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Top quark physics at CMS

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Summary. — Top quark production cross sections and properties are studied at different centre of mass energies in proton-proton collisions in the CMS experiment at the LHC. The recent results include total and differential top cross sections, mass determinations and searches for rare standard model and new physics processes involving top quarks.

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1. – Introduction

The top quark is the heaviest elementary particle with very short lifetime, preventing it from hadron formation before its decay. This feature makes the top quark unique among strongly interacting particles and allows probing of the properties of the quark that are otherwise masked by the long-distance QCD effects. Top quark plays important role in the mechanism of electroweak symmetry breaking providing the largest contribution to the Higgs field self-energy correction. Many models addressing the hierarchy problem predict enhanced coupling of the beyond standard model (BSM) states to the top quark. Therefore, searches for new physics in the top sector are the important component of the new physics program at the LHC. Large top quark production cross section at the LHC provides an opportunity to study the production mechanism and properties of the top quark in detail. In this contribution the recent results from CMS [2] on top cross sections (sect. **2**), mass determinations (sect. **3**) and searches for rare standard model and BSM processes (sect. **4**) are reviewed.

2. – Top production cross sections

The total production cross section of top quarks is one of the fundamental quantities that can be measured at the LHC with high precision. In quantum chromodynamics

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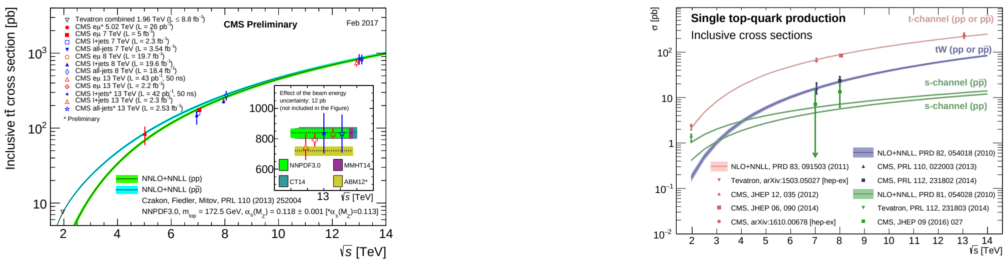


(a) (b)

Fig. 1.: The total top pair (a) and single top (b) production cross sections as functions of proton-proton centre of mass collision energy. Measurements are shown as dots with error bars indicating the total combined systematic and statistical uncertainty. Theoretical predictions (lines) are calculated at NNLO+NNLL and NLO+NNLL precision for $t\bar{t}$ and single-top cross sections, respectively. The shaded bands indicate the uncertainty on the predictions. Taken from [1]

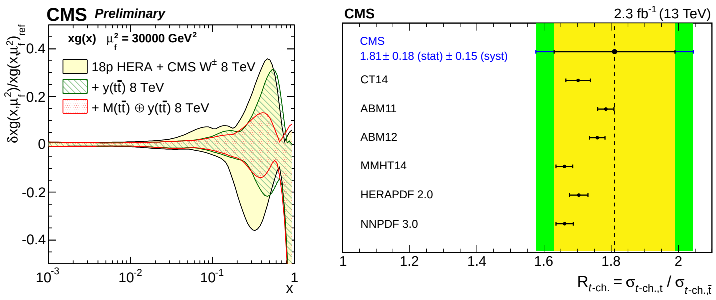
(QCD), the production cross section can be calculated using a factorised approach (eq. 1):

$$\sigma = \int f_a(x_1, \mu_F) f_b(x_2, \mu_F) d\sigma_{ab}(x_1, x_2, \mu_R, \mu_F; \alpha_s, m_t). \tag{1}$$

The prediction depends on the fundamental parameters of the QCD Lagrangian such as strong coupling, α_s, and the top quark mass, m_t. Therefore, the measurements of top cross sections provide means to scrutinize perturbative QCD predictions and determine these parameters.

Figure 1 shows the summary of the measurements of the total $t\bar{t}$ (a) and single top (b) production cross sections measured by the CMS collaboration at different collision energies. In particular, the recent measurement of $t\bar{t}$ cross section at $\sqrt{s}$ =13 TeV was performed in the $e\mu$ channel with 2.2 fb^{-1} dataset [3]. The measured cross section was found to be $\sigma_{t\bar{t}} = 792 \pm 8$ (stat) ± 37 (syst) ± 21 (lumi) pb and is consistent with the SM prediction of $\sigma_{t\bar{t}} = 832^{+40}_{-46}$ pb, the ATLAS measurement [4] and supersedes the existing CMS result [5].

An alternative measurement of $\sigma_{t\bar{t}}$ and a determination of the top quark pole mass, m_t^{pole}, was performed in [6] in a complementary l+jets channel where l denotes single muon or electron. Since different background sources provide different contribution in various event categories, splitting the sample according to the jet and b tags multiplicity, lepton charge and flavour provides powerful constrains on the normalization of the main background sources (W+jets and multijet production). For example, due charge asymmetry of the beam, the W^+ production cross section is significantly higher than that for W^-, therefore, these components can be accurately determined using the events with different charge of the final state lepton. The analysis exploits a maximum likelihood fit to the invariant mass distribution of the isolated lepton and a jet identified as coming from the hadronisation of a bottom quark to determine the $\sigma_{t\bar{t}}$ and m_t^{pole} using the predicted dependence $\sigma_{t\bar{t}}(m_t^{pole})$. The event selection was optimized in order to minimize the uncertainties arising from extrapolation to the full phase. The obtained cross section



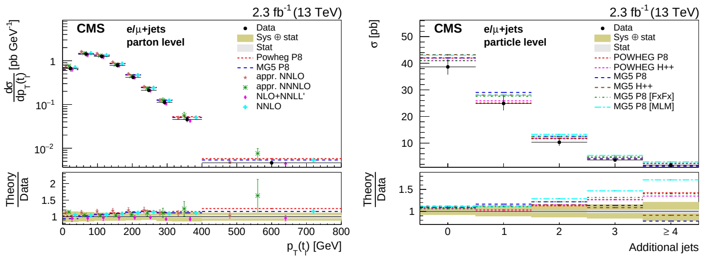
(a) (b)

Fig. 2.: (a) Comparison of relative uncertainties on the gluon component of the proton PDF determined in the fit to HERA and CMS $W^{\pm}$ data and combined datasets additionally including single and double differential cross sections [8]. (b) Comparison of the measured ratio of the single top and anti-top quark $t-$channel production cross section from [9] to theoretical predictions based on different pPDF sets.

value is $\sigma_{t\bar{t}} = 835 \pm 3$ (stat) ± 23 (syst) ± 23 (lumi) pb. The corresponding top quark pole mass value determined using next-to-next-to-leading order (NNLO) predictions based on CT14 NNLO pdf set [7] is $m_t^{pole} = 172.7^{+2.4}_{-2.7}$ GeV, where the uncertainties correspond to the quadratic sum of statistical and systematic components. The obtained value of m_t^{pole} is consistent with other mass determinations using alternative techniques (sec. **3**).

Besides the total top pair production cross section, single and double differential measurements were performed using $\sqrt{s} = 8$ and 13 TeV datasets. In [8], the comprehensive measurement of single and double differential normalized cross sections characterizing the properties of the $t\bar{t}$ system and individual top quarks was performed using the $e^{\pm}\mu^{\mp}$ final state. In this study, theoretical NLO and approximate NNLO pQCD predictions were scrutinized. In addition, NLO predictions using different proton parton density functions (pPDFs) were compared to the data. None of the tested calculations is able to model all aspects of the observed spectra correctly. The approximate NNLO calculations using recent PDF sets describe the data reasonably well. The sensitivity of the data to the pPDFs was demonstrated in the combined QCD fits to the datasets including HERA DIS and CMS $W^{\pm}$ charge asymmetry data as well as the measured single or double differential $t\bar{t}$ cross sections. The inclusion of the new $t\bar{t}$ dataset resulted in significant reduction of the gluon component of the pPDF at large values of the parton momentum fraction, x. The strongest constraint is provided by the double differential cross sections as function of $|y\,(t\bar{t})|$ and invariant mass, $M\,(t\bar{t})$ as demonstrated in fig. 2 (a).

Another measurement, sensitive to the parton distributions, was performed using a dataset with 2.3 fb^{-1} of integrated luminosity collected at $\sqrt{s}$ =13 TeV [9]. In this analysis the production cross section of single top quarks in the $t-$channel was determined in events with single isolated muon and two jets one of which is identified as originating from a bottom quark. A dedicated multivariate discriminant was trained to distinguish signal events containing the decay products of a single top quark or an antiquark from the background. Simultaneous fit of the Monte Carlo templates to the data distributions in multiple jet and b tag multiplicity categories yielded the total cross section $\sigma_{t-\text{ch.}} = 232 \pm 13$ (stat) ± 28 (syst) pb and the ratio of top and anti-top quark production $R_{t-\text{ch.}} =$



(a) (b)

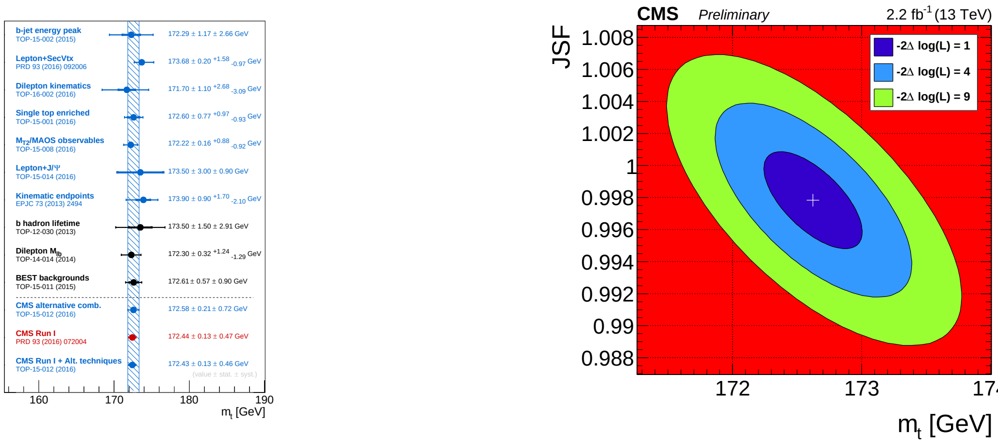
Fig. 3.: (a) Single differential $t\bar{t}$ production cross sections at $\sqrt{s}$ =13 TeV at the parton level as function of transverse momentum of a top (anti-)quark decaying in the semileptonic channel. (b) Single differential cross section unfolded to the particles level as a function of the number of additional jets not attributed to the decay products of the top pair system. The measurements are compared to perturbative analytical calculations as well as to predictions by different event generators. The plots are taken from [11].

1.81 ± 0.18 (stat) $\pm$ 0.15 (exp). The comparison of the single top production cross sections at different centre of mass energies is shown in fig. 1 (b). Next-to-leading order predictions including next-to-next-to-leading-logarithmic (NNLL) contributions [10] were found to be in excellent agreement with the observed energy dependence. Theoretical predictions for the ratio, $R_{t-\mathrm{ch.}}$ based on different PDF sets are compared to the measured value in fig. 2 (b) were found in agreement with the measurement within experimental uncertainty. The future analyses using larger datasets will be able to test the predictions and further constrain PDFs. Single top production in the $t-$channel is also a direct probe of the absolute magnitude of the V_{tb} element of the Cabibbo-Kobayashi-Maskawa (CKM) mixing matrix

$$|f_{LV}V_{tb}| = \sqrt{\frac{\sigma_{t-\mathrm{ch.},\bar{t}+t}}{\sigma^{th}_{t-\mathrm{ch.},\bar{t}+t}}}. \tag{2}$$

In eq. 2, new physics effects are parametrized by the anomalous form factor, f_{LV}, while $\sigma^{th}_{t-\mathrm{ch.},\bar{t}+t}$ is the standard model prediction. The analysis did not reveal any deviations from the standard model. The determined value was found to be $V_{tb} = 1.03 \pm 0.07$ (exp)$\pm$ 0.02 (th) which is consistent with the indirect determination of V_{tb} assuming the unitarity of the CKM matrix.

Top pair production in $e, \mu+$jets decay mode was also investigated at $\sqrt{s}$ =13 TeV using the dataset corresponding to an integrated luminosity of 2.3 fb^{-1} [11]. The cross sections were measured differentially as functions of $p_T(t), p_T(t\bar{t}), y(t), y(t\bar{t}), M(t\bar{t})$ as well as a function of additional jets at parton and particle levels. The measurements at parton level are dominated by the uncertainties in the parton shower and hadronisation modelling. The dependence on these model assumptions is minimized for the particle-level observables, for which the experimental uncertainties of b tagging efficiency and jet energy calibration are dominant. Theoretical calculations using event generators were confronted with the measurements revealing general agreement with the data except for $M(t\bar{t})$ and $p_T(t\bar{t})$, fig. 3 (a), distributions. The data were also compared to approximate NNNLO predictions [12] that were available for a limited number of observables. The



(a) (b)

Fig. 4.: (a) Comparison of the CMS mass determinations and their combination [16]. (b top) Invariant mass of three jets from the top quark decay. (b bottom) Confidence contours in JSF–m_t plane [27].

highest order pQCD calculations are in a reasonable agreement with the data. A softer p_T spectrum observed in previous studies and predicted by NNLO [13] and NLO+NNLL' [14] QCD calculations, was confirmed in the new analysis. Jet multiplicity in $t\bar{t}$ events was found to be typically lower than that predicted by MC programs, as can be seen in fig. 3 (b).

3. – Top mass

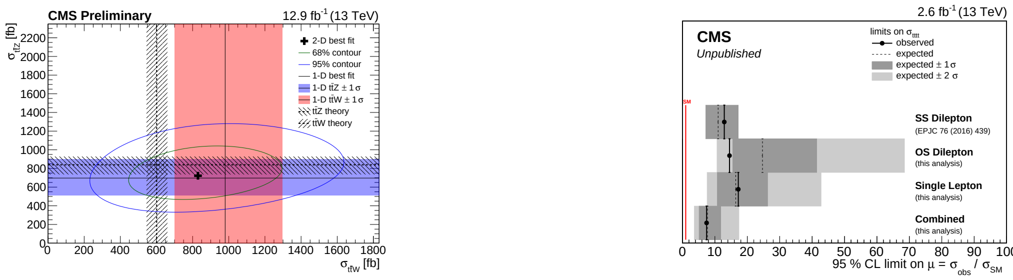
A new combination of top quark mass measurements from CMS exploiting alternative analysis techniques that were not included in the Run I legacy result [15] was recently performed and reported in [16]. The original combined value $m_t = 172.44 \pm 0.13$ (stat) $\pm$ 0.47 (syst) GeV features 3 permille precision and is systematics-dominated. A significant effort have been made to develop new mass measurement approaches not sensitive to some of the significant systematics effects. Most of them have been recently finalised and their combination provides an independent cross check of the published result. Unlike Run I legacy result which is based on the analyses that exploit kinematic constraints to fully reconstruct the $t\bar{t}$ event, ten new measurements used in the new combination do not rely on the full event reconstruction. Five measurements [17, 18, 19, 20, 21] were performed in the dilepton channel. Three analysed both single-lepton and dilepton $t\bar{t}$ decay modes [22, 23, 24]; one — only the l+jets events [25] and yet another one was performed utilising the single-top enriched dataset [26]. Except for the mass determination reported in [17], that is based on the sample collected during the $\sqrt{s}$ =7 TeV data taking, all determinations were performed on $\sqrt{s}$ =8 TeV dataset. Among dilepton analyses three invoke fits to lepton – b jet invariant mass distribution, M_{lb}. The other two exploit the dependence of the position of the maximum of the energy spectrum of the b quark or the shape of the transverse momentum spectrum of $e\mu$ pairs on the top quark mass. The single-lepton analysis is based on the so-called Bi-Event Subtraction

(BEST) method relying on the m_t-dependence of the ratio m_t/m_W of the three- and dijet invariant masses of the hadronically decaying top quark candidates. The determinations using both l+jets and dilepton datasets exploit properties of the invariant mass spectrum of the vertices formed by an isolated lepton from a W boson decay and a jet consistent with the same vertex or the dependence of the decay length in the plane transverse to the proton beam direction of the B-hadrons emerging in the decay chain of the top quark. The third method in this category takes the advantage of the relation between the invariant mass $M = \left(p_l + p_{\mu^+\mu^-}\right)^2$ of a four-vector of an isolated lepton from a W boson and the vector corresponding to a J/ψ meson decaying to a pair of muons. These nine $t\bar{t}$ analyses were complemented by the study of single top sample enriched sample. The different production modes for $t\bar{t}$ and $t-$channel single top production is expected to have different sensitivity to non-perturbative QCD effects (*e.g.* colour reconnection). This behaviour will be explored with larger datasets. The summary of the all measurements that were included in the new combination is compiled in fig. 4 (a). The systematic uncertainties affecting each of the measurements can be grouped into four distinct categories: one experimental category and three theoretical categories that describe the modelling uncertainties. The experimental group covers the uncertainties that arise from the precision of the calibration and resolution of the CMS detector and the effects coming from the signal backgrounds and pileup. The other three categories cover the modelling of the hard scattering process and the associated radiation; non-perturbative QCD effects, such as the simulation of the underlying event and colour reconnection; and the modelling of the light- and b-quark hadronisation. A best linear unbiased estimator (BLUE) was used to combine the results. The method correctly takes into account correlations between input data and provides a linear combination of the measurements that minimises the total uncertainty of the combined result. The new combined value is $m_t = 172.58 \pm 0.21$ (stat) $\pm\, 0.72$ (sys) GeV. It has only slightly larger uncertainty than the published Run I combination. However, when combined with the old value, the global combination features almost the same central value and uncertainty as the legacy result due to statistical correlation between the two combinations and higher precision of the former result.

Besides finalizing 7 and 8 TeV results, the CMS enters the precision domain with 13 TeV data. For example, in [27] one of the first determinations of the m_t parameter was performed using 2.2 fb^{-1} of the Run II data. The analysis method is based on the so-called ideogram technique [28, 29]. In this approach, for each event the mass is reconstructed from a kinematic fit of the decay products to a $t\bar{t}$ hypothesis. The top quark mass is determined simultaneously with an overall jet energy scale factor (JSF), constrained by the known mass of the W boson in $q\bar{q}'$ decays. The new 13 TeV determination has the total uncertainty very similar to the above mentioned new combination $m_t = 172.62 \pm 0.38$ (stat) $\pm\, 0.70$ (sys) GeV. The overall jet-energy-scale factor was found to be consistent with unity indicating excellent calibration of the CMS detectors. The likelihood level contours of the simultaneous fit are shown in fig. 4 (b). The systematic uncertainty of the new mass measurement is dominated by effects that cannot be significantly improved with better calibrations, but require more precise modelling of the non-perturbative effects including underlying event and hadronisation.

4. – Rare processes

As was mentioned, at the LHC, the top quarks are predominantly produced in pairs via strong interactions or individually in electroweak-induced processes. Other processes



(a) (b)

Fig. 5.: (a) Comparison of measured ttW and ttZ production cross sections with the SM predictions from [30]. (b) Summary of the 95% confidence level upper limits on the SM $t\bar{t}t\bar{t}$ production from CMS obtained using 2015 dataset [31].

are significantly suppressed. Nevertheless, the cross sections of rare phenomena like top pair production in association with electroweak gauge bosons or $t\bar{t}t\bar{t}$ are high enough to be directly probed with existing datasets or in the near future. The measurement of $t\bar{t}Z$ production cross sections is important because it provides direct access to the tZ coupling. Moreover, this processes together with $t\bar{t}W$ constitute important background to several new physics searches. In [30], the evidence for $t\bar{t}Z$ and $t\bar{t}W$ production at $\sqrt{s}$ =13 TeV is presented. This is one of the first observations profiting from increased statistics accumulated during 2016 data taking. A data sample corresponding to an integrated luminosity of 12.9 fb^{-1} is used. Only leptonic decays of associated gauge bosons resulting in e, μ (including those from leptonic τ decays) final state were considered. The $t\bar{t}Z$ process was measured in events with three or four leptons, with a pair of same-flavour opposite-sign leptons with invariant mass close to the Z boson mass, while $t\bar{t}W$ was measured exploiting a pair of same-sign leptons as a main signature. The observed significance of the $t\bar{t}W$ signal is 3.9 standard deviations while combined significance of $t\bar{t}Z$ process in $3l$ and $4l$ decay modes is 4.6; the measured cross section values are $\sigma\,(t\bar{t}W) = 0.98^{+0.23}_{-0.22}$ (stat.)$^{+0.22}_{-0.18}$ (sys.) pb and $\sigma\,(t\bar{t}Z) = 0.70^{+0.16}_{-0.15}$ (stat.)$^{+0.14}_{-0.12}$ (sys.) pb, respectively. The determined values together with the standard model predictions are demonstrated in fig. 5 (a). The measurements are found to be in a good agreement with SM expectations and can be used to constrain potential new physics scenarios predicting enhanced $t\bar{t}Z$ and/or $t\bar{t}W$ production.

The search [31] for the SM $t\bar{t}t\bar{t}$ production in e,μ+jets and $e^{\pm}e^{\mp}, \mu^{\pm}\mu^{\mp}, e^{\pm}\mu^{\mp}$+jets decay modes was performed using the data corresponding to an integrated luminosity of 2.6 fb^{-1} that were collected during the $\sqrt{s}$ =13 TeV data taking campaign in 2015. The interest in $t\bar{t}t\bar{t}$ production is twofold. In the SM this process is suppressed by almost five orders of magnitude compared to $t\bar{t}$ production. Perturbative QCD calculations predict the cross section $\sigma_{\mathrm{SM}}\,(t\bar{t}t\bar{t}) = 9.2$ fb [32, 33]. Experimental observation of $t\bar{t}t\bar{t}$ production will be a valuable test of perturbative QCD or can even give an evidence for BSM physics if significantly enhanced rate is observed. Multivariate analysis techniques were applied to identify trijets that are products of the hadronically decaying tops and to distinguish between the signal and dominant $t\bar{t}$ background. The combined expected (observed) limit from single lepton and opposite sign dilepton searches is $\sigma(t\bar{t}t\bar{t}) < 118^{+76}_{-41}$ (94) fb. When the results were combined with the existing like-sign dilepton search, the most stringent limit (at the time of the conference) on the SM $t\bar{t}t\bar{t}$ production was obtained, $\sigma(t\bar{t}t\bar{t}) < 71^{+38}_{-24}$ (69) fb. The summary of existing $t\bar{t}t\bar{t}$ searches at $\sqrt{s}$ =13 TeV performed by CMS are summarised in fig. 5 (b).

5. – Summary

The CMS collaboration finalizes the Run I results and already has precise measurements with the 13 TeV dataset. The exploration of rare phenomena in Run II has started. In this contribution, the measurements of $t\bar{t}$ and single differential cross sections as well as new mass determinations and searches for $t\bar{t}Z$, $t\bar{t}W$ and $t\bar{t}t\bar{t}$ production have been presented.

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