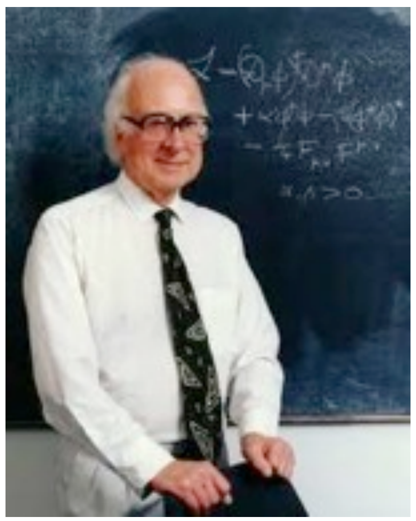
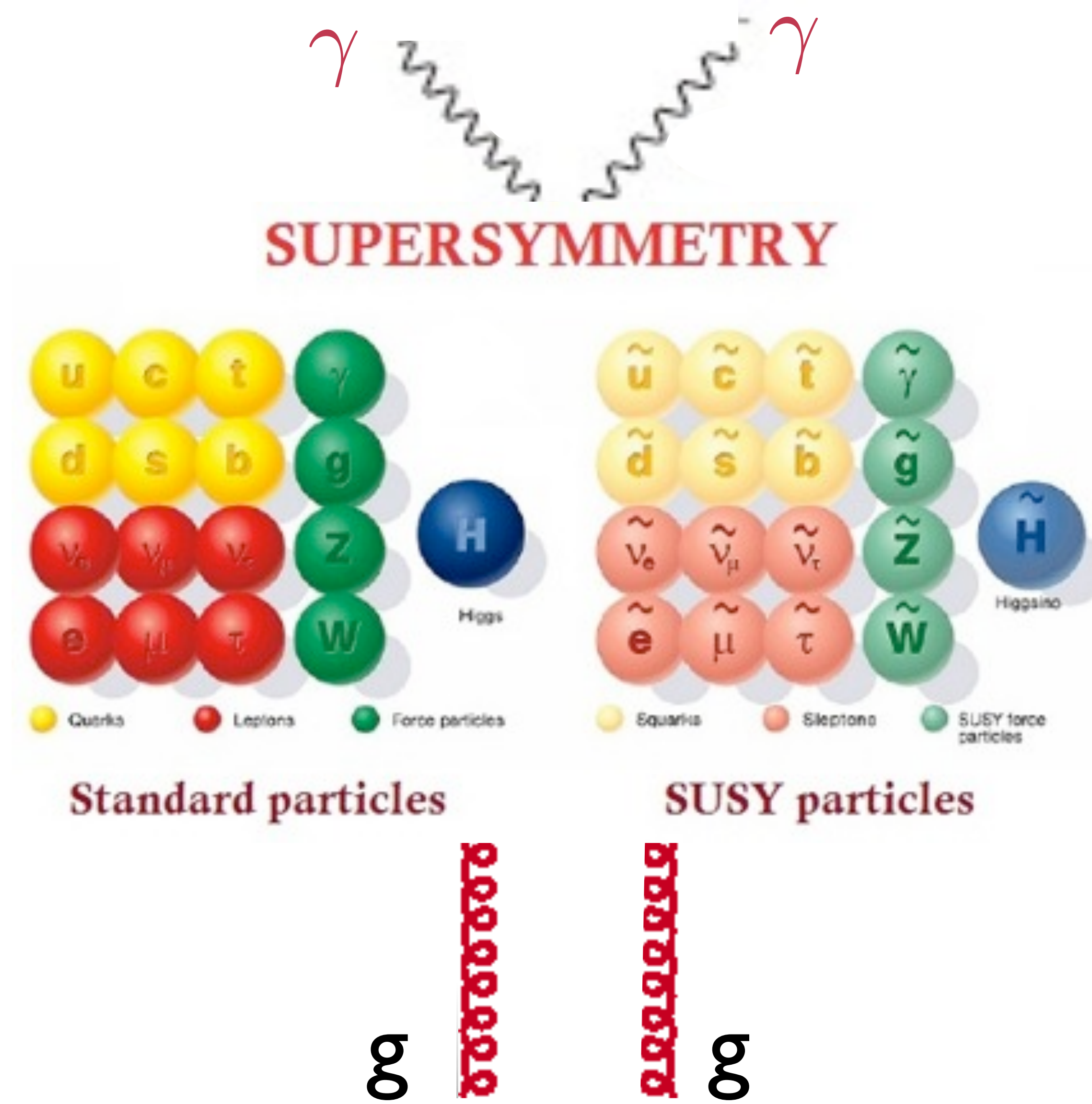
Modified Higgs Couplings in the MSSM

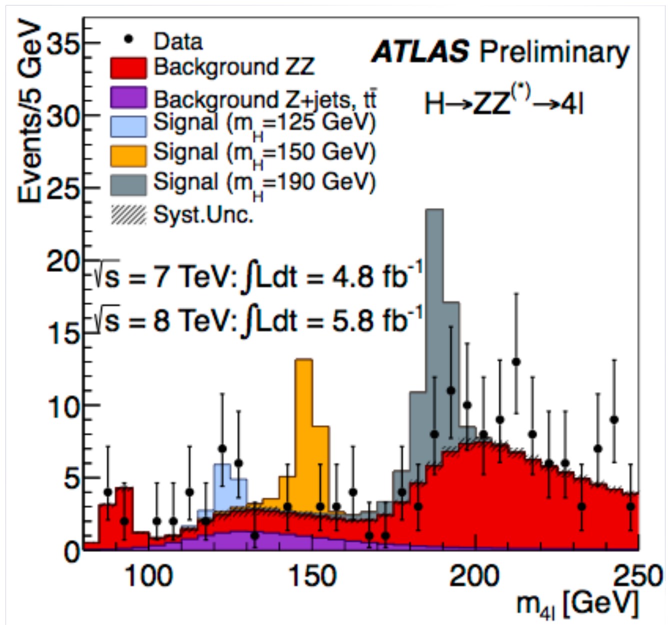


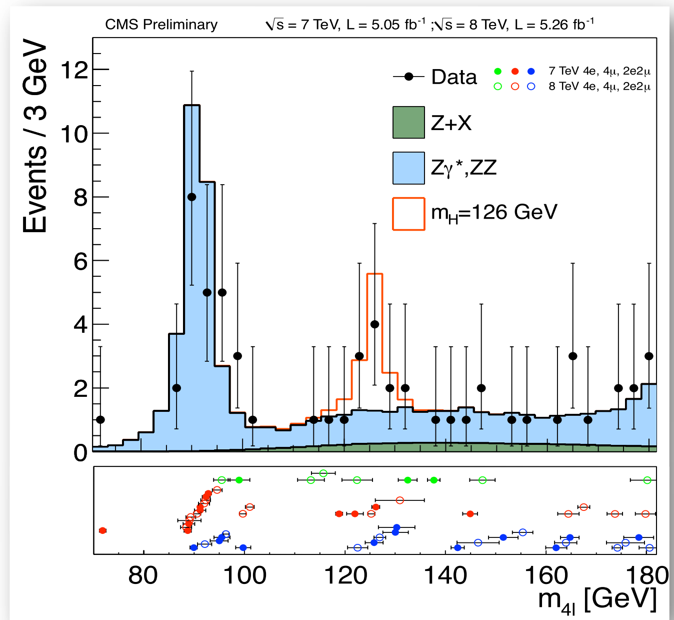


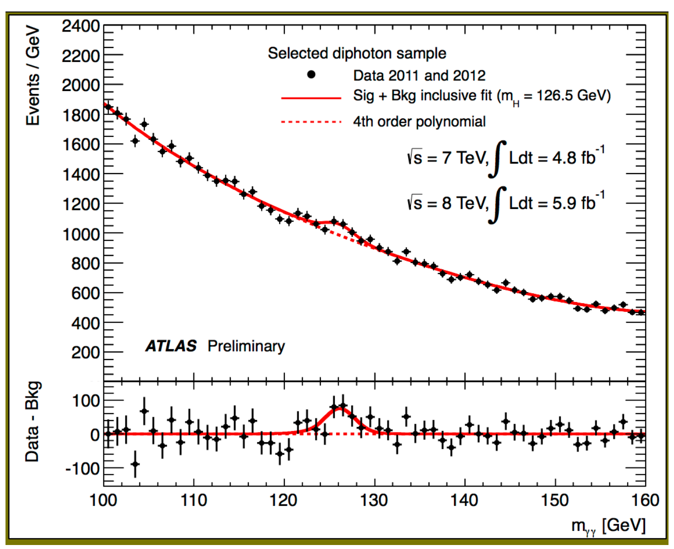
Carlos E.M. Wagner
KICP and EFI, Univ. of Chicago
HEP Division Argonne National Lab

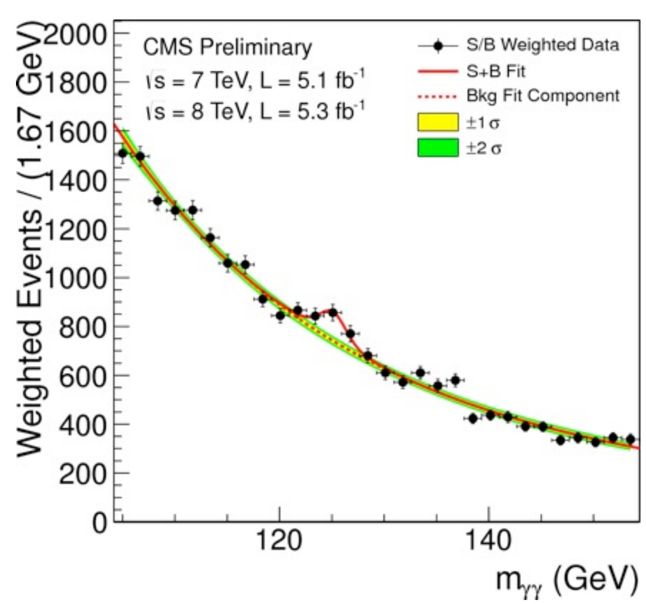
KITP LHC Conference, Santa Barbara, 07.09.13

A Standard Model-like Higgs particle has been discovered by the ATLAS and CMS experiments at CERN









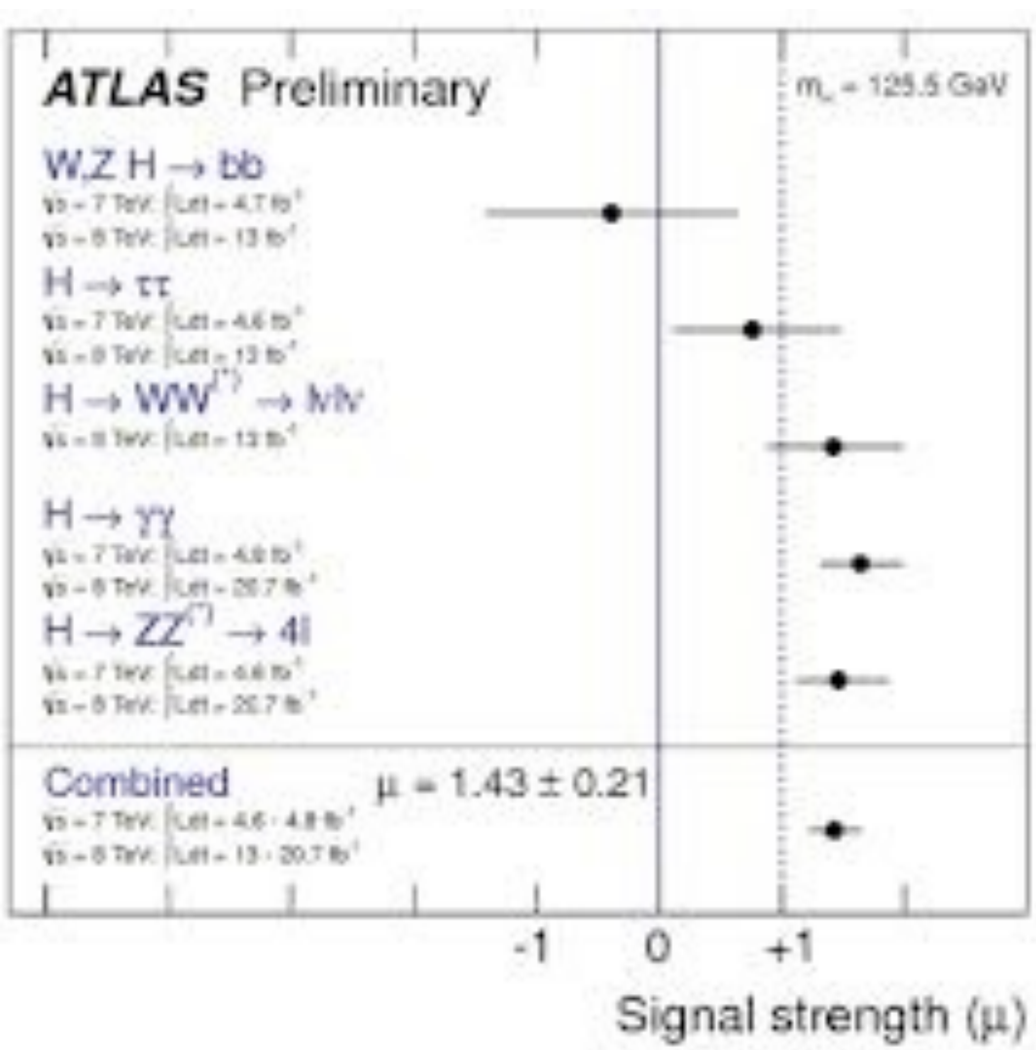
We see evidence
of this particle
in multiple channels.

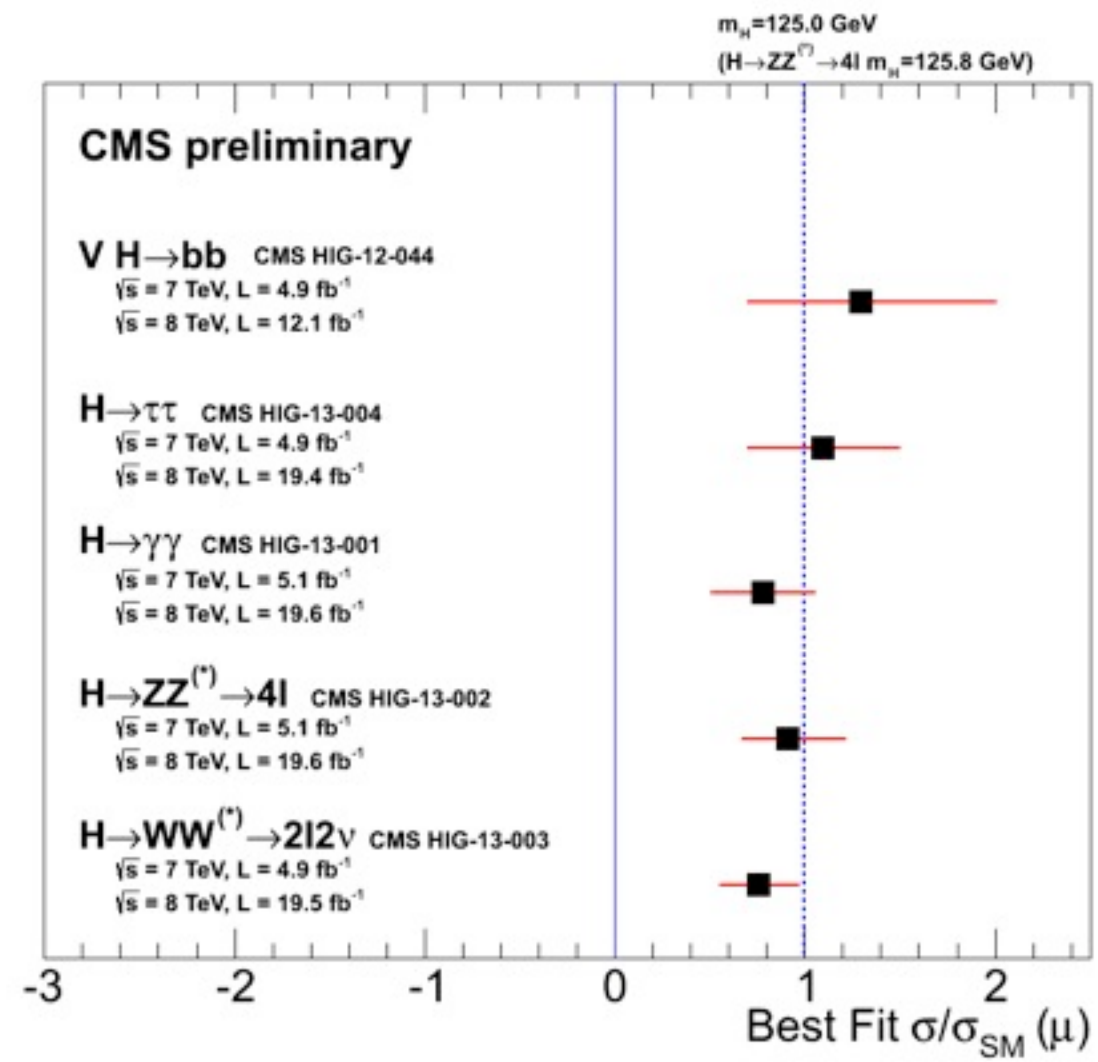
We can reconstruct
its mass and we know
that is about 125 GeV.

The rates are consistent
with those expected
in the Standard Model.

But we cannot determine the Higgs couplings very accurately

Large Variations of Higgs couplings are still possible



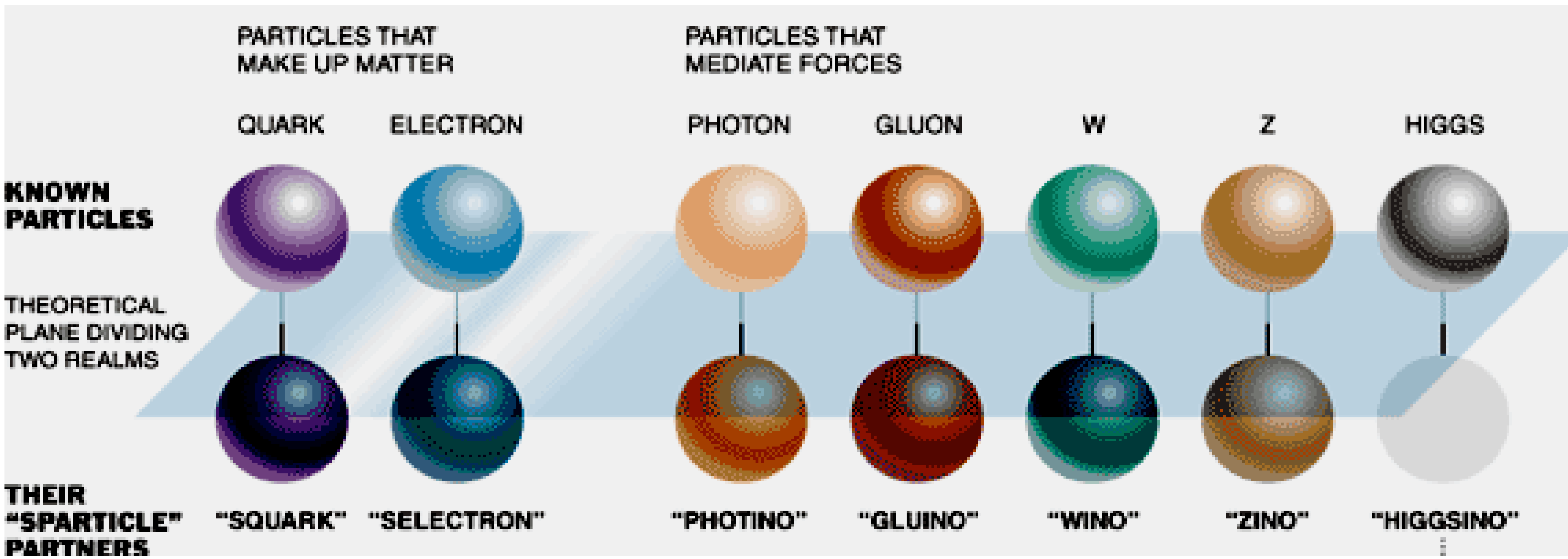


As these measurements become more precise, they constrain possible extensions of the SM, and they could lead to the evidence of new physics.

It is worth studying what kind of effects one could obtain in well motivated extensions of the Standard Model, like SUSY.

Supersymmetry

fermions bosons



Photino, Zino and Neutral Higgsino: Neutralinos

Charged Wino, charged Higgsino: Charginos

Particles and Sparticles share the same couplings to the Higgs. Two superpartners of the two quarks (one for each chirality) couple strongly to the Higgs with a Yukawa coupling of order one (same as the top-quark Yukawa coupling)

$$\text{Two Higgs doublets necessary} \rightarrow \tan\beta = \frac{v_2}{v_1}$$

Why Supersymmetry ?

- Helps to stabilize the weak scale—Planck scale hierarchy: $\delta\, m_H^2 \approx (-1)^{2 S_i} \frac{n_i\, g_i^2}{16\pi^2} \Lambda^2$
- Supersymmetry algebra contains the generator of space-time translations.
  Possible ingredient of theory of quantum gravity.
- Minimal supersymmetric extension of the SM :
  Leads to Unification of gauge couplings.
- Starting from positive masses at high energies, electroweak symmetry breaking is induced radiatively.
- If discrete symmetry, $P = (-1)^{3B+L+2S}$ is imposed, lightest SUSY particle neutral and stable: Excellent candidate for cold Dark Matter.

Minimal Supersymmetric Standard Model

SM particle	SUSY partner	G_{SM}
(S = 1/2)	(S = 0)	
$Q = (t, b)_L$	$(\tilde{t}, \tilde{b})_L$	(3,2,1/6)
$L = (\nu, l)_L$	$(\tilde{\nu}, \tilde{l})_L$	(1,2,-1/2)
$U = \left(t^C\right)_L$	$\tilde{t}^*_R$	($\bar{3}$,1,-2/3)
$D = \left(b^C\right)_L$	$\tilde{b}^*_R$	($\bar{3}$,1,1/3)
$E = \left(l^C\right)_L$	$\tilde{l}^*_R$	(1,1,1)
(S = 1)	(S = 1/2)	
B_μ	$\tilde{B}$	(1,1,0)
W_μ	$\tilde{W}$	(1,3,0)
g_μ	$\tilde{g}$	(8,1,0)

In supersymmetric theories, there is one Higgs doublet that behaves like the SM one.

$$H_{SM} = H_d \cos\beta + H_u \sin\beta, \qquad \tan\beta = v_u/v_d$$

The orthogonal combination may be parametrized as

$$H = \begin{pmatrix} H + iA \\ H^{\pm} \end{pmatrix}$$

where H, $H^{\pm}$ and A represent physical CP-even, charged and CP-odd scalars (non standard Higgs).

Strictly speaking, the CP-even Higgs modes mix and none behave exactly as the SM one.

$$h = -\sin\alpha \; \mathrm{Re}(H_d^0) + \cos\alpha \; \mathrm{Re}(H_u^0)$$

In the so-called decoupling limit, in which the non-standard Higgs bosons are heavy, $\sin\alpha = -\cos\beta$ and one recovers the SM as an effective theory.

Lightest SM-like Higgs mass strongly depends on:

* CP-odd Higgs mass m_A
* tan beta
* the top quark mass
* the stop masses and mixing

$$M^2_{\tilde{t}} = \begin{pmatrix} m_Q^2 + m_t^2 + D_L & m_t X_t \\ m_t X_t & m_U^2 + m_t^2 + D_R \end{pmatrix}$$

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

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

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

$$t = \log(M_{SUSY}^2 / m_t^2) \qquad \tilde{X}_t = \frac{2X_t^2}{M_{SUSY}^2}\left(1 - \frac{X_t^2}{12 M_{SUSY}^2}\right)$$

$X_t = A_t - \mu / \tan\beta \rightarrow$ LR stop mixing

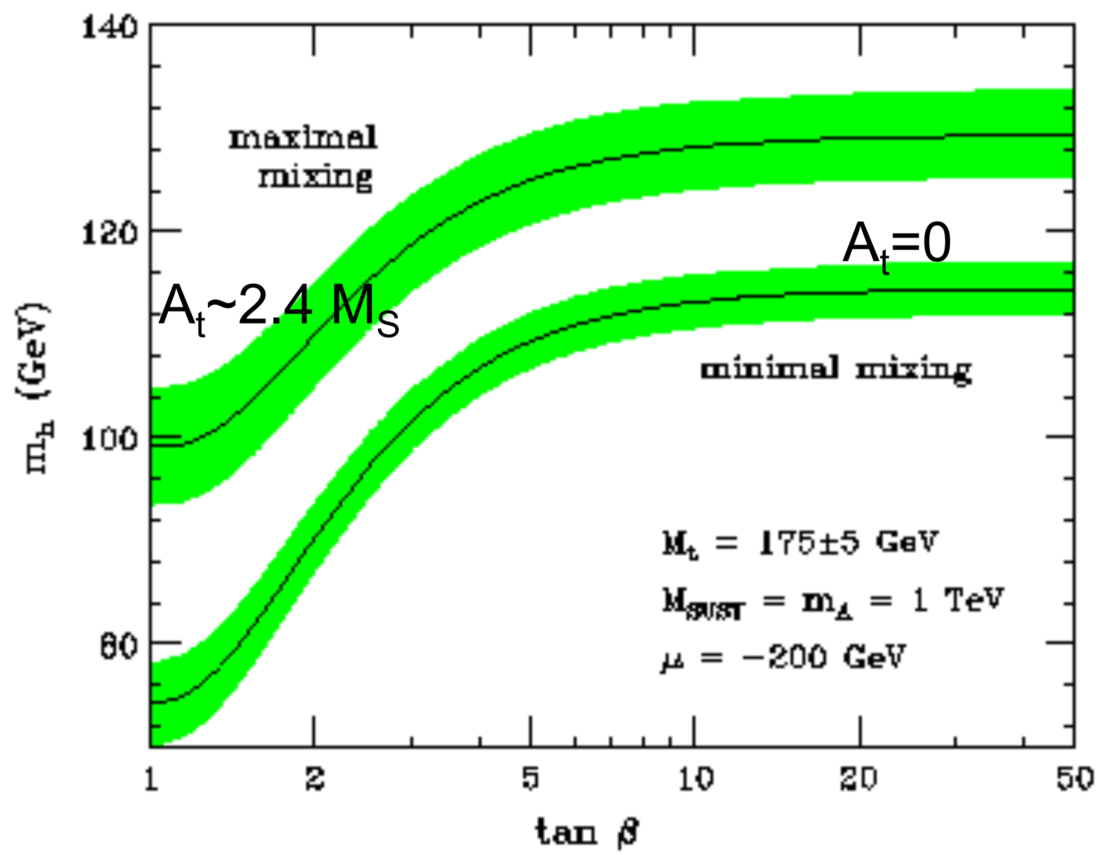
M.Carena, J.R. Espinosa, M. Quiros, C.W.'95
M. Carena, M. Quiros, C.W.'95

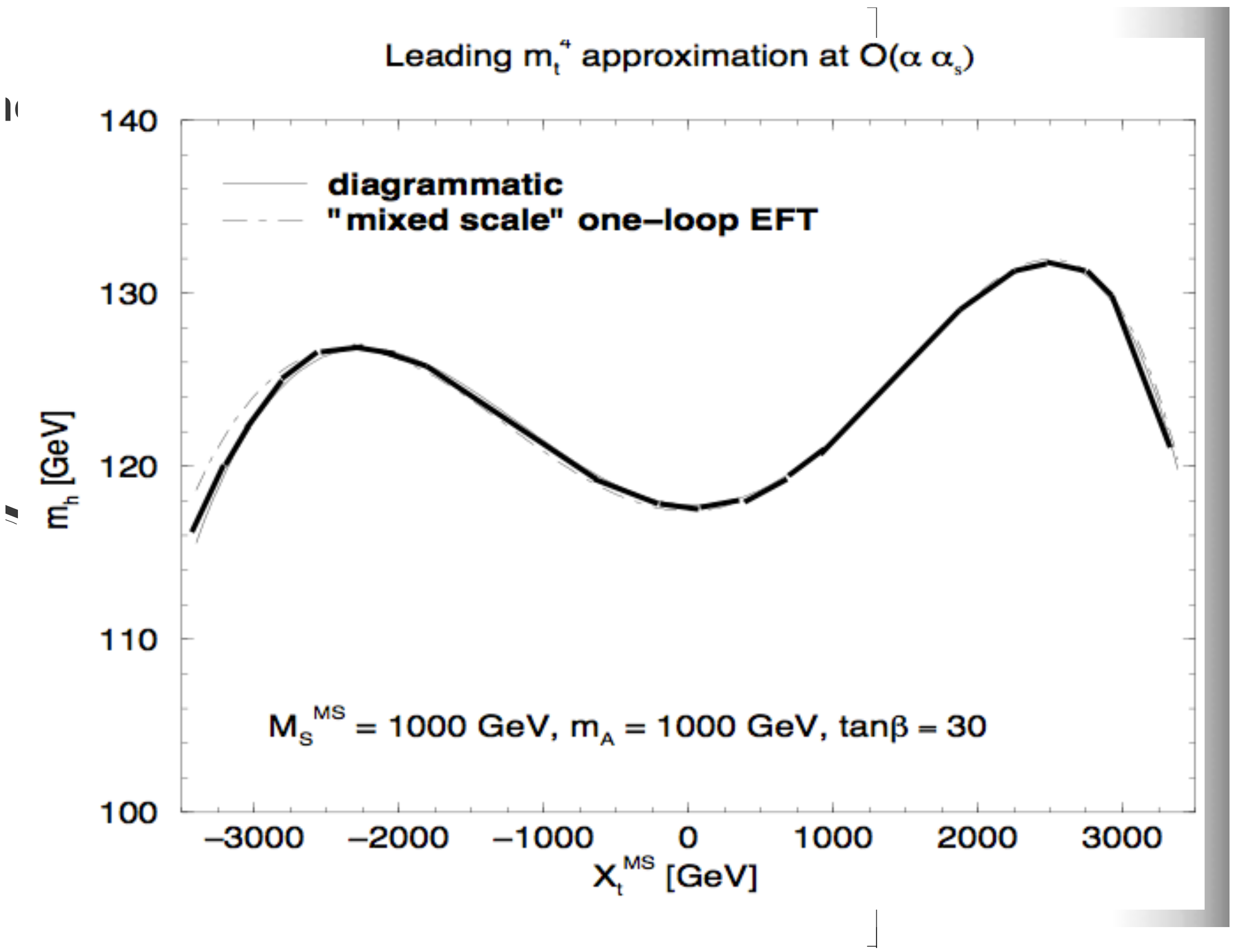
Analytic expression valid for $M_{SUSY} \sim m_Q \sim m_U$

Standard Model-like Higgs Mass

Long list of two-loop computations: Carena, Degrassi, Ellis, Espinosa, Haber, Harlander, Heinemeyer, Hempfling, Hoang, Hollik, Hahn, Martin, Pilaftsis, Quiros, Ridolfi, Rzehak, Slavich, C.W., Weiglein, Zhang, Zwirner

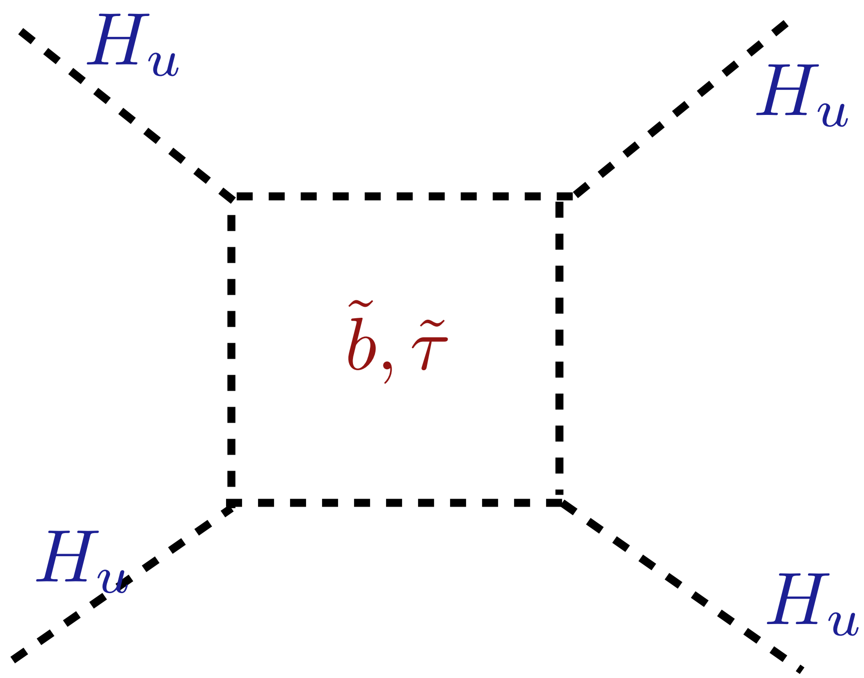
Carena, Haber, Heinemeyer, Hollik, Weiglein, C.W.'00





$$X_t = A_t - \mu/\tan\beta, \qquad X_t = 0 : \text{ No mixing;} \qquad X_t = \sqrt{6} M_S : \text{ Max. Mixing}$$

Large $\tan\beta$ corrections



Corrections from the sbottom sector :
Negative contributions to the Higgs mass

$$\Delta m_h^2 \simeq -\frac{h_b^4 v^2}{16\pi^2}\frac{\mu^4}{M_{\rm SUSY}^4}$$

$$h_b \simeq \frac{m_b}{v\cos\beta(1+\tan\beta\Delta h_b)}$$

Similar negative corrections, often ignored,
appear from the stau sector

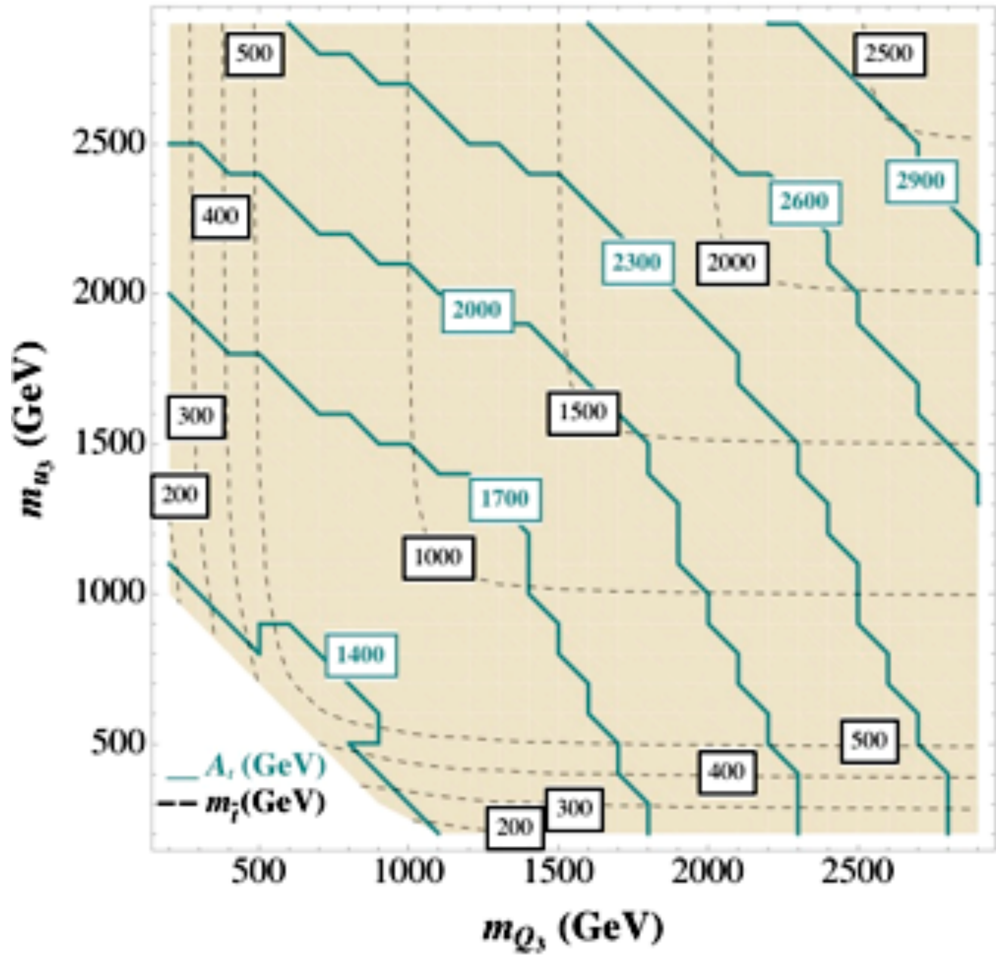
$$\Delta m_h^2 \simeq -\frac{h_\tau^4 v^2}{48\pi^2}\frac{\mu^4}{M_{\tilde{\tau}}^4}\,,$$

$$h_\tau \simeq \frac{m_\tau}{v\cos\beta(1+\tan\beta\Delta h_\tau)}$$

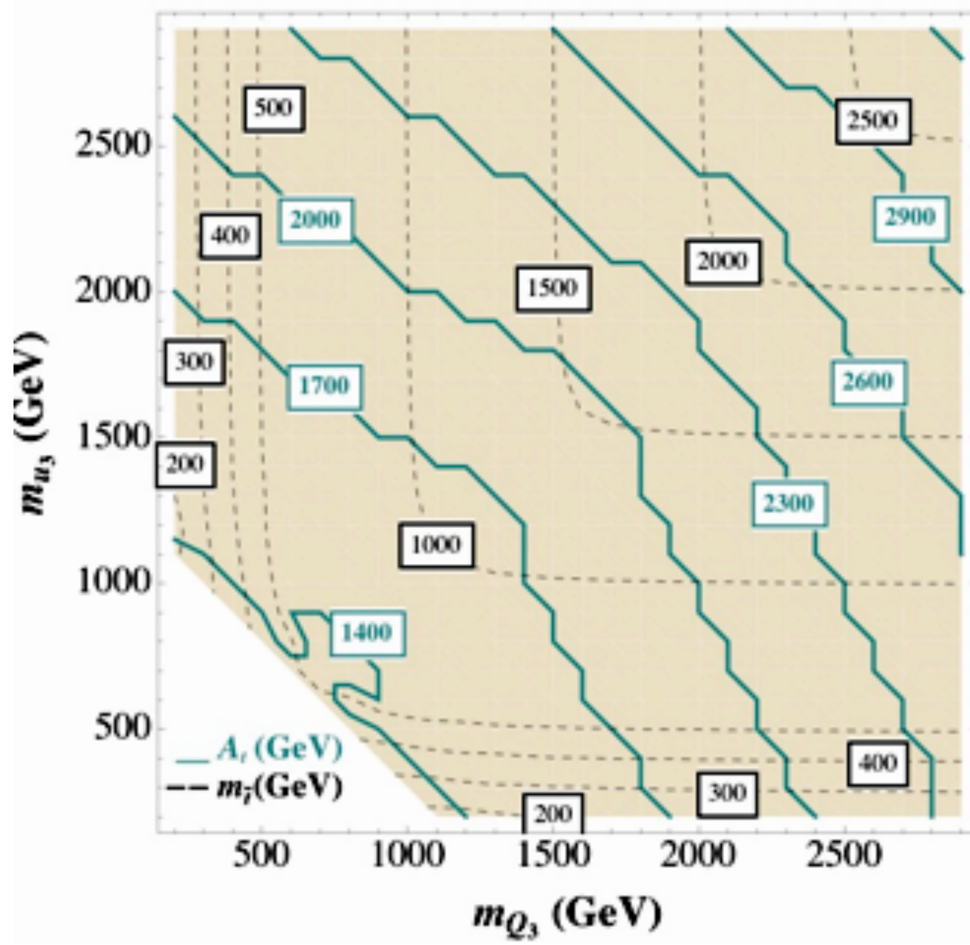
Soft supersymmetry Breaking Parameters

M. Carena, S. Gori, N. Shah, C. Wagner, arXiv:1112.336, +L.T.Wang, arXiv:1205.5842

A_t and $m_{\tilde{t}}$ for 124 GeV < m_h < 126 GeV and Tan $\beta = 10$



A_t and $m_{\tilde{t}}$ for 124 GeV < m_h < 126 GeV and Tan $\beta = 60$



Large stop sector mixing
A_t > 1 TeV

No lower bound on the lightest stop
One stop can be light and the other heavy
or
in the case of similar stop soft masses.
both stops can be below 1TeV

Intermediate values of tan beta lead to the largest values of m_h for the same values of stop mass parameters

At large tan beta, light staus/sbottoms can decrease mh by several GeV's via Higgs mixing effects and compensate tan beta enhancement

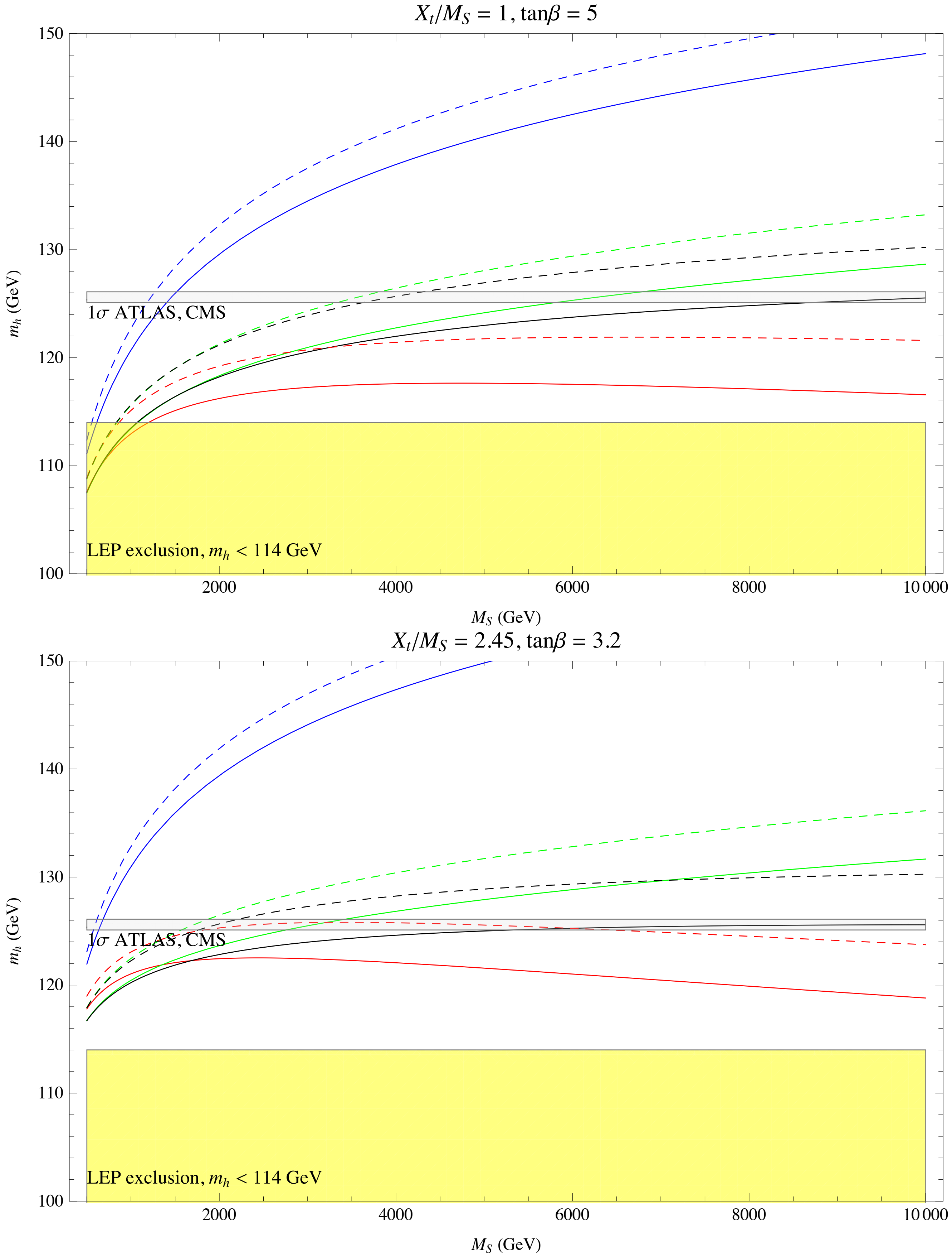
Light stop coupling to the Higgs

$$m_Q \gg m_U; \qquad m_{\tilde{t}_1}^2 \simeq m_U^2 + m_t^2 \left(1 - \frac{X_t^2}{m_Q^2}\right)$$

Lightest stop coupling to the Higgs approximately vanishes for $X_t \simeq m_Q$

Higgs mass pushes us in that direction

Modification of the gluon fusion rate milder due to this reason.



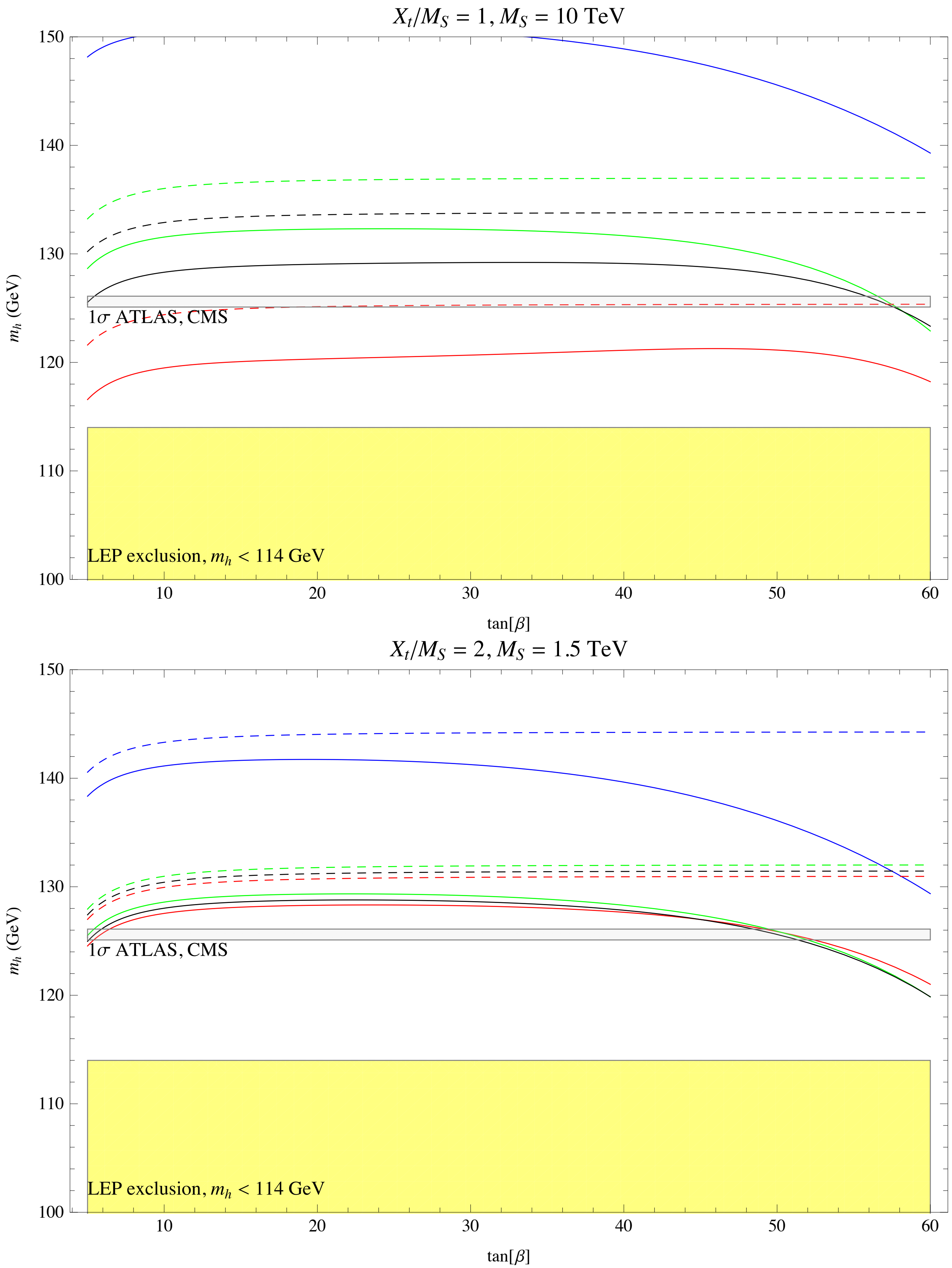
Impact of higher loops

Recalculation of RG prediction including up to 4 loops in RG expansion

Agreement with S. Martin'07 and Espinosa and Zhang'00, Carena, Espinosa, Quiros,C.W.'00, Carena, Haber, Heinemeyer, Weiglein, Hollik and C.W.'00, in corresponding limits.

Two loops results agree w FeynHiggs and CPsuperH results

G. Lee, C.W'13
(see also Feng et al.'13)



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Higgs Boson Properties

The gauge boson masses still proceed from the kinetic terms

$$\mathcal{L} = (\mathcal{D}^\mu H_u)^\dagger \mathcal{D}_\mu H_u + (\mathcal{D}^\mu H_d)^\dagger \mathcal{D}_\mu H_d + \rightarrow g^2 (H_u^\dagger W_\mu W^\mu H_u + H_d^\dagger W_\mu W^\mu H_d)$$

Therefore, the order parameter is $v = \sqrt{v_u^2 + v_d^2}$.

The fermion mass terms proceed from the Yukawa interactions

$$\mathcal{L} = -h_d \bar{D}_L H_d d_R - h_u \bar{U}_L H_u u_R + h.c.$$

Therefore, $m_d = h_d \, v \cos\beta$, and

$$\mathcal{L} \rightarrow -\frac{m_d}{v}(h + \tan\beta H)$$

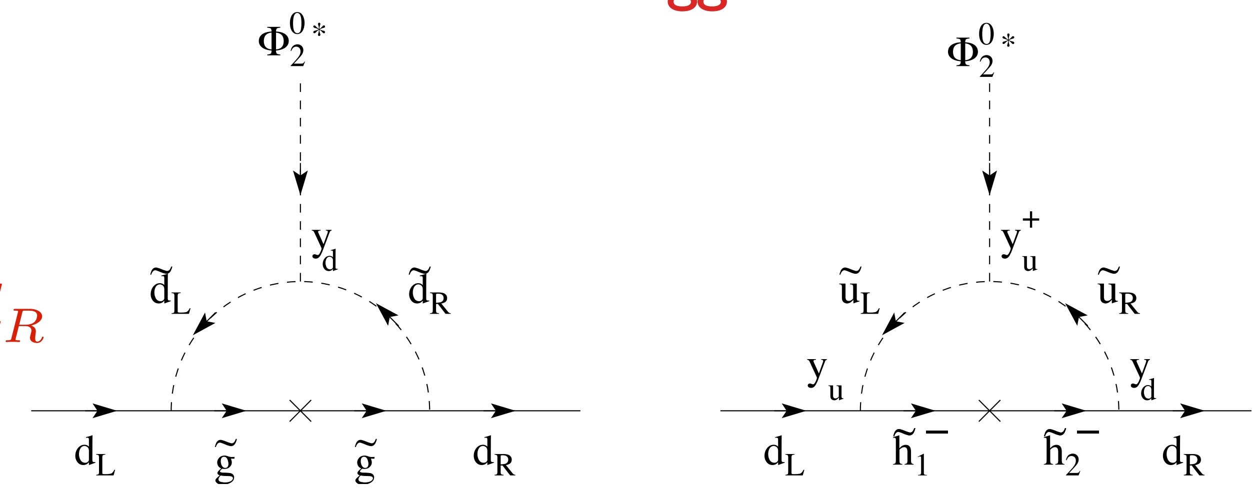
and the down sector has $\tan\beta$ enhanced couplings to the non-standard Higgs bosons.

Hempfling '93
Hall, Rattazzi, Sarid'93
Carena, Olechowski, Pokorski, C.W.'93

Radiative Corrections to Flavor Conserving Higgs Couplings

- Couplings of down and up quark fermions to both Higgs fields arise after radiative corrections.

$$\mathcal{L} = \bar{d}_L (h_d H_1^0 + \Delta h_d H_2^0) d_R$$



- The radiatively induced coupling depends on ratios of supersymmetry breaking parameters

$$m_b = h_b v_1 \left(1 + \frac{\Delta h_b}{h_b} \tan\beta\right)$$

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

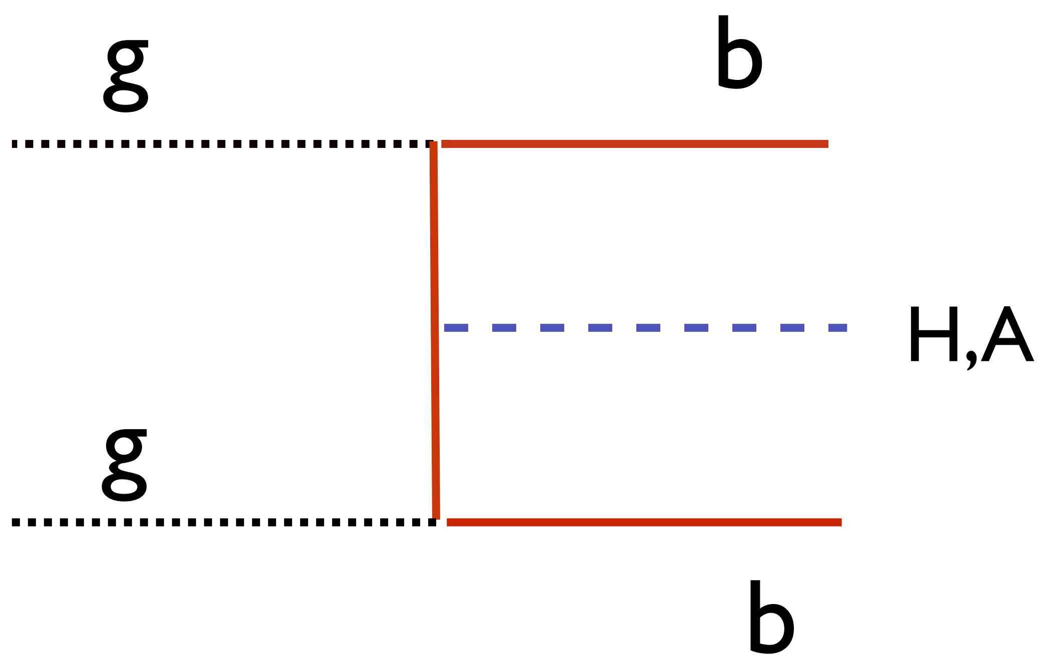
$$\frac{\Delta_b}{\tan\beta} = \frac{\Delta h_b}{h_b} \simeq \frac{2\alpha_s}{3\pi} \frac{\mu M_{\tilde{g}}}{\max(m_{\tilde{b}_i}^2, M_{\tilde{g}}^2)} + \frac{h_t^2}{16\pi^2} \frac{\mu A_t}{\max(m_{\tilde{t}_i}^2, \mu^2)}$$

$$X_t = A_t - \mu/\tan\beta \simeq A_t \qquad \Delta_b = (E_g + E_t h_t^2) \tan\beta$$

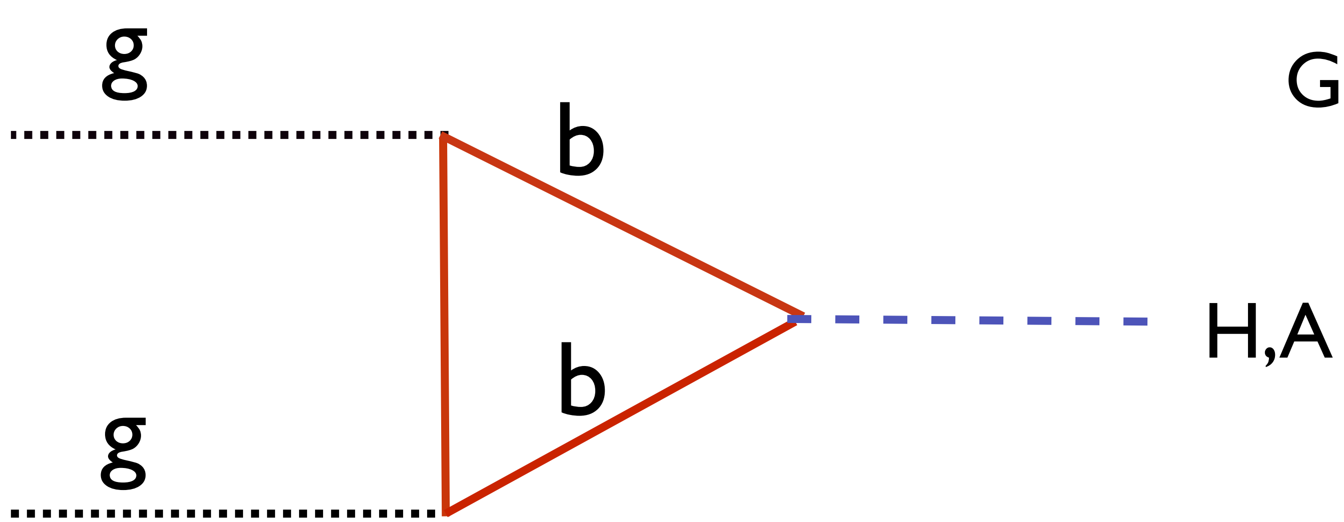
Resummation : Carena, Garcia, Nierste, C.W.'00

Non-Standard Higgs Production

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



Associated Production



Gluon Fusion

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

Searches for non-standard Higgs bosons

M. Carena, S. Heinemeyer, G.Weiglein,C.W, EJPC'06

- Searches at the Tevatron and the LHC are induced by production channels associated with the large bottom Yukawa coupling.

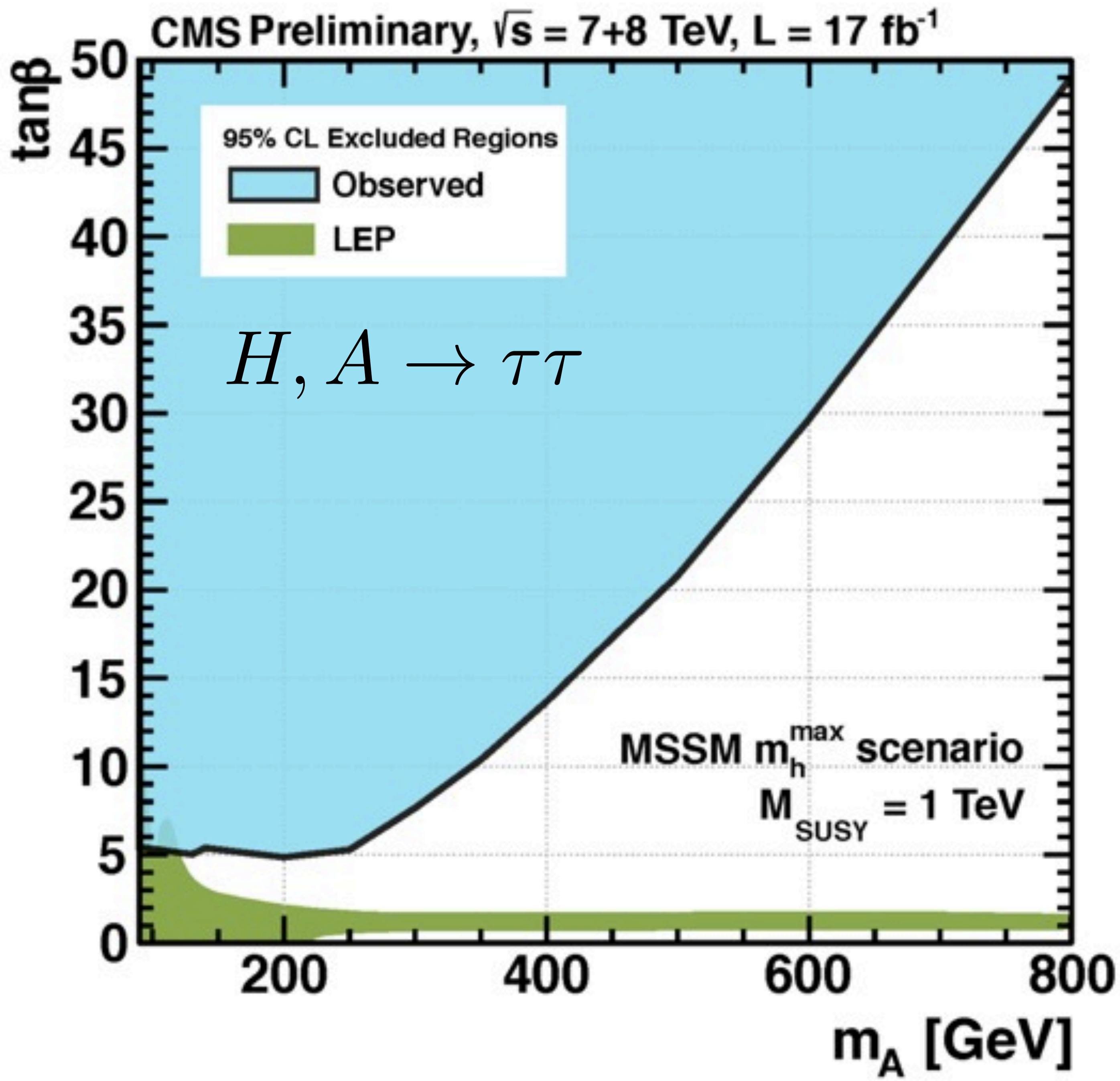
$$\sigma(b\bar{b}A) \times BR(A \to b\bar{b}) \simeq \sigma(b\bar{b}A)_{\rm SM} \frac{\tan^2\beta}{(1+\Delta_b)^2} \times \frac{9}{(1+\Delta_b)^2 + 9}$$

$$\sigma(b\bar{b}, gg \to A) \times BR(A \to \tau\tau) \simeq \sigma(b\bar{b}, gg \to A)_{\rm SM} \frac{\tan^2\beta}{(1+\Delta_b)^2 + 9}$$

- There may be a strong dependence on the parameters in the bb search channel, which is strongly reduced in the tau tau mode.

Validity of this approximation confirmed by NLO computation by D. North and M. Spira, arXiv:0808.0087
Further work by Mhulleitner, Rzehak and Spira, 0812.3815

In the MSSM, non-standard Higgs may be produced via its large couplings to the bottom quark, and searched for in its decays into bottom quarks and tau leptons



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

See Carena, Haber, Logan, Mrenna '01

Couplings of SM Higgs to Fermions and Gauge Bosons

Down-type Fermions

$$g_{hbb,h\tau\tau} = -h_{b,\tau}\sin\alpha + \Delta h_{b,\tau}\cos\alpha$$

$$g_{hbb,h\tau\tau} = -\frac{m_{b,\tau}\sin\alpha}{v\cos\beta(1+\Delta_{b,\tau})}\left(1 - \frac{\Delta_{b,\tau}}{\tan\beta\tan\alpha}\right)$$

Up-type Fermions

$$g_{htt} = \frac{m_t\cos\alpha}{v\sin\beta}$$

Gauge Bosons

For moderate values of m_A and $\tan\beta$,
the top and W, Z couplings go fast to SM values

$$g_{hWW,hZZ} \simeq \sin(\alpha-\beta)$$

$$\frac{\cos\alpha}{\sin\beta} \simeq \sin(\beta-\alpha)$$

$$\cos(\alpha-\beta) \simeq \frac{M_h^2}{M_A^2\tan\beta}$$

The BR can still be affected by variations of the bottom
and tau couplings.

General two Higgs Doublet Models

H. Haber and J. Gunion'03

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

In the MSSM, at tree-level, only the first four couplings are non-zero and are governed by D-terms in the scalar potential. At loop-level, all of them become non-zero via the trilinear and quartic interactions with third generation sfermions.

Haber, Hempfling'93

$$\lambda_1 = \lambda_2 = \frac{1}{4}(g_1^2 + g_2^2) = \frac{m_Z^2}{v^2} ,$$
$$\lambda_3 = \frac{1}{4}(g_1^2 - g_2^2) = -\frac{m_Z^2}{v^2} + \frac{1}{2}g_2^2 ,$$
$$\lambda_4 = -\frac{1}{2}g_2^2 ,$$

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

MSSM

$$v^2 L_{11} = M_Z^2 \cos^2\beta + \text{Loop11}$$
$$v^2 L_{12} = -M_Z^2 \cos\beta \sin\beta + \text{Loop12}$$
$$v^2 L_{22} = M_Z^2 \sin^2\beta + \text{Loop22}$$

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

The mixing of the two CP-even Higgs bosons may be determined from the matrix elements

$$s_\alpha = \frac{\mathcal{M}_{12}}{\sqrt{(\mathcal{M}_{12})^2 + (\mathcal{M}_{11} - m_h^2)^2}}$$

For $\tan\beta \geq 5$ and $m_A \geq 200$ GeV,

In the MSSM, if Loop12 and Loop11 are small

$$\sin\alpha = -\cos\beta \left(\frac{m_A^2 + M_Z^2}{m_A^2 - m_h^2}\right)$$

Deviations from SM behavior depend only on m_A and not on $\tan\beta$

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

Now, if we demand the recovery of the modulus of the SM Higgs couplings to down fermions, one obtains

$$-m_A^2 s_\beta^2 c_\beta + v^2 L_{12} s_\beta = \pm(m_A^2 s_\beta^2 c_\beta + c_\beta v^2 L_{11} - c_\beta m_h^2)$$

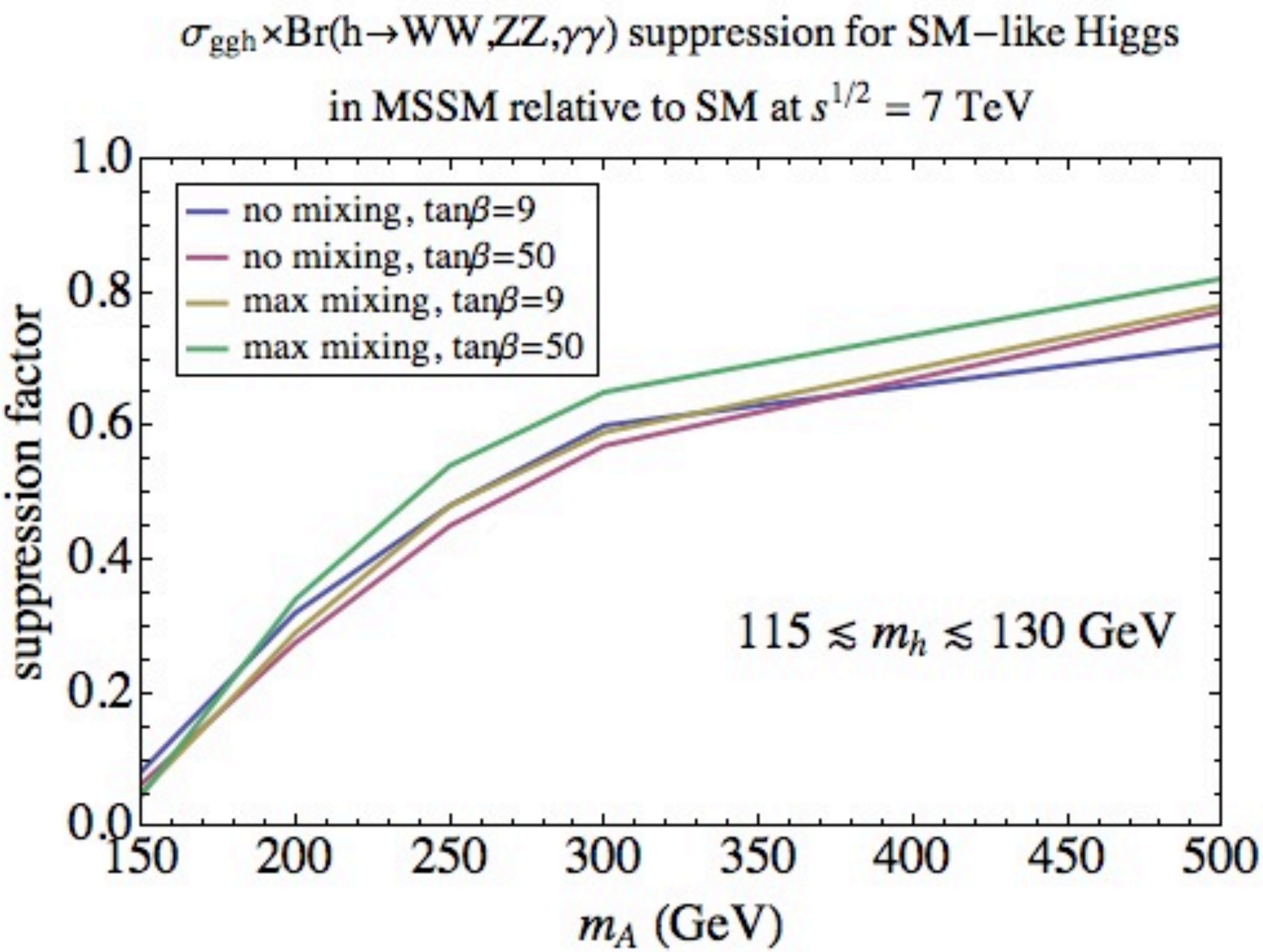
where the negative sign is the one leading to the SM sign, and it is independent of mA !

This is a general condition, valid in 2 Higgs doublet models.

See Haber and Gunion'03. for a similar demonstration in the physical basis (Z6 = 0).
Results in Mariano Quiros talk also can be seen as a particular case of this rule.

Suppression Factors at the LHC
If loop corrections are small

M. Carena, P. Draper, T. Liu, C. W. ,arXiv:1107.4354



MSSM condition to obtain SM coupling to fermions (true for moderate or large tanbeta)

$$\tan\beta = \frac{m_h^2 - M_Z^2 - \mathrm{Loop11}}{\mathrm{Loop12}}$$

Observe that if Loop12 is small, there is no solution for reasonable values of tanbeta.

Loop12 has to be sizable. Loop11 tends to be smaller than the radiative corrections to the Higgs mass and is negative in the region of parameters where Loop12 is positive.

Large or small deviations in the wedge depend on if Loop12 is positive or negative and on its magnitude.

For Loop12 small, we should recover couplings that are approximately independent of tanbeta and larger than in the SM !

M. Carena, S. Gori, N. Shah, C.Wagner, arXiv:1112.336

Mixing Effects in the CP- even Higgs Sector

- Mixing can have relevant effects in the production and decay rates

$$\mathcal{M}_H^2 = \begin{bmatrix} m_A^2 \sin^2\beta + M_Z^2 \cos^2\beta & -(m_A^2 + M_Z^2)\sin\beta\cos\beta + \mathrm{Loop}_{12} \\ -(m_A^2 + M_Z^2)\sin\beta\cos\beta + \mathrm{Loop}_{12} & m_A^2 \cos^2\beta + M_Z^2 \sin^2\beta + \mathrm{Loop}_{22} \end{bmatrix}$$

$$\mathrm{Loop}_{12} = \frac{m_t^4}{16\pi^2 v^2 \sin^2\beta} \frac{\mu \bar{A}_t}{M_{\mathrm{SUSY}}^2} \left[\frac{A_t \bar{A}_t}{M_{\mathrm{SUSY}}^2} - 6 \right] + \frac{h_b^4 v^2}{16\pi^2} \sin^2\beta \frac{\mu^3 A_b}{M_{\mathrm{SUSY}}^4} + \frac{h_\tau^4 v^2}{48\pi^2} \sin^2\beta \frac{\mu^3 A_\tau}{M_{\tilde{\tau}}^4}$$

effects through radiative corrections
to the CP-even mass matrix
which defines the mixing angle alpha

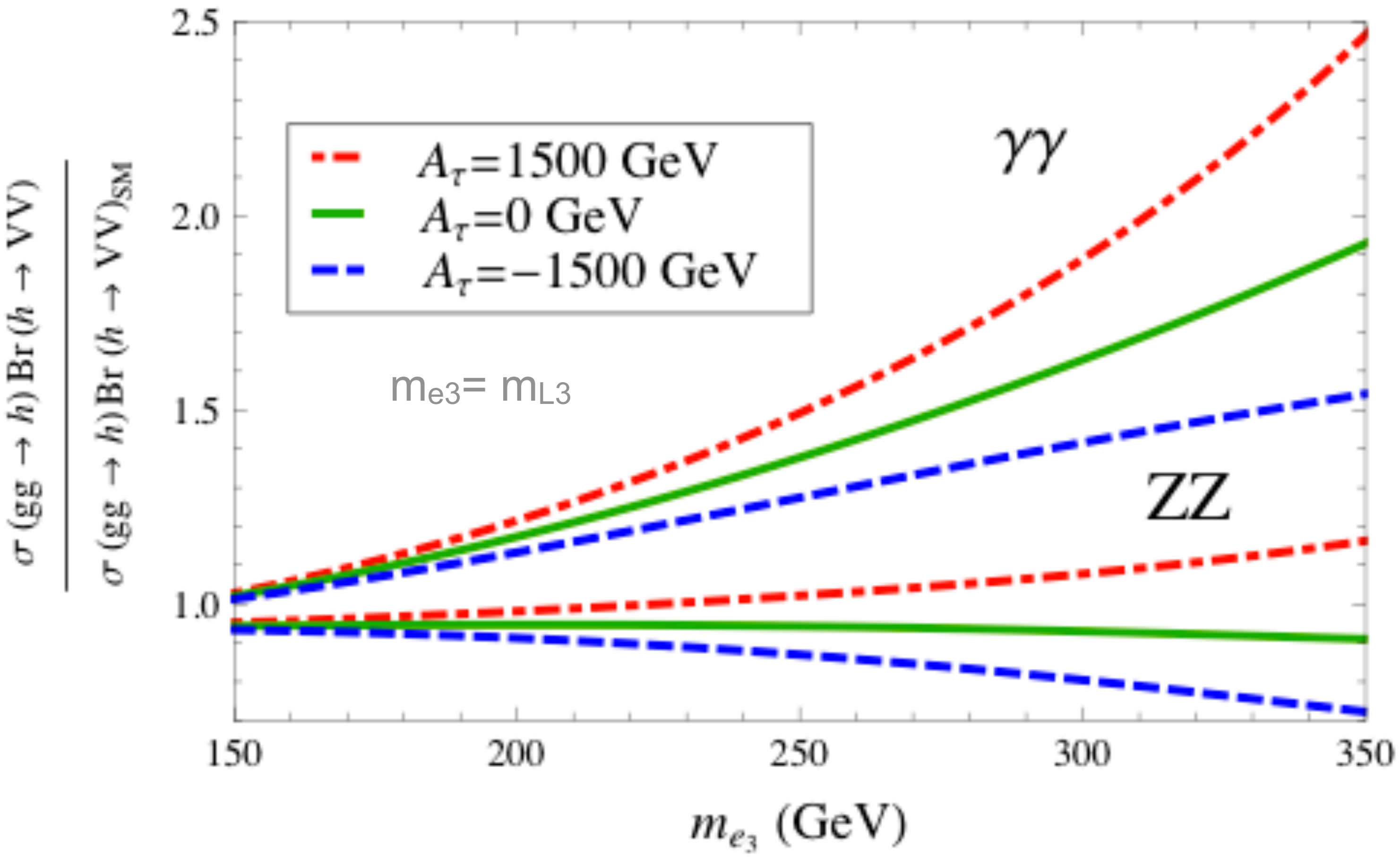
$$\sin\alpha\cos\alpha = M_{12}^2 / \sqrt{\left(\mathrm{Tr}\, M^2\right)^2 - 4 \det M^2}$$

$$h b\bar{b} : \quad -\frac{\sin\alpha}{\cos\beta}\left[1 - \frac{\Delta h_b \tan\beta}{1 + \Delta h_b \tan\beta}\left(1 + \frac{1}{\tan\alpha\tan\beta}\right)\right]$$

Small Variations in the Br(Hbb) can induce
significant variations in the other Higgs Br’s

Additional modifications of the Higgs rates into gauge bosons via stau induced mixing effects in the Higgs sector

M. Carena, S. Gori, N. Shah, C. Wagner, arXiv:1112.336,+L.T. Wang, arXiv:1205.5842



m_{Stau}~ 90 GeV; m_h~ 125 GeV

Important A_τ induced radiative corrections to the mixing angle α that defines the bottom coupling to Higgs

hbb ~ sinα/cosβ

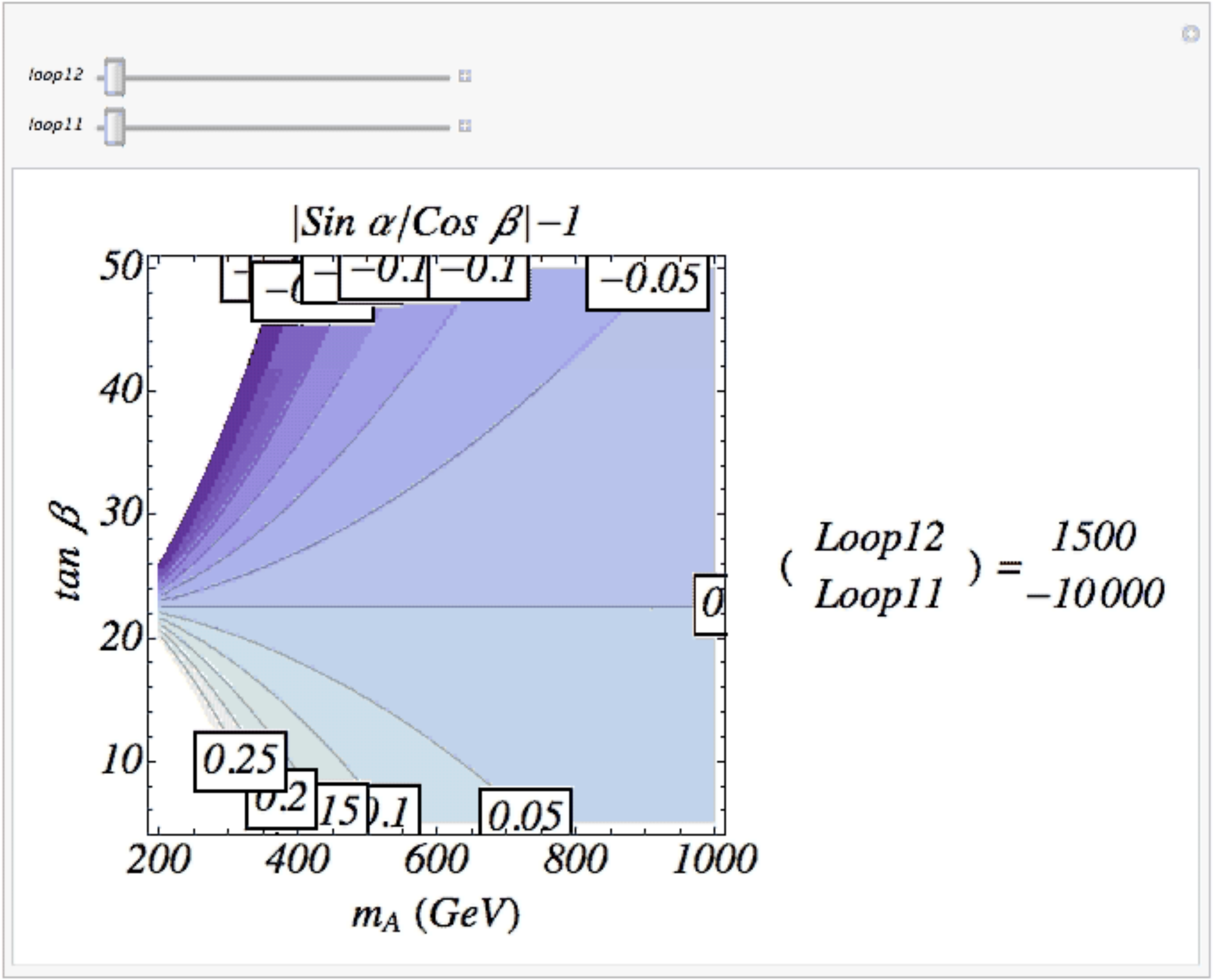
↓

Small variations in BR [Hbb] induce significant variations in the other Higgs BR's

Values of the soft parameters larger than 250 GeV tend to lead to vacuum stability problems

Gluon fusion production rate can be varied for light stops

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

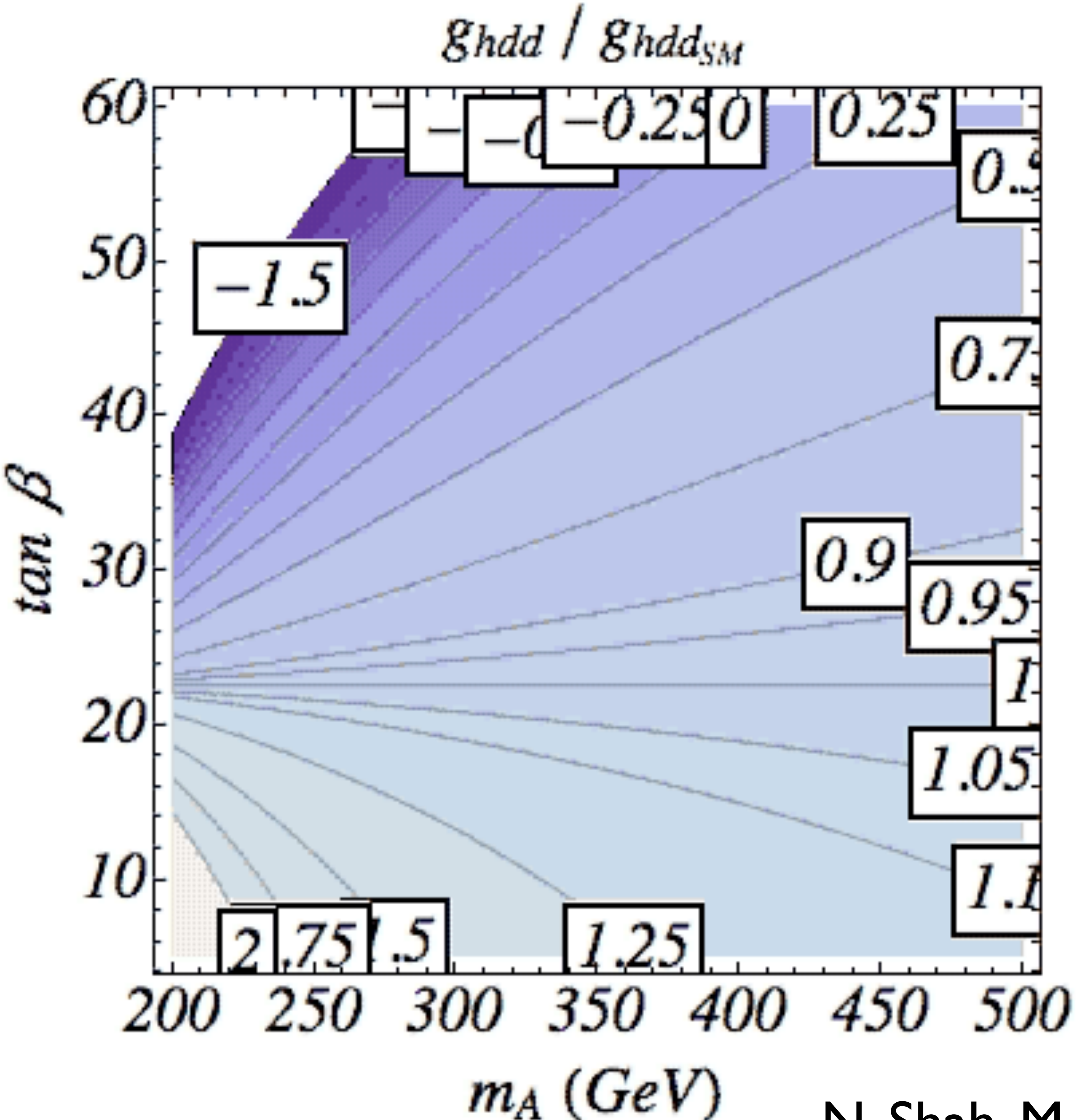


N. Shah, M. Carena, I. Low, C.W'13

$$\Delta_{b,\tau} = \epsilon \tan \beta$$

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

$\Delta_{b,\tau} = \epsilon \tan\beta$



$\epsilon = -0.01$

$Loop12 = 1500$

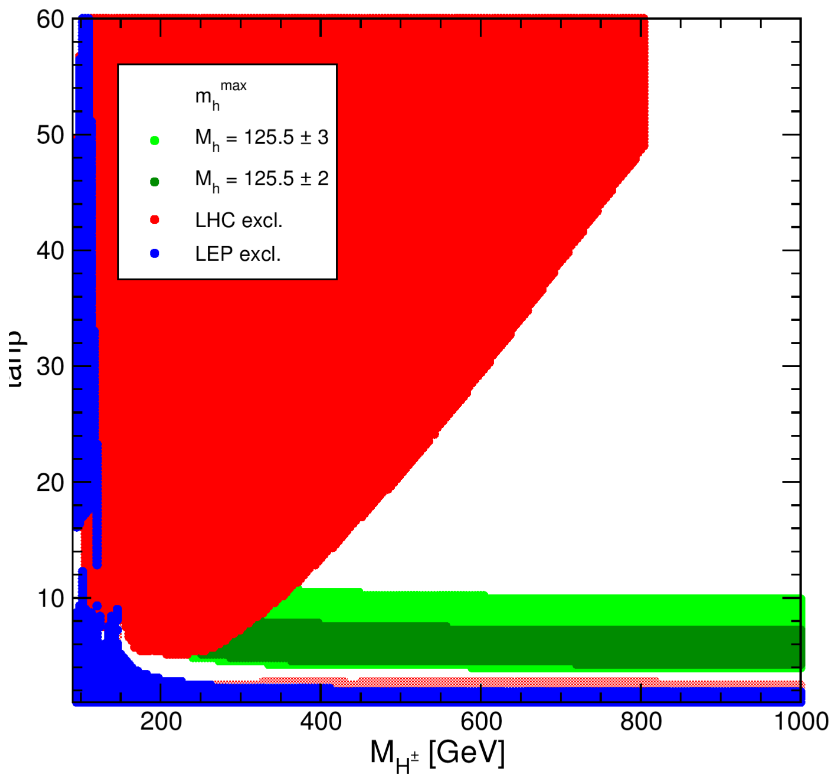
$Loop11 = -10000$

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

M. Carena, S. Heinemeyer, O. Stål, C.E.M. Wagner, G. Weiglein,
arXiv:1302.7033

The $m_h^{\max}$ scenario

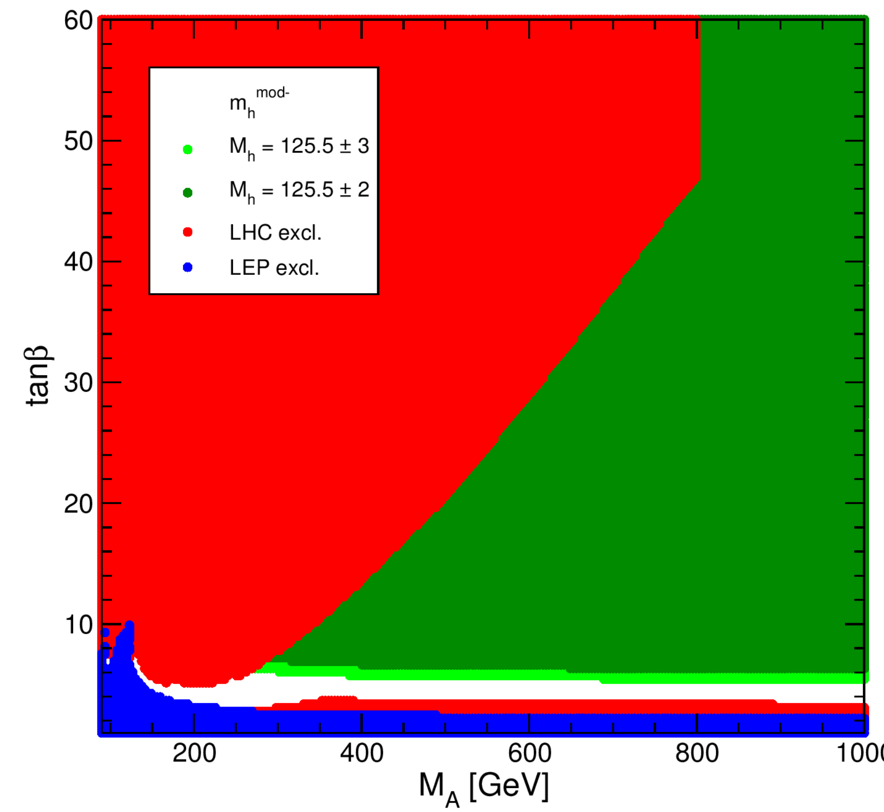
Gives the lowest value of tan(beta) consistent with the measured Higgs mass



$$
\begin{aligned}
M_{\rm SUSY} &= 1000 \text{ GeV}, \\
\mu &= 200 \text{ GeV}, \\
M_2 &= 200 \text{ GeV}, \\
X_t^{\rm OS} &= 2\, M_{\rm SUSY} \text{ (FD calculation)}, \\
X_t^{\overline{\rm MS}} &= \sqrt{6}\, M_{\rm SUSY} \text{ (RG calculation)}, \\
A_b = A_\tau &= A_t, \\
m_{\tilde g} &= 1500 \text{ GeV},
\end{aligned}
$$

The $m_h^{\rm mod}$ scenario

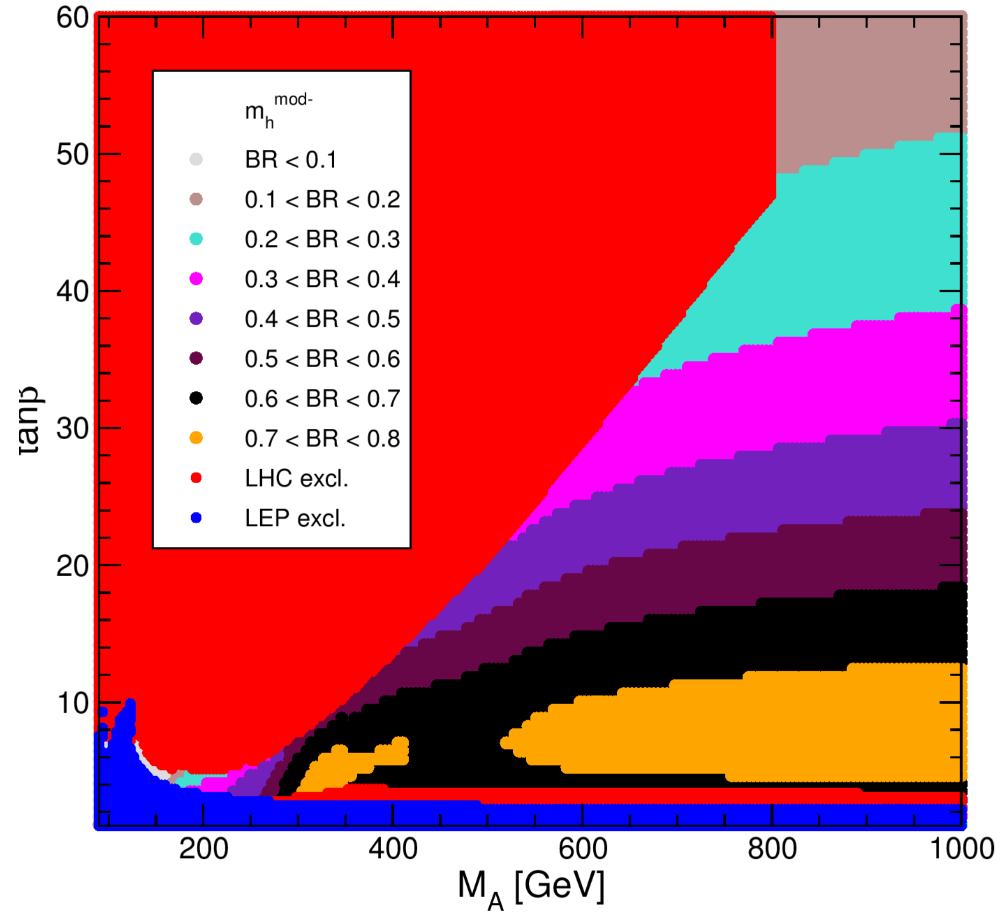
Moderate values of the stop mixing allow for consistency with the Higgs mass value in a broad region of the mA-tan(beta) plane

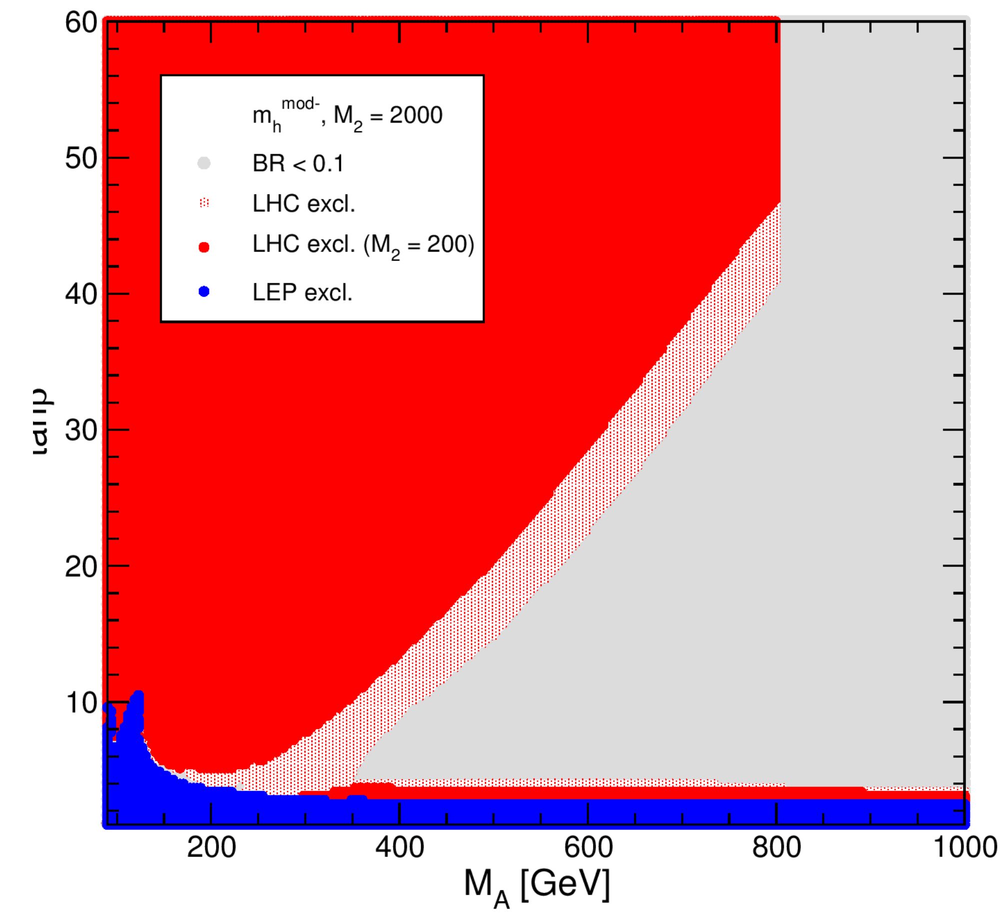


$$
\begin{aligned}
M_{\rm SUSY} &= 1000 \text{ GeV}, \\
\mu &= 200 \text{ GeV}, \\
M_2 &= 200 \text{ GeV}, \\
X_t^{\rm OS} &= 1.5\, M_{\rm SUSY} \text{ (FD calculation)}, \\
X_t^{\overline{\rm MS}} &= 1.6\, M_{\rm SUSY} \text{ (RG calculation)}, \\
A_b = A_\tau &= A_t, \\
m_{\tilde g} &= 1500 \text{ GeV},
\end{aligned}
$$

Decays of the non-standard Higgs bosons into EWKinos in the $m_h^{\rm mod}$ scenario

M. Carena, S. Heinemeyer, O. Stål, C.E.M. Wagner, G. Weiglein, arXiv:1302.7033



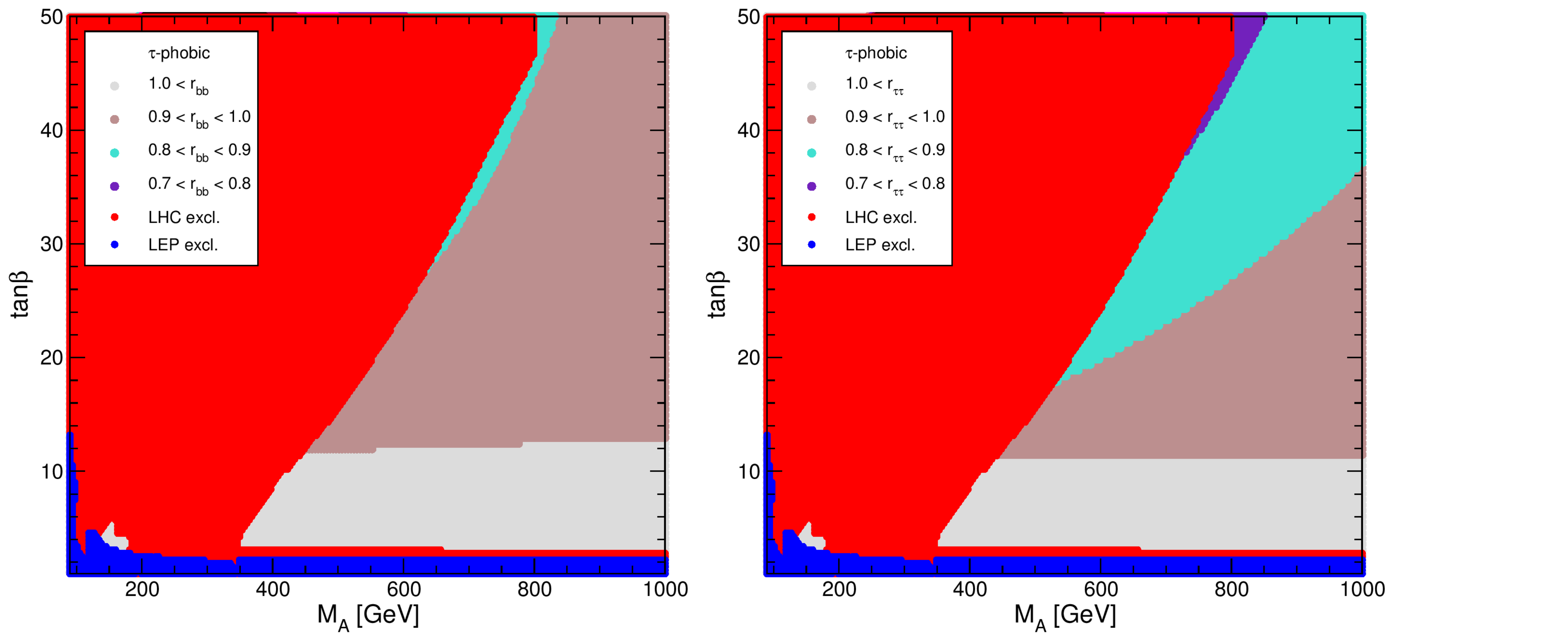


Reach of non-standard Higgs bosons in tau decays modified
Opportunity for dedicated search of these decays.

Also $BR(H \to hh)$ may become important for small values of $\tan\beta$

The τ-phobic Higgs scenario

Suppression of down-type fermion couplings to the Higgs due to Higgs mixing effects. Staus play a relevant role. Decays into staus relevant for heavy non-standard Higgs bosons.



$$
\begin{aligned}
M_{\rm SUSY} &= 1500\ \text{GeV}, \\
\mu &= 2000\ \text{GeV}, \\
M_2 &= 200\ \text{GeV}, \\
X_t^{\rm OS} &= 2.45\, M_{\rm SUSY}\ (\text{FD calculation}), \\
X_t^{\overline{\rm MS}} &= 2.9\, M_{\rm SUSY}\ (\text{RG calculation}), \\
A_b = A_\tau &= A_t\ , \\
m_{\tilde{g}} &= 1500\ \text{GeV}, \\
M_{\tilde{l}_3} &= 500\ \text{GeV}\ .
\end{aligned}
$$

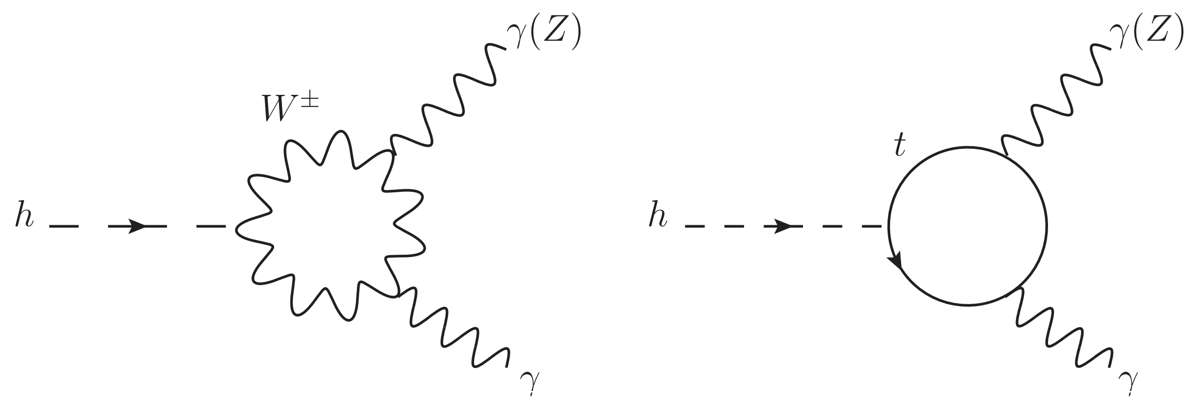
M. Carena, S. Heinemeyer, O. Stål, C.E.M. Wagner, G. Weiglein, arXiv:1302.7033

$$
\text{Loop}_{12} = \frac{m_t^4}{16\pi^2 v^2 \sin^2\beta} \frac{\mu \tilde{A}_t}{M_{\rm SUSY}^2} \left[\frac{A_t \tilde{A}_t}{M_{\rm SUSY}^2} - 6 \right] + \frac{h_b^4 v^2}{16\pi^2} \sin^2\beta \frac{\mu^3 A_b}{M_{\rm SUSY}^4} + \frac{h_\tau^4 v^2}{48\pi^2} \sin^2\beta \frac{\mu^3 A_\tau}{M_{\tilde{\tau}}^4}
$$

Loop Induced Couplings

(see also S. Gori's talk)

Dominant Contributions to the Diphoton Width in the Standard Model



Similar corrections appear from other scalar, fermion or vector particles. Clearly, similarly to the top quark, chiral fermions tend to reduce the vector boson contributions

Higgs Diphoton Decay Width in the SM

$$\Gamma(h \to \gamma\gamma) = \frac{G_F \alpha^2 m_h^3}{128\sqrt{2}\pi^3} \left| A_1(\tau_w) + N_c Q_t^2 A_{1/2}(\tau_t) \right|^2 \qquad \tau_i \equiv 4m_i^2/m_h^2$$

A. Djouadi'05

For particles much heavier than the Higgs boson

$$A_1 \to -7\ , \qquad N_c Q_t^2\, A_{1/2} \to \frac{4}{3} N_c Q_t^2 \ \simeq 1.78, \quad \text{for } N_c = 3, Q_t = 2/3$$

In the SM, for a Higgs of mass about 125 GeV

$$m_h = 125 \ \ \text{GeV} : \ A_1 = -8.32\ , \quad N_c Q_t^2 A_{1/2} = 1.84$$

Dominant contribution from W loops. Top particles suppress by 40 percent the W loop contribution. One can rewrite the above expression in terms of the couplings of the particles to the Higgs as :

$$\Gamma(h \to \gamma\gamma) = \frac{\alpha^2 m_h^3}{1024\pi^3} \left| \frac{g_{hWW}}{m_W^2} A_1(\tau_w) + \frac{2 g_{ht\bar{t}}}{m_t} N_c Q_t^2 A_{1/2}(\tau_t) + N_c Q_S^2 \frac{g_{hSS}}{m_S^2} A_0(\tau_S) \right|^2$$

Inspection of the above expressions reveals that the contributions of particles heavier than the Higgs boson may be rewritten as

$$\mathcal{L}_{h\gamma\gamma} = -\frac{\alpha}{16\pi}\frac{h}{v}\left[\sum_i 2b_i \frac{\partial}{\partial \log v}\log m_i(v)\right] F_{\mu\nu}F^{\mu\nu}$$

$$\left\{ \begin{array}{lll} b = \frac{4}{3}N_c Q^2 & \text{for a Dirac fermion ,} \\ b = -7 & \text{for the } W \text{ boson ,} \\ b = \frac{1}{3} N_c Q_S^2 & \text{for a charged scalar .} \end{array} \right.$$

where in the Standard Model

$$\frac{g_{hWW}}{m_W^2} = \frac{\partial}{\partial v}\log m_W^2(v) \ , \qquad \frac{2g_{ht\bar{t}}}{m_t} = \frac{\partial}{\partial v}\log m_t^2(v)$$

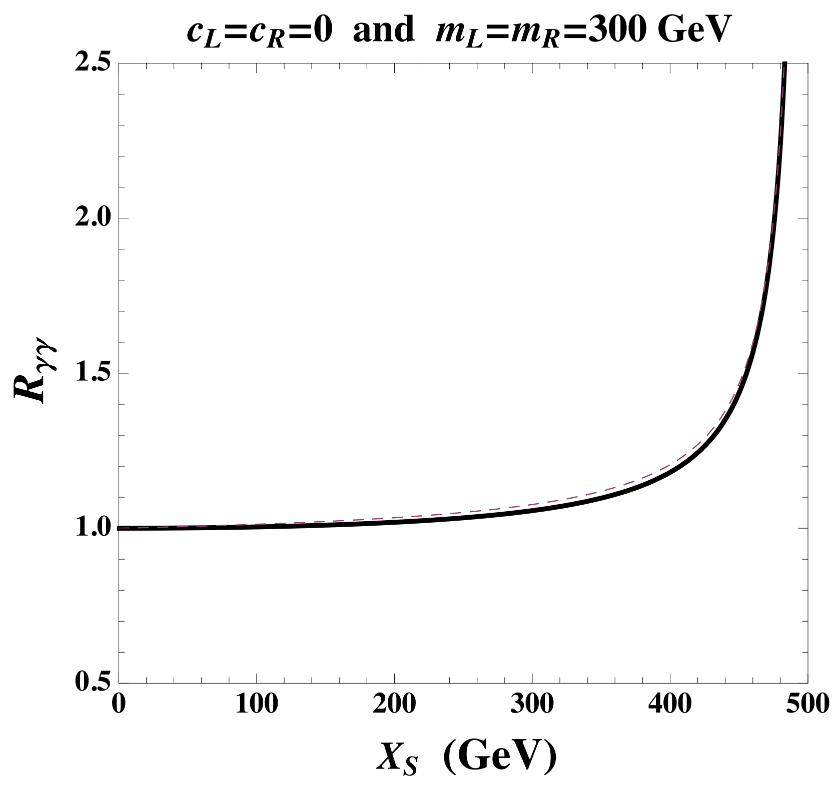
This generalizes for the case of fermions with contributions to their masses independent of the Higgs field. The couplings come from the vertex and the inverse dependence on the masses from the necessary chirality flip (for fermions) and the integral functions.

$$\mathcal{L}_{h\gamma\gamma} = \frac{\alpha}{16\pi}\frac{h}{v}\left[\sum_i b_i \frac{\partial}{\partial \log v}\log\left(\det \mathcal{M}_{F,i}^\dagger \mathcal{M}_{F,i}\right) + \sum_i b_i \frac{\partial}{\partial \log v}\log\left(\det \mathcal{M}_{B,i}^2\right)\right] F_{\mu\nu}F^{\mu\nu}$$

M. Carena, I. Low, C.W., arXiv:1206.1082, Ellis, Gaillard, Nanopoulos'76, Shifman, Vainshtein, Voloshin, Zakharov'79

Similar considerations apply to the Higgs gluon coupling

Two Scalars with Mixing



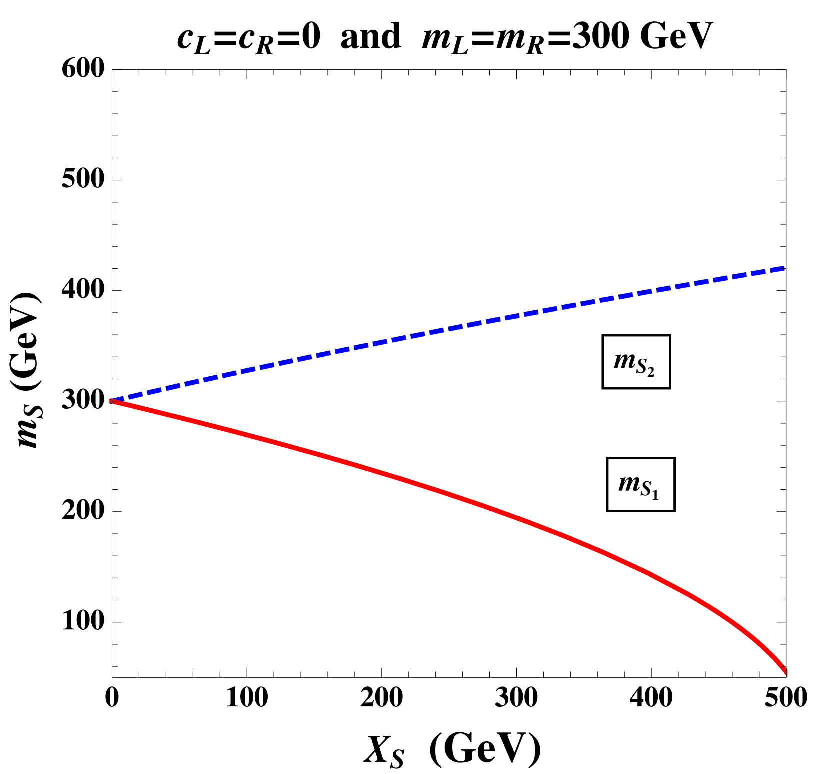
Similar to light stau scenario,
M. Carena, S. Gori, N. Shah, C.W., arXiv: 1112.3336,
M. Carena, S. Gori, N. Shah, C.W., L.T. Wang, arXiv:1205.5842

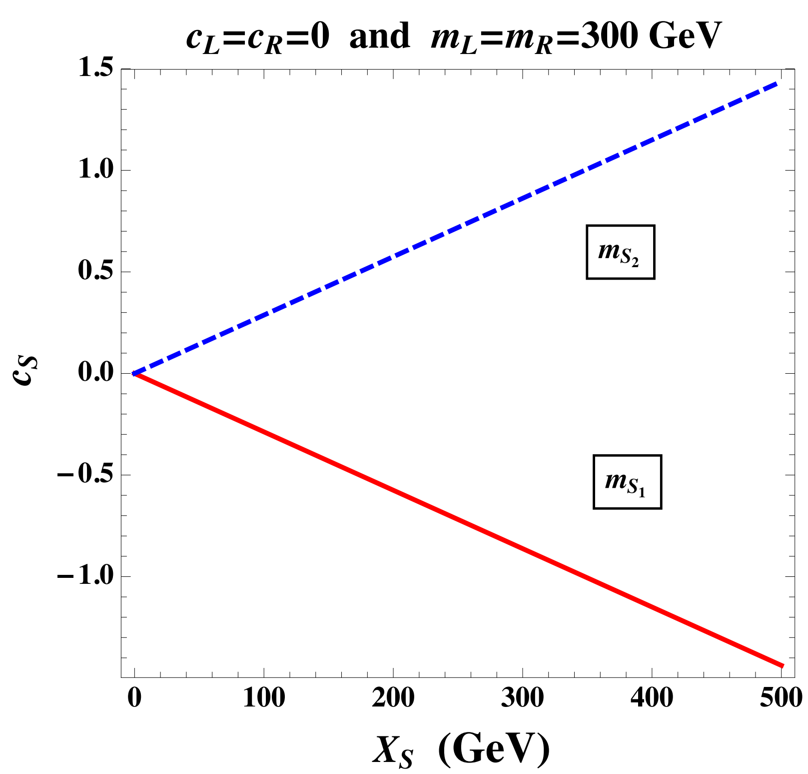
$$\mathcal{M}_S^2 = \begin{pmatrix} \tilde{m}_L(v)^2 & \frac{1}{\sqrt{2}} v X_S \\ \frac{1}{\sqrt{2}} v X_S & \tilde{m}_R(v)^2 \end{pmatrix}$$

$$\frac{\partial \log(\mathrm{Det} M_S^2)}{\partial v} \simeq -\frac{X_S^2 v}{m_{S_1}^2 m_{S_2}^2}$$

Negative Effective Coupling of lightest scalar

Large mixing and small value of the lightest scalar mass leads to enhancement of the diphoton amplitude



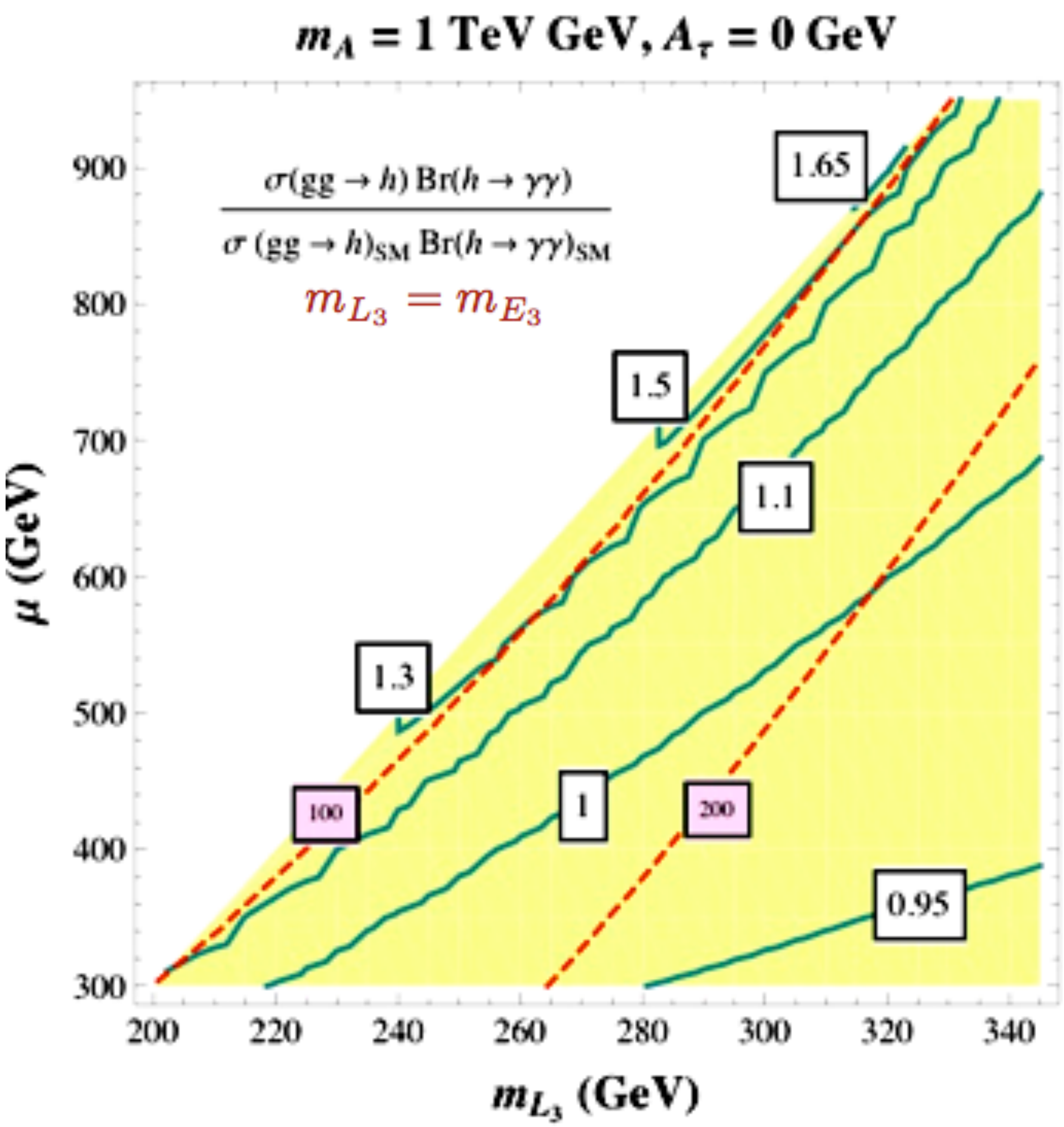


Lightest scalar, with mass below 200 GeV gives the dominant contribution in this case.

M. Carena, I. Low, C.W., arXiv:1206.1082

Higgs Decay into two Photons in the MSSM

Charged scalar particles with no color charge can change di-photon rate without modification of the gluon production process



$$\mathcal{M}^2_{\tilde{\tau}} \simeq \begin{bmatrix} m^2_{L_3} + m^2_\tau + D_L & h_\tau v(A_\tau \cos\beta - \mu \sin\beta) \\ h_\tau v(A_\tau \cos\beta - \mu \sin\beta) & m^2_{E_3} + m^2_\tau + D_R \end{bmatrix}$$

Light staus with large mixing

[sizeable μ and tan beta]:

➔ **enhancement of the Higgs to di-photon decay rate**

$$\delta\mathcal{A}_{h\gamma\gamma}/\mathcal{A}^{\rm SM}_{h\gamma\gamma} \simeq -\frac{2\,m^2_\tau}{39\,m^2_{\tilde{\tau}_1} m^2_{\tilde{\tau}_2}}\left(m^2_{\tilde{\tau}_1} + m^2_{\tilde{\tau}_2} - X^2_\tau\right)$$

$$X_\tau = A_\tau - \mu \tan\beta$$

M. Carena, S. Gori, N. Shah, C. Wagner, arXiv:1112.336, +L.T.Wang, arXiv:1205.5842

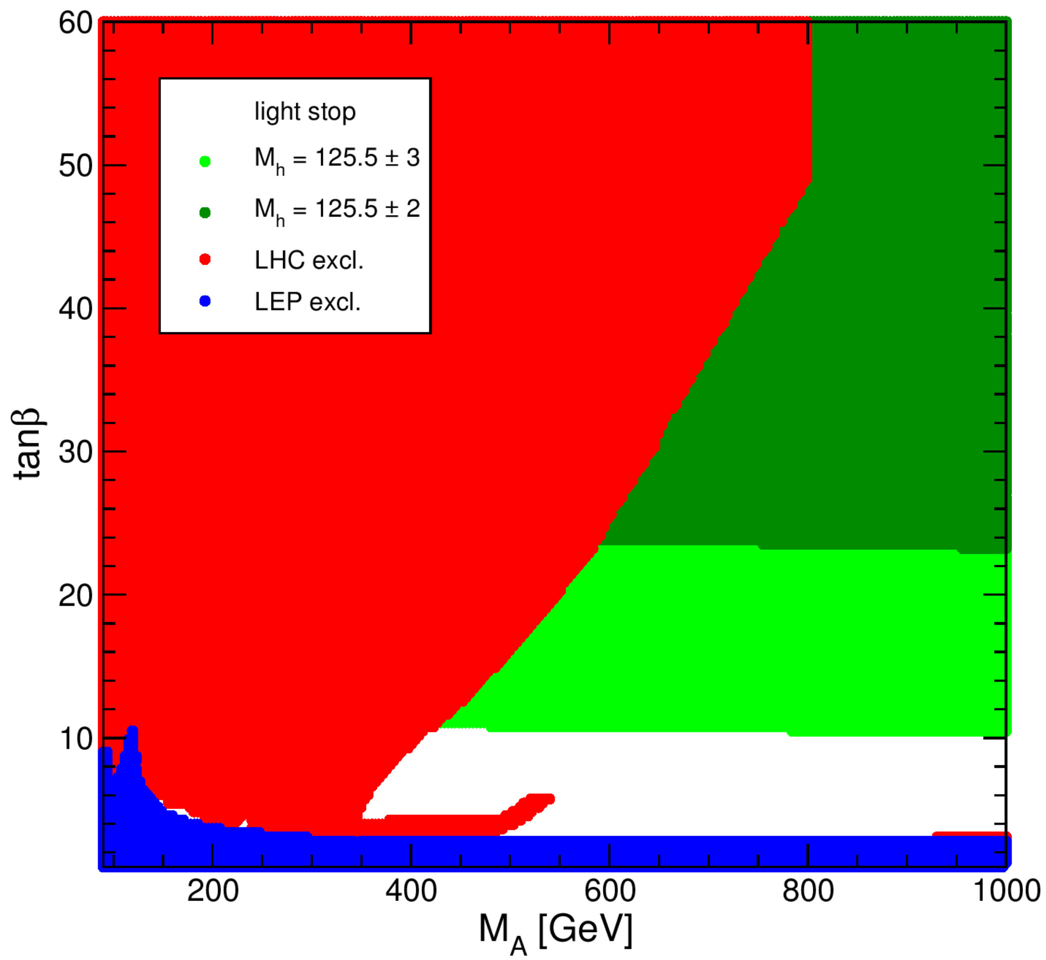
For a more generic discussion of modified diphoton width by new charged particles, see M. Carena, I. Low and C. Wagner, arXiv:1206.1082

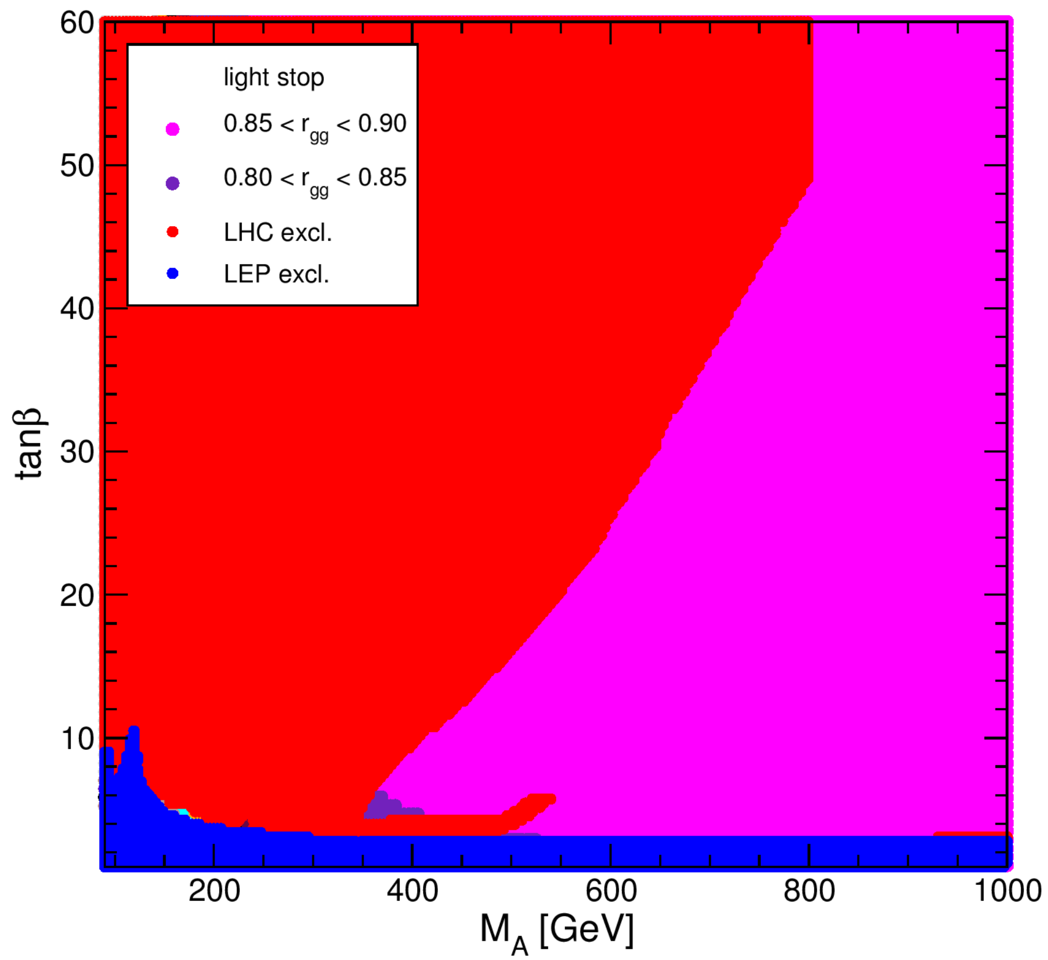
M. Carena, S. Heinemeyer, O. Stål,
C.E.M. Wagner, G. Weiglein,
arXiv:1302.7033

The Light Stop Scenario

Stop mixing large, lightest stop mass of order 320 GeV.
Heaviest stop mass of order 650 GeV.
Reduction of the gluon fusion process rate.

$$\delta\mathcal{A}_{hgg}/\mathcal{A}_{hgg}^{\rm SM} \simeq \frac{m_t^2}{4m_{\tilde t_1}^2 m_{\tilde t_2}^2}\left(m_{\tilde t_1}^2 + m_{\tilde t_2}^2 - X_t^2\right)$$





$$M_{\rm SUSY} = 500 \text{ GeV},\quad \mu = 350 \text{ GeV},\quad M_2 = 350 \text{ GeV},$$

$$X_t^{\rm OS} = 2.0\, M_{\rm SUSY} \text{ (FD calculation)},$$
$$X_t^{\overline{\rm MS}} = 2.2\, M_{\rm SUSY} \text{ (RG calculation)},$$
$$A_b = A_t = A_\tau,$$
$$m_{\tilde g} = 1500 \text{ GeV},$$

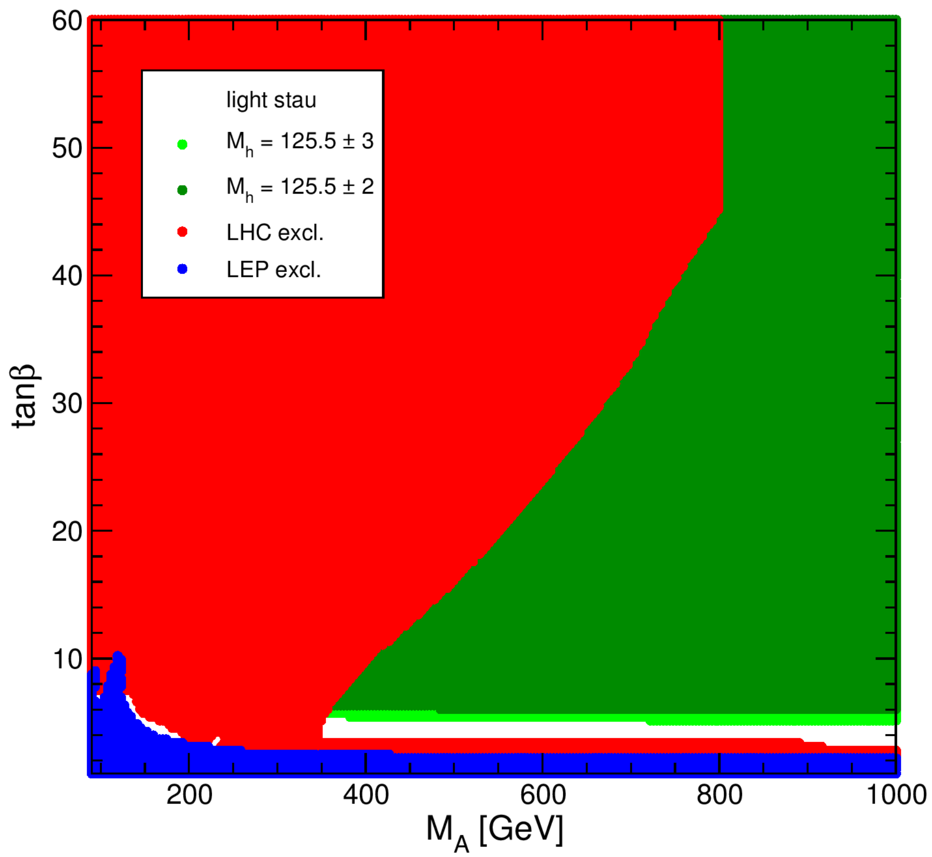
M. Carena, S. Heinemeyer, O. Stål,
C.E.M. Wagner, G. Weiglein,
arXiv:1302.7033

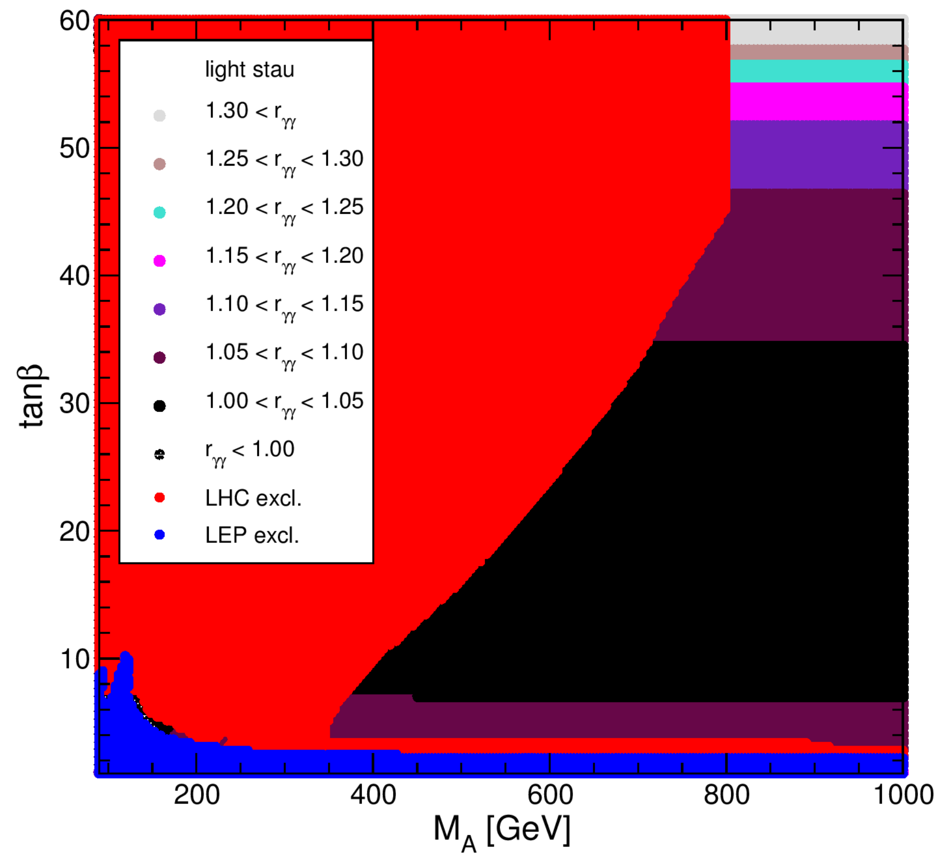
The Light Stau Scenario

Enhancement of diphoton decay rate at large values of tan(beta).

$$\delta\mathcal{A}_{h\gamma\gamma}/\mathcal{A}^{\rm SM}_{h\gamma\gamma} \simeq -\frac{2\, m_\tau^2}{39\, m^2_{\tilde\tau_1} m^2_{\tilde\tau_2}} \left(m^2_{\tilde\tau_1} + m^2_{\tilde\tau_2} - X_\tau^2\right)$$

$$X_\tau = A_\tau - \mu \tan\beta$$





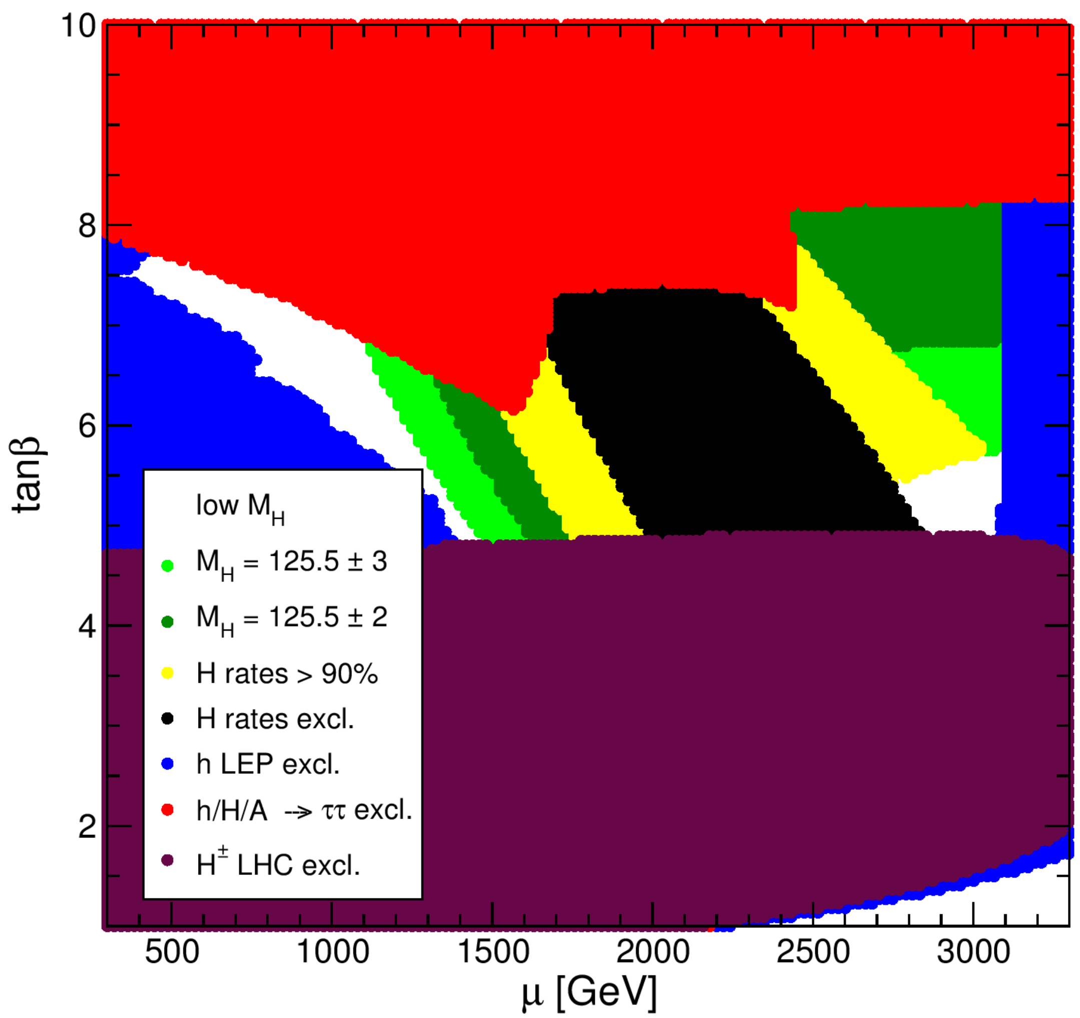
$$M_{\rm SUSY} = 1000 \text{ GeV},$$
$$\mu = 500 \text{ GeV},$$
$$\mu = 450 \text{ GeV } (\Delta_\tau \text{ calculation}),$$
$$M_2 = 200 \text{ GeV},$$
$$M_2 = 400 \text{ GeV } (\Delta_\tau \text{ calculation}),$$

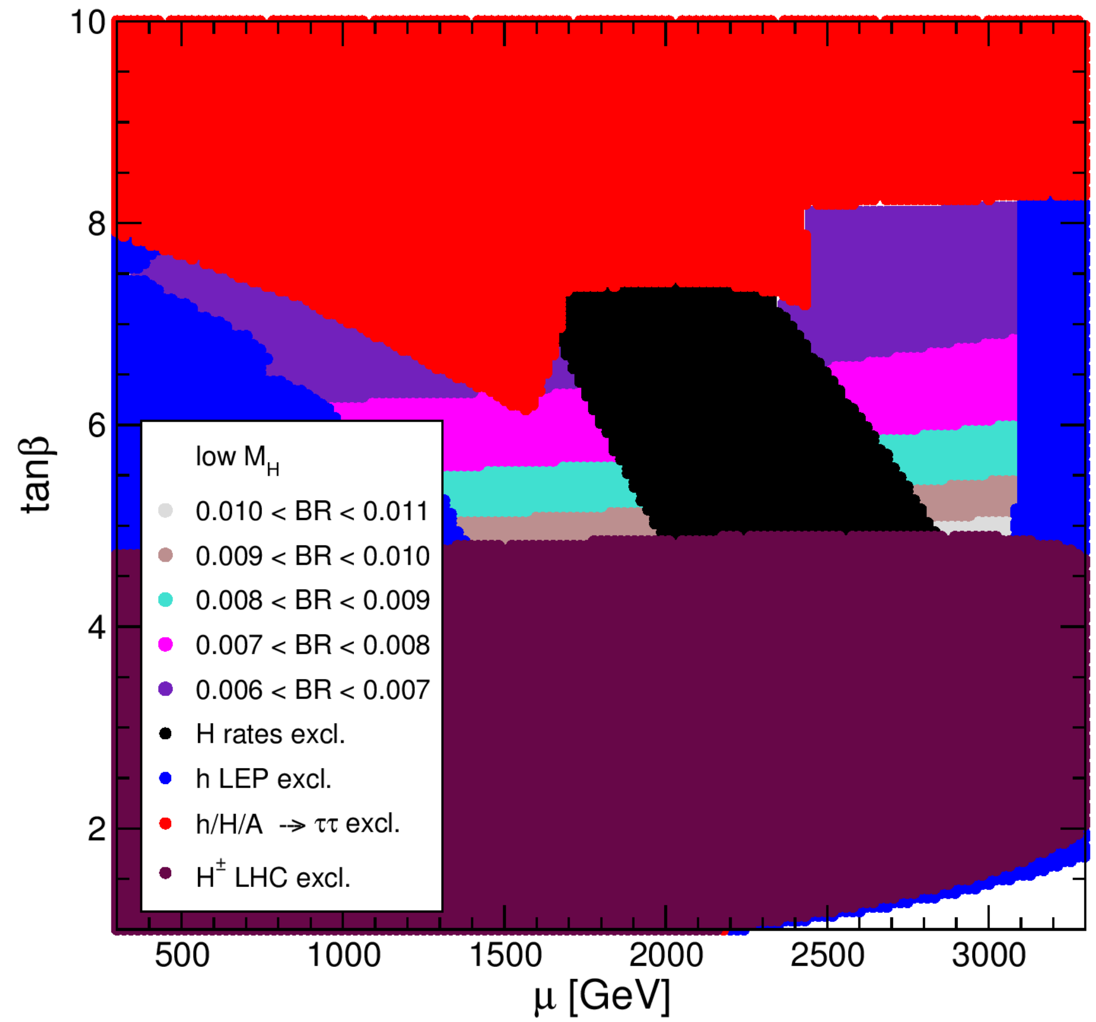
$$X_t^{\rm OS} = 1.6\, M_{\rm SUSY} \text{ (FD calculation)},$$
$$X_t^{\overline{\rm MS}} = 1.7\, M_{\rm SUSY} \text{ (RG calculation)},$$
$$A_b = A_t\ ,$$
$$A_\tau = 0\ ,$$
$$m_{\tilde g} = 1500 \text{ GeV},$$
$$M_{\tilde l_3} = 245 \text{ GeV},$$
$$M_{\tilde l_3} = 250 \text{ GeV } (\Delta_\tau \text{ calculation}).$$

The low-M_H scenario

Heavy CP-even Higgs boson is SM-like

M. Carena, S. Heinemeyer, O. Stål, C.E.M. Wagner, G. Weiglein, arXiv:1302.7033





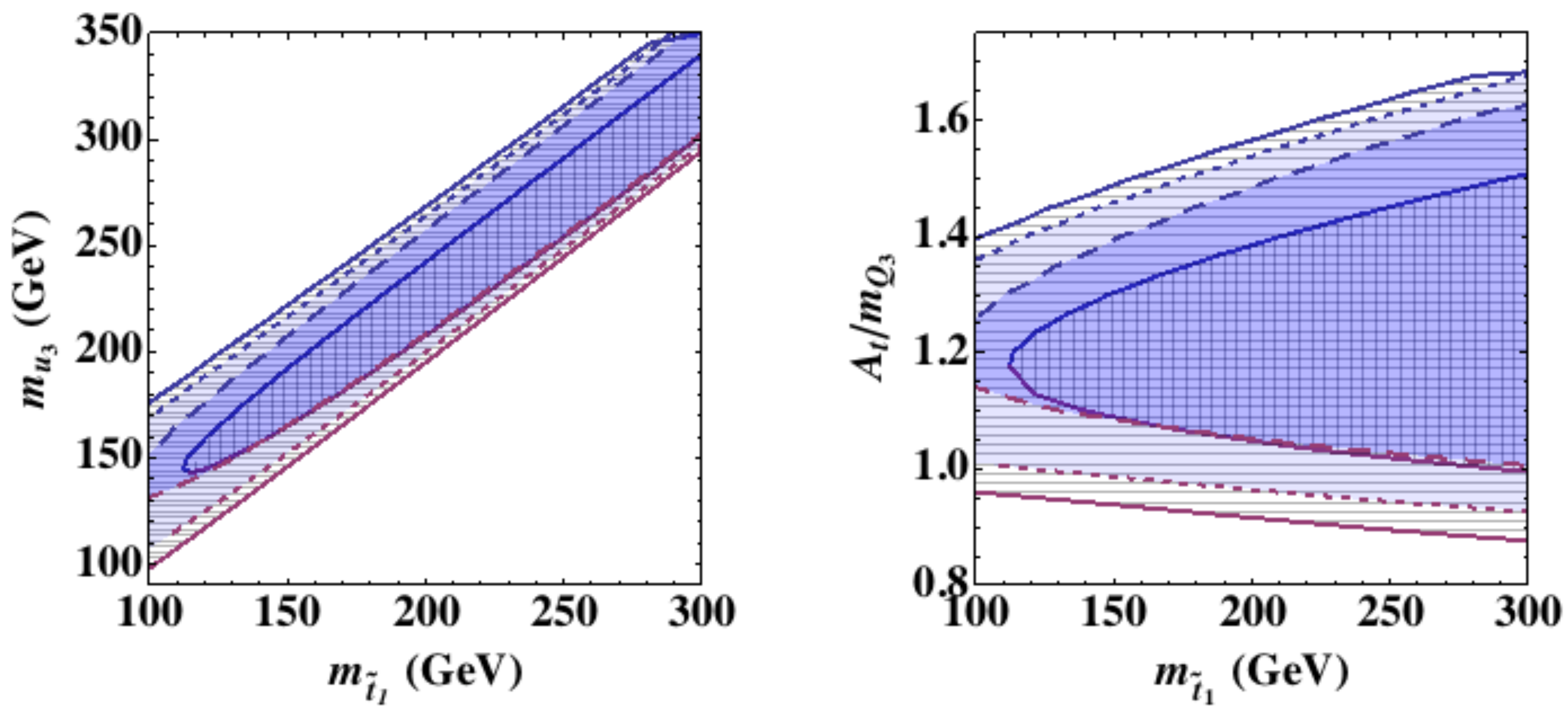
$$
\begin{aligned}
M_A &= 110 \text{ GeV}, \\
M_{\text{SUSY}} &= 1500 \text{ GeV}, \\
M_2 &= 200 \text{ GeV}, \\
X_t^{\text{OS}} &= 2.45\, M_{\text{SUSY}} \text{ (FD calculation)}, \\
X_t^{\overline{\text{MS}}} &= 2.9\, M_{\text{SUSY}} \text{ (RG calculation)}, \\
A_b &= A_\tau = A_t, \\
m_{\tilde{g}} &= 1500 \text{ GeV}, \\
M_{\tilde{l}_3} &= 1000 \text{ GeV} .
\end{aligned}
$$

Top decay into charged Higgs bosons at the edge of being tested.
Whole parameter space consistent with this scenario may be probed in the near future

M. Carena, S. Gori, N. Shah, C.W. and L.T. Wang, arXiv:1303.4414

Light Stops, Light Staus and the 125 GeV Higgs

Cases	$\tan\beta$	$m_{\tilde{\tau}_1}$ (GeV)	m_{e_3} (GeV)	μ (GeV)	m_{Q_3} (TeV)	A_τ (TeV)	m_A (TeV)
(a) Shaded dashed	70	95	250	380	2	0	2
(b) Shaded dotted	70	95	230	320	2	1	1
(c) Horizontal hatch	105	95	240	225	2	1	1
(d) Vertical hatch	70	100	300	575	3	1.5	1

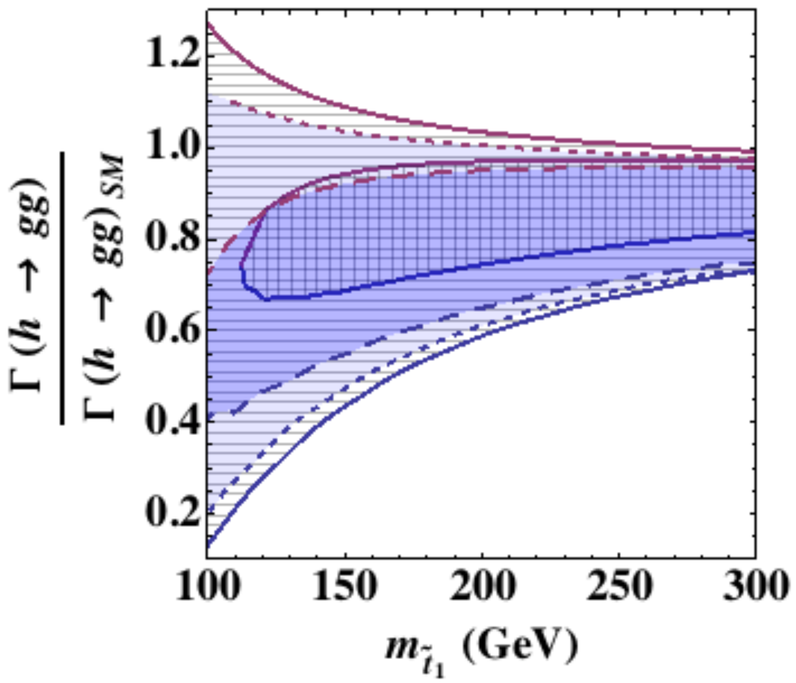


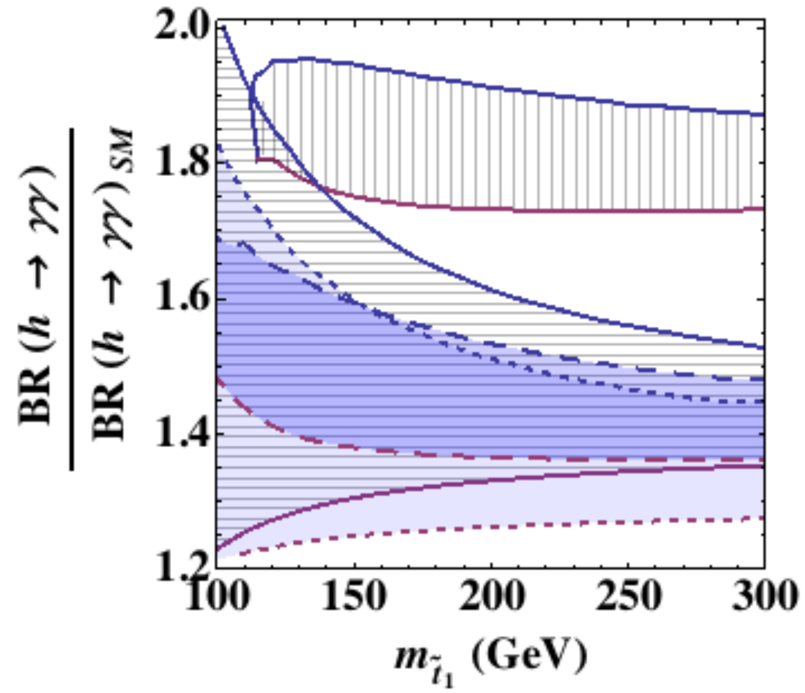
(a) to (c) : Consistent with vacuum stability constraints

M. Carena, S. Gori, I. Low, N. Shah, C.W., arXiv:1211.6136

Variation of Production Cross sections and Decay Rates

M. Carena, S. Gori, N. Shah, C.W. and L.T.Wang, arXiv:1303.4414

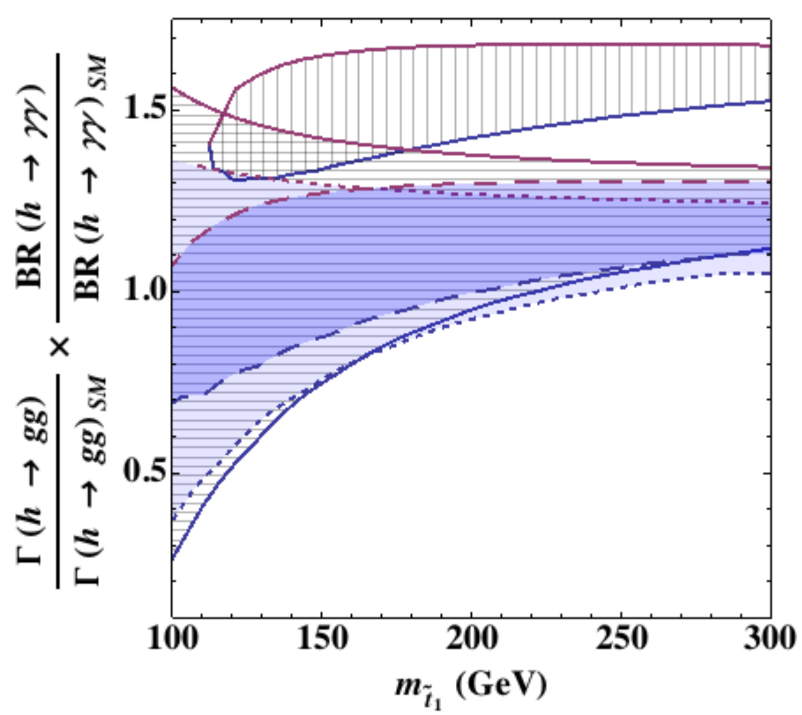




$$\delta\mathcal{A}_{hgg}/\mathcal{A}_{hgg}^{\rm SM} \simeq \frac{m_t^2}{4m_{\tilde{t}_1}^2 m_{\tilde{t}_2}^2}\left(m_{\tilde{t}_1}^2 + m_{\tilde{t}_2}^2 - X_t^2\right)$$

$$\delta\mathcal{A}_{h\gamma\gamma}/\mathcal{A}_{h\gamma\gamma}^{\rm SM} \simeq -\frac{2\,m_\tau^2}{39\,m_{\tilde{\tau}_1}^2 m_{\tilde{\tau}_2}^2}\left(m_{\tilde{\tau}_1}^2 + m_{\tilde{\tau}_2}^2 - X_\tau^2\right)$$

m_τ = 95 GeV

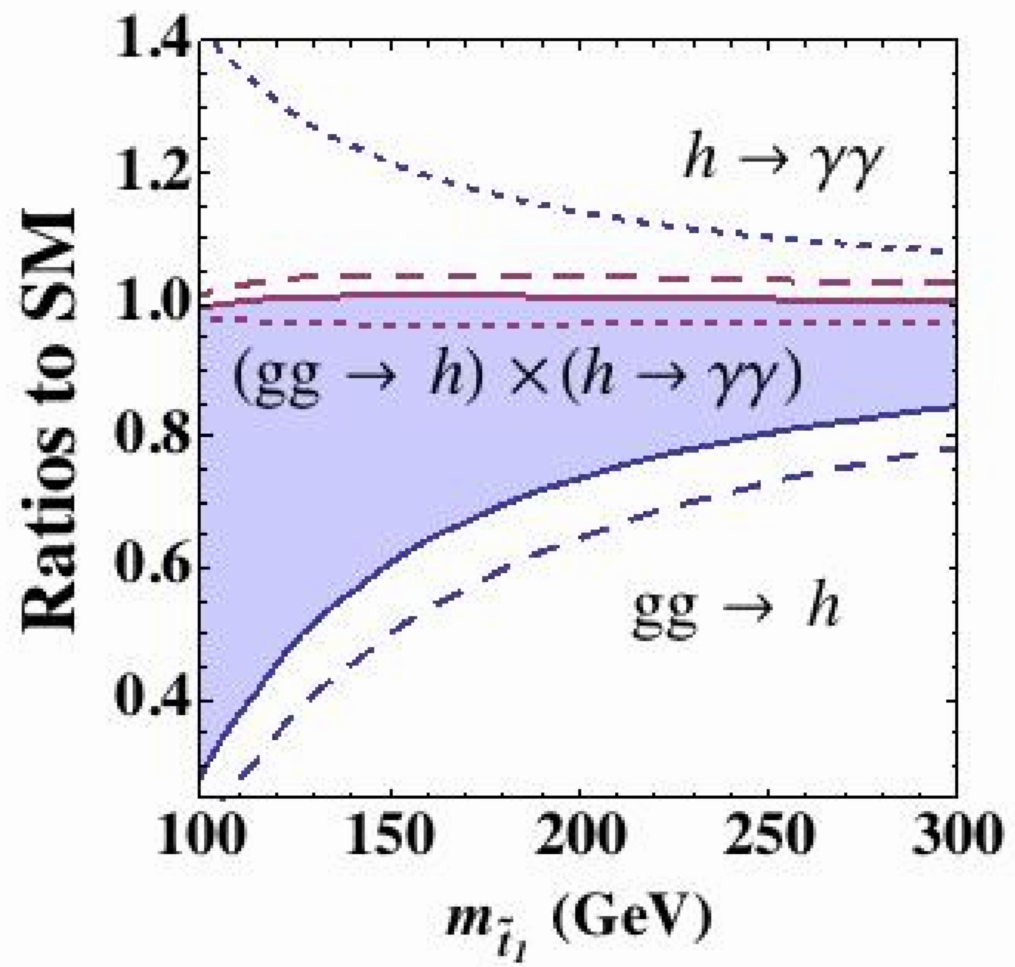


Light Staus can enhance the diphoton decay width
Light stops can either enhance or suppress gluon copling
Combination can lead to large variations of production in both gluon fusion and weak boson fusion (ratios of branching ratios)

Case of heavy Staus

Only stop loop effects relevant in this case

M. Carena, S. Gori, N. Shah, L.T. Wang and C.W'13



Moderate enhancement of the Higgs to diphoton rate may be obtained in weak boson fusion. Gluon fusion induced rate tend to be smaller than in the SM.

Impact of Light staus on heavy Higgs Boson Searches

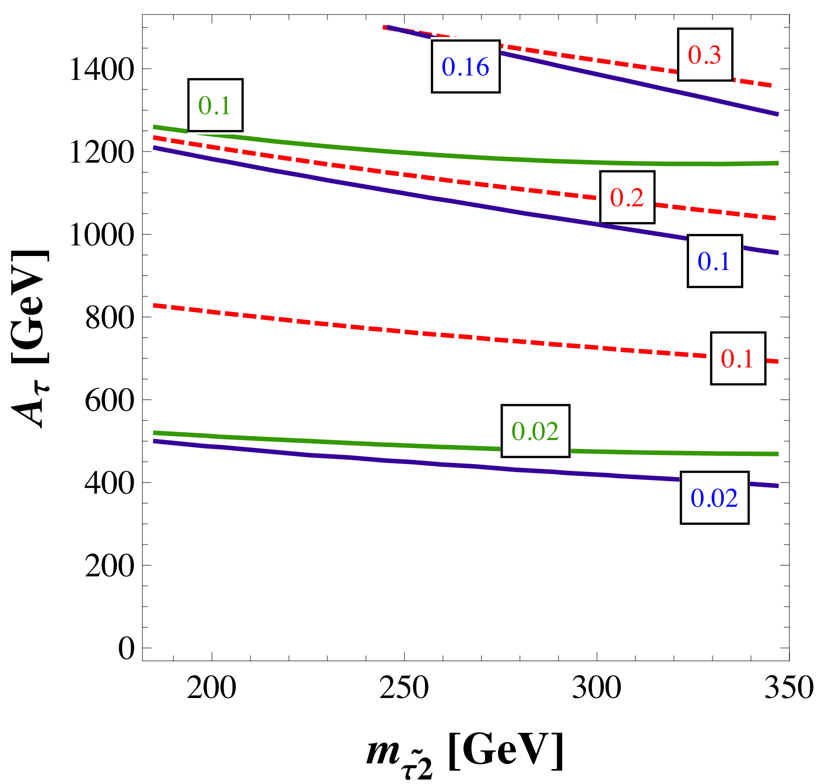
M. Carena, S. Gori, N. Shah, C.W. and L.T.Wang, arXiv:1303.4414

- Previous analysis performed under the assumption of no additional decays apart from the ones into bottom-quarks and tau-leptons.
- Light staus can lead to relevant extra contributions to the decay width.
- For large values of A_τ, the non-standard Higgs bosons couple strongly to staus at large $\tan\beta$.
- The additional width of the Higgs bosons leads to a reduction in the branching ratios into both bottoms and taus, and make searches more challenging.
- Searches for staus in decays of non-standard Higgs bosons should be also considered.

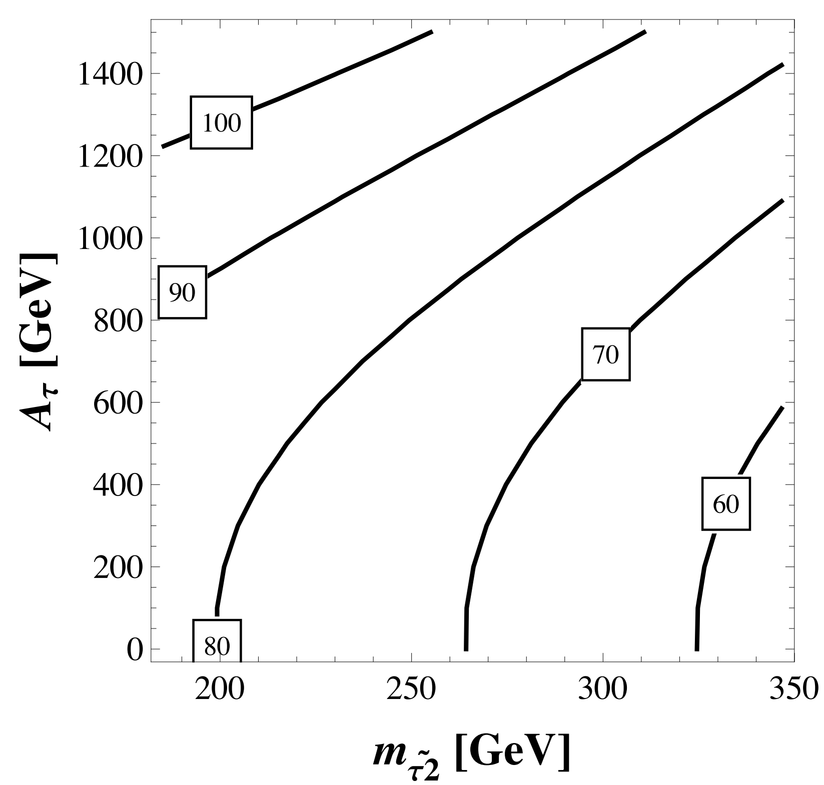
Branching Ratios and Widths of Non-Standard Higgs Decays into Staus

M. Carena, S. Gori, N. Shah, C.W. and L.T.Wang, arXiv:1303.4414

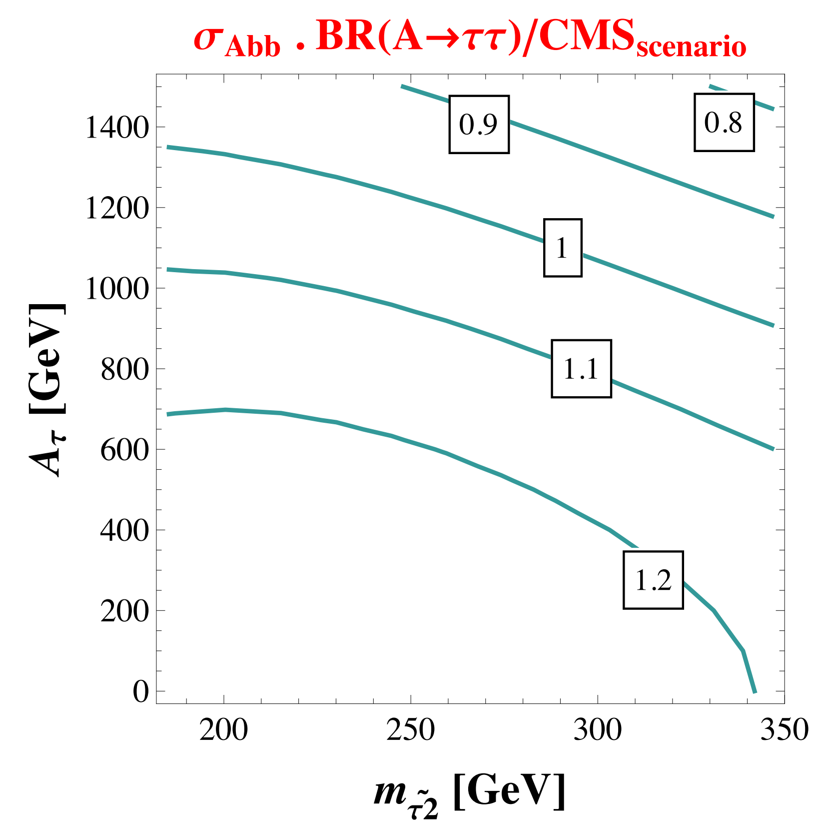
$$\sigma(pp \to (H,A) \to \tau^+\tau^-) \propto \frac{m_b^2 \tan^2\beta}{\left[\left(3\frac{m_b^2}{m_\tau^2} + \frac{\left(M_W^2+M_Z^2\right)(1+\Delta_b)^2}{m_\tau^2\tan^2\beta}\right)(1+\Delta_\tau)^2 + (1+\Delta_b)^2\left(1+\frac{A_\tau^2}{m_A^2}\right)\right]}$$



Decay branching ratio of heavy non-standard Higgs boson to staus



Total heavy Higgs boson width



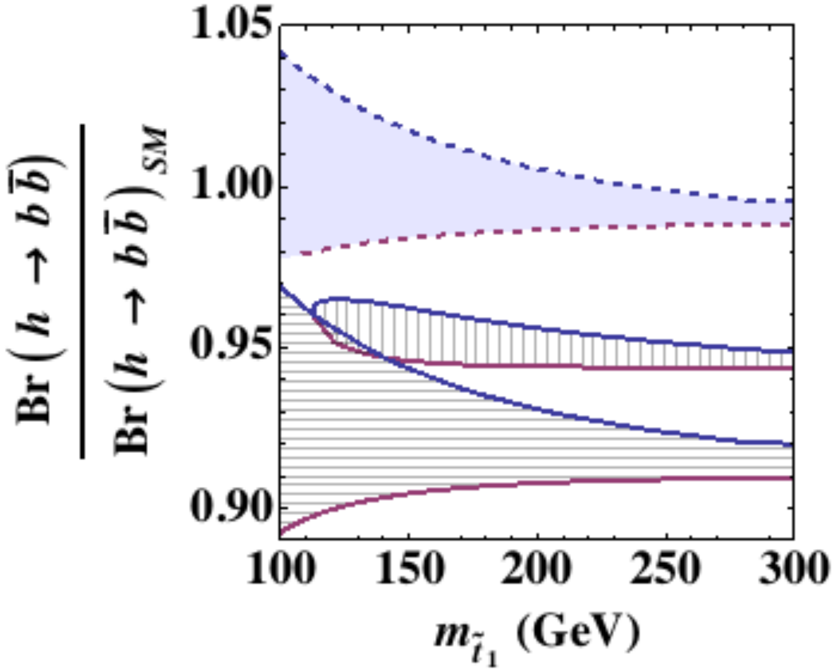
Decay branching ratio into taus, compared to the mhmax scenario.

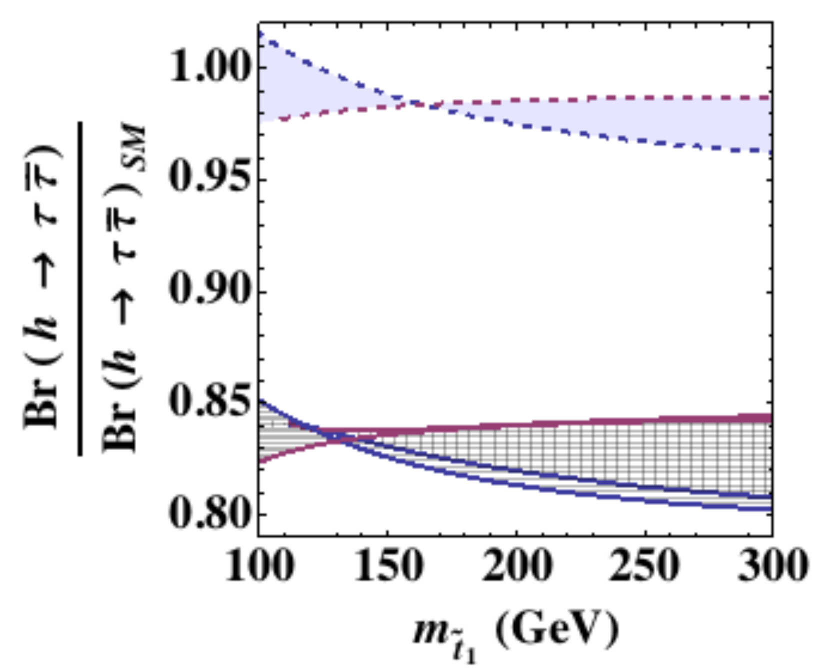
Conclusions

- Resonance discovered at the LHC has properties consistent with SM Higgs ones.
- Precise production rates and branching ratios may be affected by new physics. As an example, we have studied the MSSM case
- This model has a rich phenomenology that can led to large variations of the couplings and to new related signatures at colliders.
- Higher than two loop corrections should be considered at large Msusy.
- Down fermion couplings suffer variations in the wedge that vary from a few to a few tens of percent depending of mainly sign and magnitude of Loop12.
- Third generation sfermions play a very relevant role and, if they are light, they can have a relevant impact on the loop induced couplings and Higgs phenomenology.
- Search for non-standard Higgs in new channels including inos, standard Higgs bosons and staus can provide alternative ways of checking the Higgs wedge.

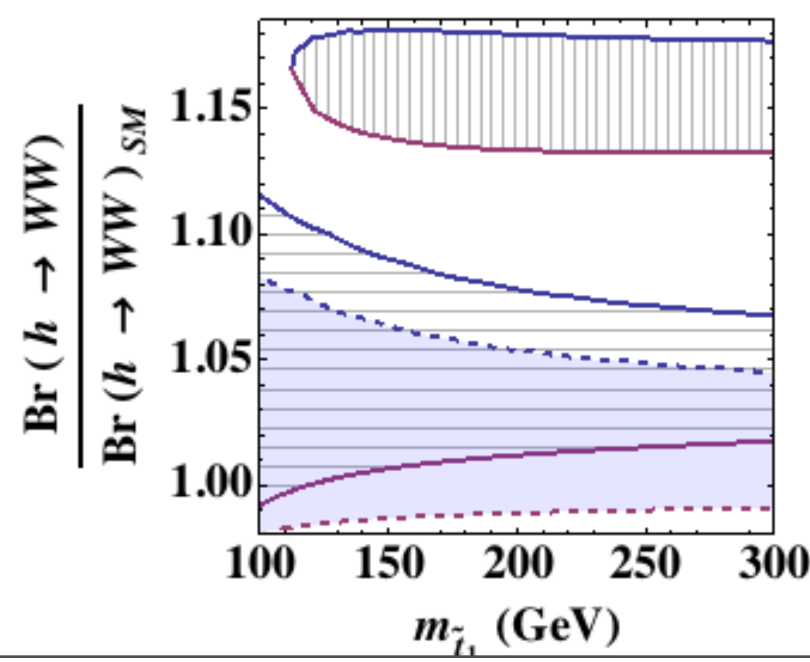
Coupling to Fermions and Weak Gauge Bosons

M. Carena, S. Gori, N. Shah, C.W. and L.T. Wang, arXiv:1303.4414





(iii)



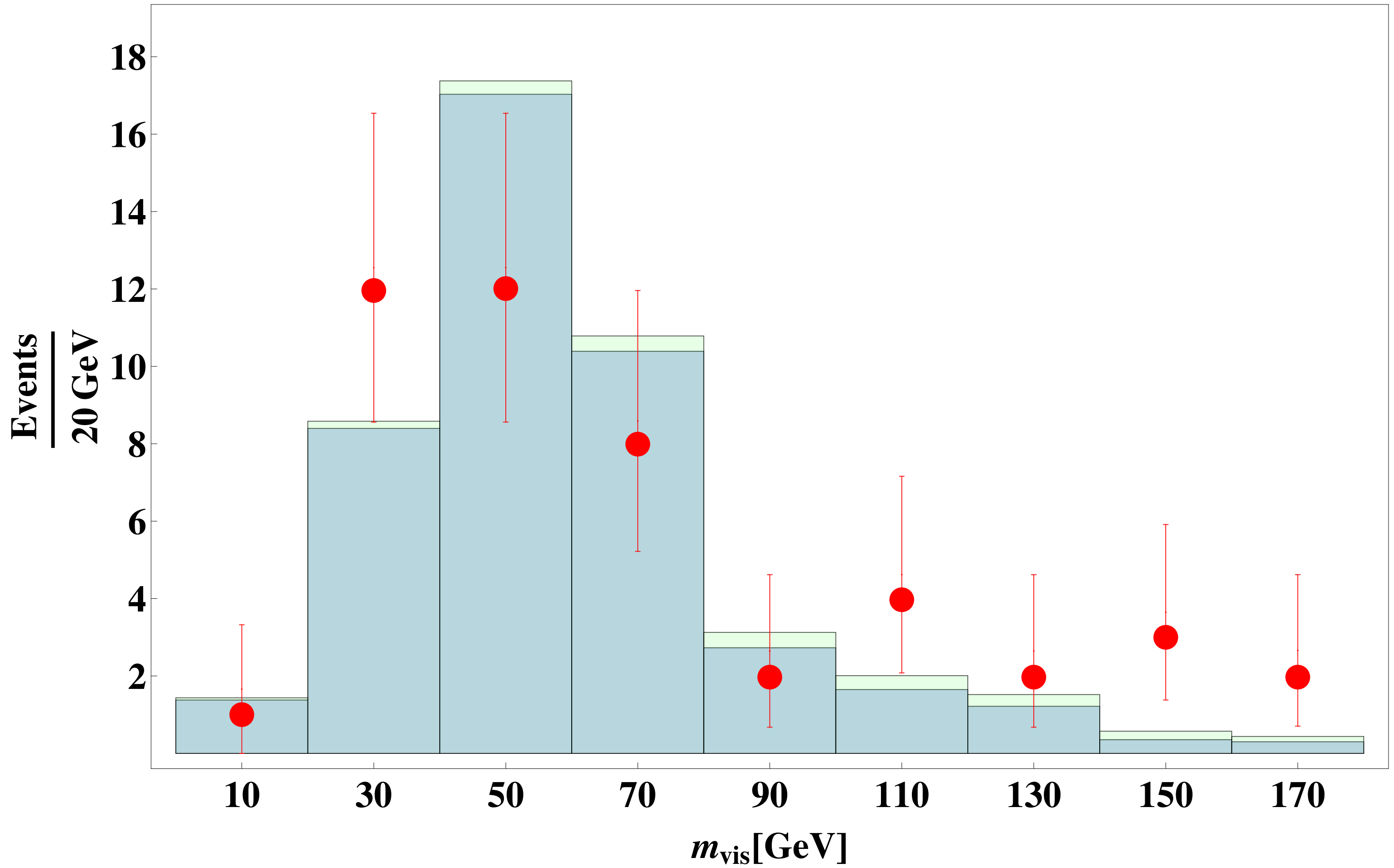
Searches for staus in associated production with sneutrinos.

M. Carena, S. Gori, N. Shah, C.W. and L.T. Wang, arXiv:1303.4414

Final State in $pp \to Wh$, followed by $h \to \tau^+\tau^-$ is similar to the one in

$pp \to \tilde{\tau}\tilde{\nu}_\tau$, followed by $\tilde{\nu}_\tau \to \tilde{\tau} + \chi_1^0$.

Look for leptonic decay of the W, and one hadronic and one leptonic tau decay. Same selection cuts as in the Higgs search analysis.



Cut in visible mass increase signal to background ratio, but very low statistics. Dedicated search with optimized selection cuts should be performed.

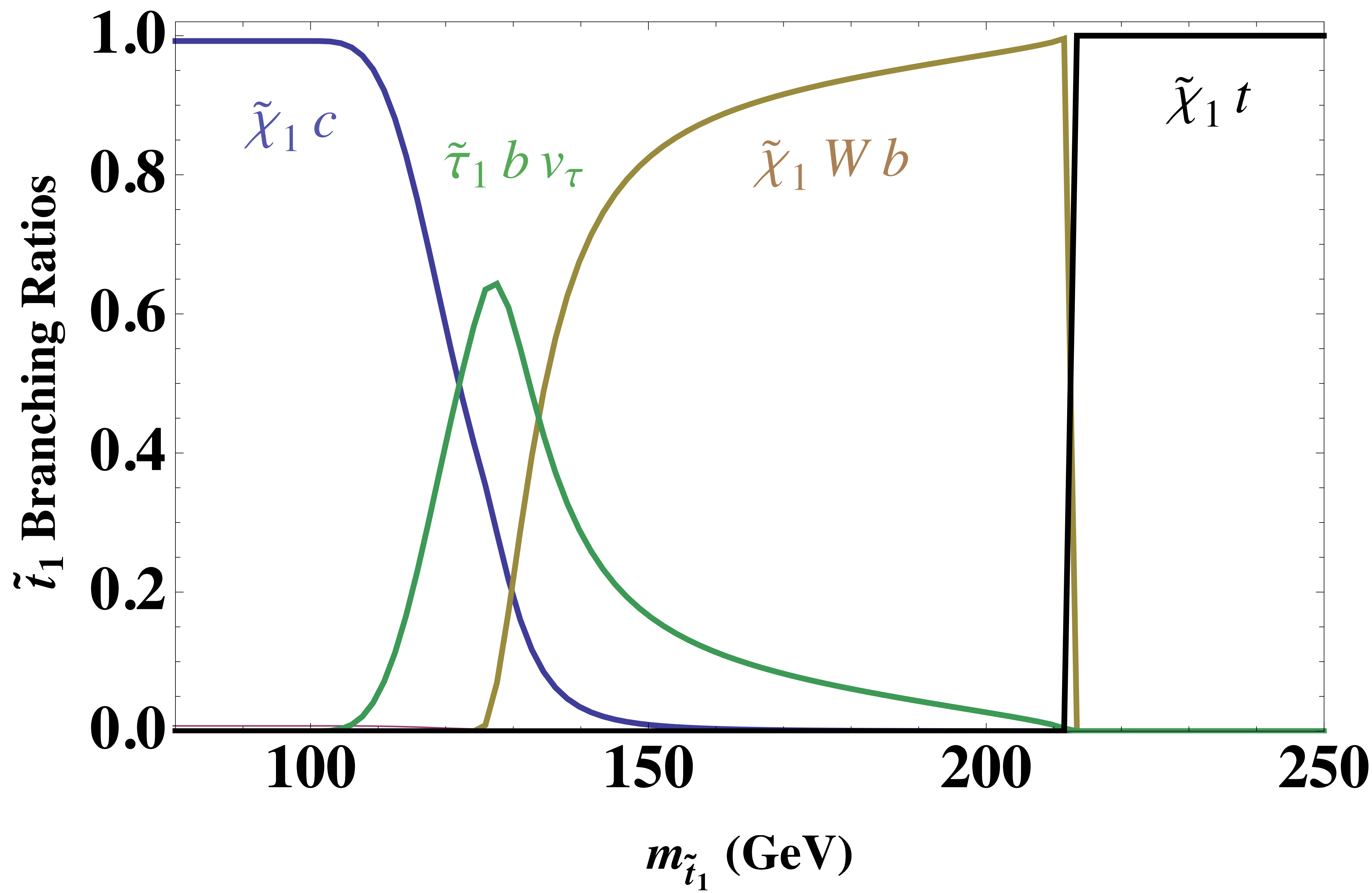
M. Carena, S. Gori, N. Shah, C.W. and L.T.Wang, arXiv:1303.4414

Light Stop Searches

- Light stops, mainly right handed, may be present without affecting the Higgs mass predictions and without affecting precision electroweak measurements.
- If present, they have an impact on both gluon fusion cross section as well as in $\gamma\gamma$ Higgs decay width. There are strong direct search constraints.
- Three body decay into staus may become the dominant stop decay mode, when three body decay into a neutralino, a W and a b is closed.
- For a neutralino mass of about 40 to 50 GeV, this happens for stop masses of about 130 GeV.

Stop Branching Ratios in Light Stau Scenario

M. Carena, S. Gori, N. Shah, C.W. and L.T.Wang, arXiv:1303.4414



Apart from region close to top neutralino decay threshold, decays of stops into staus open new possibilities

M. Carena, S. Gori, I. Low, N. Shah, C.W., arXiv:1211.6136

Vacuum stability

For large values of the mu parameter and the tau Yukawa coupling, one can generate new charge breaking minima deeper than the electroweak minimum

$$V = \left|\mu \frac{h_u}{\sqrt{2}} - y_\tau \tilde{\tau}_L \tilde{\tau}_R\right|^2 + \frac{g_2^2}{8}\left(|\tilde{\tau}_L|^2 + \frac{h_u^2}{2}\right)^2 + \frac{g_1^2}{8}\left(|\tilde{\tau}_L|^2 - 2|\tilde{\tau}_R|^2 - \frac{h_u^2}{2}\right)^2$$
$$+ m_{H_u}^2 \frac{h_u^2}{2} + m_{L_3}^2 |\tilde{\tau}_L|^2 + m_{E_3}^2 |\tilde{\tau}_R|^2 + \frac{g_1^2 + g_2^2}{8}\,\delta_H\,\frac{h_u^4}{4}\ ,$$

This occures in this improved tree-level potential, but also occurs in the full one-loop effective potential we shall analyze

Vacuum Stability

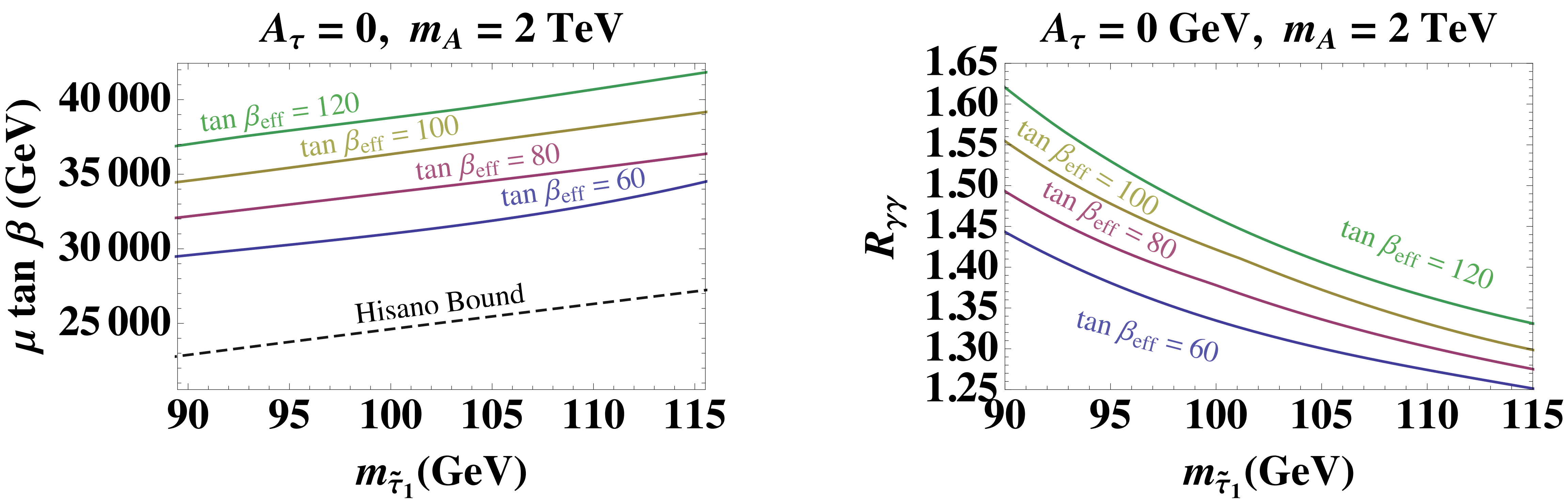
Electroweak Minimum is in general metastable in this scenario
Hisano, Sugiyama'11

Metastability bound depends on tan(beta)

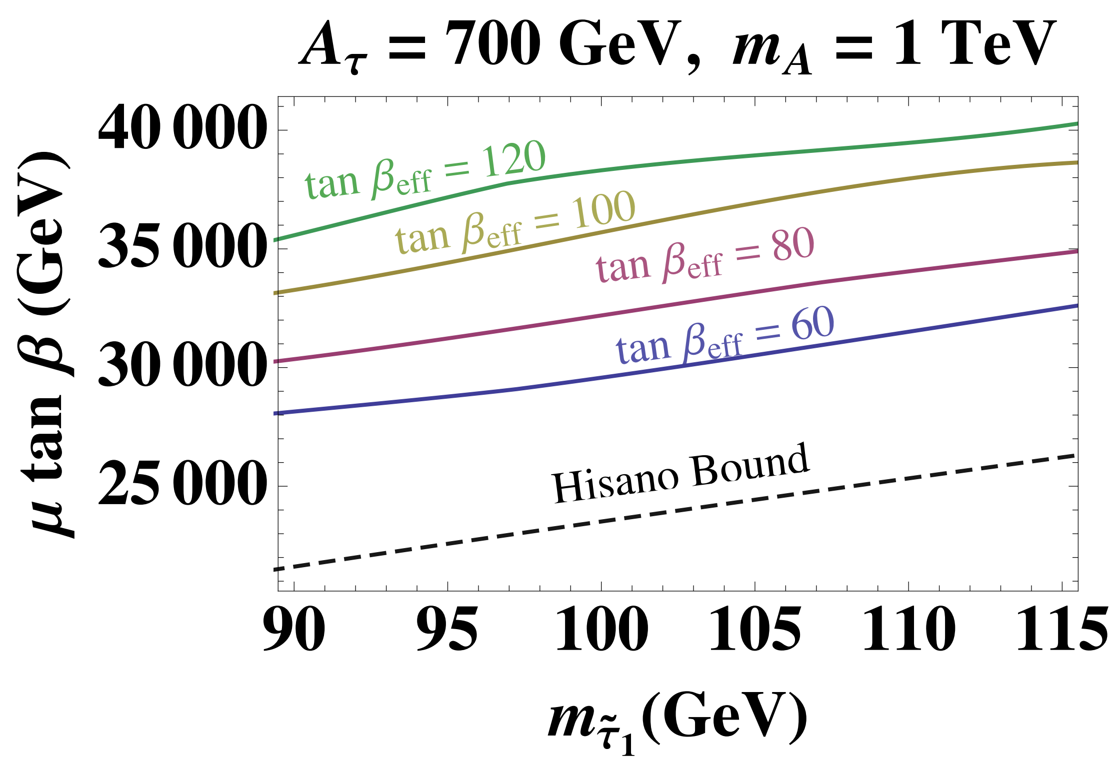
Effective values include one loop correction effects, and it is different for bottoms as for tau leptons. In the following, we refer to the tau one.

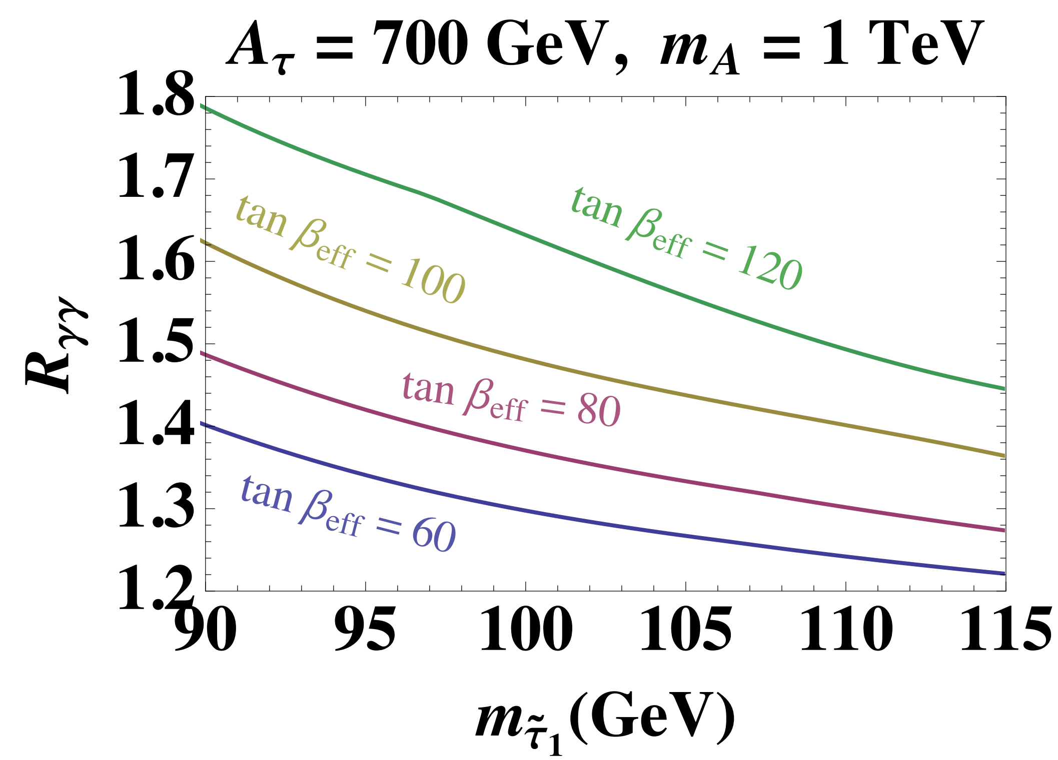
$$h_{b,\tau} \simeq \frac{m_b \tan\beta}{v(1+\Delta_{b,\tau})}, \qquad (\tan\beta_{\rm eff})_{b,\tau} = \frac{\tan\beta}{(1+\Delta_{b,\tau})}$$

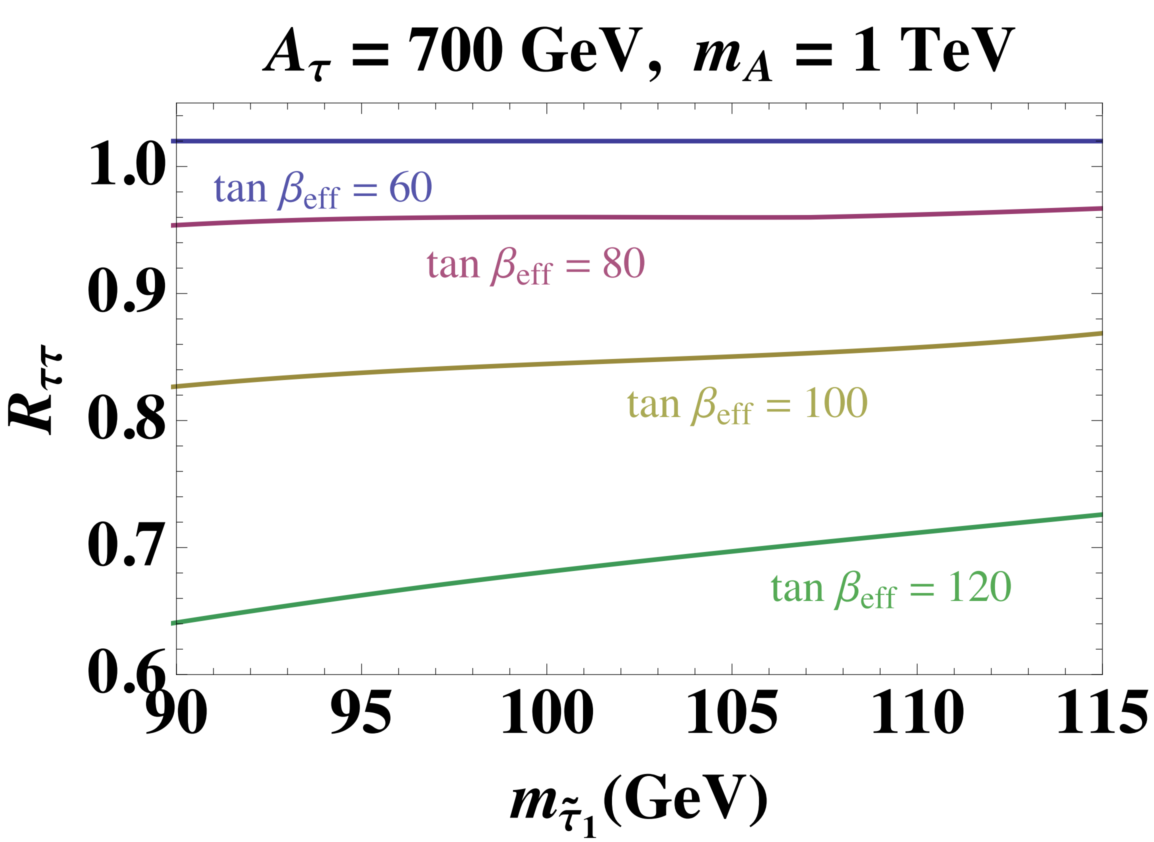
S. Gori, I. Low, N. Shah, M. Carena, C.E.M.W.'12



Inclusion of Mixing in the CP-even Higgs sector







[CPsuperH : arXiv:1208.2212]

S. Gori, I. Low, N. Shah, M. Carena, C.E.M.W.'12

$$\frac{g_{hbb}}{g_{h\tau\tau}} = \frac{m_b(1+\Delta_\tau)\,(1-\Delta_b/(\tan\beta\tan\alpha))}{m_\tau(1+\Delta_b)\,(1-\Delta_\tau/(\tan\beta\tan\alpha))}.$$

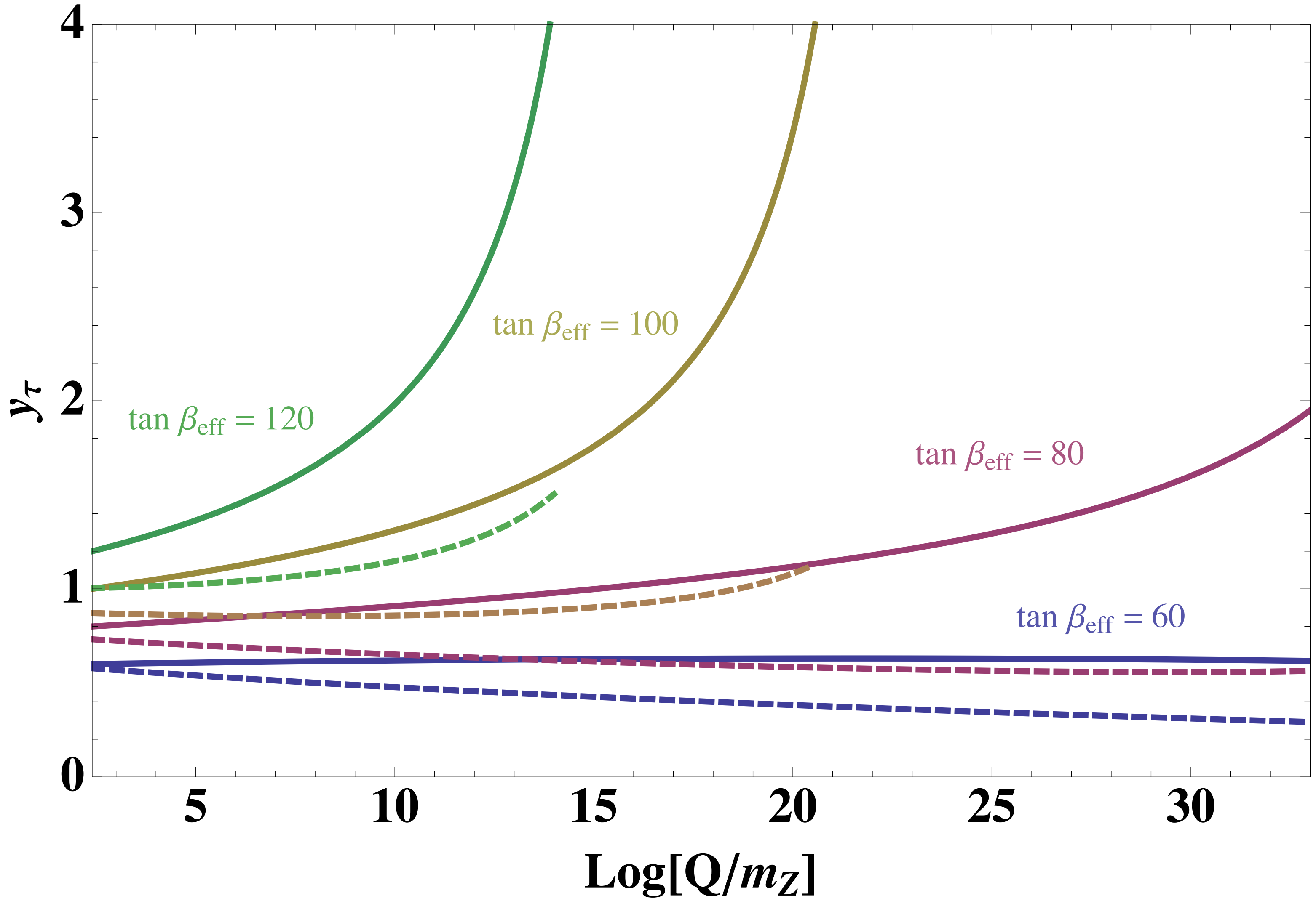
Branching ratio of decay into bottom quarks remain larger than 95 percent

Calculated with FeynHiggs (no Δ_τ but full one-loop corrections.)

New CPsuperH includes all Δ_f.
Leads to similar gamma gamma rates, but slightly smaller τ suppressions.

Evolution of Yukawa Couplings

S. Gori, I. Low, N. Shah, M. Carena, C.E.M.W.'12



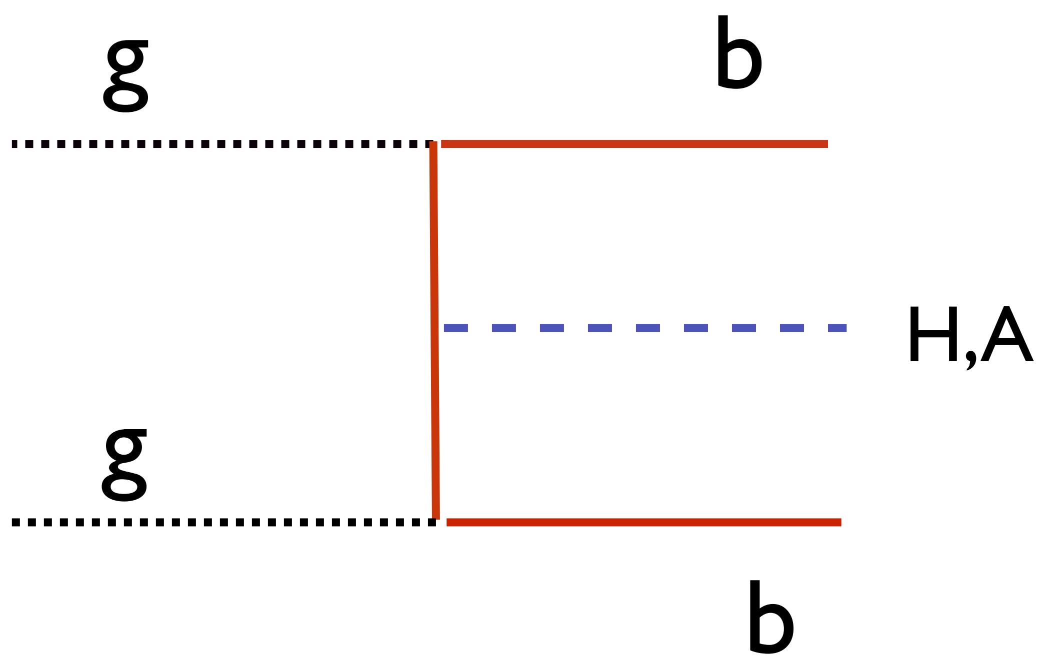
Large suppression of Higgs decay into taus, keeping metastability, may only be achieved at large values of the effective tan(beta) of tau leptons.

Values of effective tan(beta) larger than 90 imply the existence of a Landau pole before the GUT scale

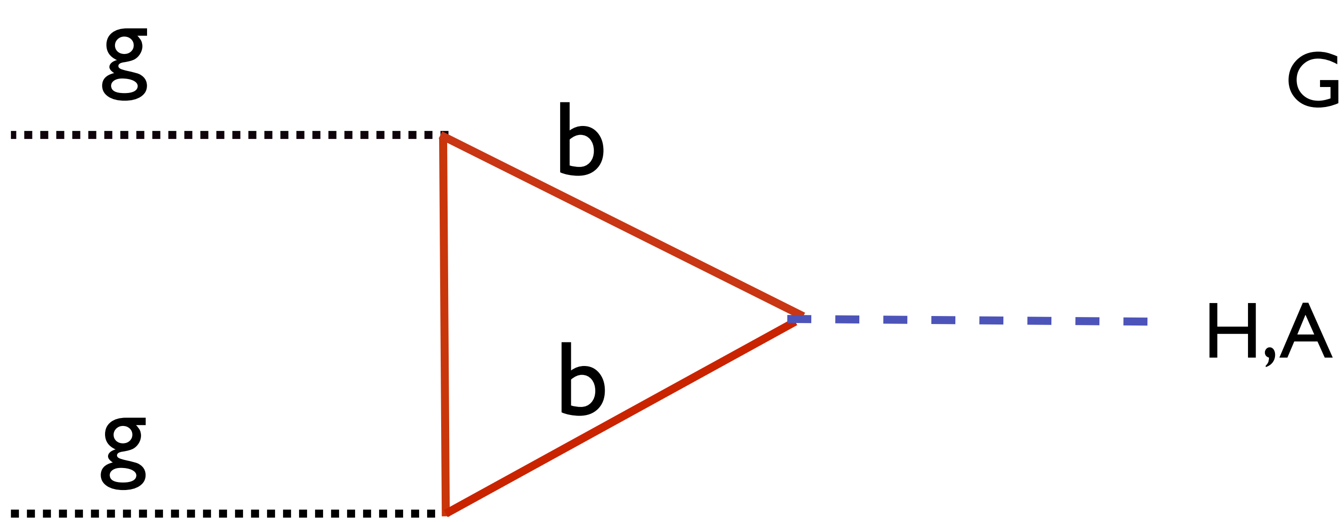
An ultraviolet completion would be therefore necessary at high scales.

Non-Standard Higgs Production

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



Associated Production



Gluon Fusion

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

Searches for non-standard Higgs bosons

M. Carena, S. Heinemeyer, G.Weiglein, C.W, EJPC'06

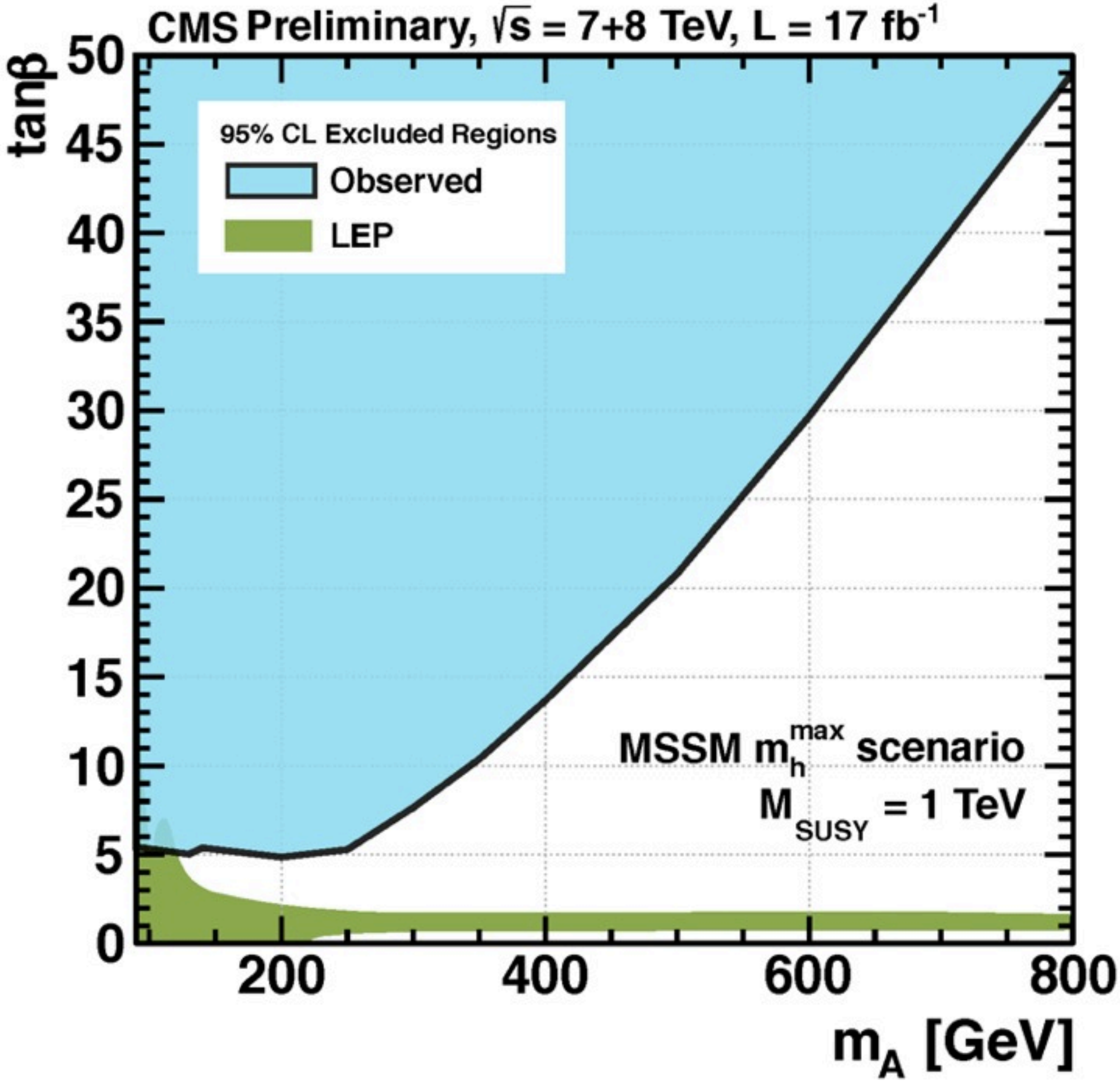
- Searches at the Tevatron and the LHC are induced by production channels associated with the large bottom Yukawa coupling.

$$\sigma(b\bar{b}A) \times BR(A \to b\bar{b}) \simeq \sigma(b\bar{b}A)_{\rm SM} \frac{\tan^2\beta}{(1+\Delta_b)^2} \times \frac{9}{(1+\Delta_b)^2 + 9}$$

$$\sigma(b\bar{b}, gg \to A) \times BR(A \to \tau\tau) \simeq \sigma(b\bar{b}, gg \to A)_{\rm SM} \frac{\tan^2\beta}{(1+\Delta_b)^2 + 9}$$

- There may be a strong dependence on the parameters in the bb search channel, which is strongly reduced in the tau tau mode.

Validity of this approximation confirmed by NLO computation by D. North and M. Spira, arXiv:0808.0087
Further work by Mhulleitner, Rzehak and Spira, 0812.3815



CMS Preliminary, √s = 7+8 TeV, L = 17 fb-1
tanβ
50
45
40
35
30
25
20
15
10
5
0
95% CL Excluded Regions
Observed
LEP
MSSM m_h^max scenario
M_SUSY = 1 TeV
200
400
600
800
m_A [GeV]