda 6 and 7 are zero, since this condition appears naturally in models with flavor conservation. However, this condition is basis dependent and it is not necessary.

- We will therefore concentrate on the general 2HDM, with all quartic couplings different from zero. As it is well known an important parameter in these models is

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

This model is subject to many theoretical bounds, including the ones coming from perturbative unitarity, bounded from below and stability constraints

Bahl, Carena, Coyle, Ireland, C.W. arXiv:2210.00024

Z_2 symmetric case : Motivation

- In 2HDM, one can define independent Yukawa couplings for each charge eigenstate fermion sector

$$Y_1^{ij} \bar{\Psi}_L^i H_1 \psi_R^j + Y_2^{ij} \bar{\Psi}_L^i H_2 \psi_R^j + h.c.$$

- Here the Yukawas are 3x3 matrices in flavor space

- This leads to a mass matrix

$$M = Y_1 \frac{v_1}{\sqrt{2}} + Y_2 \frac{v_2}{\sqrt{2}}$$

- The problem is that, contrary to the SM, diagonalization of this mass matrix does not lead to diagonal terms for the Yukawa interactions and there is in general dangerous flavor violation interactions the Higgs sector.

- This may be avoided by a simple parity symmetry, where for instance

$$H_1 \to H_1, \quad H_2 \to -H_2, \quad L \to L, \quad R \to \pm R$$

- This marries even scalar fields with even fermion fields and odd with odd and kills the flavor violating interactions while keeping

$$\lambda_6 = \lambda_7 = 0$$

Higgs Basis

- An interesting basis for the phenomenological analyses of these models is the Higgs basis

$$H_1 = \Phi_1 \cos\beta + \Phi_2 \sin\beta$$
$$H_2 = \Phi_1 \sin\beta - \Phi_2 \cos\beta$$

$$H_1 = \begin{pmatrix} G^+ \\ \frac{1}{\sqrt{2}}(v + \phi_1^0 + iG^0) \end{pmatrix}, \quad H_2 = \begin{pmatrix} H^+ \\ \frac{1}{\sqrt{2}}(\phi_2^0 + ia^0) \end{pmatrix}$$

- The field ϕ_1^0 is therefore associated with the field direction that acquires a vacuum expectation value and acts as a SM-like Higgs

- The behavior of the neutral mass eigenstates depend on the projection on the fields in this basis.

- Typically, it is the lightest neutral Higgs boson that behaves like the SM-like Higgs. The case in which one can identify the state ϕ_1^0 with the mass eigenstate is called alignment.

- In the alignment limit the tree-level couplings agree with the SM ones. Large departures from the alignment limit are heavily restricted by LHC measurements.

Relation between couplings

$$\langle\Phi_1\rangle = \frac{1}{\sqrt{2}}\begin{pmatrix}0\\ v_1\end{pmatrix}\ ,\quad \langle\Phi_2\rangle = \frac{1}{\sqrt{2}}\begin{pmatrix}0\\ v_2 e^{i\eta}\end{pmatrix}$$

δ=η

The opposite relation between quartic couplings in the Higgs basis and those in the weak basis can be obtained by changing β by -β

$$\lambda_1 = Z_1 c_\beta^4 + Z_2 s_\beta^4 + \frac{1}{2} Z_{345} s_{2\beta}^2 - 2 s_{2\beta}\left(\mathrm{Re}[Z_6 e^{i\delta}] c_\beta^2 + \mathrm{Re}[Z_7 e^{i\delta}] s_\beta^2\right)\ ,$$

$$\lambda_2 = Z_1 s_\beta^4 + Z_2 c_\beta^4 + \frac{1}{2} Z_{345} s_{2\beta}^2 + 2 s_{2\beta}\left(\mathrm{Re}[Z_6 e^{i\delta}] s_\beta^2 + \mathrm{Re}[Z_7 e^{i\delta}] c_\beta^2\right)\ ,$$

$$\lambda_3 = \frac{1}{4}\left(Z_1 + Z_2 - 2Z_{345}\right) s_{2\beta}^2 + Z_3 + \mathrm{Re}[(Z_6 - Z_7)e^{i\delta}] s_{2\beta} c_{2\beta}\ ,$$

$$\lambda_4 = \frac{1}{4}\left(Z_1 + Z_2 - 2Z_{345}\right) s_{2\beta}^2 + Z_4 + \mathrm{Re}[(Z_6 - Z_7)e^{i\delta}] s_{2\beta} c_{2\beta}\ ,$$

$$\begin{aligned}\lambda_5 e^{2i\delta} &= \frac{1}{4}(Z_1 + Z_2 - 2Z_{345}) s_{2\beta}^2 + \mathrm{Re}[Z_5 e^{2i\delta}] + i\,\mathrm{Im}[Z_5 e^{2i\delta}] c_{2\beta} \\ &\quad + \mathrm{Re}[(Z_6 - Z_7)e^{i\delta}] s_{2\beta} c_{2\beta} + i\,\mathrm{Im}[(Z_6 - Z_7)e^{i\delta}] s_{2\beta}\ ,\end{aligned}$$

$$\begin{aligned}\lambda_6 e^{i\delta} &= \frac{1}{2}(Z_1 c_\beta^2 - Z_2 s_\beta^2 - Z_{345} c_{2\beta} - i\,\mathrm{Im}[Z_5 e^{2i\delta}]) s_{2\beta} \\ &\quad + \mathrm{Re}[Z_6 e^{i\delta}] c_\beta c_{3\beta} + i\,\mathrm{Im}[Z_6 e^{i\delta}] c_\beta^2 + \mathrm{Re}[Z_7 e^{i\delta}] s_\beta s_{3\beta} + i\,\mathrm{Im}[Z_7 e^{i\delta}] s_\beta^2\ ,\end{aligned}$$

$$\begin{aligned}\lambda_7 e^{i\delta} &= \frac{1}{2}(Z_1 s_\beta^2 - Z_2 c_\beta^2 + Z_{345} c_{2\beta} + i\,\mathrm{Im}[Z_5 e^{2i\delta}]) s_{2\beta} \\ &\quad + \mathrm{Re}[Z_6 e^{i\delta}] s_\beta s_{3\beta} + i\,\mathrm{Im}[Z_6 e^{i\delta}] s_\beta^2 + \mathrm{Re}[Z_7 e^{i\delta}] c_\beta c_{3\beta} + i\,\mathrm{Im}[Z_7 e^{i\delta}] c_\beta^2\ ,\end{aligned}$$

Mass Matrix in the Higgs Basis

- The neutral Higgs mass matrix takes a particularly simple form in the Higgs basis

$$\mathcal{M}^2 = v^2 \begin{pmatrix} Z_1 & Z_6^R & -Z_6^I \\ Z_6^R & \frac{M_{H^\pm}^2}{v^2} + \frac{1}{2}(Z_4 + Z_5^R) & -\frac{1}{2} Z_5^I \\ -Z_6^I & -\frac{1}{2} Z_5^I & \frac{M_{H^\pm}^2}{v^2} + \frac{1}{2}(Z_4 - Z_5^R) \end{pmatrix}$$

- Two things are obvious from here. First, in the CP-conserving case, the condition of alignment, $Z_6 \ll 1$ implying small mixing between the lightest and heavier eigenstates is given by

$$\cos(\beta - \alpha) = -\frac{Z_6 v^2}{m_H^2 - m_h^2} \qquad \mathrm{Decoupling:} \quad Z_6 v^2 \ll m_H^2$$

- Second, while in the alignment limit the real part of Z_5 contributes to the splitting of the two heavier mass eigenstates, its imaginary part contributes to the splitting and their mixing.

$$M^2_{h_3,h_2} = M^2_{H^\pm} + \frac{1}{2}(Z_4 \pm |Z_5|)v^2 \, .$$

$$m_h^2 = Z_1 v^2, \qquad m_h = 125 \ \mathrm{GeV}$$

Modifying the top and bottom couplings in two Higgs Doublet Models

- Modification of about ten (or fifteen) percent are still possible
- Large modifications are certainly ruled out, with the exception of an inversion of the sign of the bottom Yukawa coupling.

$$\Phi_1 = H_d, \qquad \Phi_2 = H_u, \qquad (\bar{Q}_L H_u u_R, \qquad \bar{Q}_L \tilde{H}_d d_R)$$ (type II 2HDM}

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

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

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

Different types of Higgs models are differentiated by the choice of the fermion couplings. In type I models all fermions couple to Phi_2

- Alignment condition : $\cos(\beta-\alpha) = 0$

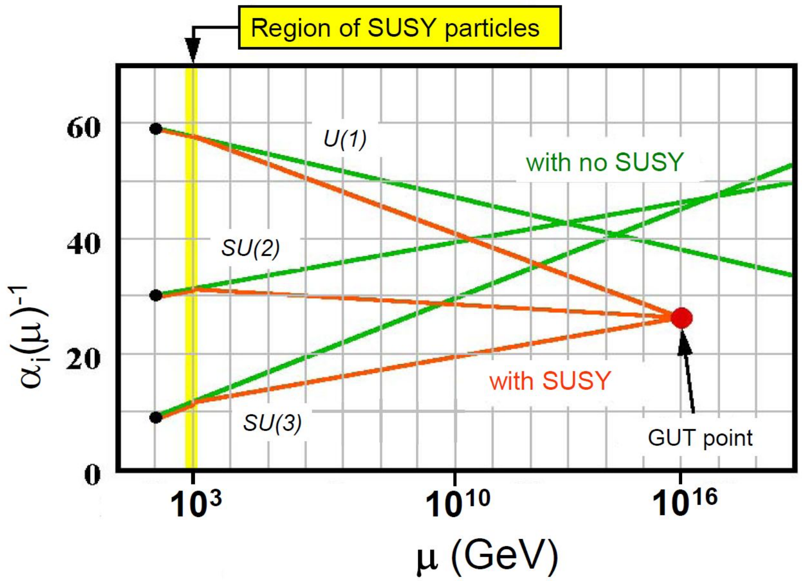
J. Gunion, H. Haber '02

$$h = \sin(\beta-\alpha) H_1^0 + \cos(\beta-\alpha) H_2^0$$
$$H = \cos(\beta-\alpha) H_1^0 - \sin(\beta-\alpha) H_2^0$$

(Neutral Higgs bosons in the Higgs basis)

A well motivated example : Supersymmetry

Unification



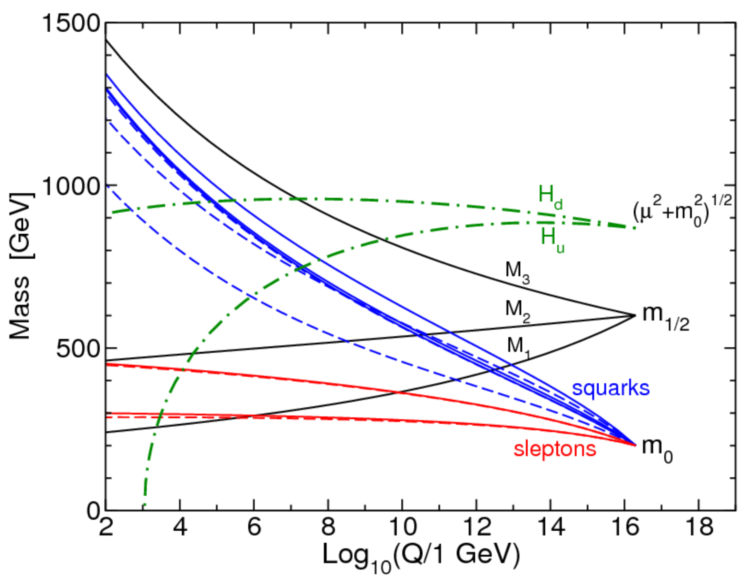
SUSY Algebra

$$\{Q_\alpha, \bar{Q}_{\dot\alpha}\} = 2\sigma^\mu_{\alpha\dot\alpha} P_\mu$$

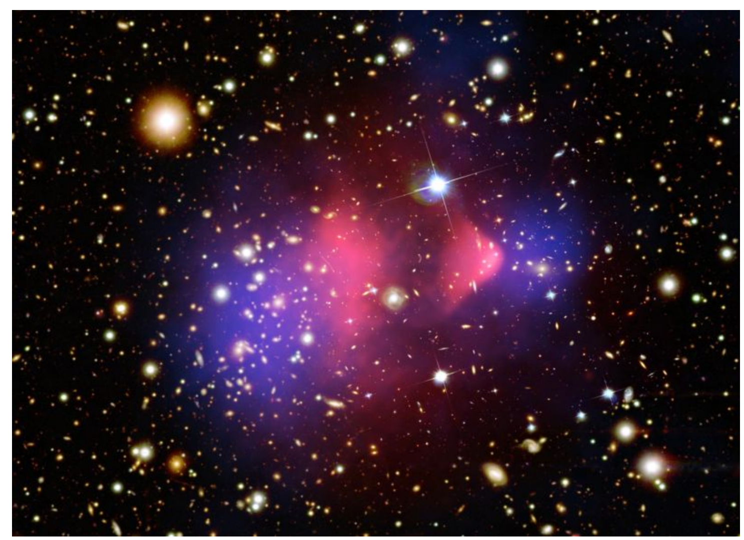
$$[Q_\alpha, P_\mu] = [\bar{Q}_{\dot\alpha}, P_\mu] = 0$$

Quantum Gravity ?

Electroweak Symmetry Breaking



Ultraviolet Insensitivity



If R-Parity is Conserved the Lightest SUSY particle is a good Dark Matter candidate

Stop Searches : MSSM Guidance ?

Lightest SM-like Higgs mass strongly depends on:

* CP-odd Higgs mass m_A
* tan beta $= \frac{v_u}{v_d}$
* 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 sbottom/stau sectors for large tan beta]

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

Carena, Espinosa, Quiros, C.W.'95,96

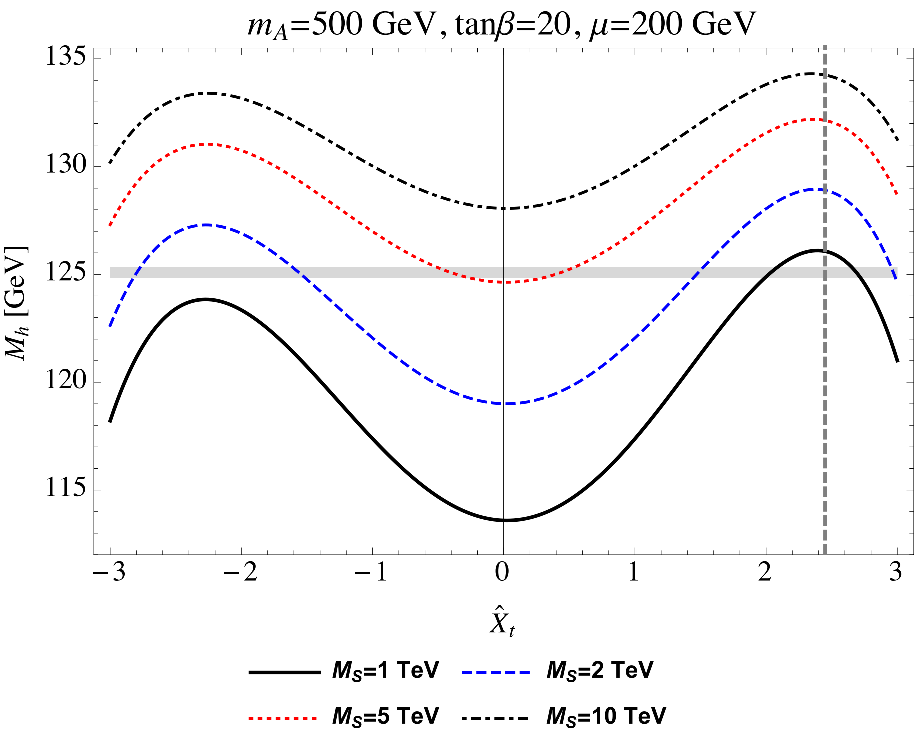
Analytic expression valid for $M_{SUSY} \sim m_Q \sim m_U$

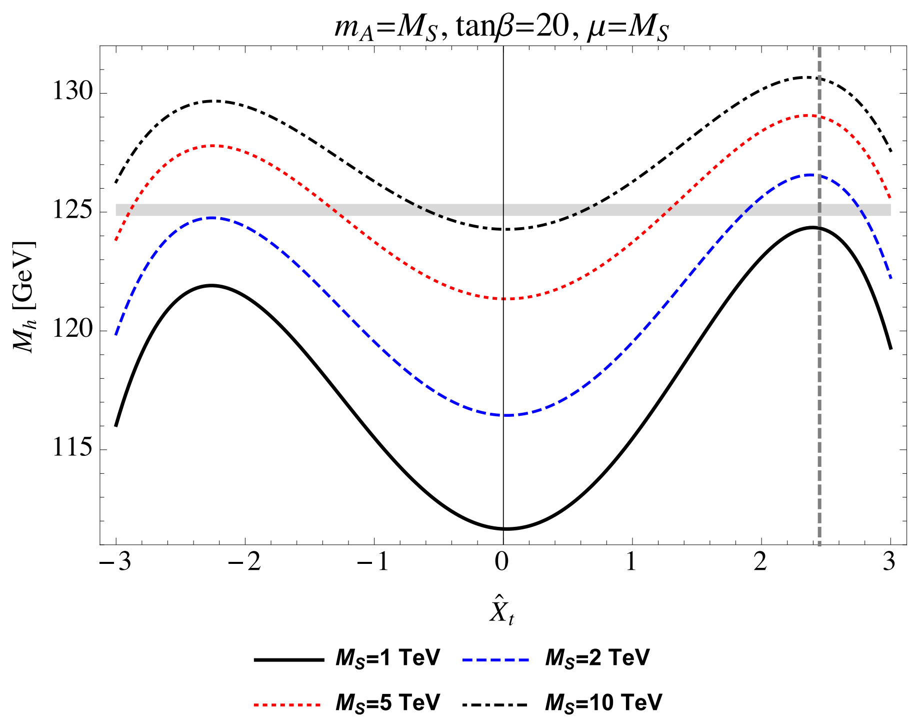
MSSM Guidance:
Stop Masses above about 1 TeV lead to the right Higgs Masss

P. Slavich, S. Heinemeyer et al, arXiv:2012.15629

P. Draper, G. Lee, C.W.'13, Bagnaschi et al' 14, Vega and Villadoro '14, Bahl et al'17

G. Lee, C.W. arXiv:1508.00576

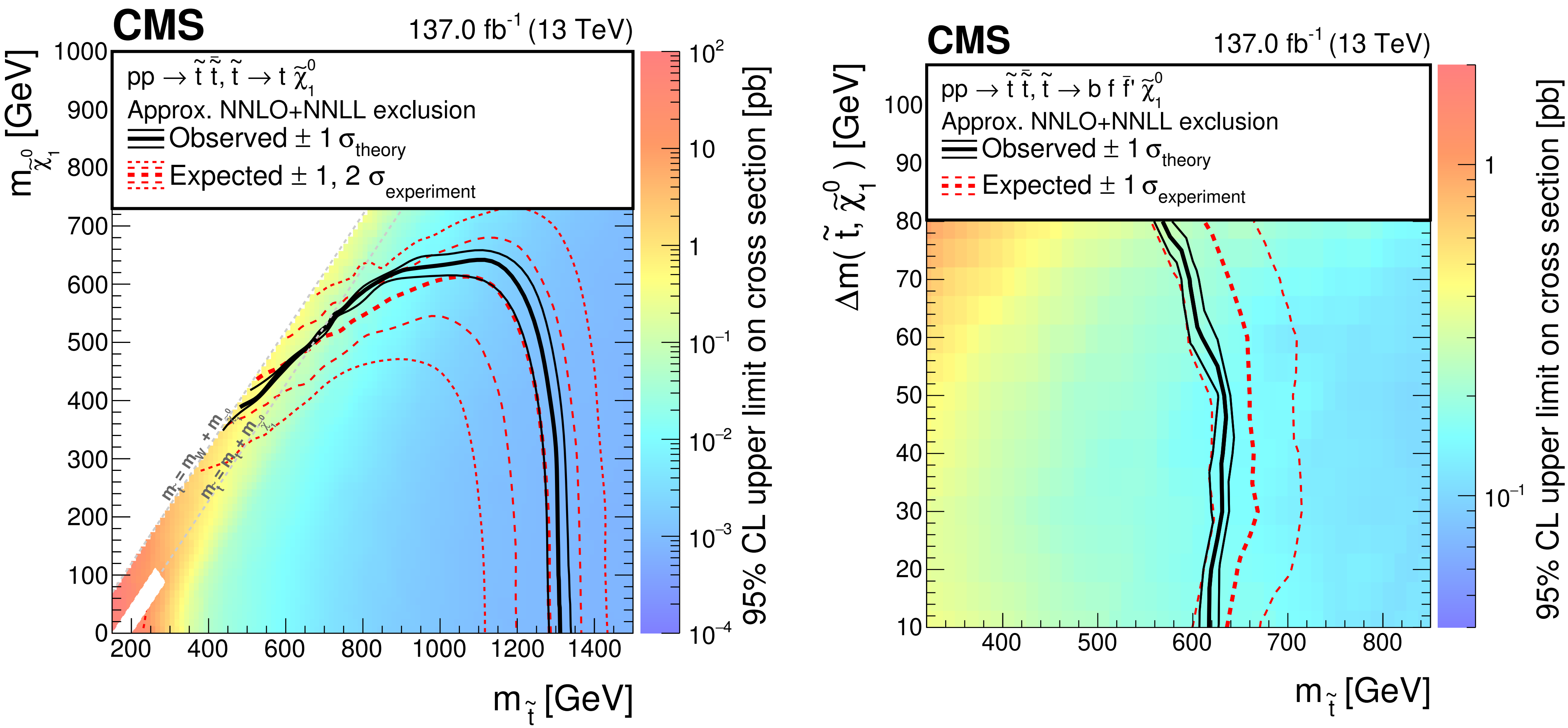




Necessary stop masses increase for lower values of tanβ, larger values of μ smaller values of the CP-odd Higgs mass or lower stop mixing values.

Lighter stops demand large splittings between left- and right-handed stop masses

Stop Searches



Combining all searches, in the simplest decay scenarios, it is hard to avoid the constraints of 700 GeV for sbottoms and 600 GeV for stops. Islands in one search are covered by other searches.

We are starting to explore the mass region suggested by the Higgs mass determination !

MSSM

$$
\begin{aligned}
\lambda_1 &= \frac{g_1^2+g_2^2}{4}\left(1-\frac{3}{8\pi^2}\,h_b^2\,t\right)\\
&+\frac{3}{8\pi^2}\,h_b^4\left[t+\frac{X_b}{2}+\frac{1}{16\pi^2}\left(\frac{3}{2}\,h_b^2+\frac{1}{2}\,h_t^2-8\,g_3^2\right)\left(X_b\,t+t^2\right)\right]\\
&-\frac{3}{96\pi^2}\,h_t^4\,\frac{\mu^4}{M_{\rm SUSY}^4}\left[1+\frac{1}{16\pi^2}\left(9\,h_t^2-5h_b^2-16g_3^2\right)t\right]
\end{aligned}
$$

$$
\begin{aligned}
\lambda_2 &= \frac{g_1^2+g_2^2}{4}\left(1-\frac{3}{8\pi^2}\,h_t^2\,t\right)\\
&+\frac{3}{8\pi^2}\,h_t^4\left[t+\frac{X_t}{2}+\frac{1}{16\pi^2}\left(\frac{3\,h_t^2}{2}+\frac{h_b^2}{2}-8\,g_3^2\right)\left(X_t\,t+t^2\right)\right]\\
&-\frac{3}{96\pi^2}\,h_b^4\,\frac{\mu^4}{M_{\rm SUSY}^4}\left[1+\frac{1}{16\pi^2}\left(9\,h_b^2-5h_t^2-16g_3^2\right)t\right]
\end{aligned}
$$

$$
\begin{aligned}
\lambda_3 &= \frac{g_2^2-g_1^2}{4}\left(1-\frac{3}{16\pi^2}(h_t^2+h_b^2)\,t\right)\\
&+\frac{6}{16\pi^2}\,h_t^2\,h_b^2\left[t+\frac{A_{tb}}{2}+\frac{1}{16\pi^2}\left(h_t^2+h_b^2-8\,g_3^2\right)\left(A_{tb}\,t+t^2\right)\right]\\
&+\frac{3}{96\pi^2}\,h_t^4\left[\frac{3\mu^2}{M_{\rm SUSY}^2}-\frac{\mu^2A_t^2}{M_{\rm SUSY}^4}\right]\left[1+\frac{1}{16\pi^2}\left(6\,h_t^2-2h_b^2-16g_3^2\right)t\right]\\
&+\frac{3}{96\pi^2}\,h_b^4\left[\frac{3\mu^2}{M_{\rm SUSY}^2}-\frac{\mu^2A_b^2}{M_{\rm SUSY}^4}\right]\left[1+\frac{1}{16\pi^2}\left(6\,h_b^2-2h_t^2-16g_3^2\right)t\right]
\end{aligned}
$$

$$
\begin{aligned}
\lambda_4 &= -\frac{g_2^2}{2}\left(1-\frac{3}{16\pi^2}(h_t^2+h_b^2)\,t\right)\\
&-\frac{6}{16\pi^2}\,h_t^2\,h_b^2\left[t+\frac{A_{tb}}{2}+\frac{1}{16\pi^2}\left(h_t^2+h_b^2-8\,g_3^2\right)\left(A_{tb}\,t+t^2\right)\right]\\
&+\frac{3}{96\pi^2}\,h_t^4\left[\frac{3\mu^2}{M_{\rm SUSY}^2}-\frac{\mu^2A_t^2}{M_{\rm SUSY}^4}\right]\left[1+\frac{1}{16\pi^2}\left(6\,h_t^2-2h_b^2-16g_3^2\right)t\right]\\
&+\frac{3}{96\pi^2}\,h_b^4\left[\frac{3\mu^2}{M_{\rm SUSY}^2}-\frac{\mu^2A_b^2}{M_{\rm SUSY}^4}\right]\left[1+\frac{1}{16\pi^2}\left(6\,h_b^2-2h_t^2-16g_3^2\right)t\right]
\end{aligned}
$$

$$
\begin{aligned}
\lambda_5 &= -\frac{3}{96\pi^2}\,h_t^4\,\frac{\mu^2A_t^2}{M_{\rm SUSY}^4}\left[1-\frac{1}{16\pi^2}\left(2h_b^2-6\,h_t^2+16g_3^2\right)t\right]\\
&-\frac{3}{96\pi^2}\,h_b^4\,\frac{\mu^2A_b^2}{M_{\rm SUSY}^4}\left[1-\frac{1}{16\pi^2}\left(2h_t^2-6\,h_b^2+16g_3^2\right)t\right]
\end{aligned}
$$

$$
\begin{aligned}
\lambda_6 &= \frac{3}{96\pi^2}\,h_t^4\,\frac{\mu^3A_t}{M_{\rm SUSY}^4}\left[1-\frac{1}{16\pi^2}\left(\frac{7}{2}h_b^2-\frac{15}{2}h_t^2+16g_3^2\right)t\right]\\
&+\frac{3}{96\pi^2}\,h_b^4\,\frac{\mu}{M_{\rm SUSY}}\left(\frac{A_b^3}{M_{\rm SUSY}^3}-\frac{6A_b}{M_{\rm SUSY}}\right)\left[1-\frac{1}{16\pi^2}\left(\frac{1}{2}h_t^2-\frac{9}{2}h_b^2+16g_3^2\right)t\right]
\end{aligned}
$$

$$
\begin{aligned}
\lambda_7 &= \frac{3}{96\pi^2}\,h_b^4\,\frac{\mu^3A_b}{M_{\rm SUSY}^4}\left[1-\frac{1}{16\pi^2}\left(\frac{7}{2}h_t^2-\frac{15}{2}h_b^2+16g_3^2\right)t\right]\\
&+\frac{3}{96\pi^2}\,h_t^4\,\frac{\mu}{M_{\rm SUSY}}\left(\frac{A_t^3}{M_{\rm SUSY}^3}-\frac{6A_t}{M_{\rm SUSY}}\right)\left[1-\frac{1}{16\pi^2}\left(\frac{1}{2}h_b^2-\frac{9}{2}h_t^2+16g_3^2\right)t\right]
\end{aligned}
$$

$$
\begin{aligned}
X_t &= \frac{2A_t^2}{M_{\rm SUSY}^2}\left(1-\frac{A_t^2}{12M_{\rm SUSY}^2}\right)\\
X_b &= \frac{2A_b^2}{M_{\rm SUSY}^2}\left(1-\frac{A_b^2}{12M_{\rm SUSY}^2}\right)\\
A_{tb} &= \frac{1}{6}\left[-\frac{6\mu^2}{M_{\rm SUSY}^2}-\frac{(\mu^2-A_bA_t)^2}{M_{\rm SUSY}^4}+\frac{3(A_t+A_b)^2}{M_{\rm SUSY}^2}\right].
\end{aligned}
$$

$$
\begin{aligned}
h_t &= m_t(M_t)/(v\sin\beta)\\
h_b &= m_b(M_t)/(v\cos\beta)
\end{aligned}
$$

$$
t=\log\frac{M_{\rm SUSY}^2}{M_t^2}
$$

Couplings in low energy supersymmetry : Type II 2HDM

Modifying the top and bottom couplings in two Higgs Doublet Models

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

Alignment : $\cos(\beta - \alpha) = 0$

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

$$h = \sin(\beta - \alpha) H_1^0 + \cos(\beta - \alpha) H_2^0$$
$$H = \cos(\beta - \alpha) H_1^0 - \sin(\beta - \alpha) H_2^0$$

(Neutral Higgs bosons in the Higgs basis)

$$\cos(\beta - \alpha) = -\frac{Z_6 v^2}{m_H^2 - m_h^2}$$

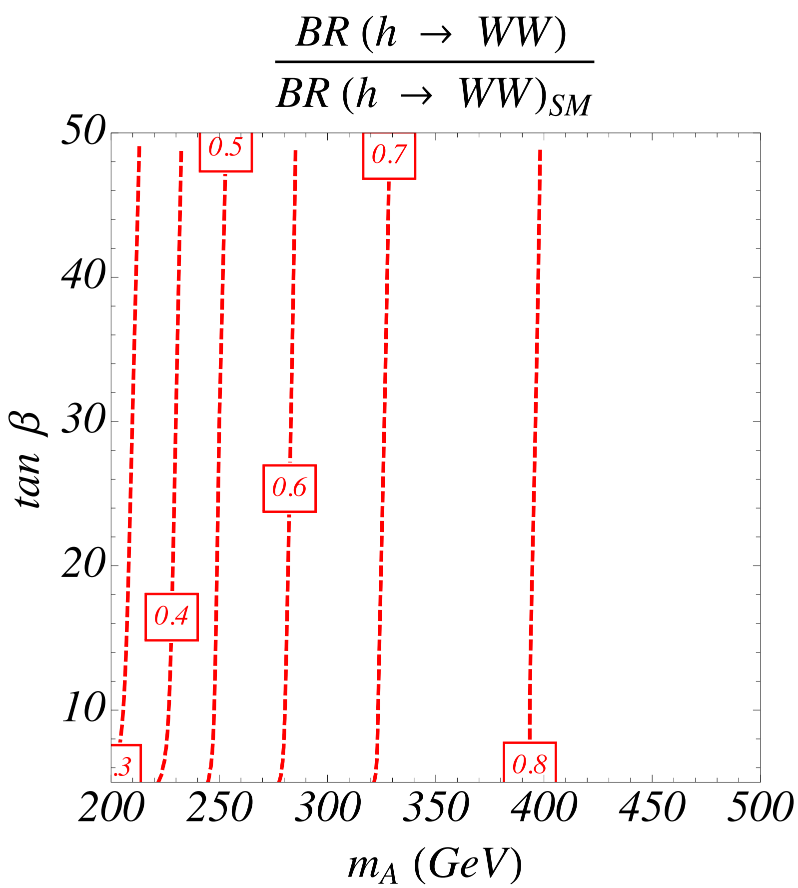
Carena, Haber, Low, Shah, C.W.'14
M. Carena, I. Low, N. Shah, C.W.'13

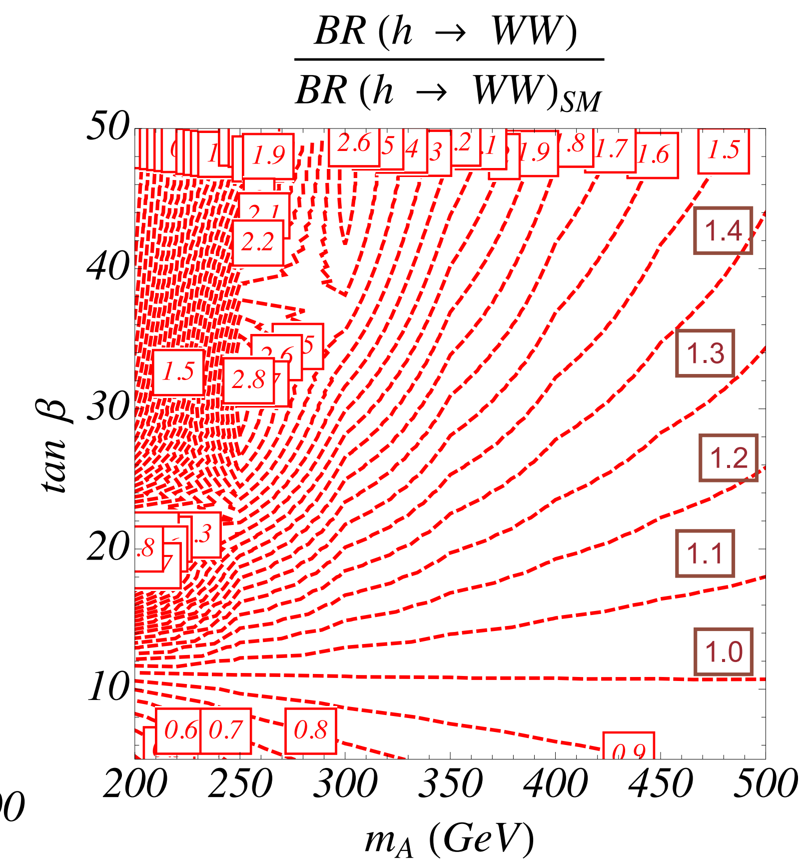
MSSM : Higgs Decay into Gauge Bosons

Mostly determined by the change of width

Decoupling Small μ

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





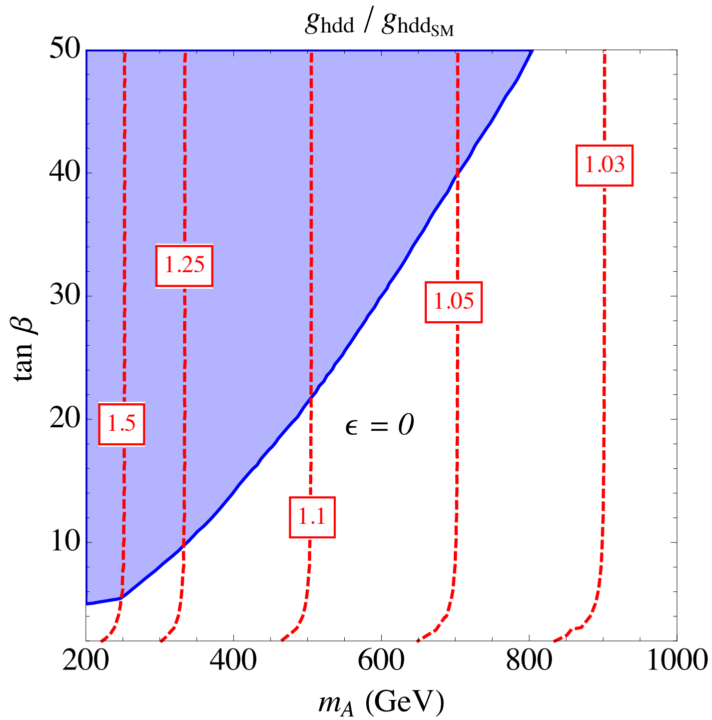
CP-odd Higgs masses of order 200 GeV and tanβ = 10 OK in the alignment case

Down Couplings in the MSSM for low values of μ

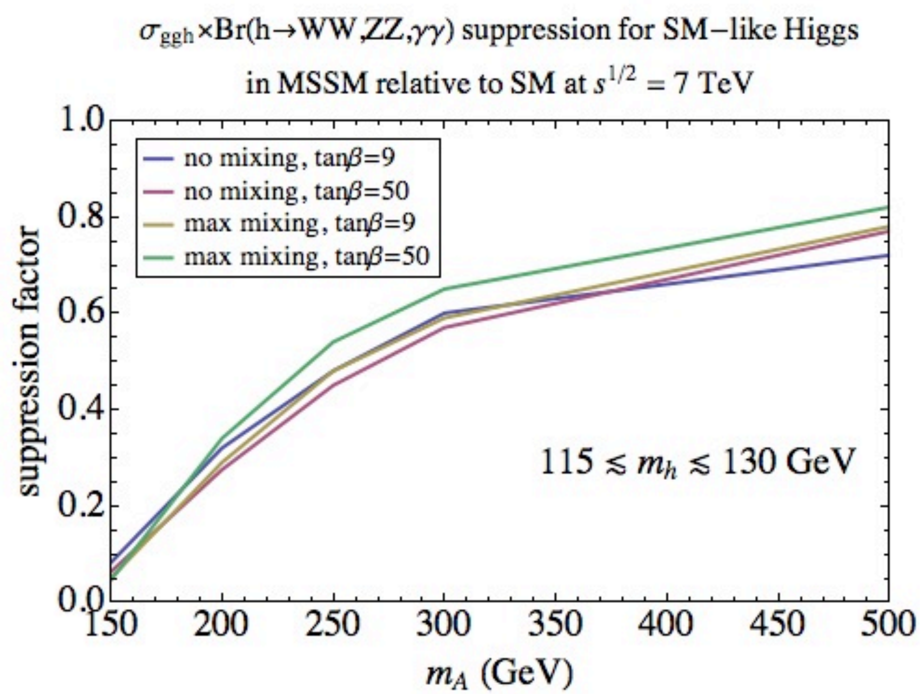
- Higgs Decay into bottom quarks is the dominant one
- A modification of the bottom quark coupling affects all other decays

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

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



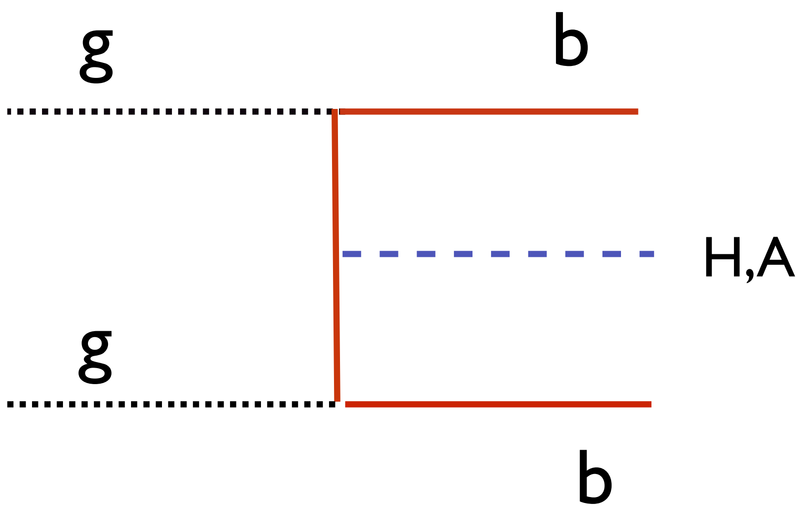
Carena, Low, Shah, C.W.'13



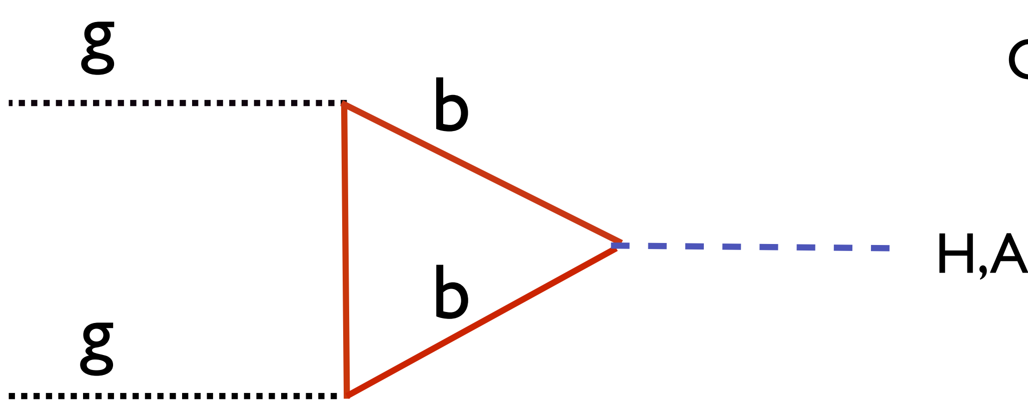
Enhancement of bottom quark and tau couplings independent of tan β

Non-Standard Higgs Production

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



Associated Production

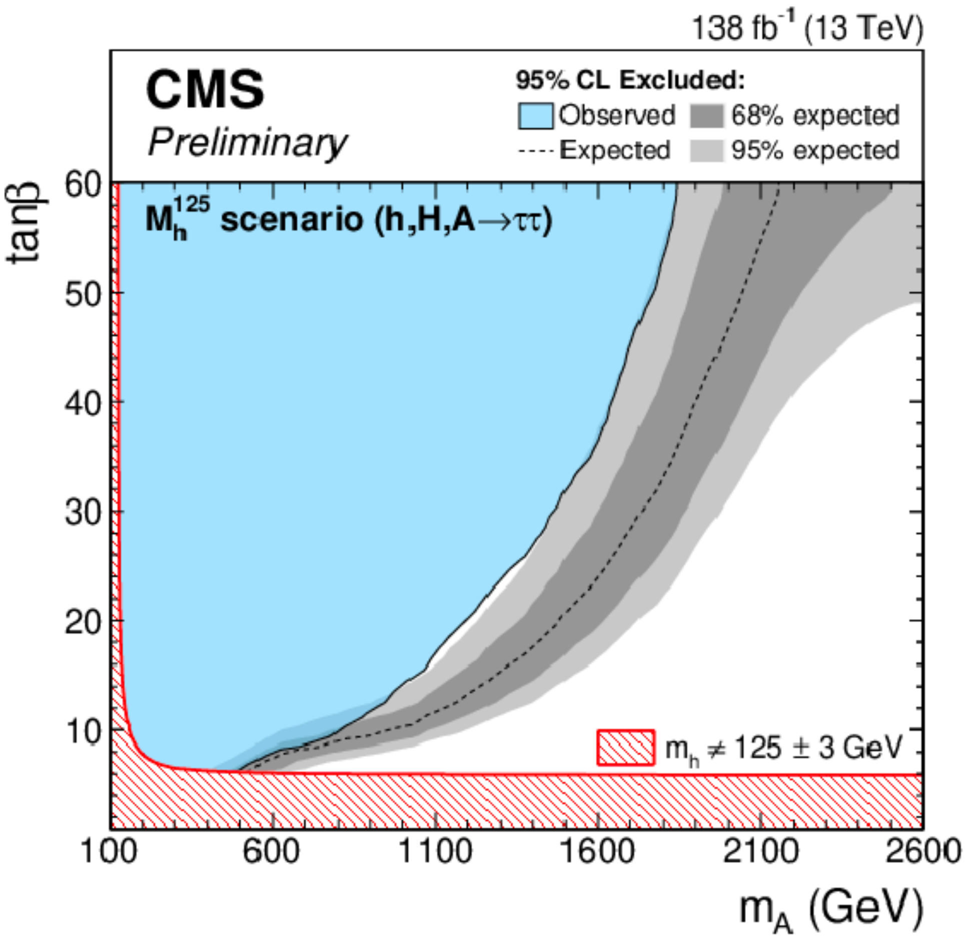


Gluon Fusion

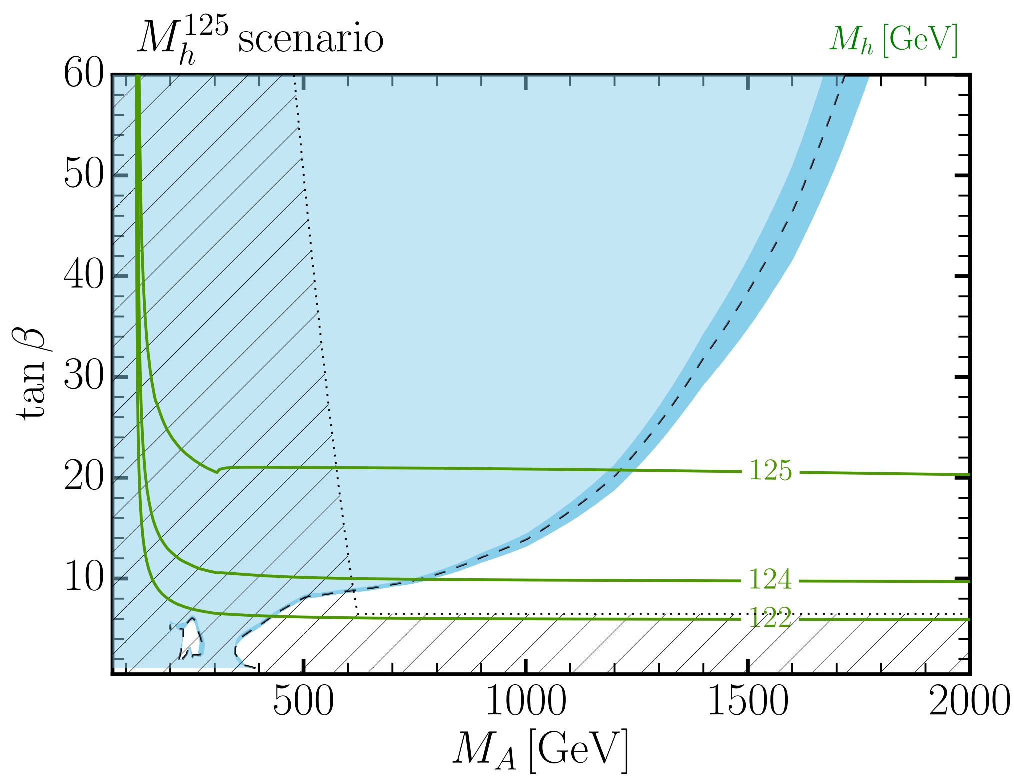
$$g_{Abb} \simeq g_{Hbb} \simeq \frac{m_b \tan\beta}{(1+\Delta_b)v}, \qquad g_{A\tau\tau} \simeq g_{H\tau\tau} \simeq \frac{m_\tau \tan\beta}{v}$$

Complementarity of Direct and Indirect Bounds

Bahl, Fuchs, Hahn, Heinemeyer, Liebler, Patel, Slavich, Stefaniak, Weiglein, C.W. arXiv:1808.07542



Dashed area, constrained by precision measurements.
Low values of the Higgsino Mass assumed in this Figure.



Interesting but not compelling excess appears at CMS.
No similar excess appears at ATLAS.

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

Naturalness and Alignment in the (N)MSSM

see also Kang, Li, Li,Liu, Shu'13, Agashe,Cui,Franceschini'13

- It is well known that in the NMSSM there are new contributions to the lightest CP-even Higgs mass,

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

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

- It is perhaps less known that it leads to sizable corrections to the mixing between the MSSM like CP-even states. In the Higgs basis, (correction to $\Delta\lambda_4 = \lambda^2$)

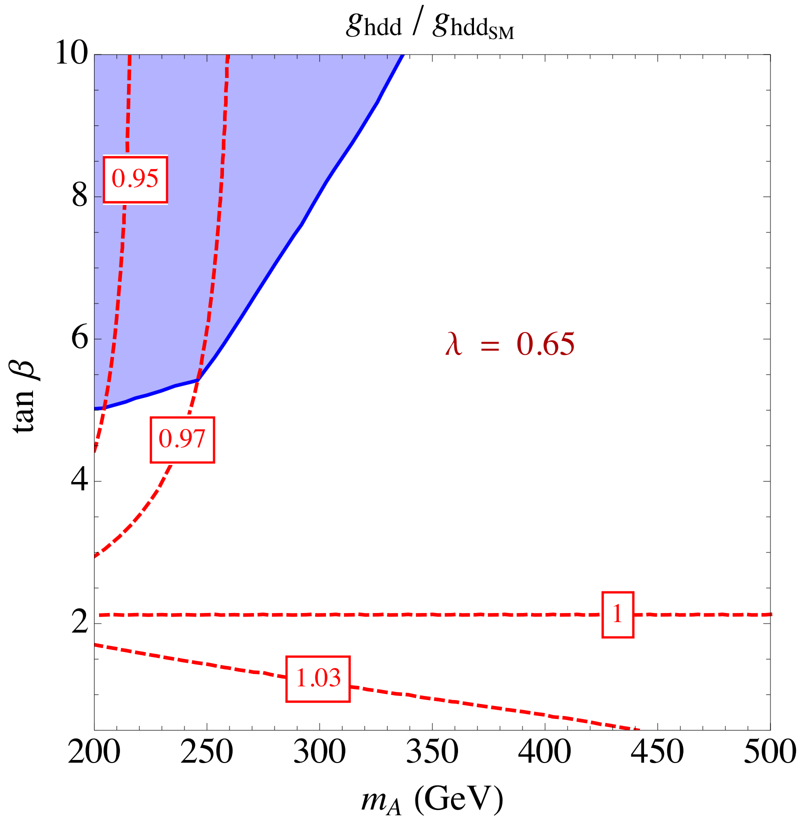
$$M_S^2(1,2) \simeq \frac{1}{\tan\beta}\left(m_h^2 - M_Z^2 \cos 2\beta - \lambda^2 v^2 \sin^2\beta + \delta_{\tilde{t}}\right) \equiv Z_6 v^2$$

- The values of lambda end up in a very narrow range, between 0.65 and 0.7 for all values of tan(beta), that are the values that lead to naturalness with perturbativity up to the GUT scale

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

Alignment in the NMSSM (heavy or Aligned singlets)

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



It is clear from this plot that the NMSSM does an amazing job in aligning the MSSM-like CP-even sector, provided $\lambda \sim 0.65$

Very relevant phenomenological properties

This range of couplings, and the subsequent alignment, may appear as emergent properties in a theory with strong interactions at high energies

N. Coyle, C.W. arXiv:1912.01036

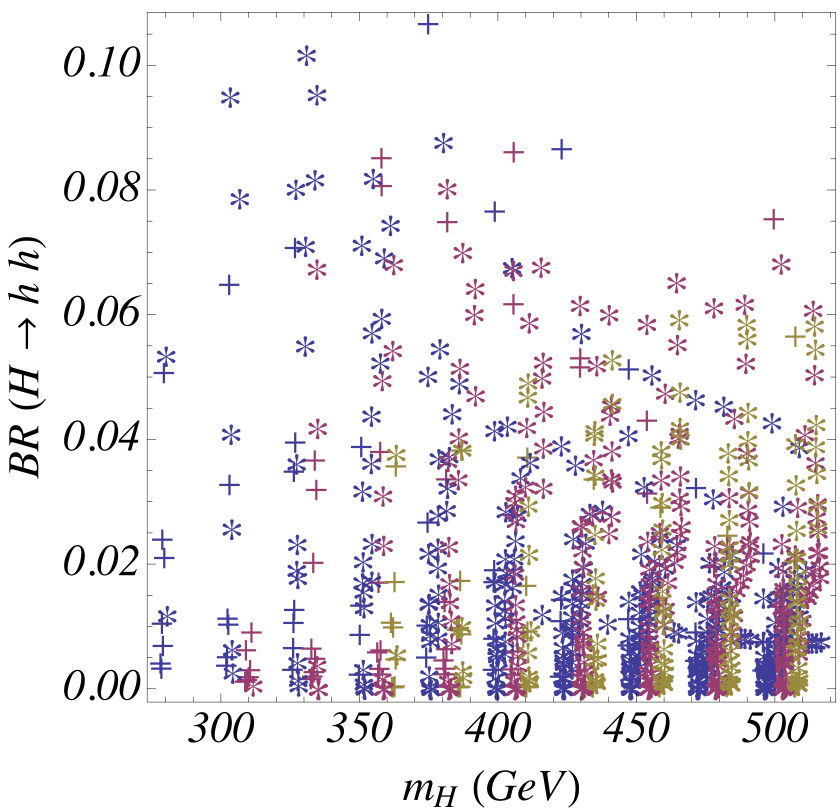
Decays into pairs of SM-like Higgs bosons suppressed by alignment

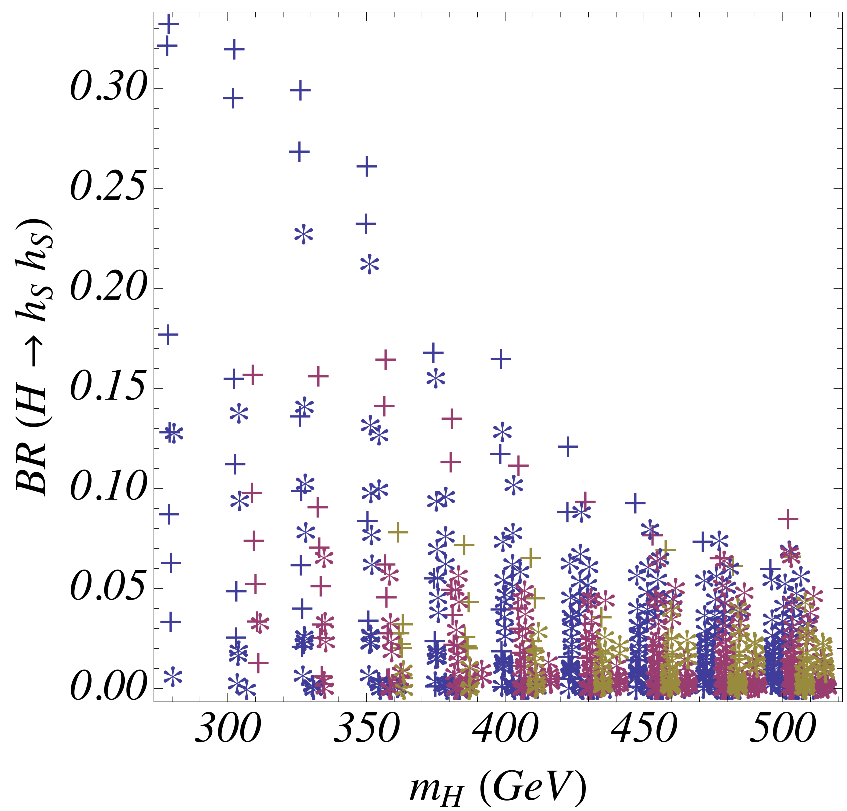
Carena, Haber, Low, Shah, C.W.'15

See also S. Su talk

Crosses : H1 singlet like
Asterix : H2 singlet like

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





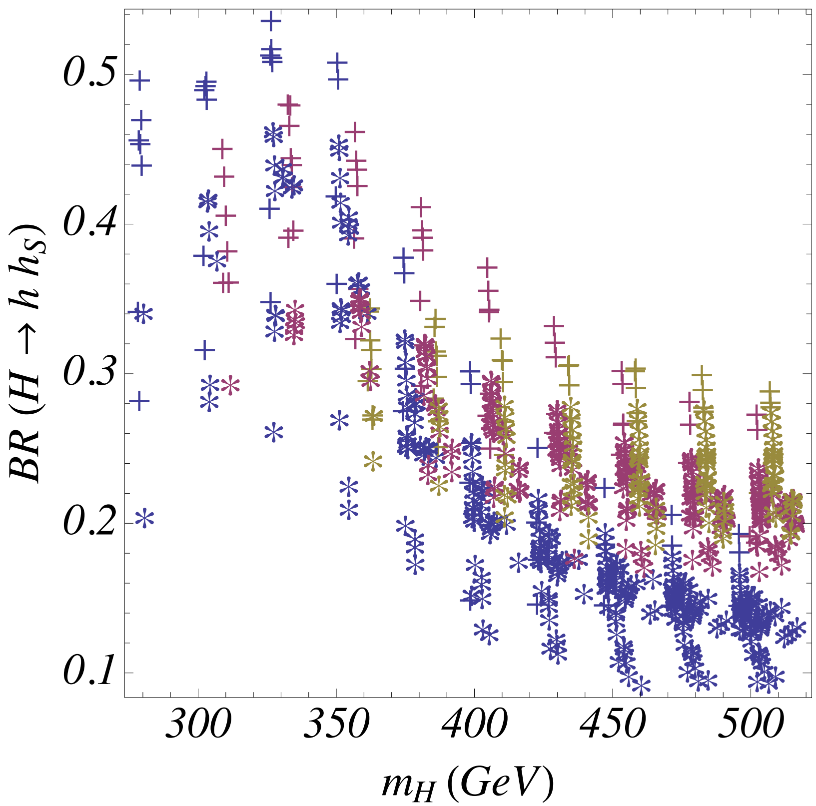
Significant decays of heavier Higgs Bosons into lighter ones and Z's

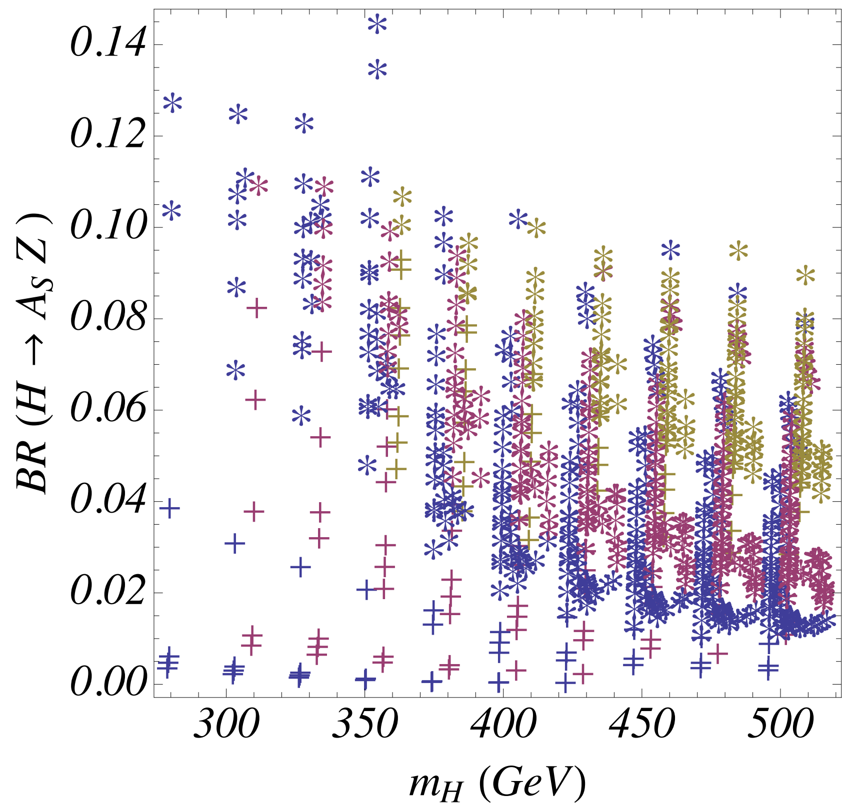
Relevant for searches for Higgs bosons

Crosses : H1 singlet like
Asterix : H2 singlet like

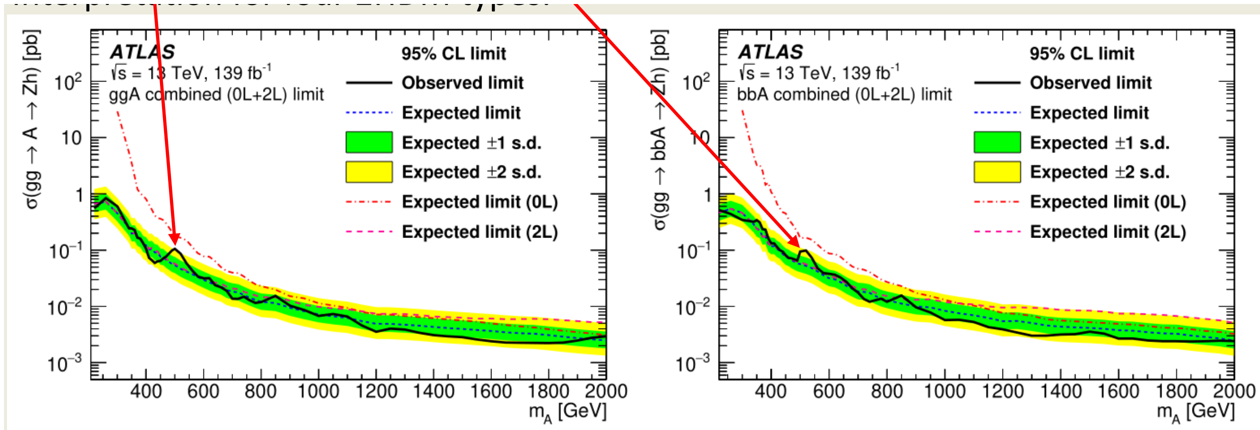
Blue : $\tan\beta = 2$
Red : $\tan\beta = 2.5$
Yellow: $\tan\beta = 3$

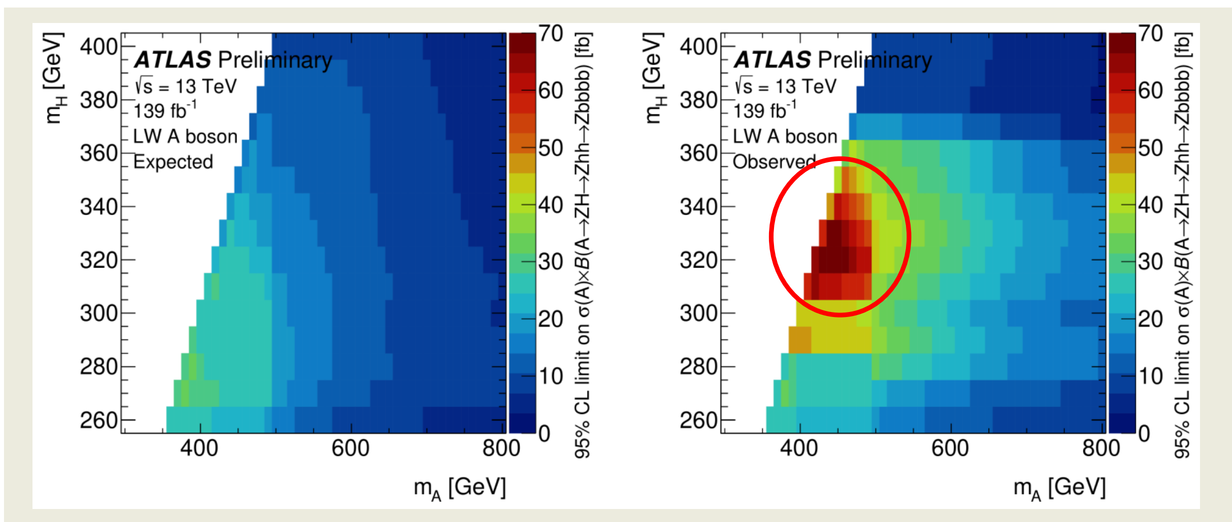
Carena, Haber, Low, Shah, C.W.'15





Search for (pseudo-)scalars decaying into lighter ones





It is relevant to perform similar analyses replacing
the Z by a SM Higgs (and changing the CP property of the Higgs)

CP violation

- The general 2HDM allows for more sources of CP violation than in the case of $\lambda_6 = \lambda_7 = 0$
- This can be simply seen by the fact that in such a case, due to the minimization conditions, there is only one independent phase, and this phase must be zero in the alignment limit,

$$Z_6^I = Z_6^R = 0$$

- On the contrary when the Z2 symmetry is not imposed one may still have a large CP-violation in the heavy Higgs sector, namely

$$Z_5^I \neq 0$$

- CP violating interactions are restricted by the search for electric dipole moment of the electron, which in the SM appears only a high loop levels and is quite suppressed.

SM-like Higgs Contribution

$$O_{11} \simeq 1$$

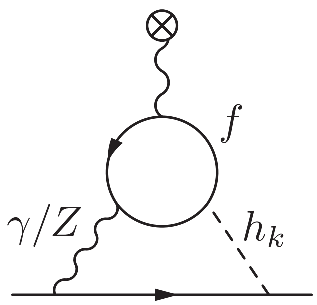
$$O_{21} \simeq -\frac{Z_6^R v^2}{m_H^2}$$

$$O_{31} \simeq -\frac{Z_6^I v^2}{m_H^2}$$

type II 2HDM

$$g^S_{H_1 dd} \simeq O_{11} - \tan\beta \, O_{21}$$

$$g^P_{H_1 dd} \simeq -O_{31} \tan\beta .$$

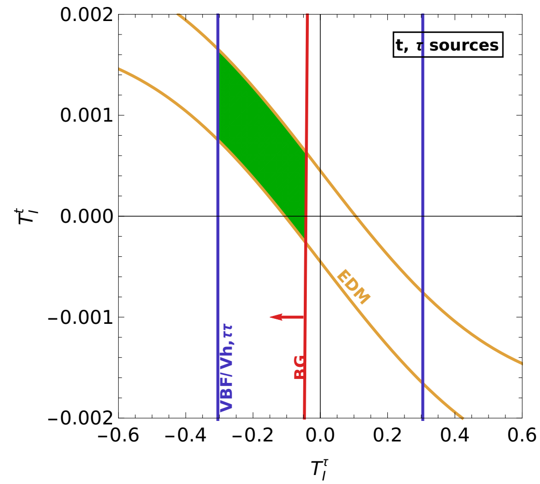


X_I^f : CP odd component of couplings

$$\frac{d_e^{(t)}}{e} \simeq -\frac{16}{3} \frac{e^2}{(16\pi^2)^2} \frac{m_e}{m_t} \frac{v}{\Lambda^2} X_I^t \left(2 + \ln \frac{m_t^2}{m_h^2}\right),$$

$$\frac{d_e^{(b)}}{e} \simeq -4 N_c Q_b^2 \frac{e^2}{(16\pi^2)^2} \frac{m_e m_b}{m_h^2} \frac{v}{\Lambda^2} X_I^b \left(\frac{\pi^2}{3} + \ln^2 \frac{m_b^2}{m_h^2}\right),$$

$$\frac{d_e^{(\tau)}}{e} \simeq -4 Q_\tau^2 \frac{e^2}{(16\pi^2)^2} \frac{m_e m_\tau}{m_h^2} \frac{v}{\Lambda^2} X_I^\tau \left(\frac{\pi^2}{3} + \ln^2 \frac{m_\tau^2}{m_h^2}\right).$$



Altmannshofer, Gori, Hamer, Patel,’20
Fuchs, Losada, Nir, Viernik’20

In extensions of the SM, additional contributions from new particles are possible and should be included.

Cancellations between different contributions are possible.

Carena, Ellis, Lee, Pilaftsis, C.W. arXiv:1512.00437

Still Unexplored : Self-Couplings of the Higgs Boson

- In the Standard Model, the self couplings are completely determined by the Higgs mass and the vacuum expectation value

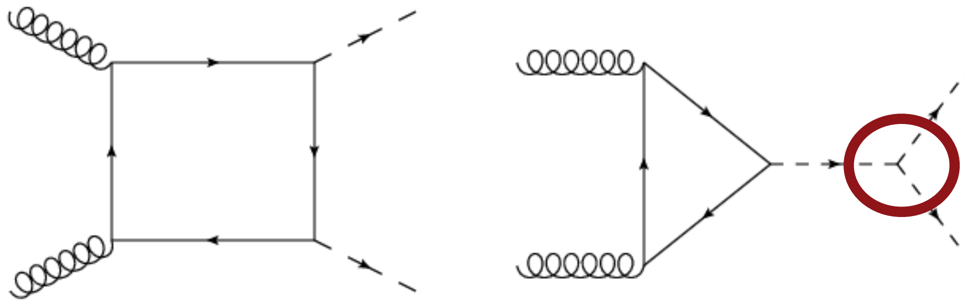
$$V_{SM}(h) = \frac{m_h^2}{2}h^2 + \frac{m_h^2}{2v}h^3 + \frac{m_h}{8v^2}h^4$$

- In particular, the trilinear coupling is given by

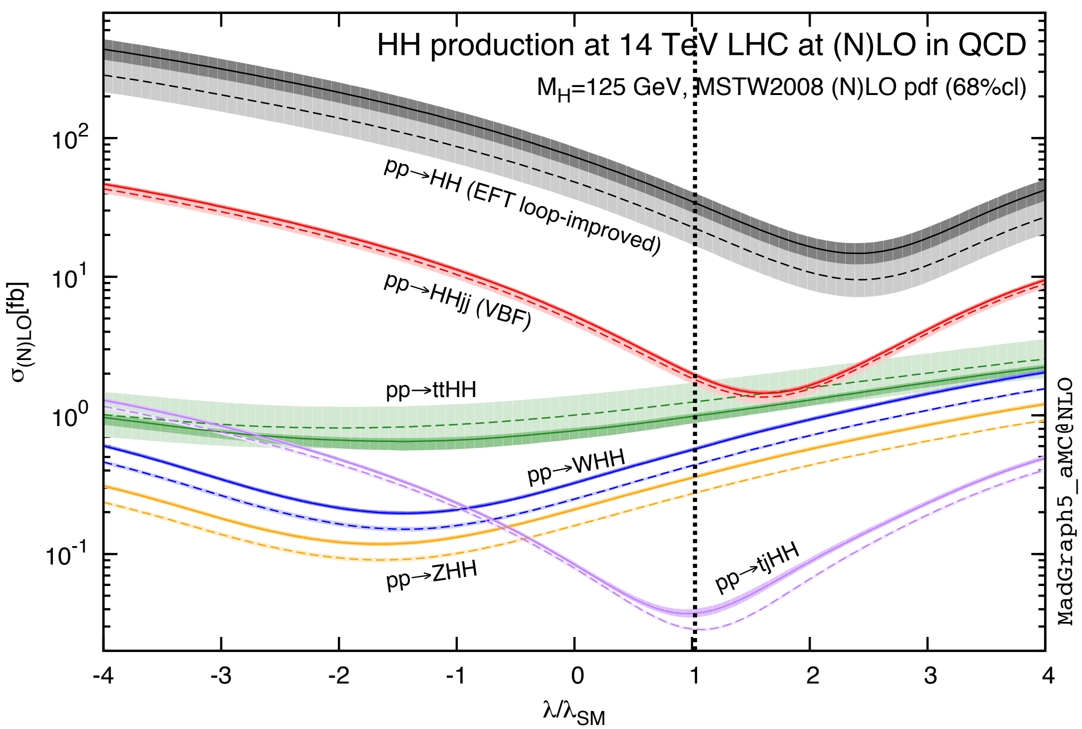
$$g_{hhh} = \frac{3m_h^2}{v}$$

- The Higgs potential can be quite different from the SM potential. So far, we have checked only the Higgs vev and the mass, related to the second derivative of the Higgs at the minimum.
- Therefore, it is important to measure the trilinear and quartic coupling to check its consistency with the SM predictions.
- Double Higgs production allows to probe the trilinear Higgs Coupling.

Di-Higgs Production dependence on the Higgs self coupling



Top Coupling Fixed
to the SM value.

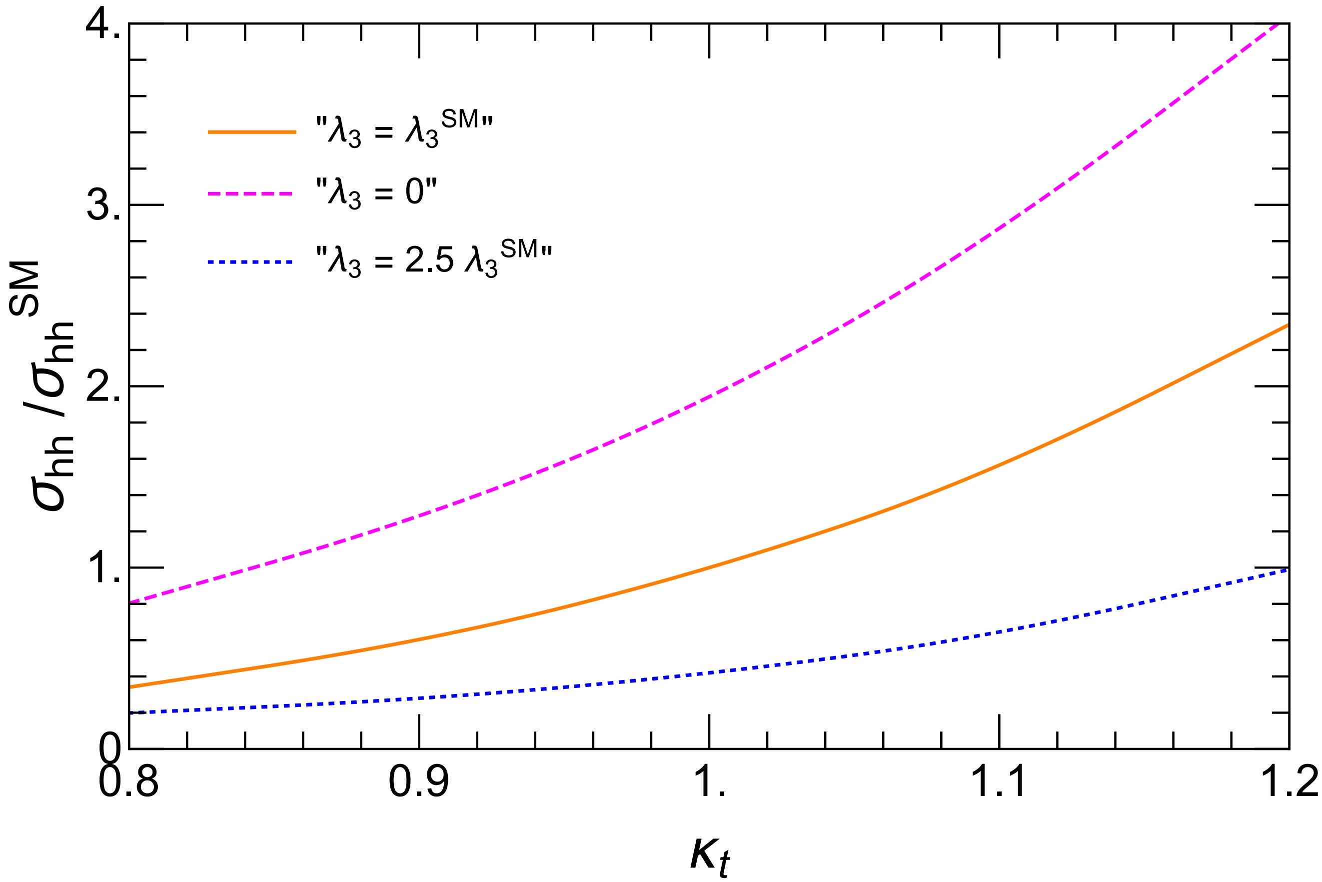


Frederix et al’14

Box Diagram is dominant, and hence interference in the gluon fusion channel tends to be enhanced for larger values of the coupling. At sufficiently large values of the coupling, or negative values, the production cross section is enhanced.

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

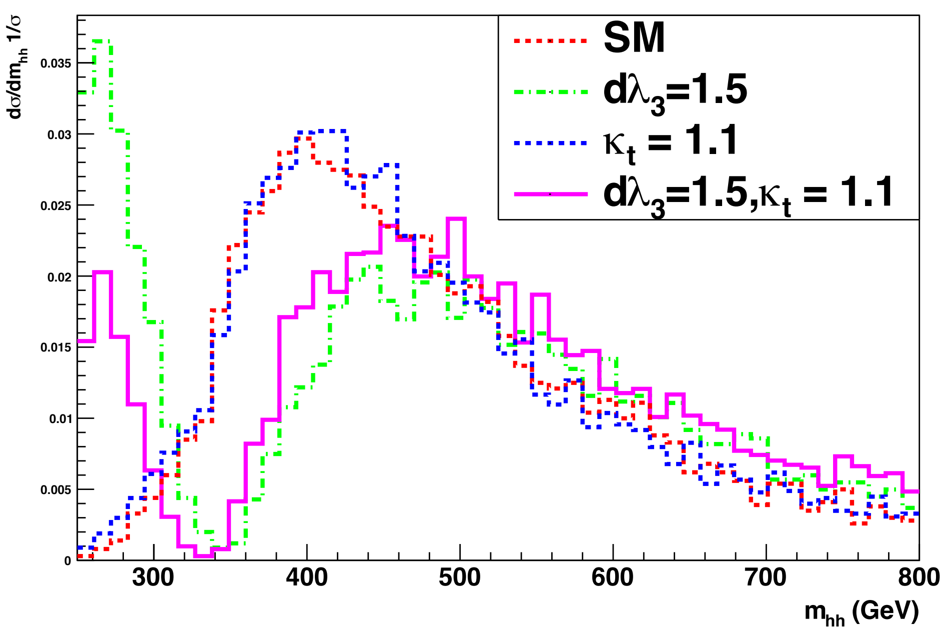
Huang, Joglekar, Li, C.W.'17

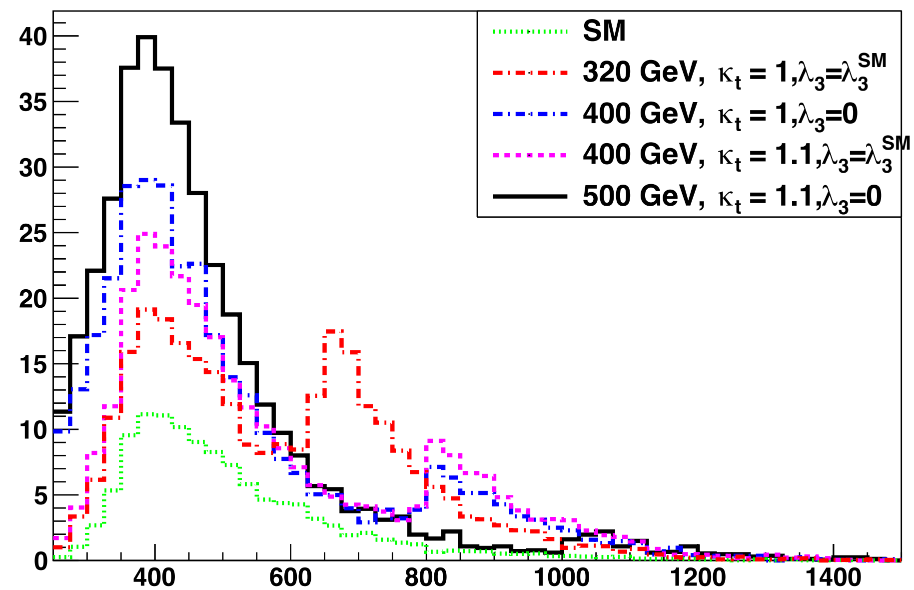


Strong dependence on the value of k_t and λ_3

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

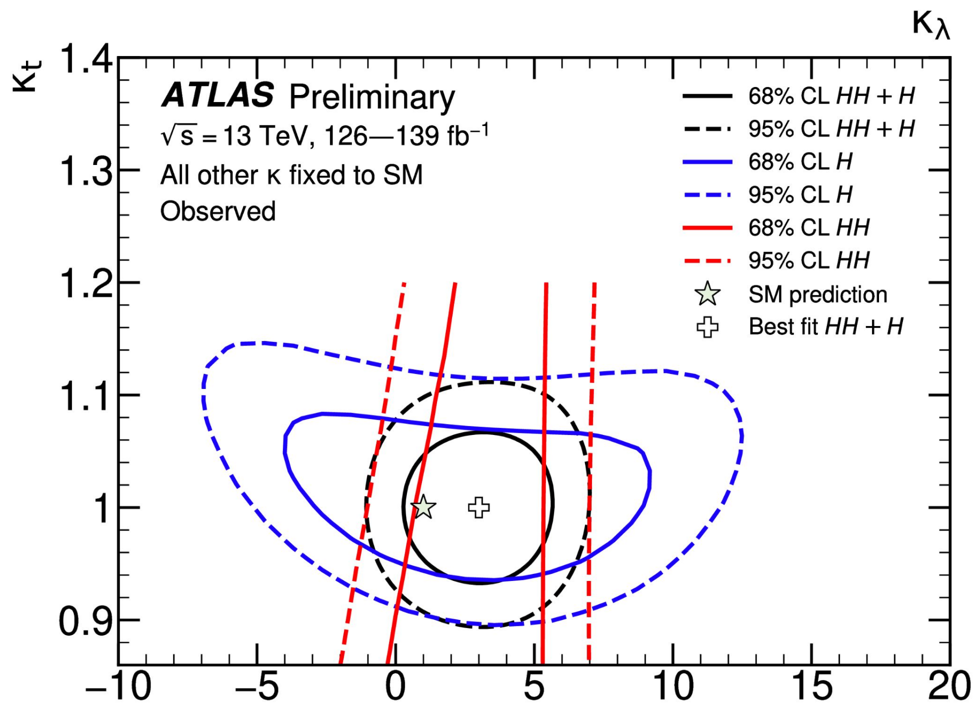
Invariant Mass Distributions





Provided lambda3 is not shifted to large values, acceptances similar as in the Standard Model

Amazing Experimental Progress



κ_λ

ATLAS-CONF-2022-050

HH+H combination	$-0.4 < \kappa_\lambda < 6.3$	$-1.9 < \kappa_\lambda < 7.6$	$\kappa_\lambda = 3.0^{+1.8}_{-1.9}$
HH+H combination (2019)	$-2.3 < \kappa_\lambda < 10.3$	$-5.1 < \kappa_\lambda < 11.2$	$\kappa_\lambda = 4.6^{+3.2}_{-3.8}$
HH+H combination, κ_t floating	$-0.4 < \kappa_\lambda < 6.3$	$-1.9 < \kappa_\lambda < 7.6$	$\kappa_\lambda = 3.0^{+1.8}_{-1.9}$
HH+H combination, κ_t, κ_V, κ_b, κ_τ floating	$-1.4 < \kappa_\lambda < 6.1$	$-2.2 < \kappa_\lambda < 7.7$	$\kappa_\lambda = 2.3^{+2.1}_{-2.0}$
HH+H combination (2019), κ_t, κ_V, κ_b, κ_ℓ floating	$-3.7 < \kappa_\lambda < 11.5$	$-6.2 < \kappa_\lambda < 11.6$	$\kappa_\lambda = 5.5^{+3.5}_{-5.2}$

Why do we care about the potential ?

- First of all, it is a fundamental part of the Standard Model. If new physics is at very high scales, one expects a renormalizable potential, like in the SM

$$V(\phi, 0) = \frac{m^2}{2}(\phi^\dagger \phi) + \frac{\lambda}{4}(\phi^\dagger \phi)^4 + \sum_{n=1}^{\infty} \frac{c_{2n+4}}{2^{(n+2)}\Lambda^{2n}} \left(\phi^\dagger \phi\right)^{n+2}$$

- All terms beyond the first two would cancel.

- If, however, there is new physics coupled to the Higgs close to the weak scale, one would expect non-trivial modifications to the potential, that should be measurable.

- The trilinear coupling may be obtained, in general,

P. Huang, A. Joglekar, B. Li, C.W.'15

$$\lambda_3 = \frac{3m_h^2}{v}\left(1 + \frac{8v^2}{3m_h^2}\sum_{n=1}^{\infty} \frac{n(n+1)(n+2)c_{2n+4}v^{2n}}{2^{n+2}\Lambda^{2n}}\right).$$

- Hence, the departures from the SM prediction are a probe of the potential modifications.

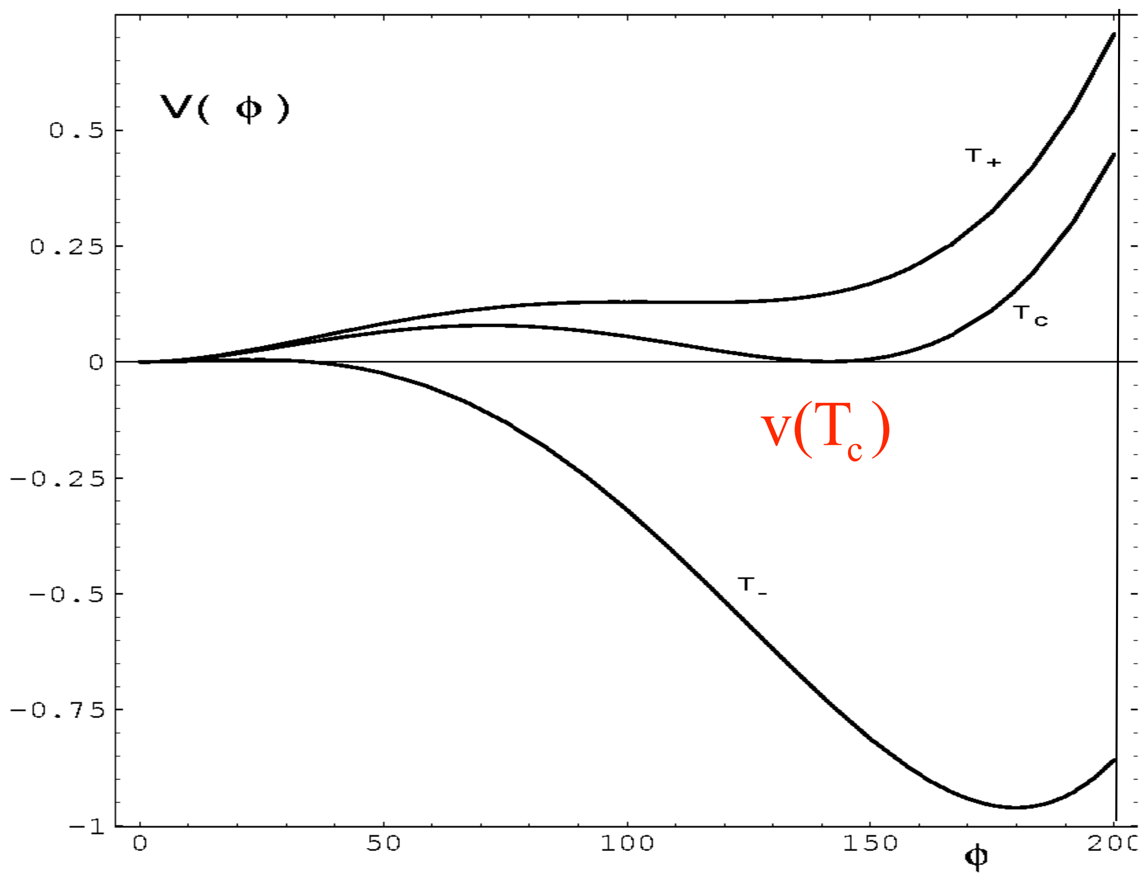
$$\delta = \frac{\lambda_3}{\lambda_3^{SM}} - 1 = \frac{8v^2}{3m_h^2}\sum_{n=1}^{\infty} \frac{n(n+1)(n+2)c_{2n+4}v^{2n}}{2^{n+2}\Lambda^{2n}}$$

See Marcela Carena's talk, this conference

Electroweak Phase Transition

Higgs Potential Evolution in the case of a first order

Phase Transition



For the generation of the matter-antimatter asymmetry at the weak scale, (electroweak baryogengesis)

$$\frac{v(T_c)}{T_c} \geq 1$$

Gravitational Waves may be produced at the Phase Transition

Ghosh, this workshop

First Order Phase Transition

Grojean, Servant, Wells'06
Joglekar, Huang, Li, C.W.'15

- Simpler case

$$V(\phi, T) = \frac{m^2 + a_0 T^2}{2}\left(\phi^\dagger \phi\right) + \frac{\lambda}{4}\left(\phi^\dagger \phi\right)^2 + \frac{c_6}{8\Lambda^2}\left(\phi^\dagger \phi\right)^3$$

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

- Demanding the minimum at the critical temperature to be degenerate with the trivial one, we obtain

$$\left(\phi_c^\dagger \phi_c\right) = v_c^2 = -\frac{\lambda \Lambda^2}{c_6}. \qquad\qquad \lambda + \frac{3c_6}{2\Lambda^2} v^2 = \frac{m_h^2}{2v^2}$$

- Negative values of the quartic coupling, together with positive corrections to the mass coming from non-renormalizable operators demanded.

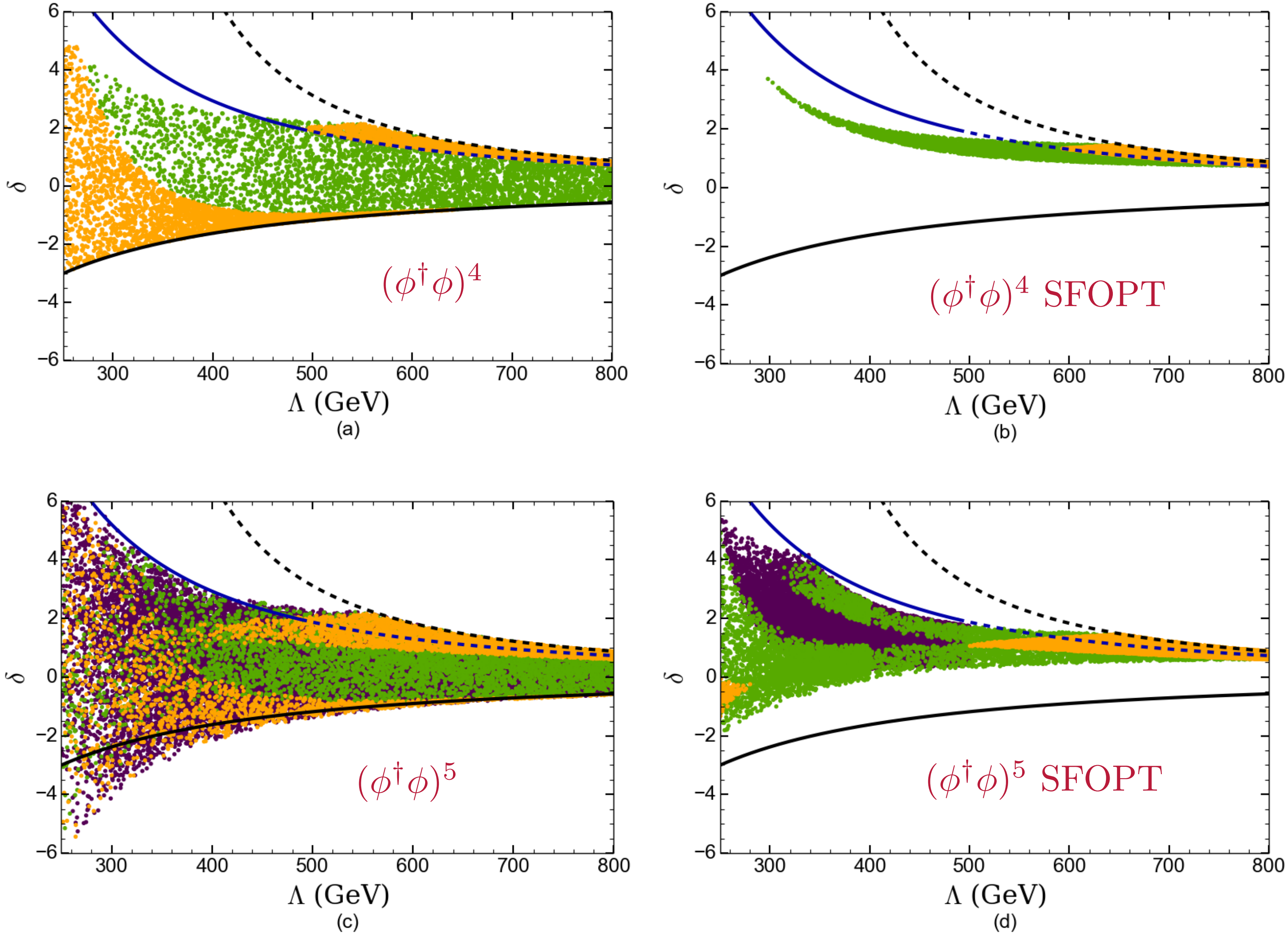
- It is simple algebra to demonstrate that, $T_c^2 = \frac{3c_6}{4\Lambda^2 a_0}\left(v^2 - v_c^2\right)\left(v^2 - \frac{v_c^2}{3}\right).$

$$\frac{v_c}{T_c} > 1 \Rightarrow \qquad\qquad \frac{2}{3} \leq \delta \leq 2.$$

- Now, in the two extremes, either vc or Tc go to zero, so in order to fulfill the baryogengesis conditions one would like to be somewhat in between.

More General Modifications of the Potential

In general, it is difficult to obtain negative values of δ and at the same time a strongly first order phase transition (SFOPT)



Joglekar, Huang, Li, C.W.'15

Conclusions

- Precision Higgs measurement show a good agreement of all couplings with respect to the SM expectations
- This is surprising since this sector is very sensitive to the ultraviolet completion of the theory.
- Two Higgs Doublet Models and singlet extensions provide a good effective field theory to the study of LHC data
- Some phenomenological properties of these models were discussed, based on our present experimental knowledge
- Higgs physics remains as one of the most vibrant field of particle physics, one in which many surprises may lay ahead, with profound implications for our understanding of Nature.

Backup

Realizing the Effective Theory

- It turns out that one can realize the effective theory by integrating out a singlet.
- In this case, there is a relation between the modifications of the potential and the trilinear coupling with the mixing of the singlet with the SM Higgs

$$V(\phi_h, \phi_s, T) = \frac{m_0^2 + a_0 T^2}{2}\phi_h^2 + \frac{\lambda_h}{4}\phi_h^4 + a_{hs}\phi_s\phi_h^2 + \frac{\lambda_{hs}}{2}\phi_s^2\phi_h^2 + t_s\phi_s + \frac{m_s^2}{2}\phi_s^2 + \frac{a_s}{3}\phi_s^3 + \frac{\lambda_s}{4}\phi_s^4$$

- Integrating out the singlet, for as and lambdas small, one obtains a modification of the effective quartic and c6 couplings

Menon, Morrissey, C.W.'04
Carena, Shah, C.W.'12

$$V(h,T) = \frac{m^2(T)}{2}\phi_h^2 + \frac{\lambda_h}{4}\phi_h^4 - \frac{\left(t_s + a_{hs}\phi_h^2\right)^2}{2\left(m_s^2 + \lambda_{hs}\phi_h^2\right)}.$$

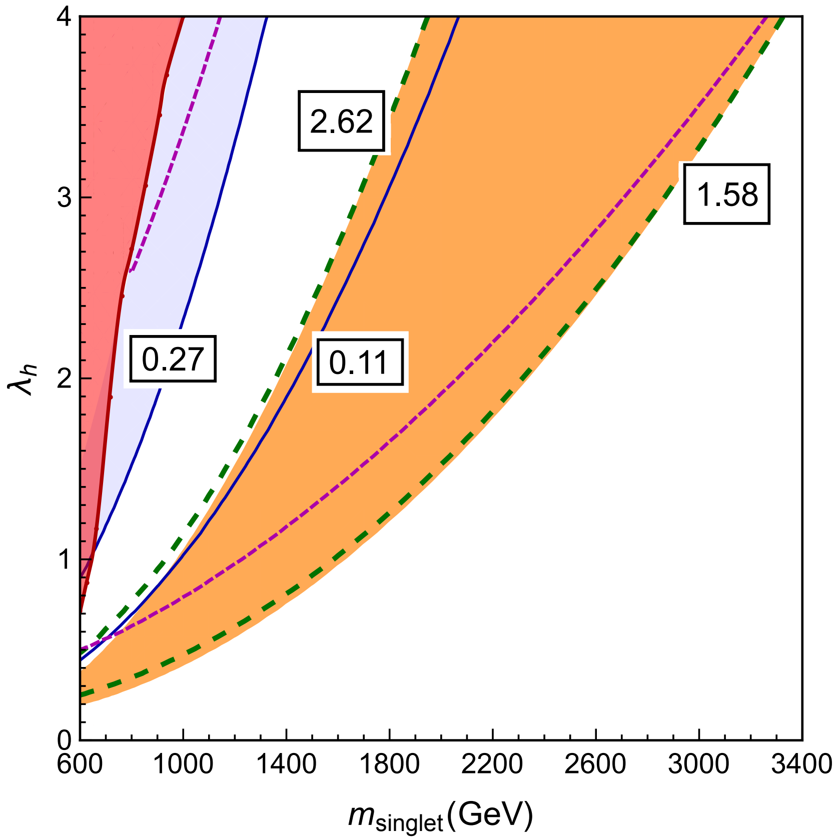
- Moreover, the trilinear coupling can be rewritten in terms of the mixing with the singlet

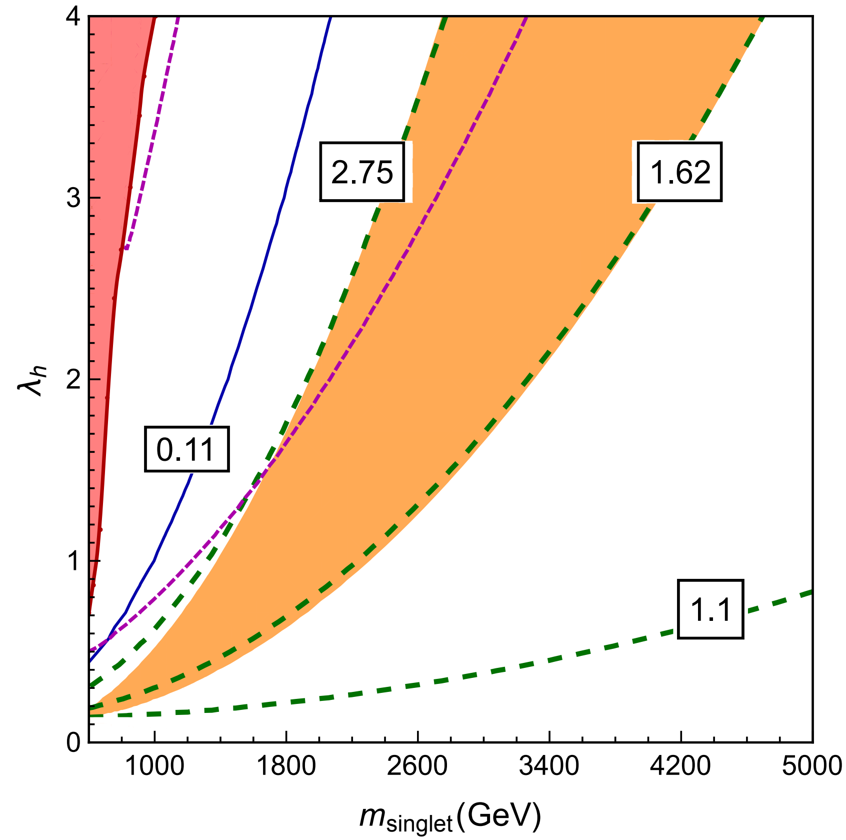
$$\lambda_3 = 6\lambda_h v_h \cos^3\theta \left[1 + \left(\frac{\lambda_{hs}v_s + a_{hs}}{\lambda_h v_h}\right)\tan\theta + \frac{\lambda_{hs}}{\lambda_h}\tan^2\theta\right].$$

Modified λ_3, mixing angle and SFOPT

Orange :SFOPT
Solid lines : Higgs mixing angle
Dashed lines : 1 + δ

Joglekar, Huang, Li, C.W.'15





Positive corrections to λ_3
Mixing angle suppresses Higgs coupling to the top
Difficult to test experimentally

Obtaining $\lambda_6, \lambda_7 \neq 0$

- Flavor symmetries may be preserved while generating the extra couplings in models in which additional fields, which softly broke the symmetry, are generated.
- The symmetry is still preserved in the ultraviolet, but broken in the effective low energy theory, which is represented by the 2HDM. An example is the MSSM, where they appear at the loop level.
- The corrections may also appear at the tree-level, by for instance the decoupling of singlets. An example will be presented below.
- Beyond this, the cancellation of these quartic couplings only hold in one particular basis and is not preserved by the unitarity rotation of the Higgs fields, like for instance the transformation to the Higgs basis
- Therefore, we shall work in a general, basis independent framework considering the 2HDM as an effective theory valid up to scales much larger than the electroweak breaking scale.

Obtaining $\lambda_6, \lambda_7 \neq 0$: NMSSM

- In the MSSM the Higgs quartic couplings are too small to give any relevant correction.
- The NMSSM allows for a correction of the Higgs quartic couplings

$$Z_4 \;=\; -\tfrac{1}{2}\left[\lambda^2 - \tfrac{1}{2}(g^2 + g'^2)\right] s_{2\beta}^2 - \tfrac{1}{2} g^2 + \lambda^2$$

- It is simpler to study the case in which the singlets are decoupled, by pushing their mass up.
- This can be done, for instance, by using tadpole terms.

$$\Delta V = \;\xi_S \; S + h.c. \qquad\qquad \langle S \rangle = \frac{\mu}{\lambda} \simeq -\frac{\xi_S}{m_S^2}$$

- The effect of singlet decoupling is to introduce relevant threshold corrections to the quartic couplings Z_4, Z_5 and Z_6.
- The Z_6 corrections are relevant, since otherwise large misalignments are expected when λ is pushed up.

N. Coyle, C.W., arXiV:1802.09122

Singlet Decoupling : Threshold Corrections
Large values of tanβ

$$
\begin{aligned}
\delta\lambda_4 &\simeq -\lambda^2\left(\frac{A_\lambda^2}{2m_{h_S}^2}+\frac{A_\lambda^2}{2m_{A_S}^2}\right)+2\lambda^2\kappa\frac{\xi_S A_\lambda}{m_{h_S}^2}\left(\frac{1}{m_{h_S}^2}-\frac{1}{m_{A_S}^2}\right)\\
&+\frac{\xi_F A_\lambda^2\kappa\lambda^2}{2}\left(\frac{1}{m_{h_S}^4}-\frac{1}{m_{A_S}^4}\right)+\frac{\kappa^2\lambda^2A_\lambda^2\xi_S^2}{m_{h_S}^4}\left(\frac{3}{m_{h_S}^4}+\frac{1}{m_{A_S}^4}\right)\\
\delta\lambda_5 &\simeq -\lambda^2\left(\frac{A_\lambda^2}{2m_{h_S}^2}-\frac{A_\lambda^2}{2m_{A_S}^2}\right)+2\lambda^2\kappa\frac{\xi_S A_\lambda}{m_{h_S}^2}\left(\frac{1}{m_{h_S}^2}+\frac{1}{m_{A_S}^2}\right)\\
&+\frac{\xi_F A_\lambda^2\kappa\lambda^2}{2}\left(\frac{1}{m_{h_S}^4}+\frac{1}{m_{A_S}^4}\right)+\frac{\kappa^2\lambda^2A_\lambda^2\xi_S^2}{m_{h_S}^4}\left(\frac{3}{m_{h_S}^4}-\frac{1}{m_{A_S}^4}\right)\\
\delta\lambda_7 &\simeq -\lambda^3\frac{\xi_S A_\lambda}{m_{h_S}^4}
\end{aligned}
$$

← Essential to allow alignment !

$$
\begin{aligned}
\delta Z_4 &\simeq -\lambda^2\left(\frac{A_\lambda^2}{2m_{h_S}^2}+\frac{A_\lambda^2}{2m_{A_S}^2}\right)\\
\delta Z_5 &\simeq -\lambda^2\left(\frac{A_\lambda^2}{2m_{h_S}^2}-\frac{A_\lambda^2}{2m_{A_S}^2}\right)\\
\delta Z_6 &\simeq \lambda^2\frac{A_\lambda^2}{t_\beta m_{h_S}^2}-\lambda^2\frac{\mu A_\lambda}{m_{h_S}^2}
\end{aligned}
$$

$$\boxed{-Z_6 v^2\tan\beta}$$

Alignment Condition :

$$t_\beta\, c_{\beta-\alpha}\approx\frac{1}{m_H^2-m_h^2}\left[\left(\lambda^2\left(1-\frac{A_\lambda^2}{m_{h_S}^2}+\frac{\mu A_\lambda t_\beta}{m_{h_S}^2}\right)v^2-m_h^2-M_Z^2\right)\right].$$

$$\frac{g_{hbb}}{g_{hbb}^{\rm SM}} = \sin(\beta-\alpha)-\cos(\beta-\alpha)t_\beta$$

N. Coyle, C.W., arXiV:1802.09122
M. Carena, I. Low, N. Shah, X. Wang, C.W., to appear

ΔM_W : Two Higgs Doublet Model Contribution

Higgs Basis : $< H_1^0 >= \frac{v}{\sqrt{2}}, \quad < H_2 >= 0$

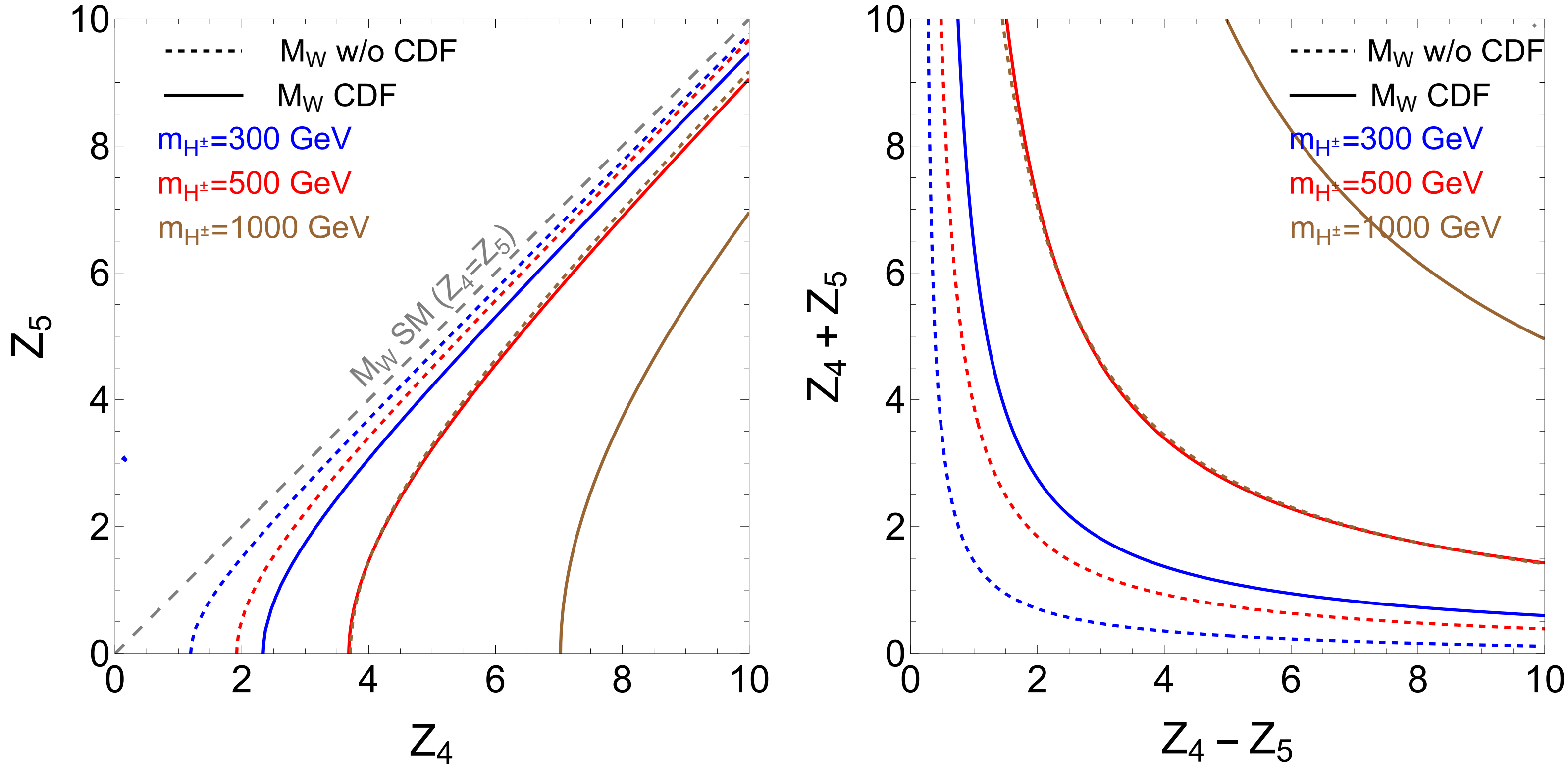
Haber, Gunion hep-ph/0207010
Haber'93, D. O Neil, arXiv : 0908.1363

Higgs Contribution : In the alignment limit, $|Z_6| \ll 1 \qquad M_h^2 = Z_1 v^2$

$$M_H^2 = M_A^2 + Z_5 v^2 = M_{H^\pm}^2 + \frac{1}{2}(Z_5 + Z_4) v^2$$

$$\frac{\Delta M_W^2}{M_W^2} \simeq 1 \times 10^{-4} \left[5\left(Z_4^2 - Z_5^2\right) - Z_4\right] \frac{v^2}{M^2}.$$

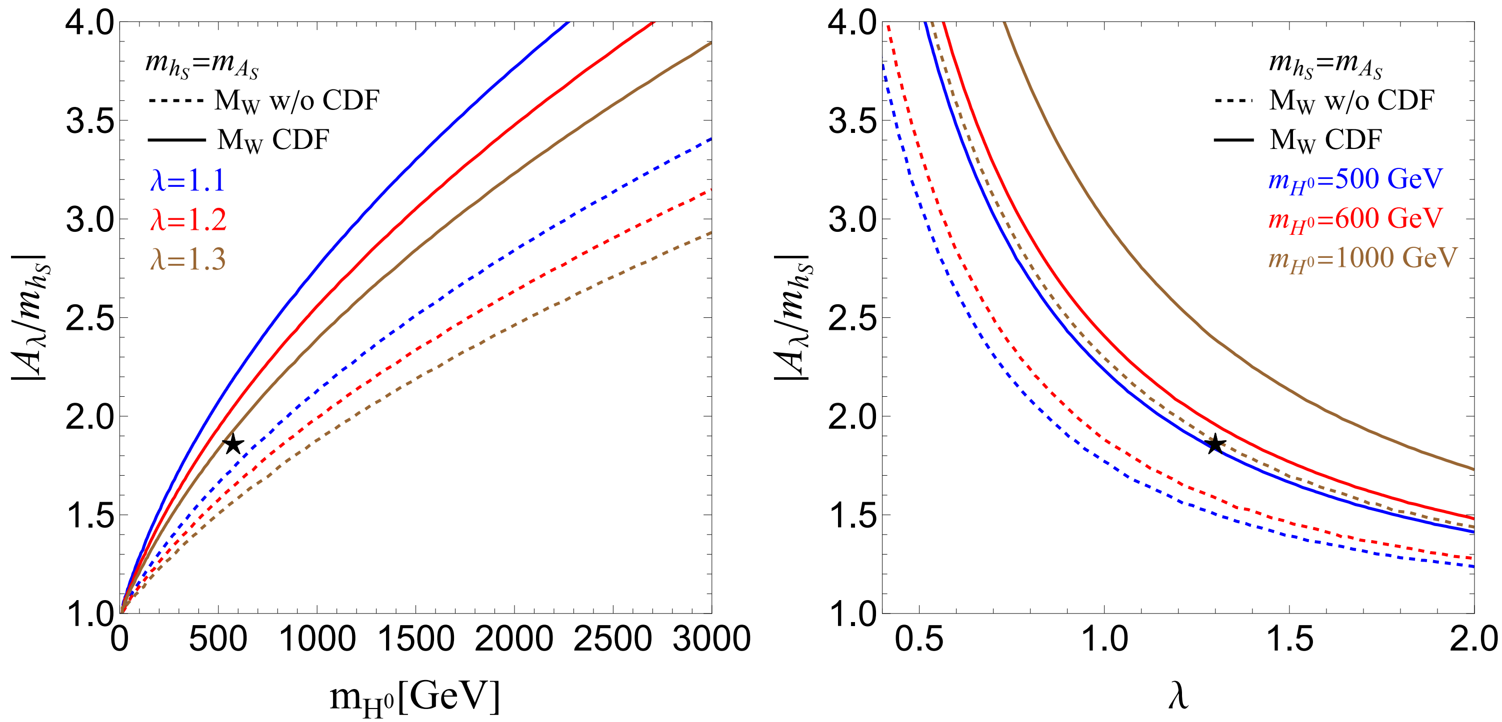
M. Carena, N. Shah, I. Low, X. Wang, C.W.'22 (to appear)
Two loop corrections : Bahl, Braathen, Weiglein ' 22



Sizable values of the quartic couplings are generally demanded.

$$\Delta M_W \sim 5\ \lambda^4\ \left(\frac{500\ \text{GeV}}{m_H}\right)^4 \left(1 - \frac{A_\lambda^2}{m_{h_S}^2}\right)\left(1 - \frac{A_\lambda^2}{m_{A_s}^2}\right)\ \text{MeV}.$$

M. Carena, I. Low, N. Shah, X. Wang, C.W.'22, to appear



At large values of tanβ, and λ = 0.65, alignment implies, approximately

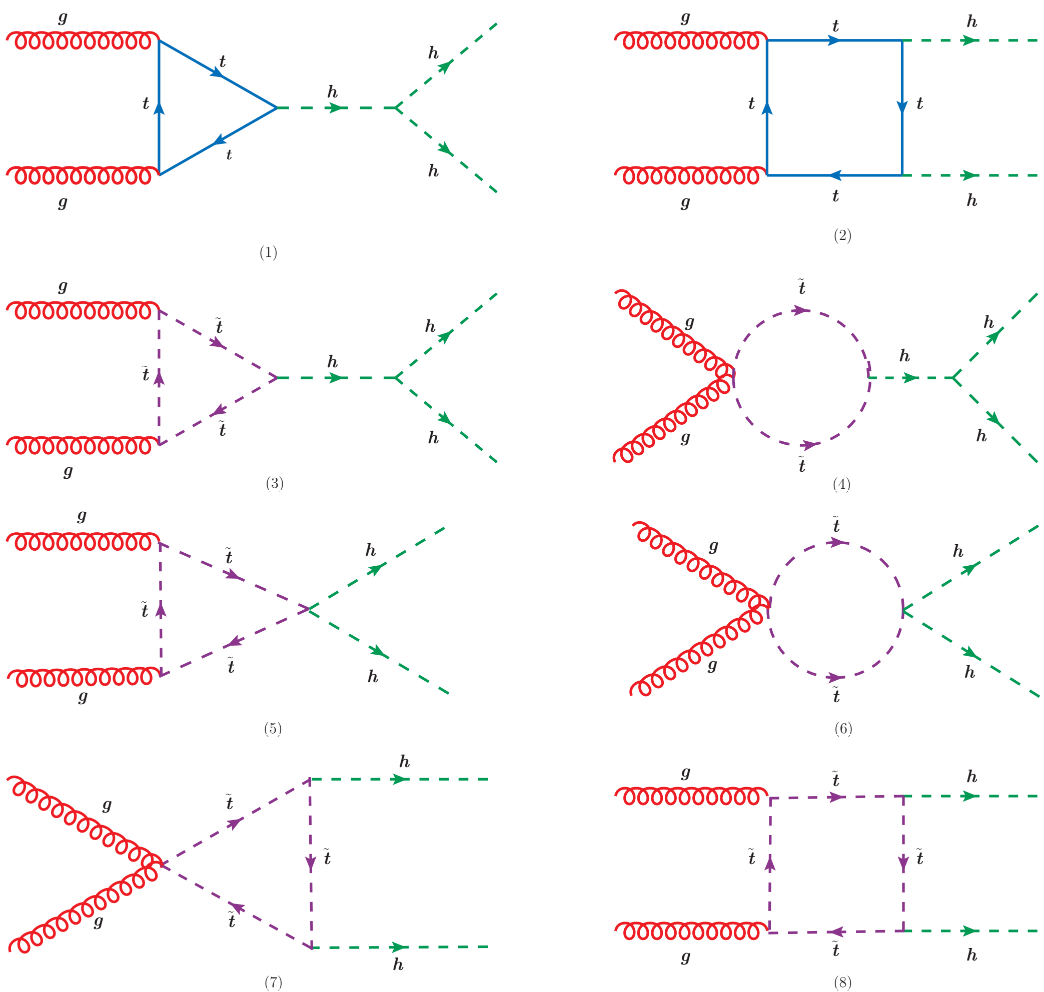
$$A_\lambda \simeq \mu \tan\beta$$

Large contributions are possible, but demand either a sizable value of λ, breaking perturbative consistency below the GUT scale, or sizable values of the trilinear coupling A_λ.

Light non-standard Higgs bosons, below a scale of about a TeV, are preferred

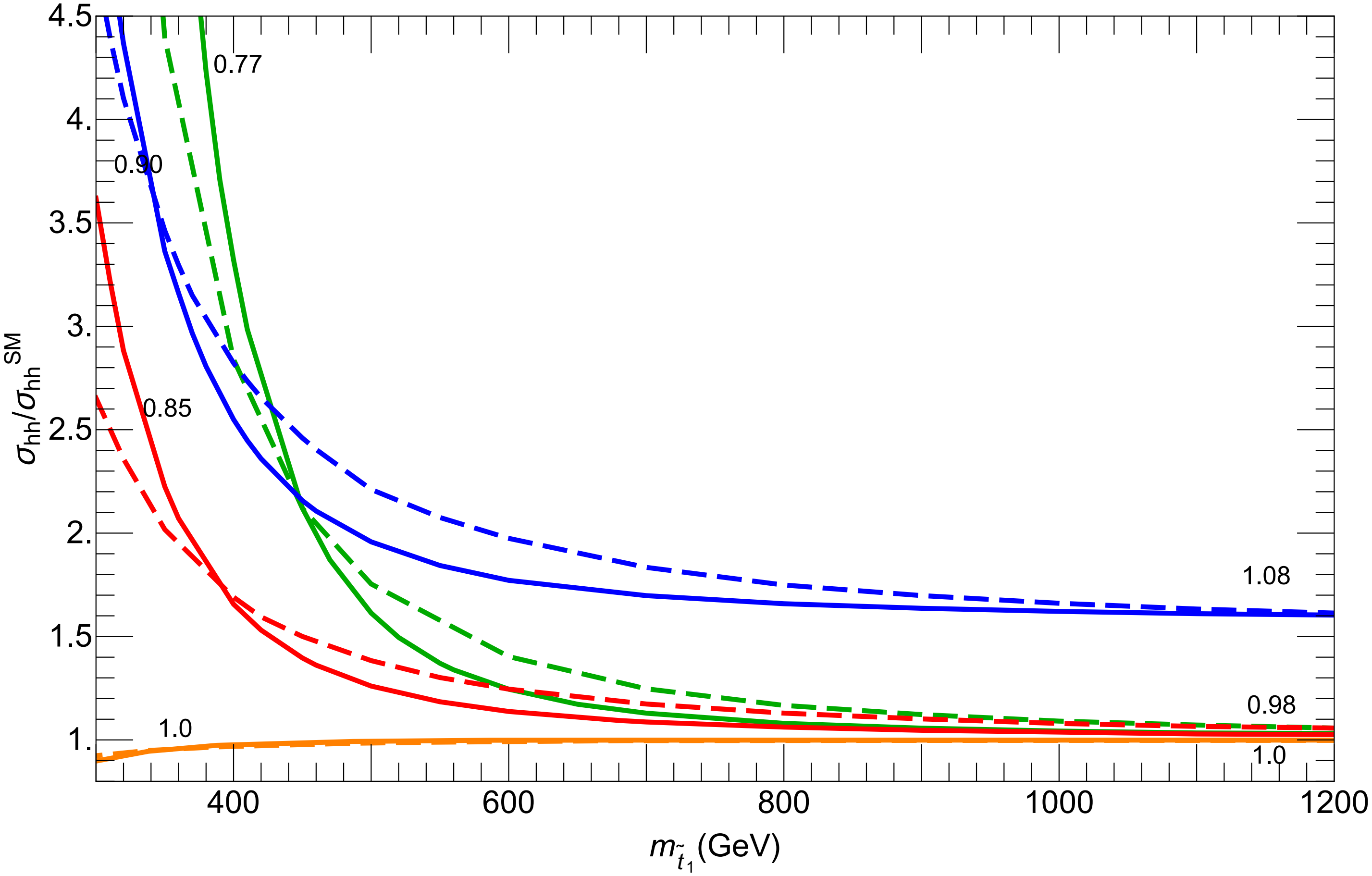
Huang, Joglekar, Li, C.W.'17

Stop Contributions



Stop Effects on Di-Higgs Production Cross Section

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



Orange : Stop corrections to kappa_g decoupled
Red : X_t fixed at color breaking vacuum boundary value, for light mA
Green : X_t fixed at color breaking boundary value, for mA = 1.5 TeV
Blue : Same as Red, but considering \kappa_t = 1.1