Recent results on top-quark physics by CMS

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Abstract. The article reports a selection of recent results on top-quark physics by the CMS experiment at the CERN Large Hadron Collider. Results on inclusive and differential cross sections, as well as measurements of properties of the top quark, are reported.

1. Introduction
The top quark plays a special role in the Standard Model of particle physics: it is in fact the heaviest elementary particle known to date and has a preferential coupling to the Higgs boson. Its mass is so large that it decays, typically to a W boson and a b quark, before hadronization. In addition, many new physics scenarios beyond the Standard Model foresee a preferred coupling to the top-quark sector. For these reasons, the experiments at the CERN Large Hadron Collider (LHC) have rich programs of measurements related to the top quark physics. For reasons of time, this talk only reported a selection of recent results by the CMS experiment: the whole list of measurements can be found online at [1].

2. Cross section measurements
At the LHC, the main production mechanism for top quarks is via QCD processes, which yield tt̄ pairs. The inclusive cross section for tt̄ pairs production has been measured at proton-proton center-of-mass energies of 7, 8 and 13 TeV [2] and found to be in very good agreement with next-to-next-to-leading order plus next-to-next-to-leading logarithm calculations [3]. The precision of single measurements is around 3.5%. CMS also measured the tt̄ pair production inclusive cross section at a proton-proton center-of-mass energy of 5.02 TeV [4] and in proton-lead [5] and lead-lead collisions [6]: from these measurements a probe of nuclear gluon density in the high Bjorken-x region can be derived.

Measurements of tt̄ pairs differential cross sections [2] have been performed at either the parton level, via extrapolation to the full phase space and allowing a comparison with fixed-order calculations, and at the particle level, that features a reduced model dependence because there is no extrapolation to the full phase space. CMS reported one, two and three dimensional differential cross sections as a function of various reconstructed quantities of the top quark, of the tt̄ pairs or even of the whole event, allowing to derive precise tests of perturbative QCD and to search for new physics in corners of the phase space. In general, one can observe a very good agreement with Montecarlo generators and theoretical calculations, however a softer than expected transverse momentum spectrum is apparent.

Top quarks can also be produced via electroweak diagrams, yielding the so called "single top" production. Inclusive cross sections for single top production have also been measured at 7, 8
and 13 TeV [2], and there is enough statistics to perform differential cross sections in the t and tW channels. Single top cross sections allow to derive the best direct determination to date of the $V_{tb}$ parameter of the Cabibbo-Kobayashi-Maskawa mixing matrix.

Measurements of cross sections for $t\bar{t}$ pairs in association with bosons have been reported that allow to derive limits on anomalous couplings. Also, approaches using effective field theories have been used to search for new physics effects: in a very recent result in this framework, CMS analysed the associated production of top quarks with additional leptons by simultaneously studying 16 6D operators and defining observables at detector-level to enhance sensitivity to all operators [7].

No evidence has been reported yet by CMS for the so-called "4 top" process, $t\bar{t}t\bar{t}$ [8], the cross section of which is indeed foreseen to be very small in the Standard Model. CMS also measured the cross section for the associated production of $t\bar{t}$ with $b\bar{b}$, $c\bar{c}$ and a pair of jets [9], [10], [11]: these represent sizeable backgrounds for the $t\bar{t}$+Higgs process, when the Higgs boson decays hadronically, and are difficult to model theoretically.

3. Properties of the top quark

The mass of the top quark is a fundamental parameter in the Standard Model. It can be derived both in direct and indirect ways. Direct determinations of the top mass exploit full or partial reconstruction of top and antitop decay products and reached a precision regime [2], with single measurements having uncertainties around 0.5 GeV. The mass can also be extracted from fits to various sensitive observables, such as the top pole mass from the cross section measurement: also such indirect determinations are reaching a precision regime. For the first time, CMS measured the running of the top-quark mass [12]: a comparison of the differential $t\bar{t}$ cross section as a function of the invariant mass of the $t\bar{t}$ system to next-to-leading-order theoretical predictions allows to derive the mass of the top quark in the modified minimal subtraction renormalization scheme, and the extracted mass running is found to agree with the scale dependence predicted by the corresponding renormalisation group equation.

The Standard Model foresees a very tiny violation of the discrete CP symmetry in the top-quark sector. CMS sought for CP violation by looking for potential effects induced by anomalous couplings, in particular, in the most recent measurement, through a chromoelectric dipole moment [13]. Two CP-odd observables are constructed and an asymmetry variable is defined: no significant deviation with respect to the Standard Model is observed.

Flavour-changing neutral currents (FCNC) transitions, in which a quark undergoes a transition to a different-flavour quark of the same charge, are forbidden at tree level in the Standard Model: they are only possible via higher-order diagrams, which are strongly suppressed, with branching ratios of around $10^{-11}$ or below; however they can be enhanced, even at the level of $10^{-4}$, in several new physics scenarios. CMS has sought for many FCNC processes, reporting upper limits that start to challenge some new physics scenarios [2] and can rule some of them out with more statistics.

Searches for anomalies in the angular distribution of produced $t\bar{t}$ pairs allow to derive forward-backward asymmetries. These can be caused by new physics induced modifications of the $t\bar{t}g$ vertex or by the presence of heavy states coupled to top quarks. CMS measured a forward-backward asymmetry consistent with the Standard Model [14].

In the $t\bar{t}$ production, electroweak mediated corrections are of the order $\alpha_s^2\alpha_{ewk}$, where $\alpha_s$ and $\alpha_{ewk}$ are the strong and electroweak coupling constants, respectively: these corrections are too small to affect the cross sections but can alter kinematic distributions. This feature was used to derive the Yukawa coupling of the top quark by studying two proxy variables related to the invariant mass and rapidity distribution of reconstructed $t\bar{t}$ pairs [15]. The coupling strength with respect to the Standard Model value was found to be smaller than 1.54 at a 95% confidence level.
4. Conclusions
CMS reported a very large number of results on top-quark physics: this talk only presented a selection of recent results. After having reported several measurements at 7 and 8 TeV, CMS promptly analysed the 13 TeV data: excellent-quality results have soon been obtained, from measurements of inclusive and differential cross sections for both $tt$ and single top quark, to measurement of a wide range of properties of top quarks. In all cases, excellent agreement with Standard Model is observed.

More data, new analysis techniques and refined experimental and theoretical tools will allow to reduce the statistical and systematic uncertainties, allowing to improve the results even further. In addition, the LHC will start a new period of data taking with higher luminosity and larger center-of-mass energy: new interesting measurements are soon to come.

5. References
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