Top Properties in ATLAS and CMS

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Recent top quark properties measurements using 2012 data at 8 TeV recorded by ATLAS and CMS are presented. This overview focusses on the latest results on the $W_{tb}$ vertex together with the top spin and polarisation. Furthermore, the cross-section measurement of a top quark pair produced in association with a photon is shown.

1 Top Properties

The top quark is the heaviest known elementary particle and decays almost exclusively into a bottom quark and a $W$ boson. Its lifetime is shorter than the hadronization time scale. Therefore, its bare quark properties are accessible.

The top properties are measured in single top or $t\bar{t}$ events. The measurements can take advantage of the polarised top quarks in single top events and the high cross-section in $t\bar{t}$ events. Single top events are produced via the weak interaction and $t\bar{t}$ events via the strong interaction.

If not stated otherwise, all measurements discussed in this overview use the full 2012 data set from the LHC at a center of mass energy of 8 TeV. The full 2012 data set corresponds to an integrated luminosity of 20.2 fb$^{-1}$ for ATLAS and 19.8 fb$^{-1}$ for CMS.

2 $W_{tb}$ Vertex

The Properties of the top decay vertex ($W_{tb}$) are determined by the weak interaction. The general structure of the $W_{tb}$ vertex is:

$$\mathcal{L}_{W_{tb}} = -\frac{g}{\sqrt{2}} b\gamma_\mu(V_L P_L + V_R P_R) t W^-_\mu - \frac{g}{\sqrt{2}} b\frac{-i\sigma^{\mu\nu}q_\nu}{m_W}(g_L P_L + g_R P_R) t W^-_\mu + h.c..$$ (1)

In the Standard Model only the left-handed vector coupling $V_L = V_{tb}$ contributes to the vertex, all other couplings ($V_R$, $P_L$, $P_R$) are zero. The $W_{tb}$ vertex is not only present in the top decay but also in the production of single top quarks.

2.1 $W$ Helicity

In the $W_{tb}$ vertex the $W$ bosons can be produced with left-, right-handed or longitudinal polarisation. The corresponding fractions $F_0$, $F_L$, $F_R$ of the polarisation state are well predicted in the Standard Model and are calculated at NNLO ($F_0 = 0.687$, $F_L = 0.311$, $F_R = 0.0017$) $^3$. The so called helicity angle is defined as the angle between the $W$ boson momentum in the top quark rest frame and the momentum of the decay fermion in the rest frame of the $W$ boson.

The fractions are extracted from a differential cross-section measurement as a function of the
cosine of the helicity angle. There are several ATLAS and CMS analyses measuring $W$ helicity in the single and dilepton final states, see Fig. 1. The latest ATLAS and CMS results using the full 2012 data set in the single lepton channel are the most precise ones. All $W$ helicity measurements agree with the Standard Model.

2.2 Beyond $W$ Helicity

In addition to the well-known helicity fractions ATLAS measured the $W$ polarisation along two directions orthogonal to its momentum in the single top channel\(^5\).\(^6\). The polarisation observables are extracted from forward-backward asymmetries in angular distributions. The extracted $W$ boson spin observables are in Fig. 2, additional results on the top polarisation with the spin analysing power $\alpha$ and top-quark degree of polarisation $P$ are:

\[
\alpha P = 0.97 \pm 0.05 \text{ (stat.)} \pm 0.11 \text{ (syst.)}, \quad (2)
\]

\[
P (F_R + F_L) = 0.25 \pm 0.08 \text{ (stat.)} \pm 0.14 \text{ (syst.)}. \quad (3)
\]

2.3 Anomalous $Wtb$ coupling

The $W$ helicity measurements in the single top channel by ATLAS and in the $t\bar{t}$ channel by CMS are used to set limits on anomalous $Wtb$ coupling, see Fig. 4\(^7\)\(^8\). Additionally, CMS set limits by using a Bayesian neural network in the single top channel\(^9\). The limits using the Bayesian neural network are obtained from the 7 and 8 TeV data set corresponding to an integrated luminosity of 5.0 fb\(^{-1}\) and 19.7 fb\(^{-1}\).

3 Top Quark Spin and Polarisation

A nice property of top quarks is that the top quark spin does not become decorrelated due to its short lifetime. Therefore, the spin information is transferred to their decay products and can be measured.

The top quark spin density matrix with all the coefficients has been measured by ATLAS for the
first time\cite{10}. Angular observables of the top decay products in the $t\bar{t}$ channel are used to measure the six polarisation and nine spin correlation coefficients. The top quark spin observables are measured on parton level in the full phase space and on particle level in a fiducial detector region. The results in Fig. 5 are in agreement with the Standard Model.

A first measurement of top quark polarisation in single top channel has been performed by CMS\cite{11}. The analysis makes use of the highly polarised top quarks along the direction of the momentum of the spectator quark in single top events. With this information a top quark spin asymmetry $A_X$ is defined in the number of instances in which that top quark decay product is aligned or anti-aligned relative to the direction of the spectator quark momentum:

$$A_X = \frac{1}{2} P_t \alpha_X = \frac{N(\uparrow) - N(\downarrow)}{N(\uparrow) + N(\downarrow)}.$$  \hspace{1cm} (4)

The measured asymmetry $A = 0.26 \pm 0.11$ deviates by about $2\sigma$ from the Standard Model prediction $A_{SM} = 0.44$.

4 $tt\gamma$ Production

The cross-section measurements of top pair production in association with a photon provide the opportunity to study top couplings to photons. ATLAS measured the fiducial and differential cross-sections of a top quark pair produced in association with a photon\cite{12}. The analysis selection enhances photons emitted by top quark in the single lepton channel. The extraction of
Figure 5 – Top spin observables measured in the $t\bar{t}$ channel in comparison with SM predictions (JHEP 12 (2015) 026) at the parton level. 

the total and differential cross sections is based on a likelihood fit using three templates, one for the prompt-photon events, one for the hadronic-fake photon events and one for electrons misidentified as photons. The normalisations of the first two templates are free parameters in the likelihood fit, while for the third template the normalisation is fixed to the data-driven estimate of the number of events with an electron misidentified as a photon. The results are in agreement with Standard Model prediction, see Fig. 3, Eqs. 5 and 6 with results from the corresponding CMS analysis. 

\[ \sigma_{\text{fid}, \text{ATLAS}}^{t\bar{t} \gamma} = 139 \pm 7 \, \text{(stat.)} \, 17 \pm \text{(syst.)} \, \text{fb} \] (5) 
\[ \sigma_{\text{fid}, \text{CMS}}^{t\bar{t} \gamma} = 127 \pm 27 \, \text{(stat. + syst.)} \, \text{fb} \] (6) 

5 Conclusion

Measurements of top properties using ATLAS and CMS data taken at 8 TeV have been presented. The measurements show good agreement with the Standard Model predictions. Future analyses using 13 TeV data with up to 100 fb$^{-1}$ will allow unprecedented precision measurements.

References

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