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Top production at large p_t at NLO+NLL accuracy

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We introduce a new version of the FONLL code, now capable of calculating differential distributions for top quark production with next-to-leading-log resummation of $\log(p_t/m)$ terms. Numerical results for LHC and FCC kinematics are presented. In the transverse momentum region presently explored by ATLAS and CMS, no significant difference with respect to available fixed order predictions is predicted by FONLL. The large transverse momentum resummation of FONLL may instead become relevant if top is ever measured at transverse momentum scales of several TeV.

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1. Introduction

Heavy quark (charm, bottom and top) production in proton-proton collisions has been measured at the LHC from the very beginning of its run in 2010. Data for charm and bottom cross sections are available in a wide range of rapidity and transverse momentum, and have generally been found to be in good agreement with QCD predictions. The same is true for inclusive top cross sections, which have been found to be correctly described by next-to-next-to-leading order (NNLO) QCD calculations.

In recent years, the LHC has delivered an integrated luminosity sufficiently large to allow for measurements of differential top cross sections in a regime where the transverse momentum p_t starts being significantly larger than the top mass m: recent papers from ATLAS [1] and CMS [2] report measurements up to transverse momenta of the order of 1 TeV. The question of the performance of the theoretical predictions in this previously unexplored regime[1] becomes therefore a pertinent one. Moreover, design studies for large future hadron colliders like the FCC, where top quarks may be measured in the multi-TeV range, could start making use of such knowledge.

Perturbative QCD predictions for transverse-momentum distributions of heavy quarks have existed since a long time at next-to-leading order (NLO) accuracy [3, 4], and more recently have also become available at NNLO [5, 6, 7]. These calculations have been compared to the ATLAS and CMS data from refs. [1, 2] and found in good agreement with the experimental data.

Nevertheless, reasons exist to pursue alternative calculations. On one hand, while transverse momenta of the order of 1 TeV for top production are likely not large enough to make resummation to all orders of $\log(p_t/m)$ terms necessary, it is worth starting to ask the question of the range of validity of a fixed order perturbative calculation. On the other hand, the NNLO calculation for the transverse momentum distribution is only available in numerical form, and no results presently exist for top production at the FCC because the numerics become challenging in this kinematical regime.

These reasons have motivated our choice of extending the FONLL [8] calculation and code to the case of top production. FONLL has been used in the past twenty years to evaluate charm and bottom production at very large transverse momenta, $p_t \gg m$, resumming $\log(p_t/m)$ terms to all orders to next-to-leading-log (NLL) accuracy. Matching with the NLO fixed order calculation of [3] gives an overall NLO+NLL result.

While in principle straightforward, some work is needed to obtain an explicit extension of the FONLL code to the top quark production case, because the implementation of the calculation was originally performed for charm and bottom quarks only, with the number of flavours hard-coded to a maximum of five. Other necessary ingredients are an implementation of the running of the strong coupling α_s with six flavours, which is easily written, and parton distribution functions (PDFs) also evolved with six flavours and providing distributions also for top quarks. This latter ingredient was not easily available twenty years ago, but today many modern PDF groups routinely publish sets with this feature.

[1] While one may argue that a similar regime has already been probed by charm and bottom data, in that case a non-perturbative fragmentation function is an unavoidable part of the theoretical prediction, and it may to some extent "compensate" for possible shortcomings of the perturbative calculation. This won't be the case for top quark data.

2. FONLL

We recall here briefly the structure of the FONLL calculation.

FONLL [8] matches a massive, fixed-order (NLO) calculation of heavy quark production [3] with a massless calculation that resums to all orders (to NLL accuracy) massive logarithms of the form $\alpha_s^n \log^k(p_t/m)$, originating from gluon emission off massive quarks and from gluon splitting [9]. The matched calculation (called "FONLL" for historical reasons, but it could also be called "NLO+NLL") provides therefore all the mass terms up to order α_s^3, but also the resummation of the aforementioned logs, that become important in the $p_t \gg m$ region. A direct consequence of the resummation is that the perturbative uncertainty band of FONLL is usually much smaller than that of the NLO calculation (except, of course, in the region $p_t \simeq m$ or below, where the matching is dominated by the NLO result), and the FONLL p_t distribution tends to be softer than the NLO one at large p_t, a direct consequence of a larger energy loss due to multiple gluon emissions.

Schematically, the FONLL matching can be written as

$$\mathrm{FONLL} = \mathrm{FO} + (\mathrm{RS} - \mathrm{FOM0})G(p_t, m)\,. \tag{2.1}$$

In this equation, FO is the massive NLO calculation, RS is the massless resummed one, and FOM0 is the massless limit of FO, where only $\alpha_s \log(p_t/m)$ terms are kept. Therefore, the RS - FOM0 subtraction ensures that terms that are present in both FO and in RS are not double-counted. Finally, $G(p_t, m)$ is a (to some extent) arbitrary damping function that prevents spurious higher order (but artificially massless) terms from giving an unphysically large contribution. An ambiguity similar to the one related to the arbitrariness in the choice of G is present in essentially all calculations of matched type[2].

The RS result can, also schematically, be written as

$$\mathrm{RS} = \mathrm{PDF}_i \otimes \mathrm{PDF}_j \otimes d\sigma_{ij\to k}(p_t) \otimes \mathrm{FF}_k\,, \tag{2.2}$$

where PDF_i are parton distribution functions (including the one for the nominally heavy quark that one is interested in calculating), $d\sigma_{ij\to k}(p_t)$ are massless partonic cross sections, and FF_k are fragmentation functions. i, j and k are flavour indices, and they run over all active flavours, including the heavy one. DGLAP evolution of the PDFs and of the FF resums the $\alpha_s^n \log^k(p_t/m)$ terms to all orders to NLL accuracy.

3. Results

The new FONLL code for top has been run at LHC ($\sqrt{S} = 13$ TeV) and FCC ($\sqrt{S} = 100$ TeV) energies, and top production has been studied up to very large transverse momenta.

Figure 1 compares the predictions for the top quark transverse momentum distribution at the LHC at NLO and FONLL accuracy. As expected, the perturbative uncertainty of the NLO prediction tends to increase with p_t (the subsequent apparent reduction at larger p_t being simply due to accidental compensations between scale variations), while the FONLL prediction's uncertainty

[2]See [8] for a more in-depth discussion about the choice of the damping function and about the formulation of FONLL in general.

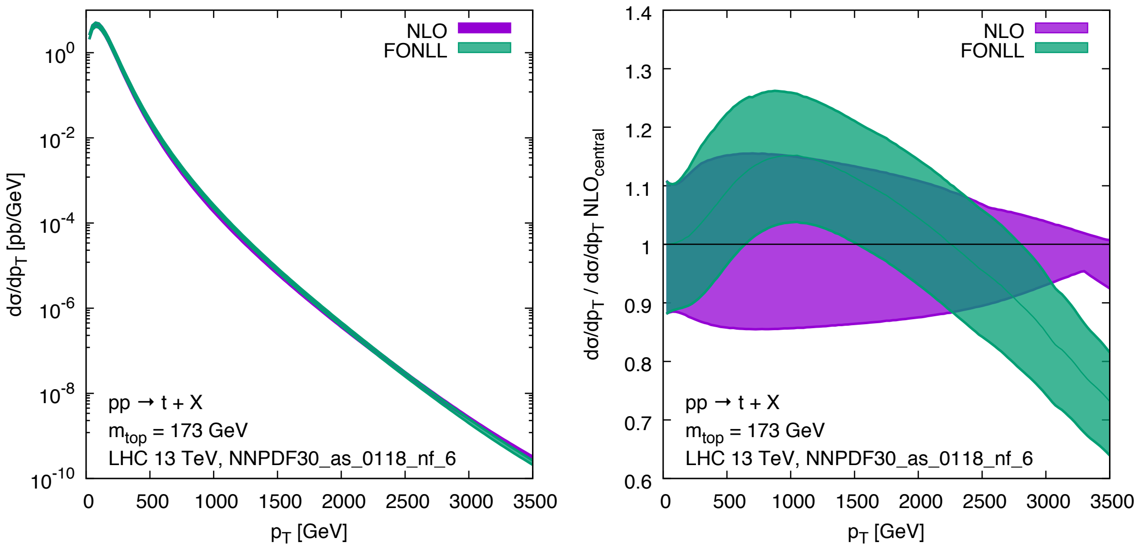

Figure 1: Comparison of NLO and FONLL transverse momentum distribution for top quark production at the LHC.

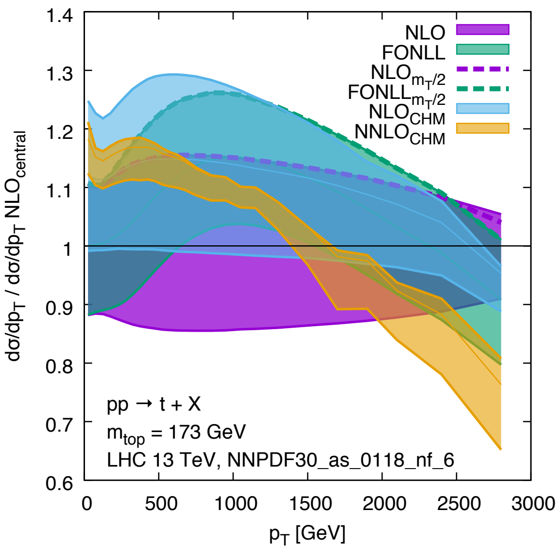

Figure 2: Comparison of FONLL transverse momentum distribution for top quark production at the LHC with other calculations.

band is smaller and more stable with increasing p_t. One can also note that the two calculations are consistent with each other up to $p_t \simeq 3$ TeV, and only above this value FONLL starts predicting a significantly smaller cross section.

Figure 2 shows further comparisons of the FONLL result with other calculations, and most notably with the NNLO fixed-order result from Czakon, Heymes and Mitov (CHM) [7]. An FONLL curve obtained setting the factorisation and renormalisation scales to $m_T/2 \equiv \sqrt{m^2+p_t^2}/2$, rather than the default m_T, is shown in this plot because $m_T/2$ is the default choice for the CHM calculations. The main take-away from this plot is probably that, at large p_t, the NNLO calculations seems to reproduce the softer behaviour suggested by the resummation in FONLL. Nevertheless, in the region where data are presently available ($p_t < 1$ TeV) the various calculations are likely not discriminable by the data.

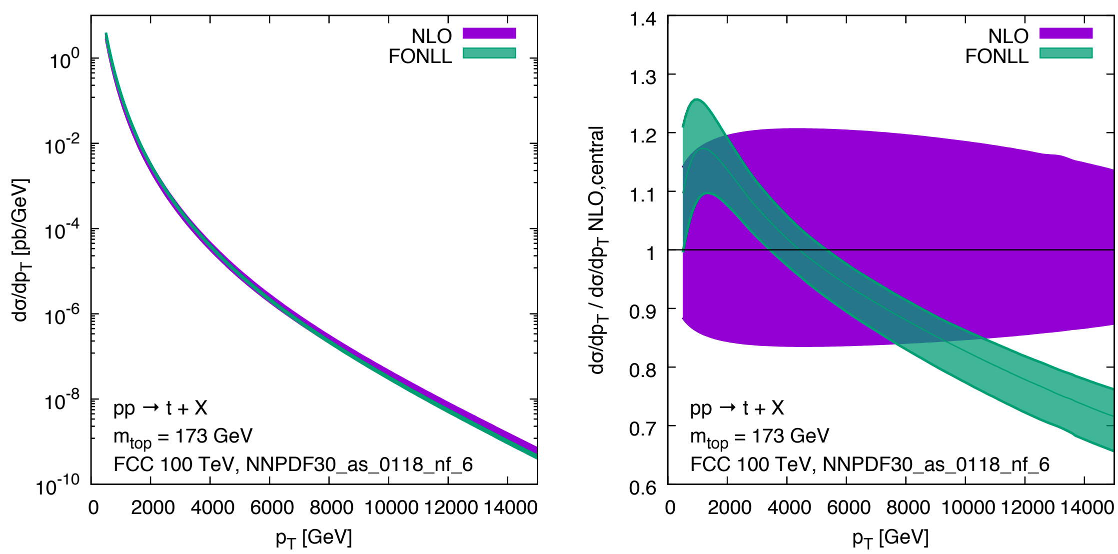

Figure 3: Comparison of NLO and FONLL transverse momentum distribution for top quark production at the FCC.

Finally, Figure 3 shows the NLO and FONLL comparison for the hypothetical future hadron collider at $\sqrt{S} = 100$ TeV, the FCC, and up to extremely large top quark transverse momenta, $p_t = 15$ TeV. At these very large transverse momentum scales we observe a behaviour already seen for charm and bottom at typical LHC scales (i.e. order one hundred GeV), namely an FONLL band decisively narrower than the NLO one, and a clearly softer transverse momentum distribution that leads to predicting a smaller cross section at very large p_t.

4. Conclusions

A new version of the FONLL code, now implementing also top quark production and delivering NLO+NLL accurate predictions for transverse momenta distributions, has been presented. Numerical results have been obtained for LHC and FCC kinematics. They show that, at least in the transverse momentum region presently explored by ATLAS and CMS, no significant difference with respect to available fixed order predictions is predicted by FONLL. The large transverse momentum resummation of FONLL may instead become relevant if top is ever measured at transverse momentum scales of several TeV.

The new version of the FONLL code will be made public in the near future, accompanied by a paper [10] containing more extensive comparisons to other calculations and to the data that are presently available.

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