

Progress in top-quark pair production cross section calculations and impact on parton distribution functions of the proton

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We discuss the impact of eligible top-quark pair production differential cross-section measurements at the LHC with a collision energy of 13 TeV on the parton distribution functions (PDFs) of the proton as well as the impact of approximate next-to-next-to-next-to-leading order (aN³LO) QCD corrections combined with next-to-leading order (NLO) electroweak (EW) corrections on $t\bar{t}$ observables. We illustrate the effects on the gluon PDF at large x from an optimal baseline selection of data in NNLO global fits, and show comparisons between the theory prediction for $t\bar{t}$ total and differential cross sections at aN³LO QCD combined with NLO EW and recent measurements from the ATLAS and CMS collaborations at the LHC.

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1. Introduction

The next precision frontier of Run-3 of the Large Hadron Collider (LHC) and beyond requires high-precision and high-accuracy theory predictions for particle reaction cross sections in perturbation theory to guarantee meaningful comparisons between theory and experiment. To this end, a combined effort in advancing the current knowledge of the structure of the proton encoded in the parton distribution functions (PDFs) as well as progress in higher-order computations in perturbation theory is indispensable. The QCD factorization formula describing proton-proton collisions at the LHC depends on two fundamental ingredients: the PDFs of the proton, that are non-perturbative objects determined through global QCD analyses of world data, and the short-distance hard scattering contributions which are obtained using a variety of multi-loop techniques for Feynman diagram calculations in relativistic quantum field theories. Top-quark pair production cross section measurements are a clean probe for PDFs at intermediate and large longitudinal momentum fraction x where they are currently poorly constrained and where jet-production measurements may complement those from $t\bar{t}$ in absence of tensions between these measurements. The impact of recent $t\bar{t}$ high-precision measurements at ATLAS and CMS on global QCD analyses of CTEQ PDFs at next-to-next-to-leading order (NNLO) is discussed in Ref. [1], while a recent study of the impact of corrections from soft-gluon contributions at approximate next-to-next-to-next-to-leading order (aN³LO) in QCD combined with electroweak (EW) corrections at next-to-leading order (NLO) are discussed in Ref. [2].

2. Gluon impact from optimal combinations of 13 TeV top-quark measurements

In this section, we report the results published in Ref. [1]. Future CTEQ PDF releases require substantial efforts in selecting sensitive data from the large amount of novel high-precision measurements at the LHC. In particular, we studied the impact of single differential cross section measurements of top-pair production at the LHC at 13 TeV from the ATLAS [3, 4] and CMS [5, 6] collaborations on the gluon and other CTEQ PDFs [1]. The PDF impact from these measurements has been analyzed by including each individual measurement on top of the CT18 baseline using the ePump [7, 8] code first for a rapid assessment, and then in individual global fits. In such global fits, we analyzed the effect of including statistical correlations when these were available in the case of combined measurements (see Refs. [1, 4]), the impact from including the same distribution but with different binning, the interplay between top-quark and jet production data, the dependence on the factorization, renormalization and top-quark mass $m_t^{(pole)}$ scales, and EW radiative corrections at NLO when available. The NNLO QCD theory predictions are obtained through fastNNLO tables [9–12] as well as NNLO/NLO K -factors obtained with the MATRIX code [13–15] and NLO APPLgrid tables [16] with MCFM [17]. EW corrections at NLO, either taken from Ref. [10] or calculated with MadGraph_aMC@NLO [18]/MCFM [19] were also considered when available. The most sensitive PDF information is obtained using two optimal combinations of measurements labelled CT18+nTT1 and CT18+nTT2 which minimize the tensions between data in the extended baseline, maximize the sensitivity and have optimal χ^2/N_{pt} . CT18+nTT1 includes the rapidity distribution of the top-quark pair $y_{t\bar{t}}$ at ATLAS in the hadronic [3] and lepton+jet [4] channels and at CMS in the dilepton channel [5], and the invariant mass distribution of the top-quark pair $m_{t\bar{t}}$

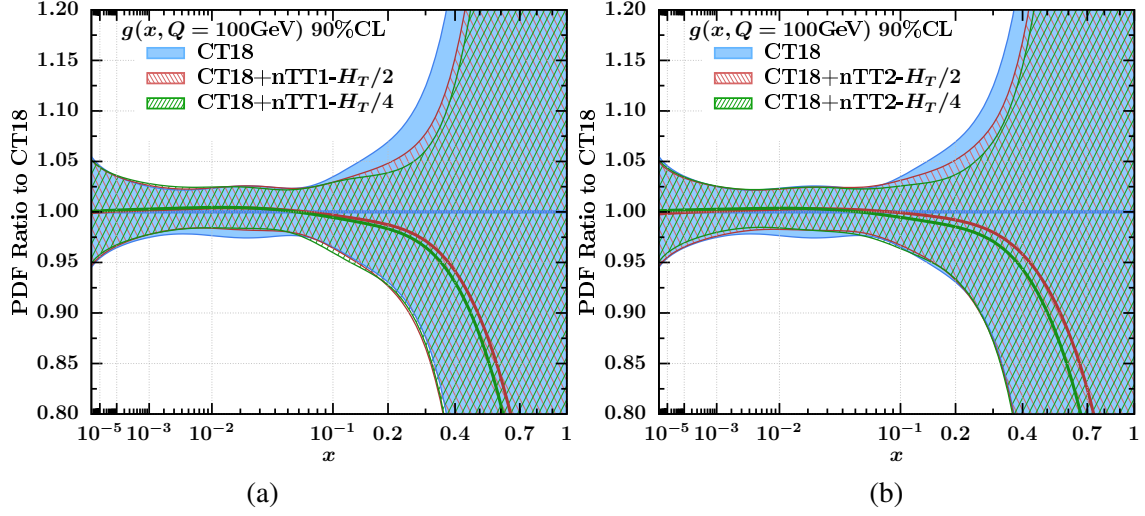


Figure 1: Gluon PDFs and uncertainties. In (a) the CT18+nTT1 and (b) CT18+nTT2 global QCD analyses at NNLO, plotted as ratios to CT18 NNLO. PDF uncertainties are evaluated at the 90% CL.

at CMS in the lepton+jet channel [6]. CT18+nTT2 includes the same distributions except for the ATLAS lepton+jet $y_{t\bar{t}}$ that is replaced by the $y_{t\bar{t}} + y_{t\bar{t}}^B + m_{t\bar{t}} + H_T^{t\bar{t}}$ combination. Here, $H_T^{t\bar{t}}$ is the scalar sum of the transverse momenta of the hadronic and leptonic top quarks, and $y_{t\bar{t}}^B$ is the rapidity distribution for the boosted topology. The impact on the CTEQ gluon from the global fit with the CT18+nTT1 and CT18+nTT2 extended baselines is illustrated in Fig. 1. Hatched error bands represent the $H_T/2$ (red) and $H_T/4$ (green) choices for the central scale in the 13 TeV $t\bar{t}$ theory predictions. Most of the impact from the new data is visible in the large x region and mostly due to the high-luminosity 137 fb^{-1} data at CMS. The overall quality-of-fit of the CT18+nTT1 and CT18+nTT2 fits is essentially the same as that of CT18, with $\chi^2/N_{pt} \approx 1.16$.

3. Top-quark cross sections and distributions at aN^3LO

In this section, we report the results published in Ref. [2]. Top-quark physics plays a central role in current and future research programs at the LHC. In fact, $t\bar{t}$ production is one of the most important processes at this collider; it has the ability to constrain proton PDFs and is important for searches of new physics interactions. Measurements of top-quark pair production total and differential cross section are going to be delivered with unprecedented precision and accuracy at the LHC in the near future. Therefore, it is critical to push forward the precision frontier of the theory calculations predicting this standard-candle observable. Theory predictions for top-quark cross sections and differential distributions in $t\bar{t}$ production have been computed at NLO $\mathcal{O}(\alpha_s^3)$ in Refs. [20–25], and NNLO at $\mathcal{O}(\alpha_s^4)$ in Refs. [13, 14, 26–33] in QCD, while EW corrections to this process were studied in Refs. [18, 19, 34–50]. Logarithmic enhancements from soft-gluon emissions provide an important subset of QCD corrections which are dominant in the LHC kinematic regime and have been extensively studied in the literature in the past three decades [2, 51–84]. Perturbative QCD corrections from soft gluons at third order in perturbative QCD were calculated in Refs. [81, 82] based on the formalism of Refs. [53, 54, 57, 64, 69, 71, 79, 81–84]. In Ref. [2] these corrections are

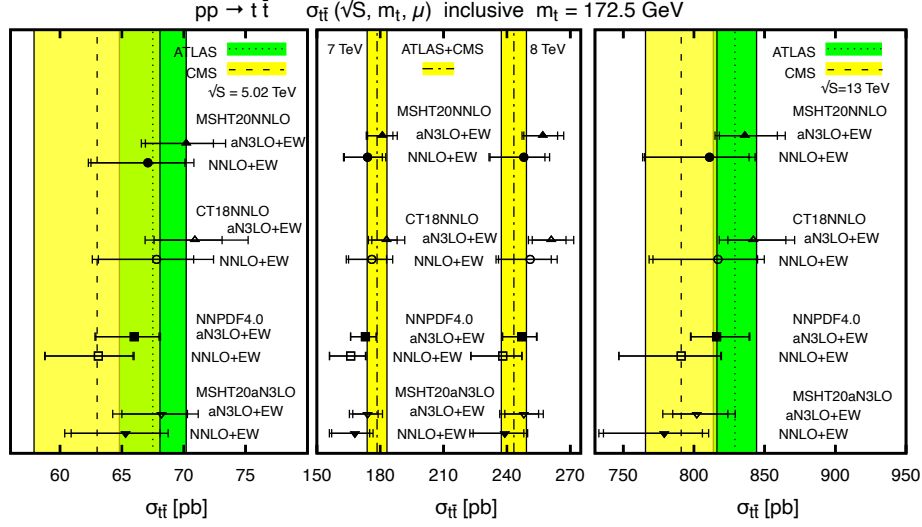


Figure 2: $t\bar{t}$ total inclusive cross sections compared to recent measurements at the LHC at different collision energies.

added on top of the exact NNLO cross section to obtain QCD results at approximate N³LO (aN³LO) which are combined with Electroweak (EW) corrections included at NLO. This calculation is used to obtain new results for the top-quark pair production total and differential cross sections which are compared to recent measurements from the LHC. The expression of the partonic contributions from soft-gluon corrections in QCD is in the form of $C_{ij}^{(k)} [\ln^k(s_4/m_t^2)/s_4]_+$. In general, the coefficients $C_{ij}^{(k)}$, with $k \leq 5$ at N³LO, depend on the Mandelstam variables s , t_1 , u_1 , the top-quark mass m_t , and the renormalization and factorization scales μ_R and μ_F respectively. The threshold variable s_4 is defined by $s_4 = s + t_1 + u_1$. More details about these corrections can be found in Refs. [81, 82].

In Figure 2, we compare our theoretical predictions at aN³LO obtained with different PDFs (CT18 [85], MSHT20 [86, 87], and NNPDF4.0 [88]) to recent LHC measurements for various collision energies such as ATLAS [89] and CMS [90] at $\sqrt{s} = 5.02$ TeV; ATLAS and CMS combined at $\sqrt{s} = 7$ and 8 TeV [91]; ATLAS [92] and CMS [6] at $\sqrt{s} = 13$ TeV. The theory error bars represent scale uncertainty (inner bar), and scale added to PDF uncertainties in quadrature (outer bar). The experimental error bands represent all the given errors added in quadrature. The NNLO theory predictions are calculated using Top++2.0 [75] while the NLO QCD+EW are obtained with MadGraph5_aMC@NLO [93, 94]. More results are available in Ref. [2]. In Figure 3, we illustrate ratio plots where we compare the theory results for the top-quark transverse momentum p_T^t distribution at NNLO and aN³LO with EW corrections to recent measurements at ATLAS [3] and CMS [5] at 13 TeV. The orange band represents the sum of statistical and systematic experimental uncertainties added in quadrature. Inner (outer) bars represent scale (scale plus MSHT20 PDFs at aN³LO or NNLO, respectively) theoretical uncertainties. The NLO EW corrections are obtained from Ref. [49] while the combined QCD×EW corrections incorporate $\mathcal{O}(\alpha_s^2\alpha)$ terms and the subleading $\mathcal{O}(\alpha_s\alpha^2)$, $\mathcal{O}(\alpha^3)$, $\mathcal{O}(\alpha_s^3\alpha)$ terms which are included using the multiplicative method

discussed in Ref. [49]. Similar results with other PDFs as well as for the rapidity distributions of the top quark are presented in Ref. [2].

4. Conclusions

We reported recent progress in top-quark pair production cross section calculations and presented a comprehensive study of the impact of recent high-precision measurements from ATLAS and CMS at the LHC at 13 TeV on CTEQ PDFs. We identified two optimal combinations of $t\bar{t}$ measurements that are added on top of the CT18 baseline and maximize the information extracted from the data. Both combinations have mild impact on the CT18 gluon and overall have the same fit quality of CT18.

We studied the impact of radiative corrections at aN^3LO in QCD from soft-gluon resummation including EW corrections at NLO on total and differential $t\bar{t}$ cross sections. These new predictions have been compared to recent $t\bar{t}$ cross section measurements at the LHC, and the QCD corrections substantially increase the rates for $\sigma_{t\bar{t}}$ and the differential distributions while the EW corrections play an important role at large p_T^t .

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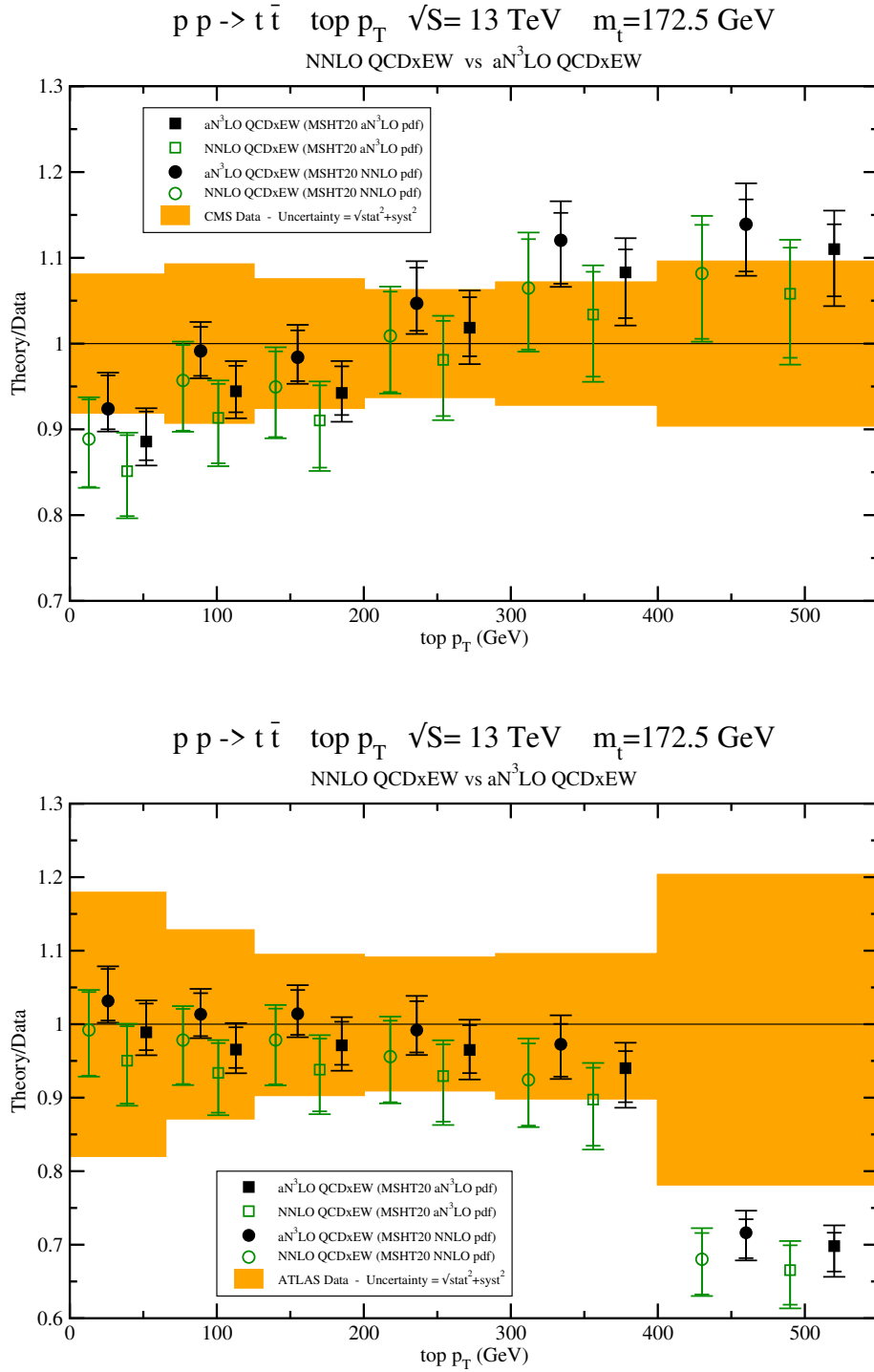


Figure 3: Comparison of NNLO QCD $\times$ EW and aN³LO QCD $\times$ EW theory predictions using MSHT20 NNLO and aN³LO PDF with CMS (upper plot) and ATLAS (lower plot) top-quark transverse momentum data.

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