Top Quark Pair Production: theory overview

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In this talk we present the current status of the theoretical description of the production of top-quark pairs at the LHC, detailing recent progress for predictions at the stable-top level as well as for predictions that include the decay of the top quarks.

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1 Stable tops at high precision

With the calculation of higher-order QCD and EW corrections, in addition to the inclusion of various resummations, the production of a pair of onshell stable top-quarks is one of the LHC processes known with highest theoretical precision.

Predictions probing event kinematics in the multi-TeV regime for the $p_{T,t}$, $M_{tt}$, $y_t$ and $y_{\bar{t}}$ distributions are all known through NNLO in QCD [1, 2, 3]. An important study that these calculations have enabled is the choice of dynamical factorization and renormalization scales, which becomes particularly crucial to describe these regions. The choice of scale is certainly not unique, may be different for each distribution studied, and the best choice is often the subject of lively debate. However, when deciding which of two scales is more suited for a given distribution in fixed-order perturbation theory, using the guiding principle of ‘fastest perturbative convergence’, namely picking the scale that leads to smallest $K$-factors, as done in ref. [3] seems perfectly reasonable. Reassuringly, the authors also find that of the set scales investigated, the scale resulting in fastest perturbative convergence also leads to the smallest scale uncertainty bands. The findings of this study are that for the four principle distributions known through NNLO, the optimal choices of central scales are $\mu = H_T/4$ for $M_{tt}$, $y_t$ and $y_{\bar{t}}$ and $\mu = m_T/2$ for $P_{T,t}$. These choices now form the default choices for the NNLO predictions of these distributions at the LHC. When examining more extreme regions of phase space, or more complex observables, such as double-differential cross sections, the study of scale choices may require revisiting.

Despite the impressive nature of the NNLO calculations, typical run-times of $O(10^5)$ CPU-hours per setup mean that the full physics potential of these predictions may be difficult to reach. This problem becomes particularly acute when using these predictions for PDF-fitting, where often tens of thousands of re-evaluations of the partonic cross section with different PDFs are required. A major development on this front has been the interfacing of Stripper [4] to fastNLO [5]. This allows for tables to be produced for the $t\bar{t}$ process, for any distribution with fixed bins and a fixed functional form for the scale [6]. Using these, obtaining the NNLO prediction for a given distribution for any desired PDF choice is reduced to $O$(seconds).

Further progress has been made at the stable-top level by combining NNLO-QCD with NLO-EW corrections [7, 8]. These were discussed in a dedicated talk [9]. We highlight here that particularly stark EW-effects are observed for the $p_{T,t}$ distribution, where the EW corrections tend to soften the tail, by up to $-25\%$ for $p_{T,t} \sim 3$ TeV. These effects are larger than the pure-QCD scale uncertainties and therefore will be important to include for the shape-modelling of this distribution, as the LHC experiments begin to measure the high tail with better statistical errors.

It is well-known that the differential $t\bar{t}$ cross section contains large logarithms in regions of soft-gluon phase space and that in order to maintain perturbatively well-behaved predictions it is often necessary to resum these logarithms. This has been the
subject of more than two decades of work, however, as reviewed in a separate talk [10], there has been recent progress on this front regarding the numerical implementation of soft-gluon resummation for boosted top-quark production. This is particularly relevant for the $M_{t\bar{t}}$ distribution where large logs $\sim \log(m_t/M_{t\bar{t}})$ are present in the tail. In the tail region, the resummation reduces the dependence on the choice of dynamical scale. There is ongoing work to consistently match the NNLO fixed order results with these soft-gluon resummed cross sections.

NNLO results for distributions, including fastNLO tables and EW-rescaling factors are collected at http://www.precision.hep.phy.cam.ac.uk/results/.

1.1 Application: constraining PDFs with distributions

One of the lasting impacts of the top-quark physics program at the LHC will be the precise ways in which it can probe QCD. Perhaps the most important of these will be providing non-trivial constraints on PDFs. Extensive investigations of the constraints provided by the inclusive $t\bar{t}$ cross section can be found for example, in ref.s [11, 12].

A study exploring the extent to which the ATLAS and CMS 8 TeV differential $t\bar{t}$ measurements, together with differential NNLO predictions, can provide constraints beyond those provided by $t\bar{t}$ cross section measurements, was presented in ref. [13]. The picture is promising, particularly for the gluon PDF at high-$x$, where including the differential top data tends to reduce the PDF-uncertainty bands by better than a factor of 2. The study indicates that in this region, top data can be competitive with inclusive-jet data, in terms of the potential constraints they can provide.

Another outcome of this study was the recommendation of the $y_t$ and $y_{t\bar{t}}$ normalized distributions from ATLAS and CMS respectively, as the differential 8 TeV measurements that are most suitable for use in a PDF fit. The reasons behind this seemingly eclectic choice were that for this combination of observables one can achieve good agreement between theoretical predictions and the measurements by both experiments, as well as good constraints on the PDFs. These distributions are also less sensitive to ‘typical’ beyond-the-SM effects, which may show up as enhancements in the tails of $p_{T,t}$ and $M_{t\bar{t}}$, as well as to the uncertainty on the value of $m_t$. Unfortunately, it was not possible to use multiple distributions from the same experiment in the fitting, since experimental and theoretical systematics correlating distributions are not available. Once these correlations are known, this is certainly one aspect where there is potential to achieve further constraining power from measurements.

2 Precision for top-pair production and decay

2.1 Why bother with the decay?

The presence of top quarks is always inferred via measurements of their decay products in phase space that is constrained by experimental detector geometries. In order
to be compared against theoretical predictions for stable top quarks, this means that experimental measurements must (a) be extrapolated from the fiducial regions to the full phase space, and (b) be modelled from the particle-level back to some definition of ‘top partons.’ Because these extrapolations are performed using Parton Shower Monte Carlos (MCs), which include the top decay formally only at LO, an estimate of the systematic uncertainty introduced on the shape and normalization of such measurements, due to missing higher order corrections in the decay, is currently not possible. Since different MCs may have different parton shower algorithms and different methods of attaching the decay to the production subprocess, the very definition of a ‘top parton,’ in the way this modelling is currently done, seems likely to be MC-dependent. To fully exploit the recent advances in precision at the level of stable top quarks, these observations must be better understood, and the underlying systematics better controlled.

Measurements presented at the level of the top-quark decay products can be compared without such extrapolations (and hence without this missing systematic uncertainty) to theoretical predictions. In this section, recent work on including higher-order corrections to the decay subprocess as well as on including finite-width and non-resonant effects is summarized. What emerges is a consistent picture; that higher-order corrections to the decay (particularly NLO) are generically important to describe regions of phase space constrained by experimental selection cuts.

2.2 High precision production and decay at fixed order

The decay of the top quark is included in theoretical predictions either by treating the decaying top as strictly onshell – the narrow-width approximation (NWA) – or in offshell approaches, typically by using the complex-mass renormalization scheme.

In the NWA top-pair production was until recently known up to NLO [14, 15, 16]. In these works the importance of including NLO corrections in the top-quark decay, was already pointed out. In recent work [17], fully-differential predictions containing an approximation to NNLO in production (with decays included up to NLO) [18] were combined with the differential decay at NNLO [19], providing the most precise predictions at fixed-order, to date, for the di-lepton channel at 8 TeV. The best predictions are dubbed ˆNNLO to distinguish the fact that the production includes an approximation to the exact NNLO. In fig. 1 these new predictions are compared to recently published ATLAS differential measurements [20] in a fiducial region defined through selection cuts on charged leptons. There are two main messages to take from fig. 1, namely that the corrections beyond NLO are significant ∼ 10% and result in smaller scale variation uncertainties, and also that including them improves the comparison of theory to measurement.

Ref. [17] additionally highlighted that the size of higher-order corrections in the decay can depend on selection cuts. In particular, the size of these corrections and
Figure 1: Distributions of the azimuthal angle between the charge leptons, $\Delta \Phi(l^+, l^-)$ and the invariant mass, $M(l^+, l^-)$, and transverse momentum, $p_T(l^+, l^-)$, of the lepton-pair. The plots show the ATLAS measurements [20] as well as the LO, NLO and $\hat{\text{NNLO}}$ predictions normalized to $\hat{\text{NNLO}}$. The errorbars and shaded bands indicate the experimental and theoretical uncertainties respectively. Comparisons to similar measurements by CMS [21] have been made in [17].

in particular the NLO, can be significant, $O(-10\%)$, when cuts are placed on $b$-jets. This indicates that including the decay at LO alone is not sufficient to generically describe fiducial regions well. We point out that this is not an academic observation – effects such as these from the decay will propagate through to measurements of the inclusive $t\bar{t}$ cross section, since the latter relies on extrapolations from measurements in fiducial regions.

While the NWA is an excellent approximation for a large class of observables, by construction it does not capture finite-top-width effects and the effects of non-resonant contributions. As such, certain regions of phase-space, crucial for example the $W$-$b$-jet invariant-mass and the edge of the lepton-$b$-jet invariant mass, $M_{lb}$, are poorly described by the NWA. Furthermore, these effects are not only important to include for measurements of top-pair production, but additionally play a role in accurately describing top-quark backgrounds to processes such as $H \rightarrow WW^{(*)}$ [22, 23]. The past years have seen a serious effort to include these effects, up to NLO for the process of $t\bar{t}$ in the dilepton channel [24, 25, 26, 27, 28, 22, 23]. Very recently the hugely complex fully-offshell calculations of $t\bar{t}$ in the lepton+jets channel [29] and of $t\bar{t}j$ [30, 31] at NLO-QCD have been completed.

An in-depth discussion of the findings of all these works is beyond the scope of these proceedings. What we emphasise here is that, in support of the discussion above, where the NWA is a good approximation, this is only generally the case when corrections to the decay subprocesses are also included. This is not only found for $t\bar{t}$, but also in the recent NWA vs offshell comparison in ref. [32] for $t\bar{t}j$ where again it was
shown that including NLO production, but not decay, corrections has a detrimental effect to the quality of description the NWA provides.

Finally, NLO-EW corrections are now known for offshell $t\bar{t}$ production in the di-lepton channel [33]. As expected, at the inclusive level, EW corrections are found to be small, below a per-cent. However, as with onshell $t\bar{t}$, significant negative EW corrections are observed in the high-$p_T$ tails of the leptons or $b$-jets, reaching $-15\%$ for values of $p_T \approx 800$ GeV.

2.3 NLO+PS for offshell $t\bar{t}$

Translating the progress in including the decay at fixed order, to predictions matched to parton showers has not been straightforward. This required the development of a modified NLO+PS matching scheme [34], and for $t\bar{t}$ this was subsequently applied to the offshell process in the di-lepton channel [35]. This work and ongoing developments are discussed in more detail in these proceedings [37]. In the spirit of the rest of this section, we would like to highlight one aspect, namely the comparisons between available MCs with different underlying approximations for the hard matrix elements. Unsurprisingly, the MC with underlying NLO production-and-decay NWA matrix elements approximates the fully-offshell MC better than the commonly-used MC with an underlying $t\bar{t}$ with NLO corrections in production. This further cements the pattern that decay corrections are a crucial ingredient to accurately model top-quark final states in fiducial regions. We also point to ongoing work within the HW7 collaboration on including full NLO top-decays in their shower framework [36]. It is important to understand whether, compared to using MCs which use stable $t\bar{t}$ matrix elements, this improved perturbative modelling has an impact on top-quark mass extractions. This was discussed in a dedicated talk at this conference [38].

As a final remark, as discussed in the sec. 1, the theoretical description of stable $t\bar{t}$ production is at a very high level of precision and sophistication. This has the potential for hugely impactful applications, such as PDF-extractions. However, to fully exploit these theoretical predictions it is vital to understand the dynamics of top-quark final states and systematically study the systematics associated with extrapolating from particle to parton level. Sec. 2 highlighted that the tools to do this at high precision are already becoming available, and particular importance is placed on the inclusion of corrections to the decay as well as to the production subprocesses.

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