Abstract

Total and fiducial top pair ($t\bar{t}$) production cross sections in proton-lead (pPb) collisions at $\sqrt{s_{NN}} = 8.16$ TeV are computed at next-to-next-to-leading-order (NNLO) accuracy including next-to-next-to-leading-log (NNLL) gluon resummation, using the CT14 and CT10 proton parton distribution functions (PDF), and the EPPS16 and EPS09 nuclear PDF parametrizations for the lead ion. The total cross sections amount to $\sigma(pPb \rightarrow t\bar{t} + X) = 59.0 \pm 5.3$ (CT14+EPPS16) +1.6 −2.1 (scale) nb, and $57.5 \pm 5.3$ (CT10+EPS09) +1.5 (scale) nb, with small modifications with respect to the result computed using the free proton PDF alone. The normalized ratio of pPb to pp cross sections (nuclear modification factor) is $R_{pPb} = 1.04 \pm 0.07$ (EPPS16) ±0.03 (EPS09). In the lepton+jets decay mode, $t\bar{t} \rightarrow b\bar{b}W(\ell\nu)W(q\bar{q}')$, one expects 600 $t\bar{t}$ events in the 180 nb$^{-1}$ integrated luminosity collected in pPb collisions at the LHC so far, after typical acceptance and efficiency losses. Differential cross sections at NLO accuracy are presented as a function of transverse momentum and rapidity of the top quarks, and of their decay $b$-jets and isolated leptons.

1 Introduction

The top quark is the heaviest elementary particle in the Standard Model (SM) and remains unobserved so far in nuclear collisions [1]. Its cross section in hadronic collisions is dominated by pair production in gluon-gluon fusion ($gg \rightarrow t\bar{t} + X$), which is theoretically computable today with great accuracy via perturbative quantum chromodynamics methods. Calculations at next-to-next-to-leading-order (NNLO) including next-to-next-to-leading-log (NNLL) soft-gluon resummations are available using e.g. Top++ [2]. Differential $t\bar{t}$ cross sections are also available at NLO accuracy using the MCFM code [3]. The study of the $t\bar{t}$ cross section modifications in proton-nucleus compared to pp collisions at the same nucleon-nucleon center-of-mass energy ($\sqrt{s_{NN}}$) provides a novel well-calibrated probe of the nuclear gluon density at the LHC [4], in particular in the unexplored high-$x$ region ($x \gtrsim 2 m_t/\sqrt{s_{NN}} \approx 0.05$) where “antishadowing” and “EMC” effects are expected to modify its shape compared to the free proton case (Fig. 1).

![Figure 1: Ratio of the lead-to-proton gluon densities in the antishadowing ($x \approx 0.05 - 0.1$) and EMC ($x \approx 0.1 - 0.6$) regions probed by $t\bar{t}$ production at virtualities $Q^2 = m_t^2 \approx 3 \cdot 10^4$ GeV$^2$ in pPb collisions at the LHC, for three different NLO nuclear PDF sets: EPS09 [5], DSSZ [6], and FGS10 [7].](image)

1 At NLO, we find that more than 85% of the $t\bar{t}$ cross section at 8.16 TeV involves initial-state gluons from the colliding nucleons.
The study of production of top quarks in pPb collisions provides information on the nuclear PDF that is complementary to that from similar studies with electroweak bosons \([8,11]\). The cross sections of the latter are more sensitive to quark (rather than gluon) densities, at Bjorken-\(x\) values about twice smaller \([12]\). In addition, a good understanding of top quark in proton-nucleus collisions is crucial as a baseline for upcoming studies of heavy-quark energy loss in the quark-gluon-plasma formed in nucleus-nucleus collisions \([4,13]\).

The top quark decays very rapidly before hadronizing \((\tau = h/\Gamma_t \approx 0.15 \text{ fm/c})\) into \(t \to W b\) with \(\approx 100\%\) branching ratio, with the \(W\) themselves decaying either leptonically \((t \to W (\ell \nu) b, 1/3\text{ of the times})\) or hadronically \((t \to W (q\bar{q}) b, 2/3\text{ of the times})\) \([14]\). In Pb-Pb collisions, the charged leptons \(\ell = e, \mu\) from the fully-leptonic final-state \((t \to b\bar{b} \ell \nu 2\nu)\) are totally unaffected by final-state interactions, thereby providing the cleanest channel for its observation in the complicated heavy-ion environment \([4]\), though at the price of a relatively low branching ratio \((\text{BR} \approx 4\%\) for the \(e\), \(e\mu\) and \(\mu\mu\) modes combined). In the p-Pb case, thanks to the lower backgrounds and the absence of final-state effects for jets compared to Pb-Pb collisions, the leptons+jets final-state \((t \to b\bar{b} \ell \nu 2\nu)\) is easily measurable and has a much larger branching ratio \((\text{BR} \approx 30\%\) for \(\ell = e, \mu\), increasing to \(\text{BR} \approx 34\%\) when including also \(e, \mu\) final-states from \(\tau\) decays in \(t \to b\bar{b} \tau \nu 2\nu\)) \([14]\) than the purely leptonic decay. In this work, we present predictions for total, fiducial, and differential (for the \(\ell\ell\) channel) cross sections for \(t\bar{t}\) production in p-Pb at the center-of-mass energy of the last LHC run for this colliding system \((\sqrt{s_{\text{NN}}} = 8.16 \text{ TeV})\).

## 2 Total and fiducial \(t\ell\) cross sections

The total and differential \(p\bar{p}\) and \(pPb\) \(t\ell + X\) cross sections are computed first at NLO accuracy with the MCFM v8.0 code \([3]\), using the CT10 \([15]\) and CT14 \([16]\) proton parton distribution functions (PDF), and the nuclear PDF combination for the Pb ion given by the EPS09 \([5]\) and EPPS16 \([17]\) nuclear PDF (nPDF) sets. Then, a K-factor, \(K = \sigma(\text{NNLO} + \text{NNLL})/\sigma(\text{NLO}) \approx 1.20\) is computed with the NNLO CT10 and CT14 PDFs alone, in order to scale up the NLO MCFM cross section to NNLO+NNLL accuracy. The total cross sections are then computed first at NLO accuracy with the NNLO CT10 and CT14 PDFs alone, in order to scale up the NLO MCFM cross section to NNLO+NNLL accuracy. The theoretical uncertainty linked to the scales is estimated by modifying \(\mu_R\) and \(\mu_F\) within a factor of two with respect to their default value. In the pp case, such a theoretical NNLO+NNLL setup yields theoretical cross sections in very good agreement with the experimental data \([18,23]\). The computed nucleon-nucleon cross sections are then scaled by the Pb mass number \((A = 208)\) to obtain the corresponding PbPb cross sections.

### Table 1: Total and fiducial \(t\ell\) production in pp and pPb collisions at \(\sqrt{s_{\text{NN}}} = 8.16 \text{ TeV}\) at NNLO+NNLL accuracy with different proton (CT10 and CT14) and Pb ion (EPS09 and EPPS16) PDF. The first and second errors quoted correspond to the PDF and scale uncertainties.

|                  | \(\sigma(t\ell)\) total | \(\sigma(t\ell \to b\bar{b} \ell \nu 2\nu)\) fiducial |
|------------------|--------------------------|-----------------------------------------------|
| \(pp\)           | 265.8 \(^{+17.4}_{-14.3}\) (CT10) \(^{+9.9}_{-6.9}\) \(\text{pb}\) | 272.6 \(^{+17.2}_{-15.3}\) (CT14) \(^{+7.9}_{-6.7}\) \(\text{pb}\) |
| \(pPb\)          | 57.5 \(^{+4.3}_{-3.3}\) (CT10+EPS09) \(^{+1.9}_{-1.2}\) \(\text{nb}\) | 59.0 \(\pm 5.3\) (CT14+EPPS16) \(^{+1.6}_{-2.4}\) \(\text{nb}\) |
| \(R_{pPb}\)      | 1.04 \(^{+0.01}_{-0.02}\) (EPS09) | 1.04 \(\pm 0.07\) (EPPS16) |

The total \(t\ell\) cross sections for pp and pPb collisions for various proton and Pb PDF are listed in the first two columns of Table 1 as well as the nuclear modification factor \(R_{pPb} = \sigma_{pPb}/(A \sigma_{pp})\). For pPb, the CT14+EPPS16 calculations give a central \(t\ell\) cross section which is 2.6\% larger than that computed with CT10+EPS09. The cross section uncertainties linked to the PDF choice are \(\pm 9\%\) for CT14+EPPS16, and \(\pm 7.5\% - 5.8\%\) for CT10+EPS09. The theoretical \(\mu_F, \mu_R\) scale uncertainties amount to \(\pm 2.5\% - 3.5\%\). Compared to the corresponding pp results, a small net overall antishadowing effect increases the total top-quark pair cross section by a meager 4\% for both EPPS16 and EPS09 sets, \(R_{pPb} = 1.04 \pm 0.07\) (EPPS16) \(\pm 0.03\) (EPS09), where we have considered that proton PDF and theoretical scale uncertainties cancel out in the ratio.

Fiducial top-pair production cross sections can be measured in the \(\ell\) + jets channel at the LHC taking into account...
their decay branching ratio (BR ≈ 30%), basic ATLAS/CMS detector acceptance constraints, and standard final-state selection criteria applied to remove W+jets and QCD multijet backgrounds \cite{18,21,22}, such as:

- One isolated charged lepton (ℓ = e, µ) with \( p_T > 30 \) GeV, |\( \eta \)| < 2.5, and \( R_{\text{isol}} = 0.3 \)
- Four jets (reconstructed with the anti-\( k_T \) algorithm with \( R = 0.5 \) \cite{24}) with \( p_T > 25 \) GeV, |\( \eta \)| < 3.0
- Lepton-jets separation of \( \Delta R(\ell, j) > 0.4 \)

[Often such cuts are sufficient to carry out the \( t\bar{t} \) measurement although, if needed, a threshold on the missing transverse momentum from the unobserved \( \nu \) can be added.] The impact of such cuts, evaluated with MCFM, indicates a 39.5% acceptance of the total cross section, with a very small dependence on the underlying PDF (the maximum difference in acceptances using the proton and ion PDF amounts to ±0.7% on the final cross section). The events that pass such selection criteria are then often required in addition to have two b-tagged jets. For a typical b-tagging efficiency of 70%, this results in a final combined acceptance × efficiency of ~20% for a \( t\bar{t} \)-enriched sample consisting of one isolated charged lepton, two light-quark jets, and two b-jets. Taking into account the \( \ell + \) jets branching ratio, the aforementioned acceptance and efficiency, and the 180 nb\(^{-1}\) integrated luminosities collected by ATLAS and CMS in pPb collisions at 8.16 TeV, we expect about 600 top-quark pair events reconstructed in this decay channel.

3 Differential \( t\bar{t} \rightarrow \ell + \text{jets} \) distributions

As seen in the previous section, the total integrated \( t\bar{t} \) cross sections are modified by a few percent only due to nuclear PDF effects in pPb compared to pp collisions at 8.16 TeV, \( R_{\text{pPb}} = 1.04 \). However, Fig. 1 indicates that \( gg \rightarrow t\bar{t} \) processes at different \( x \) values, i.e. probed at different rapidities and/or transverse momenta of the produced top quarks, should be much more sensitive to the underlying positive (antishadowing) and negative (EMC and shadowing) modifications. This was quantitatively confirmed in \cite{4} that showed that rapidity distributions of the isolated leptons in the fully-leptonic \( t\bar{t} \) decay mode, are indeed sensitive to the underlying nPDF, and can be used to reduce the uncertainties of the EPS09 nuclear gluon density. We present a similar study here, but for the \( \ell + \) jets channel, \( t\bar{t} \rightarrow b\bar{b} \ell \nu 2j \), and using the more updated EPPS16 nPDF set. Figure 2 shows the nuclear modification ratios, \( R_{\text{pPb}}(X) = (d\sigma_{\text{pPb}}/dX)/(d\sigma_{\text{pp}}/dX) \) as a function of transverse momentum (\( X = p_T \), left panels) and rapidity (\( X = y \), right panels) for (i) the produced top quarks (top), (ii) the decay isolated-leptons (middle), and (iii) the decay b-jets (bottom) as obtained using the EPPS16 (dashed curves) and EPS09 (solid curves). We note that any effect related to the choice of the proton PDF (CT10 or CT14) mostly cancels out in the pPb/pp ratio, which is mostly sensitive to modifications of the nuclear gluon densities alone. The effect of antishadowing (shadowing or EMC) in the nPDF results in small 5–10% enhancements (deficits) in the distributions at lower (higher) \( p_T \) values as well as at central (forward and backward) rapidities \( y \approx 0 \) (\( |y| \gtrsim 2 \)). In general, the effects are larger for the originally produced top quarks than for their decay products (isolated leptons and b-jets), but nonetheless visible also for the latter.

4 Summary

Total, fiducial, and differential cross sections for top-quark pair production in proton-lead collisions at \( \sqrt{s_{\text{NN}}} = 8.16 \) TeV have been computed at up to NNLO+NNLL accuracy using the CT14 and CT10 proton PDF and the EPPS16 and EPS09 nuclear PDF parametrizations. The total cross sections amount to \( \sigma(pPb \rightarrow t\bar{t} + X) = 59.0 \pm 5.3 \) (CT14+EPPS16) \( \pm 1.6 \) (scale) nb, and \( 57.5 \pm 1.3 \) (CT10+EPS09) \( \pm 1.0 \) (scale) nb, with few percent modifications with respect to the result obtained using the free proton PDF alone, \( R_{\text{pPb}} = 1.04 \pm 0.07 \) (EPPS16). In the lepton+jets decay mode, \( t\bar{t} \rightarrow b\bar{b} W(\ell\nu) W(q\bar{q}) \), one expects about 600 \( t\bar{t} \) events in the 180 nb\(^{-1}\) integrated luminosity collected at the LHC, after typical ATLAS/CMS acceptance and efficiency losses. Ratios of \( t\bar{t} \) differential cross sections in pPb over pp collisions as a function of the transverse momentum and rapidity of the charged decay leptons and of the b-jets are sensitive to the size of antishadowing and EMC gluon density modifications at high virtualities in the nucleus. Precise differential measurements of top-quark pair production provide thereby a novel tool to study the nuclear parton distribution functions in a so-far unexplored kinematical regime.
Figure 2: Nuclear modification factors as a function of transverse momentum (left) and rapidity (right) for $t\bar{t}$ production in the $\ell^{+}\text{jets}$ channel at $\sqrt{s_{NN}} = 8.16$ TeV for: (i) the produced top quarks (top), their (ii) decay isolated leptons (middle), and (iii) decay b-jets (bottom), obtained at NLO accuracy with the central PDF sets of CT14+EPPS16 (dashed curves) and CT10+EPS09 (solid curves).
Acknowledgments—Discussions with Hannu Paukkunen on the interface of the EPPS16 PDF parametrization with MCFM are gratefully acknowledged.

References

[1] D. d’Enterria, arXiv:1701.08047 [hep-ex].
[2] M. Czakon, P. Fiedler and A. Mitov, Phys. Rev. Lett. 110 (2013) 252004
[3] J. M. Campbell and R. K. Ellis, Nucl. Phys. Proc. Suppl. 205-206 (2010) 10; and J. Phys. G 42 (2015) 015005
[4] D. d’Enterria, K. Krajczár and H. Paukkunen, Phys. Lett. B 746 (2015) 64
[5] K. J. Eskola, H. Paukkunen and C. A. Salgado, JHEP 0904 (2009) 065
[6] D. de Florian, R. Sassot, P. Zurita and M. Stratmann, Phys. Rev. D 85 (2012) 074028
[7] L. Frankfurt, V. Guzey and M. Strikman, Phys. Rept. 512 (2012) 255
[8] V. Khachatryan et al. [CMS Collaboration], Phys. Lett. B 750 (2015) 565
[9] V. Khachatryan et al. [CMS Collaboration], Phys. Lett. B 759 (2016) 36
[10] G. Aad et al. [ATLAS Collaboration], Phys. Rev. C 92 (2015) 044915
[11] J. Adam et al. [ALICE Collaboration], JHEP 1702 (2017) 077
[12] H. Paukkunen and C. A. Salgado, JHEP 1103 (2011) 071
[13] A. Dainese, U.A. Wiedemann, N. Armesto, D. d’Enterria, J.M. Jowett et al., CERN Yellow Report (2017) 635; [arXiv:1605.01389 [hep-ph]]; and L. Apolinário, N. Armesto, G. Milhano, G. Salam and C.A. Salgado, to be submitted.
[14] C. Patrignani et al. [Particle Data Group], Chin. Phys. C 40 (2016) 100001
[15] J. Gao et al., Phys. Rev. D 89 (2014) 033009
[16] S. Dulat et al., Phys. Rev. D 93 (2016) 033006
[17] K. J. Eskola, P. Paakkinen, H. Paukkunen and C. A. Salgado, Eur. Phys. J. C 77 (2017) 163
[18] S. Chatrchyan et al. [CMS Collaboration], Eur. Phys. J. C 71 (2011) 1721
[19] S. Chatrchyan et al. [CMS Collaboration], JHEP 1107 (2011) 049
[20] G. Aad et al. [ATLAS Collaboration], JHEP 1205 (2012) 059
[21] S. Chatrchyan et al. [CMS Collaboration], Eur. Phys. J. C 73 (2013) 2386
[22] G. Aad et al. [ATLAS Collaboration], Phys. Rev. D 91 (2015) 112013
[23] V. Khachatryan et al. [CMS Collaboration], Phys. Rev. Lett. 116 (2016) 052002
[24] M. Cacciari, G. P. Salam and G. Soyez, JHEP 0804 (2008) 063