Higgs and Supersymmetry Physics in the light of LHC Data

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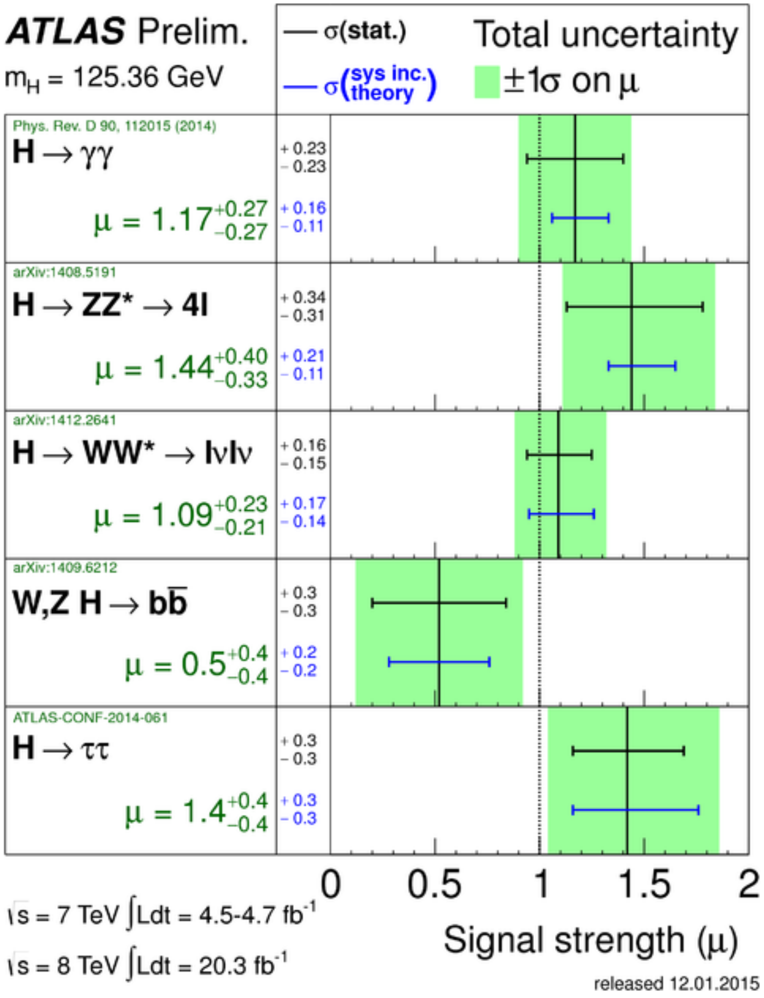
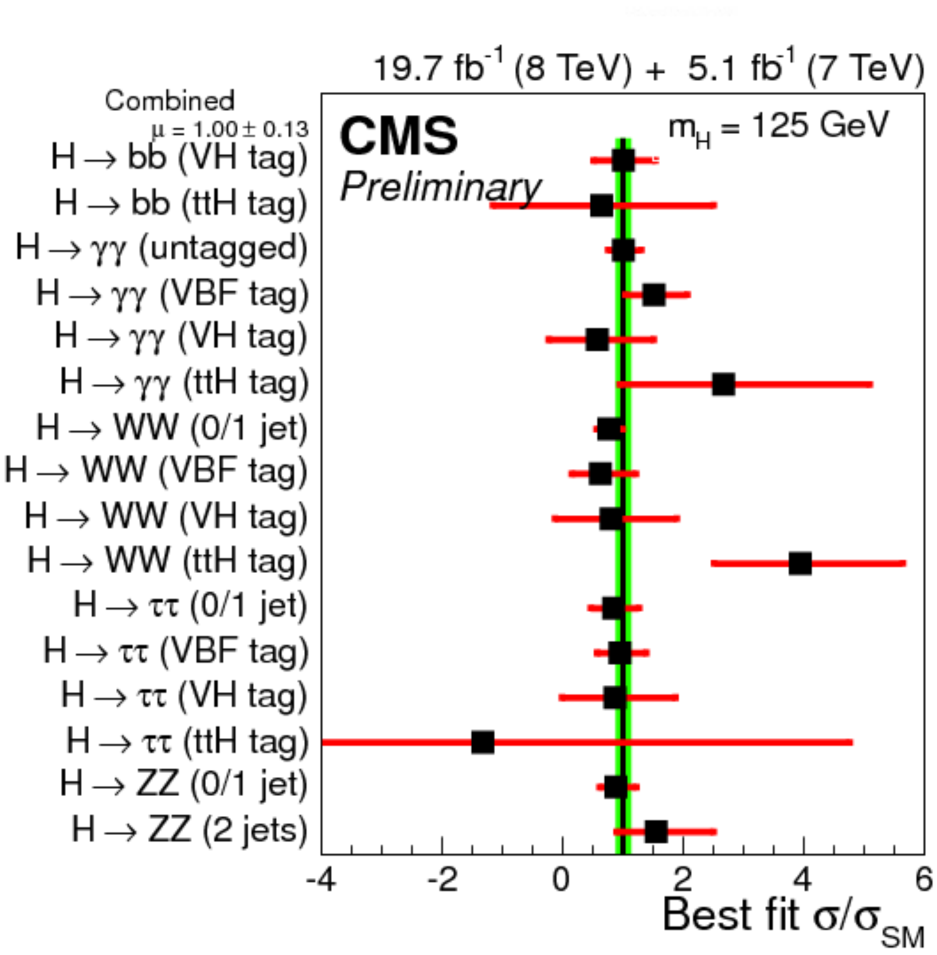
Higgs Hunting 2016
LPNHE Paris, September 1, 2016

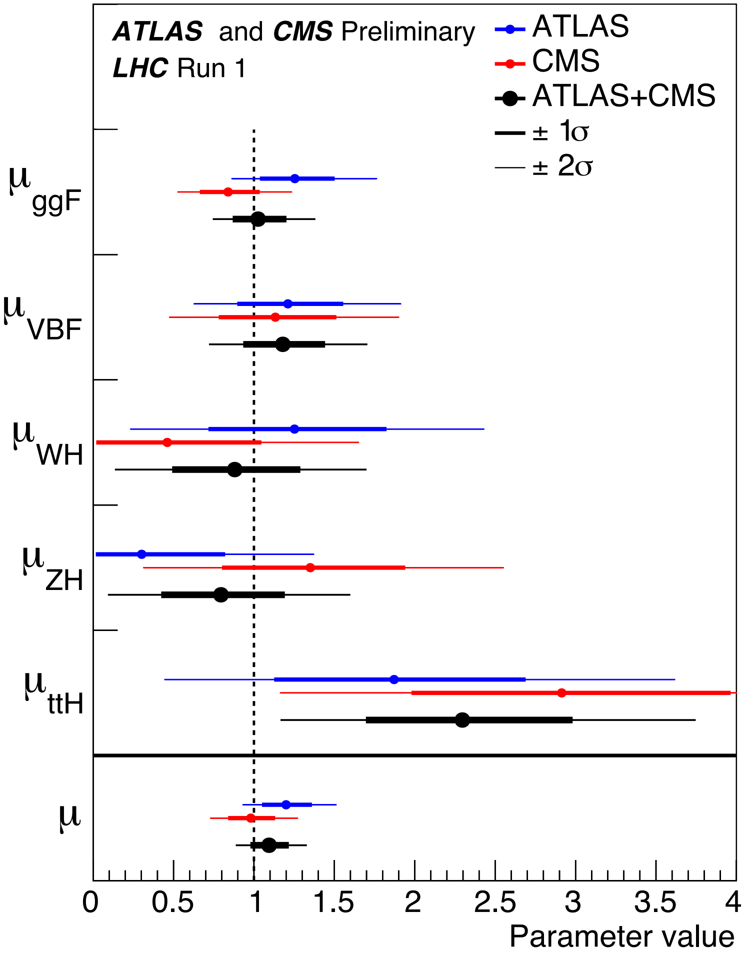
Higgs Boson Discovery at the LHC :

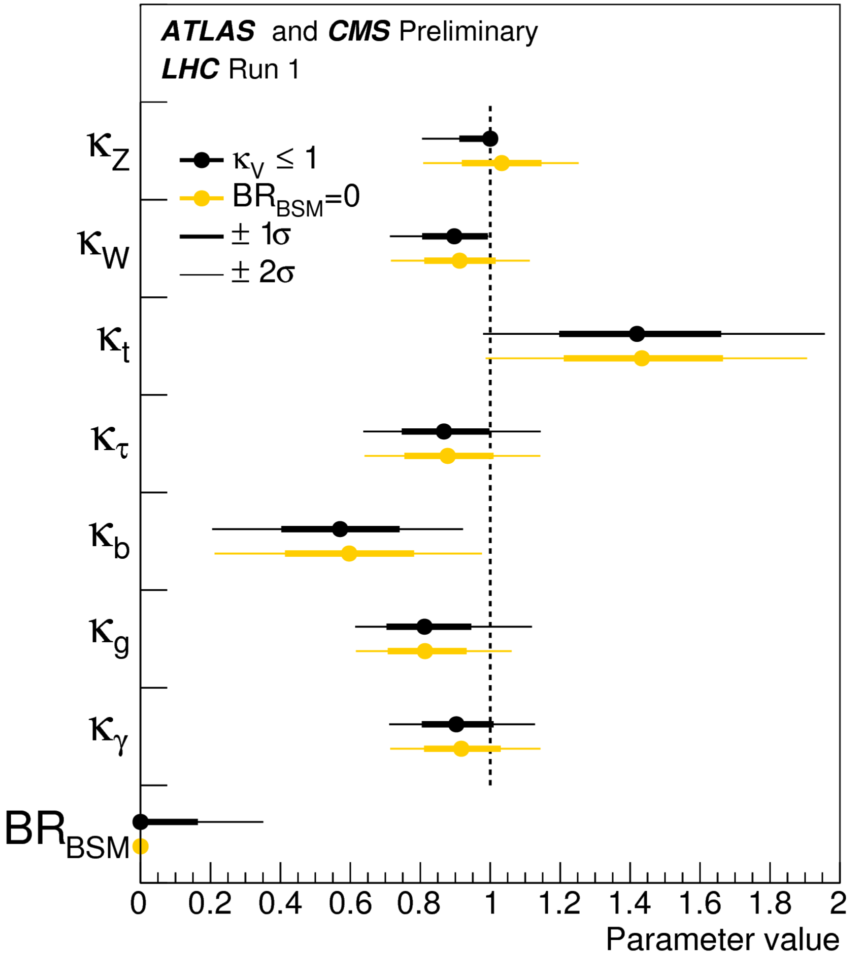
Very good agreement of Higgs Physics Results with SM Predictions





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.

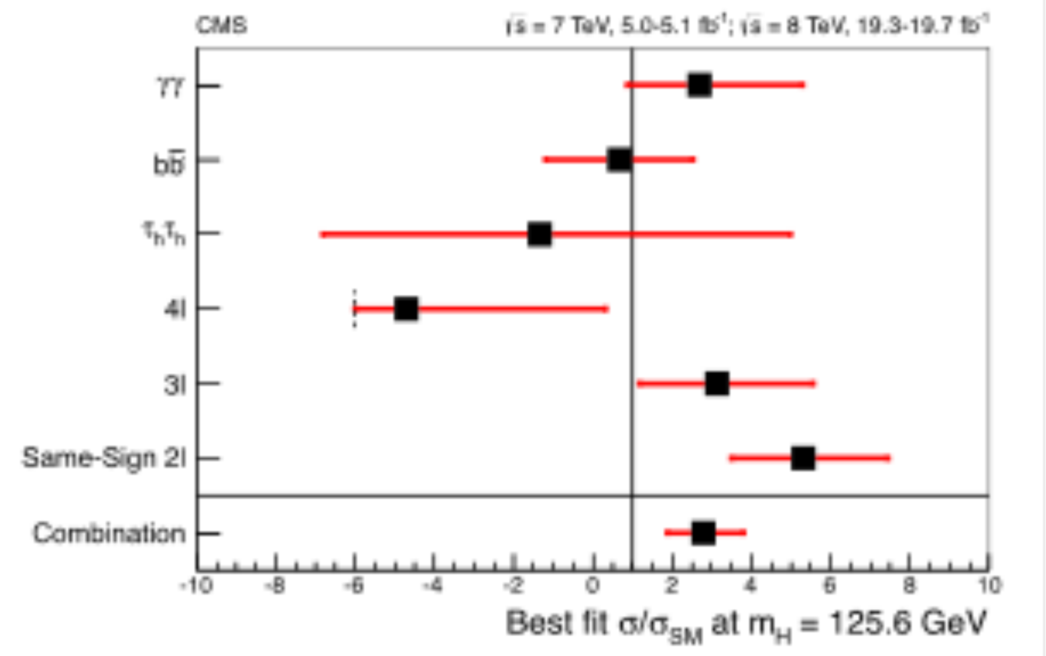
In particular, low bottom coupling has a major impact on the rest of the couplings.

Top Quark Coupling Enhancement ?

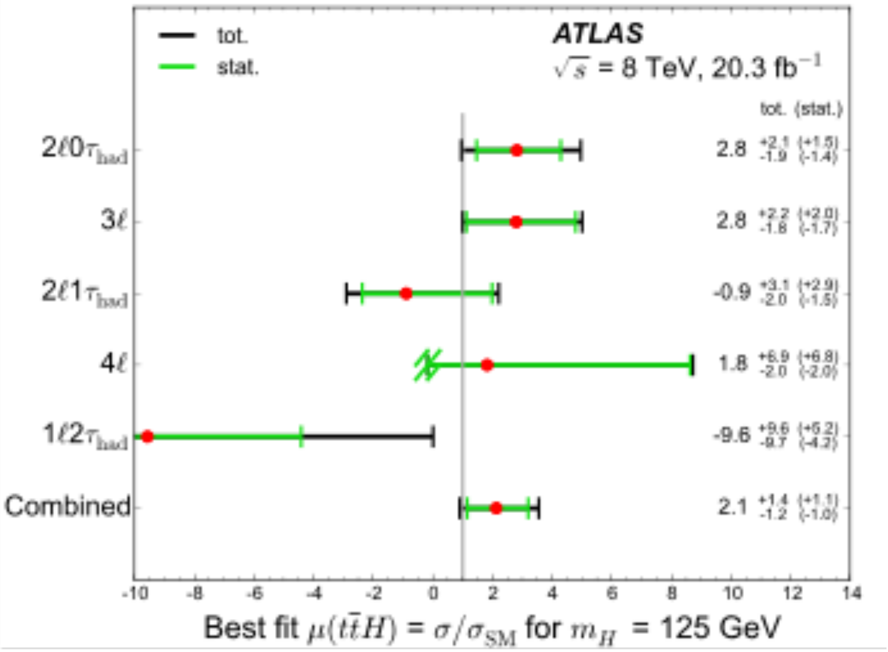
Excess at both experiments

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

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



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

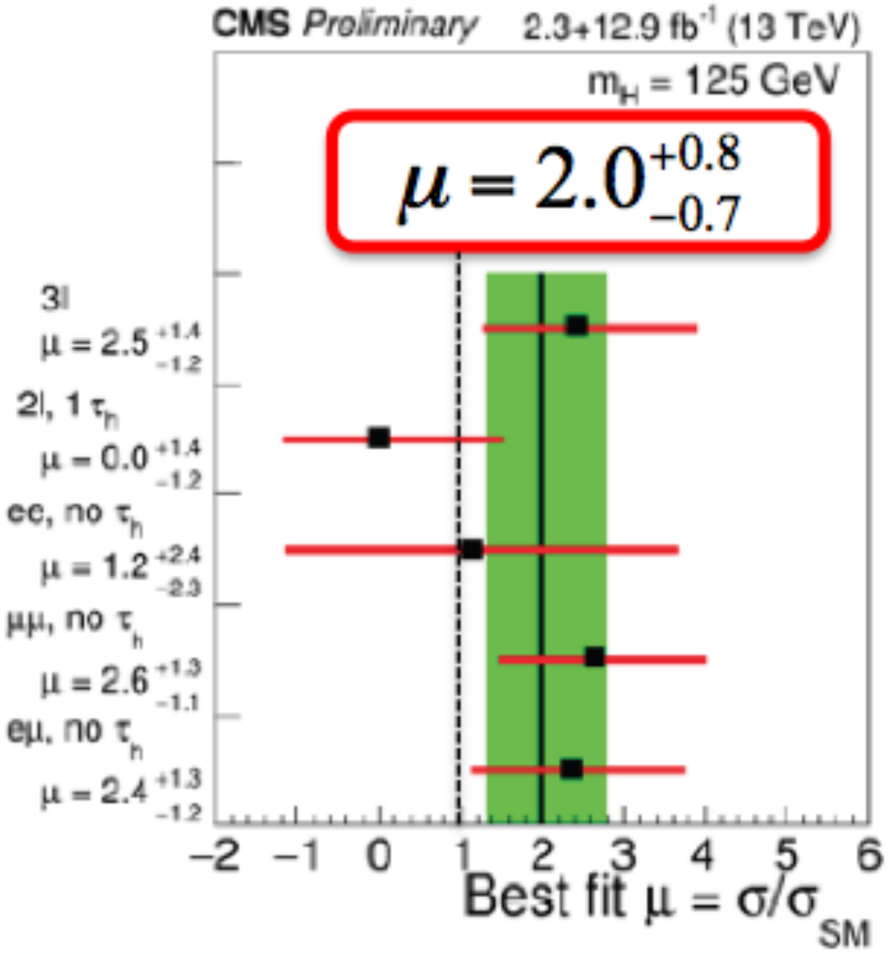


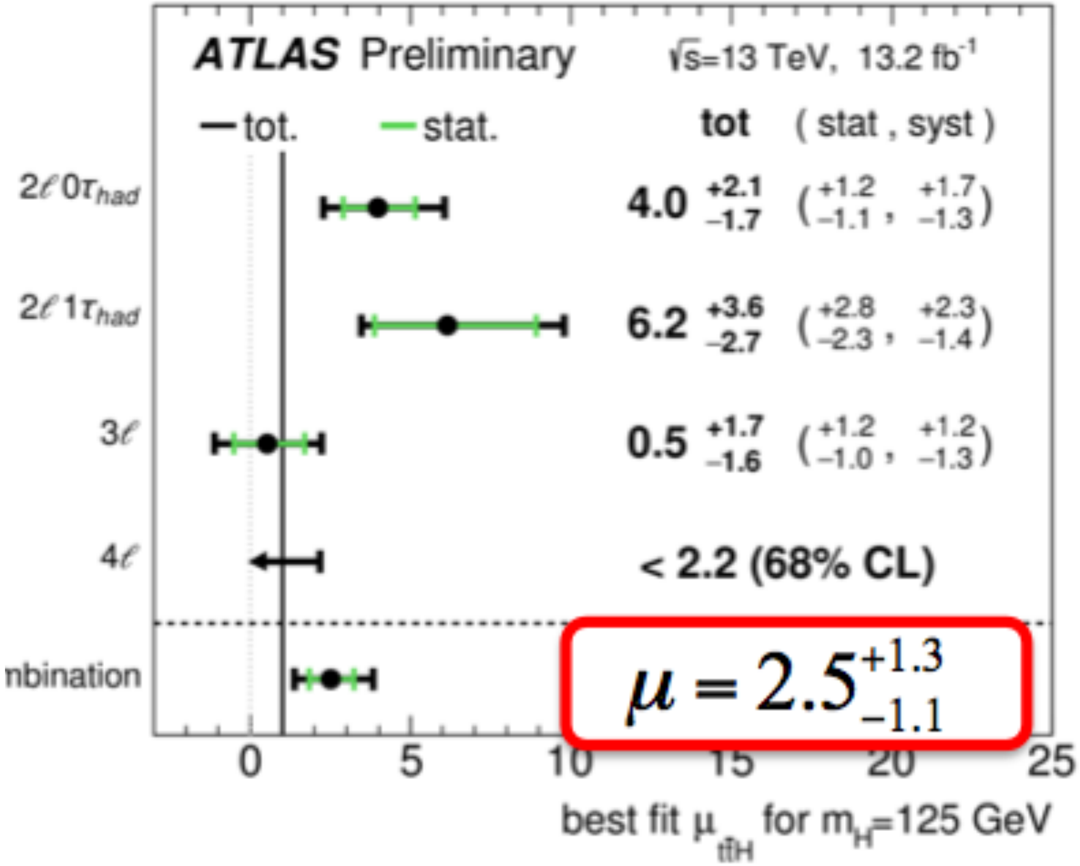
CMS 1408.1682, local significance 2.6σ

ATLAS 1506.05988

Top Quark Coupling Enhancement ?

Excess at both runs

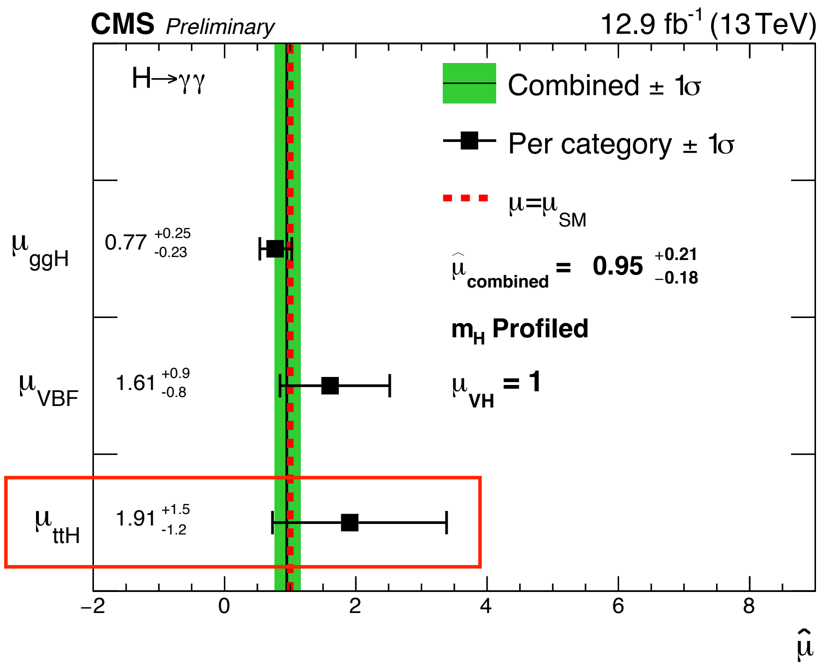


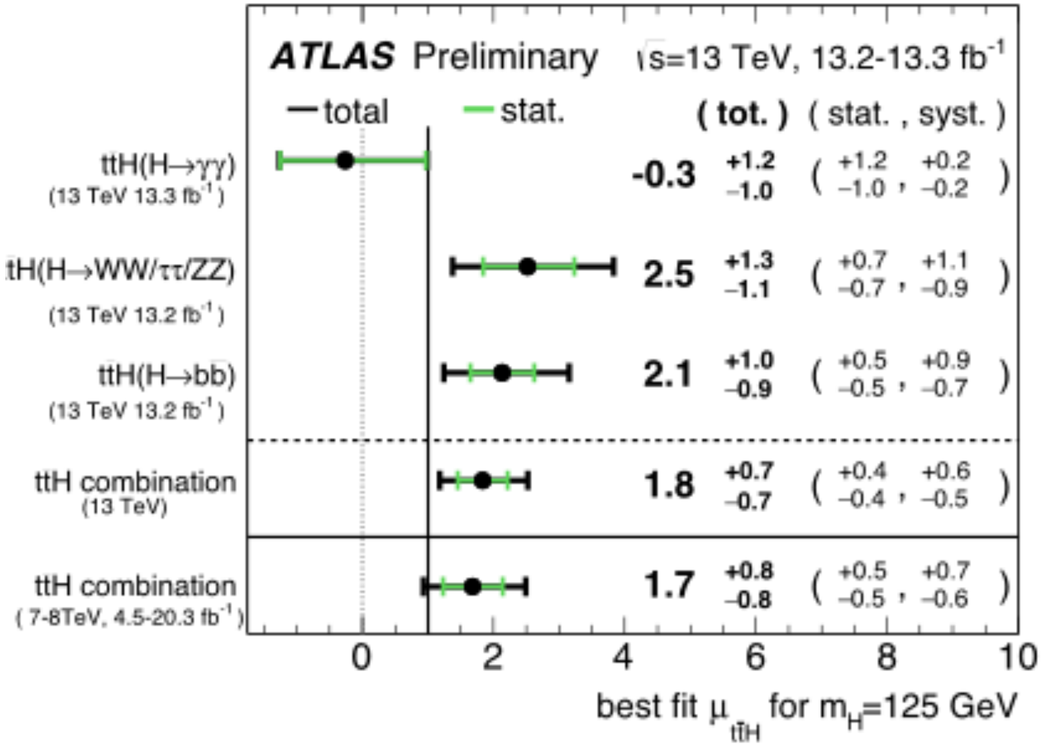


Canelli, ICHEP 2016

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

Badziak, C.W., arXiv:1602.06198, JHEP

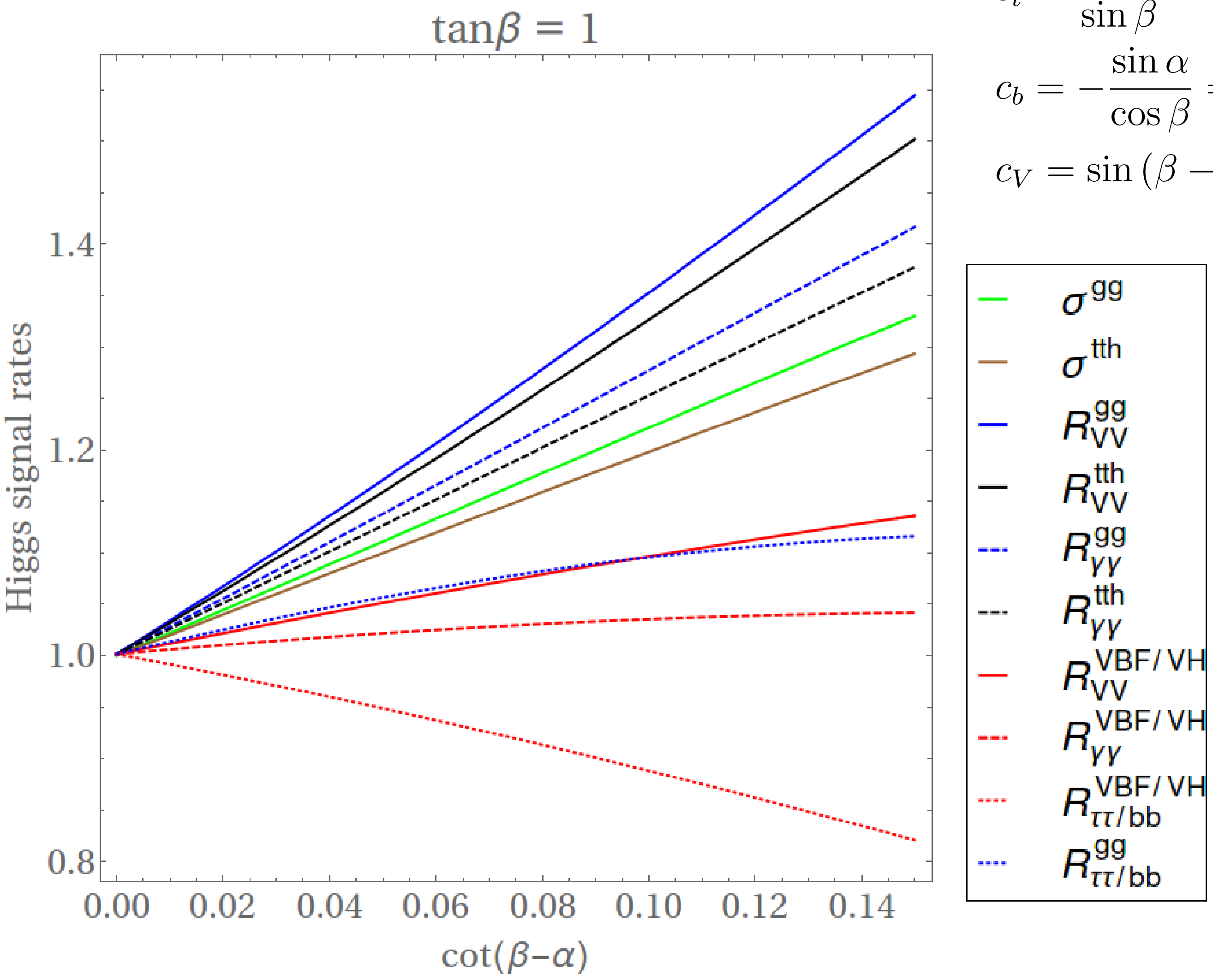
Top Quark Coupling Enhancement ?

Simple Example : Type II Higgs Doublet Models
Enhancing (suppressing) the tth (bbh) Coupling

$$c_t = \frac{\cos\alpha}{\sin\beta} = \sin(\beta-\alpha) + \cot\beta\cos(\beta-\alpha)\ ,$$

$$c_b = -\frac{\sin\alpha}{\cos\beta} = \sin(\beta-\alpha) - \tan\beta\cos(\beta-\alpha)\ ,$$

$$c_V = \sin(\beta-\alpha)\ ,$$

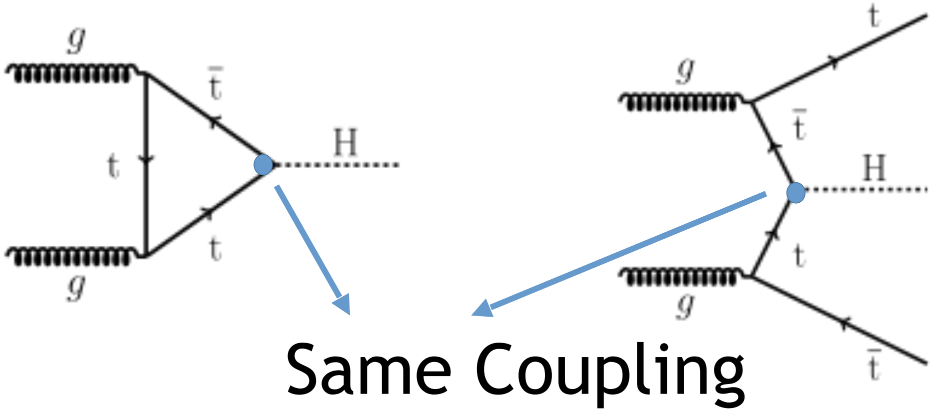


Type II
Two Higgs Doublet Models

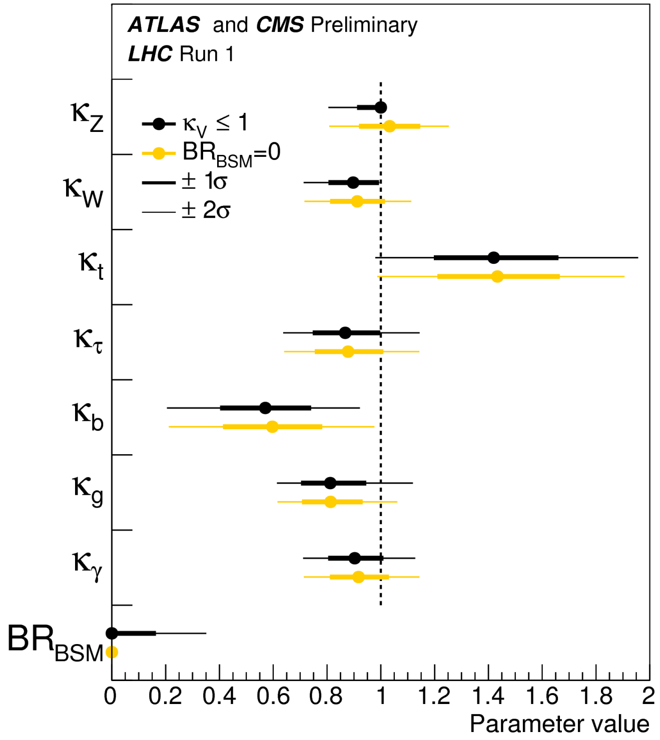
Strong Correlation between
Different Channels
Relevant enhancement
(suppression) of tth (bbh)
not possible without
affecting gluon fusion
channels

What is the problem in 2HDM ?

SM+ a enhanced top Yukawa coupling?



Same Coupling



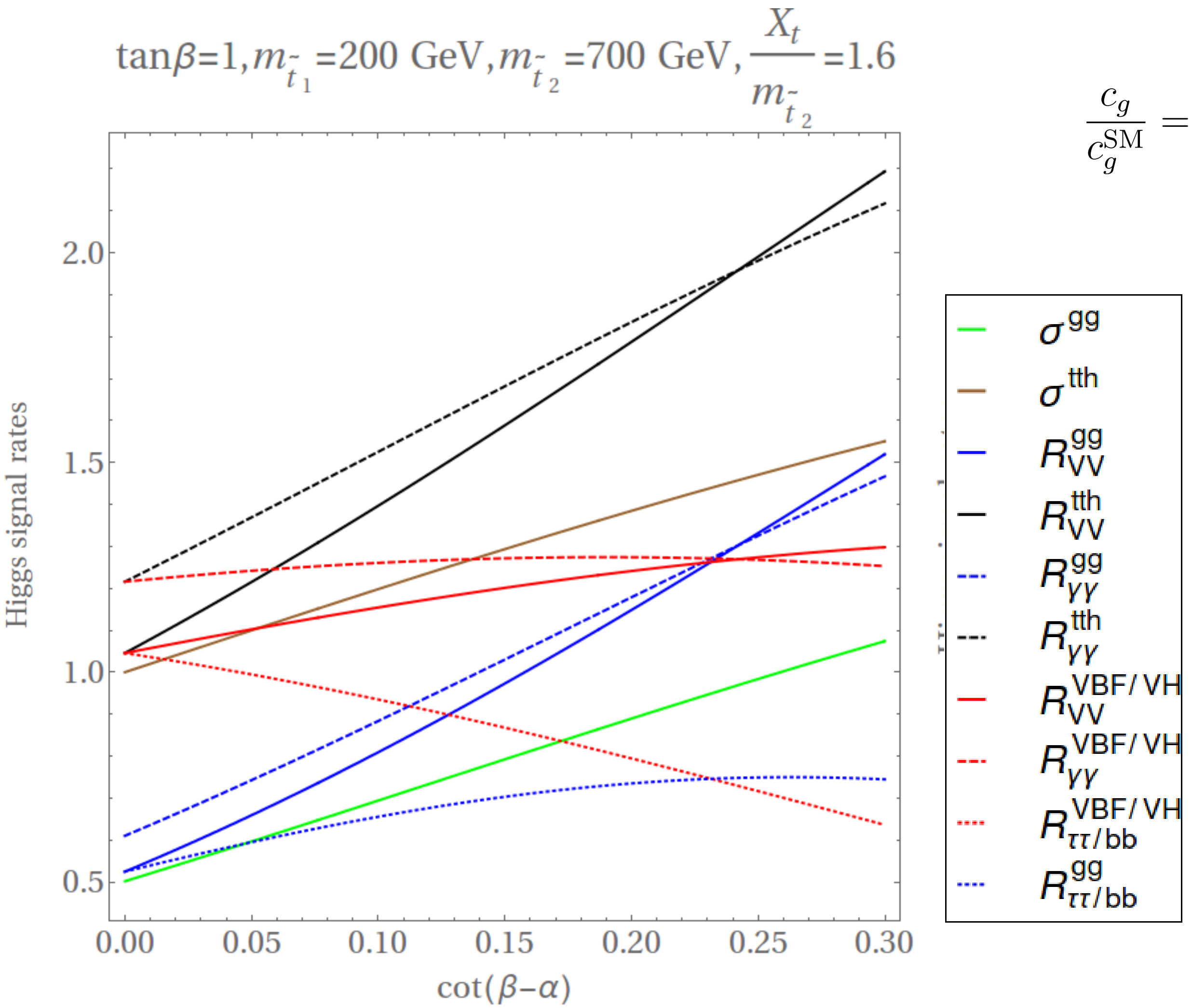
Would expect gluon fusion to be high as well !

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

Additional Loop Effects in Low Energy Supersymmetry

Stop Effects

Badziak, C.W. '16



$$\frac{c_g}{c_g^{\rm SM}} = c_t + \frac{m_t^2}{4}\left[c_t\left(\frac{1}{m_{\tilde{t}_1}^2}+\frac{1}{m_{\tilde{t}_2}^2}\right) - \frac{\tilde{X}_t^2}{m_{\tilde{t}_1}^2 m_{\tilde{t}_2}^2}\right]$$

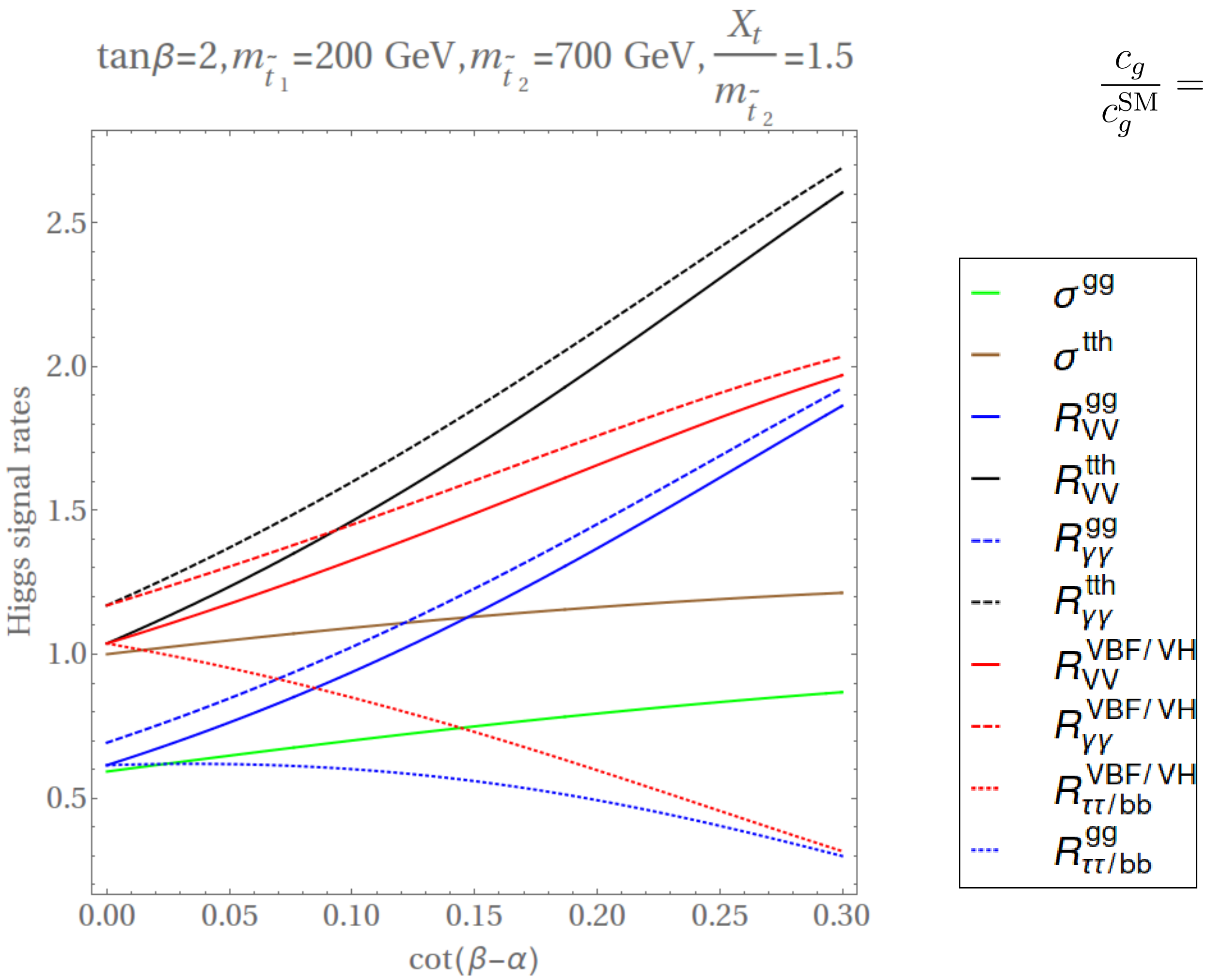
Loop Effects in the couplings of Higgs to gluons may dramatically affect the previous conclusions.

ATLAS+CMS fit to Higgs data

Channel	ATLAS+CMS combined result
$\mu_{\gamma\gamma}^{\mathrm{gg}}$	$1.19^{+0.28}_{-0.25}$
μ_{ZZ}^{gg}	$1.44^{+0.38}_{-0.34}$
μ_{WW}^{gg}	$1.00^{+0.23}_{-0.20}$
$\mu_{\tau\tau}^{\mathrm{gg}}$	$1.10^{+0.61}_{-0.58}$
μ_{bb}^{gg}	$1.09^{+0.93}_{-0.89}$
$\mu_{\gamma\gamma}^{\mathrm{VBF/VH}}$	$1.05^{+0.44}_{-0.41}$
$\mu_{ZZ}^{\mathrm{VBF/VH}}$	$0.48^{+1.37}_{-0.91}$
$\mu_{WW}^{\mathrm{VBF/VH}}$	$1.38^{+0.41}_{-0.37}$
$\mu_{\tau\tau}^{\mathrm{VBF/VH}}$	$1.12^{+0.37}_{-0.35}$
$\mu_{bb}^{\mathrm{VBF/VH}}$	$0.65^{+0.30}_{-0.29}$

Additional Loop Effects in Low Energy Supersymmetry
Stop Effects

Badziak, C.W. '16



$$\frac{c_g}{c_g^{\rm SM}} = c_t + \frac{m_t^2}{4}\left[c_t\left(\frac{1}{m_{\tilde{t}_1}^2} + \frac{1}{m_{\tilde{t}_2}^2}\right) - \frac{\tilde{X}_t^2}{m_{\tilde{t}_1}^2 m_{\tilde{t}_2}^2}\right]$$

Loop Effects in the couplings of Higgs to gluons may dramatically affect the previous conclusions.

Values of tanβ closer to one give better fit (more symmetric deviations of bottom and top couplings).

Some Benchmarks

Badziak, C.W. ‘16

	B1	B2	B3
$\tan\beta$	1	1.5	2
$\cot(\beta-\alpha)$	0.25	0.22	0.18
$m_{\tilde{t}_1}$	200	200	210
$m_{\tilde{t}_2}$	700	700	700
$\tilde{X}_t/m_{\tilde{t}_2}$	1.7	1.6	1.6
$R_{VV}^{\rm tth}$	2.02	1.96	1.90
$R_{\gamma\gamma}^{\rm tth}$	2.09	2.09	2.07
$R_{VV}^{\rm gg}$	1.18	1.21	1.19
$R_{\gamma\gamma}^{\rm gg}$	1.22	1.29	1.29
$R_{VV}^{\rm VBF/VH}$	1.29	1.49	1.60
$R_{\gamma\gamma}^{\rm VBF/VH}$	1.33	1.59	1.74
$R_{\tau\tau}^{\rm VBF/VH}$	0.73	0.67	0.66

This provides a rather good agreement with the run I data analysis from the ATLAS/CMS combination

This cannot be achieved in the MSSM

Reasons :

a) Obtaining the Right Higgs mass is a problem.

b) Bottom coupling suppression only possible in regions forbidden by searches for heavy Higgs bosons.

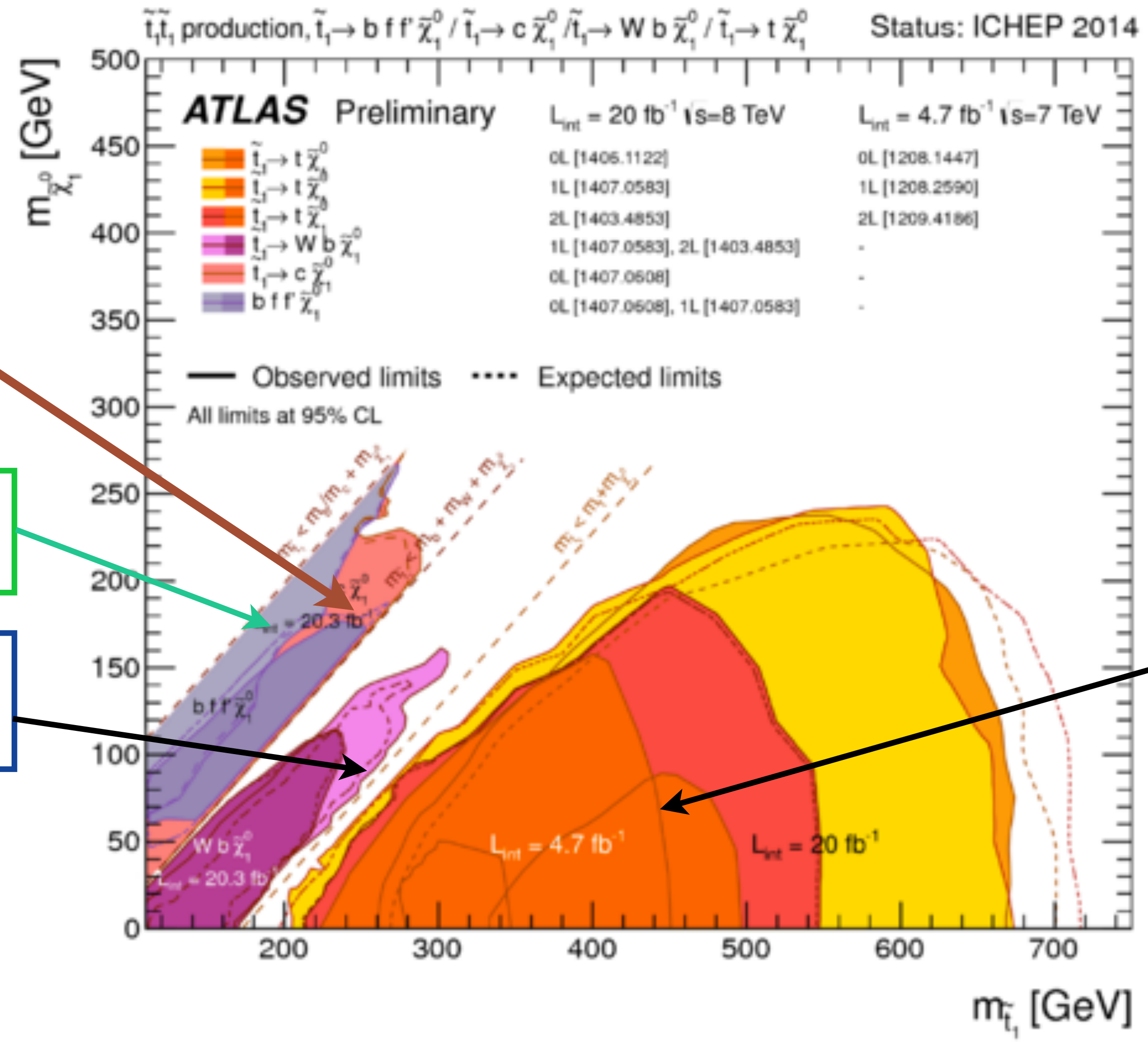
Possible in the NMSSM, for SHuHd couplings lambda > 0.7 (heavy singlet) or for light singlets. NMSSM case is more restrictive than these benchmark scenarios.

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

Carena, Haber, Low, Shah, C.W.’15

Stop Searches

Provided the lightest neutralino (DM) is heavier than about 250 GeV, there are no limits on stops. Even for lighter neutralinos, there are big holes.



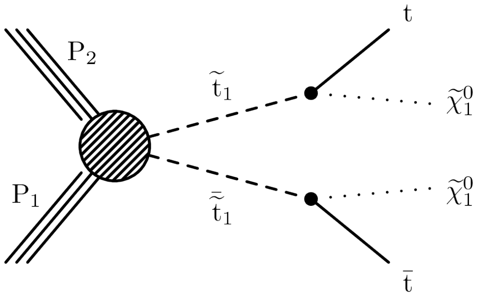
Charm Tagging

Monojet

b + W
+ Miss. ET

top +
Miss ET

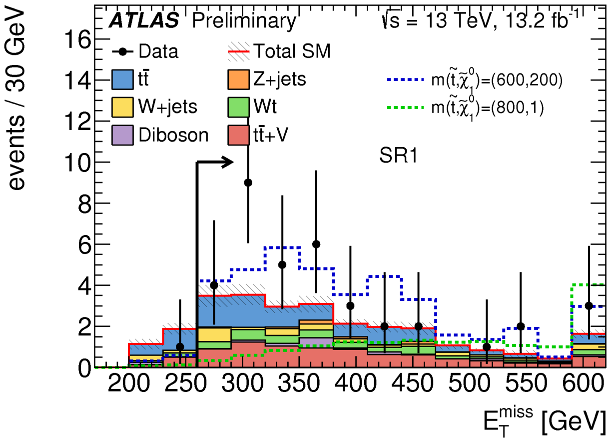
Top squarks

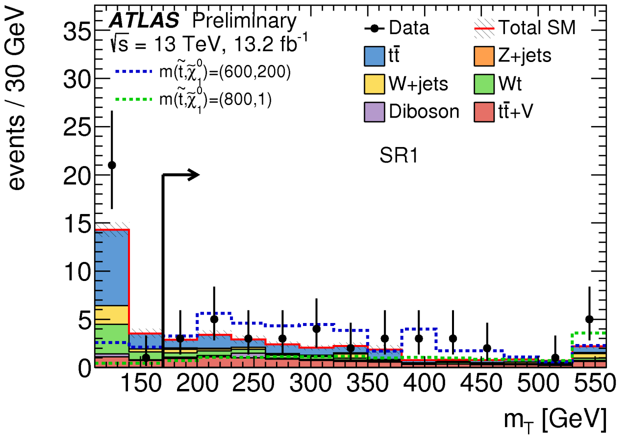


Single-lepton search

ATLAS-CONF-2016-050

- basic selection on jets, b-jets, MET
- signal regions optimized for different Δm and stop decays





Dilepton search (ATLAS)

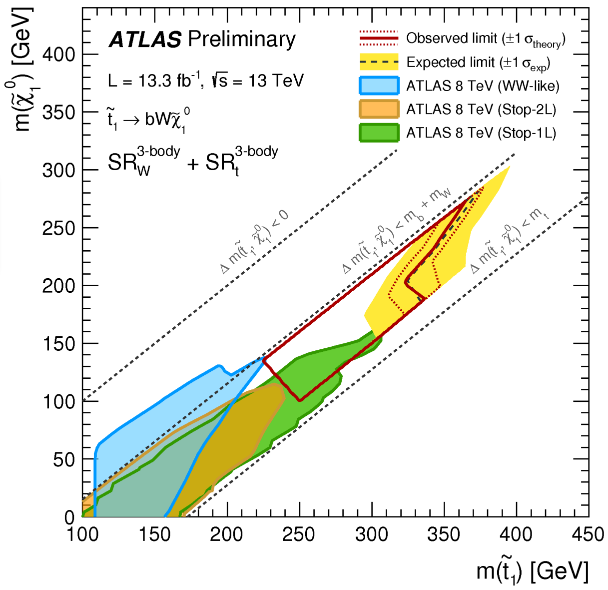
ATLAS-CONF-2016-076

- basic selection on 2 OS leptons
- use of derived observables - super-razor, M_{T2}

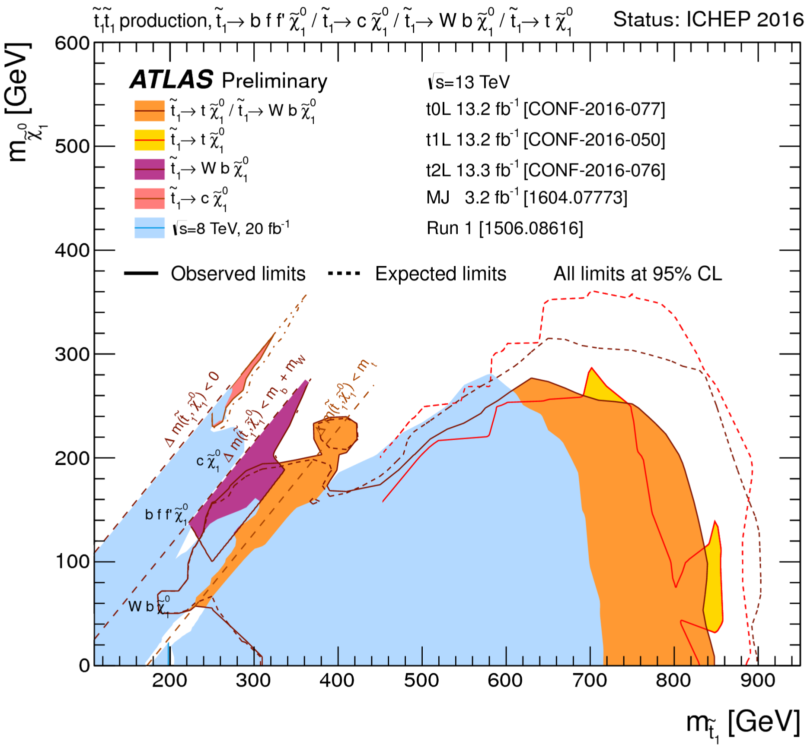
Distributions in one of the 1l signal regions

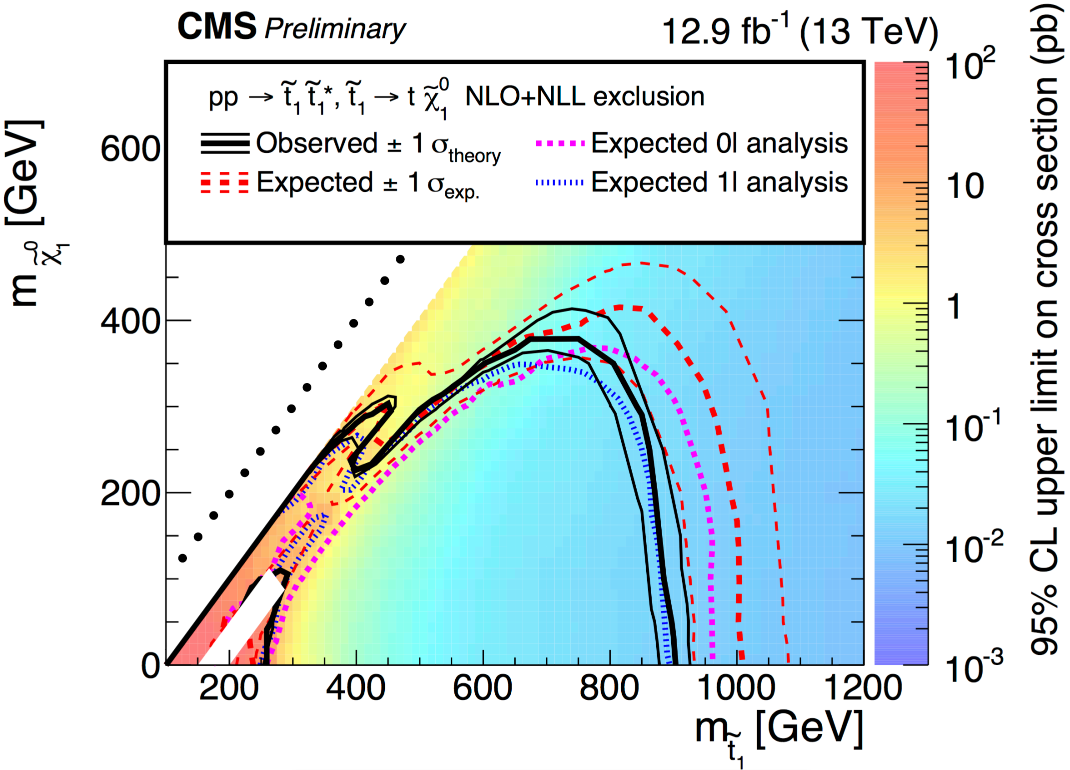
exclusion for 3-body decays

Other results
CMS-SUS-16-029
CMS-SUS-16-030
+ various inclusive searches



Top squarks - summaries



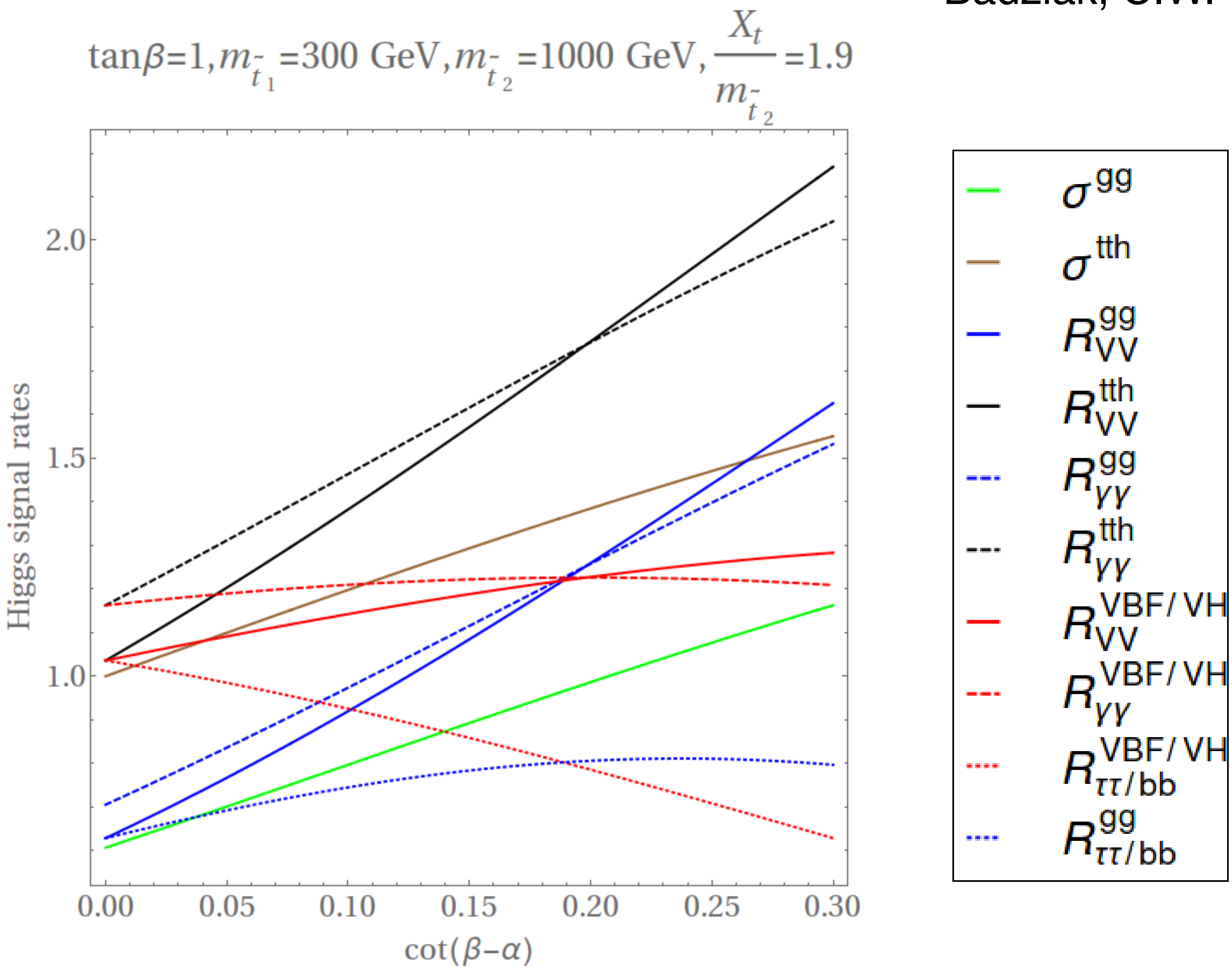


ATLAS summary

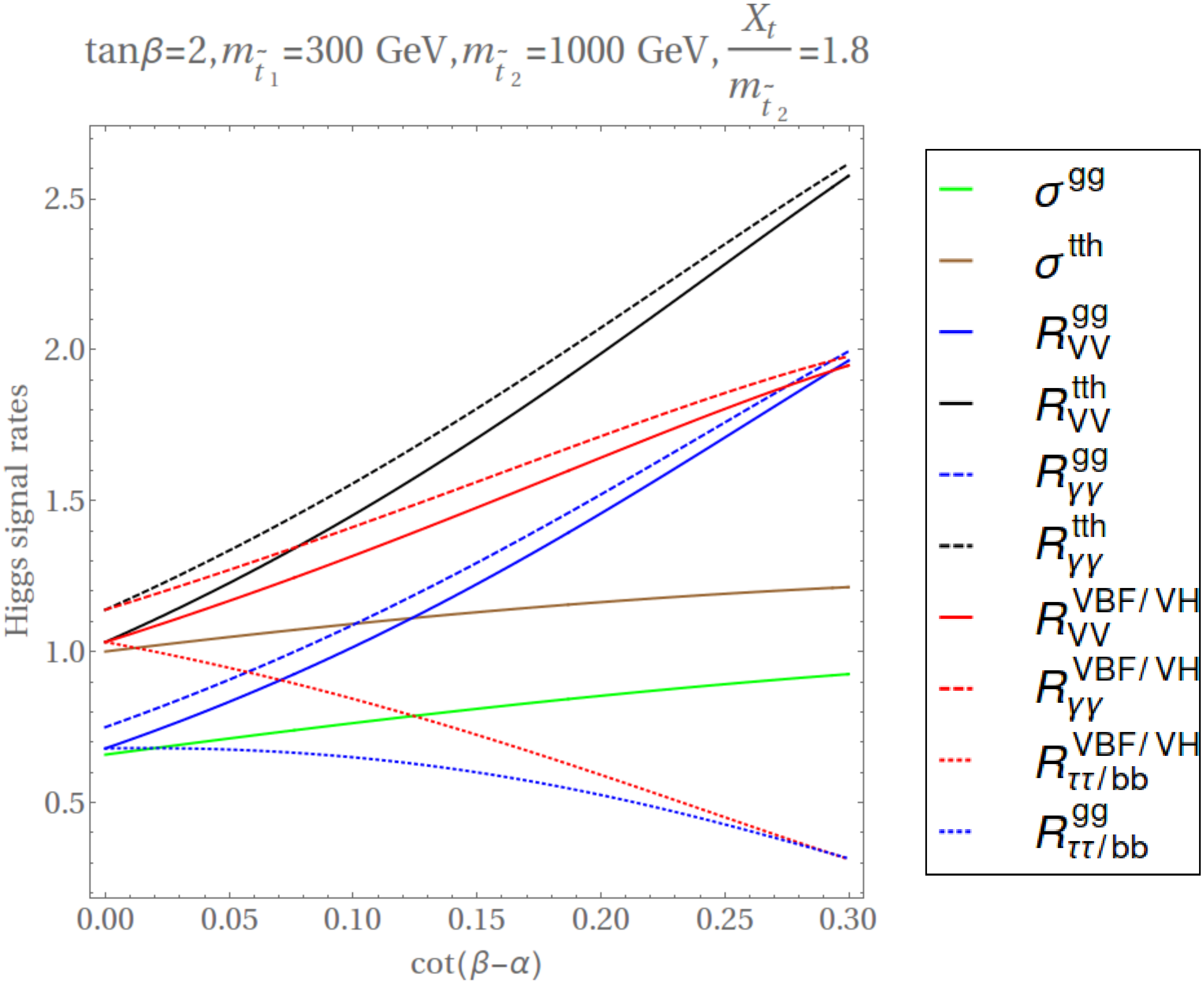
CMS 0l+1l combination
for 2-/3-body decay

Alternative Benchmarks with higher stop masses

Badziak, C.W. ‘16



Alternative Benchmarks with higher stop masses



NMSSM Scenarios with light singlets

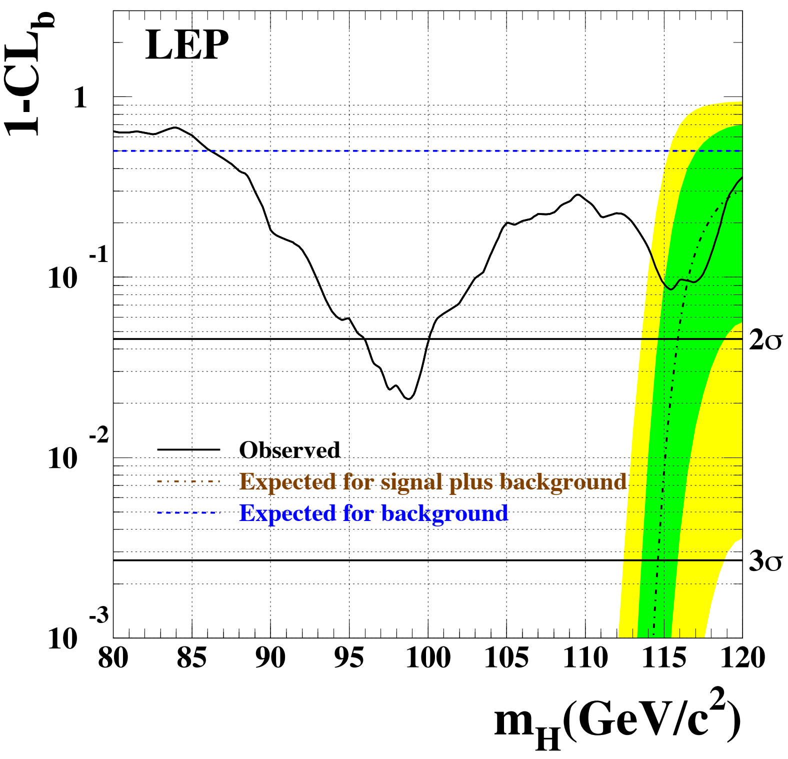
	P1	P2	P3
λ	0.5	0.53	0.53
$\tan\beta$	1.6	1.6	1.6
m_{Q_3}	800	800	800
m_{U_3}	320	350	360
A_t	-1500	-1400	-1500
μ	600	1000	800
μ'	330	450	500
M_A	300	400	300
M_P	248	360	364
A_λ	910	1680	1137
m_s	98	98	98
m_h	125.6	126.4	126.2
m_H	318	424	382
$m_{H^\pm}$	236	321	212
m_a	101	72	137
m_A	330	481	402
$m_{\tilde{\chi}_1^0}$	243	246	245
$m_{\tilde{t}_1}$	282	284	295
$m_{\tilde{t}_2}$	954	968	965

R_{VV}^{tth}	1.76	1.80	1.77
$R_{\gamma\gamma}^{\mathrm{tth}}$	2.00	2.03	2.00
R_{VV}^{gg}	1.15	1.12	1.12
$R_{\gamma\gamma}^{\mathrm{gg}}$	1.31	1.26	1.27
$R_{VV}^{\mathrm{VBF/VH}}$	1.38	1.40	1.42
$R_{\gamma\gamma}^{\mathrm{VBF/VH}}$	1.57	1.58	1.60
$R_{\tau\tau}^{\mathrm{VBF/VH}}$	0.62	0.62	0.70
$\xi_{b\bar{b}}^{\mathrm{LEP}}$	0.14	0.13	0.07
$\mathrm{BR}(H \to t\bar{t})$	0	0.065	0.027
$\mathrm{BR}(H \to ss)$	0.33	0.28	0.004
$\mathrm{BR}(H \to aa)$	0.25	0.25	0.65
$\mathrm{BR}(H \to aZ)$	0.23	0.23	0.14
$\mathrm{BR}(H \to hs)$	0.17	0.13	0.013
$\mathrm{BR}(A \to t\bar{t})$	0	0.15	0.14
$\mathrm{BR}(A \to as)$	0.61	0.44	0.33
$\mathrm{BR}(A \to Zs)$	0.21	0.20	0.23
$\mathrm{BR}(A \to ah)$	0.13	0.05	0.01
$\mathrm{BR}(A \to H^\pm W^\mp)$	0.03	0.14	0.27
$\mathrm{BR}(H^+ \to t\bar{b})$	0.52	0.36	0.62
$\mathrm{BR}(H^+ \to W^+ a)$	0.26	0.40	0
$\mathrm{BR}(H^+ \to W^+ s)$	0.21	0.23	0.38

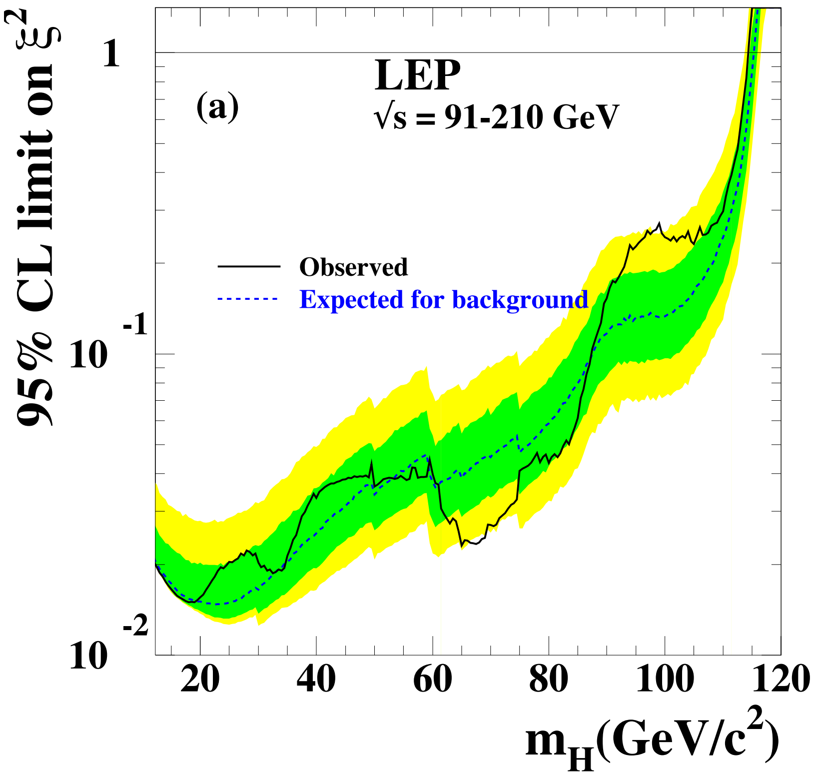
Consistent with the LEP2 Excess

LEP2 Excess

LHWG-2003-011



$$\xi^2 = g^2_{ZZh}/g^2_{ZZh_{SM}}$$



Alternative Interpretation of tth excess ?

Take a closer look at the main signature

What are we seeing exactly?

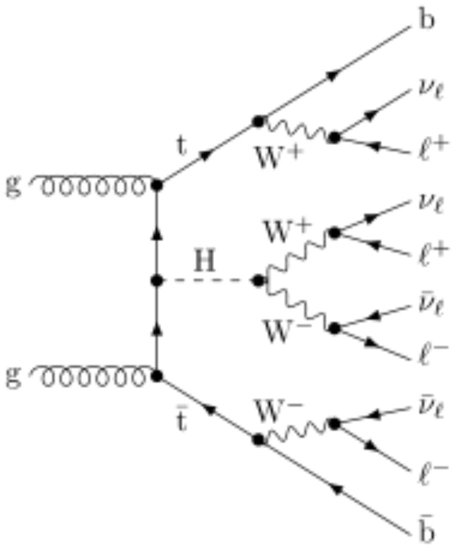
tth, h->W^+W^-

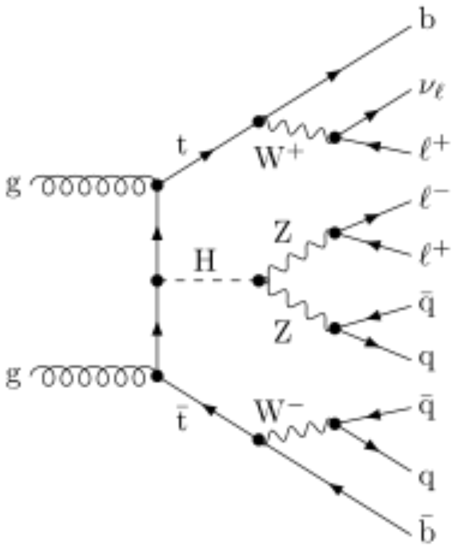
It is really a search for 2t + 2W, or equivalently 2b+4W

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!

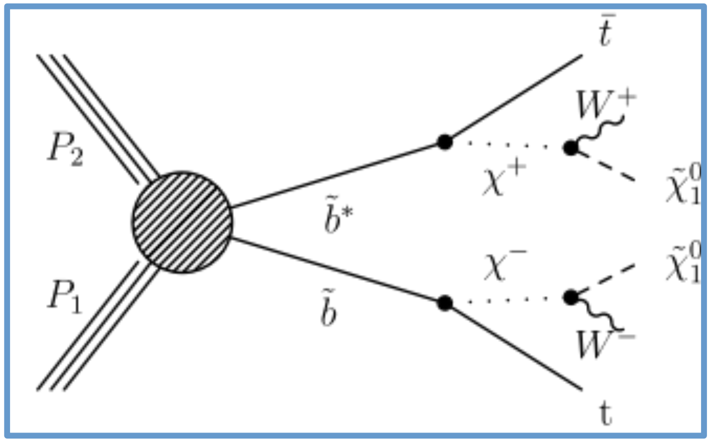


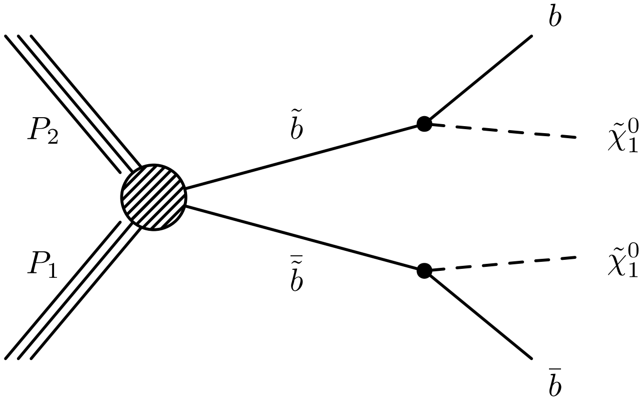


Excesses in multi-lepton + b-jets + MET

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

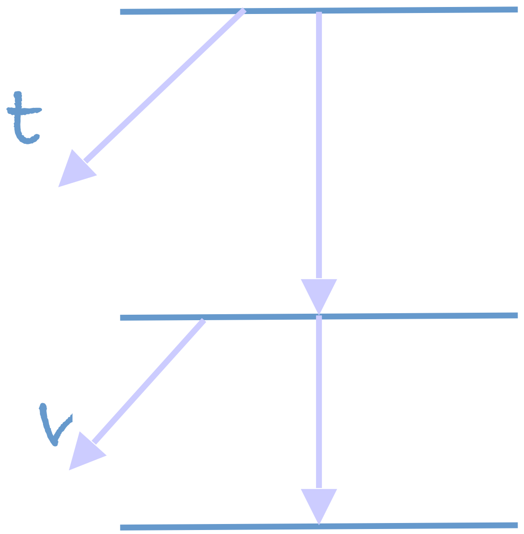




CMS-SUS-13-008

Just an example, a right-handed stop

Stops are pair produced, 2t + 2W



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

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

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

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

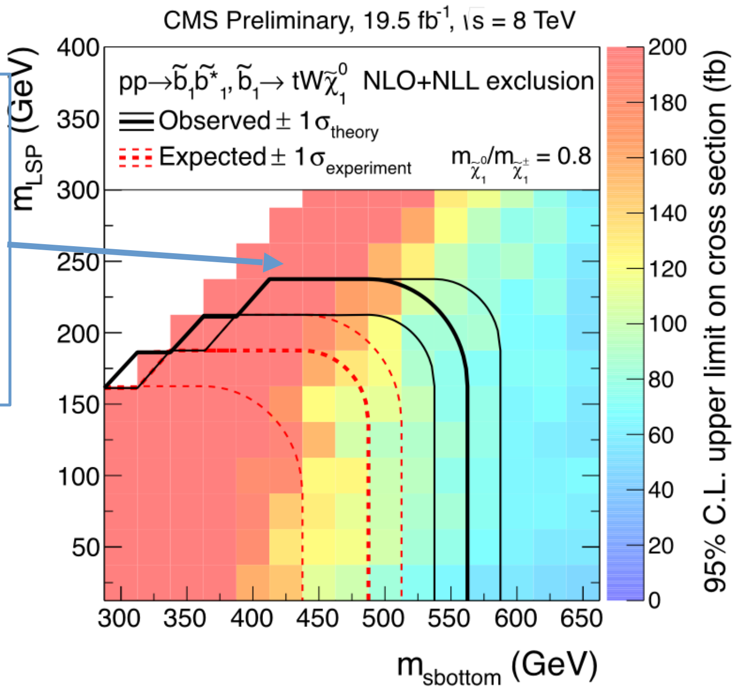
The neutralino mass difference is smaller than the Higgs mass, 100% BR

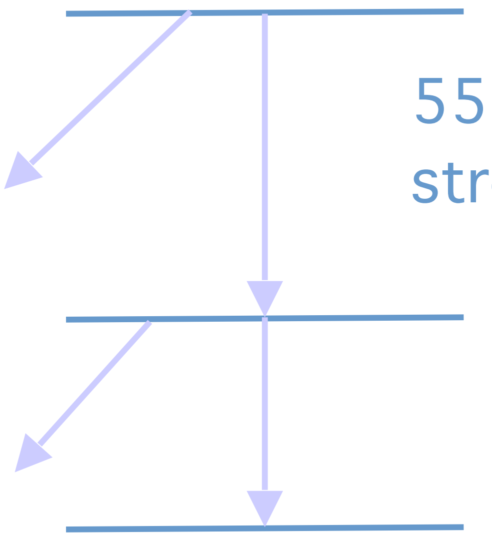
P. Huang, A. Ismail, I. Low, C. Wagner, 1507.01601

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

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

$\tilde\chi_2^0 = \tilde B$;

$\tilde\chi_1^\pm = \tilde W^\pm$; $\chi_1^0 = \tilde W^0$; 260 GeV

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

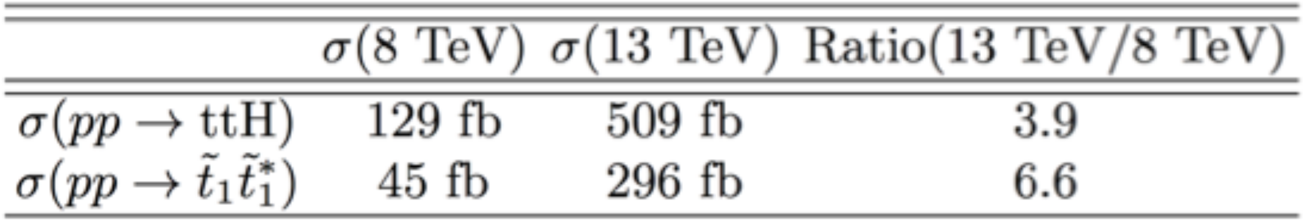
$\mathrm{CMS}: \mu = 53^{+2.1}_{-1.8}$

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

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

Distinguishing stops/sbottoms from enhanced top Yukawa

Stops are heavier , cross section increases faster from the pdf



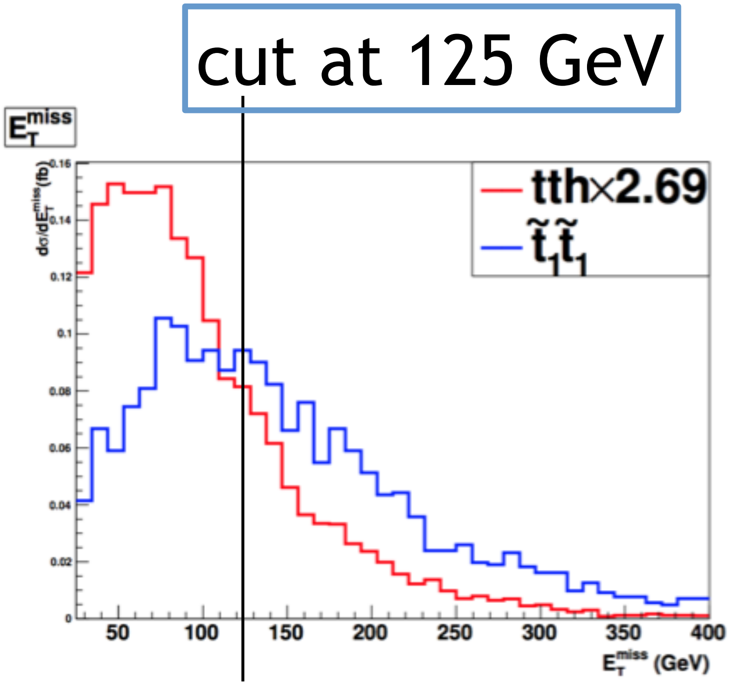
	$\sigma(8\text{ TeV})$	$\sigma(13\text{ TeV})$	Ratio(13 TeV/8 TeV)
$\sigma(pp \to \mathrm{ttH})$	129 fb	509 fb	3.9
$\sigma(pp \to \tilde{t}_1\tilde{t}_1^*)$	45 fb	296 fb	6.6

Expect a signal strength ~ 3.69 at 13 TeV

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

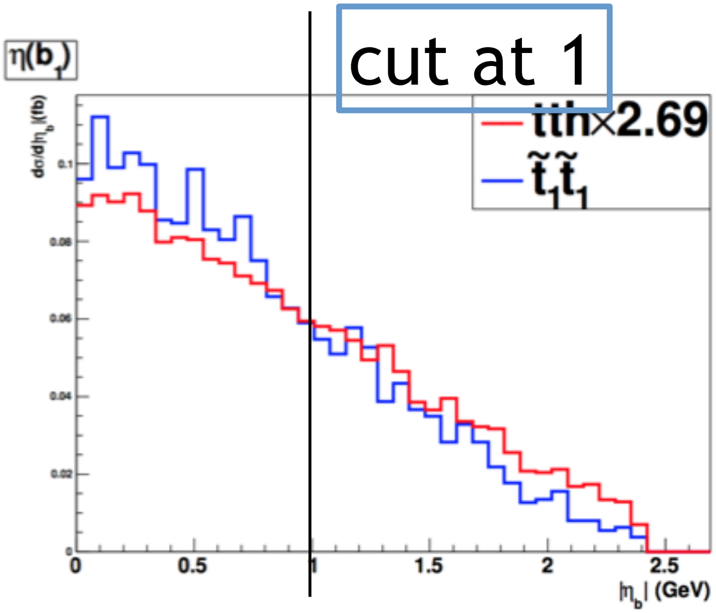
Distinguishing sbottom from enhanced top Yukawa

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



cut at 125 GeV

More missing energy from stop than tth



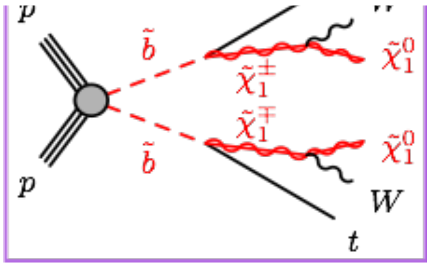
cut at 1

μ (13 TeV) ~ 6.94
reach 5 σ with about 40 fb^{-1}

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.

Current Searches at 13 TeV

Sbottom vs. Stop



Same-sign dilepton Excess arXiv:1507.01601

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

mapping:

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

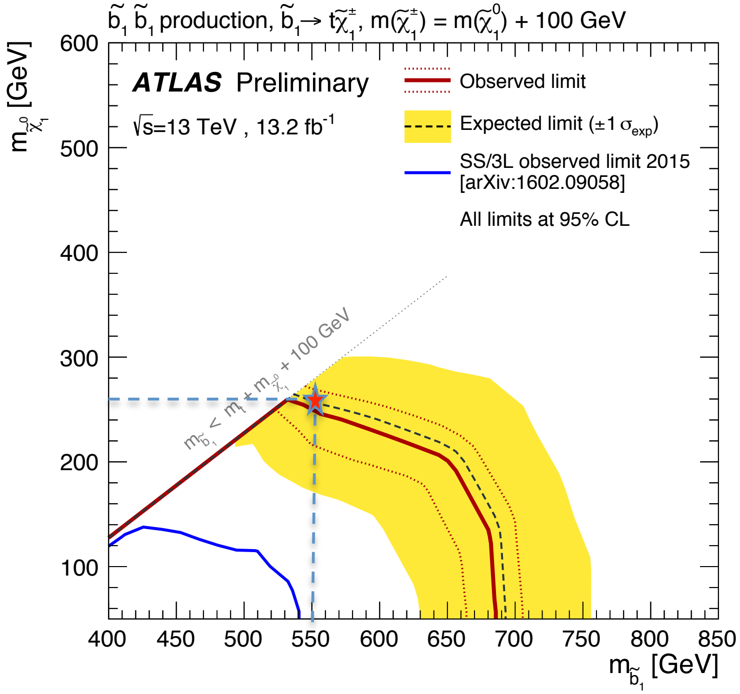
Mass point proposed:

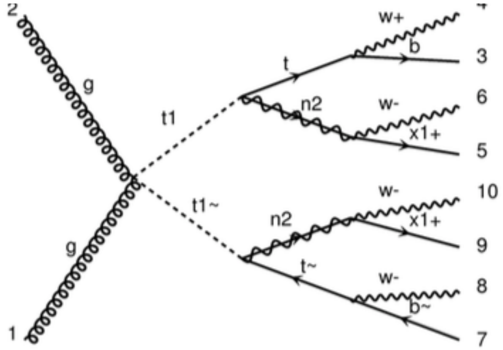
$$m_{\tilde{t}_1} = 550 \text{ GeV}, \quad m_{\tilde{\chi}_2^0} = 340 \text{ GeV}, \quad m_{\tilde{\chi}_1^\pm} \approx m_{\tilde{\chi}_1^0} = 260 \text{ GeV}$$

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

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

$$pp \to \tilde{t}_1 \tilde{t}_1^* \to b\bar{b} + \left\{ \begin{matrix} W^+W^-W^-W^- \\ W^-W^+W^+W^+ \\ W^+W^-W^-W^+ \\ W^+W^-W^+W^- \end{matrix} \right\} + E_T^{\text{miss}}$$





Benchmark should be redefined in terms of current data

The Future :
Will the couplings differ from the SM values

What happens if at higher luminosities all production and decay widths converge to the SM values ?

Two simple possibilities :

a) Decoupling : SM a good effective theory until high scales.

b) Alignment : Extended Higgs Sector present, but Higgs mass eigenvalues are aligned with the V.E.V. direction

Low Energy Supersymmetry : Type II Higgs doublet models

- In Type II models, the Higgs H1 would couple to down-quarks and charge leptons, while the Higgs H2 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 $\cos(\beta-\alpha)=0$

$$\sin\alpha = -\cos\beta,$$

$$\cos\alpha = \sin\beta$$

then the coupling of the lightest Higgs to fermions and gauge bosons is SM-like. This limit is called decoupling limit. Is it possible to obtain similar relations for lower values of the CP-odd Higgs mass ? We shall call this situation ALIGNMENT

- Observe that close to the decoupling limit, the lightest Higgs couplings are SM-like, while 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 coupling of the CP-odd Higgs boson

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

Alignment in General two Higgs Doublet Models

H. Haber and J. Gunion'03

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

Symmetry arguments : 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

Craig, Galloway and Thomas'13

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

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

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

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

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

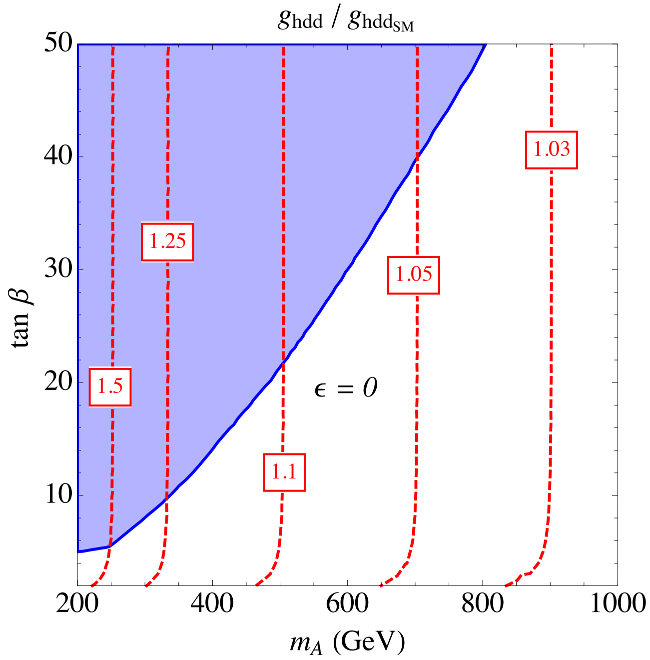
- Conditions not fulfilled in the MSSM, where both $\lambda_1, \tilde{\lambda}_3 < \lambda_{\rm SM}$

Down Couplings in the MSSM for low values of μ
(no Alignment)

- In this regime, $\lambda_{6,7} \simeq 0$, and

$$\lambda_1 \simeq -\tilde{\lambda}_3 = \frac{g_1^2 + g_2^2}{4} = \frac{M_Z^2}{v^2} \simeq 0.125 \qquad \lambda^{\rm SM} \simeq 0.26$$

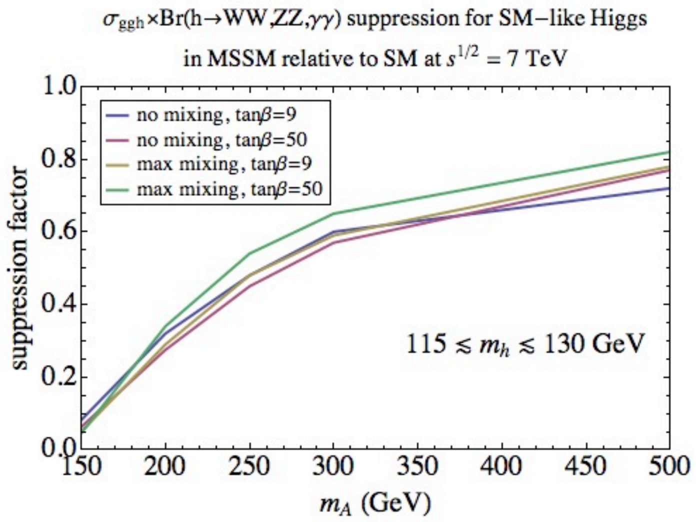
$$\lambda_2 \simeq \frac{M_Z^2}{v^2} + \frac{3}{8\pi^2} h_t^4 \left[\log\left(\frac{M_{\rm SUSY}^2}{m_t^2}\right) + \frac{A_t^2}{M_{\rm SUSY}^2}\left(1 - \frac{A_t^2}{12 M_{\rm SUSY}^2}\right)\right]$$



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

For moderate or large values of tanβ

Draper,Liu,C.W.'10



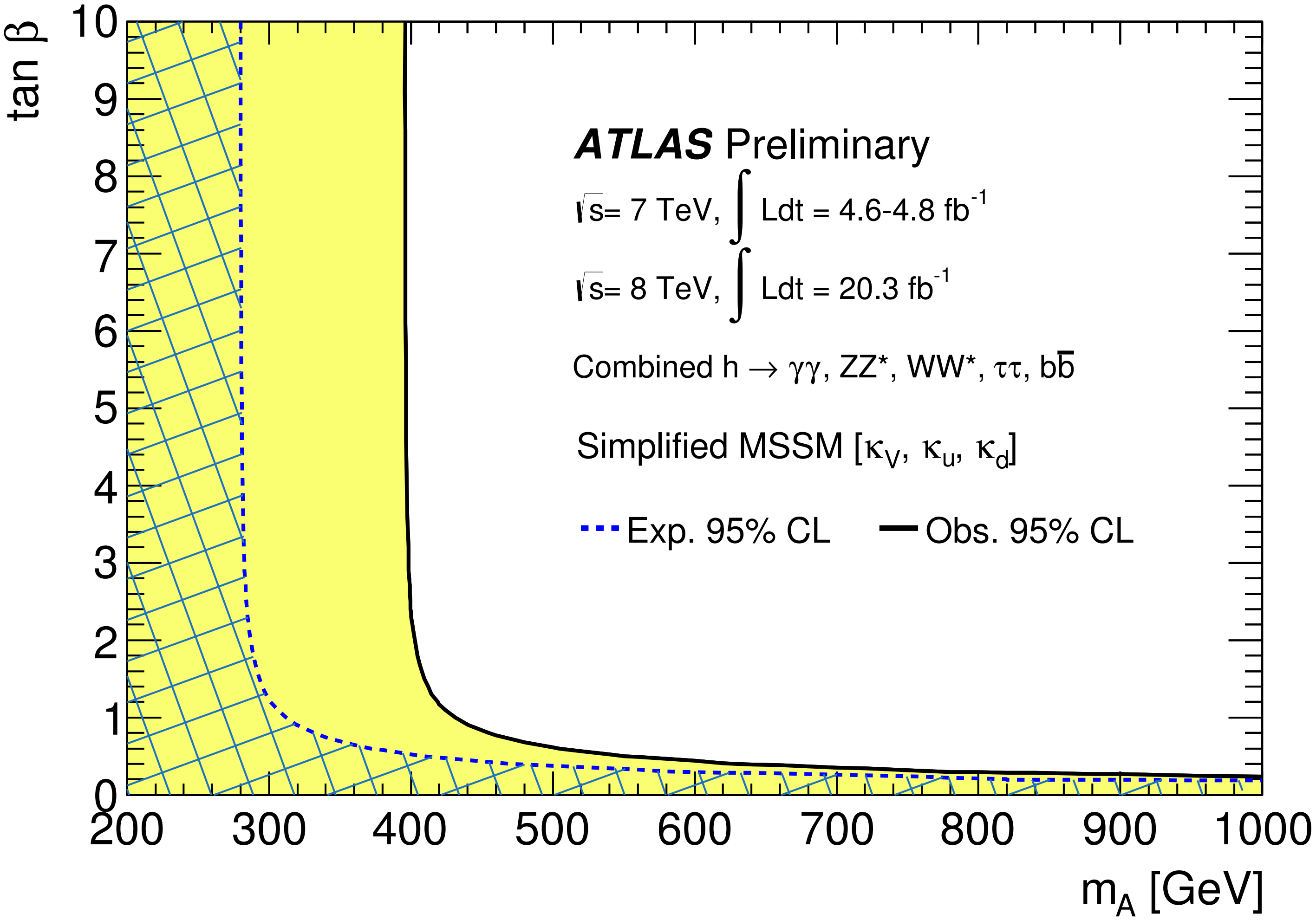
All vector boson branching ratios suppressed by enhancement of the bottom decay width

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

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

Low values of μ similar to the ones analyzed by ATLAS

ATLAS-CONF-2014-010



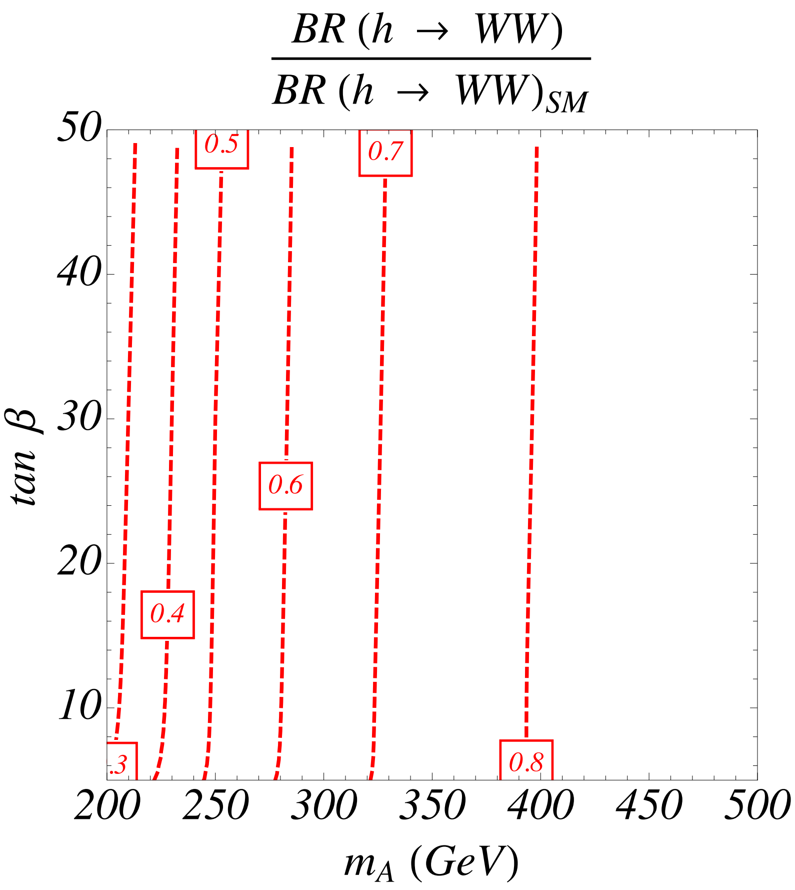
Bounds coming from precision h measurements

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

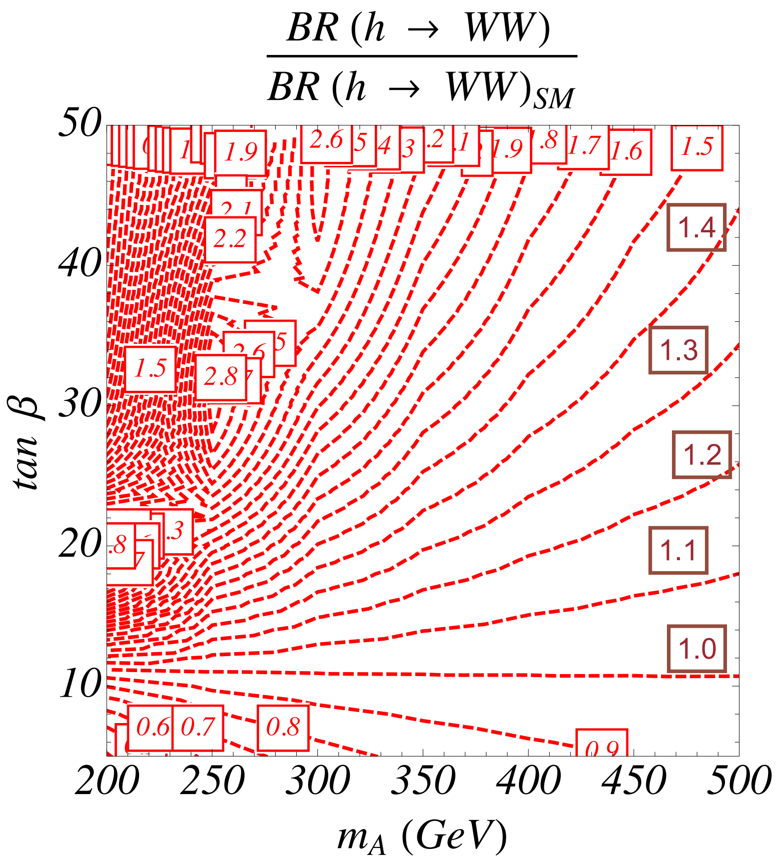
Higgs Decay into Gauge Bosons

Mostly determined by the change of width

Small μ



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



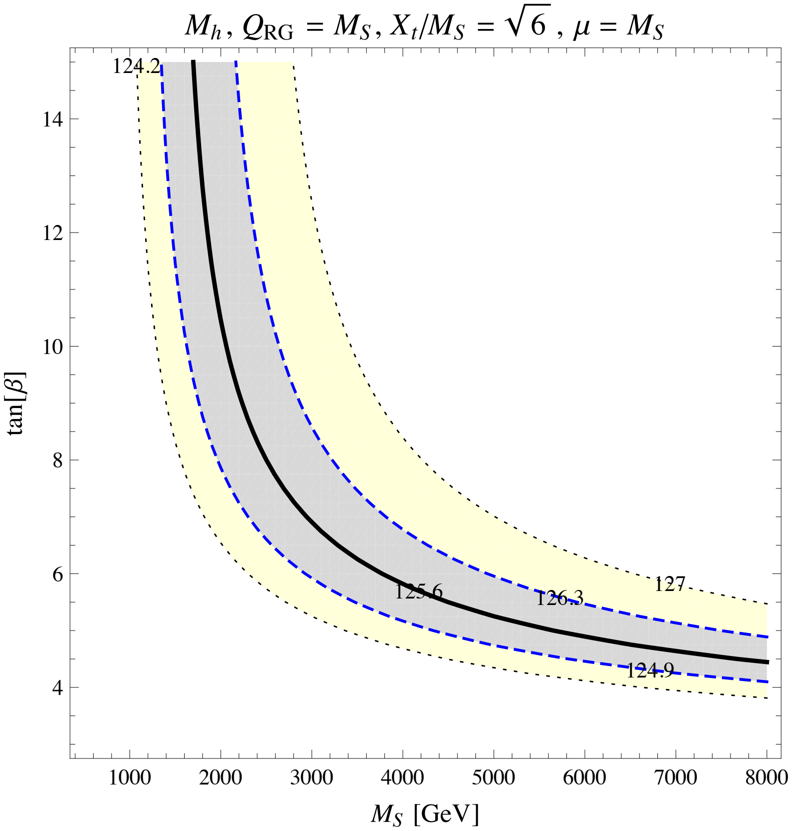
CP-odd Higgs masses of order 200 GeV and tanβ = 10 OK in the alignment case

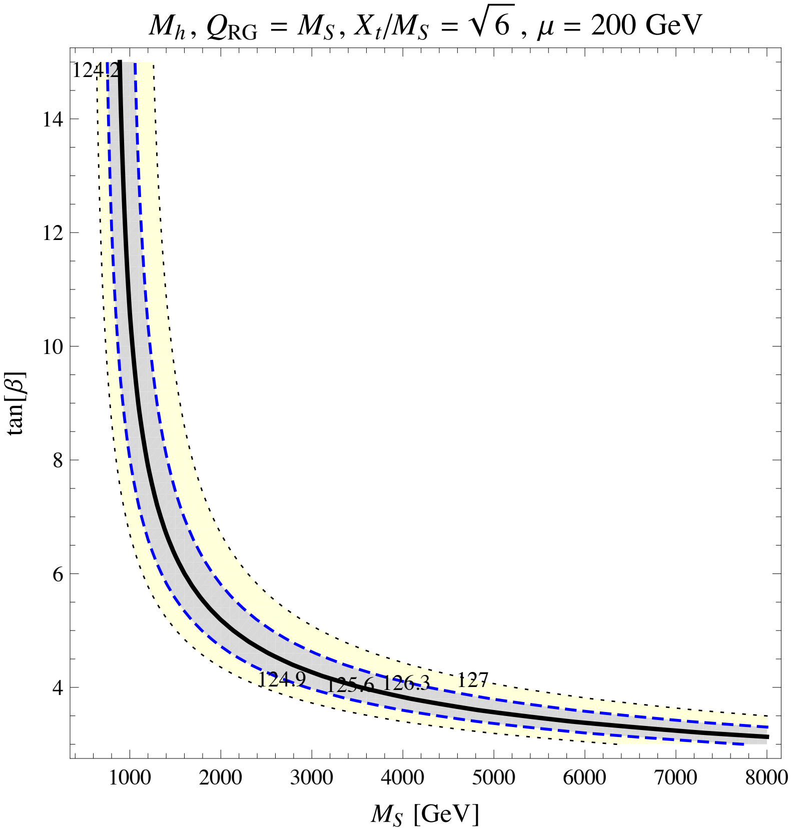
Higgs Mass.

Away from maximal mixing, heavier stop masses necessary. In the MSSM light stops like decoupling.

Draper, Lee, C.W.'13, Lee, C.W.'15

Necessary stop mass values to get the proper Higgs mass for Maximal mixing in the stop sector

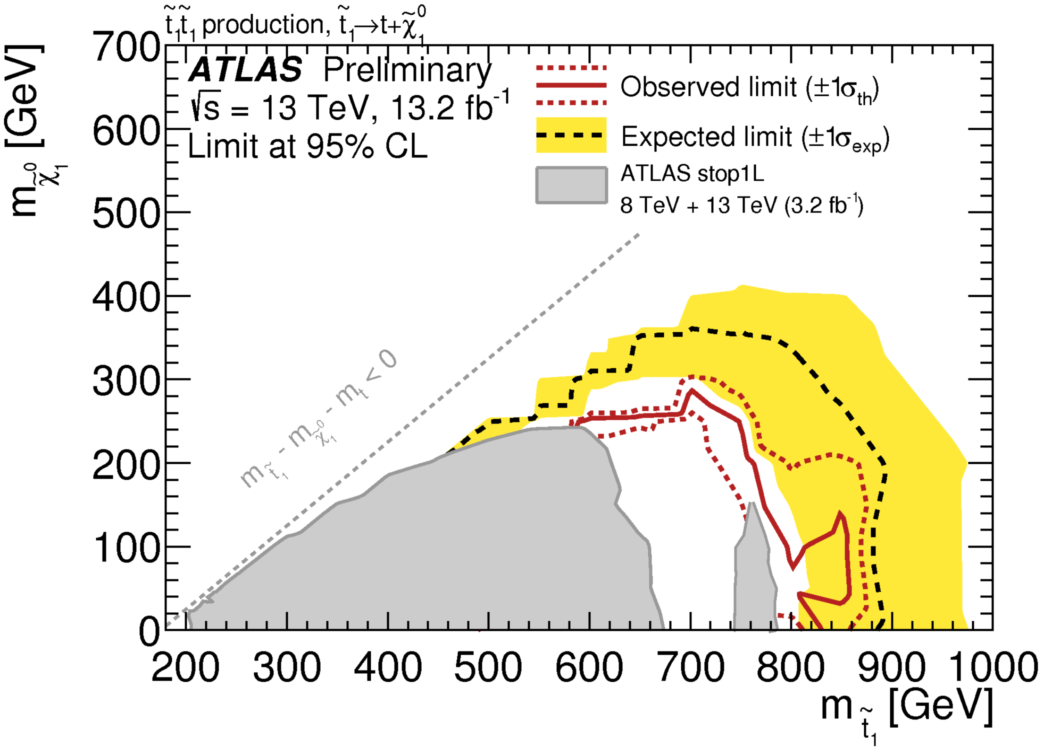

M_h, $Q_{\rm RG} = M_S$, $X_t/M_S = \sqrt{6}$, $\mu = M_S$

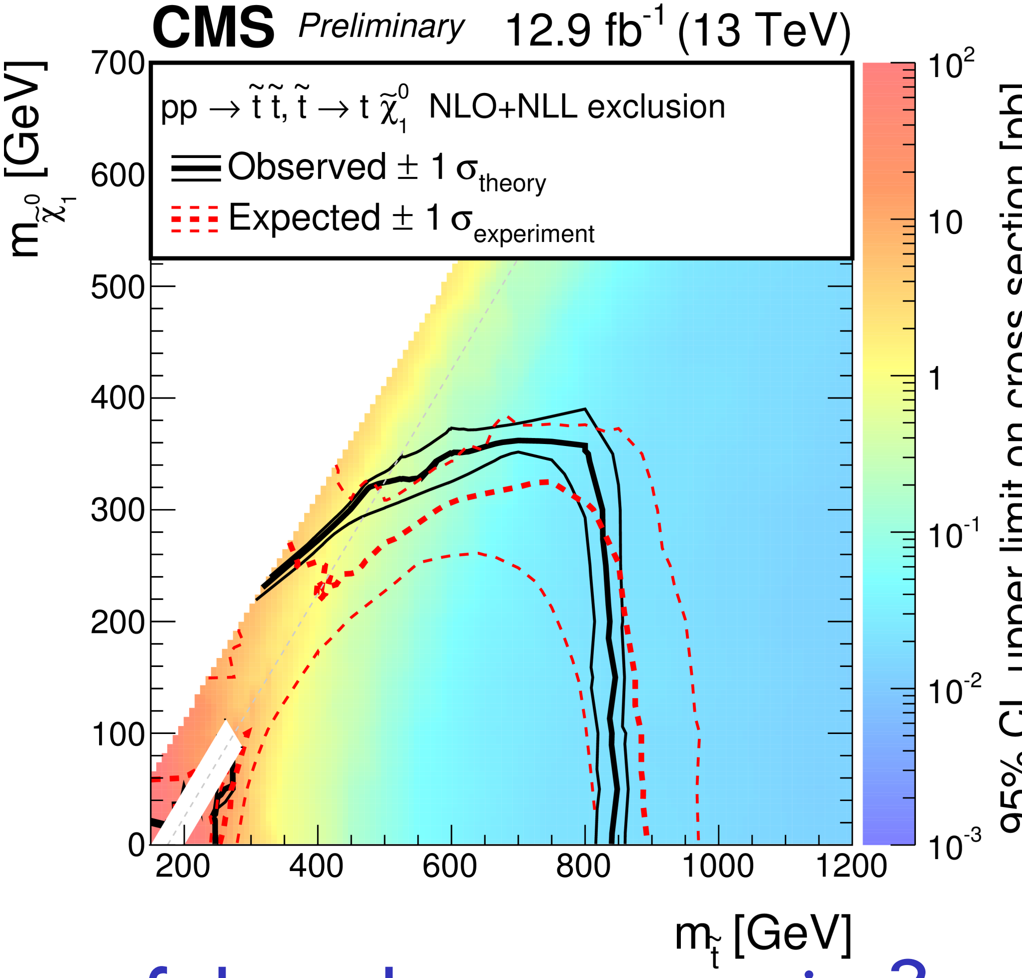

M_h, $Q_{\rm RG} = M_S$, $X_t/M_S = \sqrt{6}$, $\mu = 200$ GeV

Light Stops at the reach of the LHC for large mixing in the Stop sector and moderate values of tanβ

Searches for Stops at the LHC

Prediction of mhmax scenario :
Lightest stop mass 825 GeV



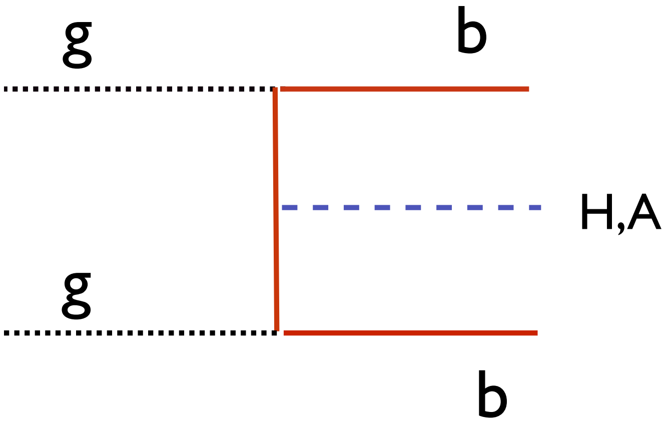


Are we seeing the first hints of the mhmax scenario ?

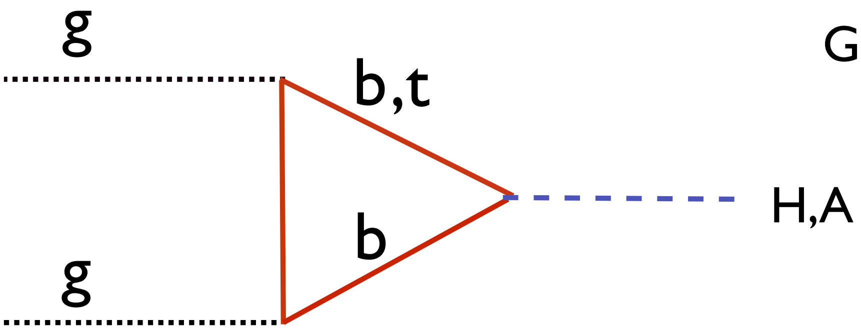
Carena, Heinemeyer, Wagner, Weiglein '03…'13

Non-Standard Higgs Production

QCD: S. Dawson, C.B. Jackson, L. Reina, D. Wackeroth, hep-ph/06031

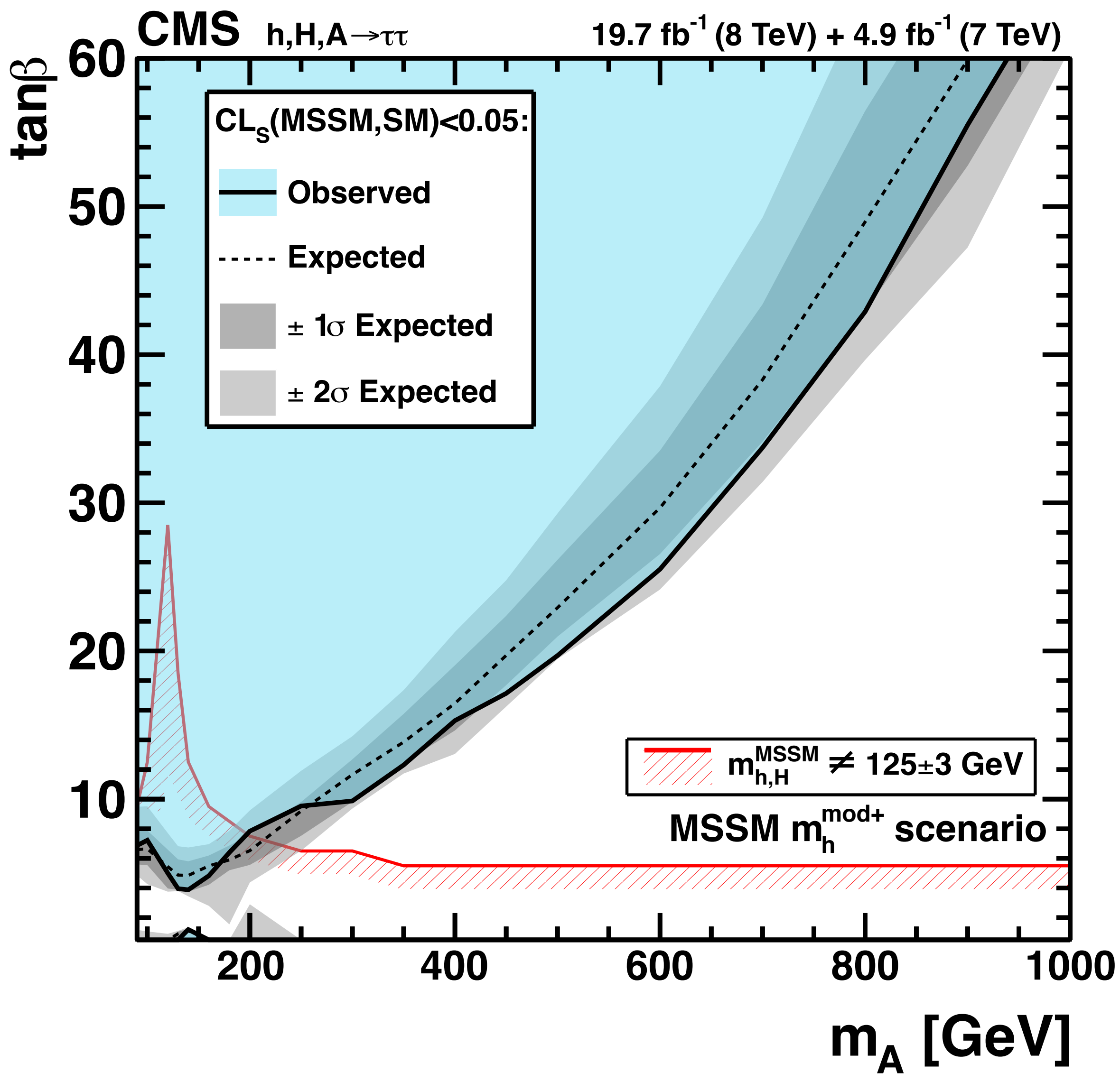


Associated Production



Gluon Fusion

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



How to test the
region of low tanbeta
and moderate mA ?

Decays of non-standard
Higgs bosons into paris
of standard ones, charginos
and neutralinos may be
a possibility.

Can change in couplings help
there ?

It depends on radiative corrections

We shall assume light gauginos,
$M_2 = 2\ M_1 \simeq 200$ GeV.

This is an example of a low μ scenario

$A_t \simeq 1.5\ M_{\rm SUSY}, \quad \mu = 200$ GeV

At low values of $\tan\beta$, the SUSY mass scale must be raised.

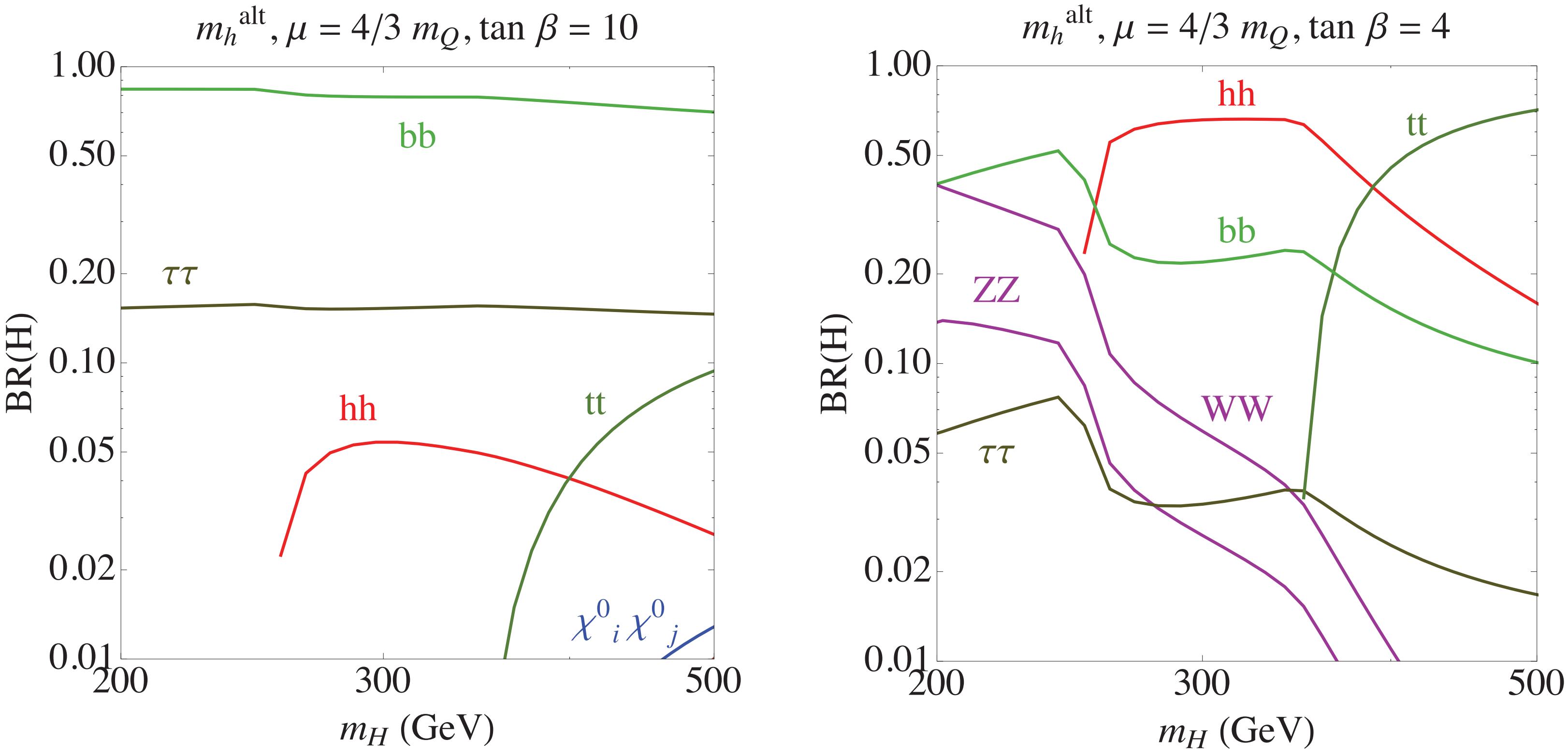
Heavy Supersymmetric Particles

Heavy Higgs Bosons : A variety of decay Branching Ratios

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

Craig, Galloway, Thomas'13

Depending on the values of μ and tanβ different search strategies must be applied.

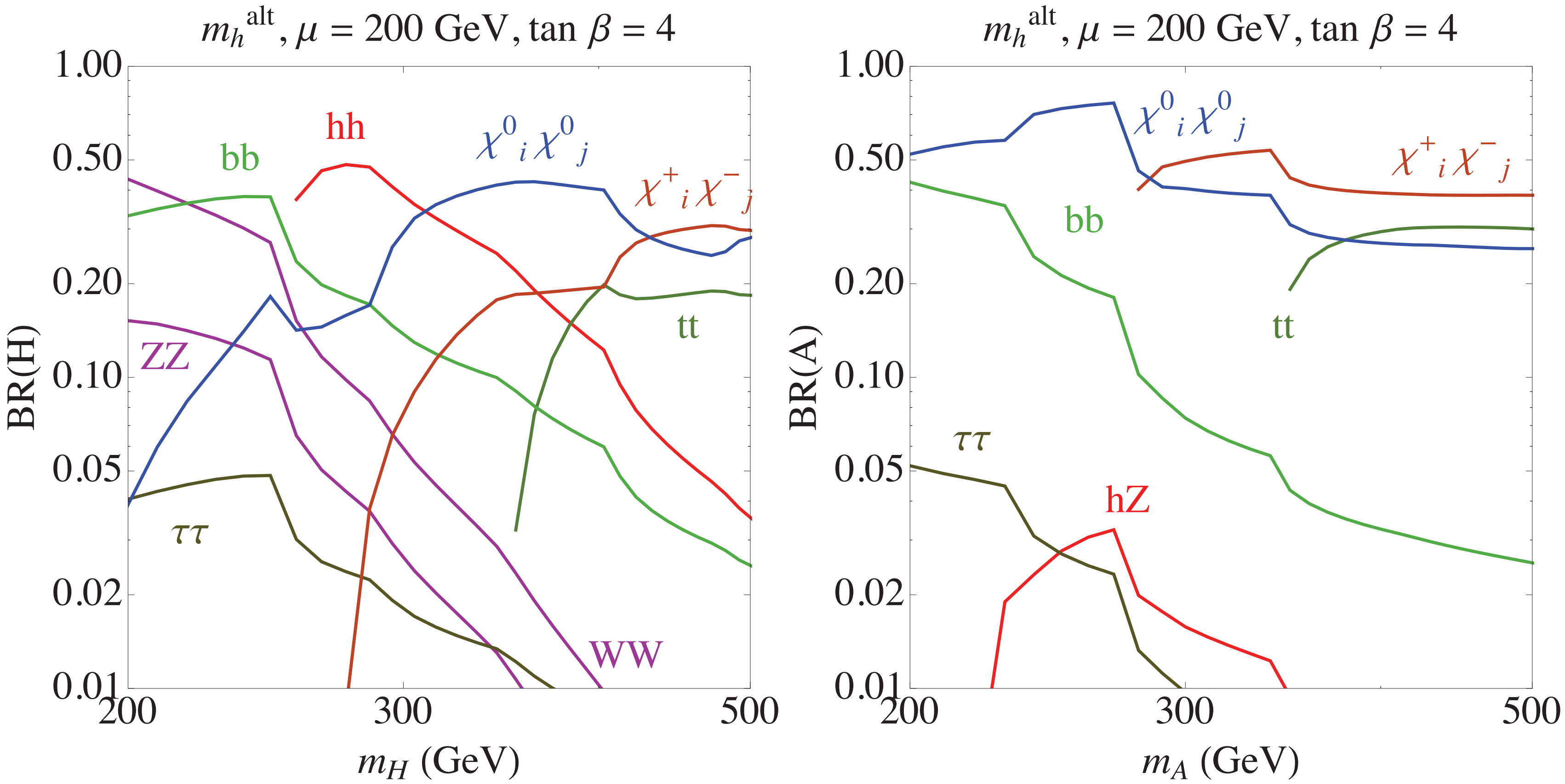


At large tanβ, bottom and tau decay modes dominant.

As tanβ decreases decays into SM-like Higgs and wek bosons become relevant

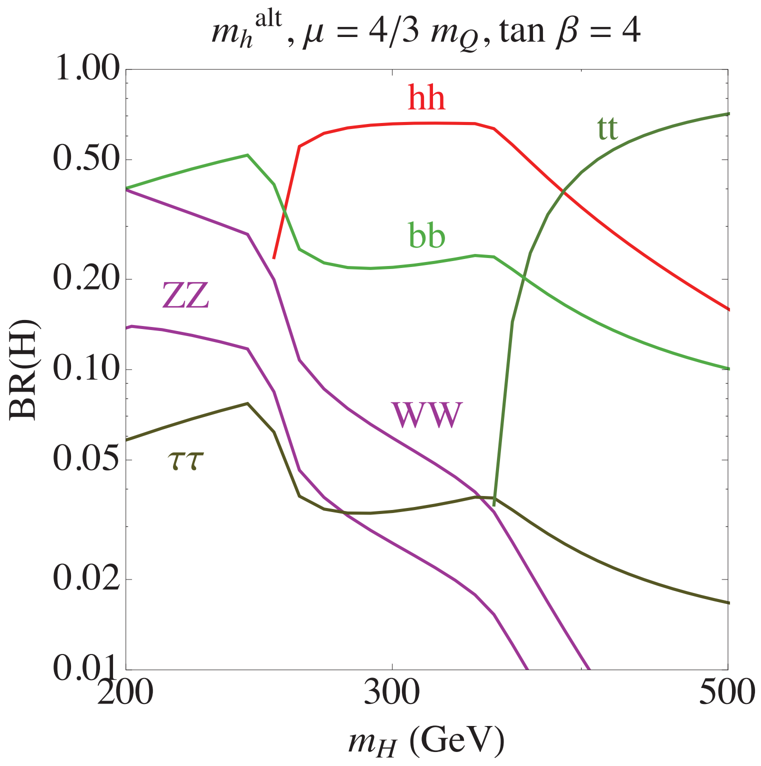
Light Charginos and Neutralinos can significantly modify M the CP-odd Higgs Decay Branching Ratios

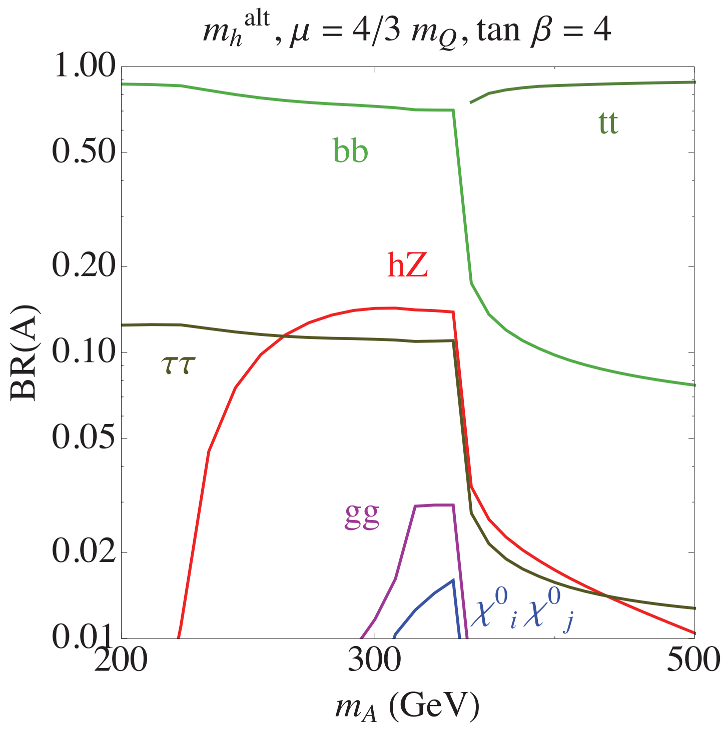
Carena, Haber, Low, Shah, C.W.'14



At small values of tanβ, and small μ, heavy Higgs decay into top quarks and electroweakinos become dominant. Still, decays into pairs of Higgs very relevant.

Large μ and small tanβ

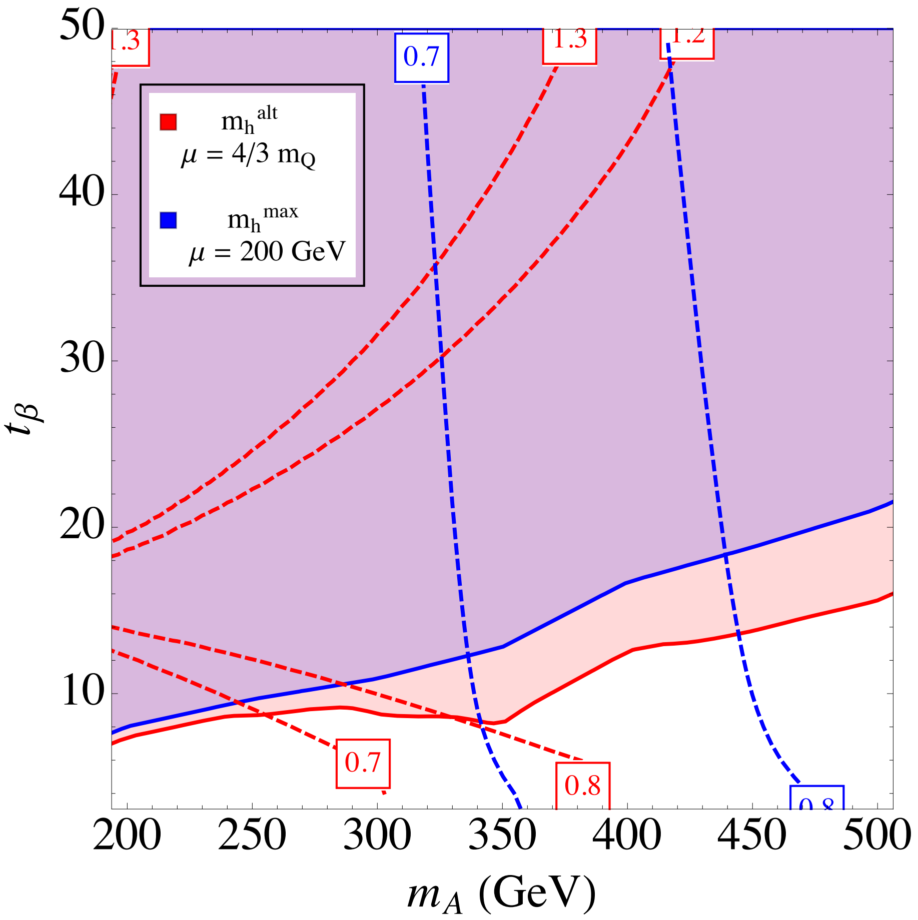




Decays into gauge and Higgs bosons become important. Observe, however that the BR(A to τ τ) remains large up to the top-quark threshold scale

Complementarity between different search channels

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



— $\sum_{\phi_i = A, H} \sigma(bb\phi_i + gg\phi_i) \times BR(\phi_i \to \tau\,\tau)$ (8 TeV)

--- $\sigma(bbh + ggh) \times BR(h \to VV)/SM$

Limits coming from measurements of h couplings become weaker for larger values of μ

Limits coming from direct searches of $H, A \to \tau\tau$ become stronger for larger values of μ

Bounds on m_A are therefore dependent on the scenario and at present become weaker for larger μ

With a modest improvement of direct search limit one would be able to close the wedge, below top pair decay threshold

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,

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

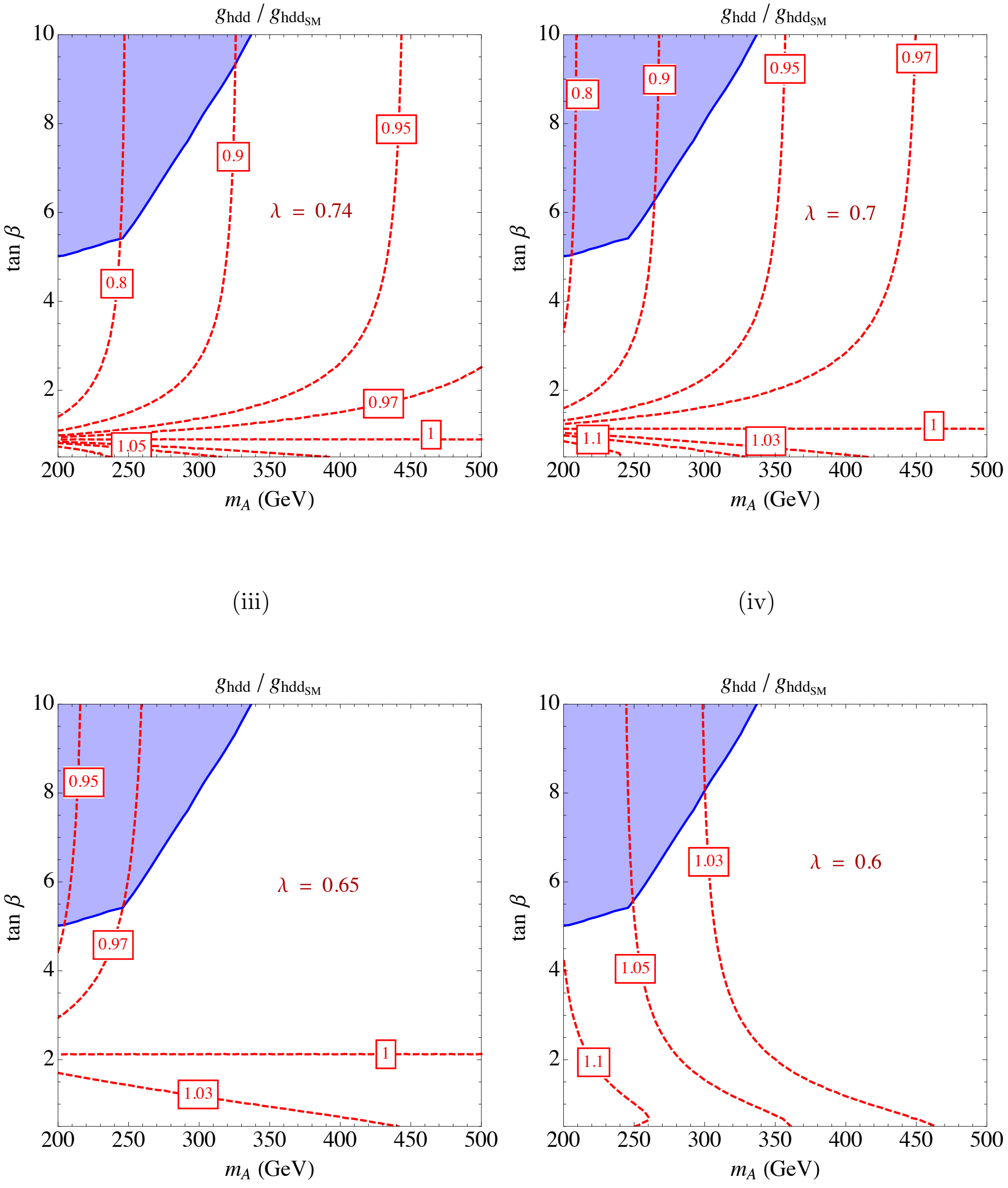
- The last term is the one appearing in the MSSM, that are small for moderate mixing and small values of $\tan\beta$. The corrections Δt and δt are the same as in the MSSM.

- So, alignment leads to a determination of lambda,

- The values of lambda end up in a very narrow range, between 0.65 and 0.7 for all values of tanβ, that are the values that lead to naturalness with perturbative consistency up to the GUT scale

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

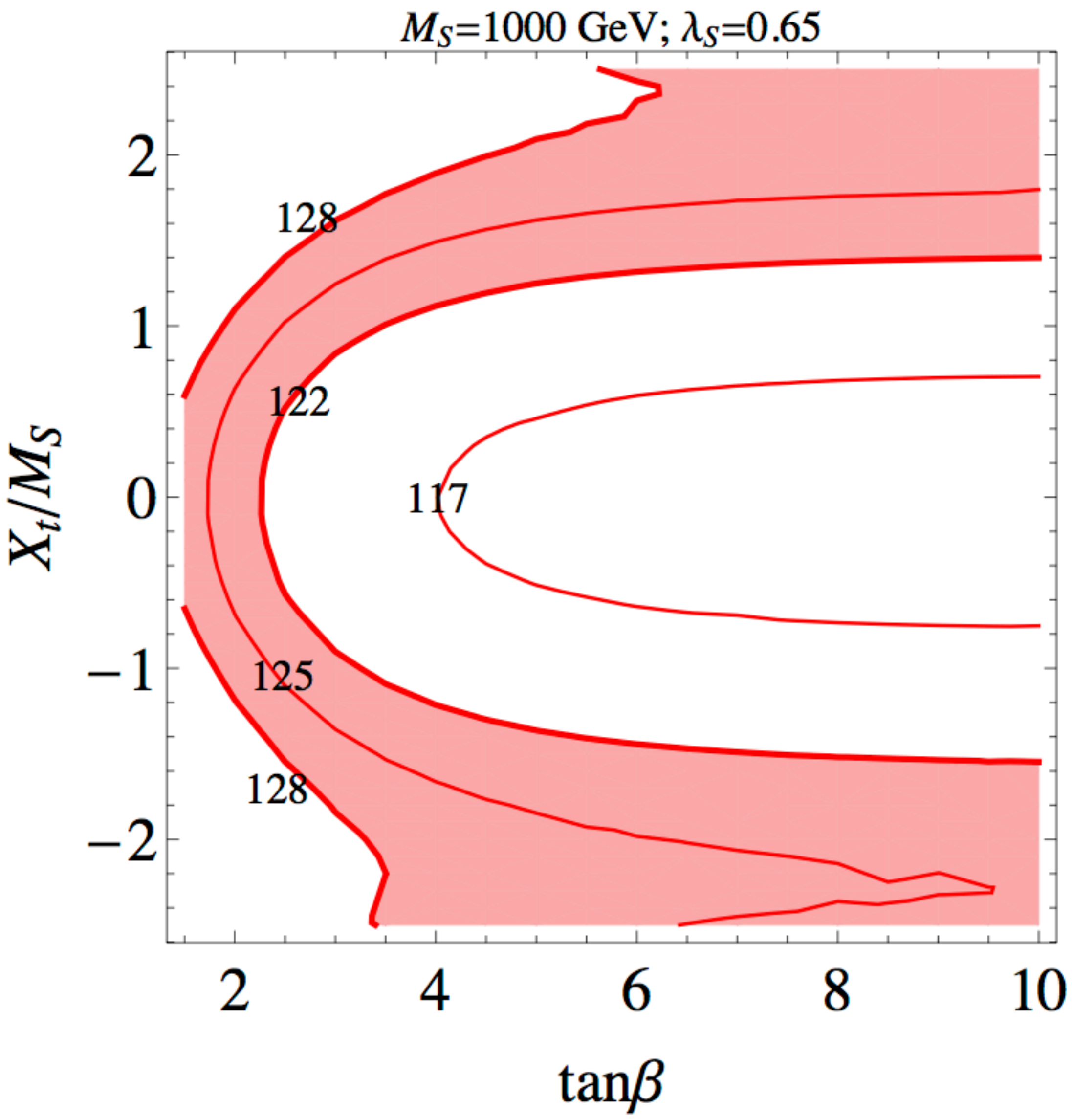
Alignment in the NMSSM (heavy or aligned singlets)



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

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

NMSSM Higgs Mass predictions

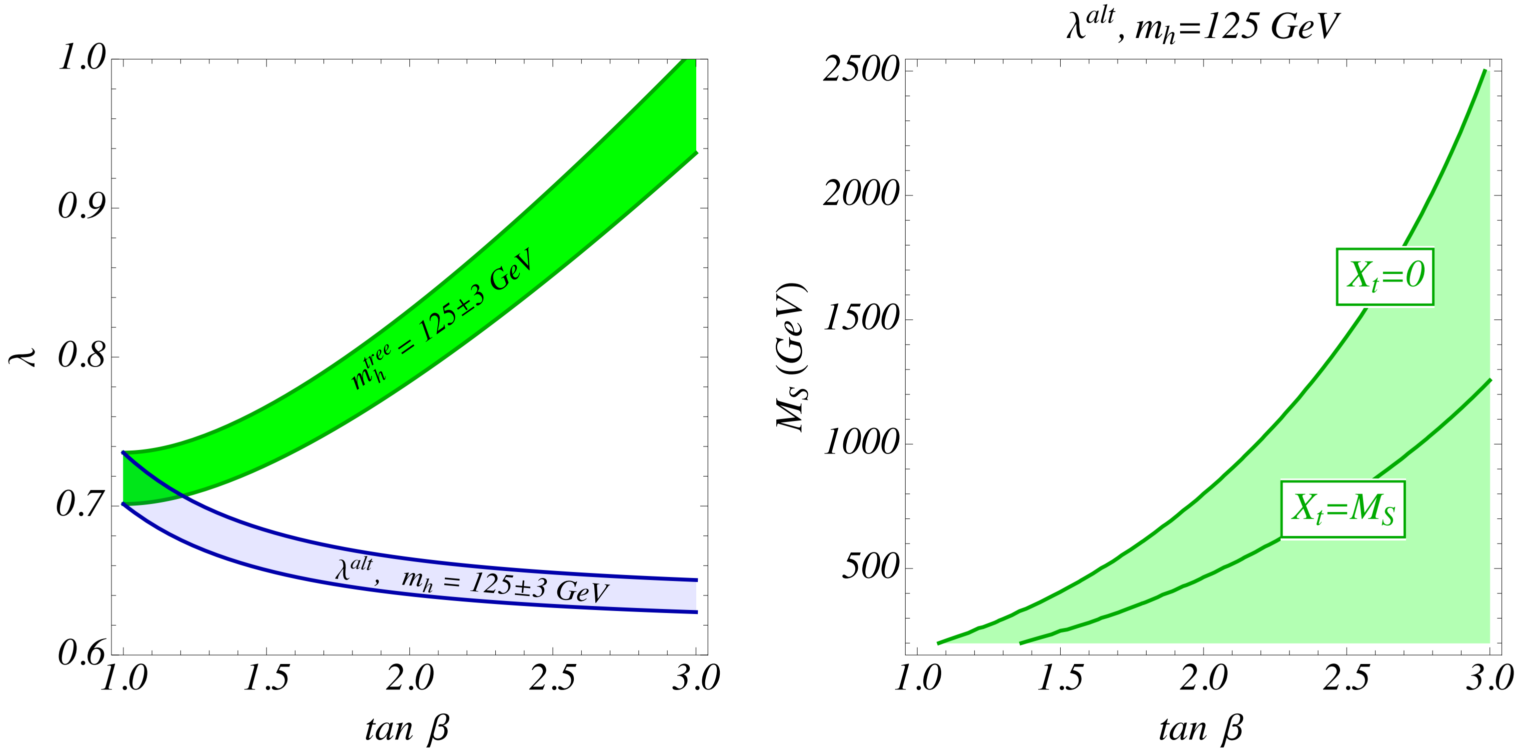


Stop Contribution at alignment

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

Interesting, after some simple algebra, one can show that

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

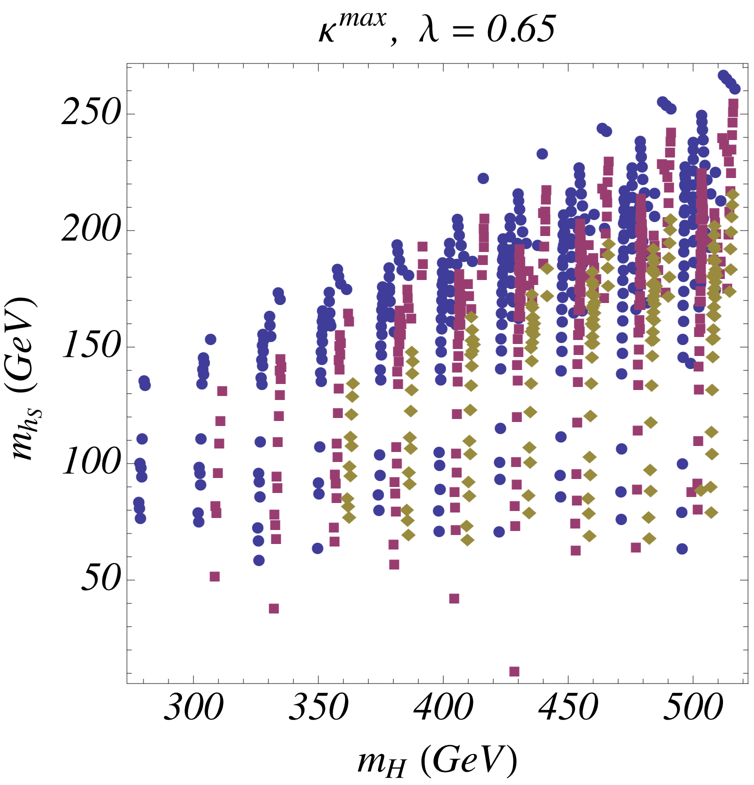


For moderate mixing, It is clear that low values of $\tan\beta < 3$
lead to lower corrections to the Higgs mass parameter at the alignment values

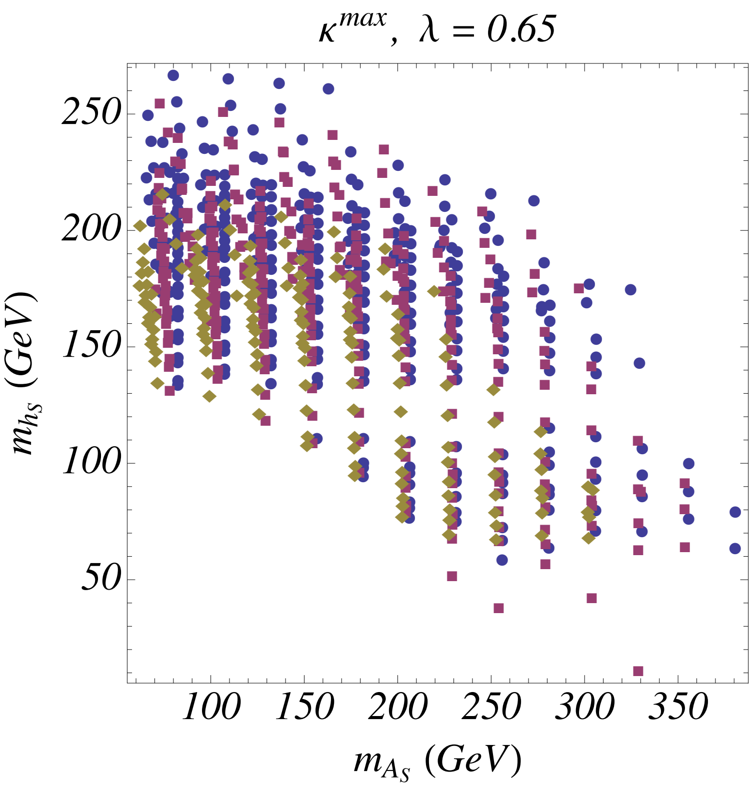
Allowed CP-even and CP-odd Masses

$\tan\beta = 2$ (blue), 2.5 (red) 3 (yellow)

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



Heavier CP-even Higgs
can decay to lighter ones



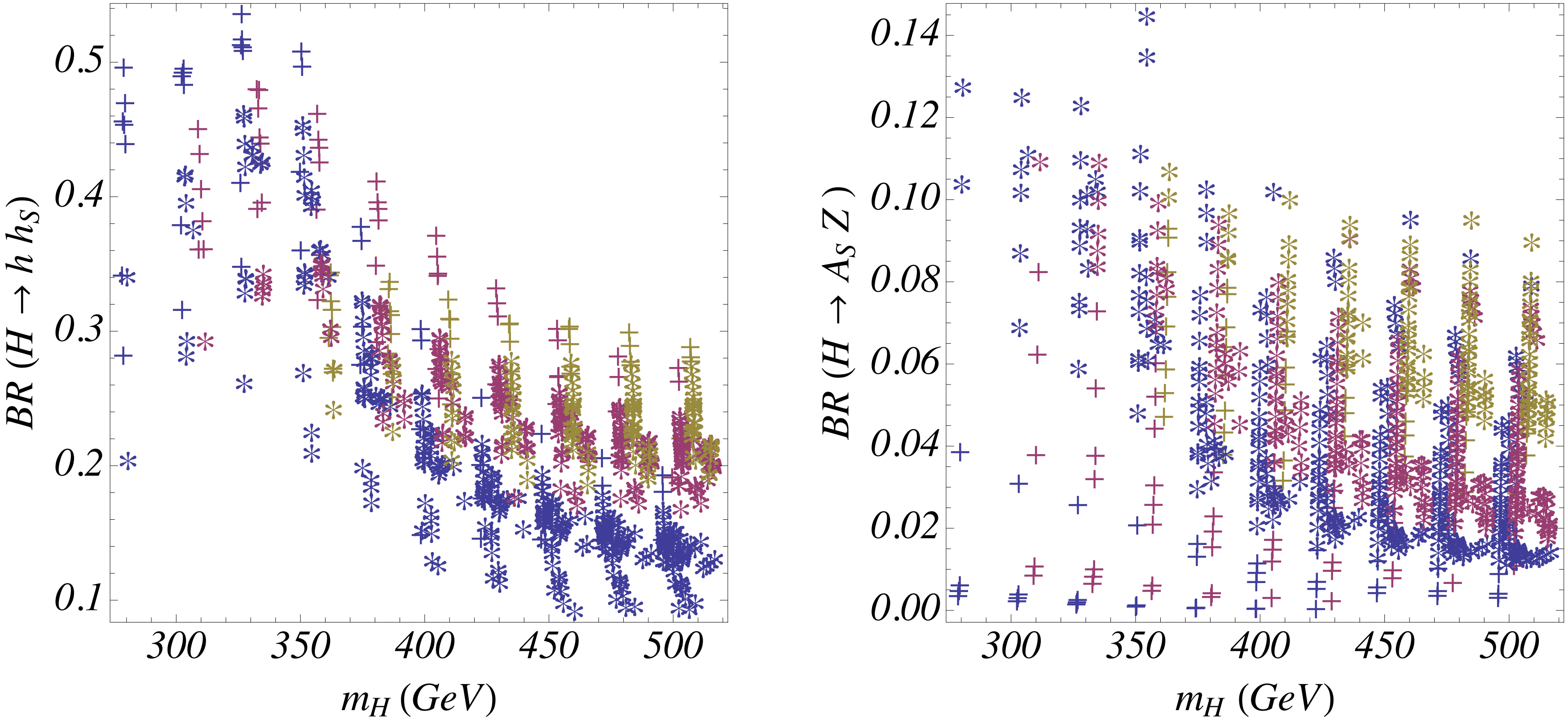
Anti-correlation between
singlet-like CP-even and odd masses

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

tanβ = 2 (blue), 2.5 (red) 3 (yellow)

Crosses : H1 singlet like
Asterix : H2 singlet like

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

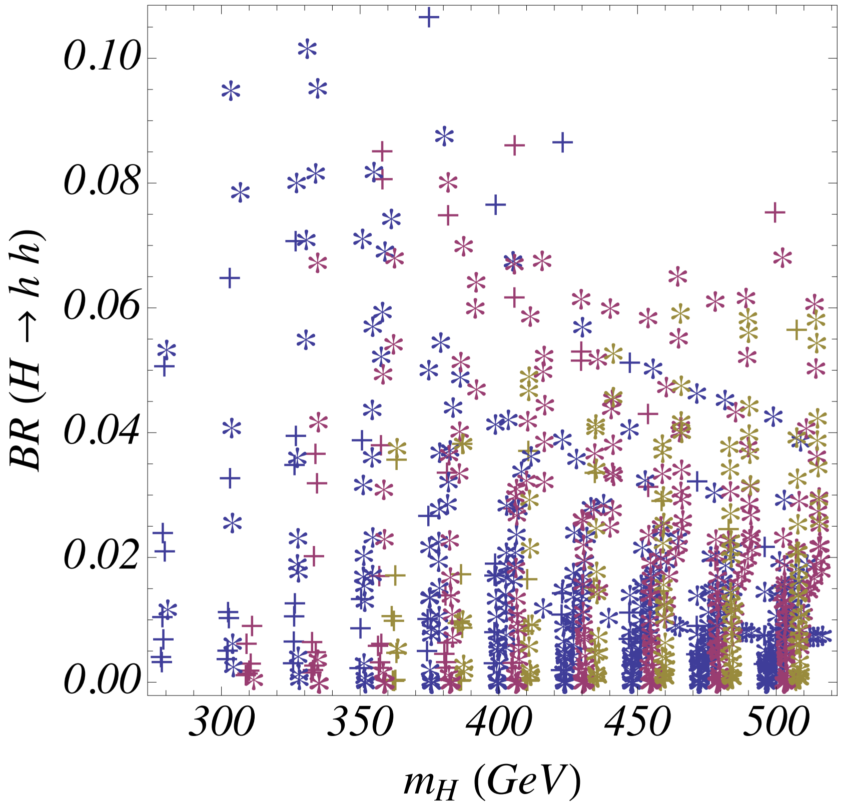


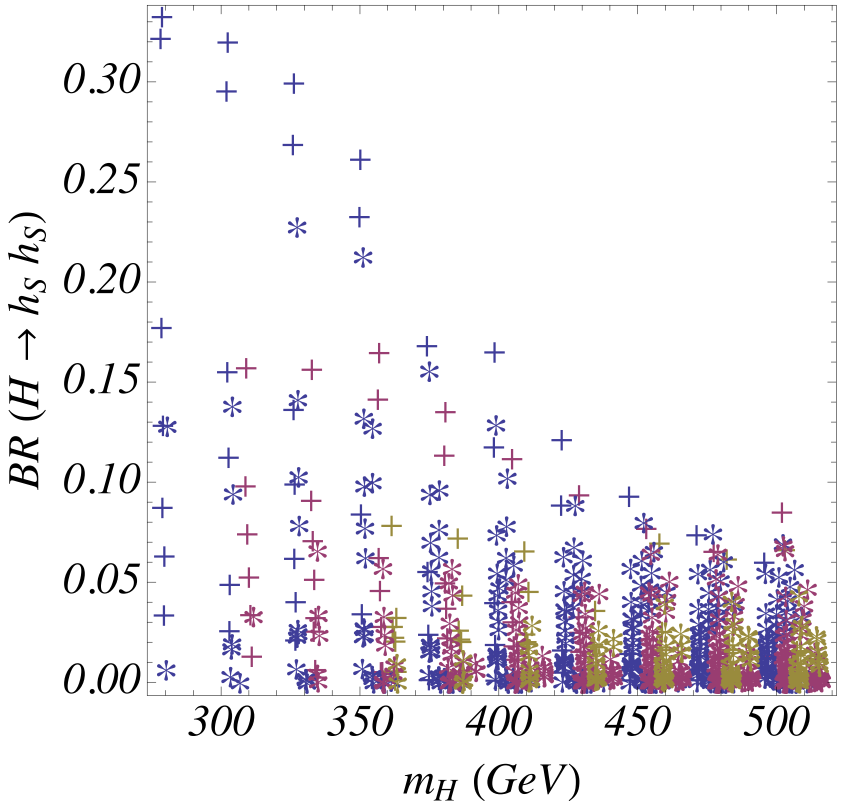
Decays into pairs of SM-like Higgs bosons suppressed by alignment

tanβ = 2 (blue), 2.5 (red) 3 (yellow)

Crosses : H1 singlet like
Asterix : H2 singlet like

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

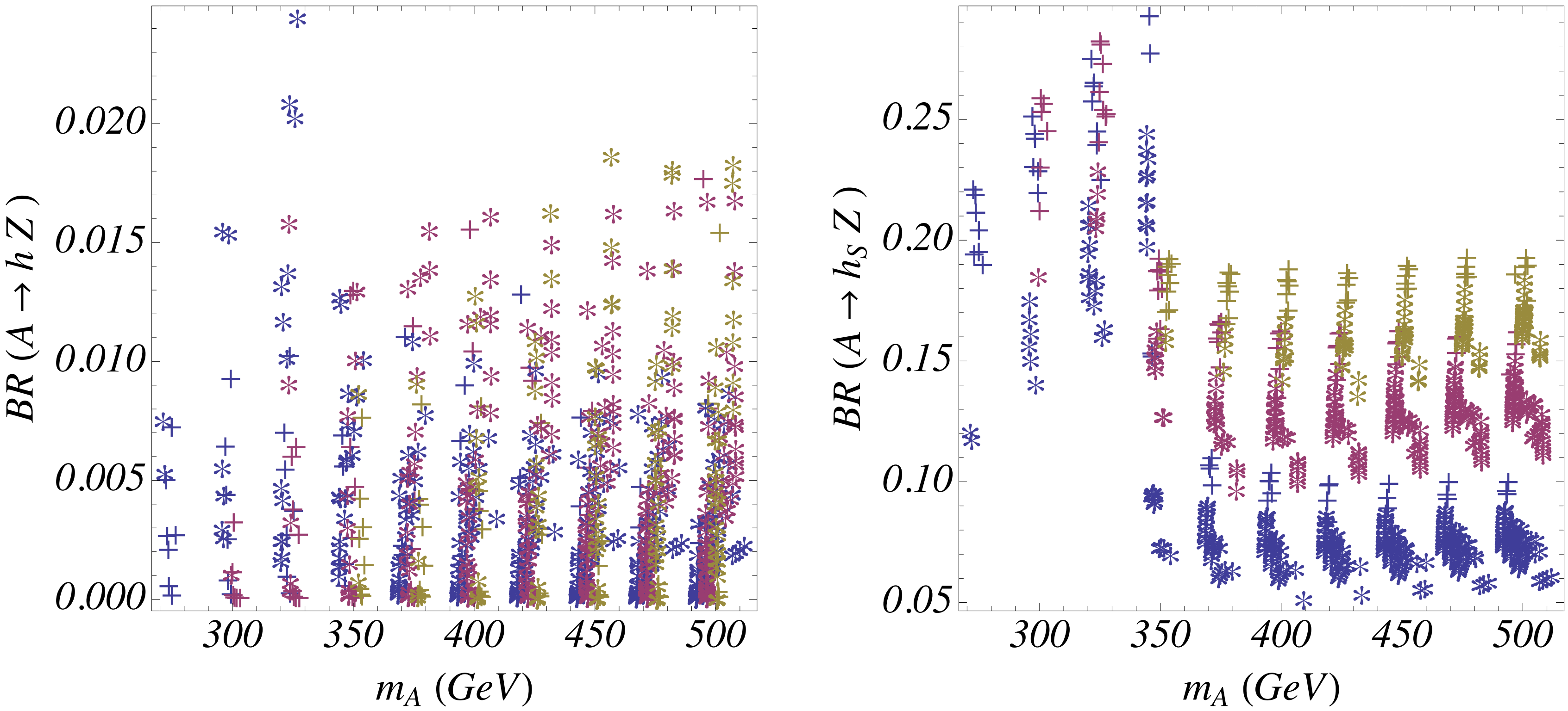




Heavy CP-odd Higgs Bosons have similar decay modes

tanβ = 2 (blue), 2.5 (red) 3 (yellow)

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

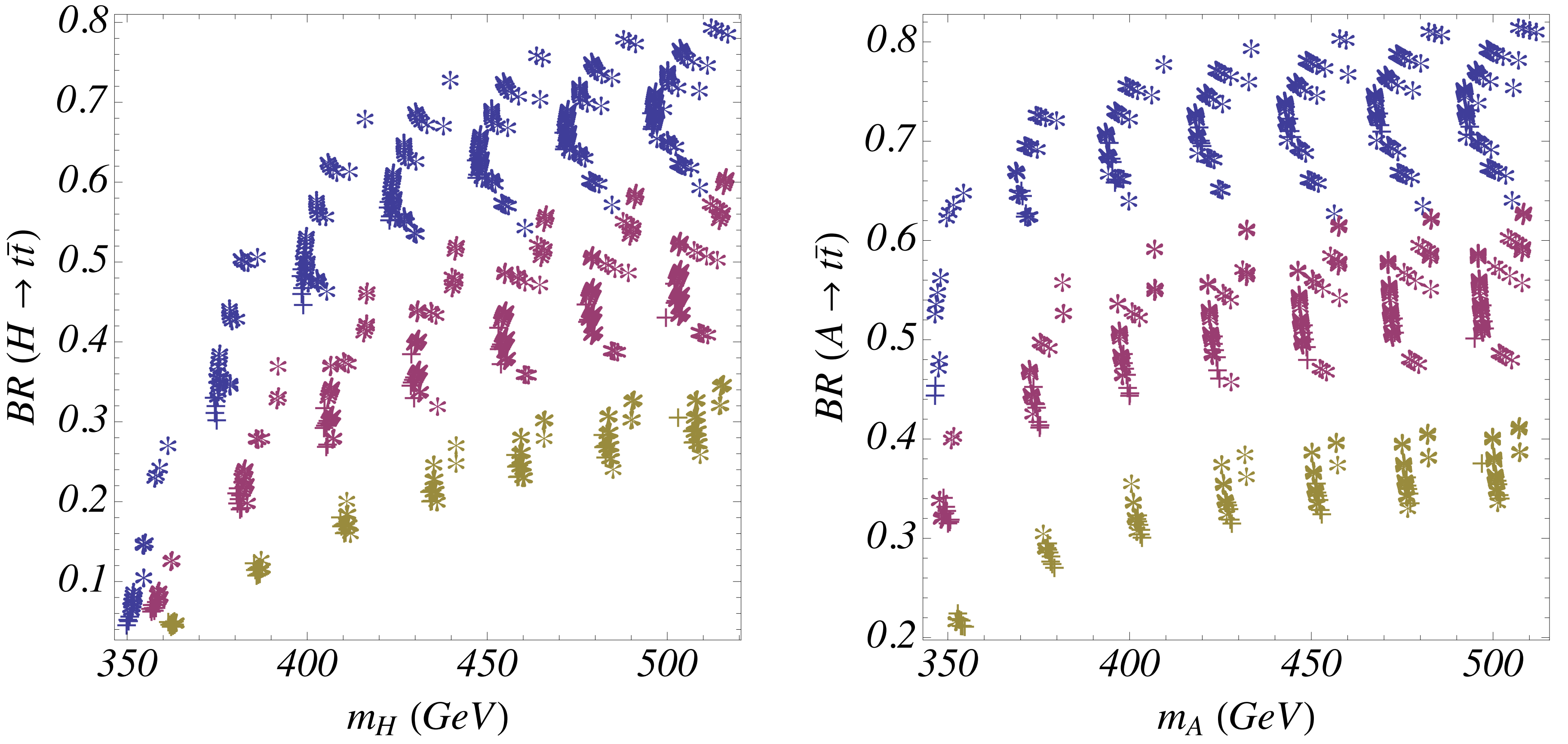


Significant decay of heavy CP-odd
Higgs bosons into singlet like states plus Z

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

tanβ = 2 (blue), 2.5 (red) 3 (yellow)

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



Conclusions

- Current Higgs precision data leaves room for somewhat large deviations of the SM-like Higgs couplings with respect to the SM values. In particular, the couplings to bottom and top quarks are still uncertain, and may be smaller/ larger than the SM values, respectively

- Such deviations may be accommodated in type II 2HDM. Top coupling deviations demand a modification of the gluon fusion process by new light colored particles like the stop.

- Difficult to implement these ideas in the MSSM, but simpler to do it in the NMSSM, for either large values of lambdas or light singlets (that could be consistent with the LEP2 excess). Light MSSM-like Higgs always required.

- Eventually, convergence of all couplings to the SM values will call for decoupling or alignment. In the alignment limit additional Higgs bosons may be light.

- Alignment in the MSSM requires large trilinear couplings and heavy stop quarks. Alignment in the NMSSM may be obtained more naturally, for values of lambda consistent with perturbation theory.

- Experimental prospect to test these scenarios were defined in this talk.