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Search for s-channel single top-quark production in proton–proton collisions at $\sqrt{s} = 8$ TeV with the ATLAS detector

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ABSTRACT

This Letter presents a search at the LHC for s-channel single top-quark production in proton–proton collisions at a centre-of-mass energy of 8 TeV. The analyzed data set was recorded by the ATLAS detector and corresponds to an integrated luminosity of 20.3 fb^{-1}. Selected events contain one charged lepton, large missing transverse momentum and exactly two b-tagged jets. A multivariate event classifier based on boosted decision trees is developed to discriminate s-channel single top-quark events from the main background contributions. The signal extraction is based on a binned maximum-likelihood fit of the output classifier distribution. The analysis leads to an upper limit on the s-channel single top-quark production cross-section of 14.6 pb at the 95% confidence level. The fit gives a cross-section of $\sigma_s = 5.0 \pm 4.3$ pb, consistent with the Standard Model expectation.

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1. Introduction

At hadron colliders, top-quarks are produced predominantly in pairs ($t\bar{t}$) via the strong interaction but can also be produced singly through the electroweak interaction. At leading order in perturbation theory, there are three possible single top-quark production modes: an exchange of a virtual W boson either in the t-channel or in the s-channel, or the associated production of a top-quark and a W boson. In the s-channel, the exchange of a time-like W boson produces a top-quark and a bottom-quark in the final state [1]. Independent measurements of these three modes are of great interest since different impacts on their production rates are predicted by the various proposed scenarios beyond the Standard Model [2].

Single top-quark production was first observed at the Tevatron in proton–antiproton collisions by the CDF and D0 Collaborations in measurements of the combined s- and t-channel production [3,4]. The observation of the s-channel process alone through the combination of the CDF [5] and D0 [6] cross-section measurements was reported recently [7]. At the Large Hadron Collider (LHC), the production cross-section of single tops in proton–proton (pp) collisions was measured both in the t-channel and in association with a W boson by the CMS [8–11] and ATLAS [12–14] Collaborations. Measuring the s-channel process is more difficult due to a much smaller signal-to-background ratio, this production mode being disadvantaged at the LHC due to the need for a sea anti-quark in the initial state.

Calculations at approximate next-to-next-to-leading-order (NNLO) precision in QCD are available for the production cross-section of single tops [15–17]. These approximate NNLO results include the contributions due to the next-to-next-to-leading-logarithm (NNLL) resummation of soft-gluon bremsstrahlung. For the s-channel process, the total inclusive cross-section for pp collisions at a centre-of-mass energy of 8 TeV is predicted to be $\sigma_s = 5.61 \pm 0.22$ pb. This assumes a top-quark mass of 172.5 GeV and uses the MSTW2008 [18] NNLO set of parton distribution functions (PDFs). The quoted uncertainty includes the QCD scale uncertainty and the correlated PDF–α_s uncertainty. The cross-sections calculated at approximate NNLO for the dominant t-channel and Wt processes are $\sigma_t = 87.8^{+3.4}_{-1.9}$ pb [15] and $\sigma_{Wt} = 22.4 \pm 1.5$ pb [16], respectively.

This Letter presents a search for s-channel single top-quark production in pp collisions at $\sqrt{s} = 8$ TeV carried out at the LHC by the ATLAS Collaboration. Only leptonic decay modes of the top-quark giving an electron or a muon are considered and the signal is extracted from a likelihood fit to the distribution of a multivariate discriminant. For all reported results, the electron and muon channels are merged independently of the lepton charge in order to measure the combined production cross-section of top-quarks and top-antiquarks.

2. Data sample

The analysis is performed on pp collision data collected by the ATLAS detector [19] in 2012 at a centre-of-mass energy of 8 TeV and corresponding to an integrated luminosity of 20.3 ± 0.6 fb^{-1} [20].

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The ATLAS detector is a multipurpose apparatus consisting of a precise tracking system, calorimeters and a muon spectrometer. The inner tracking system contains a high-granularity silicon pixel detector, a silicon microstrip tracker and a straw-tube transition radiation tracker. This system exploits a 2 T axial magnetic field and provides charged-particle tracking in the pseudorapidity[1] region $|\eta| < 2.5$. The central calorimeter system (barrel) is divided into a liquid-argon electromagnetic sampling calorimeter with high granularity and a hadron calorimeter consisting of iron and scintillator tiles. The former covers a range of $|\eta| < 1.47$, while the latter extends to $|\eta| = 1.7$. The two endcap regions are equipped with liquid-argon calorimeters for electromagnetic and hadronic energy measurements up to $|\eta| = 4.9$. The muon spectrometer consists of three large superconducting toroids with eight coils each, and includes precision tracking chambers for momentum measurements up to $|\eta| = 2.7$ and fast trigger chambers covering the range $|\eta| < 2.4$. A three-level trigger system, consisting of custom-made hardware followed by two software-based selections, is used to yield a recorded event rate of about 400 Hz.

Events recorded by single-electron or single-muon triggers under stable beam conditions and with good quality data from all detector subsystems are selected for the analysis. The chosen trigger thresholds give a constant efficiency for lepton candidates passing the offline selections. Each triggered event includes on average about 20 additional pp collisions (pile-up) from the same bunch crossing.

3. Event reconstruction and selection

The experimental signature of the searched-for s-channel single top events consists of a single isolated electron or muon, significant missing transverse momentum due to the undetected neutrino from the W boson leptonic decay, and exactly two b-tagged jets, one of them being associated with the top-quark decay. Events in which the W boson decays to a τ lepton are also included if the τ lepton decays subsequently to an electron or a muon.

Electron candidates are reconstructed from an isolated electromagnetic energy deposit matched to an inner detector track and passing tight identification requirements [21]. The candidates are required to have a transverse energy greater than 30 GeV and a pseudorapidity $|\eta| < 2.47$, excluding the barrel–endcap transition regions of the electromagnetic calorimeters, $1.37 < |\eta| < 1.52$. Muon candidates are reconstructed by combining tracks reconstructed in both the inner detector and the muon spectrometer [22,23]. The candidates are required to have a transverse momentum p_{T} greater than 30 GeV and $|\eta| < 2.5$. The electron and muon candidates must also fulfill isolation requirements, as described in Ref. [24], in order to reduce contributions from misidentified jets, non-prompt leptons from heavy-flavour decays and non-prompt electrons from photon conversions.

Jets are reconstructed, using the anti-k_t algorithm [25] with a radius parameter of 0.4, from calorimeter energy clusters calibrated with the local cluster weighting method [26]. Jets are calibrated using an energy- and η-dependent simulation-based calibration scheme with in situ corrections based on data [27]. In this analysis, jets with $p_{\mathrm{T}} > 30$ GeV and $|\eta| < 2.5$ are selected. Jets likely to originate from the hadronization of b-quarks are identified using a multivariate discriminant which makes use of track impact parameters and reconstructed secondary vertices [28]. Jets are defined to be b-tagged (hereinafter referred to as b-jets) if the discriminant value is above a threshold corresponding to a b-tagging efficiency of 70% for simulated $t\bar{t}$ events [29]; the associated rejection factors against light-quark and charm-quark jets are about 140 and 5, respectively [28].

The missing transverse momentum, with magnitude $E_{\mathrm{T}}^{\mathrm{miss}}$, is reconstructed from the vector sum of all clusters of energy deposits in the calorimeters calibrated at the electromagnetic scale; the contributions associated with the reconstructed electrons and jets are corrected to the corresponding energy scales [30]. Contributions from muons are also taken into account using their measured transverse momentum. The $E_{\mathrm{T}}^{\mathrm{miss}}$ is a measurement of the escaping neutrinos but also includes energy losses due to detector inefficiencies. In this analysis, $E_{\mathrm{T}}^{\mathrm{miss}}$ is required to be greater than 35 GeV.

Events are required to have at least one reconstructed primary vertex with at least five associated tracks with $p_{\mathrm{T}} > 400$ MeV, and no jets failing reconstruction quality requirements. To enhance the signal content of the sample of events containing a single isolated lepton and exactly two b-jets, the events are in addition not allowed to contain any other jets with a transverse momentum greater than 25 GeV. In addition, the W boson transverse mass,[2] m_{T}^{W}, must be greater than 50 GeV in order to reduce the multijet background contribution.

The kinematics of the neutrino and of the top-quark are reconstructed. The transverse momentum of the neutrino is assumed to be given by the x- and y-components of the missing transverse momentum, while the unmeasured longitudinal component of the neutrino momentum is extracted by imposing a W boson mass constraint on the lepton–neutrino system. The latter leads to a quadratic equation in the longitudinal momentum component of the neutrino, p_z^{ν}. If there are two real solutions the ambiguity is resolved by choosing the one with the smallest $|p_z^{\nu}|$. For complex solutions due to the non-perfect resolution of the missing transverse momentum measurement, the imaginary component is eliminated by modifying $E_{\mathrm{T}}^{\mathrm{miss}}$ in such a way that the transverse mass of the W candidate fulfills the W mass constraint, while preserving the direction of the missing transverse momentum. The kinematics of two top-quark candidates are then reconstructed by combining the four-momenta of the lepton and neutrino with each of the two b-jets (called leading and sub-leading jets according to their ranking in p_{T}). The top-quark candidate with an invariant mass closest to 172.5 GeV defines the best candidate. To improve the signal-to-background ratio of the selected events, events for which the transverse momentum of the b-jet corresponding to the best top-quark candidate is lower than 50 GeV are rejected.

After all selection requirements, 16 031 events are selected from the analyzed data sample.

4. Simulated samples

Simulated event samples are used in the analysis for comparison with the data as well as to evaluate signal and background contributions and uncertainties. The simulation samples for the single top and $t\bar{t}$ processes are produced with the next-to-leading-order (NLO) matrix-element generator POWHEG-BOX (v1_r2129) [31] using the CT10 PDF set [32]. The generator is interfaced to PYTHIA (6.42) [33] for parton showering, hadronization and underlying-event modelling with parameters set to the values of the Perugia 2011C tune [34].

[1] ATLAS uses a right-handed coordinate system with its origin at the nominal interaction point in the centre of the detector and the z-axis along the beam pipe. The pseudorapidity is defined in terms of the polar angle θ as $\eta = -\ln\tan(\theta/2)$. Distances in (η, ϕ) space are defined by $\Delta R = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2}$, where ϕ denotes the azimuthal angle around the beam pipe.

[2] The W boson transverse mass is computed from the lepton transverse momentum p_{T}^{ℓ}, the missing transverse momentum $E_{\mathrm{T}}^{\mathrm{miss}}$ and their difference in azimuthal angle as $m_{\mathrm{T}}^{W} = \sqrt{2E_{\mathrm{T}}^{\mathrm{miss}} p_{\mathrm{T}}^{\ell}(1 - \cos(\Delta\phi(E_{\mathrm{T}}^{\mathrm{miss}}, p_{\mathrm{T}}^{\ell})))}$.

For the evaluation of the uncertainty due to the generator and parton shower modelling, additional samples for the s-channel, Wt and $t\bar{t}$ processes are produced using the MC@NLO generator (4.03) [35–38] interfaced to Herwig (6.52) [39,40] for parton showering and Jimmy (4.31) [41] for the underlying-event modelling with the ATLAS AUET2 tune [42] and the CT10 PDFs. For single-top t-channel production, the MadGraph5_aMC@NLO (2.0) [43] generator also interfaced with Herwig and Jimmy is employed. To estimate the uncertainty coming from the amount of initial-state and final-state radiation, samples of $t\bar{t}$ events are produced with the leading-order (LO) AcerMC (3.8) [44] generator using the CTEQ6L1 PDF set [45]. The generator is interfaced to Pythia (6.42) and the parameters controlling the radiation emission are varied. The parameter settings are constrained by jet activity measurements in $t\bar{t}$ production [46]. The impact of scale variations on the signal events is studied using s-channel samples generated with Powheg-Box, interfaced to Pythia, with values of the factorization and renormalization scales being increased or decreased by a factor of two; this scale variation also causes the jet multiplicity to vary.

All samples involving top-quark production are generated using a top-quark mass of 172.5 GeV. The single top samples are normalized to the approximate NNLO cross-section predictions [15–17] presented in Section 1. The $t\bar{t}$ samples are normalized to the cross-section, $\sigma_{t\bar{t}} = 253^{+13}_{-15}$ pb, calculated at NNLO in QCD including resummation of NNLL soft-gluon terms with Top++ 2.0 [47–52].

Event samples simulating the production of W and Z bosons in association with jets (W + jets and Z + jets) are produced using the LO multiparton generator Alpgen (2.14) [53], with the CTEQ6L1 set of PDFs, and interfaced to Pythia (6.42). The Alpgen matrix elements include diagrams with up to five partons. W + jets samples with only light-quark jets as well as samples with heavy-flavour quarks ($Wb\bar{b}$ + jets, $Wc\bar{c}$ + jets, Wc + jets) are produced separately. To evaluate the modelling uncertainty related to W + jets production, alternative samples are produced using the LO multiparton generator Sherpa (1.4.1) [54] with the CT10 PDF set. The diboson processes (WW, WZ, ZZ) are simulated using the Herwig (6.52) and Jimmy generators with the ATLAS AUET2 tune and the CTEQ6L1 PDF set. The single-boson and diboson samples are normalized to their inclusive production cross-sections calculated at NNLO [55] or NLO [56] precision.

All generated events are passed through the full ATLAS detector simulation [57] based on Geant4 [58], or through a faster simulation making use of parameterized calorimeter showers [59]. Minimum-bias events, generated with Pythia (8.1) [60], are overlaid to simulate the pile-up effects from additional pp collisions in the same and nearby bunch crossings. All simulated events are then processed using the same reconstruction and analysis chain as for data.

5. Background estimation

The predicted event yields for the signal and backgrounds after the selection described in Section 3 are summarized in Table 1 with a comparison of the total expectation to the data.

The main background contribution is due to $t\bar{t}$ events, which account for 67% of the total expected yield. The two next-largest backgrounds come from t-channel single top and W + heavy-flavour production, each process accounting for 12% of the total expectation. The rather large predicted cross-sections for these processes which involve one lepton and one or two b-jets, coupled to a non-negligible misidentification of jets originating from lighter quark flavours, explain their significant contributions. The individual contributions associated with the Wt, W + light-jets, Z + jets and diboson background processes are all lower than 3%.

Table 1
Predicted and observed event yields after all selection requirements. The quoted errors include all systematic uncertainties described in Section 7 added in quadrature with the simulation statistical uncertainties. For the multijet background, the data-driven estimate is reported.

Process	Event yield
Single top s-channel	457 ± 50
Single top t-channel, Wt	2270 ± 240
$t\bar{t}$	$10\,200 \pm 1600$
W + jets	1900 ± 1200
Z + jets, diboson	108 ± 68
Multijet	230 ± 120
Total expectation	$15\,200 \pm 2000$
Data	16 031

The estimated contribution due to multijet events is about 2%. Multijet events pass the signal selection if in addition to two reconstructed and b-tagged jets an extra jet is misidentified as an isolated lepton, or a non-prompt lepton appears to be isolated (both referred to as a fake lepton). This background is estimated from data using the matrix method [61]. In this approach, a set of equations is solved, which relates the observed sample composition in terms of selected leptons of two different categories, loose and tight, to its true composition in terms of prompt (real) and fake leptons. The tight category corresponds to the signal selection mentioned in Section 3, while the isolation requirements are removed to define the loose category, which also has a loosened identification quality in the electron case. The real and fake efficiencies are measured using dedicated samples of data enriched in real and fake isolated leptons. An uncertainty of 50% on the multijet event yield is evaluated from comparisons with alternative procedures for the efficiency extraction and alternative criteria for the selection of the real- and fake-enriched samples.

The modelling of the backgrounds is validated by comparing the expected event distributions to the data in two control regions. The first control sample is defined by requiring both jets to pass a relaxed b-tagging selection with an efficiency of 80%, while requiring at least one of them to fail the tighter 70% b-tagging selection used for the signal selection. The dominant contribution, which comes from the W + jets process, is expected to represent 56% of the events while the expected signal-to-background ratio is lower than 1%. The second control sample is selected by requiring two jets that are not b-tagged in addition to the two signal b-jets. This control region is dominated by $t\bar{t}$ events (around 90% of the total) with a negligible s-channel single top contribution. For both control selections, the threshold on the W boson transverse mass is lowered to 30 GeV and the selection on the p_{T} of the b-jet associated with the best top-quark candidate is not applied. Good overall agreement between data and expectation is observed in both control regions.

6. Multivariate analysis

After event selection, the estimated signal-to-background ratio is about 3%. To improve the separation of s-channel single top events from backgrounds, several kinematic and topological variables are combined into one discriminant through a multivariate classification technique. The event classification is based on boosted decision trees (BDTs) [62] in the TMVA framework [63].

Nineteen variables with significant separation power are used as input to the BDT classifier. The number of variables is chosen in order to maximize the expected signal significance and all of the retained variables are well modelled by simulation in the sig-

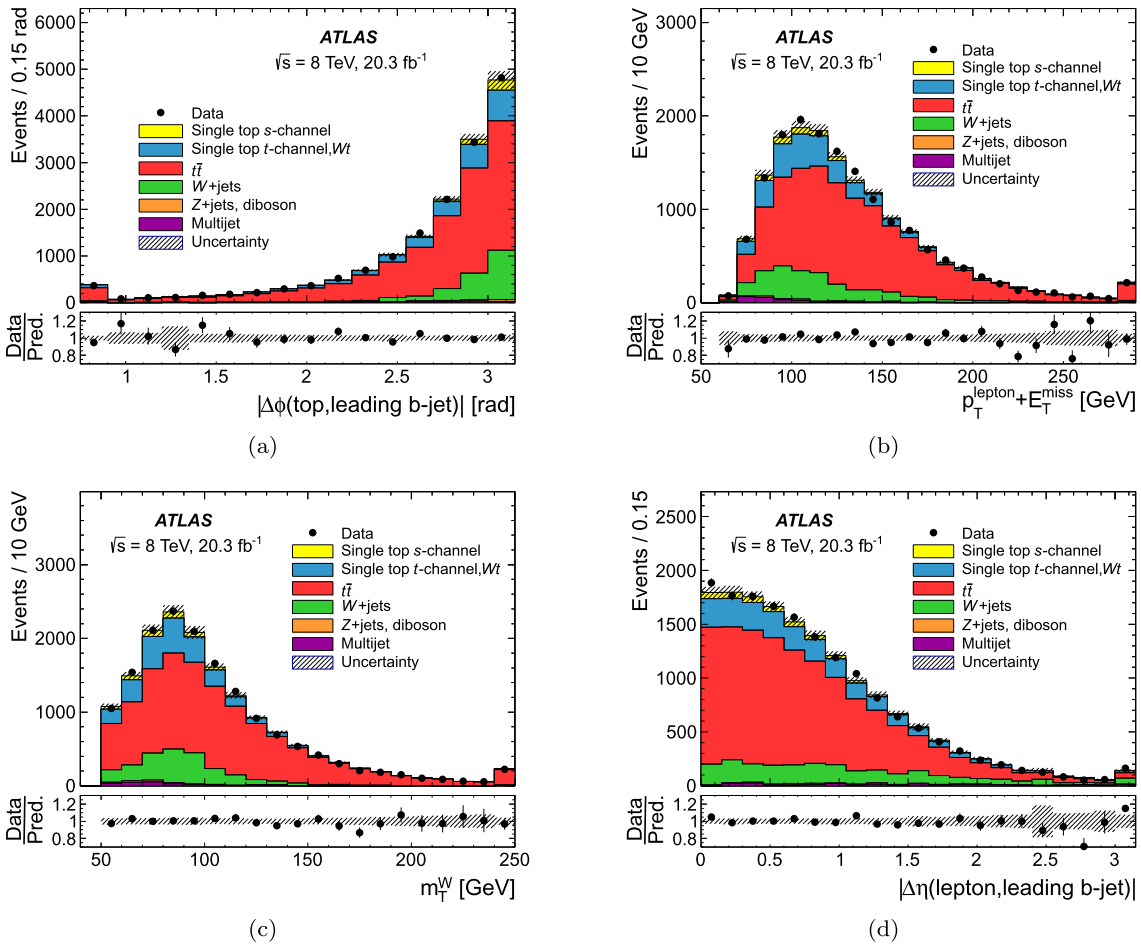

Fig. 1. Observed and predicted distributions in the signal region of four of the most discriminating variables used in the BDT classifier (a) azimuthal angle between the leading b-jet and the top-quark candidate reconstructed with the sub-leading b-jet, (b) scalar sum of the lepton momentum and the missing transverse momentum, (c) W boson transverse mass, and (d) difference in pseudorapidity between the lepton and the leading b-jet. The simulated distributions are normalized to the result of the binned maximum-likelihood fit described in Section 8. The hatched bands represent the normalization uncertainty of all processes after the fit added in quadrature with the simulation statistical uncertainty. The lower panels show the ratio of data to prediction. The first (last) bin of the histograms includes underflows (overflows).

nal region and in the two control regions defined in Section 5. The two most discriminating variables are the differences in azimuthal angle ($|\Delta\phi|$) between the leading (sub-leading) b-jet and the top-quark candidate reconstructed with the sub-leading (leading) b-jet. The four next-most important variables are the scalar sum of the lepton p_{T} and $E_{\mathrm{T}}^{\mathrm{miss}}$, $E_{\mathrm{T}}^{\mathrm{miss}}$, the W boson transverse mass, and the lepton p_{T}. The other variables, which have a smaller discriminating power, are (grouped according to their type): (i) the differences in pseudorapidity ($|\Delta\eta|$) between the lepton and the leading (sub-leading) b-jet, the $|\Delta\eta|$ between the leading b-jet and the top-quark candidate reconstructed with the sub-leading b-jet, the $|\Delta\eta|$ between the reconstructed neutrino and the b-jet not associated with the best top-quark candidate, (ii) the $|\Delta\phi|$ between the lepton and the missing transverse momentum, the $|\Delta\phi|$ between the two b-jets, (iii) the scalar sum of the p_{T} of all objects (lepton, b-jets, neutrino), the magnitude of the vector sum of the p_{T} of the two b-jets, the invariant mass of the two b-jets, and (iv) the cosine of the angle ($\cos\vartheta$) between the missing transverse momentum and the sub-leading b-jet, the $\cos\vartheta$ between the lepton in the W rest frame and the W boson in the top-quark candidate rest frame reconstructed with the leading b-jet, the $\cos\vartheta$ between the lepton in the top-quark candidate rest frame and the top-quark candidate reconstructed with the leading (sub-leading) b-jet in the centre-of-mass frame defined with all objects.

The multivariate classifier is trained using simulated events selected with relaxed criteria: the threshold on the W boson transverse mass is lowered to 30 GeV and the selection on the transverse momentum of the b-jet associated with the best top-quark candidate is not applied. The classifier response is tuned with the gradient boosting algorithm [63] and with only the $t\bar{t}$ and W + heavy-flavour background contributions included in the training phase.

Fig. 1 shows the comparison between data and prediction for four of the main discriminating variables used as input to the BDT classifier. The observed and expected distributions of the BDT response are presented in Fig. 2. The observed and expected signal distributions of the BDT response are shown in Fig. 3; the former is obtained by subtracting the background contributions from the data. The simulated distributions are normalized to the result of the binned maximum-likelihood fit performed to extract the signal content from the observed distribution (see Section 8). The t-channel and Wt single top contributions as well as the Z + jets and diboson components are merged.

7. Systematic uncertainties

Several sources of systematic uncertainty affect the signal acceptance and the background normalizations, as well as the shape of the BDT distribution. The impact on the distribution of using

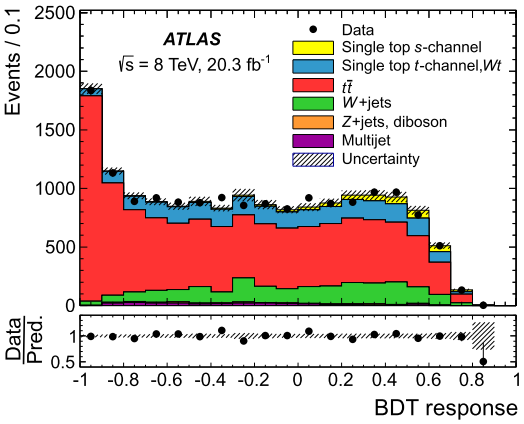

Fig. 2. Observed and predicted distributions of the BDT response. The simulated distributions are normalized to the result of the binned maximum-likelihood fit. The hatched band represents the normalization uncertainty of all processes after the fit added in quadrature with the simulation statistical uncertainty. The lower panel shows the ratio of data to prediction.

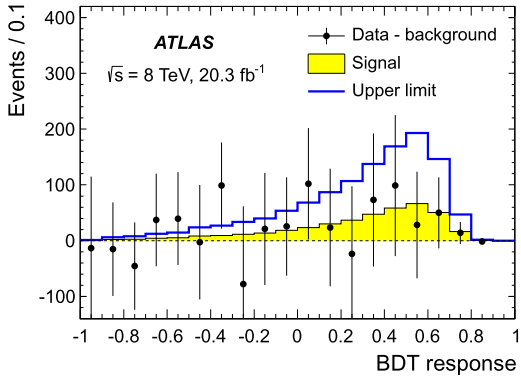

Fig. 3. Observed and predicted (filled histogram) signal distributions of the BDT response after background subtraction. The signal and subtracted simulated background contributions are normalized to the result of the binned maximum-likelihood fit. The error bars represent the statistical uncertainty of the data added in quadrature with the simulation statistical uncertainties and with the systematic uncertainties on the background normalizations described in Section 7. The empty histogram represents the predicted signal distribution renormalized to the observed cross-section upper limit reported in Section 9.

simulation samples of limited size is also taken into account. The various sources of systematic uncertainties considered when extracting the s-channel single top signal are described below.

Systematic uncertainties on the reconstruction and energy calibration of jets, electrons and muons are propagated in the analysis through variations in the modelling of the detector response. For the jets, the main source of uncertainty is the energy scale, evaluated using a combination of in situ techniques [27]. Other jet-related uncertainty sources are the modelling of the energy resolution [64] and reconstruction efficiency [27], and the modelling of the tagging efficiencies of b-jets, c-jets and light-quark jets [28,29]. Uncertainties related to the leptons come from trigger, identification and isolation efficiencies, as well as from the energy scale and resolution [21,23]. The uncertainties from the energy scale and resolution corrections applied to leptons and jets are propagated to the computation of the missing transverse momentum. The scale and resolution uncertainties due to soft jets ($p_{\mathrm{T}} < 20$ GeV) and to contributions of calorimeter energy deposits not associated with any reconstructed objects are also considered and evaluated independently (uncertainties referred to as $E_{\mathrm{T}}^{\mathrm{miss}}$ scale and resolution).

The luminosity measurement is calibrated using dedicated beam-separation scans and the same methodology as that detailed in Ref. [20]. The resulting uncertainty on the integrated luminosity is 2.8%.

Systematic uncertainties on the simulation of the signal and background processes ($t\bar{t}$, t-channel single top, Wt and $W+$jets) are also taken into account in the analysis. They include contributions from the modelling of the hard process, parton showers and hadronization and of initial-state and final-state radiation (ISR/FSR). The uncertainty due to the choice of renormalization and factorization scales is also considered for the signal. These various uncertainties are estimated by comparing simulation samples produced, as described in Section 4, with different generators, different shower models and different settings for the amount of additional radiation ($t\bar{t}$) or for the scales (s-channel).

The systematic uncertainties associated with the PDFs are taken into account for all simulated samples. They are assessed according to the PDF4LHC prescription [65] and using the MSTW2008 [18], CT10 [32], and NNPDF2.1 [66] sets.

Other sources of uncertainty are related to the background normalizations, which are taken from the theory predictions with their associated uncertainties, except for the multijet production for which a data-driven normalization is used. Theoretical uncertainties of 6% and 5% are considered for $t\bar{t}$ and for the combination of the t-channel and Wt single top contributions, respectively. For $t\bar{t}$, the PDF and α_{S} uncertainties, calculated using the PDF4LHC prescription [65] with the MSTW2008 NNLO [18,67], CT10 NNLO [32,68] and NNPDF2.3 5f FFN [66] PDF sets, are added in quadrature to the QCD scale uncertainty. The normalization uncertainties for the $W+$jets and for the combined $Z+$jets and diboson backgrounds are estimated to be 60%; they include an estimate of the uncertainty on the heavy-flavour fraction of 50%, added in quadrature with a theory uncertainty of 5% for the inclusive process, and a Berends scaling uncertainty of 24% for each extra jet [69,70]. For multijet events, a normalization uncertainty of 50% is estimated (see Section 5). The theoretical uncertainty of 4% on the s-channel single-top cross-section is considered when evaluating the signal significance.

8. Signal extraction

The signal contribution to the selected sample of data is extracted by performing a binned maximum-likelihood fit to the BDT output distribution. The likelihood function is given by the product of Poisson probability terms for the individual distribution bins (see Ref. [12]), combined with the product of Gaussian functions to constrain the background rates to their predicted values within the associated uncertainties. The rates of the $t\bar{t}$, $W+$jets, and combined t-channel/Wt and $Z+$jets/diboson backgrounds are thus fitted within their theoretical uncertainties described in Section 7; since the multijet component is obtained from the data it is not allowed to vary and is fixed to its data-driven estimate. The production cross-section is derived from the adjusted signal rate for which the logarithm of the likelihood function reaches its maximum.

The systematic uncertainties on the measurement are determined using pseudo-experiments involving variations of the signal and background rates and of the shape of the BDT distributions, due to all the sources of uncertainty described in Section 7. The uncertainties due to the limited size of the data and simulation samples are also assessed via pseudo-experiments implementing statistical fluctuations. The impact of an individual source of uncertainty is evaluated by running dedicated pseudo-experiments with only the corresponding variation included. The total uncertainty is evaluated from pseudo-experiments including all variations simultaneously.

Table 2
Contributions of the sources of statistical and systematic uncertainty to the total uncertainty on the measured cross-section. They are given in percent.

Source	$\Delta\sigma/\sigma$ [%]
Data statistics	±35
Simulation statistics	±29
$E_{\mathrm{T}}^{\mathrm{miss}}$ scale	±54
$E_{\mathrm{T}}^{\mathrm{miss}}$ resolution	+0/−3
Jet energy scale	±39
Jet energy resolution	±5
Jet tagging efficiencies	±4
Jet reconstruction efficiency	<1
Lepton energy scale/resolution	<1
Lepton efficiencies	+2/−1
Signal modelling and scale	±11
$t\bar{t}$ modelling	±6
W + jets shape modelling	±8
ISR/FSR	±3
PDF	<1
Background normalization	±7
Multijet normalization	±12
Integrated luminosity	±5
Total systematic	±80
Total	±87

The sensitivity to the s-channel single top signal is determined by testing both the background-only and the signal-plus-background hypotheses via the generation of dedicated sets of pseudo-experiments; in the second case, the signal yield is set to the approximate NNLO prediction. A test statistic, defined as the logarithm of the ratio combining the maximum-likelihood estimates of the two alternative hypotheses, is computed for each pseudo-experiment. The test statistic distribution is used to derive the p-value of the background-only ensemble test, which is then interpreted in terms of signal significance. A cross-section upper limit is extracted using the CLs procedure [71,72], which is based on the p-values calculated for both the background-only and the signal-plus-background ensemble tests.

9. Results

Using the frequentist approach presented above, the observed (expected) significance of the s-channel single top measurement is found to be 1.3 (1.4) standard deviations and an observed (expected) upper limit on the production cross-section of 14.6 pb (15.7 pb, 9.4 pb) is set at the 95% confidence level. The two quoted expected upper limits correspond to the signal-plus-background and background-only hypotheses, respectively. The simulated BDT distribution of the signal events renormalized to the observed upper limit is presented in Fig. 3 for comparison with the signal distribution extracted from the data.

The fitted value of the cross-section is found to be: $\sigma_s = 5.0 \pm 1.7\ (\mathrm{stat.}) \pm 4.0\ (\mathrm{syst.})\ \mathrm{pb} = 5.0 \pm 4.3\ \mathrm{pb}$; this measurement should be compared with the cross-section of 5.61 ± 0.22 pb calculated at approximate NNLO. Table 2 summarizes the various contributions to the measurement uncertainty. The largest systematic uncertainties arise from the scale of the missing transverse momentum (54%) and of the jet energy (39%). These large uncertainties are due to a strongly distorted shape of the BDT distribution obtained when adding bin-per-bin the systematic variations affecting the signal and background contributions. The limited size of the data sample and the simulated samples also contribute significantly to the final uncertainty (35% and 29%, respectively). Smaller uncertainties are due to the background normalizations (12% for the data-driven multijet contribution and 7% from theory for the simulated backgrounds) and process modelling (11%, 8% and 6% for signal, W + jets and $t\bar{t}$, respectively). Other modelling and instrumental effects play only a minor role.

10. Summary

This Letter presents a search for s-channel single top production at the LHC from the pp collision data sample of 20.3 fb^{-1} recorded by the ATLAS detector at a centre-of-mass energy of 8 TeV. A multivariate analysis, based on boosted decision trees, is carried out to discriminate signal from background events. The observed signal significance is 1.3 standard deviations, the expected sensitivity being 1.4 standard deviations. The observed upper limit on the s-channel single top cross-section is 14.6 pb at the 95% confidence level. The evaluated production cross-section is $\sigma_s = 5.0 \pm 1.7\ (\mathrm{stat.}) \pm 4.0\ (\mathrm{syst.})\ \mathrm{pb} = 5.0 \pm 4.3\ \mathrm{pb}$ and it is consistent with the Standard Model prediction.

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