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Precise predictions for Higgs cross sections at the Large Hadron Collider

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The status of the theoretical predictions for the most important Higgs production processes at the Large Hadron Collider is reviewed. Both the Standard Model and neutral Higgs production in the MSSM are considered.

1. Introduction

Within the last few years, the inclusive cross sections for the dominant Higgs production mechanisms at hadron colliders have become under very good theoretical control. This is to a large part due to the development of new techniques for the evaluation of radiative corrections. These precise results have brought confidence into the – in some cases very large – theoretical K-factors. They should now be (and already are) used for experimental analyses concerning the discovery potential of a Higgs boson or measurements of Higgs couplings and other properties.

We will start our overview with the four dominant production modes in the Standard Model (SM): Gluon fusion, weak boson fusion, associated $t\bar{t}H$ production, and Higgs Strahlung. Then we will discuss some aspects of Higgs production in the Minimal Supersymmetric Standard Model (MSSM), in particular the effect of squark loops in the gluon fusion process, and the associated Higgs production with bottom quark pairs.

2. Gluon Fusion

Gluon fusion is the Higgs production process with the largest cross section at the LHC (and also at the Tevatron). The next-to-leading order (NLO) corrections are very large, amounting up to 70%–100% of the leading order (LO) result [1, 2]. They are extremely well approximated by the limit $m_t \gg M_H$, even at Higgs boson masses that are far beyond this limit (for a detailed discussion, see Ref. [3]).

Nevertheless, even in this "heavy-top limit," the next-to-next-to-leading order (NNLO) calculation was not performed before the development of new techniques for the evaluation of loop and phase space integrals. For example, the corrections from virtual gluon exchange could be evaluated for the first time [4] with the help of new equivalence relations among Feynman integrals [5].

For the phase space integrals of the double-gluon emission contributions, two new techniques were introduced: The method of "expansion and inversion" [6–8], and the method of "generalized Cutkosky rules" [9]. The contributions from real radiation in gluon fusion were later confirmed [10] by extending the integral tables of Ref. [11] (see also Ref. [12]).

The NNLO prediction for gluon fusion is shown in Fig. 1, together with the lower order results. This figure gives the desired confidence in the perturbative prediction of this process. The bands indicate the variation of the result when changing the unphysical factorization and renormalization scales μ_F and μ_R by a factor of two around the Higgs mass.

Resummation of soft gluon effects were shown to contribute less than 6% [13], thus confirming the stability of the NNLO prediction.

Electroweak corrections in the large-m_t limit give a very small effect of below 1% [14]. Recently, electroweak corrections arising from light fermions were evaluated and found to be quite sizable around $M_H = 2M_W$ [15].

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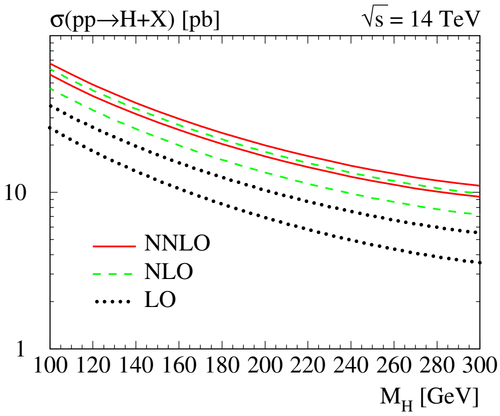

Figure 1. LO, NLO, and NNLO prediction for Higgs production in gluon fusion in the SM [6, 9,10].

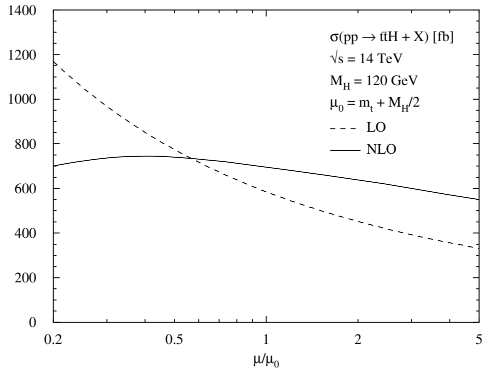

Figure 2. Variation of the inclusive cross section for $pp \to t\bar{t}H$ at the LHC with $\mu = \mu_R = \mu_F$ (from the first reference in Ref. [20]).

3. Weak Boson Fusion

This process has been shown to be extremely useful both for Higgs discovery at the LHC in almost all of the relevant mass range, as well as for measurements in the Higgs sector, in particular Higgs couplings and CP properties of the Higgs boson(s) (see Ref. [16] and references therein).

Among the welcome features of this process is the smallness of the QCD corrections to it, and their technical simplicity at NLO. The latter results from the absence of pentagon diagrams due to their vanishing color factor. Thus, all of the NLO corrections are analogous to Deep Inelastic Scattering.

The NLO total cross section for weak boson fusion has thus been known for a long time [17]. Only recently, however, has a fully differential partonic NLO Monte Carlo program become available [18]. Differential analyses are particularly important for this process because the tagging of the forward-scattered jets is essential for an identification of the WBF signal.

4. Associated $t\bar{t}H$ production

Even though the cross section for the production of a Higgs with a $t\bar{t}$ pair is rather small, this mode is very attractive because of its remarkable signature: four b quarks in association with two W bosons. In addition, this process is directly sensitive to the top–Yukawa coupling.

The calculation of the NLO corrections is rather challenging. One of the obstacles are massive pentagon diagrams. In fact, the $t\bar{t}H$ processes triggered the development of new, efficient algorithms for the evaluation of this class of integrals, avoiding the occurrence of spurious singularities in the Gram determinants [19].

From the theoretical point of view, the NLO terms have a very satisfactory effect [20]. The variation of the cross section prediction with renormalization and factorization scale reduces drastically, as one can see in Fig. 2. The overall effect on the total rate is of the order of +20% at the central scale of $\mu_R = \mu_F = m_t + M_H/2$.

5. Higgs Strahlung [21]

At LO, the production of a Higgs boson in association with a vector boson, $pp \to VH + X, (V = W, Z)$ proceeds through $q\bar{q}$ annihilation, $q\bar{q}' \to V^* \to VH$. The NLO QCD corrections coincide with those to the Drell-Yan process and increase the cross section by about 30% [17]. Beyond NLO, the QCD corrections to VH production differ from those to the Drell-Yan process by contributions where the Higgs boson couples to a heavy fermion loop. The impact of these additional terms is, however, expected to be small in general [22]. Moreover, for ZH production the one-loop-induced process $gg \to ZH$ contributes at NNLO. The NNLO corrections corresponding to the Drell-Yan mechanism as well as the $gg \to ZH$ contribution have been calculated in Ref. [23]. These NNLO corrections further increase the cross section by the order of 5–10%. Most importantly, a successive reduction of the scale dependence is observed when going from LO to NLO to NNLO. The respective scale uncertainties are about 10%, 5%, and 2% at the LHC. At this level of accuracy, electroweak corrections become significant and need to be included to further improve the theoretical prediction. In Ref. [24], the electroweak $\mathcal{O}(\alpha)$ corrections have been calculated; they turn out to be negative and about -5% or -10% depending on whether the weak couplings are derived from G_μ or $\alpha(M_Z^2)$, respectively.

A combined analyses of QCD and electroweak effects has been presented in Ref. [21]. Fig. 3 shows the sum of the cross sections for W^+H and W^-H production at the LHC, including LO, NLO, and NNLO QCD effects, as well as the $\mathcal{O}(\alpha)$ electroweak corrections. The inclusion of all higher order effects makes Higgs Strahlung by now the most precise Higgs production process at hadron colliders. The remaining uncertainties are estimated to be of the order of 5–10%.

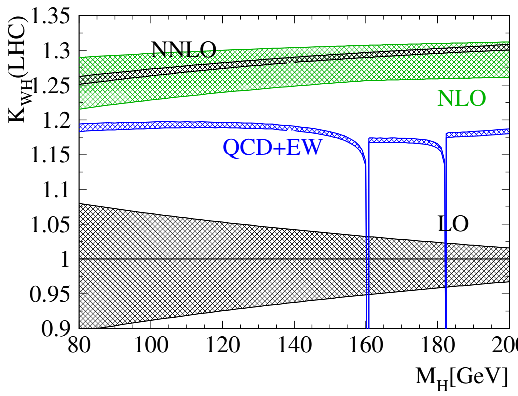

Figure 3. K-factor for WH production at the LHC after inclusion of the NNLO QCD and electroweak $\mathcal{O}(\alpha)$ corrections. The bands reflect the variation of the cross section upon variation of μ_F and μ_R within a factor of three around M_H+M_W.

6. Supersymmetry

In the MSSM, several aspects have to be taken into account when considering the production of a neutral Higgs boson: For example, for large $\tan\beta$, the bottom quark can contribute significantly to the gluon-Higgs coupling. This effect has been studied at NLO in Ref. [2]. A large value of $\tan\beta$ also brings in the associated production of a Higgs boson with bottom quarks as one of the main production mechanisms. This will be discussed in Sect. 6.2, while the influence of supersymmetric particles to the gluon fusion process will be discussed in Sect. 6.1. The production of pseudoscalar Higgs bosons through gluon fusion for small $\tan\beta$ is known through NNLO [8,25], with very similar conclusions as in the case of scalar Higgs production.

6.1. Squarks

Motivated by its success in the SM case, one can construct an effective Lagrangian for the gluon-Higgs interaction also in the MSSM. This corresponds to integrating out the top quark and all supersymmetric particles. Within the framework of this effective Lagrangian, all calculations can be performed in standard five-flavor QCD. They can thus be taken over from the SM case.

At sufficiently small values of $\tan\beta$, the dominant effects to the gluon-Higgs coupling from MSSM particles are due to top-squarks. In comparison to the SM particles, this contribution goes like $(m_t/m_{\tilde{t}}^2)^2$, however, with a possible enhancement for large absolute values of the trilinear coupling A_t. For moderate values of A_t, however, only top squarks with $m_{\tilde{t}} \lesssim 400\,\mathrm{GeV}$ give a sizable effect.

At NLO, the SUSY relation between the top and the stop Yukawa coupling requires to include also gluino effects in order to arrive at finite results. In a very simplifying limit without squark mixing,

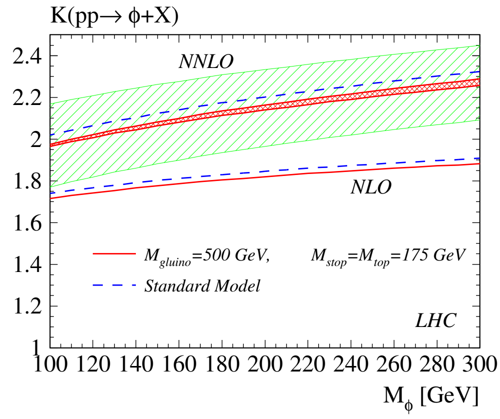

Figure 4. K-factor for gluon fusion at the LHC in the SM (dashed blue) and including squark effects (solid red) at NLO and NNLO. The width of the dark shaded NNLO band is an estimate of the uncertainty due to neglected NNLO terms to the gluon-Higgs coupling. The light shaded band is the uncertainty induced by scale variation at NNLO. From Ref. [29].

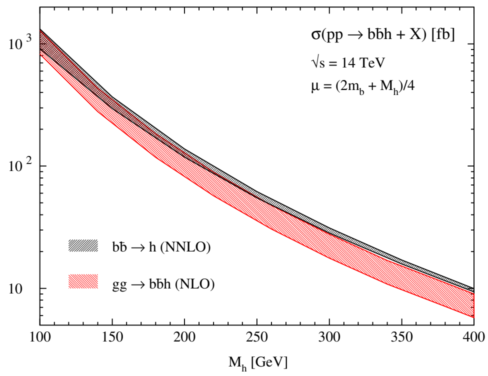

Figure 5. Total cross section for $pp \to b\bar{b}\phi + X$ in the four- and the five-flavor approach ($gg \to bbh$ [32] [light shaded] and $b\bar{b} \to h$ [30] [dark shaded], respectively). The width of the bands corresponds to the theoretical uncertainty as estimated from scale variation. From [33].

the NLO corrections were found to be very similar to the SM case [26] (see also Ref. [27]). A more general analysis of the SUSY parameter space will be presented in Ref. [28].

The dominant corrections to the Higgs production cross section originate from real gluon emission. Thus, it is possible to derive a rather precise estimate of the NNLO terms based on the NNLO result in the SM [6,9,10] and the NLO effective Higgs-gluon coupling [26]. In this way, the reduced scale uncertainty of the NNLO in the SM directly carries forward to the supersymmetric case. The result is shown in Fig. 4, details can be found in Ref. [29].

6.2. Associated $b\bar{b}H$ production

There are two complementary approaches to calculate the inclusive cross section for this process: The so-called four-flavor scheme, assuming $gg \to b\bar{b}H$ as the LO partonic process, and the five-flavor scheme, where $b\bar{b} \to H$ is the LO contribution. The latter resums collinear logarithms $\sim \ln(m_b/M_H)$ arising from small transverse bottom momenta $p_{T,b}$. However, the LO of the five-flavor scheme neglects contributions from large $p_{T,b}$; they are re-introduced through higher order QCD corrections. In fact, a NNLO calculation [30] consistently combines the all-order resummation of the low-$p_{T,b}$ region with the LO contributions from large $p_{T,b}$.

Recently, the NLO corrections for the four-flavor scheme became available. The total cross section is in good agreement with the result from the five-flavor scheme for small values of M_ϕ. For larger values, the agreement becomes worse as it is expected because the collinear logarithms become numerically more important. For more details, see Ref. [31].

7. Conclusions

We have reviewed the theoretical status of the most important (neutral) Higgs production processes in the SM and the MSSM. All of them are under very good theoretical control due to recent advances in the evaluation of radiative corrections. The precision for the inclusive cross section is in all cases at least of the order of the expected experimental precision.

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