

Full off-shell NLO QCD predictions for $t\bar{t}b\bar{b}$ at the LHC

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We report on state-of-the-art theoretical predictions for $pp \rightarrow t\bar{t}b\bar{b}$ including full off-shell effects in the di-lepton decay channel at NLO QCD accuracy. We briefly discuss the impact of NLO QCD corrections on differential distributions and also assess theoretical uncertainties from scale and PDF dependence. Furthermore, we propose a simple kinematic reconstruction in order to distinguish b jets originating from top-quark decays from arising from gluon splittings.

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1. Introduction

The precise understanding of the production of top-quark pairs in association with b jets is critical for current LHC and future HL-LHC measurements. This is especially true for the $pp \rightarrow t\bar{t}H$ production in the $H \rightarrow b\bar{b}$ decay channel, since $t\bar{t}b\bar{b}$ is the dominant QCD background and therefore has direct impact on the top-quark Yukawa measurements in this channel. Furthermore, the $t\bar{t}b\bar{b}$ process is a main background for the production of four top quarks, $pp \rightarrow t\bar{t}t\bar{t}$. Besides, being a background to rare processes the $pp \rightarrow t\bar{t}b\bar{b}$ process is also interesting by itself as a probe of QCD dynamics within a multi-scale environment.

On the theoretical side the $pp \rightarrow t\bar{t}b\bar{b}$ process has been studied in great detail. For instance, theoretical predictions at NLO QCD accuracy for the on-shell production have been reported in Refs. [1–5]. Furthermore, $t\bar{t}b\bar{b}/t\bar{t}jj$ cross section ratios have been studied in Ref. [6]. Theoretical predictions for $t\bar{t}b\bar{b}$ have also been matched to parton showers in the 4-flavor [7–9] as well as in the 5-flavor scheme [10, 11]. To further improve the understanding of QCD radiation patterns in this process also the $pp \rightarrow t\bar{t}b\bar{b}j$ process has been studied at fixed-order in NLO QCD in Ref. [12]. Eventually, first NLO predictions including full off-shell effects for the $t\bar{t}b\bar{b}$ process in the di-lepton decay channel have become available in Refs. [13, 14] as well as in the Narrow-width-approximation in Ref. [15].

Here, we report on our recent studies of the $pp \rightarrow t\bar{t}b\bar{b}$ process [13, 15] in the di-lepton channel.

2. Outline of the calculation

We briefly summarize the outline of the calculations. For a detailed description we refer the reader to Refs. [13, 15]. We compute NLO QCD corrections for $pp \rightarrow b\bar{b}b\bar{b}e^+\nu_e\mu^-\bar{\nu}_\mu$ at $\mathcal{O}(\alpha_s^5\alpha^4)$ for the LHC at $\sqrt{s} = 13$ TeV. In this calculation, we employ matrix elements at the fully

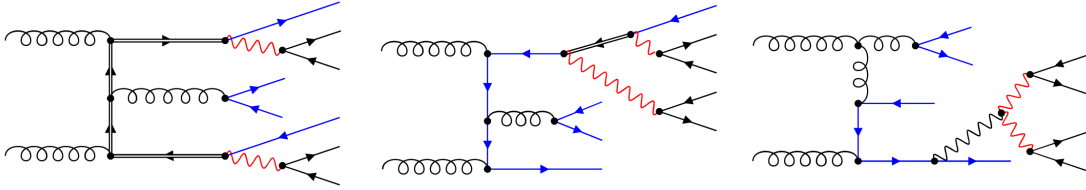


Figure 1: Illustrative Feynman diagrams for double, single and non-resonant contributions to the full matrix elements of $pp \rightarrow b\bar{b}b\bar{b}e^+\nu_e\mu^-\bar{\nu}_\mu$. Figure taken from Ref. [13].

decayed stage. Therefore, they include Feynman diagrams with double, single and non-resonant top-quarks as shown in Fig. 1. The computation is performed with the HELAC-NLO [17] framework, that consists out of HELAC-1LOOP [18–20] for the evaluation of high-multiplicity one-loop matrix elements and HELAC-DIPOLES [21–23] that deals with the infrared subtraction of the real radiation contributions. The framework has been applied already for many $pp \rightarrow t\bar{t}V$ processes including full off-shell effects to obtain state-of-the-art predictions, see for instance Refs. [24–30]. Following ideas of Ref. [31] we store our theoretical predictions in form of modified Les Houches Event

files [32] and ROOT Ntuples [33]. This allows us to obtain predictions for different scale and PDF choices via reweighting as well as to study new observables.

3. Phenomenological results

In the following, we present results for for $pp \rightarrow b\bar{b}b\bar{b}e^+\nu_e\mu^-\bar{\nu}_\mu$ at $\sqrt{s} = 13$ TeV. We require two charged leptons and at least four b jets, where jets are formed using the anti- k_T jet algorithm with $R = 0.4$. Furthermore, we employ the following selection cuts:

$$p_T(\ell) > 20 \text{ GeV}, \quad p_T(b) > 25 \text{ GeV}, \quad |y(\ell)| < 2.5, \quad |y(b)| < 2.5. \quad (1)$$

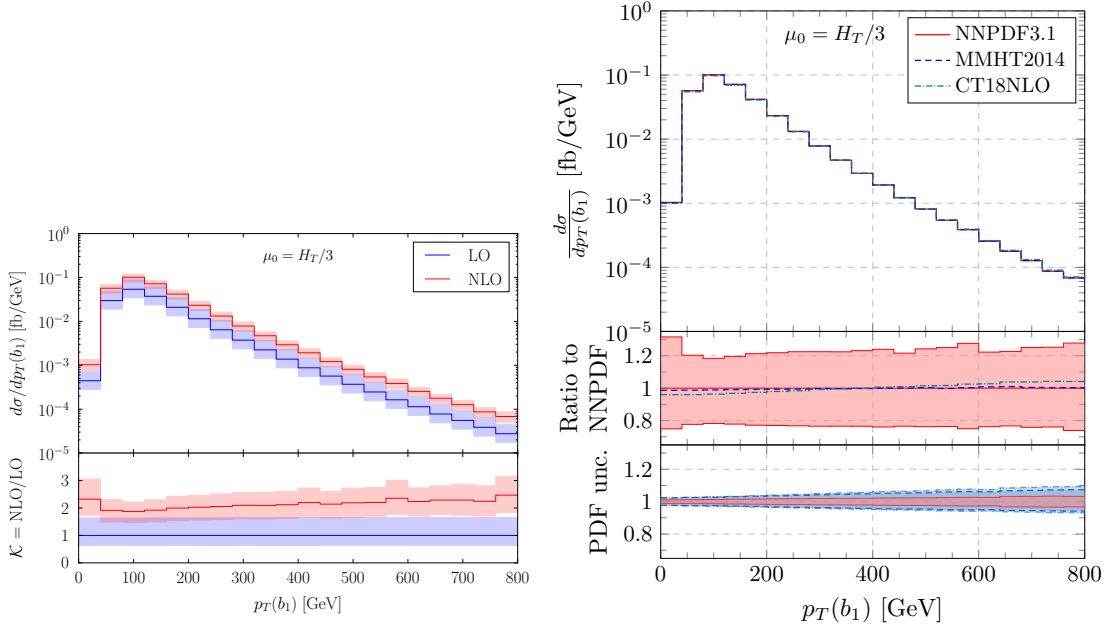


Figure 2: Theoretical predictions for the transverse momentum of the leading b jet. Figures taken from Ref. [13].

In Fig. 2 the transverse momentum of the leading b jet is shown. The plot on the left hand-side shows the impact of NLO QCD corrections on the spectrum. We observe that NLO QCD corrections are large and of the order of 90 – 135%. Furthermore, the theoretical uncertainties, estimated by independent variations of the renormalization and factorization scales, are reduced to 20 – 30% at NLO. Even though the uncertainties are still sizable they barely overlap with the uncertainty estimates at leading order. On the right hand-side of Fig. 2 we also show PDF uncertainties, which are at most of the order of $\pm 10\%$. Therefore, theoretical uncertainties are still dominated by missing higher-order corrections.

We also studied the possibility to differentiate between b jets originating from top decays and *prompt* b jets stemming from $g \rightarrow b\bar{b}$ splittings. Being able to distinguish these jets could be beneficial for $pp \rightarrow t\bar{t}H$ measurements in the $H \rightarrow b\bar{b}$ decay channel. We found that, by minimizing the following function

$$Q = |M(t) - m_t| \times |M(\bar{t}) - m_{\bar{t}}| \times M^{\text{prompt}}(bb) \quad (2)$$

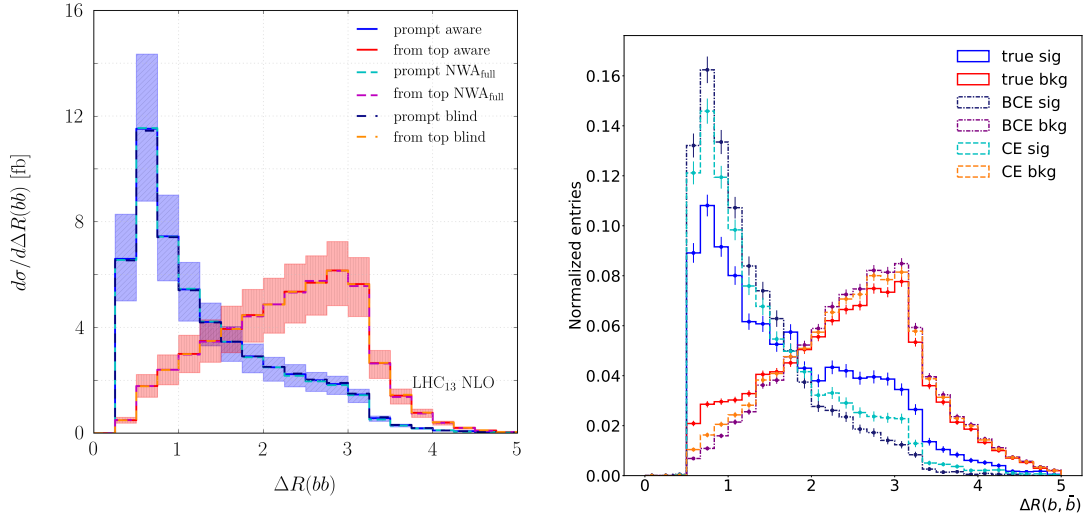


Figure 3: $\Delta R(bb)$ distribution for prompt b jets and those of top decays. Left figure taken from Ref. [13] and right figure from Ref. [16].

over all possible momentum assignments for t, \bar{t} and bb , we achieve a good categorization of the b jets. For instance, on the left side of Fig. 3 the $\Delta R(bb)$ observable for prompt b jets and those from top decays is shown using our method. Our simple kinematic reconstruction is consistent with results obtained by employing Neural Networks [16] as shown on the right of Fig. 3.

4. Summary

We presented some of our recent results for full off-shell $t\bar{t}b\bar{b}$ production at the LHC. We have investigated in detail the impact of NLO QCD corrections on differential distributions. Furthermore, we estimated theoretical uncertainties by scale variations and the incomplete knowledge of PDFs. We found large NLO corrections of the order of 90% and the theoretical uncertainties are clearly dominated by missing higher-order corrections. In addition, we proposed a simple kinematic reconstruction that allows us to distinguish b jets from top-quark decays and prompt b jets stemming from $g \rightarrow b\bar{b}$ splittings. For more detailed information we refer to the reader to Refs. [13, 15].

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