SUSY ENHANCEMENT OF HEAVY HIGGS PRODUCTION

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Outline

This work is a study of cross-section of heavy Higgs production at the LHC within the framework of the constrained MSSM.

- We know that this cross-section is not only enhanced by $\tan^2\beta$ but sometimes is also enhanced by the squark contribution.

- First, we consider the universal scenario within MSSM and find out that to get the desired enhancement one needs large negative values of A_0, which seems to be incompatible with the $b \rightarrow s \gamma$ decay rate.

- To improve the situation, we release the unification requirement in the Higgs sector.

- Then it becomes possible to satisfy all requirements simultaneously and enhance the squark contribution.

- The latter can gain a factor of several units increasing the overall cross-section which, however, is still smaller than the cross-section of the associated Hbb production.

- We consider also some other consequences of the chosen benchmark point.

Introduction

The Higgs boson and possible new physics - actual.

The production of heavy particles is suppressed by their masses

Expect to find the light particles first.

Heavy particle production can be enhanced by some factors; for instance, production of H^0 in the MSSM A. Djouadi: hep-ph/0503173, S. Dittmaier *et.al.*: 1101.0593 [hep-ph].

Our study: Not only tanβ, but also squarks C. Beskidt, W. de Boer, T. Hanisch, E. Ziebarth, V. Zhukov, D.I. Kazakov: 1008.2150 [hep-ph].

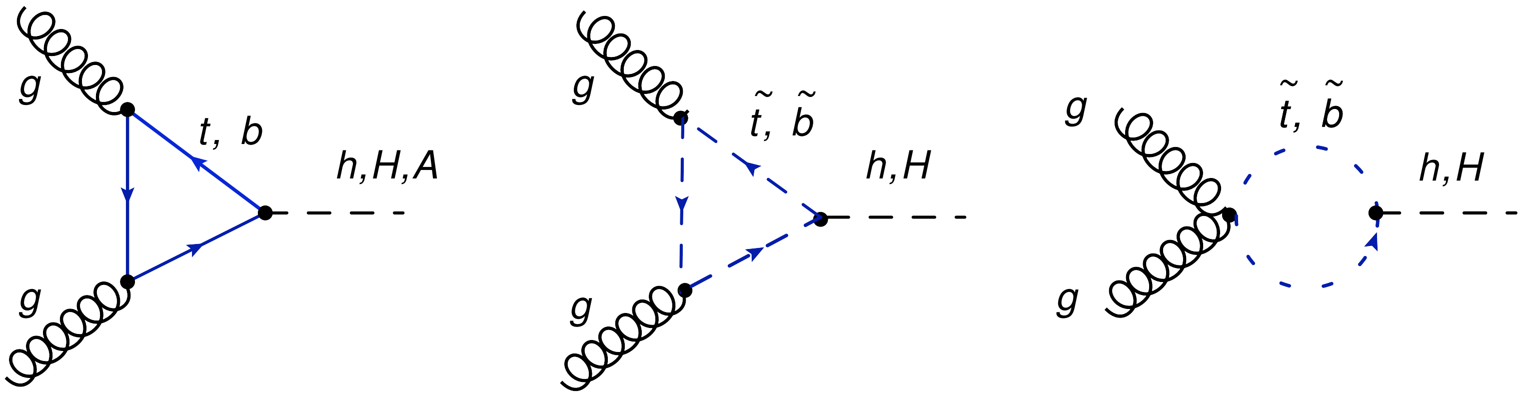
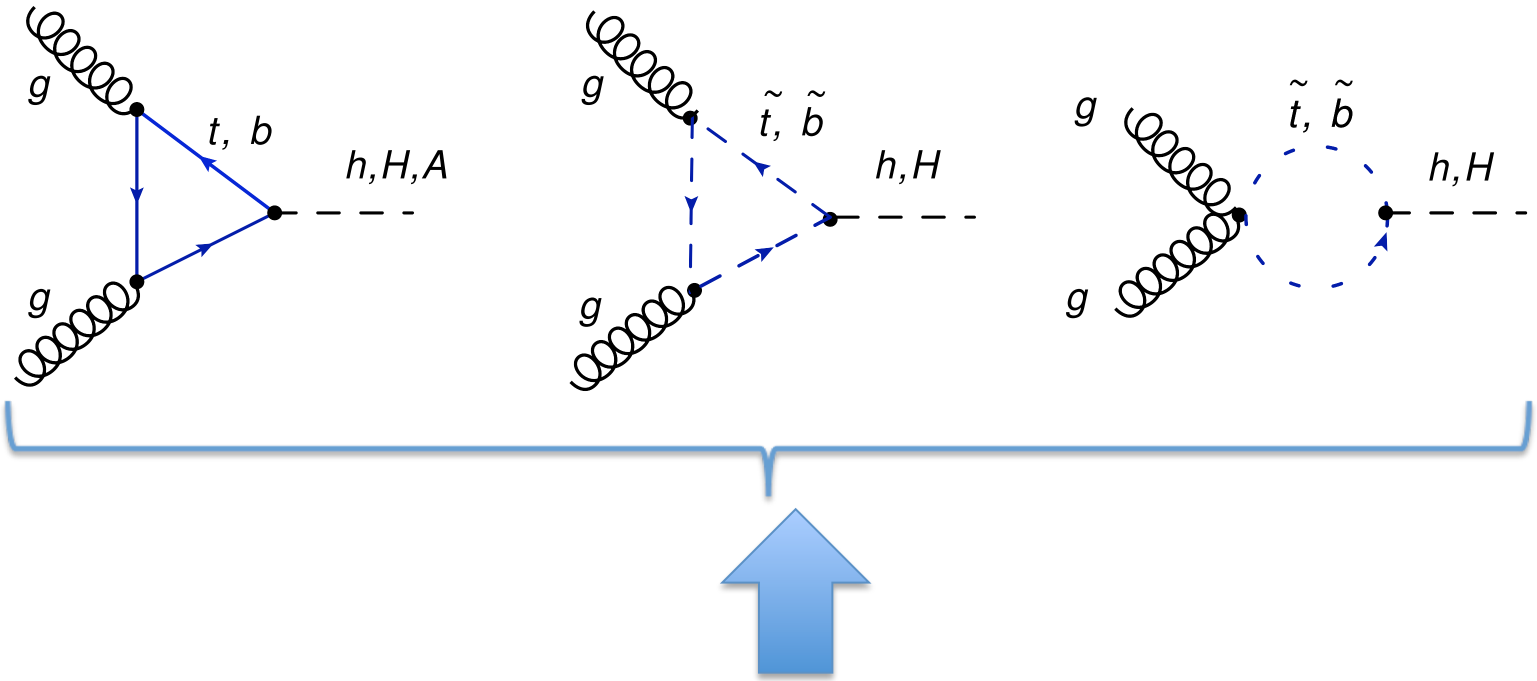


Fig. 1. The leading order (LO) diagrams for the Higgs boson production via gluon fusion.

Production of Φ at hadron colliders within the SM mainly goes through the gluon fusion process H. M. Georgi, S. L. Glashow, M. E. Machacek *et al.*, Phys. Rev. Lett. 40, 692 (1978).



This is also true in the MSSM, though in this case the associated production with two b-quarks (two b-jets) is even more favorable A. Djouadi: hep-ph/0503173.
The latter process is realized at the tree level and, hence, has no new virtual particles involved contrary to the loop diagrams. Nevertheless, the triangle diagrams do not give additional b-jets in the final states and presumably can be distinguished from the associated production by b-tagging of these jets.

Fullfilment of various constraints

$B \rightarrow X_s \gamma$ E. Barberio *et al.* : 0808.1297 [hep-ex]

$B_s \rightarrow \mu^+ \mu^-$ T. Aaltonen *et al.* : 0712.1708 [hep-ex],
V. M. Abazov *et al.* : 1006.3469 [hep-ex]

g - 2 of muon D. Stockinger : hep-ph/0609168

Relic density of the Dark Matter (DM) E. Komatsu *et al.* : 0803.0547 [astro-ph] using SuperIso (Relic) code F. Mahmoudi : 0808.3144, A. Arbey and F. Mahmoudi : 0906.0369.

Electroweak precision data on M_W and $\sin^2 \theta_{eff}$
S. Heinemeyer, W. Hollik, G. Weiglein : hep-ph/0412214

and

Light Higgs mass; $h \approx 118$ GeV

We proceed in two ways:

First: Universal soft SUSY breaking framework
Initial parameters
- Unification of the gaugino [bino, wino and gluino] masses: m1/2
- Universal scalar [*i.e.* sfermion and Higgs boson] masses: m0
- Universal trilinear couplings: A0
- tanβ

Second: Non-universal soft SUSY breaking framework
Initial parameters: m0, m1/2, A0, tanβ, CP-odd heavy Higgs boson mA and Higgs mixing term μ

-- Evaluate masses and mixings with the help of SOFTSUSY 3.1.6.

-- Calculate the cross-section for various points of parameter space.

$$\sigma_{Higgs} = \frac{1}{32}\int_0^1 dx_1 dx_2\; g[x_1]\; g[x_2]\; |\mathcal{M}_{Higgs}|^2 \frac{2\pi}{m^2_{Higgs}} \delta(E^2 x_1 x_2 - m^2_{Higgs})$$

g[x] is the gluon distribution function inside the proton that implicitly depends on the factorization scale Q.

In our case, we take it equal to the Higgs boson mass.

The matrix elements

$$\mathcal{M}_h = \frac{\alpha_s}{4\pi}\frac{m_h^2}{2\sqrt{2}v}\left(\frac{\cos\alpha}{\sin\beta}F^h_{1/2}[\frac{4m_t^2}{m_h^2}] - \frac{\sin\alpha}{\cos\beta}F^h_{1/2}[\frac{4m_b^2}{m_h^2}]\right)$$

$$\mathcal{M}_H = \frac{\alpha_s}{4\pi}\frac{m_H^2}{2\sqrt{2}v}\left(\frac{\sin\alpha}{\sin\beta}F^H_{1/2}[\frac{4m_t^2}{m_H^2}] + \frac{\cos\alpha}{\cos\beta}F^H_{1/2}[\frac{4m_b^2}{m_H^2}]\right)$$

$$\mathcal{M}_A = \frac{\alpha_s}{4\pi}\frac{m_A^2}{2\sqrt{2}v}\left(\frac{\cos\beta}{\sin\beta}F^A_{1/2}[\frac{4m_t^2}{m_A^2}] + \frac{\sin\beta}{\cos\beta}F^A_{1/2}[\frac{4m_b^2}{m_A^2}]\right)$$

where ν = 175 GeV.

α : neutral Higgs mixing angle; $\tan 2\alpha = \tan 2\beta\,(m^2_A+M^2_Z)/(m^2_A-M^2_Z)$, $\alpha \approx -\pi/2+\beta$

$-\pi/2 \le \alpha \le 0$ ➔ $\sin\alpha<0$ and the sign of the t-quark contribution - different for h and H.

It is known that for the lightest Higgs boson h (with the mass mh < 400 - 500 GeV) the loops with the bottom and top quarks interfere destructively A. Djouadi : hep-ph/0503173.

In contrast, in the case of the heavy boson H the interference is constructive (becomes destructive only when the mH > 400-500 GeV).

$$\mathcal{M}_h = \frac{\alpha_s}{4\pi}\frac{m_h^2}{2\sqrt{2}v}\left(\frac{\cos\alpha}{\sin\beta}F^h_{1/2}[\frac{4m_t^2}{m_h^2}] - \frac{\sin\alpha}{\cos\beta}F^h_{1/2}[\frac{4m_b^2}{m_h^2}]\right)$$

$$\mathcal{M}_H = \frac{\alpha_s}{4\pi}\frac{m_H^2}{2\sqrt{2}v}\left(\frac{\sin\alpha}{\sin\beta}F^H_{1/2}[\frac{4m_t^2}{m_H^2}] + \frac{\cos\alpha}{\cos\beta}F^H_{1/2}[\frac{4m_b^2}{m_H^2}]\right)$$

$$\mathcal{M}_A = \frac{\alpha_s}{4\pi}\frac{m_A^2}{2\sqrt{2}v}\left(\frac{\cos\beta}{\sin\beta}F^A_{1/2}[\frac{4m_t^2}{m_A^2}] + \frac{\sin\beta}{\cos\beta}F^A_{1/2}[\frac{4m_b^2}{m_A^2}]\right)$$

h production is almost not influenced by tanβ

H and A production by the contribution of the bquark is enhanced by tanβ and that of the t-quark is suppressed by tanβ

Hence, for high tanβ (which is of interest for us due to the enhancement of the cross-section) only the b-quark is essential.

$$
\begin{aligned}
\Delta\mathcal{M}_h = \frac{\alpha_s}{4\pi}\frac{m_h^2}{2\sqrt{2}v}\Bigg(&\frac{\cos\alpha}{\sin\beta}\sum_{i=1,2}[(1 \pm \frac{\sin 2\theta_t}{2m_t}(A_t + \mu\tan\alpha)]\frac{m_t^2}{\tilde{m}_{ti}^2}F_0[\frac{4\tilde{m}_{ti}^2}{m_h^2}] \\
&-\frac{\sin\alpha}{\cos\beta}\sum_{i=1,2}[(1 \pm \frac{\sin 2\theta_b}{2m_b}(A_b + \mu\cot\alpha)]\frac{m_b^2}{\tilde{m}_{bi}^2}F_0[\frac{4\tilde{m}_{bi}^2}{m_h^2}] \\
&-\sin(\alpha+\beta)\sum_{i=1,2}(\frac{1}{2}\left\{\begin{matrix}\cos^2\theta_t \\ \sin^2\theta_t\end{matrix}\right\} \mp \frac{2}{3}\sin^2\theta_W\cos 2\theta_t)\frac{M_Z^2}{\tilde{m}_{ti}^2}F_0[\frac{4\tilde{m}_{ti}^2}{m_h^2}] \\
&+\sin(\alpha+\beta)\sum_{i=1,2}(\frac{1}{2}\left\{\begin{matrix}\cos^2\theta_b \\ \sin^2\theta_b\end{matrix}\right\} \mp \frac{1}{3}\sin^2\theta_W\cos 2\theta_b)\frac{M_Z^2}{\tilde{m}_{bi}^2}F_0[\frac{4\tilde{m}_{bi}^2}{m_h^2}]\Bigg)
\end{aligned}
$$

$$\Delta\mathcal{M}_H = \frac{\alpha_s}{4\pi}\frac{m_H^2}{2\sqrt{2}v}\left(\frac{\sin\alpha}{\sin\beta}\sum_{i=1,2}[(1\pm\frac{\sin 2\theta_t}{2m_t}(A_t-\mu\cot\alpha)]\frac{m_t^2}{\tilde{m}_{ti}^2}F_0[\frac{4\tilde{m}_{ti}^2}{m_H^2}]\right.$$

$$+\frac{\cos\alpha}{\cos\beta}\sum_{i=1,2}[(1\pm\frac{\sin 2\theta_b}{2m_b}(A_b-\mu\tan\alpha)]\frac{m_b^2}{\tilde{m}_{bi}^2}F_0[\frac{4\tilde{m}_{bi}^2}{m_H^2}]$$

$$+\cos(\alpha+\beta)\sum_{i=1,2}(\frac{1}{2}\left\{\begin{matrix}\cos^2\theta_t\\ \sin^2\theta_t\end{matrix}\right\}\mp\frac{2}{3}\sin^2\theta_W\cos 2\theta_t)\frac{M_Z^2}{\tilde{m}_{ti}^2}F_0[\frac{4\tilde{m}_{ti}^2}{m_H^2}]$$

$$\left.-\cos(\alpha+\beta)\sum_{i=1,2}(\frac{1}{2}\left\{\begin{matrix}\cos^2\theta_b\\ \sin^2\theta_b\end{matrix}\right\}\mp\frac{1}{3}\sin^2\theta_W\cos 2\theta_b)\frac{M_Z^2}{\tilde{m}_{bi}^2}F_0[\frac{4\tilde{m}_{bi}^2}{m_H^2}]\right),$$

$$\Delta\mathcal{M}_A = 0,$$

squark mixing parameters and the mixing angles :

$$X_b = A_b - \mu \tan\beta, \quad X_t = A_t - \mu \cot\beta, \quad \sin 2\theta_q = \frac{2 m_q X_q}{\tilde{m}_{q1}^2 - \tilde{m}_{q2}^2}$$

Note that due to the appearance of the quark mass squared versus tanβ, the main contribution comes from the t-squarks and not from the b-squarks.

The triangle functions :
L. B. Okun, Leptons and Quarks, (Elsevier Science Pub Co, March 1, 1985

$$\begin{aligned}
F_{1/2}^{h,H}[x] &= -2x(1+(1-x)f(x)), \\
F_{1/2}^{A}[x] &= -2xf(x), \\
F_0[x] &= x(1-xf(x)), \\
f(x) &= \theta(x-1)[ArcTan\frac{1}{\sqrt{x-1}}]^2 + \theta(1-x)[\frac{i}{2}Log(\frac{1+\sqrt{1-x}}{1-\sqrt{1-x}}) + \frac{\pi}{2}]^2.
\end{aligned}$$

$$F^{h,H}_{1/2}[x] = -2x(1+(1-x)f(x)),$$
$$F^{A}_{1/2}[x] = -2xf(x),$$
$$F_0[x] = x(1-xf(x)),$$
$$f(x) = \theta(x-1)[ArcTan\frac{1}{\sqrt{x-1}}]^2 + \theta(1-x)[\frac{i}{2}Log(\frac{1+\sqrt{1-x}}{1-\sqrt{1-x}}) + \frac{\pi}{2}]^2.$$

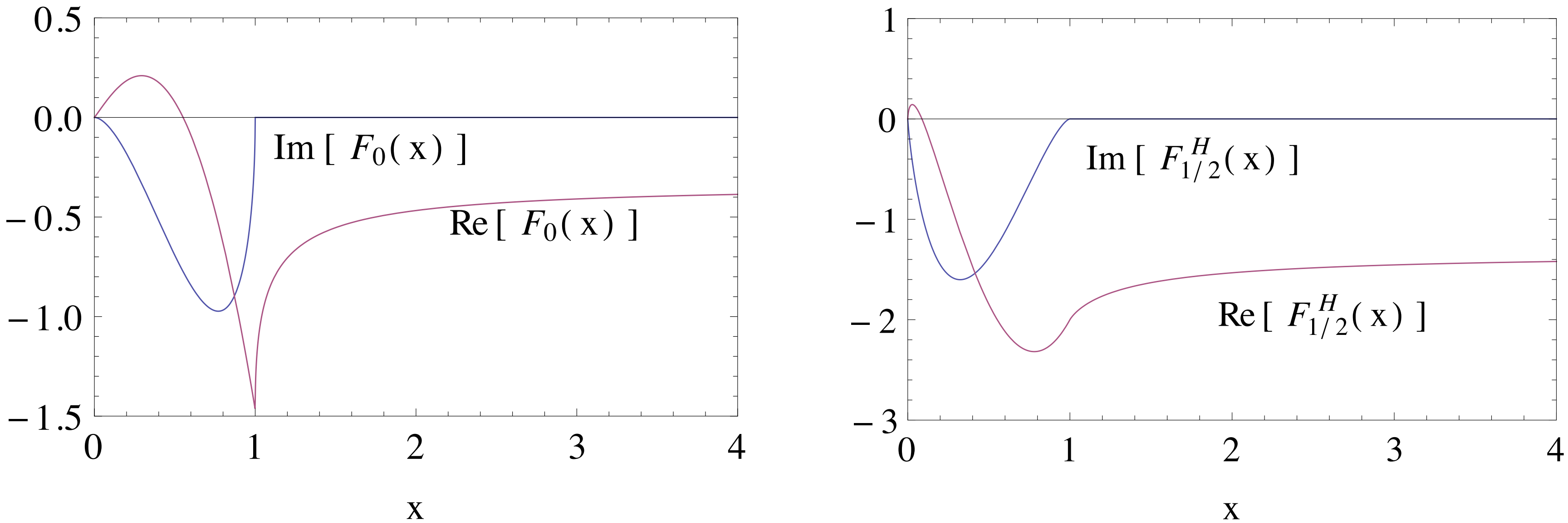


Fig. 2. The dependence of the functions $F_0(x)$ and $F^H_{1/2}(x)$ on x.

At the threshold the modulus of F_0 is maximal and saturates the squark contribution.

Universal soft supersymmetry breaking

Benchmark points:

(m0,m1/2) = (900, 300) GeV,
(m0,m1/2) = (1100, 300) GeV
(m0,m1/2) = (1700, 200) GeV

Allow A0 to be positive and negative.

This choice is dictated;

on the one hand, by the requirement of smallness of ˜mt1 which gives the main contribution to the cross-section,

on the other hand, by restrictions on the parameter space coming from the other physical constraints D. I. Kazakov : 1010.5419.

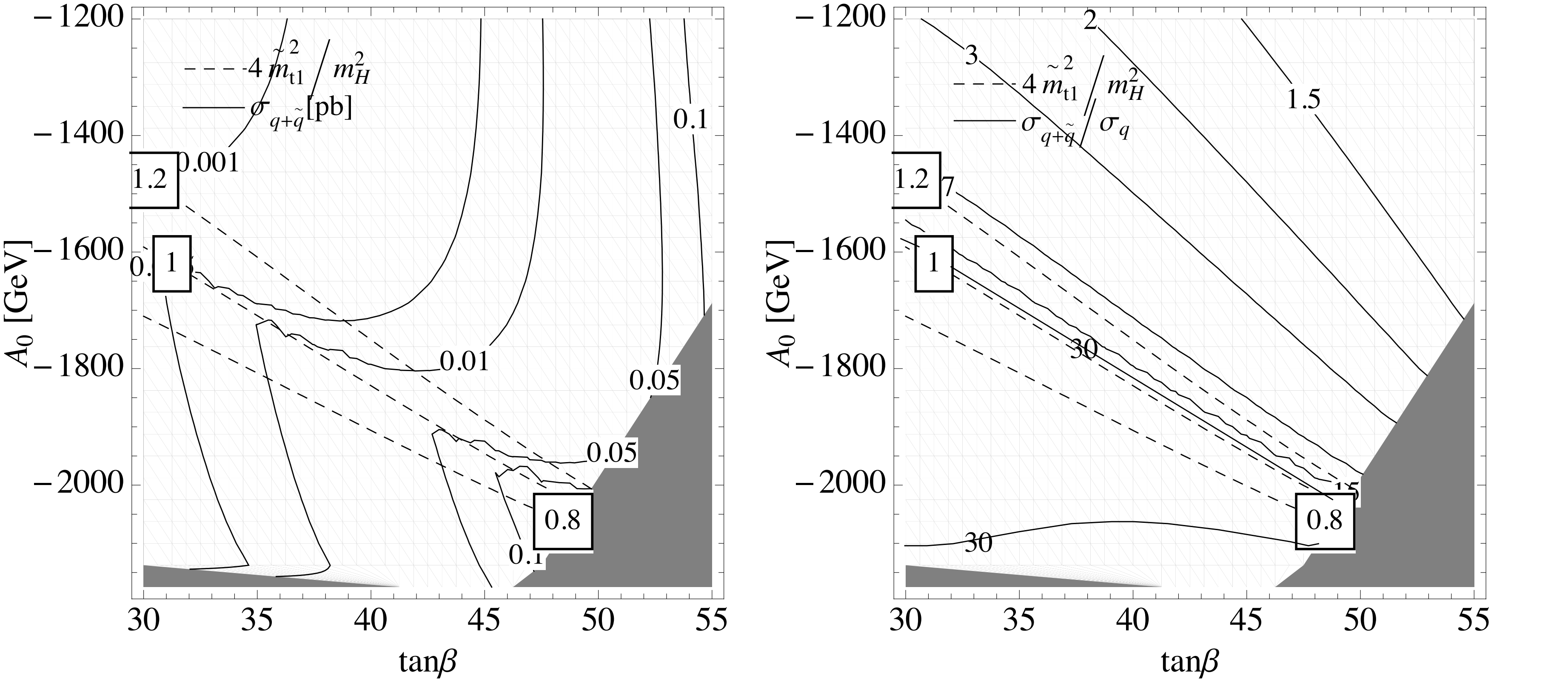


Fig. 3a. The cross-section (√s = 14 TeV) of the heavy Higgs production (left) and the ratio of squark+quark to quark loop contribution (right) as functions A0 and tanβ for the point (m0;m1/2) = (900; 300) GeV. The dashed lines correspond to the resonance values of $4\,m^2_{\sim t1}/m^2_H$. At the threshold $4m^2_{\sim t1}/m^2_H=1$ and the enhancement is maximal.
The gray regions are prohibited by the LSP constraint or due to the existence of a tachyon in the parameter space.

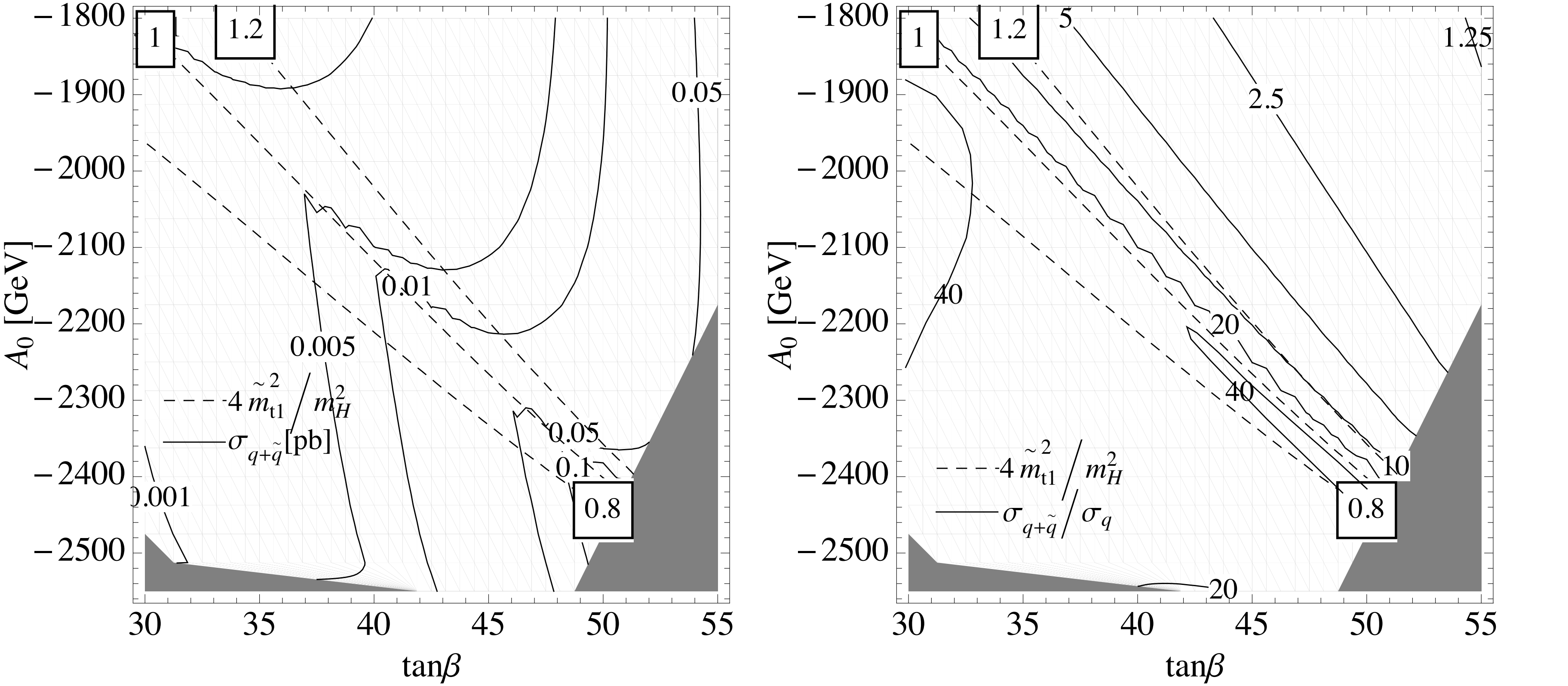


Fig. 3b. The cross-section (√s = 14 TeV) of the heavy Higgs production (left) and the ratio of squark+quark to quark loop contribution (right) as functions A0 and tanβ for the point (m0;m1/2) = (1100; 300) GeV. The dashed lines correspond to the resonance values of 4 $m^2_{\sim t1}/m^2_H$. At the threshold $4m^2_{\sim t1}/m^2_H=1$ and the enhancement is maximal.
The gray regions are prohibited by the LSP constraint or due to the existence of a tachyon in the parameter space.

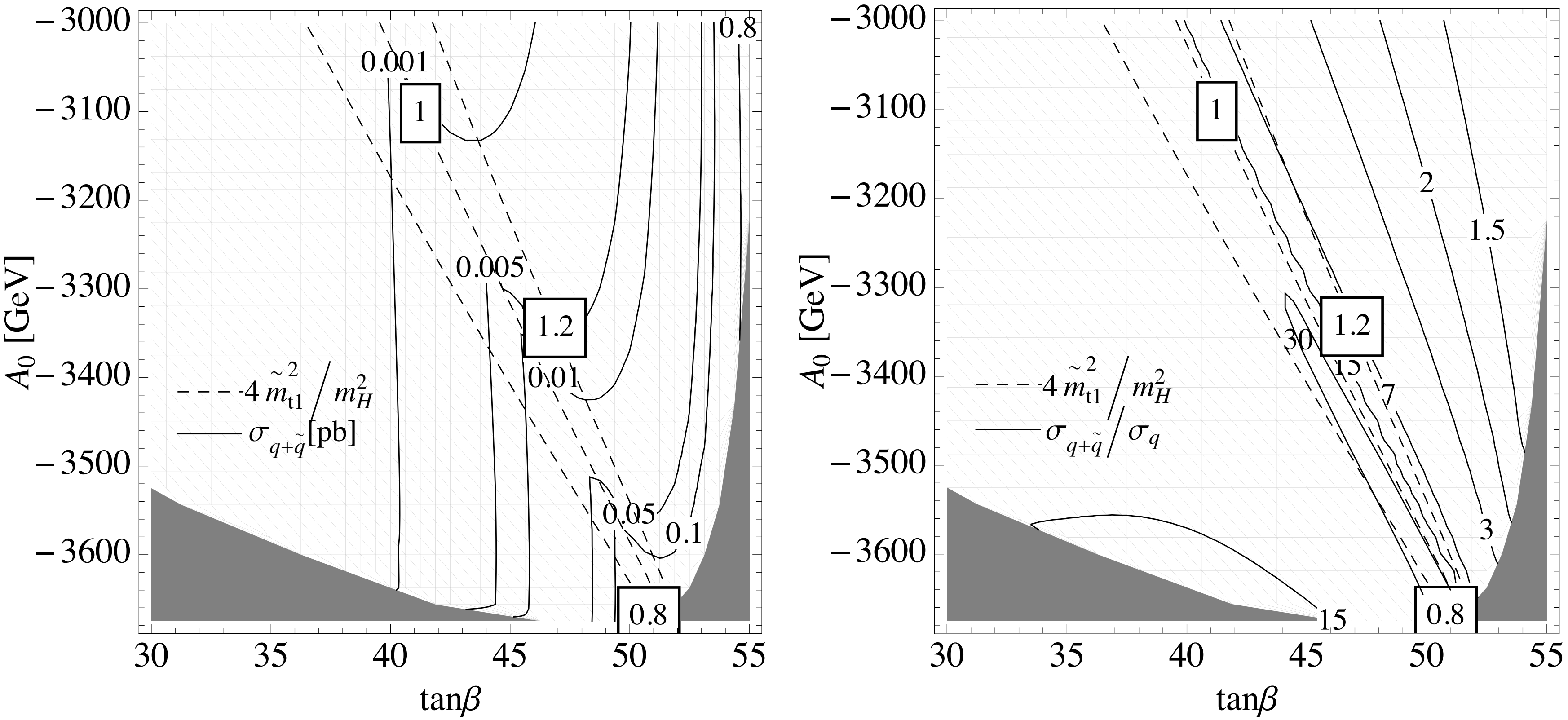


Fig. 3c. The cross-section (√s = 14 TeV) of the heavy Higgs production (left) and the ratio of squark+quark to quark loop contribution (right) as functions A0 and tanβ for the point (m0;m1/2) = (1700; 200) GeV. The dashed lines correspond to the resonance values of 4 $m^2_{\sim t1}/m^2_H$. At the threshold $4m^2_{\sim t1}/m^2_H=1$ and the enhancement is maximal.
The gray regions are prohibited by the LSP constraint or due to the existence of a tachyon in the parameter space.

Non-universal soft supersymmetry breaking

Benchmark points:

$m_{1/2}$ = 250 GeV
m_0 = 625 GeV
μ = 240 GeV
m_A = 340 GeV
$A_0 = -1175$ GeV,
$\tan\beta$ = 30.

For the large $\tan\beta$ scenarios $m_H \simeq m_A$ and we have enough freedom to obtain significant enhancement in the $gg \to H$ cross-section by adjusting m_A.

Moreover, since we also can adjust the μ-parameter, it is possible to fulfill the $b \to s\gamma$ constraint by the increase of the chargino contribution mentioned in the previous section.

Fig. 4a. m0-A0 plane

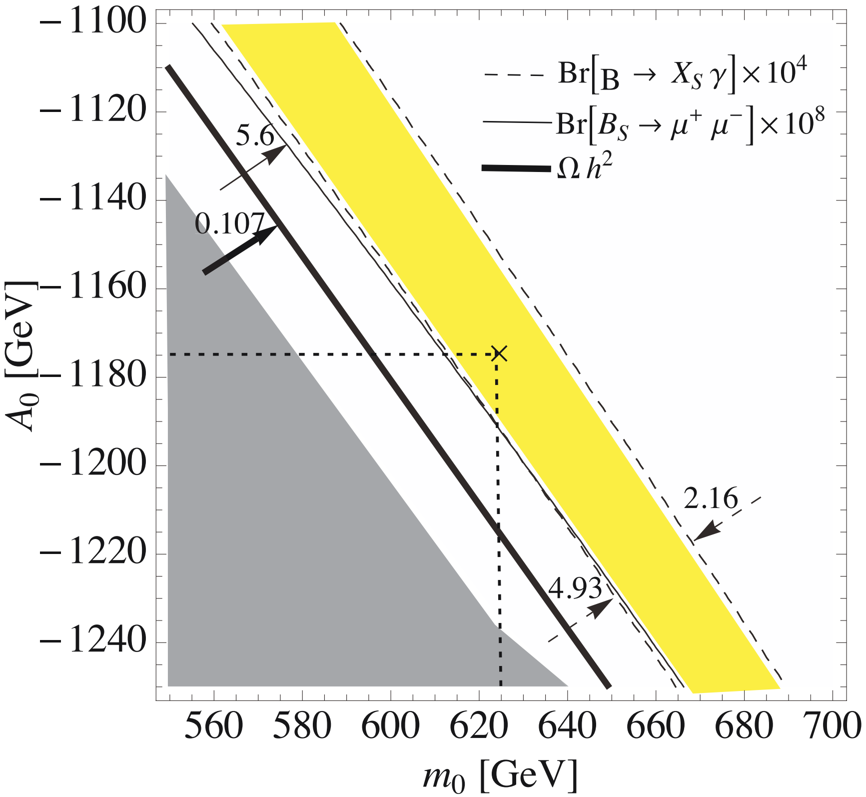
tanβ=30, m1/2=250 GeV,

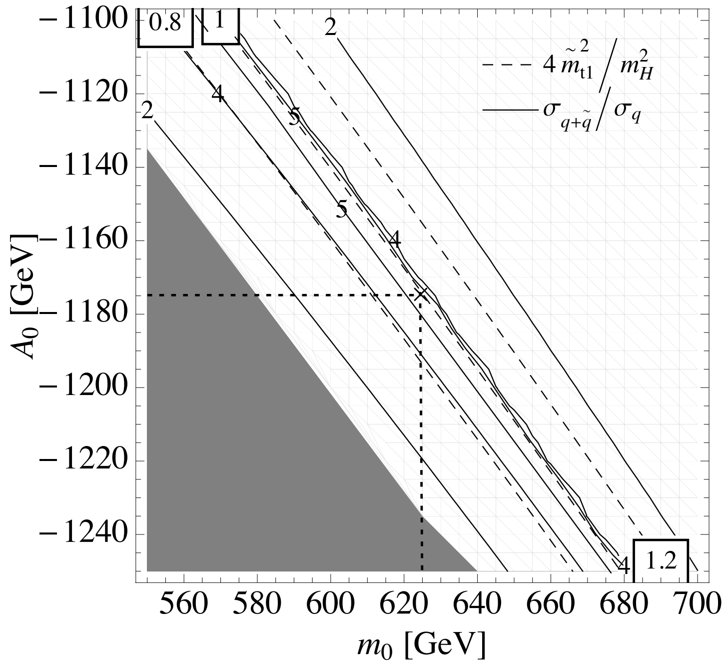
mA=340 GeV, μ=240 GeV

The ratio of the cross-sections R_H=(q+~q)/q and the total cross-section q+~q at √s = 14 TeV.

The numbers 0.8; 1.0; 1.2 ≈ 4 $\tilde{m}^2_{\tilde{t}1} / \tilde{m}^2_H$.

The benchmark point is marked by a cross.





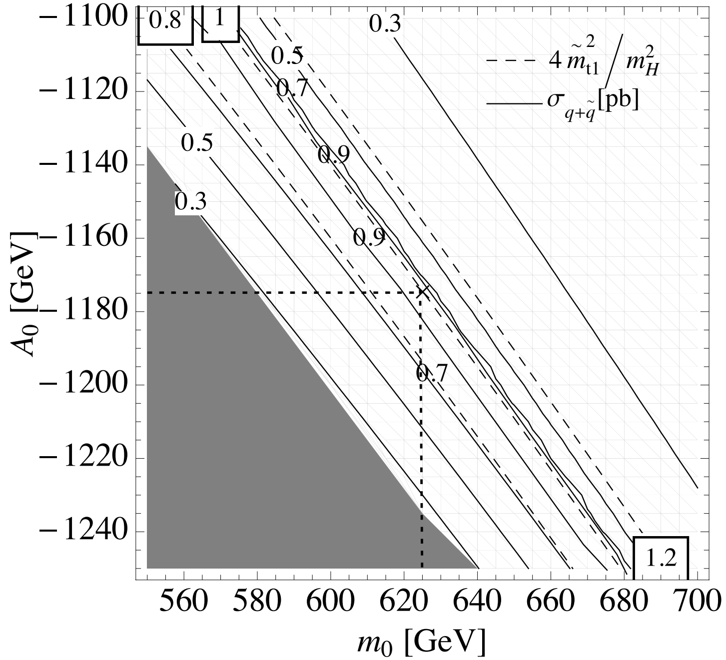


Fig. 4b. mA-μ plane

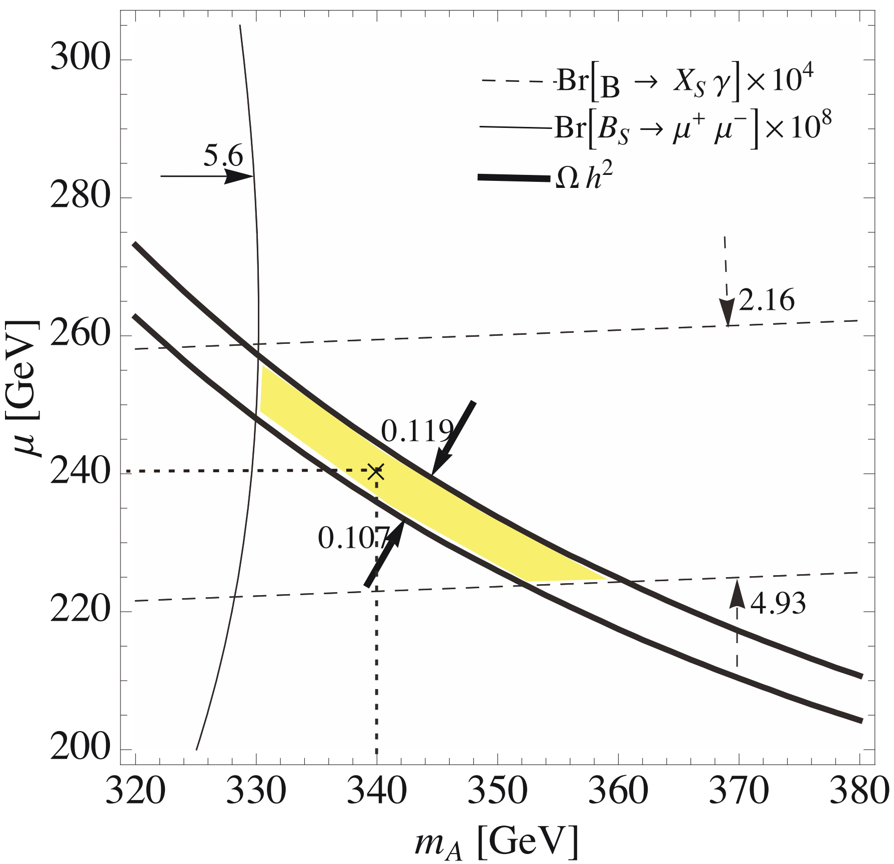
tanβ=30, m0=625 GeV,

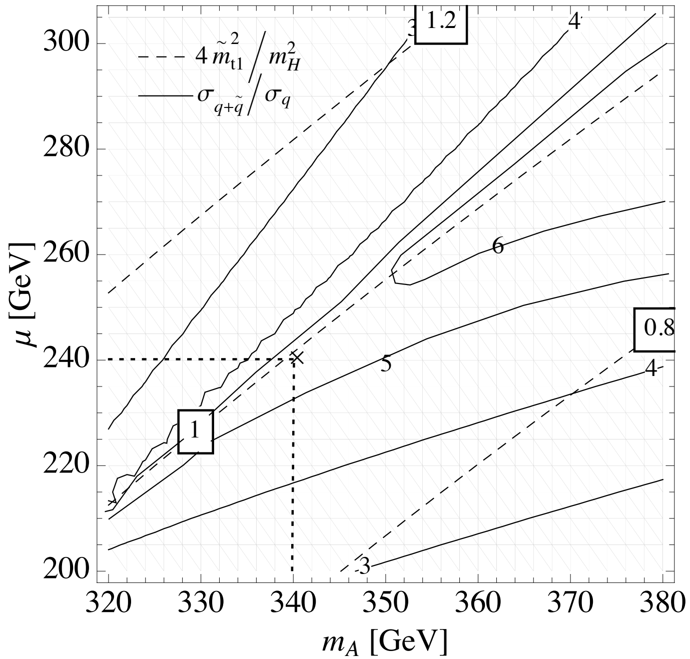
m1/2=250 GeV, A0=-1175 GeV

The ratio of the cross-sections R_H=(q+~q)/q and the total cross-section q+~q at √s = 14 TeV.

The numbers 0.8; 1.0; 1.2 ≈ 4 $\tilde{m}^2_{\tilde{t}1}$ / $\tilde{m}^2_H$.

The benchmark point is marked by a cross.





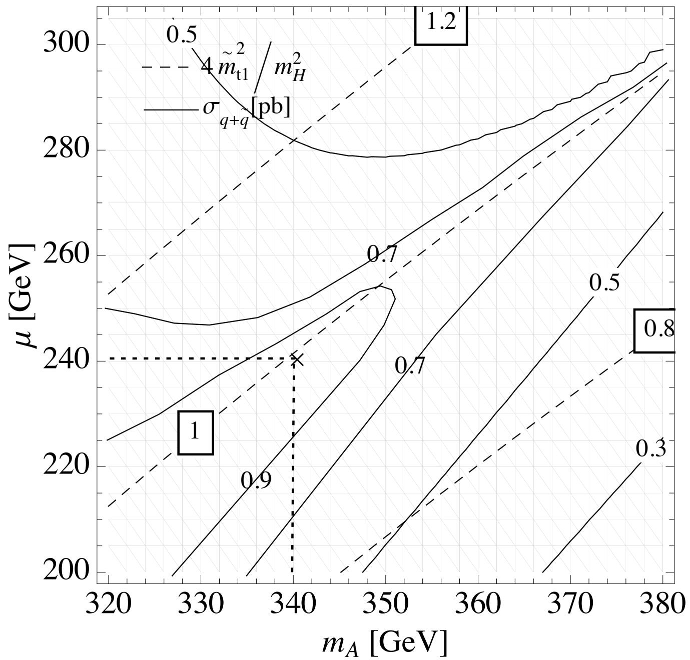


Fig. 4c. tanβ-A0 plane

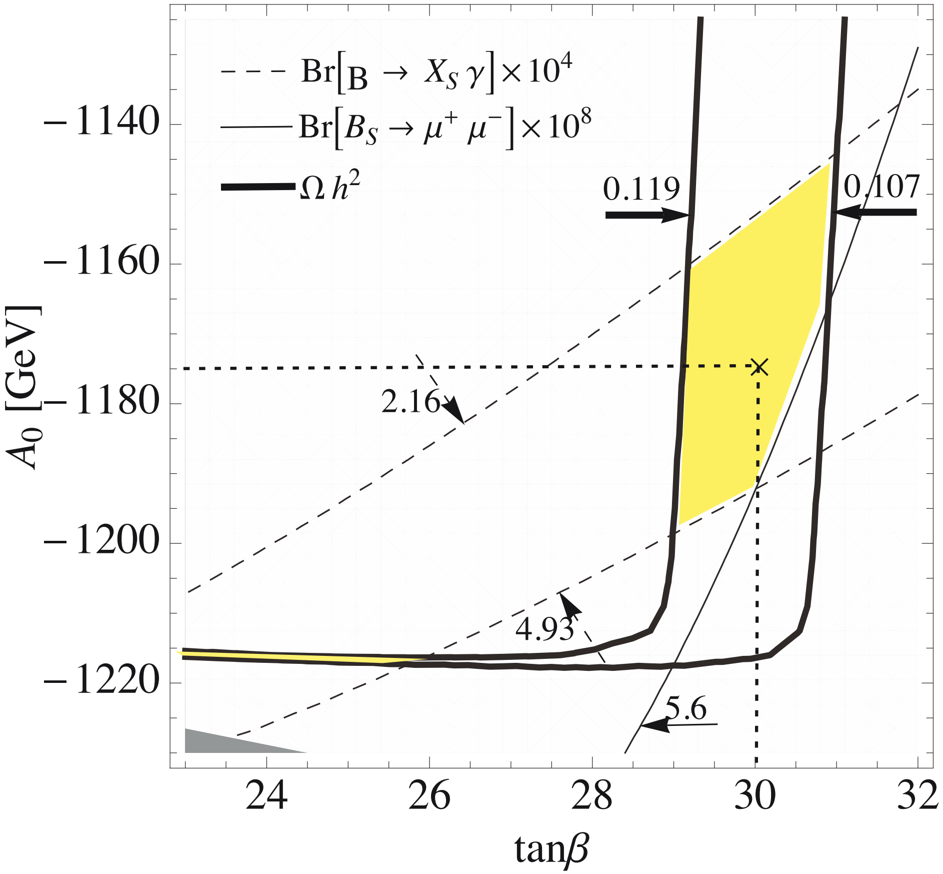
m0=625 GeV, m1/2=250 GeV,

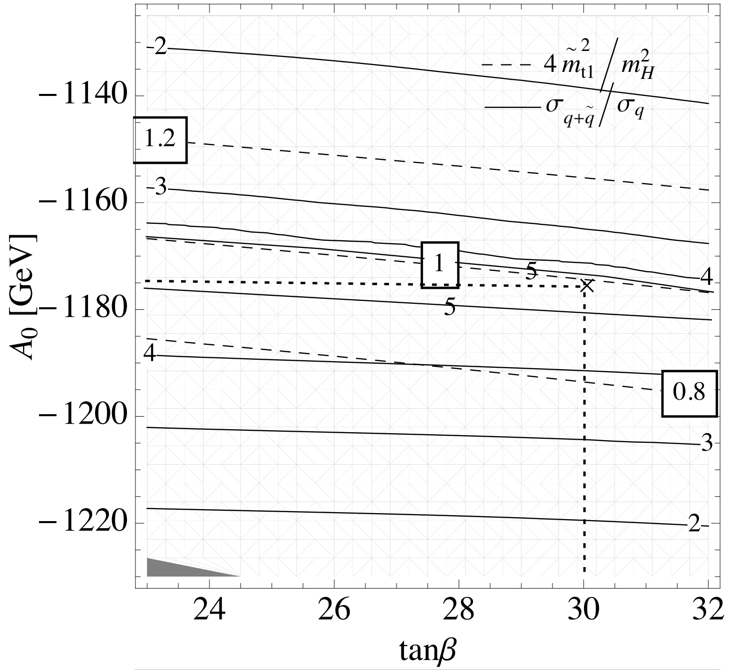
mA=340 GeV, μ=240 GeV

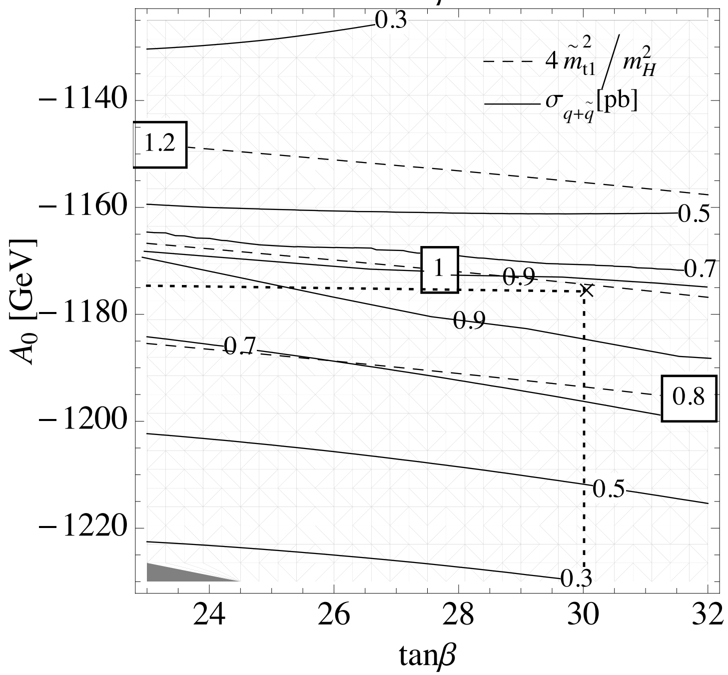
The ratio of the cross-sections R_H=(q+~q)/q and the total cross-section q+~q at √s = 14 TeV.

The numbers 0.8; 1.0; 1.2 ≈ 4 $\tilde{m}^2_{\tilde{t}1}$ / $\tilde{m}^2_H$.

The benchmark point is marked by a cross.







Discussion

- If SUSY or some other heavy particles exist, the enhancement of the Higgs production can be pushed not only by tanβ but also by squarks.

- Requirements: one of the intermediate particles (the lightest top squark ~t1 in our case) (1.) has to be relatively light and (2.) has to be close to the resonance with the Higgs boson.

- The allowed region in the parameter space found here seems to be very narrow mostly due to the relic density constraint.

-However, this impression is not true since in each plane shown in Fig. 4abc all the other parameters are fixed. In the whole parameter space the allowed volume with q+~q ≤ 1 pb and R_H≈3−5 is obviously bigger. For example, the benchmark point parameters can be shifted to tanβ=25 and μ=210 GeV at the price of slightly lower values of R_H≈3 and q+~q≈0.5 pb.

- In the considered scenarios compatible with known experimental constraints it is still lower than the associated production accompanied by two b-quarks (see diagrams shown in Fig. 5).

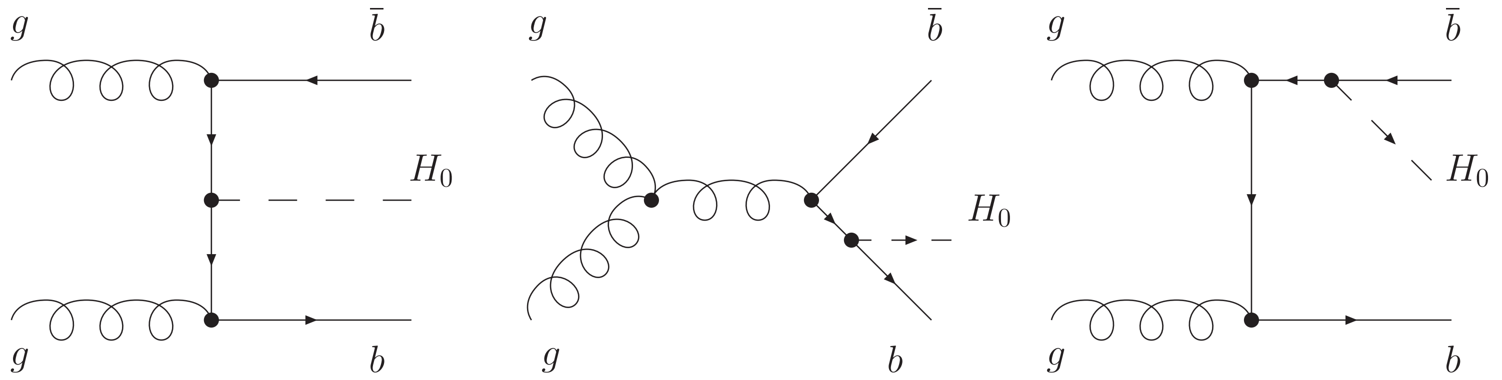


Fig. 5. The LO diagrams for the associated heavy Higgs production with the two b-jets in the so-called four-flavor scheme (4FS), where one does not consider b-quarks as partons in the proton. For large tanβ this contribution to the total production cross-section is dominant.

- In the MSSM, the associated production with two b-quarks (two b-jets) is even more favorable. These process is realized at the tree level and, hence, has no new virtual particles involved contrary to the loop diagrams. Nevertheless, the triangle diagrams do not give additional b-jets in the final states and presumably can be distinguished from the associated production by b-tagging of these jets.

-Two b-jets coming from the decay of the stops, missing energy. $\not{E}_T$ from two neutralinos, and light-quark jets or leptons from the virtual W-bosons (see Fig. 6).

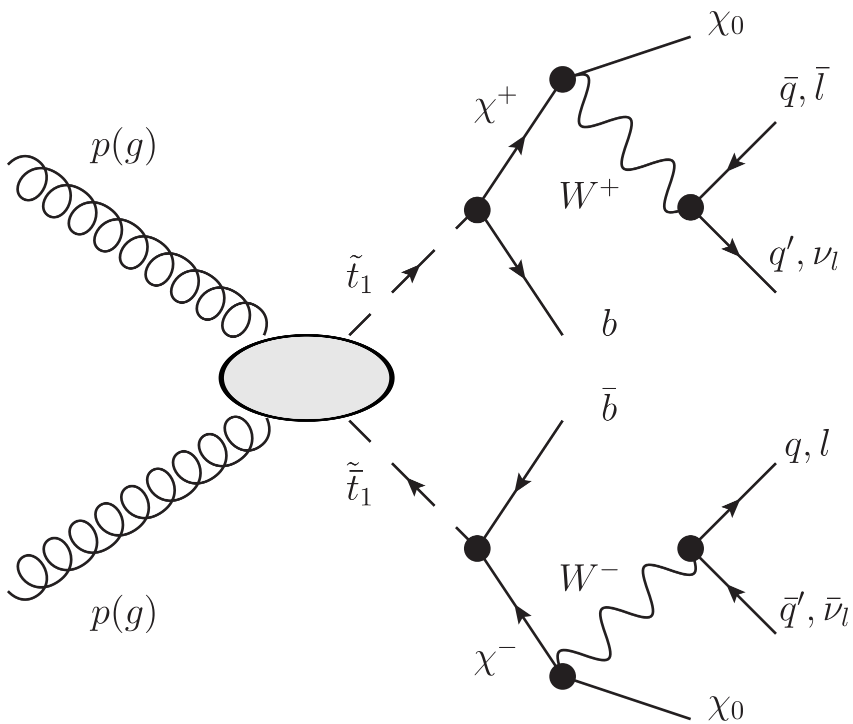


Fig. 6. The lightest stop pair-production process at the LHC energies in proton-proton collisions.

The lightest stop pair-production process at the LHC energies in proton–proton collisions.

The blob corresponds to all the tree-level diagrams contributing to the stop production.

The final states include two b-jets, missing energy $\not{E}_T$ the light-quark jets, and leptons.

With almost equal probability (45%) the virtual W-boson produces either four jets or two jets accompanied by a charged lepton and additional missing energy from neutrino.

In 10% of cases two W-bosons decay leptonically, and instead of the light-quark jets we have two charged leptons and additional $\not{E}_T$ from two neutrinos.

This work was done by A. V. Bednyakov, D. I. Kazakov and Ş. H. Tanyıldızı.

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