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Precision tools for Higgs physics *

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We present theoretical predictions for the hadroproduction of $\mathrm{t\bar{t}+b\bar{b}}$ final state matching numerical computations at NLO accuracy in QCD with shower Monte Carlo programs. We propose to use half of the sum of transverse masses as renormalization and factorization scales, which gives small NLO K-factor and scale dependence. The events stored according to the Les Houches accord can be used as input in shower Monte Carlo programs to simulate parton showering and hadronization. We show that the decay of the heavy particles may affect the kinematic distributions most, while the changes due to PS and hadronization are small except in regions dominated by Sudakov suppression.

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PoS(LL2014)031

The Higgs-boson was discovered by the LHC experiments almost two years ago [1, 2]. Since then many of its properties have been measured and found in agreement with the Standard Model expectations within the uncertainties of the measurements: (i) the branching ratios are as predicted, (ii) it is a $J^P = 0^+$ particle, (iii) couples to masses of the heavy gauge bosons [3, 4]. The only property not predicted is its mass, obtained consistently by the two experiments: $m_H/\text{GeV} = 125.5 \pm 0.2_{\text{stat}} \pm 0.6_{\text{syst}}$ by ATLAS [5] and $125.6 \pm 0.4_{\text{stat}} \pm 0.2_{\text{syst}}$ by CMS [6].

The quest for the properties of the Higgs-boson however, is not yet over. The t-quark plays a special role due to its large mass. The recent combined result of the LHC and TeVatron experiments, $m_{\text{t}}/\text{GeV} = 173.34 \pm 0.64$ implies a Yukawa-coupling $y_{\text{t}} = 0.997 \pm 0.003$. A perhaps accidental, yet tantalizing relation is that the geometric mean of the masses of the Z-boson and t-quark coincides with the observed mass of the Higgs boson, $\sqrt{m_Z m_{\text{t}}} = (125.7 \pm 0.3)^2 \text{GeV}^2$. These observations hint that the t-quark has a special role in the Standard Model and calls for precise and independent measurement of the Yukawa coupling y_{t}. However, y_{t} cannot be measured in $H \to \text{t}\bar{\text{t}}$ decay as $m_H < m_{\text{t}}$.

The decay of the Higgs-boson into a photon pair is sensitive to y_{t} through the t-quark loop. However, the Branching ratio is small, and not only the t-quark, also the W-bosons can circulate in the loop. In the production channel, gluon-gluon fusion produces a Higgs-boson mainly through a t-quark, provided only particles of the SM exist. In fact, the argument is usually turned around, and gluon-gluon fusion is considered sensitive to physics beyond the SM provided y_{t} is measured independently. The coupling y_{t} can be measured from $\text{t}\bar{\text{t}}+H$ final states, which is an important goal at the LHC.

Measuring the $\text{t}\bar{\text{t}}+H$ production cross section is very challenging due to the small production rates and large backgrounds. Presently, experiments concentrate on studying many decay channels sorted into three main categories: (i) the hadronic, (ii) the leptonic and the (iii) di-photon channels. In the hadronic channel the Higgs-boson is assumed to decay into a $\text{b}\bar{\text{b}}$ or into $\tau^+\tau^-$ pair, while one or both t-quarks decay leptonically (hadrons with single lepton or dilepton). In the leptonic channel the Higgs-boson decays into charged leptons and missing energy (through heavy vector bosons), while one or both t-quarks decay again leptonically. Finally, in the di-photon channel the Higgs-boson decays into a photon pair, while the t-quarks decay into jets (di-photon with hadrons), or into the semileptonic channel. Common characteristics of all these channels is the large background from other SM processes. Thus a precise measurement needs to be aided by theory through precise predictions of distributions at the hadron level for the hadroproduction of a $\text{t}\bar{\text{t}}$ -pair in association of one or two hard object(s) X, with $X = H$ [7], Z^0 [8, 9], $W^{\pm}$ [10], photon [11], jet [12], $\text{b}\bar{\text{b}}$-pair [13], photon-pair [14], two jets etc.

As the t-quarks decay before hadronization, those are not detected, so predictions including the decays of the heavy particles are more useful. The theoretically most precise framework to make such predictions is the matching of predictions at the next-to-leading order (NLO) accuracy with shower Monte Carlo (SMC) programs, such as provided by the POWHEG method [15, 16], and implemented in the `POWHEG-BOX` [17]. The `POWHEG-BOX` program requires input from the user – the Born phase space and various matrix elements: (i) the Born squared matrix element (SME), (ii) the spin- and (iii) color-correlated Born SME, (iv) the SME for real and (v) the virtual corrections. In the `PowHel` framework [18] we obtain all these ingredients from the `HELAC-NLO` code [19]. The result of `PowHel` is pre-showered events (with kinematics up to Born plus first

PoS(LL2014)031

radiation) stored in Les Houches event (LHE) files [20]. These events can be fed into SMC codes to evolve up to the hadronic stage, where any experimental cut can be used, so a realistic analysis becomes feasible. The distributions obtained this way are formally correct at the NLO accuracy in perturbation theory, but the parton shower may have significant effect on distributions, especially in regions of phase space dominated by collinear emissions (due to the Sudakov suppression).

In the rest of this contribution we concentrate on the $\mathrm{t\bar{t}+b\bar{b}}$ final state. At the NLO accuracy this process was first computed in Refs. [21, 22] and studied in detail in Ref. [23]. The choice for the renormalization and factorization scales influences the stability of the theoretical predictions significantly. The fixed default scales $\mu_0 = m_\mathrm{t}$ or $\mu_0 = m_\mathrm{t} + \frac{1}{2} m_{b\bar{b}}$, with $m_{b\bar{b}}$ being the invariant mass of the b and $\bar{b}$-jets [1], lead to large QCD corrections (about 70 %) and large scale uncertainty. The dynamical scale $\mu_\mathrm{dyn} = (m_\mathrm{t}^2 p_{\perp,b} p_{\perp,\bar{b}})^{1/4}$ proposed in Ref. [23] reduces the NLO K-factor to 1.25 implying better convergence by emulating higher order effects through CKKW-type scale choice. However, in our approach we simulate the higher order effects by the PS. Then the dynamical scale related to the geometric mean becomes too small near threshold where cross section is the largest. For instance, even for a b-jet of 100 GeV and a $\bar{b}$ jet of 20 GeV transverse momentum, we find $\mu_\mathrm{dyn} = 90$ GeV, significantly smaller than the mass of the t-quark, resulting in an artificially large cross section at leading order.

Instead of the CKKW-inspired scale choice, we propose to use the dynamical scale as default scale $\mu_0 = H_T/2$, where H_T is the scalar sum of transverse masses of final-state particles that is a good scale also near threshold. With this scale the K-factor is even smaller, K = 1.18, implying good convergence [13]. The cross sections are much smaller than predicted in Ref. [23] obtained with the same selection cuts:

$$\sigma^\mathrm{LO} = 534\,\mathrm{fb}\,, \qquad \sigma^\mathrm{NLO} = 630\,\mathrm{fb}\,,$$

with NLO scale dependence +32 % and –25 %, being the largest when the renormalization and factorization scales are kept equal and varied simultaneously in the range $[\mu_0/2, 2\mu_0]$. With this scale the shapes of distributions change hardly when going from LO to NLO accuracy [13] as seen in Fig. 1.

The formal accuracy of a differential distribution for an observable O obtained from the LHE's is [24]

$$\frac{\mathrm{d}\sigma_\mathrm{LHE}}{\mathrm{d}O} = \frac{\mathrm{d}\sigma_\mathrm{NLO}}{\mathrm{d}O} + \mathrm{O}(\alpha_\mathrm{s}) \int \mathrm{d}\Phi_R R(\Phi_R) \Big[\delta(O(\Phi_R) - O) - \delta(O(\Phi_B) - O)\Big]\,. \tag{1}$$

In this equation Φ_B and Φ_R denote the phase space for the Born cross section and real correction $R(\Phi_R)$, respectively. The size of the $\mathrm{O}(\alpha_\mathrm{s})$ factor scales with the NLO K-factor. For all the final states we studied so far we checked the ratios of the LHE and NLO predictions and found agreement within at most several per cent. For the $\mathrm{t\bar{t}+b\bar{b}}$ final state we show two representative comparisons in Fig. 2. More can be found in Ref. [13] where the selection cuts are also specified.

Once the agreement between the predictions from the LHE's and at NLO is established, we can make predictions and study the effect of the parton shower (PS) as well as that of the full SMC. For this purpose we use the last version of the SMC program `PYTHIA` 6.428 [26]. There are four different stages of event evolution where we can make predictions: (i) from the LHEs, which gives

[1] Throughout this paper for jet reconstruction we use the anti-$k_\perp$ algorithm [27] as implemented in `FastJet` [28].

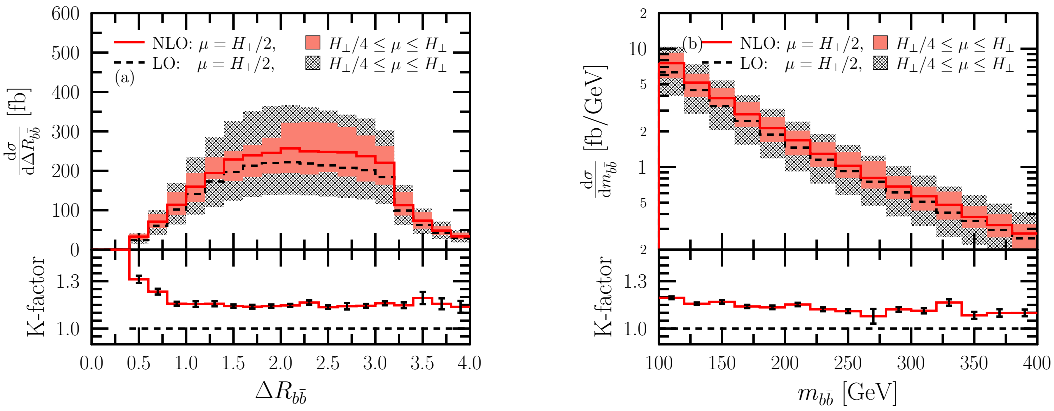

Figure 1: Distributions of a) ΔR-separation and b) invariant mass of the $b\bar{b}$-jet pair at LO and NLO accuracy. The bands represent the scale uncertainties of the predictions. The lower plots show the NLO K-factor with error bars representing the combined statistical uncertainty of the NLO calculation.

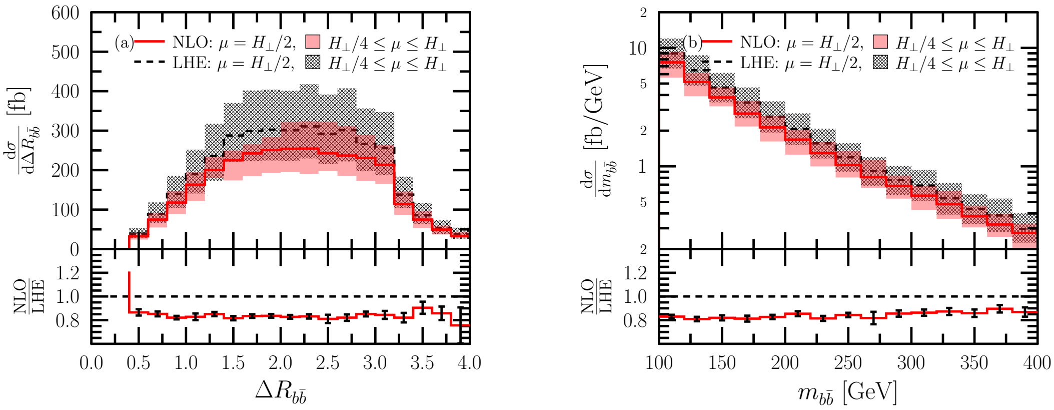

Figure 2: Distributions of a) ΔR-separation and b) invariant mass of the $b\bar{b}$-jet pair at NLO accuracy and from LHEs. The bands represent the scale uncertainties of the predictions. The lower plots show the ratio of predictions at NLO as compared to those from the LHEs, with error bars representing the combined statistical uncertainty.

distributions from events at Born+1st radiation; (ii) after decay, which gives distributions with on-shell decays of heavy particles (t-quarks), shower and hadronization effects turned off; (iii) after PS, when parton showering is included, but t-quarks kept stable; (iv) and finally, after full SMC, when decays, parton showering and hadronization are included generated by the SMC. Extensive study of these effects will be presented in a dedicated publication [25]. Here we show some sample distributions made for proton-proton collisions at 14 TeV c.m. energy.

For the $\mathrm{t\bar{t}+b\bar{b}}$ final state at vanishing transverse momentum of the b-quarks or vanishing invariant mass of the $\mathrm{b\bar{b}}$-pair the Born cross section becomes singular (our b-quarks are massless). While this can never happen in a LO computation due to the selection cuts, it is a problem in the POWHEG method because the selection cuts can only be applied after event generation. The traditional way of treating this problem is the introduction of a generation cut [29]. We use $p_{\perp,\mathrm{b}} \geq 2$ GeV for both the anti-b and b-quark and a cut $m_{\mathrm{b\bar{b}}} \geq 2$ GeV. With these cuts the LO cross section becomes finite.

Number and type of particles are very different at various stages of the evolution, so in order to study the effect of SMC we employ selection cuts only on the LHEs to keep the cross section fixed. Taking into account that physical cuts should always be well above the technical ones, we consider the following set of physical cuts:

1. All hadronic tracks with $|\eta| < 5$ were used to build jets using the $k_\perp$ algorithm [27], with a recombination parameter $R = 0.4$, as implemented in `FastJet`-3.0.6 [28].

2. We require at least one b and one $\bar{b}$ jet with $p_{\perp,j} > 20\,\mathrm{GeV}$ and $|\eta_j| < 2.5$ and invariant mass of the $b\bar{b}$ jet pair $m_{b\bar{[}b} > 100\,\mathrm{GeV}$.

The LHEs selected this way are let evolve according to the SMC and the particle momenta found at a later stage of evolution are used to define the final jets with $p_{\perp,j} > 20\,\mathrm{GeV}$ and $|\eta_j| < 2.5$, charged leptons with $p_{\perp,\ell} > 25\,\mathrm{GeV}$, $|\eta_\ell| < 2.5$ and isolated from jets using a ΔR-separation with $\Delta R_{j,\ell} > 0.4$. Objects that do not satisfy these criteria are not taken into account for the kinematic distributions.

In order to show the power of the method as well as the effect of the SMC, in Figs. 3 and 4 we show four example plots. For making these predictions we used the value $m_\mathrm{t} = 172.6\,\mathrm{GeV}$. While the b-quark masses were set zero in generating the hard-scattering amplitudes, their default values, implemented in `PYTHIA` in the SMC evolution to B-hadrons, were kept. In the configuration of the SMC, for all other mass and width parameters, including light quark masses, we used the default values. We use the `CT10NLO` parton distribution functions from `LHAPDF` with $\Lambda_5 = 226\,\mathrm{MeV}$ and strong coupling α_s computed with 2-loop running. The renormalization and factorization scales were set equal to μ_0.

Fig. 3 presents the distributions of a) ΔR-separation and b) invariant mass of the $b\bar{b}$-jet pair at NLO accuracy and at all four different stages event evolution. We find that the predictions at NLO and after PS differ very little, but by a couple of percent except for small values of ΔR-separation (below one) where the difference can increase to 15 %. In the case of the ΔR-separation the largest change is due to the decay of the t-quarks, and the subsequent PS and hadronization hardly has any effect. In the case of the invariant mass of the $b\bar{b}$-jet pair the largest change is again caused by the decay of the t-quarks, but the PS also makes the spectrum softer as expected.

The hardest non-b jet appears first in the real contribution of the NLO correction therefore, the NLO prediction for the the transverse momentum of of this jet is actually at LO accuracy. As seen in Fig. 4.a, the fixed order prediction diverges for small transverse momenta, which is smeared by the Sudakov suppression in the LHEs. The effect of the decay of t-quarks is even larger here than for the distributions in Fig. 3. Finally, in Fig. 4.b the invariant mass of the hardest b-jet and positron is presented. As charged leptons are not present in the LHEs, we can make predictions only after decay of t-quarks, or after full SMC. The effect of PS and hadronization is softening the spectrum, significant only below 100 GeV.

We expect that our LHE's available at our web page [30] constitute a useful starting point for performing an analysis for final states involving a $\mathrm{t\bar{t}}$-pair at hadron colliders. For generating events with other values of the (physical and non-physical) parameters the `PowHel` code, also available on the web page, can be downloaded, or we can provide the events on request.

PoS(LL2014)031

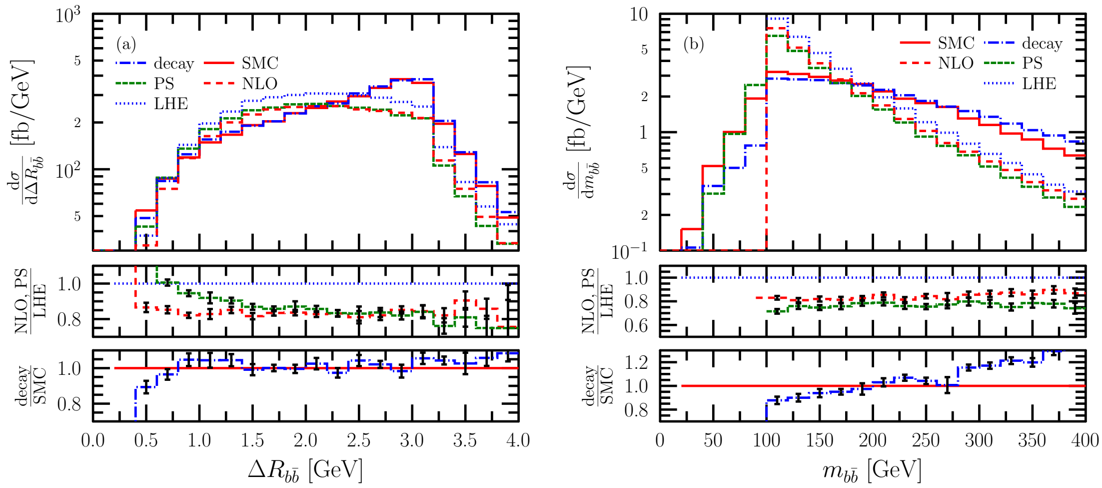

Figure 3: Distributions of a) ΔR-separation and b) invariant mass of the $b\bar{b}$-jet pair at NLO accuracy and four different stages of event evolution.

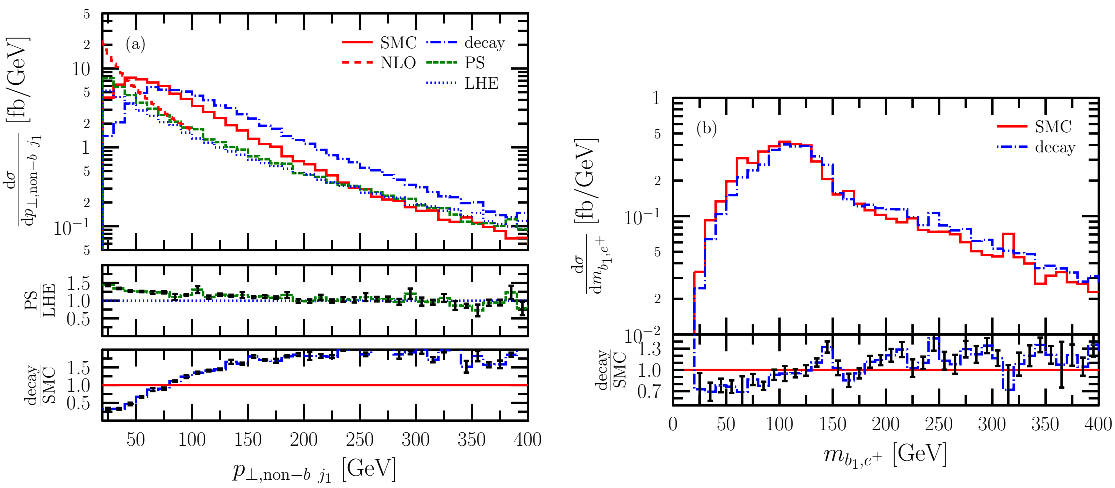

Figure 4: a) Distribution of the transverse momentum of the hardest non-b jet at NLO accuracy and four different stages of event evolution. b) Distribution of the invariant mass of the hardest b-jet and positron.

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