Latest top quark measurements with the CMS detector

Hideki Okawa
On behalf of the CMS Collaboration
Institute of Modern Physics and Key Laboratory of Nuclear Physics and Ion-beam Application (MOE), Fudan University, Yangpu, Shanghai, China

Presented at DIS2022: XXIX International Workshop on Deep-Inelastic Scattering and Related Subjects, Santiago de Compostela, Spain, May 2-6 2022.

More than 120 million top quark pairs have been produced in CMS during the second data taking period at the Large Hadron Collider. CMS provides opportunities to precisely measure the inclusive and differential cross sections of various top quark processes as well as the top quark properties, and to search for rare processes and decays, which are promising windows for physics beyond the standard model. In these proceedings, highlights of the most recent results are presented.

1 Introduction

The top quark is a unique particle, the heaviest elementary particles with the near-unity Yukawa coupling. It decays before hadronizing and maintains the spin-correlation in its decay products, allowing us to measure the bare-quark properties. The top quark provides large corrections to the calculation of the electroweak observables and an insight to the origin of the Higgs potential as well as the lifetime of the Universe [1].

The CMS [2] experiment at the Large Hadron Collider (LHC) [3] at CERN is a "top quark factory", covering $\mathcal{O}(10^6)$ range in the top quark production cross section. It provides a wide range of programs to precisely measure various production cross sections inclusively and differentially as well as properties, and to search for physics beyond the standard model (BSM).

2 Cross-section measurements in the $\mathrm{t\bar{t}}$ production

The inclusive $\mathrm{t\bar{t}}$ production cross section has been measured at four center-of-mass energies [4]: $\sqrt{s}$ =5.02, 7, 8, and 13 TeV. At $\sqrt{s}$ =5.02 TeV, the inclusive cross section has been newly measured in the dilepton channel and has been combined with the previous result from the single-lepton channel [5]. The measured inclusive cross sections at the four center-of-mass energies, including the latest full Run-2 measurements detailed just below, are in agreement with the next-to-next-to-leading-order (NNLO) QCD calculations and the next-to-next-to-leading-log (NNLL) resummation as shown in Figure 1 (left).

With the full Run-2 dataset at $\sqrt{s}$ =13 TeV, both the inclusive and differential cross sections are measured in the single-lepton channel [6]. This analysis utilizes four event categories: two categories of fully resolved events discriminated by the tightness of the b-jet identification criteria, and two categories of "boosted" events based on the multiplicity of the boosted top quark jets identified. This analysis exploits the first combination of resolved and boosted events

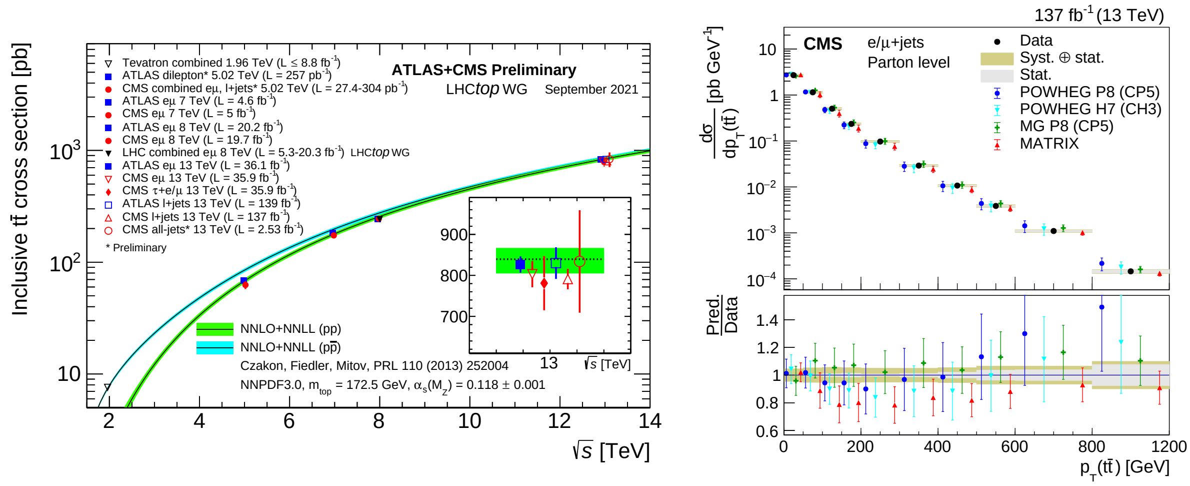

Figure 1 – Inclusive $t\bar{t}$ cross section as a function of the center-of-mass energy (left), and the differential cross section at the parton level as a function of $p_{\mathrm{T}}(t\bar{t})$ with the full Run-2 dataset at $\sqrt{s}$ =13 TeV, measured in the single-lepton channel (right).

for the $t\bar{t}$ cross section measurement. In the resolved categories, the top quark pair system is reconstructed with constraints on the invariant mass of the hadronically decaying W bosons and top quarks. In the boosted categories, the top quark tagger with a neural network on anti-k_{T} jets with a distance parameter R=0.8 is used. The fixed-order NNLO prediction (MATRIX) [7,8] can be directly compared to the parton-level differential cross sections. The prediction from MATRIX generally describes the kinematic distributions, but a 2σ-level discrepancy exists in the low $p_{\mathrm{T}}(t\bar{t})$ region as seen in Figure 1 (right).

3 Mass measurements in the $t\bar{t}$ production

The top quark mass has been measured mainly with two methods: the direct and indirect measurements. The former corresponds to the mass parameter defined in Monte-Carlo (MC) event generators, and is sometimes called the "MC mass". The latter relies on more fundamental and field theoretical definitions, such as the pole mass or the $\overline{\mathrm{MS}}$ mass scheme. Relating these different mass definitions precisely has not been pursued rigorously until now due to the complexities in both the perturbative and non-perturbative aspects as well as the limitations in the MC generators. Such an ambiguity in the mass "interpretation" is considered to add up to around 0.5 GeV of an uncertainty.

CMS has been providing mass measurements for all three schemes, including the first measurement of the running of the top quark mass in the $\overline{\mathrm{MS}}$ mass scheme [9]. In these proceedings, we present the most recent updates in the direct mass and the pole mass measurements [10,11].

The latest direct mass measurement has been pursued in the single-lepton channel in the top quark pair production using 35.9 fb^{-1} from the Run-2 data [10]. The goodness-of-fit defined as $P_{\mathrm{gof}} = \exp(-1/2\chi^2)$ is considered for the jet-parton assignment. Applying $P_{\mathrm{gof}} \geq 0.2$ significantly reduces "unmatched" events as shown in Figure 2 (left), in which at least one of the quarks is not matched to any of the selected jets. Considerable improvement is seen from the previous results by utilizing a profile likelihood fit with five kinematic variables: the invariant mass of the hadronically decaying top quarks ($m_{\mathrm{t}}^{\mathrm{reco}}$), the invariant mass of the hadronically decaying W bosons ($m_{\mathrm{W}}^{\mathrm{reco}}$), the ratio of the scalar sum of the transverse momenta of the two b-tagged jets (b1, b2) and the two untagged jets (q1, q2) ($R_{\mathrm{b,q}}^{\mathrm{reco}} = (p_{\mathrm{T}}^{\mathrm{b1}} + p_{\mathrm{T}}^{\mathrm{b2}})/(p_{\mathrm{T}}^{\mathrm{q1}} + p_{\mathrm{T}}^{\mathrm{q2}})$), the invariant mass of the lepton and the b-tagged jet assigned to the leptonic side ($m_{\mathrm{lb}}^{\mathrm{reco}}$; only considered for events failing the goodness-of-fit)), and $m_{\mathrm{lb}}^{\mathrm{reco}}/m_{\mathrm{t}}^{\mathrm{reco}}$. The variables $R_{\mathrm{b,q}}^{\mathrm{reco}}$, $m_{\mathrm{lb}}^{\mathrm{reco}}$, and $m_{\mathrm{lb}}^{\mathrm{reco}}/m_{\mathrm{t}}^{\mathrm{reco}}$ are considered for the first time in CMS for the single-lepton channel. The

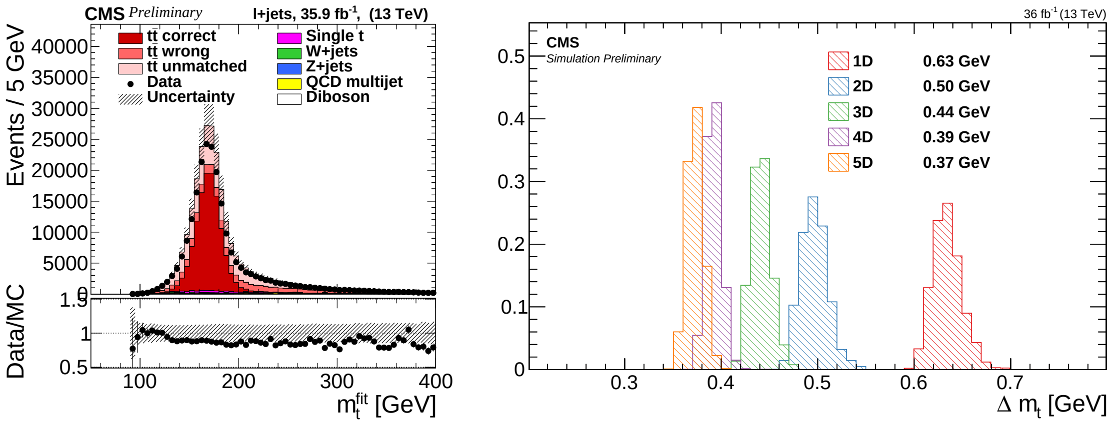

Figure 2 – The reconstructed top quark mass distribution after the $P_{\rm gof} \geq 0.2$ selection and the kinematic fit (left), and comparison of the expected total uncertainty on $m_{\rm t}$ with different multiplicities of kinematic fits (right).

most precise direct measurement for the top quark mass of 171.77 ± 0.38 GeV is obtained.

The most recent measurement for the pole mass is performed in the dilepton channel utilizing 36.3 fb^{-1} of the Run-2 dataset [11]. The $\rm t\bar{t}$+jets events are considered, as the additional parton radiation is sensitive to the top quark mass. A multivariate analysis is used for the kinematic reconstruction and the pole mass is extracted from an inverse invariant mass (ρ) of the $\rm t\bar{t}$+jets system: $\rho = 2m_0/m_{\rm t\bar{t}+jets}$. For the consistency with the previous measurements, m_0 is set to be 170 GeV, although the result does not depend on the choice of m_0. The pole mass with the NLO theory prediction is obtained for two parton distribution functions (PDFs): 172.94 ± 1.37 GeV (ABMP16NLO), 172.16 ± 1.44 GeV (CT18NLO). The most precise pole mass measurement still comes from a previous measurement in the dilepton channel using triple-differential measurements on jet multiplicity, $m_{\rm t\bar{t}}$ and $y_{\rm t\bar{t}}$, leading to the measured pole mass of 170.5 ± 0.8 GeV [12].

4 Searches for rare processes and anomalous couplings

Precision measurements of rare processes are important windows to BSM. Their inclusive and differential cross section measurements are powerful probes to test the standard model. They also provide useful inputs to constrain anomalous couplings in the effective field theory interpretations. Furthermore, observing strongly-suppressed processes in the standard model would be a direct evidence of BSM. In this section, we will present the recent measurements and searches of rare processes.

4.1 Cross-section measurements in the single top quark productions

The main production modes of the single top quark consist of the t-channel, W-association (Wt) channel, and s-channel in the order of their cross sections. Their inclusive cross sections have been precisely measured and are generally in agreement with the NLO+NNLL prediction and even with the NNLO prediction for the t-channel.

The Z-association (tZq) mode is a very rare and pure-electroweak single top quark production. It was observed in 2018 for the first time [13]. With the full Run-2 dataset, the most precise inclusive cross section so far as well as the first differential cross section are measured for the tZq production [14]. The analysis utilizes a binned fit to the multivariate classifier in events with three leptons categorized with the jet and b-jet multiplicities. The differential cross section and the top quark spin asymmetry are found to be consistent with predictions from the standard model.

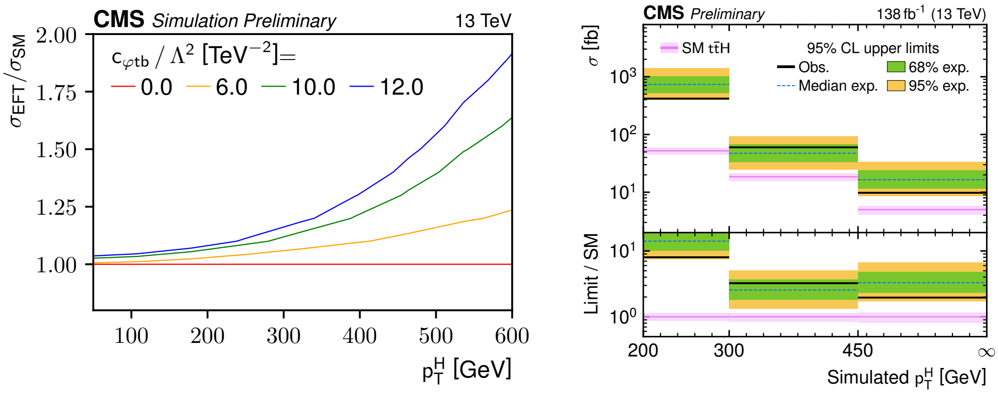

Figure 3 – The $t\bar{t}H$ cross section in the SM EFT, as ratios to the corresponding SM predictions, as a function of $c_{\varphi tb}/\Lambda^2$ and the Higgs-boson p_T (left), and observed and expected 95% confidence level (CL) upper limits on the $t\bar{t}H$ differential cross sections as a function of Higgs-boson p_T (right).

4.2 $t\bar{t}V$ production and effective field theory

The $t\bar{t}V$ productions offer direct measurements of the top quark coupling to the gauge bosons and crucial inputs for the effective field theory (EFT) interpretation. Furthermore, $t\bar{t}W$ and $t\bar{t}Z$ events are dominant irreducible background for the $t\bar{t}H$. Thus, precise prediction and modeling of these production modes are mandatory for the BSM searches and Higgs boson measurements.

The $t\bar{t}\gamma$ production is measured in the dilepton channel with the full Run-2 dataset [15]. The photon can radiate off from the top quarks or from their decay products. The measured fiducial cross section is $173.5\pm2.5(\text{stat})\pm6.3(\text{syst})$ fb, whereas the theoretical prediction with an NLO k-factor gives 153 ± 27 fb with a caveat that the photon contributions from the top quark decays are not included in the theory calculation and thus is underestimated. Differential cross section measurements are performed on various kinematic observables reconstructed from lepton, jet and photon momenta. This measurement provides improved constraints on the Wilson coefficients by combining with the $t\bar{t}Z$ results.

The $t\bar{t}W$ production is measured with the full Run-2 dataset, utilizing the same-sign dilepton and three-lepton events [16]. A multi-classification neural network is used for the same-sign dilepton category, whereas the invariant mass of the three leptons is considered as the discriminant in the three-lepton category. The measured inclusive cross section is $868\pm40(\text{stat})\pm51(\text{syst})$ fb, which is visibly larger than the NLO+NNLL prediction of $592^{+155}_{-96}(\text{scale})\pm12(\text{PDF})$ fb with improved FxFx matrix-element merging [17]. Furthermore, the cross section ratio between $t\bar{t}W^+$ and $t\bar{t}W^-$ processes ($R_{t\bar{t}W^+/t\bar{t}W^-}$) is lower than the standard model prediction by 2σ.

The $t\bar{t}Z$ and $t\bar{t}H$ processes with boosted Z or H bosons are measured with the full Run-2 dataset [18]. The boosted Z and H p_T regions offer high sensitivity to BSM as shown in Figure 3 (left). The DeepAK8 algorithm [19] utilizing a deep neural network is used to identify the boosted Z or H bosons. The signal strength of $\mu^{\text{boost}}_{t\bar{t}Z} = 0.65^{+1.05}_{-0.98}$ and $\mu^{\text{boost}}_{t\bar{t}H} = 0.33^{+0.87}_{-0.85}$ are obtained, where the uncertainties are still statistically dominated. A maximum-likelihood unfolding is exploited to obtain upper limits on the signal strength in three boosted-boson-p_T bins as presented in Figure 3 (right).

4.3 Flavor-Changing Neutral Current in $t\bar{t}$

The flavor-changing neutral current (FCNC) is forbidden at the tree level and highly suppressed at the loop level down to $\mathcal{O}(10^{-12})$ in the branching ratio (BR) for the top quarks. An observation of FCNC would be a direct evidence of BSM. The tHu and tHc couplings are searched in the resonant and non-resonant productions in zero- and single-lepton events with two photons, categorized to eight regions with boosted decision tree (BDT) considered respectively. A simul-

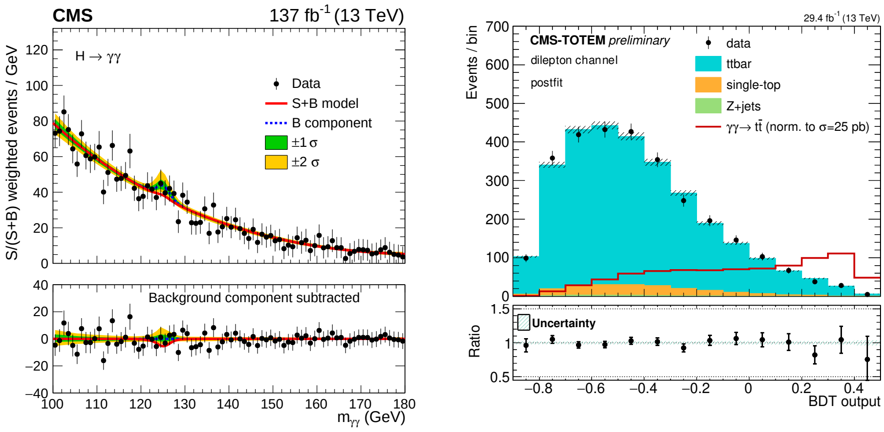

Figure 4 – The diphoton invariant mass distribution for the categories targeting t→Hu FCNC interactions. The data (black points), the fit results to the signal plus background models (solid red curve) and the background model alone (dotted blue curve) are shown (left). Distribution of the BDT score from the central exclusive $t\bar{t}$ production search in the dilepton signal region for data and simulated events after the fit (right).

taneous fit to the BDT scores and the diphoton invariant mass spectrum (Figure 4 (left)) is performed. The most stringent limits of BR(t→Hu)<0.019% (0.031%) and BR(t→Hc)<0.073% (0.051%) are obtained with 95% confidence level for the observed (expected) [20].

4.4 Central exclusive $t\bar{t}$ *production*

The central exclusive $t\bar{t}$ production occurs through a totally different mechanism than the standard inclusive production. The top quark pairs are produced from the exchange of colorless particles such as photons or pomerons, and one or two protons remain intact. The predicted cross section suffer from large uncertainty, but is usually in the range of $\mathcal{O}(0.1$ fb). Thus, the observation of this process is only expected at the HL-LHC, but the BSM effects could enhance the production.

CMS has searched for this exclusive $t\bar{t}$ production for the first time using the CMS-TOTEM Precision Proton Spectrometer to tag the intact protons using 29.4 fb^{-1} of the Run-2 data [21]. Both the single-lepton and dilepton channels are considered, and a multivariate analysis has been performed with the BDT (Figure 4 (right)). Among various kinematic variables, the fractional momentum loss of protons (ξ) and its variants play key roles to select the signals. The cross section limit of 0.59 pb (1.14 pb) is obtained at the 95% confidence level for the observed (expected). The statistical uncertainty still dominates and updates with more data are eagerly awaited.

5 Conclusions

In these proceedings, various measurements and searches with higher precision or sensitivity have been presented, with many of which utilize the full LHC Run-2 dataset. Further analyses are under way and more updates will follow with the upcoming LHC Run-3 data, which would expand the exciting opportunities at the LHC as the unprecedented “top quark factory”.

Acknowledgments

The author is supported by the Natural Science Foundation of China under contract No. 12075060 and No. 12061141002.

References

1. A. Andreassen, W. Frost, and M.D. Schwartz. Scale-invariant instantons and the complete lifetime of the standard model. *Phys. Rev. D*, 97:056006, 2018.
2. CMS Collaboration. The CMS experiment at the CERN LHC. *JINST*, 3:S08004, 2008.
3. L. Evans and P. Bryant (editors). LHC Machine. *JINST*, 3:S08001, 2008.
4. CMS Collaboration. CMS Top Quark Physics Summary Figures. https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsTOPSummaryFigures.
5. CMS Collaboration. Measurement of the inclusive $\mathrm{t\bar{t}}$ production cross section in proton-proton collisions at $\sqrt{s} = 5.02$ TeV. *JHEP*, 04:144, 2022.
6. CMS Collaboration. Measurement of differential $\mathrm{t\bar{t}}$ production cross sections in the full kinematic range using lepton+jets events from proton-proton collisions at $\sqrt{s} = 13$ TeV. *Phys. Rev. D*, 104:092013, 2021.
7. 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*, 99:051501, 2019.
8. 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*, 07:100, 2019.
9. CMS Collaboration. Running of the top quark mass from proton-proton collisions at $\sqrt{s} = 13$ TeV. *Phys. Lett. B*, 803:135263, 2020.
10. CMS Collaboration. A profile likelihood approach to measure the top quark mass in the lepton+jets channel at $\sqrt{s} = 13$ TeV. CMS-PAS-TOP-20-008, 2022.
11. CMS Collaboration. Measurement of the top quark pole mass using $\mathrm{t\bar{t}} + \mathrm{jet}$ events in the dilepton final state at $\sqrt{s} = 13$ TeV. CMS-PAS-TOP-21-008, 2022.
12. CMS Collaboration. Measurement of $\mathrm{t\bar{t}}$ 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*, 80:658, 2020.
13. CMS Collaboration. Observation of Single Top Quark Production in Association with a Z Boson in Proton-Proton Collisions at $\sqrt{s} = 13$ TeV. *Phys. Rev. Lett.*, 122:132003, 2019.
14. 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. *JHEP*, 03:107, 2022.
15. 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. *JHEP*, 05:091, 2022.
16. CMS Collaboration. Measurement of the cross section of top quark-antiquark pair production in association with a W boson in proton-proton collisions at $\sqrt{s} = 13$ TeV. CMS-PAS-TOP-21-011, 2022.
17. R. Frederix, I. Tsinikos. On improving NLO merging for $\mathrm{t\bar{t}W}$ production. *JHEP*, 11:29, 2021.
18. 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, 2022.
19. CMS Collaboration. Identification of heavy, energetic, hadronically decaying particles using machine-learning techniques. *JINST*, 15:P06005, 2020.
20. 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, accepted by Phys. Rev. Lett.*, 2021.
21. CMS Collaboration, TOTEM Collaboration. Search for central exclusive production of top quark pairs in proton-proton collisions at $\sqrt{s} = 13$ TeV with tagged protons. CMS-PAS-TOP-21-007, TOTEM-NOTE-2022-002, 2022.