Top-quark pair production at NNLO QCD and NLO EW accuracy

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ABSTRACT

We present phenomenological predictions at NNLO QCD and NLO EW accuracy for $t\bar{t}$ distributions at the LHC (8 and 13 TeV). We discuss the impact of the electroweak corrections and quantify the theory errors from scale and PDF uncertainties. Moreover, we show the relevance of a precise determination of the photon PDF for $t\bar{t}$ distributions.

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1 Introduction

In these proceeding we present predictions for $t\bar{t}$ distributions for the LHC at 8 and 13 TeV, at NNLO QCD accuracy and including also EW corrections. Results are based on the calculation that is described in detail in ref. [1]. We provide results for the following distributions: the top-quark pair invariant mass $m(t\bar{t})$, the average transverse momentum ($p_{T,avt}$) and rapidity ($y_{avt}$) of the top and antitop quarks, and the rapidity $y(t\bar{t})$ of the $t\bar{t}$ system. In the case of $p_{T,avt}$ ($y_{avt}$) distributions, we average the results for the transverse momentum (rapidity) of the top and the antitop at the histogram level.

We use the same input parameters and choice of scale of ref. [1], which has been studied and motivated in ref. [2]. Scale uncertainties are evaluated via the 7-point variation of $\mu_r$ and $\mu_f$ in the standard interval \{1/2, 2\mu\} with 1/2 $\leq \mu_r/\mu_f \leq 2$. QCD and EW corrections are independently combined for each value of $\mu_{f,r}$. NNLO QCD predictions are calculated following ref. [2], while EW corrections have been obtained in a completely automated way thanks to an extension of the code MadGraph5_@NLO [3] that has already been validated in refs. [4, 5, 6].

In Section 2 we provide phenomenological predictions for the LHC at the 8 and 13 TeV at NNLO QCD and NLO EW accuracy. In fact, we do not include only NNLO QCD and NLO EW corrections but also all the subleading LO and NLO contributions, i.e. all the terms of $O(\alpha_s^i\alpha^j)$ with $i + j = 2$ and $i + j = 3$ as well as the $O(\alpha_s^3)$ terms. Moreover, we combine QCD and EW corrections in the multiplicative approach, which we denote as “QCD $\times$ EW” and represents our best prediction. Details can be found in ref. [1]. We use as PDF set for our best prediction LUXQED [7, 8], which is NNLO QCD and NLO QED accurate and includes a photon density with a very small uncertainty.

In Section 3 we show the impact of the photon PDF by comparing predictions based on LUXQED and NNPDF3.0QED PDF set [9], similarly to what has been done also in ref. [10]. At variance with LUXQED, the photon PDF in NNPDF3.0QED gives a contribution with both a large central value and especially uncertainty, showing the relevance of the photon PDF for top distributions.

2 Phenomenological predictions for the LHC at 8 and 13 TeV

Distributions for $m(t\bar{t})$, $p_{T,avt}$, $y_{avt}$ and $y(t\bar{t})$ for 13 and 8 TeV are displayed in Figures 1 and 2 respectively. We show our best prediction QCD $\times$ EW and the comparison with the result at NNLO QCD accuracy, denoted as QCD. In the first inset we provide the relative scale and PDF uncertainty as well as their sum in quadrature for the QCD $\times$ EW prediction. In the lower inset we show the ratio of QCD $\times$ EW/QCD, i.e., the impact of EW corrections on top on NNLO QCD prediction. Plots in Figure 1 (13 TeV) have been taken directly from ref. [1], while plots in Figure 2 (8 TeV) are available at the web repository [11], where many other results can be found. The data files used for drawing plots can also be found as ancillary documentation in the arXiv submission for ref. [1].

One can see that the impact of EW corrections strongly depends on the kinematic distribution, but is in general within the scale(+PDF) uncertainty. The largest corrections can be observed in the $p_{T,avt}$ distribution, where they are significant and comparable to the scale-variation band already at $p_{T,avt} \sim 500\text{GeV}$. Also, the fraction of the theory uncertainty originating from the PDFs strongly depends on kinematics. For the $y_{avt}$ and $y(t\bar{t})$ distributions, the PDF error is similar to the scale uncertainty for central rapidities, but is larger in the peripheral region, especially for 8 TeV and for the $y(t\bar{t})$ distribution. For large values of $p_{T,avt}$ and $m(t\bar{t})$, PDF error are the dominant uncertainty.

By comparing 8 and 13 TeV results we can see that the QCD $\times$ EW/QCD ratio is very similar for $p_{T,avt}$ and $m(t\bar{t})$ and it is slightly enhanced in the peripheral region in the $y_{avt}$ and $y(t\bar{t})$ distributions at 8 TeV, similar to the case of the PDF uncertainties. On the other hand, given a value of $p_{T,avt}$ ($m(t\bar{t})$) scale uncertainties are typically larger at 13 TeV.

We remind that these predictions have been obtained in the so-called multiplicative approach for combining QCD and EW corrections. Predictions based on the standard additive approach have been provided in ref. [1], where we show that, in general, the difference between these two approaches is tiny and well within the scale-uncertainty band. The difference between the two approaches is more pronounced only for large values $p_{T,avt}$ distributions. This kinematic regime is the one where the multiplicative approach is
expected to be superior to the additive one and has to be preferred. The multiplicative approach leads to a reduction of the scale uncertainty, which in the case of the $p_{T,\text{avt}}$ distribution does not overlap with the one from NNLO QCD predictions, however, these features may be sensitive to the choice of the factorisation and renormalisation scales. See ref. [1] for details.

3 Impact of the photon PDF

In this section we quantify the different impact of the LUXQED and NNPDF3.0QED photon densities on $t\bar{t}$ differential distributions at 8 and 13 TeV. A similar and more detailed comparison has been performed also in ref. [10], where other PDF sets have been considered. We compare the impact of EW corrections including or not the contribution of the photon PDF. Figure 3 refers to 13 TeV and it is taken from ref. [1], while Figure 4 refers to 8 TeV. We shows results for the for $m(t\bar{t})$, $p_{T,\text{avt}}$, $y_{\text{avt}}$ and $y(t\bar{t})$ distributions and in each plot both LUXQED and NNPDF3.0QED results, with and without photon PDF, are present.

In each plot we display the EW/QCD ratio, namely the EW corrections divided by the NNLO QCD
result. We also show the PDF uncertainty band from the EW corrections only in the cases where the photon PDF is included.

By comparing the difference between the green (NNPDF3.0QED) and red (NNPDF3.0QED with the photon PDF set to zero) lines, one can evaluate the impact of the photon PDF in NNPDF3.0QED. Similarly, this can be done by comparing the blue (LUXQED) and violet (LUXQED with the photon PDF set to zero) lines in the case of LUXQED.

As can be seen in Figures 3 and 4, while the impact of the photon PDF is negligible in the case of LUXQED, with NNPDF3.0QED it is large for all the $p_{T,\text{avt}}$, $m(\bar{t}t)$, $y_{\text{avt}}$ and $y(\bar{t}t)$ distributions and especially has large uncertainties. The sizable uncertainties that are present at very large $p_{T,\text{avt}}$ and $m(\bar{t}t)$ for LUXQED are not induced by the photon but from the other PDFs of the coloured partons, which are probed at large Bjorken-$x$. By setting the photon PDF to zero we have verified that the same argument applies also to NNPDF3.0QED.

The comparison between plots at 8 and 13 TeV shows that the only case that is sensitive to the energy of the collider is NNPDF3.0QED with the photon PDF. Not only the central value but also the PDF uncertainties are typically larger in the 8-TeV case. On the contrary, the remaining three cases (LUXQED
with and without the photon PDF and NNPDF3.0QED with the photon PDF) are all very close and very slightly affected by the energy of the collider.

4 Conclusions

We presented results at QCD × EW accuracy for differential distributions with stable top quarks at 8 and 13 TeV. In general, we find that the effect of EW corrections is within the current total theory uncertainty from PDF and scale variation. However, in the boosted regime (large \( p_{T,\text{avt}} \)) EW corrections are comparable to the theory error both at 8 and 13 TeV. All results are available in electronic form [11] and can be exploited for further studies.

We have also shown that a precise determination of the photon PDF is essential in order to obtain accurate predictions for differential distributions with stable top quarks.
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[11] Repository with results and additional plots of NNLO QCD + EW t\bar{t} differential distributions: http://www.precision.hep.phy.cam.ac.uk/results/ttbar-nnloqcd-nloew/