On the higher loop Corrections to the Higgs Mass in the MSSM

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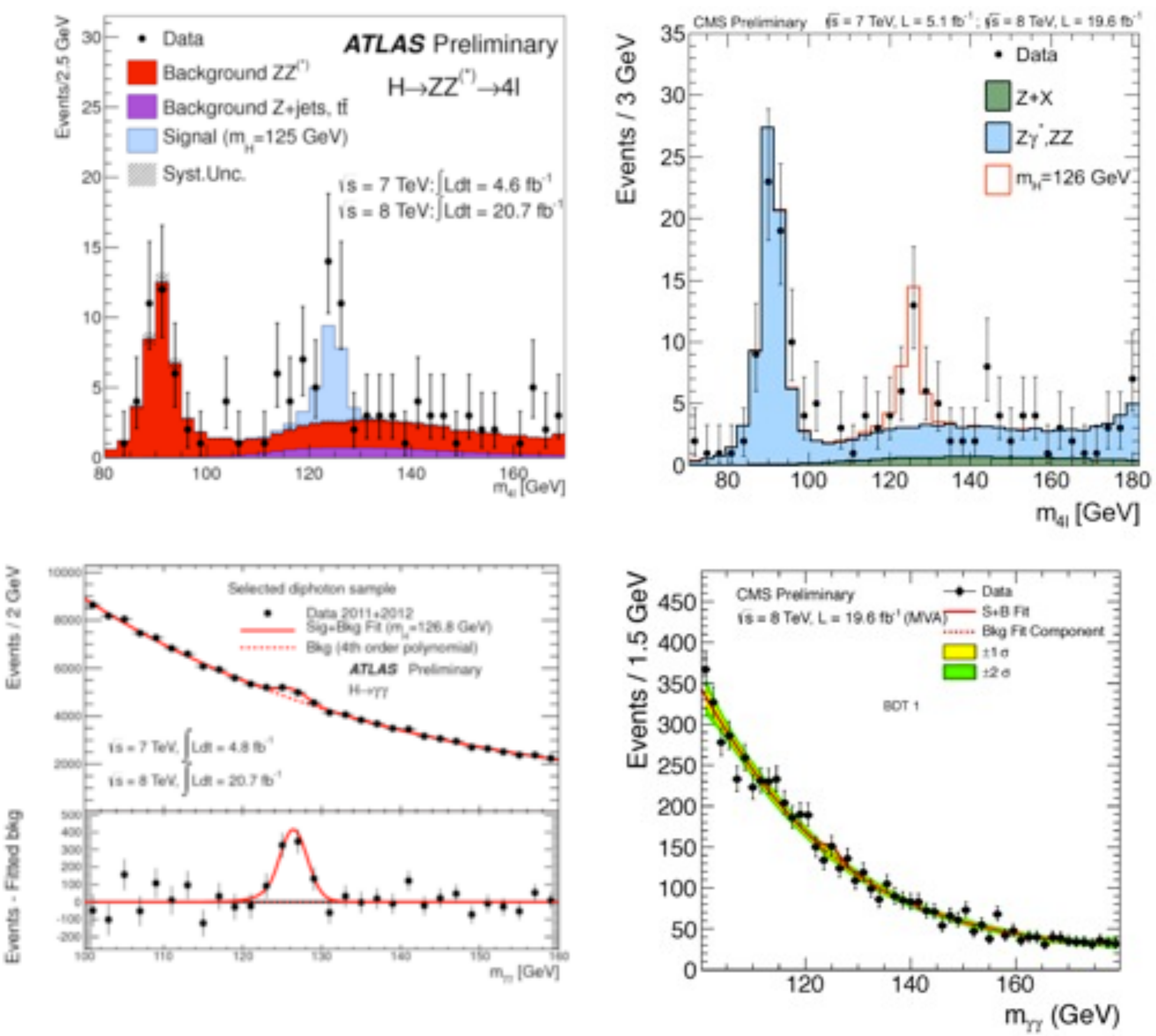
Work done in collaboration with P. Draper and G. Lee, to appear soon

Higgs Mass Workshop, Ann Arbor, Michigan, 12.14.13

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



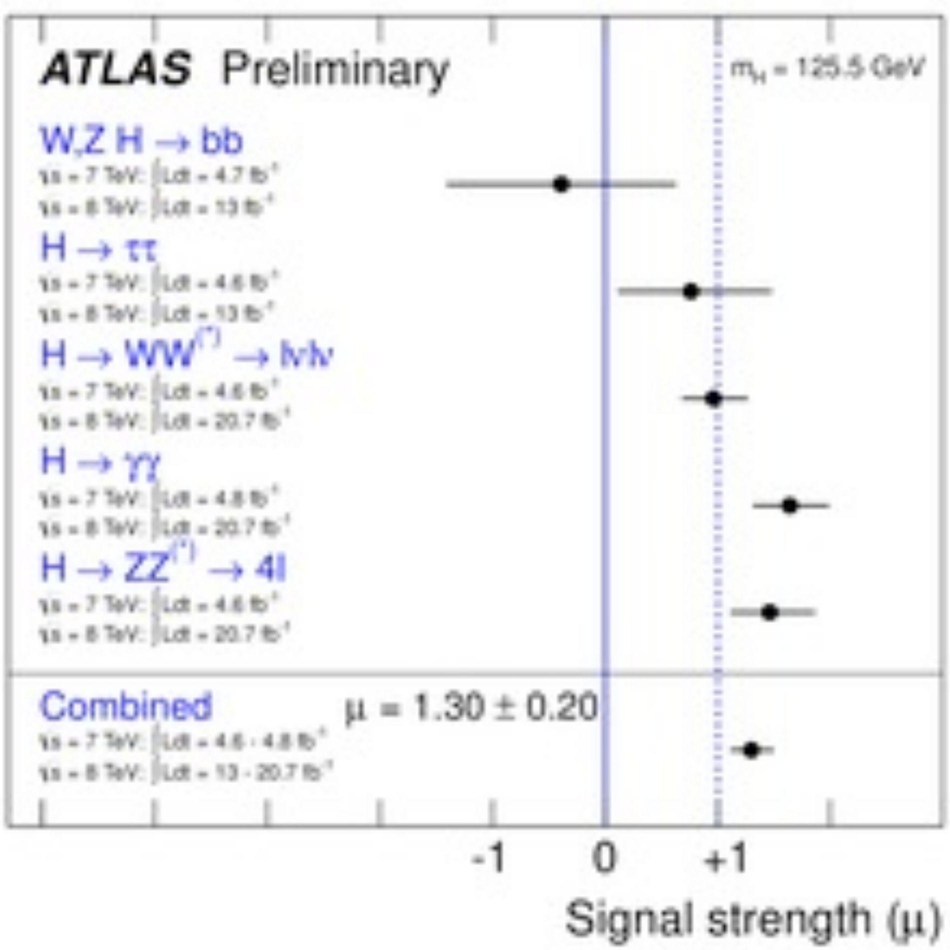
We see evidence of this particle in multiple channels.

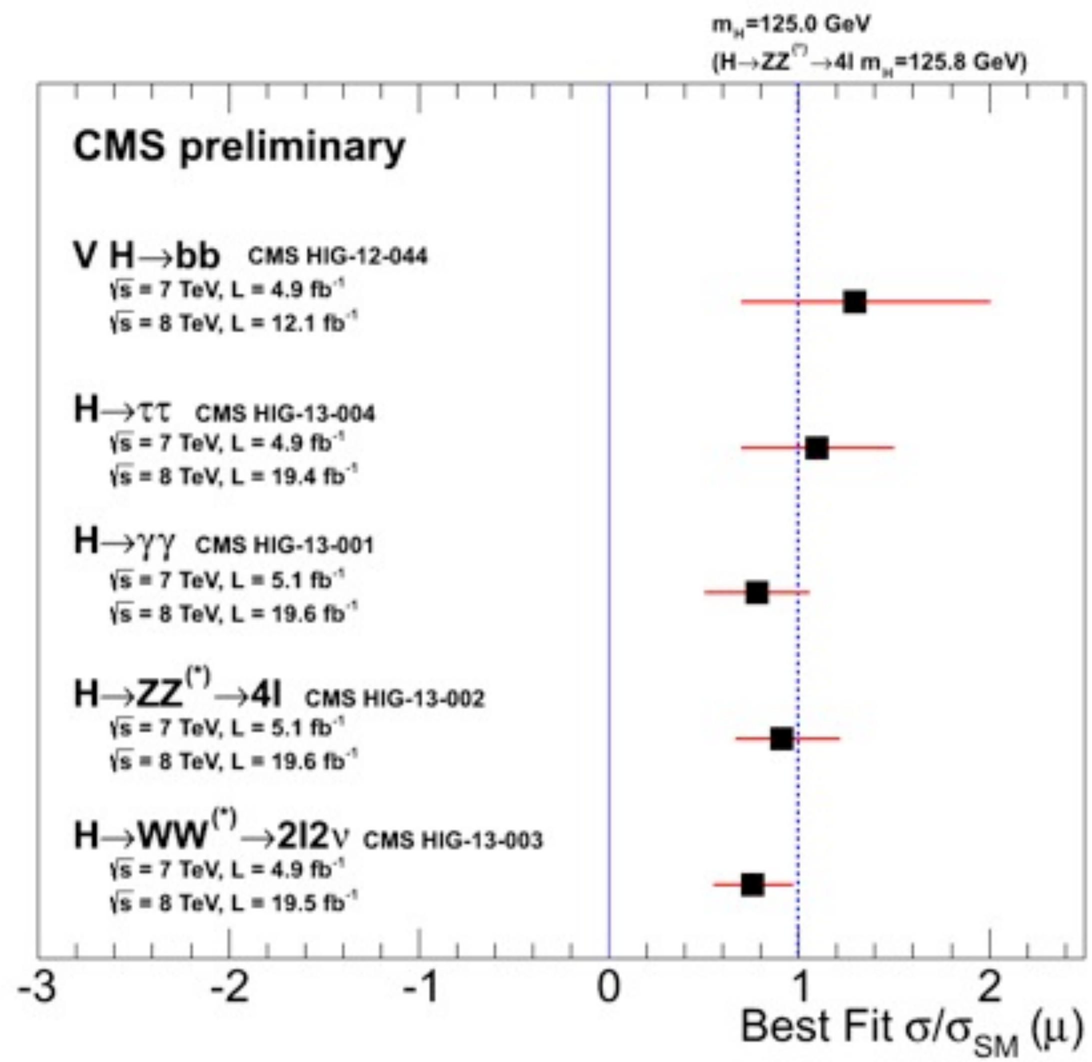
We can reconstruct its mass and we know that is about 125 GeV.

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.

Marcela talking to Peter Higgs
Fabiola Gianotti listening

With Oscar Stal, Fabiola Gianotti, Lars Brink and Paul Langacker

With legendary t'Hooft and his wife

With Brout's wife

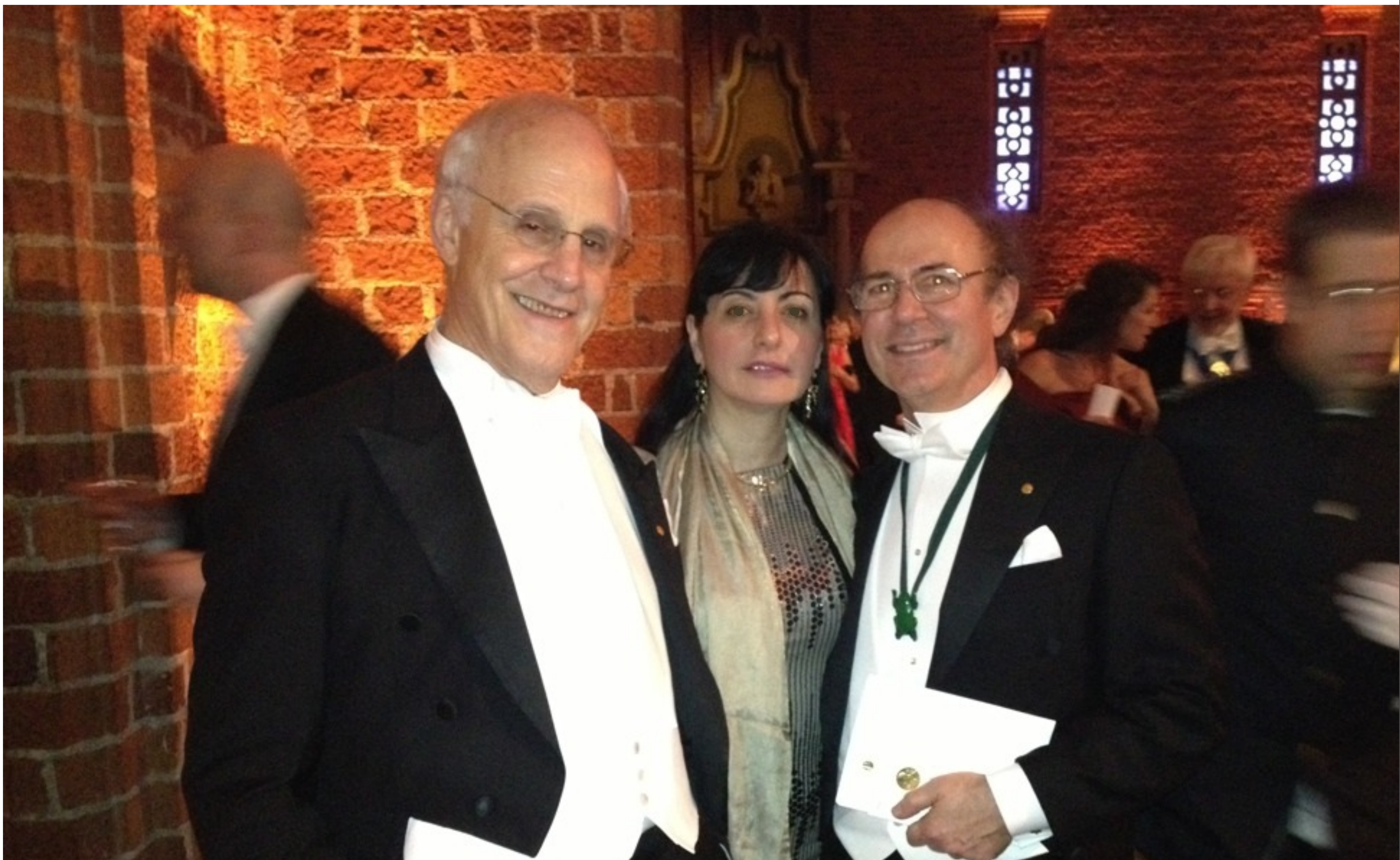
I claim no resemblance at all

With Discovery Announcers

Banquet

The Beast and the Beauty

Marcela feeling asymptotically free



The Ballroom

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

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

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

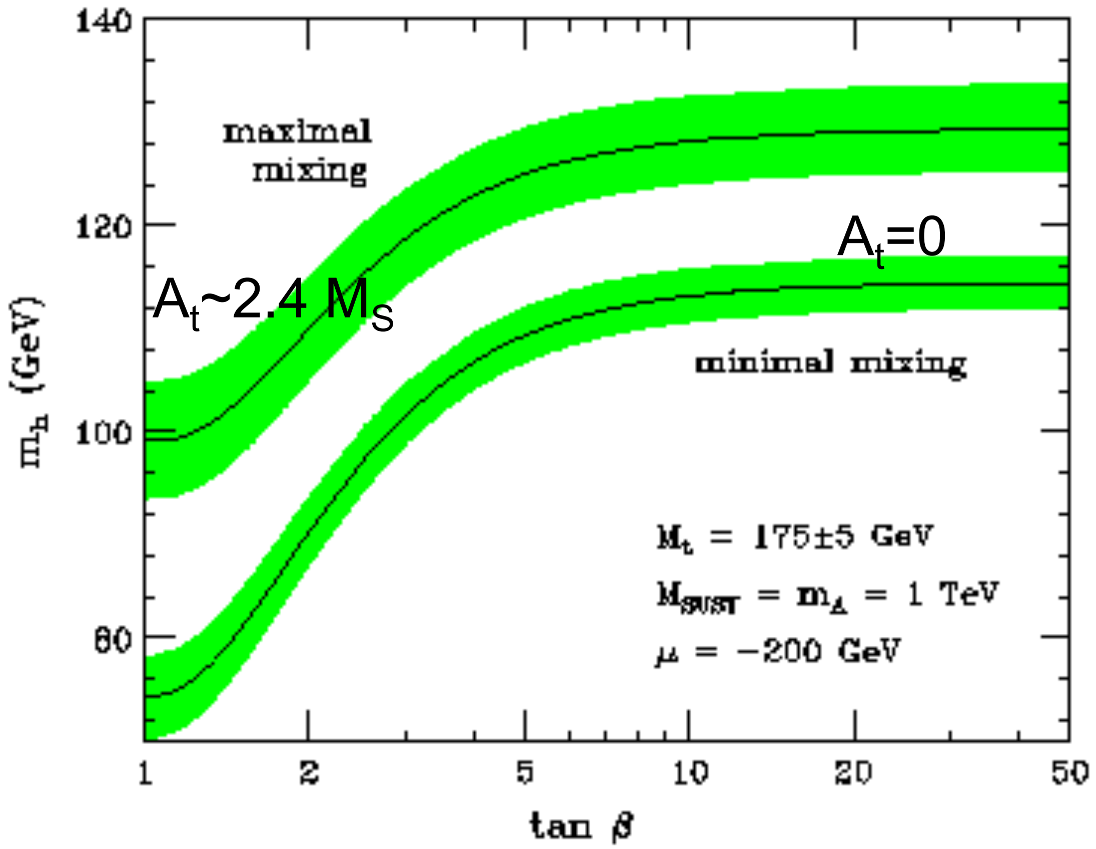
M.Carena, J.R. Espinosa, M. Quiros, C.W.'95
M. Carena, M. Quiros, C.W.'95

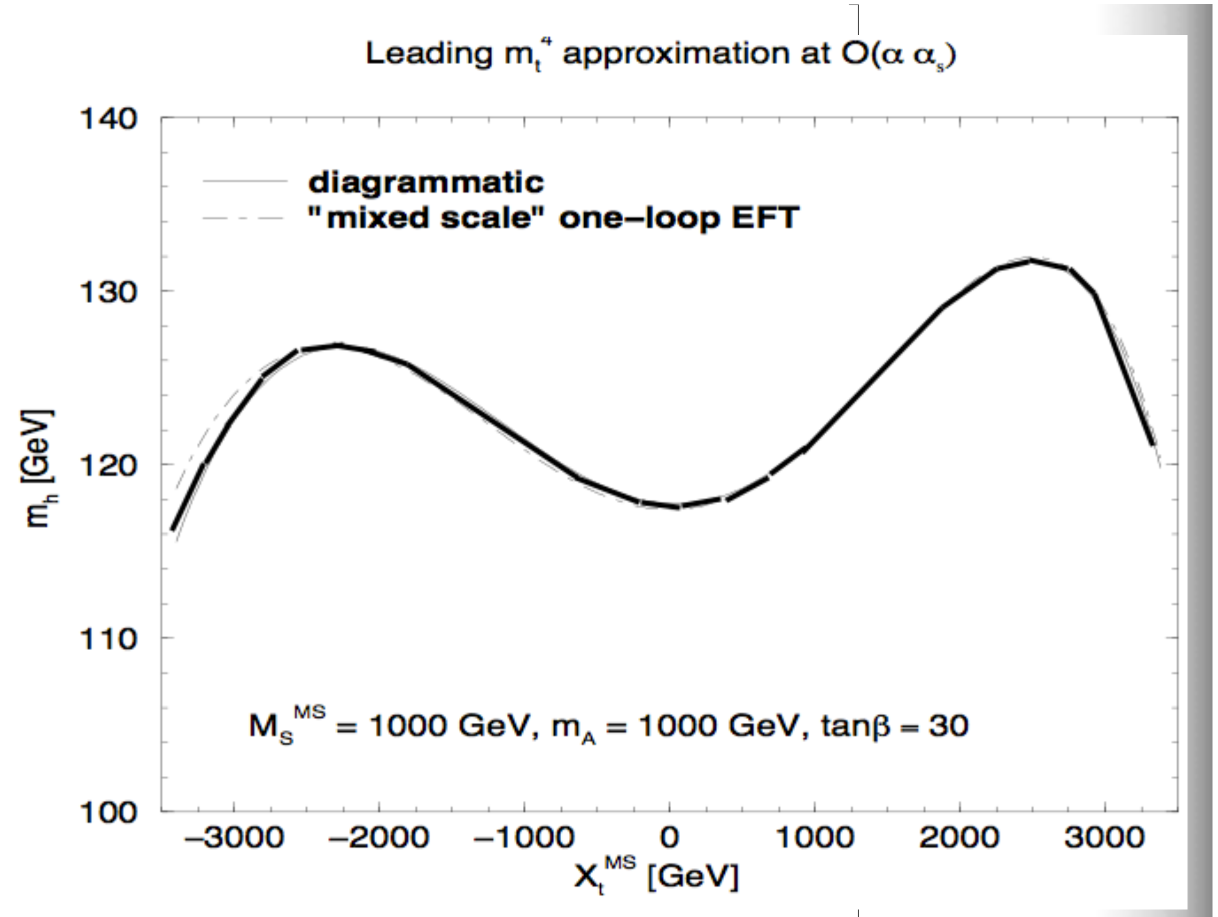
Analytic expression valid for $M_{SUSY} \sim m_Q \sim m_U$

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

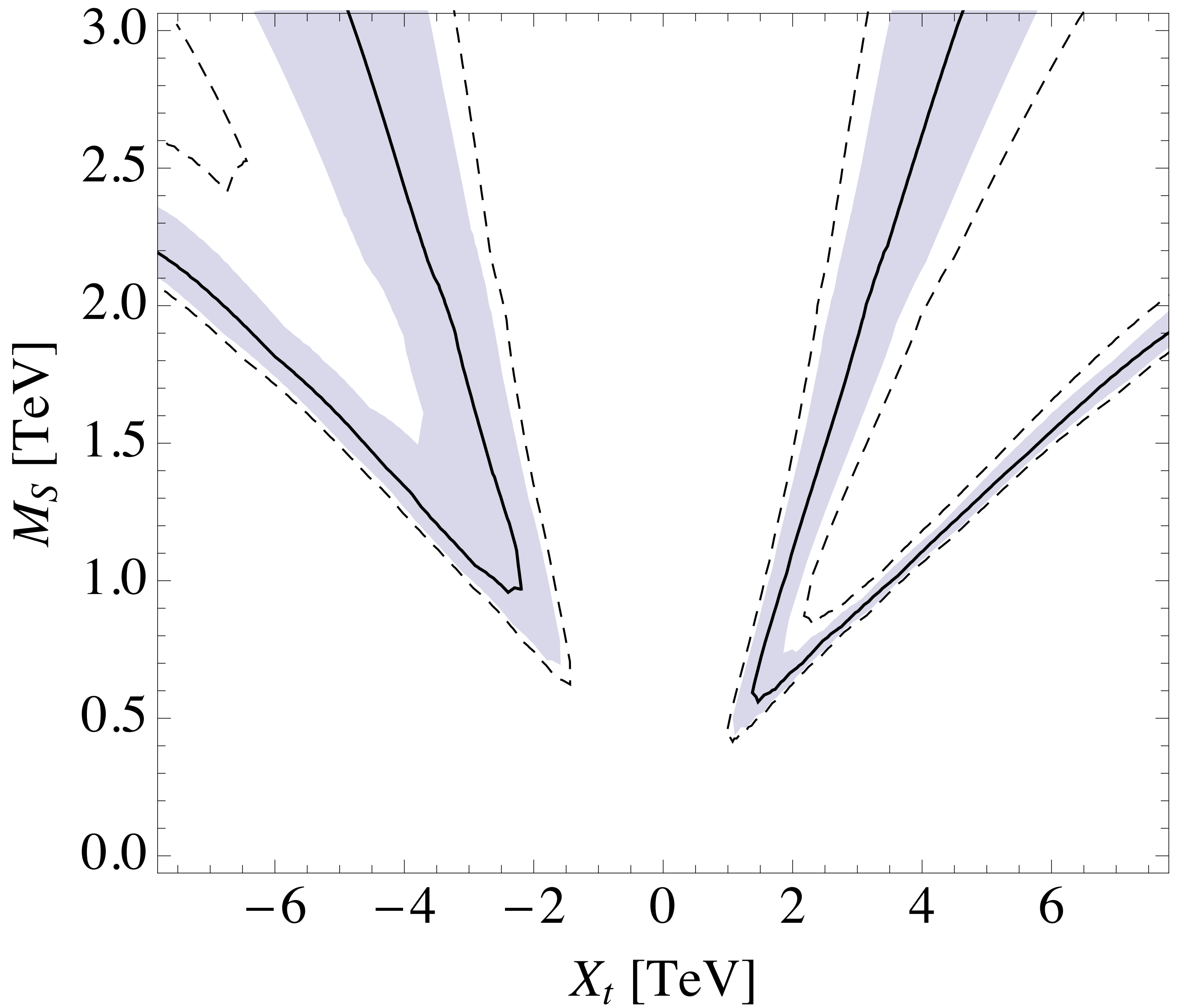
Carena, Haber, Heinemeyer, Hollik, Weiglein, C.W.'00





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

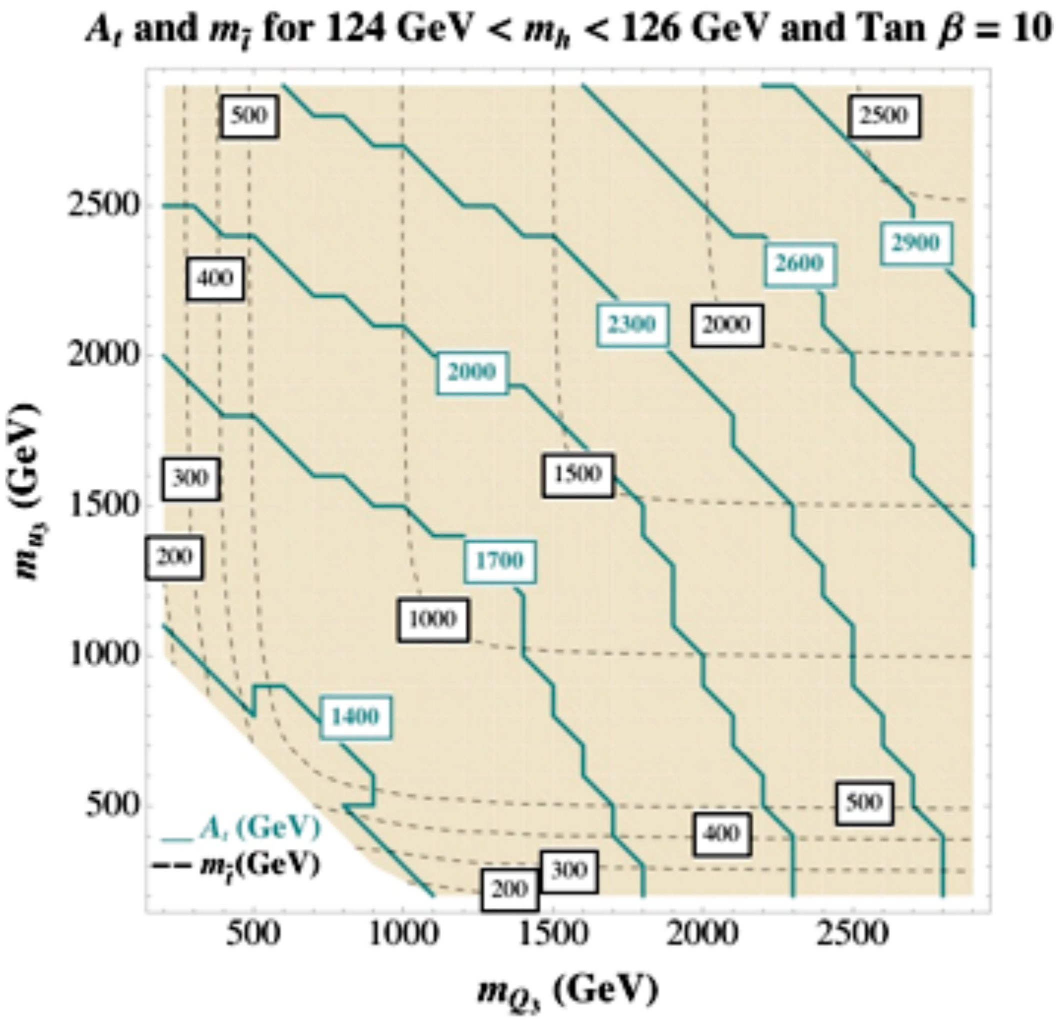
Large Mixing in the Stop Sector Necessary

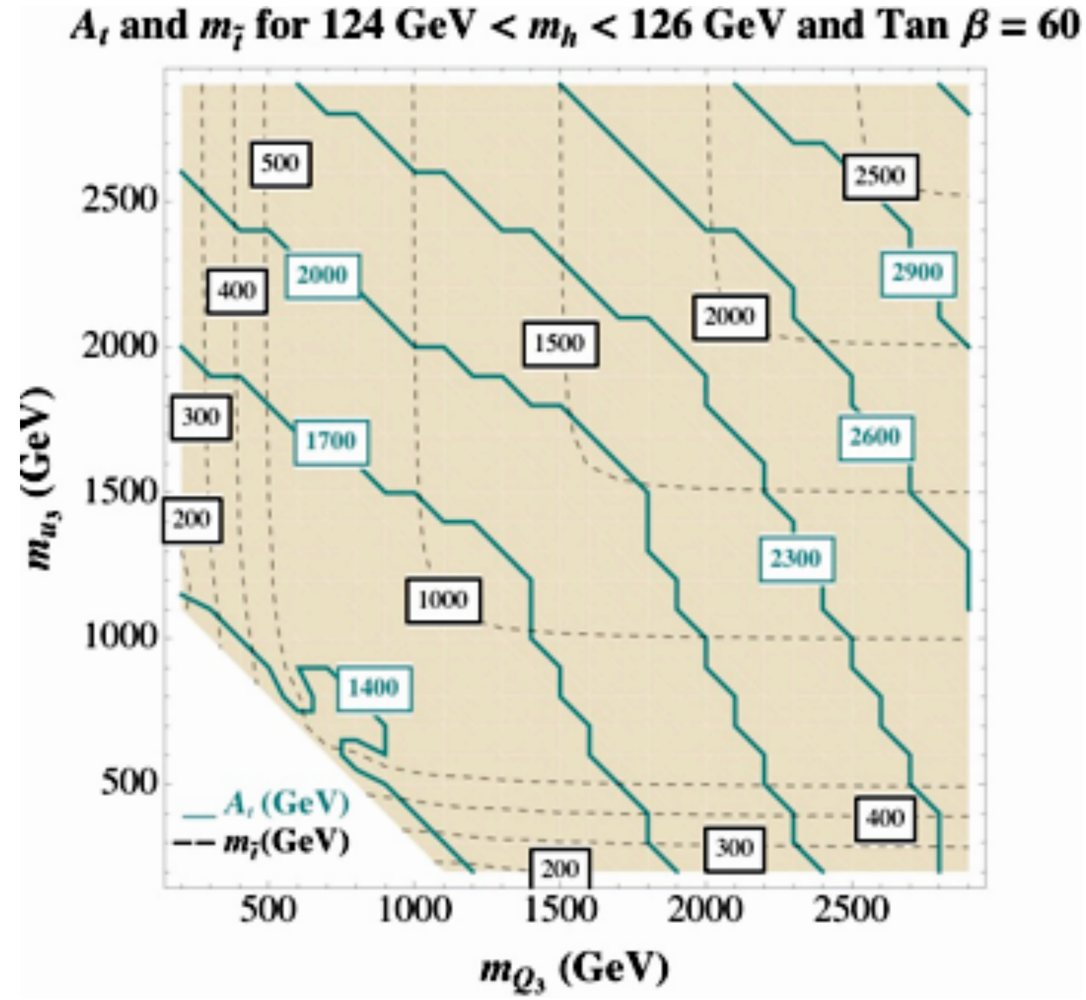


P. Draper, P. Meade, M. Reece, D. Shih'11
L. Hall, D. Pinner, J. Ruderman'11
M. Carena, S. Gori, N. Shah, C. Wagner'11
A. Arbey, M. Battaglia, A. Djouadi, F. Mahmoudi, J. Quevillon'11
S. Heinemeyer, O. Stal, G. Weiglein'11
U. Ellwanger'11
...

Soft supersymmetry Breaking Parameters

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





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

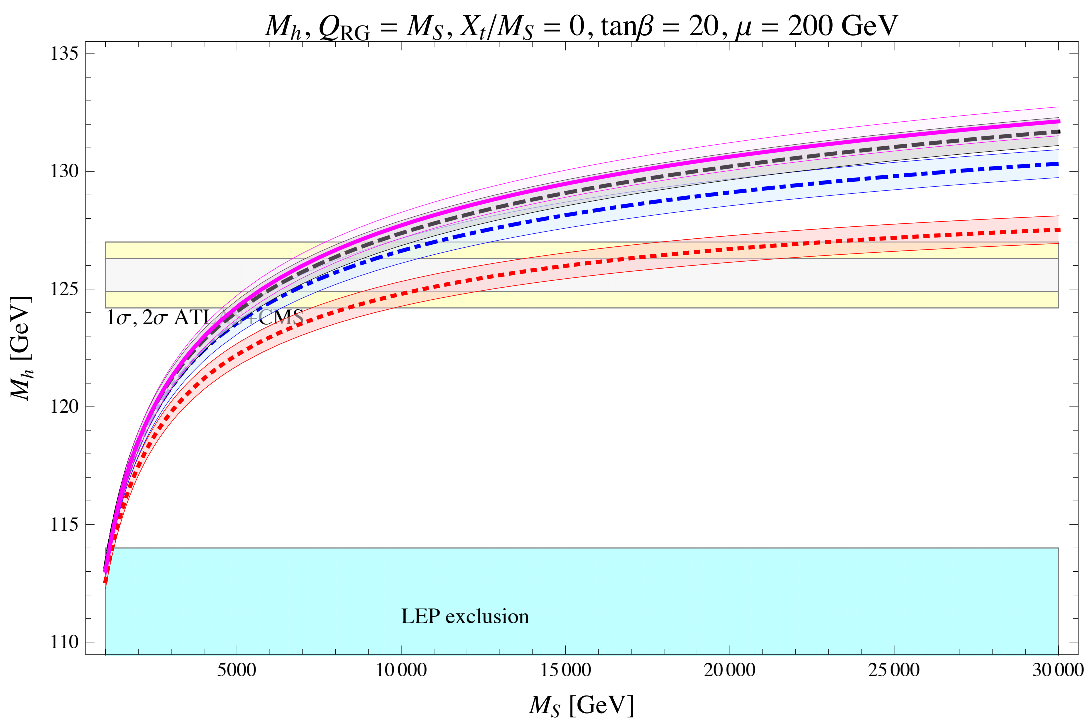
Intermediate values of tan beta lead to the largest values of m_h for the same values of stop mass parameters

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

Case of heavy Stops
Impact of higher loops

G. Lee, C.W'13

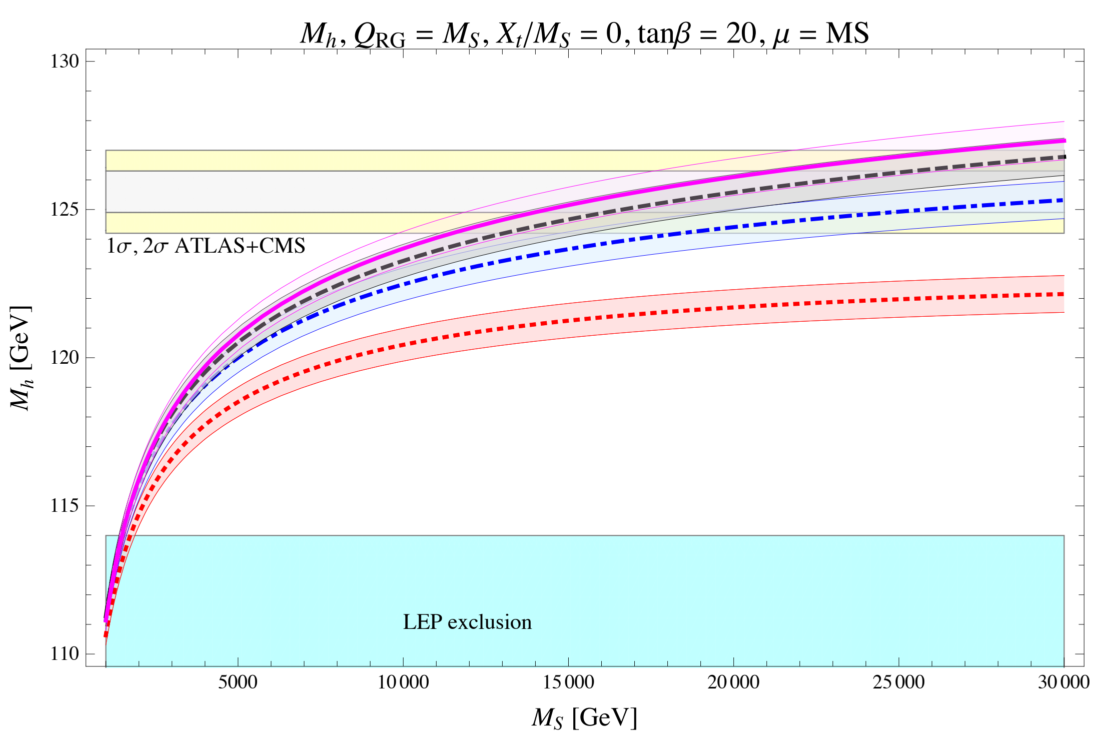
(See also S. Martin'07,
P. Kant, R. Harlander, L. Mihalla, M. Steinhauser'10
J. Feng, P. Kant, S. Profumo, D. Sanford.'13,)

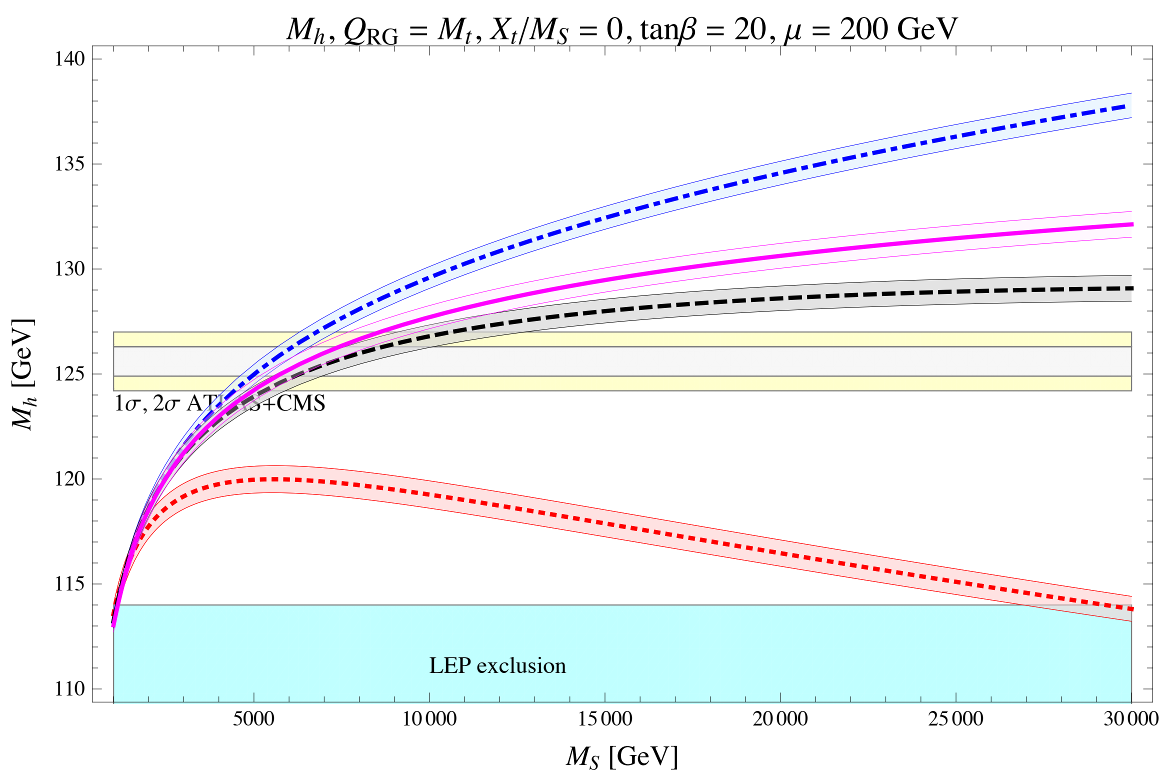


Recalculation of RG prediction including up to 4 loops in RG expansion.

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





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.

CP-even Higgs Mixing Angle and Alignment

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

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

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

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

Details of the Calculation

Tree-level coupling, should be evaluated at the SUSY breaking scale :

$$\lambda_{\rm tree} = \frac{1}{4}(g_Y^2 + g_2^2)c_{2\beta}^2$$

Simplified stop spectrum :

$$\mathcal{M}_{\tilde{t}}^2 = \begin{pmatrix} m_{\tilde{t}_L}^2 + m_t^2 + c_{2\beta}\left(\frac{1}{2} - \frac{2}{3}s_W^2\right)m_Z^2 & m_t X_t \\ m_t X_t & m_{\tilde{t}_R}^2 + m_t^2 + \frac{2}{3}c_{2\beta}s_W^2 m_Z^2 \end{pmatrix}$$

$$\mathcal{M}_{\tilde{t}}^2 = \begin{pmatrix} M_S^2 & m_t X_t \\ m_t X_t & M_S^2 \end{pmatrix}$$

$$m_{\tilde{t}_{1,2}}^2 = M_S^2 \mp |m_t X_t|.$$

This approximation is abandoned at the one-loop level, in the evaluation of the thresholds to the quartic coupling

One loop thresholds to the quartic coupling and Yukawas in the MS scheme

$$\Delta_{\rm th}^{(\alpha_t)}\lambda = 6\kappa h_t^4 s_\beta^4 \widehat{X}_t^2\left(1-\frac{\widehat{X}_t^2}{12}\right)+\frac{3}{4}\kappa h_t^2 s_\beta^2 (g_2^2+g_Y^2)\widehat{X}_t^2 c_{2\beta},$$
$$\Delta_{\rm th}^{(\alpha_b)}\lambda = -\frac{1}{2}\kappa h_b^4 s_\beta^4 \hat{\mu}^4,$$
$$\Delta_{\rm th}^{(\alpha_\tau)}\lambda = -\frac{1}{6}\kappa h_\tau^4 s_\beta^4 \hat{\mu}^4,$$

$$y_t = h_t s_\beta, \qquad y_b = h_b c_\beta, \qquad y_\tau = h_\tau c_\beta;$$

$$h_t = \frac{y_t}{s_\beta}\frac{1}{1-\kappa(\Delta h_t + \cot\beta\,\delta h_t)},$$
$$h_b = \frac{y_b}{c_\beta}\frac{1}{1-\kappa(\Delta h_b + t_\beta\,\delta h_b)},$$
$$h_\tau = \frac{y_\tau}{c_\beta}\frac{1}{1-\kappa t_\beta\,\delta h_\tau},$$

$$\Delta h_t = \frac{8}{3} g_3^2 m_{\tilde{g}} X_t\, I(m_{\tilde{t}_1}, m_{\tilde{t}_2}, m_{\tilde{g}}) - h_b^2 \mu \cot\beta X_b\, I(m_{\tilde{b}_1}, m_{\tilde{b}_2}, \mu), \tag{14}$$

$$\begin{aligned}\delta h_t = {}& g_2^2 M_2 \mu \Big([c_b^2 I(m_{\tilde{b}_1}, M_2, \mu) + s_b^2 I(m_{\tilde{b}_2}, M_2, \mu)] + \frac{1}{2}[c_t^2 I(m_{\tilde{t}_1}, M_2, \mu) + s_t^2 I(m_{\tilde{t}_2}, M_2, \mu)] \Big) \\ &+ \frac{1}{3} g_Y^2 M_1 \Big(\frac{2}{3} X_t t_\beta I(m_{\tilde{t}_1}, m_{\tilde{t}_2}, M_1) - \frac{1}{2}\mu [c_t^2 I(m_{\tilde{t}_1}, M_1, \mu) + s_t^2 I(m_{\tilde{t}_2}, M_1, \mu)] \\ &+ 2\mu [s_t^2 I(m_{\tilde{t}_1}, M_1, \mu) + c_t^2 I(m_{\tilde{t}_2}, M_1, \mu)] \Big), \end{aligned} \tag{15}$$

$$\Delta h_b = \frac{8}{3} g_3^2 m_{\tilde{g}} X_b\, I(m_{\tilde{b}_1}, m_{\tilde{b}_2}, m_{\tilde{g}}) - h_t^2 \mu t_\beta X_t\, I(m_{\tilde{t}_1}, m_{\tilde{t}_2}, \mu), \tag{16}$$

$$\begin{aligned}\delta h_b = {}& g_2^2 M_2 \mu \Big([c_t^2 I(m_{\tilde{t}_1}, M_2, \mu) + s_t^2 I(m_{\tilde{t}_2}, M_2, \mu)] + \frac{1}{2}[c_b^2 I(m_{\tilde{b}_1}, M_2, \mu) + s_b^2 I(m_{\tilde{b}_2}, M_2, \mu)] \Big) \\ &+ \frac{1}{3} g_Y^2 M_1 \Big(-\frac{1}{3} X_b \cot\beta\, I(m_{\tilde{b}_1}, m_{\tilde{b}_2}, M_1) + \frac{1}{2}\mu [c_b^2 I(m_{\tilde{b}_1}, M_1, \mu) + s_b^2 I(m_{\tilde{b}_2}, M_1, \mu)] \\ &+ \mu [s_b^2 I(m_{\tilde{b}_1}, M_1, \mu) + c_b^2 I(m_{\tilde{b}_2}, M_1, \mu)] \Big), \end{aligned} \tag{17}$$

$$\begin{aligned}\delta h_\tau = {}& g_2^2 M_2 \mu \Big(I(m_{\tilde{\nu}_\tau}, M_2, \mu) + \frac{1}{2}[c_\tau^2 I(m_{\tilde{\tau}_1}, M_2, \mu) + s_\tau^2 I(m_{\tilde{\tau}_2}, M_2, \mu)] \Big) \\ &- g_Y^2 M_1 \Big(X_\tau \cot\beta\, I(m_{\tilde{\tau}_1}, m_{\tilde{\tau}_2}, M_1) + \frac{1}{2}\mu [c_\tau^2 I(m_{\tilde{\tau}_1}, M_1, \mu) + s_\tau^2 I(m_{\tilde{\tau}_2}, M_1, \mu)] \\ &- \mu [s_\tau^2 I(m_{\tilde{\tau}_1}, M_1, \mu) + c_\tau^2 I(m_{\tilde{\tau}_2}, M_1, \mu)] \Big), \end{aligned} \tag{18}$$

$$I(a,b,c) = \frac{ab\log(a/b) + bc\log(b/c) + ac\log(c/a)}{(a-b)(b-c)(a-c)}$$

$$\begin{aligned} I(1,1,1-\delta) &= \frac{1}{2} + \frac{\delta}{6} + \ldots \qquad (\mu \sim M_S), \\ I(1,1,\delta) &= 1 + \delta(1+\log\delta) + \ldots \qquad (\mu \ll M_S). \end{aligned}$$

Two loop thresholds to the quartic Couplings in the SM scheme

$$\Delta_{\rm th}^{(\alpha_s\alpha_t)}\lambda = 16\kappa^2 h_t^4 g_3^2\left\{-2\widehat{X}_t^2 + \frac{1}{3}\widehat{X}_t^3 - \frac{1}{12}\widehat{X}_t^4\right\},$$

$$\begin{aligned}\Delta_{\rm th}^{(\alpha_t^2)}\lambda = 3\kappa^2 h_t^6\Bigg\{ & -\frac{3}{2} + 6\hat{\mu}^2 - 2(4+\hat{\mu}^2)f_1(\hat{\mu}) + 3\hat{\mu}^2 f_2(\hat{\mu}) + 4f_3(\hat{\mu}) - \frac{\pi^2}{3} \\ & + \left[-\frac{17}{2} - 6\hat{\mu}^2 - (4+3\hat{\mu}^2)f_2(\hat{\mu}) + (4-6\hat{\mu}^2)f_1(\hat{\mu})\right]\widehat{X}_t^2 \\ & + \left[23 + 4s_\beta^2 + 4\hat{\mu}^2 + 2f_2(\hat{\mu}) - 2(1-2\hat{\mu}^2)f_1(\hat{\mu})\right]\frac{\widehat{X}_t^4}{4} - \frac{13}{24}\widehat{X}_t^6 s_\beta^2 \\ & + c_\beta^2\Bigg[-\frac{9}{2} + 60K + \frac{4\pi^2}{3} + \left(\frac{27}{2} - 24k\right)\widehat{X}_t^2 - 6\widehat{X}_t^4 \\ & \qquad - (3+16K)(4\widehat{X}_t + \widehat{Y}_t)\widehat{Y}_t + 4(1+4K)\widehat{X}_t^3\widehat{Y}_t \\ & \qquad + \left(\frac{14}{3} + 24K\right)\widehat{X}_t^2\widehat{Y}_t^2 - \left(\frac{19}{12} + 8K\right)\widehat{X}_t^4\widehat{Y}_t^2\Bigg]\Bigg\}.\end{aligned}$$

$$K = -\frac{1}{\sqrt{3}}\int_0^{\pi/6} dx\,\log(2\cos x) \sim -0.1953256,$$

$$\widehat{Y}_t = (A_t - \mu t_\beta)/M_S = \widehat{X}_t + \frac{2\hat{\mu}}{\sin 2\beta},$$

$$f_1(\hat{\mu}) = \frac{\hat{\mu}^2}{1-\hat{\mu}^2}\log\hat{\mu}^2,$$

$$f_2(\hat{\mu}) = \frac{1}{1-\hat{\mu}^2}\left[1 + \frac{\hat{\mu}^2}{1-\hat{\mu}^2}\log\hat{\mu}^2\right],$$

$$f_3(\hat{\mu}) = \frac{-1+2\hat{\mu}^2+2\hat{\mu}^4}{(1-\hat{\mu}^2)^2}\left[\log\hat{\mu}^2\log(1-\hat{\mu}^2) + Li_2(\hat{\mu}^2) - \frac{\pi^2}{6} - \hat{\mu}^2\log\hat{\mu}^2\right]$$

Evolution of the quartic Coupling

$$\kappa \equiv \frac{1}{16\pi^2}, \qquad t \equiv \log Q, \qquad \beta_\lambda^{(n,k)}(t) \equiv \frac{\mathrm{d}^k \beta_\lambda^{(n)}}{\mathrm{d}t^k}(t)$$

We want to evaluate the coupling at the weak scale (mt) starting from the stop mass scale. It can be done in two ways, depending on where the couplings are evaluated. Taking $L \equiv \tilde{t} - t = \log(\widetilde{Q}/Q) > 0\,, \quad \beta_\lambda^{(n)} \equiv \beta_\lambda^{(n,0)}.$

$$\lambda(Q) = \lambda(\widetilde{Q}) - \sum_{n=1}^{\infty} \kappa^n \sum_{k=0}^{\infty} (-1)^k \frac{\beta_\lambda^{(n,k)}(\tilde{t})}{(k+1)!} L^{k+1}$$

These two expressions are not equivalent, and represent a different reorganization of the perturbativexpansion. The second one is implemented in CPsuperH. The first one leads to a faster convergence

$$\lambda(\widetilde{Q}) = \lambda(Q) + \sum_{n=1}^{\infty} \kappa^n \sum_{k=0}^{\infty} \frac{\beta_\lambda^{(n,k)}(t)}{(k+1)!} L^{k+1}$$

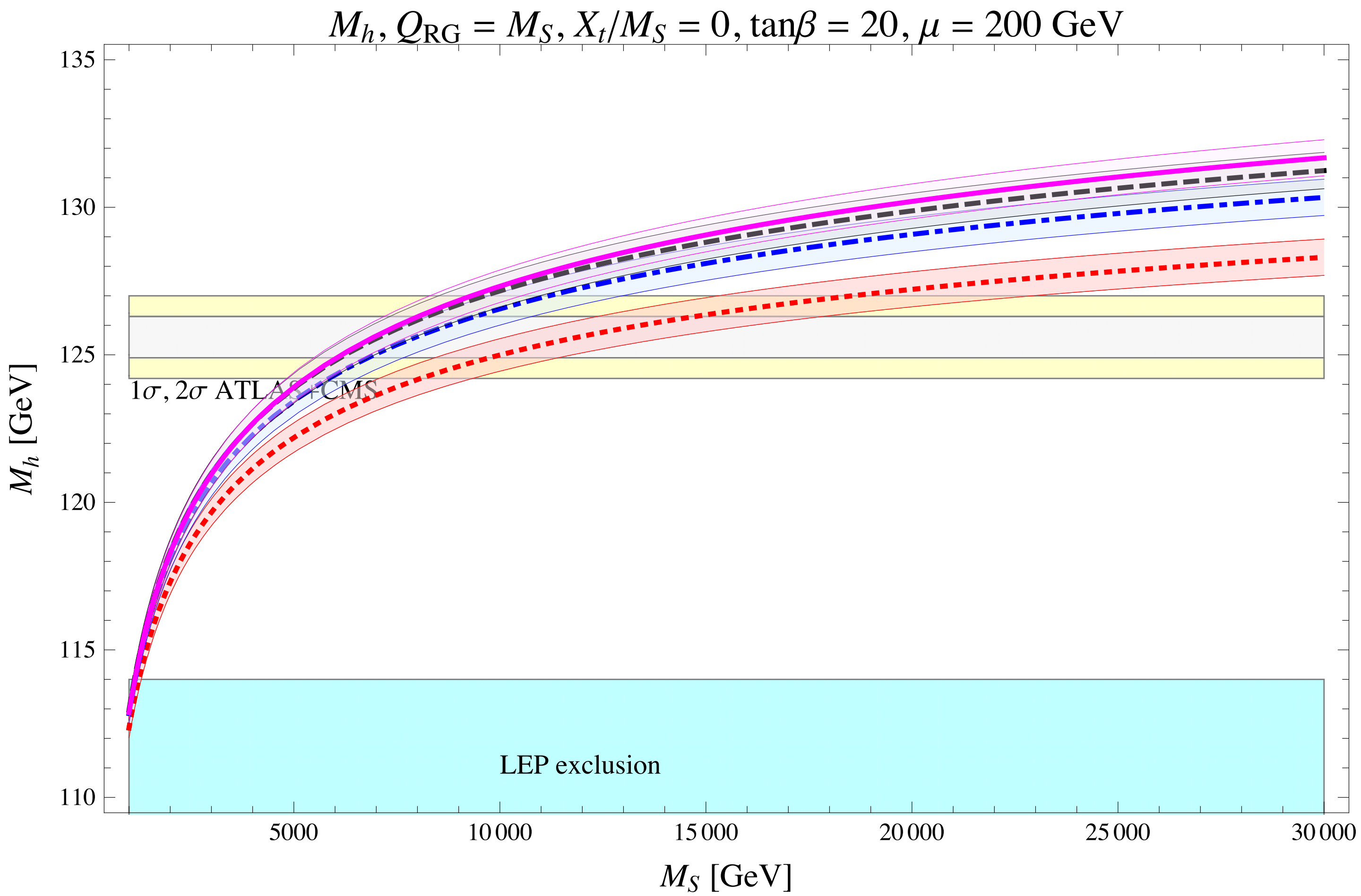
$$
\begin{aligned}
\delta_1\lambda = &\Bigg\{ -12\lambda^2 - \lambda\Big[12y_t^2 + 12y_b^2 + 4y_\tau^2 - 9g_2^2 - \frac{9}{5}g_1^2\Big] + 12y_t^4 + 12y_b^4 + 4y_\tau^4 \\
&\quad - \frac{9}{4}g_2^4 - \frac{9}{10}g_2^2g_1^2 - \frac{27}{100}g_1^4\Bigg\}L \\
&+ \Bigg\{ -6\lambda\Big[g_2^2 + \frac{1}{5}g_1^2\Big] + \Big[g_2^2 + \frac{3}{5}g_1^2\Big]^2 + 4g_2^4\Big[1 - 2s_\beta^2c_\beta^2\Big]\Bigg\}L_\mu, \qquad (46)
\end{aligned}
$$

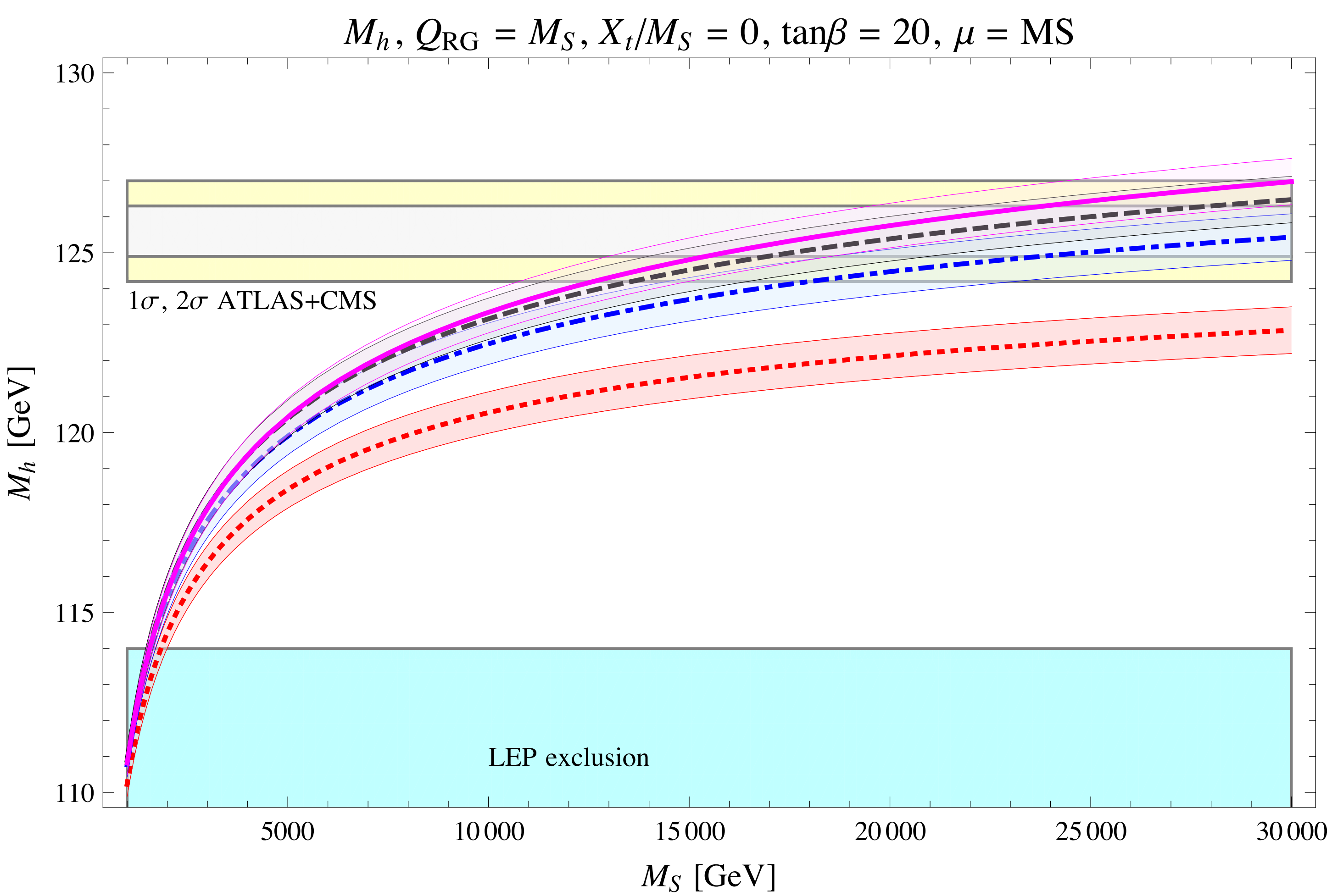
$$
\begin{aligned}
\delta_2\lambda = &\Bigg\{144\lambda^3 + \lambda^2\Big[216y_t^2 - 108g_2^2 - \frac{108}{5}g_1^2\Big] + \lambda\Big[-18y_t^4 + 27g_2^4 + \frac{54}{5}g_2^2g_1^2 + \frac{81}{25}g_1^4\Big] \\
&\quad + \lambda y_t^2\Big[-96g_3^2 - 81g_2^2 - 21g_1^2\Big] + y_t^4\Big[-180y_t^2 + 192g_3^2 + 54g_2^2 + \frac{102}{5}g_1^2\Big] \\
&\quad + y_t^2\Big[\frac{27}{2}g_2^4 + \frac{27}{5}g_2^2g_1^2 + \frac{81}{50}g_1^4\Big]\Bigg\}L^2 \\
&- \Bigg\{\Big[24\lambda + 12y_t^2 - 9g_2^2 - \frac{9}{5}g_1^2\Big]\Big[6\lambda\Big[g_2^2 + \frac{1}{5}g_1^2\Big]^2 - \Big[g_2^2 + \frac{3}{5}g_1^2\Big]^2 - 4g_2^4\Big[1 - 2s_\beta^2c_\beta^2\Big]\Big]\Bigg\}LL_\mu \\
&+ \Bigg\{3\Big[g_2^2 + \frac{1}{5}g_1^2\Big]\Big[6\lambda\Big[g_2^2 + \frac{1}{5}g_1^2\Big]^2 - \Big[g_2^2 + \frac{3}{5}g_1^2\Big]^2 - 4g_2^4\Big[1 - 2s_\beta^2c_\beta^2\Big]\Big]\Bigg\}L_\mu^2 \\
&+ \Bigg\{78\lambda^3 + 72\lambda^2y_t^2 + \lambda y_t^2(3y_t^2 - 80g_3^2) - 60y_t^6 + 64g_3^2y_t^4\Bigg\}L, \qquad (47)
\end{aligned}
$$

$$
\begin{aligned}
\delta_3\lambda = &\Bigg\{ -1728\lambda^4 - 3456\lambda^3y_t^2 + \lambda^2y_t^2(-576y_t^2 + 1536g_3^2) \\
&\quad + \lambda y_t^2(1908y_t^4 + 480y_t^2g_3^2 - 960g_3^4) + y_t^4(1548y_t^4 - 4416y_t^2g_3^2 + 2944g_3^4)\Bigg\}L^3 \\
&+ \Bigg\{ -2340\lambda^4 - 3582\lambda^3y_t^2 + \lambda^2y_t^2(-378y_t^2 + 2016g_3^2) \\
&\quad + \lambda y_t^2(1521y_t^4 + 1032y_t^2g_3^2 - 2496g_3^4) + y_t^4(1476y_t^4 - 3744y_t^2g_3^2 + 4064g_3^4)\Bigg\}L^2 \\
&+ \Bigg\{ -1502.84\lambda^4 - 436.5\lambda^3y_t^2 - \lambda^2y_t^2(1768.26y_t^2 + 160.77g_3^2) \\
&\quad + \lambda y_t^2(446.764\lambda y_t^4 + 1325.73y_t^2g_3^2 - 713.936g_3^4) \\
&\quad + y_t^4(972.596y_t^4 - 1001.98y_t^2g_3^2 + 200.804g_3^4)\Bigg\}L, \qquad (48)
\end{aligned}
$$

$$\delta_4\lambda = \Big\{20736\lambda^5 + 51840\lambda^4 y_t^2 + \lambda^3 y_t^2(21600 y_t^2 - 23040 g_3^2)$$
$$+ \lambda^2 y_t^2(-30780 y_t^4 - 18720 g_3^2 y_t^2 + 14400 g_3^4)$$
$$+ \lambda y_t^2(-22059 y_t^6 + 28512 g_3^2 y_t^4 + 10560 g_3^4 y_t^2 - 10560 g_3^6)$$
$$+ y_t^4(-8208 y_t^6 + 56016 y_t^6 g_3^2 - 84576 y_t^2 g_3^4 + 44160 g_3^6)\Big\} L^4$$
$$+ \Big\{48672\lambda^5 + 101808\lambda^4 y_t^2 + \lambda^3 y_t^2(30546 y_t^2 - 49152 g_3^2 y_t^2)$$
$$\lambda^2 y_t^2(-50292 y_t^4 - 40896 y_t^2 g_3^2 + 45696 g_3^4)$$
$$+ \lambda y_t^2(-33903 y_t^6 + 41376 y_t^4 g_3^2 + 35440 g_3^4 y_t^2 - 45184 g_3^6)$$
$$+ y_t^4(-15588 y_t^6 + 86880 y_t^4 g_3^2 - 161632 y_t^2 g_3^4 + 112256 g_3^6)\Big\} L^3$$
$$+ \Big\{63228.2\lambda^5 + 72058.1\lambda^4 y_t^2 + \lambda^3 y_t^2(25004.6 y_t^2 - 11993.5 g_3^2)$$
$$+ \lambda^2 y_t^2(27483.8 y_t^4 - 52858 y_t^2 g_3^2 + 18215.3 g_3^4)$$
$$+ \lambda y_t^2(-51279 y_t^6 - 5139.56 y_t^4 g_3^2 + 50795.3 y_t^2 g_3^4 - 33858.8 g_3^6)$$
$$y_t^4(-24318.2 y_t^6 + 72896 y_t^4 g_3^2 - 73567.3 y_t^2 g_3^4 + 36376.5 g_3^6)\Big\} L^2.$$

$$M_h^2 = \lambda(M_t) v^2(M_t) + \kappa \Big\{ 3 y_t^2 (4\overline{m}_t^2 - m_h^2) B_0(\overline{m}_t, \overline{m}_t, m_h) - \frac{9}{2}\lambda m_h^2 \Big[2 - \frac{\pi}{\sqrt{3}} - \log\frac{m_h^2}{Q^2}\Big]$$
$$- \frac{v^2}{4}\Big[3 g_2^4 - 4\lambda g_2^2 + 4\lambda^2\Big] B_0(m_W, m_W, m_h)$$
$$- \frac{v^2}{8}\Big[3(g_2^2 + g_Y^2)^2 - 4\lambda(g_2^2 + g_Y^2) + 4\lambda^2\Big] B_0(m_Z, m_Z, m_h)$$
$$+ \frac{1}{2} g_2^4 \Big[g_2^2 - \lambda\Big(\log\frac{m_W^2}{Q^2} - 1\Big)\Big] + \frac{1}{4}(g_2^2 + g_Y^2)\Big[(g_2^2 + g_Y^2)) - \lambda\Big(\log\frac{m_Z^2}{Q^2} - 1\Big)\Big]\Big\}$$


M_h, $Q_{RG} = M_S$, $X_t/M_S = 0$, tanβ = 20, μ = 200 GeV
1σ, 2σ ATLAS+CMS
LEP exclusion
M_h [GeV]
M_S [GeV]
135
130
125
120
115
110
5000
10 000
15 000
20 000
25 000
30 000


M_h, $Q_{RG} = M_S$, $X_t/M_S = 0$, tanβ = 20, μ = MS
1σ, 2σ ATLAS+CMS
LEP exclusion
M_h [GeV]
M_S [GeV]
130
125
120
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110
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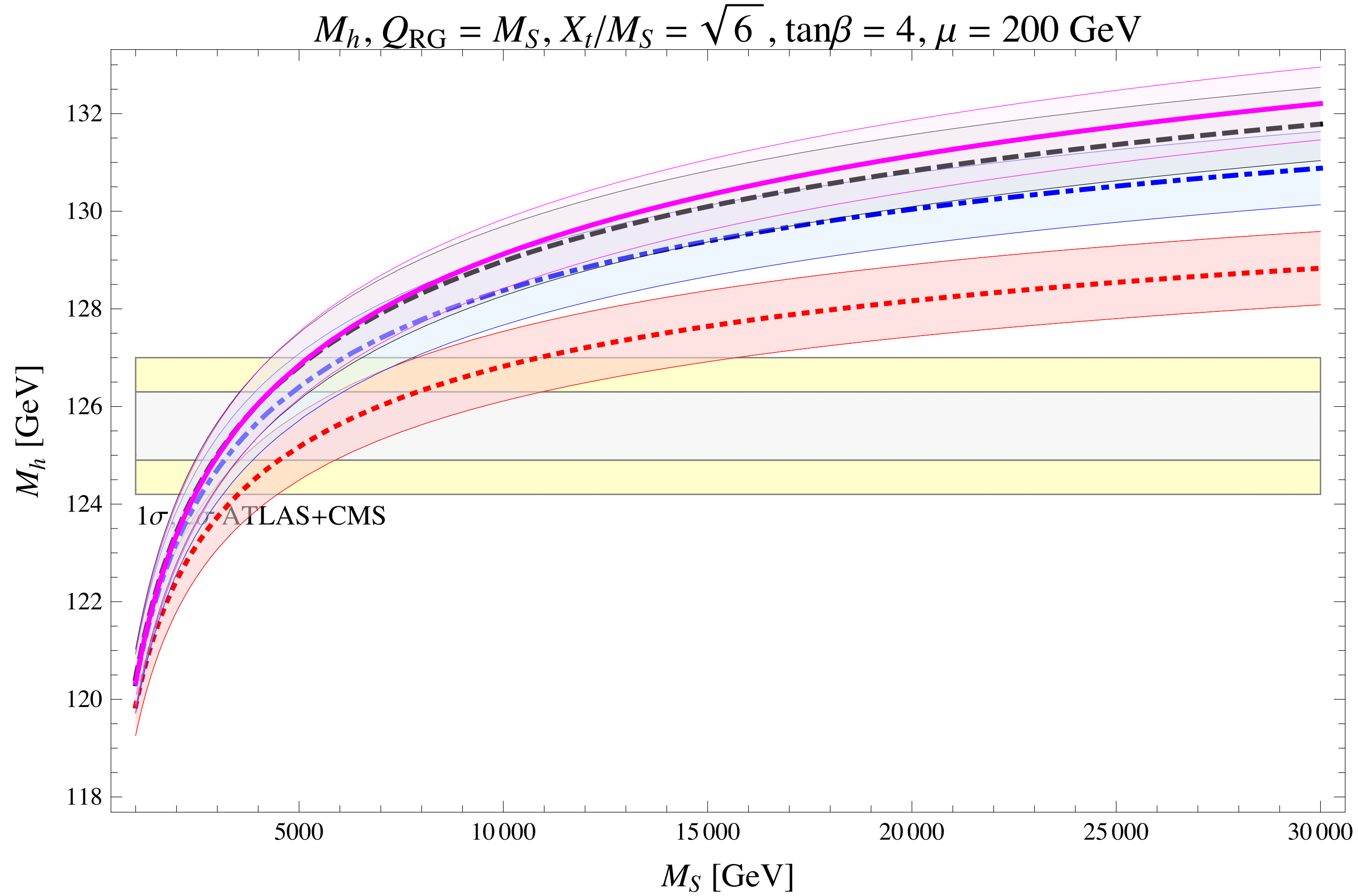
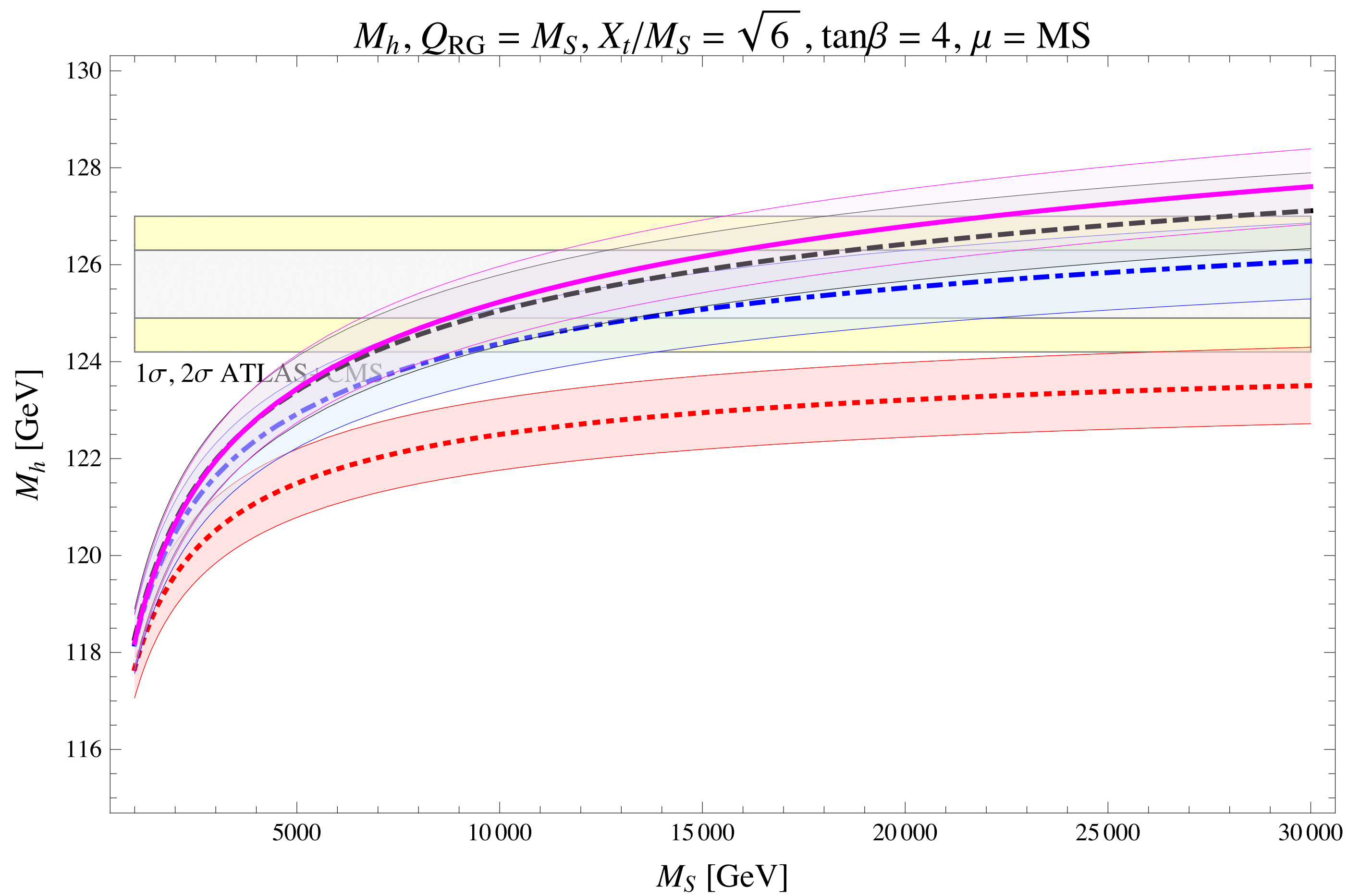
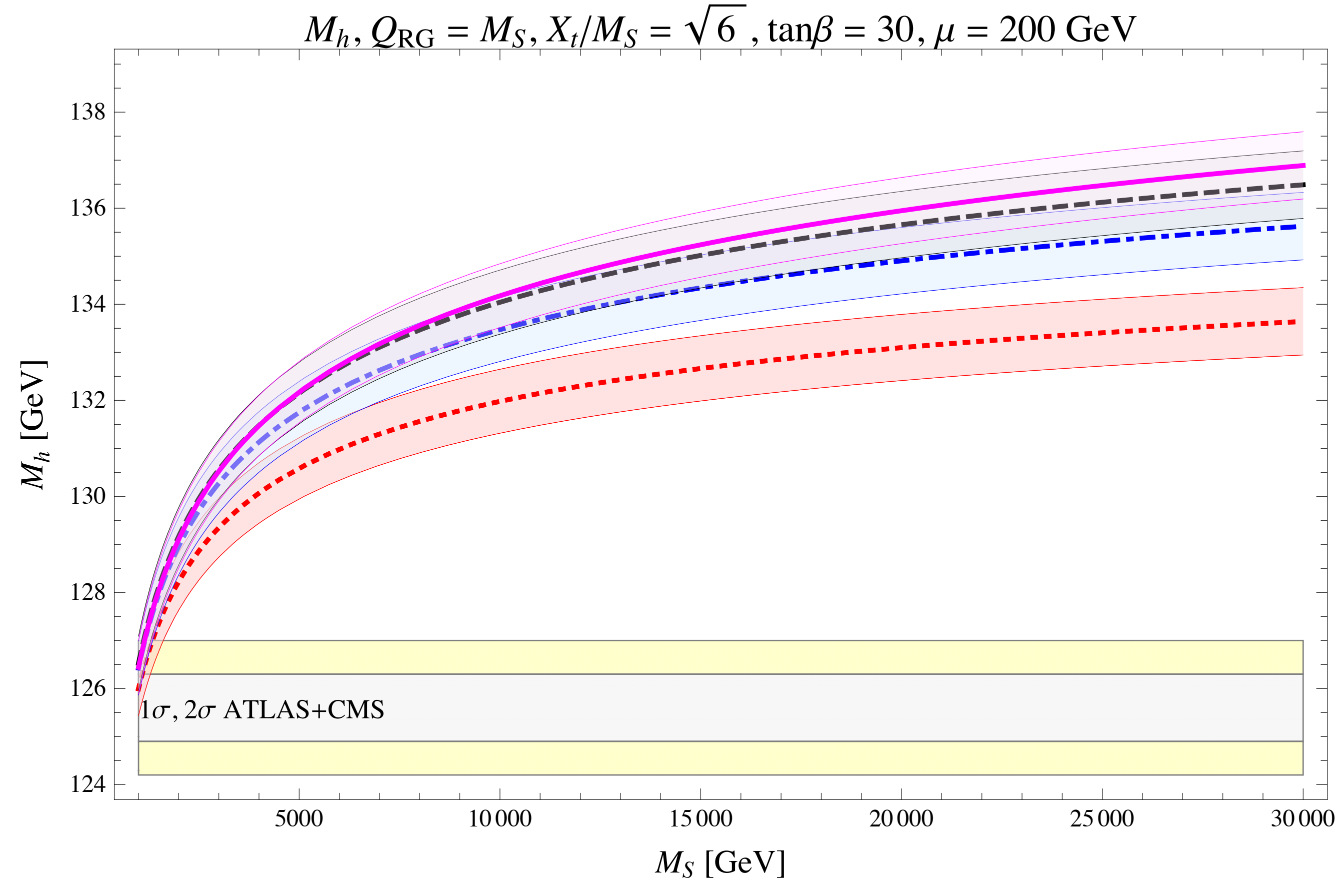
15 000
20 000
25 000
30 000

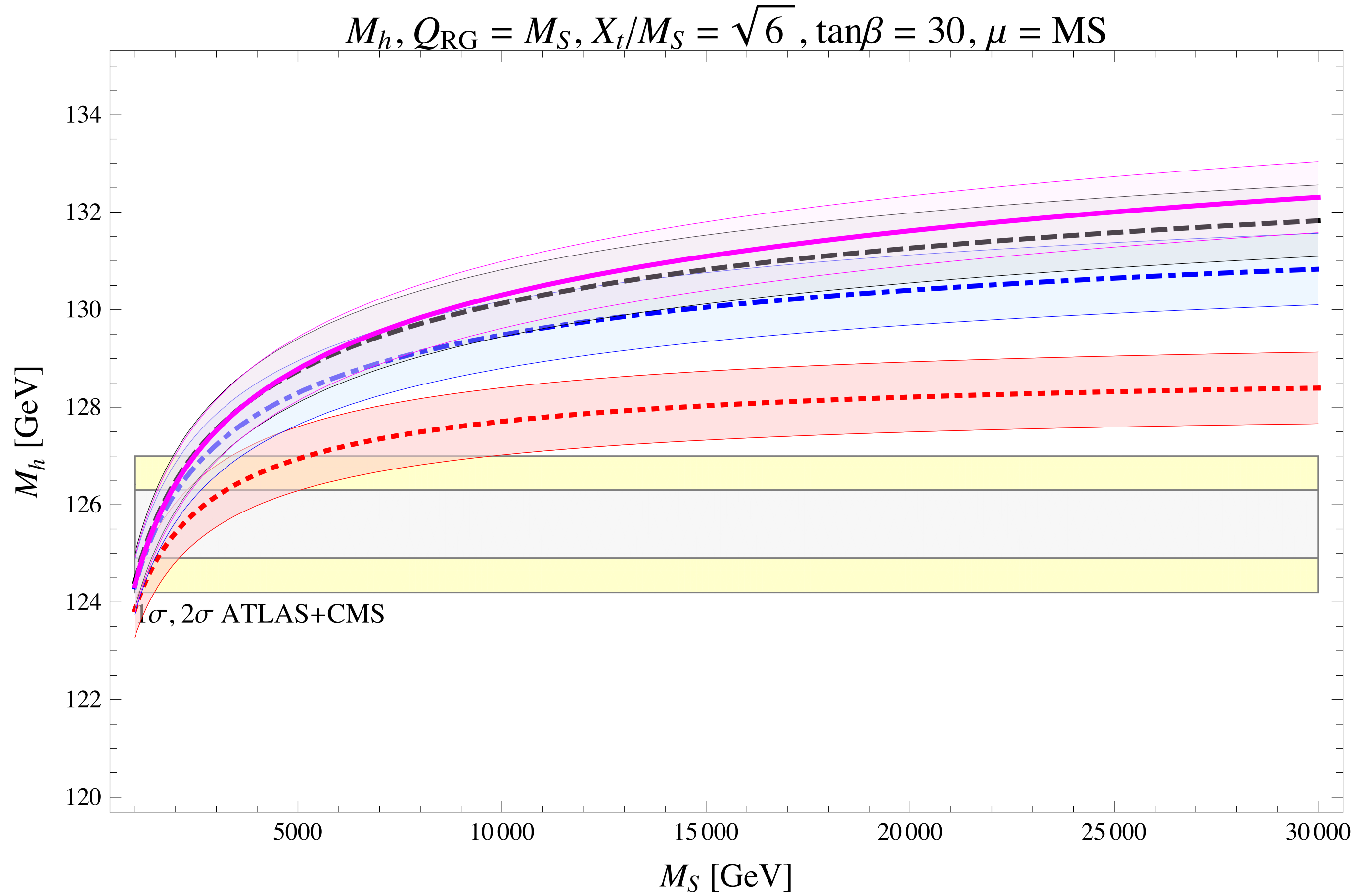


M_h, $Q_{RG} = M_S$, $X_t/M_S = \sqrt{6}$, $\tan\beta = 4$, $\mu = 200$ GeV
M_h [GeV]
M_S [GeV]
1σ, 2σ ATLAS+CMS



M_h, $Q_{RG} = M_S$, $X_t/M_S = \sqrt{6}$, $\tan\beta = 4$, $\mu = \text{MS}$
M_h [GeV]
M_S [GeV]
1σ, 2σ ATLAS+CMS


M_h, $Q_{RG} = M_S$, $X_t/M_S = \sqrt{6}$, $\tan\beta = 30$, $\mu = 200$ GeV
M_h [GeV]
M_S [GeV]
1σ, 2σ ATLAS+CMS
138
136
134
132
130
128
126
124
5000
10000
15000
20000
25000
30000


M_h, $Q_{RG} = M_S$, $X_t/M_S = \sqrt{6}$, $\tan\beta = 30$, $\mu = $ MS
M_h [GeV]
M_S [GeV]
1σ, 2σ ATLAS+CMS
134
132
130
128
126
124
122
120
5000
10000
15000
20000
25000
30000