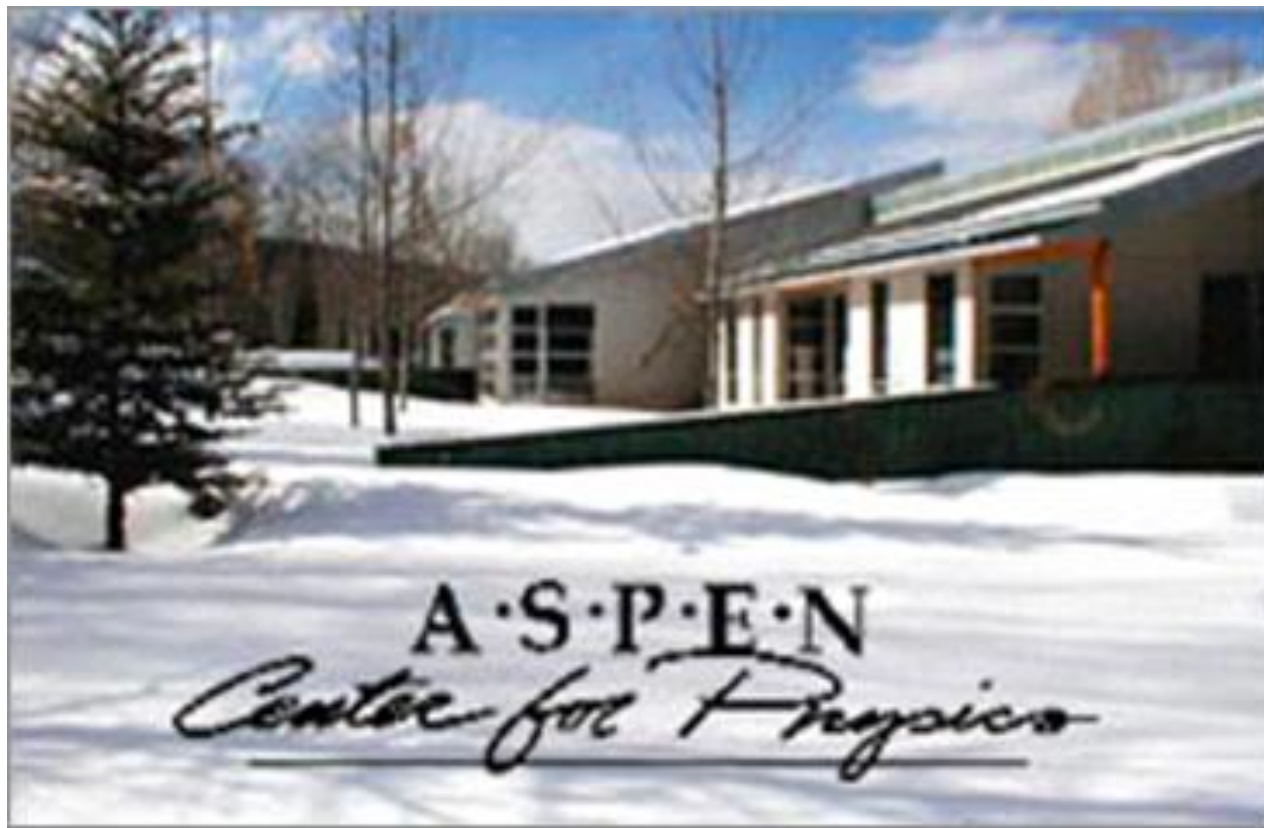


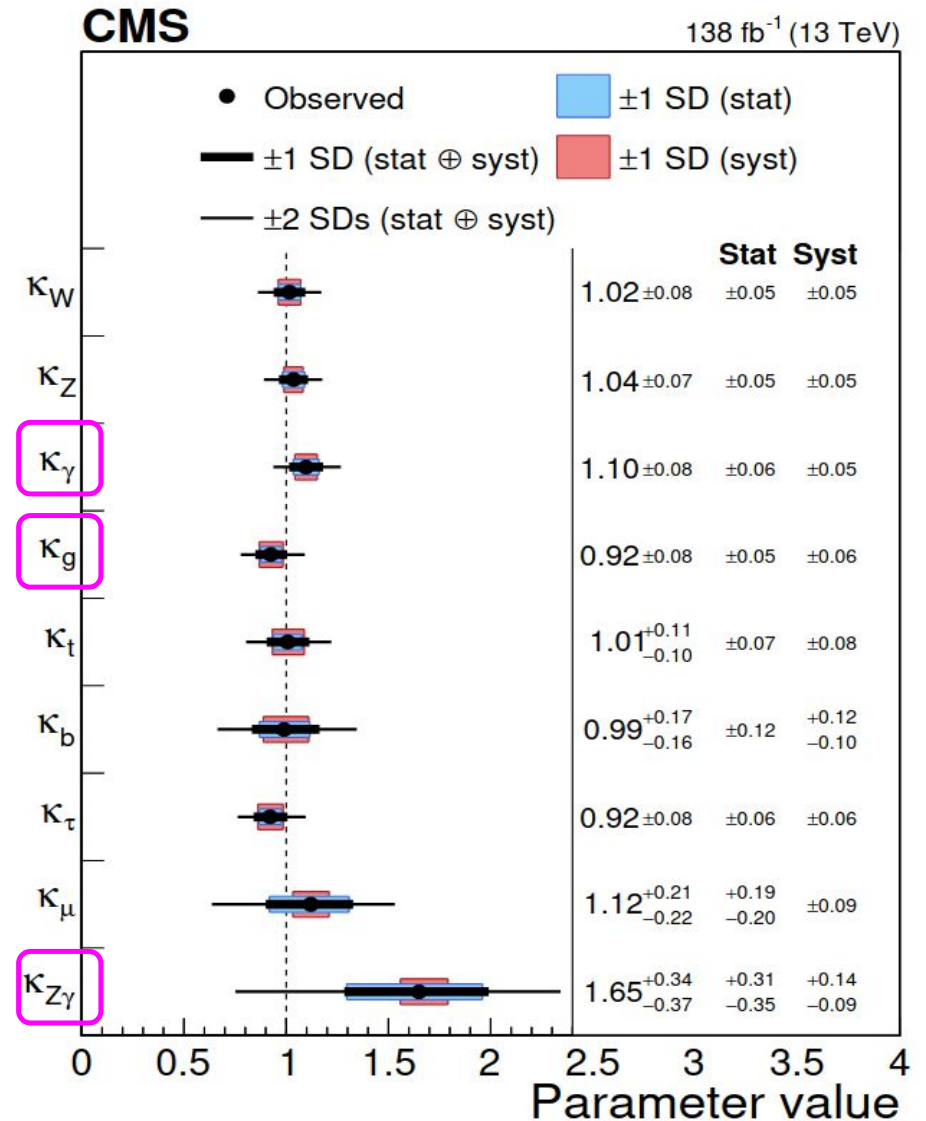
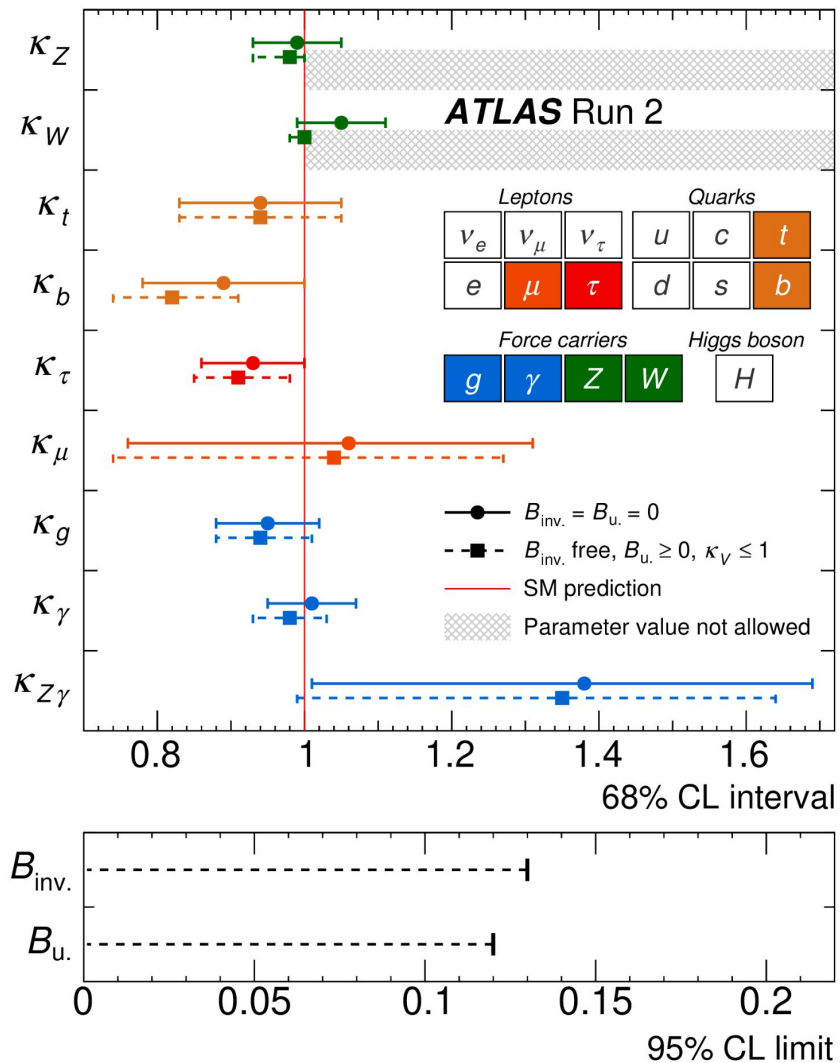
Higgs Coupling Measurements and Extended Higgs Sectors



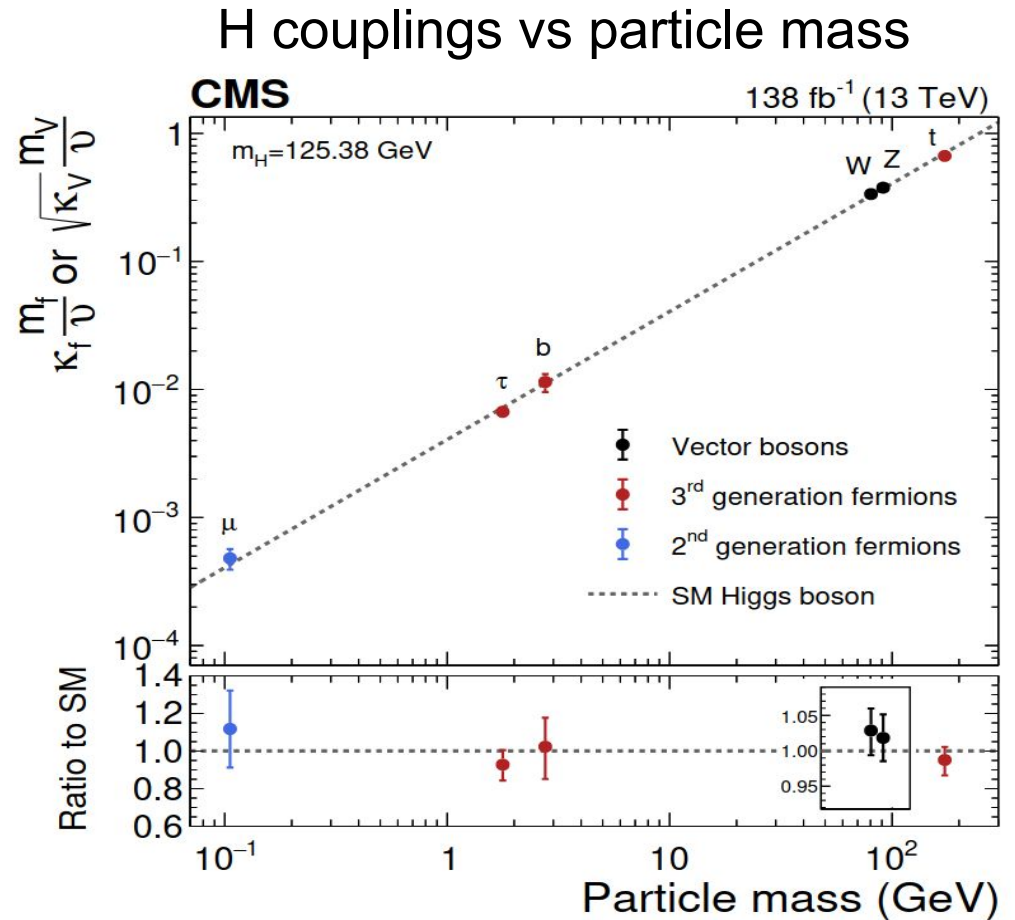
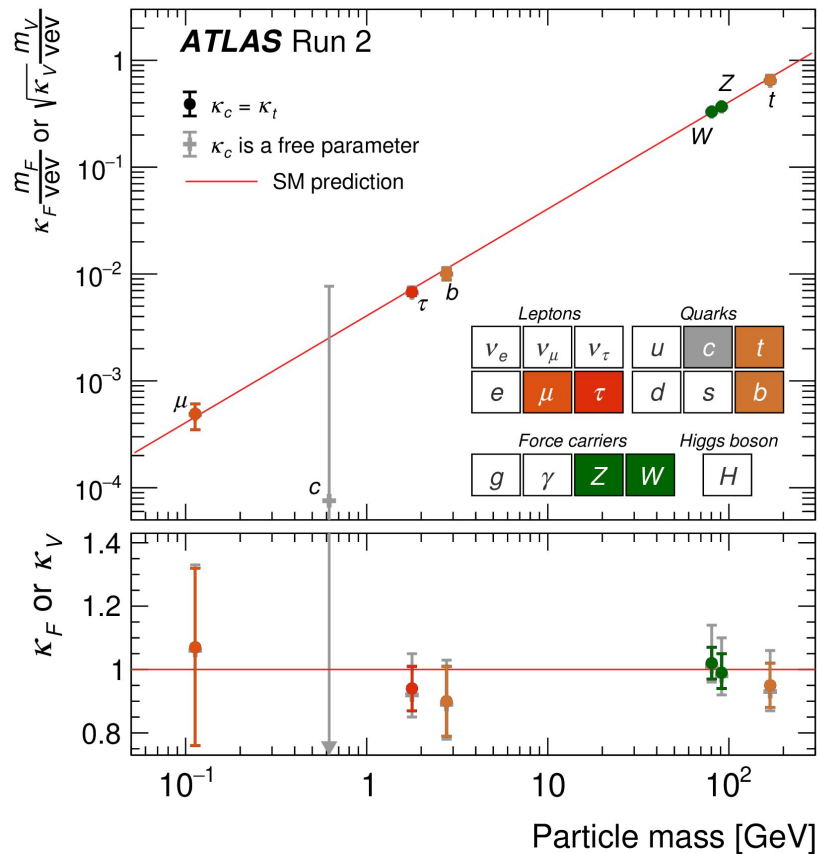
Carlos E.M. Wagner
Phys. Dept., EFI and KICP, Univ. of Chicago
HEP Division, Argonne National Lab.

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



$$g_{hf\bar{f}} = \frac{m_f}{v}, \quad g_{hVV} = \frac{m_V^2}{v}$$

All these coupling that are constrained at the 10 percent level, will be constrained at the few percent level at the end of the LHC era

Why we should not be surprised

- There is a well known, 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.

$$\mathcal{L} = -m_\phi^2 \phi^\dagger \phi + (M_\Psi \bar{\Psi} \Psi)$$

- The Appelquist-Carrazzone 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

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

- Obviously decoupling doesn't occur if the masses are proportional to the v.e.v.
- These properties are behind the EFT 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

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

- 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 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

$$m_\nu = \frac{m_D^2}{M} \equiv \frac{y^2 v^2}{M} \quad \text{Slowest decoupling, dimension 5 operator}$$

- Corrections to the Higgs mass

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

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

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

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

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

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

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

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

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

$$\lambda_6 = \lambda_7 = 0$$

- However, in a complete theory these couplings could be generated at the loop level, and it is interesting to consider the general case.

Higgs Basis

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

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

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

$$H_1 = \left(\frac{1}{\sqrt{2}}(v + \phi_1^0 + iG^0) \right), \quad H_2 = \left(\frac{1}{\sqrt{2}}(H^+ + i\phi_2^0) \right)$$

- 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.

Mass Matrix in the Higgs Basis

- The neutral Higgs mass matrix takes a particularly simple form in the Higgs basis (Z_i are the quartic couplings)

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

- 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

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

- 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.

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

$$m_h^2 = Z_1 v^2, \quad m_h = 125 \text{ GeV}$$

Theoretical Constraints

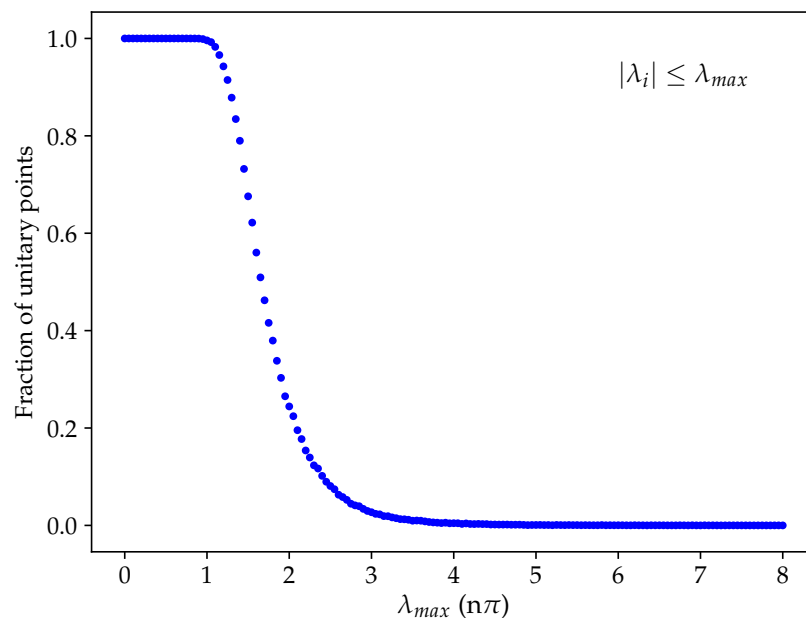
- Theoretical constraints can be set on the general 2HDM, based on perturbative unitarity, boundedness from below as well as stability of the Higgs vacuum.
- We recently performed such a study, trying to obtain analytical expressions.

H. Bahl, M. Carena, N. Coyle, A. Ireland, C.W. , arXiv:2210.00024, JHEP03 (2023) 165

- Just as an example, some necessary conditions for boundedness from below and unitarity are

$$\begin{aligned} \sqrt{\lambda_1 \lambda_2} + \lambda_3 + \lambda_4 + \lambda_5^R - 2 \left| \tilde{\lambda}_6^R + \tilde{\lambda}_7^R \right| &> 0, \\ \sqrt{\lambda_1 \lambda_2} + \lambda_3 + \lambda_4 - \lambda_5^R - 2 \left| \tilde{\lambda}_6^I + \tilde{\lambda}_7^I \right| &> 0, \\ \sqrt{\lambda_1 \lambda_2} + \lambda_3 + \lambda_4 + \lambda_5^I - \sqrt{2} \left| (\tilde{\lambda}_6^R + \tilde{\lambda}_7^R) + (\tilde{\lambda}_6^I + \tilde{\lambda}_7^I) \right| &> 0, \\ \sqrt{\lambda_1 \lambda_2} + \lambda_3 + \lambda_4 - \lambda_5^I - \sqrt{2} \left| (\tilde{\lambda}_6^R + \tilde{\lambda}_7^R) - (\tilde{\lambda}_6^I + \tilde{\lambda}_7^I) \right| &> 0. \end{aligned}$$

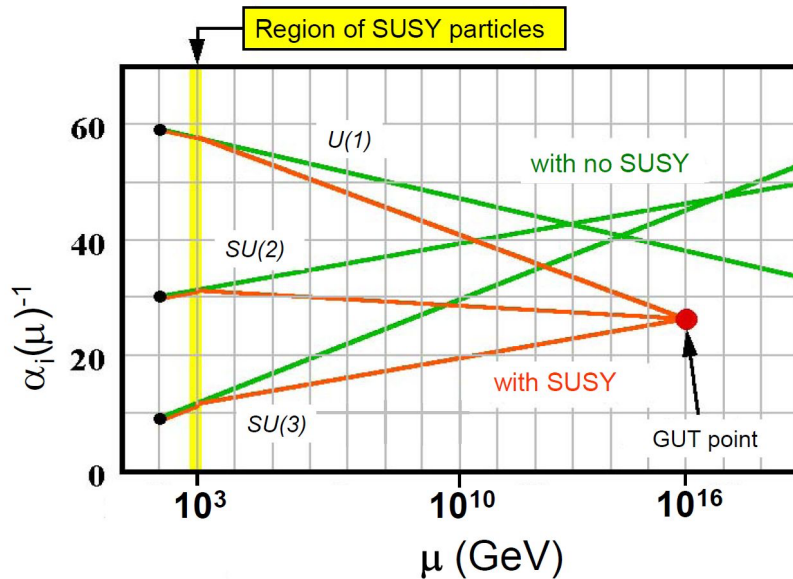
$$\begin{aligned} 64\pi^2 + (\lambda_3 - 16\pi)\lambda_3 + (4(\lambda_3 + \lambda_4) - 32\pi)\lambda_4 - 9|\lambda_5|^2 &> 0 \\ 64\pi^2 - 8\pi(\lambda_3 + 3\lambda_2 + 2\lambda_4) + 3\lambda_3\lambda_2 + 6\lambda_2\lambda_4 - 9|\lambda_7|^2 &> 0 \end{aligned}$$



- The plot shows how bad is your perturbative constraint, in general, if you just demand that all the couplings to be below a certain bound and you let the couplings to vary randomly

A well motivated example : Supersymmetry

Unification



SUSY Algebra

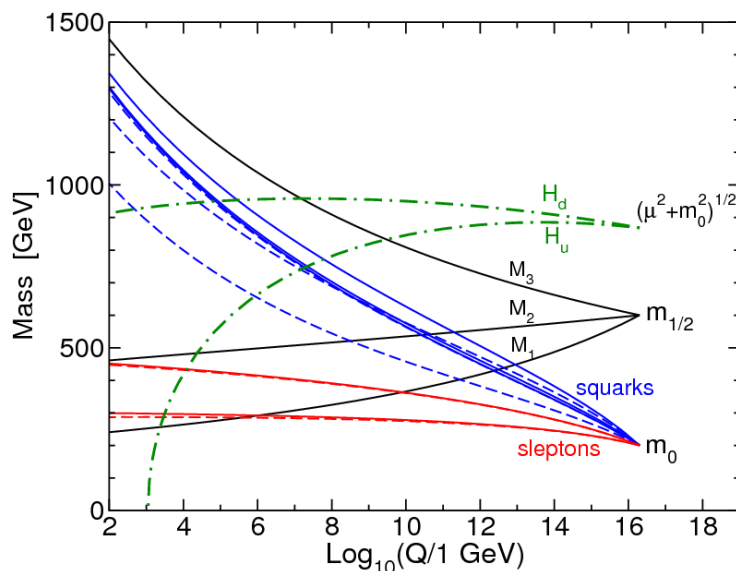
$$\{Q_\alpha, \bar{Q}_{\dot{\alpha}}\} = 2\sigma^\mu_{\alpha\dot{\alpha}} P_\mu$$

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

Quantum Gravity ?

Ultraviolet Insensitivity

Electroweak Symmetry Breaking



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

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

M_h depends logarithmically on the averaged stop mass scale M_{SUSY} and has a quadratic and quartic dep. on the stop mixing parameter X_t . [and on sbottom/stau sectors for large $\tan \beta$]

For moderate to large values of $\tan \beta$ and large non-standard Higgs masses

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

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

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

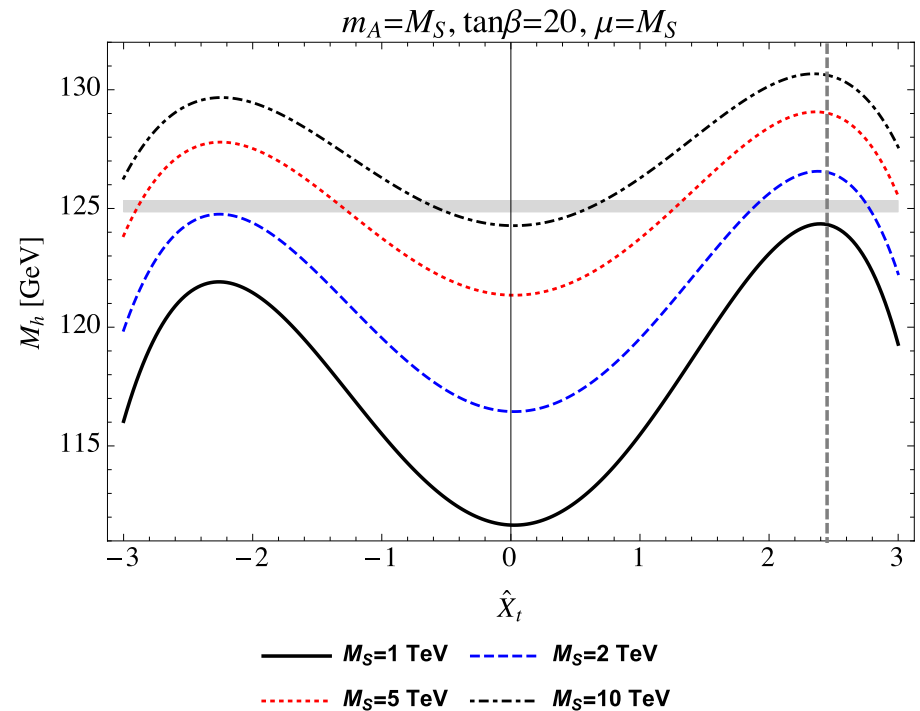
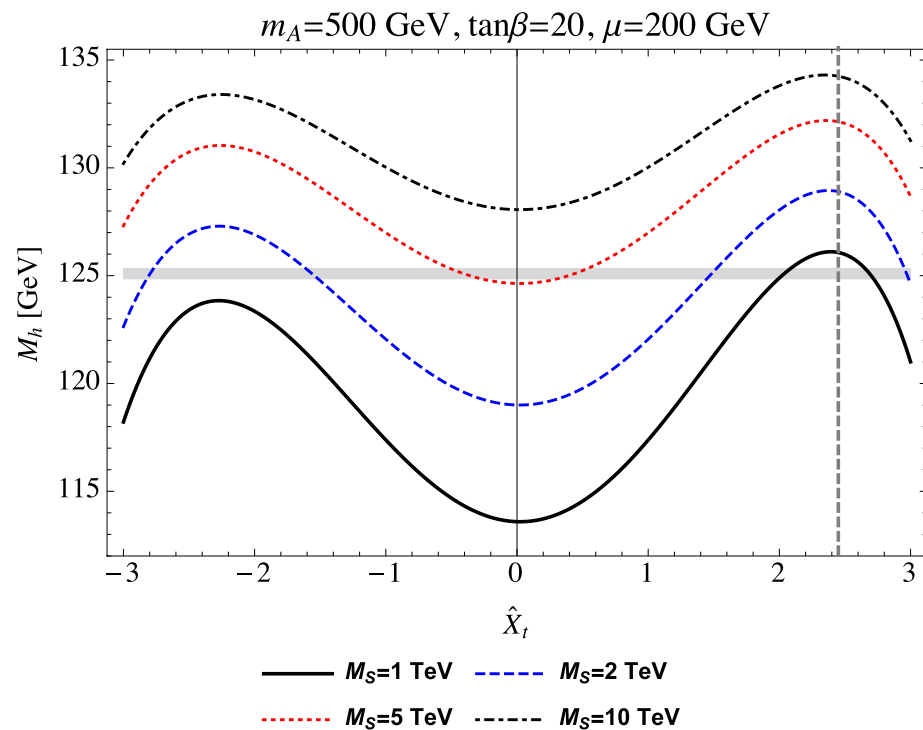
Analytic expression valid for $M_{\text{SUSY}} \sim m_Q \sim m_U$

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

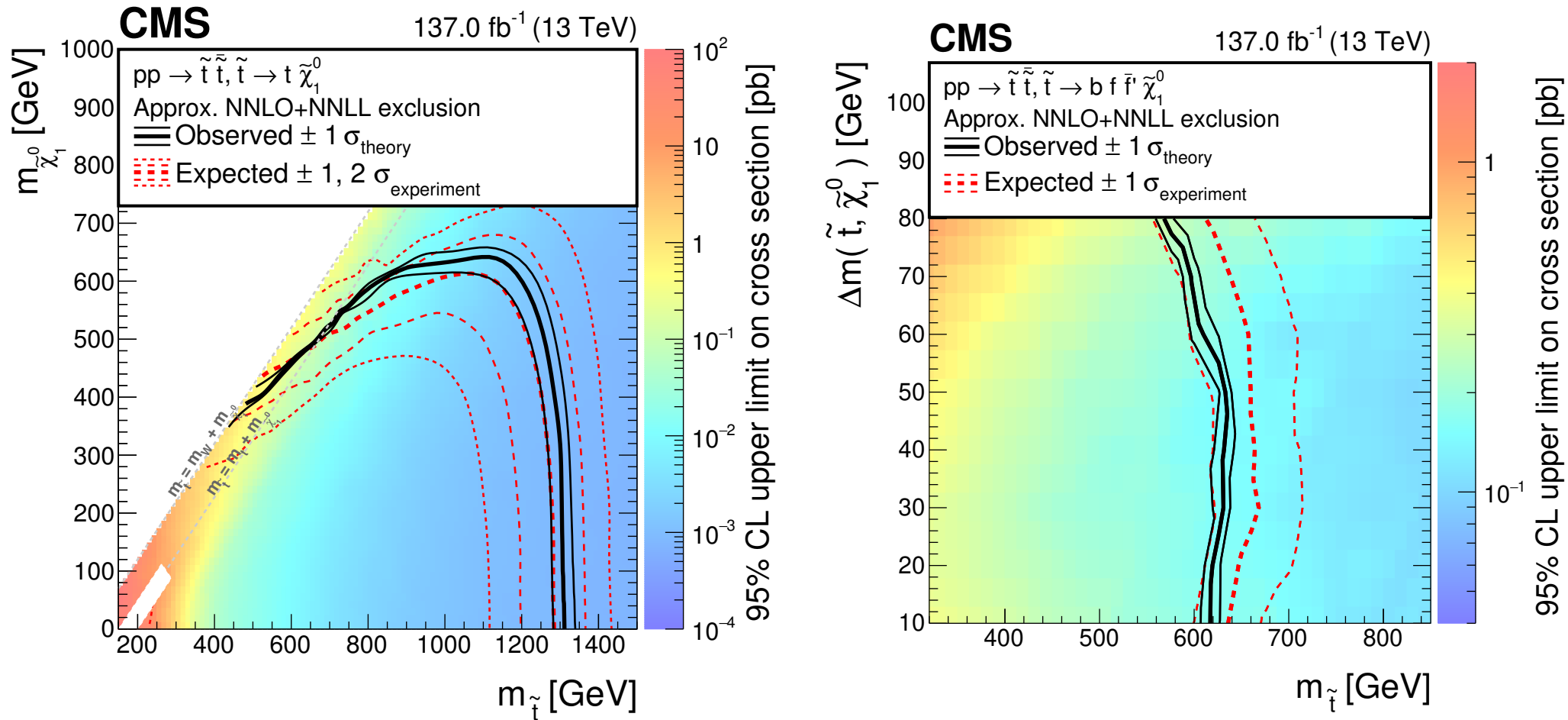
G. Lee, C.W. arXiv:1508.00576



Necessary stop masses increase for lower values of $\tan\beta$, 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

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

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

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

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

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

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

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

$$X_t = \frac{2A_t^2}{M_{\text{SUSY}}^2} \left(1 - \frac{A_t^2}{12M_{\text{SUSY}}^2}\right)$$

$$X_b = \frac{2A_b^2}{M_{\text{SUSY}}^2} \left(1 - \frac{A_b^2}{12M_{\text{SUSY}}^2}\right)$$

$$A_{tb} = \frac{1}{6} \left[-\frac{6\mu^2}{M_{\text{SUSY}}^2} - \frac{(\mu^2 - A_b A_t)^2}{M_{\text{SUSY}}^4} + \frac{3(A_t + A_b)^2}{M_{\text{SUSY}}^2} \right].$$

$$h_t = m_t(M_t)/(v \sin \beta)$$

$$h_b = m_b(M_t)/(v \cos \beta)$$

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

Relation between couplings

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

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

$$\begin{aligned} \lambda_1 &= Z_1 c_\beta^4 + Z_2 s_\beta^4 + \frac{1}{2} Z_{345} s_{2\beta}^2 - 2s_{2\beta} \left(\text{Re}[Z_6 e^{i\delta}] c_\beta^2 + \text{Re}[Z_7 e^{i\delta}] s_\beta^2 \right), \\ \lambda_2 &= Z_1 s_\beta^4 + Z_2 c_\beta^4 + \frac{1}{2} Z_{345} s_{2\beta}^2 + 2s_{2\beta} \left(\text{Re}[Z_6 e^{i\delta}] s_\beta^2 + \text{Re}[Z_7 e^{i\delta}] c_\beta^2 \right), \\ \lambda_3 &= \frac{1}{4} (Z_1 + Z_2 - 2Z_{345}) s_{2\beta}^2 + Z_3 + \text{Re}[(Z_6 - Z_7) e^{i\delta}] s_{2\beta} c_{2\beta}, \\ \lambda_4 &= \frac{1}{4} (Z_1 + Z_2 - 2Z_{345}) s_{2\beta}^2 + Z_4 + \text{Re}[(Z_6 - Z_7) e^{i\delta}] s_{2\beta} c_{2\beta}, \\ \lambda_5 e^{2i\delta} &= \frac{1}{4} (Z_1 + Z_2 - 2Z_{345}) s_{2\beta}^2 + \text{Re}[Z_5 e^{2i\delta}] + i \text{Im}[Z_5 e^{2i\delta}] c_{2\beta} \\ &\quad + \text{Re}[(Z_6 - Z_7) e^{i\delta}] s_{2\beta} c_{2\beta} + i \text{Im}[(Z_6 - Z_7) e^{i\delta}] s_{2\beta}, \\ \lambda_6 e^{i\delta} &= \frac{1}{2} (Z_1 c_\beta^2 - Z_2 s_\beta^2 - Z_{345} c_{2\beta} - i \text{Im}[Z_5 e^{2i\delta}]) s_{2\beta} \\ &\quad + \text{Re}[Z_6 e^{i\delta}] c_\beta c_{3\beta} + i \text{Im}[Z_6 e^{i\delta}] c_\beta^2 + \text{Re}[Z_7 e^{i\delta}] s_\beta s_{3\beta} + i \text{Im}[Z_7 e^{i\delta}] s_\beta^2, \\ \lambda_7 e^{i\delta} &= \frac{1}{2} (Z_1 s_\beta^2 - Z_2 c_\beta^2 + Z_{345} c_{2\beta} + i \text{Im}[Z_5 e^{2i\delta}]) s_{2\beta} \\ &\quad + \text{Re}[Z_6 e^{i\delta}] s_\beta s_{3\beta} + i \text{Im}[Z_6 e^{i\delta}] s_\beta^2 + \text{Re}[Z_7 e^{i\delta}] c_\beta c_{3\beta} + i \text{Im}[Z_7 e^{i\delta}] c_\beta^2, \end{aligned}$$

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

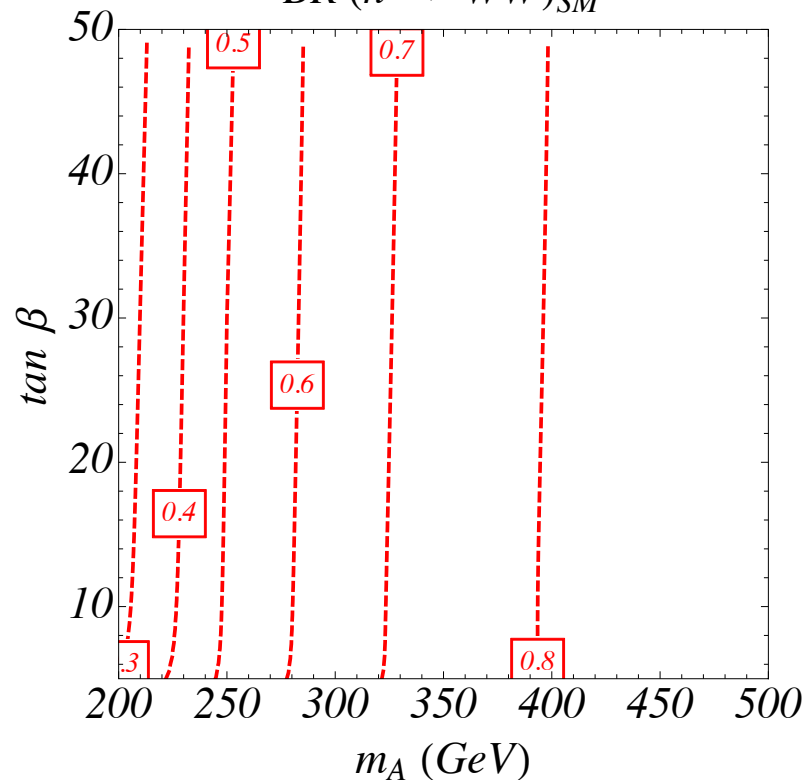
MSSM : Higgs Decay into Gauge Bosons

Mostly determined by the change of width

Decoupling

Small μ

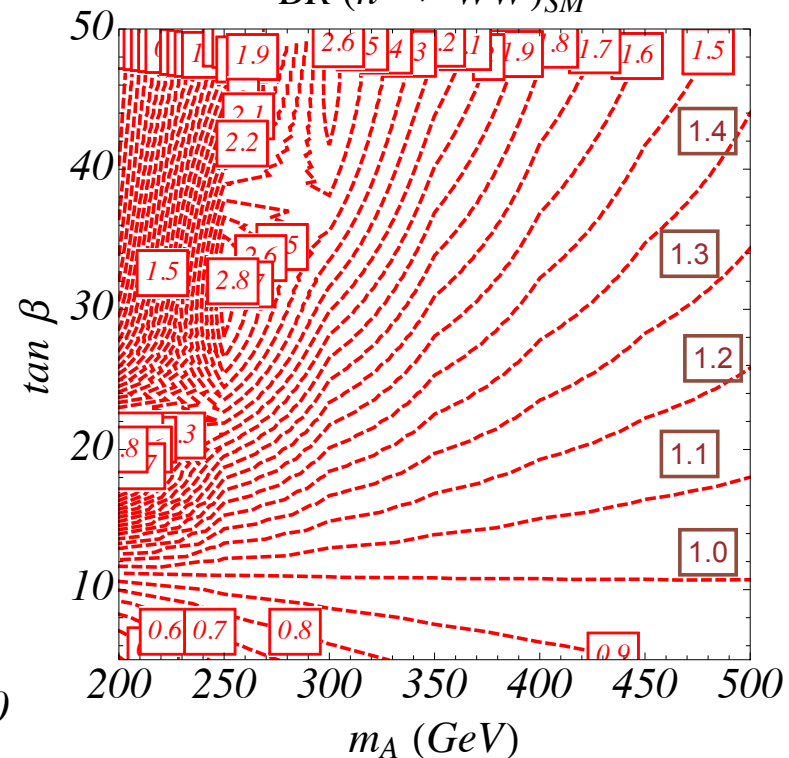
$$\frac{BR(h \rightarrow WW)}{BR(h \rightarrow WW)_{SM}}$$



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

Alignment

$$\frac{BR(h \rightarrow WW)}{BR(h \rightarrow WW)_{SM}}$$



CP-odd Higgs masses of order 200 GeV and $\tan \beta = 10$ OK in the alignment case

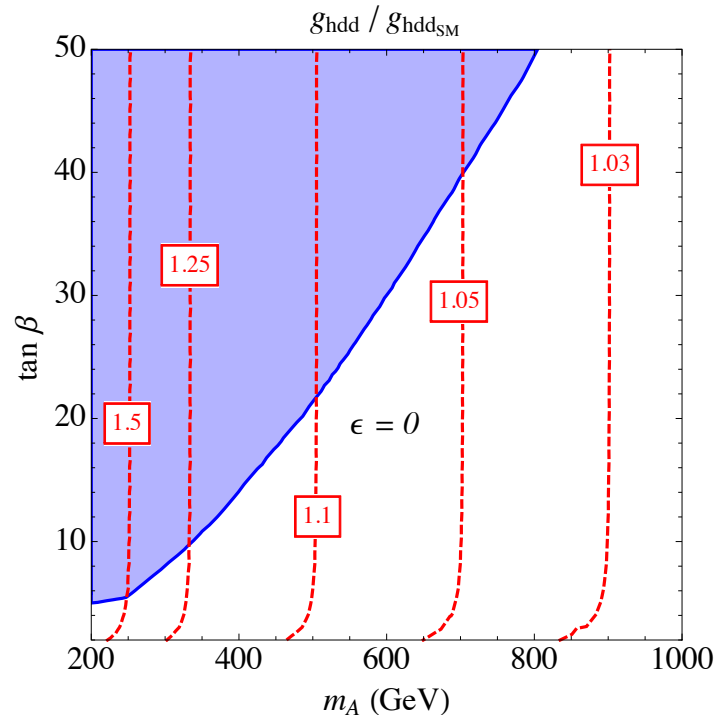
Down Couplings in the MSSM for low values of μ

Higgs Decay into bottom quarks is the dominant one

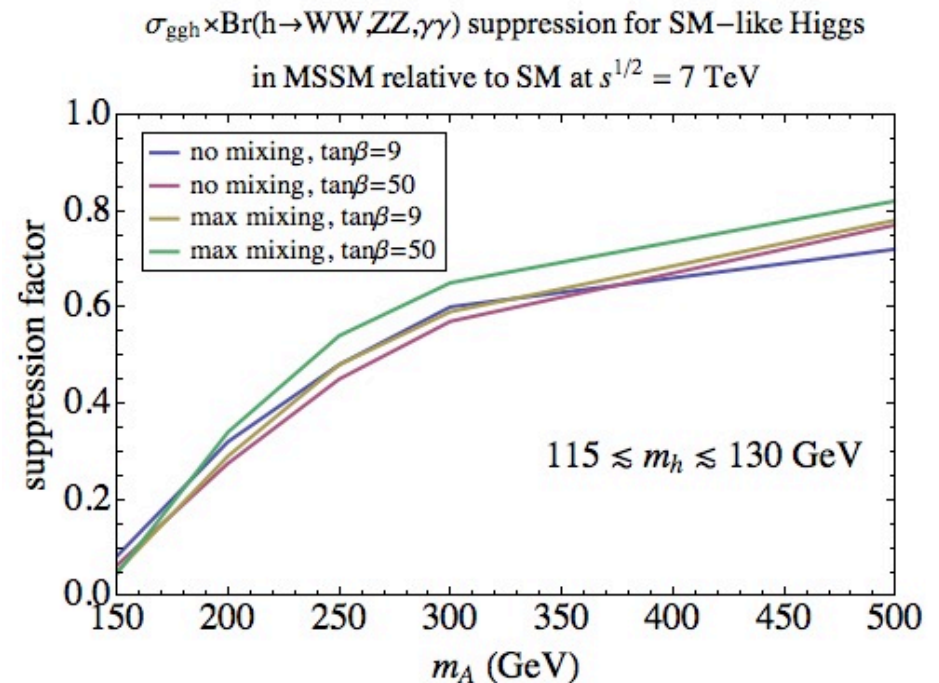
A modification of the bottom quark coupling affects all other decays

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

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



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



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

Decoupling of SUSY

- The decoupling of SUSY particles induces a breakdown of the type II coupling relations.
- Coupling of the down quarks to the Higgs H_d and of the up quarks to the Higgs H_u appear.
- This is, I believe, a general phenomenon in the case of a complete theory, beyond the bare 2HDM. These couplings are not only a perturbation, but in general, the induced couplings will not be aligned in flavor space with the tree-level coupling.
- A general expression, considering flavor violating couplings may be obtained, and is a beautiful one, that is in a sense parametrization invariant, valid for any general two Higgs doublet model, including the flavor dependence.

General expression for neutral Higgs couplings

$$\mathcal{L}_{h_1^0} = -\frac{m_i}{v} \left[\sin(\beta - \alpha) - \frac{\cos(\beta - \alpha)}{(1 + \Delta_i)} \left(\tan \beta - \frac{\Delta_i}{\tan \beta} \right) \right] h_1^0 \bar{f}_i f_i$$

$$+ \left[\left(\frac{\text{Re}(\bar{y}_2^{ij})}{\cos \beta \sqrt{2}} \cos(\beta - \alpha)(1 - \delta^{ij}) + i \frac{\text{Im}(\bar{y}_2^{ij})}{\cos \beta \sqrt{2}} \cos(\beta - \alpha) \right) h_1^0 \bar{f}_L^i f_R^j + h.c. \right]$$

$$= -\frac{m_i}{v} \left[\sin(\beta - \alpha) + \frac{\cos(\beta - \alpha)}{(1 + \tilde{\Delta}_i)} \left(\frac{1}{\tan \beta} - \tilde{\Delta}_i \tan \beta \right) \right] h_1^0 \bar{f}_i f_i$$

$$- \left[\left(\frac{\text{Re}(\bar{y}_1^{ij})}{\sin \beta \sqrt{2}} \cos(\beta - \alpha)(1 - \delta^{ij}) + i \frac{\text{Im}(\bar{y}_1^{ij})}{\sin \beta \sqrt{2}} \cos(\beta - \alpha) \right) h_1^0 \bar{f}_L^i f_R^j + h.c. \right]$$

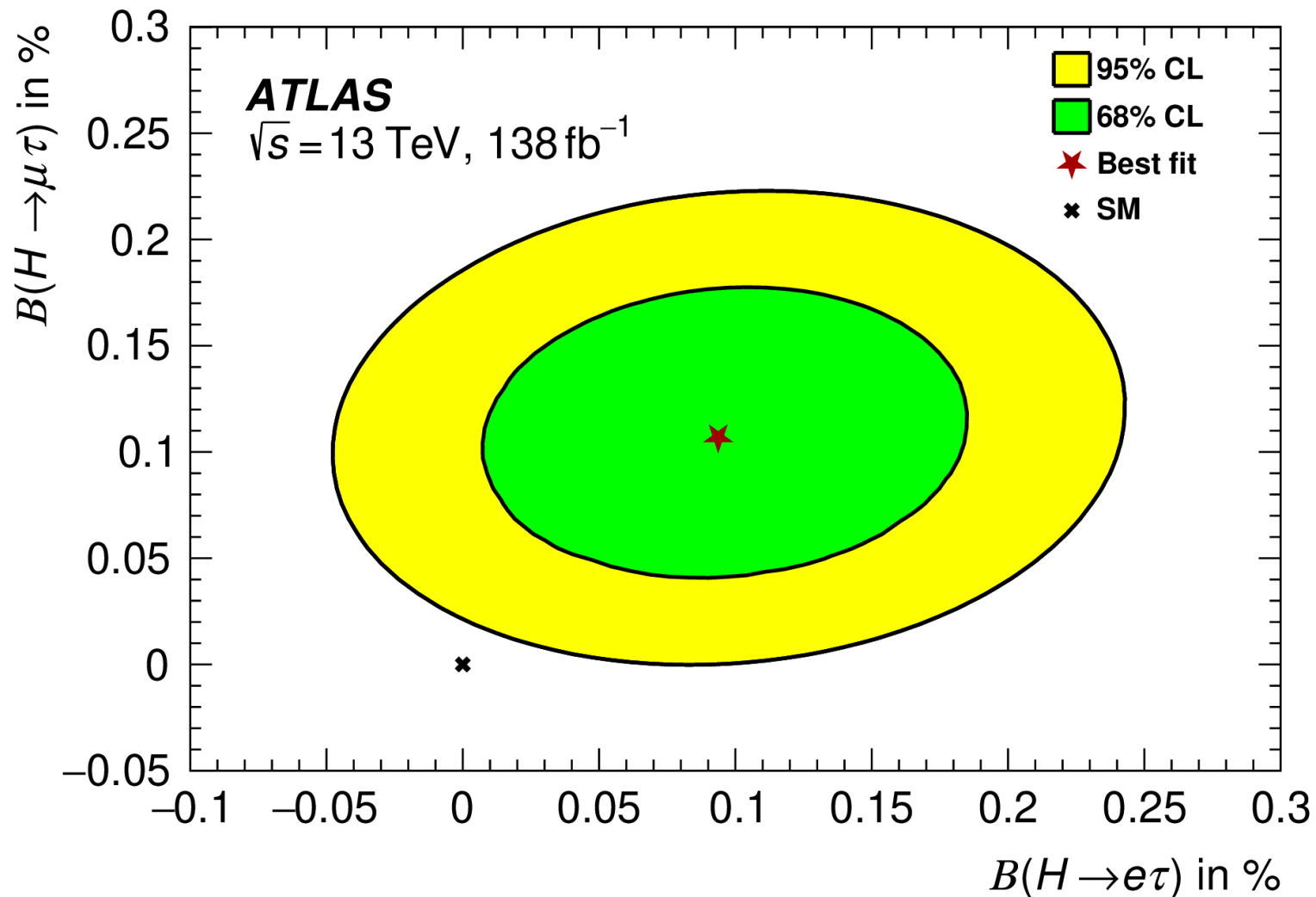
$$M_d = U_L M U_R^\dagger$$

$$\bar{y}_i = U_L y_i U_R^\dagger$$

$$\Delta_i = \frac{\text{Re}(\bar{y}_2^{ii})}{\text{Re}(\bar{y}_1^{ii})} \tan \beta$$

$$\tilde{\Delta}_i = \frac{1}{\Delta_i}$$

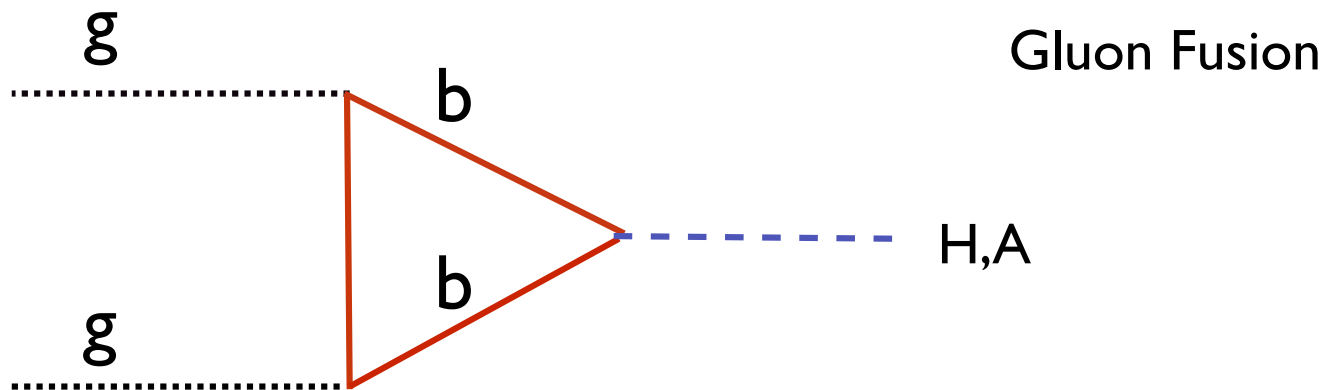
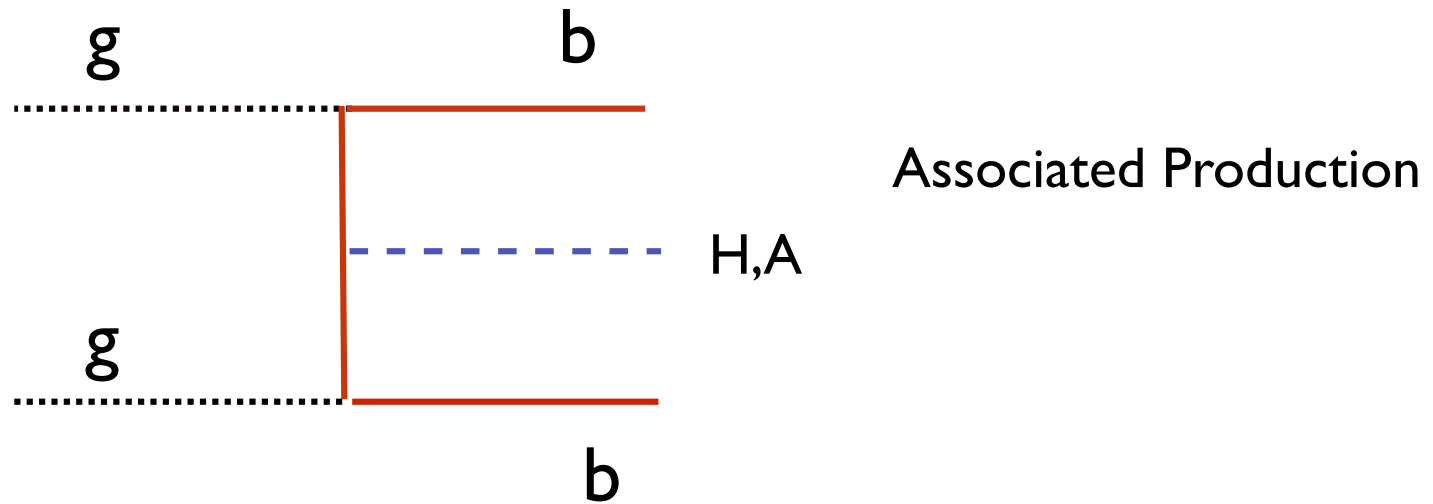
Possible flavor violation in Higgs decays



No hint from CMS, though : $BR(H \rightarrow \tau\mu, e) < 0.15\%$

Non-Standard Higgs Production

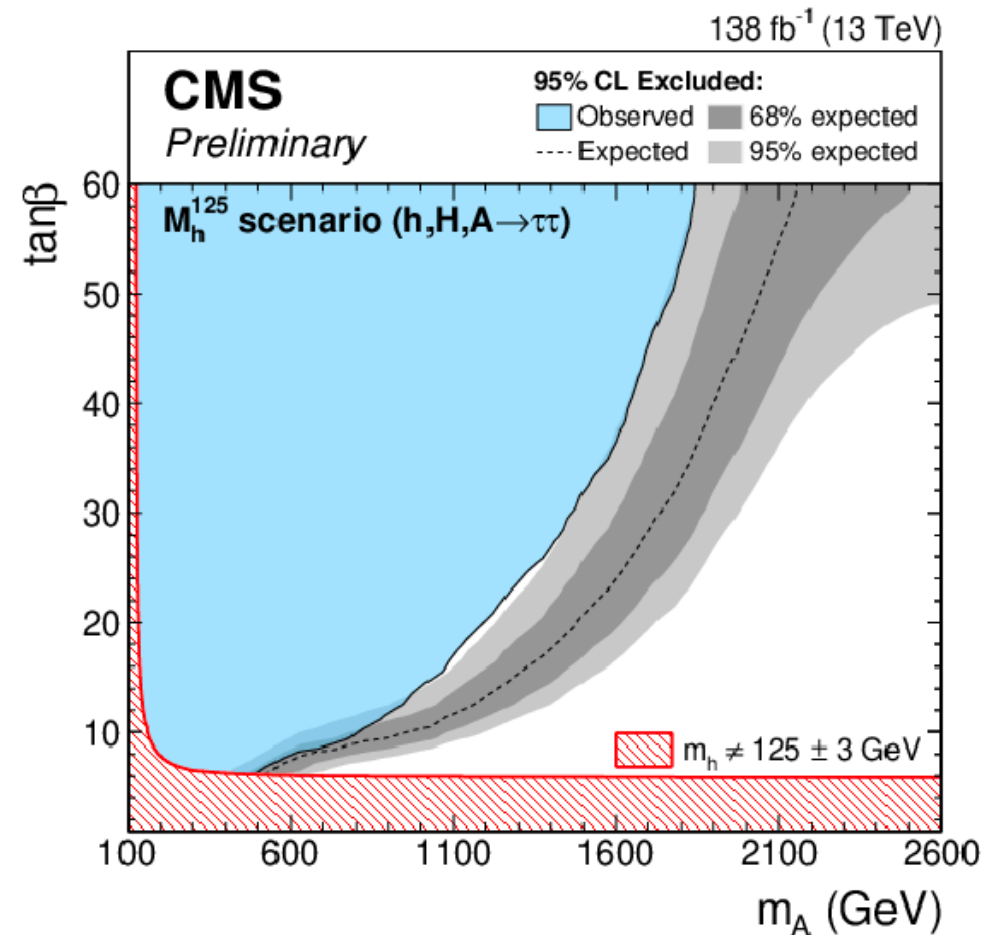
QCD: S. Dawson, C.B. Jackson, L. Reina, D. Wackeroth, hep-ph/0603112



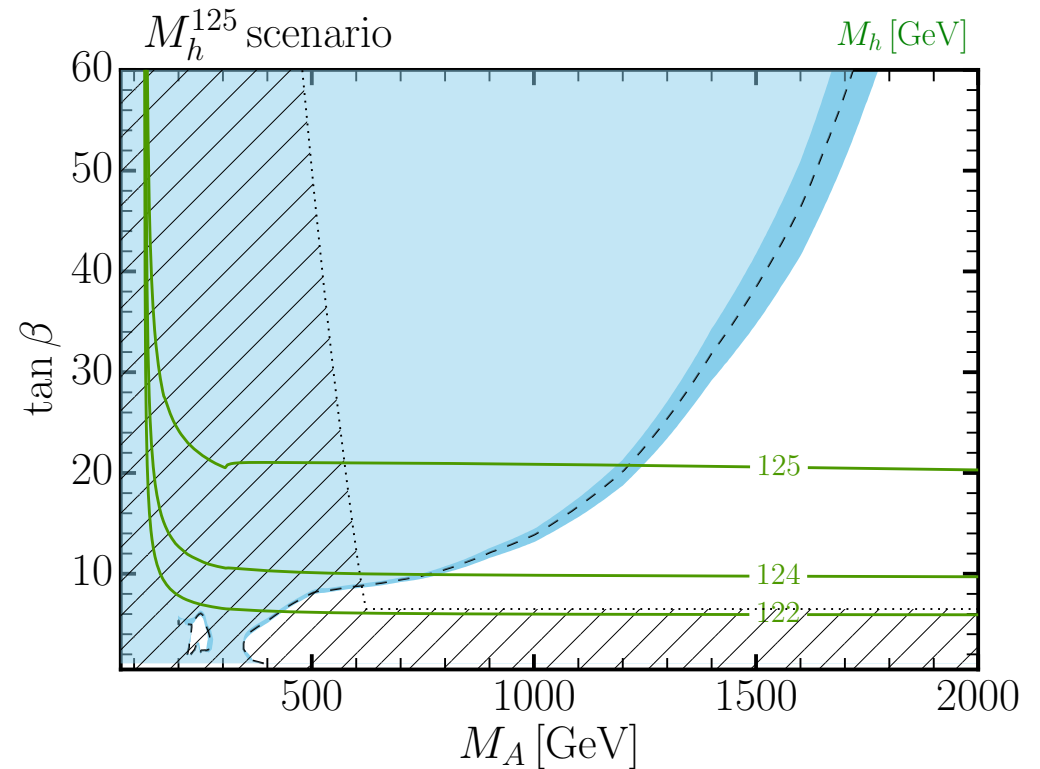
$$g_{Abb} \simeq g_{Hbb} \simeq \frac{m_b \tan \beta}{(1 + \Delta_b)v}, \quad g_{A\tau\tau} \simeq g_{H\tau\tau} \simeq \frac{m_\tau \tan \beta}{v}$$

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.

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 $\Delta\lambda_4 = \lambda^2$)

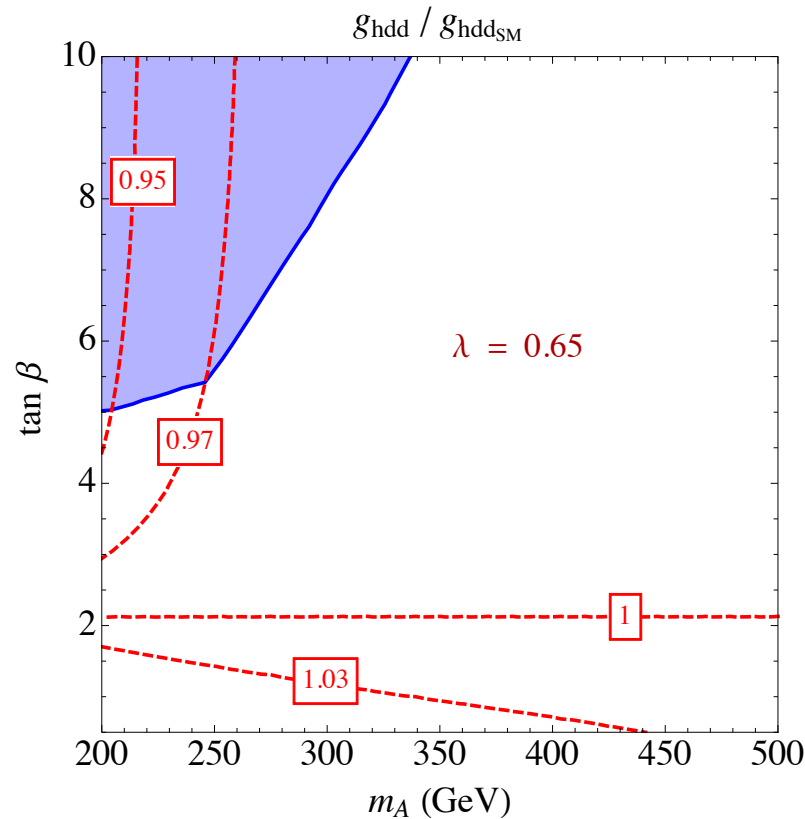
$$M_S^2(1, 2) \simeq \frac{1}{\tan \beta} (m_h^2 - M_Z^2 \cos 2\beta - \lambda^2 v^2 \sin^2 \beta + \delta_{\tilde{t}}) \equiv Z_6 v^2$$

- 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

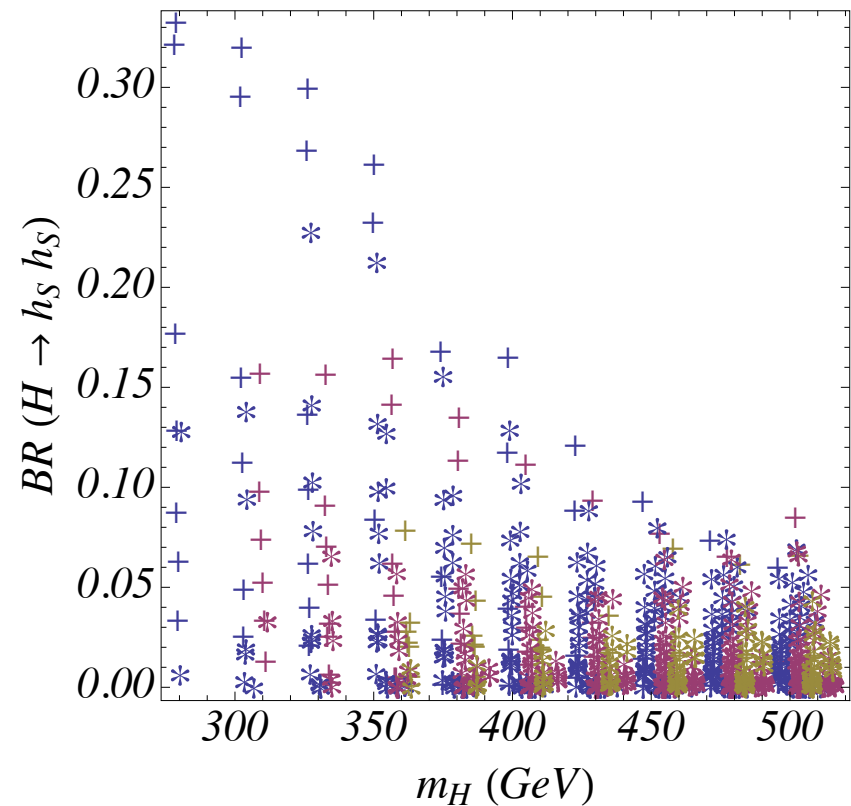
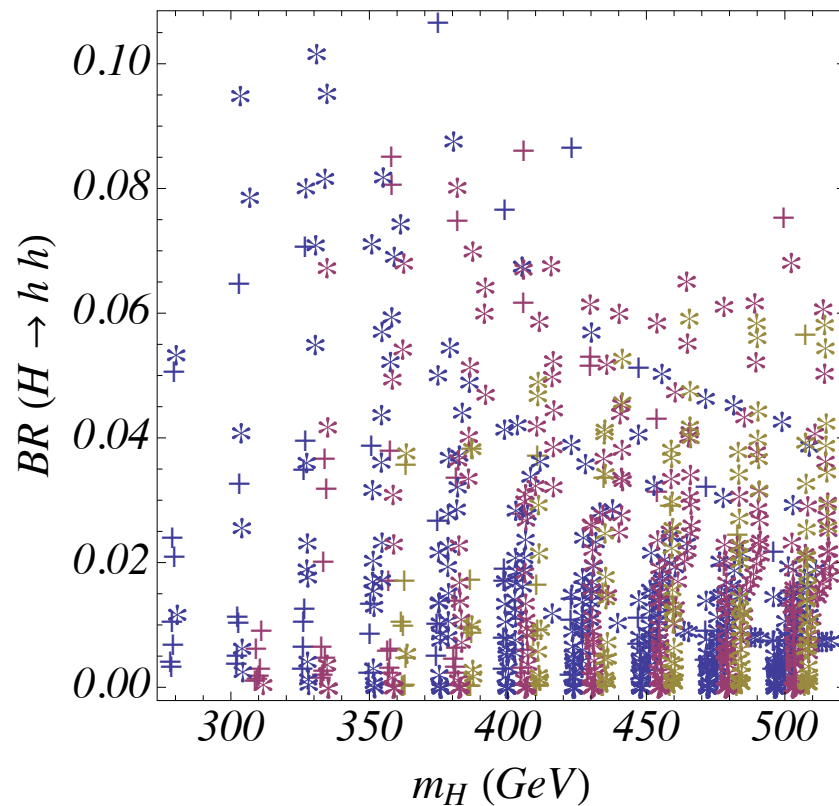
Decays into pairs of SM-like Higgs bosons suppressed by alignment

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



Crosses : H1 singlet like
Asterix : H2 singlet like

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



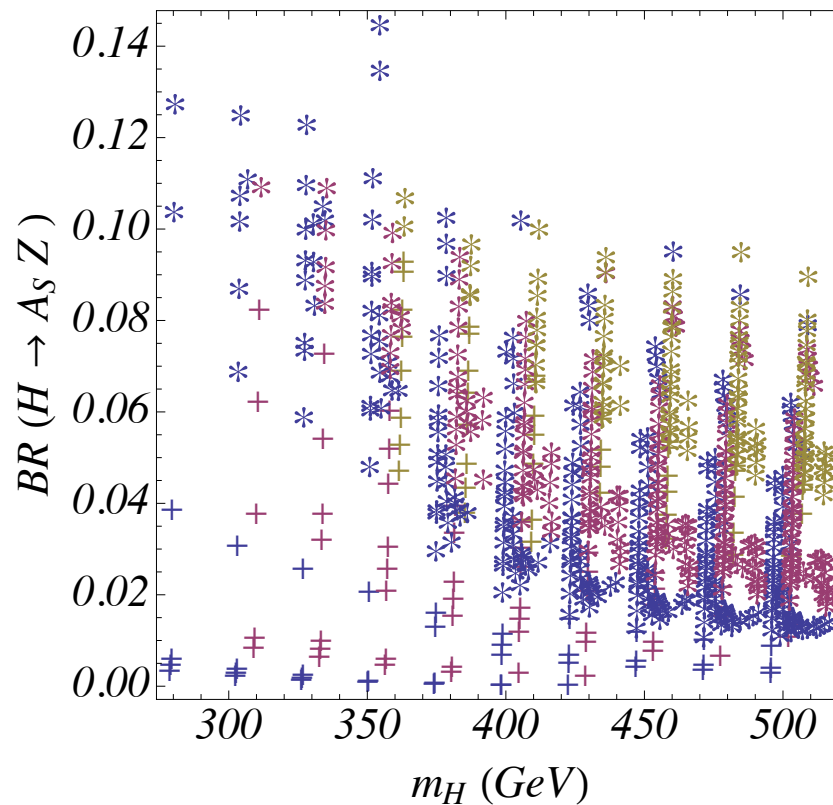
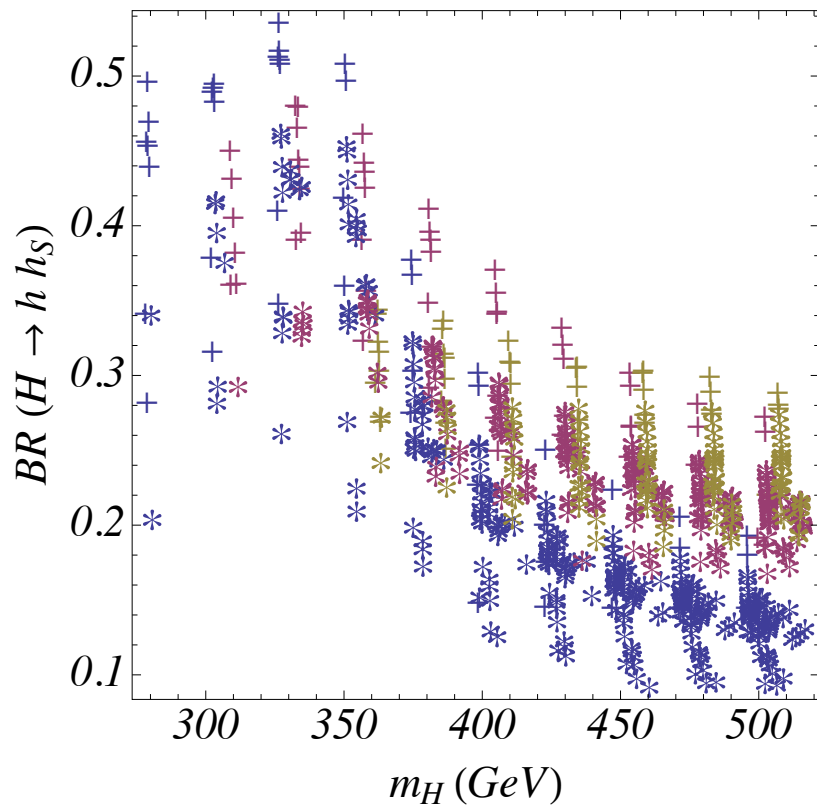
Significant decays of heavier Higgs Bosons into lighter ones and Z's

Relevant for searches for Higgs bosons

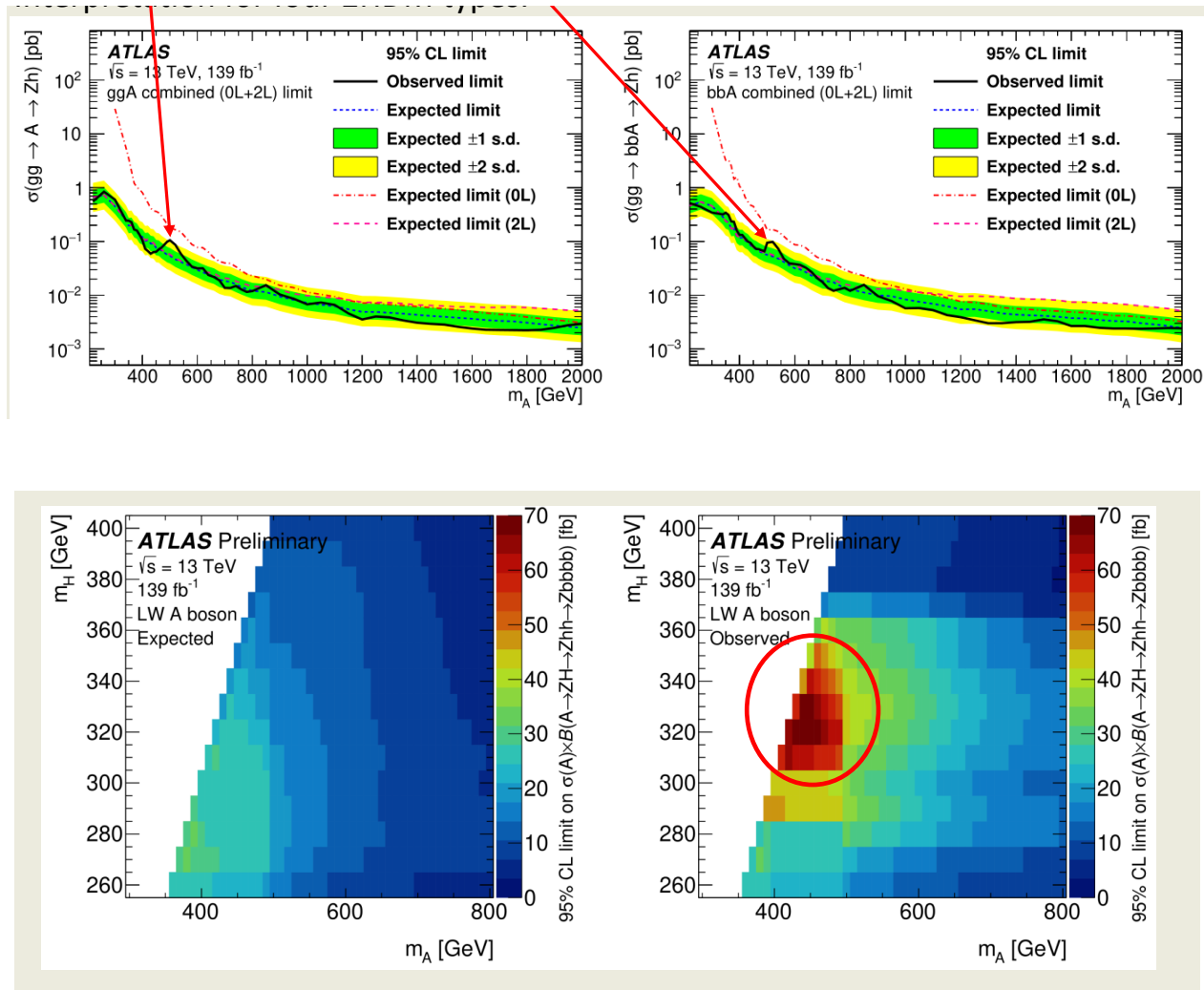
Crosses : H1 singlet like
Asterix : H2 singlet like

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,

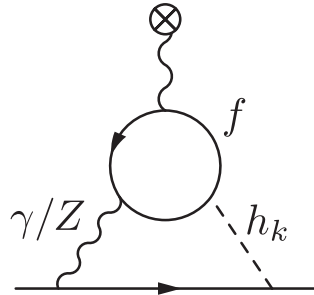
$$Z_6^I = Z_6^R = 0$$

- 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 at high loop levels and is quite suppressed.

SM-like Higgs Contribution



type II 2HDM

$$g_{H_1 dd}^S \simeq O_{11} - \tan \beta \, O_{21}$$

$$g_{H_1 dd}^P \simeq -O_{31} \tan \beta.$$

$$O_{11} \simeq 1$$

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

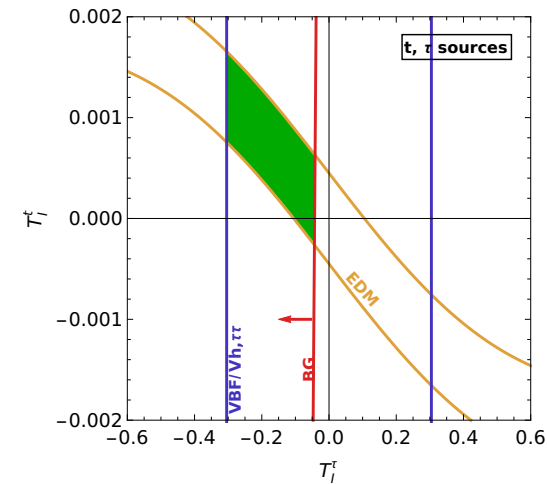
$$O_{31} \simeq -\frac{Z_6^I v^2}{m_H^2}$$

X_I^f : CP odd component of couplings

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

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

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



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

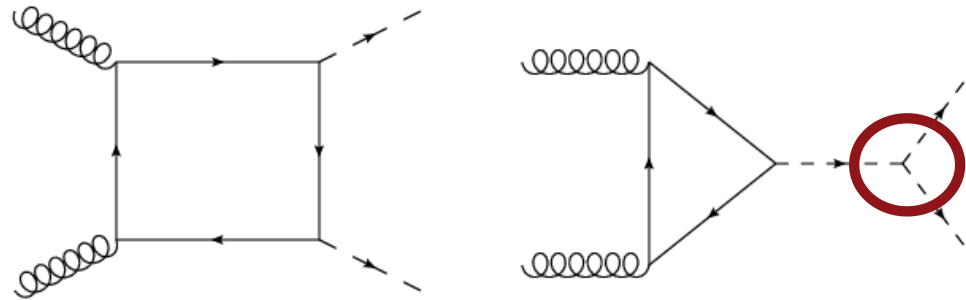
$$V_{SM}(h) = \frac{m_h^2}{2}h^2 + \frac{m_h^2}{2v}h^3 + \frac{m_h}{8v^2}h^4$$

- In particular, the trilinear coupling is given by

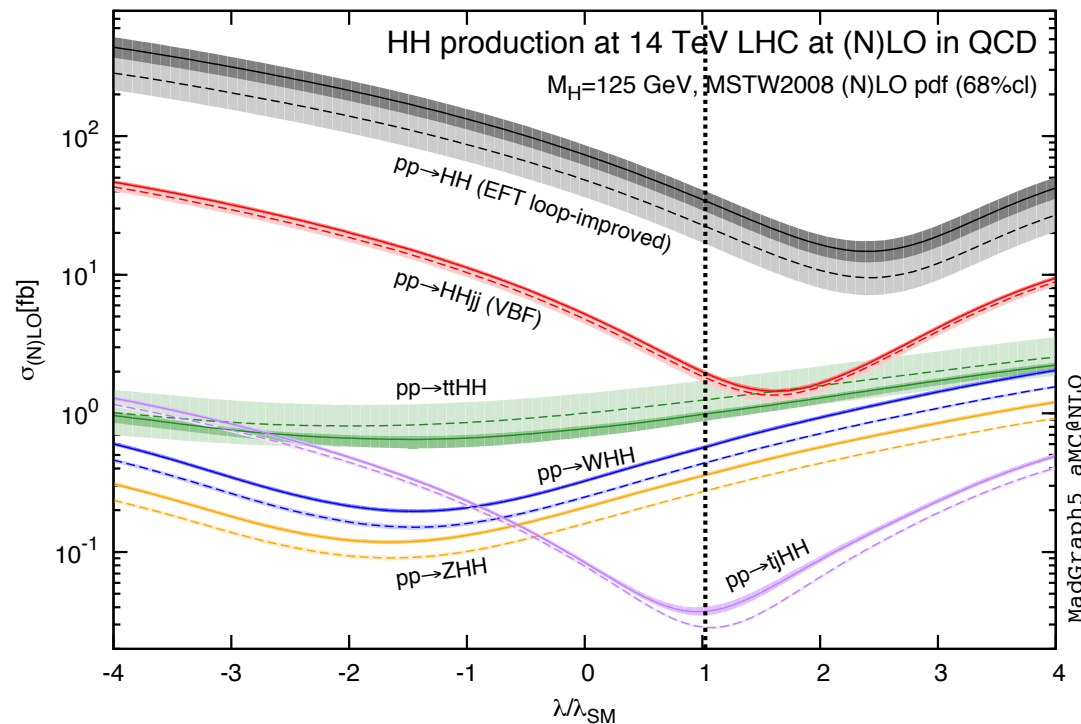
$$g_{hhh} = \frac{3m_h^2}{v}$$

- 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.

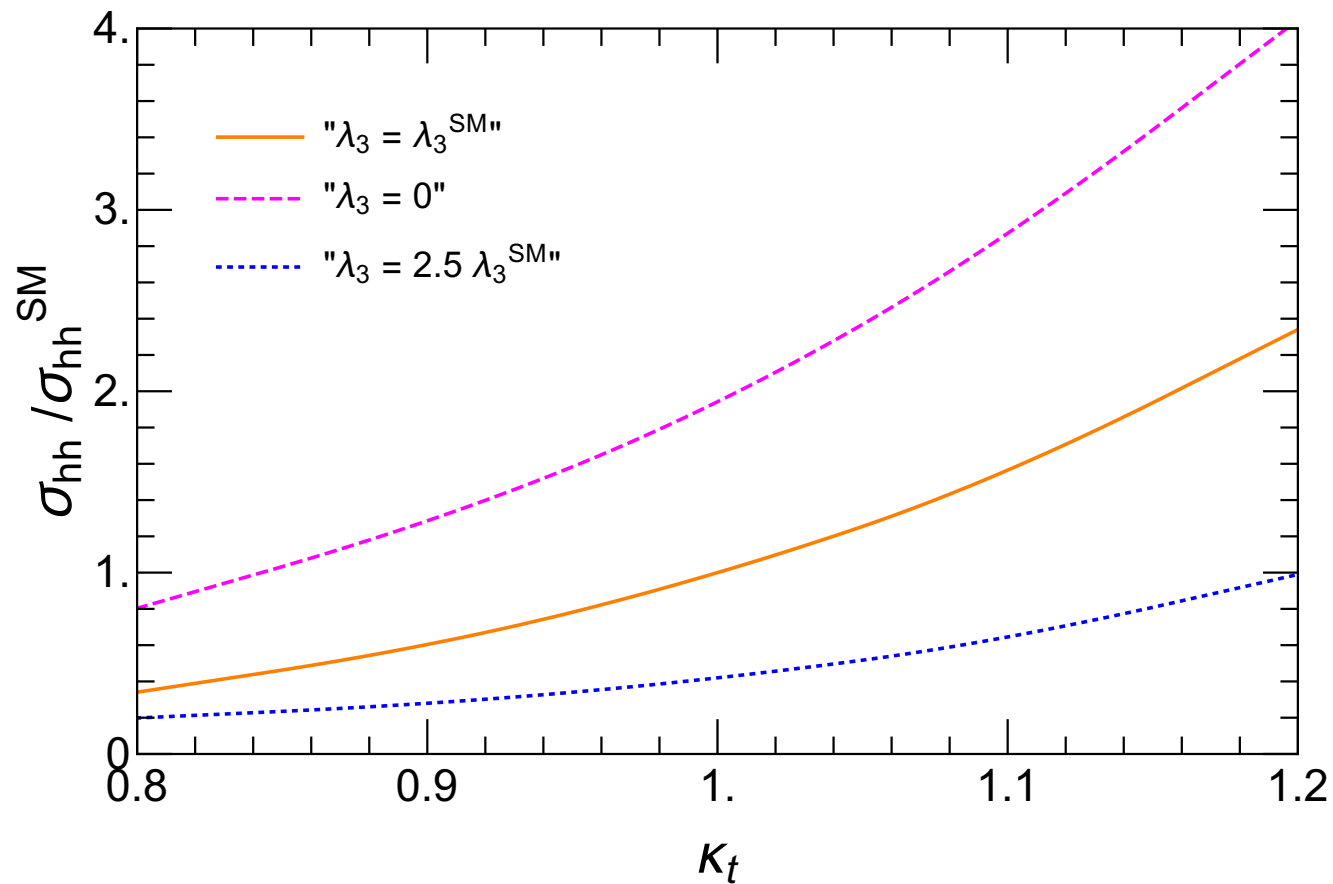


Frederix et al'14

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

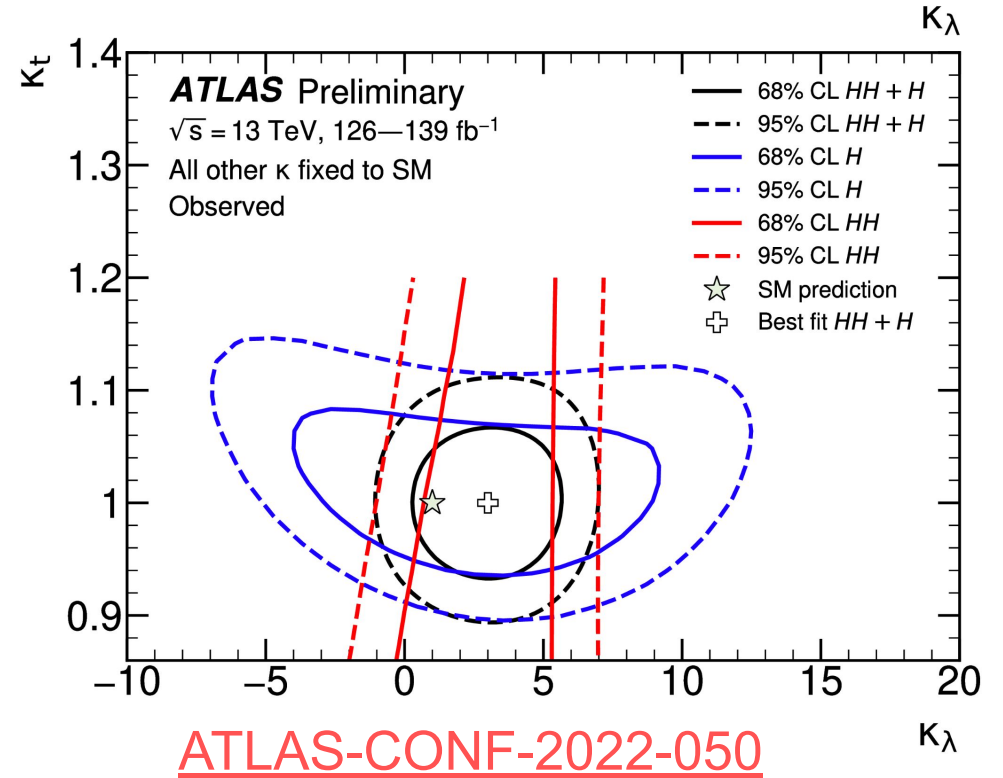
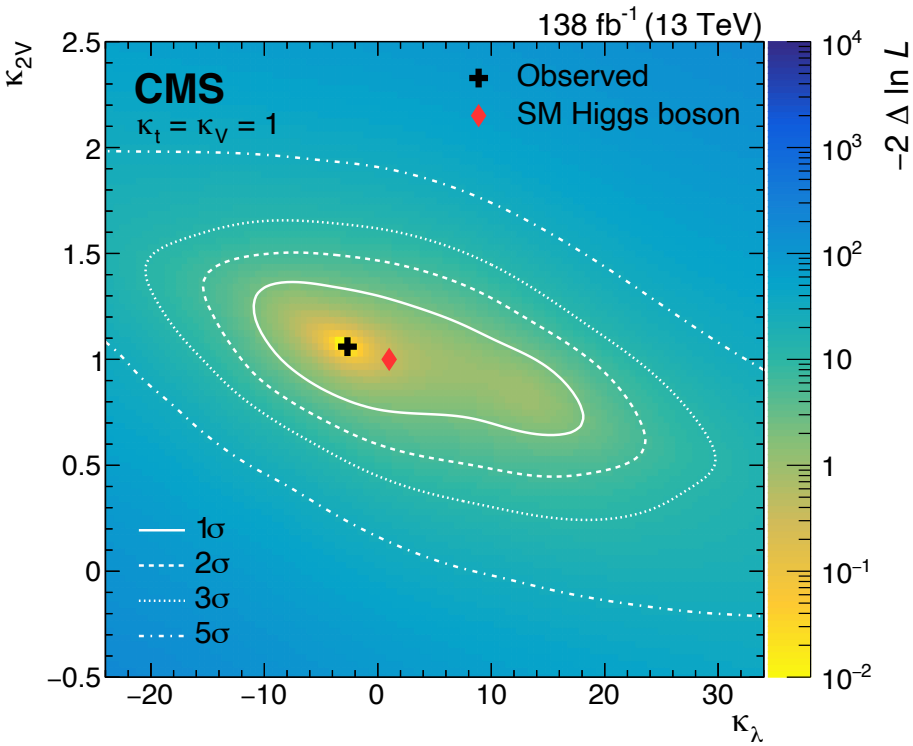
Huang, Joglekar, Li, C.W.'17



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

Amazing Experimental Progress



$HH+H$ 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, $\kappa_t, \kappa_V, \kappa_b, \kappa_\tau$ 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), $\kappa_t, \kappa_V, \kappa_b, \kappa_\ell$ 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

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

- 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.

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

Baryogenesis at the weak scale

- Under natural assumptions, there are three conditions, enunciated by Sakharov, that need to be fulfilled for baryogenesis. The SM fulfills them :
- **Baryon number violation:** Anomalous Processes
- **C and CP violation:** Quark CKM mixing
- **Non-equilibrium:** Possible at the electroweak phase transition.

Baryon Asymmetry Preservation

If Baryon number generated at the electroweak phase transition,

$$\frac{n_B}{s} = \frac{n_B(T_c)}{s} \exp\left(-\frac{10^{16}}{T_c(\text{GeV})} \exp\left(-\frac{E_{\text{sph}}(T_c)}{T_c}\right)\right)$$

$$E_{\text{sph}} \propto \frac{8\pi v}{g}$$

Kuzmin, Rubakov and Shaposhnikov, '85—'87

Klinkhamer and Manton '85, Arnold and Mc Lerran '88

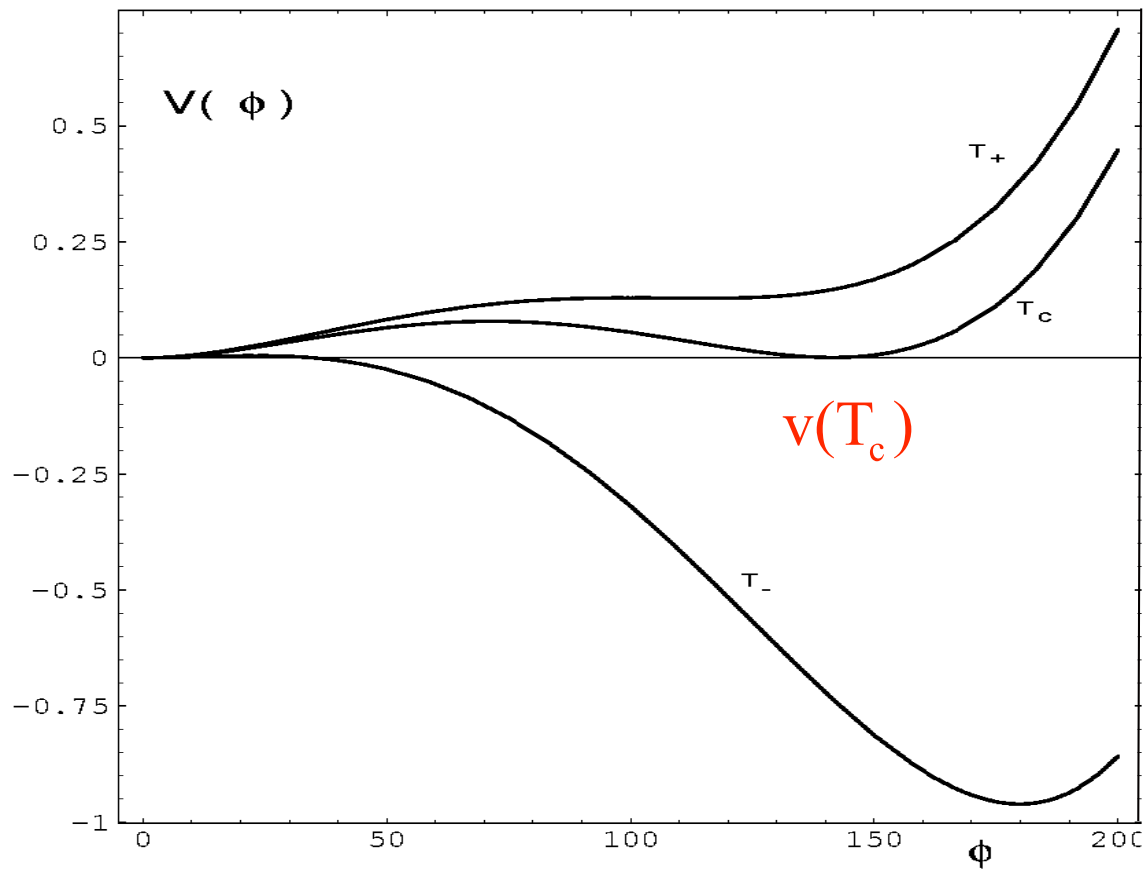
Baryon number erased unless the baryon number violating processes are out of equilibrium in the broken phase.

Therefore, to preserve the baryon asymmetry, a strongly first order phase transition is necessary:

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

Electroweak Phase Transition

*Higgs Potential Evolution in the case of a first order
Phase Transition*



Gravitational Waves may be produced at the Phase Transition

First Order Phase Transition

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

- Simpler case

$$V(\phi, T) = \frac{m^2 + a_0 T^2}{2} (\phi^\dagger \phi) + \frac{\lambda}{4} (\phi^\dagger \phi)^2 + \frac{c_6}{8\Lambda^2} (\phi^\dagger \phi)^3$$
$$\lambda_3 = \frac{3m_h^2}{v} \left(1 + \frac{2c_6 v^4}{m_h^2 \Lambda^2} \right)$$

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

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

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

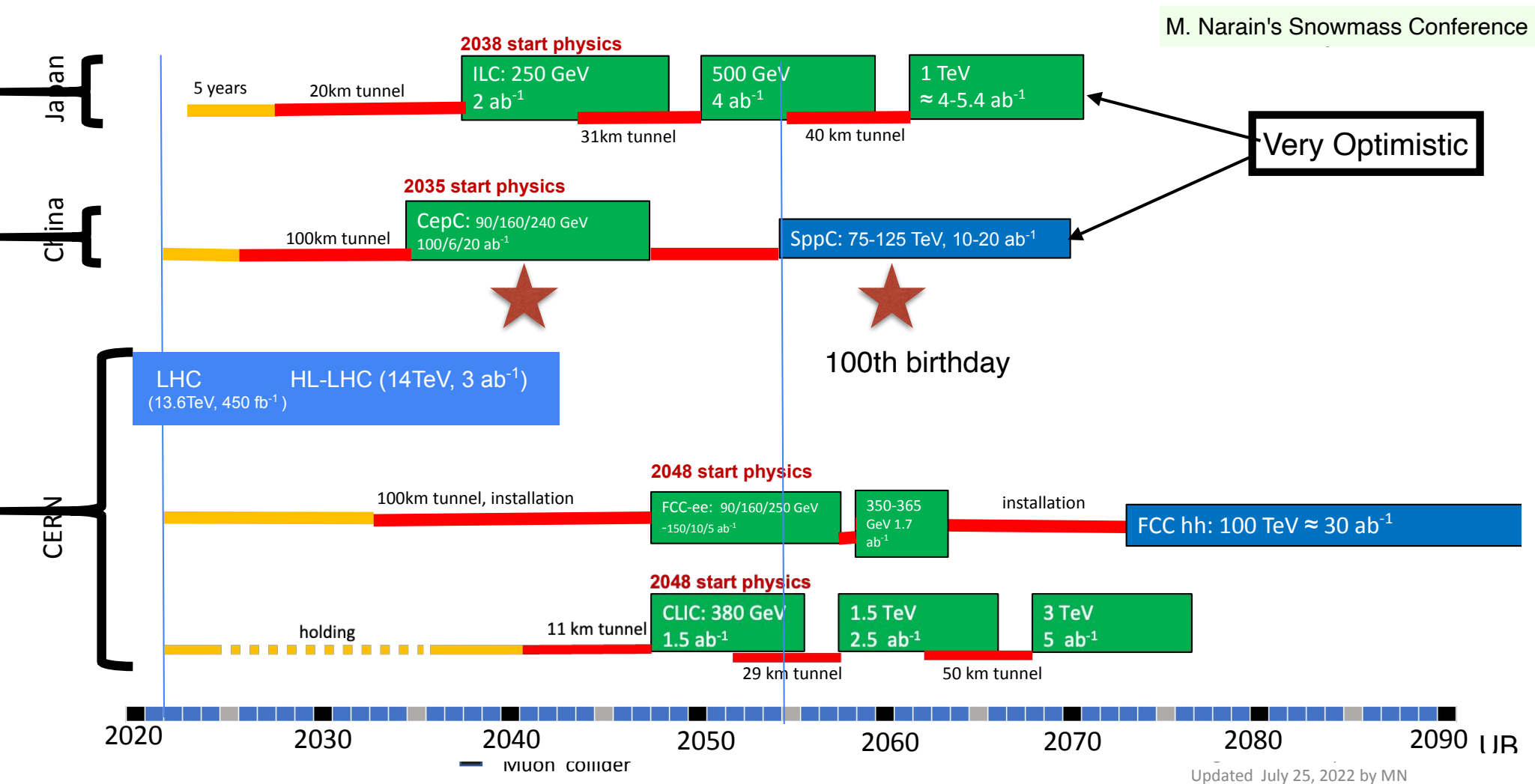
- It is simple algebra to demonstrate that, $T_c^2 = \frac{3c_6}{4\Lambda^2 a_0} (v^2 - v_c^2) \left(v^2 - \frac{v_c^2}{3} \right).$

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

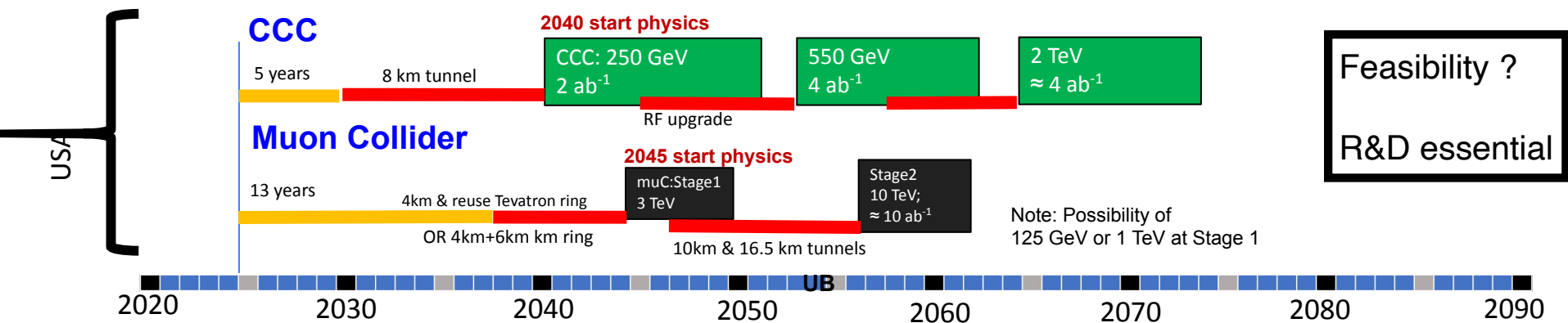
- Now, in the two extremes, either v_c or T_c go to zero, so in order to fulfill the baryogenesis conditions one would like to be somewhat in between.

Great Times

- We are living in great times. We have a set of working and near future experiments that are exploring all aspects of high energy physics, from neutrino physics to Dark Matter
- Never before we have seen such a marriage between the interests of particle physics and cosmologists, not only regarding Dark Matter, but also big bang nucleosynthesis, new light degrees of freedom and of course gravitational wave experiments.
- In the high energy frontier, we have the LHC. Let me emphasize how fantastic the LHC is. It is both a precision as well as a discovery machine.
- LHC is exploring the Higgs couplings at a great precision, and at the same time looking for new physics. It will be, most, likely the only high energy collider for the next two decades and we should use its capabilities in the most efficient way possible.
- I am persuaded that there are great times ahead and the LHC program will lead to the first convincing hints either by direct or indirect observations of what lies beyond the fantastic SM.



Proposals emerging from this Snowmass for a US based collider



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 the most vibrant field of particle physics, one in which many surprises may lay ahead, with profound implications for our understanding of Nature.

Backup

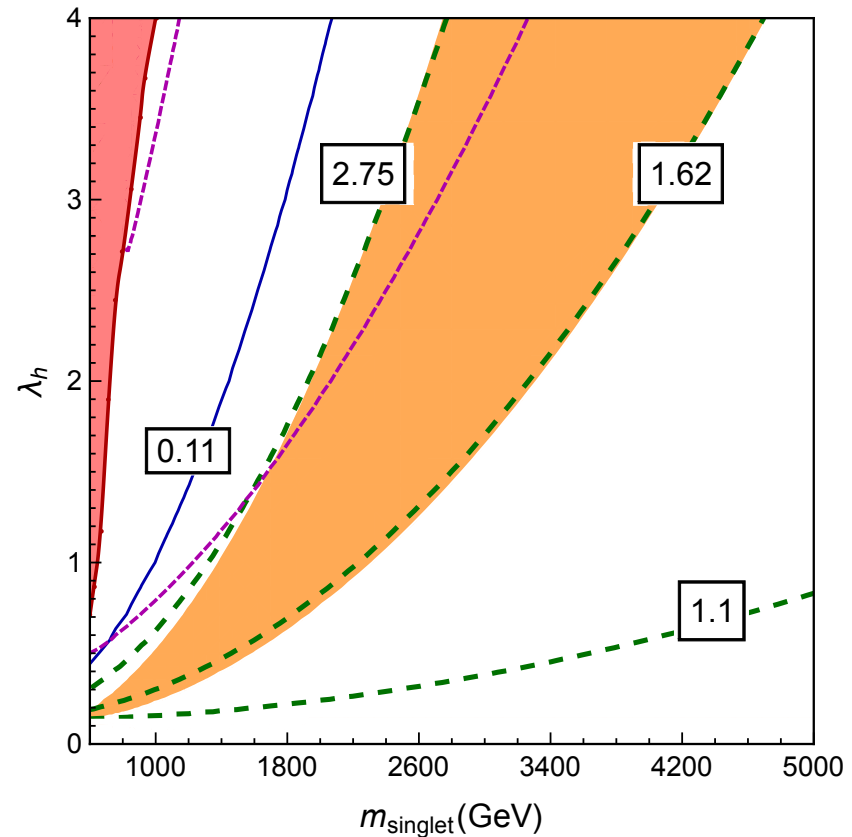
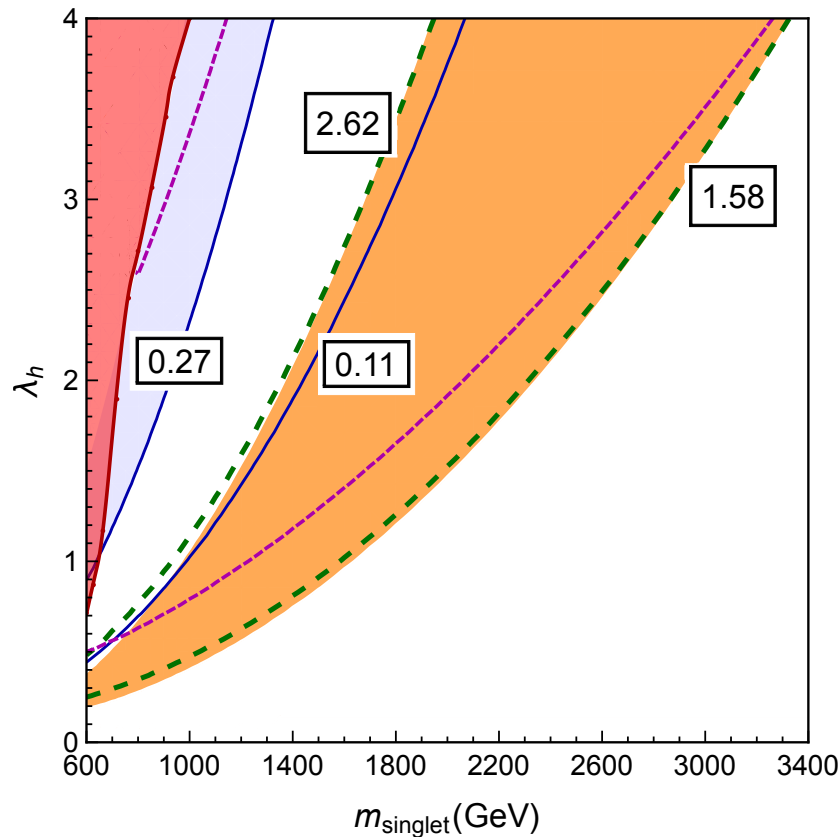
Modified λ_3 , mixing angle and SFOPT

Orange :SFOPT

Solid lines : Higgs mixing angle

Dashed lines : $1 + \delta$

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

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

- 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.

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

- 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.

Singlet Decoupling : Threshold Corrections

Large values of $\tan\beta$

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

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

Alignment Condition :

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

$$-Z_6 v^2 \tan\beta$$

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

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 : $\langle H_1^0 \rangle = \frac{v}{\sqrt{2}}, \quad \langle H_2 \rangle = 0$

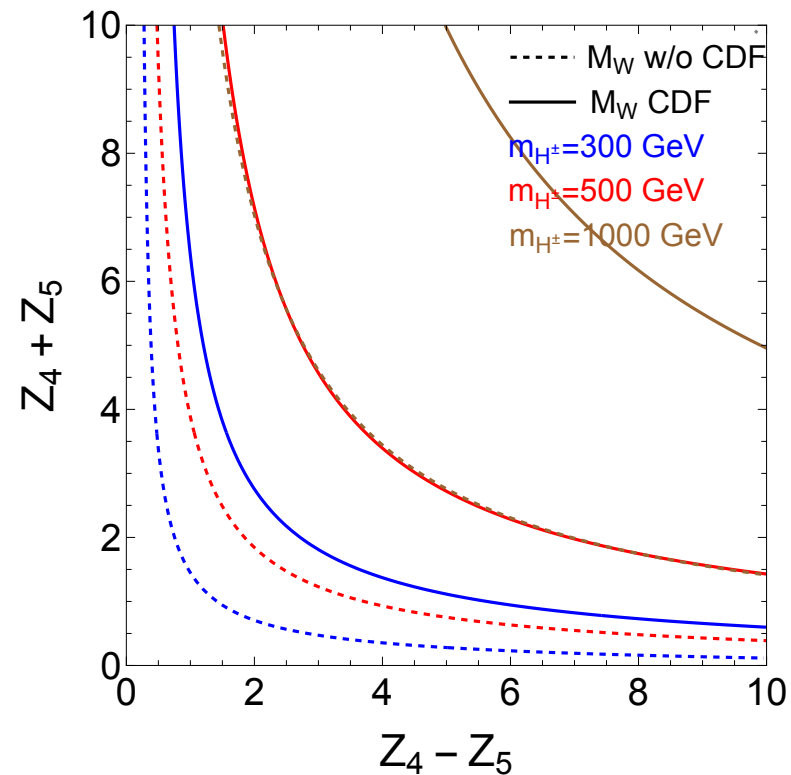
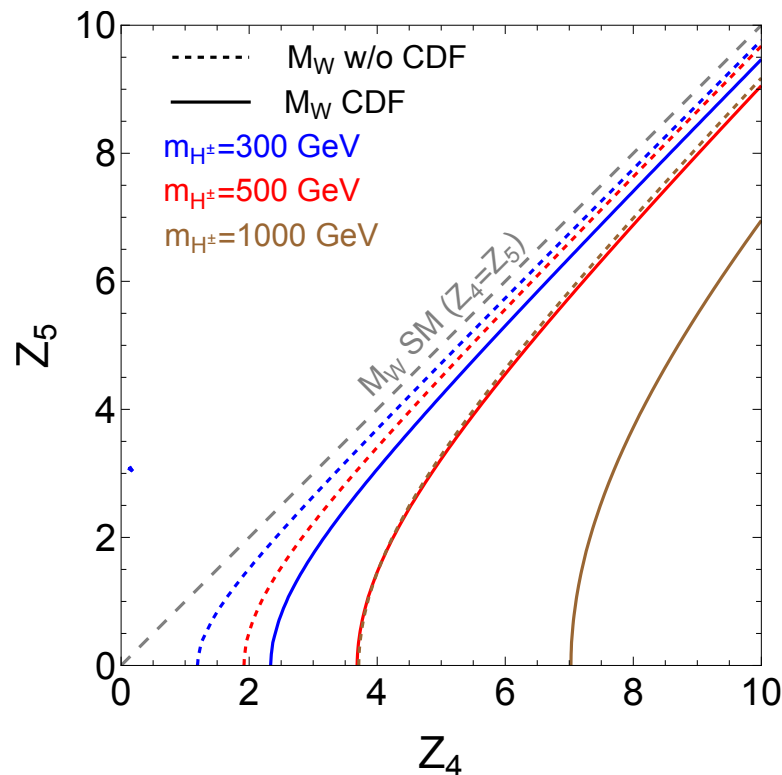
Haber, Gunion hep-ph/0207010
Haber'93, D. O Neil, arXiv : 0908.1363

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

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

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

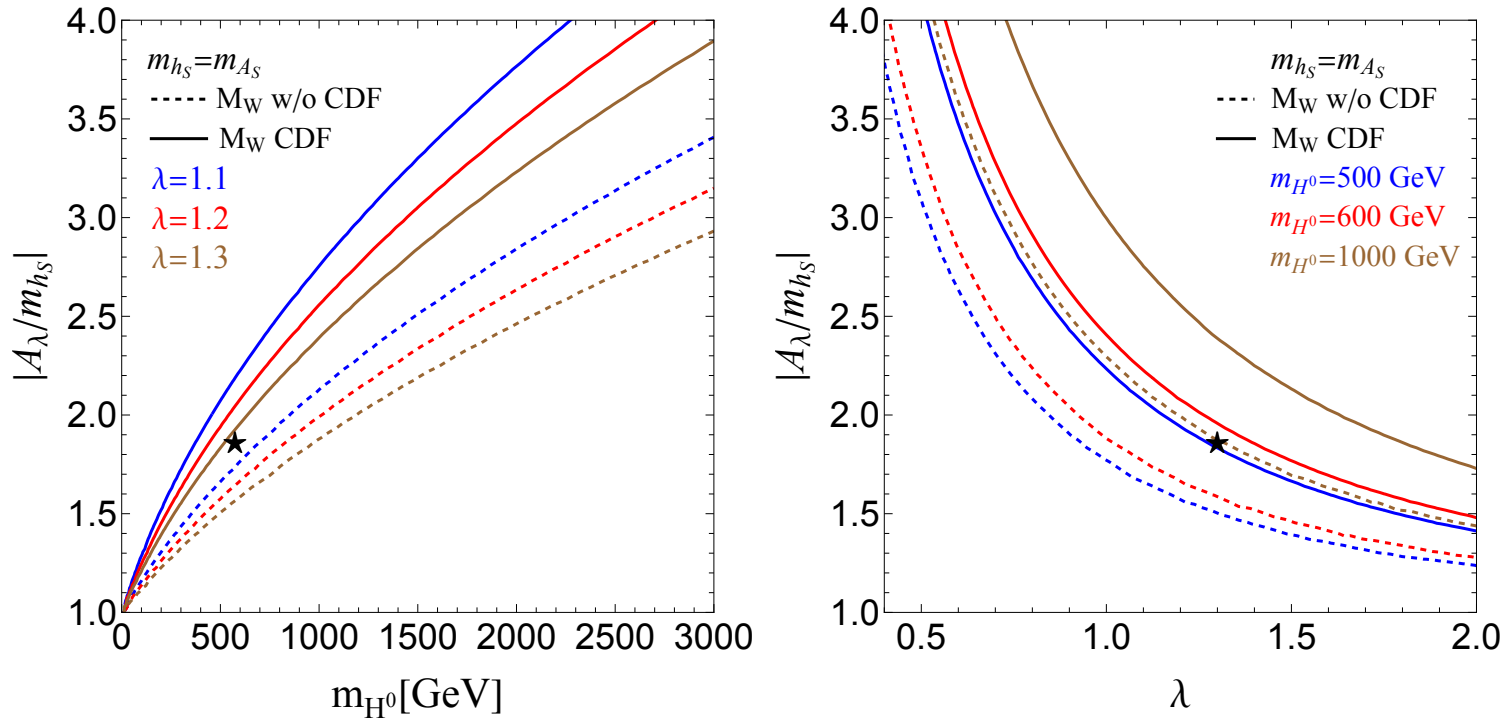
M. Carena, N. Shah, I. Low, X. Wang, C.W.'22 (to appear)
Two loop corrections : Bahl, Braathen, Weiglein '22



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



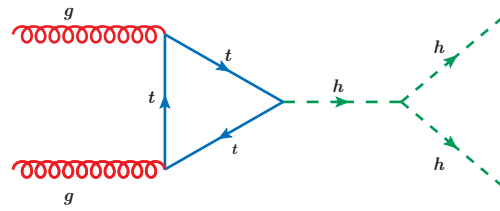
At large values of $\tan\beta$, and $\lambda = 0.65$, alignment implies, approximately

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

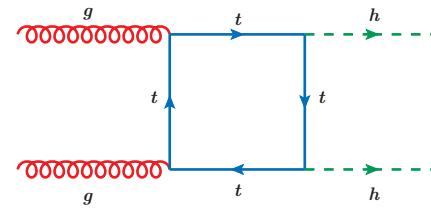
Large contributions are possible, but demand either a sizable value of λ , breaking perturbative consistency below the GUT scale, or sizable values of the trilinear coupling A_λ .

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

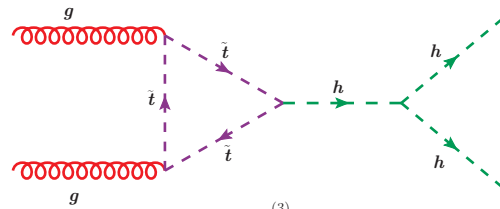
Stop Contributions



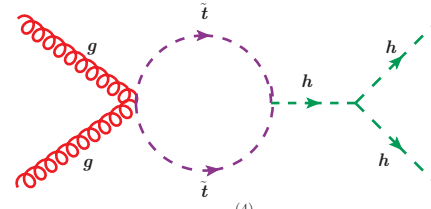
(1)



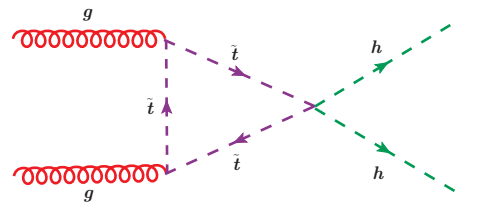
(2)



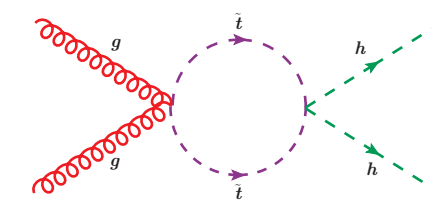
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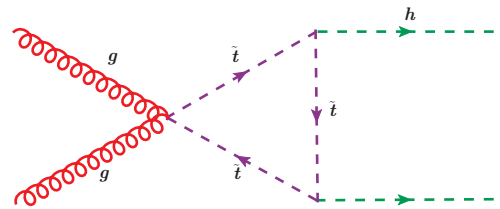
(4)



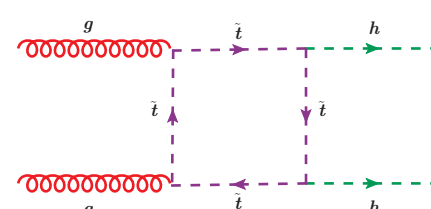
(5)



(6)



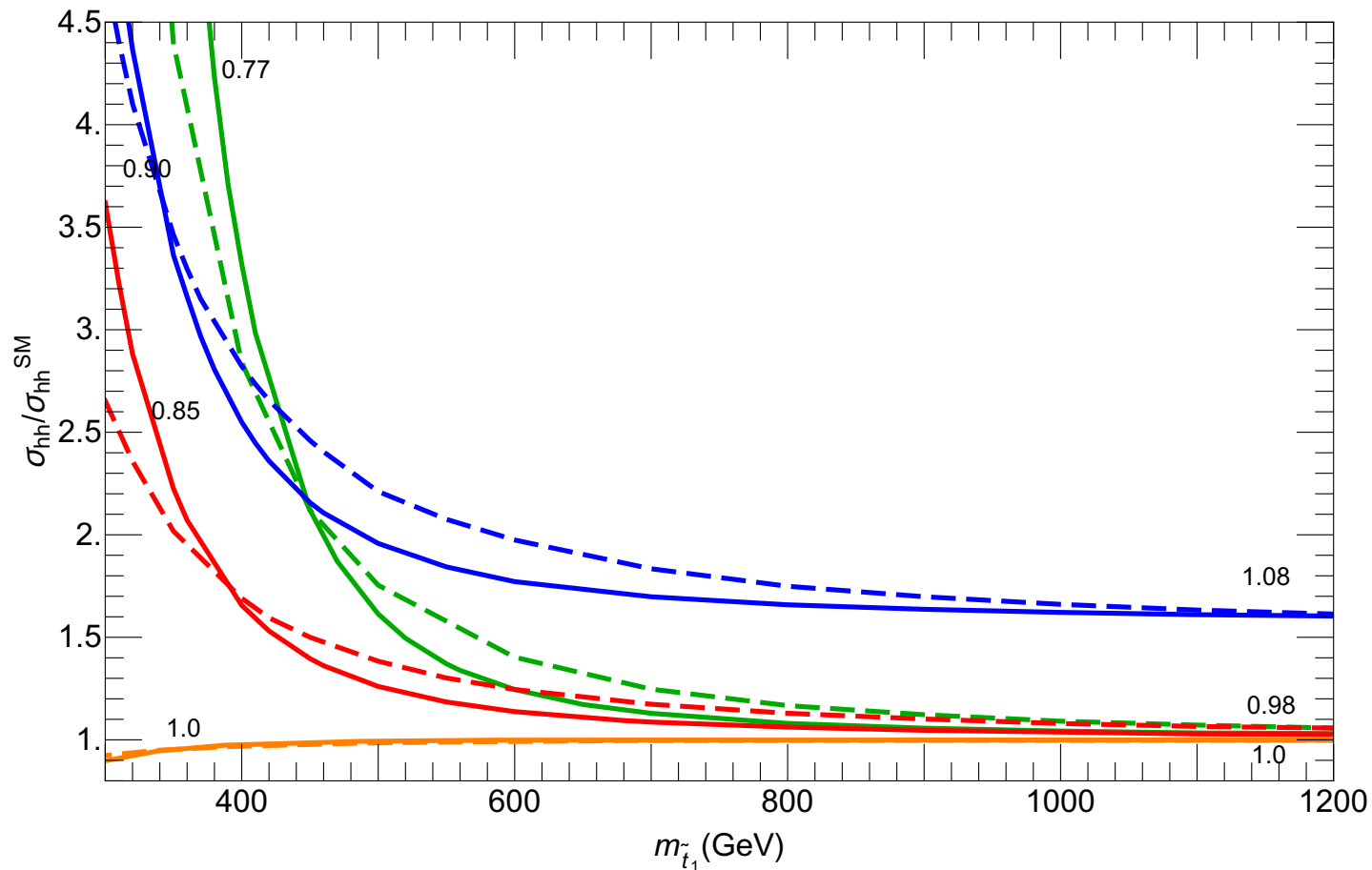
(7)



(8)

Stop Effects on Di-Higgs Production Cross Section

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



Orange : Stop corrections to κ_g decoupled

Red : X_t fixed at color breaking vacuum boundary value, for light m_A

Green : X_t fixed at color breaking boundary value, for $m_A = 1.5$ TeV

Blue : Same as Red, but considering $\kappa_t = 1.1$

Example : Modifying the up and down couplings in type II 2HDM

- 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.

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

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

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

$$\kappa_t = \sin(\beta - \alpha) + \cot \beta \cos(\beta - \alpha)$$

$$\kappa_b = \sin(\beta - \alpha) - \tan \beta \cos(\beta - \alpha)$$

$$\kappa_V = \sin(\beta - \alpha) \simeq 1$$

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

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

Relation between couplings

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

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

$$\begin{aligned} \lambda_1 &= Z_1 c_\beta^4 + Z_2 s_\beta^4 + \frac{1}{2} Z_{345} s_{2\beta}^2 - 2s_{2\beta} \left(\text{Re}[Z_6 e^{i\delta}] c_\beta^2 + \text{Re}[Z_7 e^{i\delta}] s_\beta^2 \right), \\ \lambda_2 &= Z_1 s_\beta^4 + Z_2 c_\beta^4 + \frac{1}{2} Z_{345} s_{2\beta}^2 + 2s_{2\beta} \left(\text{Re}[Z_6 e^{i\delta}] s_\beta^2 + \text{Re}[Z_7 e^{i\delta}] c_\beta^2 \right), \\ \lambda_3 &= \frac{1}{4} (Z_1 + Z_2 - 2Z_{345}) s_{2\beta}^2 + Z_3 + \text{Re}[(Z_6 - Z_7) e^{i\delta}] s_{2\beta} c_{2\beta}, \\ \lambda_4 &= \frac{1}{4} (Z_1 + Z_2 - 2Z_{345}) s_{2\beta}^2 + Z_4 + \text{Re}[(Z_6 - Z_7) e^{i\delta}] s_{2\beta} c_{2\beta}, \\ \lambda_5 e^{2i\delta} &= \frac{1}{4} (Z_1 + Z_2 - 2Z_{345}) s_{2\beta}^2 + \text{Re}[Z_5 e^{2i\delta}] + i \text{Im}[Z_5 e^{2i\delta}] c_{2\beta} \\ &\quad + \text{Re}[(Z_6 - Z_7) e^{i\delta}] s_{2\beta} c_{2\beta} + i \text{Im}[(Z_6 - Z_7) e^{i\delta}] s_{2\beta}, \\ \lambda_6 e^{i\delta} &= \frac{1}{2} (Z_1 c_\beta^2 - Z_2 s_\beta^2 - Z_{345} c_{2\beta} - i \text{Im}[Z_5 e^{2i\delta}]) s_{2\beta} \\ &\quad + \text{Re}[Z_6 e^{i\delta}] c_\beta c_{3\beta} + i \text{Im}[Z_6 e^{i\delta}] c_\beta^2 + \text{Re}[Z_7 e^{i\delta}] s_\beta s_{3\beta} + i \text{Im}[Z_7 e^{i\delta}] s_\beta^2, \\ \lambda_7 e^{i\delta} &= \frac{1}{2} (Z_1 s_\beta^2 - Z_2 c_\beta^2 + Z_{345} c_{2\beta} + i \text{Im}[Z_5 e^{2i\delta}]) s_{2\beta} \\ &\quad + \text{Re}[Z_6 e^{i\delta}] s_\beta s_{3\beta} + i \text{Im}[Z_6 e^{i\delta}] s_\beta^2 + \text{Re}[Z_7 e^{i\delta}] c_\beta c_{3\beta} + i \text{Im}[Z_7 e^{i\delta}] c_\beta^2, \end{aligned}$$

MSSM

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

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

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

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

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

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

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

$$X_t = \frac{2A_t^2}{M_{\text{SUSY}}^2} \left(1 - \frac{A_t^2}{12M_{\text{SUSY}}^2}\right)$$

$$X_b = \frac{2A_b^2}{M_{\text{SUSY}}^2} \left(1 - \frac{A_b^2}{12M_{\text{SUSY}}^2}\right)$$

$$A_{tb} = \frac{1}{6} \left[-\frac{6\mu^2}{M_{\text{SUSY}}^2} - \frac{(\mu^2 - A_b A_t)^2}{M_{\text{SUSY}}^4} + \frac{3(A_t + A_b)^2}{M_{\text{SUSY}}^2} \right].$$

$$h_t = m_t(M_t)/(v \sin \beta)$$

$$h_b = m_b(M_t)/(v \cos \beta)$$

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

Beyond the Standard Model

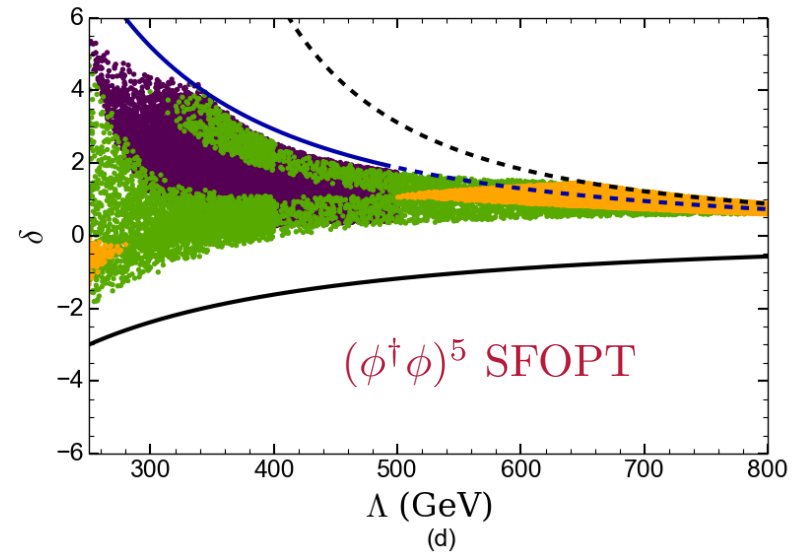
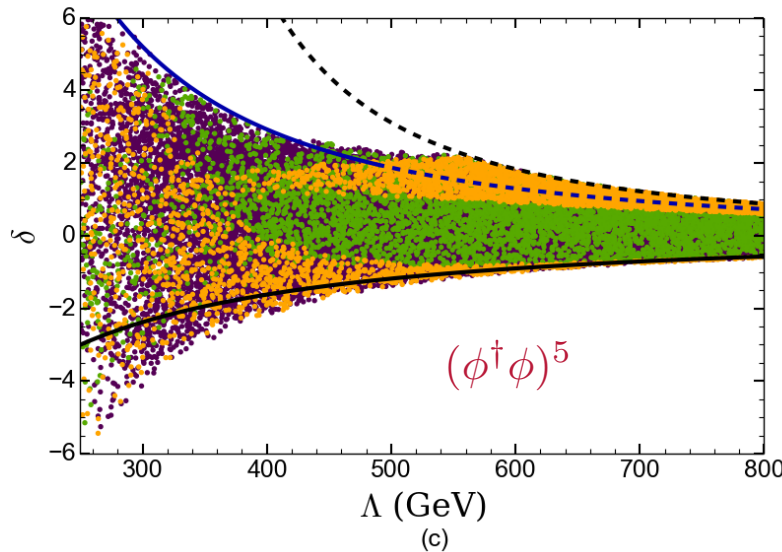
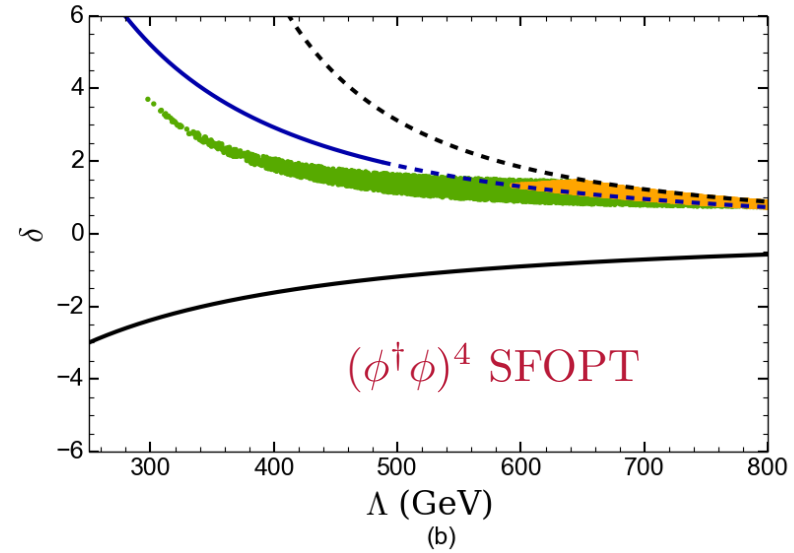
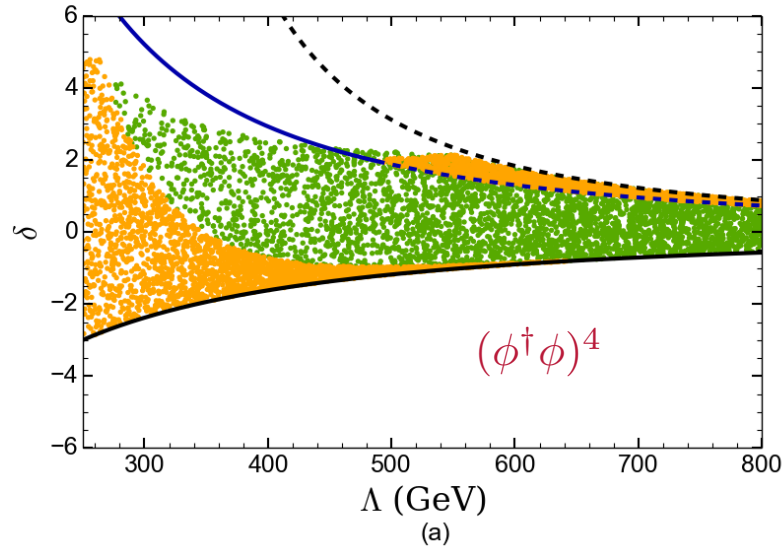
- The Higgs mass parameter is sensitive to new physics effects that could modify its value to values of the order of the new physics scale.
- For this reason, one expects new physics not far above the TeV scale.
- Such new physics could lead to a modification of the Higgs couplings to SM particles, and also of the Higgs self couplings.
- In particular, modifications of the top Yukawa coupling or the trilinear Higgs coupling would lead to a modification of the loop induced rate.

Other things may happen :

- New particles can appear in the loop, leading to modified Double Higgs production cross section.
- New resonances can appear, decaying to Higgs pairs.

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)



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 a_s and λ_{hs} small, one obtains a modification of the effective quartic and λ_3 couplings

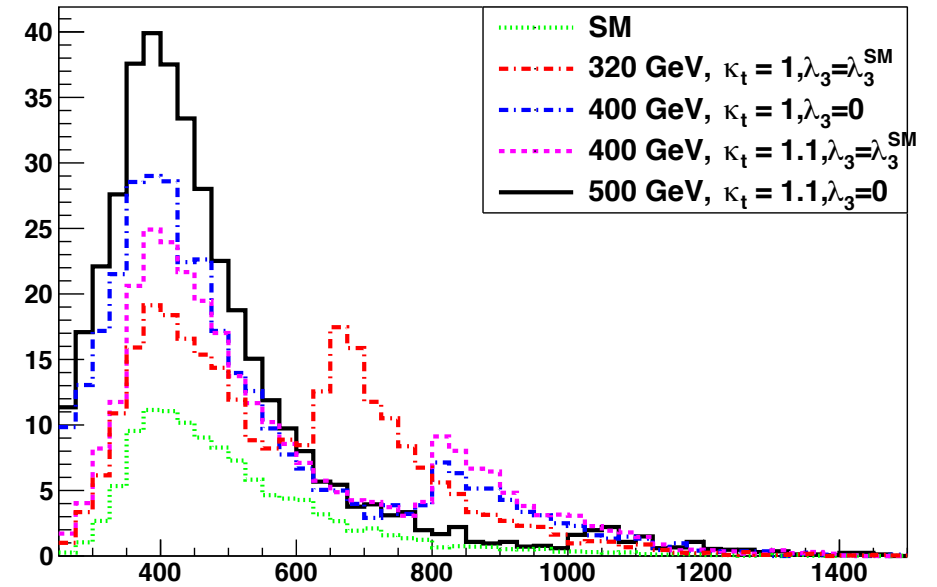
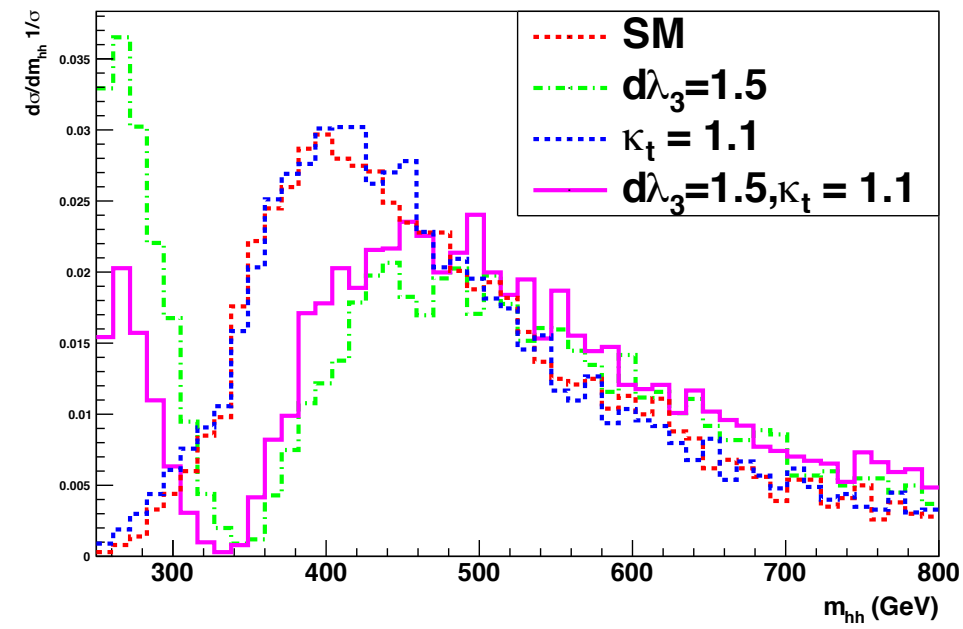
Menon, Morrissey, C.W.'04
Carena, Shah, C.W.'12

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

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

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

Invariant Mass Distributions



Provided λ_3 is not shifted to large values, acceptances similar as in the Standard Model