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SUSY-QCD corrections to MSSM Higgs boson production via gluon fusion

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In the MSSM scalar h,H production is mediated by heavy quark and squark loops. The higher order QCD corrections have been obtained some time ago and turned out to be large. The full SUSY QCD corrections have been obained recently including the full mass dependence of the loop particles. We describe our calculation and present first numerical results. We also address the question of the proper treatment of the large gluino mass limit, *i.e.* the consistent decoupling of heavy gluino effects, and present the effective Lagrangian for decoupled gluinos.

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1. Introduction

One of the major goals at the LHC is the production of Higgs boson(s) [1]. In the Minimal Supersymmetric Extension of the Standard Model (MSSM) two complex Higgs doublets are introduced to give masses to up- and down-type fermions [2]. After electroweak symmetry breaking there are five physcial Higgs states, two CP-even neutral Higgs bosons h,H, one neutral CP-odd Higgs state A and two charged Higgs bosons $H^\pm$. At tree level, the Higgs sector can be parameterized by two independent parameters, the pseudoscalar Higgs boson mass M_A and the ratio of the two vacuum expectation values (VEV) of the two complex Higgs doublets, $\tan\beta = v_2/v_1$. The Higgs couplings to quarks and gauge bosons are modified with sin and cos of the mixing angles α and β with respect to the Standard Model (SM) couplings, where α denotes the h,H mixing angle. The bottom (top) Yukawa couplings are enhanced (suppressed) for large values of $\tan\beta$, so that top Yukawa couplings play a dominant role at small and moderate values of $\tan\beta$.

At the LHC and Tevatron neutral Higgs bosons are copiously produced via gluon fusion $gg \to h,H,A$, which is mediated in the case of h,H by (s)top and (s)bottom loops [3]. The pure QCD corrections to the (s)quark loops have been obtained including the full Higgs and (s)quark mass dependences and increase the cross sections by $\sim$ 100% [4]. This result can be approximated by very heavy top (s)quarks with $\sim 20-30\%$ accuracy for $\tan\beta \lesssim 5$ [5]. In this limit the next-to-leading order (NLO) QCD [6] and later the next-to-next-to-leading order (NNLO) QCD corrections [7] have been obtained, the latter leading to a moderate increase of 20-30%. Finite top mass effects at NNLO have been discussed in [8]. Finally, the estimate of the next-to-next-to-next-to-leading order effects [9] indicates improved perturbative convergence. The full supersymmetric (SUSY) QCD corrections have been obtained in the limit of heavy SUSY particle masses [10] and more recently including the full mass dependence [11]. The electroweak loop effects have been calculated in [12]. In this article we will describe in Section 2 the calculation of the full SUSY-QCD corrections in gluon fusion to h,H, and we will present for the first time numerical results for the total cross section. In Section 3 we will discuss the consistent derivation of the effective Lagrangian for the scalar Higgs couplings to gluons after the gluino decoupling.

2. Gluon Fusion

At leading order (LO) the gluon fusion processes $gg \to h/H$ are mediated by heavy quark and squark triangle loops, *cf.* Fig.1, the latter contributing significantly for squark masses $\lesssim 400$ GeV. The LO cross section in the narrow-width approximation can be obtained from the h/H gluonic decay widths, [3,13]

$$\sigma_{LO}(pp \to h/H) = \sigma_0^{h/H} \tau_{h/H} \frac{d\mathscr{L}^{gg}}{d\tau_{h/H}} \tag{2.1}$$

$$\sigma_0^{h/H} = \frac{\pi^2}{8M_{h/H}^3} \Gamma_{LO}(h/H \to gg)$$

$$\sigma_0^{h/H} = \frac{G_F \alpha_s^2(\mu_R)}{288\sqrt{2}\pi} \left| \sum_Q g_Q^{h/H} A_Q^{h/H}(\tau_Q) + \sum_{\widetilde{Q}} g_{\widetilde{Q}}^{h/H} A_{\widetilde{Q}}^{h/H}(\tau_{\widetilde{Q}}) \right|^2 , \tag{2.2}$$

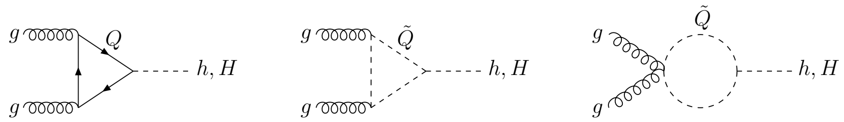

Figure 1: Diagrams contributing to $gg \to h, H$ at leading order.

where $\tau_{h/H} = M_{h/H}^2/s$ with s being the squared hadronic c.m. energy and $\tau_{Q/\tilde{Q}} = 4m_{Q/\tilde{Q}}^2/M_{h/H}^2$. The LO form factors are given by

$$\begin{aligned} A_Q^{h/H}(\tau) &= \frac{3}{2}\tau[1+(1-\tau)f(\tau)] \\ A_{\tilde{Q}}^{h/H}(\tau) &= -\frac{3}{4}\tau[1-\tau f(\tau)] \\ f(\tau) &= \begin{cases} \arcsin^2 \dfrac{1}{\sqrt{\tau}} & \tau \geq 1 \\ -\dfrac{1}{4}\left[\log\dfrac{1+\sqrt{1-\tau}}{1-\sqrt{1-\tau}} - i\pi\right]^2 & \tau < 1 \end{cases} . \end{aligned} \tag{2.3}$$

And the gluon luminosity at the factorization scale μ_F is defined as

$$\frac{d\mathscr{L}^{gg}}{d\tau} = \int_\tau^1 \frac{dx}{x}\, g(x,\mu_F^2) g(\tau/x,\mu_F^2)\,,$$

where $g(x,\mu_F^2)$ denotes the gluon parton density of the proton. The NLO SUSY-QCD corrections consist of the virtual two-loop corrections, *cf.* Fig.2, and the real corrections due to the radiation processes $gg \to gh/H, gq \to qh/H$ and $q\overline{q} \to gh/H$, *cf.* Fig.3. The final result for the total hadronic

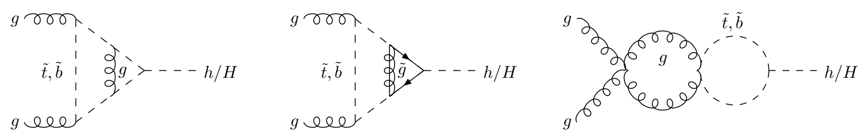

Figure 2: Some generic diagrams for the virtual NLO SUSY-QCD corrections to the squark contributions to the gluonic Higgs couplings.

cross sections can be split accordingly into five parts,

$$\sigma(pp \to h/H + X) = \sigma_0^{h/H}\left[1 + C^{h/H}\frac{\alpha_s}{\pi}\right]\tau_{h/H}\frac{d\mathscr{L}^{gg}}{d\tau_{h/H}} + \Delta\sigma_{gg}^{h/H} + \Delta\sigma_{gq}^{h/H} + \Delta\sigma_{q\bar{q}}^{h/H}\,. \tag{2.4}$$

The strong coupling constant is renormalized in the $\overline{\rm MS}$ scheme, with the top quark and squark contributions decoupled from the scale dependence. The quark and squark masses are renormalized on-shell. The parton densities are defined in the $\overline{\rm MS}$ scheme with five active flavors, i.e. the top quark and the squarks are not included in the factorization scale dependence. After renormalization we are left with collinear divergences in the sum of the virtual and real corrections which are

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absorbed in the renormalization of the parton density functions, so that the result Eq. (2.4) is finite and depends on the renormalization and factorization scales μ_R and μ_F, respectively. The natural scale choices turn out to be $\mu_R = \mu_F \sim M_{h/H}$. The numerical results are presented for the modified

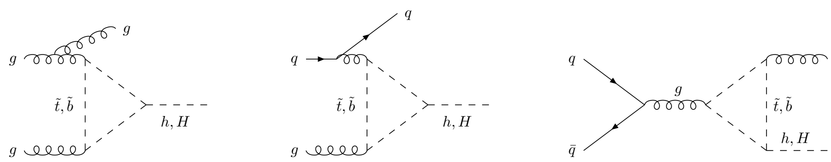

Figure 3: Typical diagrams for the real NLO QCD corrections to the squark contributions to the gluon fusion processes.

small α_{eff} scenario [14], defined by the following choices of MSSM parameters [$m_t = 172.6$ GeV],

$$\begin{aligned} M_{\tilde{Q}} &= 800 \text{ GeV} & \tan\beta &= 30 \\ M_{\tilde{g}} &= 1000 \text{ GeV} & \mu &= 2 \text{ TeV} \\ M_2 &= 500 \text{ GeV} & A_b = A_t &= -1.133 \text{ TeV} . \end{aligned} \tag{2.5}$$

In this scenario the squark masses amount to

$$\begin{aligned} m_{\tilde{t}_1} &= 679 \text{ GeV} & m_{\tilde{t}_2} &= 935 \text{ GeV} \\ m_{\tilde{b}_1} &= 601 \text{ GeV} & m_{\tilde{b}_2} &= 961 \text{ GeV} . \end{aligned} \tag{2.6}$$

Fig. 4 displays the genuine SUSY QCD corrections normalized to the LO bottom quark form factor,

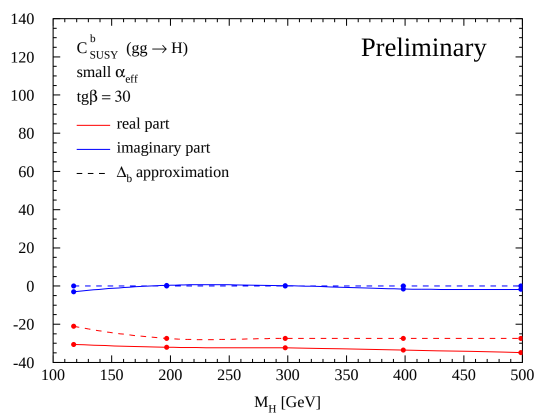

Figure 4: The genuine SUSY QCD corrections normalized to the LO bottom quark form factor. Real corrections: red (light gray), virtual corrections: blue (dark gray), compared to the Δ_b approximation (dashed lines). A_b has been renormalized in the $\overline{\text{MS}}$ scheme.

i.e. $A_b^{h/H}(\tau_b) \to A_b^{h/H}(\tau_b)(1 + C^b_{SUSY}\frac{\alpha_s}{\pi})$. The corrections can be sizeable, but can be described reasonably with the usual Δ_b approximation [15], if A_b is renormalized in the $\overline{\text{MS}}$ scheme.

3. Decoupling of the Gluinos

In this section we will address the limit of heavy quark, squark and gluino masses, where in addition the gluinos are much heavier than the quarks and squarks. For the derivation of the effective Lagrangian for the scalar Higgs couplings to gluons we analyze the relation between the quark Yukawa coupling λ_Q and the Higgs coupling to squarks $\lambda_{\tilde{Q}}$ in the limit of large gluino masses. We define these couplings at leading order in the case of vanishing mixing,

$$\lambda_Q = g_Q^{\mathscr{H}} \frac{m_Q}{v} , \qquad \lambda_{\tilde{Q}} = 2 g_Q^{\mathscr{H}} \frac{m_Q^2}{v} = \kappa \lambda_Q^2 , \qquad \text{with } \kappa = 2 \frac{v}{g_Q^{\mathscr{H}}} , \tag{3.1}$$

where $g_Q^{\mathscr{H}}$ denotes the normalization factor of the MSSM Higgs couplings to quark pairs with respect to the SM. In the following we will sketch how the modified relation between these couplings for scales *below* the gluino mass $M_{\tilde{g}}$ is derived. For details, see Ref. [16]. We start with the unbroken relation between the running $\overline{\text{MS}}$ couplings of Eq. (3.1) and the corresponding renormalization group equations (RGE) for scales *above* $M_{\tilde{g}}$. If the scales decrease *below* $M_{\tilde{g}}$ the gluino decouples from the RGEs leading to modified RGEs which are different for the two couplings $\lambda_{\tilde{Q}}$ and $\kappa\lambda_Q^2$ so that the two couplings deviate for scales below $M_{\tilde{g}}$. The proper matching at the gluino mass scale yields a finite threshold contribution for the evolution from the gluino mass scale to smaller scales, while the logarithmic structure of the matching relation is given by the solution of the RGEs *below* $M_{\tilde{g}}$. In order to decouple consistently the gluino from the RGE for gluino mass scales large compared to the chosen renormalization scale, a momentum substraction of the gluino contribution for vanishing momentum transfer has to be performed [17]. We refer the reader to [16] for details and give here directly the result for the modified relation between the quark Yukawa coupling and the effective Higgs coupling to squarks taking into account the proper gluino decoupling:

$$2 g_Q^{\mathscr{H}} \frac{m_Q^2}{v} = \bar{\lambda}_{\tilde{Q},MO}(m_{\tilde{Q}}) \left\{ 1 + C_F \frac{\alpha_s}{\pi} \left(\log \frac{M_{\tilde{g}}^2}{m_{\tilde{Q}}^2} + \frac{3}{2} \log \frac{m_{\tilde{Q}}^2}{m_Q^2} + \frac{1}{2} \right) \right\} , \tag{3.2}$$

where m_Q is the pole mass and MO denotes the momentum substracted coupling, which is taken at the squark mass scale, which is the proper scale choice of the effective Higgs coupling to squarks and which is relevant for an additional large gap between the quark and squark masses.

Taking into account the radiative corrections to the relation between the effective couplings after decoupling the gluinos leads to the following effective Lagrangian in the limit of heavy squarks and quarks,

$$\mathscr{L}_{eff} = \frac{\alpha_s}{12\pi} G^{a\mu\nu} G^a_{\mu\nu} \frac{\mathscr{H}}{v} \left\{ \sum_Q g_Q^{\mathscr{H}} \left[1 + \frac{11}{4} \frac{\alpha_s}{\pi} \right] + \sum_{\tilde{Q}} \frac{g_{\tilde{Q}}^{\mathscr{H}}}{4} \left[1 + C_{SQCD} \frac{\alpha_s}{\pi} \right] + \mathscr{O}(\alpha_s^2) \right\} , \tag{3.3}$$

where $g_{\tilde{Q}}^{\mathscr{H}} = v \bar{\lambda}_{\tilde{Q},MO}(m_{\tilde{Q}})/m_{\tilde{Q}}^2$. The cofficient C_{SQCD} is given by

$$C_{SQCD} = \frac{37}{6} . \tag{3.4}$$

It is well-defined in the limit of large gluino masses and thus fulfills the constraint of the Appelquist–Carazzone decoupling theorem [18].

4. Conclusions

We have presented first results for the NLO SUSY QCD corrections to gluon fusion into CP-even MSSM Higgs bosons, including the full mass dependence of the loop particles. The genuine SUSY-QCD corrections can be sizeable. We furthermore demonstrated, that the gluino contributions can be decoupled in the large $M_{\tilde{g}}$ limit in accordance with the Appelquist-Carazzone theorem.

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