

Compatibility between theoretical predictions and experimental data for top-antitop hadroproduction at NNLO QCD accuracy

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We compare double-differential normalized production cross sections for top-antitop +X hadroproduction at NNLO QCD accuracy, as obtained through a customized version of the MATRIX framework interfaced to PineAPPL, with recent data by the ATLAS and CMS collaborations.

We take into account theory uncertainties due to scale variation and we see how predictions vary as a function of parton distribution function (PDF) choice and top-quark pole mass value, considering different state-of-the-art PDF fits with their uncertainties.

Notwithstanding the overall reasonable good agreement, we observe discrepancies at the level of a few σ 's between data and theoretical predictions in some kinematical regions, which can be alleviated by refitting the top-quark mass value, and/or the PDFs and/or $\alpha_s(M_Z)$, considering the correlations between these three quantities.

In a fit of top-quark mass standalone, we notice that, for all considered PDF + $\alpha_s(M_Z)$ sets used as input, some datasets point towards top-quark pole mass values lower by about 2σ 's than those emerging from fitting other datasets, suggesting a possible tension between experimental measurements using different decay channels, and/or the need of better estimating uncertainties on the latter.

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1. Introduction

Top-quark measurements at the Large Hadron Collider (LHC) play a crucial role in modern particle physics in order to precisely extract key parameters of the Standard Model (SM). Furthermore, they provide insights into the electroweak symmetry breaking mechanism and are a vital component of searches for physics beyond the SM.

The present study aims at the determination of the top-quark mass, here extracted from a comparison of inclusive and differential cross-section data for $t\bar{t} + X$ production collected by the LHC experiments ATLAS and CMS with theoretical predictions including higher-order corrections in quantum chromodynamics (QCD) and computed for the top-quark mass in the on-shell renormalization scheme, m_t^{pole} . We use a customized version of MATRIX [1, 2], optimized for the $pp \rightarrow t\bar{t} + X$ process and interfaced to PineAPPL [3], for the computation of all NNLO QCD theory predictions with NNLO QCD uncertainties (without utilizing K -factors and any further approximation linking NNLO results to lower-order ones). These are the first fits of m_t^{pole} with exact NNLO accuracy using LHC double-differential $t\bar{t} + X$ data, to the best of our knowledge.

2. Modified MATRIX+PineAPPL framework for theoretical calculations

We started from the MATRIX version used for the computations presented in Ref. [1] and we performed a number of optimizations in the program flow and execution. A few per mill accuracy requires the generation of various billions of $t\bar{t} + X$ NNLO events, which takes $O(10^5)$ CPU hours. A general solution to this problem is to use interpolation grids, where partonic matrix elements are stored in such a way that they can be convoluted later with any (PDF + $\alpha_s(M_Z)$) set. We choose the PineAPPL library [3] which is capable of generating grids and dealing with them in an accurate way to any fixed order in the strong and electroweak couplings, and which supports variations of the renormalization and factorization scales, μ_r and μ_f .

In order to validate our implementation of the interface to PineAPPL, we compared the genuine theoretical predictions from MATRIX with those obtained using the PineAPPL interpolation grids and found them to agree within a few per mill. We also compared our theoretical predictions with those from Ref. [4] and found them to agree within the $\approx 1\%$ uncertainties of the latter. Based on these validation studies, we assign a 1% uncorrelated uncertainty in each bin of our predictions.

3. NNLO fits of the top-quark pole mass value

For our analysis, we use measurements of the absolute total and normalized differential inclusive $t\bar{t} + X$ cross sections. We collect all available and up-to-date ATLAS and CMS measurements of total $t\bar{t} + X$ cross sections which appear on the summary plot of the total $t\bar{t} + X$ cross sections by the LHC Top working group as of June 2023 [6]. For differential measurements, we choose cross sections as a function of the invariant mass of the $t\bar{t}$ pair, $M(t\bar{t})$, and, if available, double-differential cross sections as a function of $M(t\bar{t})$ and rapidity $|y(t\bar{t})|$ of the $t\bar{t}$ pair [5, 7–13]. We use four state-of-the-art NNLO proton PDF + $\alpha_s(M_Z)$ sets as input of the theory computations: ABMP16 [14], CT18 [15], MSHT20 [16] and NNPDF4.0 [17].

As an example of data-to-theory comparison, in Fig. 1 the rapidity distribution of the $t\bar{t}$ -quark pair, $|y(t\bar{t})|$, is plotted in various $t\bar{t}$ invariant mass $M(t\bar{t})$ bins, corresponding to different panels, and

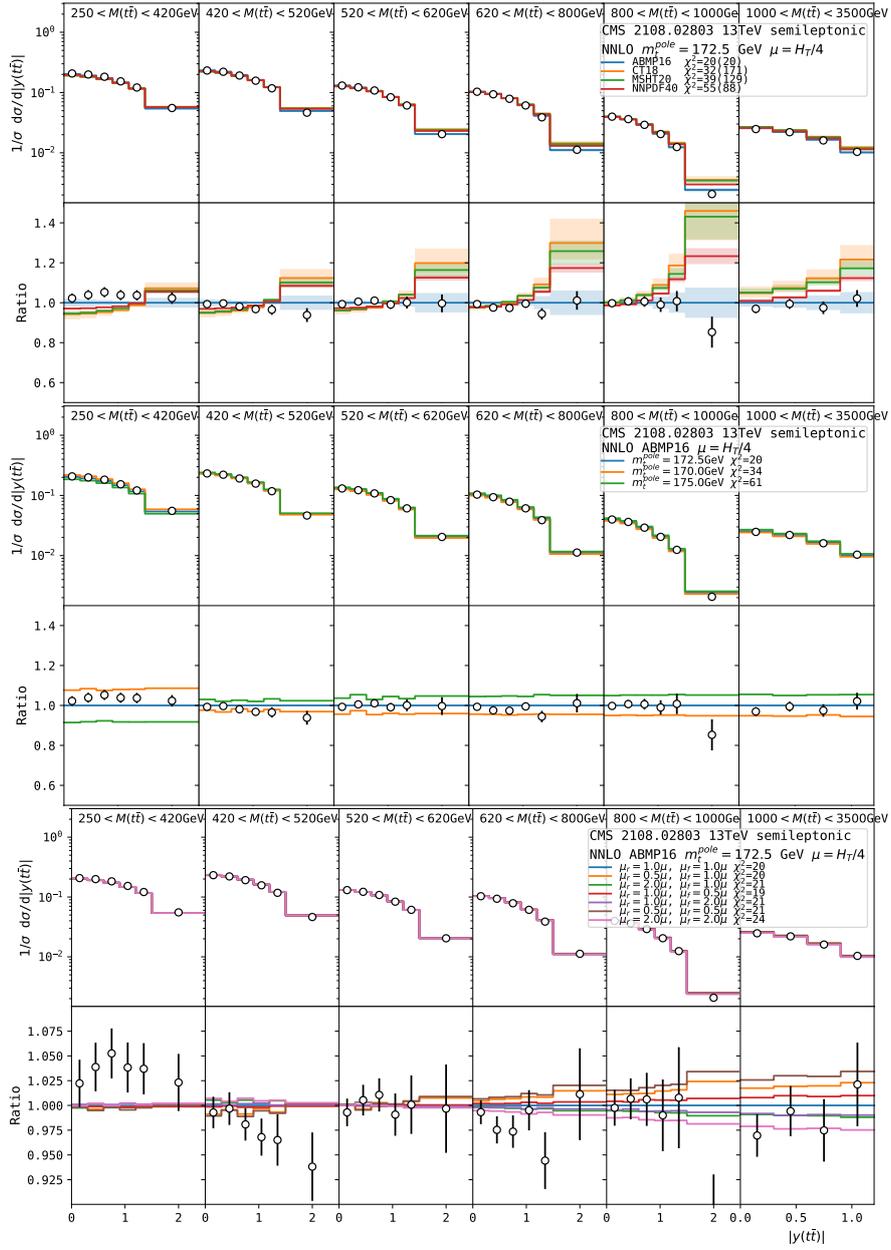


Figure 1: Comparison of the experimental data from Ref. [5] to the NNLO predictions obtained using different PDF sets (upper), and, for the ABMP16 central PDF member, different m_t^{pole} values (middle) and different μ_R, μ_F scales varied by factor of two around the central value $\mu_{R,0} = \mu_{F,0} = \mu_0 = H_T/4$ (lower).

compared to the experimental data of Ref. [5], a state-of-the-art CMS analysis with $t\bar{t}$ -quark pairs decaying in the semileptonic channel. From the first row of plots, it emerges that the best agreement between theoretical predictions and experimental data as for the shape of the distributions, that is probed when considering normalized cross-sections, is achieved when using the ABMP16 PDFs. Predictions with the CT18, MSHT20 and NNPDF4.0 PDFs show a similar trend among each other, but shapes systematically different from those of the experimental distributions at large $|y(t\bar{t})|$, overestimating them. The plots of the second row, all obtained with the ABMP16 PDFs, show that

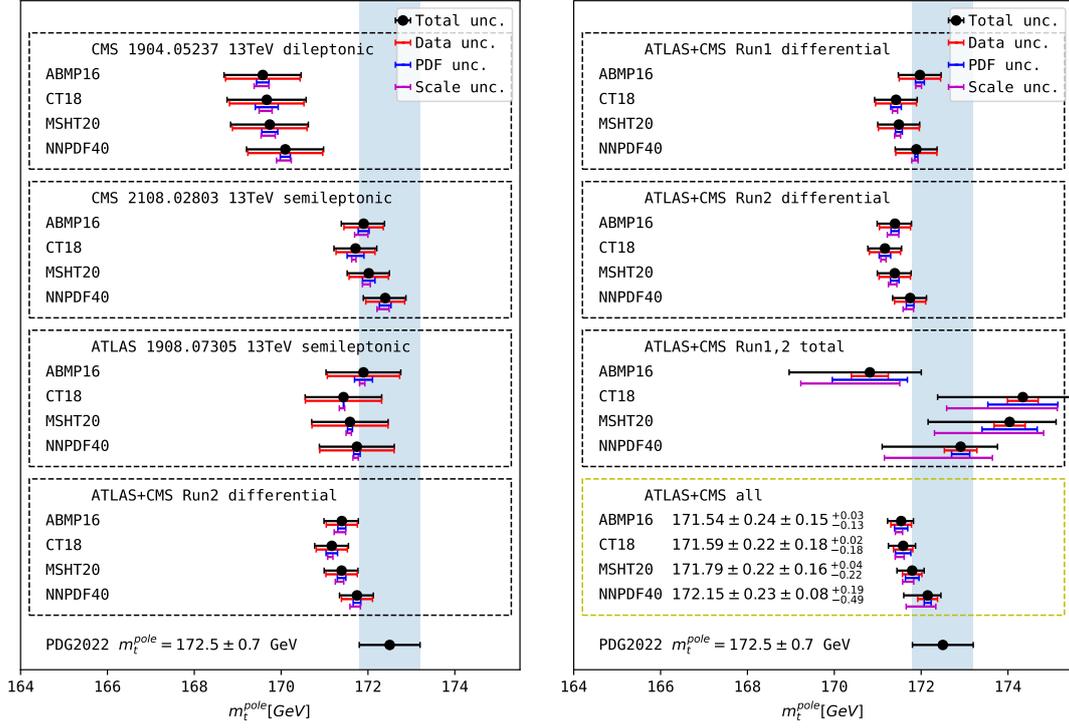


Figure 2: Summary of the m_t^{pole} values extracted from Run2 measurements of differential cross sections (left), and Run1 and Run2 measurements of differential and total $t\bar{t} + X$ cross sections (right). We assign as scale uncertainty the maximum difference on m_t^{pole} from the 7-point (μ_R, μ_F) variation.

the largest is m_t^{pole} , varied in the range $170 \text{ GeV} < m_t^{\text{pole}} < 175 \text{ GeV}$, the smallest is the cross-section for low $M(t\bar{t})$ close to threshold, while the opposite is true for large $M_{t\bar{t}} > 420 \text{ GeV}$ because of the cross-section normalization. The plots of the third row show the behaviour of the $|y(t\bar{t})|$ distribution under (μ_R, μ_F) variation. Scale uncertainties increase at large $M(t\bar{t})$, reaching values up to $\pm 3\%$ in the largest $M(t\bar{t})$ bin, an amount comparable to data uncertainties in this kinematic region.

The m_t^{pole} fits were then performed using the xFitter framework [18], an open source QCD fit framework. In Fig. 2 the results for the m_t^{pole} extraction from various experimental datasets are shown. In the left panel, results related to individual Run 2 measurements of differential $t\bar{t} + X$ cross sections are shown separately, while the right panel reports the results of the global fit, including both total and differential cross-section Run 1 and 2 data. The results of the extraction using either differential or total cross sections agree with each other within $\approx 1\sigma$, for any PDF set. The compatibility of the results obtained is a sign of their robustness. We observe that data related to $t\bar{t}$ decays in the dileptonic channel (Refs. [7, 10]) point towards central m_t^{pole} values smaller than data related to decays in the semileptonic channel (Refs. [5, 8]). The values extracted from all ATLAS and all CMS differential measurements are compatible within 2.5σ , and the same level of compatibility is observed for the results extracted from the measurements either in the dileptonic or in the semileptonic $t\bar{t}$ decay channels. In both cases, the difference arises almost entirely from the CMS measurements of Refs. [7, 10] which point to a central value of m_t^{pole} lower than all other measurements. More detail is available in Ref. [19].

4. Conclusions

In summary, adding the differential data to the m_t^{pole} fit only including total $t\bar{t} + X$ cross sections plays a crucial role in decreasing the uncertainties on m_t^{pole} by a factor of ~ 3 . The result of the most comprehensive fit has an uncertainty band ranging from 0.3 to 0.5 GeV, depending on the PDF set. These uncertainties are a factor 2.5 smaller than those of the most recent average presented in the PDG [20], $m_t^{\text{pole}} = 172.5 \pm 0.7$ GeV. One should also observe that uncertainties related to the data used have similar size to (scale + PDF variation) uncertainty at fixed PDF set. We expect that forthcoming experimental data from Run 3 and Run 4 will seriously challenge theoretical capabilities of reducing theory uncertainties to a similar level as well.

Our present work can be regarded as a proof-of-principle that a simultaneous fit of m_t^{pole} , PDFs and $\alpha_s(M_Z)$ at NNLO accuracy, considering the correlations among them and using state-of-the-art total and multi-differential $t\bar{t}$ production data, is within reach. We plan to perform such a fit in a next work, upgrading the precision and accuracy of the NLO fit results we presented in Ref. [21].

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References

- [1] 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].
- [2] M. Grazzini, S. Kallweit and M. Wiesemann, *Fully differential NNLO computations with MATRIX*, *Eur. Phys. J. C* **78** (2018) 537 [1711.06631].
- [3] 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].
- [4] M. Czakon, D. Heymes and A. Mitov, *Dynamical scales for multi-TeV top-pair production at the LHC*, *JHEP* **04** (2017) 071 [1606.03350].
- [5] 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].
- [6] LHC Top Physics Working Group
<https://twiki.cern.ch/twiki/bin/view/LHCPhysics/LHCTopWGSummaryPlots>.
Accessed: 2023-07-27.
- [7] CMS collaboration, *Measurement of $t\bar{t}$ normalised multi-differential cross sections in pp collisions at $\sqrt{s} = 13$ TeV, and simultaneous determination of the strong coupling strength, top quark pole mass, and parton distribution functions*, *Eur. Phys. J. C* **80** (2020) 658 [1904.05237].

- [8] ATLAS collaboration, *Measurements of top-quark pair differential and double-differential cross-sections in the ℓ +jets channel with pp collisions at $\sqrt{s} = 13$ TeV using the ATLAS detector*, *Eur. Phys. J. C* **79** (2019) 1028 [[1908.07305](#)].
- [9] 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](#)].
- [10] CMS collaboration, *Measurement of double-differential cross sections for top quark pair production in pp collisions at $\sqrt{s} = 8$ TeV and impact on parton distribution functions*, *Eur. Phys. J. C* **77** (2017) 459 [[1703.01630](#)].
- [11] ATLAS collaboration, *Measurements of top-quark pair differential cross-sections in the lepton+jets channel in pp collisions at $\sqrt{s} = 8$ TeV using the ATLAS detector*, *Eur. Phys. J. C* **76** (2016) 538 [[1511.04716](#)].
- [12] ATLAS collaboration, *Measurement of top quark pair differential cross-sections in the dilepton channel in pp collisions at $\sqrt{s} = 7$ and 8 TeV with ATLAS*, *Phys. Rev. D* **94** (2016) 092003 [[1607.07281](#)].
- [13] ATLAS collaboration, *Measurements of normalized differential cross sections for $t\bar{t}$ production in pp collisions at $\sqrt{s} = 7$ TeV using the ATLAS detector*, *Phys. Rev. D* **90** (2014) 072004 [[1407.0371](#)].
- [14] S. Alekhin, J. Blümlein, S. Moch and R. Placakyte, *Parton distribution functions, α_s , and heavy-quark masses for LHC Run II*, *Phys. Rev. D* **96** (2017) 014011 [[1701.05838](#)].
- [15] 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](#)].
- [16] 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](#)].
- [17] NNPDF collaboration, *The path to proton structure at 1% accuracy*, *Eur. Phys. J. C* **82** (2022) 428 [[2109.02653](#)].
- [18] S. Alekhin et al., *HERAFitter*, *Eur. Phys. J. C* **75** (2015) 304 [[1410.4412](#)].
- [19] M.V. Garzelli, J. Mazzitelli, S.O. Moch and O. Zenaiev, *Top-quark pole mass extraction at NNLO accuracy, from total, single- and double-differential cross sections for $t\bar{t} + X$ production at the LHC*, [2311.05509](#).
- [20] PARTICLE DATA GROUP collaboration, *Review of Particle Physics*, *PTEP* **2022** (2022) 083C01.
- [21] M.V. Garzelli, L. Kemmler, S. Moch and O. Zenaiev, *Heavy-flavor hadro-production with heavy-quark masses renormalized in the $\overline{\text{MS}}$, MSR and on-shell schemes*, *JHEP* **04** (2021) 043 [[2009.07763](#)].