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Next-to-leading order QCD predictions for top-quark pair production with up to two jets merged with a parton shower

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ABSTRACT

We present differential cross sections for the production of top-quark pairs in conjunction with up to two jets, computed at next-to-leading order in perturbative QCD and consistently merged with a parton shower in the SHERPA+OPENLOOPS framework. Top quark decays including spin correlation effects are taken into account at leading order accuracy. The calculation yields a unified description of top-pair plus multi-jet production, and detailed results are presented for various key observables at the Large Hadron Collider. A large improvement with respect to the multi-jet merging approach at leading order is found for the total transverse energy spectrum, which plays a prominent role in searches for physics beyond the Standard Model.

The top quark as the heaviest particle in the Standard Model is believed to play a fundamental role in many new physics scenarios. In a large variety of measurements at the Large Hadron Collider (LHC), top-quark events form either part of the signal or contribute a significant background in Higgs boson studies and new physics searches. Top quarks are produced in abundance at the LHC, either in pairs or singly, and frequently in conjunction with several hard QCD jets. Some first measurements of both inclusive production cross sections and of important kinematic distributions have already been reported by the ATLAS and CMS experiments [1]. Top-quark pair production at hadron colliders suffers from large theoretical uncertainties at the leading order (LO) in perturbative QCD. These uncertainties grow rapidly with the number of additional jets and represent a serious limitation for searches based on multi-jet signatures. A number of precision calculations were completed recently, aimed at reducing these uncertainties: The inclusive production cross section has been determined at next-to-next-to-leading order (NNLO) in the perturbative expansion [2]. Parton-level predictions of top-quark pair production in association with up to two jets have been computed at the next-to-leading order (NLO) in the strong coupling [3], and NLO calculations for top-quark pair production in association with one jet [4] and with a bottom-quark pair [5] were matched to parton showers.

The need for increasingly accurate and realistic simulations of $t\bar{t}$+jets production calls for a combination of parton showering with NLO calculations up to the highest possible jet multiplicity. Addressing this need in this letter NLO matrix elements for the production of top-quark pairs in association with up to two jets are matched to the parton shower. Additionally, we also merge, for the first time, NLO matrix elements with lower jet multiplicities, i.e. we combine $t\bar{t}$, $t\bar{t}j$ and $t\bar{t}jj$, thereby extending previous results for $t\bar{t}+0$, 1 jets [6,7]. This provides a fully inclusive simulation, which simultaneously describes $t\bar{t}+0$, 1, 2 jet configurations at NLO accuracy supplemented by the resummation of large logarithmic corrections provided by the parton shower.

Parton shower simulations in conjunction with LO QCD calculations of the hard scattering process have been the de-facto standard for computing observables at hadron colliders for decades. Parton showers dress hard-scattering events with multiple emissions of QCD partons, thereby resumming large logarithmic corrections to all orders in perturbation theory. Being based on the collinear approximation, they lack however a proper description of jet production at high transverse momenta or at wide angular separation. The first techniques to remedy this deficiency were LO merging algorithms [8,9], which consistently combine a description of multiple hard-jet emissions through higher-order

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tree-level matrix elements with the resummation of large soft and collinear logarithms through the parton-shower. Another method to improve parton-shower simulations consists of matching them to a full NLO calculation for a given final state [10,11], which yields NLO accurate predictions for observables that are inclusive with respect to extra jet radiation. This method is however limited to improvements to first order in the strong coupling and therefore does not lead to an improved description of multiple jet production, unless it is supplemented with a suitable scale choice and Sudakov reweighting [12].

Recent theoretical developments have led to new methods that combine the complementary advantages of matching and merging, resulting in an NLO accurate description of final states with varying jet multiplicity [6,13,14]. One of these new NLO merging techniques, the MEPS@NLO method [13] is used in this publication. In this approach, NLO-matched simulations with increasing jet multiplicity are merged by vetoing emissions above a predefined hardness threshold, $Q_{\rm cut}$, denoted as merging scale. In analogy to LO merging, an optimal renormalization scale choice in presence of multiple jet emissions is defined, and the calculations with n hard, well separated jets are made exclusive by means of appropriate Sudakov form factors. The $\mathcal{O}(\alpha_s)$ corrections generated by this procedure are consistently subtracted in order to preserve both the fixed-order accuracy of the NLO calculations and the logarithmic accuracy of the parton shower [13–15]. This is a key improvement that cannot be obtained through separate S–MC@NLO simulations based on $t\bar{t}$, $t\bar{t}j$ and $t\bar{t}jj$ matrix elements. The parton-shower matching used in MEPS@NLO presents a modified version of the original MC@NLO algorithm [10], called S–MC@NLO. It is based on including the fully coherent soft radiation pattern for the first emission [16] by exponentiating dipole subtraction terms originally constructed for NLO calculations [17]. This is achieved through a reweighting technique, which allows the generation of non-probabilistic expressions as part of a Markov chain.

The MEPS@NLO simulation of $t\bar{t}+0$, 1, 2 jets presented in this letter merges multi-jet matrix elements at an unprecedented level of complexity. This is achieved by combining the event generator SHERPA [18] with OPENLOOPS [19], a fully automated one-loop generator based on a numerical recursion that allows the fast evaluation of scattering amplitudes with many external particles. For the numerically stable determination of both scalar and tensor integrals the COLLIER library [20] is employed, which implements the methods of [21]. The parton shower in SHERPA is based on Catani–Seymour subtraction [22]. The infrared subtraction is performed by the dipole method [17] automated in both the AMEGIC++ and COMIX modules of SHERPA [23,24], which also compute the tree-level amplitudes and evaluate the phase–space integrals. Top-quark decays are treated at LO including spin correlations based on $t\bar{t}$+jets Born matrix elements using spin density matrices [25,26]. Their kinematics are adjusted a posteriori according to a Breit–Wigner distribution using the top quark width as an input.

We simulate $t\bar{t}$+jets production at the 7 TeV LHC to be applicable to ongoing analyses. We use the MSTW 2008 NLO PDF set [27] and the corresponding strong coupling. Matrix elements are computed with massless b-quarks, but b-quark mass effects are consistently included in the parton shower. According to the CKKW prescription [9], the renormalization scale for $t\bar{t}+n$ jet contributions is defined to be the solution of $\alpha_s(\mu_{\rm R})^{2+n} = \alpha_s(\mu_{\rm core})^2 \prod \alpha_s(t_i)$, where the α_s terms associated with jet emissions are evaluated at the corresponding clustering scales t_i, while the scale associated with the $pp \to t\bar{t}$ core process is defined by $1/\mu_{\rm core}^2 = 1/s + 1/(m_t^2 - t) + 1/(m_t^2 - u)$. $\mu_{\rm core}$ is also used as factorization scale ($\mu_{\rm F}$) and as the parton-shower starting scale, μ_Q. The merging scale is set to $Q_{\rm cut} = 30$ GeV. To assess theoretical uncertainties we rescale $\mu_{\rm R}$ and $\mu_{\rm F}$ by factors of two, while μ_Q is varied by $\sqrt{2}$ and $Q_{\rm cut}$ is varied between 20 and 40 GeV. Additionally, intrinsic parton shower uncertainties are assessed by switching between the two recoil schemes detailed in [22,28]. The combined renormalization- and factorization-scale uncertainty is added in quadrature with the other variations to form the total theoretical uncertainty. Our results do not include the simulation of multiple parton scattering or hadronization. The publicly available version 2.1.0 of the SHERPA event generator is used, and analyses are performed with RIVET [29]. The OPENLOOPS program is publicly available at [30].

Table 1
Inclusive cross section and its uncertainties originating from a variation of μ_R and μ_F, μ_Q, $Q_{\rm cut}$ and the parton shower recoil scheme, in that order, as detailed in the text.

Method	$\sigma_{\rm incl}$
MEPS@NLO	$1.85^{+0.30+0.05+0.01+0.00}_{-0.31-0.04-0.03-0.00}$ pb
MEPS@LO	$1.11^{+0.55+0.05+0.01+0.02}_{-0.32-0.04-0.03-0.00}$ pb
S–MC@NLO	$1.85^{+0.26+0.00+0.00+0.00}_{-0.23-0.00-0.00-0.00}$ pb

To evaluate the quality of our multi-jet merged calculation the inclusive cross section and the size of its uncertainties stemming from the afore mentioned four different sources are examined in Table 1. As can be seen, the MEPS@NLO calculation reproduces the inclusive cross section of the S–MC@NLO calculation well. In each case, the uncertainties are dominated by the renormalization and factorization scale variations while the dependence on merging parameter $Q_{\rm cut}$ is minimal. This demonstrates that using a relatively small merging scale does not lead to a significant loss of accuracy within the MEPS@NLO framework. In this respect, let us remind that inclusive cross sections involve uncontrolled logarithms of the merging scale that are subleading with respect to the aimed NLO+NLL accuracy, but can become of order $\sqrt{\alpha_S}$ when the merging scale is as small as the location of the Sudakov peak [31], which is around 10 GeV in top-pair production. This observation, which is referred to as formal loss of NLO accuracy in [31], relies on an argument of purely formal nature, in the sense that the "uncontrolled" logarithms involve an unknown coefficient, which is generically assumed to be of order one. In practice, the fact that we observe a $Q_{\rm cut}$ dependence at the few percent level,[1] i.e. well below the NLO uncertainty associated with renormalization and factorization scale variations, suggests that the above mentioned coefficient is rather small in the case of MEPS@NLO merging for $t\bar{t}$+jets.

To further investigate the properties of the multi-jet merging Fig. 1 contrasts the variation of $Q_{\rm cut}$ with the combined uncertainty of the other three sources of uncertainties in a calculation where (only for this purpose) the final state tops are considered stable. As their missing decay kinematics do not introduce further jet activity the two observables found to be most sensitive to merging effects are the differential $0 \to 1$ and $1 \to 2$ $k_\perp$ jet resolutions ($R = 0.6$), defined on all final state QCD partons (except the stable top quarks). Short-comings of the merging would show up as kinks at $d_{i(i+1)} \sim Q_{\rm cut}$. Again, the dependence on $Q_{\rm cut}$ is found to be smaller than the dependence on the other three sources of uncertainties combined. The latter does not exceed the 20% level in the whole k_T spectrum, both for the first and for the second jet.

To perform a realistic analysis, we identify the top quarks through their full decay final state and select events containing

[1] Let us note that a standard method to quantify merging scale uncertainties does not exist to date, and our assessment depends on the choice of the variation range 20 GeV $< Q_{\rm cut} <$ 40 GeV. A possible systematic approach to assess merging uncertainties for the case of small merging scales was sketched in [32]. When applied to MEPS@NLO for $t\bar{t}$+jets, this method suggests that merging scale uncertainties remain below ten percent down to merging scales of the order of 10 GeV.

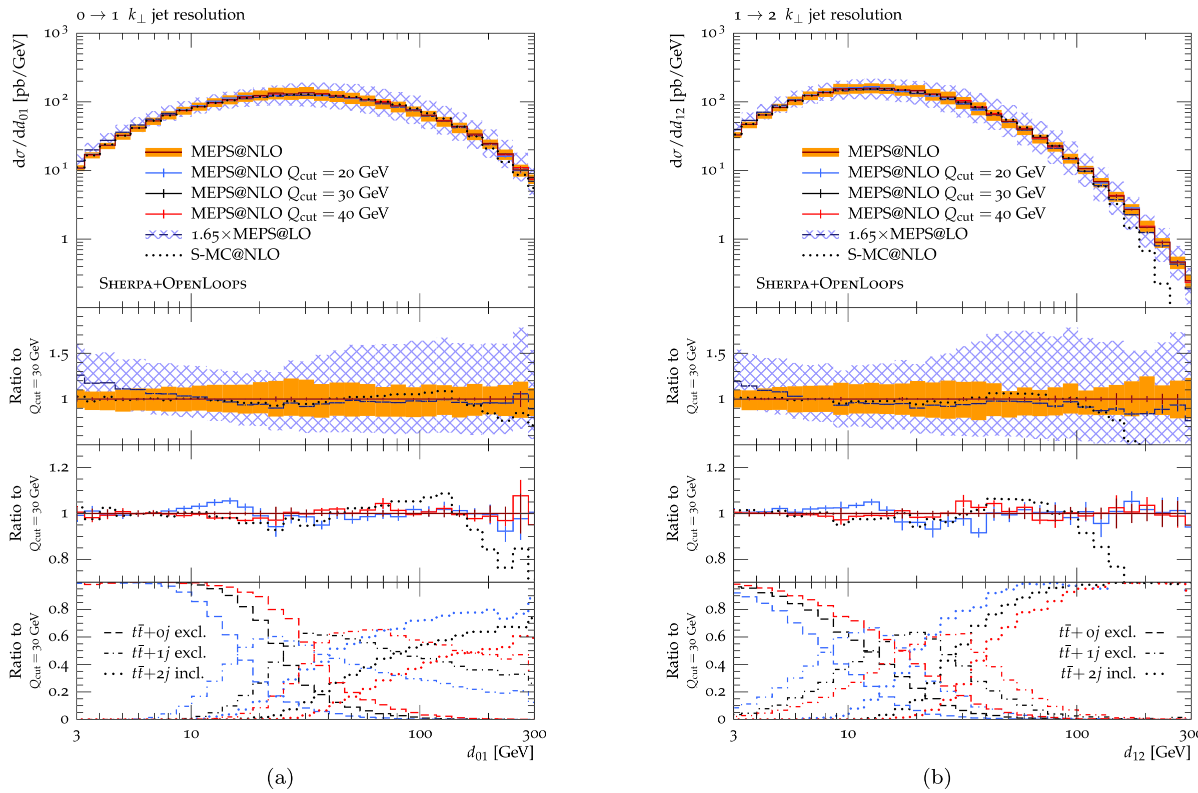

Fig. 1. Differential $k_\perp$ jet resolutions calculated from all partons (excluding top quarks) without any restrictions on their phase–space in a calculation with stable top final states. Solid lines indicate the MEPS@NLO prediction for three different values of the merging scale, Q_{cut} = 20 GeV (blue), 30 GeV (red), and 40 GeV (green). They are contrasted with the combined μ_R–μ_F–μ_Q-uncertainties of the central MEPS@NLO (orange full band) and MEPS@LO (blue hatched band) predictions. The center ratio highlights the Q_{cut}-variation only, while the lower ratio details the relative contributions of the individual matched $pp \to t\bar{t}+n$ jets calculations and how they vary with Q_{cut}. Statistical uncertainties are indicated by error bars. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

a positron and a muon with $p_T > 25$ GeV and $|\eta| < 2.5$, $E_T^{miss} > 30$ GeV is directly reconstructed from the neutrinos. Jets are defined using the anti-k_t algorithm [33] with $R = 0.4$. Ideal b-jet tagging is modeled based on the flavor of the jet constituent partons. Defining the sign of each b-jet according to its b-quark contents, exactly one b- and one anti-b-jet with $p_T > 25$ GeV and $|\eta| < 2.5$ are required.

Figs. 2–3 feature various observables that characterize multiple light-jet emissions in this $t\bar{t}$+jets event selection. Our best predictions, based on MEPS@NLO next-to-leading order merging, are compared to leading-order merged results (MEPS@LO), evaluated in an identical setting but rescaled by the inclusive K-factor of 1.65, and to an inclusive S–Mc@Nlo simulation for $pp \to t\bar{t}$. The latter two simulations represent the typical level of theoretical accuracy that is currently attained in the analysis of LHC data. It is important to point out that all differential observables discussed in the following are dominated by different exclusive jet multiplicity calculations in different regions, necessitating a multi-jet merged approach to achieve the highest accuracy throughout. This is exemplified by detailing the composition of the observables of Fig. 3 in terms of their input matched $pp \to t\bar{t}+n$ jets calculations in the lower ratio panel.

Uncertainty estimates are only shown for the merging approaches, while the S–Mc@Nlo matching approach does not allow for a realistic uncertainty estimate in multi-jet final states, whose description is entirely based on parton shower emissions.[2] In fact, the systematic reduction of theory uncertainties and the possibility to estimate them in a realistic way through scale variations is one of the main advantages of NLO multi-jet merging.

The multiplicity distribution of light-flavor jets is displayed for thresholds of $p_T > 40$, 60 and 80 GeV in Fig. 2(a). As compared to MEPS@LO, the uncertainty of the inclusive MEPS@NLO cross section within acceptance cuts is steeply reduced from 48% to 16%, while that for events with at least one light-flavor jet of $p_T > 40/60/80$ GeV is reduced from 64/65/66% to 18/18/18%. Particularly striking is the reduction in the uncertainty of the cross section of producing the $t\bar{t}$-pair in association with at least two jets: 79/81/82% to 19/19/19%. The Q_{cut} dependence of MEPS@NLO predictions is typically well below ten percent, while the combined theoretical uncertainty is dominated by renormalization scale variations.

The jet transverse momentum distributions are shown in Fig. 2(b). For the first two jets, MEPS@NLO predictions feature scale variations of about 20%. Apart from a slight increase in the hard region, which is in part due to statistical fluctuations, these uncertainties are rather independent of p_T. For the third jet the uncertainty tends to be similarly small as for the first two ones, especially at low transverse momenta. This is due to the fact that at relatively soft transverse momenta the production of the third jet proceeds predominantly via parton shower emissions on top of $t\bar{t}jj$ events, which are described in terms of NLO accurate matrix elements. Let us note that the resulting uncertainty is not fully realistic since, as pointed out above, uncertainties associated with parton shower emissions are not correctly reflected by the standard scale variation approach.

Fig. 3(a) shows the transverse momentum of the reconstructed top quark. Again we observe a strong reduction of uncertainties,

[2] At present there is no parton shower implementation that allows for consistent scale variations for the α_S terms associated with shower emissions. Moreover, it is not possible to assess the uncertainty related to the underlying soft and collinear approximations in the parton shower framework.

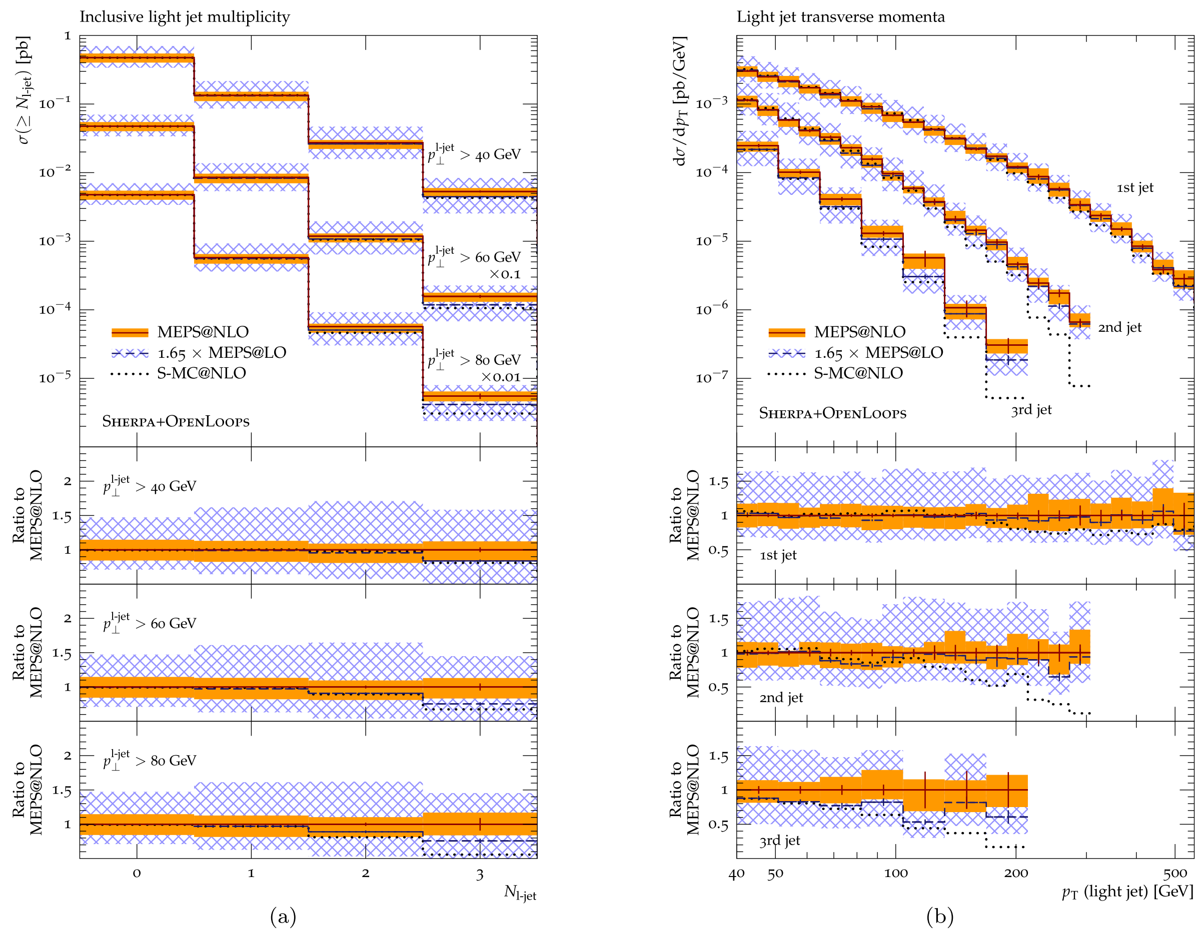

Fig. 2. Light-flavor jet multiplicity distribution (including c- but not b-jets) for transverse momentum thresholds of 40, 60 and 80 GeV (a) and transverse momentum spectra of the three leading light-flavor jets (b). Solid (red) lines indicate MEPs@NLO predictions, and the full (orange) band shows the corresponding total theoretical uncertainty. Dashed lines indicate MEPs@LO predictions, with the corresponding uncertainties shown as hatched (blue) bands. S–Mc@NLO predictions are shown as dotted histograms. Statistical uncertainties for each calculation are indicated by error bars. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

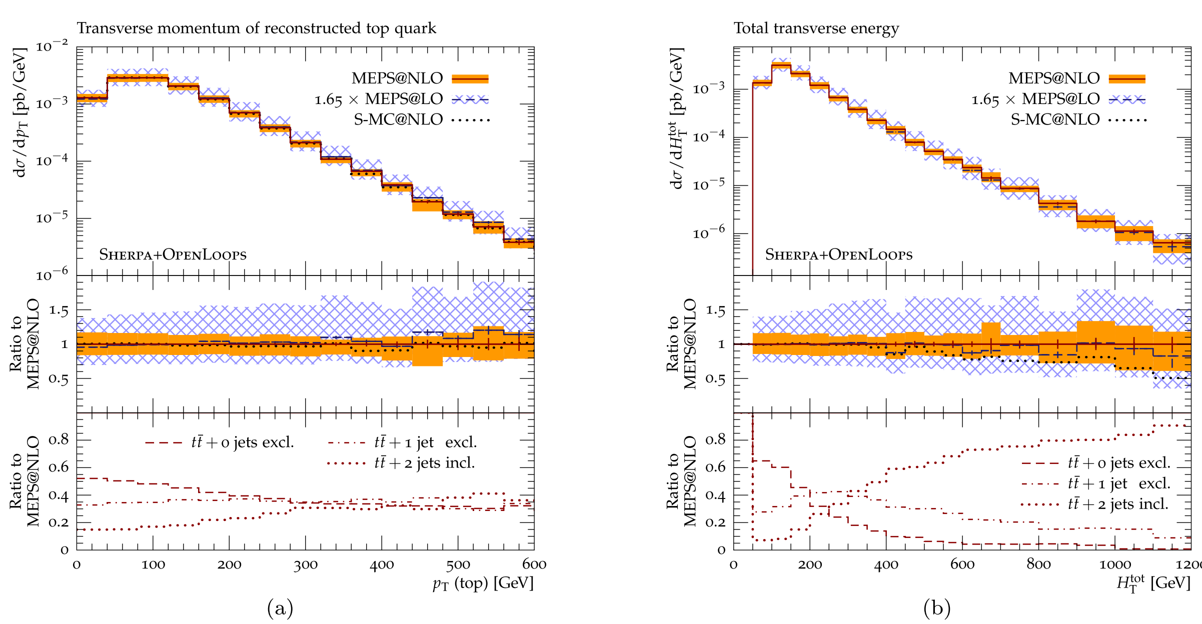

Fig. 3. Transverse momentum of the reconstructed top quark (a) and total transverse energy (b), see Fig. 2 for details. The lower ratio details the contributions of the individual matched $pp \to t\bar{t} + n$ jets calculations.

particularly at larger transverse momenta. This will significantly increase the precision in measurements of Standard Model $t\bar{t}$ production. Finally, we analyze the total transverse energy, $H_T^{tot} = \sum p_{T,b\text{-jet}} + \sum p_{T,l\text{-jet}} + \sum p_{T,lep} + E_T^{miss}$, of the full final state, where only light jets with $p_T > 40$ GeV are taken into account. This observable plays a key role in searches for new physics, and its high sensitivity to QCD radiation requires accurate modeling of multi-jet emissions. Fig. 3(b) shows a strong reduction of perturbative uncertainties, especially in the high-H_T^{tot} region. We believe that this makes MEPS@NLO the prime tool for estimating the theoretical precision of multi-jet merged predictions in $t\bar{t}$+jets backgrounds to new-physics searches. It is worth mentioning that for various observables in Figs. 1–2 the MEPS@NLO, MEPS@LO and S–MC@NLO predictions agree remarkably well. This encourages the use of the less compute-intensive LO merging technique for making nominal predictions including full detector simulation in experimental analyses. Purely matched calculations, such as S–MC@NLO are generally insufficient. This can be seen, for example, in the p_T-distributions, which are systematically low in the case of the 2nd and 3rd jet.

In summary we have presented the first unified simulation of top-quark pair production in association with up to two jets including top-quark decays and merging with the parton shower at the next-to-leading order in perturbative QCD. Residual theoretical uncertainties are reduced to the level of 20%. A wide range of experimental analyses based on multi-jet final states can strongly benefit from this improvement. In particular, as compared to simulations based on multi-jet merging at leading order, we observe a drastic reduction of uncertainties for large values of the total transverse energy, H_T^{tot}, which is highly relevant for new physics searches at the Large Hadron Collider.

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References

[1] G. Aad, et al., ATLAS Collaboration, Eur. Phys. J. C 73 (2013) 2261, arXiv:1207.5644 [hep-ex];
S. Chatrchyan, et al., CMS Collaboration, J. High Energy Phys. 1402 (2014) 024, arXiv:1312.7582 [hep-ex].

[2] M. Czakon, P. Fiedler, A. Mitov, Phys. Rev. Lett. 110 (2013) 252004, arXiv:1303.6254 [hep-ph].

[3] S. Dittmaier, P. Uwer, S. Weinzierl, Phys. Rev. Lett. 98 (2007) 262002, arXiv:hep-ph/0703120;
A. Bredenstein, A. Denner, S. Dittmaier, S. Pozzorini, Phys. Rev. Lett. 103 (2009) 012002, arXiv:0905.0110 [hep-ph];
A. Bredenstein, A. Denner, S. Dittmaier, S. Pozzorini, J. High Energy Phys. 1003 (2010) 021, arXiv:1001.4006 [hep-ph];
G. Bevilacqua, M. Czakon, C. Papadopoulos, R. Pittau, M. Worek, J. High Energy Phys. 0909 (2009) 109, arXiv:0907.4723 [hep-ph];
G. Bevilacqua, M. Czakon, C. Papadopoulos, M. Worek, Phys. Rev. Lett. 104 (2010) 162002, arXiv:1002.4009 [hep-ph];
G. Bevilacqua, M. Czakon, C. Papadopoulos, M. Worek, Phys. Rev. D 84 (2011) 114017, arXiv:1108.2851 [hep-ph].

[4] A. Kardos, C. Papadopoulos, Z. Trocsanyi, Phys. Lett. B 705 (2011) 76, arXiv:1101.2672 [hep-ph];
S. Alioli, S.-O. Moch, P. Uwer, J. High Energy Phys. 1201 (2012) 137, arXiv:1110.5251 [hep-ph].

[5] A. Kardos, Z. Trocsanyi, arXiv:1303.6291 [hep-ph], 2013;
F. Cascioli, P. Maierhöfer, N. Moretti, S. Pozzorini, F. Siegert, arXiv:1309.5912 [hep-ph], 2013.

[6] R. Frederix, S. Frixione, J. High Energy Phys. 1212 (2012) 061, arXiv:1209.6215 [hep-ph].

[7] S. Höche, J. Huang, G. Luisoni, M. Schönherr, J. Winter, Phys. Rev. D 88 (2013) 014040, arXiv:1306.2703 [hep-ph].

[8] S. Catani, F. Krauss, R. Kuhn, B.R. Webber, J. High Energy Phys. 11 (2001) 063, arXiv:hep-ph/0109231;
L. Lönnblad, J. High Energy Phys. 05 (2002) 046, arXiv:hep-ph/0112284;
F. Krauss, J. High Energy Phys. 0208 (2002) 015, arXiv:hep-ph/0205283;
M.L. Mangano, M. Moretti, R. Pittau, Nucl. Phys. B 632 (2002) 343, arXiv:hep-ph/0108069;
J. Alwall, et al., Eur. Phys. J. C 53 (2008) 473, arXiv:0706.2569 [hep-ph];
K. Hamilton, P. Richardson, J. Tully, J. High Energy Phys. 11 (2009) 038, arXiv:0905.3072 [hep-ph].

[9] S. Höche, F. Krauss, S. Schumann, F. Siegert, J. High Energy Phys. 05 (2009) 053, arXiv:0903.1219 [hep-ph].

[10] S. Frixione, B.R. Webber, J. High Energy Phys. 06 (2002) 029, arXiv:hep-ph/0204244;
S. Frixione, P. Nason, B.R. Webber, J. High Energy Phys. 08 (2003) 007, arXiv:hep-ph/0305252.

[11] P. Nason, J. High Energy Phys. 11 (2004) 040, arXiv:hep-ph/0409146;
S. Frixione, P. Nason, C. Oleari, J. High Energy Phys. 11 (2007) 070, arXiv:0709.2092 [hep-ph].

[12] K. Hamilton, P. Nason, G. Zanderighi, J. High Energy Phys. 10 (2012) 155, arXiv:1206.3572 [hep-ph].

[13] S. Höche, F. Krauss, M. Schönherr, F. Siegert, J. High Energy Phys. 1304 (2013) 027, arXiv:1207.5030 [hep-ph];
T. Gehrmann, S. Höche, F. Krauss, M. Schönherr, F. Siegert, J. High Energy Phys. 1301 (2013) 144, arXiv:1207.5031 [hep-ph].

[14] L. Lönnblad, S. Prestel, J. High Energy Phys. 1303 (2013) 166, arXiv:1211.7278 [hep-ph].

[15] N. Lavesson, L. Lönnblad, J. High Energy Phys. 12 (2008) 070, arXiv:0811.2912 [hep-ph].

[16] S. Höche, F. Krauss, M. Schönherr, F. Siegert, J. High Energy Phys. 09 (2012) 049, arXiv:1111.1220 [hep-ph];
S. Höche, F. Krauss, M. Schönherr, F. Siegert, Phys. Rev. Lett. 110 (2013) 052001, arXiv:1201.5882 [hep-ph];
S. Höche, M. Schönherr, Phys. Rev. D 86 (2012) 094042, arXiv:1208.2815 [hep-ph].

[17] S. Catani, M.H. Seymour, Nucl. Phys. B 485 (1997) 291, arXiv:hep-ph/9605323;
S. Catani, S. Dittmaier, M.H. Seymour, Z. Trocsanyi, Nucl. Phys. B 627 (2002) 189, arXiv:hep-ph/0201036.

[18] T. Gleisberg, S. Höche, F. Krauss, M. Schönherr, S. Schumann, F. Siegert, J. Winter, J. High Energy Phys. 02 (2009) 007, arXiv:0811.4622 [hep-ph].

[19] F. Cascioli, P. Maierhöfer, S. Pozzorini, Phys. Rev. Lett. 108 (2012) 111601, arXiv:1111.5206 [hep-ph].

[20] A. Denner, D. Dittmaier, L. Hofer, in preparation.

[21] A. Denner, S. Dittmaier, Nucl. Phys. B 658 (2003) 175, arXiv:hep-ph/0212259;
A. Denner, S. Dittmaier, Nucl. Phys. B 734 (2006) 62, arXiv:hep-ph/0509141;
A. Denner, S. Dittmaier, Nucl. Phys. B 844 (2011) 199.

[22] S. Schumann, F. Krauss, J. High Energy Phys. 03 (2008) 038, arXiv:0709.1027 [hep-ph].

[23] T. Gleisberg, F. Krauss, Eur. Phys. J. C 53 (2008) 501, arXiv:0709.2881 [hep-ph].

[24] T. Gleisberg, S. Höche, J. High Energy Phys. 12 (2008) 039, arXiv:0808.3674 [hep-ph].

[25] P. Richardson, J. High Energy Phys. 11 (2001) 029, arXiv:hep-ph/0110108.

[26] S. Höche, S. Kuttimalai, S. Schumann, F. Siegert, Eur. Phys. J. C 75 (2015) 135, arXiv:1412.6478 [hep-ph].

[27] A.D. Martin, W.J. Stirling, R.S. Thorne, G. Watt, Eur. Phys. J. C 63 (2009) 189, arXiv:0901.0002 [hep-ph].

[28] S. Höche, S. Schumann, F. Siegert, Phys. Rev. D 81 (2010) 034026, arXiv:0912.3501 [hep-ph].

[29] A. Buckley, et al., Comput. Phys. Commun. 184 (2013) 2803, arXiv:1003.0694 [hep-ph].

[30] F. Cascioli, J. Lindert, P. Maierhöfer, S. Pozzorini, The OPENLOOPS one-loop generator, publicly available at http://openloops.hepforge.org.

[31] K. Hamilton, P. Nason, C. Oleari, G. Zanderighi, J. High Energy Phys. 1305 (2013) 082, arXiv:1212.4504.

[32] Talk by S. Pozzorini at the "Higgs (N)NLO MC and Tools Workshop for LHC RUN-2", https://indico.cern.ch/event/345455, see pp. 22–24.

[33] M. Cacciari, G.P. Salam, G. Soyez, J. High Energy Phys. 0804 (2008) 063, arXiv:0802.1189 [hep-ph].

[34] L. Bauerdick, et al., Open Science Grid, J. Phys. Conf. Ser. 396 (2012) 042048.