PROCEEDINGS OF SCIENCE

B-hadron production in NNLO QCD: application to LHC $t\bar{t}$ events with leptonic decays

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The fragmentation of partons to hadrons has been implemented for the first time in a general framework for the computation of cross sections at next-to-next-to-leading order (NNLO) in QCD. I will present the first application of this tool to top-quark pair production in association with a bottom-flavoured hadron. I will also discuss recent efforts to include the decay of the B-hadron to either a J/ψ meson or a muon.

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1. Introduction

Precisely measuring the mass of the top quark has been the goal of many measurements since the discovery of the top quark almost three decades ago. Of special interest have been studies involving B-hadrons originating from the top-quark decay [1–4]. Such studies have demonstrated that the kinematics of the B-hadron significantly depends on the value of the top-quark mass and that measurements of certain observables can be used to extract the value of the top-quark mass with great precision.

However, all of those past studies were performed at next-to-leading order (NLO) in QCD. As measurements have become progressively more precise over the years, it has become increasingly desirable to increase the precision of such theory predictions by including the NNLO corrections. Fully differential descriptions of the production and decay of top-quark pairs at the LHC with NNLO precision first became available a few years ago [5]. However, that calculation was performed at the level of partons, studying b-jets rather than B-hadrons.

Any perturbative calculation at the parton level can be turned into a calculation for the production of a hadron using the fragmentation function formalism [6]. Within this formalism, the cross section for the production of a hadron is factorised into a convolution of the partonic cross section and a fragmentation function. The fragmentation function describes the transition from a parton to a hadron. This is in full analogy to the way parton distribution functions (PDFs) are used to describe the transition from hadrons to partons in the initial state. Fragmentation has been implemented for the first time in a general code for the computation of NNLO QCD cross sections in ref. [7]. This makes it possible to study, for the first time, top-quark pair production and decay in association with a B-hadron at the LHC at NNLO in QCD. While this application is indeed what is presented here, the software is completely general and able to compute the NNLO-accurate cross sections for any process involving any final-state hadron.

Central to predictions involving fragmentation are the fragmentation functions. They are inherently non-perturbative objects and are obtained from fits to data, typically data from lepton colliders. For consistency, the theory predictions used for this fit have to be at least of the same perturbative order as the calculation in which they are subsequently employed. No fits consistent with our approach were available in the literature, so in ref. [8] we performed such a fit ourselves. This resolved a minor inconsistency in the calculations of ref. [7], where fragmentation functions extracted using either a NLO computation [9] or a NNLO computation within a different approach [10] were used. While such an inconsistency leads to only small numerical differences, as was tested in ref. [7], using a fully consistent set of fragmentation functions is vital to achieving the desired theoretical precision.

From the experimental side, the precision of the extracted value of the top-quark mass can be significantly improved if the decay of the B-hadron is incorporated into the theory predictions. This is because fully reconstructing a B-hadron is difficult in practice and can be achieved in only a small fraction of all events. If the theory predictions can include a description of the decay of the B-hadron to a specific descendent particle, then only this descendant will need to be reconstructed in an experiment. A novel approach to describing the decay of a hadron within the fragmentation function formalism is described in ref. [8]. I will present some of the differential distributions involving the decay products of B-hadrons.

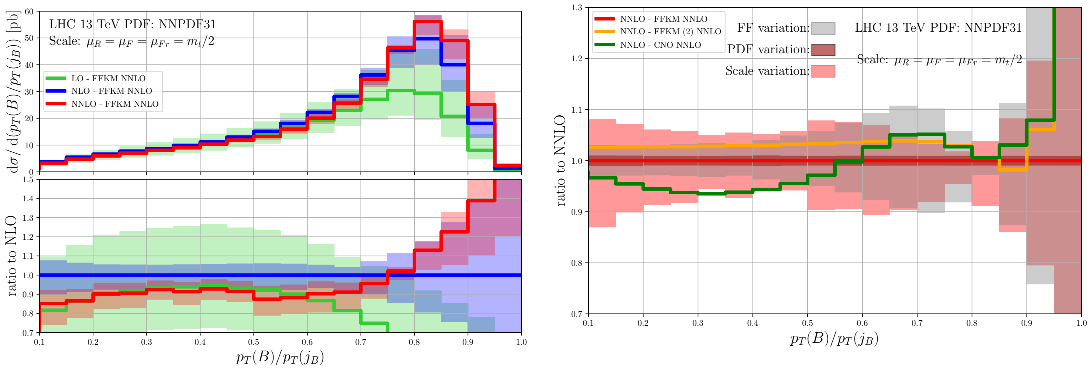

Figure 1: Left: the distribution of $p_T(B)/p_T(J_B)$, the ratio of the transverse momenta of the B-hadron and the jet that contains it, at LO (green), NLO (blue) and NNLO (red). Right: a comparison of the sizes of different uncertainties.

2. Results

B-hadron fragmentation functions are typically fitted to data collected at e^+e^- colliders [9, 11–14]. Indeed, the fit presented in ref. [8] is based on data from the ALEPH [15], DELPHI [16], OPAL [17] and SLD [18] collaborations. One of the observables studied in ref. [7] is particularly sensitive to the shape of the fragmentation function, potentially making it useful for extracting the fragmentation function from LHC data. This observable is the ratio of the transverse momentum of the B-hadron to the transverse momentum of the jet that contains the B-hadron, $p_T(B)/p_T(J_B)$.

The distribution of this observable is shown in fig. 1. The jet is clustered using the anti-k_T algorithm using $R = 0.8$. The only phase space cuts applied to the calculation of this distribution are $p_T(B) > 10$ GeV and $|\eta(B)| < 2.4$. For the central prediction, the renormalisation scale μ_R, factorisation scale μ_F and fragmentation scale μ_{Fr} were set to $\mu_R = \mu_F = \mu_{Fr} = m_t/2$. The scale bands are obtained by varying these three scales independently by a factor of 2 around their central values, subject to the constraint $1/2 \le \mu_i/\mu_j \le 2$, where $i, j \in \{R, F, Fr\}$.

Near the peak of the distribution, the NNLO curve (red) is consistent with the NLO one (blue) within the scale uncertainties. The size of the scale uncertainties is likewise reduced at NNLO compared to NLO. Away from the peak, however, slow perturbative convergence is observed. This effect is exacerbated for smaller values of R, suggesting that the cause is out-of-cone radiation. In the right panel of fig. 1, the NNLO scale uncertainty, fragmentation function uncertainty and PDF uncertainty are compared. While the scale uncertainty is similar in magnitude to the fragmentation function uncertainty, the PDF uncertainty is much smaller. Varying the PDF also does not change the shape of the spectrum. This suggests that B-hadron fragmentation functions could be extracted from LHC data in a PDF-insensitive manner.

Of particular interest for top-quark mass extractions is the invariant mass of the B-hadron or its descendant with the lepton from the decay of the intermediate W-boson in semi-leptonic top-quark decays. Ideally, the B-hadron is always paired with the lepton from the decay of the same top-quark. In practice, a good approximation is to compute the invariant mass for both leptons and choose the smaller invariant mass. This observable is referred to as $m(F\ell)_{\min}$, where F can be the B-hadron or one of its descendants.

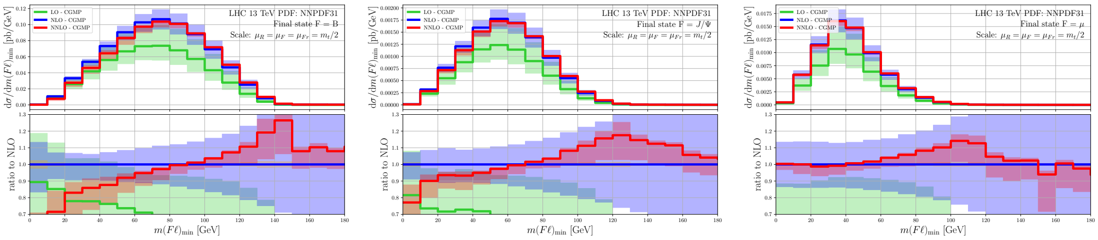

Figure 2: The invariant mass $m(F\ell)_{\text{min}}$ at LO (green), NLO (blue) and NNLO (red). Shown are the results for $F = B$ (left), $F = J/\psi$ (centre) and $F = \mu$ (right). The green, blue and red bands correspond to the 15-point scale uncertainty bands, while the yellow bands indicate the fragmentation function uncertainty.

Shown in fig. 2 is the distribution of $m(F\ell)_{\text{min}}$ for B-hadrons (left), as well as for J/ψ mesons (centre) and muons (right) coming from the decay of a B-hadron. These results were computed using the following event selection requirements:

- $p_T(\ell) > 25$ GeV, $|\eta(\ell)| < 2.5$,
- at least 2 anti-k_T jets ($R = 0.4$) with $p_T(j) > 25$ GeV and $|\eta(j)| < 2.5$,
- $\Delta R(\ell, j) > 0.4$,
- $p_T(F) > 8$ GeV and $|\eta(F)| < 2.5$, F must be part of one jet .

The scales were again chosen as for fig. 1. Unlike fig. 1, these results use the new fragmentation functions fitted in ref. [8].

The NNLO curve (red) is always consistent with the NLO result (blue) within the scale uncertainties, except for the case of B-hadrons, where the NNLO corrections are large at small invariant masses. Other results in ref. [8] suggest this effect is caused by the specific selection cuts used to produce fig. 2. Similarly, the scale uncertainties are significantly reduced at NNLO compared to NLO, except for the same region of low invariant masses for $F = B$. The distribution for muons from B-hadron decays is especially stable, receiving only minor shape corrections at NNLO. The reduction of scale uncertainties is also largest for $F = \mu$.

The uncertainty on the fragmentation function is shown in fig. 2 as a yellow band around the NLO results. It is only barely visible, as the fragmentation function uncertainty is significantly smaller than the scale uncertainties, even at NNLO.

3. Conclusions

I have presented some of the results from the first calculations of top-quark pair production at the LHC in association with a B-hadron at NNLO in QCD. These results demonstrate the possibility of extracting fragmentation functions from LHC data in a manner which does not introduce a dependence on the choice of PDF. The results also significantly improve on the precision of previous studies of the process in the context of top-quark mass extractions.

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References

[1] A. Kharchilava, *Top mass determination in leptonic final states with J/ψ*, Phys. Lett. B **476**, 73-78 (2000) [arXiv:hep-ph/9912320].

[2] S. Biswas, K. Melnikov and M. Schulze, *Next-to-leading order QCD effects and the top quark mass measurements at the LHC*, JHEP **08**, 048 (2010) [arXiv:1006.0910].

[3] K. Agashe, R. Franceschini and D. Kim, *Simple "invariance" of two-body decay kinematics*, Phys. Rev. D **88**, no.5, 057701 (2013) [arXiv:1209.0772].

[4] K. Agashe, R. Franceschini, D. Kim and M. Schulze, *Top quark mass determination from the energy peaks of b-jets and B-hadrons at NLO QCD*, Eur. Phys. J. C **76**, no.11, 636 (2016) [arXiv:1603.03445].

[5] A. Behring, M. Czakon, A. Mitov, A. S. Papanastasiou and R. Poncelet, *Higher order corrections to spin correlations in top quark pair production at the LHC*, Phys. Rev. Lett. **123**, no.8, 082001 (2019) [arXiv:1901.05407].

[6] S. M. Berman, J. D. Bjorken and J. B. Kogut, *Inclusive Processes at High Transverse Momentum*, Phys. Rev. D **4**, 3388 (1971)

[7] M. Czakon, T. Generet, A. Mitov and R. Poncelet, *B-hadron production in NNLO QCD: application to LHC $t\bar{t}$ events with leptonic decays*, JHEP **10**, 216 (2021) [arXiv:2102.08267].

[8] M. Czakon, T. Generet, A. Mitov and R. Poncelet, *NNLO B-fragmentation fits and their application to $t\bar{t}$ production and decay at the LHC*, [arXiv:2210.06078].

[9] M. Cacciari, P. Nason and C. Oleari, *A Study of heavy flavored meson fragmentation functions in e+ e- annihilation*, JHEP **04**, 006 (2006) [arXiv:hep-ph/0510032].

[10] M. Fickinger, S. Fleming, C. Kim and E. Mereghetti, *Effective field theory approach to heavy quark fragmentation*, JHEP **11**, 095 (2016) [arXiv:1606.07737].

[11] G. Corcella and A. D. Mitov, *Bottom quark fragmentation in top quark decay*, Nucl. Phys. B **623**, 247-270 (2002) [arXiv:hep-ph/0110319].

[12] M. Cacciari, G. Corcella and A. D. Mitov, *Soft gluon resummation for bottom fragmentation in top quark decay*, JHEP **12**, 015 (2002) [arXiv:hep-ph/0209204].

[13] G. Corcella and V. Drollinger, *Bottom-quark fragmentation: Comparing results from tuned event generators and resummed calculations*, Nucl. Phys. B **730**, 82-102 (2005) [arXiv:hep-ph/0508013].

[14] B. A. Kniehl, G. Kramer, I. Schienbein and H. Spiesberger, *Finite-mass effects on inclusive B meson hadroproduction*, Phys. Rev. D **77**, 014011 (2008) [arXiv:0705.4392].

[15] A. Heister *et al.* [ALEPH], *Study of the fragmentation of b quarks into B mesons at the Z peak*, Phys. Lett. B **512**, 30-48 (2001) [arXiv:hep-ex/0106051].

PoS(LHCP2022)103

[16] J. Abdallah *et al.* [DELPHI], *A study of the b-quark fragmentation function with the DELPHI detector at LEP I and an averaged distribution obtained at the Z Pole*, Eur. Phys. J. C **71**, 1557 (2011) [arXiv:1102.4748].

[17] G. Abbiendi *et al.* [OPAL], *Inclusive analysis of the b quark fragmentation function in Z decays at LEP*, Eur. Phys. J. C **29**, 463-478 (2003) [arXiv:hep-ex/0210031].

[18] K. Abe *et al.* [SLD], *Measurement of the b quark fragmentation function in Z0 decays*, Phys. Rev. D **65**, 092006 (2002) [erratum: Phys. Rev. D **66**, 079905 (2002)] [arXiv:hep-ex/0202031].