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Measurements of top-quark properties at CMS

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Summary. — Recent measurements of top-quark properties by the CMS experiment are presented. The measurements were performed using the data collected in proton-proton collisions at centre-of-mass energies of 7 and 8 TeV in the years 2011 and 2012. These results include measurements of the top-quark mass, the top-quark charge asymmetry, the $t\bar{t}$ spin correlations and polarisation as well as the W-helicity in top-quark decays. Furthermore searches for flavour-changing neutral currents in decays and production of top quarks are performed. The results are found to agree with the predictions from the standard model within uncertainties.

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1. – Introduction

The top quark, discovered in 1995 at the Tevatron [1, 2], is the heaviest elementary particle known to date. Unlike other quarks, the top quark has a very short lifetime and decays before hadronization. From measurements of its decay products, the properties of the top quark, such as spin, polarisation and mass can be determined. Top quarks are also an important probe to new physics. It is also a major background to several physics beyond-standard-model (BSM) searches. The data collected at the Large Hadron Collider (LHC), during the first years of its operation, allow us to perform unprecedented tests and precision measurements on different top-quark properties.

The central feature of the CMS apparatus is a superconducting solenoid, which provides an axial magnetic field of 3.8 T. Within the field volume there are a silicon pixel and strip tracker, a lead tungstate crystal electromagnetic calorimeter, and a brass/scintillator hadron calorimeter. Charged-particle trajectories are measured by the tracker, covering $0 \leq \phi \leq 2\pi$ in azimuth and $|\eta| < 2.5$ in pseudorapidity, where η is defined as $-\ln[\tan(\theta/2)]$ and θ is the polar angle of the trajectory of the particle with respect to the counterclockwise proton beam direction. Muons are identified and measured in gas-ionization detectors embedded in the steel flux return yoke outside the solenoid. A detailed description of the CMS detector can be found in [3].

2. – Top mass measurements

The top-quark mass is an important parameter of the standard model. Precision measurements allow us to perform consistency tests as the masses of the W-boson, the top quark, and the Higgs boson are coupled through electro-weak loop-corrections [4]. Theoretically, to measure a free and non-confined particle of top quark, there are difficulties for its scheme dependence and non-perturbative effects of Λ_{QCD}. Experimentally, good jet reconstruction and high performance b-jet tagging algorithm play key roles on the top-quark mass measurements.

2·1. *Ideogram method*. – Traditionally, the top-quark mass measurement is done using the ideogram method, by using a kinematic fit and constructing two-dimensional likelihood functions for each event (ideograms), to obtain the top-quark mass and jet energy scaling (JES) simultaneously [5]. Here, the invariant mass of the two jets associated with the hadronically decaying W-boson, whose mass determined from previous measurements, serves directly as an estimator for the JES.

In the study done at CMS, a sample with one isolated e or μ together with four or more jets, including at least two b-tagged jets, is used. This data corresponding to $5\,\mathrm{fb}^{-1}$ collected at 7 TeV is put into a two-dimensional ideogram fitter. The measured top-quark mass $m_t = 173.49 \pm 0.43(\mathrm{stat.} + \mathrm{JES}) \pm 0.98(\mathrm{syst.})\,\mathrm{GeV}$ while $\mathrm{JES} = 0.994 \pm 0.003(\mathrm{stat.}) \pm 0.008(\mathrm{syst.})$.

An effort has been made to combine the top-quark mass measurements of the LHC experiments. Using the results corresponding to integrated luminosities $\mathcal{L}_{\mathrm{int.}} = 3.5$–$4.9\,\mathrm{fb}^{-1}$ collected at $\sqrt{s} = 7\,\mathrm{TeV}$, the average top-quark mass is $173.29 \pm 0.23(\mathrm{stat.}) \pm 0.26(\mathrm{JES}) \pm 0.88(\mathrm{syst.})\,\mathrm{GeV}$ with the BLUE method [6] that combines the correlated systematical uncertainties. This is done with in situ calibration using the W mass constraint. The dominate uncertainty is jet energy scale. By comparing with the averaged result from Tevatron experiment, we can see that LHC experiments have reached the precision of Tevatron experiment results, but more efforts to reduce their systematical uncertainties are needed.

2·2. *Alternative methods*. – The combined top-quark mass measurements of CMS using data collected at 7 and 8 TeV gives $m_t = 173.44 \pm 0.37(\mathrm{stat.}) \pm 0.91(\mathrm{syst.})$ [7]. To further improve the precision, the focus would be on the reduction of systematic uncertainties in spite of the increased data and higher collision energy in the new runs after the long shutdown. Projection studies for 14 TeV runs with 300–$3000\,\mathrm{fb}^{-1}$ have been performed and the key systematic uncertainties are listed in [8]. The uncertainty on the b fragmentation and hadronization can be improved with data. One would need to see the results from NNLO calculations to determine whethere those can explain the difference between the data and the MC on the top-quark p_T modeling. There are also alternative ways on the top-quark mass measurement being performed: the end-points method, B-meson lifetime method, and top-quark pole mass method.

2·2.1. End-points method. The invariant mass and transverse mass of reconstructed events are sensitive to the top-quark mass:

$$\mu_{bb}^{\max} = \frac{M_t}{2}\left(1 - \frac{M_W^2}{M_t^2}\right) + \sqrt{\frac{M_t^2}{4}\left(1 - \frac{M_W^2}{M_t^2}\right)^2 + \widetilde{M_W^2}}\,, \tag{1a}$$

(1b) $$M_{b\ell}^{\max} = \sqrt{m_b^2 + \left(1 - \frac{M_W^2}{M_t^2}\right)(E_W^* + p^*)(E_b^* + p^*)}\,.$$

One can measure the top-quark mass based on endpoint determinations in kinematic distributions.

A simultaneous fit to the top-quark, W-boson, and neutrino masses is reported [9] using $t\bar{t}$ events selected in the dilepton final state. A sample of $5\,\mathrm{fb}^{-1}$ data collected at 7 TeV is used. The events with exactly two isolated e or μ with at least two b-tagged jets are put into the fitter. By constraining the neutrino and W-boson masses to their world-average values, the measured top-quark mass is obtained as: $m_t = 173.9 \pm 0.9(\mathrm{stat.})^{+1.7}_{-2.1}(\mathrm{syst.})$.

2˙2.2. *B*-meson lifetime method. The top-quark mass can also be determined from b decay length using a b hadron lifetime based technique. The decay length in the transverse direction has the following relation: $L_{xy} = \gamma_b \beta_B \tau_B \sim 0.4 \frac{m_t}{m_B} \beta_B \tau_B$. So a linear dependency can be seen to the top-quark mass: $\Delta L_{xy}/\mathrm{GeV} = 25$–$30\,\mu\mathrm{m}$. This method is done in CDF experiment [10] for the first time. Since the study is done based on tracks and thus it has complementary systematical uncertainties to that of traditional measurements (JES). In CMS, a study [11] selects a secondary vertex with the largest L_{xy} in each event and uses its median value to extract the top-quark mass as $m_t = 173.5 \pm 1.5(\mathrm{stat.}) \pm 1.3(\mathrm{syst.}) \pm 2.6(\mathrm{p_T})$ GeV. The data used in this study correspond to integrated. luminosity 19.3–19.6 fb^{-1}, collected at $\sqrt{s} = 8$ TeV in 2012. The dominant systematics is W+jet normalization.

2˙2.3. Pole mass from top cross section. Measuring the pole mass of the top quark from its production cross section is theoretical well understood and motivated. The study [12] done at CMS is based on the most precise top-quark production cross section measurement [13]. One can constrain the top-quark pole mass with the theoretical production cross section and the strong coupling constant α_S at the next-to-next leading order (NNLO) calculation. The results obtained using the NNPDF 2.3 are: $m_t^{\mathrm{pole}} = 176.7^{+3.8}_{-3.4}$ GeV and $\alpha_S(m_Z) = 0.1151^{+0.0033}_{-0.0032}$. These results are consistent with the measurement of $m_t^{\mathrm{pole}} = 173.2$ GeV done at Tevatron and the world average $\alpha_S = 0.1184$ from PDG.

2˙2.4. Further studies. A study looking at J/ψ particles in $t\bar{t}$ events is done at CMS [14]. The full data collected in 2012 at $\sqrt{s} = 8$ TeV with one isolated lepton or dilepton events are used. The di-muon decays of J/ϕ from the b-jets of top-quark daughters have been studied. This can help us on the understanding of background modeling and b-hadron fragmentation by studying the J/ϕ properties. One can find from the study results that the distance distribution between the b-jet and J/ϕ agrees with the Monte Carlo prediction. The ratio of p_T between the nearest b-jet and J/ϕ also agrees with the default MC. This study can lead to a better control on the systematic uncertainties for the top-quark mass measurements.

The study on the underlying event (UE) activities using $t\bar{t}$ events is also done with the full 2012 data. The UE activities consist of the hadron activities of initial-state radiation (ISR), final-state radiation (FSR), multiple-parton interactions (MPI), and beam-beam remnants (BBR). The UE studies are aiming for better MC tunings to reduce the MC modeling systematics. The study [14] is done by looking at $e + \mu$ high purity $t\bar{t}$ sample with $S/(S+B) \sim 0.96$. The charged tracks that not used in the jet clusters are used to calculate the UE sensitive variables: charged particle multiplicity N_{ch}, transverse momentum sum Σp_T, and averaged transverse momentum $\langle p_T \rangle$. An event-by-event reference direction is from the leading reconstructed top-quark candidate of the event. The observables are checked in the "toward", "transverse", and "away" regions based on the $\Delta\phi$ to the reference axis in the transverse plan. The backgrounds are subtracted based on the MC predictions. Pythia Z2* and P11 tunes are used to study the validity of MC tunings. By comparing MC of different models, one can see a clear role of event Q^2 as well as the effect of color reconnection model.

3. – Top-quark properties

Various properties of the top-quark production or decays are being studied. Those are to test the standard model (SM) predictions and good candles for new physics searches.

3˙1. *Top-quark charge asymmetry.* – The difference between the top quarks and anti quarks in the pp collisions, the $t\bar{t}$ charge asymmetry, is measured with lepton plus jets events. The corresponds to the forward-backward asymmetry of $t\bar{t}$ production in $p-\bar{p}$ collisions, which has been studied in Tevatron experiments. At the LHC, the initial state quarks are mainly valence quarks while the antiquarks are always sea quarks. This lead an excess of top quarks in the forward directions for the larger momentum fraction of quarks in average. The reported study done at CMS is an 8 TeV update [15] with full 2012 data of the 7 TeV published result. Events containing one charged lepton (e or μ) with at least four jets, one of which passes the b-jet tagging, are used. An inclusive and three differential measurements of the charge asymmetry as a function of rapidity, transverse momentum, and $t\bar{t}$ invariant mass are presented. The measured inclusive charge asymmetry is $0.005 \pm 0.007(\text{stat.}) \pm 0.006(\text{syst.})$. This result and the three differential measurements are consistent with the SM predictions.

3˙2. *Top-quark polarization.* – In the SM, top quarks are produced with a small amount of polarization that can be attributed to electroweak corrections to the QCD-dominated production process. Deviations on the top-quark polarization from the SM predictions can be attributed to contributions from physics beyond the SM. The polarization of top quark are measured using dilepton event collected at $\sqrt{s} = 7\,\text{TeV}$ which corresponds to integrated luminosity of $5\,\text{fb}^{-1}$ [16]. The measurements are performed using dilepton events with significant missing E_T, and two or more jets with at least one of them identified as a b-quark jet. The polarization is measured through asymmetry in angular distribution of the two selected leptons. The results are unfolded back to the parton level. The measurements are found to be agreed with SM predictions.

3˙3. *W helicity in top-quark decays.* – The W-boson helicity fractions in top-quark decays are very sensitive to the Wtb vertex couplings. Anomalous Wtb couplings, which do not arise from the SM, would alter the value of one or more helicity fractions. The W helicity fractions (F_R, F_L, and F_0) are measured using the helicity angle θ^*, which is defined as the angle between the direction of the charged lepton in W rest frame and W direction in the top-quark rest frame. Their relations can be written as

$$\frac{1}{\Gamma}\frac{\mathrm{d}\Gamma}{\mathrm{d}\cos\theta^*} = \frac{3}{8}(1-\cos\theta^*)^2 F_L + \frac{3}{8}(1+\cos\theta^*)^2 F_R + \frac{3}{4}(\sin\theta^*)^2 F_0, \tag{2a}$$

$$F_R + F_L + F_0 = 1, \text{ where } F_x = \frac{\Gamma_x}{\Gamma}\,. \tag{2b}$$

The latest result [17] done with 8 TeV collision data has improved precision comparing with the 7 TeV published one. The measured helicity fractions are $F_0 = 0.659 \pm 0.015(\text{stat.}) \pm 0.023(\text{syst.})$ and $F_L = 0.350 \pm 0.010(\text{stat.}) \pm 0.024(\text{syst.})$. By assuming unitarity, one can get $F_R = -0.009 \pm 0.006(\text{stat.}) \pm 0.020(\text{syst.})$. These results are in agreement with SM predictions.

3˙4. *Top-quark FCNC searches.* – The flavor-changing neutral current (FCNC) processes are highly suppressed in SM at order of $O(10^{-15})$. However, several models extend SM predict enhancements on FCNC up to order of $O(10^{-3})$. Thus, any detection of FCNC processes is a direct hint of physics beyond standard model (BSM). In CMS, several studies about the top-quark FCNC processes are being conducted:

3˙4.1. Search for $t \to Zq$. The latest result on $t \to Zq$ search [18] looks at the process $t\bar{t} \to WbZq \to bj\ell^+\ell^-\ell'$ trilepton events. The full 2012 data collected at 8 TeV is used. By combining the previous 7 TeV result, the limit on the $\mathcal{B}(t \to Zq) < 0.05\%$ is given at 95% confidence level (CL) which is the current best limit. Projection studies on future LHC data are also performed. With the same cut based approach, the limit with $3000\,\text{fb}^{-1}$ data at $\sqrt{s} = 14\,\text{TeV}$ will be $< 0.01\%$ [19]. Further improvements on the analysis approach are needed for this study.

3˙4.2. Search for $t \to Vq$. The search for $t \to Vq$ in single top production is also performed with $5\,\text{fb}^{-1}$ data at $\sqrt{s} = 7\,\text{TeV}$ [20]. The study also looks at trilepton events and the following limits are given: $\mathcal{B}(t \to gu) < 0.56\%$, $\mathcal{B}(t \to gc) < 7.12\%$, $\mathcal{B}(t \to Zu) < 0.51\%$, and $\mathcal{B}(t \to Zc) < 11.40\%$ at 95% CL.

3˙4.3. Search for $t \to Hq$. The Higgs particle was discovered by Atlas and CMS. Its mass has been measured as $\sim 125.5\,\text{GeV}$ which is lighter than the mass of the top quark. Theoretically $t \to H$ decay is also an FCNC process and suppressed by GIM mechanism. The branching fraction of $t \to Hc$ is also at order of $O(10^{-15})$ in SM. Some models, extending SM predicts, enhancement of this process up to detectable level for LHC.

While direct searches of $t \to Hq$ are currently working in progress at CMS, a reinterpretation of supersymmetry (SUSY) multi-lepton searches [21] has been conducted. Ten most sensitive channels have been examined. The searching signatures are three leptons with no opposite-signed same-flavored (OSSF) or with one OSSF pair of leptons off the Z-boson peak together with a b-tagged jet. This is complement to the direct FCNC with $H \to \gamma\gamma$ search. The derived limit at 95% CL is $\mathcal{B}(t \to Hc) < 1.28\%$, corresponding to a bound on the top-charm flavor violating Higgs Yukawa couplings of $\sqrt{|\lambda^h_{tc}|^2 + |\lambda^h_{ct}|^2} < 0.21$.

4. – Summary and prospects

Top-quark mass measurements at the LHC have already reached the precision of the Tevatron results. Several alternative approaches, like end point method, b-lifetime method, and pole mass measurement from top-quark production cross section, have been carried out to improve the systematical uncertainties. Various top-quark properties, including W helicity, charge asymmetries, spin correlation and polarization, as well as FCNC couplings, are tested and so far no significant deviations from SM predictions are seen. Therefore, precision measurements are needed for the search of possible new physics contributions. There are still many studies to finish using the 7 and 8 TeV data before LHC restarts in 2015 with increased energy and luminosity. This is a new milestone ahead and we are expecting more exciting results.

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