Neutral MSSM Higgs and Z boson associated production at the LHC

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We study the associated hadroproduction of a neutral Higgs and a Z Boson within the minimal supersymmetric standard model (MSSM). We calculate the partonic cross sections for producing CP-odd neutral Higgs boson plus Z boson analytically to lowest order. To LO, the contributing partonic cross sections include tree-level quark-antiquark ($q\overline{q}$) annihilation and one-loop gluon-gluon (gg) fusion, which proceeds via quark and squark loops. The cross sections are expressed in terms of helicity amplitudes. We present cross sections as functions of the Higgs mass and $\tan\beta$ assuming LHC experimental conditions.

We focus on the hadronic production of a neutral CP-odd MSSM Higgs boson in association with a Z boson. We describe and list the lowest order contribution to the hadronic production cross section and explore the phenomenological consequence under experimental conditions of the LHC.

We present the LO cross sections of the partonic subprocesses $q\overline{q} \to ZA^0$ and $gg \to ZA^0$ in the MSSM. We work in the parton model of QCD with $n_f = 5$ active quark flavors $q = u, d, s, c, b$, which we take to be massless. However, we retain the b-quark Yukawa couplings at their finite values, in order not to suppress possibly sizeable contributions. The various couplings v_{Zqq}, a_{Zqq}, $g_{\phi qq}$, $g_{h^0A^0Z}$, $g_{H^0A^0Z}$, g_{h^0ZZ}, and g_{H^0ZZ} are readily available in the literature.

Considering the generic partonic subprocess $ab \to ZA^0$, we denote the four-momenta of the incoming partons, a and b, and the outgoing Z and A^0 bosons by p_a, p_b, p_Z, and p_{A^0}, respectively, and define the partonic Mandelstam variables as $s = (p_a + p_b)^2$, $t = (p_a - p_Z)^2$, and $u = (p_b - p_Z)^2$. The on-shell conditions read $p_a^2 = p_b^2 = 0$, $p_Z^2 = m_Z^2 = z$, and $p_{A^0}^2 = m_{A^0}^2 = h$. Four-momentum coservation implies that $s + t + u = z + h$. Furthermore, we have $sp_T^2 = tu - zh = N$, where p_T is the absolute value of transverse momentum common to the Z and A^0 bosons in the center-of-mass (c.m.) frame.

The differential cross section for the tree-level $b\bar{b}$ annihilation may be generically written as

$$\frac{d\sigma}{dt}\left(b\bar{b} \to ZA^0\right) = \frac{G_F^2 c_w^4 z}{3\pi s}\left[\lambda|S|^2 - 4sp_T^2\left(\frac{1}{t}+\frac{1}{u}\right)g_{A^0bb}a_{Zbb}\Re S + g_{A^0bb}^2\left(v_{Zbb}^2 T_+ + a_{Zbb}^2 T_-\right)\right], \tag{1}$$

where G_F is the Fermi constant, $\lambda = s^2+z^2+h^2-2(sz+zh+hs)$, and $S = g_{h^0A^0Z}g_{h^0bb}\mathcal{P}_{h^0}(s) +$

$g_{H^0A^0Z}g_{H^0bb}\mathcal{P}_{H^0}(s)$, $T_\pm = 2 \pm 2 + 2p_T^2 \left[z\left(\frac{1}{t} \pm \frac{1}{u}\right) \mp \frac{2s}{tu}\right]$. Here, $\mathcal{P}_X(s) = \frac{1}{s-m_X^2+im_X\Gamma_X}$ is the propagator function of particle X, with mass m_X and total decay width Γ_X.

We express the quark and squark one-loop contributions to the gg fusion in terms of helicity amplitudes. We label the helicity states of the two gluons and the Z boson in the partonic c.m. frame by $\lambda_a = -1/2, 1/2, \lambda_b = -1/2, 1/2$, and $\lambda_Z = -1, 0, 1$. The helicity amplitudes of the quark and squark triangle contributions read

$$\begin{aligned}
\mathcal{M}^{\triangle}_{\lambda_a\lambda_b 0} &= 8i\sqrt{\frac{\lambda}{z}}(1+\lambda_a/\lambda_b)\sum_q m_q \left(g_{h^0A^0Z}g_{h^0qq}\mathcal{P}_{h^0}(s) + g_{H^0A^0Z}g_{H^0qq}\mathcal{P}_{H^0}(s)\right) F_\triangle\left(s, m_q^2\right), \\
\tilde{\mathcal{M}}^{\triangle}_{\lambda_a\lambda_b 0} &= -2i\sqrt{\frac{\lambda}{z}}(1+\lambda_a/\lambda_b)\sum_{\tilde{q}_i} \left(g_{h^0A^0Z}g_{h^0\tilde{q}_i\tilde{q}_i}\mathcal{P}_{h^0}(s) + g_{H^0A^0Z}g_{H^0\tilde{q}_i\tilde{q}_i}\mathcal{P}_{H^0}(s)\right) \tilde{F}_\triangle\left(s, m_{\tilde{q}_i}^2\right).
\end{aligned}$$

where $F_\triangle(s, m_q^2) = 2 + (4m_q^2 - s)C^{00}_{qqq}(s)$, and $\tilde{F}_\triangle(s, m_{\tilde{q}_i}^2) = 2 + 4m_{\tilde{q}_i}^2 C^{00}_{\tilde{q}_i\tilde{q}_i\tilde{q}_i}(s)$ are the quark and squark triangle form factors, respectively, and $C^{00}_{qqq}(s) = C_0(0, 0, m_q^2, m_q^2, m_q^2)$ is the scalar three-point function. As for the quark box contribution, all twelve helicity combinations contribute. Due to Bose symmetry, they are related by $\mathcal{M}^{\square}_{\lambda_a\lambda_b\lambda_Z}(t,u) = (-1)^{\lambda_Z}\mathcal{M}^{\square}_{\lambda_b\lambda_a\lambda_Z}(u,t)$, $\mathcal{M}^{\square}_{\lambda_a\lambda_b\lambda_Z}(t,u) = \mathcal{M}^{\square}_{-\lambda_a-\lambda_b-\lambda_Z}(t,u)$. Keeping $\lambda_Z = \pm 1$ generic, we thus only need to specify four expressions. These read

$$\begin{aligned}
\mathcal{M}^{\square}_{++0} &= -\frac{8i}{\sqrt{z\lambda}}\sum_q g_{A^0qq}a_{Zqq}m_q\left[F^0_{++} + (t \leftrightarrow u)\right], \\
\mathcal{M}^{\square}_{+-0} &= -\frac{8i}{\sqrt{z\lambda}}\sum_q g_{A^0qq}a_{Zqq}m_q\left[F^0_{+-} + (t \leftrightarrow u)\right], \\
\mathcal{M}^{\square}_{++\lambda_Z} &= -4i\sqrt{\frac{2N}{s}}\sum_q g_{A^0qq}a_{Zqq}m_q\left[F^1_{++} - (t \leftrightarrow u)\right], \\
\mathcal{M}^{\square}_{+-\lambda_Z} &= -4i\sqrt{\frac{2N}{s}}\sum_q g_{A^0qq}a_{Zqq}m_q\left[F^1_{+-} - (t \leftrightarrow u, \lambda_Z \to -\lambda_Z)\right].
\end{aligned} \tag{2}$$

The quark box form factors, $F^{|\lambda_Z|}_{\lambda_a\lambda_b}$, are functions of s, t, u, and depend on the scalar three- and four-point function. They are quite lengthy to be included here. We recall that $\tilde{\mathcal{M}}_{\lambda_a\lambda_b\lambda_Z} = 0$.

The differential cross section of $gg \to ZA^0$ is then given by

$$\frac{d\sigma}{dt}(gg \to ZA^0) = \frac{\alpha_s^2(\mu_r)G_F^2 m_W^4}{256(4\pi)^3 s^2}\sum_{\lambda_a,\lambda_b,\lambda_Z}\left|\mathcal{M}^{\triangle}_{\lambda_a\lambda_b\lambda_Z} + \mathcal{M}^{\square}_{\lambda_a\lambda_b\lambda_Z} + \tilde{\mathcal{M}}^{\triangle}_{\lambda_a\lambda_b\lambda_Z}\right|^2, \tag{3}$$

where $\alpha_s(\mu_r)$ is the strong-coupling constant at renormalization scale μ_r. Due to Bose symmetry, the right-hand side of Eq. (3) is symmetric in t and u.

We are now in a position to explore the phenomenological implications of our results. The SM input parameters for our numerical analysis are taken to be $G_F = 1.16637 \times 10^{-5}$ GeV^{-2}, $m_W = 80.398$ GeV, $m_Z = 91.1876$ GeV, $m_t = 171.3$ GeV , and $\overline{m}_b(\overline{m}_b) = 4.20$ GeV [1]. We adopt the LO proton PDF set CTEQ6L1 [2]. We evaluate $\alpha_s(\mu_r)$ and $m_b(\mu_r)$ from the LO formulas, which may be found, *e.g.*, in Eqs. (23) and (24) of Ref. [3], respectively, with $n_f = 5$ quark flavors and asymptotic scale parameter $\Lambda^{(5)}_{QCD} = 165$ MeV [2]. We identify the

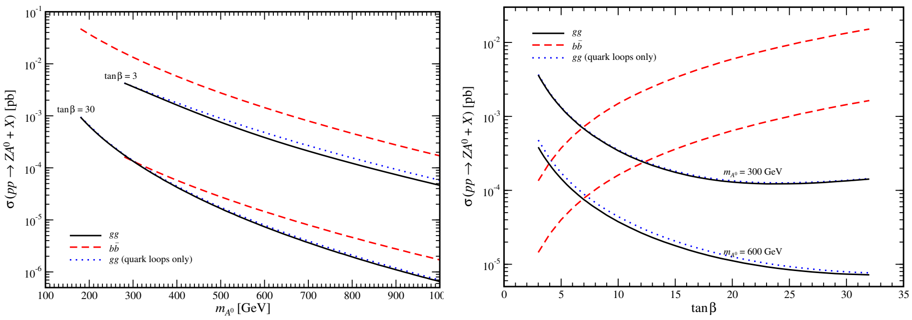

Figure 1: Total cross sections σ (in fb) of the $p\overline{p} \to ZA^0 + X$ via $b\overline{b}$ annihilation (dashed lines) and gg fusion (solid lines) at the LHC as functions of m_{A^0} for $\tan\beta = 3$ and 30, and as functions of $\tan\beta$ for $m_{A^0} = 300$ GeV and 600 GeV. The dotted lines correspond to gg fusion originating from quark loops only.

renormalization and factorization scales with the $Z\phi$ invariant mass $\sqrt{s}$. We vary $\tan\beta$ and m_{A^0} in the ranges $3 < \tan\beta < 32 \approx m_t/m_b$ and 180 GeV $< m_{A^0} <$ 1 TeV, respectively. As for the GUT parameters, we choose $m_{1/2} = 150$ GeV, $A = 0$, and $\mu < 0$, and tune m_0 so as to be consistent with the desired value of m_{A^0}. All other MSSM parameters are then determined according to the SUGRA-inspired scenario as implemented in the program package SUSPECT [4]. We do not impose the unification of the τ-lepton and b-quark Yukawa couplings at the GUT scale, which would just constrain the allowed $\tan\beta$ range without any visible effect on the results for these values of $\tan\beta$. We exclude solutions which do not comply with the present experimental lower mass bounds of the sfermions, charginos, neutralinos, and Higgs bosons [1].

Figure 1 shows the fully integrated cross sections of $pp \to ZA^0 + X$ at the LHC as functions of m_{A^0} for $\tan\beta = 3$ and 30, and as functions of $\tan\beta$ for $m_{A^0} = 300$ GeV and 600 GeV, with c.m. energy $\sqrt{S} = 14$ TeV. We note that the SUGRA-inspired MSSM with our choice of input parameters does not permit $\tan\beta$ and m_{A^0} to be simultaneously small, due to the experimental lower bound on the selectron mass [1]. This explains why the curves for $\tan\beta = 3$ only start at $m_{A^0} \approx 280$ GeV, while those for $\tan\beta = 30$ already start at $m_{A^0} \approx 180$ GeV. The $b\overline{b}$-annihilation contribution (dashed lines), which originates from the Yukawa-enhanced amplitudes, and the total gg-fusion contributions (solid lines), corresponding to the coherent superposition of quark and squark loop amplitudes, are given separately. It shows that the $b\overline{b}$-annihilation dominates at large to moderate values of $\tan\beta$. On the other hand, the gg-fusion dominates at small values of $\tan\beta$. We note further that the squark loop contribution, although minimal, tend to decrease the total gg-fusion contribution.

References

[1] Particle Data Group, C. Amsler *et al.*, Phys. Lett. B **667**, 1 (2008).

[2] J. Pumplin, D. R. Stump, J. Huston, H.-L. Lai, P. Nadolsky, and W.-K. Tung, JHEP **0207**, 012 (2002) [arXiv:hep-ph/0201195].

[3] B. A. Kniehl, Z. Phys. C **72**, 437 (1996) [arXiv:hep-ph/9403386].

[4] A. Djouadi, J. L. Kneur, and G. Moultaka, Comput. Phys. Commun. **176**, 426 (2007) [arXiv:hep-ph/0211331].