Top-quark production at the LHC: differential cross section and phenomenological applications.

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We discuss top-quark pair production at hadron colliders and review available calculations of differential top-pair production cross section in perturbative QCD at approximate next-to-next-to-leading order (NNLO) within the threshold resummation formalism. These calculations are implemented into an open source program under development. We present phenomenological studies at the LHC that include transverse momentum and rapidity distribution of the top quarks at a center-of-mass energy of 7 TeV. Preliminary results obtained with this program are in very good agreement with the recent LHC measurements.

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Introduction. Top-quark phenomenology at hadron colliders will be prominent in the near future and a new realm of precision calculations has been reached in order to analyze the large inflow of data from LHC with unprecedented accuracy. Precise measurements of top-quark pair total and differential cross sections at a center-of-mass energy $\sqrt{s} = 7$ TeV are already published by the CMS [1] and ATLAS [2] collaborations and data at 8 TeV are publicly available. The top-quark's "on shell" mass m_t has been recently determined [3] within few GeV uncertainty and, for the first time, the strong coupling constant $\alpha_s(M_Z)$ is extracted by using $t\bar{t}$ events. The cross section for top-quark pair production gives us the possibility of investigating the correlation between parton distribution functions (PDFs) of the proton (in particular the gluon), top-quark mass m_t, and α_s. In fact, about 80% of the total cross section is ascribed to the gluon-gluon channel at the LHC at $\sqrt{s} = 7$ TeV. Therefore, top-quark pair production is a standard candle to test QCD factorization, properties of the Standard Model (SM), and also to investigate physics beyond the SM. Studies are going on in order to establish the role of quantum corrections to the top mass and the vacuum stability conditions which are driven by the precise value of the mass of the Higgs boson [4, 5]. Furthermore, new observables to measure the top-quark mass at hadron colliders have been recently proposed [6]. Therefore, there is a clear demand of precise theoretical predictions at highest possible order for comparisons with the data, in which systematic uncertainties associated with renormalization/factorization (μ_R, μ_F) and other scales are reduced by including higher orders in perturbative calculations. The computation of the $t\bar{t}$ production cross section is a big challenge and required continuous efforts by the QCD community for reaching the state-of-art of QCD radiative corrections and the development of calculational tools. QCD corrections to heavy quark production at colliders in the next-to-leading order (NLO) approximation are known since many years [7, 8, 9], but the full NNLO $O(\alpha_s^4)$ inclusive cross section has been computed only recently [10, 11]. Available exact NLO calculations for $t\bar{t}$ total and differential cross sections have been implemented into Monte Carlo numerical codes such as MCFM [12], MC@NLO [13], POWHEG [14], MADGRAPH/MADEVENT [15, 16] while the state-of-the-art QCD computation for the $t\bar{t}$ production total cross section at NNLO is implemented in the C++ computer programs TOP++ [10] and HATHOR [17].

Resummation. In the kinematic region near the partonic threshold of the $t\bar{t}$ pair, remnants of soft-gluon dynamics in hard scattering functions can be large and dominate high-order corrections. These enhancements have logarithmic structures which are resummed by threshold resummation techniques [18, 19] that organize double-logarithmic corrections to all orders and extend the predictive power of QCD to these kinematic regions. In the past years, many efforts have been put into developments of approximate NNLO QCD calculations that include threshold resummation to assess $t\bar{t}$ total and differential cross section [20, 21]. Novel techniques in soft-collinear effective theory (SCET) have been also recently developed [22] and some of the differences between SCET and the traditional resummation approach are outlined in [23]. Threshold resummation can be derived in two different kinematic domains in which we have different kinds of logarithms that have to be resummed. These two kinematic regimes give the same prediction when the $t\bar{t}$ pair is produced at the mass threshold. In the single-particle inclusive (1PI) kinematic, heavy quark hadroproduction is dominated by the partonic subprocess $i(k_1) + j(k_2) \to Q(p_1) + X[\bar{Q}](p'_2)$, where $k_{1,2}$ are the incoming momenta of partons (i, j), $p'_2 = \bar{p}_2 + k$, k is any additional radiation, and $s_4 = p'^2_2 - m_t^2 \to 0$ is the momentum at the threshold. The pair-invariant mass (PIM) kinematic is defined by the reaction $i(k_1)+j(k_2)\to Q\bar{Q}(p')+X'(k)$, where the threshold $p'^2 = M^2$ is reached when $X'(k)=0$. The approximate NNLO differential cross section at parton level in 1PI kinematic can be written in a compact form as

$$s^2\frac{\hat{\sigma}_{ij}}{du_1 dt_1}|_{1PI} = F^{Born}_{ij}\frac{\alpha_s^2(\mu_R^2)}{\pi^2}\left\{D^{(3)}_{ij}\left[\frac{\ln^3(s_4/m_t^2)}{s_4}\right]_+ + D^{(2)}_{ij}\left[\frac{\ln^2(s_4/m_t^2)}{s_4}\right]_+\right.$$
$$\left. + D^{(1)}_{ij}\left[\frac{\ln(s_4/m_t^2)}{s_4}\right]_+ + D^{(0)}_{ij}\left[\frac{1}{s_4}\right]_+ + R_{ij}\delta(s_4)\right\}$$

where $s_4 = s+t_1+u_1$, $t_1=(k_2-p_1)^2-m_t^2$, $u_1=(k_1-p_1)^2-m_t^2$, μ_R is the renormalization scale, and $D^{(k)}_{ij}$ and R_{ij} (which depend on Mandelstam invariants s, t_1, and u_1) are defined by soft and hard structures of partonic reactions.

Phenomenological applications. Motivated by the rapid inflow of very precise LHC data of $t\bar{t}$ differential cross sections, we illustrate phenomenological applications obtained by our program which is under development and designed for calculations of total and differential cross sections for heavy-quark pair production at hadron colliders in both 1PI and PIM kinematics. The package incorporates an approximate NNLO QCD calculation within the threshold resummation formalism (details in [24]). Our goal is to create a flexible open source code for phenomenological analyses and quantitative comparisons of theory with data. The cross section at hadronic level contains several input parameters such as m_t, μ_R, μ_F, PDFs, and $\alpha_s(M_Z)$, which can be varied to explore the sensitivity of the theory prediction and estimate systematic uncertainties. This is of particular interest in a global fit analysis of PDFs in which one studies the impact of the variation of these parameters on the extracted PDFs and in particular the correlation of the gluon PDF with $\alpha_s(M_Z)$ and top mass. Measurements of differential cross sections of top-quark pair production have potential sensitivity to determine the gluon distribution in the proton [25], but the correlation between PDFs, m_t and α_s has to be carefully taken into account. Simultaneous determination of these QCD parameters using top-pair production measurements at the LHC requires in particular fast computing tools for the calculation of top-pair differential cross sections at highest available order in QCD.

Results. In Fig. 1 we show a comparison between the exact NLO calculation (black dot-dashed line) of the top-quark differential P_T^t distribution at the LHC $\sqrt{s}=7$ TeV, obtained by using the MCFM code [12] with MSTW [26] NLO PDFs and the approximate NLO calculation based on the threshold logarithms (solid), obtained with our code. The default scale choice which we adopt here is $\mu_R=\mu_F=m_t$ and the value of the pole mass is set to $m_t = 173$ GeV [20]. The excellent agreement shown in the P_T^t range around the threshold region is an indication of the fact that threshold resummation, supplemented with NLO matching conditions for hard and soft functions, controls the large logarithms which dominate the cross section in this kinematic range and gives a very good estimate of the P_T^t spectrum. Differences are below the percent level and cannot be resolved by the accuracy of the current data. Similar features are found in the rapidity distribution of top quarks. In Fig. 2 we compared the normalized approximate NNLO predictions for top-quark transverse momentum and rapidity (y_t) distributions to the recent measurements [1] of the CMS experiment. Predictions obtained by using different PDF sets are represented by histograms in which we show MSTW [26] (solid), CT10 [27] (dot-dashed), and ABM11 [28] (dashed). The shape of both P_T^t and y_t differential distributions is well reproduced and the agreement to data is generally good for all PDFs where the recommended value of $\alpha_s(M_Z)$ is adopted in each case. A spread in

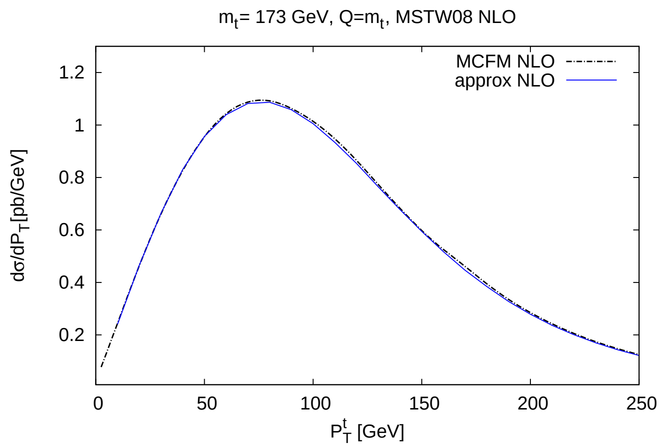

Figure 1: Exact NLO calculation obtained by using MCFM vs. approximate NLO.

the theory predictions, more visible in the rapidity distribution, can be explained by different heavy quark treatments in the PDFs, different $\alpha_s(M_Z)$ values, and different preferred values (generally smaller in the ABM11 case) of the top-quark's pole mass.

Conclusions. The development of the open-source computing program at approximate NNLO for calculation of differential distributions of top-pair production in proton-(anti)proton collisions has started. We have shown phenomenological studies at the LHC in which $t\bar{t}$ pair production differential cross sections are compared to recent CMS data. The NNLO approximate predictions are in overall good agreement with the data.

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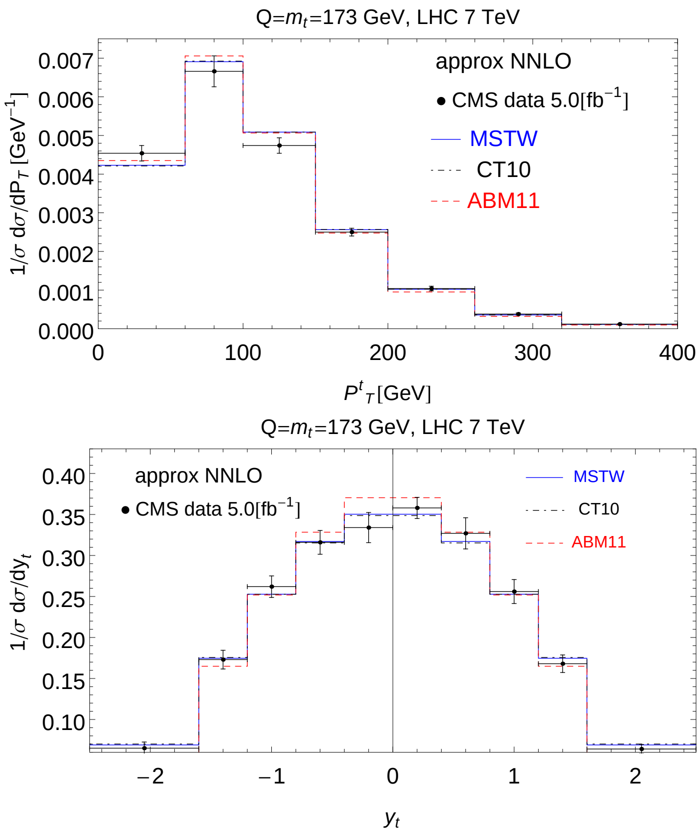

Figure 2: Upper inset: normalized differential $t\bar{t}$ production cross section as a function of the transverse momentum of the top quarks. Lower inset: same as upper inset but as a function of the rapidity distribution.

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