PROCEEDINGS OF SCIENCE

# Progress in top-quark pair production cross section calculations and impact on parton distribution functions of the proton

**A. Ablat,[a] S. Dulat,[a,b] M. Guzzi,[c,*] T.-J. Hou,[d] N. Kidonakis,[c] I. Sitiwaldi,[a] A. Tonero,[e,c] K. Xie[b] and C.-P. Yuan[b]**

[a] *School of Physics Science and Technology, Xinjiang University, Urumqi, Xinjiang 830046 China.*
[b] *Department of Physics and Astronomy, Michigan State University, East Lansing, MI 48824, USA*
[c] *Department of Physics, Kennesaw State University, Kennesaw, GA 30144, USA.*
[d] *School of Nuclear Science and Technology, University of South China, Hengyang, Hunan 421001, China.*
[e] *Department of Chemistry and Physics, Florida Gulf Coast University, Fort Myers, FL 33965, USA*

*E-mail:* mguzzi@kennesaw.edu, alimablat@stu.xju.edu.cn, sdulat@hotmail.com, tjhou@msu.edu, nkidonak@kennesaw.edu, ibrahim010@sina.com, atonero@fgcu.edu, xiekepi1@msu.edu, yuanch@msu.edu

We discuss the impact of eligible top-quark pair production differential cross-section measurements at the LHC with a collision energy of 13 TeV on the parton distribution functions (PDFs) of the proton as well as the impact of approximate next-to-next-to-next-to-leading order (aN$^3$LO) QCD corrections combined with next-to-leading order (NLO) electroweak (EW) corrections on $t\bar{t}$ observables. We illustrate the effects on the gluon PDF at large $x$ from an optimal baseline selection of data in NNLO global fits, and show comparisons between the theory prediction for $t\bar{t}$ total and differential cross sections at aN$^3$LO QCD combined with NLO EW and recent measurements from the ATLAS and CMS collaborations at the LHC.

PREPRINT: MSUHEP-24-021

*12th Edition of the Large Hadron Collider Physics Conference (LHCP2024)*
*3-7 June 2024*
*Boston, USA*

*Speaker





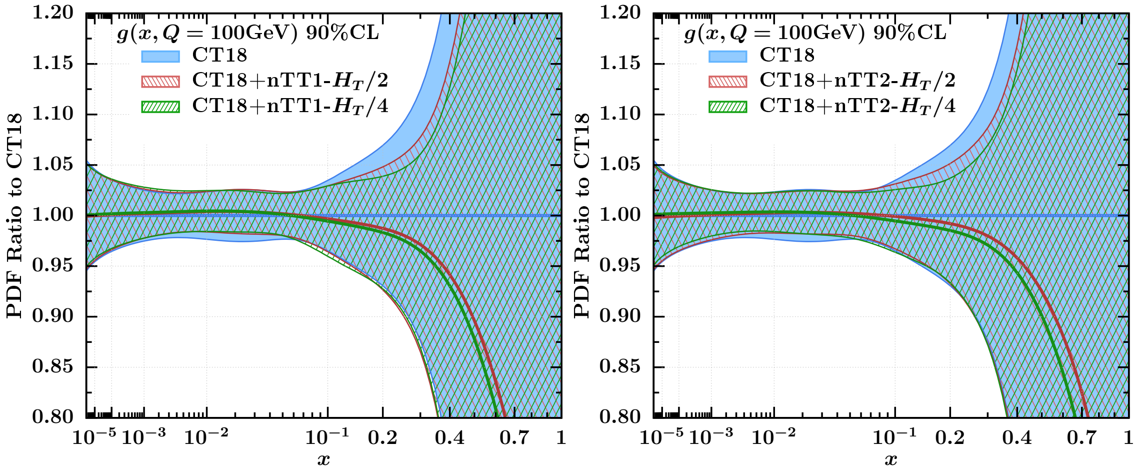
PoS(LHCP2024)332

## 1. Introduction

The next precision frontier of Run-3 of the Large Hadron Collider (LHC) and beyond requires high-precision and high-accuracy theory predictions for particle reaction cross sections in perturbation theory to guarantee meaningful comparisons between theory and experiment. To this end, a combined effort in advancing the current knowledge of the structure of the proton encoded in the parton distribution functions (PDFs) as well as progress in higher-order computations in perturbation theory is indispensable. The QCD factorization formula describing proton-proton collisions at the LHC depends on two fundamental ingredients: the PDFs of the proton, that are non-perturbative objects determined through global QCD analyses of world data, and the short-distance hard scattering contributions which are obtained using a variety of multi-loop techniques for Feynman diagram calculations in relativistic quantum field theories. Top-quark pair production cross section measurements are a clean probe for PDFs at intermediate and large longitudinal momentum fraction $x$ where they are currently poorly constrained and where jet-production measurements may complement those from $t\bar{t}$ in absence of tensions between these measurements. The impact of recent $t\bar{t}$ high-precision measurements at ATLAS and CMS on global QCD analyses of CTEQ PDFs at next-to-next-to-leading order (NNLO) is discussed in Ref. [1], while a recent study of the impact of corrections from soft-gluon contributions at approximate next-to-next-to-next-to-leading order (aN$^3$LO) in QCD combined with electroweak (EW) corrections at next-to-leading order (NLO) are discussed in Ref. [2].

## 2. Gluon impact from optimal combinations of 13 TeV top-quark measurements

In this section, we report the results published in Ref. [1]. Future CTEQ PDF releases require substantial efforts in selecting sensitive data from the large amount of novel high-precision measurements at the LHC. In particular, we studied the impact of single differential cross section measurements of top-pair production at the LHC at 13 TeV from the ATLAS [3, 4] and CMS [5, 6] collaborations on the gluon and other CTEQ PDFs [1]. The PDF impact from these measurements has been analyzed by including each individual measurement on top of the CT18 baseline using the `ePump` [7, 8] code first for a rapid assessment, and then in individual global fits. In such global fits, we analyzed the effect of including statistical correlations when these were available in the case of combined measurements (see Refs. [1, 4]), the impact from including the same distribution but with different binning, the interplay between top-quark and jet production data, the dependence on the factorization, renormalization and top-quark mass $m_t^{(pole)}$ scales, and EW radiative corrections at NLO when available. The NNLO QCD theory predictions are obtained through `fastNNLO` tables [9–12] as well as NNLO/NLO $K$-factors obtained with the `MATRIX` code [13–15] and NLO APPLgrid tables [16] with `MCFM` [17]. EW corrections at NLO, either taken from Ref. [10] or calculated with `MadGraph_aMC@NLO` [18]/`MCFM` [19] were also considered when available. The most sensitive PDF information is obtained using two optimal combinations of measurements labelled CT18+nTT1 and CT18+nTT2 which minimize the tensions between data in the extended baseline, maximize the sensitivity and have optimal $\chi^2/N_{pt}$. CT18+nTT1 includes the rapidity distribution of the top-quark pair $y_{t\bar{t}}$ at ATLAS in the hadronic [3] and lepton+jet [4] channels and at CMS in the dilepton channel [5], and the invariant mass distribution of the top-quark pair $m_{t\bar{t}}$




(a) (b)

**Figure 1:** Gluon PDFs and uncertainties. In (a) the CT18+nTT1 and (b) CT18+nTT2 global QCD analyses at NNLO, plotted as ratios to CT18 NNLO. PDF uncertainties are evaluated at the 90% CL.

at CMS in the lepton+jet channel [6]. CT18+nTT2 includes the same distributions except for the ATLAS lepton+jet $y_{t\bar{t}}$ that is replaced by the $y_{t\bar{t}} + y^B_{t\bar{t}} + m_{t\bar{t}} + H_T^{t\bar{t}}$ combination. Here, $H_T^{t\bar{t}}$ is the scalar sum of the transverse momenta of the hadronic and leptonic top quarks, and $y^B_{t\bar{t}}$ is the rapidity distribution for the boosted topology. The impact on the CTEQ gluon from the global fit with the CT18+nTT1 and CT18+nTT2 extended baselines is illustrated in Fig. 1. Hatched error bands represent the $H_T/2$ (red) and $H_T/4$ (green) choices for the central scale in the 13 TeV $t\bar{t}$ theory predictions. Most of the impact from the new data is visible in the large $x$ region and mostly due to the high-luminosity 137 fb$^{-1}$ data at CMS. The overall quality-of-fit of the CT18+nTT1 and CT18+nTT2 fits is essentially the same as that of CT18, with $\chi^2/N_{pt} \approx 1.16$.

## 3. Top-quark cross sections and distributions at aN$^3$LO

In this section, we report the results published in Ref. [2]. Top-quark physics plays a central role in current and future research programs at the LHC. In fact, $t\bar{t}$ production is one of the most important processes at this collider; it has the ability to constrain proton PDFs and is important for searches of new physics interactions. Measurements of top-quark pair production total and differential cross section are going to be delivered with unprecedented precision and accuracy at the LHC in the near future. Therefore, it is critical to push forward the precision frontier of the theory calculations predicting this standard-candle observable. Theory predictions for top-quark cross sections and differential distributions in $t\bar{t}$ production have been computed at NLO $O(\alpha_s^3)$ in Refs. [20–25], and NNLO at $O(\alpha_s^4)$ in Refs. [13, 14, 26–33] in QCD, while EW corrections to this process were studied in Refs. [18, 19, 34–50]. Logarithmic enhancements from soft-gluon emissions provide an important subset of QCD corrections which are dominant in the LHC kinematic regime and have been extensively studied in the literature in the past three decades [2, 51–84]. Perturbative QCD corrections from soft gluons at third order in perturbative QCD were calculated in Refs. [81, 82] based on the formalism of Refs. [53, 54, 57, 64, 69, 71, 79, 81–84]. In Ref. [2] these corrections are

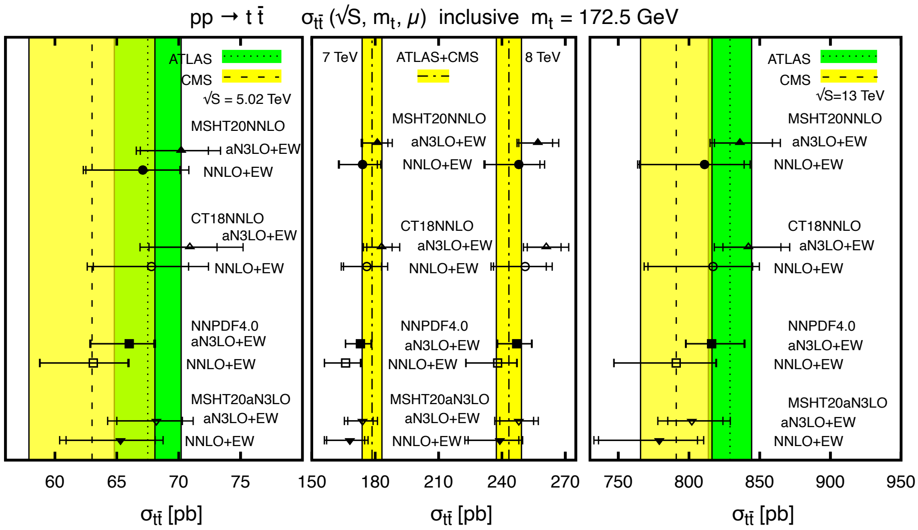



**Figure 2:** $t\bar{t}$ total inclusive cross sections compared to recent measurements at the LHC at different collision energies.

added on top of the exact NNLO cross section to obtain QCD results at approximate N$^3$LO (aN$^3$LO) which are combined with Electroweak (EW) corrections included at NLO. This calculation is used to obtain new results for the top-quark pair production total and differential cross sections which are compared to recent measurements from the LHC. The expression of the partonic contributions from soft-gluon corrections in QCD is in the form of $C_{ij}^{(k)}\left[\ln^k(s_4/m_t^2)/s_4\right]_+$. In general, the coefficients $C_{ij}^{(k)}$, with $k \leq 5$ at N$^3$LO, depend on the Mandelstam variables $s$, $t_1$, $u_1$, the top-quark mass $m_t$, and the renormalization and factorization scales $\mu_R$ and $\mu_F$ respectively. The threshold variable $s_4$ is defined by $s_4 = s + t_1 + u_1$. More details about the these corrections can be found in Refs. [81, 82].

In Figure 2, we compare our theoretical predictions at aN$^3$LO obtained with different PDFs (CT18 [85], MSHT20 [86, 87], and NNPDF4.0 [88]) to recent LHC measurements for various collision energies such as ATLAS [89] and CMS [90] at $\sqrt{S}$ = 5.02 TeV; ATLAS and CMS combined at $\sqrt{S}$ = 7 and 8 TeV [91]; ATLAS [92] and CMS [6] at $\sqrt{S}$ = 13 TeV. The theory error bars represent scale uncertainty (inner bar), and scale added to PDF uncertainties in quadrature (outer bar). The experimental error bands represent all the given errors added in quadrature. The NNLO theory predictions are calculated using `Top++2.0` [75] while the NLO QCD+EW are obtained with `MadGraph5_aMC@NLO` [93, 94]. More results are available in Ref. [2]. In Figure 3, we illustrate ratio plots where we compare the theory results for the top-quark transverse momentum $p_T^t$ distribution at NNLO and aN$^3$LO with EW corrections to recent measurements at ATLAS [3] and CMS [5] at 13 TeV. The orange band represents the sum of statistical and systematic experimental uncertainties added in quadrature. Inner (outer) bars represent scale (scale plus MSHT20 PDFs at aN$^3$LO or NNLO, respectively) theoretical uncertainties. The NLO EW corrections are obtained from Ref. [49] while the combined QCD×EW corrections incorporate $O(\alpha_s^2\alpha)$ terms and the subleading $O(\alpha_s\alpha^2)$, $O(\alpha^3)$, $O(\alpha_s^3\alpha)$ terms which are included using the multiplicative method discussed in Ref. [49]. Similar results with other PDFs as well as for the rapidity distributions of the top quark are presented in Ref. [2].

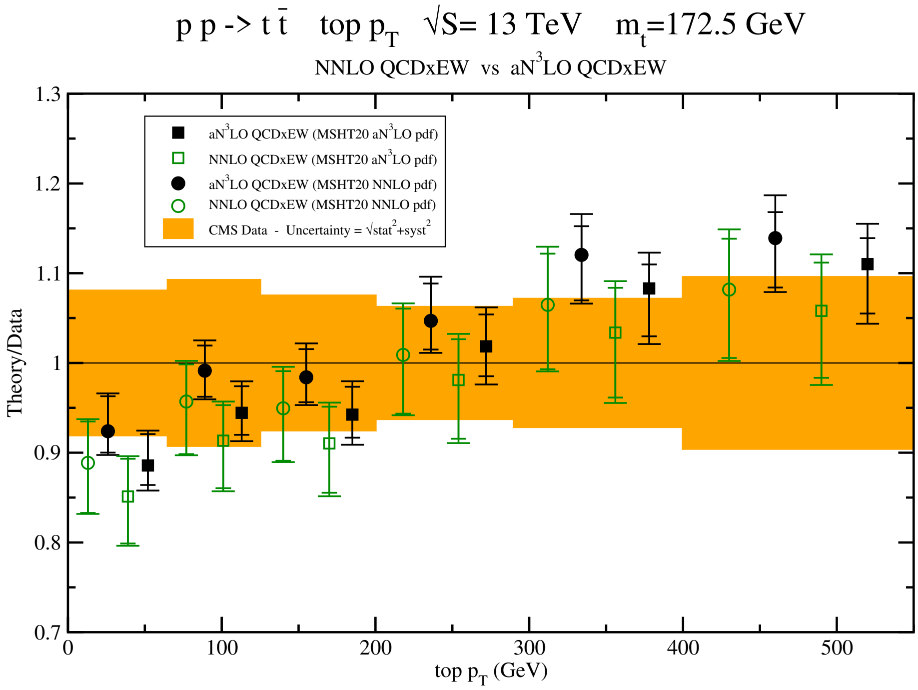
## 4. Conclusions

We reported recent progress in top-quark pair production cross section calculations and presented a comprehensive study of the impact of recent high-precision measurements from ATLAS and CMS at the LHC at 13 TeV on CTEQ PDFs. We identified two optimal combinations of $t\bar{t}$ measurements that are added on top of the CT18 baseline and maximize the information extracted from the data. Both combinations have mild impact on the CT18 gluon and overall have the same fit quality of CT18.

We studied the impact of radiative corrections at aN$^3$LO in QCD from soft-gluon resummation including EW corrections at NLO on total and differential $t\bar{t}$ cross sections. These new predictions have been compared to recent $t\bar{t}$ cross section measurements at the LHC, and the QCD corrections substantially increase the rates for $\sigma_{t\bar{t}}$ and the differential distributions while the EW corrections play an important role at large $p_T^t$.

## Acknowledgments

The work of A.A., S.D. and I.S. is supported by the National Natural Science Foundation of China under Grants No. 11965020 and No. 11847160. The work of M.G., N.K. and A.T. has been supported by the National Science Foundation under Grants No. PHY 2112025 and No. PHY 2412071. The work of T.-J. Hou was supported by Natural Science Foundation of Hunan province of China under Grant No. 2023JJ30496. C.-P.Y. and K.X. at MSU are supported by the U.S. National Science Foundation under Grants No. PHY 2310291 and PHY 2310497. This work used resources of high-performance computing clusters from MSU HPCC, KSU HPCs, as well as Pitt CRC.



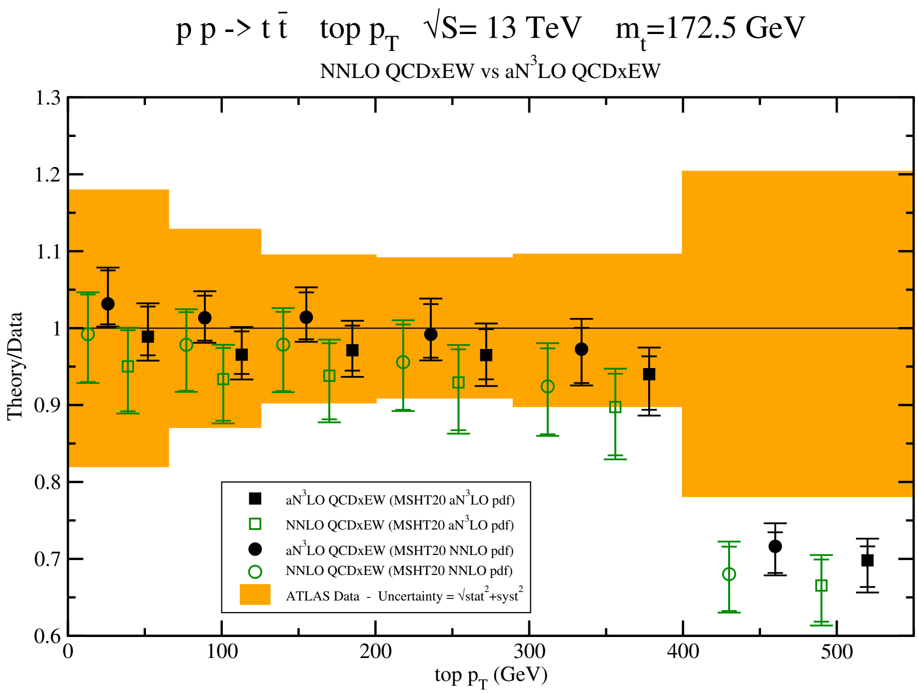




**Figure 3:** Comparison of NNLO QCD×EW and aN$^3$LO QCD×EW theory predictions using MSHT20 NNLO and aN$^3$LO PDF with CMS (upper plot) and ATLAS (lower plot) top-quark transverse momentum data.

## References


[1] A. Ablat, M. Guzzi, K. Xie, S. Dulat, T.-J. Hou, I. Sitiwaldi et al., *Exploring the impact of high-precision top-quark pair production data on the structure of the proton at the LHC*, *Phys. Rev. D* **109** (2024) 054027 [2307.11153].

[2] N. Kidonakis, M. Guzzi and A. Tonero, *Top-quark cross sections and distributions at approximate N$^3$LO*, *Phys. Rev. D* **108** (2023) 054012 [2306.06166].

[3] ATLAS collaboration, *Measurements of top-quark pair differential and double-differential cross-sections in the $\ell$+jets channel with $pp$ collisions at $\sqrt{s} = 13$ TeV using the ATLAS detector*, *Eur. Phys. J. C* **79** (2019) 1028 [1908.07305].

[4] ATLAS collaboration, *Measurements of top-quark pair single- and double-differential cross-sections in the all-hadronic channel in $pp$ collisions at $\sqrt{s} = 13$ TeV using the ATLAS detector*, *JHEP* **01** (2021) 033 [2006.09274].

[5] CMS collaboration, *Measurements of $\mathrm{t\bar{t}}$ differential cross sections in proton-proton collisions at $\sqrt{s} = 13$ TeV using events containing two leptons*, *JHEP* **02** (2019) 149 [1811.06625].

[6] CMS collaboration, *Measurement of differential $t\bar{t}$ production cross sections in the full kinematic range using lepton+jets events from proton-proton collisions at $\sqrt{s} = 13$ TeV*, *Phys. Rev. D* **104** (2021) 092013 [2108.02803].

[7] C. Schmidt, J. Pumplin, C. P. Yuan and P. Yuan, *Updating and optimizing error parton distribution function sets in the Hessian approach*, *Phys. Rev.* **D98** (2018) 094005 [1806.07950].

[8] T.-J. Hou, Z. Yu, S. Dulat, C. Schmidt and C. P. Yuan, *Updating and optimizing error parton distribution function sets in the Hessian approach. II.*, *Phys. Rev. D* **100** (2019) 114024 [1907.12177].

[9] D. Britzger, G. S. Klaus Rabbertz, F. Stober and M. Wobisch, *Recent Developments of the fastNLO Toolkit*, *PoS* **DIS2015** (2015) 055.

[10] M. Czakon, D. Heymes and A. Mitov, *fastNLO tables for NNLO top-quark pair differential distributions*, 1704.08551.

[11] "Repository with $t\bar{t}$ fastNNLO tables." https://www.precision.hep.phy.cam.ac.uk/results/ttbar-fastnlo/.

[12] M. Czakon, D. Heymes and A. Mitov, *Dynamical scales for multi-TeV top-pair production at the LHC*, *JHEP* **04** (2017) 071 [1606.03350].

[13] M. Grazzini, S. Kallweit and M. Wiesemann, *Fully differential NNLO computations with MATRIX*, *Eur. Phys. J. C* **78** (2018) 537 [1711.06631].

[14] S. Catani, S. Devoto, M. Grazzini, S. Kallweit, J. Mazzitelli and H. Sargsyan, *Top-quark pair hadroproduction at next-to-next-to-leading order in QCD*, *Phys. Rev. D* **99** (2019) 051501 [1901.04005].

[15] "Repository with MATRIX code." https://matrix.hepforge.org/.

[16] T. Carli, D. Clements, A. Cooper-Sarkar, C. Gwenlan, G. P. Salam, F. Siegert et al., *A posteriori inclusion of parton density functions in NLO QCD final-state calculations at hadron colliders: The APPLGRID Project*, *Eur. Phys. J. C* **66** (2010) 503 [0911.2985].

[17] J. M. Campbell, R. K. Ellis and W. T. Giele, *A Multi-Threaded Version of MCFM*, *Eur. Phys. J. C* **75** (2015) 246 [1503.06182].

[18] D. Pagani, I. Tsinikos and M. Zaro, *The impact of the photon PDF and electroweak corrections on $t\bar{t}$ distributions*, *Eur. Phys. J. C* **76** (2016) 479 [1606.01915].

[19] J. M. Campbell, D. Wackeroth and J. Zhou, *Study of weak corrections to Drell-Yan, top-quark pair, and dijet production at high energies with MCFM*, *Phys. Rev. D* **94** (2016) 093009 [1608.03356].

[20] P. Nason, S. Dawson and R. K. Ellis, *The Total Cross-Section for the Production of Heavy Quarks in Hadronic Collisions*, *Nucl. Phys. B* **303** (1988) 607.

[21] W. Beenakker, H. Kuijf, W. L. van Neerven and J. Smith, *QCD Corrections to Heavy Quark Production in p anti-p Collisions*, *Phys. Rev. D* **40** (1989) 54.

[22] P. Nason, S. Dawson and R. K. Ellis, *The One Particle Inclusive Differential Cross-Section for Heavy Quark Production in Hadronic Collisions*, *Nucl. Phys. B* **327** (1989) 49.

[23] R. Meng, G. A. Schuler, J. Smith and W. L. van Neerven, *Simple Formulae for the Order $\alpha_s^3$ QCD Corrections to the Reaction $p\bar{p} \to Q\bar{Q}\,X$*, *Nucl. Phys. B* **339** (1990) 325.

[24] W. Beenakker, W. L. van Neerven, R. Meng, G. A. Schuler and J. Smith, *QCD corrections to heavy quark production in hadron hadron collisions*, *Nucl. Phys. B* **351** (1991) 507.

[25] M. L. Mangano, P. Nason and G. Ridolfi, *Heavy quark correlations in hadron collisions at next-to-leading order*, *Nucl. Phys. B* **373** (1992) 295.

[26] P. Bärnreuther, M. Czakon and A. Mitov, *Percent Level Precision Physics at the Tevatron: First Genuine NNLO QCD Corrections to $q\bar{q} \to t\bar{t} + X$*, *Phys. Rev. Lett.* **109** (2012) 132001 [1204.5201].

[27] M. Czakon and A. Mitov, *NNLO corrections to top-pair production at hadron colliders: the all-fermionic scattering channels*, *JHEP* **12** (2012) 054 [1207.0236].

[28] M. Czakon and A. Mitov, *NNLO corrections to top pair production at hadron colliders: the quark-gluon reaction*, *JHEP* **01** (2013) 080 [1210.6832].

[29] M. Czakon, P. Fiedler and A. Mitov, *Total Top-Quark Pair-Production Cross Section at Hadron Colliders Through $O(\alpha_S^4)$*, *Phys. Rev. Lett.* **110** (2013) 252004 [1303.6254].

[30] M. Czakon, D. Heymes and A. Mitov, *High-precision differential predictions for top-quark pairs at the LHC*, *Phys. Rev. Lett.* **116** (2016) 082003 [1511.00549].

[31] M. Czakon, P. Fiedler, D. Heymes and A. Mitov, *NNLO QCD predictions for fully-differential top-quark pair production at the Tevatron*, *JHEP* **05** (2016) 034 [1601.05375].

[32] S. Catani, S. Devoto, M. Grazzini, S. Kallweit and J. Mazzitelli, *Top-quark pair production at the LHC: Fully differential QCD predictions at NNLO*, *JHEP* **07** (2019) 100 [1906.06535].

[33] S. Catani, S. Devoto, M. Grazzini, S. Kallweit and J. Mazzitelli, *Top-quark pair hadroproduction at NNLO: differential predictions with the $\overline{MS}$ mass*, *JHEP* **08** (2020) 027 [2005.00557].

[34] W. Beenakker, A. Denner, W. Hollik, R. Mertig, T. Sack and D. Wackeroth, *Electroweak one loop contributions to top pair production in hadron colliders*, *Nucl. Phys. B* **411** (1994) 343.

[35] W. Bernreuther, M. Fücker and Z. G. Si, *Mixed QCD and weak corrections to top quark pair production at hadron colliders*, *Phys. Lett. B* **633** (2006) 54 [hep-ph/0508091].

[36] J. H. Kuhn, A. Scharf and P. Uwer, *Electroweak corrections to top-quark pair production in quark-antiquark annihilation*, *Eur. Phys. J. C* **45** (2006) 139 [hep-ph/0508092].

[37] W. Bernreuther, M. Fuecker and Z.-G. Si, *Weak interaction corrections to hadronic top quark pair production*, *Phys. Rev. D* **74** (2006) 113005 [hep-ph/0610334].

[38] J. H. Kuhn, A. Scharf and P. Uwer, *Electroweak effects in top-quark pair production at hadron colliders*, *Eur. Phys. J. C* **51** (2007) 37 [hep-ph/0610335].

[39] W. Hollik and M. Kollar, *NLO QED contributions to top-pair production at hadron collider*, *Phys. Rev. D* **77** (2008) 014008 [0708.1697].

[40] W. Bernreuther, M. Fucker and Z.-G. Si, *Weak interaction corrections to hadronic top quark pair production: Contributions from quark-gluon and b anti-b induced reactions*, *Phys. Rev. D* **78** (2008) 017503 [0804.1237].

[41] W. Bernreuther and Z.-G. Si, *Distributions and correlations for top quark pair production and decay at the Tevatron and LHC.*, *Nucl. Phys. B* **837** (2010) 90 [1003.3926].

[42] W. Hollik and D. Pagani, *The electroweak contribution to the top quark forward-backward asymmetry at the Tevatron*, *Phys. Rev. D* **84** (2011) 093003 [1107.2606].

[43] J. H. Kuhn and G. Rodrigo, *Charge asymmetries of top quarks at hadron colliders revisited*, *JHEP* **01** (2012) 063 [1109.6830].

[44] A. V. Manohar and M. Trott, *Electroweak Sudakov Corrections and the Top Quark Forward-Backward Asymmetry*, *Phys. Lett. B* **711** (2012) 313 [1201.3926].

[45] W. Bernreuther and Z.-G. Si, *Top quark and leptonic charge asymmetries for the Tevatron and LHC*, *Phys. Rev. D* **86** (2012) 034026 [1205.6580].

[46] J. H. Kühn, A. Scharf and P. Uwer, *Weak Interactions in Top-Quark Pair Production at Hadron Colliders: An Update*, *Phys. Rev. D* **91** (2015) 014020 [1305.5773].

[47] J. M. Campbell, D. Wackeroth and J. Zhou, *Electroweak Corrections at the LHC with MCFM*, *PoS* **DIS2015** (2015) 130 [1508.06247].

[48] A. Denner and M. Pellen, *NLO electroweak corrections to off-shell top-antitop production with leptonic decays at the LHC*, *JHEP* **08** (2016) 155 [1607.05571].

[49] M. Czakon, D. Heymes, A. Mitov, D. Pagani, I. Tsinikos and M. Zaro, *Top-pair production at the LHC through NNLO QCD and NLO EW*, *JHEP* **10** (2017) 186 [1705.04105].

[50] S. Carrazza, E. R. Nocera, C. Schwan and M. Zaro, *PineAPPL: combining EW and QCD corrections for fast evaluation of LHC processes*, *JHEP* **12** (2020) 108 [2008.12789].

[51] G. F. Sterman, *Summation of Large Corrections to Short Distance Hadronic Cross-Sections*, *Nucl. Phys. B* **281** (1987) 310.

[52] S. Catani and L. Trentadue, *Resummation of the QCD Perturbative Series for Hard Processes*, *Nucl. Phys. B* **327** (1989) 323.

[53] N. Kidonakis and G. F. Sterman, *Subleading logarithms in QCD hard scattering*, *Phys. Lett. B* **387** (1996) 867.

[54] N. Kidonakis and G. F. Sterman, *Resummation for QCD hard scattering*, *Nucl. Phys. B* **505** (1997) 321 [hep-ph/9705234].

[55] R. Bonciani, S. Catani, M. L. Mangano and P. Nason, *NLL resummation of the heavy quark hadroproduction cross-section*, *Nucl. Phys. B* **529** (1998) 424 [hep-ph/9801375].

[56] E. Laenen, G. Oderda and G. F. Sterman, *Resummation of threshold corrections for single particle inclusive cross-sections*, *Phys. Lett. B* **438** (1998) 173 [hep-ph/9806467].

[57] N. Kidonakis, *High order corrections and subleading logarithms for top quark production*, *Phys. Rev. D* **64** (2001) 014009 [hep-ph/0010002].

[58] C. W. Bauer, S. Fleming, D. Pirjol and I. W. Stewart, *An Effective field theory for collinear and soft gluons: Heavy to light decays*, *Phys. Rev. D* **63** (2001) 114020 [hep-ph/0011336].

[59] N. Kidonakis, E. Laenen, S. Moch and R. Vogt, *Sudakov resummation and finite order expansions of heavy quark hadroproduction cross-sections*, *Phys. Rev. D* **64** (2001) 114001 [hep-ph/0105041].

[60] C. W. Bauer, D. Pirjol and I. W. Stewart, *Soft collinear factorization in effective field theory*, *Phys. Rev. D* **65** (2002) 054022 [hep-ph/0109045].



PoS(LHCP2024)332

[61] M. Beneke, A. P. Chapovsky, M. Diehl and T. Feldmann, *Soft collinear effective theory and heavy to light currents beyond leading power*, Nucl. Phys. B **643** (2002) 431 [hep-ph/0206152].

[62] N. Kidonakis and R. Vogt, *Next-to-next-to-leading order soft gluon corrections in top quark hadroproduction*, Phys. Rev. D **68** (2003) 114014 [hep-ph/0308222].

[63] N. Kidonakis and R. Vogt, *The Theoretical top quark cross section at the Tevatron and the LHC*, Phys. Rev. D **78** (2008) 074005 [0805.3844].

[64] N. Kidonakis, *Two-loop soft anomalous dimensions and NNLL resummation for heavy quark production*, Phys. Rev. Lett. **102** (2009) 232003 [0903.2561].

[65] M. Czakon, A. Mitov and G. F. Sterman, *Threshold Resummation for Top-Pair Hadroproduction to Next-to-Next-to-Leading Log*, Phys. Rev. D **80** (2009) 074017 [0907.1790].

[66] V. Ahrens, A. Ferroglia, M. Neubert, B. D. Pecjak and L. L. Yang, *Threshold expansion at order $\alpha_s^4$ for the $t\bar{t}$ invariant mass distribution at hadron colliders*, Phys. Lett. B **687** (2010) 331 [0912.3375].

[67] V. Ahrens, A. Ferroglia, M. Neubert, B. D. Pecjak and L. L. Yang, *Renormalization-Group Improved Predictions for Top-Quark Pair Production at Hadron Colliders*, JHEP **09** (2010) 097 [1003.5827].

[68] M. Aliev, H. Lacker, U. Langenfeld, S. Moch, P. Uwer and M. Wiedermann, *HATHOR: HAdronic Top and Heavy quarks crOss section calculatoR*, Comput. Phys. Commun. **182** (2011) 1034 [1007.1327].

[69] N. Kidonakis, *Next-to-next-to-leading soft-gluon corrections for the top quark cross section and transverse momentum distribution*, Phys. Rev. D **82** (2010) 114030 [1009.4935].

[70] V. Ahrens, A. Ferroglia, M. Neubert, B. D. Pecjak and L.-L. Yang, *RG-improved single-particle inclusive cross sections and forward-backward asymmetry in $t\bar{t}$ production at hadron colliders*, JHEP **09** (2011) 070 [1103.0550].

[71] N. Kidonakis, *The top quark rapidity distribution and forward-backward asymmetry*, Phys. Rev. D **84** (2011) 011504 [1105.5167].

[72] V. Ahrens, A. Ferroglia, M. Neubert, B. D. Pecjak and L. L. Yang, *Precision predictions for the $t\bar{t}$ production cross section at hadron colliders*, Phys. Lett. B **703** (2011) 135 [1105.5824].

[73] M. Beneke, P. Falgari, S. Klein and C. Schwinn, *Hadronic top-quark pair production with NNLL threshold resummation*, Nucl. Phys. B **855** (2012) 695 [1109.1536].

[74] M. Cacciari, M. Czakon, M. Mangano, A. Mitov and P. Nason, *Top-pair production at hadron colliders with next-to-next-to-leading logarithmic soft-gluon resummation*, Phys. Lett. B **710** (2012) 612 [1111.5869].

[75] M. Czakon and A. Mitov, *Top++: A Program for the Calculation of the Top-Pair Cross-Section at Hadron Colliders*, Comput. Phys. Commun. **185** (2014) 2930 [1112.5675].

[76] A. Ferroglia, B. D. Pecjak and L. L. Yang, *Soft-gluon resummation for boosted top-quark production at hadron colliders*, Phys. Rev. D **86** (2012) 034010 [1205.3662].

[77] M. Beneke, P. Falgari, S. Klein, J. Piclum, C. Schwinn, M. Ubiali et al., *Inclusive Top-Pair Production Phenomenology with TOPIXS*, JHEP **07** (2012) 194 [1206.2454].

[78] A. Ferroglia, B. D. Pecjak, L. L. Yang, B. D. Pecjak and L. L. Yang, *The NNLO soft function for the pair invariant mass distribution of boosted top quarks*, JHEP **10** (2012) 180 [1207.4798].

[79] N. Kidonakis, *NNLL threshold resummation for top-pair and single-top production*, Phys. Part. Nucl. **45** (2014) 714 [1210.7813].

[80] A. Ferroglia, S. Marzani, B. D. Pecjak and L. L. Yang, *Boosted top production: factorization and resummation for single-particle inclusive distributions*, JHEP **01** (2014) 028 [1310.3836].

[81] N. Kidonakis, *NNNLO soft-gluon corrections for the top-antitop pair production cross section*, Phys. Rev. D **90** (2014) 014006 [1405.7046].

[82] N. Kidonakis, *NNNLO soft-gluon corrections for the top-quark $p_T$ and rapidity distributions*, Phys. Rev. D **91** (2015) 031501 [1411.2633].

[83] N. Kidonakis, *The top quark forward-backward asymmetry at approximate $N^3LO$*, Phys. Rev. D **91** (2015) 071502 [1501.01581].

[84] N. Kidonakis, *Top-quark double-differential distributions at approximate $N^3LO$*, Phys. Rev. D **101** (2020) 074006 [1912.10362].

[85] T.-J. Hou et al., *New CTEQ global analysis of quantum chromodynamics with high-precision data from the LHC*, Phys. Rev. D **103** (2021) 014013 [1912.10053].

[86] S. Bailey, T. Cridge, L. A. Harland-Lang, A. D. Martin and R. S. Thorne, *Parton distributions from LHC, HERA, Tevatron and fixed target data: MSHT20 PDFs*, Eur. Phys. J. C **81** (2021) 341 [2012.04684].

[87] J. McGowan, T. Cridge, L. A. Harland-Lang and R. S. Thorne, *Approximate $N^3LO$ parton distribution functions with theoretical uncertainties: MSHT20a$N^3$LO PDFs*, Eur. Phys. J. C **83** (2023) 185 [2207.04739].

[88] NNPDF collaboration, *The path to proton structure at 1% accuracy*, Eur. Phys. J. C **82** (2022) 428 [2109.02653].

[89] ATLAS collaboration, *Measurement of the $t\bar{t}$ production cross-section in pp collisions at $\sqrt{s}$ = 5.02 TeV with the ATLAS detector*, JHEP **06** (2023) 138 [2207.01354].

[90] CMS collaboration, *Measurement of the inclusive* $t\bar{t}$ *production cross section in proton-proton collisions at* $\sqrt{s} = 5.02$ *TeV*, *JHEP* **04** (2022) 144 [2112.09114].

[91] ATLAS, CMS collaboration, *Combination of inclusive top-quark pair production cross-section measurements using ATLAS and CMS data at* $\sqrt{s} = 7$ *and 8 TeV*, *JHEP* **07** (2023) 213 [2205.13830].

[92] ATLAS collaboration, *Inclusive and differential cross-sections for dilepton* $t\bar{t}$ *production measured in* $\sqrt{s} = 13$ *TeV pp collisions with the ATLAS detector*, *JHEP* **07** (2023) 141 [2303.15340].

[93] J. Alwall, R. Frederix, S. Frixione, V. Hirschi, F. Maltoni, O. Mattelaer et al., *The automated computation of tree-level and next-to-leading order differential cross sections, and their matching to parton shower simulations*, *JHEP* **07** (2014) 079 [1405.0301].

[94] R. Frederix, S. Frixione, V. Hirschi, D. Pagani, H. S. Shao and M. Zaro, *The automation of next-to-leading order electroweak calculations*, *JHEP* **07** (2018) 185 [1804.10017].

PoS(LHCP2024)332