PROCEEDINGS OF SCIENCE

Fully-differential predictions for top pair-production and decay at high precision

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We present state-of-the-art, high-precision predictions for top-quark pair production in the di-lepton channel at the LHC. Our results are based on the narrow-width approximation and include approximate NNLO corrections in the production subprocess, exact NNLO corrections in the decay subprocess as well as exact NLO×NLO production-decay interferences. We briefly outline the structure of this new calculation and discuss the importance of the corrections beyond NLO. A first comparison of the these new predictions to ATLAS and CMS fiducial-region measurements is also made.

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1. Predictions for decaying top quarks in top-pair production

The theoretical description of top-pair production at the level of stable top quarks has reached a very high level of sophistication, with the availability of fully differential fixed-order NNLO-QCD predictions [1, 2, 3, 4] (supplemented by NLO EW corrections [5] and various resummations, see for e.g. ref.s [6, 7, 8, 9, 10, 11, 12, 13, 14, 15, 16, 17]). In parallel, a significant amount of work has gone into including the effects of the top-quark decay up to NLO, both in the narrow-width approximation (NWA) [18, 19, 20] as well as in offshell approaches [21, 22, 23, 24, 25, 26, 27]. Furthermore, two state-of-the art generators have recently been developed matching the NLO NWA and fully-offshell results to parton showers [28, 29].

A big advantage to including the top-quark decay in the matrix elements (be that at fixed-order or at fixed-order plus parton shower) is that predictions made with such codes can be directly compared to measurements of the top-quark final states in visible regions of experimental detector phase space. In contrast, in order to be compared with theoretical predictions at the stable-top level, measured data must firstly be extrapolated from the fiducial to the full phase-space and secondly, be unfolded or back-modelled to some definition of onshell top-quark partons. Both of these steps depend on Monte Carlo and unavoidably introduce an additional systematic error to the data. Moreover, since the routinely used Monte Carlo generators used to perform these steps formally model the top-quark decay at LO, there is perhaps a further uncertainty, currently not estimated in such extrapolations, arising from missing higher-order corrections in the decay.

In this talk we briefly discuss recent work on $t\bar{t}$, published in ref. [30], that goes beyond NLO in the NWA, including higher order corrections in both production and decay subprocesses.

2. Approximate NNLO-production and exact NNLO-decay

At NLO in the NWA, predictions for top-quark pair production and decay consist of NLO corrections to the production (with LO decays) as well as NLO correction to the decay subprocesses (with the production described at LO). At NNLO the required contributions are: NNLO corrections to the production and decay separately (with decay and production respectively described at LO), as well as the NLO×NLO production-decay and $t$decay-$\bar{t}$decay cross terms. For all of these contributions, in order to correctly describe production-decay spin correlations, the amplitudes for the production of a $t\bar{t}$ pair as well as the decay of a top or antitop must be computed retaining the full spin information of the tops. The work presented here, based on ref. [30], includes all of these terms exactly, except for the NNLO corrections in production, for which an approximate is implemented. We note that the full set of amplitudes, with top-spin information retained, required in order to compute the NNLO corrections to the production exactly are not currently known.

We first discuss the approximate-NNLO corrections in production. These contributions were the subject of earlier work presented in ref. [31], in which an approximation to the fully-differential NNLO corrections to $t\bar{t}$ production was combined with the decays of the top quarks. The starting point for this was a factorization formula [6], derived in Soft-Collinear-Effective-Theory (SCET) for the (stable-top) $t\bar{t}$ cross section (differential in the $t\bar{t}$ invariant mass) valid in the soft-gluon limit $z = M_{t\bar{t}}/\hat{s} = (p_t + p_{\bar{t}})^2/\hat{s} \to 1$. The factorised structure makes it possible to resum large logarithms of $(1-z)$ and expanding the resummed cross section to fixed order allows one to construct an approximation to the exact NNLO. In ref. [31] this approach was generalised beyond the stable-top approximation and the spin-correlated LO decay of the top-quarks was attached to the approximate-NNLO production kernels.

One of the ways in which the approximate-NNLO and exact NNLO results differ is in the subleading power logarithms in $(1-z)$ present in the exact results but missing in the approximation. Two sources of these are (a) the higher order terms in the soft-expansion of the Altarelli-Parisi splitting functions and (b) the precise way in which the phase space is approximated in the soft limit (see ref. [32] for details). Our central predictions use the kernels of ref. [31] supplemented with the highest subleading-power logarithms in $(1-z)$, These arise from the soft-expansion of the splitting functions [33, 34] and are known to bring improvements to the NNLO approximation [33, 34, 35]. We indeed find that, when included, these terms lead to an enhancement of the inclusive cross section (of $\sim$5-6%) and bring the approximate NNLO inclusive cross section for stable top quarks into better agreement with the exact NNLO. Our central prediction also treats the soft phase space as in ref.s [6, 31].

An important aspect to the approximate-NNLO approach is providing a reliable uncertainty estimate. Simply taking the standard envelope of factorization/renormalization scale variation can lead to underestimating the uncertainty [31]. Instead, in order to construct a reliable estimate of the theoretical uncertainty, we explicitly use the freedom to additionally include different subleading effects. In detail, to make this estimate we take the envelope of scale variation together with variations (switching on and off) of subleading corrections of different origin: firstly, (a) from the splitting functions [33, 34] and secondly, (b) from the soft phase space (following the procedure performed in ref. [32]).

The quality of the NNLO approximation in the production can be assessed at the level of stable tops, where we find excellent agreement with the NNLO inclusive cross section (computed `top++` [36]) as well as good agreement with the differential results presented in ref. [1].

The exact NNLO corrections to the top quark decay are also computed retaining full spin-correlations between production and decay. Using the SCET-inspired phase-space slicing method presented in ref. [37], a small cutoff on the invariant mass (m_j) of all QCD partons from the top quark decay is introduced to split the phase space integration, in the computation of NNLO corrections to the differential top width, into resolved and unresolved regions. The resolved region receives contributions from the NLO corrections to the process of top decay plus an additional jet, and can be dealt with straightforwardly. The contribution in the unresolved region is computed using SCET via a factorization formula that is valid up to power corrections in m_j^2/m_t^2 [37]. The sum of resolved and unresolved contributions then converges to the exact NNLO correction when the cutoff is sufficiently small (in practice a cutoff of 10^{-5} on m_j^2/m_t^2 is sufficient to ensure that the remaining power corrections are negligible for all kinematic distributions considered).

The NLO×NLO production-decay and $t$decay-$\bar{t}$decay corrections have also been computed exactly. Since production and decay subprocesses can be treated separately in the NWA, these contributions are more straightforward as far as their singularity structure is concerned, and standard NLO subtraction techniques can be adapted to deal with IR-singularities.

All the contributions discussed in this section have been implemented in a parton-level Monte Carlo generator for the di-lepton channel of $t\bar{t}$. We denote our best results as $\hat{\text{N}}$NLO (not NNLO) indicating that we have an approximation to the NNLO corrections in production.

3. Results at LHC 8 TeV

In this section we present results at LO, NLO and N̂NLO that can directly be compared to the 8 TeV ATLAS $\{e^{\pm}\mu^{\mp}\}$-channel [38] and and CMS $\{e^{\pm}\mu^{\mp}, e^{+}e^{-}, \mu^{+}\mu^{-}\}$-channel [39, 40] measurements (the indirect decays $W \to \tau \to e(\mu)$ are considered as backgrounds to these measurements). The ATLAS measurements are performed in a fiducial volume defined through selection cuts on the final-state leptons, whilst CMS additionally places cuts on b-jets (these constraints are indicated in the plots of fig. 1). The input parameters used to compute the predictions are: $m_t = 173.3$ GeV, $\Gamma_t^{\mathrm{LO}} = 1.5048$ GeV, $m_W = 81.1876$ GeV, $\Gamma_W = 2.0928$ GeV, with `MMHT2014` PDFs [41] (with the appropriate value of α_s for each perturbative order). We have used fixed factorization and renormalization scales $\mu = \mu_F = \mu_R \in [0.5, 1.0, 2.0]m_t$, varying the scale in the NLO and NNLO corrections to the top width $\Gamma_t^{(1,2)}(\mu)$ for consistency. To obtain the theoretical uncertainty bands the envelope of the predictions for each scale is taken. Additionally, for the approximate-NNLO corrections in the production, the envelope of predictions computed with different subleading terms in $(1-z)$ is also taken, as mentioned in the previous section. We note that we always and consistently include the higher-order corrections in the decay appropriate for each perturbative order.

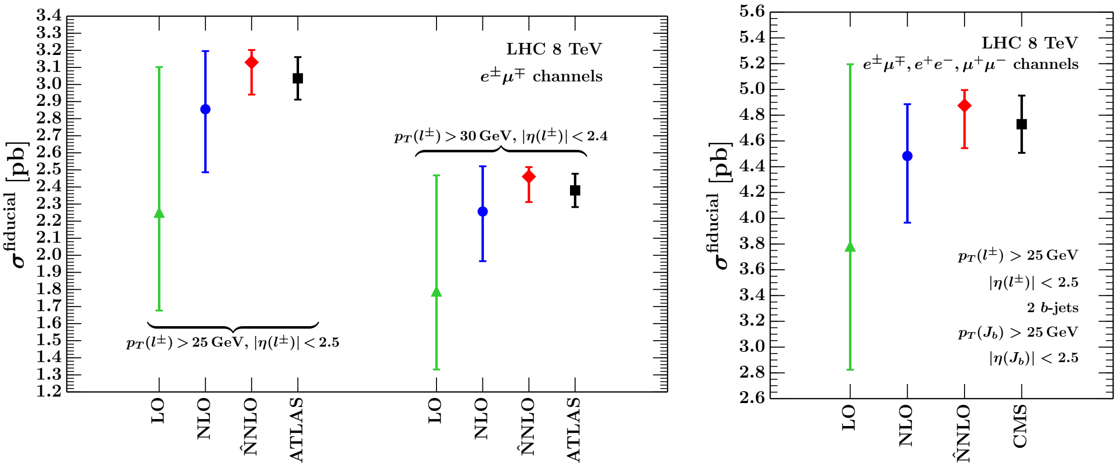

Figure 1: Fiducial cross section measurements at 8 TeV from ATLAS (left) and CMS (right) compared to LO, NLO and N̂NLO predictions. The fiducial volumes are defined by the restrictions on the final-states indicated in the plots.

The theoretical predictions for the ATLAS and CMS fiducial volumes as well as the corresponding experimental measurements are illustrated in fig. 1. It is clear that with increasing perturbative order there is a reduction in the uncertainty bands, with the N̂NLO bands being roughly half the size of the NLO bands. Furthermore, an improved perturbative convergence is seen with the corrections to the cross section going from LO to NLO and from NLO to N̂NLO being reduced. The corrections beyond NLO are significant, around 9-10%, indicating that they are important for an accurate description of fiducial regions When comparing to the experimental measurements we find that, encouragingly, the N̂NLO prediction brings the difference between the central values of theory and measurement to within 3-4% – an improvement with respect to the NLO.

It is also interesting to point out that while the higher-order corrections in the decay are small when mild restrictions are placed on the top decay products, they can grow when stronger cuts are in place. This is the case for the CMS fiducial volume, which places cuts on the *b*-jets as well as on the leptons, and where the NLO and NNLO corrections to the decay together amount to $\sim -8\%$ correction to the cross section (for the ATLAS volume the corrections in the decay amount to less than a percent). This shows that for the best description of the $t\bar{t}$ process in fiducial regions defined by constraints on the top decay products, higher order corrections must be included in *both* production and decay.

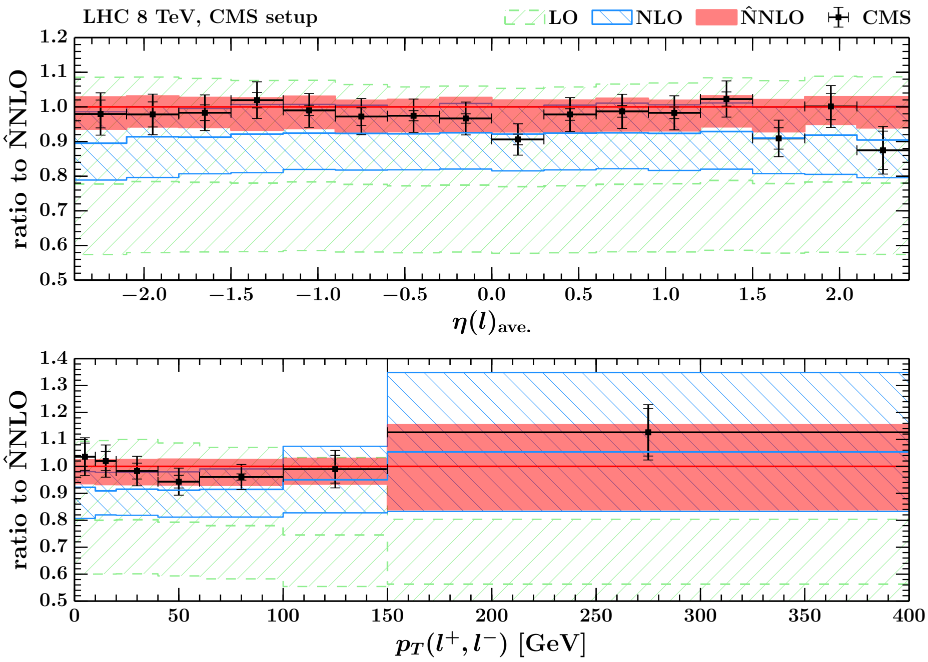

Figure 2: Distributions of the average pseudo-rapidity of the leptons, $\eta(l)_{\text{ave.}}$ and the transverse momentum of the lepton-pair, $p_T(l^+,l^-)$. The plots show the CMS measurements as well as the LO, NLO and N̂NLO predictions normalized to N̂NLO. The errorbars and shaded bands indicate the experimental and theoretical uncertainties respectively. Plots taken from ref. [30], in which further details can also be found.

Finally, a comparison is also made to differential CMS measurements [39] in the di-lepton channel. Fig. 2 shows the absolute distributions for the average lepton pseudo-rapidity, $\eta(l)_{\text{ave.}}$ and the transverse momentum of the lepton-pair, normalised to the N̂NLO prediction. As in the case of the fiducial cross sections there is again good agreement between the measurements and the N̂NLO predictions. The N̂NLO brings an improvement in the agreement not only in the overall normalization, but also in the shape of the distributions for the bulk of the ranges measured.

Given the quality of the measured cross sections and the significant improvements brought by the N̂NLO predictions, it will be very interesting to begin exploiting these state-of-the-art predictions for applications such as m_t^{pole}-extraction from fiducial cross sections.

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