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Theory overview for $t\bar{t}H$ and tH production

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In this talk, I will review the state of the art predictions for the production of a Higgs boson in association with top quarks, as well as for some of the dominant background processes. I will review recent results concerning theoretical predictions for these processes and comment upon the precise extraction ot the top Yukawa coupling at present and future colliders.

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1. Introduction

After the discovery of the Higgs boson at the LHC [1,2], lots of efforts have been devoted to the measurement of its properties. In particular, a deeper understanding of the interaction between the Higgs and the top quark may reveal some hints for new physics. Higgs production channels which are sensitive to the top-Higgs interaction are gluon fusion (ggF) and $t\bar{t}H$ associated production (for a review on the Higgs production channels, see Ref. [3] and references therein). Despite the small rate of $t\bar{t}H$ if compared to ggF, this processes is very precious since it allows for a direct extraction of the top-Higgs Yukawa coupling y_t. During the past run of the LHC, no observation of Higgs production in $t\bar{t}H$ was claimed. This situation is bound to change with the Run II, essentially thanks to the much larger number of events to be collected. Projections on the uncertainty on the extracted y_t value are at the level of 15% with 300 fb^{-1}, and can go down to 10% with 3000 fb^{-1}, assuming no reduction of theoretical errors. If one instead consider the case of a factor two reduction of theoretical errors, the uncertainty estimate can reduce to 7% with 3000 fb^{-1} [4,5].[1] The current status of theoretical predictions for $t\bar{t}H$ is quite satisfactory: next-to-leading-order (NLO) predictions in QCD are known since some time [7–10], and have been matched to parton-shower [11–13]. The computation of weak and electroweak (EW) corrections is instead more recent [14–16] as well as predictions including the effects of soft-gluon resummation [17, 18]. An impressive result, given its computational complexity, is the recent calculation of NLO QCD corrections to the process $pp \to Hb\bar{b}e^+\mu^-\nu\nu$ including both resonant and non resonant contributions [19]. For what concerns backgrounds, NLO QCD predictions, possibly matched to parton shower, are available for the main background processes $t\bar{t}b\bar{b}$ [20–24], $t\bar{t}V$ [25–31] $t\bar{t}VV$ [32–34], where $V = W^{\pm}, Z, \gamma$. EW corrections are known for $t\bar{t}W^{\pm}$ and $t\bar{t}Z$ [16, 35]. Recently, the production of a single top quark in association with a Higgs, tH, has gained some attention, and NLO QCD corrections are known also for this process both in the four- and five-flavour scheme [36–38].

In this talk, I will first review in Sec. 2 and Sec. 3 some recent results for signal and background simulation respectively. In Sec. 4 I will discuss a possible strategy to measure y_t at the 1% level at a future collider. I will conclude in Sec. 5.

2. Recent results for signal simulation

I will now turn to discuss some recent results concerning the simulation of the signal processes, both for $t\bar{t}H$ and tH. In particular I will discuss the computation of EW corrections, the inclusion of spin correlations in the simulation and their importance and comment on recent results for tH.

2.1 Electroweak corrections to $t\bar{t}H$

The computation and automation of EW corrections has seen a growing interest from the theory community in the last years [39–43]. Although their effect on total rates is usually suppressed with respect to NLO QCD corrections, they can be enhanced when hard scales are probed by the so-called Sudakov logarithms [44–47]. For what concerns $t\bar{t}H$, in particular for a precise extraction of y_t, EW corrections should be accounted for because of at least two reasons: the first is that,

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[1] Such estimates may be a bit too optimistic, see Ref. [6]

unlike QCD corrections, EW corrections spoil the $\sim y_t^2$ of the total cross-section, introducing also terms where the Higgs couples to $W^\pm$ and Z bosons, or to itself. The second reason is related to the Sudakov effects: in order to suppress backgrounds, many $t\bar{t}H$ searches are performed in a boosted regime [48–50], where Sudakov logarithms can be important.
Weak only and EW corrections for $t\bar{t}H$ have been computed in Refs. [14–16]; I will report on the results from Ref. [16]. In this paper, the effect of EW corrections is studied both on total rates for present and future colliders, and on differential distributions at the LHC Run II. Numbers are computed within the MADGRAPH5_AMC@NLO framework [51], using the NNPDF2.3 NLO set including QED effects [52], that provides prediction for the photon PDF with the associated error estimate. Together with the computation of $\mathcal{O}(\alpha^2\alpha_s^2)$ NLO corrections, the impact of the LO term at $\mathcal{O}(\alpha^2\alpha_s)$ is also investigated. The reason is that this is the first order at LO for which the photon-initiated contribution is not vanishing. At the 13 TeV LHC, an almost complete and accidental cancellation between the two terms is observed, each one being of order of 1.2% of the LO. Such an accidental cancellation disappears in a boosted regime, for example requiring that $p_T(t,\bar{t},H) > 200$GeV, where NLO EW corrections grow as large as -8% of the LO rates, while the LO term at $\mathcal{O}(\alpha^2\alpha_s)$ remains below 3%. Therefore EW corrections cannot be neglected in such boosted regimes, as they are of the same size of the QCD scale uncertainty at NLO. The effect due to photon PDFs is quite small (1-2%) and remains rather flat also on differential distributions. More details on EW corrections will be given in the talks [35, 53] at this conference.

2.2 Spin correlation effects

A realistic simulation of processes involving top quarks must take into account spin-correlation effects, which are quantum-interference effects due to the fact that the top quark is not a stable particle. A method which makes it possible to include spin correlations was proposed in Ref. [54], and is nowadays implemented as a plug-in of NLO event generators [55, 56]. The interested reader can find the details of the method and of its implementation in the original references.
For what concerns $t\bar{t}H$, many recent studies exploit spin correlations between the decay products of the two tops. I will briefly comment upon two of them.
In the first [38], the authors study the effects of a CP-violating phase in the top-Higgs Lagrangian, which is parametrised as

$$\mathscr{L}_{\text{top-Higgs}} = \bar{\psi}_t \left(\cos\alpha\,\kappa_{Htt}\,g_{Htt} + i\sin\alpha\,\kappa_{Htt}\,g_{Htt}\right)\psi_t\,, \tag{2.1}$$

in an effective-theory approach. Such an approach allows the authors to include NLO corrections and to perform a fully differential NLO+PS simulation within the MADGRAPH5_AMC@NLO framework. Assuming that both top quarks decay leptonically, spin-correlation effects are particularly visible looking at angular correlations between the two leptons or at the rapidity separation between the two b-tagged jets. The inclusion of NLO corrections has the beneficial effect of reducing the scale uncertainties. The authors also investigate the effects of requiring a boosted Higgs boson, and find that in such a regime the discriminating power of the various observables is reduced.
In the second study [57], spin correlations are exploited in order to build angular variables and asymmetries that may help in discriminating the $t\bar{t}H$ signal over the dominant $t\bar{t}b\bar{b}$ background.

The authors show that the variables they study are robust upon shower and detector effects, and that spin-correlations survive all these effects. Further studies in this direction are certainly deserved.

2.3 What can we learn from tH?

Besides the production in association with a top pair, the Higgs boson can be also produced with a single top quark [36–38]. tH production is a rather rare process at the LHC ($\sigma \lesssim 100$ fb at 13 TeV), and, in a similar fashion as single-top production, can be classified according to the virtuality of the intermediate (or final state) W boson. The dominant production mode at the LHC is in the t-channel, while the s-channel mechanism has a very small cross-section ($\sigma^{s}_{tH} \simeq 3$ fb). A third production mechanism is tHW production, with a cross-section $\sigma_{tHW} \simeq 20$ fb [58, 59]. In what follows, I will focus on the t-channel production mechanism. This mechanism features b quarks in the initial state, and, as such, it can be described either in the five- or four- flavour scheme (FS), depending upon whether the b quark is treated as massless or not. Each scheme has its advantages and disadvantages. The 5FS, by introducing a b-quark PDF, resums possible large logarithms $\log(m_b/\mu_F)$ which instead appear at all orders in the 4FS, possibly spoiling the convergence of the perturbative series. Furthermore, processes in the 5FS have one less particle in the final state, making it easier to compute higher orders. On the contrary, the 4FS fully takes into account m_b effects at the matrix-element level and gives a better description of observables which are exclusive in the kinematics of b quarks. A detailed comparison between the two schemes, both at total cross-section level and for differential observables, has appeared in Ref. [38]. The authors show that, once a judicious choice for the renormalisation and factorisation scale is performed [60], the agreement between the two schemes is in most cases close to excellent. In particular, NLO corrections play a fundamental role in reducing the ambiguities between the two schemes. The combined total cross-section (for $tH+\bar{t}H$) is estimated to be $\sigma^{NLO}_{tH} = 72$ fb, with a 8-10% residual uncertainty coming from scheme ambiguities and scale variation. Other sources of uncertainties (PDF, α_s and m_b) are found to be much smaller (2%). The agreement remains very good also when looking at NLO predictions matched to parton showers for differential observables, where the two central predictions lie very close despite the very different K-factors. This remains true also for observables which are sensitive to the b kinematics, although the limitation of the 5FS become more evident, in particular the large theoretical uncertainties. The 4FS should therefore be preferred for accurate signal simulations at fully differential level. Despite its tiny rate, the importance of tH stems from being among the few processes which are sensitive to the sign of the top-quark Yukawa coupling y_t. Indeed, in tH the Higgs can either couple to the top quark or to the W boson, and the two class of Feynman diagrams interfere destructively. A flipped-sign Yukawa would lead to a tH rate twice as large as $t\bar{t}H$. The phase of the Yukawa coupling also affects differential observables.

3. Recent results for background simulations

I will now turn to comment upon recent results concerning the simulation of $t\bar{t}H$ backgrounds. I will focus on two recent works, the first about $t\bar{t}b\bar{b}$ and the second $t\bar{t}$ in association with vector

bosons. In the first study [61], the authors investigate effects of non-pure-QCD terms in the simulation: when simulations for $t\bar{t}b\bar{b}$ are performed, only the pure-QCD term at $\mathcal{O}(\alpha_s^4)$ is included at LO, while NLO QCD corrections include effects at $\mathcal{O}(\alpha_s^5)$. LO terms of order $\alpha_s^{4-k}\alpha^k$ are typically neglected, with the argument that $\alpha \ll \alpha_s$. The authors want to study precisely the importance of these contributions in configurations where the top pair decay semi-leptonically, and to gauge also the importance of non-resonant effects (that is, to study the full $pp \to \ell\nu b\bar{b}b\bar{b}jj$ process). The authors find that, when standard cuts are applied on the (b)-jets, leptons and missing transverse energy, squared diagrams corresponding to non-QCD-initiated contributions at order $\alpha_s^2\alpha^2$ can be as large as 60% of the pure QCD ones, and feature a small, destructive interference of about the 5% of the total cross section at order $\alpha_s^2\alpha^2 + \alpha_s^4$. Non-resonant contributions are instead smaller, at the level of 8% of the total cross section. The impact of non-pure-QCD and non-resonant contributions with more realistic cuts, as those used in $t\bar{t}H$ analyses is still to be investigated.
In the second study [62], the authors perform a comprehensive investigation of all $t\bar{t}V$, $t\bar{t}VV$ processes at NLO+PS, where $V = W^{\pm}, Z, \gamma$. These processes are studied *per se* and in the framework of $t\bar{t}H$ analyses. Processes with an overall final state net charge different than zero (e.g. $t\bar{t}W^{\pm}, t\bar{t}W^{\pm}\gamma, \ldots$) are affected by large NLO QCD corrections, because no gg channel is present at LO, while at NLO the qg channel opens. The K factor grows with the collider energy, and can be as large as 2 or more at 100 TeV. Processes with a neutral final state are characterised by milder K factors, ranging between 1.2 and 1.4. The inclusion of NLO QCD correction is therefore mandatory for realistic analyses at the LHC and future colliders. Focusing on $t\bar{t}H$ searches, in particular in the $H \to \tau\tau$, $H \to WW$ and $H \to ZZ$ channels, the authors publish cross sections for all the relevant processes in three LHC signal regions used in such searches (with two, three or four charged leptons), showing the importance of a fully-differential study at NLO+PS accuracy, possibly including spin-correlation effects.

4. Is a 1% measurement measurement of y_t feasible at future colliders?

As mentioned in the introduction, a precise extraction of the top Yukawa from the $t\bar{t}H$ cross section is strongly affected by the theoretical uncertainties on the latter. At present, such uncertainties are at the 10% level. On the one hand it is therefore desirable that progresses in the computation of higher orders in QCD are made so that, for example, it will become possible to compute the NNLO corrections to $t\bar{t}H$. On the other hand it is worth to investigate if there is any way to accurately measure y_t notwithstanding the progresses on the cross-section computations. One such way is proposed in Ref. [63], and stems from the observation that $t\bar{t}H$ and $t\bar{t}Z$ are very similar processes: if one considers the dominant, gg-initiated contribution, one realizes that the Feynman diagrams are actually the same for the two processes; in addition, m_Z and m_H are not-so-different quantities, which may lead to the phase space having similar boundaries in the two cases. The author therefore propose to use the $t\bar{t}H/t\bar{t}Z$ ratio to eliminate the theoretical uncertainties which are strongly correlated between the two processes, indeed showing that theoretical uncertainties affecting the ratio are at the 1-2% level, roughly an order of magnitude lower than those affecting each of the two processes. The authors not only consider scale variation uncertainties, but also those coming from PDFs, m_t and the effects of EW corrections. While such a low precision is unreachable at the LHC, essentially due to the too-small data sample, this will not be the case for a future, hadron-hadron, 100 TeV collider, where such an accurate measurement may be possible with 20 ab^{-1}. Therefore, a precise measurement of y_t may be advocated as one of the physics cases for the FCC.

5. Conclusions

$t\bar{t}H$ gives the unique access to a direct measurement of the top-quark Yukawa coupling. The theory community is putting a great effort in providing accurate predictions for the signal and the many, complicated background processes. In this talk, I have reviewed some recent progresses on the signal and background simulation, and commented upon the possibility of a precise extraction of the top quark Yukawa at future colliders.

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