Alignment, Blind Spots and the Search for Dark Matter and new Higgs Bosons

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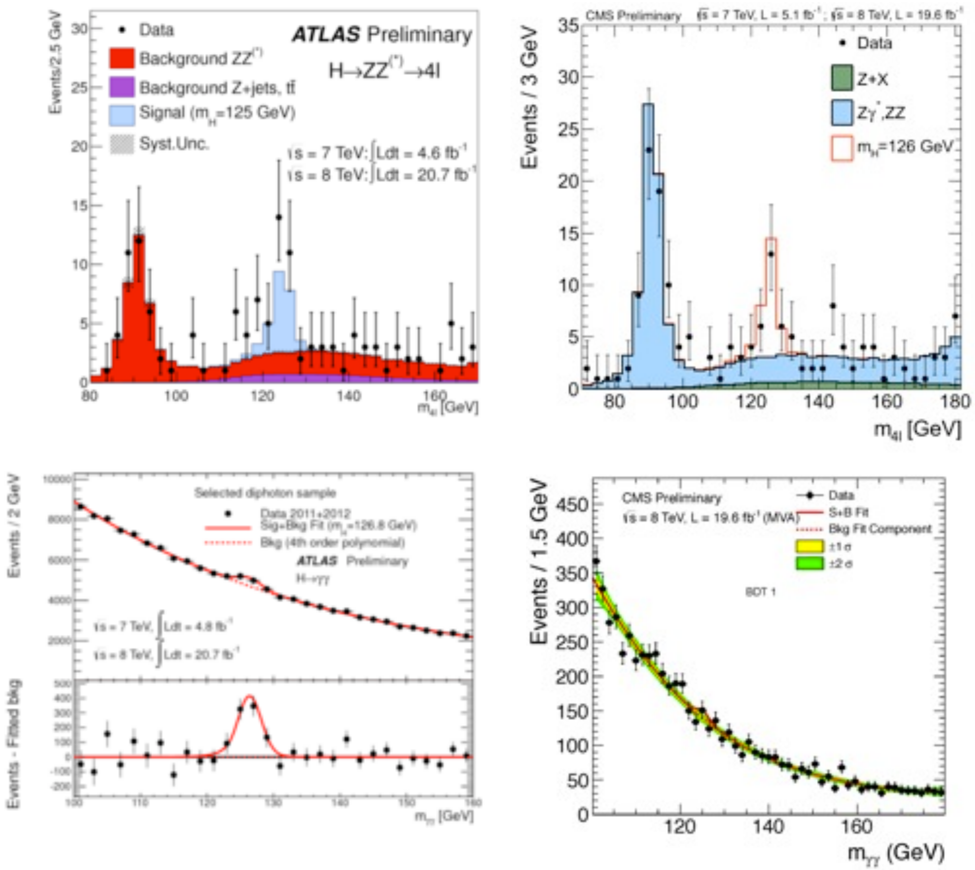
A Standard Model-like Higgs particle has been discovered by the ATLAS and CMS experiments at CERN



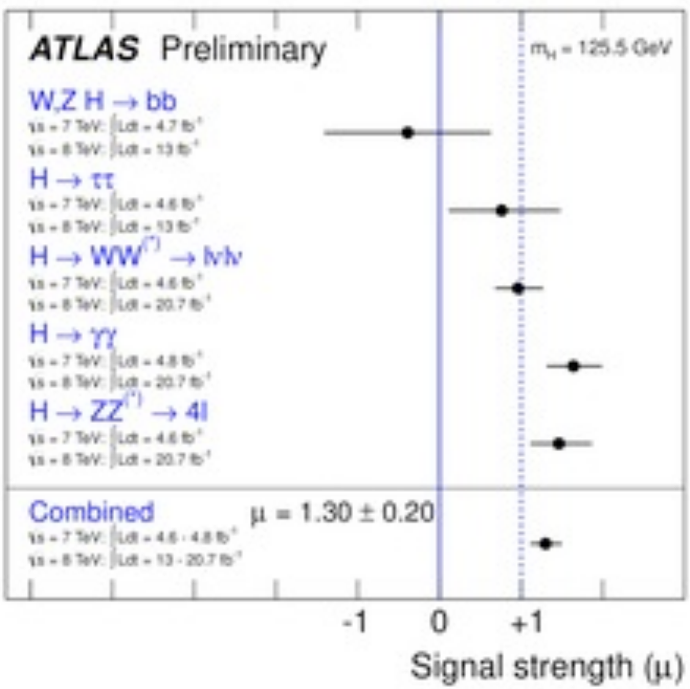
We see evidence of this particle in multiple channels.

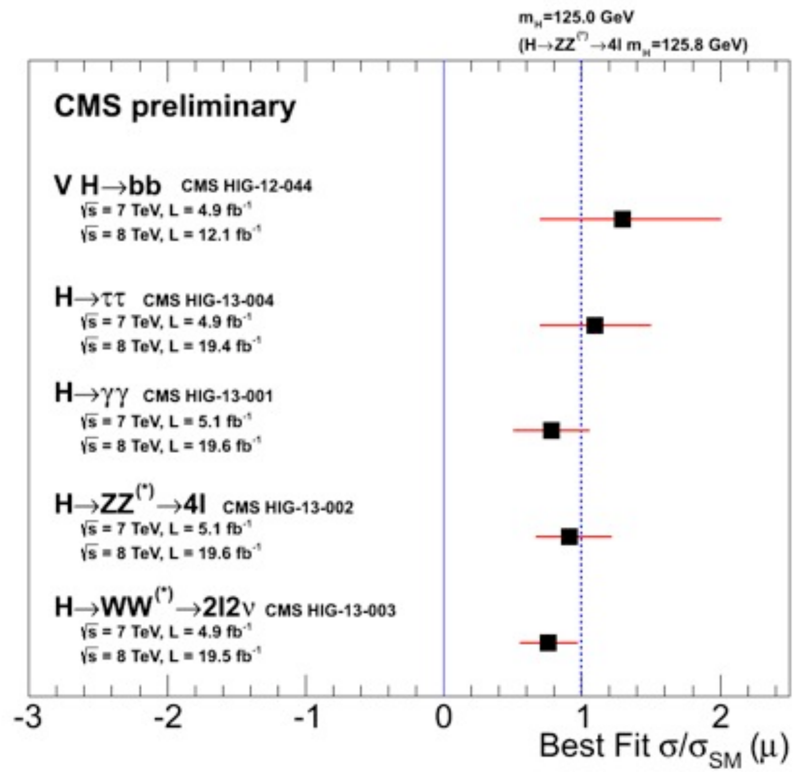
We can reconstruct its mass and we know that is about 125 GeV.

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.

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

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

$t = \log(M_{SUSY}^2/m_t^2)$ $\quad$ $\tilde{X}_t = \frac{2X_t^2}{M_{SUSY}^2}\left(1 - \frac{X_t^2}{12 M_{SUSY}^2}\right)$ $\quad$ $X_t = A_t - \mu/\tan\beta \rightarrow$ LR stop mixing

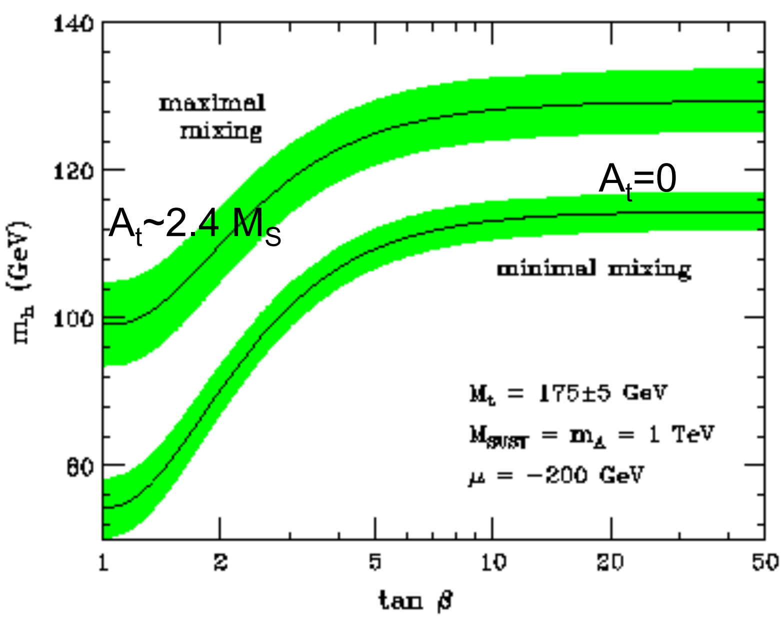
M.Carena, J.R. Espinosa, M. Quiros, C.W. '95
M. Carena, M. Quiros, C.W.'95

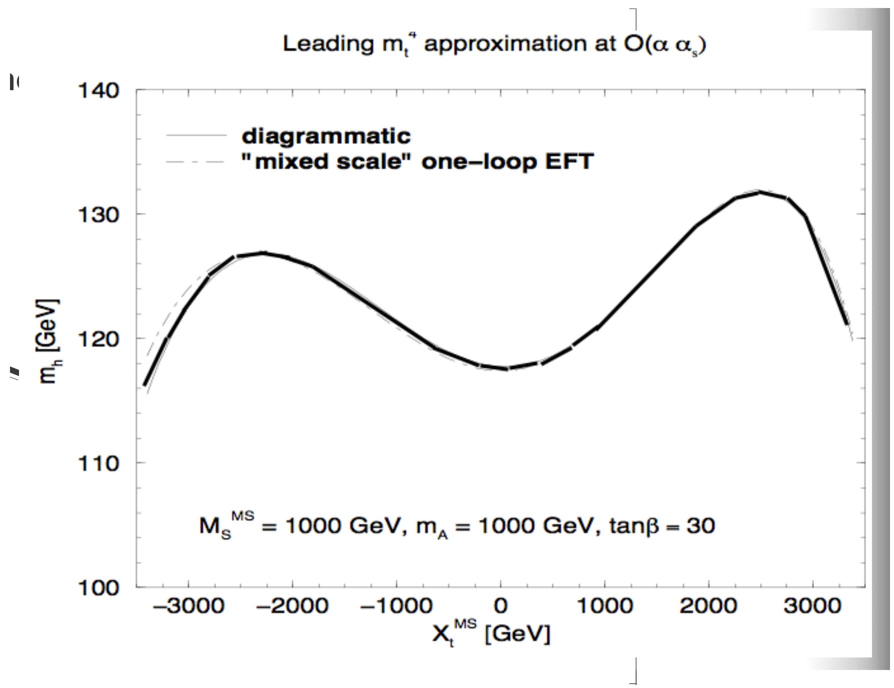
Analytic expression valid for $M_{SUSY} \sim m_Q \sim m_U$

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





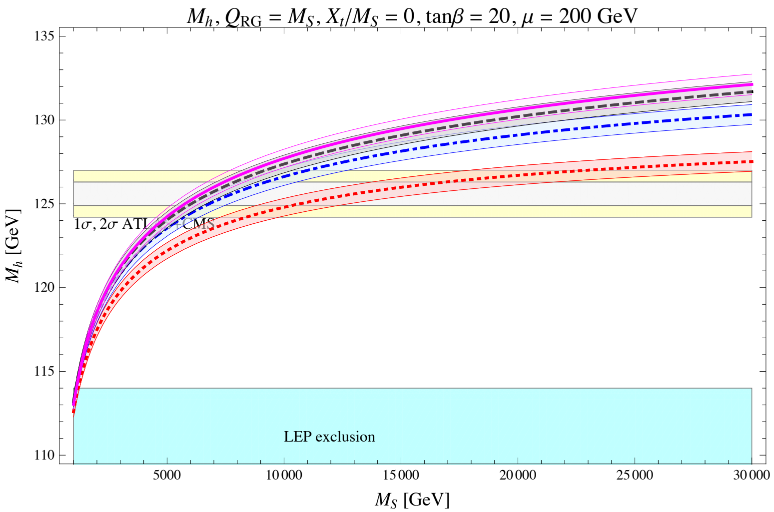
$$X_t = A_t - \mu/\tan\beta, \qquad X_t = 0 : \text{ No mixing}; \quad X_t = \sqrt{6}M_S : \text{ Max. Mixing}$$

Case of heavy Stops
Impact of higher loops

G. Lee, C.W'13

(See also S. Martin'07,
P. Kant, R. Harlander, L. Mihalla, M. Steinhauser'10
J. Feng, P. Kant, S. Profumo, D. Sanford.'13,)

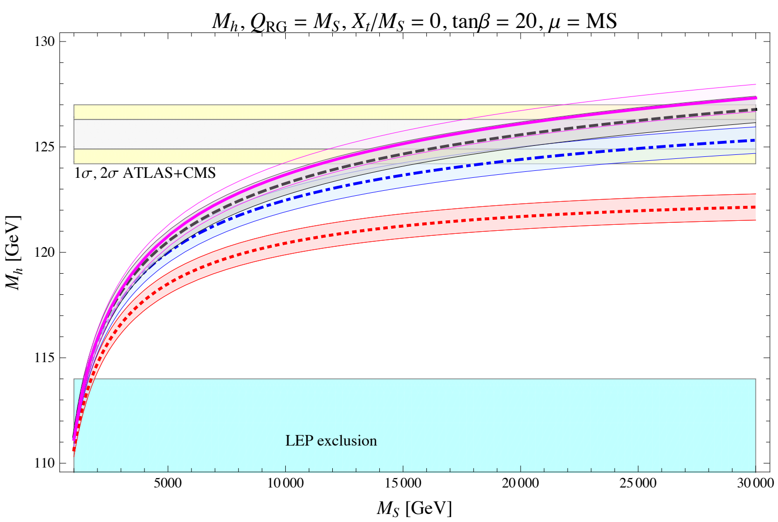
Black : Complete resummation
Orange : Two Loops
Blue : Threee Loops
Red : Four Loops

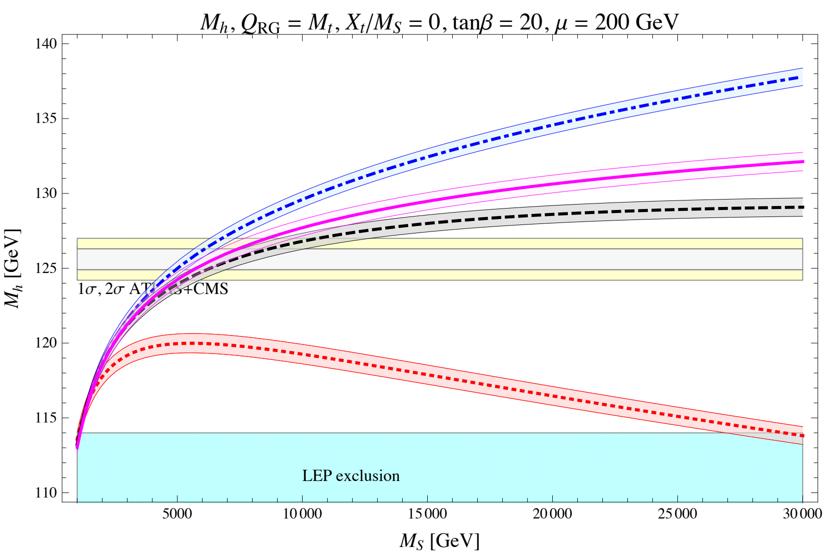


Recalculation of RG prediction including up to 4 loops in RG expansion.

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

$$\delta_4\lambda = \Big\{20736\lambda^5 + 51840\lambda^4 y_t^2 + \lambda^3 y_t^2(21600y_t^2 - 23040g_3^2)$$

$$+ \lambda^2 y_t^2(-30780y_t^4 - 18720g_3^2 y_t^2 + 14400g_3^4)$$

$$+ \lambda y_t^2(-22059y_t^6 + 28512g_3^2 y_t^4 + 10560g_3^4 y_t^2 - 10560g_3^6)$$

$$+ y_t^4(-8208y_t^6 + 56016y_t^6 g_3^2 - 84576y_t^2 g_3^4 + 44160g_3^6)\Big\}L^4$$

$$+ \Big\{48672\lambda^5 + 101808\lambda^4 y_t^2 + \lambda^3 y_t^2(30546y_t^2 - 49152g_3^2 y_t^2)$$

$$\lambda^2 y_t^2(-50292y_t^4 - 40896y_t^2 g_3^2 + 45696g_3^4)$$

$$+ \lambda y_t^2(-33903y_t^6 + 41376y_t^4 g_3^2 + 35440g_3^4 y_t^2 - 45184g_3^6)$$

$$+ y_t^4(-15588y_t^6 + 86880y_t^4 g_3^2 - 161632y_t^2 g_3^4 + 112256g_3^6)\Big\}L^3$$

$$+ \Big\{63228.2\lambda^5 + 72058.1\lambda^4 y_t^2 + \lambda^3 y_t^2(25004.6y_t^2 - 11993.5g_3^2)$$

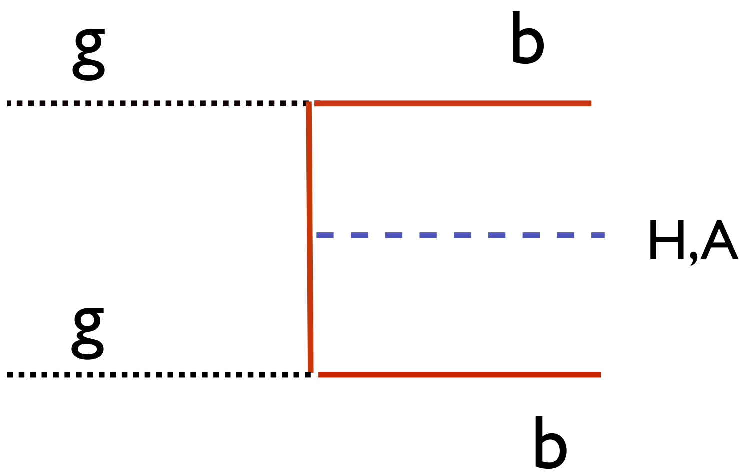
$$+ \lambda^2 y_t^2(27483.8y_t^4 - 52858y_t^2 g_3^2 + 18215.3g_3^4)$$

$$+ \lambda y_t^2(-51279y_t^6 - 5139.56y_t^4 g_3^2 + 50795.3y_t^2 g_3^4 - 33858.8g_3^6)$$

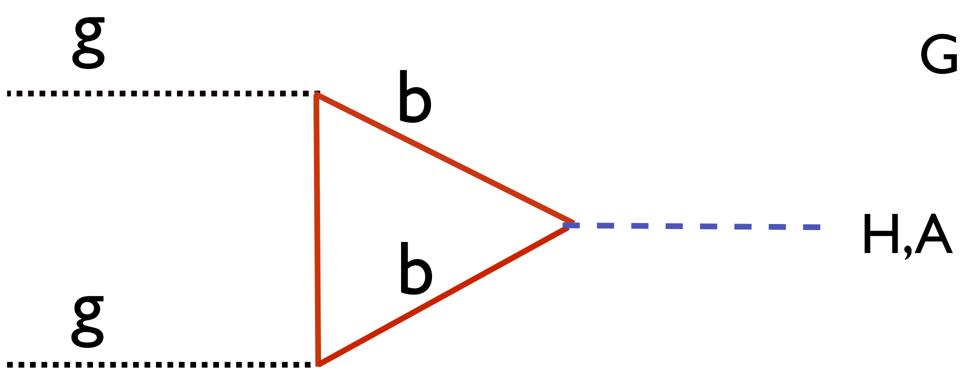
$$y_t^4(-24318.2y_t^6 + 72896y_t^4 g_3^2 - 73567.3y_t^2 g_3^4 + 36376.5g_3^6)\Big\}L^2.$$

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.

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

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

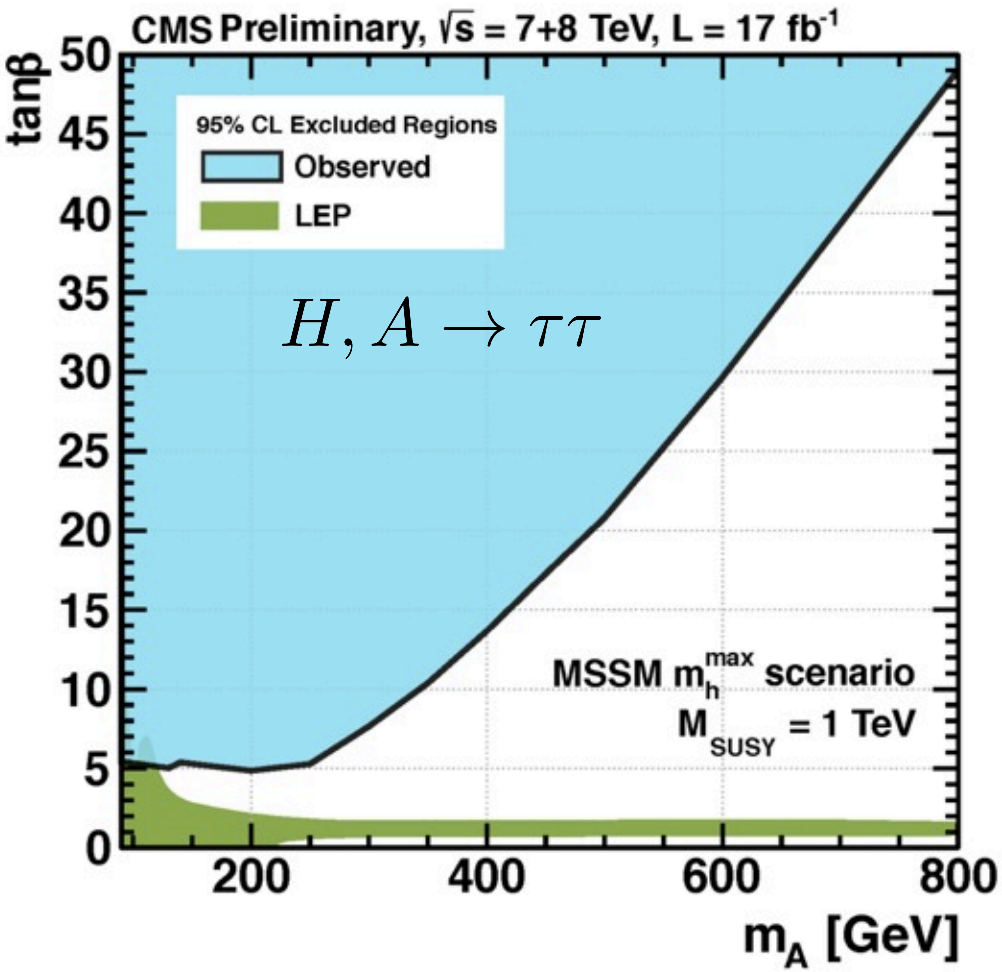
- There may be a strong dependence on the parameters in the bb search channel, which is strongly reduced in the tau tau mode.

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

Below the top threshold or at moderate or large tanβ (last term associated with light staus) :

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

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.

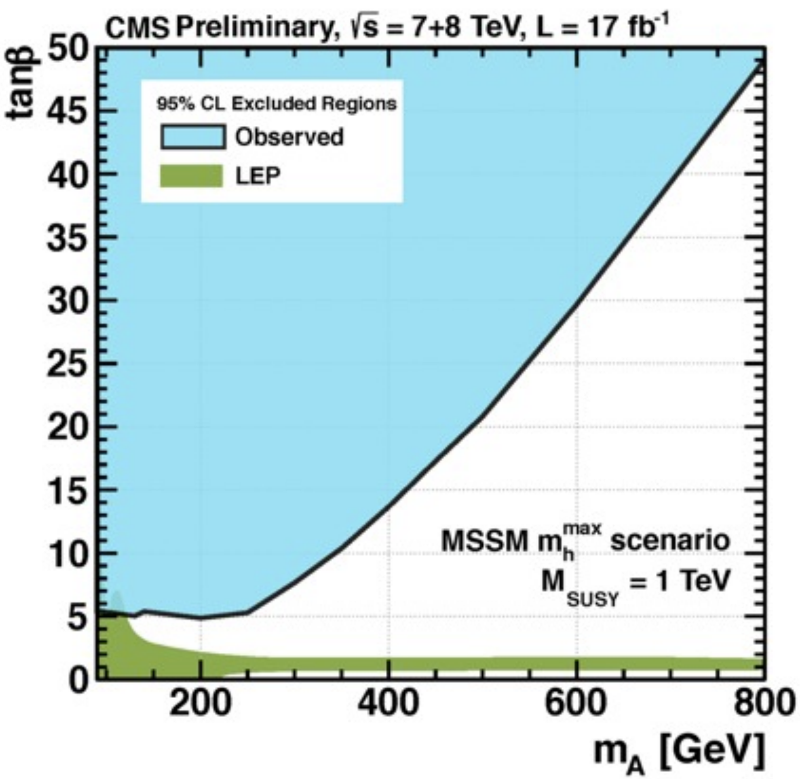
Can change in couplings help there ?

It depends on radiative corrections

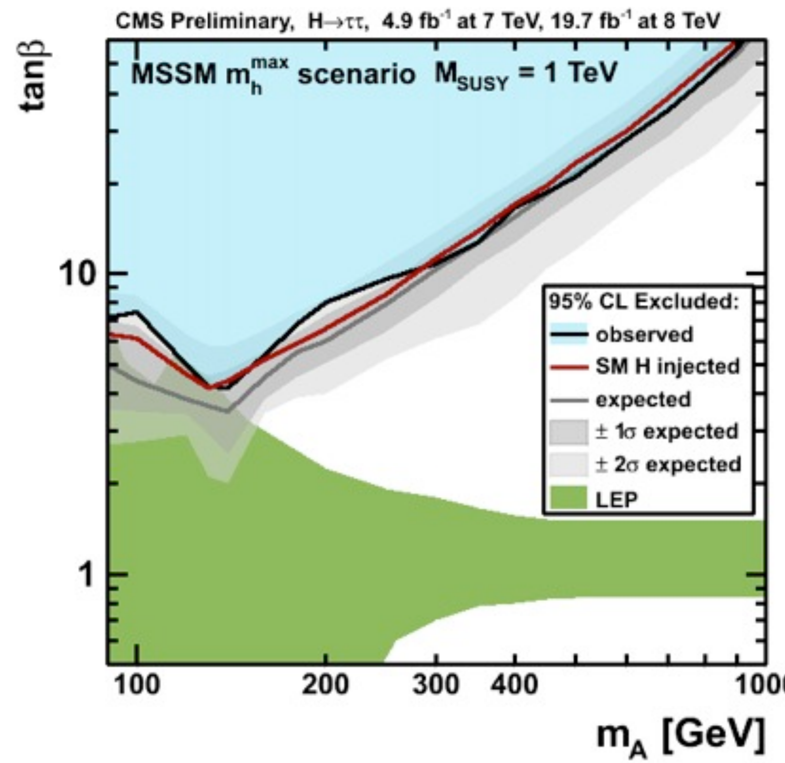
See
Carena, Haber, Logan, Mrenna '01

Small differences in final analysis... Small excess at 200 GeV and tanβ of order 10 ?

Large mixing will affect the SM-like Higgs behavior. Can we control these mixing effects ?



Bounds used



Final results

Alignment in two Higgs Doublet Models

Carena, Low, Shah, Wagner'13

Understanding Jack

Gunion, Haber '03

Alignment in General two Higgs Doublet Models

H. Haber and J. Gunion'03

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

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

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

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

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

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

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

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

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

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

CP-even Higgs Mixing Angle and Alignment

M. Carena, I. Low, N. Shah, C.W.', arXiv:1310.2248

$$\sin\alpha = \frac{\mathcal{M}_{12}^2}{\sqrt{\mathcal{M}_{12}^4 + (\mathcal{M}_{11}^2 - m_h^2)^2}}$$

$$-\tan\beta\ \mathcal{M}_{12}^2 = (\mathcal{M}_{11}^2 - m_h^2) \longrightarrow \sin\alpha = -\cos\beta$$

Condition independent of the CP-odd Higgs mass.

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

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 $\lambda_1, \tilde{\lambda}_3 < \lambda_{\rm SM}$

Deviations from Alignment

$$c_{\beta-\alpha} = t_\beta^{-1}\eta\ , \qquad s_{\beta-\alpha} = \sqrt{1 - t_\beta^{-2}\eta^2}$$

The couplings of down fermions are not only the ones that dominate the Higgs width but also tend to be the ones which differ at most from the SM ones

$$g_{hVV} \approx \left(1 - \frac{1}{2}t_\beta^{-2}\eta^2\right) g_V\ , \qquad g_{HVV} \approx t_\beta^{-1}\eta\ g_V\ ,$$

$$g_{hdd} \approx (1-\eta)\, g_f\ , \qquad g_{Hdd} \approx t_\beta(1 + t_\beta^{-2}\eta) g_f$$

$$g_{huu} \approx (1 + t_\beta^{-2}\eta)\, g_f\ , \qquad g_{Huu} \approx -t_\beta^{-1}(1-\eta) g_f$$

For small departures from alignment, the parameter η can be determined as a function of the quartic couplings and the Higgs masses

$$\eta = s_\beta^2\left(1 - \frac{\mathcal{A}}{\mathcal{B}}\right) = s_\beta^2\frac{\mathcal{B}-\mathcal{A}}{\mathcal{B}}\, , \qquad \mathcal{B}-\mathcal{A} = \frac{1}{s_\beta}\left(-m_h^2 + \tilde{\lambda}_3 v^2 s_\beta^2 + \lambda_7 v^2 s_\beta^2 t_\beta + 3\lambda_6 v^2 s_\beta c_\beta + \lambda_1 v^2 c_\beta^2\right)$$

$$\mathcal{B} = \frac{\mathcal{M}_{11}^2 - m_h^2}{s_\beta} = \left(m_A^2 + \lambda_5 v^2\right) s_\beta + \lambda_1 v^2 \frac{c_\beta}{t_\beta} + 2\lambda_6 v^2 c_\beta - \frac{m_h^2}{s_\beta}$$

Down Fermion Couplings for small values of μ

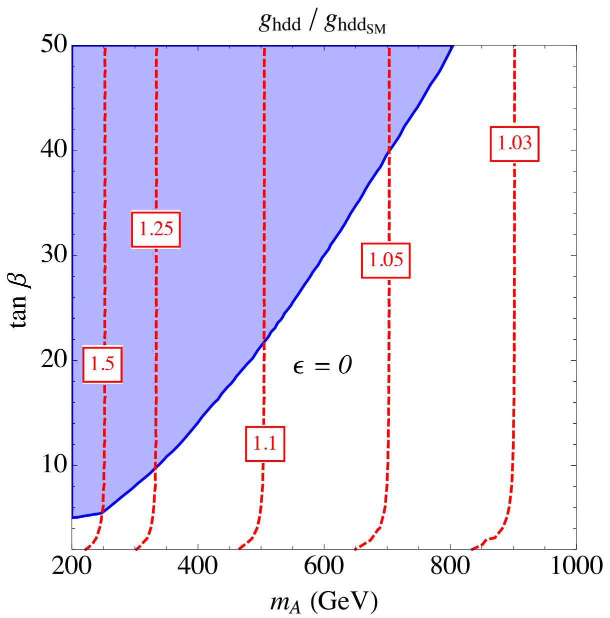
Only Loop22 relevant
(stop contribution)

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

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

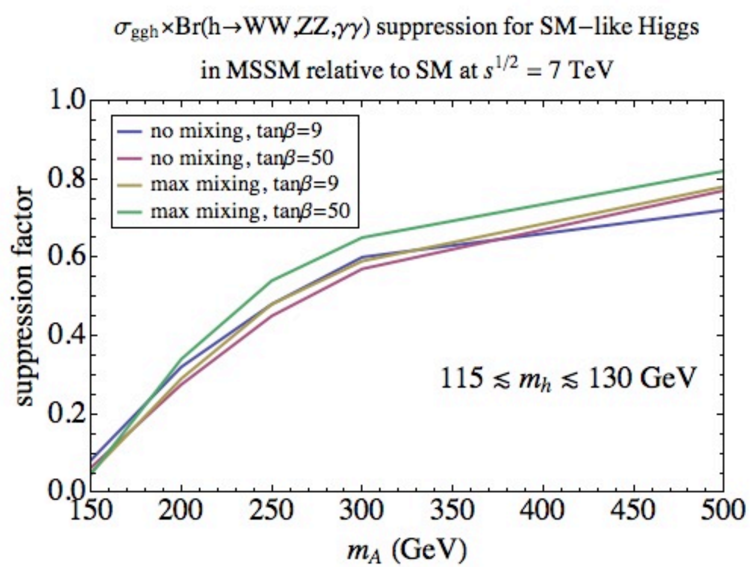
$$\sin\alpha \simeq -\cos\beta \left(\frac{m_A^2 + M_Z^2}{m_A^2 - m_h^2} \right)$$

Suppression factor in the LHC channels at the 2012--2013 run



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

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



Enhancement of bottom quark and tau couplings independent of $\tan\beta$

MSSM at large values of μ

- At large values of μ, corrections to the quartic couplings $\lambda_{5,6,7}$ become significant.

- For nonvanishing values of these couplings, a new condition of alignment at large $\tan\beta$ is obtained

$$\tan\beta = \frac{\lambda_{\rm SM} - \tilde{\lambda}_3}{\lambda_7}, \qquad \lambda_2 \simeq \lambda_{\rm SM}$$

- Alignment for $\tan\beta \simeq 10$ may be obtained, making difficult the test of the "wedge" by coupling variations.

Impact and Size of Loop Corrections

Considering

$$\Delta L_{12} = \lambda_7, \qquad \Delta\tilde{L}_{12} = \Delta\left(\lambda_3 + \lambda_4\right), \qquad \Delta L_{11} = \lambda_5, \qquad \Delta L_{22} = \lambda_2.$$

The condition of alignment reads

$$\tan\beta \simeq \frac{\lambda_{\rm SM} - \tilde{\lambda}_3^{\rm tree} - \Delta\tilde{\lambda}_3}{\lambda_7} = \frac{120 - 32\pi^2\left(\Delta L_{11} + \Delta\tilde{L}_{12}\right)}{32\pi^2 \Delta L_{12}}$$

where the loop corrections are approximately given by

$$v^2 \Delta L_{12} \simeq \frac{v^2}{32\pi^2}\left[h_t^4 \frac{\mu \tilde{A}_t}{M_{\rm SUSY}^2}\left(\frac{A_t \tilde{A}_t}{M_{\rm SUSY}^2} - 6\right) + h_b^4 \frac{\mu^3 A_b}{M_{\rm SUSY}^4} + \frac{h_\tau^4}{3}\frac{\mu^3 A_\tau}{M_{\tilde{\tau}}^4}\right],$$

$$v^2 \Delta\tilde{L}_{12} \simeq \frac{v^2}{16\pi^2}\left[h_t^4 \frac{\mu^2}{M_{\rm SUSY}^2}\left(3 - \frac{A_t^2}{M_{\rm SUSY}^2}\right) + h_b^4 \frac{\mu^2}{M_{\rm SUSY}^2}\left(3 - \frac{A_b^2}{M_{\rm SUSY}^2}\right) + h_\tau^4 \frac{\mu^2}{3M_{\tilde{\tau}}^2}\left(3 - \frac{A_\tau^2}{M_{\tilde{\tau}}^2}\right)\right].$$

$$v^2 \Delta L_{11} \simeq -\frac{v^2}{32\pi^2}\left(\frac{h_t^4 \mu^2 A_t^2}{M_{\rm SUSY}^4} + \frac{h_b^4 \mu^2 A_b^2}{M_{\rm SUSY}^4} + \frac{h_\tau^4 \mu^2 A_\tau^2}{3M_{\tilde{\tau}}^4}\right)$$

Higgs Decay into Gauge Bosons

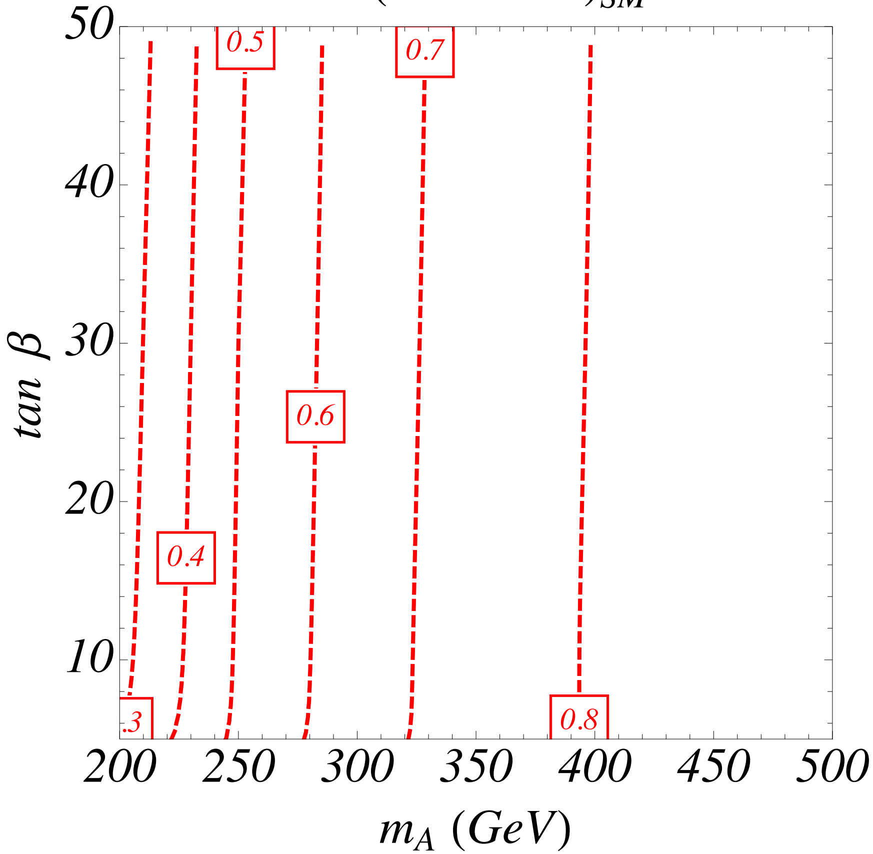
Mostly determined by the change of width

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

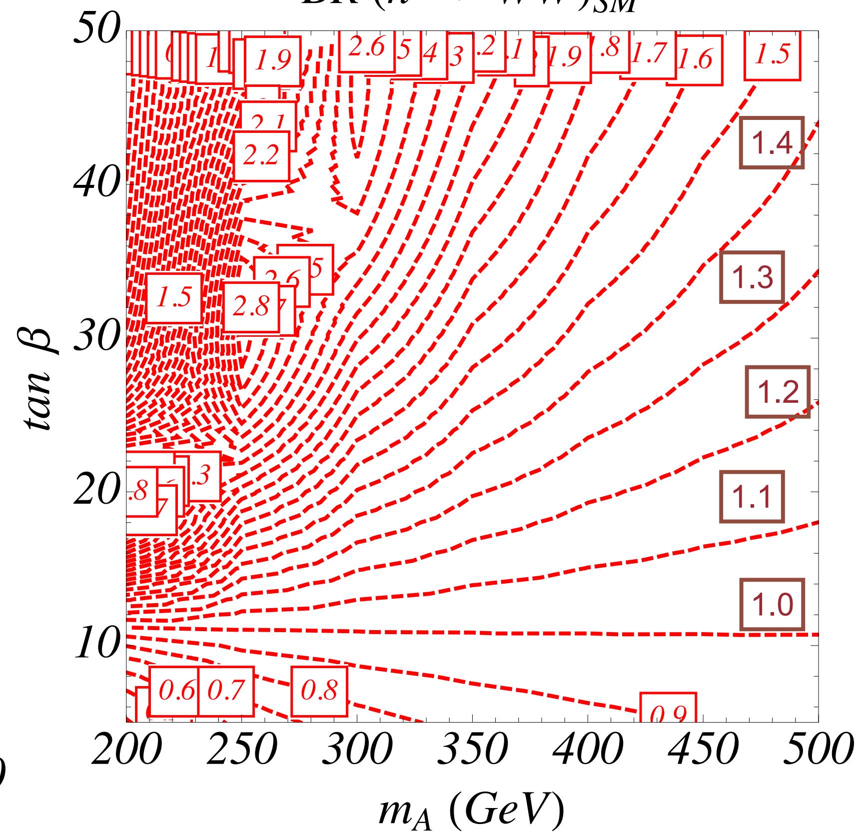
Small μ (No Alignment)

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

$$\frac{BR(h \to WW)}{BR(h \to WW)_{SM}}$$



$$\frac{BR(h \to WW)}{BR(h \to WW)_{SM}}$$



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

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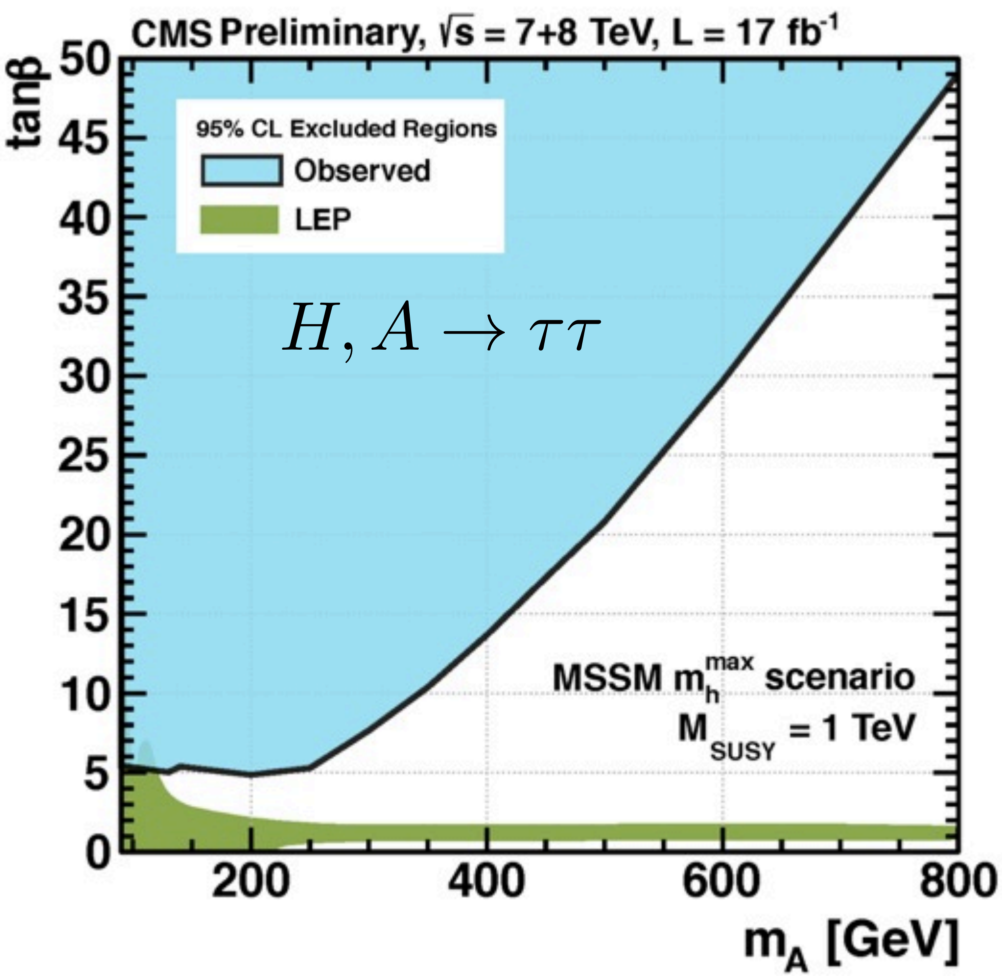

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Can change in couplings help there ?

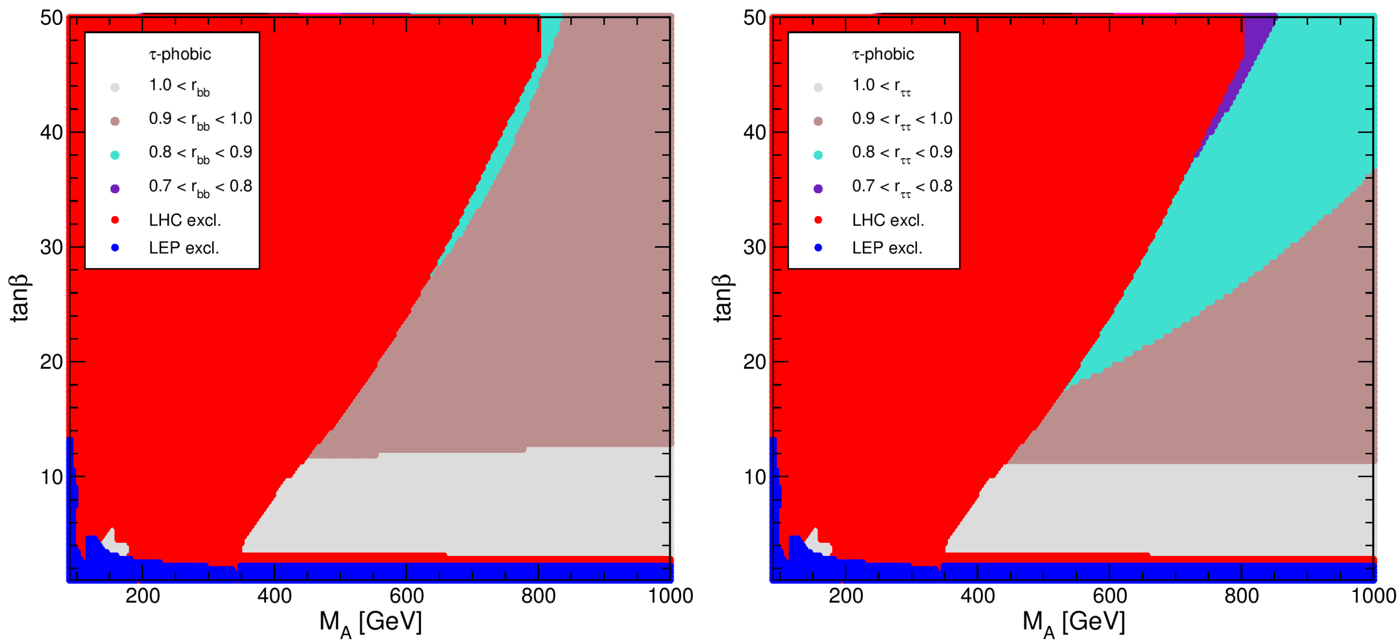
It depends on radiative corrections

See Carena, Haber, Logan, Mrenna '01

The τ-phobic Higgs scenario

(Alignment)

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

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

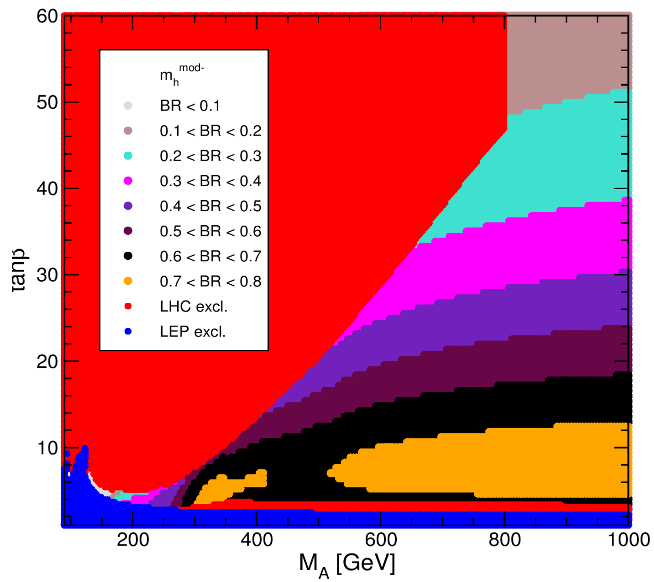
M. Carena, S. Gori, N. Shah, C.W. and L.T.Wang, arXiv:1303.4414

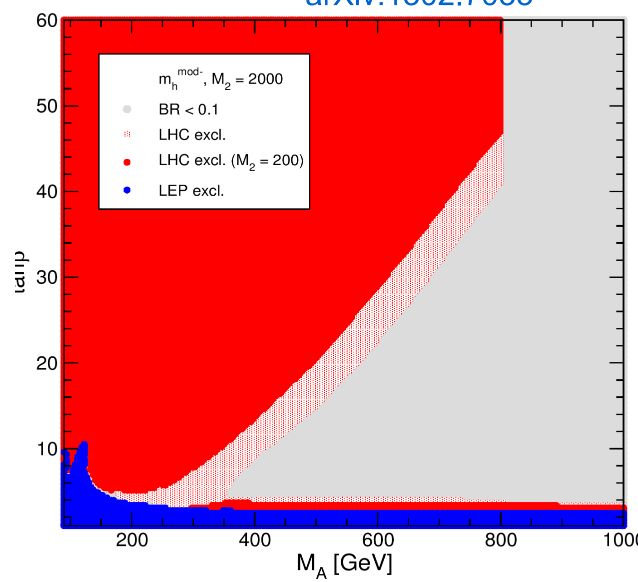
$$\sigma(pp \to (H,A) \to \tau^+\tau^-) \propto \frac{m_b^2 \tan^2\beta}{\left[\left(3\frac{m_b^2}{m_\tau^2} + \frac{(M_W^2+M_Z^2)(1+\Delta_b)^2}{m_\tau^2 \tan^2\beta}\right)(1+\Delta_\tau)^2 + (1+\Delta_b)^2\left(1+\frac{A_\tau^2}{m_A^2}\right)\right]}$$

μ=200 GeV

m_h^{mod} scenario

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





μ = 200 GeV

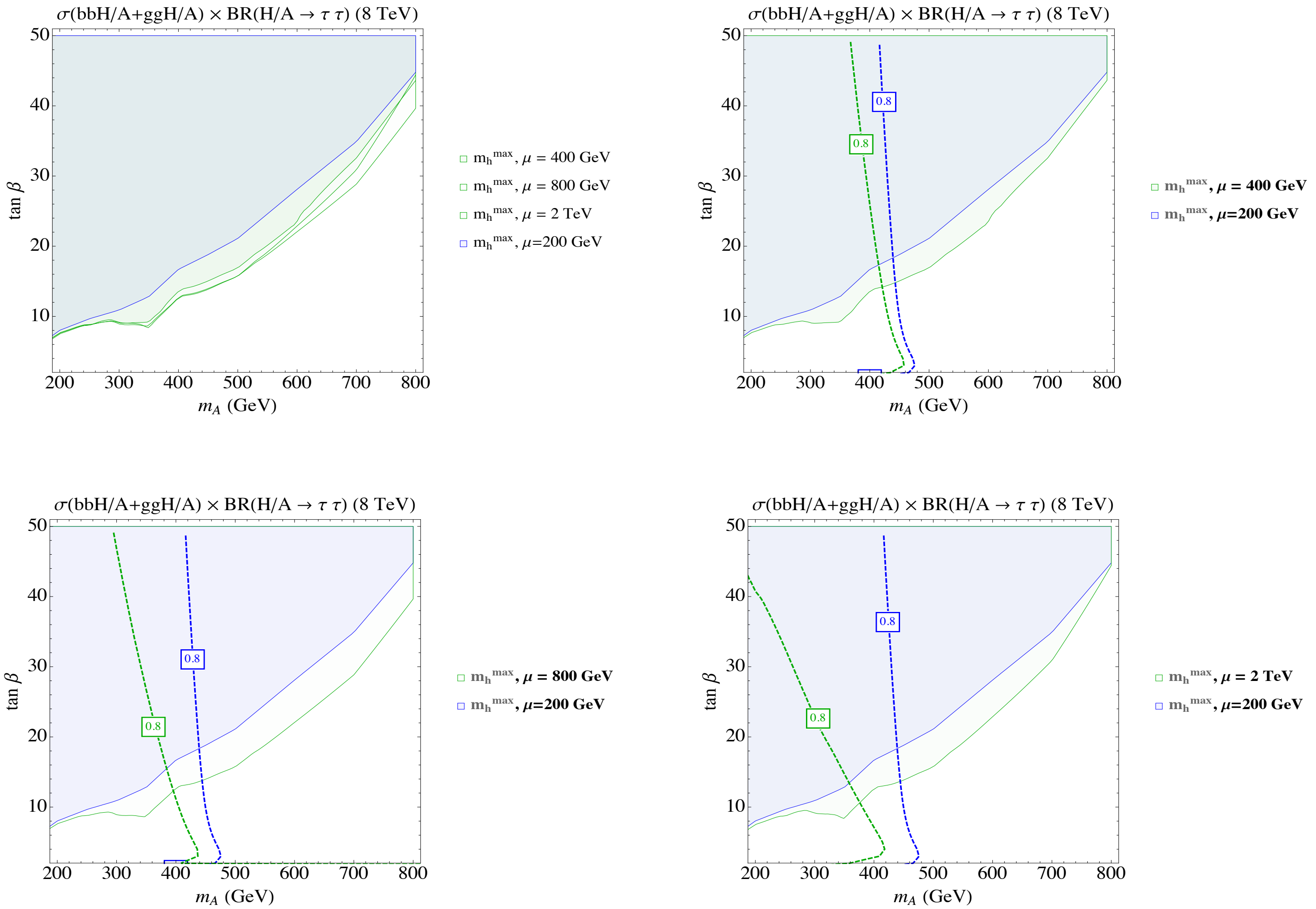
μ = 2000 GeV

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 $\tan\beta$

Precision Coupling Constraints in the mhmax Scenario

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

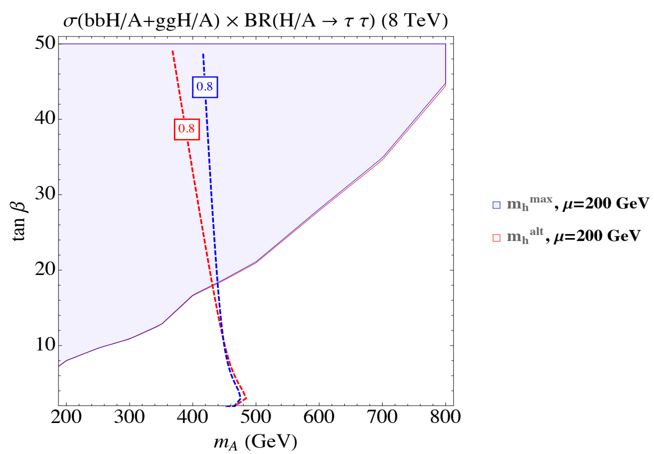


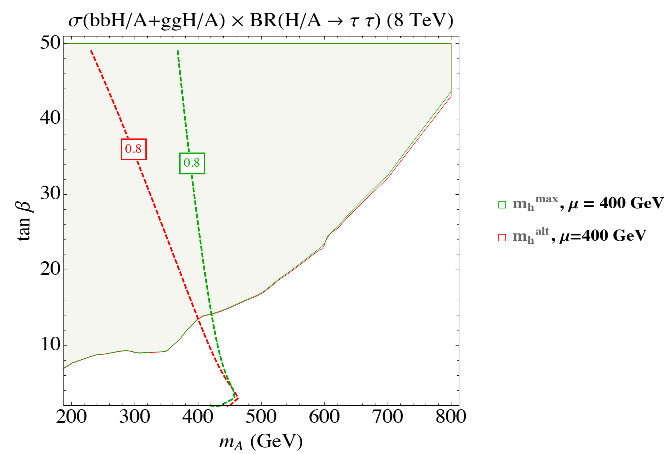
Lower bound on the CP-odd Higgs mass may be obtained

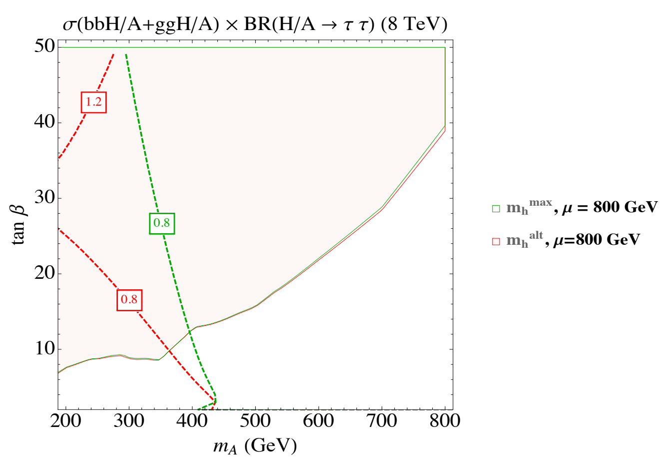
Precision Couplings in the Alignment (tauphobic) scenario

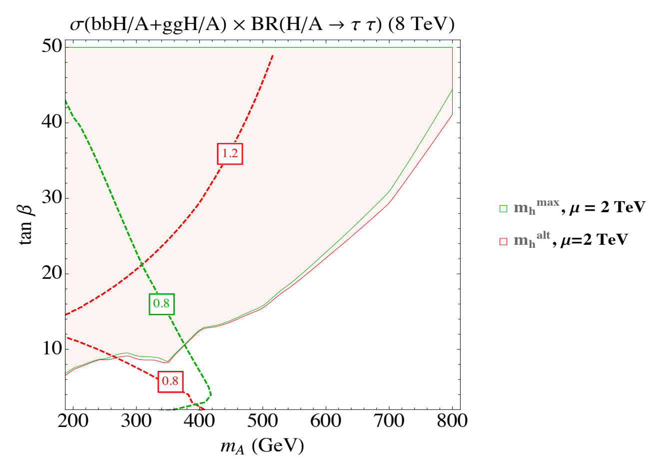
No bound on mA may be set, but complementarity with H -> τ τ searches becomes very useful. Constraints are stronger due to the absence of neutralino decays for large values of μ

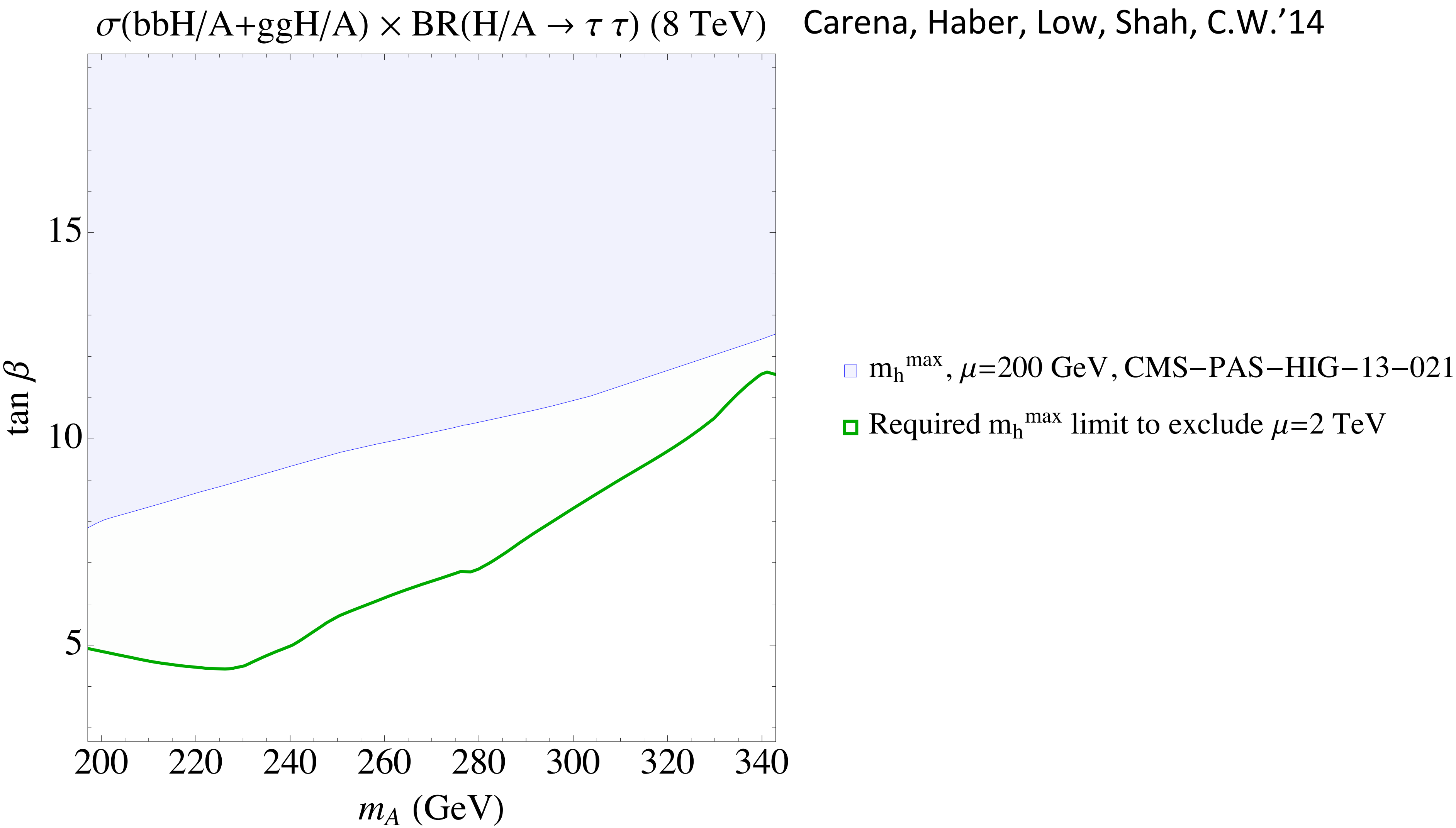
Carena, Haber, Low, Shah, C.W.'14





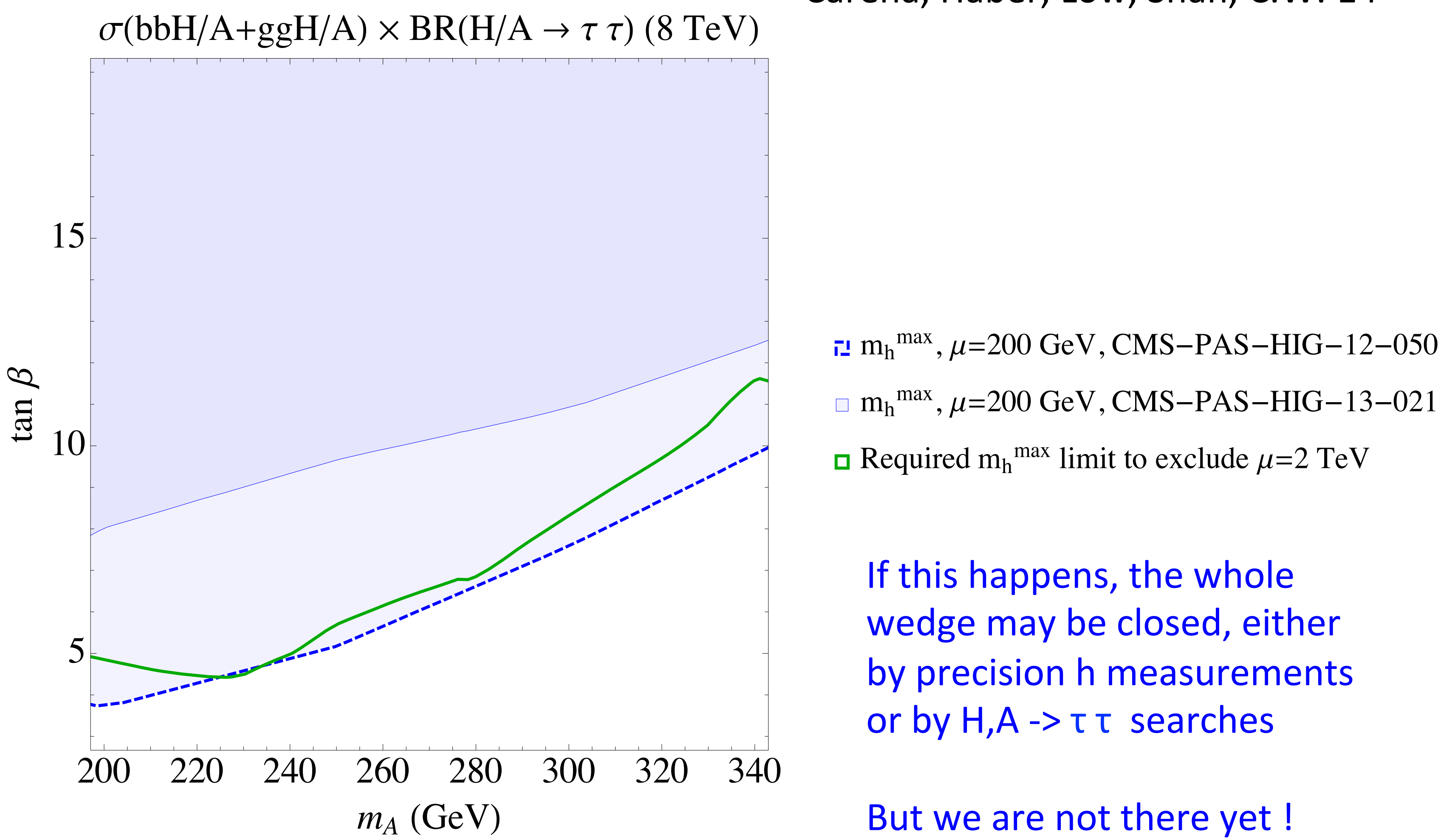





σ(bbH/A+ggH/A) × BR(H/A → τ τ) (8 TeV)
Carena, Haber, Low, Shah, C.W.'14
tan β
15
10
5
200
220
240
260
280
300
320
340
m_A (GeV)
m_h^max, μ=200 GeV, CMS−PAS−HIG−13−021
Required m_h^max limit to exclude μ=2 TeV

Bounds on tanβ in the mhmax scenario that would translate on wedge exclusion in the large μ scenario

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



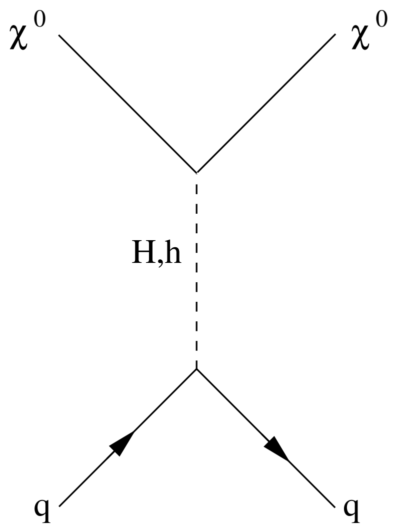
If this happens, the whole wedge may be closed, either by precision h measurements or by H,A -> τ τ searches

But we are not there yet !

Blind Spots in Direct Dark Matter Detection

Huang, C.W.'14

Spin Independent Cross Sections



Higgs and Neutralino Mixing

$$h = \frac{1}{\sqrt{2}}(\cos\alpha \; H_u - \sin\alpha \; H_d)$$
$$H = \frac{1}{\sqrt{2}}(\sin\alpha \; H_d + \cos\alpha \; H_u).$$

$$\tilde{\chi} = N_{i1} \; \tilde{B} + N_{i2} \; \tilde{W} + N_{i3} \; \tilde{H}_d + N_{i4} \; \tilde{H}_u$$

Effective Neutralino Coupling to the Higgs

$$g_{\chi\chi h} \sim (g_1 N_{i1} - g_2 N_{i2})(-\cos\alpha \; N_{i4} - \sin\alpha \; N_{i3})$$
$$g_{\chi\chi H} \sim (g_1 N_{i1} - g_2 N_{i2})(-\sin\alpha \; N_{i4} + \cos\alpha \; N_{i3})$$

Effective Amplitude of the down type quark diagram :

$$a_d \sim \frac{m_d(g_1 N_{i1} - g_2 N_{i2})}{\cos\beta}\left[N_{i4}\sin\alpha\cos\alpha\left(\frac{1}{m_h^2} - \frac{1}{m_H^2}\right) + N_{i3}\left(\frac{\sin^2\alpha}{m_h^2} + \frac{\cos^2\alpha}{m_H^2}\right)\right]$$

Neutralino Coupling and Amplitudes : Parameter Dependence

$$a_d \sim \frac{m_d(g_1 N_{i1} - g_2 N_{i2})}{\cos\beta}\left[N_{i4}\sin\alpha\cos\alpha\left(\frac{1}{m_h^2} - \frac{1}{m_H^2}\right) + N_{i3}\left(\frac{\sin^2\alpha}{m_h^2} + \frac{\cos^2\alpha}{m_H^2}\right)\right]$$

Pierce, Shah ' 14

$$N_{i3} \sim (m_\chi \cos\beta + \mu\sin\beta)$$

$$N_{i4} \sim (m_\chi \sin\beta + \mu\cos\beta)$$

Value of the effective amplitudes :

$$a_d \sim \frac{m_d}{\cos\beta}\left[\cos\beta(m_\chi + \mu\sin 2\beta)\,\frac{1}{m_h^2} - \mu\sin\beta\cos 2\beta\,\frac{1}{m_H^2}\right]$$

$$a_u \sim \frac{m_u}{\sin\beta}\left[\sin\beta(m_\chi + \mu\sin 2\beta)\,\frac{1}{m_h^2} + \mu\cos\beta\cos 2\beta\,\frac{1}{m_H^2}\right]$$

Effective Cross Sections : Parameter Dependence

Effective amplitude for Spin Independent Scattering with Nucleons

$$a_p = \left(\sum_{q=u,d,s} f_{Tq} \frac{a_q}{m_q} + \frac{2}{27} f_{TG} \sum_{q=c,b,t} \frac{a_q}{m_q} \right) m_p$$

$$F_u \equiv f_u + 2 \times \tfrac{2}{27} f_{TG} \approx 0.15 \qquad F_d = f_{Td} + f_{Ts} + \tfrac{2}{27} f_{TG} \approx 0.14$$

$$f_{Tu} = 0.017 \pm 0.008,\ f_{Td} = 0.028 \pm 0.014,\ f_{Ts} = 0.040 \pm 0.020 \text{ and } f_{TG} \approx 0.91$$

$$\sigma_p^{SI} \sim \left[(F_d + F_u)(m_\chi + \mu \sin 2\beta) \frac{1}{m_h^2} + \mu \tan\beta \cos 2\beta (-F_d + F_u / \tan^2\beta) \frac{1}{m_H^2} \right]^2$$

First term characterizes the interactions with the SM-like Higgs
Second term, interactions with the heavy Higgs

Cheung,Hall,Pinner,Ruderman'12
Huang,C.W.'14

Generalized Blind Spot :

$$2\ (m_\chi + \mu \sin 2\beta) \frac{1}{m_h^2} \simeq -\ \mu \tan\beta \frac{1}{m_H^2}$$

Cancellation of left-hand term leads to the traditional blind spot
Negative μ reduces the coupling of light Higgs and generate destructive interference between light and heavy CP-even Higgs amplitudes !

Spin Independent Cross Sections

M2 = |μ| = 2 M1 = 440 GeV

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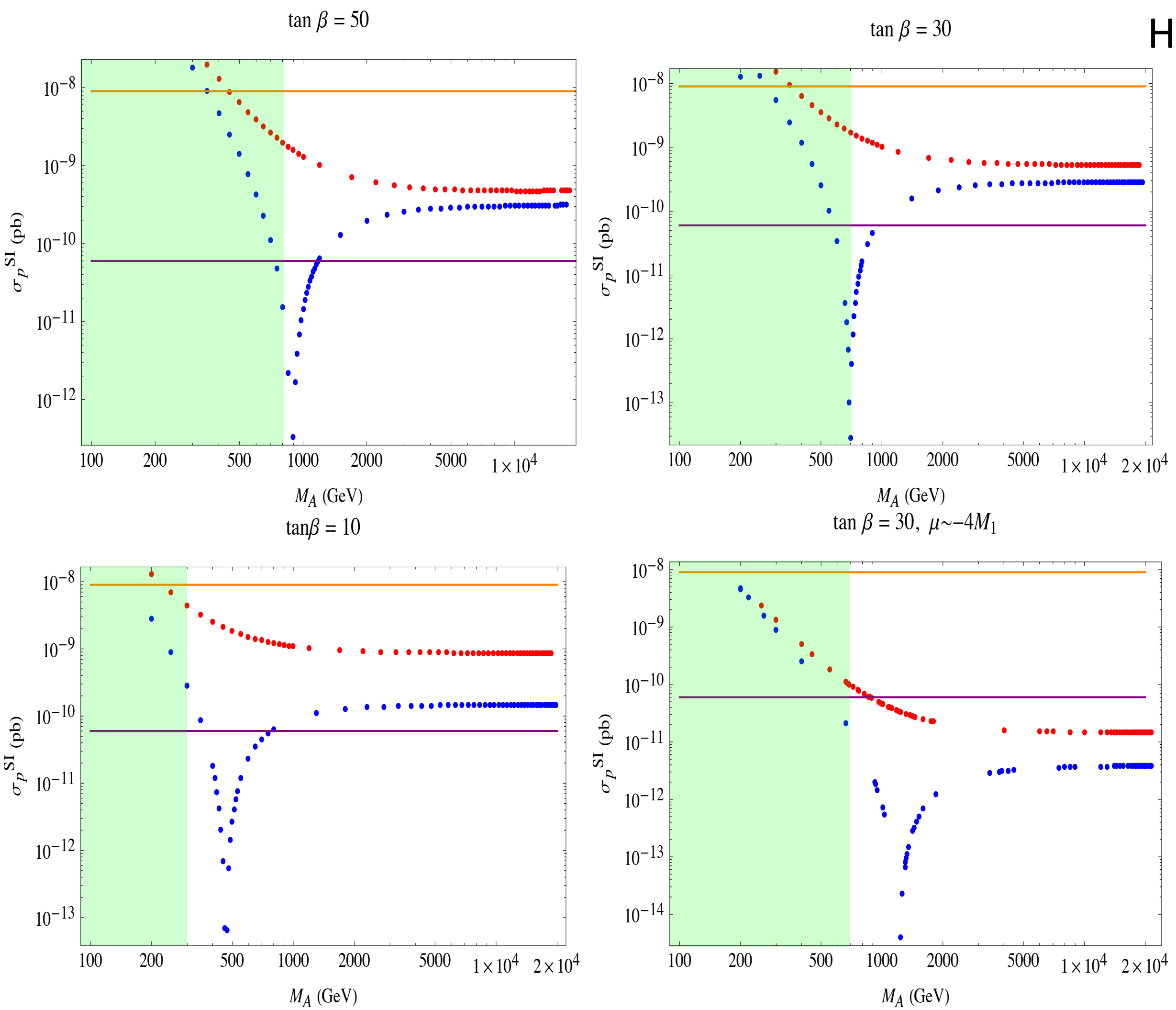
Positive μ

Negative μ

Excluded by CMS H -> τ τ

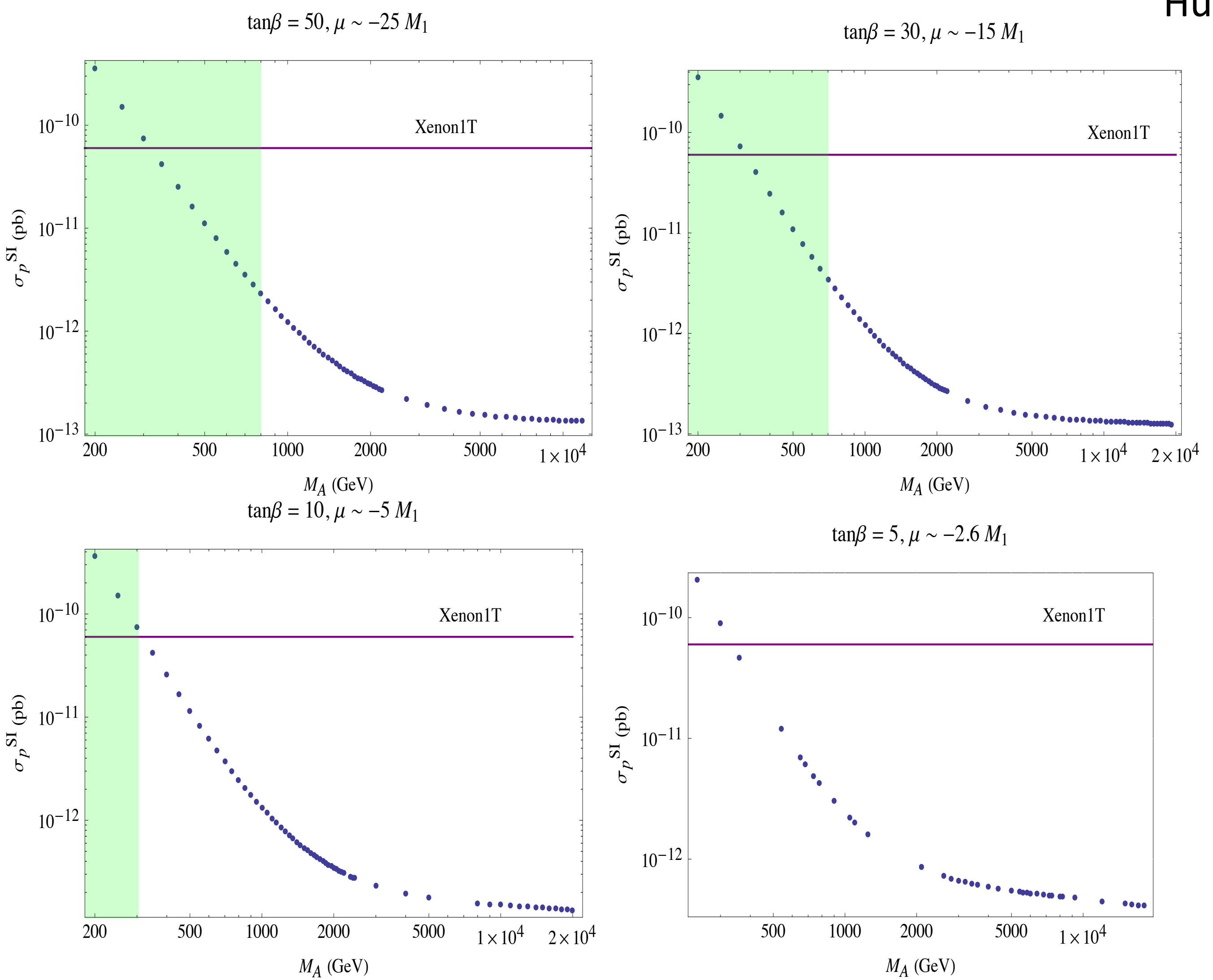


Spin Independent Cross Sections at Traditional Blind Spots

$$m_\chi + \mu \sin 2\beta = 0$$

Cheung, Hall,Pinner,Ruderman'12

Huang, C.W.'14



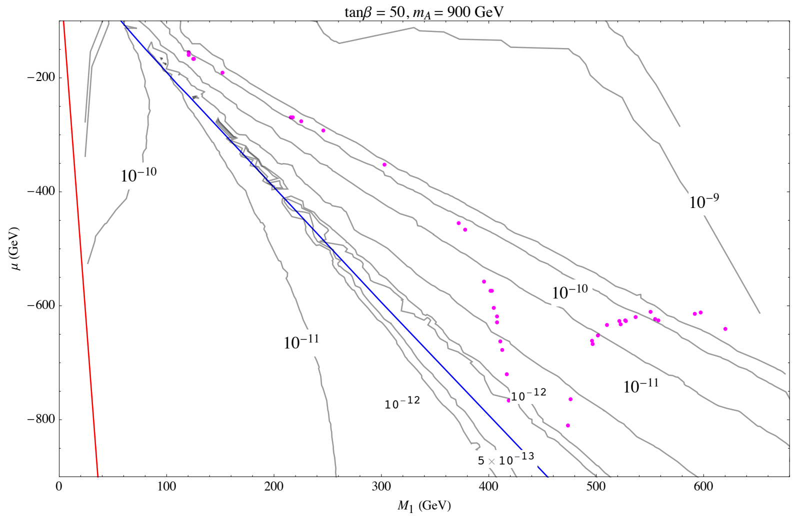
At moderate CP-odd Higgs masses and tanβ, traditional Blind Spot scenarios may be tested by future Direct DM detection experiments.

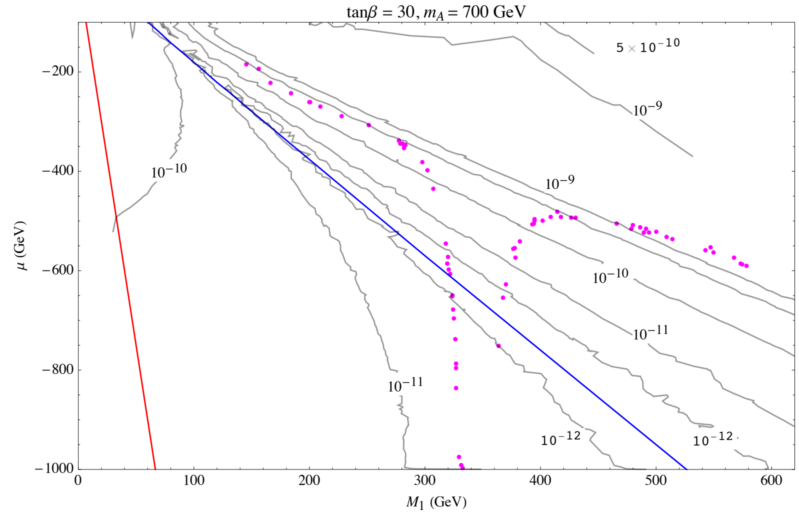
Spin Independent Cross Section and the DM Relic Density

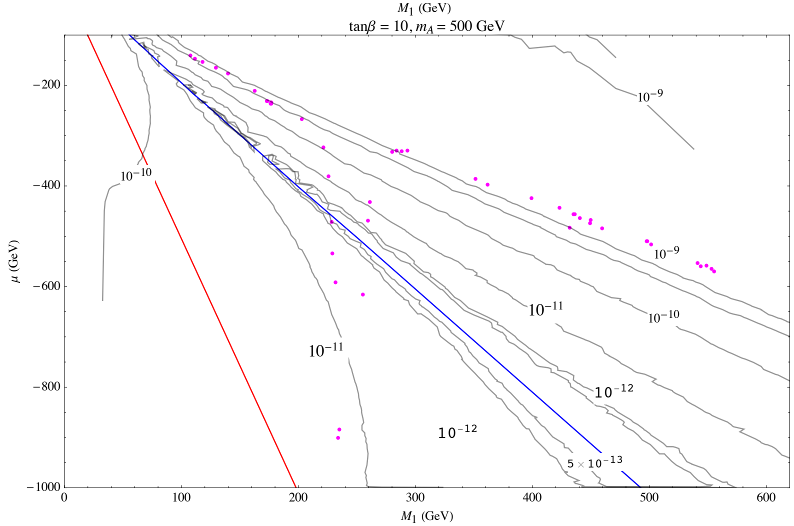
Huang, C.W.'14

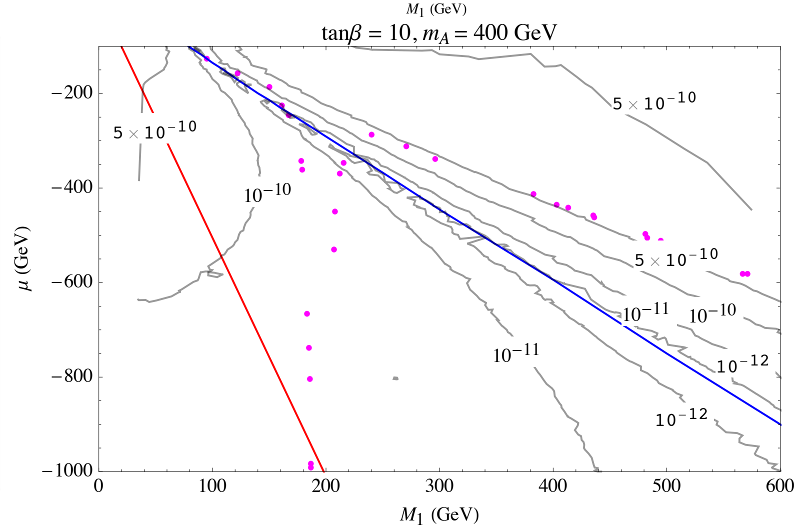
Arkani-Hamed, Guidice, Delgado'06

Traditional Blind Spots Blind Spots Relic Density









Conclusions

- Among the future studies in HEP, some of the most important are related to the search for new Higgs bosons, Dark Matter and precision Higgs couplings
- Alignment puts these Higgs searches in a new perspective. Thanks, Jack !
- Interesting complementarity in the MSSM between direct searches and precision measurement
- Direct Dark Matter detection may be affected by the presence of blind spots, which have an influence in the whole allowed MSSM parameter space for negative values of μ.

Happy Birthday Jack !