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Measurements of the top-quark properties at CMS

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Measurements of several top-quark properties, obtained from the CMS data collected in 2011 and 2012 at centre-of-mass energies of 7 and 8 TeV are presented. The results include measurements of the top pair charge asymmetry, the W helicity in top quark decays and the search for anomalous couplings, the top quark charge, and of the $t\bar{t}$ spin correlation. The fraction of top quarks decaying into a W-boson and a b-quark relative to all top quark decays, $\mathscr{R} = \mathscr{B}(t \to Wb)/\mathscr{B}(t \to Wq)$, as well as, the cross sections of ttbar events produced in association with a photon or a W or a Z boson are also presented.

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1. Introduction

The most massive particle, the top quark, has a shorter lifetime than the hadronization timescale. This makes its bare quark properties observable. The meaurements presented in this note use the data collected with the CMS [1] detector during 2011 and 2012 data taking periods with proton-proton collisions at $\sqrt{s} = 7$ and 8 TeV, respectively.

2. $t\bar{t}$ Charge Asymmetry

Tevatron experiments observed a deviation of $\sim 2-3\sigma$ from the standard model (SM) $t\bar{t}$ forward-backward asymmetry [2, 3]. The asymmetry occurs in $t\bar{t}$ production through quark-antiquark annihilation. The antiquark at the LHC is a sea quark, therefore, on average the quark has a larger momentum fraction. This results in an excess of top quarks in forward directions. Therefore, the charge asymmetry (A_C) defined using the rapidity difference of the top and the antitop quark ($\Delta|y| = |y_t| - |y_{\bar{t}}|$) is a reasonable choice for the LHC. In the lepton+jets channel, the measurement resulted in $A_C = 0.004 \pm 0.010\ (stat) \pm 0.011\ (sys.)$ [4] compatible with the SM prediction at NLO, 0.0115 ± 0.0006 [5]. In the dilepton channel, the inclusive A_C is measured to be $0.050 \pm 0.043\ (stat)^{+0.010}_{-0.039}\ (sys.)$. Inclusive A_C is also measured using lepton pseudo-rapidities and is found to be $0.010 \pm 0.015\ (stat) \pm 0.006\ (sys.)$ [6]. These are in agreement with the NLO predictions of 0.0123 ± 0.0005 and $A_C(\Delta|\eta|) = 0.0156 \pm 0.0007$ [7]. Figure 1 displays ($\Delta|y|$), rapidity ($|y_{t\bar{t}}|$), transverse momenta ($p_{T,t\bar{t}}$), and the invariant mass ($m_{t\bar{t}}$) of the $t\bar{t}$ system. $|y_{t\bar{t}}|$ depends on the ratio of events with $q\bar{q}$ and gg initial states and at small rapidities, gluon fusion dominates. Therefore, A_C increases with increasing $|y_{t\bar{t}}|$ [5] (see Figure 1 upper right). Interferences between the Born and the box diagrams and also between the initial- and final-state-radiation cause the (anti)top quark direction to be correlated to the initial state (anti)quark. In the former case, there is a positive contribution to A_C and a negative contribution in the latter. In the presence of initial- or final-state-radiation the $t\bar{t}$ system has a higher p_T, hence there is more negative contribution to A_C for such events [5] (see Figure 1 lower left). At high invariant mass of the $t\bar{t}$ system, $m_{t\bar{t}}$, number of $t\bar{t}$ events with $q\bar{q}$ production increases and therefore A_C increases (see Figure 1 lower right). However, if new heavy particles have a role in $t\bar{t}$ production, they can interfere with the SM processes and this might result in a different dependence on $m_{t\bar{t}}$. The distributions in Figure 1 are also compared to the distributions predicted by a model with an effective axial-vector coupling of the gluon [8, 9] that could describe the depence of forward-backward asymmetry vs $m_{t\bar{t}}$ observed at the Tevatron. None of the distributions in Figure 1 shows a deviation from the SM expectations however the uncertainties are still large.

3. W Boson Helicities in Top Quark Decays and Anomalous Couplings

Partial witdh of the top quark can be parametrized in terms of left-handed (F_L), right-handed (F_R), longitudinal (F_0) W boson helity fractions and the θ^* angle between the momentum of the d-type fermion in the W rest frame and of the W in the top quark rest frame. W helicities in $t\bar{t}$ events in dilepton and lepton+jets final states are measured [10, 11] . Measurements at $\sqrt{s} = 7$ TeV made by CMS and ATLAS are also combined [12]. Individual and combined measurements are

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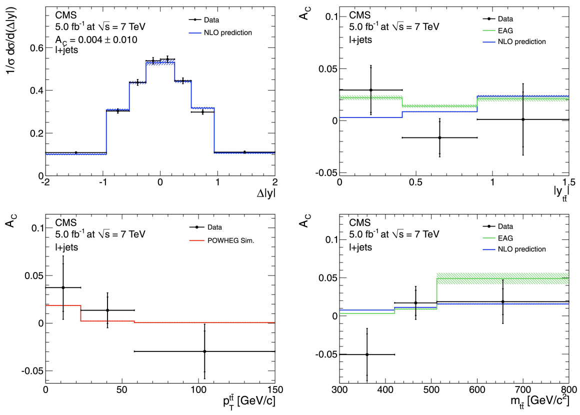

Figure 1: Unfolded inclusive $\Delta|y|$ distribution (upper left), A_C vs $|y_{t\bar{t}}|$ (upper right), $p_{t\bar{t}}$ (lower left), and $m_{t\bar{t}}$ (lower right). The measurements are compared to SM NLO calculations and to the predictions of an effective model.

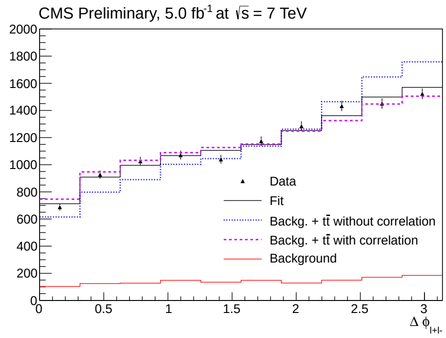

Figure 2: Result of the fit (solid line) performed on data (triangles) after the combination of the three channels. The data are also compared to the $\Delta\Phi_{\ell^+\ell^-}$ distribution of $t\bar{t}$ pair events with and without spin correlation. The background components are also shown.

found to be consistent with each other and with SM predictions at NNLO QCD. Measurement of W boson helicity fractions is also performed in single-top topologies [13] in the $\mu + jets$ final state at $\sqrt{s}$ = 7 and 8 TeV. The helicity fractions are obtained from likelihoods with reweighted signals including all processes involving the top quark. The measurements performed at $\sqrt{s}$ = 7 and 8 TeV are combined yielding $F_0 = 0.713 \pm 0.114$ (stat)$\pm$0.023 (syst), $F_L = 0.293 \pm 0.069$ (stat)$\pm$0.030 (syst) and $F_R = -0.006 \pm 0.057$ (stat)$\pm$0.027 (syst). The measurements are consistent with the SM predictions and the measurements in the $t\bar{t}$ channels. These measurements are also used to set limits on the real part of the anomalous Wtb couplings.

4. Top Quark Charge

Being the electroweak isospin partner of the b-quark, top quark has an electric charge of $+2/3e$. A measurement is made testing two different top quark charge hypotheses in the muon+jets final state at $\sqrt{s} = 7$ TeV [14]. For the measurement, charge correlations between muons from W boson decays and soft muons from B-hadron decays in b-jets are utilized to constrain the top quark charge. Using a normalized asymmetry variable, the top quark charge hypothesis of $-4/3e$ against $+2/3e$ is tested. The measurement yielded an asymmetry of $A = 0.97 \pm 0.12\ (stat.) \pm 0.31\ (sys.)$ in agreement with the SM expectation of $A = +1$.

5. t-$\bar{t}$ Spin Correlation

The spin-decorrelation timescale, $m_t/\Lambda^2_{QCD} \sim 3 \times 10^{-21}$ s, is larger than the hadronization time scale. Therefore spin effects propagate to the decay products. In the dilepton final state, the azimuthal angle between the opposite charge leptons, $|\Delta\phi_{\ell^+\ell^-}|$, in the laboratory frame is sensitive to the t-$\bar{t}$ spin correlation. This variable can be measured precisely without top quark reconstruction. At $\sqrt{s} = 7$ TeV, the t-$\bar{t}$ spin correlation in the dilepton channel is extracted from a template fit to the $|\Delta\phi_{\ell^+\ell^-}|$ distribution [15]. Three different templates are used; simulated $t\bar{t}$ events assuming the SM, simulated $t\bar{t}$ events without spin correlation and a template for the background events. A binned likelihood fit to data is used to simultaneously fit the e^+e^-, $\mu^+\mu^-$ and $e^\pm\mu^\mp$ channels to determine the fraction of events with SM spin correlation, $f = N_{SM}/(N_{SM}+N_{uncor})$. The measurement yielded $f = 0.74 \pm 0.08\ (stat.) \pm 0.24\ (sys.)$ consistent with the SM expectation of $f^{SM} = 1$. The result of this fit performed on data after the combination of the three channels is shown in Figure 2. The data are also compared to the $|\Delta\phi_{\ell^+\ell^-}|$ distributions obtain from $t\bar{t}$ events with and without spin-correlation. The fraction of events with SM spin correlation, f, can be converted to a measurement of the spin correlation coefficient A. In the helicity basis, the measurement yields $A^{meas}_{hel} = 0.24 \pm 0.02\ (stat.) \pm 0.08\ (sys.)$ consistent with the SM prediction at NLO of $A^{SM}_{hel} = 0.31$ [16]. The spin correlation is also studied using other variables and at different $m_{t\bar{t}}$ values [15]. All measurements are found to be consistent with the SM predictions.

6. Measurement of the Ratio $\mathscr{R} = \mathscr{B}(t \to Wb)/\mathscr{B}(t \to Wq)$

The top quark decays to a W boson and a b quark practically with a branching ratio of $\sim 100\%$. Decays to other down-type quarks are suppressed in the CKM matrix. A measurement of $|V_{tb}|$ is made by measuring the branching fraction ratio $\mathscr{R} = \mathscr{B}(t \to Wb)/\mathscr{B}(t \to Wq)$ in the $t\bar{t}$ di-lepton final state using $\sqrt{s}$ =8 TeV data [17]. $\mathscr{R}$ is extracted from a profile likelihood fit to data-driven analytic probability models of signal purity, number of reconstructed tops in different jet categories and number of b-tags. The fit gave $\mathscr{R} = 1.023^{+0.036}_{-0.034}$ (stat+syst). Imposing $\mathscr{R} \leq 1$, a lower limit for $\mathscr{R}$ is derived to be $\mathscr{R} > 0.945$ at 95% C.L. With the assumption of CKM unitarity and existence of three generations, the measurement is converted to a measurement of $|V_{tb}|$ yielding $1.011^{+0.018}_{-0.017}$ and a lower limit is derived to be $|V_{tb}| > 0.972$ at 95% C.L. The results obtained for $\mathscr{R}$ and $|V_{tb}|$ are consistent with the SM predictions and represent the most precise measurement of $\mathscr{R}$ and the most stringent direct limit on $|V_{tb}|$.

7. Vector Boson Production Associated with Top-Antitop Pairs

Measurement of vector boson production in association with $t\bar{t}$ pairs provides a test of the SM top quark-vector boson couplings. Measurement of these couplings are important for new physics searches and also the measurements of the Higgs boson in the $t\bar{t}H$ process. The cross section measurements of the $t\bar{t}V$ processes are made using the same-sign dilepton for $t\bar{t}W$ and $t\bar{t}Z$ and trilepton signature for $t\bar{t}Z$ process at $\sqrt{s} = 7$ TeV [18]. The cross section for $t\bar{t}V$ is measured to be $0.43^{+0.17}_{-0.15}(stat)^{+0.09}_{-0.07}(syst)$ pb and $t\bar{t}Z$ to be $0.28^{+0.14}_{-0.11}(stat)^{+0.06}_{-0.03}(syst)$ pb consistent with the SM NLO calculations [19, 20]. The $t\bar{t}Z$ measurements represent the first direct measurements of the top quark-Z boson coupling.

8. Conclusions

Measurements of top quark properties are providing thorough tests of the SM. All top quark properties measurements at the LHC are in good agreement with the SM predictions.

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