Summary of the Topical Workshop on Top Quark Differential Distributions 2014

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Abstract. We summarise the Topical Workshop on Top Quark Differential Distributions 2014, which took place in Cannes immediately before the annual Top2014 conference. The workshop was motivated by the availability of top quark differential distributions at NNLO and the forthcoming LHC 13 TeV data. The main goal of the workshop was to explore the impact of improved calculations of top quark production on precision LHC measurements, PDF determinations and searches for physics beyond the Standard Model, as well as finding ways in which the high precision data from ATLAS, CMS and LHCb can be used to further refine theoretical predictions for top production.

1. Introduction
The forthcoming availability of fully differential results for top quark production at NNLO, together with the upcoming restart of the LHC at 13 TeV, prompted us to organise a workshop centred around theoretical aspects of precision top physics. The workshop was held 26–28 September 2014 in Cannes, i.e. it immediately preceded the annual Top2014 conference.

The workshop brought together a group of theory experts working on top quark physics and closely related subjects such as parton distribution functions, parton showers and soft gluon resummation. The presence of experts in BSM physics involving top quarks was essential, as was the participation of top quark experts from ATLAS, CMS and LHCb.

The main goal of the workshop was to explore the phenomenological implications of the ongoing progress in precision calculations for top quark production, both in terms of fully differential NNLO results and in terms of realistic description of final states provided by NLO calculations matched to parton showers.

The main questions that were discussed included: which top quark differential distributions are theoretically and experimentally more interesting; what is the impact of present and future top quark data on PDF fits; progress in realistic final states with decaying top quarks; finite top quark width corrections and matching to parton showers; the role of soft and collinear
resummation; and how precision calculations in top quark physics can improve the reach of searches for BSM physics at the LHC. Some of the most relevant recent theoretical developments are schematically illustrated in Fig. 1. In addition, we convened a dedicated session on how precision theory developments can be used to improve ongoing and future measurements with top quarks at the LHC.

![Figure 1. Schematic illustration of recent theoretical progress in theory calculations of top quark production in complementary directions: NNLO calculations, merging of NLO+PS samples of different multiplicities and results beyond stable tops (courtesy of M. Schultze).](image)

In the following, we present a concise summary of the discussions that took place during the workshop. The complete agenda, with presentation slides, is available at the workshop webpage: [http://indico.cern.ch/e/top-differential-distributions-2014](http://indico.cern.ch/e/top-differential-distributions-2014)

Given the space limitation, we are unfortunately unable to cover in full detail everything that was discussed at the workshop.

2. **Top quark production and NNLO calculations**

Recent progress in techniques for NNLO QCD calculations [1-8] has led in the last few years to a dramatic increase in the availability of NNLO calculations for hadron collider processes with complex final states. The NNLO result for the total top quark pair production cross-section has been available for a while [9-12]. During the workshop, preliminary results on the extension of this calculation to differential distributions were presented. These NNLO results are consistent with the NLO scale variation estimate, and their inclusion leads to a significant reduction of the theory uncertainties. This is illustrated in Fig. 2 where we show the invariant mass distribution $M_{tt}$ for top quark pair production at the Tevatron at NNLO. These results have also recently been used to compute the corrections to the forward-backward asymmetry at the Tevatron in NNLO QCD [13], showing that perturbative corrections increase the absolute Standard Model (SM) value of the asymmetry by about 2%, thus improving the agreement of SM prediction with the measurements from CDF and DØ Collaborations.

Related techniques have also lead to the recent computation of the NNLO corrections to single top production [14], which was also discussed at the workshop. As an illustrative result,
in Fig. 2 we show the cross-section as a function of the cut in the $p_T$ of the top quark, for the LHC 7 TeV. For this observable the NNLO corrections also lead to a substantial improvement in the perturbative expansion. Another central process of the LHC program is dijet production, due to its relevance for precision Standard Model measurements, PDF determinations and new physics searches. Recent results towards the full NNLO calculation \cite{13} were presented in the workshop. Several other important LHC processes have also become available at NNLO, see for instance \cite{16,18}. More processes/observables will be computed in the near future, underscoring the trend towards NNLO QCD becoming the standard for precision phenomenology at the LHC. However, work is still required to be able to use these calculations with realistic final states, as we report below.

3. Top pair production with realistic final states

The current state-of-the-art simulations of top quark production and decay utilize merged NLO calculations matched to parton showers. Various proposals for NLO merging have been introduced recently, including the FxFx merging \cite{19}, the UNLOPS procedure \cite{20} and the MEPS@NLO \cite{21} method among others. The implications of some of these updated calculations for top quark pair production were discussed at the workshop. As a representative result, in Fig. 3 we show the $H_T$ distribution in $t\bar{t}$+jets events at LHC 7 TeV within the MEPS@NLO approach, compared to predictions based on samples with exclusive jet multiplicities. Clearly, the individual multiplicities contribute differently depending on the value of $H_T$, while the NLO merged sample could be applied to the full phase space. There has also been important progress in the matching of NNLO calculations to parton showers \cite{22,23}, though still quite some work is needed to be able to apply these methods to top quark production. Some preliminary results for matching to the Nagy-Soper parton shower with quantum interference \cite{24} at NLO have been presented \cite{25}. Though they are still restricted to on-shell top-quarks, work in the direction of realistic final states is under way.

Another important application of the recent progress in top physics calculations is to precision top quark mass determination. For instance, the top quark mass $m_t$ can be extracted from template fits to the $m_{t\bar{t}}$ invariant mass distribution with good experimental precision. However, unless the NLO corrections to the $pp \rightarrow WbWb$ process are accounted for, theoretical uncertainties due to missing higher orders will dominate the total $m_t$ uncertainty. In Fig. 4 we show the $m_{t\bar{t}}$ distribution computed at NLO at the LHC 7 TeV, for different values of the
top quark mass [26]. Similar conclusions, of course, also apply to many other differential distributions whose accurate prediction is an important ingredient in new physics searches.

4. Experimental issues

One of the workshop’s main objectives was to initiate a discussion about how ongoing theoretical progress and current and future experimental measurements can improve each other. Some of the discussed issues were triggers, pile-up subtraction, theory uncertainties that affect the selection efficiency, improvements in Monte Carlo simulations, definitions of physical observables and top quark reconstruction.

In this context, one of the most important topics for discussion was how the availability of NNLO top quark differential distributions, as well as improvements in the description of realistic final states at NLO, can help in reducing various extrapolation errors. Since state-of-the-art MC simulations are now based on NLO calculations that are merged for different topologies and matched to parton showers, it will be essential for precision top physics at LHC Run II to adopt these tools as standard. The availability of differential predictions, either NNLO with stable tops or NLO+PS with realistic final states, represents a strong motivation for all LHC measurements to be provided directly in the fiducial region, and that comparisons with theory are performed at this level. Such a “meeting point” between theory and experiment avoids inconsistencies in various comparisons or, equivalently, the unnecessary increase of theoretical uncertainties in the extrapolation to the full phase space. Of course inclusive measurements are also important in many cases, for example in comparisons with other experiments, but the original information in the fiducial region should also be available. In this respect, an important improvement in realistic analyses would be the extension of the NNLO calculation to the case of unstable tops.

An important ingredient in top production predictions made with MC event generators is the tune for the semi-hard and soft physics. Such tunes are typically performed with LO Monte Carlos (see for example the recent Monash 2013 Tune [27] of Pythia8 [28]) and then applied to NLO+PS generators. Given the importance of non-perturbative and semi-hard physics in various top quark measurements, it would be of utmost importance to produce dedicated new tunes for NLO generators that are able to describe simultaneously the hard, semi-hard and soft dynamics. Work along these lines is ongoing within the ATLAS and CMS collaborations, with the aim of obtaining dedicated NLO tunes that can then be applied to top physics at Run II.
Also discussed at the workshop was the possibility to present top measurements in terms of ratios of various cross-sections, in order to partially cancel some of the leading experimental and theoretical uncertainties. For instance, in early Run II data the LHC luminosity uncertainty could be substantial, and measurements of ratios like $\sigma(t\bar{t})/\sigma(Z)$ should allow to perform precision top quark physics already from the first months of data taking. Related proposals include ratios such as $\sigma(t\bar{b}b)/\sigma(t\bar{t}jj)$, which also provide stringent tests of MC event generators.

In addition, the ratios of top quark cross-sections between 13 TeV and 8 TeV provide a unique opportunity to constrain the gluon PDF with greatly reduced theory uncertainties from scale and $m_t$. The advantages of presenting the measurements of top quark differential distributions either with absolute normalization or normalized to the fiducial cross-section were also discussed. The consensus in the community is that the measurements should be presented both ways, i.e. if normalized measurements are published, the normalization factor should be provided as well. We recall that while for many analyses (for example searches) only an accurate measurement of the shape of the distribution is required, for others (in particular PDF analyses) the overall normalization provides precious additional information.

An important topic of the discussion was how to optimize the use of theoretical calculations when kinematical distributions are used to extract SM parameters such as $\alpha_S(M_Z)$ and $m_t$. For instance, CMS has extracted $\alpha_S(M_Z)$ from the inclusive $t\bar{t}$ cross-sections using the inclusive NNLO calculation \cite{29}, and it would be interesting to repeat the extraction from differential distributions. Concerning $m_t$ extractions, it became clear that it is essential to quantify the theory uncertainties from template fits of kinematical distributions; in particular NLO QCD should be the baseline for the computation of these templates (since LO calculations have large associated scale uncertainties). The use of double differential measurements could be beneficial here, provided one is not limited by statistics.

Finally, we discussed the fact that many searches that utilise measurements with top quarks in the final state are never unfolded and recast in terms of differential SM measurements. Translating searches into SM measurements could be very beneficial since, first, these allow new precision SM studies in extreme kinematical regions, and second, existing searches could easily be re-applied to different BSM scenarios.

5. Top quark data and PDF fits

At the LHC, top quark pairs are produced predominantly in the gluon-gluon initial state. Therefore, the recent improvements in the precision of both experimental measurements and theoretical calculations for top pair production strongly suggest that top data should provide useful constraints on the poorly-known large-$x$ gluon PDF, fully complementary to those obtained from other processes like jet production \cite{30} or photon production \cite{31,32}. Several studies have demonstrated that already at the level of inclusive cross-sections, available top quark data from ATLAS and CMS at 7 TeV and 8 TeV can provide important information on the gluon for $x \gtrsim 0.1$ \cite{33,35}. In addition, the feasibility of top quark production in the forward region by LHCb and the possible constraints in PDFs that such data would provide has also been quantified \cite{36}. Total cross-sections for $t\bar{t}$ production are already included in the recent NNPDF3.0 \cite{37} and MMHT14 \cite{38} global analysis, and are also available in the HERAFITTER open-source QCD fit framework \cite{39}.

The challenge now is to include the differential distributions of top pairs into global PDF analysis, using both the NNLO results and the recent availability of experimental measurements from ATLAS and CMS \cite{41,43}. In Fig. 4 we show the recent ATLAS 7 TeV differential measurements \cite{42} compared with different PDF sets: including these data into PDF fit will provide a handle on the large-$x$ gluon. In exploiting these measurements, it will be necessary to exploit the full power of recent theory calculation for these distributions, by combining fast interfaces to NLO calculations like AMCFAST \cite{44}, where the APPLGRID \cite{45} framework is used
to precompute MadGraph5_AMC@NLO [46] cross-sections, with the exact NNLO results. The same fast grid techniques could also be used to interface directly the very CPU-intensive NNLO calculations into PDF fits.

Another interesting observable that was discussed is the ratio of cross-sections between 13 TeV and 8 TeV [47], where many experimental and theory systematics cancels, providing a clean handle on PDFs. In the specific case of top quark production, the dependence on $m_t$ and on the scales is largely canceled in such a ratio, and theory uncertainties are mostly driven by differences in the gluon PDF. There are plans to perform these measurements by both ATLAS and CMS.

6. Approximate calculations for top pair production

In addition to exact NLO and NNLO calculations (both fixed order and matched to parton showers), we also discussed recent progress in approximate calculations in top quark production. In the case of the total cross-section, it has been recently proposed that it is possible to compute a robust estimate of yet unknown higher orders by using known results and exploiting the analytic properties of the partonic cross-sections in Mellin space. This technique has been successfully applied to Higgs production in gluon fusion [48], validated by available NNLO and partial N3LO results, and during the workshop we discussed its extension to an approximate N3LO $\sigma_{tt}$ calculation. An interesting related issue with approximate N3LO calculations is whether NNLO PDFs are sufficient, or if one really needs N3LO PDFs. This problem has been addressed in Ref. [49], finding that, interestingly, N3LO are not required for Higgs production, but that they are needed for $tt$ production. The reason for this is the fact that in top production a larger value of Bjorken-$x$ is probed that in Higgs production.

For differential distributions, approximate higher-order results can be obtained using techniques that stem from the resummation to all orders of terms enhanced in the soft and collinear limits. For instance, we discussed recent studies [50], where the renormalization group equations are used to derive approximate NNLO top quark differential distributions including semi-leptonic top quark decays computed in the narrow-width approximation. Related earlier studies include [51]. Previously, various approximations for the NNLO cross-section were also available [35,52].
7. BSM physics searches with top quarks

Top quarks are a crucial ingredient in essentially all scenarios for physics beyond the Standard Model. Their large Yukawa coupling suggest that they could play a major role in understanding the origin of the electroweak symmetry breaking mechanisms. In addition, the top quark contribution to quantum corrections to the Higgs boson mass is at the heart of the hierarchy problem, and naturalness-based solutions to this problem typically require the presence of top partners. It is therefore clear that searches for New Physics that involve top quarks in the final state are very important at the LHC.

In these searches, SM top quark production is typically the dominant background, and therefore the recent developments in precision calculations in top physics should certainly improve the reach of BSM searchers. For instance, the NNLO calculation of the total cross-section has been used in [53, 54] to improve the bounds on light stop quarks. Another example is provided by the fact that PDF uncertainties are one of the dominant modeling systematics in many searches, specially those that involve invariant masses at the TeV scale, and reducing these PDF errors, with top quark data in particular, would certainly improve the reach of these searches for New Physics [34]. Another important aspect that was emphasized during the workshop was that BSM searches typically probe top quark production in extreme kinematical regions, as illustrated schematically in Fig. 5. In particular, BSM searches require good understanding of top quark production in association with many jets or vector bosons, top quark pairs with TeV invariant masses and $t\bar{t}$ and single top production in association with substantial missing $E_T$.

![Extreme phase space $tt\bar{t}$: background for searches](Freya Blekman (IIHE,Vrije Universiteit Brussel)

Figure 5. Left plot: schematic illustration of the different extreme kinematical regions probed by BSM searches at the LHC with top quarks in the final state (courtesy of F. Blekman). Right plot: the reconstructed mass of a top quark pair $m_{t\bar{t}}$ in BSM scenarios where a heavy resonance $\rho$ decays into a $t\bar{t}$ pair (red histogram) or to other intermediate resonances which in turn decay to top quarks (blue and green histograms), from [55].

Another topic that was discussed is that recent LHC results strongly suggest that one should adopt new search strategies to look for New Physics. For instance, many searches look for heavy resonances coupled to top quarks by reconstructing the invariant mass of the $t\bar{t}$ pair and trying to identify a resonance on top of the SM background. However, in more realistic BSM scenarios this heavy resonance will instead decay to other BSM states which in turn decay to top quarks, and the peak in $t\bar{t}$ will disappear, see Fig. 5 for an illustration taken from [55]. This example shows that a cross-talk between BSM theorists, theorists involved in precision SM calculations and experimentalists is essential in order to to maximize the scientific output of the LHC data analyses.
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References

[1] Gehrmann-De Ridder A, Gehrmann T and Glover E N 2005 JHEP 0509 056 (Preprint hep-ph/0505111)
[2] Currie J, Glover E and Wells S 2013 JHEP 1304 066 (Preprint 1301.4693)
[3] Catani S and Grazzini M 2007 Phys.Rev.Lett. 98 222002 (Preprint hep-ph/0703012)
[4] Czakon M 2010 Phys.Lett. B693 259–268 (Preprint 1005.0274)
[5] Czakon M 2011 Nucl.Phys. B849 250–295 (Preprint 1101.0642)
[6] Czakon M and Heymes D 2014 (Preprint 1408.2500)
[7] Bärnreuther P, Czakon M and Fiedler P 2014 JHEP 1402 078 (Preprint 1312.6279)
[8] Henn J M 2013 Phys.Rev.Lett. 110 251601 (Preprint 1304.1806)
[9] Bärnreuther P, Czakon M and Mitov A 2012 (Preprint 1204.5201)
[10] Czakon M and Mitov A 2012 JHEP 1212 054 (Preprint 1207.2036)
[11] Czakon M and Mitov A 2013 JHEP 1301 080 (Preprint 1210.6852)
[12] Czakon M, Fiedler P and Mitov A 2013 Phys.Rev.Lett. 110 252004 (Preprint 1303.6254)
[13] Czakon M, Fiedler P and Mitov A 2014 (Preprint 1411.3007)
[14] Brucherseifer M, Caola F and Melnikov K 2014 Phys.Lett. B736 58–63 (Preprint 1404.7116)
[15] Gehrmann-De Ridder A, Gehrmann T, Glover E and Pires J 2013 Phys.Rev.Lett. 110 162003 (Preprint 1301.7310)
[16] Boughezal R, Caola F, Melnikov K, Petriello F and Schulze M 2013 JHEP 1306 072 (Preprint 1302.6216)
[17] Gehrmann T, Grazzini M, Kallweit S, Maierhfer P, von Manteuffel A et al. 2014 Phys.Rev.Lett. 113 212001 (Preprint 1408.5243)
[18] Cascioli F, Gehrmann T, Grazzini M, Kallweit S, Maierhfer P et al. 2014 Phys.Lett. B735 311–313 (Preprint 1405.2219)
[19] Frederix R and Frixione S 2012 JHEP 1212 061 (Preprint 1209.6215)
[20] Lonnblad L and Prestel S 2013 JHEP 1303 166 (Preprint 1211.7278)
[21] Hoeche S, Krauss F, Schonherr M and Siegert F 2013 JHEP 1304 027 (Preprint 1207.5050)
[22] Höche S, Li Y and Prestel S 2014 (Preprint 1407.3773)
[23] Karlberg A, Re E and Zanderighi G 2014 JHEP 1409 134 (Preprint 1407.2940)
[24] Nagy Z and Soper D E 2007 JHEP 0709 114 (Preprint 0706.0017)
[25] Czakon M, Hartanto H, Krauss M and Worek M in preparation
[26] Heinrich G, Maier A, Nisius R, Schlenk J and Winter J 2014 JHEP 1406 158 (Preprint 1312.6659)
[27] Skands P, Carrazza S and Rojo J 2014 European Physical Journal C 74 3024 (Preprint 1404.5630)
[28] Sjostrand T, Mrenna S and Skands P Z 2008 Comput. Phys. Commun. 178 852–867 (Preprint 0710.3820)
[29] Chatrchyan S et al. (CMS Collaboration) 2014 Phys.Lett. B728 496–517 (Preprint 1307.1907)
[30] Rojo J 2014 (Preprint 1401.7728)
[31] d’Enterria D and Rojo J 2012 Nucl.Phys. B860 311–338 (Preprint 1202.1762)
[32] Carminati L, Costa G, D’Enterria D, Koletsou I, Marchiori G et al. 2015 Europhys.Lett. 101 61002 (Preprint 1212.5511)
[33] Alekhn S, Bluemlein J and Moch S 2014 Phys.Rev. D89 054028 (Preprint 1310.3059)
[34] Czakon M, Mangano M L, Mitov A and Rojo J 2013 JHEP 1307 167 (Preprint 1303.7215)
[35] Beneke M, Falgari P, Klein S, Piclum J, Schwinn C et al. 2012 JHEP 1207 194 (Preprint 1206.2454)
[36] Gauld R 2014 JHEP 1402 126 (Preprint 1311.1810)
[37] Ball R D et al. (The NNPDF Collaboration) 2014 (Preprint 1410.8849)
[38] Harland-Lang L, Martin A, Motylinski P and Thorne R 2014 (Preprint 1412.3989)
[39] Alekhn S, Behnke O, Belov P, Borroni S, Botje M et al. 2014 (Preprint 1410.4412)
[40] Ball R D, Bertone V, Carrazza S, Deans C S, Del Debbio L et al. (NNPDF Collaboration) 2013 Nucl.Phys. B867 244–289 (Preprint 1207.1303)
[41] Chatrchyan S et al. (CMS Collaboration) 2013 Eur.Phys.J. C73 2339 (Preprint 1211.2220)
[42] Aad G et al. (ATLAS Collaboration) 2014 Phys.Rev. D90 072004 (Preprint 1407.0371)
[43] Aad G et al. (ATLAS Collaboration) 2013 Eur.Phys.J. C73 2261 (Preprint 1207.5644)
[44] Bertone V, Frederix R, Frixione S, Rojo J and Sutton M 2014 JHEP 1408 166 (Preprint 1406.7693)
[45] Carli T, Clements D, Cooper-Sarkar A, Gwenlan C, Salam G P et al. 2010 Eur.Phys.J. C66 503–524 (Preprint 0911.2985)
[46] Alwall J, Frederix R, Frixione S, Hirschi V, Maltoni F et al. 2014 JHEP 1407 079 (Preprint 1405.0301)
[47] Mangano M L and Rojo J 2012 JHEP 1208 010 (Preprint 1206.3557)
[48] Ball R D, Bonvini M, Forte S, Marzani S and Ridolfi G 2013 Nucl.Phys. B874 746–772 (Preprint 1303.3590)
[49] Forte S, Isgr A and Vita G 2014 Phys.Lett. B731 136–140 (Preprint 1312.6688)
[50] Broggio A, Papanastasiou A S and Signer A 2014 JHEP 1410 98 (Preprint 1407.2532)
[51] Ahrens V, Ferroglia A, Neubert M, Pecjak B D and Yang L L 2010 JHEP 1009 097 (Preprint 1003.5827)
[52] Cacciari M, Czakon M, Mangano M L, Mitov A and Nason P 2012 Phys.Lett. B710 612–622 (Preprint 1111.5869)
[53] Czakon M, Mitov A, Papucci M, Ruderman J T and Weiler A 2014 Phys.Rev.Lett. 113 201803 (Preprint 1407.1043)
[54] Aad G et al. (ATLAS Collaboration) 2014 Eur.Phys.J. C74 3109 (Preprint 1406.5375)
[55] Chala M, Juknevich J, Perez G and Santiago J 2014 (Preprint 1411.1771)