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Single top measurements at the LHC: s-channel and Wt production

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This paper summarises the latest experimental results on single top quark physics by the ATLAS and CMS collaborations using LHC proton–proton collisions at $\sqrt{s} = 8$ TeV. Searches for single top-quark production in the s-channel and associated Wt mode are presented and a determination of the CKM matrix element $|V_{tb}|$ is discussed. Evidence for s-channel production is reported by the ATLAS collaboration and the Wt process has been observed at the LHC.

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1. Introduction

In its first years of operation, the LHC has proven to be a top-quark factory, allowing ATLAS [1] and CMS [2] to study many aspects of this particle with great accuracy and to search for new physics involving the top quark. At the LHC, top quarks are either produced in pairs via the strong interaction or singly via the electroweak interaction. Single top quark production serves as a probe of the Wtb interaction and its production cross-section provides a direct determination of the magnitude of the Cabibbo–Kobayashi–Maskawa (CKM) matrix element V_{tb}. The dominant process for single top quark production is the exchange of a virtual W boson in the t-channel, accounting for about 76% of the cross-section. The associated production of a top quark and an on-shell W boson (Wt) has the second largest cross-section ($\sim 20\%$) whereas the s-channel process is comparatively rare ($\sim 5\%$).

This article presents recent measurements of the Wt and s-channel production cross-sections at the LHC. The analyses are performed using the proton–proton collisions recorded by the ATLAS and CMS experiments at 8 TeV centre-of-mass energies.

2. The production of a top quark in association with a W boson

The Wt process has been observed by the ATLAS and CMS collaborations using 8 TeV data [3, 4]. These analyses exploit the presence of two real W bosons (the associated one, and the one from top-quark decay) by selecting events with two opposite-charge leptons, electron or muon, one jet containing a b-hadron (b-jet), and large missing transverse momentum ($E_{\mathrm{T}}^{\mathrm{miss}}$) from the two neutrinos. Both collaborations consider one signal region with exactly one b-jet and two control regions with exactly two jets (one or two b-jet) in order to minimise the effect of the systematic uncertainties in the modelling of the major background, the top pair production ($t\bar{t}$). A boosted decision tree (BDT) classifier is trained with a set of kinematic variables for each region in order to optimise the discrimination between signal and background.

The CMS measurement was performed using a dataset corresponding to 12.2 fb^{-1} [4]. The most discriminating input variables to the BDT are those related with loose jets (defined by $p_{\mathrm{T}} >$ 20 GeV and $|\eta| < 4.9$) in the event. Figure 1 shows the distribution of the most important variable for 1-jet events, the number of loose jets (left), together with the resulting BDT distribution (right). A simultaneous binned likelihood fit to the three BDT distributions is performed. Systematic uncertainties are treated as constrained nuisance parameters in the fit except for the luminosity and theory uncertainties which are unconstrained. The measured cross-section is 23.4 ± 5.4 pb with an observed significance of 6.1σ compared with the expected value of 5.4σ. The largest contribution to the total uncertainty ($\sim 23\%$) is mostly the $t\bar{t}$ modelling, and in particular, the matrix-element/parton-shower matching thresholds ($\sim 14\%$).

A more recent measurement is carried out in ATLAS using an integrated luminosity of 20.3 fb^{-1} [3]. As in the previous analysis, a BDT is constructed in each of the three regions and a profile likelihood fit to the BDT distributions is used to measure the Wt cross-section. One of the major differences comes from the optimisation procedure using 0-tag [1] control regions, which are enriched in other backgrounds. ATLAS applies a set of different requirements in $E_{\mathrm{T}}^{\mathrm{miss}}$ for same-flavour and opposite-flavour leptons. The most important input variable in the 1-jet 1-tag region

[1]Throughout these proceedings, at n-tag region is a sample with n b-tagged jets.

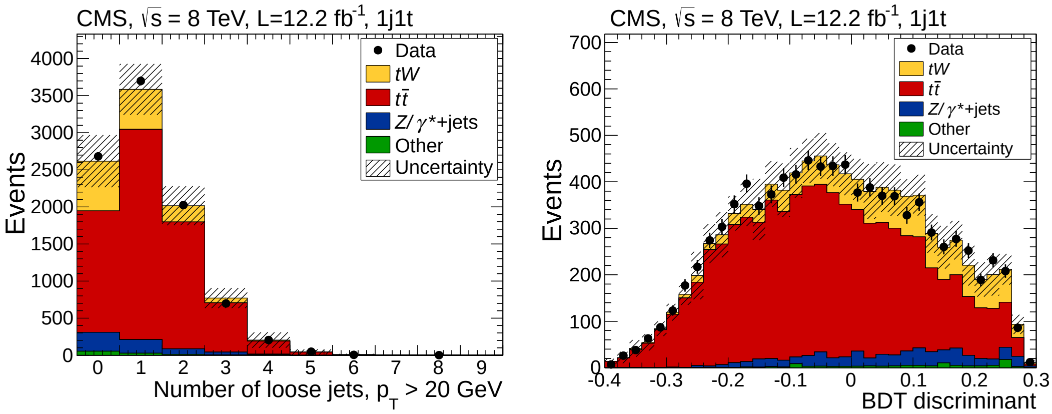

Figure 1: The observed and predicted distributions in the 1-jet 1-tag region for the number of loose jets with $p_{\mathrm{T}} > 20$ GeV (left) and the BDT discriminant (right) [4]. The hatched band represents the combined effect of all sources of systematic uncertainty.

is the transverse momentum of the system of leptons, $E_{\mathrm{T}}^{\mathrm{miss}}$ and the jet, which is sensitive to the unidentified b-quark in $t\bar{t}$ events. The BDT response for the signal region is shown in Figure 2 (left). The Wt signal is larger at positive BDT response values, while the top pair background dominates for negative BDT response values. The Wt production is observed by the ATLAS collaboration with an observed (expected) significance of $7.7(6.9)\sigma$ and the inclusive cross-section is measured to be 23.0 ± 1.3 (stat.)$^{+3.2}_{-3.5}$ (syst.) ± 1.1(lumi.) pb. The largest contribution to the total uncertainty ($\sim 17\%$) is from the initial- and final-state radiation systematic uncertainty ($\sim 9\%$).

The Wt inclusive cross-section measurements performed by both experiments at 8 TeV are in agreement with the next-to-leading order (NLO) with next-to-next-to-leading logarithmic (NNLL) SM expectation, 22.37 ± 1.52 pb [5].

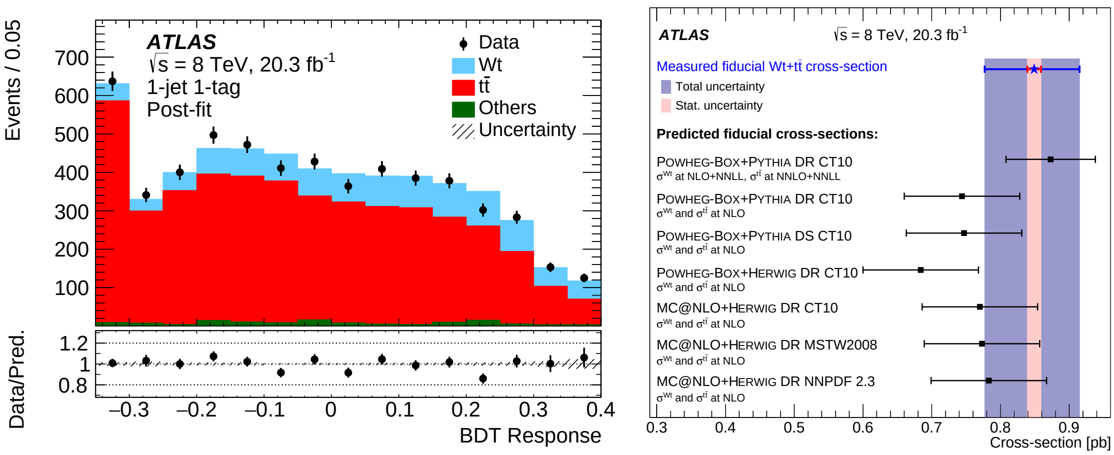

Figure 2: On the left, the observed and predicted BDT discriminant in the 1-jet 1-tag region [3]. On the right, the comparison of the measured fiducial cross-section to theoretical predictions in a fiducial acceptance requiring two leptons with $p_{\mathrm{T}} > 25$ GeV and $|\eta| < 2.5$, one jet with p_{T}>20 GeV and $|\eta| < 2.5$, and $E_{\mathrm{T}}^{\mathrm{miss}} >$ 20 GeV [3].

ATLAS also reports the first measurement of the cross-section inside a fiducial acceptance, allowing to reduce the dependence on the theory assumptions and to reduce the sensitivity to theory modelling uncertainties. The fiducial acceptance requires the presence of two leptons with $p_{\mathrm{T}} > 25$ GeV and exactly one b-jet with $p_{\mathrm{T}} > 20$ GeV at the particle level. The Wt single top-quark process overlaps and interferes with $t\bar{t}$ production at NLO where diagrams involving two top quarks are part of the real emission corrections to Wt production; because of this, the definition of signal encompasses not only Wt but also $t\bar{t}$ production where one of the b quarks is outside of the acceptance. The fiducial $Wt + t\bar{t}$ cross section within the detector acceptance is measured to be: 0.85 ± 0.01 (stat.)$^{+0.06}_{-0.07}$ (syst.) ± 0.03(lumi.) pb. Figure 2 (right) shows the comparison of this measurement with theoretical predictions for the sum of the fiducial Wt and $t\bar{t}$ cross-sections. The result is found to be in agreement with NLO predictions and with a POWHEG prediction where the Wt process is calculated at NLO+NNLL and $t\bar{t}$ at NNLO+NNLL accuracy.

3. The exchange of a virtual W boson in the s-channel

The SM s-channel single top-quark production has been searched by the ATLAS and CMS collaborations using 8 TeV data [6, 7, 8]. The experimental signature consists of an isolated electron or muon, large $E_{\mathrm{T}}^{\mathrm{miss}}$ and two b-tagged jets with large p_{T}. In contrast to the Wt analyses, ATLAS and CMS have a different strategy to separate the small s-channel signal from the two main backgrounds: top pair and W+jets production.

The first search at the LHC for the s-channel was performed by CMS at 8 TeV [8] using the leptonic decay channels of the top quark. The analysis considers one signal sample (2-jet 2-tag) enriched in s-channel events, one control sample (2-jet 0-tag) to check the W+jets modelling and another control sample (3-jet 2-tag) to constrain the $t\bar{t}$ normalisation uncertainty. Four separate BDT discriminants are extracted for the signal region and the $t\bar{t}$ control region in the e and μ channel. The highest ranked variable in 2-jet 2-tag is the transverse W boson mass in the electron channel (see Figure 3) and the transverse momentum of the system of the two jets in the muon channel. The BDT distribution in the signal sample for the electron channel is shown on the right in Figure 3. The signal extraction is based on a binned maximum-likelihood fit of the output BDT classifiers. The analysis leads to an upper limit on the s-channel single top-quark production cross-section times branching ratio of 11.5 pb, being the expected $(17.0, 9.0)$ pb, at 95% confidence level.

In contrast to a previous BDT-based analysis [6], ATLAS performs a measurement of the s-channel production cross-section at 8 TeV [7] based on an advanced matrix element (ME) technique. The ME approach is not limited by the sample sizes available for the training as is the case for the BDT technique, and as a result a significant improvement in the sensitivity to the s-channel process is observed. A signal region is defined with similar selection requirements to the CMS analysis but with a new feature to reduce the dileptonic $t\bar{t}$ background events. A veto is applied to all events with an extra reconstructed lepton with $p_{\mathrm{T}} > 5$ GeV, rejecting 30% of the selected $t\bar{t}$ events. Two control regions are also defined, one validation region for $t\bar{t}$ and another region to constrain the W+jets normalisation in the final signal extraction. The probability P(S/X) for a measured event X to be a signal event S is computed using each of the likelihood values for signal and background. This technique directly uses theoretical calculations to compute the per-event sig-

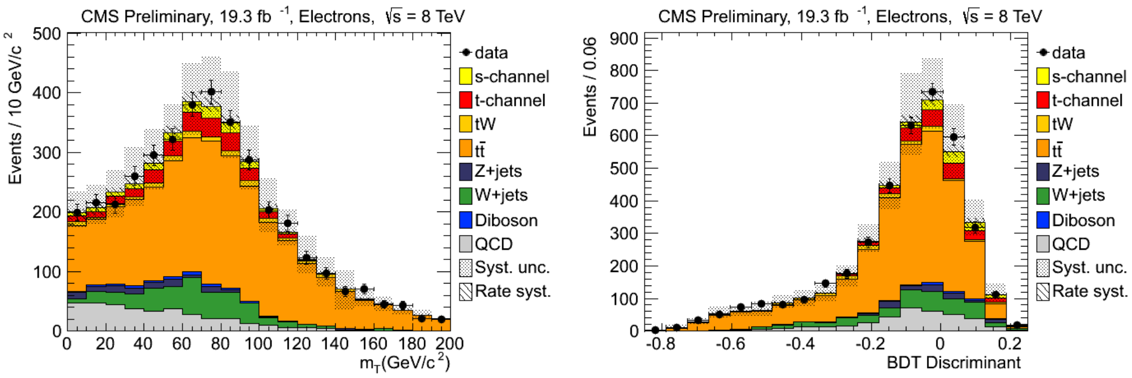

Figure 3: The observed and predicted distributions in the 2-jet 2-tag region in the electron channel for the most discriminant variable, m_T (left) and the BDT discriminant (right) [8] . The smaller error bands include the background rates uncertainties only, the larger ones include all the systematic uncertainties.

nal probability. A binned maximum-likelihood fit of the ME discriminant together with the lepton charge in the W +jets control region is performed to extract the amount of signal. The two discriminant distributions scaled by the fit results are shown in Figure 4. The s-channel signal is larger for P(S/X) values close to 1, while the $t\bar{t}$ and W+jets backgrounds dominates for low P(S/X) values. This analysis measures a cross-section of 4.8 ± 0.8 (stat.)$^{+1.6}_{-1.3}$ (syst.)pb with an observed/expected significance of 3.2/3.9 standard deviations. The measurement is found to agree within their uncertainties with the NLO+NNLL SM expectation, 5.61 ± 0.22 pb. The main contributions to the total cross-section uncertainty (34 %) are the jet energy resolution and the Monte Carlo statistics which are both 12%.

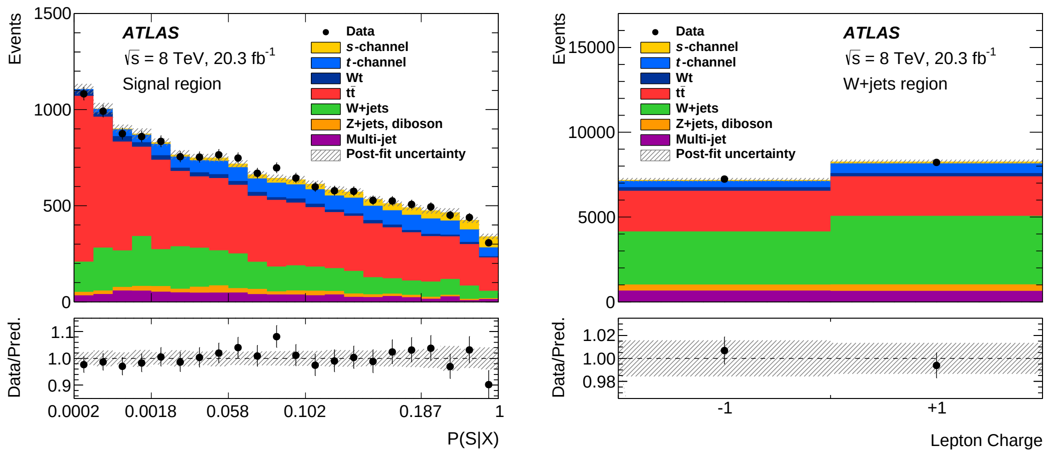

Figure 4: The post-fit distribution of the ME discriminant in the signal region (left) and of the lepton charge discriminant in the W + jets control region (right) [7]. The hatched bands indicate the total uncertainty of the post-fit result including all correlations.

4. Constraints on $|f_{\mathrm{LV}} V_{tb}|$

The measured cross-section can be interpreted in terms of the CKM matrix element V_{tb}. The ratio of the measured cross-section to the predicted cross-section (which is obtained for $|V_{tb}|^2 = 1$)

is equal to $|f_{LV}V_{tb}|^2$, where the form factor f_{LV} could be modified by new physics or radiative corrections through anomalous coupling contributions. Figure 5 summarises the single top $|f_{LV}V_{tb}|$ measurements at the LHC performed with the 2011, 2012 and 2015 datasets.

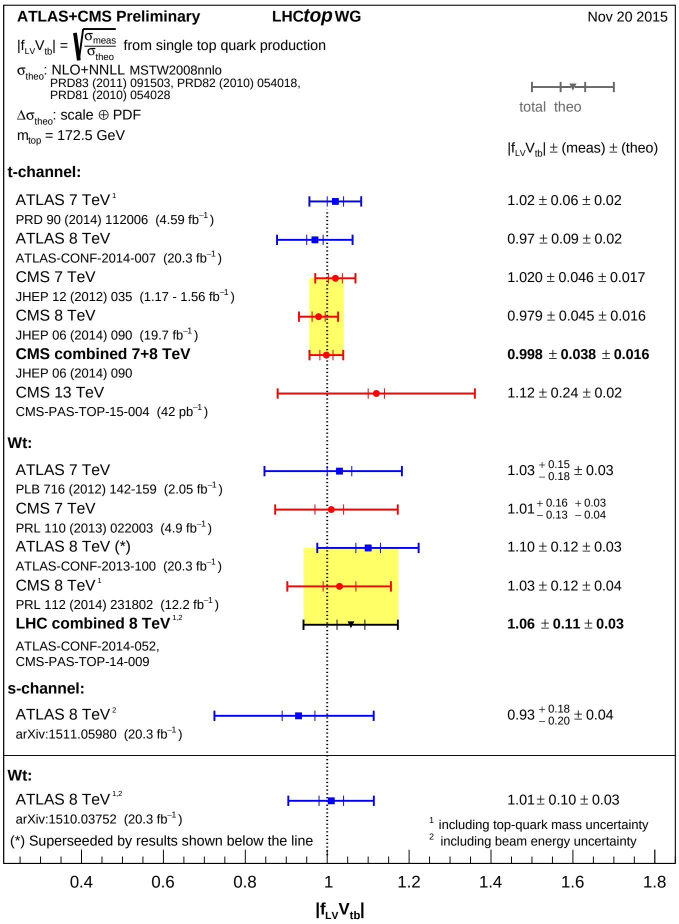

Figure 5: Summary of ATLAS and CMS $|f_{LV}V_{tb}|$ measurements [9] in the three single top channels.

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