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Top-pair events with B-hadrons at the LHC

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The production of hadrons through collinear fragmentation has recently been implemented for the first time in a general code for cross-section computations at next-to-next-to-leading order in QCD. I will discuss the first application of this framework to the production of a *B*-hadron in association with a top-quark pair at the LHC. I will then present an extension of this calculation, which incorporates the decay of the *B*-hadron.

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1. Introduction

Over the years, there has been great interest in improving the precision of top-quark mass measurements. One promising way of measuring the top-quark mass with unusually small systematic experimental uncertainties is by studying observables involving a bottom-flavoured hadron produced in the semi-leptonic decay of a top quark. Typical observables are the invariant mass of the *B*-hadron and the charged lepton produced in the same decay, as well as the energy of the *B*-hadron. While such observables do not fully reconstruct the mass of the decaying top quark, they are nonetheless highly correlated with it, as has been demonstrated in several dedicated studies [1–4].

These past studies either used parton showers or next-to-leading order (NLO) fixed-order calculations to obtain their results. It was pointed out in ref. [2] that the theoretical uncertainties of such calculations essentially limit the precision of the extracted top-quark mass to a few GeV when using parton showers and to about 1 GeV when using the fixed-order approach at NLO. As the precision of top-quark-mass extractions has since surpassed that level, there is a need to improve on the precision of theory predictions.

To achieve this, one can perform fixed-order calculations at next-to-next-to-leading order (NNLO) in QCD. The first fully-differential computation of top-quark-pair production and decay at the LHC was performed a few years ago [5], but the final state was kept at the parton level. To describe observables involving the *B*-hadron, the calculation must be extended to include the collinear fragmentation of partons to hadrons.

The fragmentation function formalism [6] states that any cross section for the production of a final state involving partons can be turned into a corresponding cross section for the production of an identified hadron. This is achieved by simply convolving the perturbative cross section with a non-perturbative fragmentation function. This is in complete analogy to the way initial-state hadrons can be treated using parton distribution functions (PDFs). In practice, the computation presented in ref. [5] was performed numerically using the sector-improved residue subtraction scheme [7–10]. Implementing the convolution of the partonic cross section with a fragmentation function within such a framework is a non-trivial task and was completed for the first time at NNLO in ref. [11] as part of the work I am presenting here.

The calculation of ref. [11] has since been improved in two major ways. The first is the fragmentation function set used. When ref. [11] was published, there were no *B*-hadron fragmentation function fits available in the literature which were fully consistent with our approach: they were either performed at a lower perturbative order, such as in ref. [12], or within an entirely different formalism, such as in ref. [13]. Several of the available fits were used and it was checked that the inconsistencies were acceptable given the uncertainties of the fits. Nevertheless, to achieve the best theoretical uncertainty, this inconsistency should be resolved. We performed a fully-consistent fit ourselves, eliminating the inconsistency and reducing the fragmentation function uncertainty relative to previous fits.

The other major improvement is the development of a novel method of including the decay of the produced *B*-hadron in the calculation. Fully reconstructing a *B*-hadron can be experimentally challenging, severely limiting the statistics of the measurement. Reconstructing a single decay product of the *B*-hadron, for example a muon or a J/ψ meson, is significantly easier. Now that
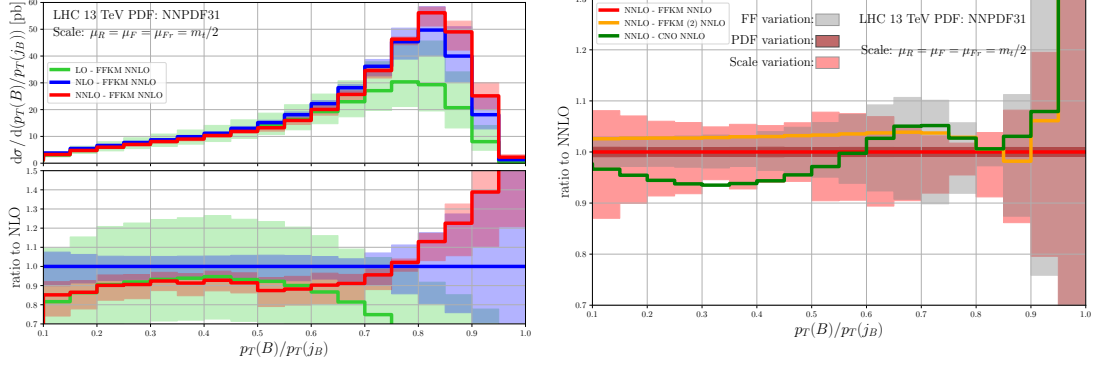
Figure 1: Left: the distribution of $p_T(B)/p_T(J_B)$, the ratio of the transverse momenta of the B-hadron and the jet that contains it, at leading order (green), NLO (blue) and NNLO (red). Right: a comparison of the sizes of different uncertainties.

such decays can be described within our framework, it is no longer required to fully reconstruct the B-hadron experimentally, significantly boosting the statistics and enabling a direct comparison with data in the future.

Both of these improvements were presented in ref. [14], together with several results. I will present some of these results below, together with some of the results of ref. [11].

2. Results

So far, B-hadron fragmentation functions have typically been fitted to data collected at e^+e^- colliders [12, 15–18]. The new fit presented in ref. [14] in particular is based on data from the ALEPH [19], DELPHI [20], OPAL [21] and SLD [22] collaborations. Given the large amount of data collected at the LHC, it is desirable to find an effective way of including LHC data in future fits. An observable can be used for this purpose if it satisfies two properties: it must be highly correlated with the shape of the fragmentation function and it must not be correlated with the shape of the PDFs. The latter property guarantees that the fragmentation function can be fitted independently of the PDFs, significantly simplifying the fit.

One of the observables investigated in ref. [11] was studied in this context: the ratio of the transverse momentum of the B-hadron to the transverse momentum of the jet that contains the B-hadron, i.e. $p_T(B)/p_T(j_B)$. This observable is a very close proxy to the fragmentation function itself, but unlike the fragmentation function, it is experimentally accessible. Indeed, at leading order (LO), there is a one-to-one correspondence between this observable and the fragmentation function.

The spectrum of $p_T(B)/p_T(j_B)$ is shown in fig. 1. The jet is clustered using the anti-k_T algorithm with $R = 0.8$. The phase space is subject to the requirements $p_T(B) > 10$ GeV and $|\eta(B)| < 2.4$. The central prediction was obtained by setting the renormalisation scale μ_R, factorisation scale μ_F and fragmentation scale μ_{Fr} to $\mu_R = \mu_F = \mu_{Fr} = m_t/2$. The scale uncertainty bands were 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 $i, j \in \{R, F, Fr\}$.
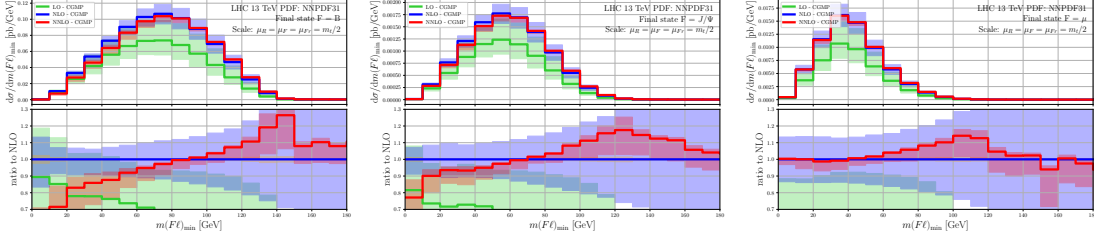
Figure 2: The invariant mass $m(F\ell)_{\min}$ at LO (green), NLO (blue) and NNLO (red). Shown are the results for $F = B$ (left), $F = J/\psi$ (centre) and $F = \mu$ (right). The green, blue and red bands correspond to the 15-point scale uncertainty bands, while the yellow bands indicate the fragmentation function uncertainty.

The left panel of fig. 1 shows that increasing the perturbative order from LO to NLO massively reduces the scale uncertainties, while increasing it further to NNLO leads to a smaller, but nonetheless appreciable, reduction. The right panel of fig. 1 compares the NNLO scale uncertainty (light red) to the fragmentation function uncertainty (grey) and the PDF uncertainty (dark red). The fragmentation function uncertainty was observed to be much larger for this observable than for the other observables studied in ref. [11]. This suggests that this observable is unusually sensitive to the shape of the fragmentation function, as expected. The PDF uncertainty is extremely small and completely flat, suggesting that the observable is PDF-insensitive. As explained above, these two properties combined make this observable an excellent candidate for future fits of B-hadron fragmentation functions to LHC data. While ref. [11] studied B-hadrons produced in association with a top-quark pair, this observable is expected to be mostly process-independent. Realistically, accurate measurements for the purpose of fragmentation function fits would be performed in open-bottom production, rather than top-quark pair production.

For the purpose of top-quark-mass extractions, the invariant mass of the B-hadron and a lepton coming from the top-quark decays is typically studied. Refs. [11, 14] considered the dileptonic decay channel of the top-quark pair, so there are two possible invariant masses for each event. Ideally, the lepton would come from the same top-quark decay as the B-hadron. In reality, this charge assignment can be difficult. As a good proxy, the smallest of both invariant masses was chosen for every event. This observable is called $m(B\ell)_{\min}$.

In ref. [14], aside from the B-hadron itself, two of its decay products were considered as well: a muon and a J/ψ meson. Substituting the B-hadron for either decay product results in two more observables: $m(\mu\ell)_{\min}$ and $m(J/\psi\ell)_{\min}$. The distributions of all three invariant masses are shown in fig. 2. These results were computed using the following cuts:

- $p_T(\ell) > 25$ 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. [14].

The scale uncertainties are again significantly reduced going from LO to NLO, but this time they are also massively reduced going from NLO to NNLO. The NNLO curve is also always

consistent with the NLO curve within the scale uncertainties, except for small values of $m(B\ell)_{\min}$. This effect is most likely caused by the specific selection cuts used, as suggested by other results of ref. [14].

The fragmentation function uncertainty is shown in fig. 2 as a yellow band around the central NLO prediction. However, it is only barely visible, as the fragmentation function uncertainty is much smaller than even the NNLO scale uncertainty.

3. Conclusion

I have presented some of the first results of a NNLO calculation of *B*-hadron production in association with top-quark pairs at the LHC. I have also presented the first results of an extension of that calculation to include the decay of the *B*-hadron. These results demonstrate a large reduction in theoretical uncertainties compared to previous studies, opening the door to *B*-hadron fragmentation function fits based on LHC data, as well as more accurate top-quark-mass extractions.

Acknowledgments

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PoS(ICHEP2022)876