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Anomalous couplings in single top quark and searches for rare top quark couplings with the ATLAS detector

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Two recent analyses that have exhaustively explored potential anomalous couplings in the Wtb vertex using t-channel single-top-quark events selected from collision data at $\sqrt{s} = 8$ TeV with the ATLAS detector are reviewed. The first one measures the top-quark polarisation and six W-boson spin observables from angular asymmetries unfolded to parton level. The second one measures the normalised triple-differential angular decay rate of top quarks to simultaneously constrain all the anomalous couplings. The limits on the anomalous couplings improve the existing limits set by ATLAS at $\sqrt{s} = 7$ TeV. In addition, searches for flavour-changing neutral current top-quark interactions based on data collected by ATLAS and CMS, are reviewed. Finally, a recent search for $t \to qH$, with $H \to \gamma\gamma$, performed by ATLAS at $\sqrt{s} = 13$ TeV is also presented, where previous LHC limits are improved.

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1. Introduction

The top quark is the heaviest known fundamental particle and probing its couplings with the other fundamental particles may open a window to physics beyond the Standard Model (SM). At the LHC, in proton–proton collisions, the dominant production of top quarks is in pairs ($t\bar{t}$) via the flavour-conserving strong interaction while the single production of top quarks happens via charged-current electroweak processes involving a Wtb vertex. The t-channel is the dominant production mechanism of single top quarks, and it allows to test the coupling between the top quark, the W boson and the b quark, since it involves the Wtb vertex in at both the top quark production and decay. Moreover, in the t-channel, top quarks are produced with a large degree of polarisation along the direction of the produced light-flavour quark, called the spectator quark [1], thereby making t-channel events the ideal probe to measure the top-quark polarisation and W-boson spin observables. The effective Lagrangian describing the Wtb vertex can be expressed in terms of complex anomalous couplings $V_{\mathrm{L,R}}$ and $g_{\mathrm{L,R}}$ following the equation:

$$\mathscr{L}_{Wtb} = -\frac{g}{\sqrt{2}}\bar{b}\gamma^{\mu}(V_{\mathrm{L}}P_{\mathrm{L}} + V_{\mathrm{R}}P_{\mathrm{R}})tW^{-}_{\mu} - \frac{g}{\sqrt{2}}\bar{b}\frac{i\sigma^{\mu\nu}q_{\nu}}{m_W}(g_{\mathrm{L}}P_{\mathrm{L}} + g_{\mathrm{R}}P_{\mathrm{R}})tW^{-}_{\mu} + h.c.$$

In the SM at leading order, $V_{\mathrm{L}} = |V_{\mathrm{tb}}| \approx 1$ and $V_{\mathrm{R}} = g_{\mathrm{L}} = g_{\mathrm{R}} = 0$. Deviations from these values would indicate physics beyond the SM. Moreover, complex values of these couplings would imply that the top-quark decay has a CP-violating component [2]. On the other hand, searches for rare top-quark decays are interesting because a wide variety of models of physics beyong the SM predicts a strong enhancement of the branching ratios of flavor-violating top quark decays [3], that are highly suppressed in the SM.

2. Anomalous couplings in the Wtb vertex using t-channel single-top-quark production

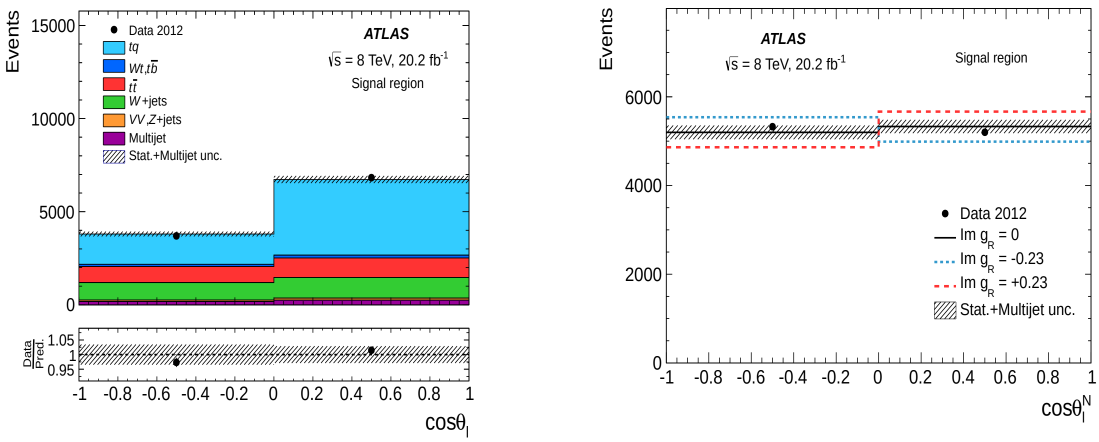
The two analyses reviewed [4, 5] have used 20.2 fb^{-1} of data collected at 8 TeV with the ATLAS detector [6] at the LHC. very similar event selections, background nomalisations and modelling. The preselection criteria of the t-channel experimental signature starts with one isolated lepton, electron or muon, with E_{T} >25 GeV, exactly two jets with E_{T} >30 GeV, only one jet b-tagged and missing transverse momentum, $E_{\mathrm{T}}^{\mathrm{miss}}$, greater that 30 GeV. After some requirements to ensure a proper reconstruction quality of the event, the transverse mass of the lepton-$E_{\mathrm{T}}^{\mathrm{miss}}$ system is required to be greater than 50 GeV and a requirement on events having the lepton and the highest-p_{T} jet with opposite directions in the transverse plane is applied to reduce the multijet background. Events with an additional lepton identified with less stringent criteria and with $p_T > 10$ GeV are rejected to reduce backgrounds with two leptons, mainly dileptonic $t\bar{t}$. A further discrimination between the t-channel signal events and background events is achieved by applying four additional requirements: $|\eta_{\mathrm{non\ b-jet}}|$ >2, $\Delta(\eta_{\mathrm{non\ b-jet}}, \eta_{\mathrm{b-jet}})$ >1.2, the mass of the reconstructed top quark between 130 GeV and 200 GeV and $H_{\mathrm{T}} > 195$ GeV. [1]

The background modelling is checked in two background-dominated regions defined right after the preselection criteria exclusing the veto of events with two leptons. A region enriched in $t\bar{t}$ events is defined with two additional untagged jets. A second region enriched in $W+$jets

[1] H_{T} is the scalar sum of the p_{T} of the lepton, the p_{T} of the jets and the $E_{\mathrm{T}}^{\mathrm{miss}}$.

events is selected with a loose b-tagged jet and vetoing jets that have been b-tagged as in the signal region. An additional region, enriched in $W+$jets events and called "anti-signal", is built with preselection requirements and failing any of the four signal selection requirements. This region has a flavour composition similar to the one in the signal region and thus it is appropiated to constrain the $W+$jets normalisation. The signal and the background event yields are determined through a maximum-likelihood fit to the number of observed data events in the signal, "anti-signal" and $t\bar{t}$ enriched regions. The shapes of signal and background are based on Monte Carlo (MC), except for the multijet background, determined using a data-driven matrix method. After the normalisation fit, the signal to background ratio is $\sim$1.18, and the relative background composition is 40% of $t\bar{t}$, 42% of $W+$jets and a remaining 18% of minor backgrounds: Wt and s-channel single-top-quark production, Z+jets, diboson production and multijet events.

The first analysis [4] has measured the top-quark polarisation P and the six independent W-boson spin observables proposed in Refs. [2, 7]: $\langle S_{1,2,3}\rangle$, $\langle T_0\rangle$ and $\langle A_{1,2}\rangle$. The observables $\langle S_{1,2}\rangle$ and $\langle A_{1,2}\rangle$ are proportional to P. The observables $\langle S_3\rangle$ and $\langle T_0\rangle$ are related the W-boson helicity fractions: F_R,F_L and F_0.[2] All these observables and P are extracted from eight different angular asymmetries, unfolded to parton level, and compare with theoretical predictions. In particular, $A_{FB}^{N}=-\frac{3}{4}\langle S_2\rangle$, the forward-backward asymmetry in the angular distribution $\cos\theta_\ell^N$ [3] is very sensitive to Im g_R (see Figure 1(a)) and the forward-backward asymmetry in the angular distribution $\cos\theta_\ell$ [4], A_{FB}^{ℓ}, is used to measure the top-quark polarisation (see Figure 1(b)).



(a) (b)

Figure 1: Angular distribution of $\cos\theta_\ell$ in the signal region (a) [4] and comparison of the measured distribution of $\cos\theta_\ell^N$ with various theoretical predictions assuming different Im g_R values (b) [4].

To unfold the eight angular asymmetries, except A_{FB}^{N}, the unfolding corrections (i.e, migration matrix and selection efficiencies) are determined with Monte Carlo samples of t-channel events produced with PROTOS [8] generator with SM values of the Wtb couplings. In the case of A_{FB}^{N},

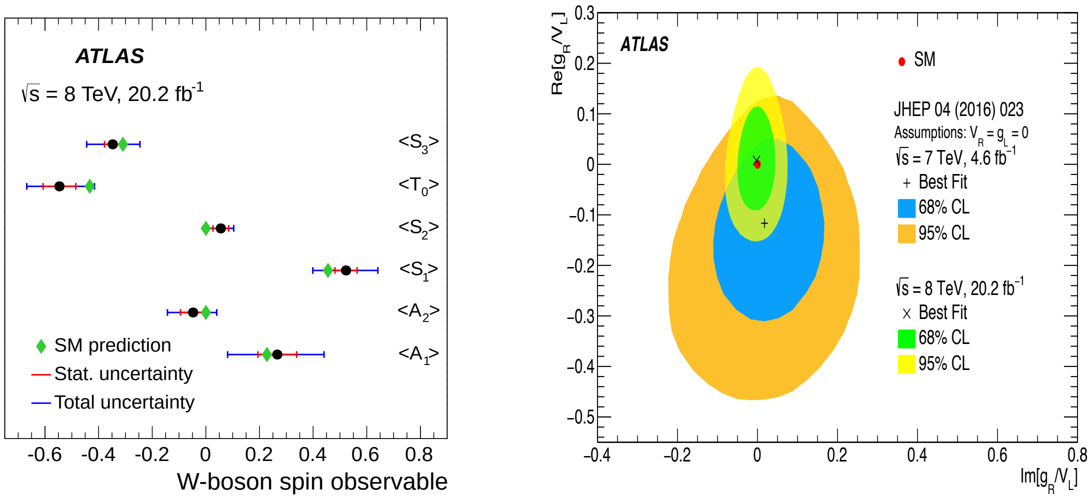
[2] The longitudinal and transverse (lelf- and right-handed) W-boson helicity fractions are F_0,F_L and F_R, respectively.

[3] The angle θ_ℓ^N is the relative angle between the lepton momentum in the W-boson rest frame and the normal axis to the plane defined by the top-quark spin direction, taken along the spectator-quark momentum in the top-quark rest frame, and the W-boson momentumn the top-quark rest frame.

[4] The angle θ_ℓ is the angle between the lepton momentum in the top-quark rest frame and the top-quark spin axis.

an iterative method with Lagrange interpolation is used to determine the unfolding corrections using MC simulation samples generated with PROTOS with non zero values of Im g_{R}. For all the eight asymmetries measured, the systematic uncertainties are larger than the statistical ones, being the dominant sources of systematics the modelling of $t\bar{t}$ events, the jet energy scale and the MC statistics.

The measurements of the six W-boson spin observables are compatible with the SM predictions with an overall p-value of 0.83 (see Figure 2(a)). The observables $\langle S_{1,}\rangle$ and $\langle A_{1,2}\rangle$ are measured for the first time. From A^{ℓ}_{FB} and $A^{\mathrm{N}}_{\mathrm{FB}}$, measured independently on any assumption on Im$\{g_R\}$ and assuming $V_{\mathrm{L}}=1$ and $V_{\mathrm{R}}=g_{\mathrm{L}}=$ Re $g_{\mathrm{R}}=0$, the limits placed on Im g_{R} at the 95% confidence level (CL) are: Im $g_{\mathrm{R}}\in[-0.18,0.06]$. These limits improve the previous limits set by ATLAS at 7 TeV [11]. The measured value of the product of the top-quark polarisation and the charged-lepton spin analysing power extracted from A^{ℓ}_{FB} : $\alpha_{\ell}P=0.97\pm0.05$ (stat.) ±0.11 (syst.) is in agreement with the theoretical predictions at NLO [9, 10].



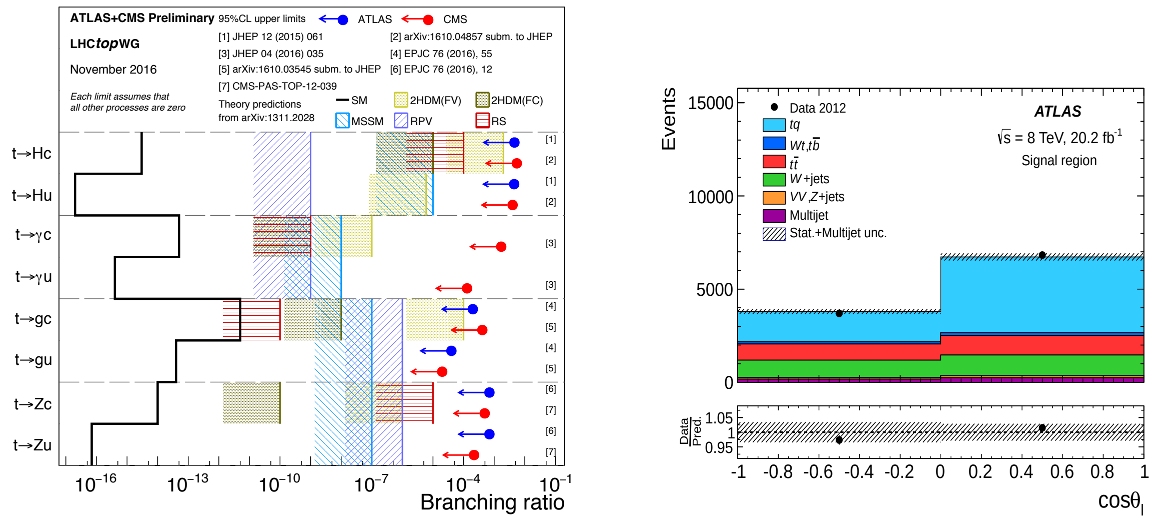
(a) (b)

Figure 2: Summary of the measured six W-boson spin observables compared with the SM predictions (a) [4]. Contour limits on complex values of the ratio of anomalous couplings $g_{\mathrm{R}}/V_{\mathrm{L}}$ (b) [5].

The second analysis of the Wtb vertex carried out by the ATLAS Collaboration [11] is based on the measurement of the triple-differential angular decay rate of single top quarks produced in t-channel events to simultaneously determine five generalised helicity fractions and phases together with the top-quark polarisation from which the anomalous couplings are constrained. The moments of the measured angular distribution are estimated using an orthonormal series density estimation technique. A multidimensional likelihood function is built, where detector effects are deconvolved from data using a Fourier technique. From numerical calculations of this likelihood function, contour limits as the one shown in Figure 2(b) are obtained and limits are placed simultaneously on possible complex values of ratios of the anomalous couplings with no assumptions on values of the other anomalous couplings: $|V_{\mathrm{R}}/V_{\mathrm{L}}|<0.37$, $|g_{\mathrm{L}}/V_{\mathrm{L}}|<0.29$, Re$[g_{\mathrm{R}}/V_{\mathrm{L}}]\in[-0.2,0.17]$ and Im$[g_{\mathrm{R}}/V_{\mathrm{L}}]\in[-0.07,0.06]$ at 95% CL. These limits improve the previous ones from the double-differential angular analysis [5] performed by ATLAS at $\sqrt{s} = 7$ TeV.

3. Searches for rare top quark decays

The branching ratios (BRs) of flavor-changing neutral curremts (FCNC) top quark decay, are highly suppressed in the SM due to the Glashow–Iliopoulos–Maiani (GIM) mechanism. However, various new physics models predict a strong enhancement in these BRs [3]. For instance, models with two Higgs-boson doublets with flavour violating Yukawa couplings, 2HDM(FV), predict BR($t \to Hc$)=2×10^{-3} and BR($t \to gc$)$\leq 10^{-4}$. The existing limits placed by ATLAS and CMS at $\sqrt{s} = 8$ TeV are summarized in Figure 3(a). It is worth to mention that the closest upper limits at $\sqrt{s} = 8$ TeV to the theoretical expectations predicted by new physics models are: BR($t \to Hc$)$< 4.0\times10^{-3}$ [12] and BR($t \to gc$)$< 2\times10^{-4}$ [13].



(a) (b)

Figure 3: Latest summary of top-quark FCNC BRs from the LHCtopWG (a) [14]. Diphoton invariant mass distribution for the best subcathegory in the hadronic mode (b) [15].

A new search for top-quark decays $t \to qH$, with $H \to \gamma\gamma$, has been performed by the ATLAS Collaboration at $\sqrt{s} = 13$ TeV [15]. Two modes are included in the analysis, the hadronic mode: $t\bar{t} \to W(\to qq')b + H(\to\gamma\gamma)b$ and the leptonic mode: $t\bar{t} \to W(\to \ell\nu)b + H(\to\gamma\gamma)b$. Besides selecting two photons, four jets and at least one b-tagged jet are required in the hadronic mode, and one lepton (electron or muon) with $p_{\mathrm{T}} > 10$ GeV and at least two jets in the leptonic one. In addition, two or one combinations of invariant masses kinematically compatible with two top quark decays are required in both modes, defining two subcathegories. The main backgrounds are the non-resonant diphoton production plus one jet $\gamma\gamma j$, $t\bar{t}\gamma\gamma$, $(W+Z)\gamma\gamma$ and $ttH(\to\gamma\gamma)$. The diphoton invariant mass $m_{\gamma\gamma}$ of signal and background is fitted to data (see Figure 3(b)). No significant excess is observed and an observed (expected) upper limit is set on BR($t \to cH$) branching ratio of 2.2 (1.6) $\times 10^{-3}$ at the 95% CL, tantalizingly close to the predictions from 2HDM(FV) models.

4. Conclusions

The ATLAS Collaboration has exhaustively probed the Wtb vertex structure using t-channel single-top-quark production at $\sqrt{s} = 8$ TeV. The eight measured asymmetries and six W boson spin observables together with the top-quark polarisation are in agreement with the SM predictions. A novel interpolation technique has allowed to constrain Im g_{R} assuming Standard Model values for the rest of the couplings. The measurement of triple-differential angular decay rates has allowed to simultaneously extract limits on complex values of ratios of the anomalous couplings with no assumptions on values of the other anomalous couplings. A recent search for FCNC interactions in top-quark decays $t \to qH$ performed with ATLAS at $\sqrt{s} = 13$ TeV has improved previous LHC limits, entering in the region of sensitivity to 2HDM with flavor violating Yukawa couplings.

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