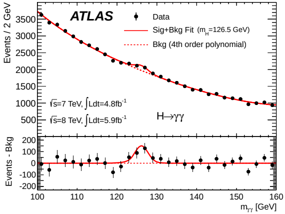
Fully Covering the MSSM Higgs Sector at the LHC

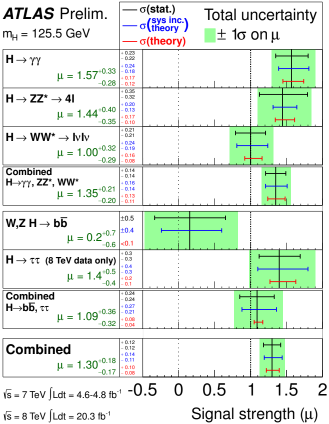
Jérémie Quevillon

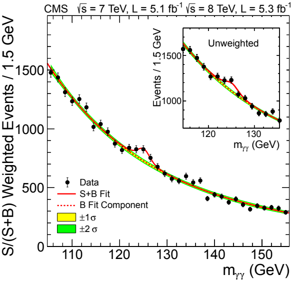
King's College London

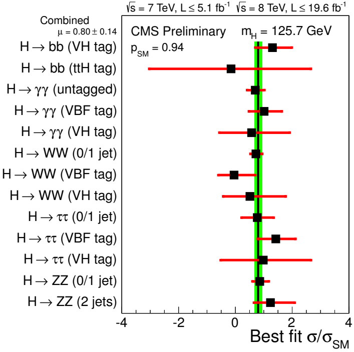
WIN 2015, Heidelberg, 9^{th} June 2015

The 4^{th} of July 2012: discovery of a new 125 GeV boson



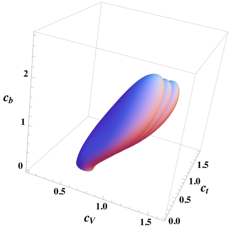






Is it a Higgs?

with Djouadi et al. (2013)



Higgs couplings as predicted by Higgs mechanism

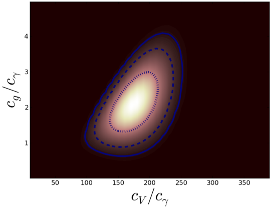
- couplings proportional to masses as expected
- couplings to WW, ZZ, $\gamma\gamma$ roughly as expected

Is it a spin 0?

- state decays into $\gamma\gamma \Rightarrow$ not spin-1 (Landau–Yang th.)
- is it a spin–2 like graviton?

  A priori no: $c_g \neq c_\gamma$, $c_V \gg 35 c_\gamma$

Ellis and You. (2012)

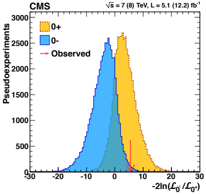


Is it CP-even?

$HV_\mu V_\mu$ vs $H\epsilon^{\mu\nu\rho\sigma}Z_{\mu\nu}Z_{\rho\sigma}$

$\Rightarrow \frac{d\Gamma(H\to ZZ^*)}{dM^*}$ and $\frac{d\Gamma(H\to ZZ)}{d\Phi}$

ATLAS/CMS: $\sim 3\sigma$ for CP-even



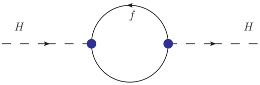
$\Rightarrow$ It is THE-A Higgs boson!

Motivations for SUSY

- The hierarchy problem: why $M_H \ll M_{Pl}$?
  - The fermion 1-loop correction to the Higgs mass:

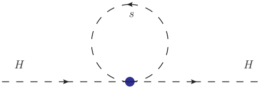
$$\delta m_H^2 \sim \int^{\Lambda} d^4k \frac{1}{k^2} \sim \Lambda^2 + m_{loop}^2 \ln \frac{\Lambda}{m_{loop}}$$

$$\delta^{(f)} m_H^2 \supset \frac{\lambda_F^2}{8\pi^2}\left[-\Lambda^2 + 6m_F^2 \ln\frac{\Lambda}{m_F}\right]$$



  - The scalar 1-loop correction to the Higgs mass:

$$\delta^{(s)} m_H^2 \supset \frac{\lambda_S}{16\pi^2}\left[-\Lambda^2 + (2m_S^2 - 2\lambda_S v^2)\ln\left(\frac{\Lambda}{m_S}\right)\right]$$



  - SUSY theory with $2N_F = N_S$ and with $\lambda_S = -\lambda_F^2 \Rightarrow$ the quadratic divergences vanish (remain the logarithmic ones):

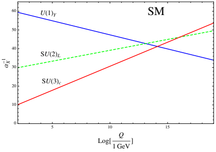
$$\delta^{(f+s)} m_H^2 = \frac{\lambda_S^2}{4\pi^2}\left[(m_F^2 - m_S^2)\ln\left(\frac{\Lambda}{m_S}\right) + 3m_F^2 \ln\left(\frac{m_S}{m_F}\right)\right]$$

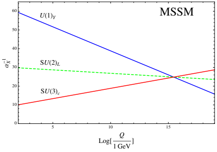
$\Rightarrow$ the hierarchy and naturalness problems solved

if $m_F = m_S \Rightarrow M_H$ is protected by SUSY

$\Rightarrow$ SUSY must be broken, $m_S \gg m_F$

- The gauge coupling unification
- A dark matter candidate (relies on R-parity)





1. Fully Covering the MSSM Higgs Sector at the LHC
   - The Higgs sector of the MSSM
   - Implications from the Higgs mass
   - Implications from the Higgs couplings
   - Implications from direct Higgs searches
2. Covering the MSSM stop sector

The Higgs sector of the MSSM

One needs 2 complex scalar doublets: $H_1 = \begin{pmatrix} H_1^0 \\ H_1^- \end{pmatrix}$ and $H_2 = \begin{pmatrix} H_2^+ \\ H_2^0 \end{pmatrix}$

- give masses to respectively d and u fermions in SUSY invariant way
- cancel the chiral anomalies

After EWSB: 3 d.o.f. to make $W_L^\pm$, Z_L $\Rightarrow$ 5 physical states left out: h, H, A, $H^\pm$

At tree-level only 2 free parameters $\tan\beta, M_A$:

$$M_{h,H}^2 = \frac{1}{2}\left[M_A^2 + M_Z^2 \mp \sqrt{(M_A^2+M_Z^2)^2 - 4M_A^2 M_Z^2 \cos^2 2\beta}\right], \quad \tan 2\alpha = \tan 2\beta \, \frac{M_A^2+M_Z^2}{M_A^2-M_Z^2}$$

$$M_{H^\pm}^2 = M_A^2 + M_W^2$$

Important constraint on the MSSM Higgs boson masses:

$$M_h \leq \min(M_A, M_Z) \cdot |\cos 2\beta| \leq M_Z, \quad M_H > \max(M_A, M_Z), \quad M_{H\pm} > M_W$$

$M_A \gg M_Z$: decoupling regime, all Higgses heavy except h:

$$M_h \sim M_Z \, |\cos 2\beta| \leq M_Z, \quad M_H \sim M_H^\pm \sim M_A, \quad \alpha \sim \pi - \beta$$

$\Rightarrow$ Inclusion of radiative corrections to M_h are essential to explain $M_h \approx 125$ GeV $> M_Z$

The radiative corrections to the Higgs mass

Dominant corrections are due to top (s)quark, at the one-loop level:

$$M_h \xrightarrow{M_A \gg M_Z} M_Z|\cos 2\beta| + \frac{3\bar{m}_t^4}{2\pi^2 v^2 \sin^2\beta}\left[\ln\frac{M_S^2}{\bar{m}_t^2} + \frac{X_t^2}{2M_S^2}\left(1 - \frac{X_t^2}{6M_S^2}\right)\right]$$

[Okada+Yamaguchi+Yanagida, Ellis+Ridolfi+Zwirner, Haber+Hempfling (1991)]
depending on $\tan\beta$, $M_S = \sqrt{\tilde{m}_{t_1}\tilde{m}_{t_2}}$, $X_t = A_t - \frac{\mu}{\tan\beta}$: $M_h^{max} \to M_Z + 30 - 50$ GeV

The mass value 125 GeV is near the upper limit for the MSSM h boson
Increase $M_h \Rightarrow$ increase R.C. :

- decoupling regime with $M_A \sim \mathcal{O}$ (TeV)
- large values of $\tan\beta \gtrsim 10$ to maximize tree-level value
- maximal mixing scenario: $X_t = \sqrt{6}M_S$
- heavy stops, i.e. large $M_S = \sqrt{\tilde{m}_{t_1}\tilde{m}_{t_2}}$

Perform a full scan of the pMSSM with 22+19 free parameters

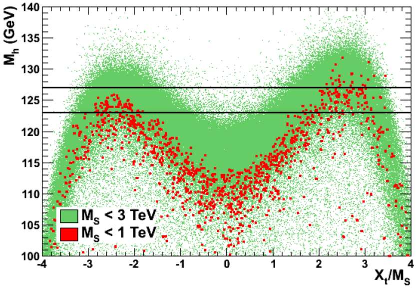
- calculate the Higgs and SUSY spectrum in the MSSM with the full one–loop + dominant two–loop corrections.
- determine the regions of parameter space where $123 \leq M_h \leq 129$ GeV (3 GeV uncertainty includes both "experimental" and "theoretical" error)

Implication of a 125 GeV Higgs for the pMSSM

[A. Arbey, M. Battaglia, A. Djouadi, F.Mahmoudi, J. Q., Phys.Lett. B708 (2012) 162]

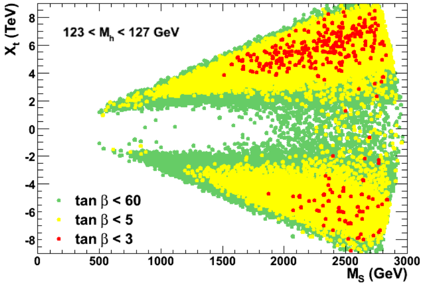
- Large M_S values required:
  - $M_S \sim 1$ TeV: only for maximal mixing
  - $M_S \sim 3$ TeV: only for typical mixing

$\Rightarrow$ no-mixing scenario excluded (unless $M_S \gg 1$ TeV)



- Large $\tan\beta$ values favored but $\tan\beta \sim 3$ allowed if $M_S \sim 3$ TeV
- Constraints on sparticles: $m_{\tilde{t}_1} \sim 500$ GeV still possible!

$\Rightarrow$ maximal mixing disfavored for large M_S and $\tan\beta$

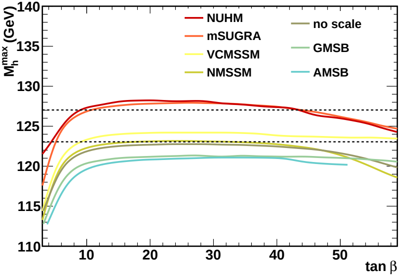


Implication of a 125 GeV Higgs for the cMSSM

Concrete schemes: SSB occurs in hidden sector

Parameters obey boundary conditions
$\Rightarrow$ small number of inputs:

- mSUGRA: $\tan\beta$, $m_{1/2}$, m_0, A_0, sign(μ)
- GMSB: $\tan\beta$, sign(μ), M_{mess}, Λ_{SSB}, N_{mess}
- AMSB: m_0, $m_{3/2}$, $\tan\beta$, sign(μ)



Full scans of the model parameters with
123 GeV $\leq M_h \leq$ 129 GeV

[A. Arbey, M. Battaglia, A. Djouadi, F.Mahmoudi, J. Q., Phys.Lett. B708 (2012) 162]

model	AMSB	GMSB	mSUGRA	no-scale	cNMSSM	VCMSSM	NUHM
$M_h^{\max}$	121.0	121.5	128.0	123.0	123.5	124.5	128.5

End of AMSB and GMSB in their minimal versions!

Implication of a 125 GeV Higgs for high scale SUSY

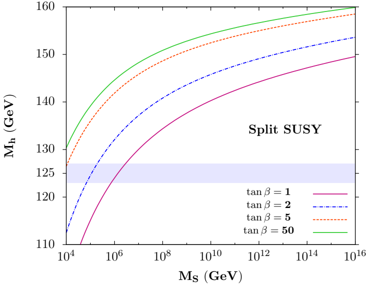
[A. Arbey, M. Battaglia, A. Djouadi, F.Mahmoudi, J. Q., Phys.Lett. B708 (2012) 162]

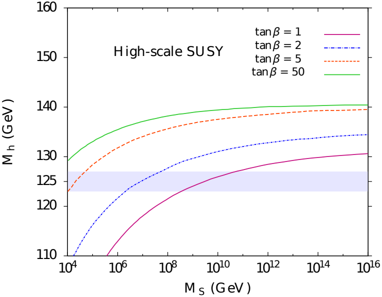
As the scale M_S seems to be large, we can consider 2 extreme possibilities:

- Split SUSY: allow fine–tuning
  - The SSB scalar mass terms at high scale (except 1 Higgs doublet)
  - Gauginos and higgsinos, are left at the EWSB scale (unification+DM still OK)
  - The parameters : M_S, 1 Higgs mass, M_1, M_2, M_3, μ and $\tan\beta$
  - Boundary condition on the quartic Higgs coupling : $\lambda(M_S) = \frac{1}{4}\left[g^2(M_S) + g'^2(M_S)\right]\cos^2 2\beta$
  - Heavy scalars $\Rightarrow$ R.C. in the Higgs sector enhanced by $\ln(M_{\rm EWSB}/M_S)$

- SUSY broken at the GUT scale:
  - Abandon fine-tuning, DM, unification
  - SUSY/EWSB matching encoded in the Higgs quartic coupling $\lambda \propto M_h^2$ related to gauge couplings

In both cases small $\tan\beta$ needed!





Determination of the h boson couplings in a generic MSSM

- Knowing [$\tan\beta, M_A$] and fixing $M_h = 125$ GeV, the couplings of the Higgs bosons can be derived, including the dominant radiative corrections that enter in the MSSM Higgs masses :

$$c_V^0 = \sin(\beta - \alpha)\ , \quad c_t^0 = \frac{\cos\alpha}{\sin\beta}\ , \quad c_b^0 = -\frac{\sin\alpha}{\cos\beta}$$

  However, there are also direct/vertex radiative corrections to the Higgs couplings not contained in the mass matrix. These can alter this simple picture!

- The two important SUSY (QCD) corrections affect the t,b couplings:

$$c_b \approx c_b^0 \times [1 - \Delta_b/(1+\Delta_b) \times (1 + \cot\alpha\cot\beta)]$$
$$c_t \approx c_t^0 \times \left[1 + \frac{m_t^2}{4 m_{\tilde{t}_1}^2 m_{\tilde{t}_2}^2}(m_{\tilde{t}_1}^2 + m_{\tilde{t}_2}^2 - (A_t - \mu\cot\alpha)(A_t + \mu\tan\alpha))\right]$$

- c_τ , c_c and c_t (from $pp \to Ht\bar{t}$) do not involve same vertex corrections
- $gg \to h$ process has $\tilde{t}$, $\tilde{b}$ loops and $h \to \gamma\gamma$ has also $\tilde{\tau}$ and $\chi_i^\pm$ loops

  $\Rightarrow$ in general, we need (at least) 7 couplings $c_t, c_b, c_c, c_\tau, c_V, c_g, c_\gamma$

  $+$ invisible decays? [Djouadi,Falkowski,Mambrini,JQ, arXiv:1205.3169]

  8 parameters fit difficult! Simpler to make reasonable approximations:

- low sensitivity on $h \to c\bar{c}$, $h \to \tau\tau$ and $pp \to t\bar{t}H$ at the LHC
- in $h \to \gamma\gamma$ additional contributions ($\tilde{b}, \tilde{\tau}, \chi_i^\pm$) smaller than those of $\tilde{t}$
  $\Rightarrow$ assume $c_c = c_t, c_\tau = c_b$ and $c_t(ttH) = c_t(ggF), c_\gamma \simeq c_g \simeq c_t$

reduce the problem to a fit of three couplings: c_t, c_b, c_V

3D-Fit in the $[c_t, c_b, c_V]$ parameter space

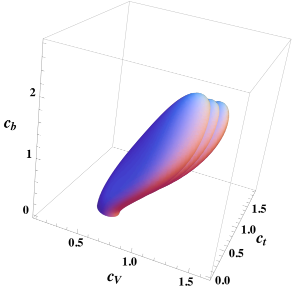
- If large direct corrections $\Rightarrow$ 3 independent h couplings : $c_c = c_t$, $c_\tau = c_b$ and $c_V = c_V^0$

- To study the h state at the LHC, we define the effective Lagrangian :

$$\mathcal{L}_h = c_V\ g_{hWW}\ h\ W^+_\mu W^{-\mu} +\ c_V\ g_{hZZ}\ h\ Z^0_\mu Z^{0\mu}$$
$$-c_t\ y_t\ h\bar{t}_L t_R - c_t\ y_c\ h\bar{c}_L c_R$$
$$-c_b\ y_b\ h\bar{b}_L b_R - c_b\ y_\tau\ h\bar{\tau}_L \tau_R\ +\ \mathrm{h.c.}$$

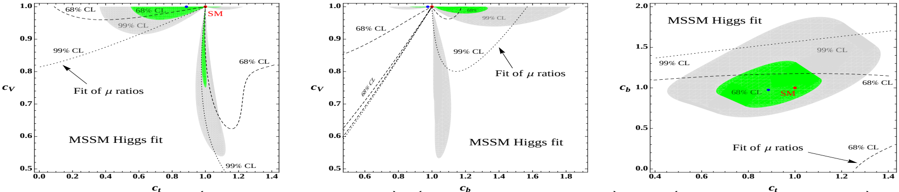
- We fit the Higgs signal strengths :

$$\mu_X \simeq \frac{\sigma(pp\to h)\times \mathrm{BR}(h\to XX)}{\sigma(pp\to h)_{\mathrm{SM}}\times \mathrm{BR}(h\to XX)_{\mathrm{SM}}}$$



Best-fit value : $c_t = 0.89$, $c_b = 1.01$ and $c_V = 1.02$ (ATLAS & CMS data)

If we neglect direct corrections $\to$ 2 parameter fits :



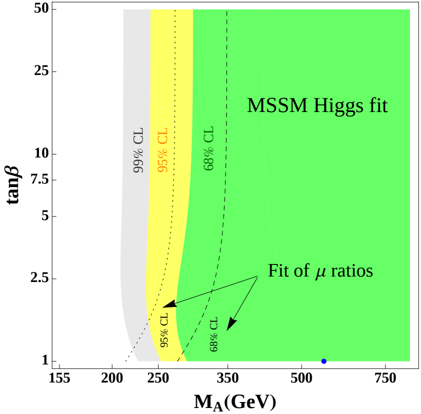
best-fit points : $(c_t = 0.88,\ c_V = 1.0)$, $(c_b = 0.97,\ c_V = 1.0)$ and $(c_t = 0.88, c_b = 0.97)$

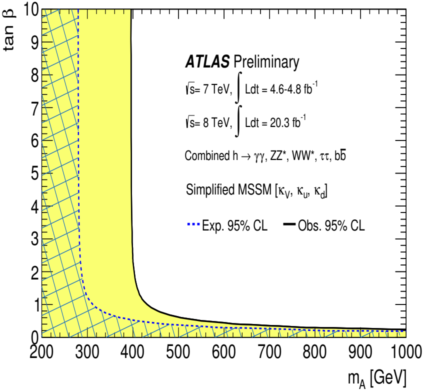
Djouadi, Maiani, Moreau, Polosa, JQ, Riquer, arXiv:1307.5205

The 2D-fit in the hMSSM

Using the expressions defining the hMSSM one can perform a fit in the plane $[\tan\beta, M_A]$:

The best-fit point : $(\tan\beta = 1$ and $M_A = 557$ GeV$)$ or
$(M_H = 580$ GeV, $M_{H^\pm} = 563$ GeV, $\alpha = -0.837$ rad$)$.





Djouadi, Maiani, Moreau, Polosa, JQ, Riquer, arXiv:1307.5205

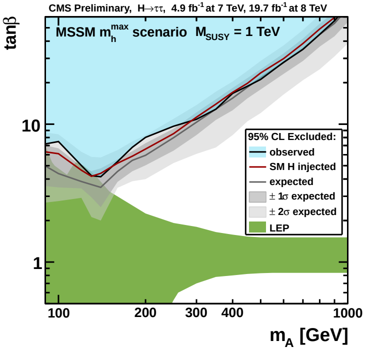
Direct heavy Higgs searches

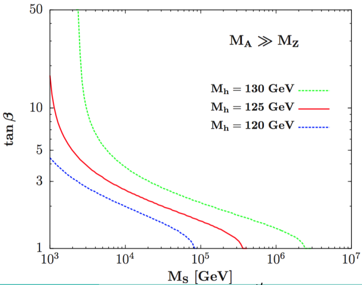
- $\tan\beta \lesssim 3$ usually thought to be "excluded" by LEP2 ($M_h \gtrsim 114$ GeV) but it assumes $M_S \sim 1$TeV!

- Caveat : ATLAS & CMS constraint apply for a specific benchmark : $X_t/M_S = \sqrt{6}$ and $M_S = 1$ TeV (the m_h^{max} scenario).

- But we can be more relaxed:
  with $M_S \gg M_Z$, $\tan\beta \approx 1$ could be allowed!

$\Rightarrow$ Let's reopen the low $\tan\beta$ regime and heavy Higgs searches,
but in a benchmark independent approach (hMSSM)





The Higgs couplings and the approach to the decoupling limit

Φ	$g_{\Phi\bar{u}u}$	$g_{\Phi\bar{d}d}$	$g_{\Phi VV}$	$g_{\Phi AZ}/g_{\Phi H^+W^-}$
h	$\cos\alpha/\sin\beta$	$-\sin\alpha/\cos\beta$	$\sin(\beta-\alpha)$	$\propto\cos(\beta-\alpha)$
H	$\sin\alpha/\sin\beta$	$\cos\alpha/\cos\beta$	$\cos(\beta-\alpha)$	$\propto\sin(\beta-\alpha)$
A	$\cot\beta$	$\tan\beta$	0	$\propto 0/1$

The decoupling limit is controlled by $g_{HVV} = \cos(\beta-\alpha)$:

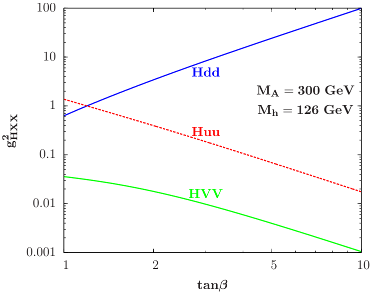
$$g_{HVV} \overset{M_A \gg M_Z}{\longrightarrow} \chi \equiv \frac{1}{2}\frac{M_Z^2}{M_A^2}\sin 4\beta - \frac{1}{2}\frac{\mathcal{M}_{22}^2}{M_A^2}\sin 2\beta \quad \to 0$$

Tree–level part: doubly suppressed in both the $\tan\beta \gg 1$ and $\tan\beta \sim 1$ cases.

$$\sin 4\beta = \frac{4\tan\beta(1-\tan^2\beta)}{(1+\tan^2\beta)^2} \to \begin{cases} -4/\tan\beta & \text{for } \tan\beta \gg 1 \\ 1-\tan^2\beta & \text{for } \tan\beta \sim 1 \end{cases} \to 0$$

The radiative part : behave as $-\mathcal{M}_{22}^2/M_A^2 \times \cot\beta$, also vanishes at high $\tan\beta$ values $\Rightarrow$ the decoupling limit $g_{HVV} \to 0$ is reached very quickly at high $\tan\beta$, as soon as $M_A \gtrsim M_h^{\max}$. Instead, for $\tan\beta \approx 1$, this radiatively generated component is maximal. Departure from the decoupling limit!

$$g_{huu} \overset{M_A \gg M_Z}{\longrightarrow} 1 + \chi\cot\beta \quad \to 1$$
$$g_{hdd} \overset{M_A \gg M_Z}{\longrightarrow} 1 - \chi\tan\beta \quad \to 1$$
$$g_{Huu} \overset{M_A \gg M_Z}{\longrightarrow} -\cot\beta + \chi \quad \to -\cot\beta$$
$$g_{Hdd} \overset{M_A \gg M_Z}{\longrightarrow} +\tan\beta + \chi \quad \to +\tan\beta$$



At low $\tan\beta$: g_{HVV} is non–zero, g_{Htt} and g_{Att} are significant.
$\Rightarrow$ $H/A/H^{\pm}$ bosons can have sizable couplings to top quarks and massive gauge bosons if $\tan\beta \sim 3$.

The hMSSM

In the basis (H_d, H_u), the CP–even Higgs mass matrix can be written as:

$$M_S^2 = M_Z^2 \begin{pmatrix} c_\beta^2 & -s_\beta c_\beta \\ -s_\beta c_\beta & s_\beta^2 \end{pmatrix} + M_A^2 \begin{pmatrix} s_\beta^2 & -s_\beta c_\beta \\ -s_\beta c_\beta & c_\beta^2 \end{pmatrix} + \begin{pmatrix} \Delta\mathcal{M}_{11}^2 & \Delta\mathcal{M}_{12}^2 \\ \Delta\mathcal{M}_{12}^2 & \Delta\mathcal{M}_{22}^2 \end{pmatrix}$$

$\Delta\mathcal{M}_{ij}^2$: radiative corrections

One derives the neutral CP-even Higgs boson masses and the mixing angle α:

$$\begin{aligned} M_{h/H}^2 &= f_{h/H}(M_A, \tan\beta, \Delta\mathcal{M}_{11}, \Delta\mathcal{M}_{12}, \Delta\mathcal{M}_{22}) \\ \tan\alpha &= f_\alpha(M_A, \tan\beta, \Delta\mathcal{M}_{11}, \Delta\mathcal{M}_{12}, \Delta\mathcal{M}_{22}) \end{aligned}$$

M_h should be an input now...

The post-Higgs MSSM scenario:

- observation of the lighter h boson at a mass of ≈ 125 *GeV*
- non-observation of superparticles at the LHC

MSSM $\Rightarrow$ SUSY–breaking scale rather high, $M_S \gtrsim 1$ TeV.

$\Delta\mathcal{M}_{22}^2$ involves the by far dominant stop–top sector correction: $\Delta\mathcal{M}_{22}^2 \gg \Delta\mathcal{M}_{11}^2, \Delta\mathcal{M}_{12}^2$

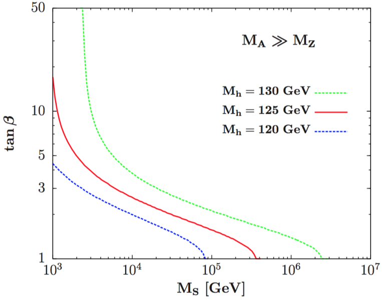
$\rightarrow$ One can trade $\Delta\mathcal{M}_{22}^2$ (M_S) for the by now known M_h

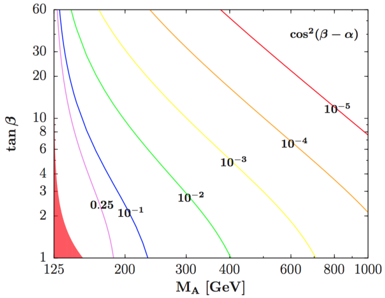
In this case, one can simply describe the Higgs sector in terms of $M_A, \tan\beta$ and M_h:

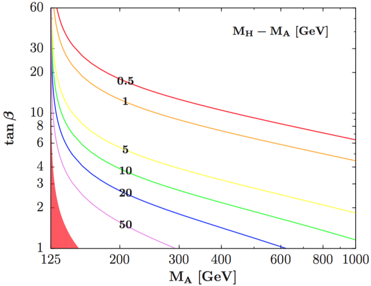
$$\text{hMSSM}: \quad \begin{aligned} M_H^2 &= \frac{(M_A^2+M_Z^2-M_h^2)(M_Z^2 c_\beta^2+M_A^2 s_\beta^2)-M_A^2 M_Z^2 c_{2\beta}^2}{M_Z^2 c_\beta^2+M_A^2 s_\beta^2-M_h^2} \\ \alpha &= -\arctan\left(\frac{(M_Z^2+M_A^2)c_\beta s_\beta}{M_Z^2 c_\beta^2+M_A^2 s_\beta^2-M_h^2}\right) \end{aligned}$$

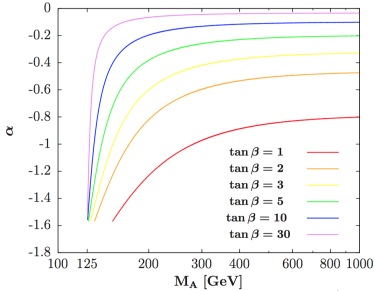
The definition of the hMSSM

Djouadi, Maiani, Polosa, JQ, Riquer, arXiv:1502.05653









2. Assumptions: standard mass matrix

The CP-even Higgs sector is usually described by the 2×2 mass matrix :

$$M_\Phi^2 = M_Z^2 \begin{pmatrix} c_\beta^2 & -s_\beta c_\beta \\ -s_\beta c_\beta & s_\beta^2 \end{pmatrix} + M_A^2 \begin{pmatrix} s_\beta^2 & -s_\beta c_\beta \\ -s_\beta c_\beta & c_\beta^2 \end{pmatrix} + \begin{pmatrix} \Delta\mathcal{M}_{11}^2 & \Delta\mathcal{M}_{12}^2 \\ \Delta\mathcal{M}_{12}^2 & \Delta\mathcal{M}_{22}^2 \end{pmatrix}$$

It is by diagonalizing this matrix that one obtains M_H, M_h and α:

- tree–level masses are given in terms of M_A and M_Z plus the angle β;
- radiative corrections (with the SUSY parameters) appear only in ΔM^2_{ij}.

Assumption clearly valid at scales M_S not far for 1 TeV (common wisdom…)

In the hMSSM, we assume that this picture is valid at much higher scales.

This is the main ‘problem’ and subject of discussion:

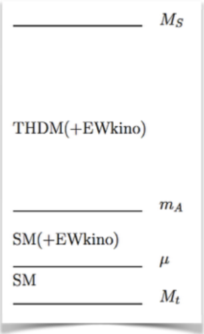
Question 1): how far can we go in M_S while retaining this simple form?

Question 2): when RGE improving, the matrix has still a convenient form?

The complete approach: effective THDM with heavy SUSY

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

Carena et al., (1410.4969)



i) Match the THDM quartic couplings to their MSSM values.

$$\lambda_1 = \lambda_2 = -(\lambda_3 + \lambda_4) = \tfrac{1}{4}(g^2 + g'^2) = m_Z^2/v^2 ,$$
$$\lambda_4 = -\tfrac{1}{2}g^2 = -2m_W^2/v^2 ,$$
$$\lambda_5 = \lambda_6 = \lambda_7 = 0 .$$

ii) Evolve (RGEs) all seven lambdas from M_S to the weak scale.

iii) CP-even Higgs mass matrix in terms of lambdas at the weak-scale:

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

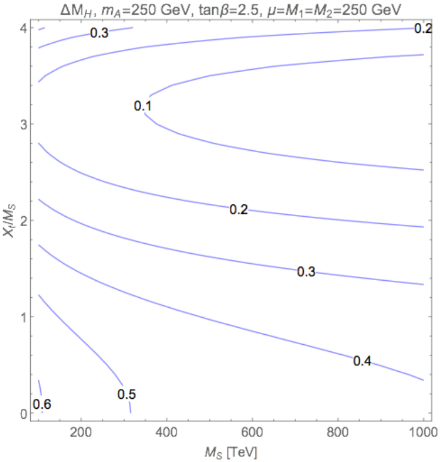
$$L_{11} = \lambda_1 c_\beta^2 + 2\lambda_6 s_\beta c_\beta + \lambda_5 s_\beta^2 ,$$
$$L_{12} = (\lambda_3 + \lambda_4) s_\beta c_\beta + \lambda_6 c_\beta^2 + \lambda_7 s_\beta^2 ,$$
$$L_{22} = \lambda_2 s_\beta^2 + 2\lambda_7 s_\beta c_\beta + \lambda_5 c_\beta^2 .$$

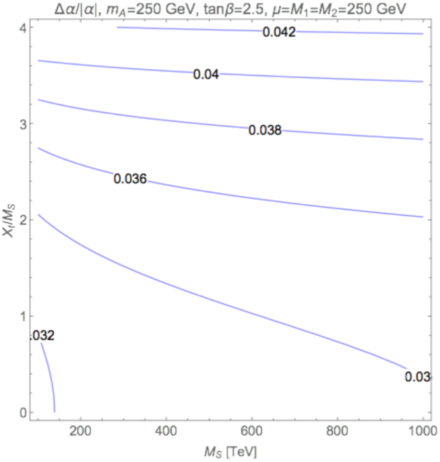
5

2. Assumptions: standard mass matrix

Comparison: hMSSM vs effective THDM with heavy SUSY at low tanβ

Gabriel Lee and Carlos Wager (work in progress)
for the HXSWG



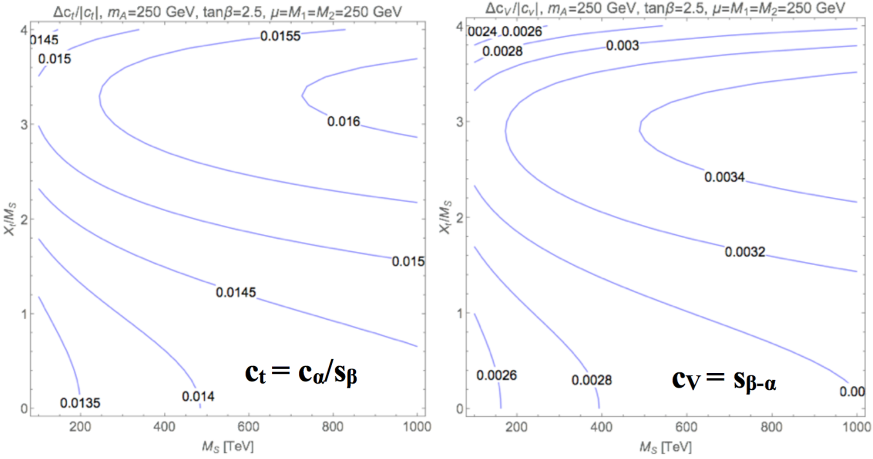


$\Delta M_H < 1\%$ $\qquad$ $\Delta\alpha/|\alpha| < 4\%$

2. Assumptions: standard mass matrix

Comparison: hMSSM vs effective THDM with heavy SUSY at low tanβ

Gabriel Lee and Carlos Wager (work in progress)
for the HXSWG



$\Delta c_t/|c_t| < 2\%$ $\Delta c_V/|c_V| < 1\%$

2. Assumptions: dominance of main correction

Dominant correction to ΔM^2 due to top/stop sector and approximately:

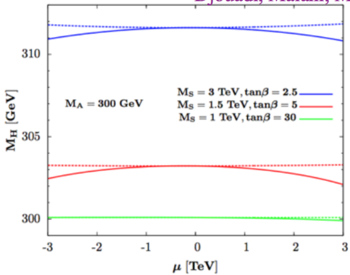
$$\Delta\mathcal{M}^2_{22} \propto \frac{3\bar{m}_t^4}{2\pi^2 v^2 \sin^2\beta}\left[\log\frac{M_S^2}{\bar{m}_t^2} + \frac{\tilde{X}_t^2}{M_S^2}\right] + \cdots \gg \Delta\mathcal{M}^2_{11}, \Delta\mathcal{M}^2_{12}$$

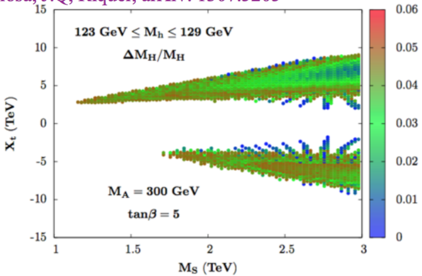
We have checked the approximation in two different configurations:

Include subleading terms in ΔM^2
(Carena, Wagner, Haber, Hempfling...)
$\lambda_t, \lambda_b, X_t = X_b$ **and varying** μ
with some choice of M_S, $\tan\beta$.

Scan of the MSSM parameters with all Higgs rad. corrections
(we use Suspect with BDSZ RC)
and impact of M_S, A_t, μ, A_b

Djouadi, Maiani, Moreau, Polosa, J.Q, Riquer, arXiv: 1307.5205

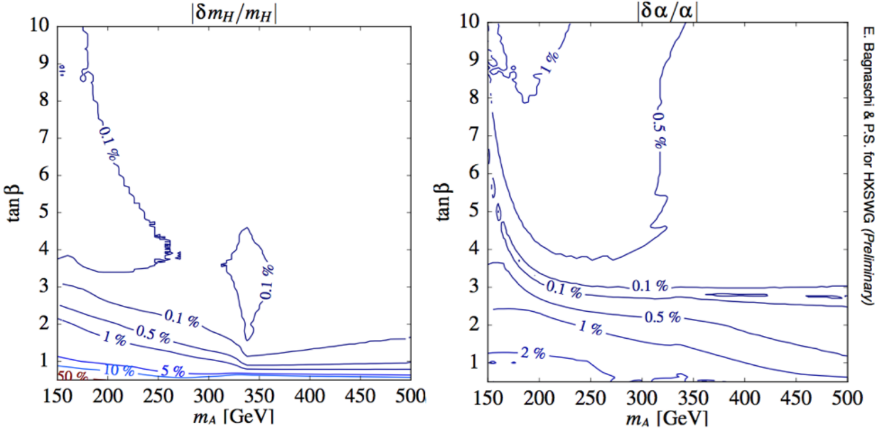




Very good approximation ($\lesssim$ few percent) for M_H, α for not too large μ.

2. Assumptions: dominance of main correction

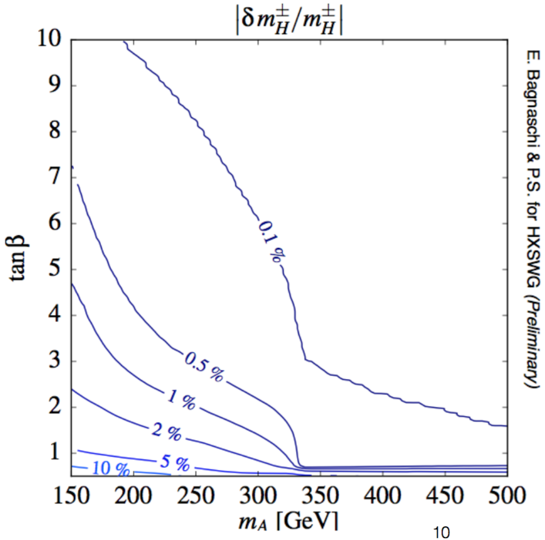
Comparing hMSSM and FeynHiggs



Agreement at the level of 0.1% – 1% except for very low *tanβ*

2. Assumptions: dominance of main correction

hMSSM vs FeynHiggs : charged Higgs mass



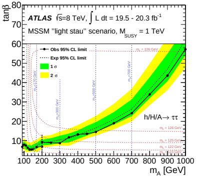
10

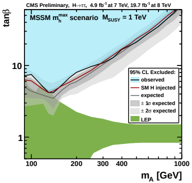
In the hMSSM approximation the charged Higgs mass sticks to its tree-level value:

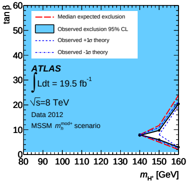
$$m_{H\pm}^2 = m_A^2 + m_W^2$$

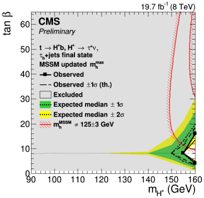
Implications from heavy Higgs searches

Combine ATLAS+CMS $pp \to H^{\pm} \to \tau\nu$ and $pp \to A/H \to \tau^+\tau^-$





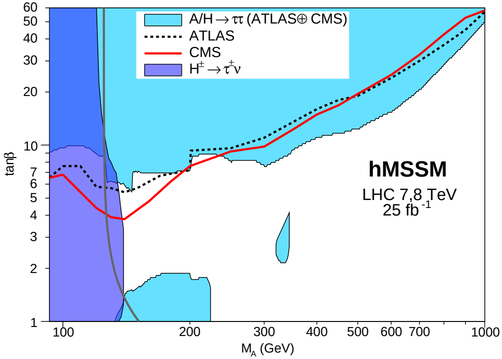




- From $t \to bH^+ \to b\tau\nu$ search: $M_A \lesssim 140$ GeV is now excluded
- $pp \to \tau\tau$ sensitive at high $\tan\beta$:
  - weaker at low M_A (no h events)
  - stronger at high M_A (no SUSY)
- low $\tan\beta$ can now be considered
  A excludes small part of low $\tan\beta$)
  $\Rightarrow$ forbidden area excluded!

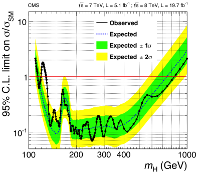
Djouadi, Maiani, Polosa, JQ, Riquer,

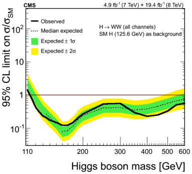
arXiv:1502.05653

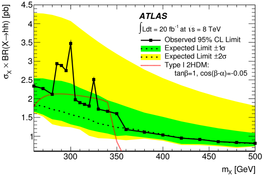


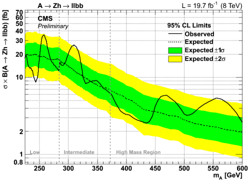
Implications from heavy Higgs searches

Extend search for heavy SM Higgs for MSSM and consider new channels:
$pp \to H \to ZZ$; $pp \to H \to WW$; $pp \to H \to hh$; $pp \to A \to hZ$

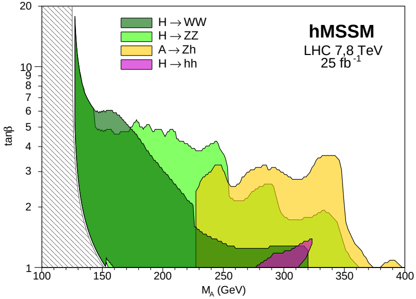






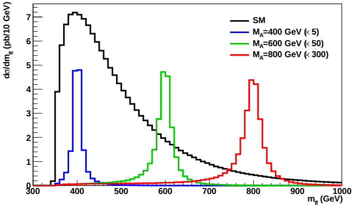


Djouadi, Maiani, Polosa, JQ, Riquer,
arXiv:1502.05653

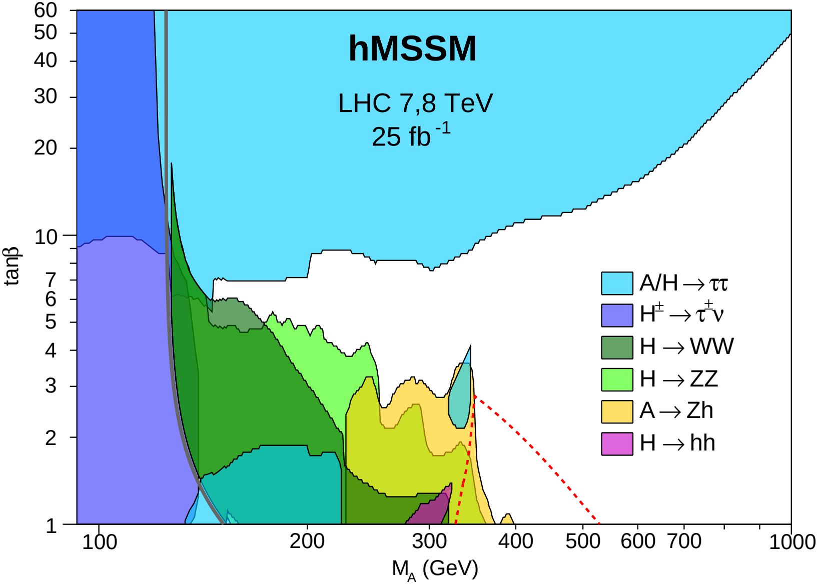


Also consider $pp \to \Phi \to tt$

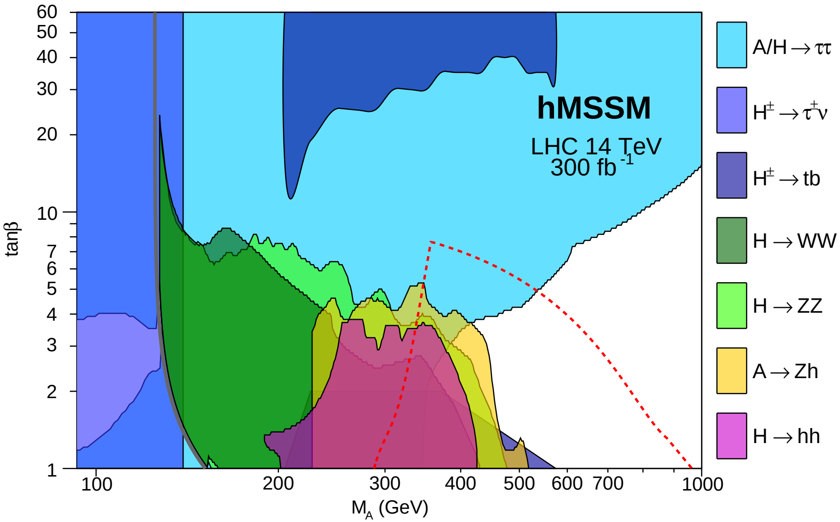
- crucial at low $\tan\beta$, high M_A
- very interesting features...



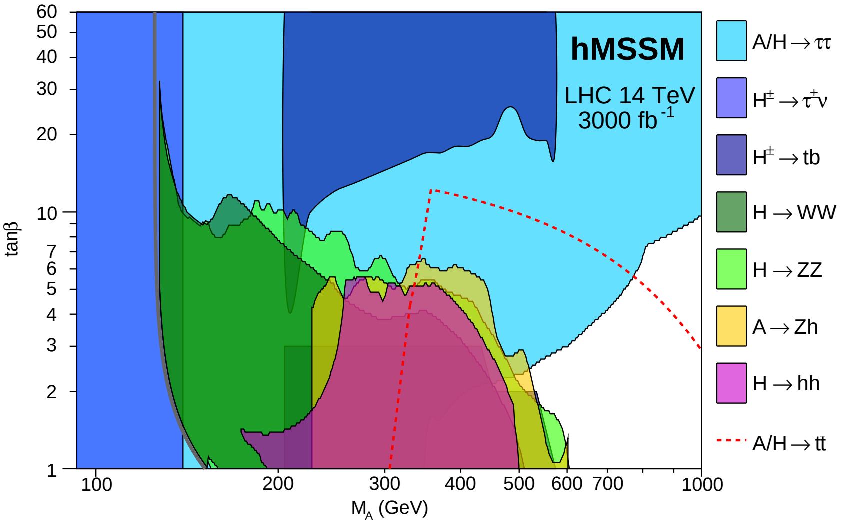
Djouadi, Maiani, Polosa, JQ, Riquer,
arXiv:1502.05653



Djouadi, Maiani, Polosa, JQ, Riquer,
arXiv:1502.05653



Djouadi, Maiani, Polosa, JQ, Riquer,
arXiv:1502.05653



Outline

1. Fully Covering the MSSM Higgs Sector at the LHC
2. Covering the MSSM stop sector

Covering the MSSM stop sector at the LHC

Matching between the MSSM and the dim6-EFT

$$\mathcal{L} = \mathcal{L}_{SM} + \sum_i c_i \frac{\mathcal{O}_i}{\Lambda^2}$$

$\mathbf{m_{stop}}$

$$\begin{aligned}
\mathcal{O}_{GG} &= g_s^2 |H|^2 G^a_{\mu\nu} G^{a,\mu\nu} \\
\mathcal{O}_{WW} &= g^2 |H|^2 W^a_{\mu\nu} W^{a,\mu\nu} \\
\mathcal{O}_{BB} &= g'^2 |H|^2 B_{\mu\nu} B^{\mu\nu} \\
\mathcal{O}_{WB} &= 2 g g' H^\dagger t^a H W^a_{\mu\nu} B^{\mu\nu} \\
\mathcal{O}_{W} &= i g (H^\dagger t^a \overleftrightarrow{D}^\mu H) D^\nu W^a_{\mu\nu} \\
\mathcal{O}_{B} &= i g' Y_H (H^\dagger \overleftrightarrow{D}^\mu H) \partial^\nu B_{\mu\nu} \\
\mathcal{O}_{3G} &= \tfrac{1}{3!} g_s f^{abc} G^{a\mu}_\rho G^{b\nu}_\mu G^{c\rho}_\nu \\
\mathcal{O}_{3W} &= \tfrac{1}{3!} g \epsilon^{abc} W^{a\mu}_\rho W^{b\nu}_\mu W^{c\rho}_\nu
\end{aligned}
\qquad
\begin{aligned}
\mathcal{O}_{H} &= \tfrac{1}{2} (\partial_\mu |H|^2)^2 \\
\mathcal{O}_{T} &= \tfrac{1}{2} (H^\dagger \overleftrightarrow{D}_\mu H)^2 \\
\mathcal{O}_{R} &= |H|^2 |D_\mu H|^2 \\
\mathcal{O}_{D} &= |D^2 H|^2 \\
\mathcal{O}_{6} &= |H|^6 \\
\mathcal{O}_{2G} &= -\tfrac{1}{2} (D^\mu G^a_{\mu\nu})^2 \\
\mathcal{O}_{2W} &= -\tfrac{1}{2} (D^\mu W^a_{\mu\nu})^2 \\
\mathcal{O}_{2B} &= -\tfrac{1}{2} (\partial^\mu B_{\mu\nu})^2
\end{aligned}$$

$$\begin{aligned}
c_{GG} &= \frac{h_t^2}{(4\pi)^2} \frac{1}{12} \left[\left(1 + \frac{1}{12} \frac{g'^2 c_{2\beta}}{h_t^2}\right) - \frac{1}{2} \frac{X_t^2}{m_{\tilde t}^2} \right] \\
c_{WW} &= \frac{h_t^2}{(4\pi)^2} \frac{1}{16} \left[\left(1 - \frac{1}{6} \frac{g'^2 c_{2\beta}}{h_t^2}\right) - \frac{2}{5} \frac{X_t^2}{m_{\tilde t}^2} \right] \\
c_{BB} &= \frac{h_t^2}{(4\pi)^2} \frac{17}{144} \left[\left(1 + \frac{31}{102} \frac{g'^2 c_{2\beta}}{h_t^2}\right) - \frac{38}{85} \frac{X_t^2}{m_{\tilde t}^2} \right]
\end{aligned}
\qquad
\begin{aligned}
c_{WB} &= -\frac{h_t^2}{(4\pi)^2} \frac{1}{24} \left[\left(1 + \frac{1}{2} \frac{g^2 c_{2\beta}}{h_t^2}\right) - \frac{4}{5} \frac{X_t^2}{m_{\tilde t}^2} \right] \\
c_{W} &= \frac{h_t^2}{(4\pi)^2} \frac{1}{40} \frac{X_t^2}{m_{\tilde t}^2} \\
c_{B} &= \frac{h_t^2}{(4\pi)^2} \frac{1}{40} \frac{X_t^2}{m_{\tilde t}^2}
\end{aligned}$$

B. Henning, X. Lu and H. Murayama
arXiv:1404.1058
Wilson coefficients for degenerate stop soft SUSY breaking masses

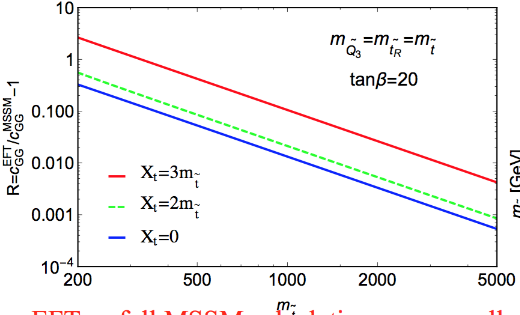
$$\begin{aligned}
c_{3G} &= \frac{g_s^2}{(4\pi)^2} \frac{1}{20} \\
c_{3W} &= \frac{g^2}{(4\pi)^2} \frac{1}{20} \\
c_{2G} &= \frac{g_s^2}{(4\pi)^2} \frac{1}{20} \\
c_{2W} &= \frac{g^2}{(4\pi)^2} \frac{1}{20} \\
c_{2B} &= \frac{g'^2}{(4\pi)^2} \frac{1}{20}
\end{aligned}$$

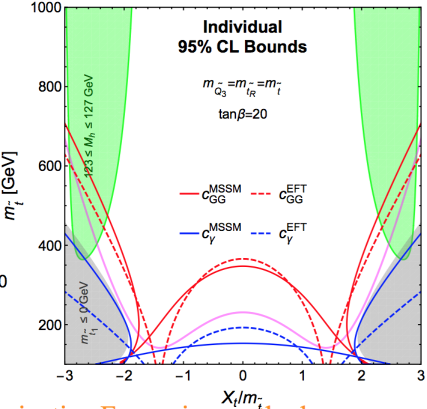
$$\begin{aligned}
c_H &= \frac{h_t^4}{(4\pi)^2} \frac{3}{4} \left[\left(1 + \frac{1}{3} \frac{g'^2 c_{2\beta}}{h_t^2} + \frac{1}{12} \frac{g'^4 c_{2\beta}^2}{h_t^4}\right) - \frac{7}{6} \frac{X_t^2}{m_{\tilde t}^2} \left(1 + \frac{1}{14} \frac{(g^2 + 2g'^2) c_{2\beta}}{h_t^2}\right) + \frac{7}{30} \frac{X_t^4}{m_{\tilde t}^4} \right] \\
c_T &= \frac{h_t^4}{(4\pi)^2} \frac{1}{4} \left[\left(1 + \frac{1}{2} \frac{g^2 c_{2\beta}}{h_t^2}\right)^2 - \frac{1}{2} \frac{X_t^2}{m_{\tilde t}^2} \left(1 + \frac{1}{2} \frac{g^2 c_{2\beta}}{h_t^2}\right) + \frac{1}{10} \frac{X_t^4}{m_{\tilde t}^4} \right] \\
c_R &= \frac{h_t^4}{(4\pi)^2} \frac{1}{2} \left[\left(1 + \frac{1}{2} \frac{g^2 c_{2\beta}}{h_t^2}\right)^2 - \frac{3}{2} \frac{X_t^2}{m_{\tilde t}^2} \left(1 + \frac{1}{12} \frac{(3g^2 + g'^2) c_{2\beta}}{h_t^2}\right) + \frac{3}{10} \frac{X_t^4}{m_{\tilde t}^4} \right] \\
c_D &= \frac{h_t^2}{(4\pi)^2} \frac{1}{20} \frac{X_t^2}{m_{\tilde t}^2}
\end{aligned}$$

A. Drozd, J. Ellis, J.Q. and T. You
arXiv 1504.02409 + work in progress..
general expression of the Wilson coefficients : non-degenerate stop masses

Covering the MSSM stop sector at the LHC

A. Drozd, J. Ellis, J.Q. and T. You arXiv 1504.02409



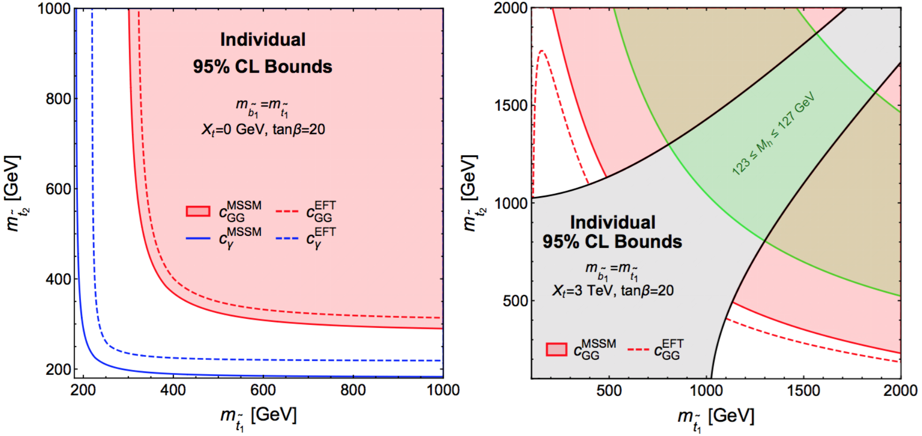


- EFT vs full MSSM calculation agrees well (non-trivial check!)
- EFT calculation simplified by Covariant Derivative Expansion method Henning, Lu & Murayama [arXiv:1412.1837]
- Systematic way of integrating out UV degrees of freedom in manifestly gauge-invariant way
- The universal 1-loop EFT facilitates extending constraints to any UV model: work in progress…

Covering the MSSM stop sector at the LHC

General case: non-degenerate stops

A. Drozd, J. Ellis, J.Q. and T. You arXiv 1504.02409

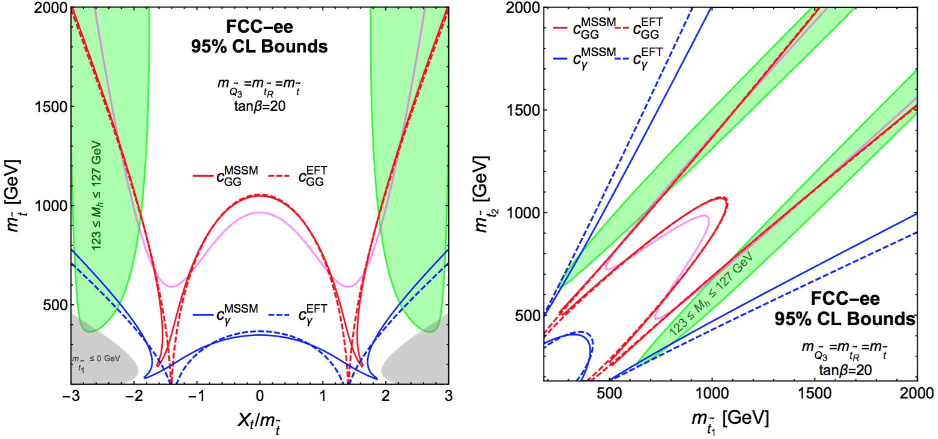


- The current sensitivity is already comparable to that of direct LHC searches

Covering the MSSM stop sector at the LHC

General case: non-degenerate stops

A. Drozd, J. Ellis, J.Q. and T. You arXiv 1504.02409



•Future FCC-ee measurements could be sensitive to stop masses above a TeV

Conclusion

- $M_h \approx 125$ GeV and the non–observation of SUSY particles, seems to indicate that the soft–SUSY breaking scale might be large
- We have discussed the hMSSM, i.e. the MSSM that we seem to have after the discovery of the Higgs boson at the LHC
  $\Rightarrow$ the MSSM Higgs sector can be described by only $(\tan\beta, M_A)$
- $H/A/H^{\pm}$ searches at the LHC are becoming very constraining
- Some search channels at low $\tan\beta$ still relevant: $H \to \tau\tau, WW, ZZ, hZ, hh, tt \Rightarrow$ need to continue/adapt the SM Higgs searches at high masses!
- 7–8 TeV LHC for the lightest h and 13–14 TeV LHC for $H/A/H^{\pm}$? and maybe some SUSY particles will show up?

- The universal 1-loop EFT facilitates extending constraints to any UV model
- The current sensitivity is already comparable to that of direct LHC searches (MSSM)
- Future FCC-ee measurements could be sensitive to stop masses above a TeV

Thanks !

The Minimal Supersymmetric Standard Model

Defined by 4 assumptions :

(a) Minimal gauge group: the MSSM is based on the group $\mathrm{SU(3)_C \times SU(2)_L \times U(1)_Y}$, i.e. the SM gauge symmetry.

(b) Minimal particle content:

gauge bosons + spin 1/2 SUSY partners : $\hat{G}^a, \hat{W}^a, \hat{B}$ (vector superfileds)

quarks and leptons + squarks and sleptons: $\hat{Q}, \hat{U}_R, \hat{D}_R, \hat{L}, \hat{E}_R$. (3 gen. of chiral superfields)

2 Higgs doublets + spin 1/2 SUSY partners: $\hat{H}_1, \hat{H}_2$

(c) Minimal Yukawa interactions and R–parity conservation: a discrete symmetry called R–parity is imposed (enforce lepton and baryon number conservation)

$$R_p = (-1)^{2s+3B+L}; \quad R_p = \pm 1 \quad \text{for SM/SUSY particule}$$

(d) Minimal set of soft SUSY–breaking terms:

- Mass for gauginos: $-\mathcal{L}_{\rm gino} = \frac{1}{2}\left[M_1 \tilde{B}\tilde{B} + M_2 \sum_{a=1}^{3} \tilde{W}^a \tilde{W}_a + M_3 \sum_{a=1}^{8} \tilde{G}^a \tilde{G}_a \ + \ \text{h.c.}\right]$
- Mass for sfermions: $-\mathcal{L}_{\rm sf} = \sum_{i=gen} m^2_{\tilde{Q}_i} \tilde{Q}_i^\dagger \tilde{Q}_i + m^2_{\tilde{L}_i} \tilde{L}_i^\dagger \tilde{L}_i + m^2_{\tilde{u}_i} |\tilde{u}_{R_i}|^2 + m^2_{\tilde{d}_i} |\tilde{d}_{R_i}|^2 + m^2_{\tilde{\ell}_i} |\tilde{\ell}_{R_i}|^2$
- Mass and bilinear for the Higgs: $-\mathcal{L}_{\rm Higgs} = m^2_{H_2} H_2^\dagger H_2 + m^2_{H_1} H_1^\dagger H_1 + B\mu(H_2 \cdot H_1 + \text{h.c.})$
- Trilinear: $-\mathcal{L}_{\rm tril.} = \sum_{i,j=gen}\left[A^u_{ij} Y^u_{ij} \tilde{u}^*_{R_i} H_2 \cdot \tilde{Q}_j + A^d_{ij} Y^d_{ij} \tilde{d}^*_{R_i} H_1 \cdot \tilde{Q}_j + A^l_{ij} Y^\ell_{ij} \tilde{\ell}^*_{R_i} H_1 \cdot \tilde{L}_j \ + \ \text{h.c.}\right]$

105 parameters (SSB) + 19 (SM) $\Rightarrow$ phenomenological analysis complicated
Only 22 for the pMSSM:
$M_1, M_2, M_3, m_{\tilde{q}}, m_{\tilde{u}_R}, m_{\tilde{d}_R}, A_u, A_d, A_e, m_{\tilde{l}}, m_{\tilde{e}_R}, m_{\tilde{Q}}, m_{\tilde{t}_R}, m_{\tilde{b}_R}, m_{\tilde{L}}, m_{\tilde{\tau}_R}, A_\tau, A_b, A_t, \tan\beta, m^2_{H_1}, m^2_{H_2}$