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Top quark production cross sections and rare processes at CMS and ATLAS

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Abstract

Inclusive and differential measurements of cross sections as well as searches for rare processes in the top quark sector provide an important test of the standard model (SM) and a powerful probe of physics beyond the SM (BSM). Recent results on inclusive and differential measurements of $\mathrm{t\bar{t}}$, tZq, and $\mathrm{t\bar{t}+X}$ processes are reported, together with searches for flavour changing neutral currents (FCNCs) and charged lepton flavour violation (CLFV) in top quark processes, and for production of four top quarks. All results are obtained in proton-proton collision data, recorded by the ATLAS and CMS experiments at the CERN LHC from 2015 to 2018 at $\sqrt{s} = 13$ TeV.

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Top quark production cross sections and rare processes at ATLAS and CMS

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Inclusive and differential measurements of cross sections as well as searches for rare processes in the top quark sector provide an important test of the standard model (SM) and a powerful probe of physics beyond the SM (BSM). Recent results on inclusive and differential measurements of $\mathrm{t\bar{t}}$, tZq, and $\mathrm{t\bar{t}} + \mathrm{X}$ processes are reported, together with searches for flavour changing neutral currents (FCNCs) and charged lepton flavour violation (CLFV) in top quark processes, and for production of four top quarks. All results are obtained in proton-proton collision data, recorded by the ATLAS and CMS experiments at the CERN LHC from 2015 to 2018 at $\sqrt{s} = 13$ TeV.

1 Introduction

The standard model (SM) of particle physics is confirmed by a wide range of experimental results. Nonetheless, this theoretical framework still fails to explain some observed phenomena such as the existence of dark matter and dark energy, and the neutrino masses. The quest for new physics is therefore essential to deepen our understanding of the still unresolved questions, and it is carried out in many different directions.
With a mass of about 173 GeV, the top quark is the heaviest of the quarks, and processes involving top quark production offer a handle on the Yukawa coupling or electroweak couplings with the photon and gauge bosons. Therefore, it is essential to deepen our understanding of known processes such as $\mathrm{t\bar{t}}$ production by means of inclusive and differential measurements; moreover, the search for processes that are forbidden by the SM at tree level, such as flavour changing neutral currents (FCNCs) and charged lepton flavour violation (CLFV), represents a powerful probe to test effective couplings that may arise from more massive undiscovered particles, under the hypothesis that the SM corresponds to a low-energy approximation of a more fundamental theory; finally, rare processes such as $\mathrm{t\bar{t}}$ production in association with a $\mathrm{Z/H/}\gamma$ bosons, single top quark production, and production of four top quarks are a powerful test of the SM and can also provide access to effective couplings. The latest results on these

searches, performed by the ATLAS [1] and CMS [2] Collaborations, are presented here. Many searches make use of machine learning for signal vs. background discrimination, and in particular of boosted decision trees (BDTs). Moreover, often searches are interpreted in the context of the SM effective field theory (SMEFT), where constraints on the Wilson coefficients are set.

2 Multi-differential $\mathrm{t\bar{t}}$ cross section measurements

Single-, double-, and tripe-differential measurements of the $\mathrm{t\bar{t}}$ production cross section are measured as a function of the top quark and $\mathrm{t\bar{t}}$ kinematics, as well as of decay products and additional jets, in a dileptonic final state. These cross sections are measured both at the parton and particle levels, and compared to the SM predictions of Monte Carlo (MC) event generators with next-to-leading-order (NLO) accuracy in quantum chromodynamics (QCD) interfaced with Parton Shower (PS). These measurements are sensitive to SM parameters such as the top quark mass m_t and α_s. Moreover, they provide useful information on the theoretical predictions used to describe this system, i.e. how well the theory is able to describe the data and which corners need improvement. Figure 1 (top) shows a double-differential measurement in bins of p_T and y of the top quark. The largest deviations of the measured values from theory are found in the multi-differential distributions. Moreover, beyond NLO calculations seem to provide a better description of the experimental data [3].

Differential cross sections are also measured at particle level in a region of the phase space where the top quark is boosted, as this is more sensitive to models beyond the SM (BSM). In the single-lepton final state, events with a boosted hadronically decaying top quark with $p_\mathrm{T} > 355$ GeV are selected, and a 2D differential measurement is displayed in Figure 1 (bottom). In general, 2D measurements show a higher disagreement between measured data and theory predictions. Moreover, the difference between NLO models is often larger than the precision of the measurements, calling for more precise generators (e.g. NNLO + PS) [4]. Measurements are also performed in the all-hadronic final state, where the two top quarks are required to have $p_\mathrm{T} > 500,\ 350$ GeV. In this case, the measurements are performed also at parton level [5]. Both boosted searches set competitive limits on SMEFT coefficients that enter in $\mathrm{t\bar{t}}$ production. For the all-hadronic search, the resulting constraints are shown in Figure 2. In particular, the four-fermion operators are very well constrained, which is potentially useful for global fits.

3 tZq and $\mathrm{t\bar{t}}$+Z/H/γ

The production of single top in association with a Z boson (tZq) is an important probe for many interactions in the SM. Measurements are performed in a final state with three leptons, two of which coming from the Z boson decay. The inclusive cross section is measured to be $87.9^{+7.5}_{-7.3}(\mathrm{stat})^{+7.3}_{-6.0}(\mathrm{syst})$ fb for a dilepton invariant mass greater than 30 GeV, and is the most precise to date. The ratio between the cross sections of tZq and $\mathrm{\bar{t}}$Zq is also measured, together with the spin asymmetry, which is sensitive to the top quark polarisation. Differential measurements are performed for the first time for this process. The differential distributions are compared to both 4- and 5-flavour schemes (Figure 3 (left)) [6], and are provided both at parton and particle level. All measurements are in agreement with the SM predictions.

Measurements of $\mathrm{t\bar{t}}$ production in association with one photon are essential to probe anomalous $\mathrm{t\bar{t}}\gamma$ electroweak interactions. The most recent results are the inclusive and differential measurements of this process in the dileptonic final state, which are all in agreement with the SM [7]. In particular, the inclusive cross section is measured to be $173.5 \pm 2.5(\mathrm{stat}) \pm 6.3(\mathrm{syst})$ fb in a fiducial phase space. Moreover, limits on the SMEFT coefficients c_tZ and c^I_tZ are set, and are combined with the previous measurement in the single-lepton final state [8]. This is shown in Figure 3 (middle).

Finally, a search for new physics is carried out in $\mathrm{t\bar{t}}$ production in association with a Z or a H

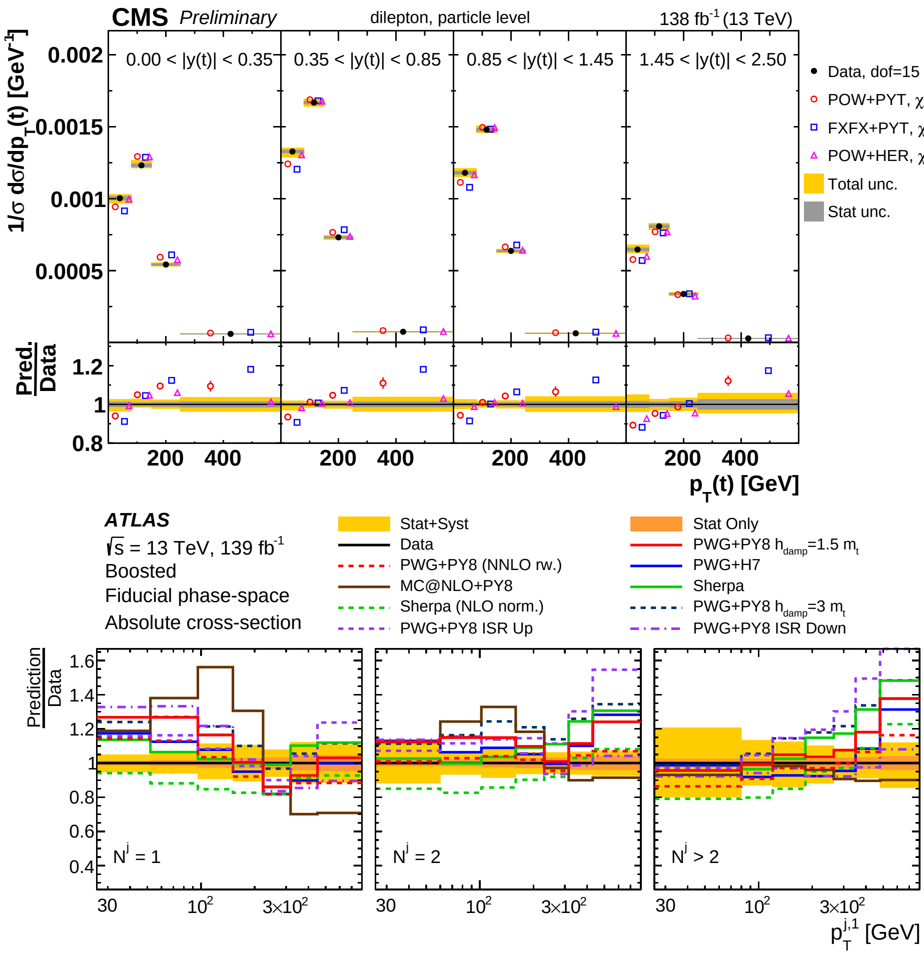


Figure 1 – Differential cross section measurement of $t\bar{t}$ production as a function of p_T and y of the top quark (top) [3], and as a function of p_T of the leading additional jet and of the jet multiplicity in a boosted top region (bottom) [4].

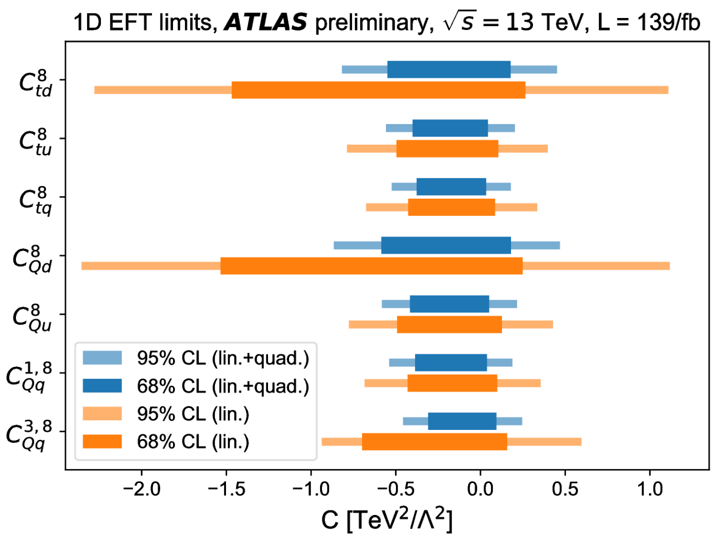


Figure 2 – Constraints on SMEFT coefficients from the boosted top measurement in the all-hadronic channel [5].

boson in a boosted region of the phase space (i.e. $p_T(Z/H) > 200$ GeV), which is most sensitive to BSM effects, in the context of EFT. Events are selected where the Z/H bosons decay to $b\bar{b}$ and in the single-lepton final state. Limits on several SMEFT coefficients affecting this process

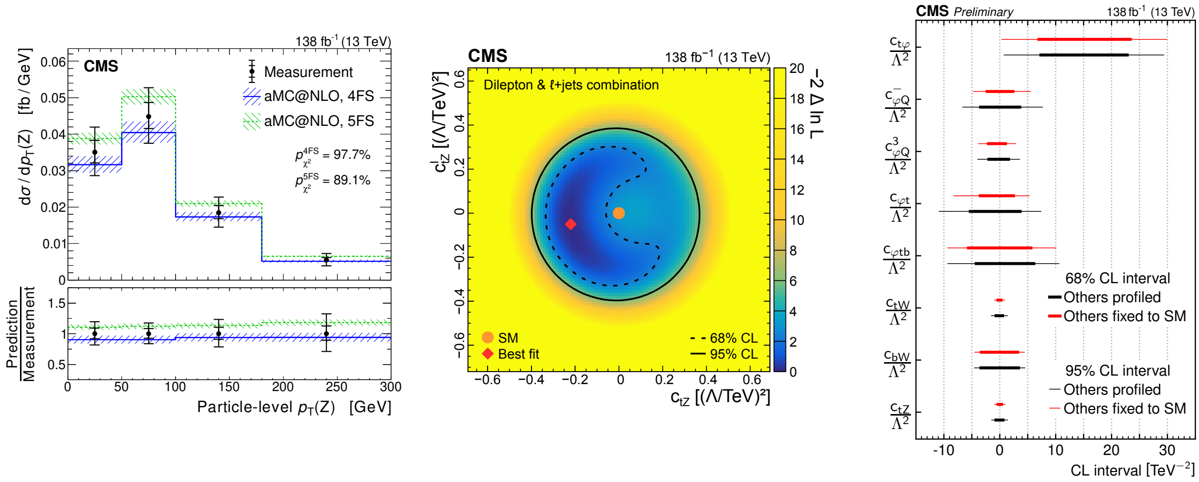


Figure 3 – Differential cross section measurement of tZq production as a function of p_T of the Z boson (left) [6]; 2D limits on SMEFT c_{tZ} and c_{tZ}^I coefficients (middle) [7]; limits on SMEFT coefficients from the measurement on $t\bar{t}Z/H$ (left) [9].

are set by reweighting the LO signal simulation and using an NLO k-factor. Results are shown in Figure 3 (right) - the tension between the measured $c_{t\phi}$ and the SM value is explained by the fact that the yield of $t\bar{t}H$ is measured to be smaller than expected [9].

4 Four-top production

Production of four top quarks is a rare process with a cross section predicted to be about 12 fb. This process is sensitive to many BSM models, such as SUSY and 2HDM, and gives direct access to four-fermion operators in the context of SMEFT. The latest result probes the one- and two-lepton final states, and the inclusive cross section is measured to be $26 \pm 8(\text{stat})^{+15}_{-13}(\text{syst})$ fb from a maximum likelihood fit on a BDT discriminant, shown in Figure 4 for one category of the search [10]. The combination with a previous measurement in the multi-lepton channel [11] yields a cross section of 24^{+7}_{-6} fb, in agreement with the SM value within 2 σ, with an observed (expected) significance of 4.7 (2.6) σ.

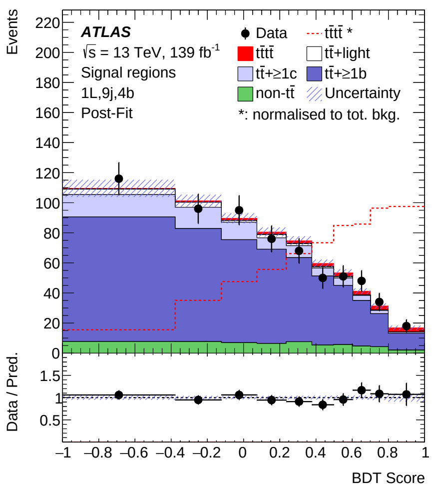


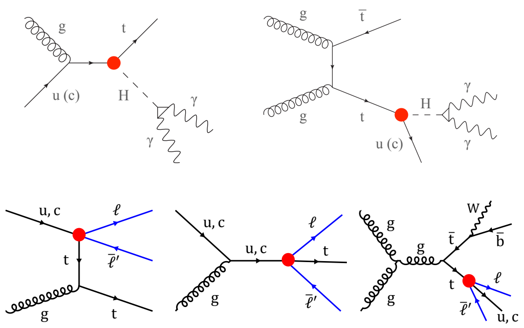
Figure 4 – BDT discriminant in one category of the four-top search used in the maximum likelihood fit [10].

5 FCNC and CLFV

Processes involving flavour-changing neutral currents are forbidden at tree-level in the SM. Therefore, they represent a powerful probe to BSM physics. The signal is modelled in an EFT scenario with a coefficient k_{Hut} or k_{Hct} depending on the flavour of the quark involved in the FCNC process, which is better seen in Figure 5 (top left) [12]. This coefficient is proportional to the square root of the branching ratio $BR(\text{t} \to \text{Hq})$ of such process and, consequently, limits on it can be easily translated to limits on the branching ratio. Results are achieved in two different decay channels of the Higgs boson:

- $\text{H} \to \gamma\gamma$: this final state yields a very clean signature. BDTs are used to maximise the separation between signal and background, and the limits are measured to be: $BR(\text{t} \to \text{Hu}) < 0.019$ $(0.031)\%$ observed (expected) and $BR(\text{t} \to \text{Hc}) < 0.073$ $(0.051)\%$ observed (expected) [12].
- $\text{H} \to \text{b}\bar{\text{b}}$: because of the high contamination from QCD processes, deep neural networks (DNNs) and BDTs are used for event reconstruction and signal vs. background discrimination, respectively. The limits are measured to be: $BR(\text{t} \to \text{Hu}) < 0.079$ $(0.11)\%$ observed (expected) and $BR(\text{t} \to \text{Hc}) < 0.094$ $(0.086)\%$ observed (expected) [13].

Processes involving charged lepton flavour violation are also suppressed in the SM, and for the same reason as FCNCs are a useful probe for BSM physics. In particular, the LHC allows for probing CLFV at high energy and in processes involving top quarks. A search for CLFV is carried out in top quark production and decay. Example of how this process may occur is show in Figure 5 (bottom left). An EFT approach is used to parametrise CLFV in production and decay modes through three coefficients (c_{vector}, c_{scalar}, and c_{tensor}), which can lead to four-fermion interactions. Also in this case, limits on these coefficients can be easily translated to limits on the branching ratio and on the cross section, which depends quadratically on them. The search makes use of a BDT to discriminate between signal and background, and Figure 5 (right) shows the resulting 95% CL upper limits [14].



Vertex	Int. type	Cross section [fb] Exp	Obs	$C_{e\mu tq}/\Lambda^2$ [TeV $^{-2}$] Exp	Obs	$\mathcal{B}(10^{-6})$ Exp	Obs
	Vector	7.02	6.78	0.12	0.12	0.14	0.13
$e\mu$tu	Scalar	5.63	6.25	0.23	0.24	0.06	0.07
	Tensor	10.01	9.18	0.07	0.06	0.27	0.25
	Vector	11.21	9.73	0.39	0.37	1.49	1.31
$e\mu$tc	Scalar	9.11	8.88	0.87	0.86	0.91	0.89
	Tensor	21.02	17.22	0.24	0.21	3.16	2.59

Figure 5 – Sketch of FCNC (top left) [12] and CLFV (bottom left) [14] in processes involving top quarks; expected and observed 95% CL upper limits on signal cross sections (production and decay modes), the CLFV Wilson coefficients, and top quark CLFV branching fractions (right) [14].

6 Conclusions

Inclusive and differential measurements of cross sections in processes involving top quarks, as well as searches for rare or SM-forbidden processes, can shed light on underlying BSM phenomena, if any. The ATLAS and CMS Collaborations at the CERN Large Hadron Collider have delivered excellent results in this regard, using the data collected from 2015 to 2018. The increased statistics of the upcoming Run 3 represents a fertile ground for even more precise measurements, and might lead to observation of some rare processes.

References

1. ATLAS Collaboration, JINST 3 S08003 (2008).
2. CMS Collaboration, JINST 3 S08004 (2008).
3. CMS Collaboration, “Measurement of differential cross sections for the production of top quark pairs and of additional jets in pp collisions at $\sqrt{s} = 13$ TeV”, CMS-PAS-TOP-20-006, CDS:2804974 (2022).
4. ATLAS Collaboration, “Measurements of differential cross-sections in top-quark pair events with a high transverse momentum top quark and limits on beyond the Standard Model contributions to top-quark pair production with the ATLAS detector at $\sqrt{s} = 13$ TeV”, arXiv:2202.12134 (2022).
5. ATLAS Collaboration, “Differential $\mathrm{t\bar{t}}$ cross-section measurements using boosted top quarks in the all-hadronic final state with 139 fb^{-1} of ATLAS data,”, ATLAS-CONF-2021-050, CDS:2782534 (2021).
6. CMS Collaboration, “Inclusive and differential cross section measurements of single top quark production in association with a Z boson in proton-proton collisions at $\sqrt{s} = 13$ TeV,” 10.1007/JHEP02(2022)107 (2022).
7. CMS Collaboration, “Measurement of the inclusive and differential $\mathrm{t\bar{t}}\gamma$ cross sections in the dilepton channel and effective field theory interpretation in proton-proton collisions at $\sqrt{s}$ =13 TeV”, arXiv:2201.07301 (2022).
8. CMS Collaboration, “Measurement of the inclusive and differential $\mathrm{t}\bar{t}\gamma$ cross sections in the single-lepton channel and EFT interpretation at $\sqrt{s} = 13$ TeV”, JHEP12(2021)180 (2021).
9. CMS Collaboration, “Search for new physics using top quark pairs produced in associated with a boosted Z or Higgs boson in effective field theory”, CMS-PAS-TOP-21-003, CDS:2802060 (2022).
10. ATLAS Collaboration, “Measurement of the $\mathrm{t}\bar{t}\mathrm{t}\bar{t}$ production cross section in pp collisions at $\sqrt{s} = 13$ TeV with the ATLAS detector”, JHEP11(2021)118 (2021).
11. ATLAS Collaboration, “Evidence for $t\bar{t}t\bar{t}$ production in the multilepton final state in proton–proton collisions at $\sqrt{s} = 13$ TeV with the ATLAS detector”, Eur. Phys. J. C 80, 1085 (2020).
12. CMS Collaboration, “Search for flavor-changing neutral current interactions of the top quark and Higgs boson in final states with two photons in proton-proton collisions at $\sqrt{s}$ =13 TeV”, arXiv:2111.02219 (2021).
13. CMS Collaboration, “Search for flavor-changing neutral current interactions of the top quark and the Higgs boson decaying to a bottom quark-antiquark pair at $\sqrt{s}$ =13 TeV”, JHEP02(2022)169 (2022).
14. CMS Collaboration, “Search for charged-lepton flavor violation in top quark production and decay in pp collisions at $\sqrt{s} = 13$ TeV”, arXiv:2201.07859 (2022).