Top quark properties and single top at CMS

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Summary. — Measurements of top-quark properties as well as single top-quark production are presented, obtained from the CMS data collected in 2011 and 2012 at centre-of-mass energies of 7 and 8 TeV. The results include measurements of the top pair charge asymmetry, the W helicity in top decays, the $t\bar{t}$ spin correlation and the search for anomalous couplings. The cross sections for the electroweak production of single top quarks in the t-channel and in association with W-bosons is measured and the results are used to place constraints on the CKM matrix element V_{tb}. In the t-channel the ratio of top and anti-top production cross sections is determined and compared with predictions from different parton density distribution functions. The results are compared with predictions from the standard model as well as new physics models.

PACS `14.65.Ha` – Top quarks.
PACS `12.15.Hh` – Determination of Cabibbo-Kobayashi & Maskawa (CKM) matrix elements.
PACS `12.60.-i` – Models beyond the standard model.

1. – Introduction

Top quark is the heaviest elementary particle ever discovered. It is an excellent candidate to study electroweak (EW) symmetry breaking mechanism and fermion mass hierarchy due to its large Yukawa coupling to Higgs boson. Top quark almost exclusively decays to a W boson and a b-quark. The lifetime of a top quark is much shorter than hadronization and spin decorrelation time scales which results in a rather clean experimental signature pf top quark production and its decay in the detector. Angular distributions of the decay objects are sensitive to such properties as W boson helicity, top quark polarization, spin correlations and charge asymmetry in $t\bar{t}$ events. The new physics could manifest itself as anomalies in top quark properties, as well as new production mechanisms involving flavor-changing neutral currents (FCNC) interactions.

There are three main production mechanisms of single top at the LHC: t-channel, s-channel and associated production with a W boson (tW production). While t- and s-channels were observed for the first time at the Tevatron, tW production mode was firstly seen at the CMS.

Study of single top production processes allows to directly probe electroweak interactions. As tWb vertex is involved in all production modes, the $|V_{tb}|$ Cabibbo-Kobayashi-Maskawa (CKM) matrix element could be directly determined from the cross-section measurement. Search for new physics including anomalous tWb couplings in the production rates of top and anti-top quarks is also performed.

The latest measurements of single top production cross sections and top quark properties from the CMS experiment are presented [1].

2. – Single top in t-channel

The measurement of single top production cross section in t-channel is performed at 8 TeV with 20 fb^{-1} of data [2]. Analysis is done in the final state with exactly one isolated lepton (electron or muon) and at least two jets. Categorization on the number of b-tagged jets is done to define the samples enriched in signal and background events: 2-jet 1-tag (signal); 3-jet 1-tag, 3-jet 2-tag, 2-jet 0-tag (background). QCD multijet background is estimated from data by performing a template fit on E_T^{miss} and $m_T(W)$ variables, where $m_T(W) = \sqrt{2p_T E_T^{miss}(1 - cos\Delta\phi)}$, p_T — lepton's transverse momentum, E_T^{miss} — missing transverse energy in event, $\Delta\phi$ — azimuthal angle difference between lepton's p_T and E_T^{miss} direction. Additional selection criteria of $E_T^{miss} > 45$ GeV (electron channel) and $m_T(W) > 50$ GeV is applied. For the main background of $t\bar{t}$ and W/Z+jets production a dedicated validation is performed in control kinematic region to measure data-to-MC correction factors. The likelihood fit is done in 2-jet 1-tag sample to extract the signal cross section using the variable corresponding to pseudorapidity of a jet which was identified as to be associated with a light quark. The cross section is measured inclusively as well as separately for top and anti-top quarks allowing to compare predictions from different PDF sets to experimental observation. The measured inclusive cross section is $\sigma_{t-ch.} = 83.6 \pm 2.3(stat) \pm 7.4(syst)$ pb. The single t and $\bar{t}$ cross sections are measured to be $\sigma_{t-ch.}(t) = 53.8 \pm 1.5(stat) \pm 4.4(syst)$ pb and $\sigma_{t-ch.}(\bar{t}) = 27.6 \pm 1.3(stat) \pm 3.7(syst)$ pb. The measured ratio of cross sections is $R_{t-ch.} = \sigma_{t-ch.}(t)/\sigma_{t-ch.}(\bar{t}) = 1.95 \pm 0.10(stat) \pm 0.19(syst)$. The combination with 7 TeV results is also performed for the measurement of $|V_{tb}|$ giving a value of $|V_{tb}| = 0.998 \pm 0.038(exp) \pm 0.016(theo)$. Obtained results are presented in Fig 1. The summary of $|V_{tb}|$ measurements is shown in Fig 2.

3. – Single top in s-channel

The search for single top production in s-channel is performed with 20 fb^{-1} of data at 8 TeV [3]. Selection criteria include the requirement of exactly one isolated lepton (electron or muon) to be present in event. As in t-channel analysis, QCD multijet background is estimated from a template fit in data. A multivariate approach (MVA) based on Boost Decision Trees (BDT) is used to discriminate signal from background events. Signal cross section is extracted from a binned maximum-likelihood fit using BDT discriminator shape in 2-jet 2-tag and 3-jet 2-tag samples. The inclusive production cross section is measured to be: $\sigma_{s-ch.} = 5.9 \pm 7.1(stat) \pm 5.0(syst)$ pb (electron channel), $\sigma_{s-ch.} = 6.9 \pm 5.6(stat) \pm 6.5(syst)$ pb (muon channel), $\sigma_{s-ch.} = 6.2 \pm 5.4(stat) \pm 5.9(syst)$ pb (combined). The corresponding observed significance for the combined result is 0.7 standard deviations.

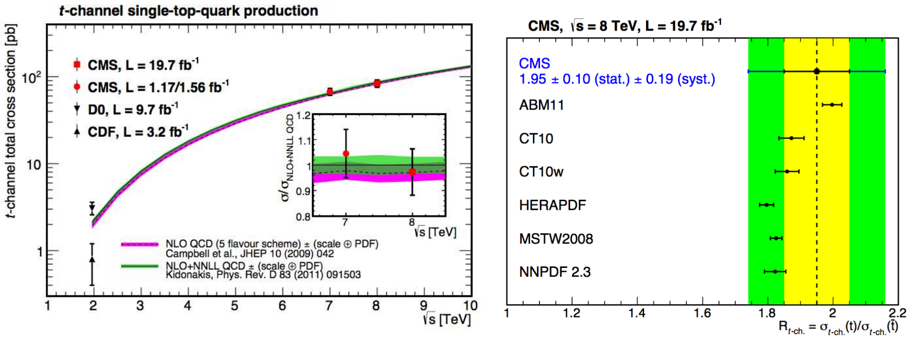

Fig. 1. – Single top-quark production cross section in the t-channel versus total center-of-mass energy (left). Comparison of the measured $R_{t-ch.}$ with the predictions obtained using different PDF sets (right).

4. – tW associated production

The first observation of a top quark associated production with a W boson is done at 8 TeV with 12 fb^{-1} of data [4]. Events with exactly two isolated opposite-sign leptons are considered. Background from Drell-Yan processes is suppressed by vetoing the dilepton invariant mass region of $81 < m(\ell\ell) < 101$ GeV. In dielectron and dimuon channels the additional requirement on $E_T^{miss} > 50$ GeV is included. A multivariate analysis (BDT) based on kinematic and topological properties is used to separate signal from the dominant $t\bar{t}$ background events. A binned maximum-likelihood fit based on BDT discriminant is used to extract the signal cross section. In addition to the main analysis approach which uses multivariate techniques, two cross-check analyses have been performed, based on cut-based approach and analysis based on the fit to the distribution of total p_T of the system. For these additional cross-checks, the cuts are also applied

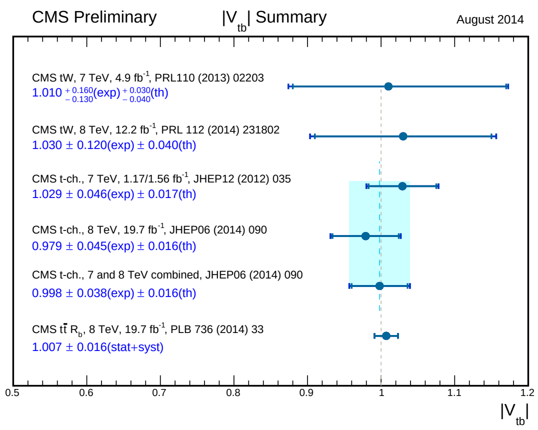

Fig. 2. – Summary of $|V_{tb}|$ measurements done at CMS.

on $H_T > 160$ GeV (instead of $E_T^{miss} > 50$ GeV), where H_T is a scalar sum of transverse momenta of selected leptons and jets in event. An excess consistent with signal hypothesis is observed with a significance of 6.1 standard deviations. The measured production cross section is 23.4 ± 5.4 pb. From cross-check analyses the cross section values of 33.9 ± 8.6 pb and 24.3 ± 8.8 pb are obtained. The cross section measurement is used to determine $|V_{tb}| = 1.03 \pm 0.12(exp) \pm 0.04(theo)$.

5. – Measurement of W boson helicity

A W boson can be produced with left-handed, longitudinal or right-handed helicity. The helicity fractions are defined as $F_i = \Gamma_i/\Gamma$ and must satisfy the relation of $\sum F_i = 1$. These values can be extracted from angular distributions of the top quark decay products. One of the important variables sensitive to such measurements is the helicity angle, θ^*, defined as an angle between W boson momentum in the t-rest frame and a lepton in the rest frame of a W boson. Helicity fractions can also be sensitive to tWb anomolous couplings. The SM predictions for W boson helicity fractions at NNLO are $F_L = 0.311 \pm 0.005$, $F_0 = 0.687 \pm 0.005$ and $F_R = 0.0017 \pm 0.0001$ [5].

The measurement of W boson helicity fractions in t-channel single top events at 8 TeV with 20 fb^{-1} of data is done at CMS [6]. The analysis selects events with exactly one isolated lepton (electron or muon) and exactly two jets, one of which is identified as a b-jet. To suppress QCD multijet background the requirement of $m_T(W) > 50$ GeV is applied. Neutrino momentum is determined from energy conservation relation at W boson decay vertex. The distribution of $\cos\theta^*$ for t-channel single top events is extracted from the binned maximum-likelihood fit with helicity factions treated as free parameters. The measured W boson helicity fractions are shown in Fig 3 and are consistent with the SM expectations: $F_L = 0.298 \pm 0.028(stat) \pm 0.032(syst)$, $F_0 = 0.720 \pm 0.039(stat) \pm 0.037(syst)$ and $F_R = -0.018 \pm 0.019(stat) \pm 0.011(syst)$.

The obtained results allow to excude tensor terms of the tWb anomalous couplings, g_L and g_R, while assuming for the vector couplings to be $V_L = 1$ and $V_R = 0$, considered in the general dimension-six Lagrangian:

$$(1)\quad \mathcal{L}_{tWb} = -\frac{g}{\sqrt{2}}\bar{b}\gamma^\mu(V_L P_L + V_R P_R)tW_\mu^- - \frac{g}{\sqrt{2}}\bar{b}\frac{i\sigma^{\mu\nu}q_\nu}{M_W}(g_L P_L + g_R P_R)tW_\mu^- + h.c.,$$

where P_L (P_R) are the left (right) projector operators, q is the difference between four-vector momenta of top and b-quark. The excluded regions for tWb anomalous couplings are also presented in Fig 3.

W boson helicity fractions can also be studied in $t\bar{t}$ events. Such analysis was done in the channel with exactly one isolated muon and at least four jets with two of them identified as b-tagged jets [7]. The analysis uses the data of 20 fb^{-1} collected at 8 TeV. The measured fractions are $F_L = 0.350 \pm 0.010(stat) \pm 0.024(syst)$, $F_0 = 0.659 \pm 0.015(stat) \pm 0.023(syst)$ and $F_R = -0.009 \pm 0.006(stat) \pm 0.020(syst)$.

6. – Top quark polarization and spin correlations

In SM top quarks are produced with a small amount of polarization arising from EW corrections for QCD production-dominated processes, while in single top production

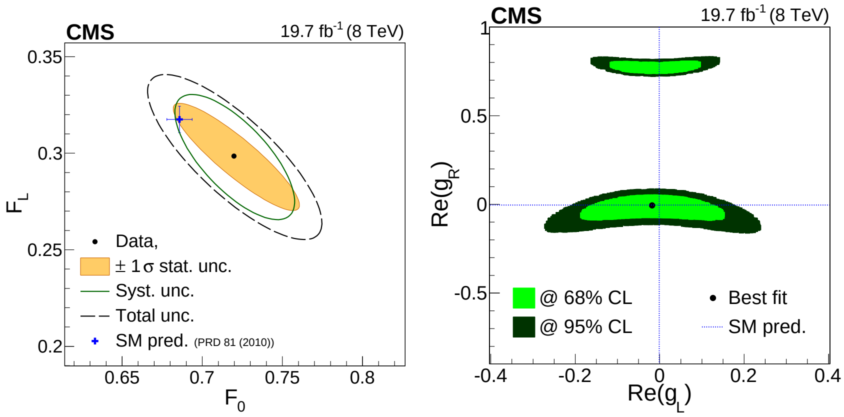

Fig. 3. – Exclusion limits on left-handed and longitudinal W boson helicity fractions (left) and the real part of anomalous couplings (right) as measured in signal top events at CMS.

quarks are almost 100% polarized. New physics models can also alter the spin of a top quark. Top quark polarization is defined via helicity angle:

$$P_t = 2\frac{N[\cos\theta^* > 0] - N[\cos\theta^* < 0]}{N[\cos\theta^* > 0] + N[\cos\theta^* < 0]}, \tag{2}$$

where N denotes the number of events corresponding to selection on $\cos\theta^*$. Discriminating kinematic variable to separate correlated and uncorrelated top quark spins can be defined in a similar way:

$$A_{\Delta\phi} = \frac{N[\Delta\phi_{\ell^+\ell^-} > \pi/2] - N[\Delta\phi_{\ell^+\ell^-} < \pi/2]}{N[\Delta\phi_{\ell^+\ell^-} > \pi/2] + N[\Delta\phi_{\ell^+\ell^-} < \pi/2]}, \tag{3}$$

where $\Delta\phi_{\ell^+\ell^-}$ is the azimuthal angle difference between the leptons from top quarks decays. Finally, spin correlation coefficient is given by:

$$A_{c_1 c_2} = \frac{N[c_1c_2 > 0] - N[c_1c_2 < 0]}{N[c_1c_2 > 0] + N[c_1c_2 < 0]}, \tag{4}$$

where $c_1 = \cos\theta_{l^+}$, $c_2 = \cos\theta_{l^-}$.

Top quark polarization and spin correlation effects are studied at 7 TeV with 5 fb^{-1} of data [8]. This analysis considers events with exactly two isolated opposite-sign leptons. In order to suppress Drell-Yan background contribution in the same-flavor final state the events are vetoed if the dilepton invariant mass satisfies the selection of $76 < m(\ell\ell) < 106$ GeV. At least two jets are required to be present in event, and at least one of them has to be identified as a b-tagged jet. Additional requirement of $E_T^{miss} > 40$ GeV is placed to provide a stronger background rejection. The reconstruction of top quark is done with the matrix weighting technique. Drell-Yan background is estimated in data from side-band regions where the correction factors are measured. QCD multijet background is estimated from data.

To extract the information about top quark spin and correlations, the variables $\Delta\phi_{\ell^+\ell^-}$ and $\cos\theta^*_\ell$ are used. The measured distributions are corrected for detector resolution and acceptance effects by unfolding procedure in order to translate obtained results to underlying parton-level distributions. The background-subtracted and unfolded distributions are shown in Fig 4. The result parton-level asymmetries are as follows: $A_{\Delta\phi} = 0.113 \pm 0.010(stat) \pm 0.006(syst) \pm 0.012(rw)$, $A_{c_1 c_2} = -0.021 \pm 0.023(stat) \pm 0.025(syst) \pm 0.010(rw)$ and $P_t = 0.010 \pm 0.026(stat) \pm 0.028(syst) \pm 0.016(rw)$, where rw denotes additional uncertainty due to top quark p_T reweighting procedure. The results are in a good agreement with SM expectations: $A_{\Delta\phi} = 0.110 \pm 0.001$, $A_{c_1 c_2} = -0.078 \pm 0.001$ and $P_t = 0.000 \pm 0.002$.

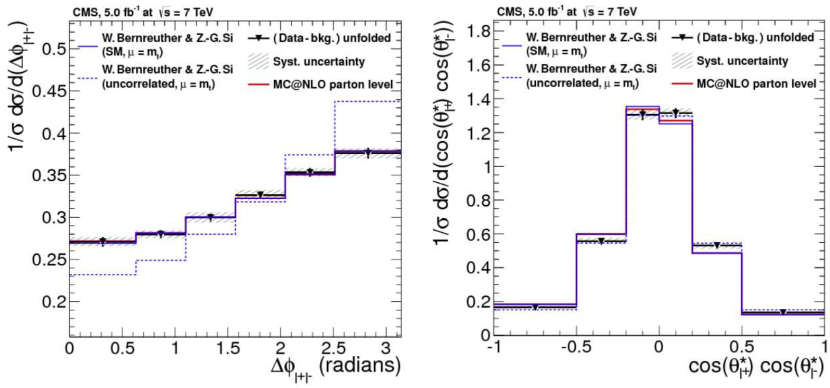

Fig. 4. – Background-subtracted and unfolded differential cross sections for $\Delta\phi_{\ell^+\ell^-}$ (left) and $\cos\theta^*_{\ell^+}\cos\theta^*_{\ell^-}$ (right) compared to NLO calculations [9, 10].

These results are also intepreted in the framework of effective model of Chromo-Magnetic Dipole Moments (CMDM) [11]. In this model the anomalous $t\bar{t}g$ couplings are considered which can significantly modify distributions sensitive to $t\bar{t}$ spin correlations. The exclusion limit on the real part of CMDM $\hat{\mu_t}$ is measured to be $-0.043 < Re(\hat{\mu_t}) < 0.117$.

Top quark polarization can also be measured in single top events. Such analysis is done at 8 TeV with 20 fb^{-1} of data where t-channel single top events are considered [12]. The unfolded top quark polarisation is measured to be $P_t = 0.82 \pm 0.12(stat) \pm 0.32(syst)$.

7. – Charge asymmetry

The charge asymmetry effects in $t\bar{t}$ production occur only in quark-antiquark or quark-gluon initial states, while the dominant gluon-gluon production mode is charge-symmetric. At the LHC initial quarks are mainly valence quarks with antiquarks being sea quarks. This leads to an excess of top quarks produced in the forward directions. In SM the charge asymmetry is explained by interference between LO and box, ISR and FSR diagrams. The asymmetry parameter is defined as:

$$A_C = \frac{N[y_t > y_{\bar{t}}] - N[y_t < y_{\bar{t}}]}{N[y_t > y_{\bar{t}}] + N[y_t < y_{\bar{t}}]}, \quad (5)$$

where y_t and $y_{\bar{t}}$ are pseudorapidities of top and anti-top quarks, respectively.

The measurement of $t\bar{t}$ charge asymmetry is done at 8 TeV with 20 fb^{-1} of data in events with one isolated lepton and at least four jets [13]. At least one jet is required to be identified as a b-tagged jet. An additional requirement of $m_T(W) > 50$ GeV is placed for background events rejection. The reconstructed top quark and antiquark four-vectors are used to obtain the distribution for rapidity and mass of the $t\bar{t}$ system, $y_{t\bar{t}}$ and $m_{t\bar{t}}$, respectively. The unfolded measured asymmetry is parametrized with these variables as shown in Fig 5. The result asymmetry yields $A_C = 0.005 \pm 0.007(stat) \pm 0.006(syst)$ and is in agreement with SM prediction of $A_C = 0.0102 \pm 0.0005$.

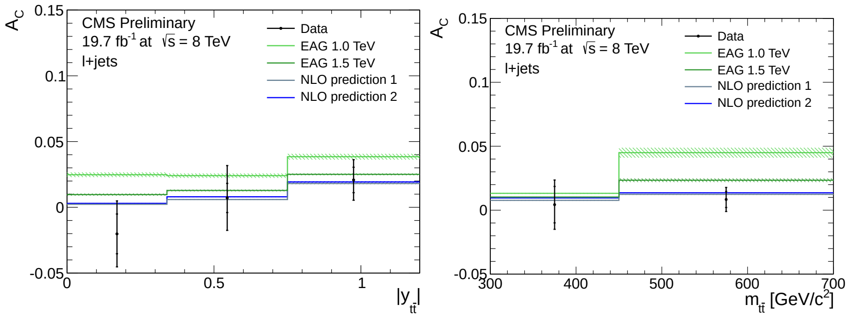

Fig. 5. – Unfolded asymmetry distributions parametrized with $y_{t\bar{t}}$ (left) and $m_{t\bar{t}}$ (right) compared to NLO calculations [14, 15] and EAG model [16, 17].

8. – Search for FCNC interactions

FCNC transition is an interaction process where a fermion undergoes the change of flavor without alteration of the charge. Such interactions in SM are forbidden by the Glashow-Iliopoulus-Maiani (GIM) mechanism [18]. However, highly GIM-suppressed FCNC transitions are possible in SM in the higher orders via penguin and box diagrams. Some extensions of SM could introduce FCNC decays at tree level including new particles.

Search for FCNC Zqt (q=u,c) couplings is done in both single top and $t\bar{t}$ events at CMS at 7 TeV with 5 fb^{-1} of data. Associated production of a top quark with Z boson via FCNC Zqt couplings is performed in events with three isolated leptons [19]. Signal event selection is based on BDT approach with the final limit extraction done on BDT discriminant distribution. The upper limits on the coupling strengths at 95% C.L. are found to be $\kappa_{Zut}/\Lambda < 0.35$ TeV^{-1} and $\kappa_{Zct}/\Lambda < 0.45$ TeV^{-1}, which correpond to the following limits on the branching ratios of $\mathcal{B}(t \to Zu) < 0.51\%$ and $\mathcal{B}(t \to Zc) < 11.40\%$, respectively. The same Zqt anomalous coupling is probed in $t\bar{t}$ events where one of the top quarks decays via FCNC vertex [20]. The analysis is done at 8 TeV with 20 fb^{-1} of data. Similar event selection based on a trilepton signature is considered. The exclusion limit on branching ratio is obtained as $\mathcal{B}(t \to Zq) < 0.06\%$. Search for $tq\gamma$ anomalous coupling was performed at 8 TeV with 19 fb^{-1} of data in the final state with one isolated lepton [21]. The result upper limits on the coupling strengths are measured to be $\kappa_{tu\gamma} < 0.028$ and $\kappa_{tc\gamma} < 0.094$, which translate to the limits on the branching ratios as $\mathcal{B}(t \to u\gamma) < 0.0161\%$ and $\mathcal{B}(t \to c\gamma) < 0.182\%$. The summary of FCNC searches is presented in Fig 6.

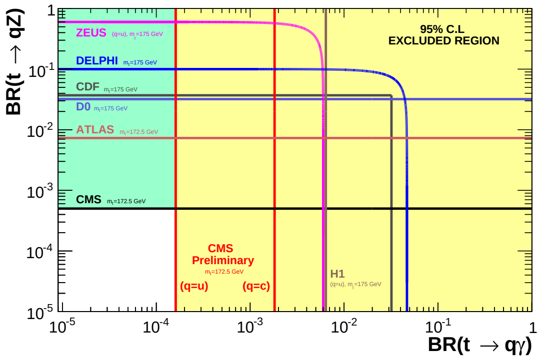

Fig. 6. – Summary of results on FCNC searches.

9. – Conclusion

The latest results on top quark properties and single top production cross-sections at CMS using Run I data were presented. Several analyses with the search for FCNC interactions involving top quarks were presented as well. All obtained results are in a good agreement with the SM predictions.

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