Fully covering the MSSM Higgs sector at the LHC

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GDR Terascale à Saclay, le 30 Mars 2015

1. The definition of the hMSSM

MSSM Higgs sector simple at tree level, only 2 inputs: M_A, tanβ

Complications due to Radiative Corrections involving $M_S, X_t, X_b, \mu, \ldots$

$$M_h^2 \overset{M_A \gg M_Z}{\to} M_Z^2 |\cos^2 2\beta| + \frac{3\bar{m}_t^4}{2\pi^2 v^2 \sin^2\beta}\left[\log\frac{M_S^2}{\bar{m}_t^2} + \frac{X_t^2}{M_S^2}\left(1 - \frac{X_t^2}{12\, M_S^2}\right)\right]$$

The LHC told us : $M_h = 125$ GeV, $M_S \gtrsim 1$TeV

hMSSM: trade the value $M_h = 125$ GeV against the radiative corrections

Back to tree-level: only 2 inputs M_A, tanβ for Higgs sector and non SUSY parameters:

$$M_H^2 = \frac{(M_A^2+M_Z^2-M_h^2)(M_Z^2 c_\beta^2+M_A^2 s_\beta^2)-M_A^2 M_Z^2 c_{2\beta}^2}{M_Z^2 c_\beta^2+M_A^2 s_\beta^2-M_h^2}$$

$$\alpha = -\arctan\left(\frac{(M_Z^2+M_A^2)c_\beta s_\beta}{M_Z^2 c_\beta^2+M_A^2 s_\beta^2-M_h^2}\right)$$

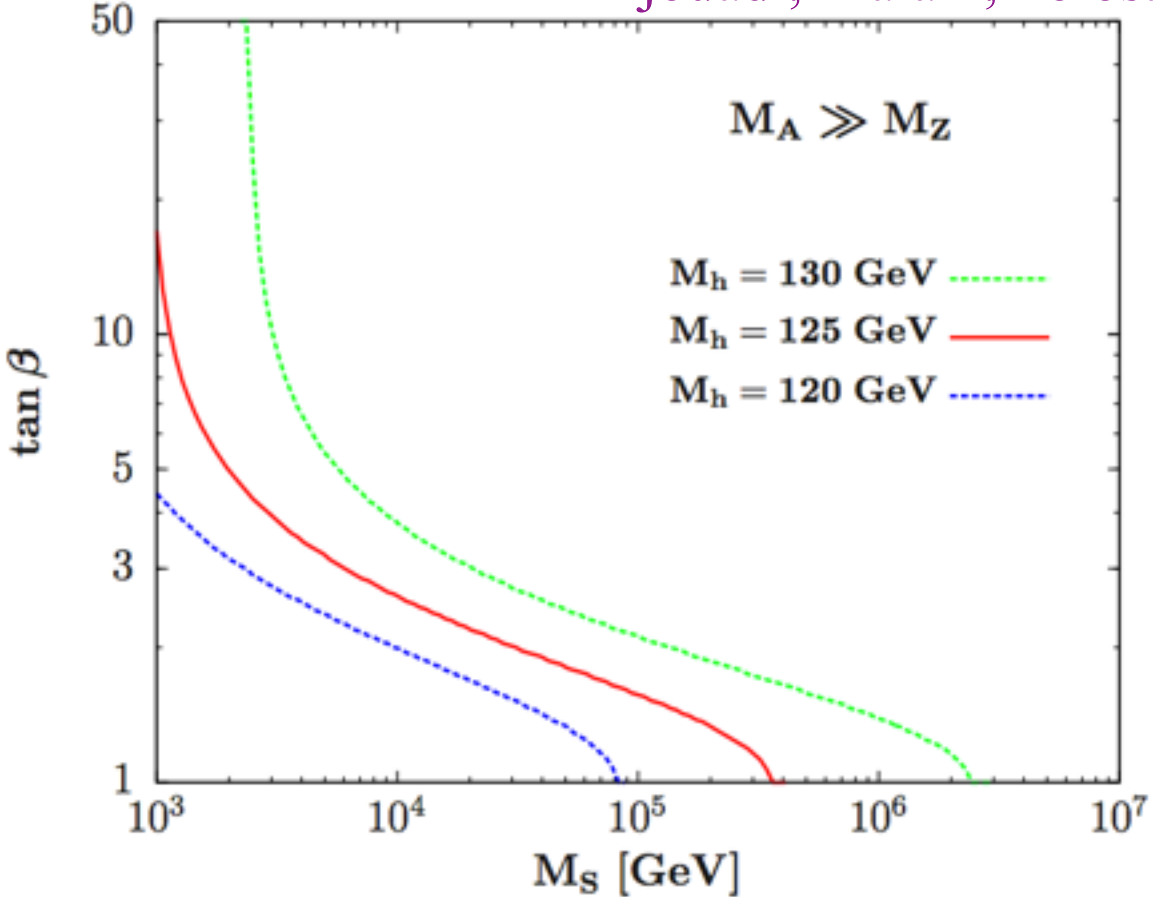
$$M_{H^\pm}^2 \simeq M_A^2 + M_W^2$$

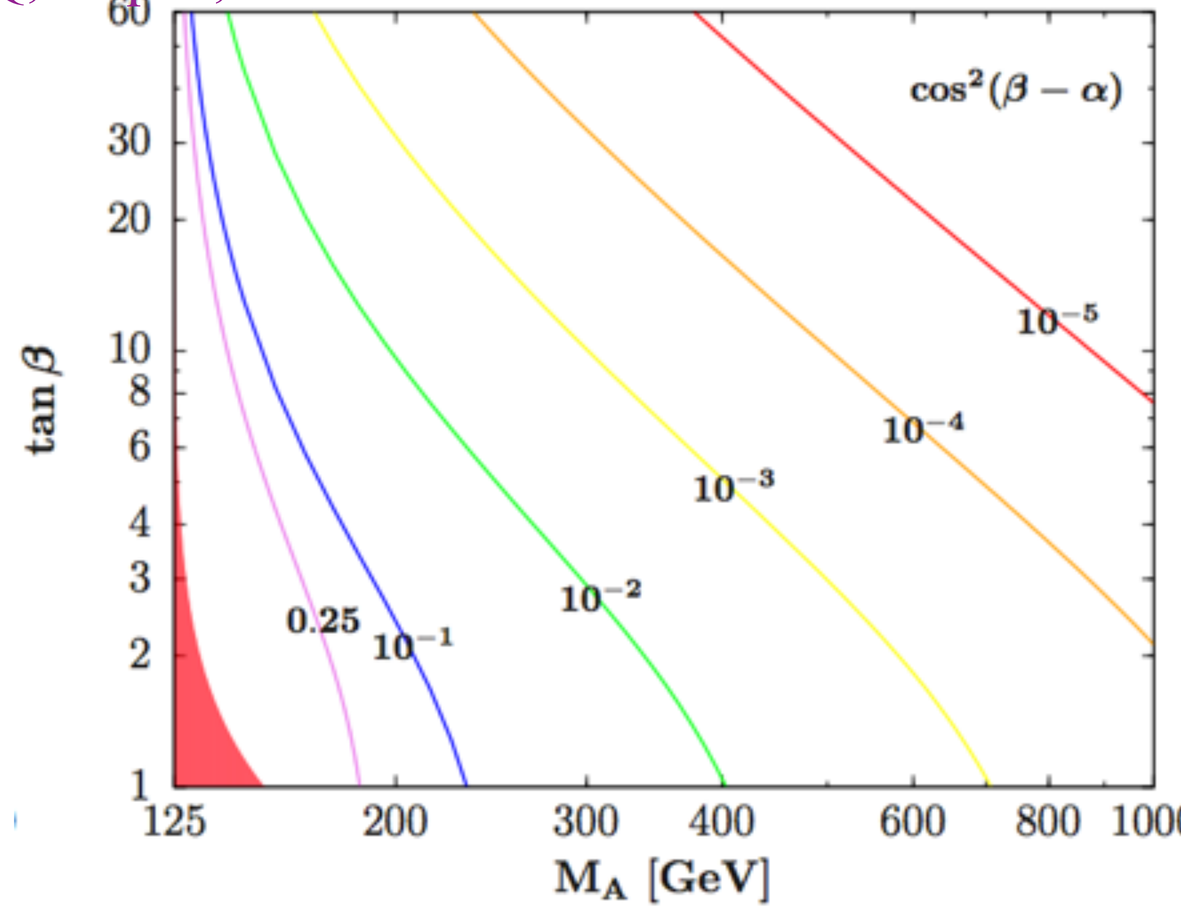
Effective and model 'independent approach' approach of the MSSM Higgs sector :

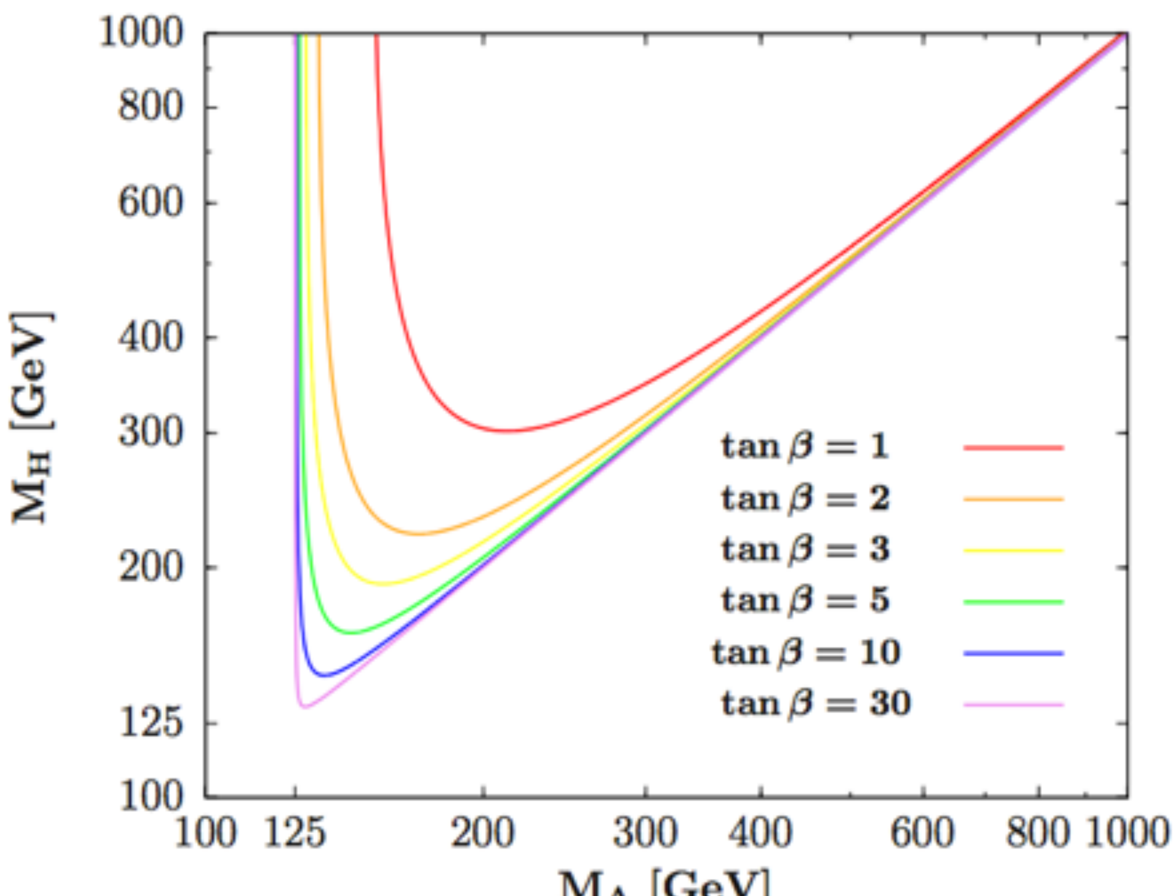
- **opens the low tanβ region in a very simple and economical and accurate way**
- **requires large M_S at low tanβ; not defined at very low M_A**
- **needs large fine-tuning (but theory already fined-tuned anyway..)**

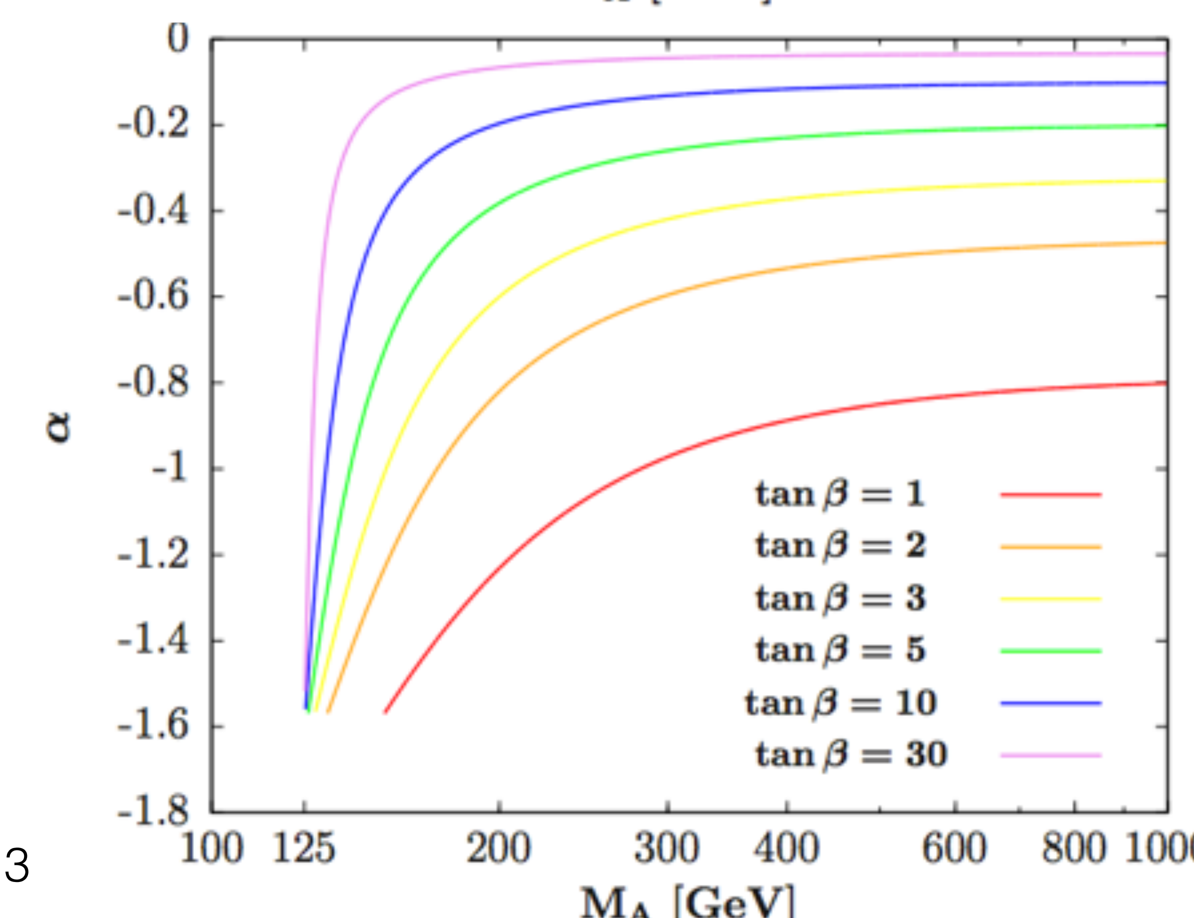
1. The definition of the hMSSM

Djouadi, Maiani, Polosa, J.Q, Riquer, arXiv: 1502.05653









2. Assumptions: standard mass matrix

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

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

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?

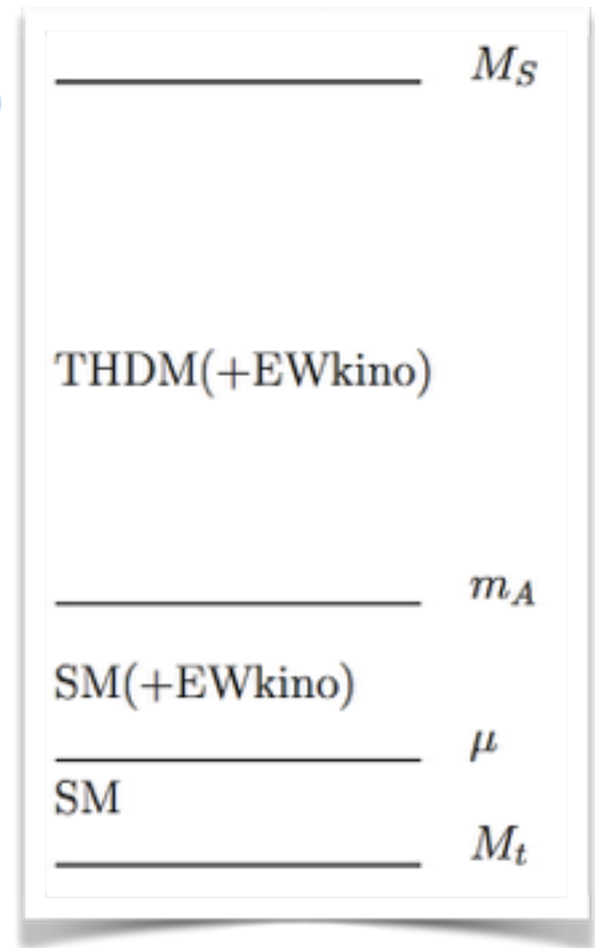
Question 2): when RGE improving, the matrix has still a convenient form?

2. Assumptions: standard mass matrix

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.

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

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:

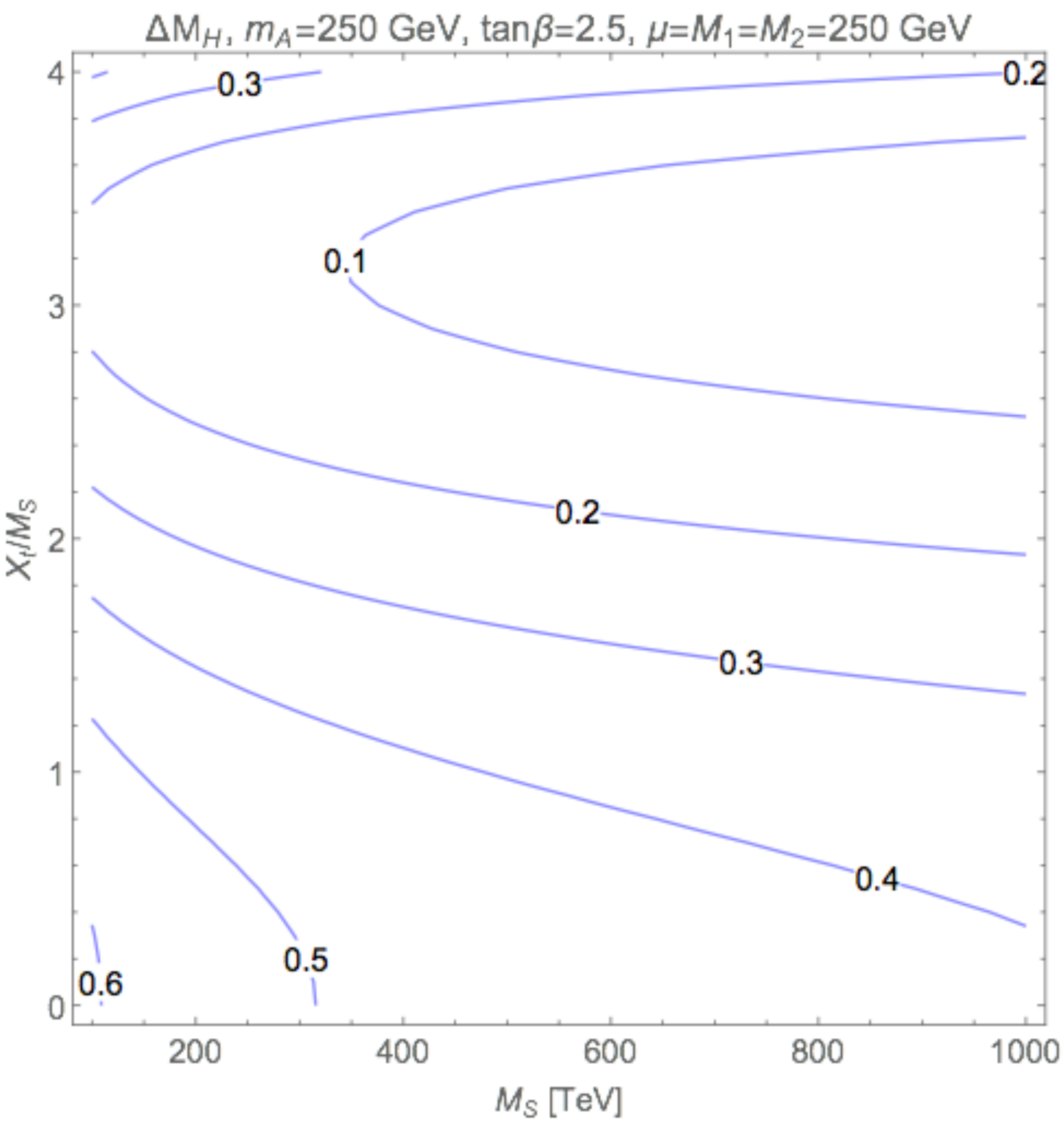
$$m_A^2 \begin{pmatrix} s_\beta^2 & -s_\beta c_\beta \\ -s_\beta c_\beta & c_\beta^2 \end{pmatrix} + v^2 \begin{pmatrix} L_{11} & L_{12} \\ L_{12} & L_{22} \end{pmatrix}$$

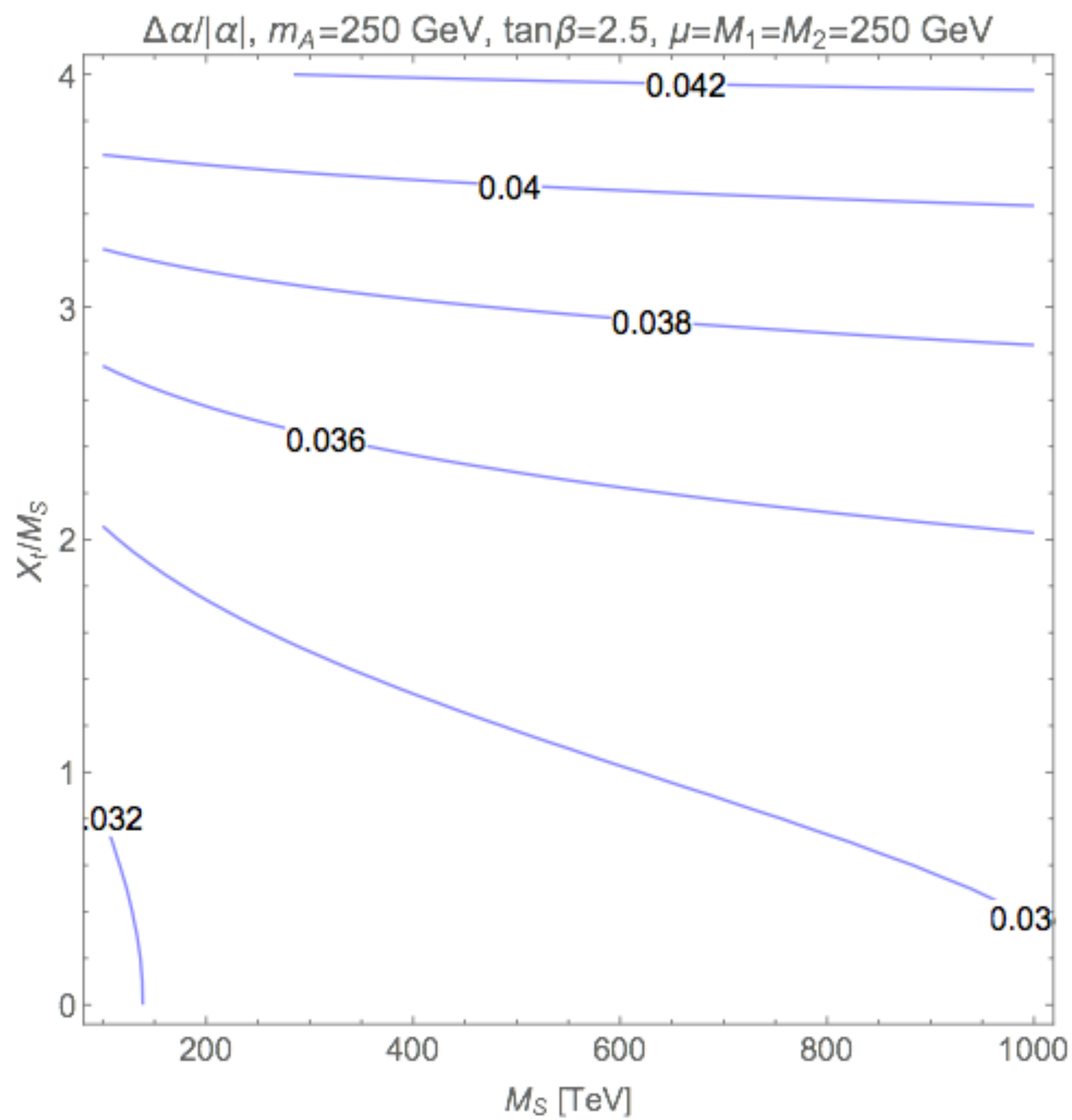
$$L_{11} = \lambda_1 c_\beta^2 + 2\lambda_6 s_\beta c_\beta + \lambda_5 s_\beta^2 ,$$
$$L_{12} = (\lambda_3 + \lambda_4) s_\beta c_\beta + \lambda_6 c_\beta^2 + \lambda_7 s_\beta^2 ,$$
$$L_{22} = \lambda_2 s_\beta^2 + 2\lambda_7 s_\beta c_\beta + \lambda_5 c_\beta^2 .$$

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





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

2. Assumptions: standard mass matrix

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

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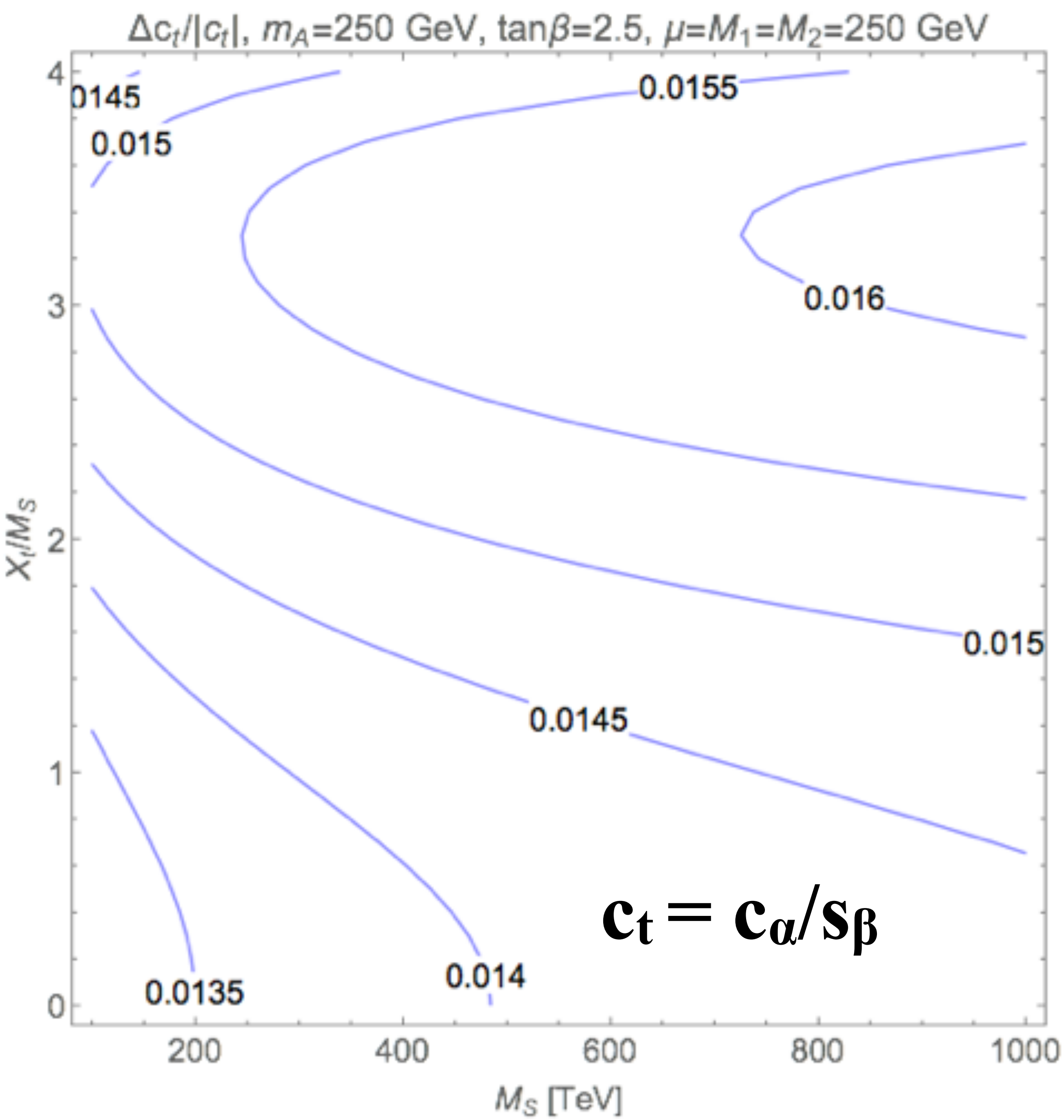
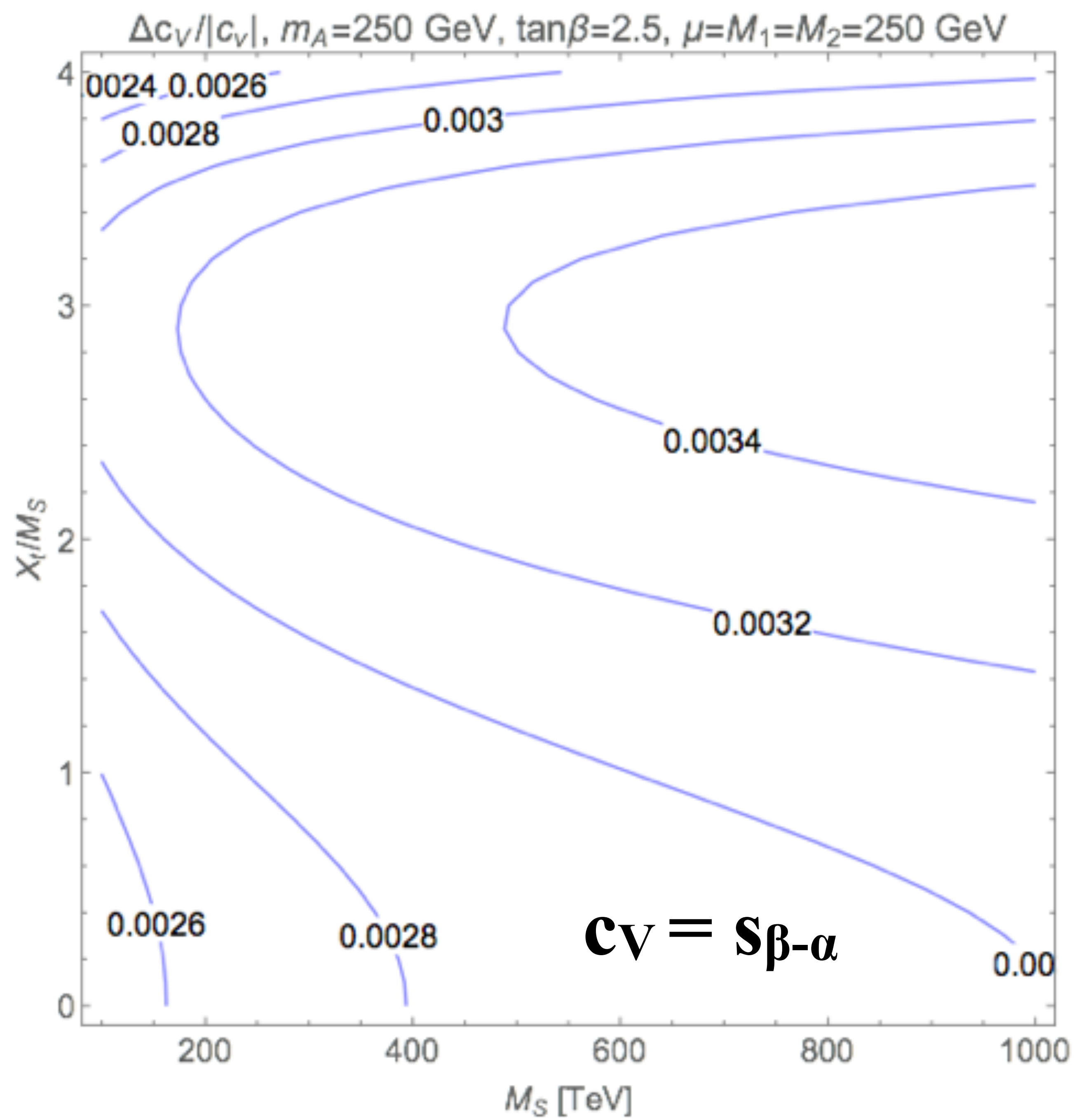




$\Delta c_t/|c_t| < 2\%$ $\Delta c_V/|c_V| < 1\%$

2. Assumptions: dominance of main correction

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

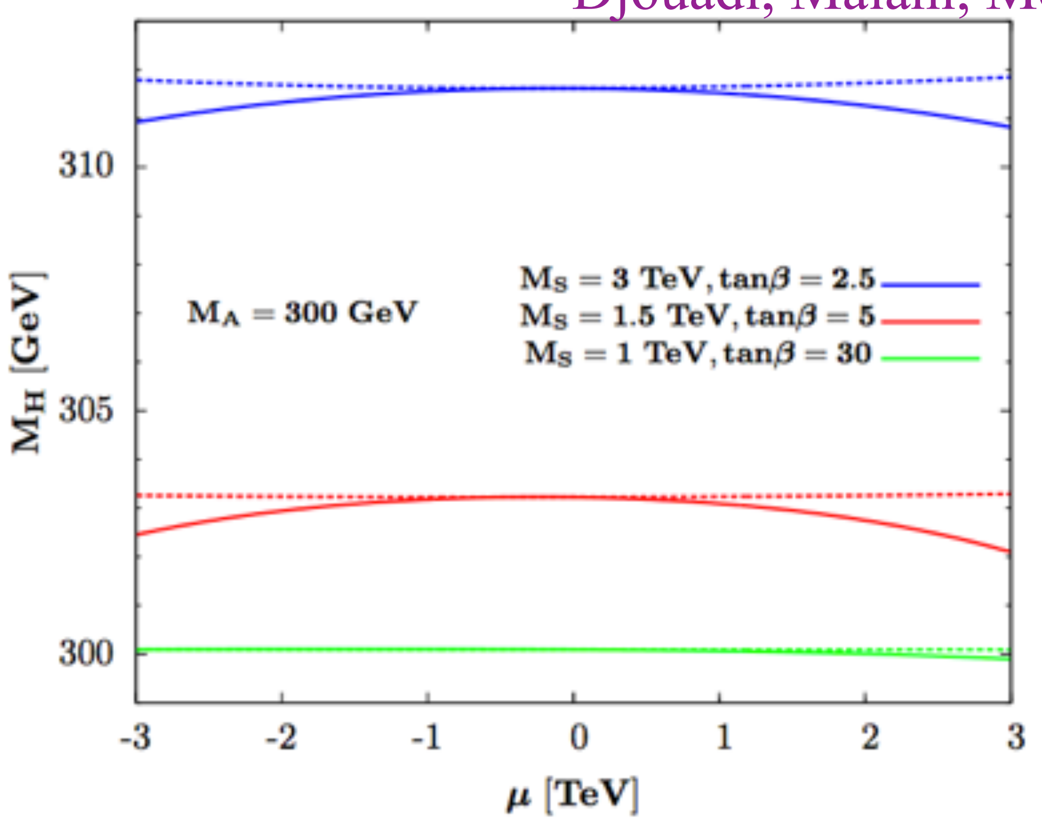
$$\Delta\mathcal{M}^2_{22} \propto \frac{3\bar{m}_t^4}{2\pi^2 v^2 \sin^2\beta}\left[\log\frac{M_S^2}{\bar{m}_t^2} + \frac{\tilde{X}_t^2}{M_S^2}\right] + \cdots \gg \Delta\mathcal{M}^2_{11}, \Delta\mathcal{M}^2_{12}$$

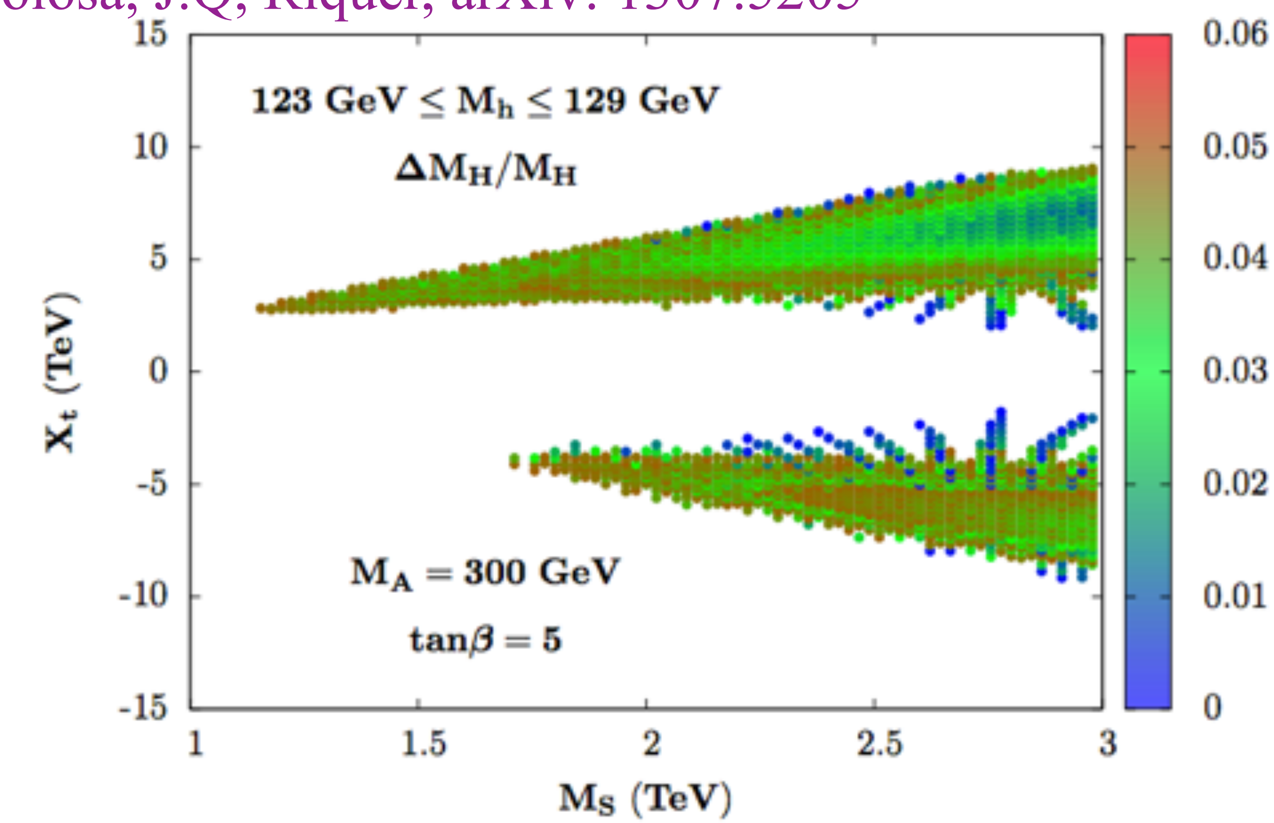
We have checked the approximation in two different configurations:

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

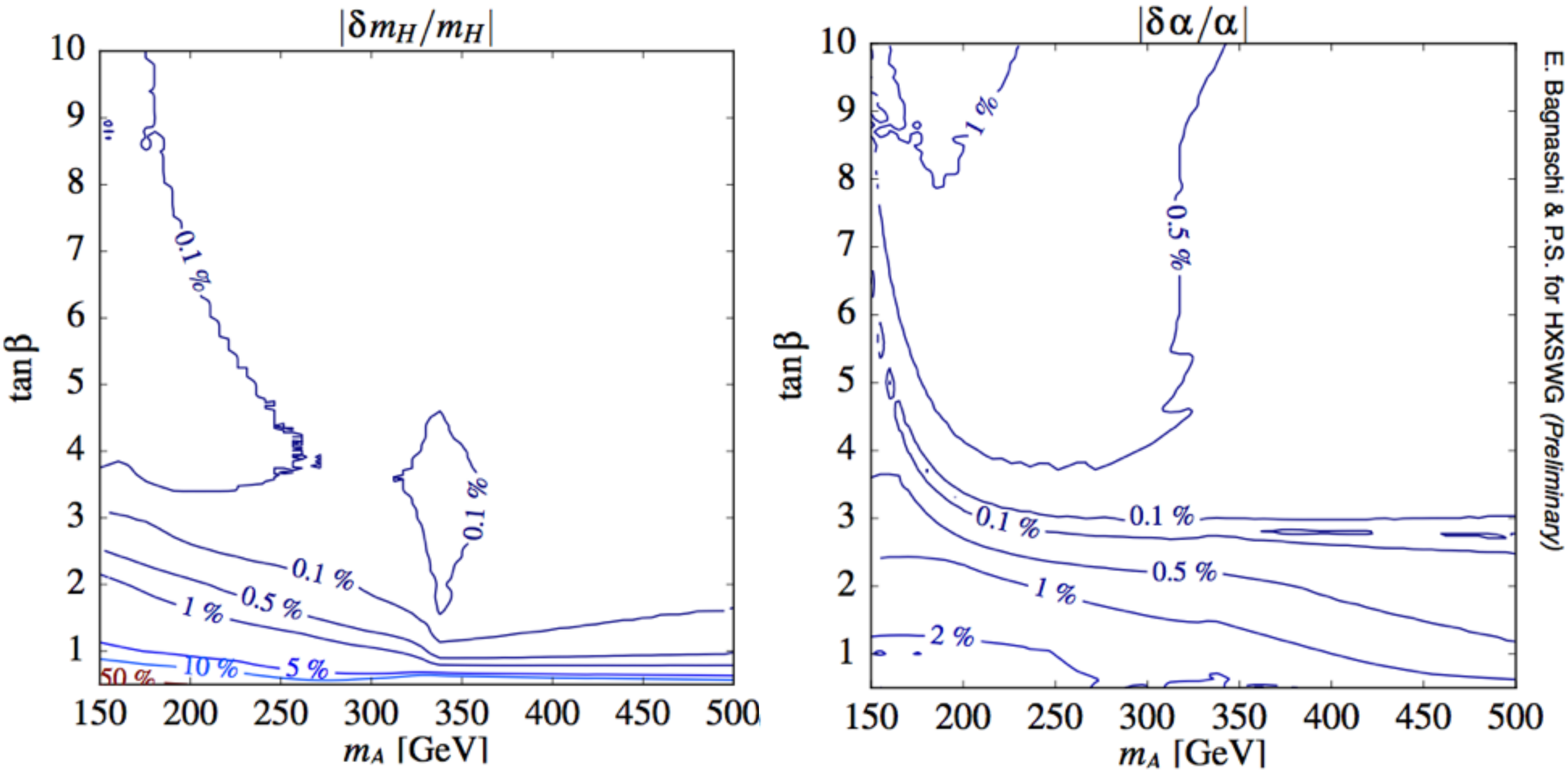




Very good approximation ($\leq$ few percent) for M_H, α for not too large μ.

2. Assumptions: dominance of main correction

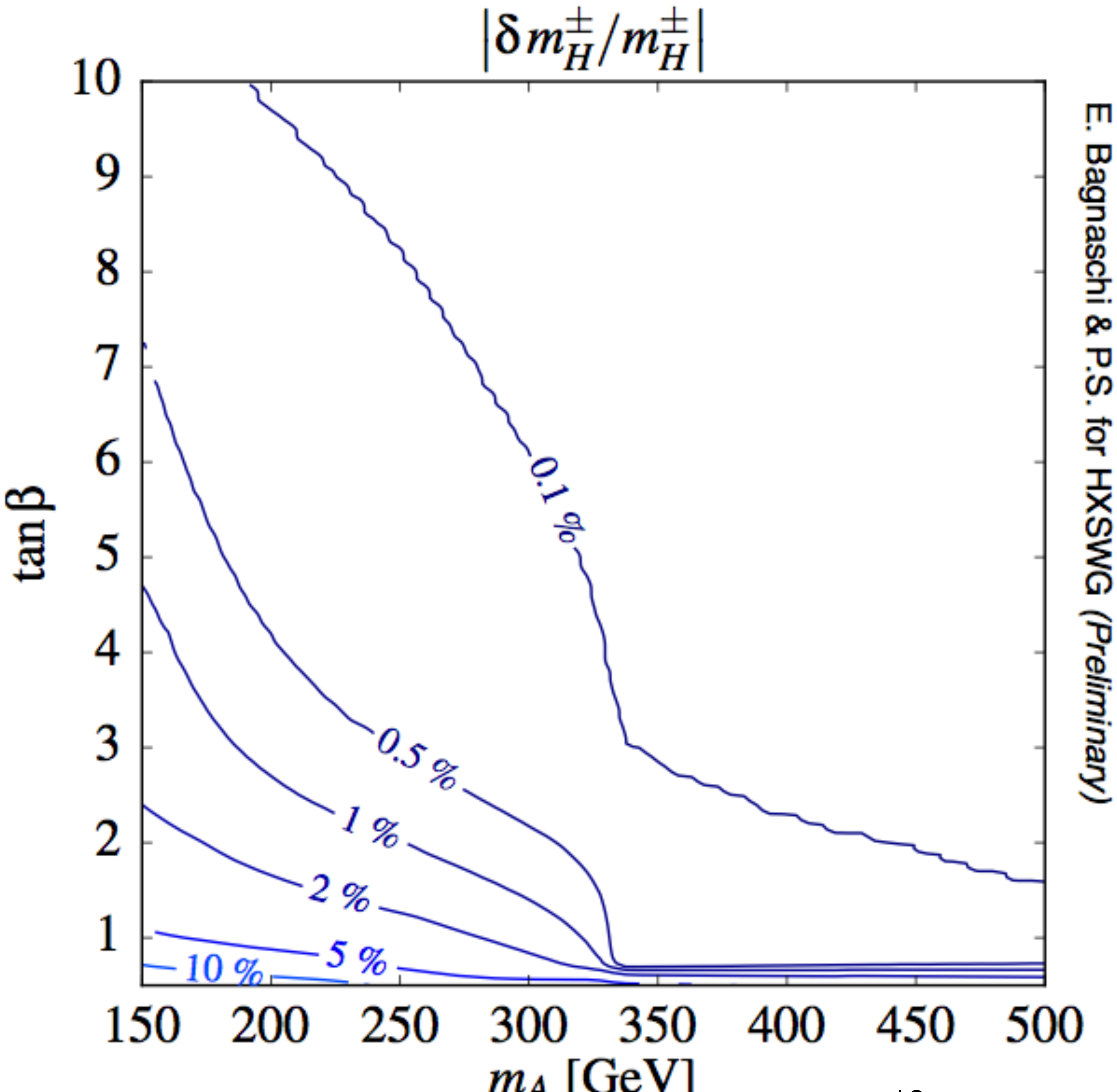
Comparing hMSSM and FeynHiggs



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



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

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

2. Assumptions: no direct corrections

Higgs couplings given by α and β: no large direct corrections

Higgs couplings to u,d and V:

Φ	$g_{\Phi\bar{u}u}$	$g_{\Phi\bar{d}d}$	$g_{\Phi VV}$
h	c_α/s_β	s_α/c_β	$s_{\beta-\alpha}$
H	s_α/c_β	c_α/c_β	$c_{\beta-\alpha}$
A	$1/t_\beta$	t_β	0

OK, but with one exception:
the $\Delta_b \propto \mu\tan\beta/M_S$ correction to $g_{\Phi bb}$

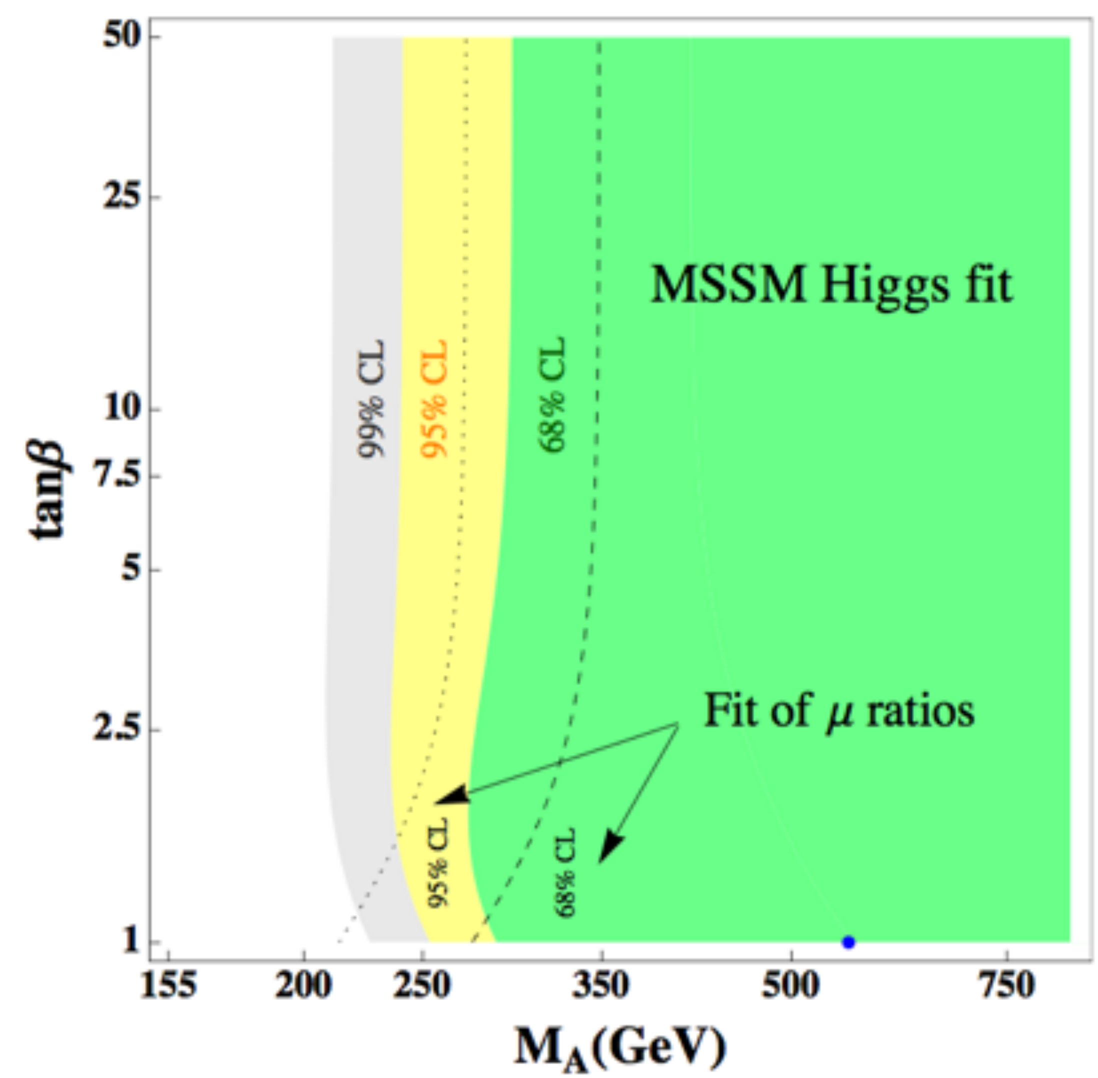
$g_{Hbb} \approx g_{Abb} = 1/(1+\Delta_b)$ important in one case: $pp \to H/A \to \tau\tau$

$\sigma(pp \to \Phi) \propto (1+\Delta_b)^{-2}$
$BR(\tau\tau) \propto \Gamma_\tau/(\Gamma_\tau + \Gamma_b)$
$\Rightarrow \sigma \times BR \propto 1 - \Delta_b/5$

Need very large $\Delta_b > 100\%$
to have impact $\Delta^{th}\sigma \approx 25\%$
$\Rightarrow$ **Not so bad!**

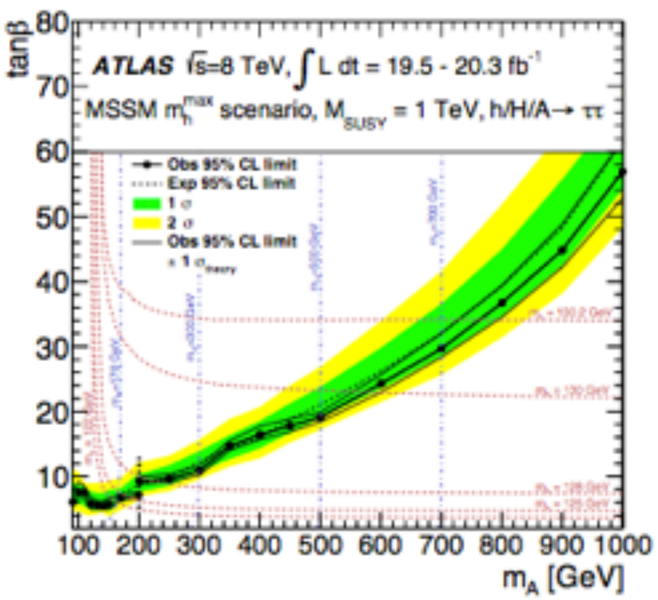
Higgs self–couplings: Hhh+hhh

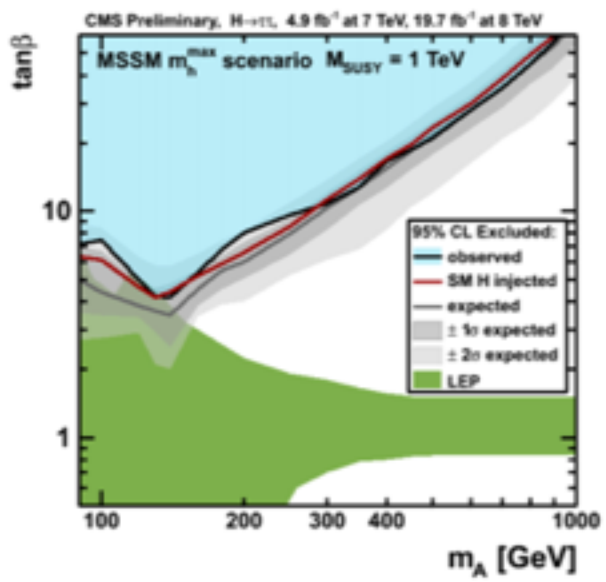
$$\lambda_{hhh} = 3c_{2\alpha}s_{\beta+\alpha} + 3dc_\alpha^3/s_\beta$$
$$\lambda_{Hhh} = 3s_{2\alpha}s_{\beta+\alpha} - c_{2\alpha}c_{\beta+\alpha} + 3ds_\alpha c_\alpha^2/s_\beta$$
$$d \simeq \Delta\mathcal{M}_{22}^2/M_Z^2$$

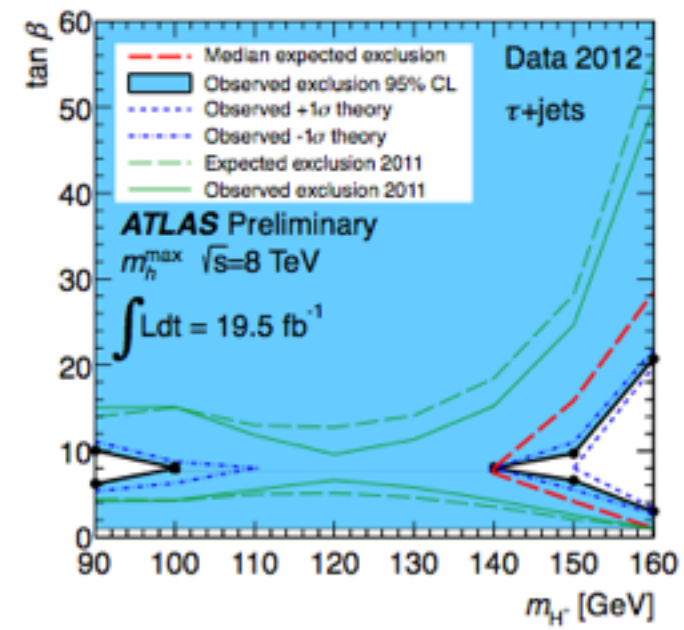


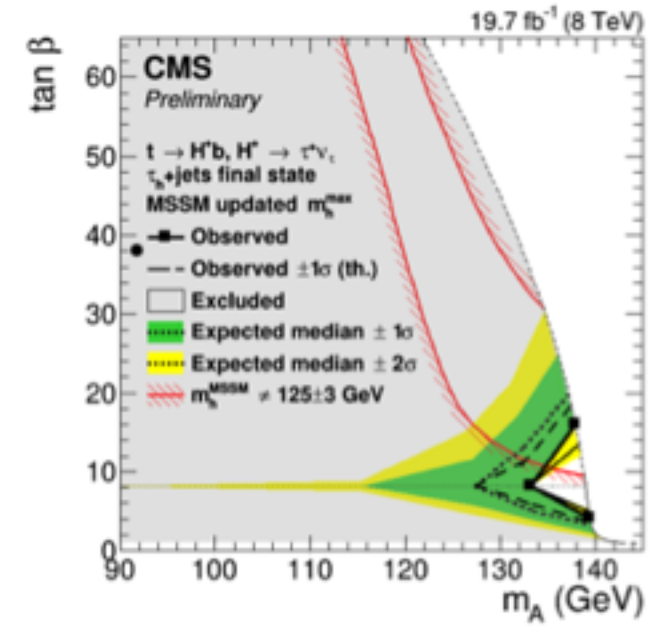
3. Consequences

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

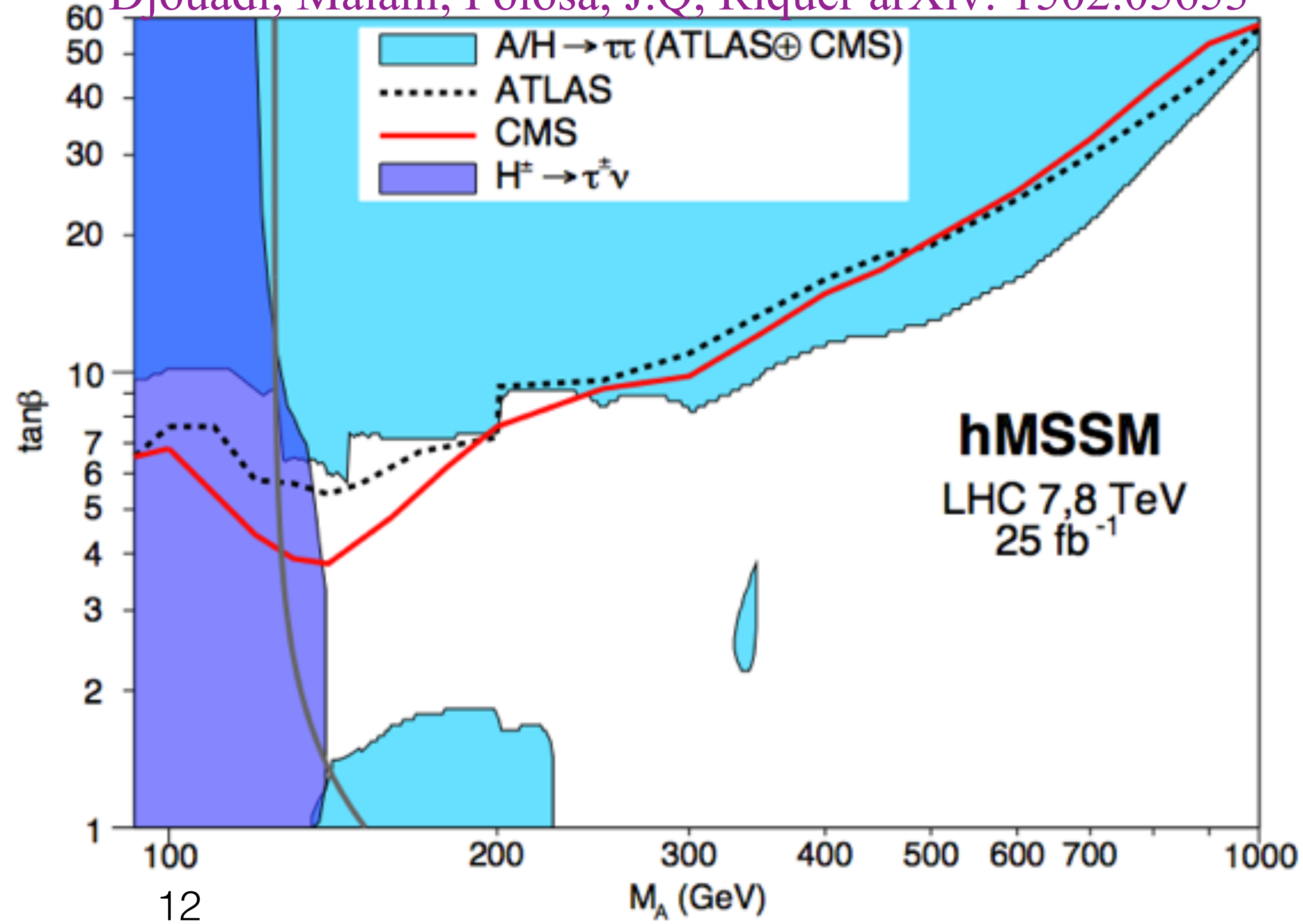








Djouadi, Maiani, Polosa, J.Q, Riquer arXiv: 1502.05653



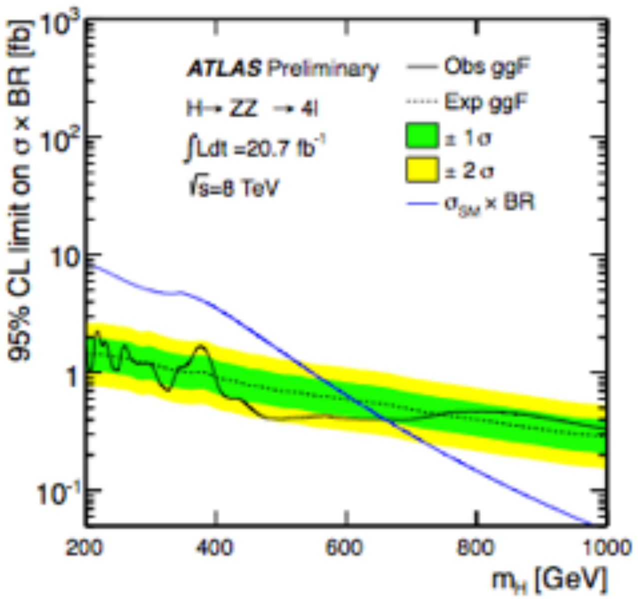
- **From $t \to bH^{+} \to b\tau\nu$ search:**
  $M_A \lesssim 140$ GeV is now excluded;
- **$pp \to \tau\tau$ sensitive at high $\tan\beta$:**
  – weaker at low M_A (no h events)
  – stronger at high M_A (no SUSY).
- **low $\tan\beta$ can now be considered.**
  (A excludes small part of low $\tan\beta$)

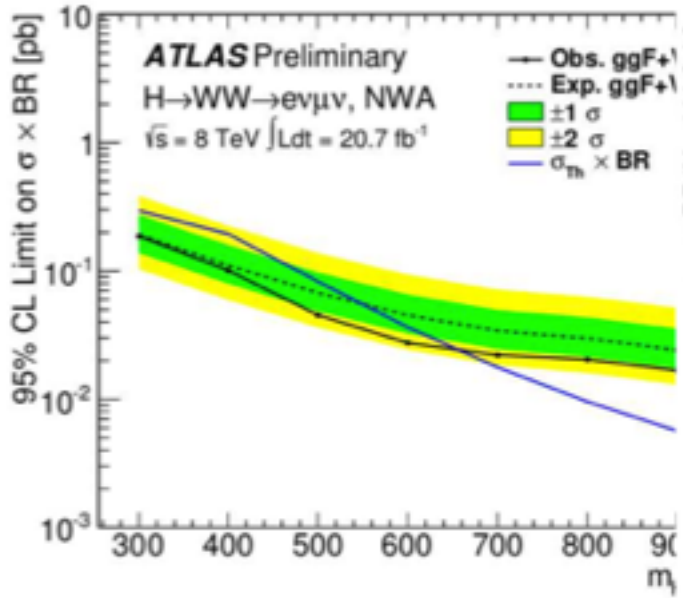
⇒ forbidden area excluded!

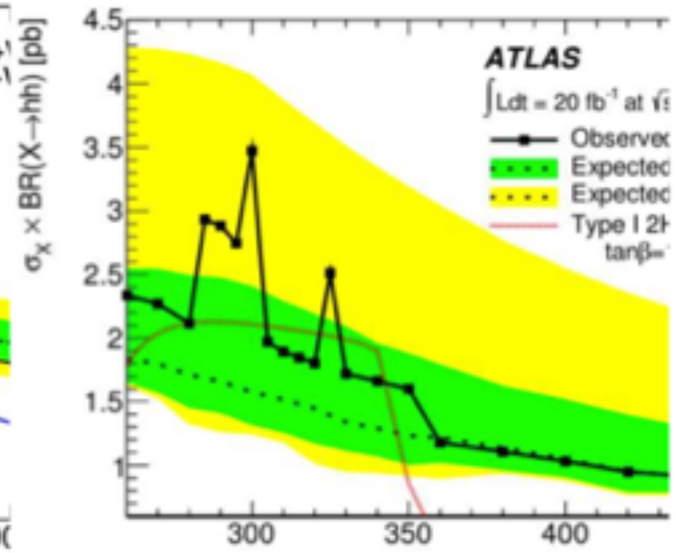
3. Consequences

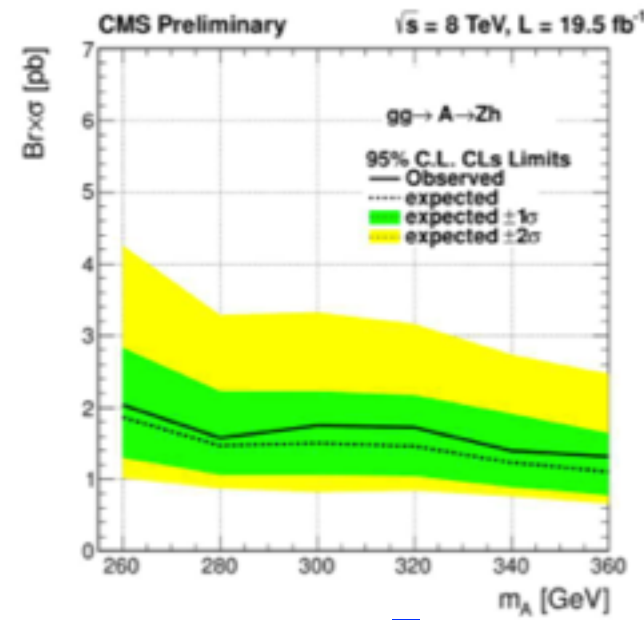
Extend search for heavy SM Higgs for MSSM and consider new channels:

pp→H→ZZ ; pp→H→WW ; pp→H→hh ; pp→A→hZ

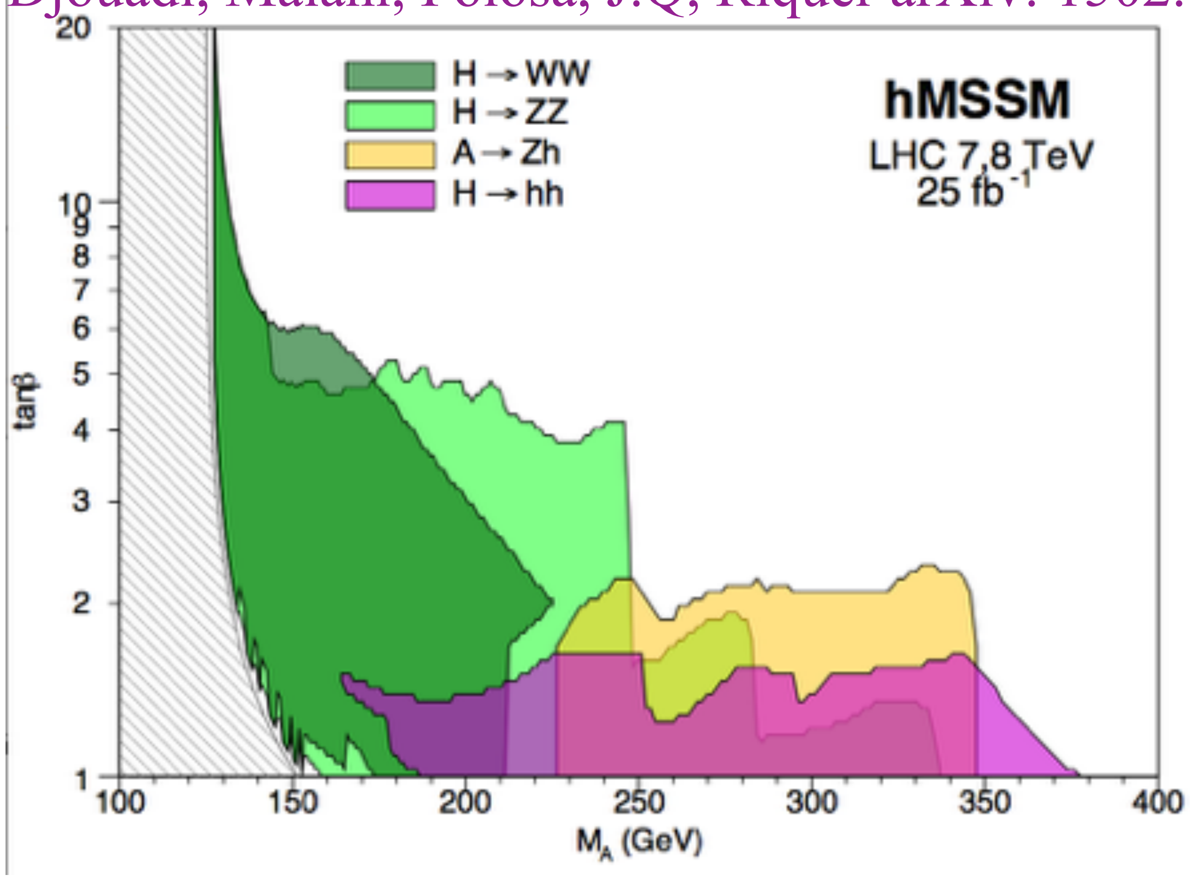








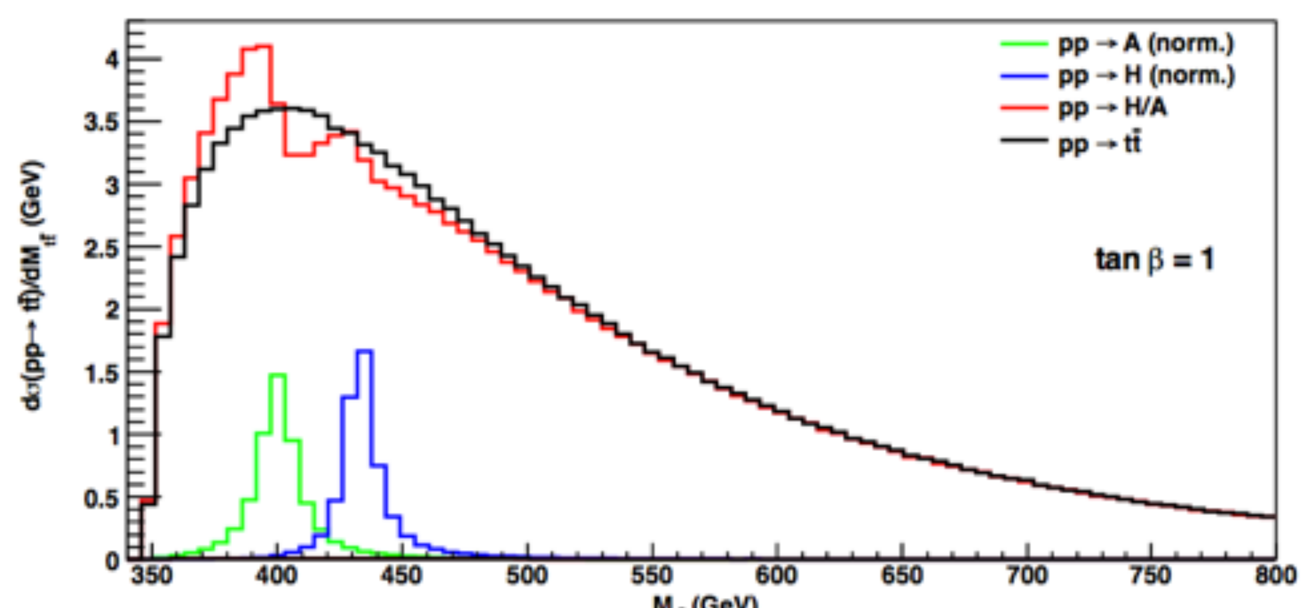
Djouadi, Maiani, Polosa, J.Q, Riquer arXiv: 1502.05653



Also consider $pp \to \Phi \to \bar{t}t$

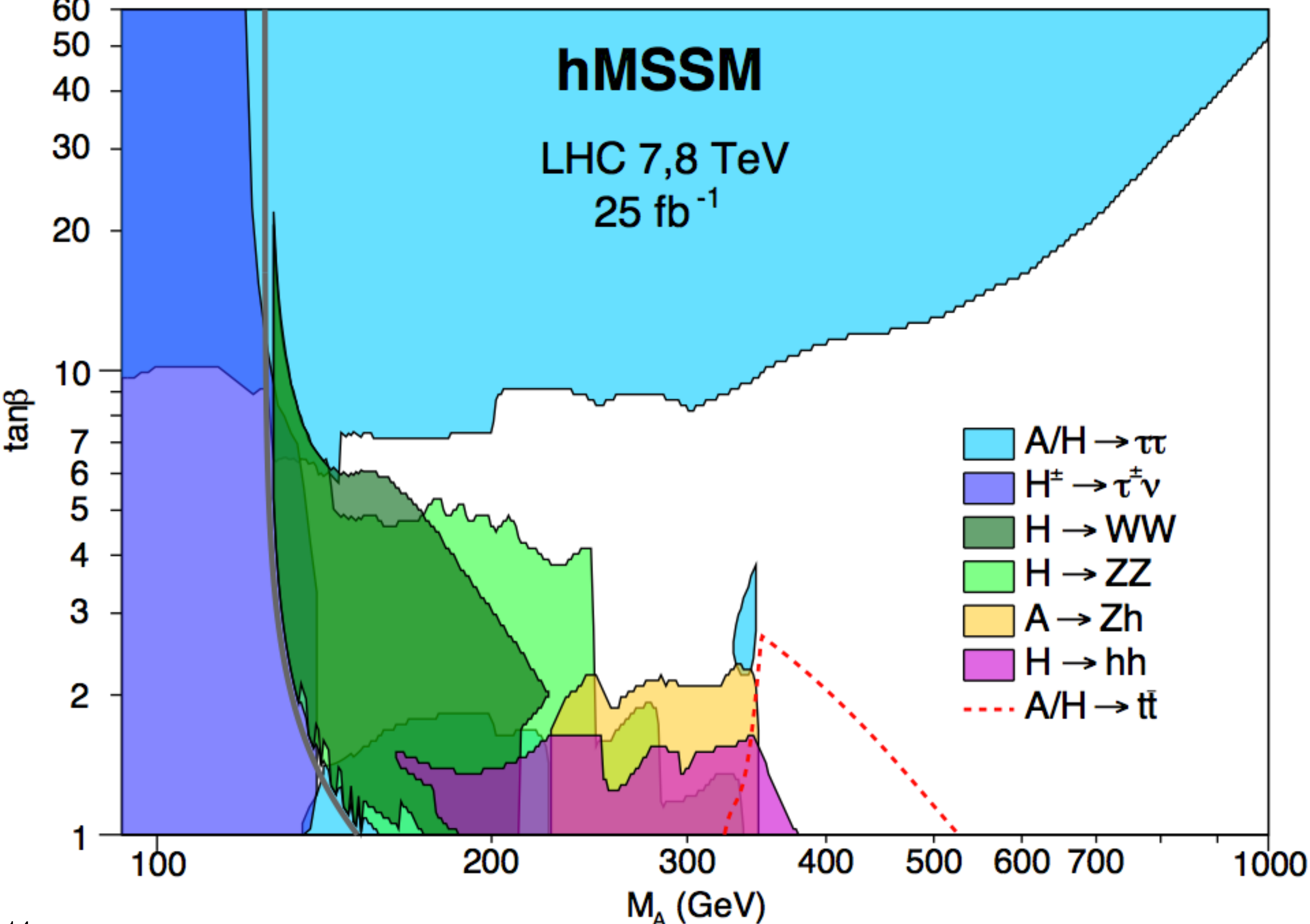
– crucial at low tanβ, high M_A

– very interesting features...



challenging and nice analyses!

Djouadi, Maiani, Polosa, J.Q, Riquer arXiv: 1502.05653



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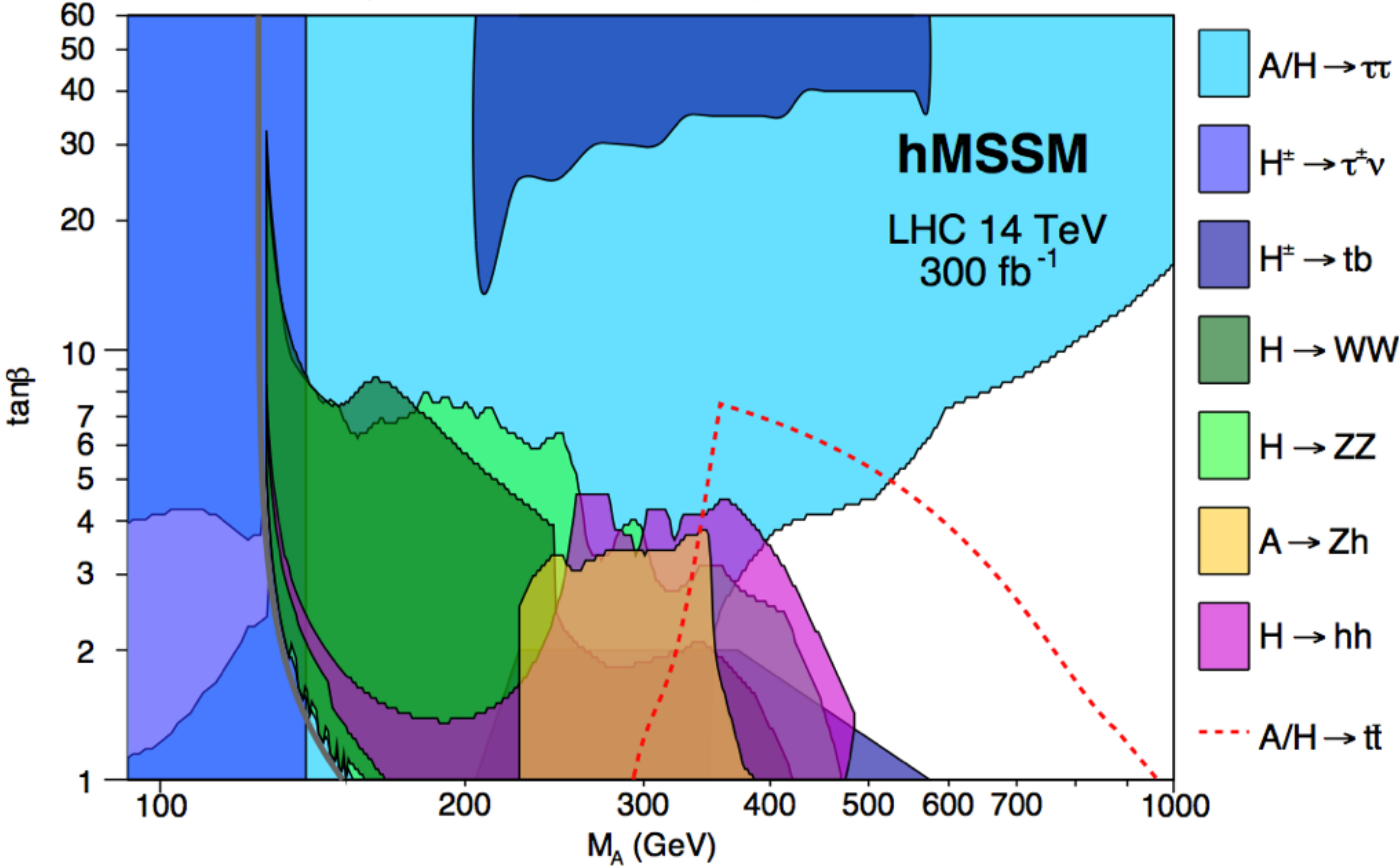

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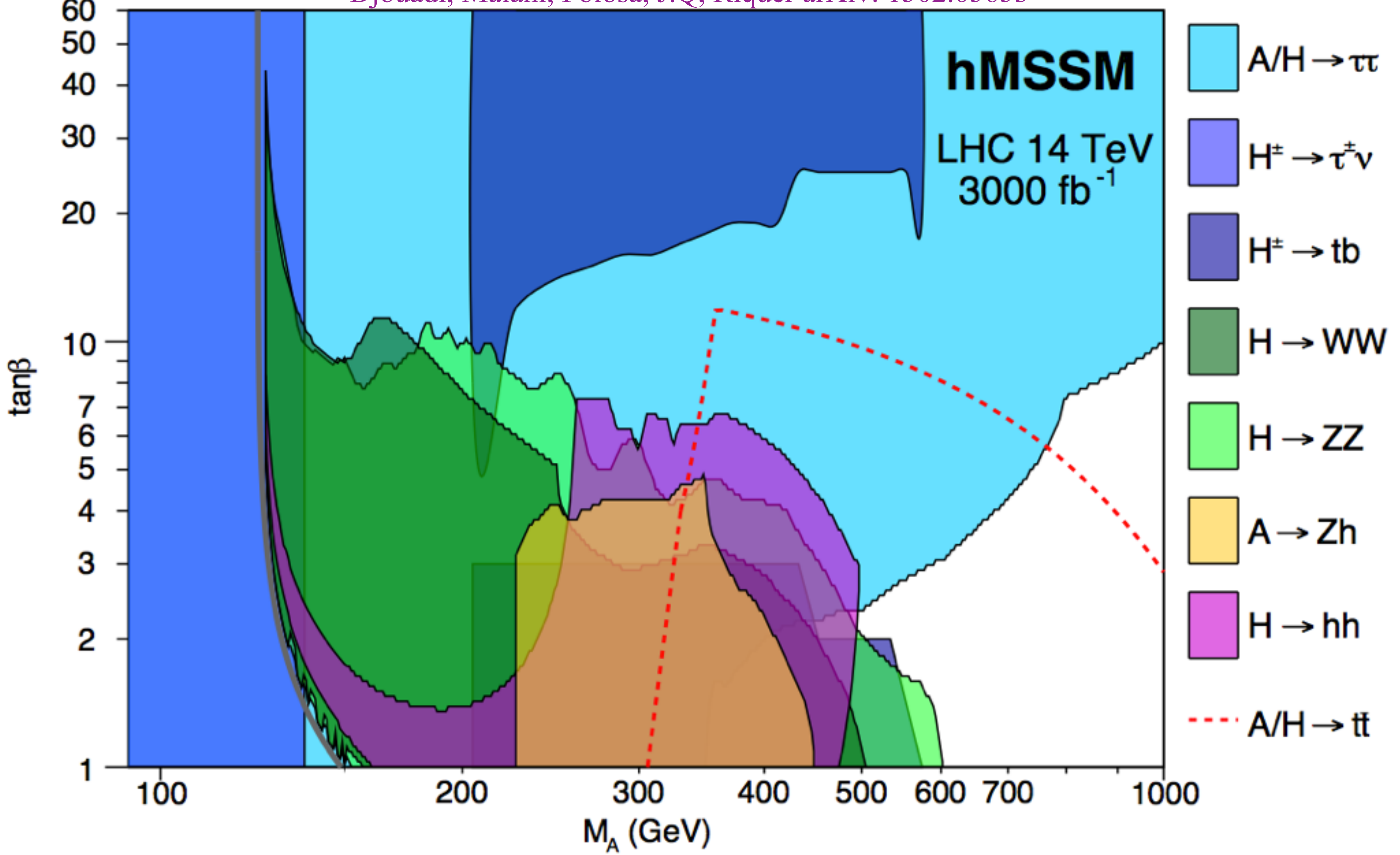


4. Covering the MSSM stop sector at the LHC

Matching between the MSSM and the dim6-EFT

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

$\mathbf{m_{stop}}$

$\mathcal{O}_{GG} = g_s^2 \lvert H\rvert^2 G^a_{\mu\nu} G^{a,\mu\nu}$	$\mathcal{O}_H = \frac{1}{2}(\partial_\mu \lvert H\rvert^2)^2$
$\mathcal{O}_{WW} = g^2 \lvert H\rvert^2 W^a_{\mu\nu} W^{a,\mu\nu}$	$\mathcal{O}_T = \frac{1}{2}(H^\dagger \overleftrightarrow{D}_\mu H)^2$
$\mathcal{O}_{BB} = g'^2 \lvert H\rvert^2 B_{\mu\nu} B^{\mu\nu}$	$\mathcal{O}_R = \lvert H\rvert^2 \lvert D_\mu H\rvert^2$
$\mathcal{O}_{WB} = 2gg' H^\dagger t^a H W^a_{\mu\nu} B^{\mu\nu}$	$\mathcal{O}_D = \lvert D^2 H\rvert^2$
$\mathcal{O}_W = ig(H^\dagger t^a \overleftrightarrow{D}^\mu H) D^\nu W^a_{\mu\nu}$	$\mathcal{O}_6 = \lvert H\rvert^6$
$\mathcal{O}_B = ig' Y_H (H^\dagger \overleftrightarrow{D}^\mu H)\partial^\nu B_{\mu\nu}$	$\mathcal{O}_{2G} = -\frac{1}{2}(D^\mu G^a_{\mu\nu})^2$
$\mathcal{O}_{3G} = \frac{1}{3!} g_s f^{abc} G_\rho^{a\mu} G_\mu^{b\nu} G_\nu^{c\rho}$	$\mathcal{O}_{2W} = -\frac{1}{2}(D^\mu W^a_{\mu\nu})^2$
$\mathcal{O}_{3W} = \frac{1}{3!} g \epsilon^{abc} W_\rho^{a\mu} W_\mu^{b\nu} W_\nu^{c\rho}$	$\mathcal{O}_{2B} = -\frac{1}{2}(\partial^\mu B_{\mu\nu})^2$

$$c_{GG} = \frac{h_t^2}{(4\pi)^2}\frac{1}{12}\left[\left(1 + \frac{1}{12}\frac{g'^2 c_{2\beta}}{h_t^2}\right) - \frac{1}{2}\frac{X_t^2}{m_{\tilde{t}}^2}\right] \qquad c_{WB} = -\frac{h_t^2}{(4\pi)^2}\frac{1}{24}\left[\left(1 + \frac{1}{2}\frac{g^2 c_{2\beta}}{h_t^2}\right) - \frac{4}{5}\frac{X_t^2}{m_{\tilde{t}}^2}\right]$$

$$c_{WW} = \frac{h_t^2}{(4\pi)^2}\frac{1}{16}\left[\left(1 - \frac{1}{6}\frac{g'^2 c_{2\beta}}{h_t^2}\right) - \frac{2}{5}\frac{X_t^2}{m_{\tilde{t}}^2}\right] \qquad c_W = \frac{h_t^2}{(4\pi)^2}\frac{1}{40}\frac{X_t^2}{m_{\tilde{t}}^2}$$

$$c_{BB} = \frac{h_t^2}{(4\pi)^2}\frac{17}{144}\left[\left(1 + \frac{31}{102}\frac{g'^2 c_{2\beta}}{h_t^2}\right) - \frac{38}{85}\frac{X_t^2}{m_{\tilde{t}}^2}\right] \qquad c_B = \frac{h_t^2}{(4\pi)^2}\frac{1}{40}\frac{X_t^2}{m_{\tilde{t}}^2}$$

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

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

$$c_H = \frac{h_t^4}{(4\pi)^2}\frac{3}{4}\left[\left(1 + \frac{1}{3}\frac{g'^2 c_{2\beta}}{h_t^2} + \frac{1}{12}\frac{g'^4 c_{2\beta}^2}{h_t^4}\right) - \frac{7}{6}\frac{X_t^2}{m_{\tilde{t}}^2}\left(1 + \frac{1}{14}\frac{(g^2+2g'^2)c_{2\beta}}{h_t^2}\right) + \frac{7}{30}\frac{X_t^4}{m_{\tilde{t}}^4}\right]$$

$$c_T = \frac{h_t^4}{(4\pi)^2}\frac{1}{4}\left[\left(1 + \frac{1}{2}\frac{g^2 c_{2\beta}}{h_t^2}\right)^2 - \frac{1}{2}\frac{X_t^2}{m_{\tilde{t}}^2}\left(1 + \frac{1}{2}\frac{g^2 c_{2\beta}}{h_t^2}\right) + \frac{1}{10}\frac{X_t^4}{m_{\tilde{t}}^4}\right]$$

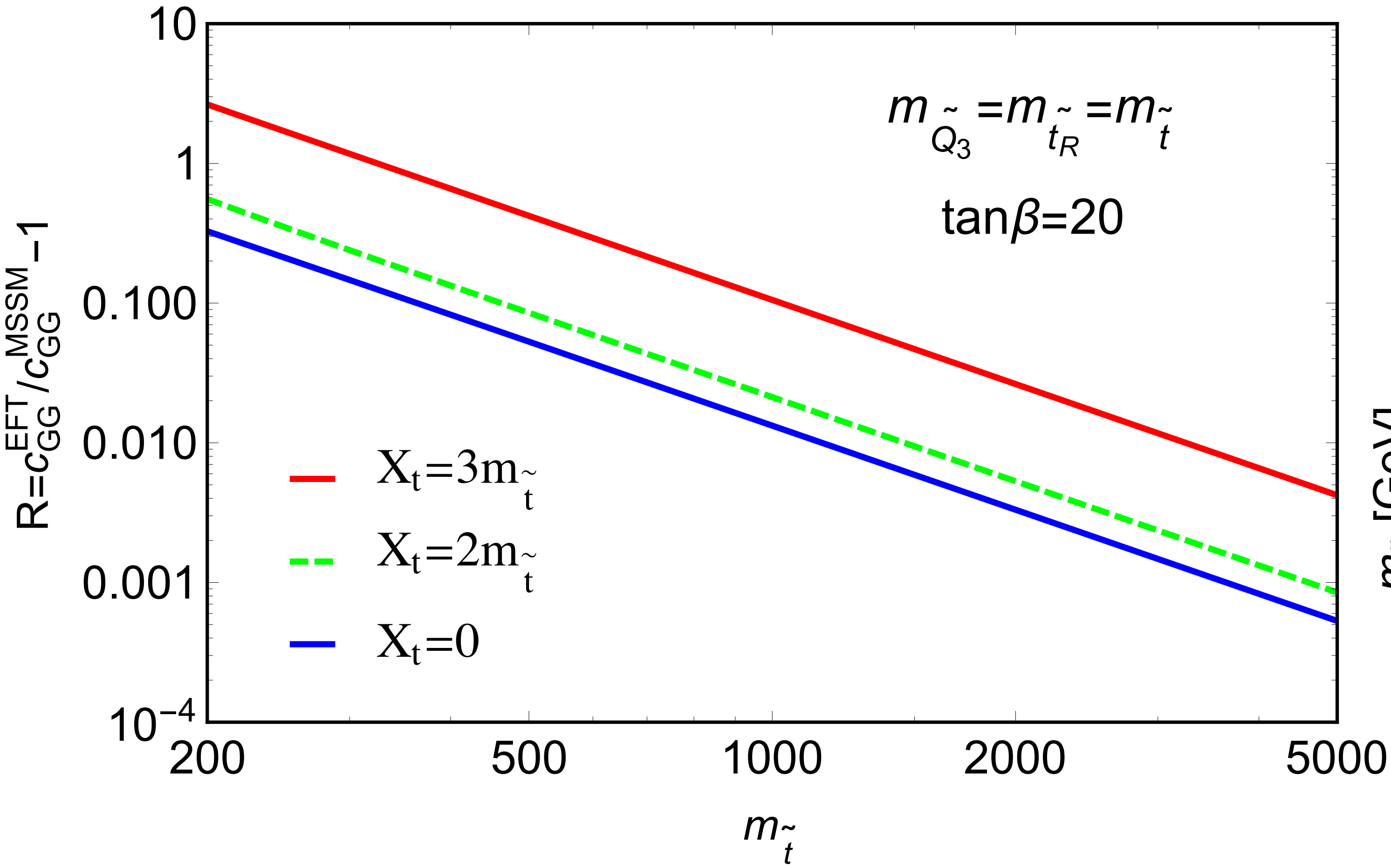
$$c_R = \frac{h_t^4}{(4\pi)^2}\frac{1}{2}\left[\left(1 + \frac{1}{2}\frac{g^2 c_{2\beta}}{h_t^2}\right)^2 - \frac{3}{2}\frac{X_t^2}{m_{\tilde{t}}^2}\left(1 + \frac{1}{12}\frac{(3g^2+g'^2)c_{2\beta}}{h_t^2}\right) + \frac{3}{10}\frac{X_t^4}{m_{\tilde{t}}^4}\right]$$

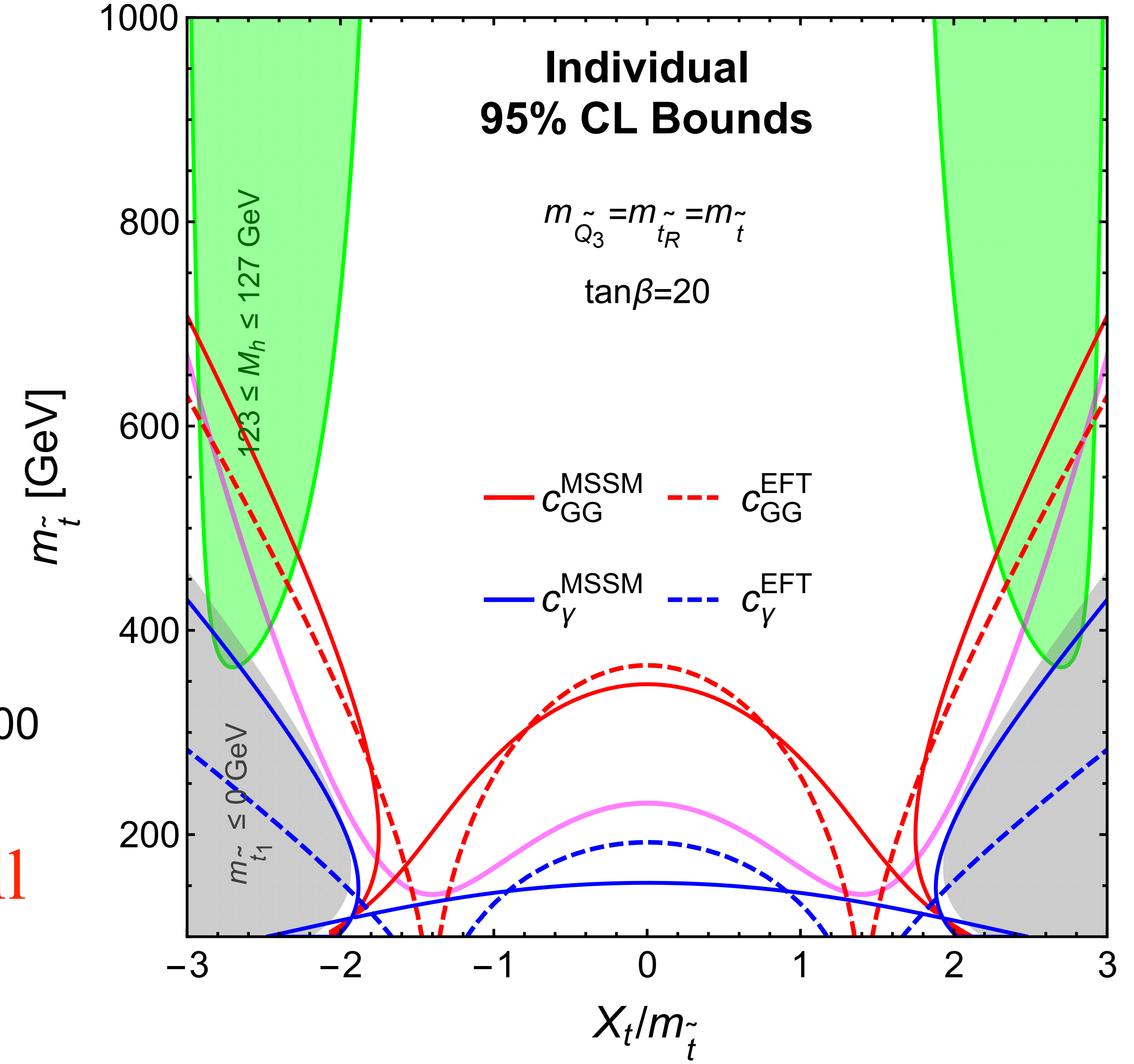
$$c_D = \frac{h_t^2}{(4\pi)^2}\frac{1}{20}\frac{X_t^2}{m_{\tilde{t}}^2}$$

A. Drozd, J. Ellis, J.Q. and T. You
appear soon…
general expression of the Wilson coefficients : non-degenerate stop masses

4. Covering the MSSM stop sector at the LHC

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





- EFT vs full MSSM calculation agrees well (non-trivial check!)

- EFT calculation simplified by Covariant Derivative Expansion method
  Henning, Lu & Murayama [arXiv:1412.1837]

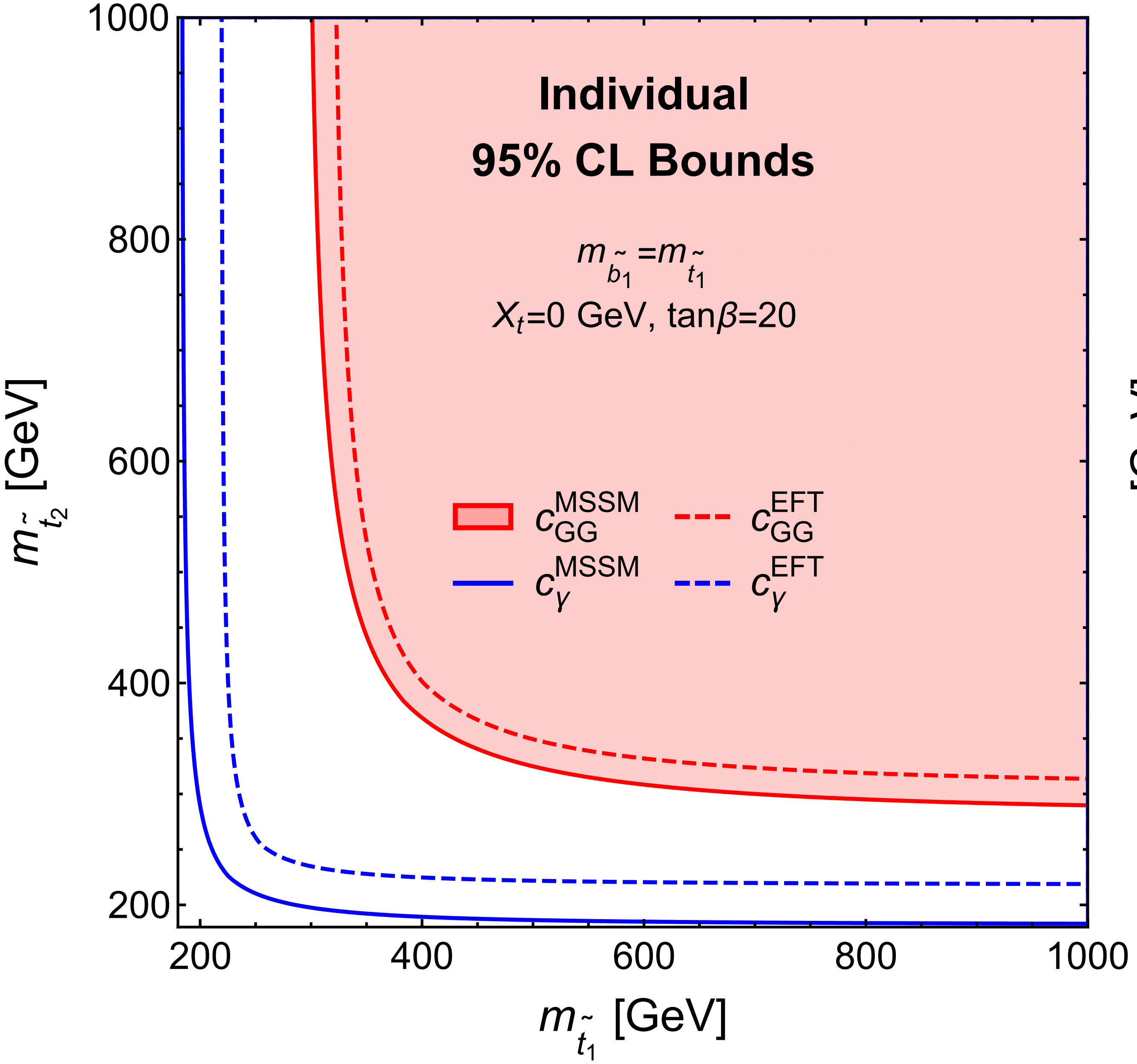
- Systematic way of integrating out UV degrees of freedom in manifestly gauge-invariant way

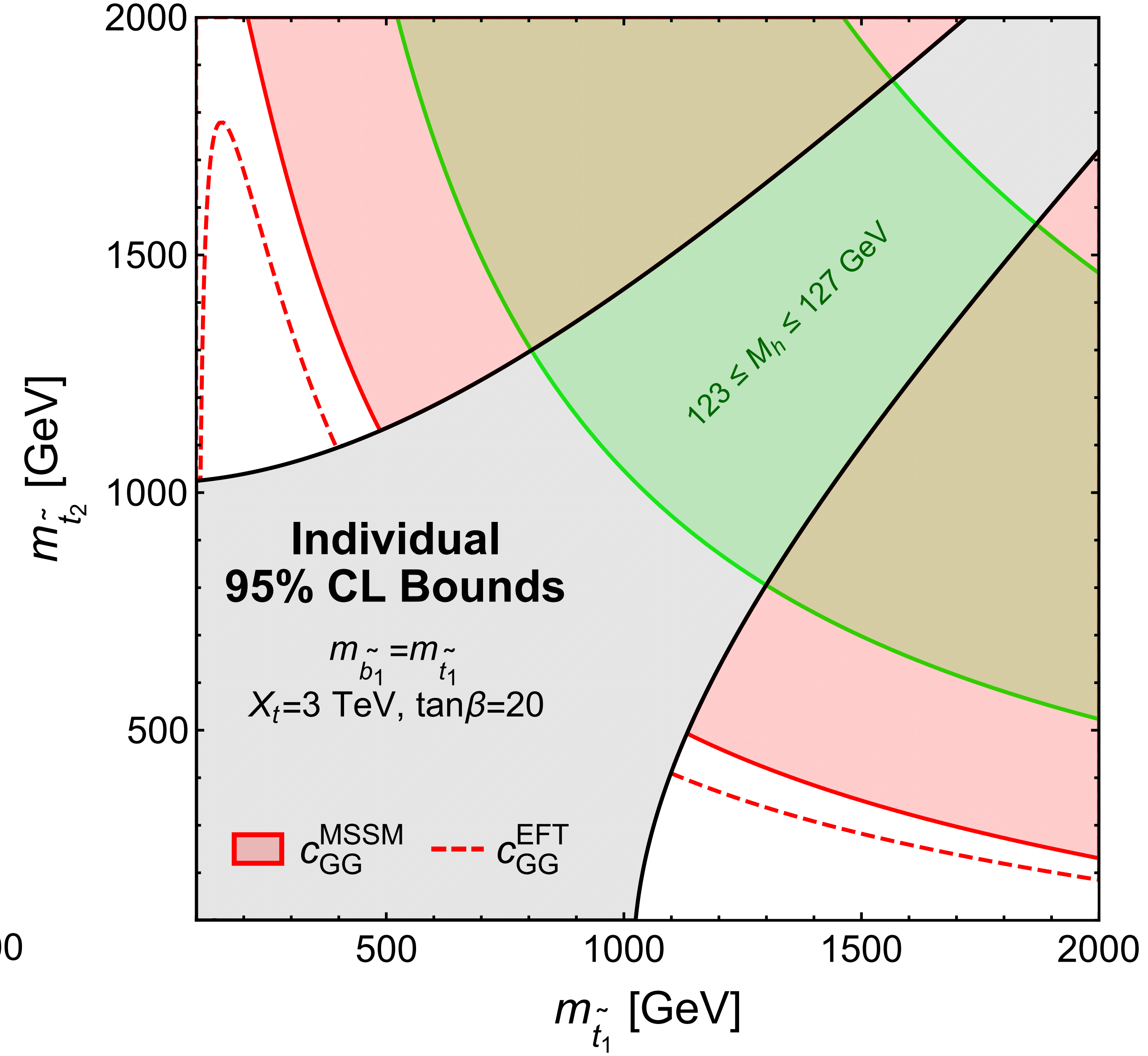
- Work in progress...

4. Covering the MSSM stop sector at the LHC

General case: non-degenerate stops

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





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

4. Covering the MSSM stop sector at the LHC

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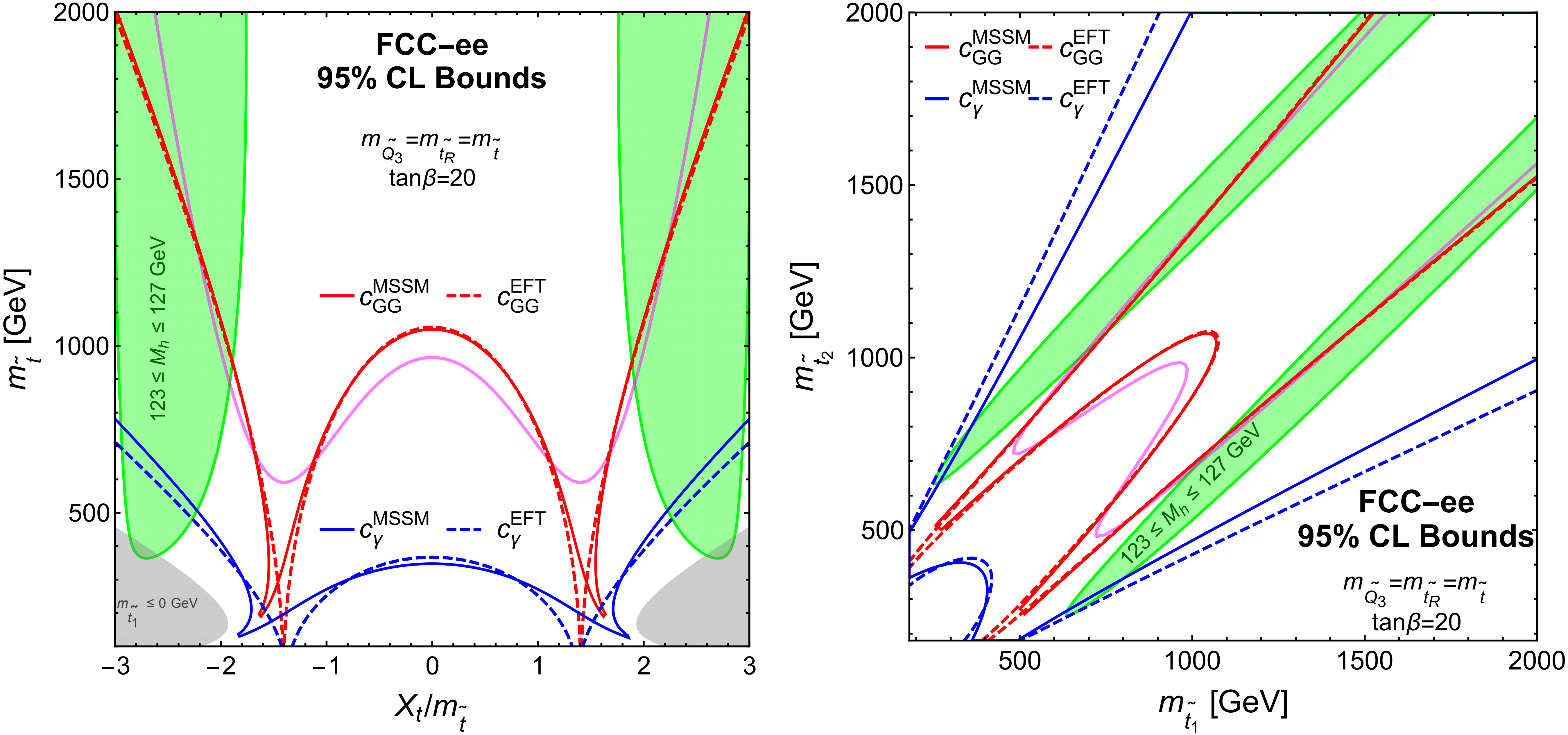

•Future FCC-ee measurements could be sensitive to stop masses above a TeV

5. Conclusion

If you "buy" these three basic assumptions:

- **Conventional mass matrix for CP Higgses**
- **Dominance of leading radiative correction**
- **No impact of direct corrections to couplings**

a very simple description of the MSSM space; easy to implement:

- **again only two inputs, so no scan, no grid, no set of benchmarks...**
- **it allows the possibility to address low tanβ "model-independently",**
- **allows more action: plenty of channels to be investigated/interpreted.**

Matching between EFT-MSSM

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

Appendix

Leading top/stop sector radiative correction:

(difficult to have tan$\beta \lesssim 4$; talk by Luciano at CERN, 15 May 2013)

$$\Delta\mathcal{M}^2_{22} = \frac{3}{2\pi^2}\frac{m_t^4}{v^2 s_\beta^2}\left[\frac{1}{2}\tilde{X}_t + \ell_S + \frac{1}{16\pi^2}\left(\frac{3}{2}\frac{m_t^2}{v^2} - 32\pi\alpha_s\right)\left(\tilde{X}_t\ell_S + \ell_S^2\right)\right]$$

$$\ell_S = \log(M_S^2/m_t^2), x_t = X_t/M_S, \tilde{X}_t = 2x_t^2(1 - x_t^2/12)$$

Including subleading radiative corrections involving μ and sbottoms:

(used to have the "blue line" with tanβ=2.5 mentioned by Carlos)

$$\Delta\mathcal{M}^2_{11} = -\frac{v^2\sin^2\beta}{32\pi^2}\bar{\mu}^2\left[x_t^2\lambda_t^4(1 + c_{11}\ell_S) + a_b^2\lambda_b^4(1 + c_{12}\ell_S)\right]$$

$$\Delta\mathcal{M}^2_{12} = -\frac{v^2\sin^2\beta}{32\pi^2}\bar{\mu}\left[x_t\lambda_t^4(6 - x_t a_t)(1 + c_{31}\ell_S) - \bar{\mu}^2 a_b\lambda_b^4(1 + c_{32}\ell_S)\right]$$

$$\Delta\mathcal{M}^2_{22} = \frac{v^2\sin^2\beta}{32\pi^2}\left[6\lambda_t^4\ell_S(2 + c_{21}\ell_S) + x_t a_t\lambda_t^4(12 - x_t a_t)(1 + c_{21}\ell\right.$$
$$\left. -\bar{\mu}^4\lambda_b^4(1 + c_{22}\ell_S)\right]$$

with $\bar{\mu} = \mu/M_S, a_{t,b} = A_{t,b}/M_S$ and for two loops factors c_{ij}.

Carena, Espinosa, Quiros and Wagner, Phys. Lett. B355 (1995) 209;
Haber, Hempfling and Hoang, Z. Phys. C75 (1997) 539;
Carena and Haber, Prog. Part. Nucl. Phys. 50 (2003) 63.

From P. Slavich

Does the full calculation show significant deviations from (2,2) dominance?

In other words: are there significant corrections to any lambdas other than λ_2?

Threshold corrections from squark loops mess things up:

$$\lambda_1 = \frac{1}{4}(g^2+g'^2) + \frac{2\,N_c}{(4\pi)^2}\left(y_b^4\frac{A_b^2}{M_S^2}(1-\frac{A_b^2}{12M_S^2}) - y_t^4\frac{\mu^4}{12M_S^4}\right)$$

$$\lambda_2 = \frac{1}{4}(g^2+g'^2) + \frac{2\,N_c}{(4\pi)^2}\left(y_t^4\frac{A_t^2}{M_S^2}(1-\frac{A_t^2}{12M_S^2}) - y_b^4\frac{\mu^4}{12M_S^4}\right)$$

$$\lambda_3 = \frac{1}{4}(g^2-g'^2) + \frac{2\,N_c}{(4\pi)^2}\left(y_b^2y_t^2\frac{A_{tb}}{2} + y_t^4(\frac{\mu^2}{4M_S^2}-\frac{\mu^2A_t^2}{12M_S^4}) + y_b^4(\frac{\mu^2}{4M_S^2}-\frac{\mu^2A_b^2}{12M_S^4})\right)$$

$$\lambda_4 = -\frac{1}{2}g^2 + \frac{2\,N_c}{(4\pi)^2}\left(-y_b^2y_t^2\frac{A_{tb}}{2} + y_t^4(\frac{\mu^2}{4M_S^2}-\frac{\mu^2A_t^2}{12M_S^4}) + y_b^4(\frac{\mu^2}{4M_S^2}-\frac{\mu^2A_b^2}{12M_S^4})\right)$$

$$\lambda_5 = -\frac{2\,N_c}{(4\pi)^2}\left(y_t^4\frac{\mu^2A_t^2}{12M_S^4} + y_b^4\frac{\mu^2A_b^2}{12M_S^4}\right),$$

$$\lambda_6 = \frac{2\,N_c}{(4\pi)^2}\left(y_b^4\frac{\mu A_b}{M_S^2}(-\frac{1}{2}+\frac{A_b^2}{12M_S^2}) + y_t^4\frac{\mu^3A_t}{12M_S^4}\right),$$

$$\lambda_7 = \frac{2\,N_c}{(4\pi)^2}\left(y_t^4\frac{\mu A_t}{M_S^2}(-\frac{1}{2}+\frac{A_t^2}{12M_S^2}) + y_b^4\frac{\mu^3A_b}{12M_S^4}\right),$$

Cheng *et al.*, (1411.7329)

also Haber-Hempfling early '90s

NOTE: stop corrections relevant only when μ, $A_t \approx M_S$

Then the RG evolution mixes the lambdas

From P. Slavich

More comparisons: zero-mixing points from Sven's "low-tb-high"

$$m_{\tilde{f}} = M_3 = 17 \text{ TeV}, \quad X_t = 0, \quad M_2 = 2M_1 = 2 \text{ TeV}, \quad \mu = 1.5 \text{ TeV}, \quad \tan\beta = 9$$

m_A = 175 GeV	FeynHiggs:	m_h = 127.03,	m_H = 177.95,	*alpha* = -0.2938
	Lee-Wagner: (y_t NLO)	m_h = 127.18,	m_H = 177.84,	*alpha* = -0.2902
	hMSSM: (m_h from FH)	m_h = 127.03,	m_H = 177.87,	*alpha* = -0.2920
m_A = 150 GeV	FeynHiggs:	m_h = 124.88,	m_H = 155.31,	*alpha* = -0.4673
	Lee-Wagner: (y_t NLO)	m_h = 124.71,	m_H = 153.96,	*alpha* = -0.4776
	hMSSM: (m_h from FH)	m_h = 124.88,	m_H = 155.00,	*alpha* = -0.4656

From P. Slavich

However...

- For $\tan\beta = 1$, Sven obtains $m_h \approx 125$ GeV with $M_S = 2\text{x}10^5$ GeV (suspiciously low)
- The resummation procedure in FH does not account for low μ, $M_{1,2}$ and m_A

The resummed logs (computed in the decoupling limit and divided by $\sin\beta^2$) are crammed in the (2,2) element of the mass matrix:

$$\mathcal{M}^2 = \begin{pmatrix} m_Z^2 c_\beta^2 + m_A^2 s_\beta^2 & -s_\beta c_\beta (m_Z^2 + m_A^2) \\ -s_\beta c_\beta (m_Z^2 + m_A^2) & m_Z^2 s_\beta^2 + m_A^2 c_\beta^2 \end{pmatrix} + \begin{pmatrix} \Delta_{11}^{2\ell} & \Delta_{12}^{2\ell} \\ \Delta_{21}^{2\ell} & \Delta_{22}^{2\ell} \end{pmatrix} + \begin{pmatrix} 0 & 0 \\ 0 & -\Delta^{\rm NLL} + \Delta^{\rm res} \end{pmatrix}$$

Is this a valid approximation at low (m_A, $\tan\beta$) ?

NOTE: the hMSSM relies on a more extreme version of this approximation

$$\mathcal{M}^2_{\rm hMSSM} = \begin{pmatrix} m_Z^2 c_\beta^2 + m_A^2 s_\beta^2 & -s_\beta c_\beta (m_Z^2 + m_A^2) \\ -s_\beta c_\beta (m_Z^2 + m_A^2) & m_Z^2 s_\beta^2 + m_A^2 c_\beta^2 \end{pmatrix} + \begin{pmatrix} 0 & 0 \\ 0 & \Delta \end{pmatrix}$$

(then one trades Δ for m_h and obtains m_H and α)

From T. You

EWPTs constraints on dim-6 operators

- χ^2 fit of theory predictions with experimental measurements

$$\chi^2(p_{\mathrm{SM}}, p_\alpha) = \sum_{i,j} (\hat{\mathcal{O}}_i^{\mathrm{th}} - \hat{\mathcal{O}}_i^{\mathrm{exp}})(\sigma^2)^{-1}_{ij}(\hat{\mathcal{O}}_j^{\mathrm{th}} - \hat{\mathcal{O}}_j^{\mathrm{exp}}) \quad , \quad (\sigma^2)_{ij} = \Delta\hat{\mathcal{O}}_i^{\mathrm{exp}}\rho_{ij}\Delta\hat{\mathcal{O}}_j^{\mathrm{exp}}$$

- Marginalized constraints on a complete non-redundant basis of dim-6 operators affecting EWPTs

Operator	Coefficient	LEP Constraints Individual	LEP Constraints Marginalized
$\mathcal{O}_W = \frac{ig}{2}\left(H^\dagger\sigma^a \overleftrightarrow{D^\mu} H\right) D^\nu W^a_{\mu\nu}$ $\mathcal{O}_B = \frac{ig'}{2}\left(H^\dagger \overleftrightarrow{D^\mu} H\right)\partial^\nu B_{\mu\nu}$	$\frac{m_W^2}{\Lambda^2}(c_W + c_B)$	$(-0.00055, 0.0005)$	$(-0.0033, 0.0018)$
$\mathcal{O}_T = \frac{1}{2}\left(H^\dagger \overleftrightarrow{D}_\mu H\right)^2$	$\frac{v^2}{\Lambda^2}c_T$	$(0, 0.001)$	$(-0.0043, 0.0033)$
$\mathcal{O}_{LL}^{(3)l} = (\bar{L}_L\sigma^a\gamma^\mu L_L)(\bar{L}_L\sigma^a\gamma_\mu L_L)$	$\frac{v^2}{\Lambda^2}c_{LL}^{(3)l}$	$(0, 0.001)$	$(-0.0013, 0.00075)$
$\mathcal{O}_R^e = (iH^\dagger \overleftrightarrow{D}_\mu H)(\bar{e}_R\gamma^\mu e_R)$	$\frac{v^2}{\Lambda^2}c_R^e$	$(-0.0015, 0.0005)$	$(-0.0018, 0.00025)$
$\mathcal{O}_R^u = (iH^\dagger \overleftrightarrow{D}_\mu H)(\bar{u}_R\gamma^\mu u_R)$	$\frac{v^2}{\Lambda^2}c_R^u$	$(-0.0035, 0.005)$	$(-0.011, 0.011)$
$\mathcal{O}_R^d = (iH^\dagger \overleftrightarrow{D}_\mu H)(\bar{d}_R\gamma^\mu d_R)$	$\frac{v^2}{\Lambda^2}c_R^d$	$(-0.0075, 0.0035)$	$(-0.042, 0.0044)$
$\mathcal{O}_L^{(3)q} = (iH^\dagger\sigma^a \overleftrightarrow{D}_\mu H)(\bar{Q}_L\sigma^a\gamma^\mu Q_L)$	$\frac{v^2}{\Lambda^2}c_L^{(3)q}$	$(-0.0005, 0.001)$	$(-0.0044, 0.0044)$
$\mathcal{O}_L^q = (iH^\dagger \overleftrightarrow{D}_\mu H)(\bar{Q}_L\gamma^\mu Q_L)$	$\frac{v^2}{\Lambda^2}c_L^q$	$(-0.0015, 0.003)$	$(-0.0019, 0.0069)$

See Wells & Zhang expansion formalism [arXiv:1406.6070 [hep-ph]]