EPJ Web of Conferences **60**, 20005 (2013)
DOI: 10.1051/epjconf/20136020005

Evidence for the associated production of a W boson and a top quark in ATLAS

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Abstract. In proton collisions at the LHC, top quarks can be produced in pairs via the strong interaction and individually via the weak interaction. The weak interaction production can be subdivided into three channels: the t-channel, the s-channel and the associated production of a W boson and a top quark. The total production cross-section of these three channels is about one third of the total top quark production cross-section. The t-channel is dominant and has been measured both at the Tevatron and the LHC. However, the Wt associated production has not yet been observed. Different final states can be used to isolate the associated Wt production from background processes, depending on the decay modes of the two W bosons. The channel with two leptons is analysed by ATLAS to present evidence for Wt associated production at $\sqrt{s} = 7$ TeV. The measurement uses a boosted decision tree to separate signal from background.

1 Introduction

Proton collisions at $\sqrt{s} = 7$ TeV at the LHC provide the possibility to measure the associated production of a W boson and a top quark for the first time. While the electroweak production of single top quarks has been measured already by the Tevatron experiments CDF and D0 and also at the LHC, the associated W boson and top-quark production is yet to be experimentally verified. Example leading-order Feynman diagrams are shown in fig. 1.

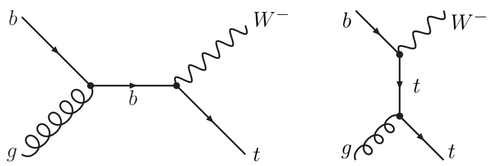

Figure 1. Leading order Feynman diagrams for the associated production of a W boson and a top quark

The final state of this process contains two W bosons and an additional bottom quark from the top quark decay. The production cross-section for a top quark mass of 172.5 GeV is estimated to be 15.7 ± 1.1 pb [1]. As it is possible to reconstruct the full final state of this process, the measurement is sensitive to a modified W-t-b coupling compared to the Standard Model. It also allows a direct measurement of the CKM matrix element $|V_{tb}|$. This analysis [2] selects a final state with two charged leptons using a dataset corresponding to an integrated luminosity of $2.05\,\text{fb}^{-1}$ recorded by the ATLAS detector [3] in 2011.

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2 Selection

To isolate the final state with two charged leptons, two neutrinos and one b-quark, the analysis requires exactly two isolated leptons (electrons or muons) with a transverse moment of $p_T > 25$ GeV in the central region of the detector ($|\eta| < 2.5$, where η denotes the pseudorapidity). A substantial missing transverse momentum $E_T^{\text{miss}} > 50$ GeV is required. To account for the b-quark in the final state, the events should contain at least one jet with $p_T > 30$ GeV in the central detector region. No special b-tagging requirement is applied as it does not offer significant rejection of the main background, top-quark pair production. One of the most important backgrounds in the dilepton channel is Z-boson decay, which can be suppressed by a cut on the invariant mass of the two leptons in ee and $\mu\mu$ events:

$$m_{\ell\ell} < 81\text{ GeV or } m_{\ell\ell} > 101\text{ GeV}.$$

Decays of Z-bosons into τ-leptons are efficiently rejected using an angular cut on the lepton and missing transverse momentum directions:

$$\Delta\phi(\ell_1, \vec{E}_T^{\text{miss}}) + (\ell_2, \vec{E}_T^{\text{miss}}) < 2.5.$$

3 Background estimation

The main background which is still present after the selection described in sect. 2 is top-quark pairs. To estimate this background, events from Monte Carlo (MC) simulation are used, reweighted according to next-to-next-to-leading order (NNLO) theory predictions of the cross-section. The overall rate is further constrained by the fit to extract the signal as described in sect. 4.1. The second largest background consists of events from diboson production (WW,

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WZ, ZZ) and is estimated in the same way. Other background events passing the selection result from decays of single Z bosons accompanied by additional jets and fake dileptons which are determined using data-driven methods as described in the following.

Decays of Z bosons into ee and $\mu\mu$ final states are estimated using a set of two signal and four background-enriched control regions defined in the variable space created by the missing transverse momentum and the dilepton invariant mass as indicated in fig. 2. The number of Drell-Yan events in the signal regions is estimated from data which are scaled by the measured ratio of events in the corresponding control regions. Contamination by non-Drell-Yan events predicted by the simulation is corrected for. The two scale and normalisation factors are determined using a likelihood fit of the data in E_T^{miss}-bins.

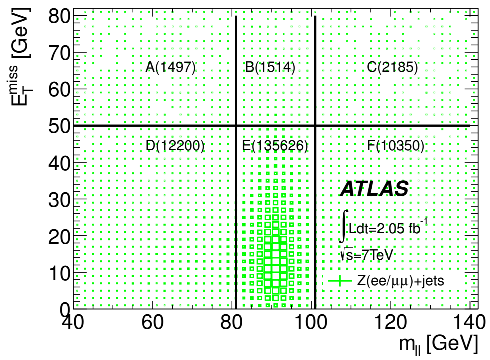

Figure 2. Scatter plot showing the dilepton invariant mass and missing transverse momentum of dielectron and dimuon data events for all selected data. The signal regions (A and C) and control regions (B, D, E and F) are indicated. The observed number of data events in each region are indicated in brackets [1].

The prediction of the number of events from $Z \to \tau\tau$ events is also verified using a data-driven technique. The requirement to veto such events as described in sect. 2 is used to define a signal and a control region. The ratio of the event yields of these regions predicted by the simulation is multiplied by the number of events found in data inside the signal region. The difference between the Monte Carlo prediction and the data-based one is included as a systematic error. Events from other background channels are subtracted from these according to the simulation prediction.

Events can also enter the signal region if a jet is misreconstructed as a lepton or includes a semileptonic heavy flavour quark decay which is accompanied by a real lepton. Such events stem from W+jets, $t\bar{t}$ or multijet production. Their contribution is calculated based on samples which use the normal lepton definitions and are referred to as *tight*, as well as using a less restrictive definition, where some lepton quality cuts are inverted and the isolation requirements are removed, which is called *loose*. The efficiency of reconstructing a fake lepton as a real one is then determined using a matrix method based on the inversion of a 4×4 matrix which relates different known efficiencies to each other.

The result of the selection and background estimation is summarized in table 1. The highest signal-to-background ratio of 18 % is achieved in the signal bin with exactly one jet and overall the expectation agrees with the measured number of data events within the uncertainties.

	1 jet	2 jets	$\geq$ 3 jets
Wt	147 ± 13	60 ± 9	17 ± 5
$t\bar{t}$	610 ± 110	1160 ± 140	740 ± 130
Diboson	130 ± 17	47 ± 5	17 ± 4
$Z \to ee$	20 ± 2	11 ± 2	5 ± 2
$Z \to \mu\mu$	29 ± 3	28 ± 3	12 ± 3
$Z \to \tau\tau$	9 ± 6	4 ± 3	2 ± 1
Fake dileptons	11 ± 11	5 ± 5	negl.
Total bkgd.	810 ± 120	1260 ± 140	780 ± 130
Total expected	960 ± 120	1320 ± 140	790 ± 130
Data observed	934	1300	825

Table 1. Observed and expected event yield in the selected dilepton sample in the 1-jet, 2-jet and $\geqslant$3-jet bins for an integrated luminosity of 2.05 fb^{-1}. The Wt, $t\bar{t}$ and diboson expectations are normalised to the theory predictions. Other backgrounds are determined as described in the text. Uncertainties are the sum of statistical and systematic sources added in quadrature [1].

4 Analysis

The analysis uses the 1-jet bin for the signal extraction as it offers the highest signal-to-background ratio. Higher jet multiplicities contain a larger contamination of top quark pair production and other backgrounds and are included to constrain their contribution. A boosted decision tree (BDT) is used to form a single classifier, as no single separating variables allow a signal isolation. The advantage of such multivariate approaches is the exploitation of correlations between the variables to improve the separation of signal and background.

A total of twenty-two variables are used to train the BDT using simulated 1-jet events. The training result is shown in fig. 3 together with a stability check. The most powerful variables in the training are the magnitude of the vectorial sum of p_T of the leading jet, both leptons and E_T^{miss}, p_T^{sys}, and the ratio $p_T^{\text{sys}} / \sqrt{H_T + \sum E_T}$. H_T is the sum of p_T of the two leptons and the leading jet, while $\sum E_T$ refers to the sum of all transverse energies deposited into the calorimeter. Other examples of separating variables are the event's centrality and the p_T of the leading jet.

4.1 Cross-section measurement

To extract a signal cross-section for Wt production, the BDT output is calculated for 1-jet, 2-jet and more than 3-jet events. The distribution of the output for the signal bin

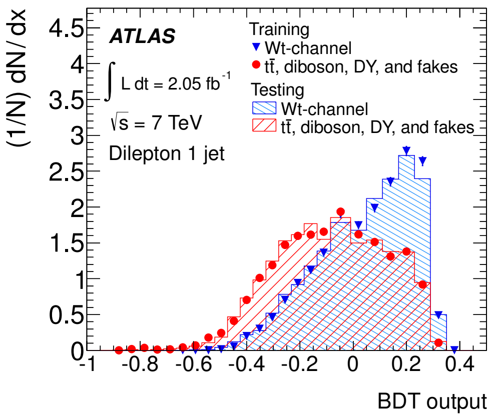

Figure 3. Distribution of BDT output for the signal and background in the signal-enriched 1-jet bin. The BDT method uses 2 statistically independent sets of MC-simulated events, indicated as training and testing samples, to check both signal and background BDT output stability [1].

is shown in fig. 4 while an example for the background-dominated 3-jet bin is shown in fig. 5.

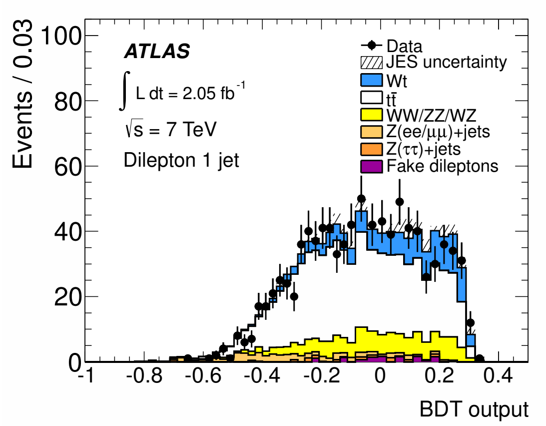

Figure 4. BDT output for selected events in 1-jet category. The Wt signal is normalised to the theory prediction [1].

Finally a simultaneous template fit of all three jet categories is performed which implements a likelihood function with Poisson terms for the expected event numbers and Gaussian terms for each source of systematic uncertainty. The cross-section can then be determined from the parameters that maximise the likelihood function. The total uncertainty of the measurement is extracted from the profile likelihood ratio which implements all sources of systematics, except for generator and parton shower ones, as variation of nuisance parameters. The main uncertainties are statistical (17 %), jet energy scale (16 %), parton shower modelling (15 %), generator systematics (10 %) and pile-up (10 %) which lead to an overall uncertainty of 34 %.

The measurement yield a result of

$$\sigma_{Wt} = 16.8 \pm 2.9\,(\text{stat.}) \pm 4.9\,(\text{syst.})\,\text{pb}.$$

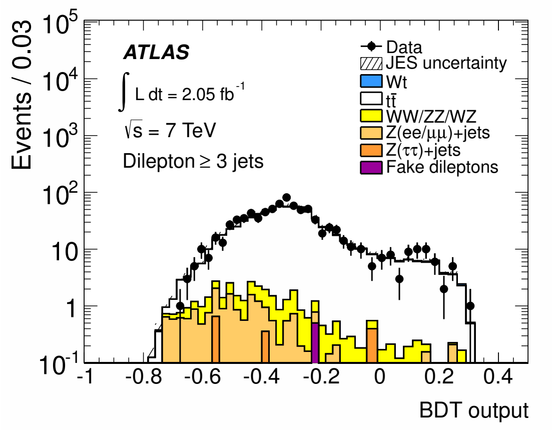

Figure 5. BDT output for selected events in $\geq$ 3-jet category. The Wt signal is normalised to the theory prediction [1].

The significance of the measurement has been computed with ensemble tests based on pseudo-experiments. Both background-only and signal + background hypotheses have been evaluated. For each pseudo-experiment, the logarithm of the likelihood ratio has been computed. The distribution of these allows to calculated the p-values for both hypotheses which are then interpreted in terms of significance. The measurement achieves an expected significance of 3.3 σ and a measured significance of 3.4 σ.

4.2 Determination of $|V_{tb}|$

The measured cross-section in the analysis is directly sensitive to the CKM matrix element $|V_{tb}|$ as the final state particles used are created in a W-t-b vertex. By assuming a minimal contribution of Wt production through $|V_{ts}|$ and $|V_{td}|$, the matrix element $|V_{tb}|$ can be directly calculated from the ratio of measured and predicted cross-sections. This leads to a value of

$$|V_{tb}| = 1.03^{+0.16}_{-0.19},$$

where the uncertainties from the measurement and the prediction have been added in quadrature.

5 Conclusions

The presented analysis shows evidence for the associated production of a W boson and a top quark using 2.05 fb^{-1} of data from collisions at $\sqrt{s}$ = 7 TeV recorded by ATLAS in 2011. A multivariate method has been used on events with two leptons to separate signal and background. A cross-section of $\sigma_{Wt} = 16.8 \pm 2.9\,(\text{stat.}) \pm 4.9\,(\text{syst.})$ pb has been measured and from this result $|V_{tb}| = 1.03^{+0.16}_{-0.19}$ is computed assuming minimal influence of $|V_{ts}|$ and $|V_{td}|$.

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