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Theoretical progress for the associated production of a Higgs boson with heavy quarks at hadron colliders

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Abstract. The production of a Higgs boson in association with a pair of $t\bar{t}$ or $b\bar{b}$ quarks plays a very important role at both the Tevatron and the Large Hadron Collider. The theoretical prediction of the corresponding cross sections has been improved by including the complete next-to-leading order QCD corrections. After a brief introduction, we review the results obtained for both the Tevatron and the Large Hadron Collider.

1 Introduction

The discovery and study of one or more Higgs bosons is among the most important goals of present and future colliders. In this context, the production of a Higgs boson with a pair of top or bottom quark and antiquark is important both for the discovery of a Higgs boson and for the study of the Higgs Yukawa couplings to quarks.

Observing $p\bar{p} \to t\bar{t}h$ at the Tevatron ($\sqrt{s} = 2$ TeV) will require very high luminosity [1] and will probably be beyond the machine capabilities. On the other hand, if $M_h \leq 130$ GeV, $pp \to t\bar{t}h$ is an important discovery channel for a SM-like Higgs boson at the LHC ($\sqrt{s} = 14$ TeV) [2, 3, 4]. Given the statistics expected at the LHC, $pp \to t\bar{t}h$, with $h \to b\bar{b}, \tau^+\tau^-, W^+W^-, \gamma\gamma$ will also be instrumental to the determination of the couplings of a discovered Higgs boson, and offer a unique handle on the top quark Yukawa coupling [5, 6, 7, 8, 9].

The associated production of a Higgs boson with a pair of $b\bar{b}$ quarks has a very small cross section in the SM, and can therefore be used to test the hypothesis of enhanced bottom quark Yukawa couplings which is common to many extensions of the SM, such as the MSSM for large values of $\tan\beta$. Both the Tevatron and the LHC will be able to search for evidence of an enhanced $b\bar{b}h$ production, in both inclusive and exclusive measurements. Detecting two bottom quarks in the final state identifies uniquely the Higgs coupling responsible for the enhanced cross section and drastically reduces the background. This is the case we will consider in the following.

In view of their phenomenological relevance, a lot of effort has been recently invested in improving the stability

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[a] Talk presented by L. Reina.

of the theoretical predictions for the hadronic total cross sections for $p\bar{p}, pp \to t\bar{t}h$ and $p\bar{p}, pp \to b\bar{b}h$ [10, 11, 12, 13, 14, 15, 16, 17]. In this proceeding we will present the results of our calculation of the NLO cross section for both the inclusive $p\bar{p}, pp \to t\bar{t}h$ [11, 12, 14, 15] and the exclusive $p\bar{p}, pp \to b\bar{b}h$ cross sections [17], where h denotes the SM Higgs boson and, in the case of $b\bar{b}h$, also the scalar Higgs bosons of the MSSM. In both cases the NLO cross sections have a drastically reduced renormalization and factorization scale dependence, of the order of 15-20% as opposed to the 100% uncertainty of the LO cross sections. This leads to increased confidence in prediction based on this results.

The calculation of the NLO corrections to the hadronic processes $p\bar{p}, pp \to t\bar{t}h$ and $p\bar{p}, pp \to b\bar{b}h$ presents challenging technical difficulties, ranging from virtual pentagon diagrams with several massive internal and external particles to real gluon and quark emission in the presence of infrared singularities. We refer to [12, 15] for a complete discussion of all technical details.

2 Results for $t\bar{t}h$ production

The impact of NLO QCD corrections on the tree level cross section for $pp \to t\bar{t}h$ production (LHC) in the SM is illustrated in Fig. 1 and 2. Similar results for the case of $p\bar{p} \to t\bar{t}h$ production (Tevatron) can be found in [11, 12]. Results for σ_{NLO} (σ_{LO}) are obtained using the 2-loop (1-loop) evolution of $\alpha_s(\mu)$ and CTEQ5M (CTEQ5L) parton distribution functions [18], with $\alpha_s^{NLO}(M_Z) = 0.118$. The top quark mass is renormalized in the OS scheme and its pole mass is fixed at $m_t = 174$ GeV. Fig. 1 illustrates the renormalization/factorization scale dependence of σ_{LO}

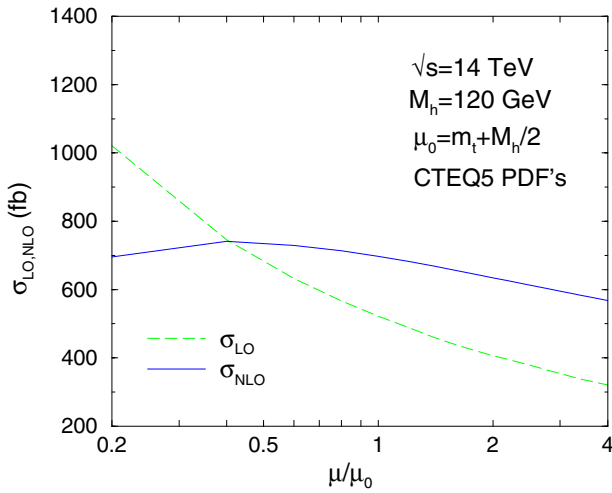**Fig. 1.** Dependence of $\sigma_{LO,NLO}(pp \to t\bar{t}h)$ on the renormalization/factorization scale μ, at $\sqrt{s_H} = 14$ TeV, for $M_h = 120$ GeV
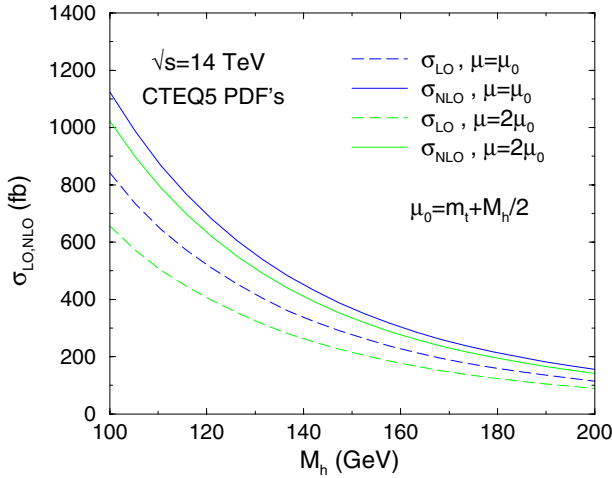

Fig. 2. $\sigma_{NLO}(pp \to t\bar{t}h)$ and $\sigma_{LO}(pp \to t\bar{t}h)$ as functions of M_h, at $\sqrt{s_H} = 14$ TeV, for $\mu = m_t + M_h/2$ and $\mu = 2m_t + M_h$

and σ_{NLO} at the LHC. The NLO cross section shows a drastic reduction of the scale dependence with respect to the lowest order prediction. Fig. 2 complements this information by illustrating the dependence of the LO and NLO cross sections on the Higgs boson mass at the LHC. For scales $\mu \geq 0.4\mu_0$ ($\mu_0 = m_t + M_h/2$) the NLO corrections enhance the cross section. We estimate the remaining theoretical uncertainty on the NLO result to be of the order of 15-20%, due to the leftover μ-dependence, the error from the PDFs, and the error on the top quark pole mass m_t.

3 Results for $b\bar{b}h$ production

We evaluate the fully exclusive cross section for $b\bar{b}h$ production by requiring that the transverse momentum of both final state bottom and anti-bottom quarks be larger

than 20 GeV ($p_T^b > 20$ GeV), and that their pseudorapidity satisfy the condition $|\eta_b| < 2$ for the Tevatron and $|\eta_b| < 2.5$ for the LHC. This corresponds to an experiment measuring the Higgs decay products along with two high p_T bottom quark jets. In order to better simulate the detector response, the final state gluon and the bottom/anti-bottom quarks are treated as distinct particles only if the separation in the azimuthal angle-pseudorapidity plane is $\Delta R > 0.4$. For smaller values of ΔR, the four momentum vectors of the two particles are combined into an effective bottom/anti-bottom quark momentum four-vector.

The set-up used for the NLO (LO) calculation of the $b\bar{b}h$ cross section is the same as for $t\bar{t}h$ (see Sect. 2). In the $b\bar{b}h$ case, however, we have also investigated the dependence of the NLO result on the choice of the renormalization scheme for the bottom quark Yukawa coupling. The strong scale dependence of the $\overline{MS}$ bottom quark mass ($\overline{m}_b(\mu)$) plays a special role in the perturbative evaluation of the $b\bar{b}h$ production cross section since it enters in the overall bottom quark Yukawa coupling. The same is not true for $t\bar{t}h$ production since the $\overline{MS}$ top quark mass has only a very mild scale dependence. The bottom quark pole mass is taken to be $m_b = 4.6$ GeV. In the OS scheme the bottom quark Yukawa coupling is calculated as $g_{b\bar{b}h} = m_b/v$, while in the $\overline{MS}$ scheme as $g_{b\bar{b}h}(\mu) = \overline{m}_b(\mu)/v$, where we use the 2-loop (1-loop) $\overline{MS}$ bottom quark mass for the NLO (LO) cross section respectively.

The impact of NLO QCD corrections on the tree level cross section for $b\bar{b}h$ exclusive production in the SM is summarized in Fig. 3 for both the Tevatron and the LHC. In both the OS and the $\overline{MS}$ schemes the stability of the cross section is greatly improved at NLO, and the corresponding theoretical uncertainty reduced to 15-20%. The $\overline{MS}$ results seem to have overall a better perturbative behavior, although the variation of the NLO cross section about its point of least sensitivity to the renormalization/factorization scale is almost the same when one uses the OS or the $\overline{MS}$ schemes for the bottom Yukawa coupling. This indicates that the running of the Yukawa coupling is not the only important factor to determine the overall perturbative stability of the cross section. The difference between the OS and the $\overline{MS}$ results at their plateau values should probably be interpreted as an additional theoretical uncertainty [17].

Finally, in Fig. 4 we illustrate the dependence of the exclusive cross section, at the Tevatron and at the LHC, on the Higgs boson mass, both in the SM and in some scenarios of the MSSM, corresponding to $\tan\beta = 10, 20$, and 40. For the Tevatron we consider the case of the light MSSM scalar Higgs boson(h^0) while for the LHC we consider the case of the heavy MSSM scalar Higgs boson (H^0). We see that the rate for $b\bar{b}h$ production can be significantly enhanced in a supersymmetric model with large values of $\tan\beta$, and makes $b\bar{b}h$ a very important mode for discovery of new physics at both the Tevatron and the LHC.
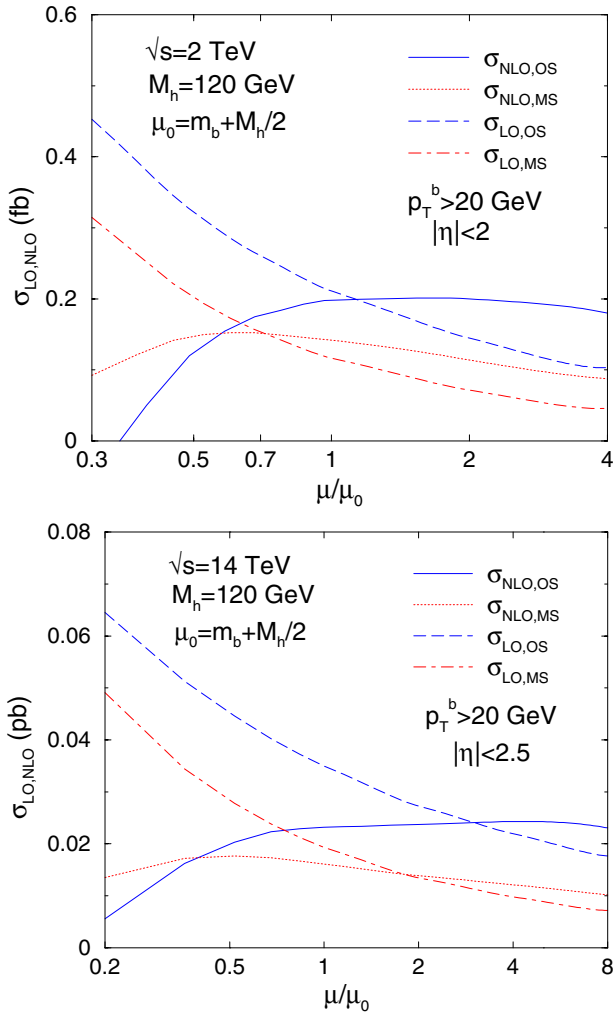
Fig. 3. σ_{NLO} and σ_{LO} for $p\bar{p} \to b\bar{b}h$ at $\sqrt{s}=2$ TeV (*top*) and for $pp \to b\bar{b}h$ at $\sqrt{s}=14$ TeV (*bottom*) as a function of the renormalization/factorization scale μ, for $M_h = 120$ GeV

Fig. 4. $\sigma_{NLO,MS}$ for $p\bar{p} \to b\bar{b}h$ production at $\sqrt{s}=2$ TeV (*top*) and $pp \to b\bar{b}h$ production at $\sqrt{s}=14$ TeV (*bottom*) in the SM and in the MSSM with $\tan\beta=10, 20$, and 40

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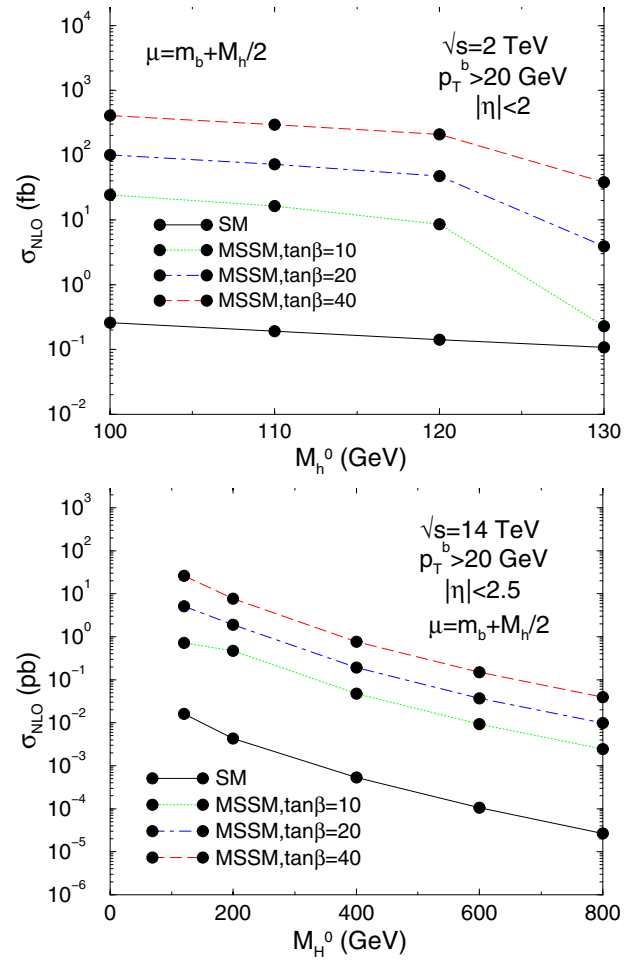9. M. Dürssen: (2003), ATL/PHYS-2003-30
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