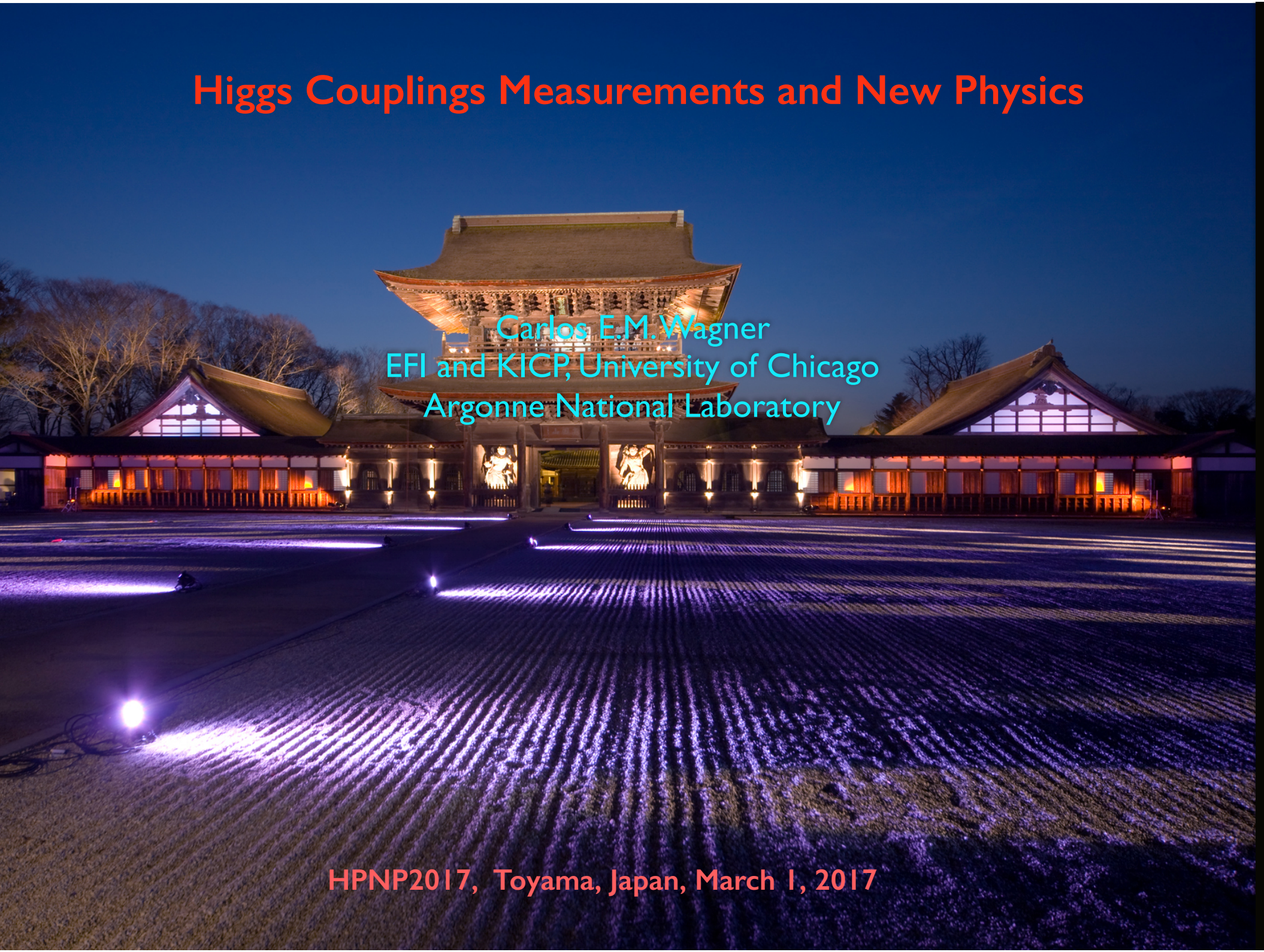
Higgs Couplings Measurements and New Physics



Carlos E.M. Wagner
EFI and KICP, University of Chicago
Argonne National Laboratory

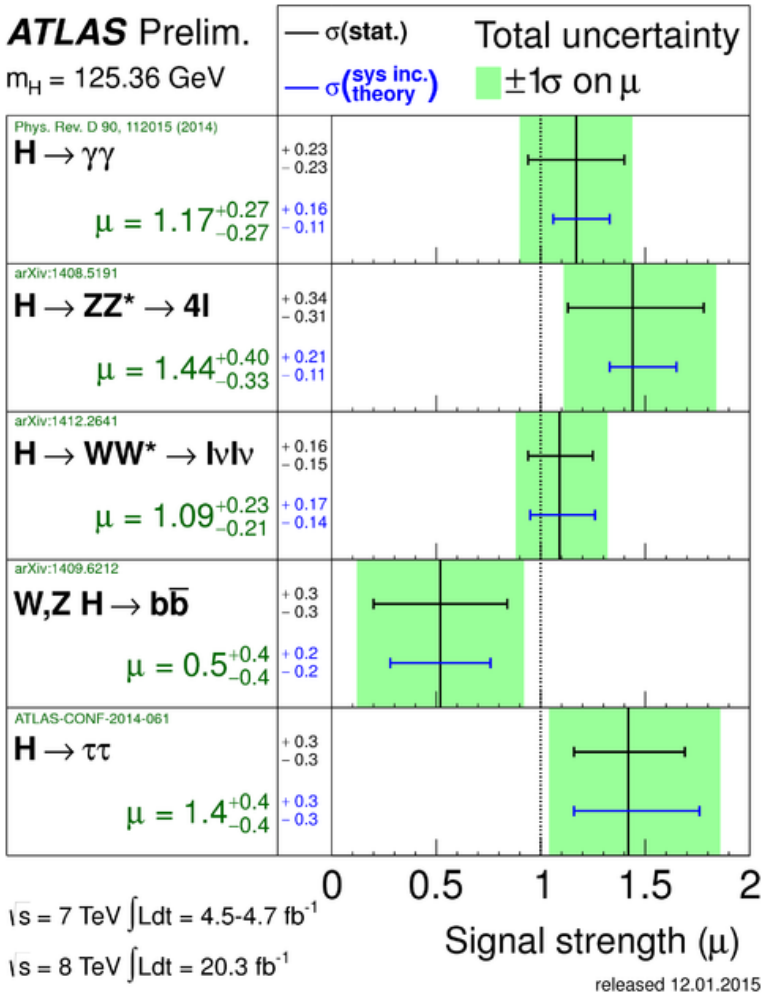
HPNP2017, Toyama, Japan, March 1, 2017

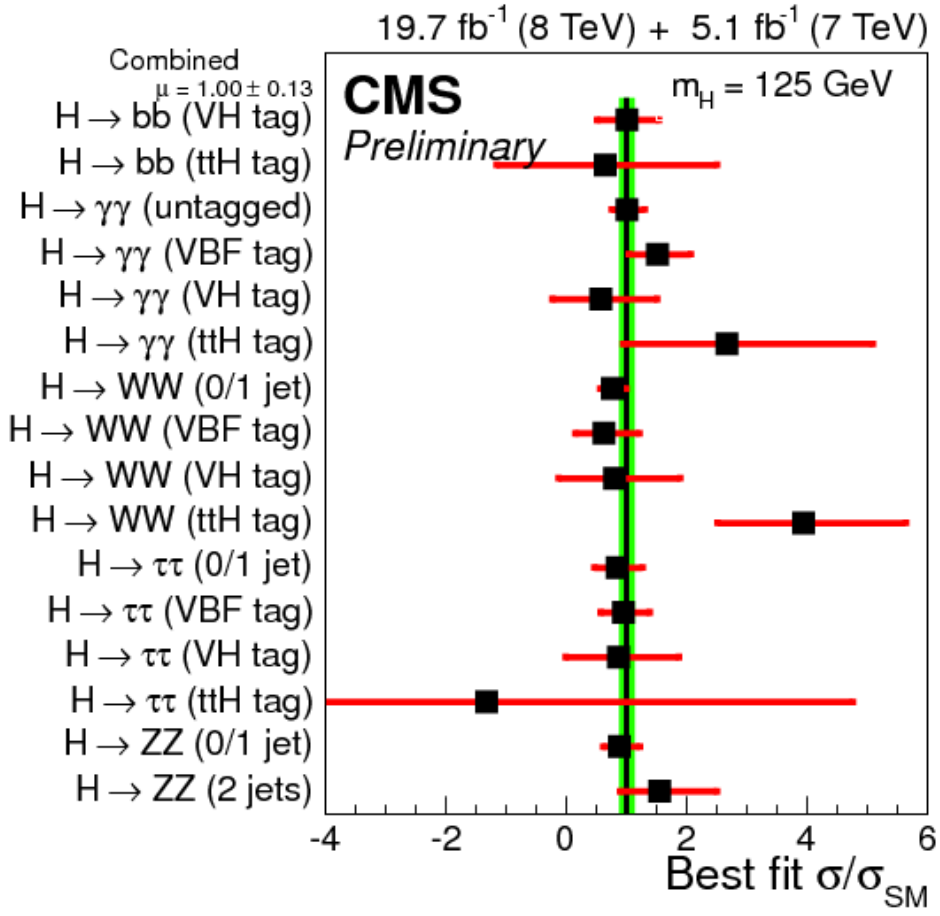
Based on the following works :

- M. Carena, I. Low, N. Shah, C.W., arXiv:1310.2248, JHEP 1404 (2014)
- M. Carena, H. Haber, I. Low, N. Shah, C.W., arXiv:1410.4969, PRD91 (2015)
- M. Carena, H. Haber, I. Low, N. Shah, C.W., arXiv:1510.09137, PRD93 (2016)
- M. Badziak, C.W. , arXiv:1602.06198, JHEP 1605 (2016)
- M. Badziak, C.W. , arXiv: 1611.02353, JHEP 1702 (2017)
- P. Huang, A. Ismail, I. Low, C.W., arXiv:1507.01601, PRD92 (2015)

Higgs Boson Discovery at the LHC :

Very good agreement of Higgs Physics Results with SM Predictions

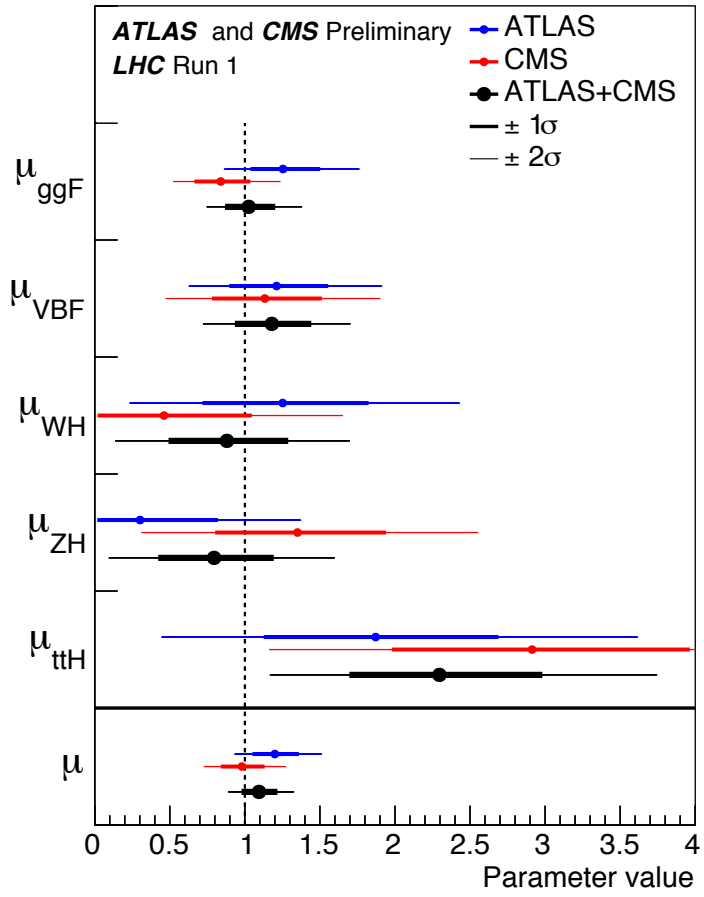




ATLAS and CMS Combination

Very good agreement of production rates with SM predictions

$$\mu_i = \frac{\sigma_i}{\sigma_i^{\mathrm{SM}}}$$



Direct Measurement of Top Couplings subject to large uncertainties : 2σ deviations from SM predictions possible

Low Energy Supersymmetry : Type II Higgs doublet models

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

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

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

- If the mixing is such that $\cos(\beta-\alpha)=0$

$$h = -\sin\alpha H^0_d + \cos\alpha H^0_u \qquad \sin\alpha = -\cos\beta, \qquad \tan\beta = \frac{v_u}{v_d}$$
$$H = \cos\alpha H^0_d + \sin\alpha H^0_u \qquad \cos\alpha = \sin\beta$$

then the coupling of the lightest Higgs to fermions and gauge bosons is SM-like. We shall call this situation ALIGNMENT

- Observe that close to the alignment limit, the heavy Higgs couplings to down quarks and up quarks are enhanced (suppressed) by a $\tan\beta$ factor. We shall concentrate on this case.

- It is important to stress that the couplings of the CP-odd Higgs boson are

$$g^{dd,ll}_{Aff} = \frac{\mathcal{M}^{\rm dd}_{\rm diag}}{v}\tan\beta, \qquad g^{uu}_{Aff} = \frac{\mathcal{M}^{\rm uu}_{\rm diag}}{v\tan\beta}$$

Alignment in General two Higgs Doublet Models

H. Haber and J. Gunion'03

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

Symmetry arguments (not general) : Bhupal Dev, Pilaftsis'14

- From here, one can minimize the effective potential and derive the expression for the CP-even Higgs mass matrix in terms of a reference mass, that we will take to be mA

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

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

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

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

Alignment Conditions

$$(m_h^2 - \lambda_1 v^2) + (m_h^2 - \tilde{\lambda}_3 v^2) t_\beta^2 = v^2 (3\lambda_6 t_\beta + \lambda_7 t_\beta^3) \ ,$$

$$(m_h^2 - \lambda_2 v^2) + (m_h^2 - \tilde{\lambda}_3 v^2) t_\beta^{-2} = v^2 (3\lambda_7 t_\beta^{-1} + \lambda_6 t_\beta^{-3})$$

- If fulfilled not only alignment is obtained, but also the right Higgs mass, $m_h^2 = \lambda_{\rm SM} v^2$, with $\lambda_{\rm SM} \simeq 0.26$ and $\lambda_3 + \lambda_4 + \lambda_5 = \tilde{\lambda}_3$

$$\lambda_{\rm SM} = \lambda_1 \cos^4\beta + 4\lambda_6 \cos^3\beta \sin\beta + 2\tilde{\lambda}_3 \sin^2\beta \cos^2\beta + 4\lambda_7 \sin^3\beta \cos\beta + \lambda_2 \sin^4\beta$$

- For $\lambda_6 = \lambda_7 = 0$ the conditions simplify, but can only be fulfilled if

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

or

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

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

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

Naturalness and Alignment in the NMSSM

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 λ_4)

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

$$\delta\tilde{\lambda}_3 = \lambda^2$$

- The last term is the one appearing in the MSSM, that are small for moderate mixing and small values of $\tan\beta$

- The values of λ 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

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

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

Coupling of the Higgs to vector bosons and quarks within type II Higgs doublet models.

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

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

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

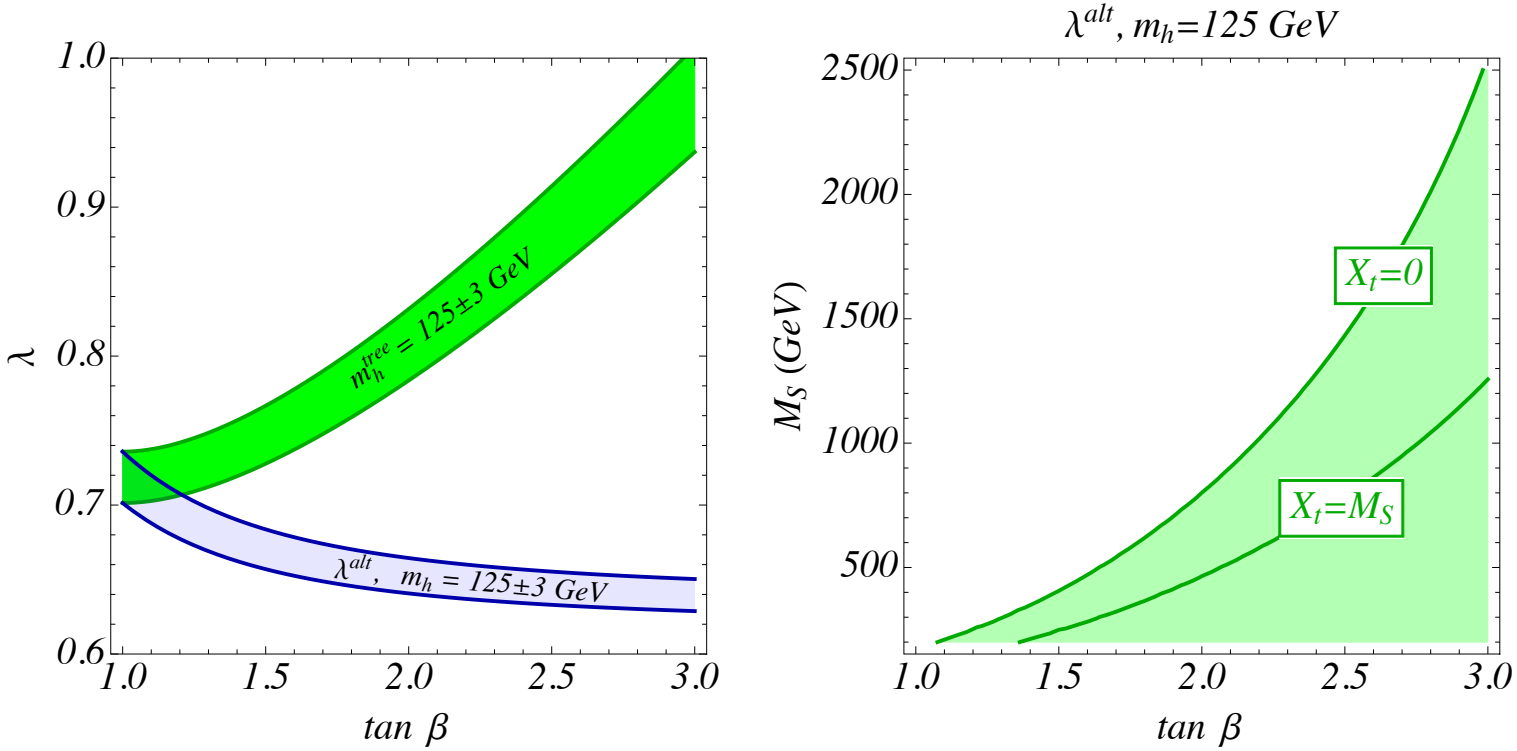
At large $\tan\beta$: $$t_\beta\, c_{\beta-\alpha} \approx \frac{-1}{m_H^2 - m_h^2}\left[(m_h^2 + m_Z^2 - \lambda^2 v^2) + \frac{3m_t^4 A_t \mu t_\beta}{4\pi^2 v^2 M_S^2}\left(1 - \frac{A_t^2}{6M_S^2}\right)\right]$$

Stop Contribution at alignment

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

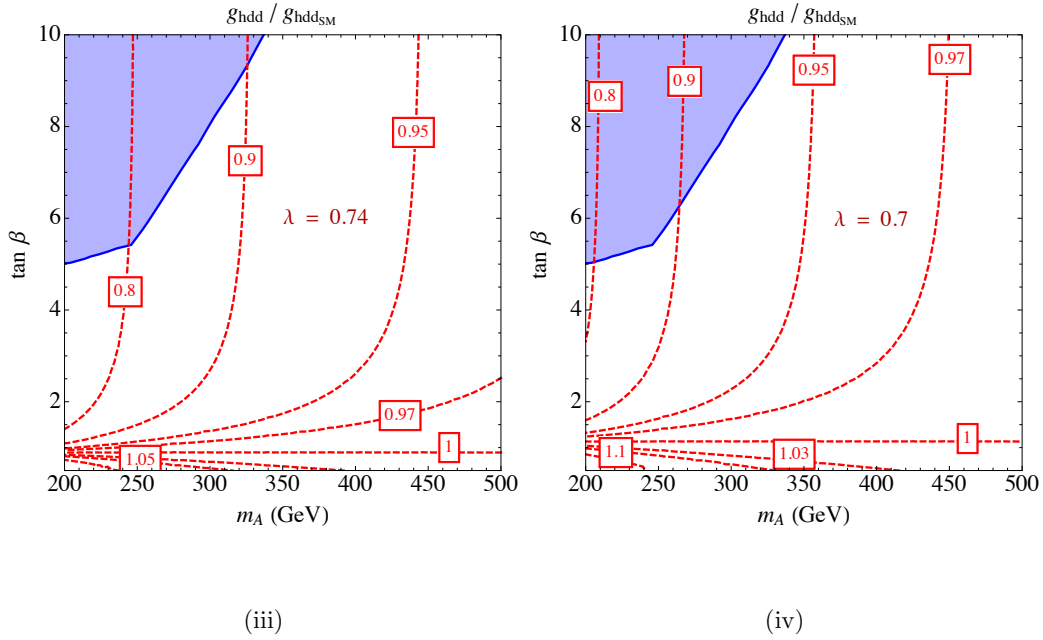
Interesting, after some simple algebra, one can show that

$$\Delta_{\tilde{t}} = -\cos 2\beta (m_h^2 - M_Z^2)$$



For moderate mixing, It is clear that low values of $\tan\beta < 3$
lead to lower corrections to the Higgs mass parameter at the alignment values

Alignment in the NMSSM (heavy or Aligned singlets)



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

It is clear from these plots that the NMSSM does an amazing job in aligning the MSSM-like CP-even sector, provided λ is about 0.65

Aligning the CP-even Singlets

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

- The previous formulae assumed implicitly that the singlets are either decoupled, or not significantly mixed with the MSSM CP-even states

- The mixing mass matrix element between the singlets and the SM-like Higgs is approximately given by

$$M_S^2(1,3) \simeq 2\lambda v \mu \left(1 - \frac{m_A^2 \sin^2 2\beta}{4\mu^2} - \frac{\kappa \sin 2\beta}{2\lambda}\right)$$

- If one assumes alignment, the expression inside the bracket must cancel

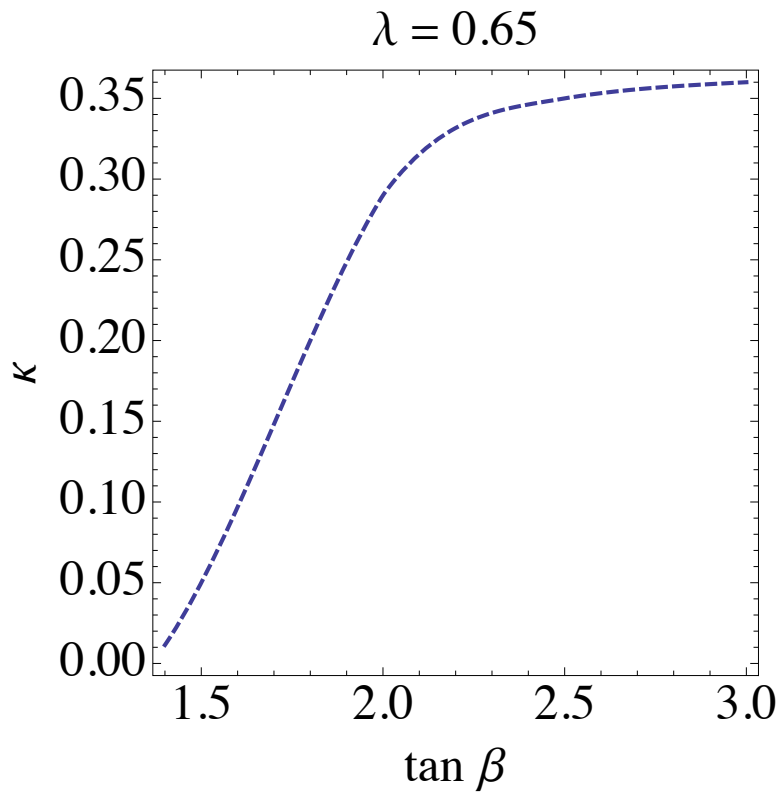
- If one assumes $\tan\beta < 3$ and lambda of order 0.65, and in addition one asks for kappa in the perturbative regime, one immediately conclude that in order to get small mixing in the Higgs sector, the CP-odd Higgs is correlated in mass with the parameter μ

- Since both of them small is a measure of naturalness, we see again that alignment and naturalness come together in a beautiful way in the NMSSM

- Moreover, this ensures also that all parameters are small and the CP-even and CP-odd singlets (and singlino) become self consistently light

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

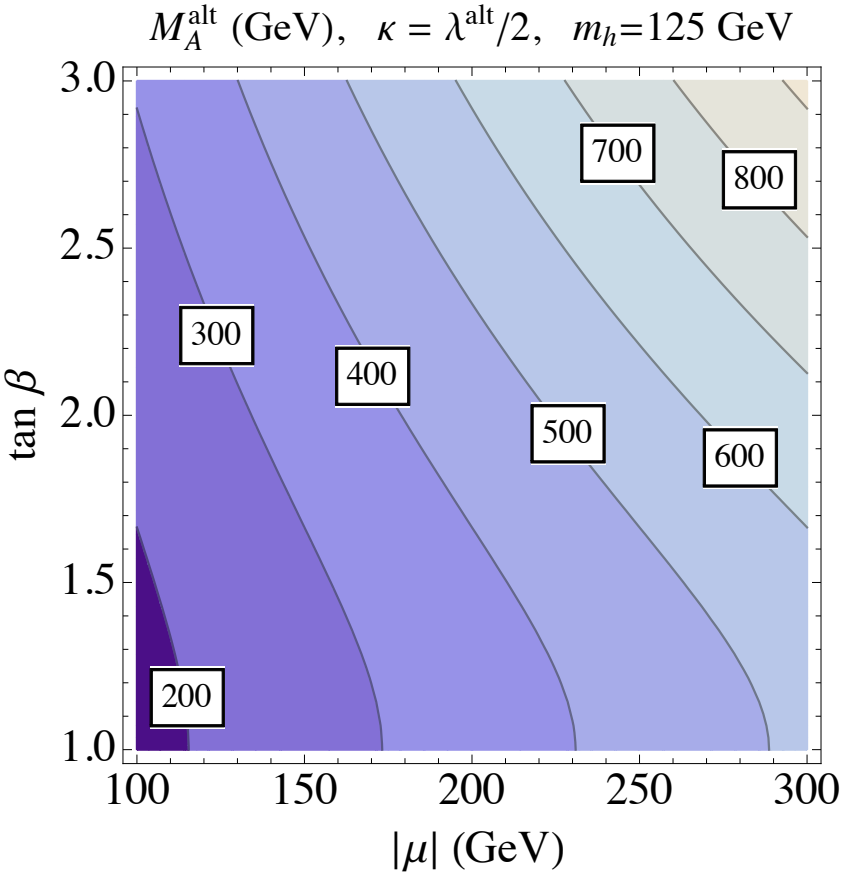
Perturbative Values of kappa

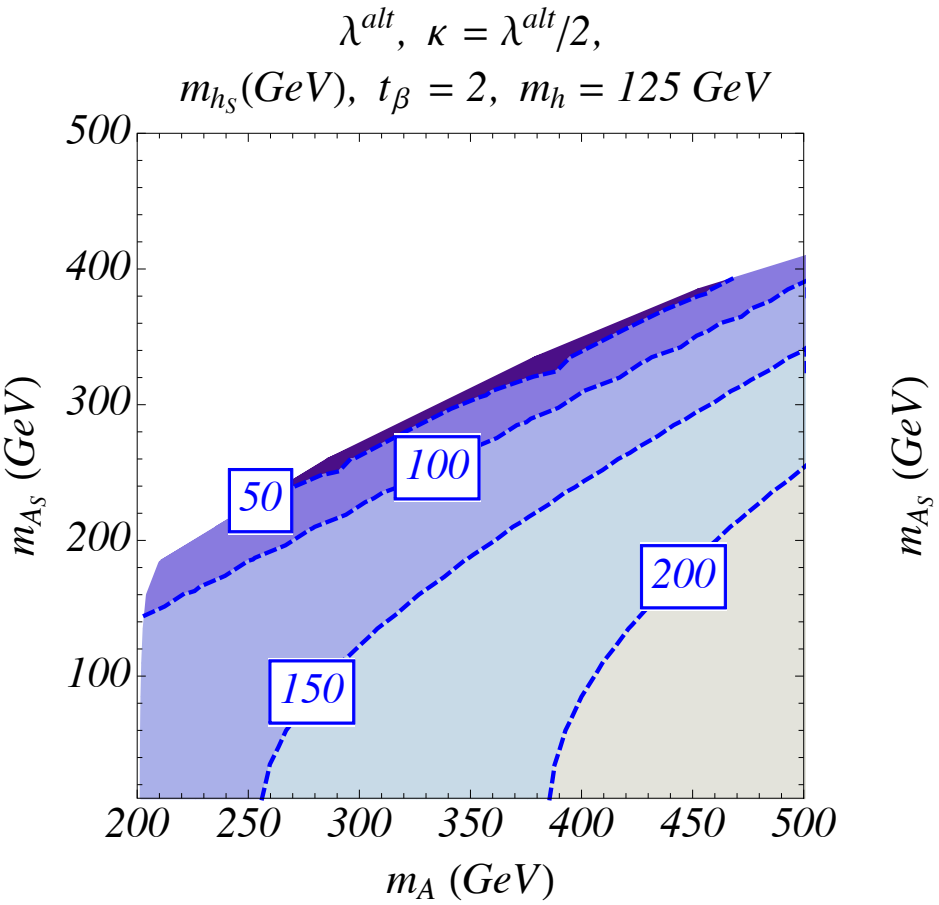


Top Yukawa Coupling becomes stronger
for smaller values of tanβ

Values of the Singlet, Higgsino and Singlino Masses

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





In this limit, the singlino mass is equal to the Higgsino mass.

$$m_{\tilde{S}} = 2\mu\frac{\kappa}{\lambda}$$

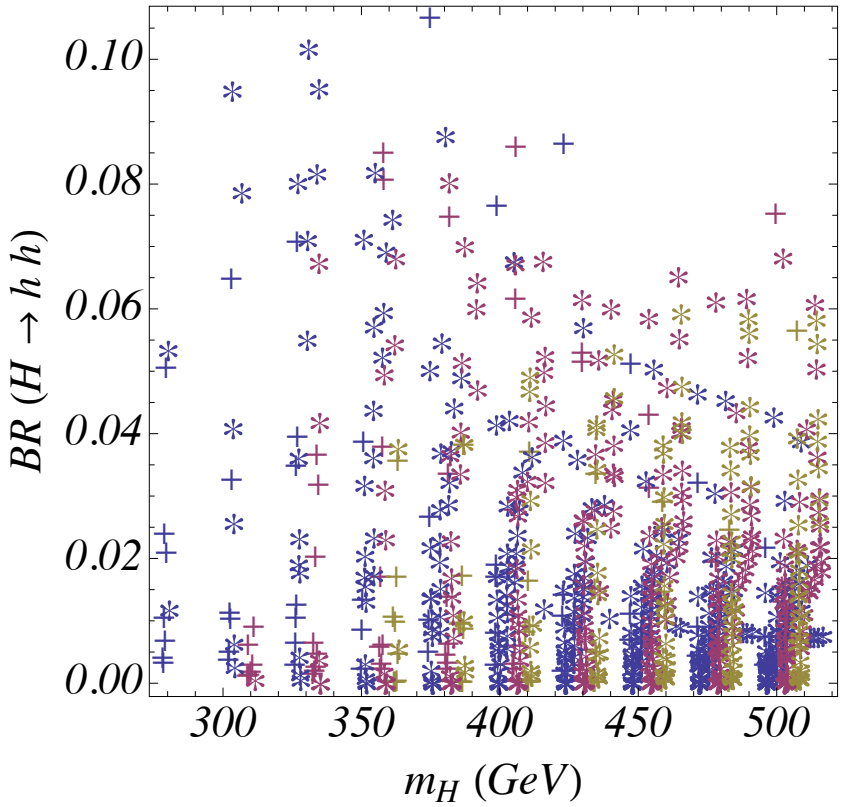
So, the whole Higgs and Higgsino spectrum remains light, as anticipated

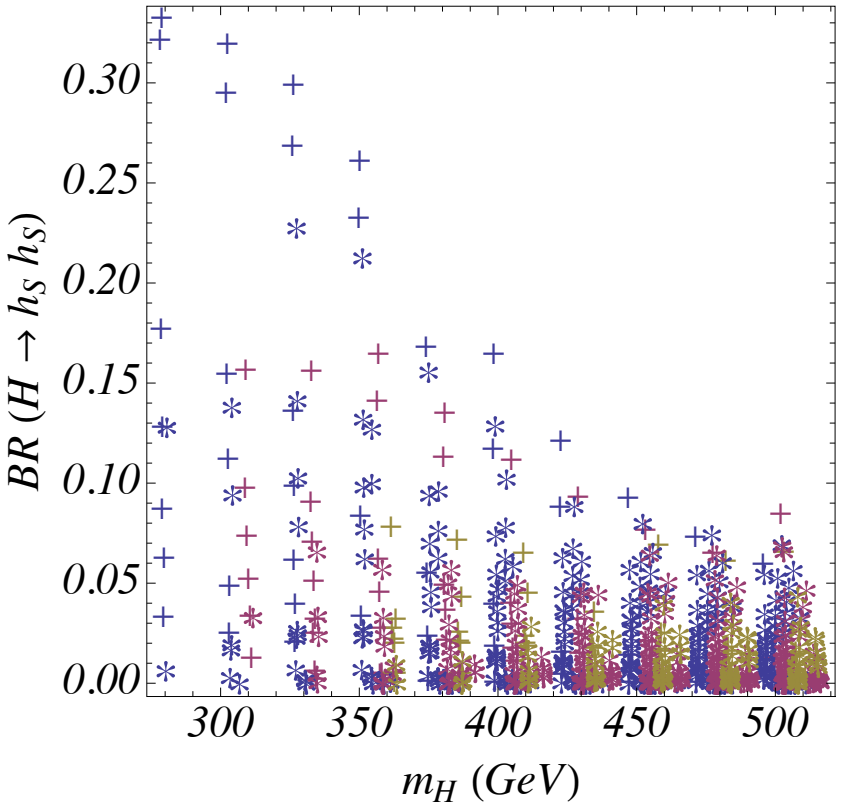
Carena, Haber, Low, Shah, C.W.'15

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

Crosses: H_1 singlet like
Stars : H_2 singlet like

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



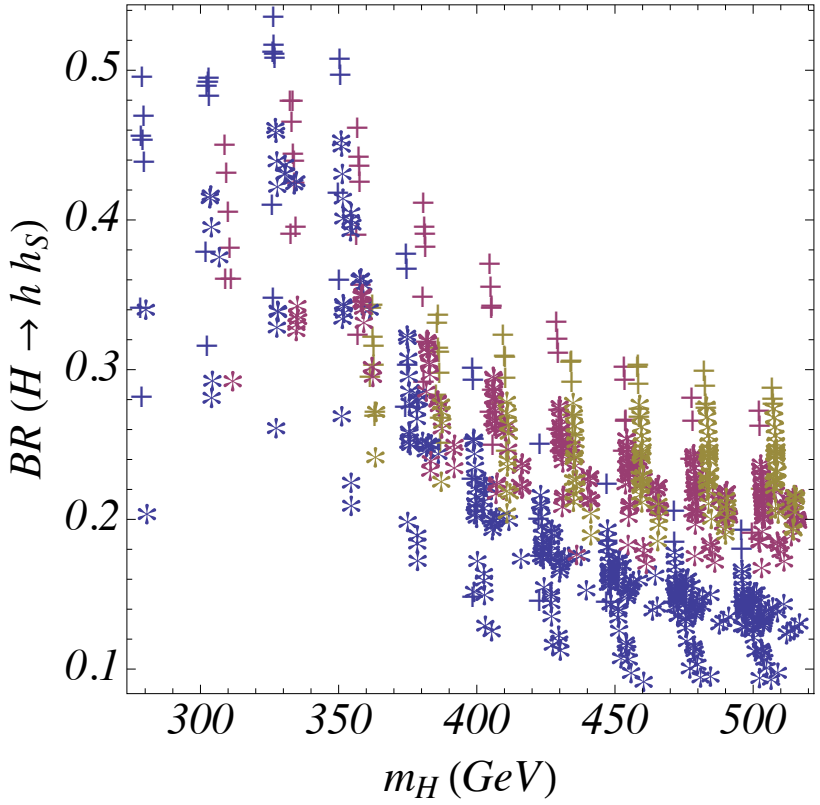


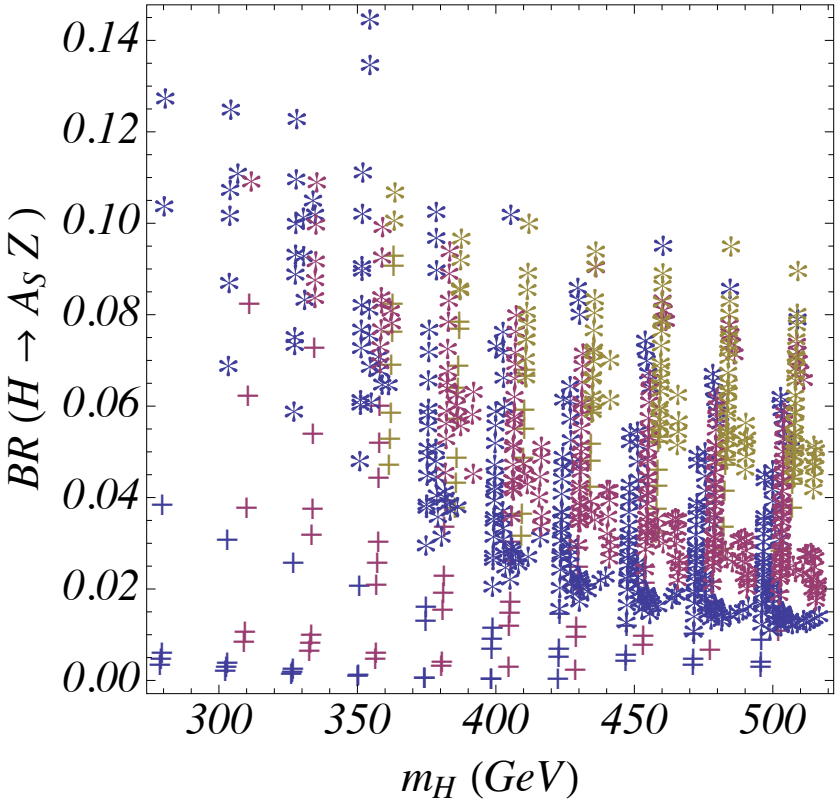
Carena, Haber, Low, Shah, C.W.'15

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

Crosses: H_1 singlet like
Stars : H_2 singlet like

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



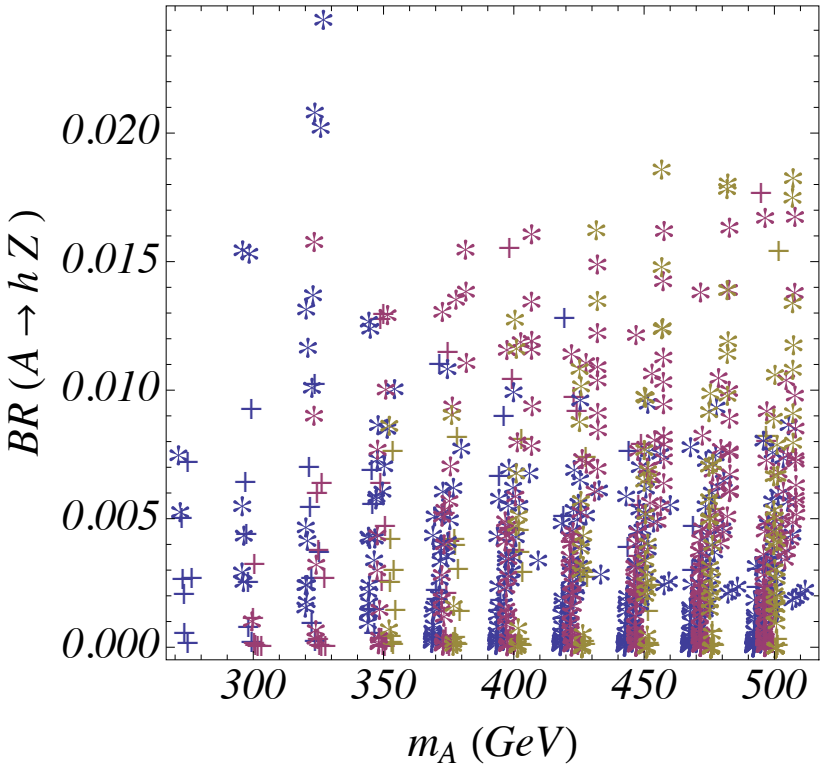


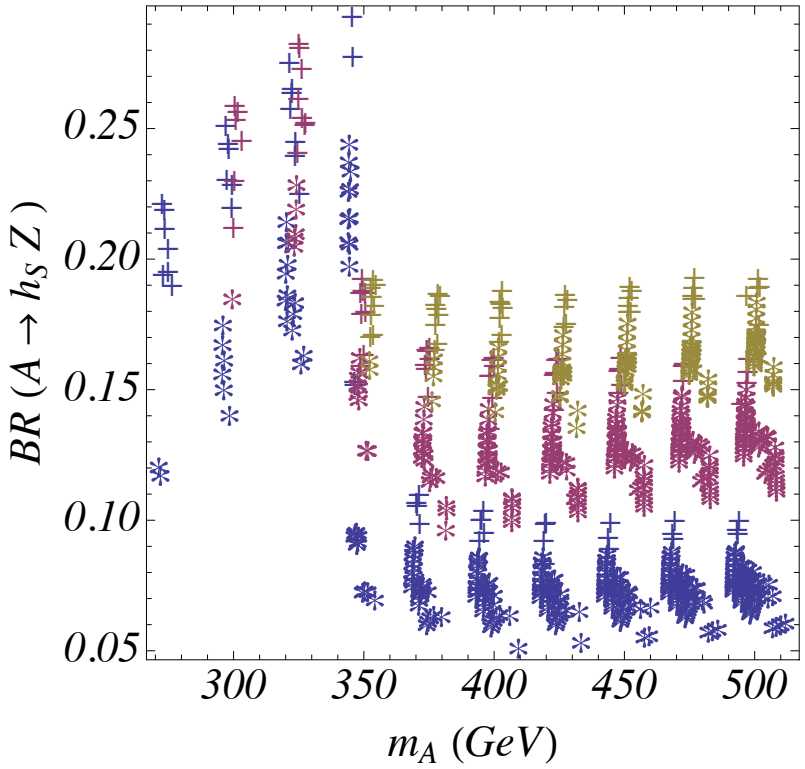
Carena, Haber, Low, Shah, C.W.'15

Heavy CP-odd Higgs Bosons have similar decay modes

Crosses: H_1 singlet like
Stars : H_2 singlet like

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





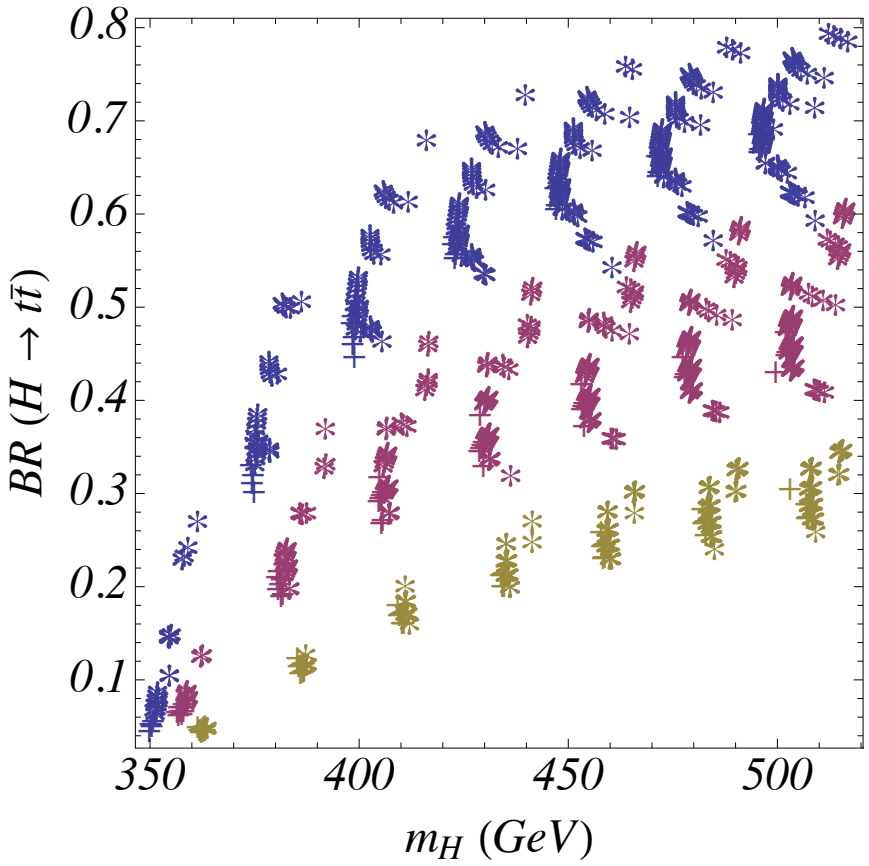
Significant decay of heavy CP-odd
Higgs bosons into singlet like states plus Z

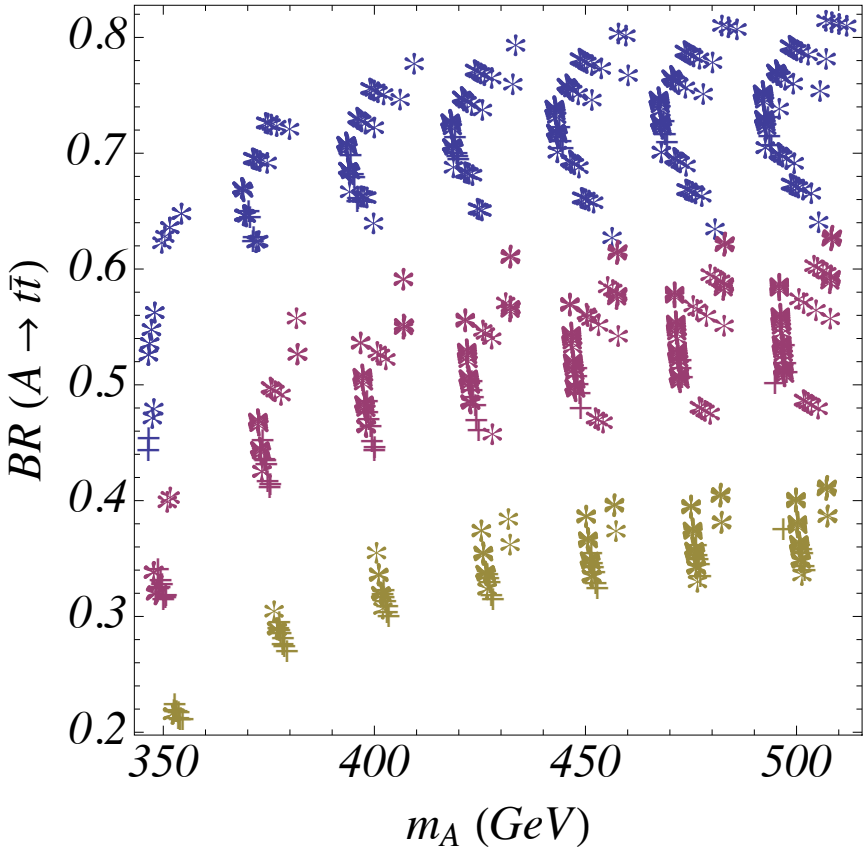
Carena, Haber, Low, Shah, C.W.'15

Decays into top significant but may be somewhat suppressed by decays into non-standard particles

Crosses: H_1 singlet like
Stars : H_2 singlet like

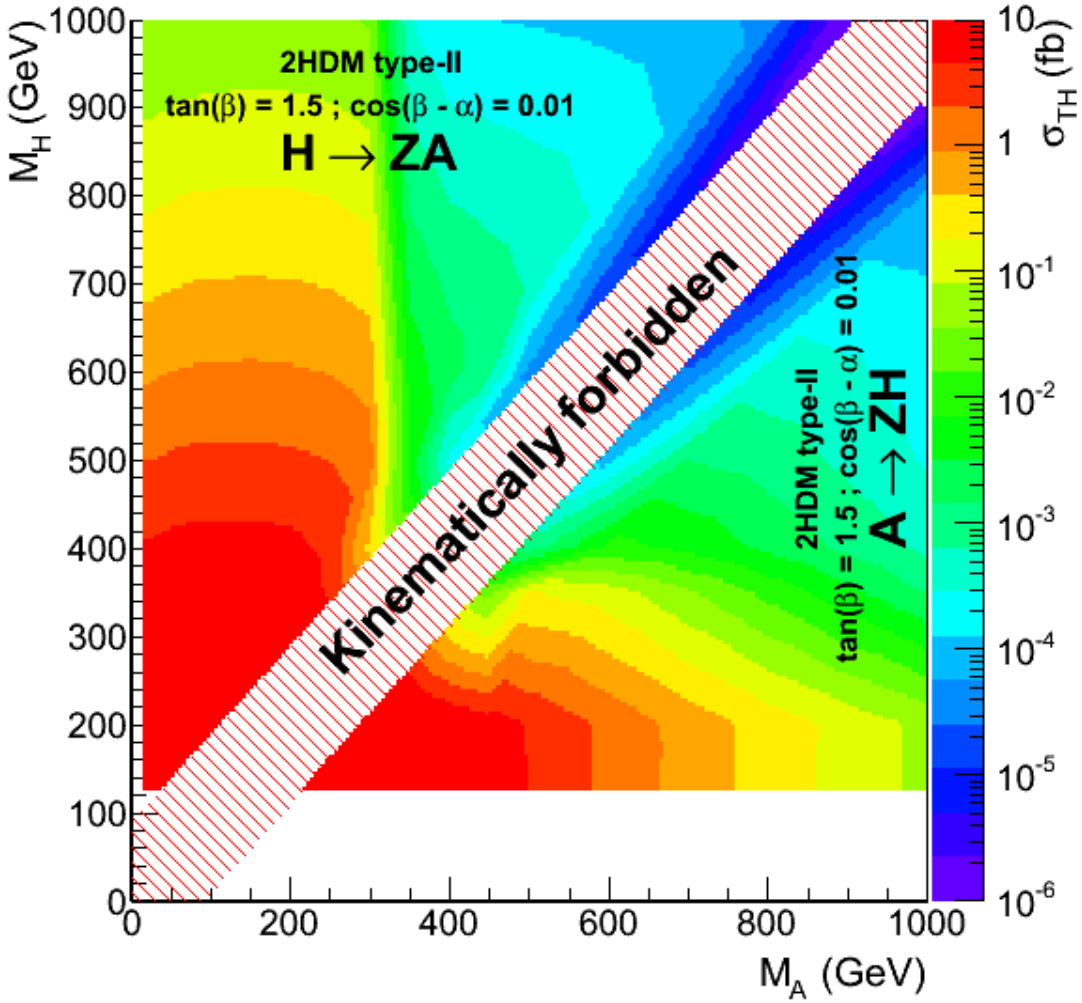
Blue : $\tan\beta = 2$
Red : $\tan\beta = 2.5$
Yellow : $\tan\beta = 3$





Search for (psudo-)scalars decaying into lighter ones

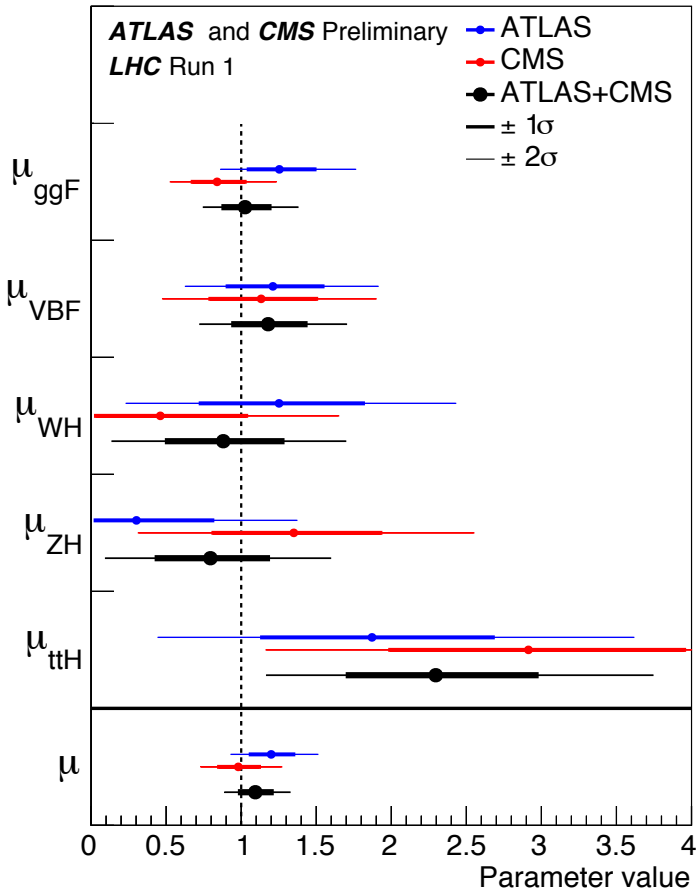
CMS-PAS-HIG-15-001

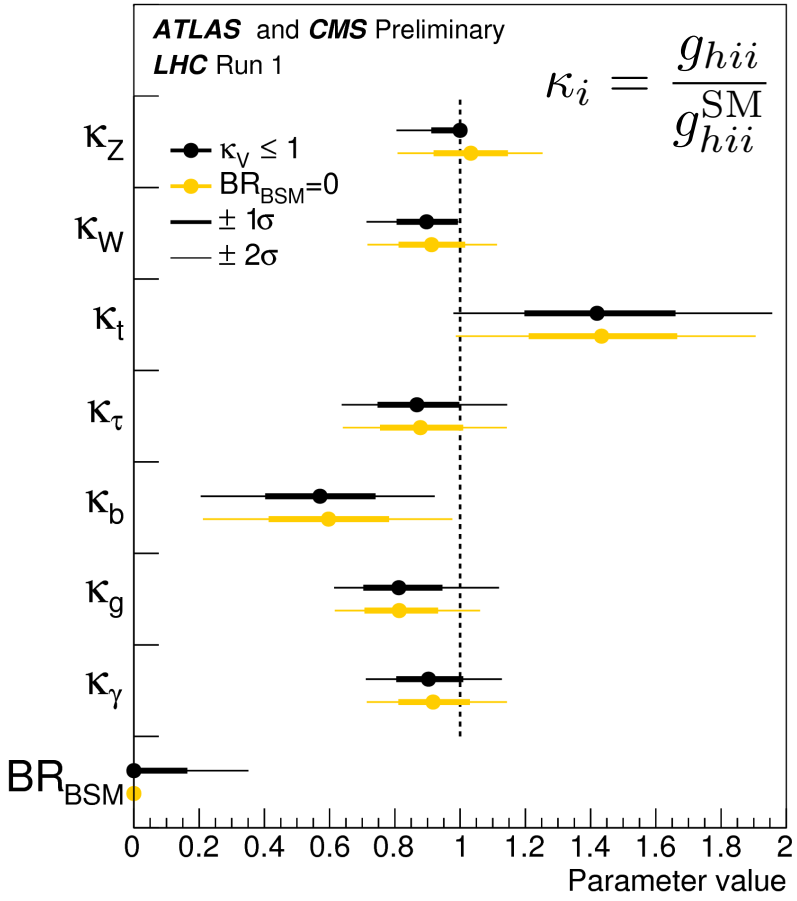


It is relevant to perform similar analyses replacing the Z by a SM Higgs (and interchanging CP properties) !

More on the Third Generation Quark Couplings to the Higgs

ATLAS and CMS Combination





Assuming no strict correlation between gluon and top couplings

Direct Measurement of Bottom and Top Couplings subject to large uncertainties : 2σ deviations from SM predictions possible (and statistically favored) if certain correlations are present.

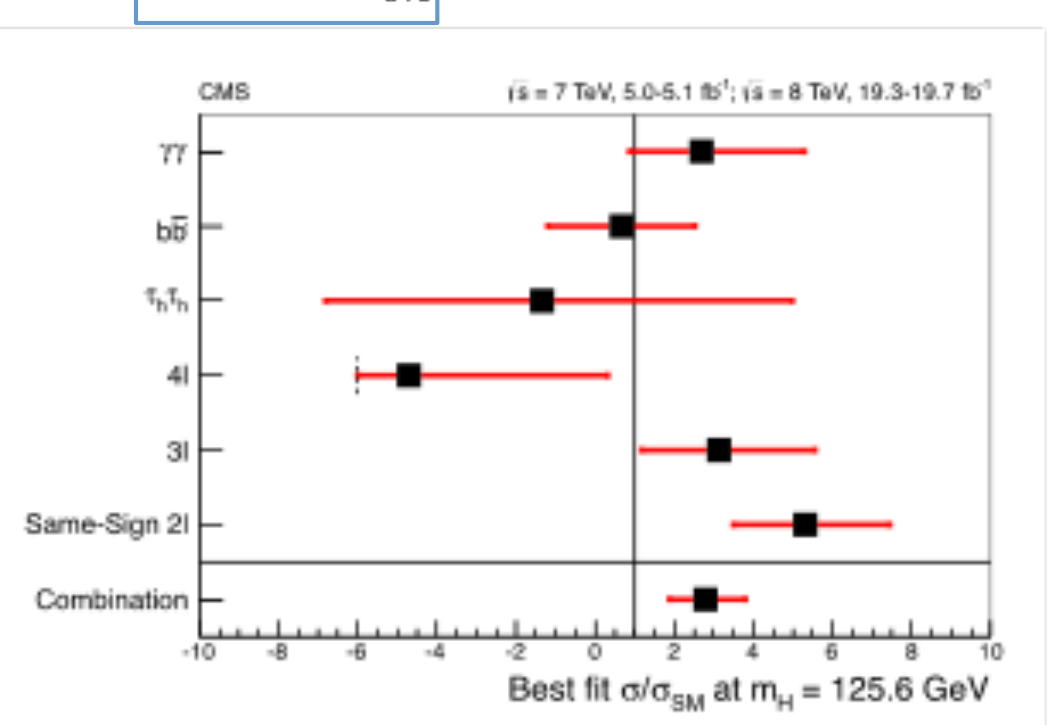
Low bottom coupling has a major impact on the fit to the rest of the couplings.

Top Quark Coupling Enhancement ?

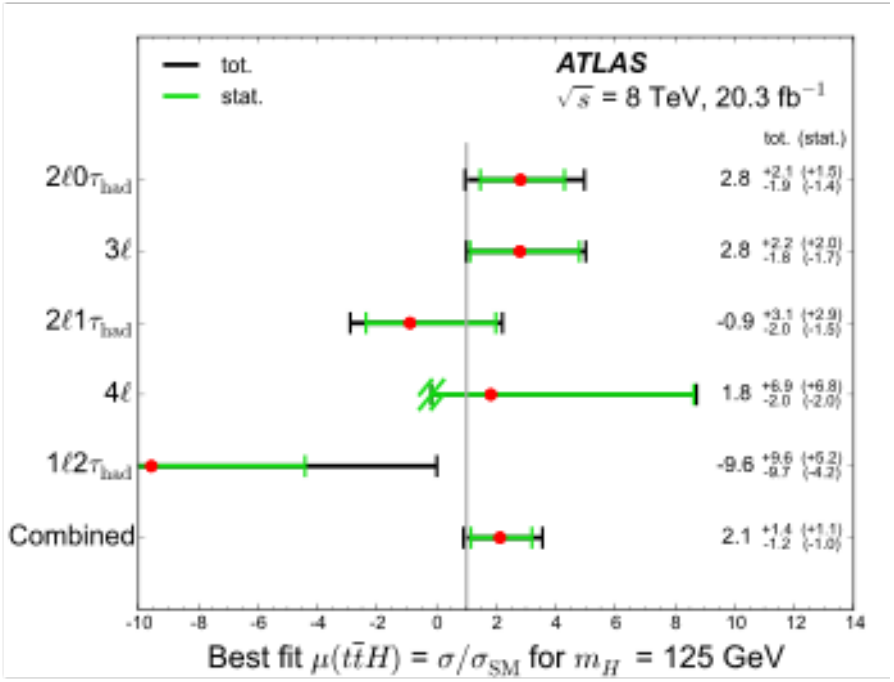
Excess at both experiments

ttH, H->W^+W^- , multi-lepton

$\mu = 2.8^{+1}_{-0.9}$



$\mu = 2.1^{+1.4}_{-1.2}$

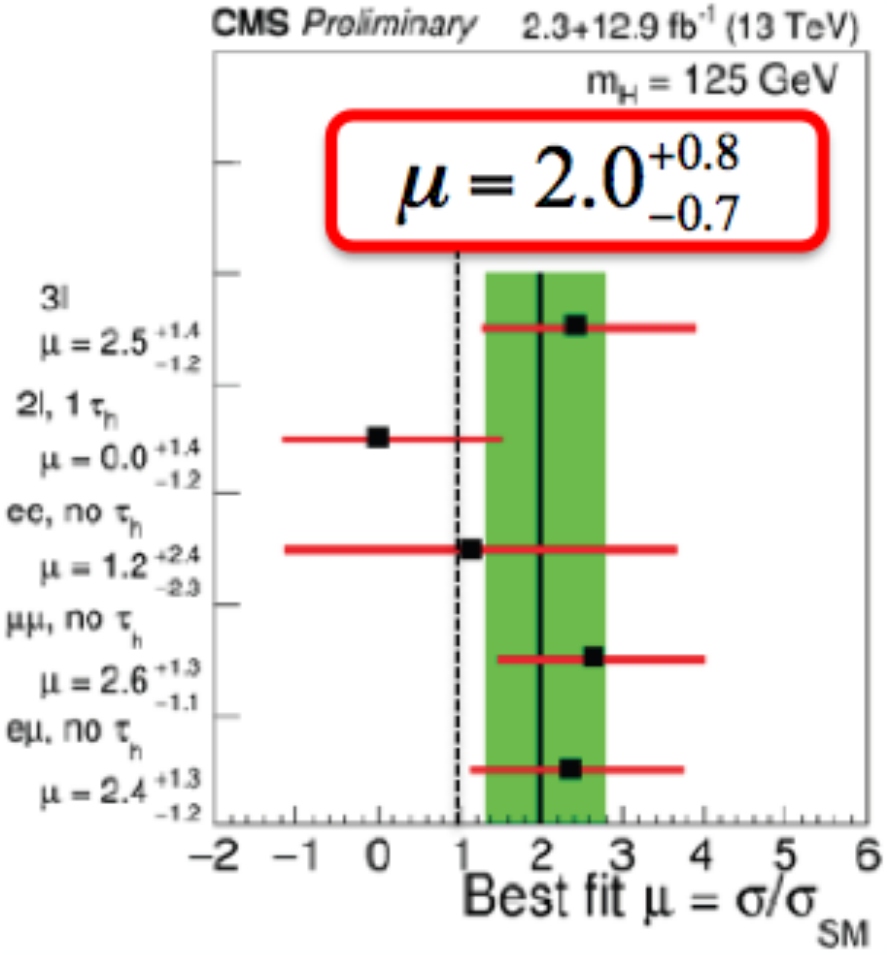


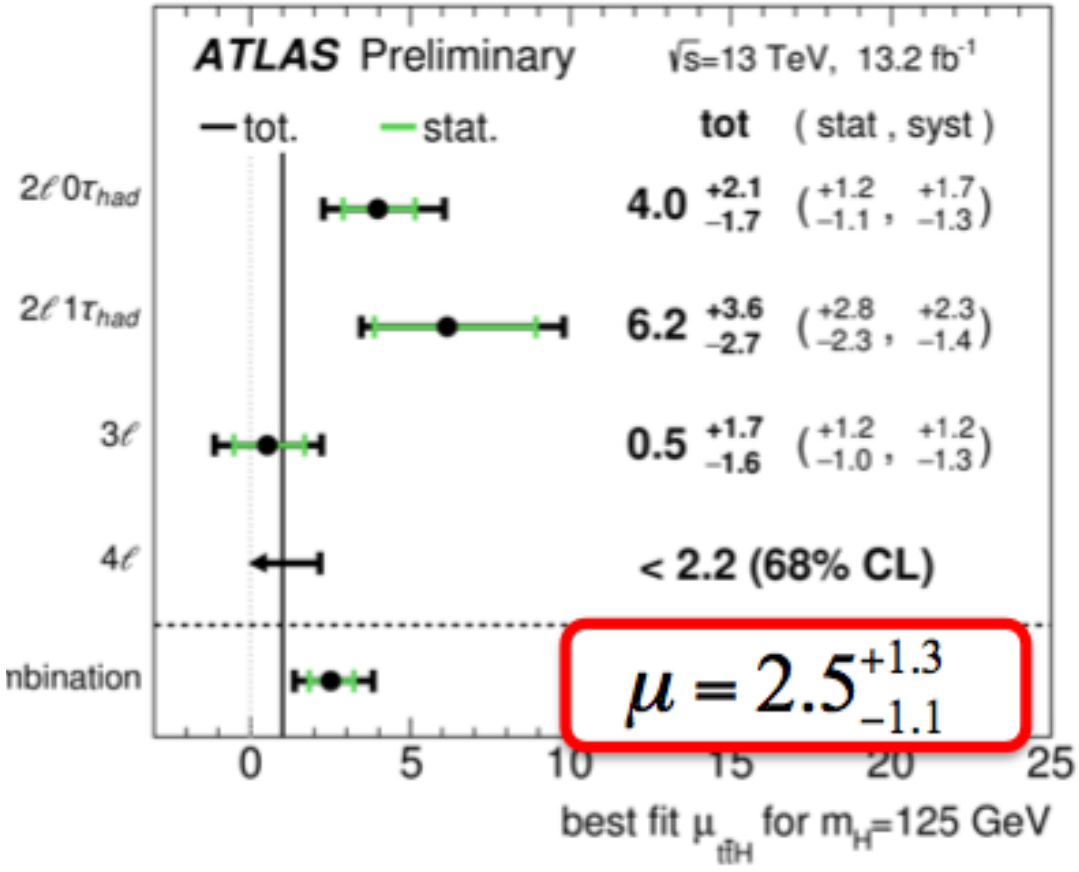
CMS 1408.1682, local significance 2.6σ

ATLAS 1506.05988

Top Quark Coupling Enhancement ?

Excess at both runs

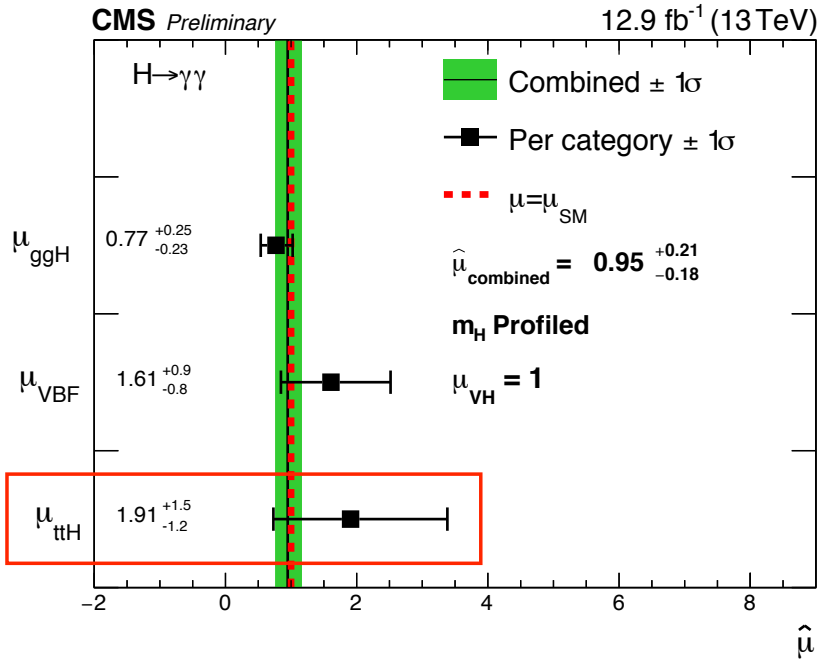


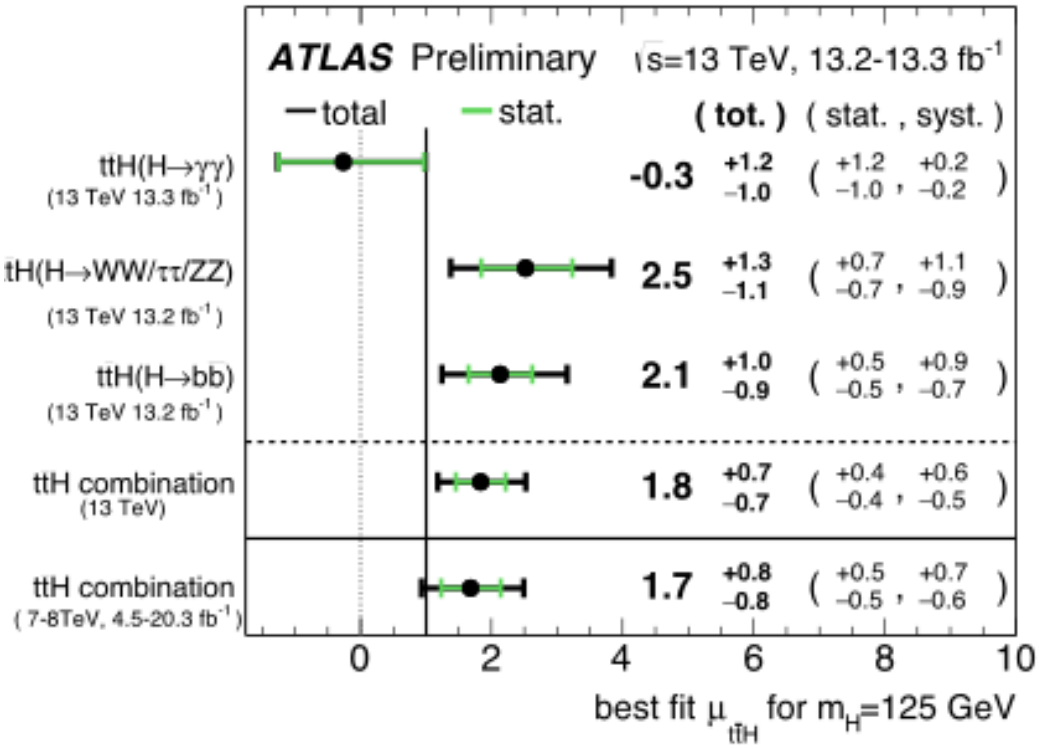


Canelli, ICHEP 2016

Top Quark Coupling Enhancement ?

If combine all channels in tth searches,
the signal strength is still about 2 times the SM value

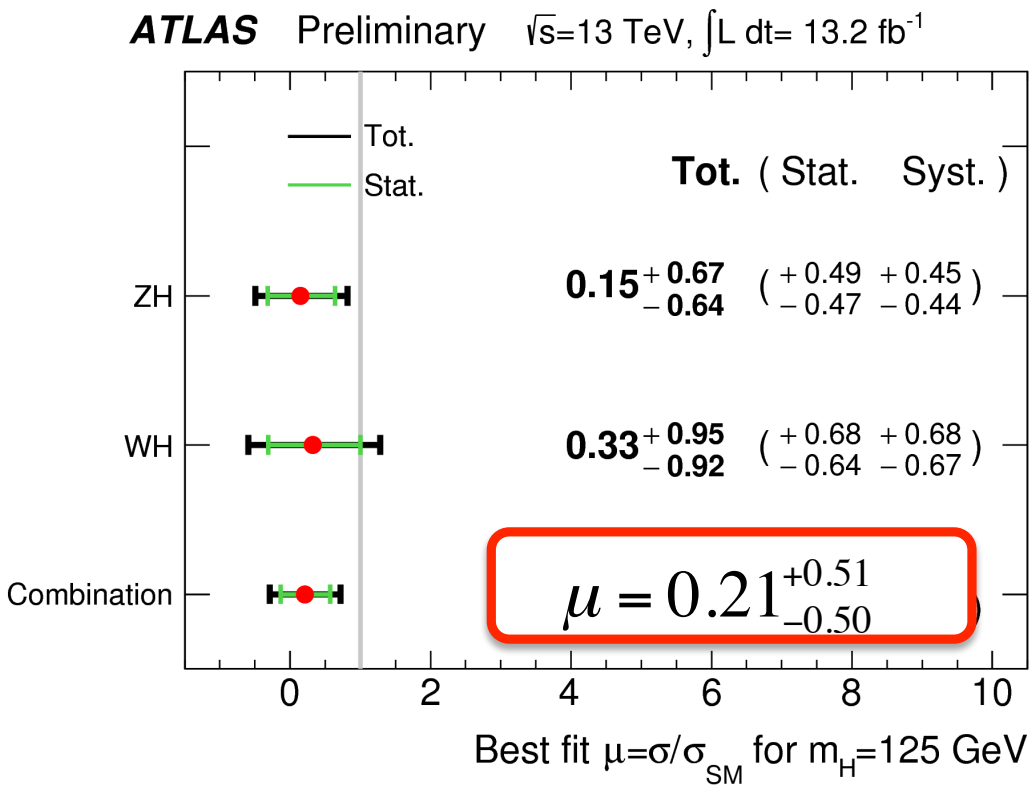




We shall interpret the results in terms
of tth coupling enhancement and also provide an alternative explanation

Bottom Coupling Suppression ?

ATLAS-CONF-2016-091



	Significance (expected)
ATLAS (13 TeV)	0.4σ (1.94σ)
ATLAS+CMS (8 TeV)	2.6σ (3.7σ)
Tevatron	2.8σ
	W(Z)Z(→bb)
Observed μ	$0.91 \pm 0.17(\text{stat})\ ^{+0.32}_{-0.27}(\text{syst})$
Significance	3.0σ (expected 3.2σ)

Fit tested on SM

The tendency still persists in recent data, presented at ICHEP

It is important to stress that a suppression of the bottom coupling would affect all Higgs BRs in a relevant way.

M. Badziak and C.W. ‘1602.06198

Away from Alignment : Enhancing tth Production

- The combination of Run I data has shown a somewhat large value of the production of Higgs bosons in association with top quarks

$$\mu^{\rm tth} = 2.3^{+0.7}_{-0.6},$$

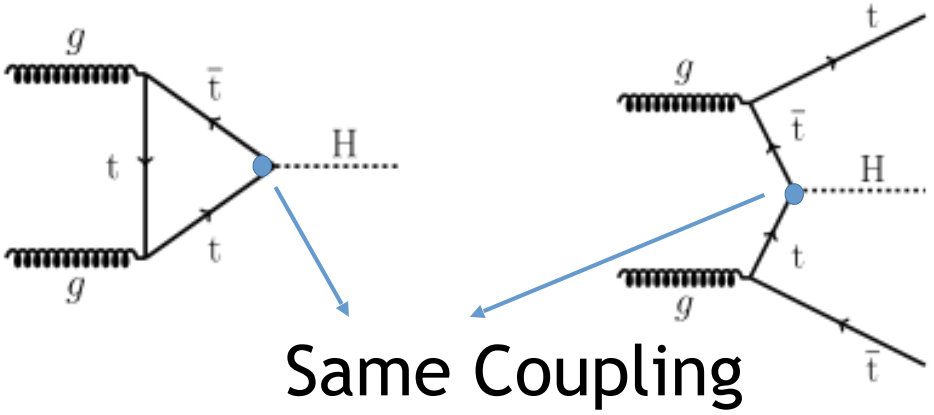
- Enhancing the top coupling is simple in type II 2HDM, but the bottom quark coupling is modified as well in an opposite direction

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

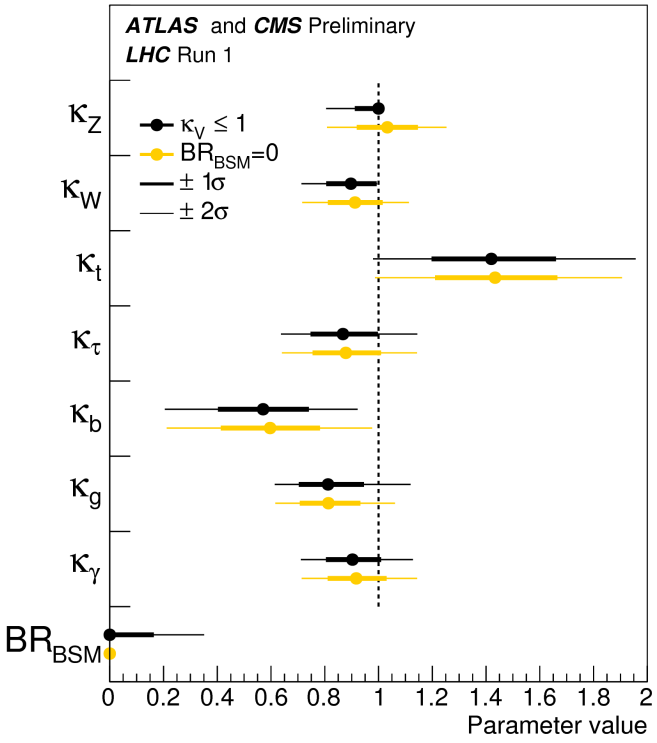
- This tendency is in agreement with the one present in the current data

What is the problem in 2HDM ?

SM+ a enhanced top Yukawa coupling?



Same Coupling



Would expect gluon fusion to be high as well !

Additional contributions necessary to suppress the ggh coupling, as reflected in the best fit.

M. Badziak and C.W. '1602.06198

Away from Alignment : Enhancing tth Production

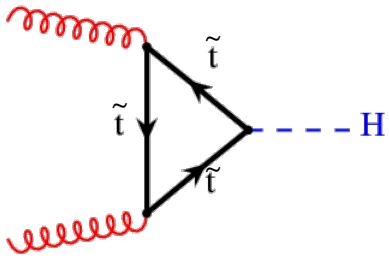
- The combination of Run I data has shown a somewhat large value of the production of Higgs bosons in association with top quarks

$$\mu^{\rm tth} = 2.3^{+0.7}_{-0.6},$$

- Enhancing the top coupling is simple in type II 2HDM, but the bottom quark coupling is modified as well in an opposite direction

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

- However, the gluon fusion cross section could also be modified in the presence of extra color particles. For instance, for scalar tops,



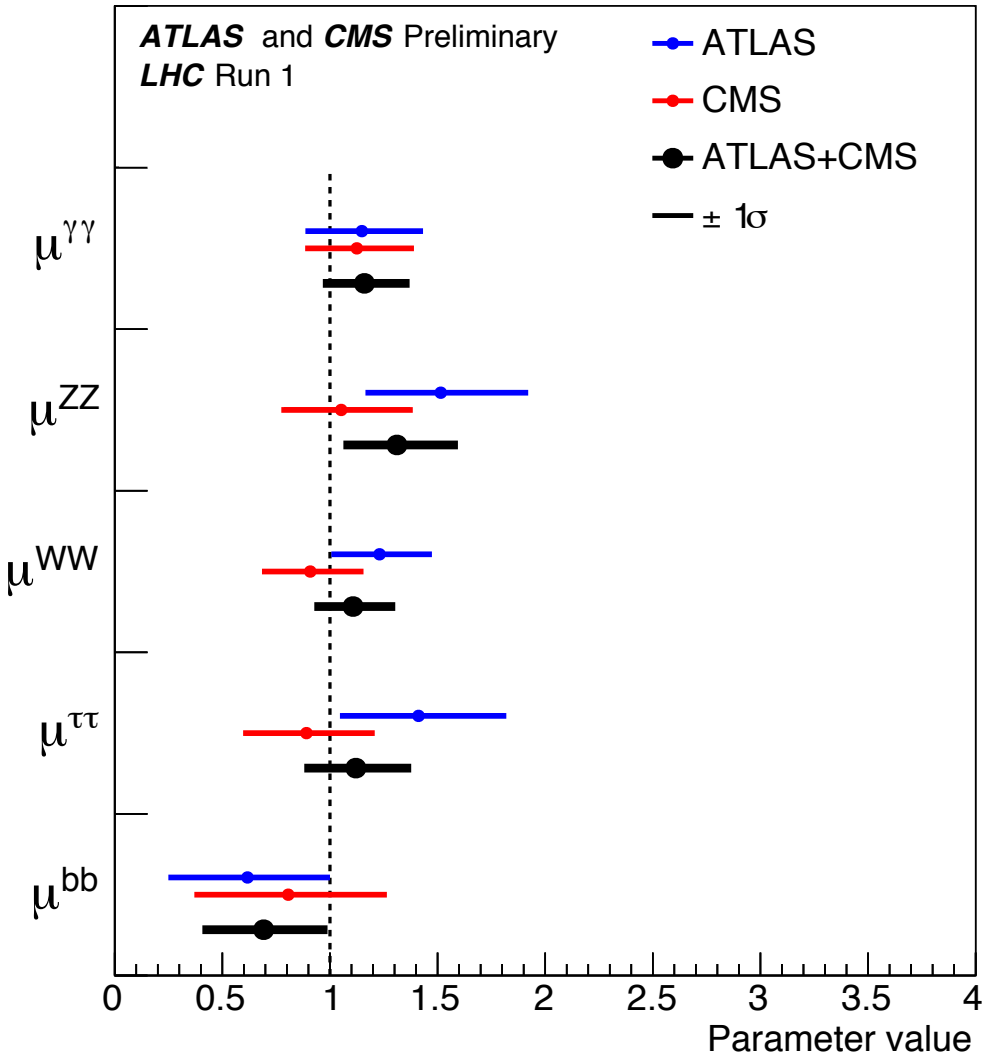
$$\frac{\kappa_g}{\kappa_g^{\rm SM}} \simeq \kappa_t \left[1 + \frac{m_t^2}{4}\left(\frac{1}{m^2_{\tilde t_1}} + \frac{1}{m^2_{\tilde t_2}} - \frac{X_t^2}{m^2_{\tilde t_1} m^2_{\tilde t_2}}\right)\right]$$

M. Badziak and C.W. '1602.06198

NMSSM Implementation : Heavy Singlets

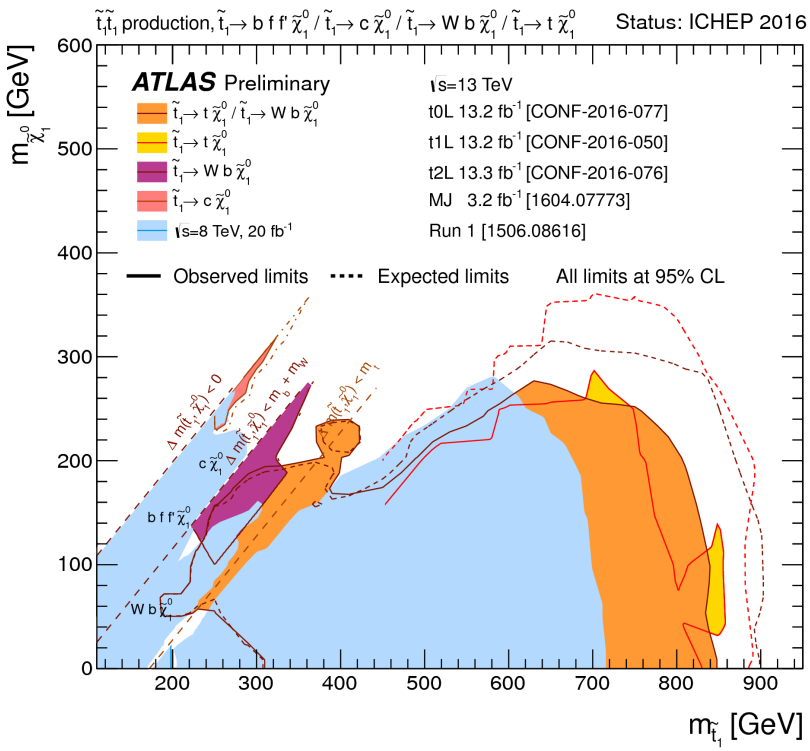
	P1	P2	P3	P4	P5
λ	0.76	0.85	1.1	1.4	1.4
$\tan\beta$	4	2	2	1.5	1.5
m_{Q_3}	700	700	700	700	700
m_{U_3}	500	480	500	480	450
A_t	-1170	-1100	-1030	-780	-1030
μ	300	770	1040	1060	390
M_2	500	500	500	500	-90
μ'	60	45	40	14	-24
M_{P_1}	193	197	277	332	357
M_{P_2}	2000	2500	3000	2400	800
m_h	125.1	125.9	125.0	124.9	125.0
m_H	192	184	262	280	299
$m_{H^\pm}$	167	161	236	257	272
m_A	195	204	293	342	344
$m_{\tilde{\chi}_1^0}$	70	65	66	63	89
$m_{\tilde{\chi}_1^\pm}$	282	504	516	514	109
$m_{\tilde{t}_1}$	236	232	241	231	222
$m_{\tilde{t}_2}$	726	752	766	757	730
$R_{VV}^{\rm tth}$	1.79	1.84	1.96	1.92	1.87
$R_{\gamma\gamma}^{\rm tth}$	1.97	2.12	2.22	2.19	1.96
$R_{VV}^{\rm gg}$	1.16	1.00	1.12	1.18	1.23
$R_{\gamma\gamma}^{\rm gg}$	1.29	1.15	1.27	1.34	1.29
$R_{VV}^{\rm VBF/VH}$	1.70	1.57	1.65	1.48	1.43
$R_{\gamma\gamma}^{\rm VBF/VH}$	1.89	1.80	1.87	1.69	1.50
$R_{\tau\tau}^{\rm VBF/VH}$	0.70	0.71	0.67	0.71	0.65
BR($H \to \tilde{\chi}_1^0\tilde{\chi}_1^0$)	0.71	0.49	0.24	0.14	0.19
BR($H \to \tilde{\chi}_1^0\tilde{\chi}_2^0$)	0	0	0	0	0.17
BR($H \to hh$)	0	0	0.47	0.71	0.54
BR($A \to \tilde{\chi}_1^0\tilde{\chi}_1^0$)	0.85	0.89	0.78	0.75	0.88
BR($A \to H^\pm W^\mp$)	0	0	0	0.05	0

- One can implement the previous idea within the NMSSM
- However, the NMSSM is more than just adding a stop to the 2HDM
- Departure of alignment here demands larger values of lambda
- Constraints on the production of heavy Higgs bosons can be easily arranged by a small amount of decay into neutralinos, that is natural in this theory.
- Most constraining observable : Diphoton production in vector boson fusion.

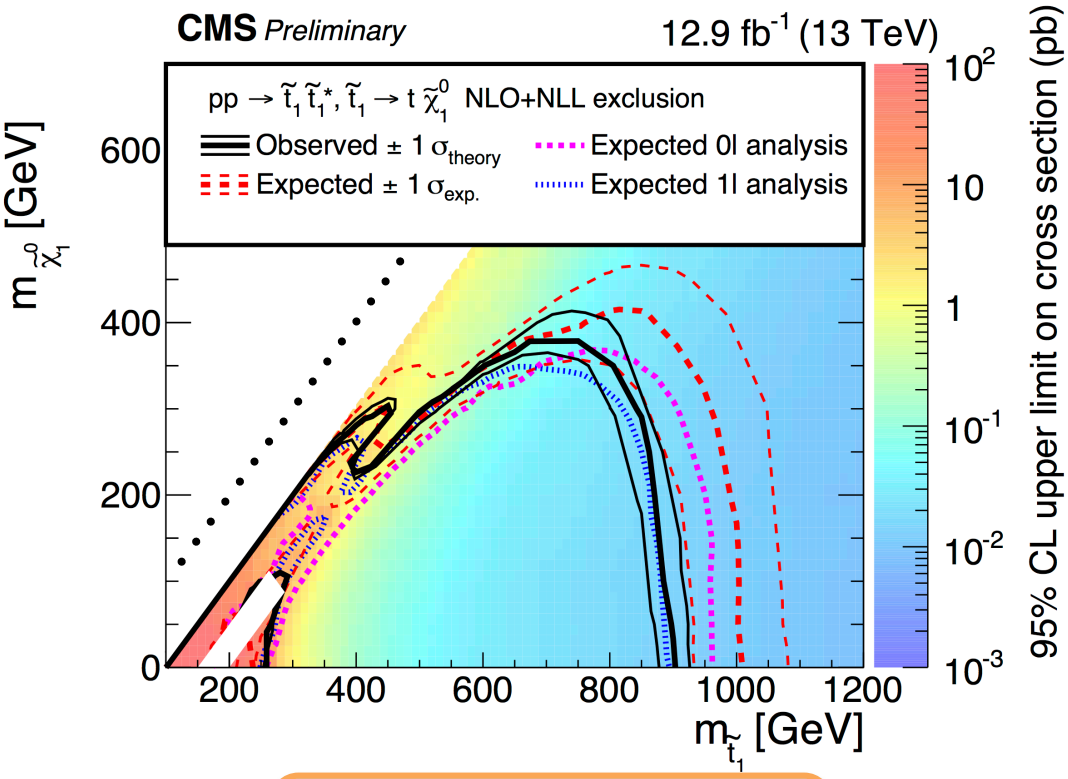


Parameter	ATLAS+CMS Measured	ATLAS+CMS Expected uncertainty	ATLAS Measured	CMS Measured
10-parameter fit of μ_F^f and μ_V^f				
$\mu_V^{\gamma\gamma}$	$1.05^{+0.44}_{-0.41}$	$^{+0.42}_{-0.38}$	$0.69^{+0.64}_{-0.58}$	$1.37^{+0.62}_{-0.56}$
μ_V^{ZZ}	$0.48^{+1.37}_{-0.91}$	$^{+1.16}_{-0.84}$	$0.26^{+1.60}_{-0.91}$	$1.44^{+2.32}_{-2.30}$
μ_V^{WW}	$1.38^{+0.41}_{-0.37}$	$^{+0.38}_{-0.35}$	$1.56^{+0.52}_{-0.46}$	$1.08^{+0.65}_{-0.58}$
$\mu_V^{\tau\tau}$	$1.12^{+0.37}_{-0.35}$	$^{+0.38}_{-0.36}$	$1.29^{+0.58}_{-0.53}$	$0.87^{+0.49}_{-0.45}$
μ_V^{bb}	$0.65^{+0.30}_{-0.29}$	$^{+0.32}_{-0.30}$	$0.50^{+0.39}_{-0.37}$	$0.85^{+0.47}_{-0.44}$
$\mu_F^{\gamma\gamma}$	$1.19^{+0.28}_{-0.25}$	$^{+0.25}_{-0.23}$	$1.31^{+0.37}_{-0.34}$	$1.01^{+0.34}_{-0.31}$
μ_F^{ZZ}	$1.44^{+0.38}_{-0.34}$	$^{+0.29}_{-0.25}$	$1.73^{+0.51}_{-0.45}$	$0.97^{+0.54}_{-0.42}$
μ_F^{WW}	$1.00^{+0.23}_{-0.20}$	$^{+0.21}_{-0.19}$	$1.10^{+0.29}_{-0.26}$	$0.85^{+0.28}_{-0.25}$
$\mu_F^{\tau\tau}$	$1.10^{+0.61}_{-0.58}$	$^{+0.56}_{-0.53}$	$1.72^{+1.24}_{-1.13}$	$0.91^{+0.69}_{-0.64}$
μ_F^{bb}	$1.09^{+0.93}_{-0.89}$	$^{+0.91}_{-0.86}$	$1.51^{+1.15}_{-1.08}$	$0.10^{+1.83}_{-1.86}$
6-parameter fit of global μ_V/μ_F and to μ_F^f				
μ_V/μ_F	$1.06^{+0.35}_{-0.27}$	$^{+0.34}_{-0.26}$	$0.91^{+0.41}_{-0.30}$	$1.29^{+0.67}_{-0.46}$
$\mu_F^{\gamma\gamma}$	$1.13^{+0.24}_{-0.21}$	$^{+0.21}_{-0.19}$	$1.18^{+0.33}_{-0.29}$	$1.03^{+0.30}_{-0.26}$
μ_F^{ZZ}	$1.29^{+0.29}_{-0.25}$	$^{+0.24}_{-0.20}$	$1.54^{+0.44}_{-0.36}$	$1.00^{+0.33}_{-0.27}$
μ_F^{WW}	$1.08^{+0.22}_{-0.19}$	$^{+0.19}_{-0.17}$	$1.26^{+0.29}_{-0.25}$	$0.85^{+0.25}_{-0.22}$
$\mu_F^{\tau\tau}$	$1.07^{+0.35}_{-0.28}$	$^{+0.32}_{-0.27}$	$1.50^{+0.66}_{-0.49}$	$0.75^{+0.39}_{-0.29}$
μ_F^{bb}	$0.65^{+0.37}_{-0.28}$	$^{+0.45}_{-0.34}$	$0.67^{+0.58}_{-0.42}$	$0.64^{+0.54}_{-0.36}$

Top squarks - summaries



ATLAS summary



CMS 0l+1l combination for 2-/3-body decay

Badziak, C.W. , arXiv:1611.02353

Alternative : Light Singlets

- The previous reasoning was adequate when one considered an effective 2x2 CP-even Higgs matrix, resulting from the decoupling of singlets.
- However, in the case of light singlets, a component of the SM-like CP-even Higgs on the doublet states may be induced by mixing with light singlets.
- This may be achieved, with values of the coupling λ that are smaller than 0.7 and therefore in the region of consistency with perturbative behavior up to the GUT scale.

Badziak, C.W. , arXiv:1611.02353

NMSSM Scenarios with light singlets

	P1	P2	P3	P4
λ	0.5	0.53	0.5	0.55
$\tan\beta$	1.6	1.6	2	2
m_{Q_3}	800	800	800	800
m_{U_3}	320	310	280	270
A_t	-1500	-1400	-1500	-1400
μ	600	800	600	800
μ'	330	500	330	310
M_A	300	300	300	400
M_P	246	382	347	382
A_λ	905	1125	1055	1610
m_s	98	98	79	85
m_h	124.5	125.8	124.7	125.1
m_H	317	390	393	465
$m_{H^\pm}$	236	200	225	325
m_a	101	136	130	89
m_A	329	412	395	496
$m_{\tilde{\chi}_1^0}$	243	245	243	245
$m_{\tilde{t}_1}$	282	282	276	275
$m_{\tilde{t}_2}$	954	960	952	954

	P1	P2	P3	P4
$R_{VV}^{\rm tth}$	1.60	1.61	1.62	1.61
$R_{\gamma\gamma}^{\rm tth}$	1.82	1.82	1.81	1.79
$R_{VV}^{\rm gg}$	1.02	1.01	1.04	1.04
$R_{\gamma\gamma}^{\rm gg}$	1.16	1.15	1.16	1.16
$R_{VV}^{\rm VBF/VH}$	1.32	1.34	1.43	1.42
$R_{\gamma\gamma}^{\rm VBF/VH}$	1.51	1.53	1.60	1.57
$R_{\tau\tau}^{\rm VBF/VH}$	0.73	0.78	0.78	0.77
$\xi_{b\bar{b}}^{\rm LEP}$	0.10	0.04	0.04	0.04
$\bar{g}_s$	0.31	0.20	0.18	0.20
${\rm BR}(H\to t\bar{t})$	0	0.024	0.036	0.071
${\rm BR}(H\to ss)$	0.37	0.04	0.002	0.15
${\rm BR}(H\to aa)$	0.23	0.63	0.42	0.24
${\rm BR}(H\to aZ)$	0.23	0.11	0.26	0.39
${\rm BR}(H\to hs)$	0.15	0.03	0.019	0.017
${\rm BR}(H\to H^\pm W^\mp)$	0	0.15	0.25	0.13
${\rm BR}(A\to t\bar{t})$	0	0.13	0.12	0.12
${\rm BR}(A\to as)$	0.64	0.26	0.26	0.31
${\rm BR}(A\to Zs)$	0.22	0.24	0.32	0.34
${\rm BR}(A\to ah)$	0.10	0.036	0.021	0.002
${\rm BR}(A\to H^\pm W^\mp)$	0.02	0.33	0.27	0.22
${\rm BR}(H^+\to t\bar{b})$	0.52	0.63	0.36	0.24
${\rm BR}(H^+\to W^+a)$	0.26	0	0.08	0.40
${\rm BR}(H^+\to W^+s)$	0.22	0.37	0.56	0.35

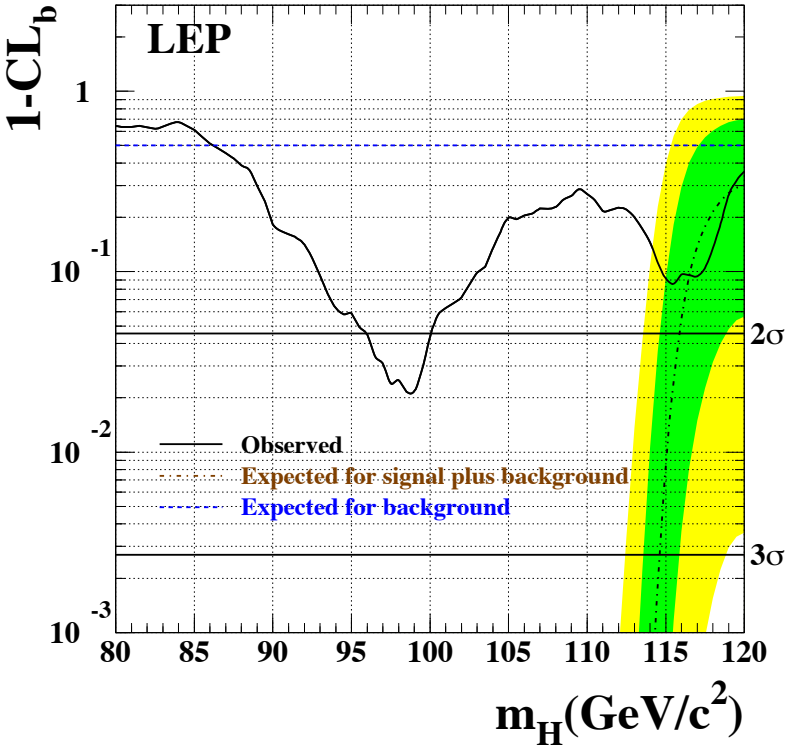
Large decay Branching ratio of MSSM Higgs into singlet states and into charged Higgs bosons

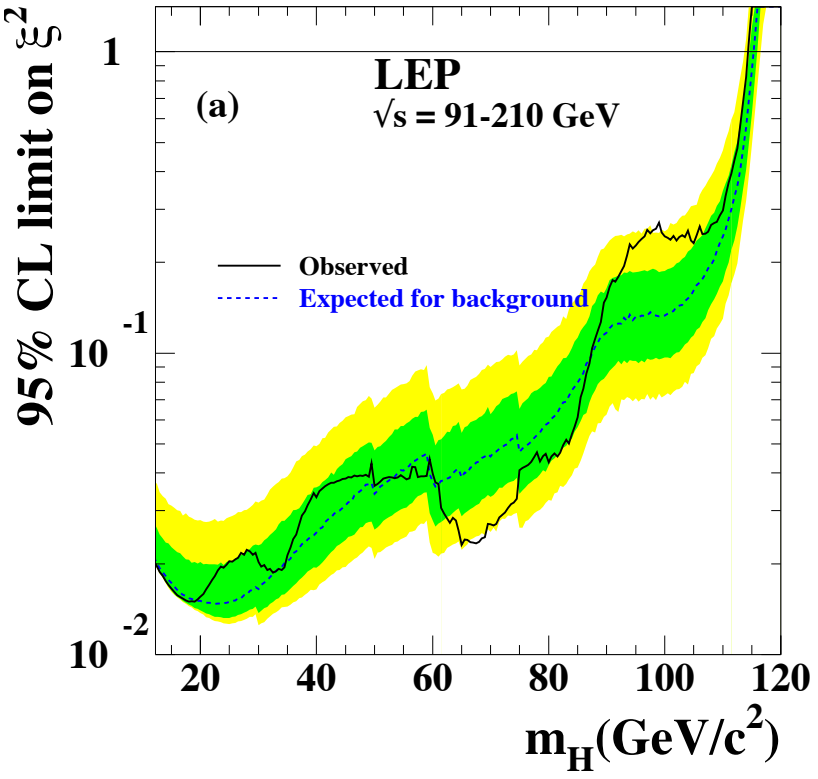
Consistent with the LEP2 Excess (not a necessary ingredient)

LEP2 Excess

LHWG-2003-011

$$\xi^2 = g^2_{ZZh}/g^2_{ZZh_{SM}} \times \frac{\mathrm{BR}(s \to b\bar{b})}{\mathrm{BR}(h^{\mathrm{SM}} \to b\bar{b})}$$





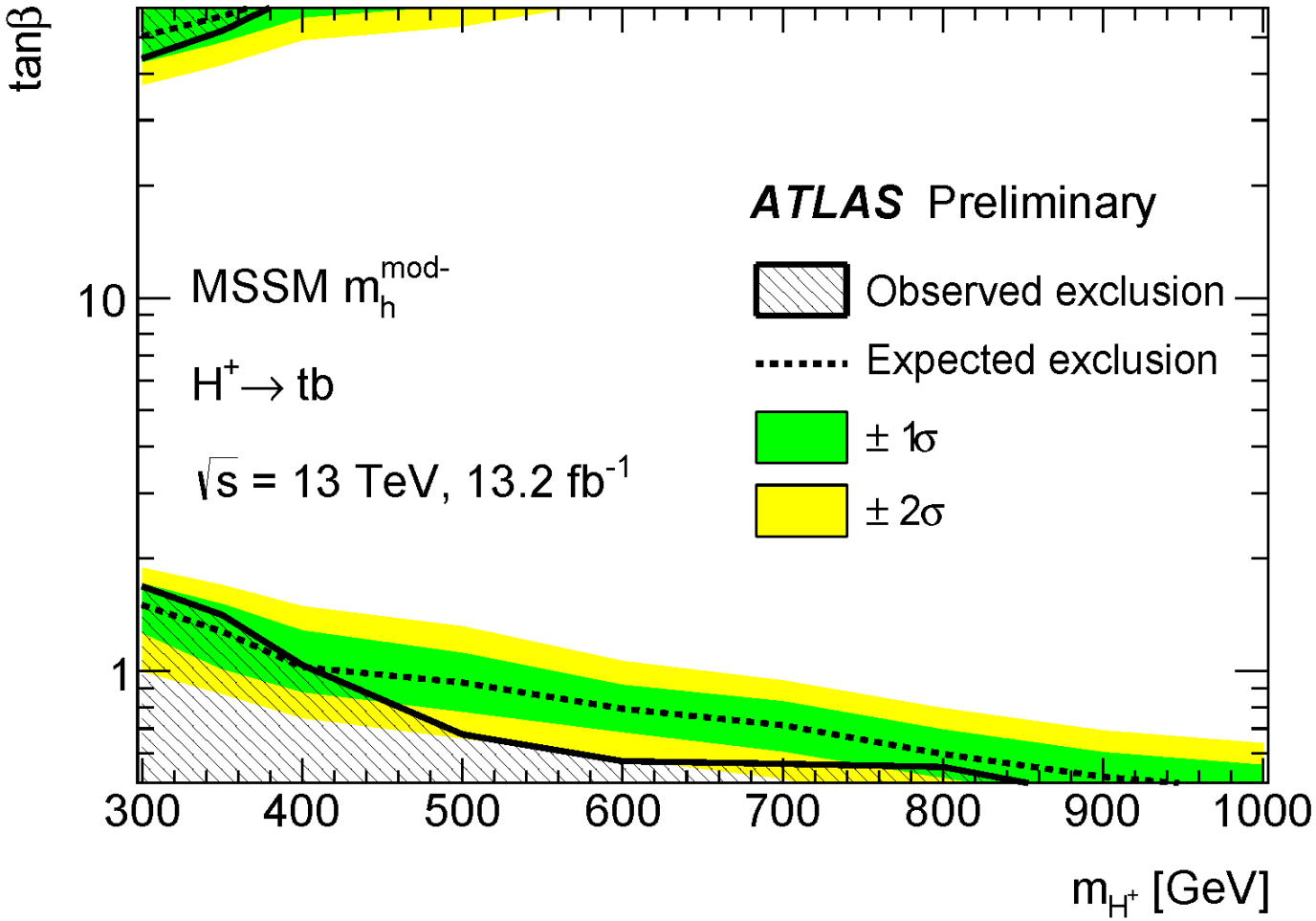
Badziak, C.W. , arXiv:1611.02353

Generic predictions of an explanation within a weak coupling extension of the SM

- Light charged and neutral scalars, decaying in standard as well as non-standard channels (flavor physics constraints may be avoided)
- Relatively light color states, contributing to gluon fusion
- Modification of all SM Higgs branching ratios in a correlated way
- In many cases, light electroweak particles to allow the new color particles to decay
- All these are still allowed by the LHC, but will be tested at higher luminosities !

Some additional relevant channels

Charged Higgs searches in top bottom final states



Already putting relevant constraints on these scenarios.

Extrapolation to lower masses ?

Alternative Interpretation of tth excess ?

Take a closer look at the main signature

What are we seeing exactly?

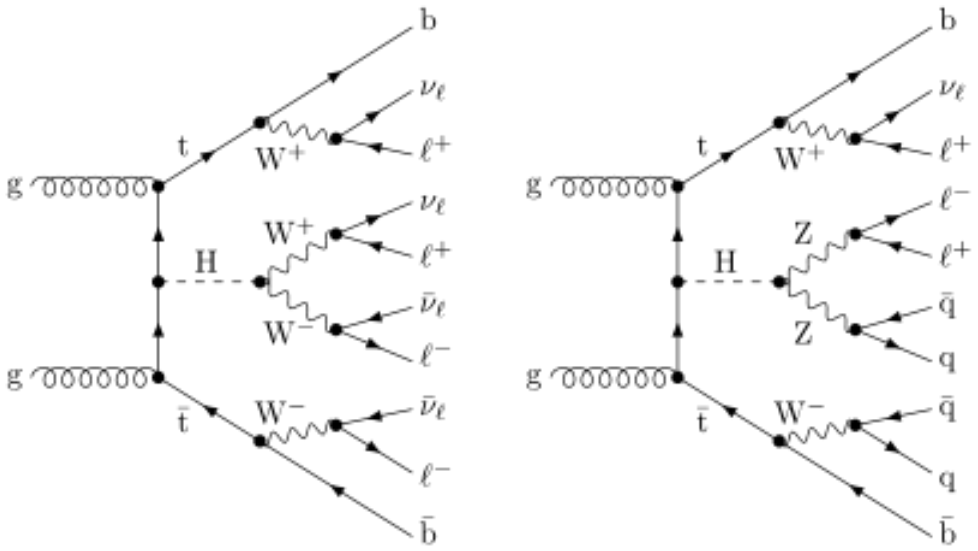
tth, h->W^+W^-

It is really a search for 2t + 2W, or equivalently 2b+4W

Final states

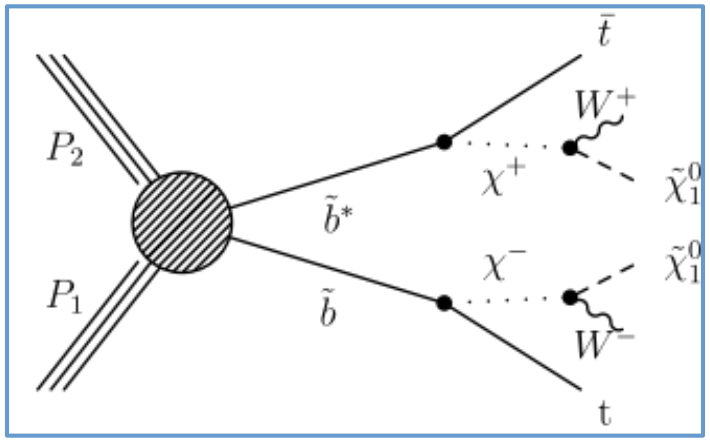
2b + 4W gives rise to the multi-lepton + multi-(b)jets + MET signatures

tth, h->W+W- is really not about tth, but about new physics!

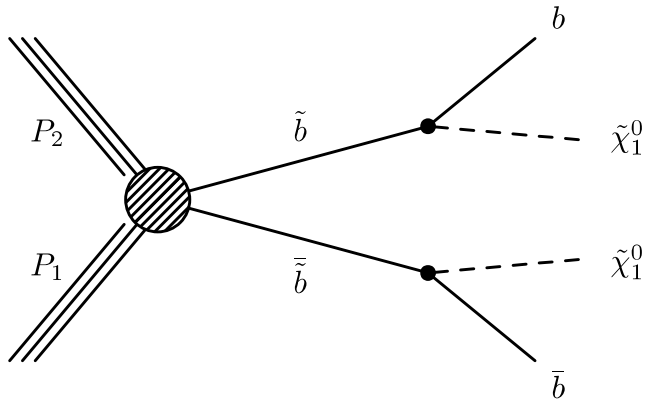


Excesses in multi-lepton + b-jets + MET

2t + 2W final states, exactly what you would do when you search for sbottoms



Caveat in the simplified model: can not have 100% Branching ratio, some BR goes to

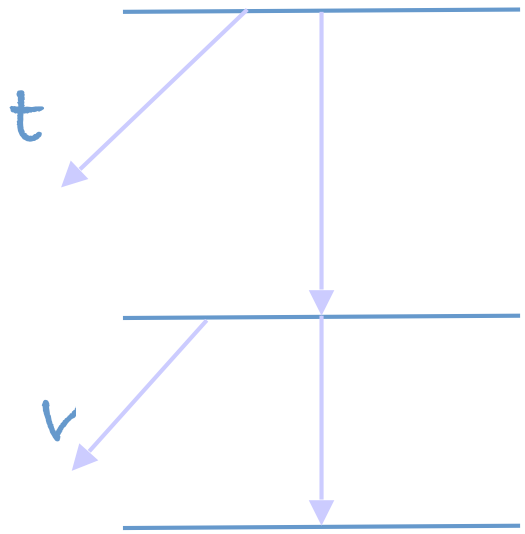


CMS-SUS-13-008

P. Huang, A. Ismail, I. Low, C. Wagner, 1507.01601

Just an example, a right-handed stop

Stops are pair produced, 2t + 2W



$\tilde{t}_1 = \tilde{t}_R$;

$\tilde{\chi}_2^0 = \tilde{B}$;

$\tilde{\chi}_1^{\pm} = \tilde{W}^{\pm}$; $\chi_1^{0\sim} = \tilde{W}^0$;

A pure right-handed stop does not couple to winos, 100% BR

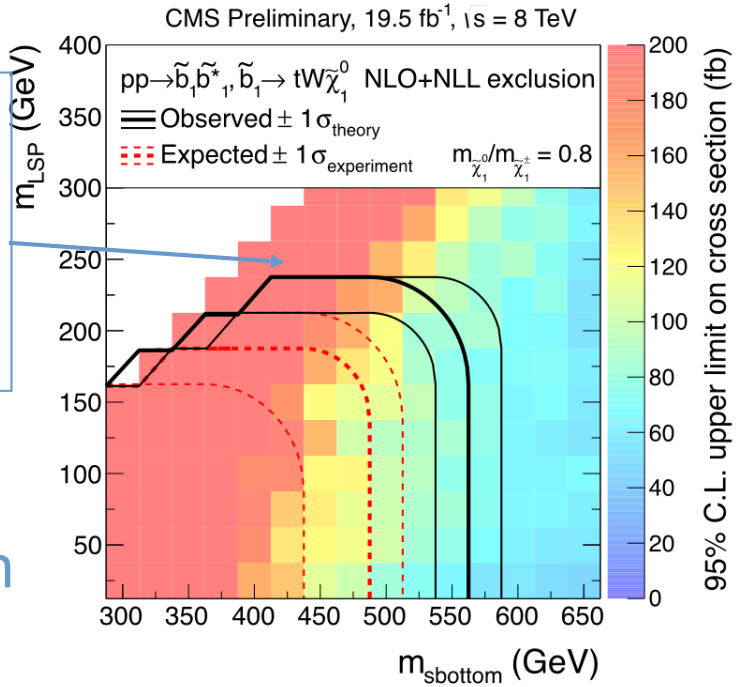
The neutralino mass difference is smaller than the Higgs mass, 100% BR

PH, A. Ismail, I. Low, C. Wagner, 1507.01601

Possible Spectrum

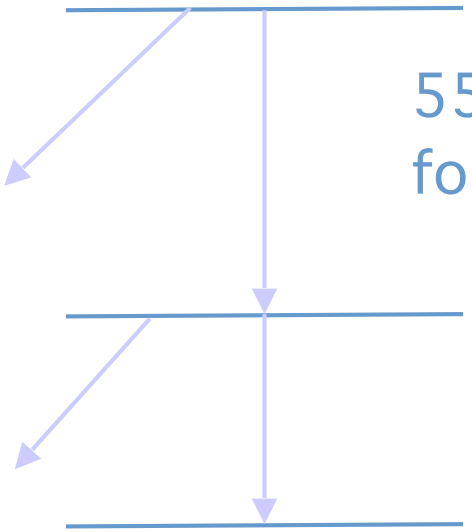
Follow the CMS tth analysis, normalize the signal strength to the SM tth

Bounds disappear once the LSP is heavier than 240 GeV



$\tilde{t}_1 = \tilde{t}_R$;

550 GeV, a signal strength for ss2l~ 2.83



$\tilde{\chi}_2^0 = \tilde{B}$;

No decay through a higgs
< 260 + 125 , call it 340 GeV

$\tilde{\chi}_1^{\pm} = \tilde{W}^{\pm}$; $\chi_1^{0\sim} = \tilde{W}^0$; 260 GeV

ATLAS : $\mu = 28^{+2.1}_{-1.9}$

CMS : $\mu = 53^{+2.1}_{-1.8}$

Significance somewhat lower now,
implying larger masses/more compressed spectrum

Distinguishing stops/sbottoms from enhanced top Yukawa

Stops are heavier , cross section increases faster from the pdf

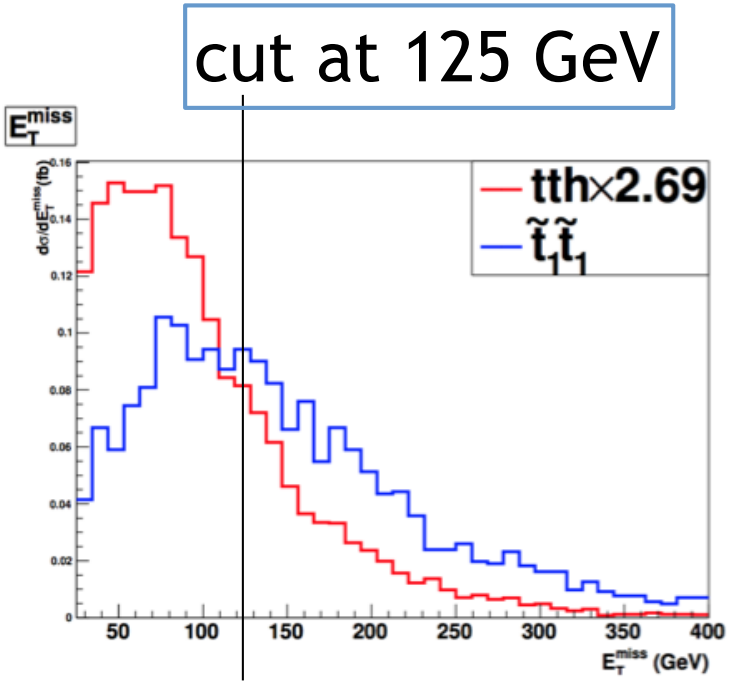
	σ(8 TeV)	σ(13 TeV)	Ratio(13 TeV/8 TeV)
$\sigma(pp \to \mathrm{ttH})$	129 fb	509 fb	3.9
$\sigma(pp \to \tilde{t}_1\tilde{t}_1^*)$	45 fb	296 fb	6.6

Expect a signal strength ~ 3.69 at 13 TeV

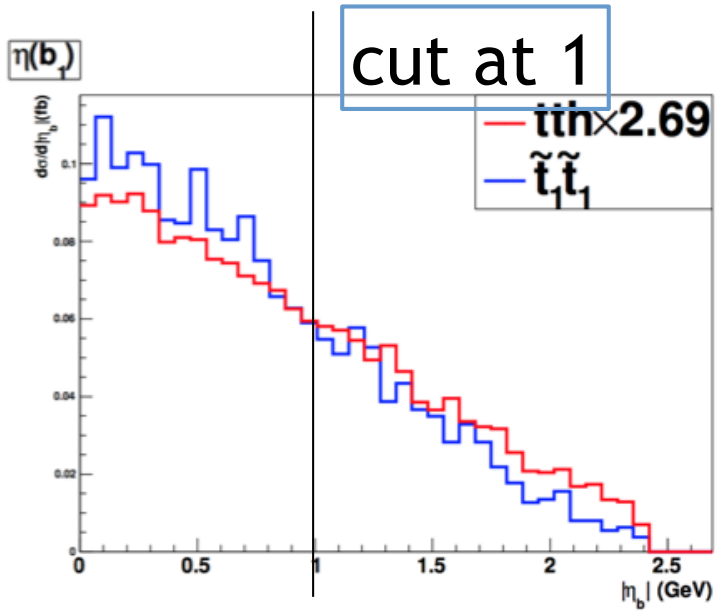
P. Huang, A. Ismail, I. Low, C. Wagner, 1507.01601

Distinguishing sbottom from enhanced top Yukawa

PH, A. Ismail, I. Low, C. Wagner, 1507.01601



More missing energy from stop than tth



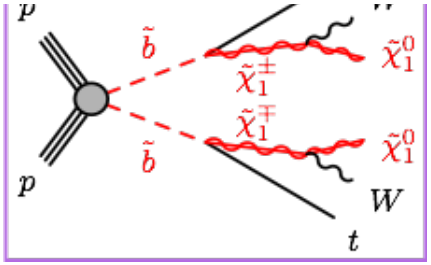
In the stop events, b-jets are more centrally produced, while the b-jets from ttH tend to be more forward, from the t-channel kinematics.

μ (13 TeV) ~ 6.94

reach 5 σ with about 40 fb^{-1}

Current Searches at 13 TeV

Sbottom vs. Stop



Same-sign dilepton Excess arXiv:1507.01601

P. Huang, A. Ismail, I. Low, C. Wagner

mapping:

$$\tilde{b} \to \tilde{t}_1$$
$$\tilde{\chi}_1^{\pm} \to \tilde{\chi}_2^0$$
$$\tilde{\chi}_1^0 \to \tilde{\chi}_1^{\pm} \sim \tilde{\chi}_1^0$$

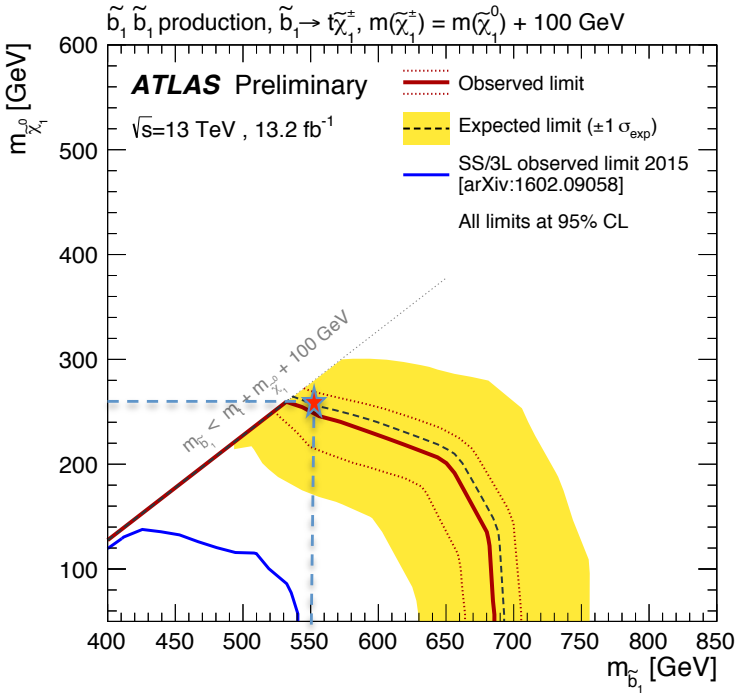
Mass point proposed:

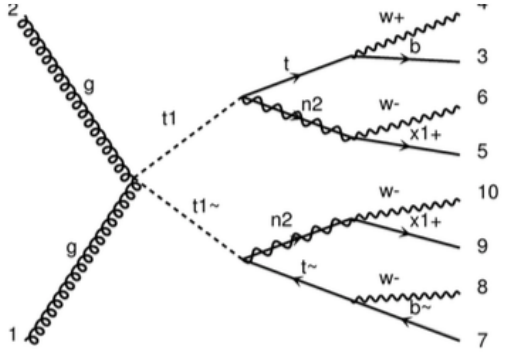
$m_{\tilde{t}_1} = 550$ GeV,
$m_{\tilde{\chi}_2^0} = 340$ GeV,
$m_{\tilde{\chi}_1^{\pm}} \approx m_{\tilde{\chi}_1^0} =$ 260 GeV

$$\tilde{b} \to t + (\tilde{\chi}_1^- \to W^- + \tilde{\chi}_1^0)$$

$$\tilde{t}_1 \to t + (\tilde{\chi}_2^0 \to W^{\mp} + (\tilde{\chi}_1^{\pm} \to W^{\pm *} + \tilde{\chi}_1^0))$$

$$pp \to \tilde{t}_1 \tilde{t}_1^* \to b\bar{b} + \left\{ \begin{array}{l} W^+W^-W^-W^- \\ W^-W^+W^+W^+ \\ W^+W^-W^-W^+ \\ W^+W^-W^+W^- \end{array} \right\} + E_{\mathrm{T}}^{\mathrm{miss}}$$





Benchmark should be redefined in terms of current data

Conclusions

- Low energy supersymmetry provides a predictive framework for the computation of the Higgs phenomenology. Alignment in the Higgs boson sector may be obtained.
- In the NMSSM, alignment occurs in regions of parameter space in which the naturalness conditions are fulfilled, with lambda of order 0.65. Stops can be light, since their relation with the Higgs mass is different from the MSSM one
- Searches for heavy Higgs bosons decaying into non-standard light Higgs, together with a SM Higgs and vector bosons is prominent and should be emphasized at the LHC.
- If the enhancement of the production of SM Higgs bosons in association with top quarks persisted, misalignment would be necessary
- In supersymmetric theories this would demand light stops and light MSSM-like Higgs bosons. Correlations between different Higgs channel rates exist that may be tested at the LHC
- Alternatively, the apparent excess in Higgs production may be related to new physics, not related to the Higgs, leading to events with bottom-quarks, leptons and missing energy
- A scenario leading to these signatures was presented.

B. Li, N. Coyle, C.W. '17 (to appear)

What about inverting the sign of the third generation couplings ?

- It turns out that is easy to achieve the inversion of the bottom coupling in type II Higgs doublet models
- In the NMSSM, in particular, this implies to go to larger values of lambda, since this is the parameter that allows to control this coupling.

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

- This causes problems with the perturbative extrapolation of the theory to large scales, and also with the spectrum, since some scalars tend to become tachyonic in the relevant region of parameters
- We cured this problem by adding a tadpole term

$$\Delta V = \; \xi_S \; S + h.c.$$

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Values of the dimensionless couplings

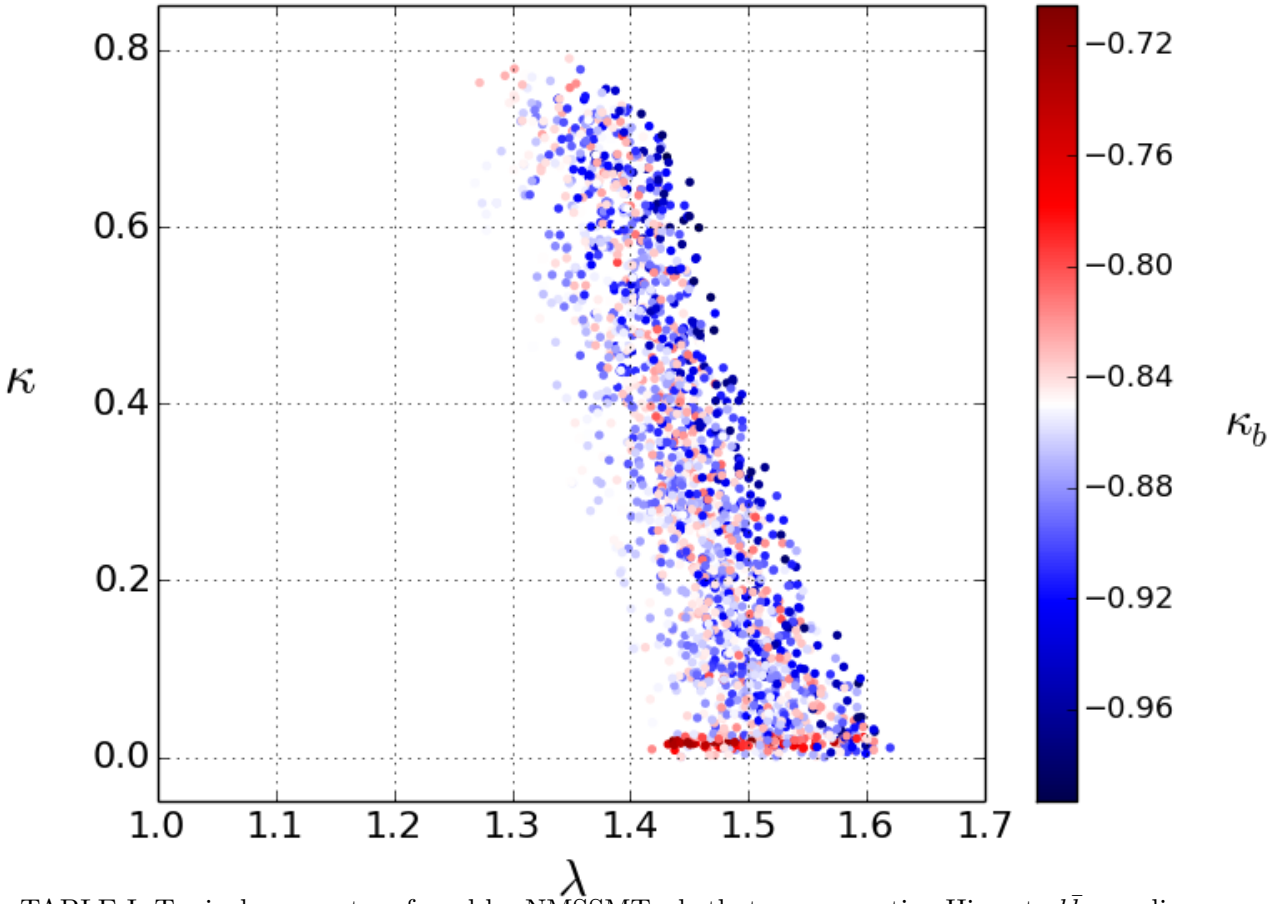

TABLE I: Typical parameters found by NMSSMTools that gave negative Higgs to $b\bar{b}$ couplings

No.	$\tan\beta$	m_A	μ	λ	κ	$M_{i,(i=1,2)}$	A_{f3}	m_{h_1}	κ_b	$BR(h_1 \to b\bar{b})$	m_{h_2}	m_{H^+}
1	8.0	335	-1121	1.51	0.076	1000	1500	124.2	-0.86	60.6%	293	158
2	7.0	338	-1089	1.50	0.280	1000	1500	128.0	-0.83	54.0%	292	160
3	8.0	347	-1096	1.42	0.423	1000	1500	124.0	-0.86	61.0%	278	157
4	8.0	339	-1020	1.36	0.730	1000	1500	126.1	-0.87	56.3%	270	157

B. Li, N. Coyle, C.W. '17 (to appear)

Typical Parameters

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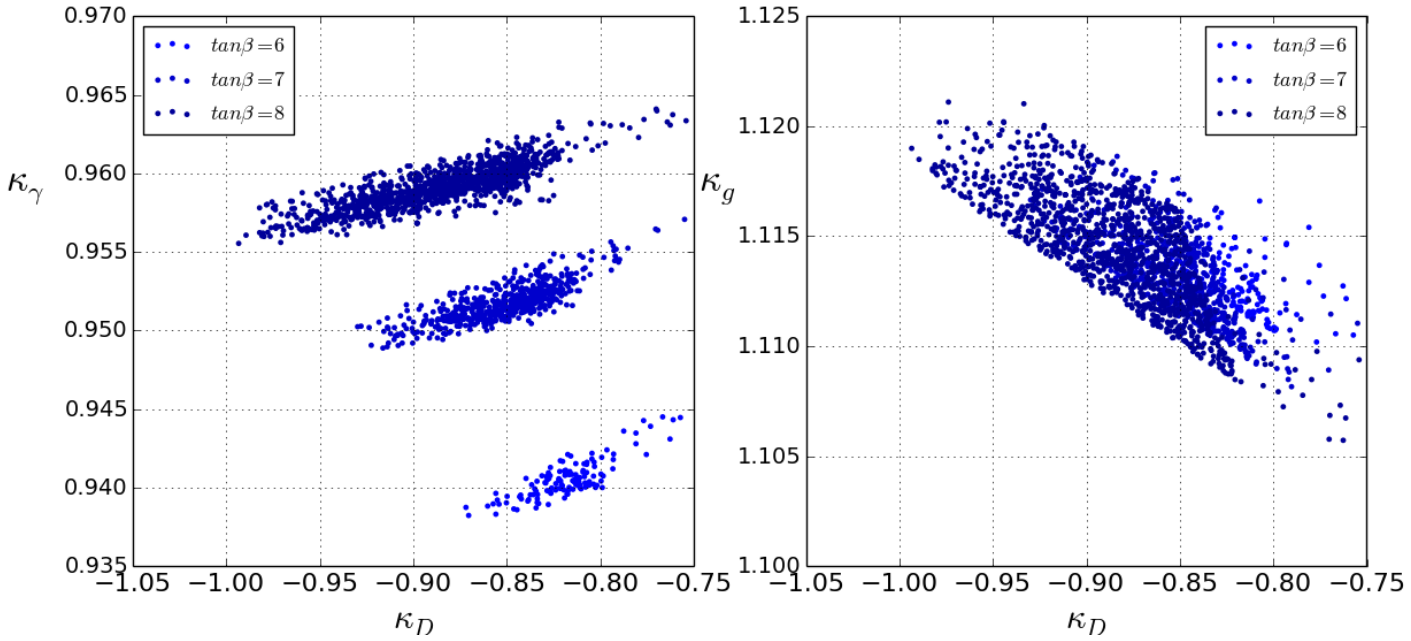

B. Li, N. Coyle, C.W. ’17 (to appear)

Fixing the perturbativity problem ?

It is known that one can add two SU(2)’s at higher energies, one that couples to the Higgs bosons and the third generation, and the other the first generation. This would break to the SM SU(2) at energies of a few TeV.

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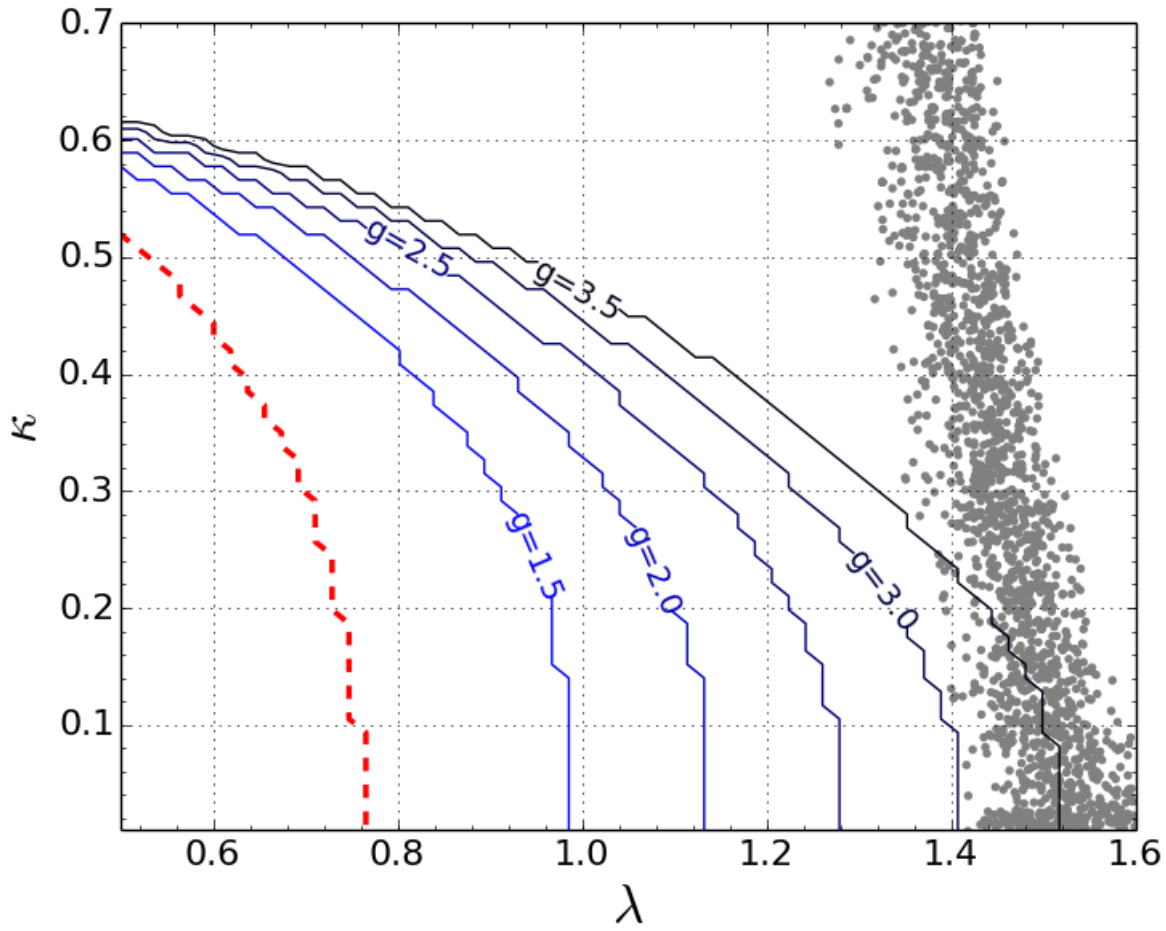
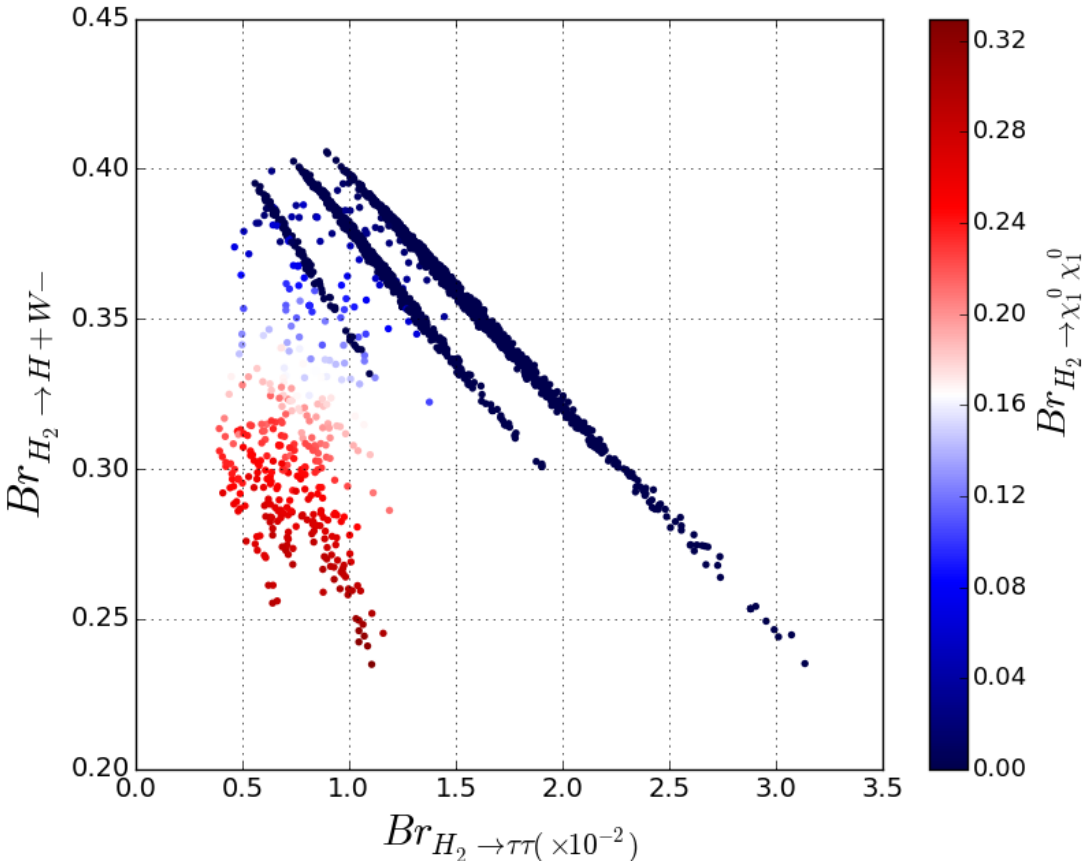
$$SU(3)_c \times SU(2)_1 \times SU(2)_2 \times U(1)_Y$$



Novelty : Decay into charged Higgs Bosons

Large values of lambda imply that the charged Higgs mass becomes lower than the neutral MSSM-like Higgs masses.

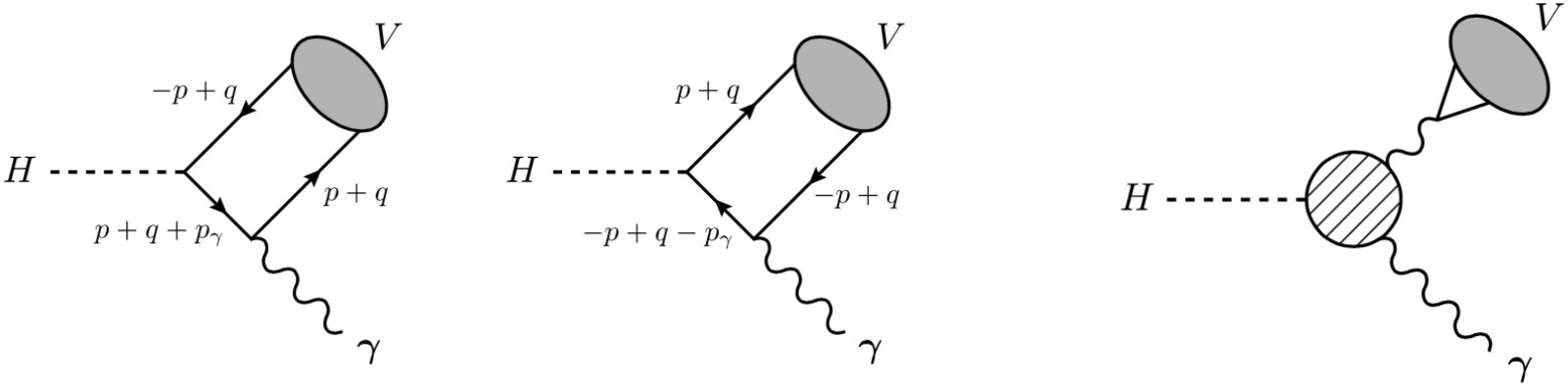


Additional tests of this idea ?

Radiative Higgs Decays

$$\Gamma[H \to \Upsilon(1S) + \gamma] = |(3.33 \pm 0.03) - (3.49 \pm 0.15)\kappa_b|^2 \times 10^{-10}\ \text{GeV}$$

$$\Gamma[H \to \Upsilon(2S) + \gamma] = |(2.18 \pm 0.03) - (2.48 \pm 0.11)\kappa_b|^2 \times 10^{-10}\ \text{GeV}$$



κ_b	$\Upsilon(1S)$	$\Upsilon(2S)$	$\Upsilon(3S)$
	Run 2 (130 fb^{-1})		
1	0.00442 ± 0.06214	0.0155 ± 0.0483	0.0178 ± 0.0414
-1	8.02 ± 0.32	3.75 ± 0.15	2.73 ± 0.11
	Run 3 (300 fb^{-1})		
1	0.0102 ± 0.1434	0.358 ± 0.1115	0.0408 ± 0.0956
-1	18.5 ± 0.7	8.65 ± 0.36	6.31 ± 0.26

Effects on gluon Fusion

- Changing the sign of the bottom coupling changes the gluon fusion rate by about 13 percent !
- It also changes the game rate by a lesser amount. The charged Higgs effects are also small.
- Assuming that no other effect is present, the LHC collaborations announce a precision of about 5 percent for the gluon coupling by the end of the LHC run.
- So, in principle there are measurable effects in Higgs production processes, but the uncertainties will be large.