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Measurement of $t\bar{t}$ and single top quark production cross sections in CMS

Denise Müller[†,*]

Inter-University Institute For High Energies, Vrije Universiteit Brussel,
Pleinlaan 2, 1050 Brussels, Belgium

E-mail: denise.muller@cern.ch

With a delivered integrated luminosity of around $140\,\mathrm{fb}^{-1}$ at a center-of-mass energy of $13\,\mathrm{TeV}$ in the CMS experiment during Run 2, almost 300 million top quarks and top antiquarks were produced. As top quarks can be produced through either strong or electroweak interaction, they are a suitable tool to probe the strong and electroweak sectors of the standard model. Precision measurements of top quark pair ($t\bar{t}$) and of single top quark production cross sections deliver constraints on several standard model parameters, e. g., the top quark mass, the strong coupling α_S, and the parton distribution functions. In addition, a sufficient amount of data has been collected to search for rare $t\bar{t}$ production modes. In this contribution, recent measurements of the differential $t\bar{t}$ cross sections and the latest inclusive and differential cross section measurement for single top quark production in association with a W boson performed by the CMS Collaboration are presented, as well as the search for exclusive $t\bar{t}$ production using the CMS-TOTEM Proton Precision Spectrometer.

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*Speaker
†On behalf of the CMS Collaboration

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1. Differential $t\bar{t}$ cross section measurements

Precision measurements of the inclusive top quark pair ($t\bar{t}$) production cross section are crucial to constrain free parameters of the standard model (SM). As $t\bar{t}$ production is the dominant background of many analyses beyond the SM, this process needs to be well understood. At $\sqrt{s} = 13$ TeV, the predicted $t\bar{t}$ cross section is 832^{+20}_{-29} (scale) $\pm$ 35 (PDF + α_S) pb at next-to-next-to-leading order (NNLO) plus next-to-next-to-leading logarithmic (NNLL) accuracy [1]. In this contribution, two recent differential $t\bar{t}$ cross section analyses are presented, both using the full Run 2 (2016–2018) data set recorded by the CMS experiment [2], corresponding to 138 fb^{-1}.

1.1 Dileptonic $t\bar{t}$ plus additional jets

This analysis [3] studies the differential cross section for dileptonic (ee, $\mu\mu$, eμ) events with additional jets stemming from either initial or final state radiation (ISR/FSR). The differential cross sections are measured as functions of one, two, or three kinematic observables for the top (anti)quark and $t\bar{t}$ systems at parton level, and for systems consisting of leptons, b jets, and additional number of jets at particle level. The results are compared to different predictions at next-to-leading order (NLO) and, for several single-differential distributions, to predictions with accuracy beyond NLO. Figure 1 shows the comparison of the measured top quark p_T distribution to different NLO predictions (left) and predictions beyond NLO (right). Like in previous analyses, the NLO models predict harder p_T spectra than observed. This trend is significantly decreased by comparing the data to beyond-NLO models.

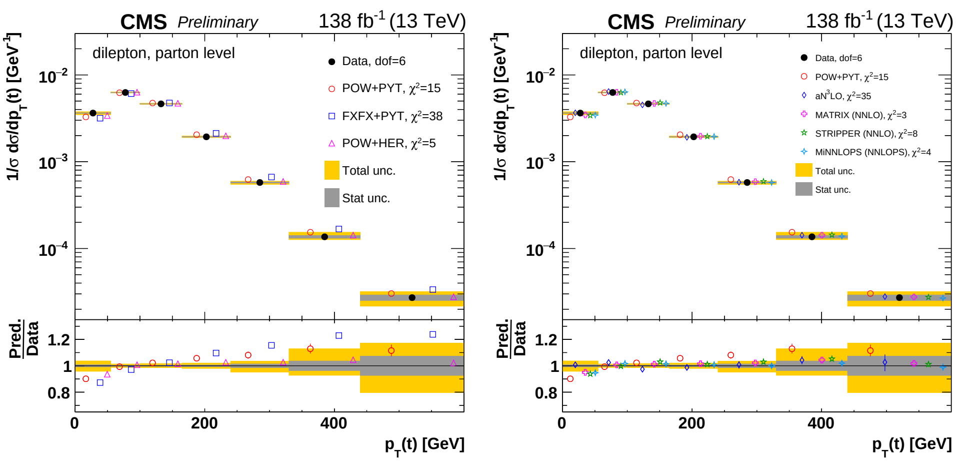

Figure 1: Differential $t\bar{t}$ cross section as a function of top quark p_T at parton level. The measured data is compared to three different NLO (left) and various beyond-NLO (right) predictions. Taken from Ref. [3].

For multi-differential distributions, more deviations of the NLO models compared to data are visible. One example, the triple-differential $t\bar{t}$ cross section as function of the $t\bar{t}$ system rapidity, the invariant $t\bar{t}$ mass, and the number of additional jets, is shown in Fig. 2. For all measured differential distributions, the dominant systematic uncertainties are the jet energy scale (JES), the renormalization and factorization scales (μ_R/μ_F), and FSR scales.

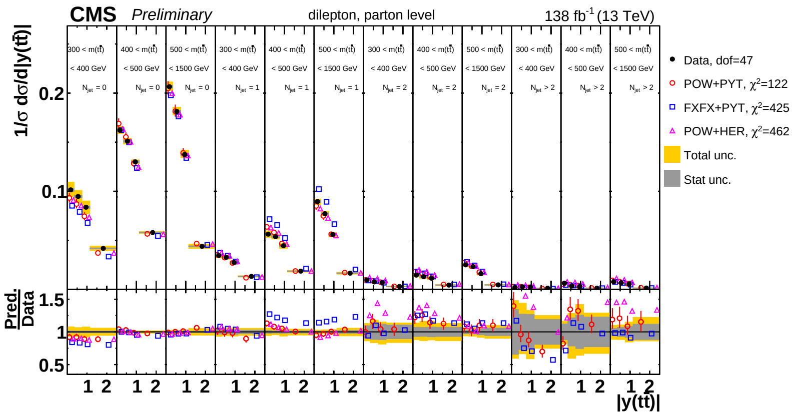

Figure 2: Triple-differential tt̄ cross section at parton level as a function of the rapidity of the tt̄ system, the invariant tt̄ mass, and the number of additional jets. The measured data is compared to three different NLO predictions. Taken from Ref. [3].

1.2 Semileptonic tt̄ in full kinematic range

This analysis [4] is the first differential measurement that combines the low top quark p_T region (resolved) with the high top quark p_T region (boosted). This combination provides additional constraints on the systematic uncertainty and thus improves the overall precision of the results. Semileptonic tt̄ events (e/μ + jets) are analyzed and different top quark reconstruction algorithms are applied, depending on whether the top quark decay products are resolved or boosted. The choice of top quark reconstruction method is used to define different event categories, which are used in a combined χ^2 fit to extract single- and double-differential cross section distributions at parton and at particle level for the top (anti)quark and tt̄ systems.

For each differential distribution, the agreement of the NLO predictions and of the NNLO prediction by MATRIX [5] with data is checked using χ^2 tests, which are shown in Fig. 3 as Z-scores. For several double-differential distributions, significant deviations of the models from data of around six standard deviations can be observed, whereas the single-differential distributions of the involved kinematic variables agree within two standard deviations. This means that the kinematic relations between top quark and tt̄ observables need to be better understood.

In Fig. 4, the top quark p_T differential cross section distribution is shown for the hadronically (left) and leptonically (right) decaying top quark. The measured distribution is compared to three different NLO models and to the NNLO model by MATRIX. The prediction at NNLO accuracy agrees better with data and in addition provides smaller uncertainties compared to the NLO models. For all measured differential cross sections, the uncertainty in JES and integrated luminosity are the dominant systematic uncertainties.

2. Search for exclusive tt̄ production

In this analysis [6], an alternative production mode for top quark pairs is studied which involves the exchange of colorless particles, e. g. photons, as shown in Fig. 5 (left), or pomerons. The expected cross section for this process, called exclusive tt̄ production, is ≈ 0.3 fb and is characterized

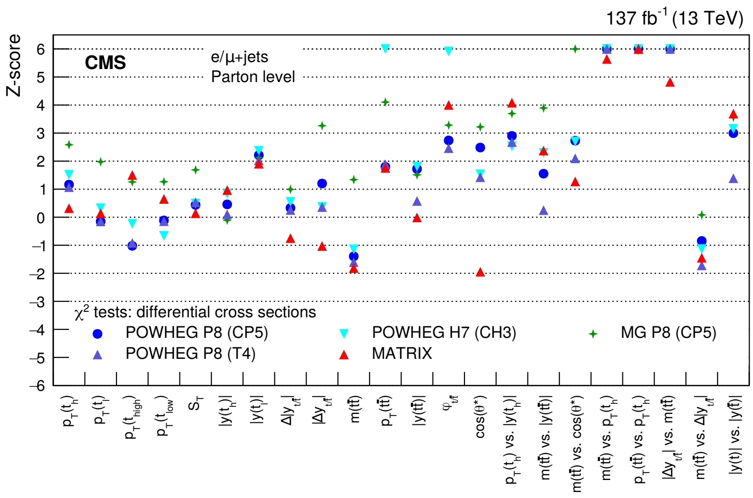

Figure 3: χ^2 tests expressed as Z-score for all $t\bar{t}$ single- and double-differential cross section measurements at parton level. The Z-scores have been determined for four different NLO predictions and for the NNLO prediction by MATRIX. Taken from Ref. [4].

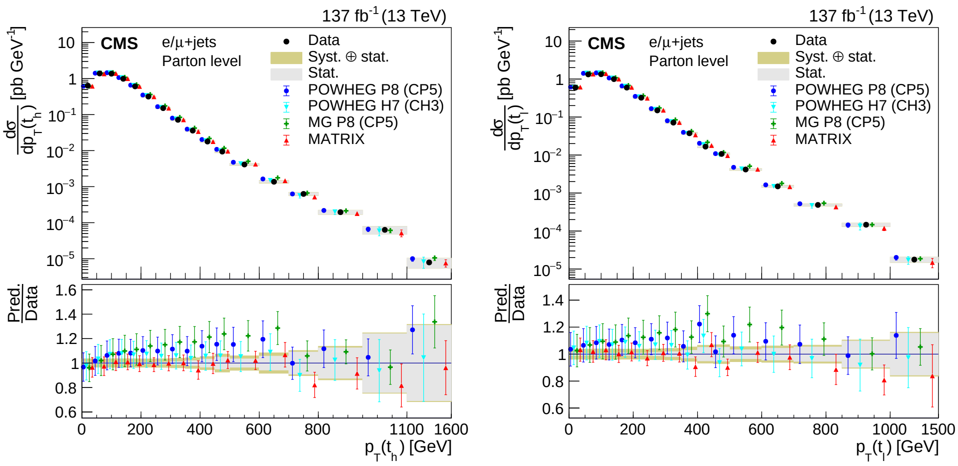

Figure 4: Differential $t\bar{t}$ cross section as a function of the p_T of the hadronically (left) and leptonically decaying top quark (right) at parton level. The measured data is compared to three different NLO predictions and the NNLO prediction by MATRIX. Taken from Ref. [4].

by either one or both protons remaining intact after interaction, hence transferring a fraction of their energy to the $t\bar{t}$ pair.

While the $t\bar{t}$ pair is reconstructed for the dilepton and for the lepton + jets channels in the CMS central detector, the two intact forward protons are detected using the CMS-TOTEM Precision Proton Spectrometer (CT-PPS) [7]. For this analysis, the 2017 data collected by the CT-PPS are analyzed, which correspond to 29.4 fb^{-1}.

The signal is enhanced by training two different boosted decision trees (BDTs), one for the dilepton and one for the lepton + jets channel. The upper limits at 95% confidence level are extracted by performing binned profile likelihood fits on the BDT output distributions, the results are illustrated in Fig. 5 (right). For the combination of the two $\mathrm{t\bar{t}}$ decay channels, an observed (expected) upper limit of 0.59 pb (1.14 pb) is obtained. Dominant systematic uncertainty sources are the normalization of background contributions, the FSR modeling, as well as the proton reconstruction.

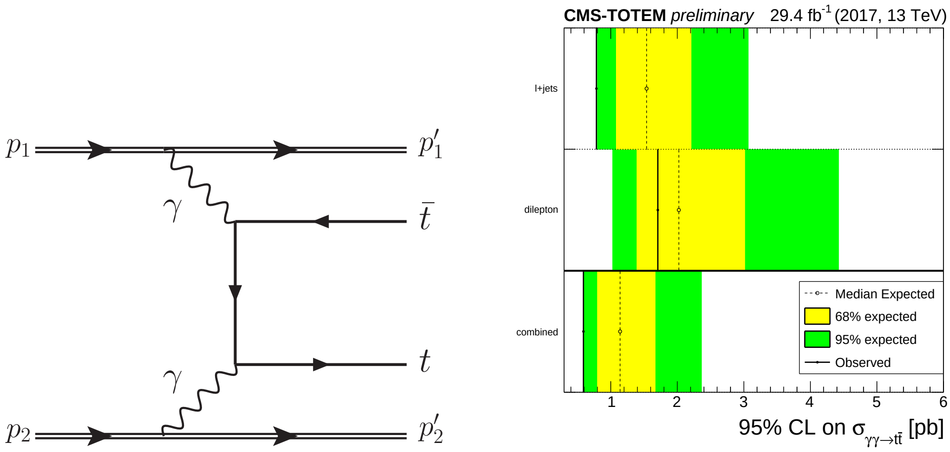

Figure 5: Left: Feynman diagram for producing exclusive top quark pairs through the exchange of photons. Right: Upper limits at 95% confidence level for exclusive $\mathrm{t\bar{t}}$ production. Taken from Ref. [6].

3. Inclusive and differential cross section measurement of single top tW-associated production

This analysis [8][1] is the first full Run 2 measurement for inclusive and differential single top tW cross section. The analysis is performed in the dilepton eμ final state by defining event categories according to the number of selected jets and b-tagged jets (mjnb), with $p_{\mathrm{T}} > 30\,\mathrm{GeV}$ and $|\eta| < 2.4$. The 1j1b category is the signal category, which is used for extracting the inclusive cross section together with the 2j1b and 2j2b control categories. The former is sensitive to tW, while the latter is used to constrain the dominant $\mathrm{t\bar{t}}$ background. The overlap of the tW process at NLO with $\mathrm{t\bar{t}}$ is considered by using the diagram removal scheme for the signal modeling. Two BDTs are trained to enhance the signal, one for the signal category and one for the 2j1b category. By performing a maximum likelihood fit on the two BDT output distributions and on the subleading jet p_{T} distribution in the 2j2b category, the measured cross section of $79.2 \pm 0.8\,(\mathrm{stat})^{+7.0}_{-7.2}\,(\mathrm{syst}) \pm 1.1\,(\mathrm{lumi})\,\mathrm{pb}$ is extracted, which agrees well with the NNLO prediction of $71.7 \pm 1.8\,(\mathrm{scale}) \pm 3.4\,(\mathrm{PDF})\,\mathrm{pb}$ [9]. The dominant systematic uncertainties are JES, and the $\mu_{\mathrm{R}}/\mu_{\mathrm{F}}$ scales for the tW process.

For the differential cross section measurement, only the 1j1b signal category is used, with the additional requirement of zero "loose jets", defined as jets with p_{T} between 20 and 30 GeV, to achieve a maximum purity in tW events of 25%. The differential cross sections are determined at particle level and are compared to different NLO predictions for the signal process, including different schemes for treating the tW/$\mathrm{t\bar{t}}$ interference (see Fig. 6). Only small differences are observed between the predictions, indicating little sensitivity to the different interference schemes.

[1] An updated version of the analysis has been published after the conference. For the latest results, please refer to the version submitted to JHEP: [2208.00924]

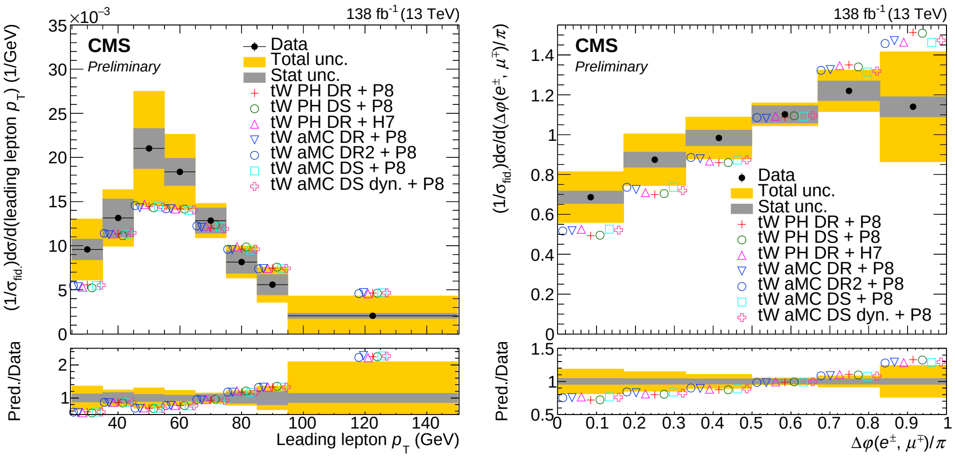

Figure 6: Differential tW cross section as a function of leading lepton p_T (left) and of $\Delta\phi(e^{\pm}, \mu^{\pm})/\pi$ (right) for different NLO predictions and several tW/$t\bar{t}$ interference schemes at particle level. Taken from Ref. [8].

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