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Measurements with top quarks at the LHC

Joscha Knolle on behalf of the ATLAS and CMS Collaborations

Abstract

The top quark, the heaviest known elementary particle, plays a crucial role in advancing our understanding of fundamental physics. In this contribution, the latest measurements of top quark production and properties from the ATLAS and CMS experiments at the LHC are discussed. Key results include precise inclusive and differential cross section measurements of top quark pair production, single top quark production, and associated production channels at different centre-of-mass energies and using different collision systems. A recent highlight is also the observation of quantum entanglement between top quark pairs.

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Measurements with top quarks at the LHC

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The top quark, the heaviest known elementary particle, plays a crucial role in advancing our understanding of fundamental physics. In this contribution, the latest measurements of top quark production and properties from the ATLAS and CMS experiments at the LHC are discussed. Key results include precise inclusive and differential cross section measurements of top quark pair production, single top quark production, and associated production channels at different centre-of-mass energies and using different collision systems. A recent highlight is also the observation of quantum entanglement between top quark pairs.

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1. Introduction

With a mass of 172.52 ± 0.33 GeV [1], the top quark is the heaviest known elementary particle, and the study of its properties plays a crucial role in advancing our understanding of fundamental particle physics. The ATLAS [2, 3] and CMS [4, 5] experiments at the CERN LHC have each collected about $140\,\mathrm{fb}^{-1}$ of proton-proton (pp) collision data at a centre-of-mass energy $\sqrt{s} = 13$ TeV during the LHC Run 2 (2015–2018). This data set contains more than 100 million top quark pair ($\mathrm{t\bar{t}}$) events, facilitating precision cross section measurements of top quark processes. Top quark production has also been measured in all Run 2 heavy-ion physics runs: PbPb and pp collisions at nucleon-nucleon centre-of-mass energy $\sqrt{s_{\mathrm{NN}}} = 5.02$ TeV, and pPb collisions at $\sqrt{s_{\mathrm{NN}}} = 8.16$ TeV. Since 2022, the experiments record pp collisions at $\sqrt{s} = 13.6$ TeV, and have performed first top quark cross section measurements with this Run 3 data set.

In this contribution, recent results on standard model (SM) measurements of top quark physics performed by the ATLAS and CMS Collaborations are presented [6–19]. Reviews of the programmes of the two experiments on top quark cross section measurements are also provided in Refs. [20, 21].

2. Differential cross section measurements of $\mathrm{t\bar{t}}$ production

Differential $\mathrm{t\bar{t}}$ cross section measurements have been performed with the full Run 2 data set, where the latest results were obtained by ATLAS in the lepton+jets channel [6] and by CMS in the dilepton channel [7]. The ATLAS measurement focuses in particular on properties of jets originating either from top quark decays or from additional gluons, whereas the CMS measurement targets properties of the dineutrino system. Example differential cross sections from the two measurements are shown in Fig. 1.

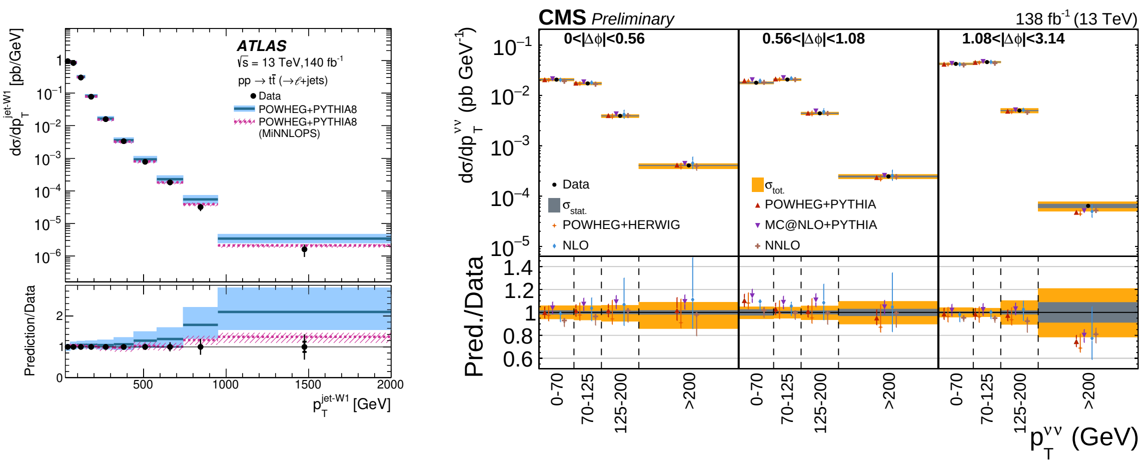

Figure 1: Left: Measured differential $\mathrm{t\bar{t}}$ cross section in the lepton+jets channel as a function of the leading W boson jet p_{T} (from the ATLAS result in Ref. [6]). Right: Measured 2D differential $\mathrm{t\bar{t}}$ cross section in the dilepton channel as a function of the dineutrino p_{T} and the smaller angle between one of the two leptons and the dineutrino system (from the CMS result in Ref. [7]).

In the ATLAS measurement, events are selected with exactly one electron or muon and at least four jets, of which at least two are b tagged. The pseudo-top algorithm is employed for the kinematic reconstruction of the tt̄ system. Three fiducial regions are defined: inclusive tt̄ production, and tt̄ production with one or two additional jets. Important uncertainties are from b tagging, detector energy scale and resolution, and background normalization. The measured differential cross sections are compared to predictions obtained with different MC generators and parton showers, where no single prediction provides a good description of all observables.

In the CMS measurement, events are selected with exactly two electrons and/or muons and at least two jets, of which at least one is b tagged. A deep neural network is employed to reduce the bias and improve the resolution of the reconstructed missing transverse momentum in the tt̄ dilepton phase space. Leading uncertainties are from jet energy resolution, lepton reconstruction, and tW modelling. The measured differential cross sections are compared to predictions obtained with different MC generators and parton showers, as well as dedicated theory calculations at NLO and NNLO accuracy, with generally good agreement.

3. Measurements of tt̄ production in heavy-ion collisions

Measuring tt̄ production in different collision systems and at different collision energies provides important inputs for the estimation of proton and nuclear parton distribution functions (PDFs). The latest results were obtained by ATLAS in pPb collisions at 8.16 TeV [8] and by CMS in pp collisions at 5.02 TeV [9][1]. The pPb data set was recorded in 2016 and corresponds to an integrated luminosity of 165 nb^{-1}. The analysed pp data set was recorded in 2017 and corresponds to an integrated luminosity of 302 pb^{-1}, with an average pileup of 2, much lower than in the 13 TeV data sets. Example distributions from the two measurements are shown in Fig. 2.

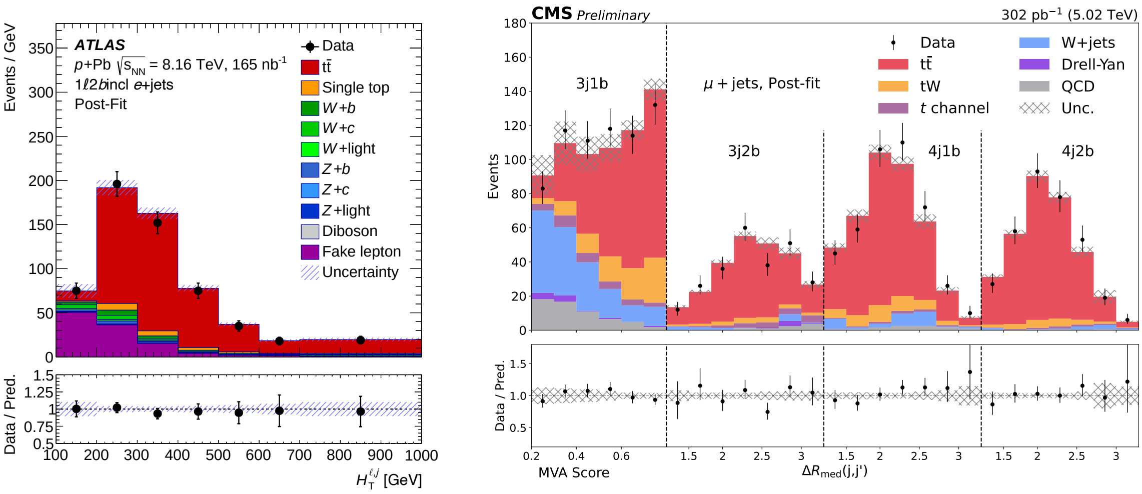

Figure 2: Left: Distribution of the scalar sum of the p_{T} of leptons and jets in the electron+jets channel with at least two b jets of the tt̄ production measurement using pPb collisions at 8.16 TeV (from the ATLAS result in Ref. [8]). Right: Distributions of the MVA score for the 3j1b category and of the median ΔR between any two jets for the other categories in the muon+jets channel of the tt̄ production measurement using pp collisions at 5.02 TeV (from the CMS result in Ref. [9]).

In the ATLAS measurement, two decay channels are analysed: events with exactly one electron or muon and at least four jets are selected for the lepton+jets channel, and events with exactly two

[1] The presented result has been superseded by Ref. [22].

electrons and/or muons and at least two jets are selected for the dilepton channel. In both cases, at least one of the jets is required to be b tagged, and the events are further categorized by the b jet multiplicity and (in the lepton+jets channel) by the lepton flavour. Leading uncertainties are from the jet energy scale and $t\bar{t}$ modelling. The $t\bar{t}$ cross section is measured to be 58.1 ± 5.1 nb, in agreement with the SM prediction. Analysing the two decay channels separately, the observation of $t\bar{t}$ production is established with a significance of more than five standard deviations above the background-only hypothesis in both cases.

In the CMS measurement, the lepton+jets channel is analysed by selecting events with exactly one electron or muon and at least three jets, of which at least one is b tagged. Events are categorized by jet and b jet multiplicity and lepton flavour. In the 3j1b category, which has the largest event yield but also the highest background fraction, a multivariate analysis (MVA) discriminate is trained to separate signal and background. Leading uncertainties are from b tagging, $t\bar{t}$ modelling, and trigger efficiency. The analysis is combined with an earlier measurement in the dilepton channel using the same data set, and the $t\bar{t}$ cross section is measured to be 61.2 ± 3.2 pb. The result is consistent with the SM prediction within two standard deviations.

4. Observation of entanglement in $t\bar{t}$ events

The $t\bar{t}$ production process in pp collisions can result in entangled top quark pairs, specifically in the phase space with either very low or very high $t\bar{t}$ invariant mass $m(t\bar{t})$. This entanglement can be probed by measuring the spin correlations between the top quarks. Results were obtained by ATLAS in the dilepton channel with the full Run 2 data set [10], by CMS in the dilepton channel with a partial Run 2 data set [11], and by CMS in the lepton+jets channel with the full Run 2 data set [12]. The measurements in the dilepton channel focus on a phase space with low $m(t\bar{t})$, whereas entanglement is probed in the lepton+jets channel both at low and high $m(t\bar{t})$. Example results for the entanglement markers are shown in Fig. 3.

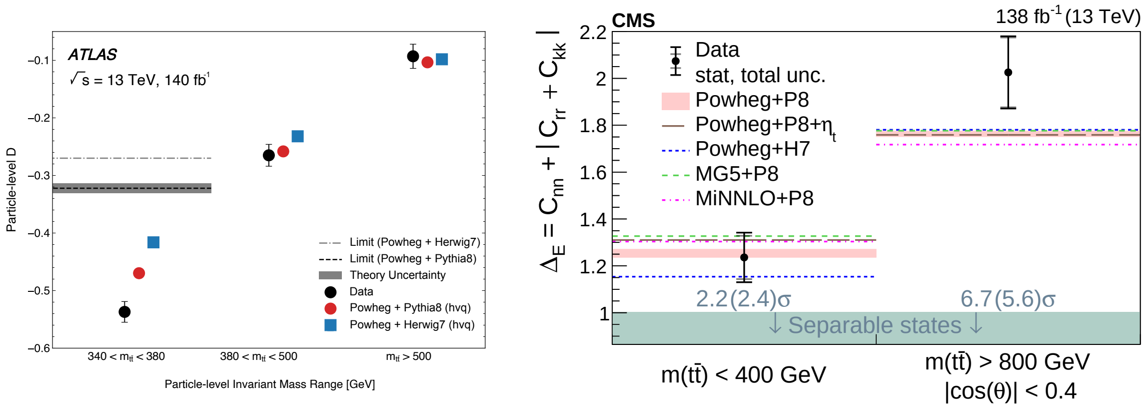

Figure 3: Left: Measured particle-level values of the entanglement marker for different $t\bar{t}$ invariant mass ranges in the dilepton channel of $t\bar{t}$ production, with dashed lines for different predictions marking the limit below which the $t\bar{t}$ system is entangled (from the ATLAS result in Ref. [10]). Right: Parton-level values of the entanglement marker extracted from the full matrix measurement for different $t\bar{t}$ invariant mass ranges in the lepton+jets channel of $t\bar{t}$ production, with values larger than unity indicating entanglement (from the CMS result in Ref. [12]).

The ATLAS measurement in the dilepton channel selects events with exactly one electron, exactly one muon, and at least two jets, of which at least one is b tagged. The measurement is performed in a phase space with $340 < m(\mathrm{t\bar{t}}) < 380\,\mathrm{GeV}$, and entanglement is observed in this phase space with a significance of more than five standard deviations.

The CMS measurement in the dilepton channel selects events with exactly two electrons and/or muons and at least two jets, of which at least one is b tagged. The measurement is performed in a phase space with $345 < m(\mathrm{t\bar{t}}) < 400\,\mathrm{GeV}$ with an additional requirement on the longitudinal boost of the $\mathrm{t\bar{t}}$ system of $\beta_z(\mathrm{t\bar{t}}) < 0.9$. Entanglement is observed in this phase space with a significance of more than five standard deviations, and better agreement with the prediction is found when a simplified model for a quasi-bound-state at the $\mathrm{t\bar{t}}$ threshold is included in the analysis[2].

The CMS measurement in the lepton+jets channel selects events with exactly one electron or muon and at least four jets, of which at least one is b tagged. Different phase spaces are probed, and entanglement is observed, e.g., in the phase space with $m(\mathrm{t\bar{t}}) > 800\,\mathrm{GeV}$ and a top quark production angle of $|\cos(\theta)| < 0.4$ with a significance of more than five standard deviations.

5. Measurements of $\mathrm{t\bar{t}}$ production with additional heavy-flavour jets

Additional heavy-flavour jets in $\mathrm{t\bar{t}}$ events can originate from gluon radiation with subsequent splitting $\mathrm{g} \longrightarrow \mathrm{b\bar{b}}$ or $\mathrm{c\bar{c}}$, or as initial-state quarks that radiate off a gluon for the $\mathrm{t\bar{t}}$ production process. The latest results were obtained by ATLAS with the full Run 2 data set for $\mathrm{t\bar{t}+b}$ [14] and $\mathrm{t\bar{t}+c}$ [15]. Both results include several fiducial cross section measurements, and the $\mathrm{t\bar{t}+b}$ result also presents differential cross sections. Example results of the two measurements are shown in Fig. 4.

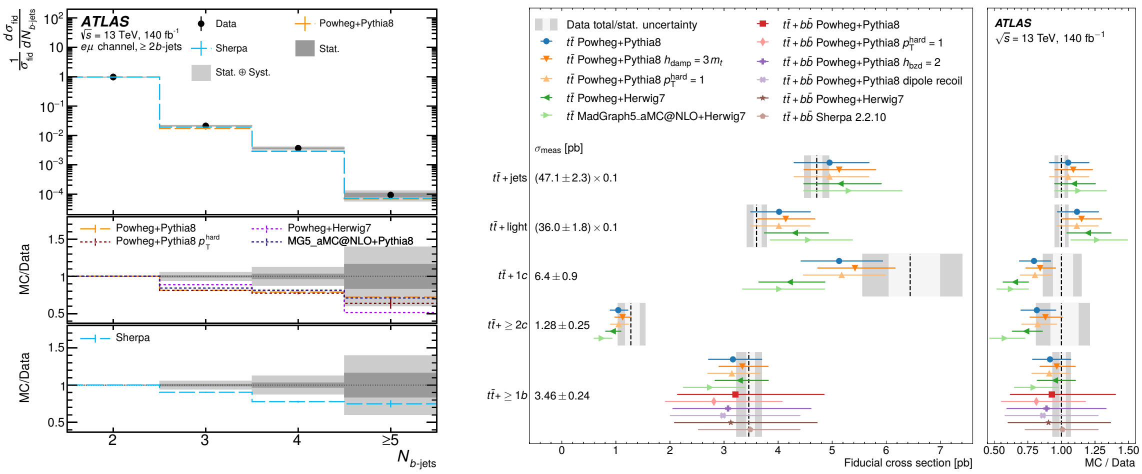

Figure 4: Left: Measured normalized differential $\mathrm{t\bar{t}}$ cross section in the dilepton channel as a function of the number of b jets (from the ATLAS result in Ref. [14]). Right: Measured fiducial cross sections of $\mathrm{t\bar{t}}$ production in association with additional light- or heavy-flavour jets in the combined lepton+jets and dilepton channel (from the ATLAS result in Ref. [15]).

[2] A recent CMS result on searches for heavy additional Higgs bosons decaying to $\mathrm{t\bar{t}}$ in the lepton+jets and dilepton channels and using spin correlation variables found an excess at the $\mathrm{t\bar{t}}$ threshold with a significance of more than five standard deviations that is well described by this simplified model [13]. Further investigations are required to understand the exact nature of this excess.

In the $t\bar{t}+b$ measurement, events are selected with exactly one electron, exactly one muon, and at least two jets, of which at least two are b tagged. Fiducial cross sections are measured for eμ production together with at least three b jets, at least three b jets and at least one c or light jet, at least four b jets, or at least four b jets and at least one c or light jet. The measured cross sections are generally better described by dedicated $t\bar{t}b\bar{b}$ simulations than $t\bar{t}$ simulation with additional heavy-flavour jets generated in the parton shower simulation. Differential cross sections are measured as functions of 39 observables, for different fiducial region definitions. No single prediction is able to describe all distributions well.

The $t\bar{t}+c$ measurement includes both the lepton+jets and dilepton channels of the $t\bar{t}$ system. A dedicated scheme for b and c jet tagging is applied. In the lepton+jets channel, events are selected with exactly one electron or muon and at least five jets, of which at least three are b or c tagged. In the dilepton channel, events are selected with exactly two electrons and/or muons and at least three jets, of which at least two are b or c tagged. Fiducial cross sections are measured for $t\bar{t}$ production with additional jets, additional light jets, exactly one additional c jet, at least two additional c jets, or at least one additional b jet. The measured $t\bar{t}+c$ cross sections are underestimated by inclusive $t\bar{t}$ predictions (no dedicated $t\bar{t}c\bar{c}$ predictions are available). The measured $t\bar{t}+b$ cross section is compatible with the result of the dedicated analysis.

6. Single top quark production in the tW channel

The tW process provides sensitivity to the CKM matrix element V_{tb} and to the b quark PDFs. The modelling of this process is challenging since NLO real-emission contributions result in an overlap with $t\bar{t}$ production, resulting in the need for an overlap removal between tW and $t\bar{t}$ samples. The latest measurements of tW production were performed by ATLAS using the full Run 2 data set [16] and by CMS using a partial Run 3 data set [17]. The ATLAS result provides an inclusive cross section measurement at 13 TeV and focuses on understanding systematic uncertainties related to $t\bar{t}$ and tW modelling; the fit distributions are shown in Fig. 5 (left). The CMS result, based on 34.7 fb^{-1} of data recorded at 13.6 TeV in 2022, includes both inclusive and differential cross section measurements, an example of which is shown in Fig. 5 (right).

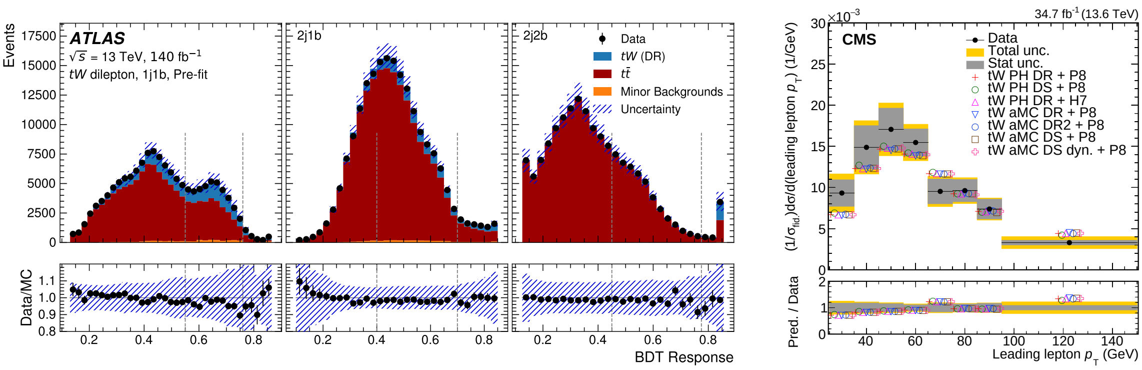

Figure 5: Left: Distributions of the BDT score for different jet and b jet multiplicity categories in the dilepton channel of the tW production measurement at 13 TeV (from the ATLAS result in Ref. [16]). Right: Measured normalized differential cross section of tW production in the dilepton channel at 13.6 TeV as a function of the leading lepton p_T (from the CMS result in Ref. [17]).

In the ATLAS measurement, events are selected with exactly one electron, exactly one muon, and one or two jets, of which at least one is b tagged. Events are grouped into three categories based on the number of jets and b-tagged jets: 1j1b, 2j2b, and 2j2b. In each category, a boosted decision tree (BDT) discriminant is trained to separate between tW and $t\bar{t}$ production. Following dedicated studies of the impact of the tW overlap removal scheme and the $t\bar{t}$ parton shower variation on the BDT score distribution, the range included in the fit is restricted in order to reduce the impact of and constraints on these uncertainties. The tW cross section is measured to be 75 ± 15 pb, in agreement with the SM prediction.

In the CMS measurement, events are selected with at least one electron and at least one muon. For the inclusive cross section measurement, the same event categories as in the ATLAS measurement are used, and random forest multiclassification discriminants are trained to distinguish between tW and the two respective dominant background processes in the 1j1b and 2j2b categories. The tW cross section is measured to be 82 ± 11 pb, in agreement with the SM prediction. For the differential cross section measurements, only events in the 1j1b category with an additional veto on further low-p_T jets is used. Particle-level differential cross section as functions of six observables are obtained.

7. Top quark production in association with neutral vector bosons

Measurements of top quark production in association with a photon or Z boson provide important probes of the electroweak couplings of the top quark. The latest result by CMS is a simultaneous measurement of $t\bar{t}Z$, tWZ, and tZq [18][3], and the latest result by ATLAS a measurement of $t\bar{t}\gamma$ [19]. Both analyses are based on the full Run 2 data set, and measure both inclusive and differential cross sections. Example results of the measured differential cross sections are shown in Fig. 6.

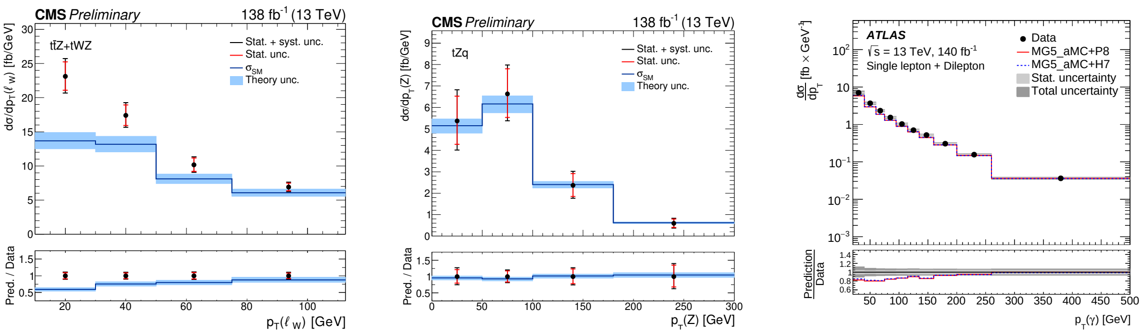

Figure 6: Left: Measured differential $t\bar{t}Z + tWZ$ cross section as a function of the W boson lepton p_T (from the CMS result in Ref. [18][4]). Centre: Measured differential tZq cross section as a function of the Z boson p_T (from the CMS result in Ref. [18]). Right: Measured differential $t\bar{t}\gamma$ production cross section as a function of the photon p_T (from the ATLAS result in Ref. [19]).

In the CMS measurement, events are selected with exactly three electrons and/or muons and at least two jets, of which at least one is b tagged. Two leptons are required to form an opposite-sign

[3] The presented result has been superseded by Ref. [23].

[4] Due to a change in nonprompt-lepton background uncertainties, the updated result in Ref. [23] has a less significant discrepancy between measured and predicted differential cross section as a function of $p_T(\ell_W)$.

same-flavour lepton pair with invariant mass close to the Z boson mass. Given the overlap between tWZ and $t\bar{t}Z$ at NLO (similar to the tW and $t\bar{t}$ overlap), the combination $t\bar{t}Z + tWZ$ is treated as a single signal process. A multiclass deep neural network is employed to separate $t\bar{t}Z + tWZ$ as first signal process, tZq as second signal process, and background contributions. The event selection is split into three classes, depending on which output score is the highest. For the inclusive cross section measurement, also an event selection with exactly four electrons and/or muons is included. The inclusive $t\bar{t}Z + tWZ$ cross section is measured to be 1140 ± 64 fb, somewhat higher than the SM prediction, whereas the inclusive tZq cross section is measured to be 801 ± 92 fb in good agreement with the SM prediction. For the differential cross section measurements, a simultaneous likelihood-based unfolding of both $t\bar{t}Z + tWZ$ and tZq is performed to obtain parton-level differential cross sections as functions of five observables.

In the ATLAS measurements, events with exactly one photon are selected. In the lepton+jets channel of the $t\bar{t}$ system, events are further required to have exactly one electron or muon and at least four jets, whereas the dilepton channel requires events to have exactly two electrons and/or muons and at least two jets. In both channels, at least one jet is required to be b tagged. The $t\bar{t}\gamma$ process is split into "$t\bar{t}\gamma$ production" where the photon originates from a top quark or initial-state radiation as signal, and "$t\bar{t}\gamma$ decay" where the photon is radiated off a charged decay product of the $t\bar{t}$ system. Neural networks are trained for a multiclass separation between production, decay, and two background classes in the lepton+jets channel, and for binary separation between production and decay plus backgrounds in the dilepton channel. The inclusive $t\bar{t}\gamma$ production cross section is measured to be 322 ± 16 fb in good agreement with the SM prediction, and results are also presented for the combined production + decay cross section. Differential cross sections at particle level are measured via profile-likelihood unfolding as functions of eleven observables, both for production and production + decay.

8. Summary

The ATLAS and CMS experiments perform comprehensive programmes of top quark measurements, using all available collision data sets and targeting a wide range of production processes. Recent highlights in proton-proton collisions at 13 TeV include differential $t\bar{t}$ cross section measurements, the observation of entanglement in $t\bar{t}$ events, cross section measurements of $t\bar{t}$ production with additional heavy-flavour jets, a single top quark measurement in the tW channel, and inclusive and differential cross section measurements of top quark production in association with a Z boson or a photon. New results based on heavy-ion physics runs include $t\bar{t}$ measurements in proton-lead collisions at 8.16 TeV and proton-proton collisions at 5.02 TeV. A first single top quark measurement at 13.6 TeV was performed in the tW channel.

Other top quark physics topics not included in this contribution are, e.g., precision measurements of the top quark mass and other properties, interpretations of top quark measurements in the framework of the SM effective field theory, and searches for beyond-the-SM physics using signatures with top quarks.

With the integrated luminosity of the partial Run 3 data set recorded in 2022–2024 already exceeding the full Run 2 integrated luminosity, exciting results can be expected from upcoming Run 3 analyses.

Acknowledgments

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