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Top quark physics experimental results at the LHC: Cross section and mass measurements with the CMS experiment

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Summary. — The top quark, the heaviest known elementary particle discovered at the Fermilab Tevatron almost exactly twenty years ago, has taken a central role in the study of fundamental interactions. Its large mass suggests that it may play a special role in Nature. With approximately 25 fb^{-1} of data collected by the CMS experiments at the Large Hadron Collider in Run 1 (2010–2012), top quark physics is at a turning point from first studies to precision measurements with sensitivity to new physics processes. This report summarizes the latest experimental results on top quark production cross section and mass measurements.

PACS 14.65.Ha – Top quarks.
PACS 13.60.Hb – Total and inclusive cross sections (including deep-inelastic processes).
PACS 12.15.Ff – Quark and lepton masses and mixing.
PACS 12.15.Hh – Determination of Cabibbo-Kobayashi & Maskawa (CKM) matrix elements.

1. – Introduction

This year marks the twentieth anniversary of the discovery of the top quark at the Fermilab proton-antiproton collider [1]. The announcement came in February 1995, after intense months of scrutiny of the data. The top quark was clearly present in the data and the CDF and D0 collaborations published papers presenting overwhelming proof the top quark had been finally found.

Many years after its discovery, the top quark still plays a fundamental role in the program of particle physics. The study of its properties has been extensively carried out in high energy hadron collisions. However, a few important questions still remain unanswered. Why is it so heavy? Is its mass generated by the Higgs mechanism? What is the role the top quark plays in the electroweak symmetry breaking (EWSB) mechanism? Does the top quark play a role in physics beyond the standard model (SM)? Are the couplings affected? Since the shutdown of the Tevatron in September 2011, the Large

Hadron Collider (LHC) is now the only place where it is possible to study the top quark production mechanism. Before the start of the LHC, most of the measurements were limited by the small number of top quarks available. The LHC has performed extremely well and the large samples of top quarks collected offer the opportunity to improve the results and enter the era of precision measurements and study rare processes. It is worth noticing that studies performed at the Tevatron and at the LHC are sometime complementary due to the different energies and production mechanisms.

The top quark is the heaviest of all known elementary particles. With a mass close to that of an atom of gold, it has a mass about 40 times heavier than the b-quark and it is heavier than the W boson, the top quark decays to $t \to Wb$ with a branching fraction close to 100%. The top quark is a fundamental particle with a mass close to the EWSB scale, and it may play an important role in the understanding of the EWSB mechanism. Furthermore, the large top quark mass implies a large coupling to the Higgs boson, thus establishing a privileged link to the Higgs sector. Due to its short lifetime, the top quark decays before hadronization and it offers the unique opportunity to study the properties of a bare quark which are preserved in the decay chain and transferred to its decay products.

At hadron colliders, top quarks are mostly produced in pairs through strong interactions, or individually (single-top production) via electroweak interaction. Depending on the production mode, the top quark therefore allows different tests of the participating forces. The top quark is present in the higher-order diagrams and its mass is related to the Higgs and W boson masses. Top quark production also plays an important role in many scenarios in the search for new physics beyond the SM. Several models predict the existence of new particles decaying to (or with large couplings to) the top quark. Therefore, the study of top quarks may provide hints to the presence of new physics processes. Furthermore, top quark production constitutes a large background to many of the searches for new physics processes, and it is therefore important to understand the properties and the characteristics of top production and decay mechanisms, and the level of precision will have an impact on the constraints on new physics processes.

Here, the latest results obtained in proton-proton collisions at $\sqrt{s} = 7$ and $8\,\text{TeV}$ collected by the CMS experiment during Run 1, *i.e.* the first period of data-taking between 2010 and 2012, are summarized.

2. – Top quark pair production

At the LHC the top quark pair production mechanism is dominated by gluon-gluon fusion processes ($\simeq 90\%$). This is due to the large gluon density in the proton at small x. The production cross section has been measured in many different final states. Deviation of the cross section from the predicted SM value may indicate new physics processes.

In each top quark pair event, there are two W bosons and two bottom quarks. From the experimental point of view, top quark pair events are classified according to the decay mode of the two W bosons: the all-hadronic final state, in which both W bosons decay into quarks, the lepton+jet final state, in which one W decays leptonically and the other to quarks, and the dilepton final state, in which both W bosons decay leptonically. The word "lepton" here refers to electrons and muons, whereas taus are somehow classified differently, and they are generally treated separately. In the dilepton channel, the final state consists of two charged leptons, missing transverse energy $E_{\mathrm{T}}^{\mathrm{miss}}$, and at least two bottom jets. The branching ratio is small (5%) but the background (mostly $Z+$jets) is also small, which makes the dilepton the best final state to select a clean sample of

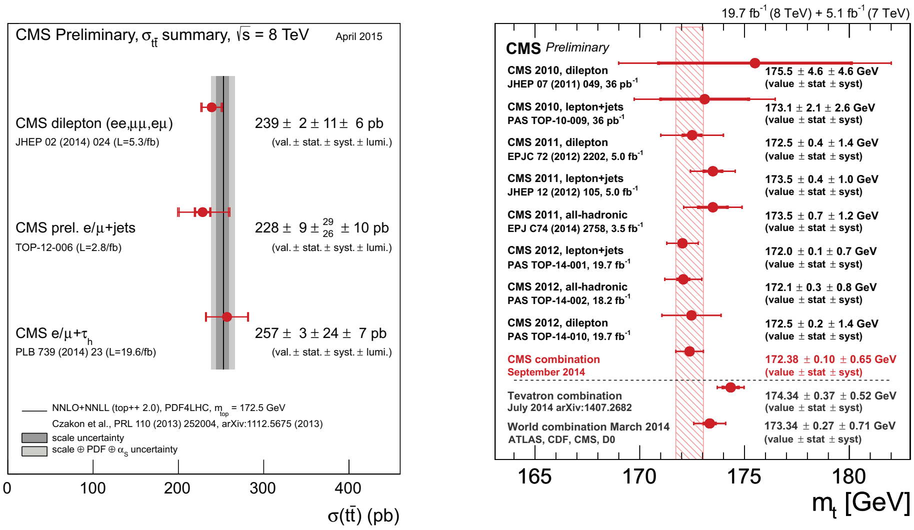

Fig. 1. – Summary of the top quark cross section (at $\sqrt{s} = 8\,\text{TeV}$) and mass measurements with the CMS experiments.

top quark events. The all-hadronic final state has an experimental signature with at least 6 jets, of which two are from bottom quarks, with a large background, mostly from multi-jet events. The measurement of the cross section in this channel is rather difficult, despite the large branching fraction (44%). The lepton+jet final state offers a compromise with a reasonably large branching fraction (36%) and a moderate background, mostly from W+jet events. The signature consists of one charged lepton, $E_{\mathrm{T}}^{\mathrm{miss}}$, and at least four jets (two of them b-jets).

2˙1. *Cross section measurements.* – Cross section measurements have been performed both at the Tevatron and at the LHC (fig. 1, left), and the accuracy of the experimental results rivals that of theory expectations [2]. The first top quark pair candidates at the LHC were already reported in the summer of 2010, after a few months of data-taking at $\sqrt{s} = 7\,\text{TeV}$. In Run 1, thousands of top quark events have been selected. Measurements of the inclusive top quark pair production cross section have been performed at the LHC in the dilepton and lepton+jet final states using electrons and muons, and provide the most precise results [3, 4]. Most of the cross section measurements are already limited by the systematic uncertainties. As an example, the cross section in the lepton+jet final state is determined with a simultaneous maximum likelihood fit to the number of jets, the number of b-tagged jets and the invariant mass of the tracks associated with the secondary vertex (to allow discriminating light and heavy quark contributions). The simultaneous fit in the jet and b-jet multiplicities allow constraining the top quark pair signal and the W+light (and heavy) flavour composition of the background.

Measurements are also performed in the τ+lepton, τ+jets, and all-hadronic channels. The interest of determining the cross section in all final states is mainly to verify the consistency of the measurements, and check for deviations. For example, the measurement of the cross section in the τ+lepton (as well as in the τ+jets) final state is important because a deviation of the measured cross section from the expected value may provide a hint for new physics. The τ+lepton channel, *i.e.* $t\bar{t} \to (\ell\nu_\ell)(\tau\nu_\tau)b\bar{b}$ (with $\ell = e,\ \mu$) is of particular interest because the existence of a charged Higgs with a mass smaller than the top quark mass $m_{H^\pm} < m_t$ could give rise to anomalous τ lepton production directly observable in this decay channel. As in the other channels, the τ+lepton cross section results [5] are consistent with the cross sections measured in the other final states, and the measurement can be used to set stringent limits on charged Higgs production [6]. Analogously, the yields of events in the dilepton final state may be altered with respect to the rates predicted by the SM by the presence of a charged Higgs boson. In particular, a charged Higgs boson with a mass heavier than that of the top quark, $m_{H^\pm} < m_t$, would be produced in association with a top quark and it would preferentially decay through $H^+ \to tb$ decay, thus affecting the top quark pair event yields.

A precise cross section measurement in the $t\bar{t}$ dilepton final state is also pursued in the measurement of the ratio of the top quark branching fractions $R = B(t \to Wb)/B(t \to Wq)$, where the denominator includes the sum over all down-type quarks (q = b, s, d). In order to quantify the purity of the signal sample, the cross section is measured by fitting the observed jet multiplicity, thereby constraining the signal and background contributions. By counting the number of b jets per event, a lower limit on the Cabibbo-Kobayashi-Maskawa matrix element $|V_{tb}|$ is set. The result is combined with a previous measurement of the t-channel single top quark cross section to determine the top quark total decay width, Γ_t. Currently, these are the most precise measurements of V_{tb} and Γ_t [7].

A recent combination of the ATLAS and CMS measurements of the top quark pair production cross section yields an improved cross section measurement (4% relative precision) [8].

2˙2. *Differential distributions.* – The large number of top quark events collected during Run 1 makes also possible the measurement of differential cross sections, $\mathrm{d}\sigma/\mathrm{d}X$, for the relevant variable X. For instance, variables of relevance may be related to the kinematics of the top or $t\bar{t}$ systems, such as p_T, $M_{t\bar{t}}$, $t\bar{t}+N$ jets. These distributions may be used to validate given Monte Carlo (MC) models as well as to check specific higher order quantum chromodynamics (QCD) calculations. Deviations could signal contribution from new physics. Differential cross section measurements [9] are performed in the dilepton and lepton+jet channels, after reconstruction of the event kinematics. Those measurements show that the transverse momentum of the top quark, p_T^{t}, is softer than predicted by the MADGRAPH simulation. In order to account for this effect, the difference between the result obtained with the nominal simulation and that obtained by using the prediction reweighted to describe the p_T^{t} is taken as an additional systematical uncertainty.

2˙3. *Top quark pair with associated (jet or boson) production.* – Top quark pair events are expected to be accompanied by additional hard jets that do not originate from the decay of the $t\bar{t}$ pair ($t\bar{t}$+jets). These processes typically arise from either initial- or final-state QCD radiation, providing an essential handle to test the validity and completeness of higher-order QCD calculations of processes leading to multijet events. Furthermore, the correct description of $t\bar{t}$+jet production is important since it constitutes an important background to processes with multijet final states, such as associated Higgs boson production with a $t\bar{t}$ pair, with the Higgs boson decaying into a $b\bar{b}$ pair, or final states predicted in supersymmetric theories. Anomalous production of additional jets accompanying a $t\bar{t}$ pair could be a sign of new physics beyond the SM. With a large number of $t\bar{t}H$ candidate events collected, it will be possible to measure the Higgs boson couplings independently of its decay mode, reducing substantially the common systematic uncertainties. The measurement of the $t\bar{t}+N$ jet distribution assesses the theoretical predictions and the simulation in the recoil of the $t\bar{t}$ system and the modelling of additional quark and gluon radiation in $t\bar{t}$ production. Experimental data are needed to validate the simulated samples and to reduce the uncertainties. Using a procedure to associate jets to decay products of the top quarks, the differential cross section of the top quark pair production is determined as a function of the additional jet multiplicity. The measurements are compared with predictions from perturbative quantum chromodynamics and no significant deviations are observed [10].

It is also important to determine the couplings of the newly found Higgs boson to fermions, especially to the top quark. In the SM, one of the most promising channels for a direct measurement of this coupling is the production of the Higgs boson in association with a top quark pair, where the Higgs boson decays to $b\bar{b}$. This final state, which has not yet been observed, has an irreducible non-resonant background from the production of a top quark pair in association with a b-quark pair. A measurement of the cross section ratio $\sigma_{t\bar{t}b\bar{b}}/\sigma_{t\bar{t}jj}$ is compatible with a theoretical QCD next-to-leading order (NLO) calculation [11]. Many kinematic distributions are expected to be similar for $t\bar{t}b\bar{b}$ and $t\bar{t}jj$, leading to reduced systematic uncertainties in the ratio.

The electroweak couplings of the top quark can also be studied in the associated production to a gauge boson, such as $t\bar{t}\gamma$, $t\bar{t}$W, and $t\bar{t}$Z events. All three processes can be used to test the internal consistency of the SM and search for the presence of new physics. Despite their small cross sections, they are significant backgrounds to analyses that probe phenomena with even smaller, or comparable, cross sections. Examples are searches for supersymmetry in same-sign dilepton and in multilepton final states. The $t\bar{t}\gamma$ production is large enough to be measured with the available data samples [12]. The leading-order (LO) cross section for this process is approximately 2 pb at $\sqrt{s} = 8\,\text{TeV}$, for a photon transverse momentum $p_T > 20\,\text{GeV}$. In this process, the photon is radiated from off-shell top quarks or incoming partons, or from on-shell top quark or one of its decay products (such as the W). The measurement in the lepton+jet final state is performed with a template fit to signal and background, where the templates are derived from data. Results agree well with SM predictions [13]. The measurements of top quark pair production in association with a W or Z boson are performed in three leptonic (electron and muon) channels: a same-sign dilepton analysis targeting $t\bar{t}W$ events, and trilepton and four-lepton analyses for $t\bar{t}Z$ events. Direct cross section measurements are compatible with SM predictions within the experimental uncertainties [14].

2·4. *Rare decays.* – With the larger centre-of-mass energy and large data samples collected, the study of rare processes involving top quarks becomes possible. One such process is the production of four top quarks ($t\bar{t}t\bar{t}$). The LO cross section for SM $t\bar{t}t\bar{t}$ production at the LHC is predicted to be extremely small: $\sigma_{SM} \simeq 1\,\text{fb}$ at $\sqrt{s} = 8\,\text{TeV}$. The main background is due to $t\bar{t}$ production, a process that has a cross section which is larger by more than five orders of magnitude. However, in many models beyond the SM involving massive coloured bosons, Higgs boson or top quark compositeness, or extra dimensions, such a cross section may be enhanced. In some supersymmetric extensions of the SM, $t\bar{t}t\bar{t}$ final states can also be produced via cascade decays of coloured supersymmetric particles such as squarks and gluinos. Hence, experimental constraints on $t\bar{t}t\bar{t}$ production may enhance the sensitivity of such searches. Events in the lepton+jet final state are selected, and kinematic reconstruction techniques and multivariate analyses are used to discriminate the $t\bar{t}t\bar{t}$ signal from the $t\bar{t}$ background. Same-sign dilepton events are also used in the search. In order to improve the sensitivity to a wide variety of possible signals beyond the SM, multiple search regions defined by $E_{\mathrm{T}}^{\mathrm{miss}}$, hadronic energy, number of jets and b-quark jets, and transverse momenta of the leptons in the events are considered. Certain SUSY models with R-parity conservation provide an excellent dark matter candidate —a stable lightest supersymmetric particle (LSP) that escapes detection. Therefore, a search for this signature involves sizable $E_{\mathrm{T}}^{\mathrm{miss}}$ due to undetected LSPs. Nevertheless, signatures without significant $E_{\mathrm{T}}^{\mathrm{miss}}$ are also considered in order to be sensitive to SUSY models with R-parity violation (RPV) which imply an unstable LSP. In general, the final state signature is chosen independently of any particular physics model, such that these searches can be applied also to probe non-supersymmetric extensions of the SM. Due to the very large $t\bar{t}$ background, direct measurement of $t\bar{t}t\bar{t}$ production is not yet sensitive to SM expectations [10, 15].

3. – Mass measurements

The top quark mass m_t is a fundamental parameter of the SM, and it is linked to the W and Higgs boson masses. Its value is measured accurately at the Tevatron with a relative precision of approximately 0.4%. The combined measurement from the CDF and D0 experiments yields $m_t = 174.34 \pm 0.64$GeV [16, 17]. Direct measurements of m_t are also performed at the LHC (fig. 1, right). Thanks to the large samples of top quarks available, stringent selections and improved analysis techniques, and to an excellent performance and good understanding of the detectors, the precision of the LHC measurements is comparable to the precision reached at the Tevatron already after the first few years of data-taking [18]. The top quark mass is measured in the dilepton, lepton+jet, and in the all-hadronic channels. The first measurement at the LHC was performed in the dilepton channel [19] from the kinematic characteristics of the events with a full kinematic analysis, and with an analytical matrix weighting technique using distributions derived from simulated samples. However, the reconstruction of m_t from dilepton events leads to an under-constrained system, since the dilepton channel contains at least two neutrinos in the final state. The lepton+jet channel provides instead a fully constrained system, and it is (so far) the "golden" channel as it yields the best accuracy in the mass measurement among all final states. Many techniques have been used, and the most accurate single measurement at the LHC is performed with the "Ideogram" method, in which a constrained kinematic fit is performed for all jet-parton assignment combinations [20]. For each event, a likelihood is calculated as function of the top quark mass (with two terms, one for signal and one for background) corresponding to the probability for the event to be either signal or background. The signal and background probabilities are parametrized using analytic functions, derived from simulation. An overall likelihood is constructed by multiplying all event likelihoods. In general, the mass measurements are limited by systematic uncertainties, and the dominant source is the jet energy scale uncertainty, *i.e.* the absolute scale, ISR/FSR, fragmentation, and single particle response in the calorimeter. In the lepton+jet channel, reduced uncertainty can be achieved with an *in-situ* calibration of the W mass from the untagged jets, using the $W \to qq'$ decays.

Direct measurements of m_t rely on the reconstruction of kinematic observables sensitive to m_t. These direct measurements depend on the details of the kinematics, reconstruction, and calibration. Furthermore, the measurement is performed in a particular definition of m_t which does not correspond to a specific renormalization scheme. Alternatively, m_t can be derived indirectly from the cross section measurement. Therefore, measurements of the cross section are used to extract m_t in a well-defined renormalization scheme, such as the pole mass (m_{pole}) or $\overline{MS}$ definitions. The measured inclusive $t\bar{t}$ production cross section is compared with fully inclusive higher-order perturbative QCD computations where the top quark mass parameter is unambiguously defined. For instance, the extraction of m_{pole} from the measured $t\bar{t}$ cross section provides complementary information compared to direct methods that rely explicitly on the details of the kinematic mass reconstruction. This extraction also tests the internal consistency of perturbative QCD calculations in a well-defined renormalization scheme, and provides an important cross check of the direct measurements.

Direct measurement of a mass difference between particle and antiparticle would indicate a violation of the CPT symmetry. Quarks carry color charge and cannot be observed directly as they hadronize to colorless particles before decaying. One exception is the top quark, as it decays before hadronization due to its short lifetime. In the measurement, carried out in the lepton+jet channel, most of the systematic uncertainties cancel out. The mass difference between top and antitop quarks Δm_t is measured and no significant deviation from zero is found [21].

In order to reduce the dependence on simulation, good progress has been made on methods using endpoints of kinematic variables to measure particle masses. These methods aim at measuring the masses of new particles, but can also be applied to measure the masses of SM particles such as the top quark [22].

Improvements in the measurement of the top quark mass can be achieved at the LHC for running conditions foreseen in the near and medium future. Predictions are carried out for large data sample of up to $3000\,\text{fb}^{-1}$ expected to be collected in the future LHC programs at a proton-proton collision energy of $\sqrt{s} = 13$–$14\,\text{TeV}$. They include investigating the possible evolution of the top quark mass precision using conventional (but also less conventional) techniques. Methods of estimating the differential mass distributions, which are currently limited by statistical uncertainties, will ultimately offer the possibility to constrain the dominant systematic uncertainties related to jet energy scale calibration and QCD modeling to unprecedented precision. Those techniques, together with the use of alternative approaches such as —for example —the L_{xy} (*i.e.* the B-hadron decay length) and J/ψ (*i.e.* leptonic final states with J/ψ from the b-quark decays) methods avoid the reconstruction of jets or rely solely on lepton reconstruction, thus reducing strongly the traditional uncertainties related to the JES calibration and QCD processes and possibly reducing dependence on pileup.

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REFERENCES

[1] Abe F. *et al.* (CDF Collaboration), *Phys. Rev. D*, **50** (1994) 2966; *Phys. Rev. Lett.*, **73** (1994) 225; Abe F. *et al.* (CDF Collaboration), *Phys. Rev. Lett.*, **74** (1995) 2626; Abachi S. *et al.* (D0 Collaboration), *Phys. Rev. Lett.*, **74** (1995) 2632.

[2] Kidonakis N., *Phys Rev. D*, **82** (2010) 114030; Cacciari M., Czakon M., Mangano M. L., Mitov A. and Nason P., *Phys. Lett. B*, **710** (2012) 612; Ahrens V., Neubert M., Pecjak B. D., Ferroglia A. and Yang L. L., *Phys. Lett. B*, **703** (2011) 135; Aliev M., Lacker H., Langenfeld U., Moch S., Uwer P. *et al.*, *Comput. Phys. Commun.*, **182** (2011) 1034. Czakon M., Fiedler P. and Mitov A., *Phys. Rev. Lett.*, **110** (2013) 252004.

[3] Chatrchyan S. *et al.* (CMS Collaboration), *JHEP*, **02** (2014) 024 (*JHEP*, **02** (2014) 102).

[4] Aad G. *et al.* (ATLAS Collaboration), arXiv:1504.04251 [hep-ex].

[5] Khachatryan V. *et al.* (CMS Collaboration), *Phys. Lett. B*, **739** (2014) 23.

[6] Chatrchyan S. *et al.* (CMS Collaboration), *JHEP*, **1207** (2012) 143, CMS-PAS-HIG-12-052 (2012); Aad G. *et al.* (ATLAS Collaboration), *JHEP*, **1206** (2012) 039; Chatrchyan S. *et al.* (CMS Collaboration), *JHEP*, **11** (2015) 018.

[7] Khachatryan V. *et al.* (CMS Collaboration), *Phys. Lett. B*, **736** (2014) 33.

[8] CMS Collaboration, CMS-PAS-TOP-14-016.

[9] Khachatryan V. *et al.* (CMS Collaboration), *Eur. Phys. J. C*, **75** (2015) 542.

[10] Chatrchyan S. *et al.* (CMS Collaboration), *Eur. Phys. J. C*, **74** (2014) 3014.

[11] Khachatryan V. *et al.* (CMS Collaboration), arXiv:1411.5621 [hep-ex]; *Phys. Lett. B*, **746** (2015) 132.

[12] CMS Collaboration, CMS-PAS-TOP-13-011.

[13] Aaltonen T. *et al.* (CDF Collaboration), *Phys. Rev. D*, **84** (2011) 031104.

[14] Khachatryan V. *et al.* (CMS Collaboration), *Eur. Phys. J. C*, **74** (2014) 3060; *JHEP*, **01** (2016) 096.

[15] Chatrchyan S. *et al.* (CMS Collaboration), *JHEP*, **01** (2014) 163 (*JHEP*, **01** (2015) 014).

[16] Aaltonen T. *et al.* (CDF and D0 Collaborations), *Phys. Rev. D*, **86** (2012) 092003.

[17] Tevatron Electroweak Working Group (CDF and D0 Collaborations), arXiv:1407.2682 [hep-ex].

[18] Chatrchyan S. *et al.* (CMS Collaboration), CMS-PAS-TOP-14-015 (2014).

[19] Chatrchyan S. *et al.* (CMS Collaboration), *JHEP*, **07** (2011) 049; Chatrchyan S. *et al.* (CMS Collaboration), *Eur. Phys. J. C*, **72** (2012) 2202.

[20] Khachatryan V. *et al.* (CMS Collaboration), arXiv:1509.04044.

[21] Chatrchyan S. *et al.* (CMS Collaboration), *JHEP*, **06** (2012) 109.

[22] Chatrchyan S. *et al.* (CMS Collaboration), *Eur. Phys. J. C*, **73** (2013) 2494.