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Search for same-sign top-quark production and fourth-generation down-type quarks in pp collisions at $\sqrt{s} = 7$ TeV with the ATLAS detector

The ATLAS collaboration

ABSTRACT: A search is presented for same-sign top-quark production and down-type heavy quarks of charge $-1/3$ in events with two isolated leptons (e or μ) that have the same electric charge, at least two jets and large missing transverse momentum. The data are selected from pp collisions at $\sqrt{s} = 7$ TeV recorded by the ATLAS detector and correspond to an integrated luminosity of 1.04 fb^{-1} . The observed data are consistent with expectations from Standard Model processes. Upper limits are set at 95% confidence level on the cross section of new sources of same-sign top-quark pair production of 1.4-2.0 pb depending on the assumed mediator mass. Upper limits are also set on the pair-production cross-section for new heavy down-type quarks; a lower limit of 450 GeV is set at 95% confidence level on the mass of heavy down-type quarks under the assumption that they decay 100% of the time to Wt .

KEYWORDS: Hadron-Hadron Scattering

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1 Introduction

The Standard Model (SM) of the electroweak and strong interactions is extremely successful in explaining most of the measurements in particle physics at energies accessible today. Its predicted behaviour at high energies, however, presents some theoretical problems which have motivated a large variety of theories encompassing and extending it. Due to the large variety of models proposed, signature-based searches are often useful when exploring the consequences of these theories in an economical way. In hadron collisions it is useful to group final states by the number of charged leptons (electrons or muons). Within this classification, a signal with two leptons of the same electric charge (same-sign leptons) is

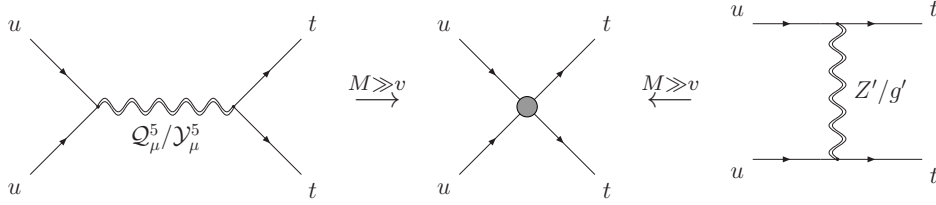


Figure 1. Production of same-sign top-quark pairs via the production of a heavy vector boson (such as color-triplet Q_μ^5 or color-sextet Y_μ^5 [17]) in the s -channel (left) or exchange of a heavy vector boson (such as Z' or g') in the t -channel (right). For large resonance masses, both cases can be described by a four-fermion interaction (middle).

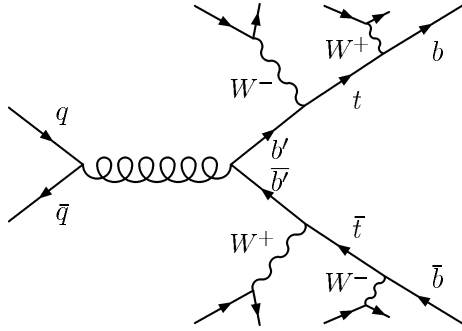


Figure 2. Pair production and decay of heavy quarks with decays to $W^+W^-\bar{b}W^-W^+b$.

interesting since it has a low background rate in the Standard Model, and potentially large contributions from new theories, for example new flavour-changing Z' bosons, proposed [1] to explain the forward-backward asymmetry (A_{FB}) measured at the Tevatron [2, 3], or new heavy quarks [4, 5].

In this paper we present a search for events characterised by two isolated same-sign leptons in association with at least two jets and large missing transverse momentum (E_T^{miss}). Two specific signal processes are considered, same-sign top-quark production [6–8] and pair production of down-type heavy quarks of charge $-1/3$ [9]. Feynman diagrams of these processes are shown in figures 1 and 2, respectively. The $uu \rightarrow tt$ process illustrated in figure 1 can be mediated at the tree level by the exchange of a s -channel resonance (left), or a t -channel resonance (right). In the case of new vector bosons exchanged in the s -channel, the new particle must be a colour-triplet or colour-sextet (respectively labelled as Q_μ^5 , Y_μ^5) with charge $4/3$, while for t -channel exchange it can be a colour-singlet Z' or colour-octet g' , both with zero charge. For resonance masses m much larger than the electroweak symmetry breaking scale v and the typical energy scales in the process, all these cases can be described by a gauge-invariant effective four-fermion interaction, as shown in figure 1 (middle). For the heavy quark search, a specific model in which the heavy quark is a fourth-generation chiral quark is taken as representative and referred to as b' . The search uses data recorded by the ATLAS detector from pp collisions at a centre-of-mass energy of $\sqrt{s} = 7$ TeV produced by the Large Hadron Collider (LHC) with an integrated luminosity of $1.04 \pm 0.04 \text{ fb}^{-1}$ [10, 11].

The CMS and CDF Collaborations searched for fourth-generation down-type quarks with same-sign leptons using 34 pb^{-1} of pp collisions [12] and 2.7 fb^{-1} of $p\bar{p}$ collisions [13], respectively. They set lower mass limits of 361 GeV and 338 GeV, respectively, at 95% confidence level. The ATLAS and CDF Collaborations searched for fourth-generation down-type quarks in single-lepton events with many jets using 1.1 fb^{-1} of pp collisions [14] and 4.8 fb^{-1} of $p\bar{p}$ collisions [15], respectively. They set lower mass limits of 480 GeV and 372 GeV, respectively, at 95% confidence level.

In this analysis, the data are found to be consistent with SM expectations, and upper limits on the same-sign top quark production cross section are presented. These limits are interpreted as constraints on the coefficients for a set of dimension-six effective operators [16] that can be used to parameterise same-sign top-quark production as four-fermion contact interactions. Limits on these coefficients are translated into limits on a wide range of SM extensions mediating same-sign top-quark production at the tree level [17], assuming that the new particles are heavy, which is consistent with the non-observation of an excess over the SM prediction. Limits are also obtained for the specific case of light flavour-changing Z' bosons [1]. Additionally, upper limits are placed on the cross section of pair production of b' , and a lower limit on the heavy quark mass is presented.

2 The ATLAS detector

The ATLAS detector [18] is a multipurpose detector with precision tracking, calorimetry and muon spectrometry. The transverse momenta (p_T) of charged particles with pseudorapidity $|\eta| < 2.5^1$ are measured by the inner detector (ID), which is a combination of a silicon pixel detector, a silicon microstrip detector and a straw-tube detector. The ID operates in a uniform 2 tesla magnetic field. Measurements from the pixel detector enable precise determination of production vertices. Electromagnetic calorimetry for electron, photon, and jet reconstruction is provided by a high granularity, three layer depth-sampling liquid-argon (LAr) detector with lead absorbers in the region $|\eta| < 3.2$. Jet reconstruction also uses hadron calorimetry provided by a scintillating tile detector with iron absorbers in the central region for $|\eta| < 1.7$, and a LAr active-medium sampling calorimeter for $1.5 < |\eta| < 4.9$. A presampler detector is used to correct for energy losses by electrons and photons in material in front of the calorimeter for $|\eta| < 1.8$.

Muons are detected with a multi-system muon spectrometer (MS). Precision measurements of the track coordinates are provided by monitored drift tubes over most of the η range. These are supplemented by cathode-strip chambers measuring both the η and ϕ coordinates for $2.0 < |\eta| < 2.7$ in the innermost endcap muon station. Fast measurements required for initiating trigger logic are provided by resistive-plate chambers for $|\eta| < 1.05$, and beyond that by thin-gap chambers for $|\eta| < 2.4$. The muon detectors operate in a

¹ATLAS uses a right-handed system with its origin at the nominal interaction point (IP) in the center of the detector and the z -axis along the beam pipe. The x -axis points from the IP to the center of the LHC ring, and the y -axis points upward. Cylindrical coordinates (r, ϕ) are used in the transverse plane, ϕ being the azimuthal angle around the beam pipe. The pseudorapidity is defined in terms of the polar angle θ as $\eta = -\ln \tan(\theta/2)$. Distances in $\eta - \phi$ space are given as $\Delta R = \sqrt{\Delta\phi^2 + \Delta\eta^2}$.

non-uniform magnetic field generated by three superconducting air-core toroid magnetic systems with eight coils per toroid.

To trigger readout, full event reconstruction and event storage by the data acquisition system, electron candidates must have transverse energy greater than 20 GeV. They must satisfy shower-shape requirements and correspond to an ID track. Muon candidates must have transverse momentum greater than 18 GeV and a consistent trajectory reconstructed in the ID and muon spectrometer. The full trigger chain uses signals from all muon detectors. These triggers reach their efficiency plateau at lepton p_T thresholds of 20 GeV for muons and 25 GeV for electrons.

3 Data and Monte Carlo samples

3.1 Data sample

The data used in this search were collected by the ATLAS detector at the CERN LHC between March and June of 2011, using a single muon or electron trigger as described above. The data sample corresponds to an integrated luminosity of $1.04 \pm 0.04 \text{ fb}^{-1}$ [10, 11].

3.2 Monte Carlo samples

Monte Carlo simulation samples have been used to develop and validate the analysis procedures, calculate the acceptance for signal events and to evaluate the contributions from some background processes. The ATLAS software [19] uses GEANT4 [20] to simulate the detector response.

In order to describe properly the effects of multiple proton-proton interactions per bunch crossing, the Monte Carlo samples contain multiple interactions per beam-crossing, weighted to match the data. Except where specifically noted, all simulated samples are generated with the CTEQ6L1 [21] parton distribution functions (PDF). Simulated samples of same-sign top-quark production with dileptonic decay have been generated by PROTOS [16], accurate to leading order (LO) in QCD, with showering and hadronisation performed by PYTHIA [22]. Samples have been generated for each of the three possible chirality configurations (left-left, left-right, right-right).

Simulated samples of heavy down-type quark pair production and decay have been generated by PYTHIA using the MRST2007 LO* PDF set [23] for several mass values, between 300 and 600 GeV; the cross section is normalized to NNLO [24].

Several background processes contribute to the final state of same-sign leptons with associated jets. The largest backgrounds (including top-quark pair production, W +jets and single top quark production) are estimated from data, as described in detail below (thereafter referred to as ‘data-driven’). Additional background estimates are described using simulated Monte Carlo samples as listed here:

- Di-boson production ($W^\pm W^\mp$, WZ , ZZ) was generated using ALPGEN [25] to explicitly account for hard emission of up to two partons and HERWIG [26, 27] to describe soft emission, showering and hadronisation. The cross sections are normalised to next-to-leading-order (NLO) theoretical calculations [28].

- $t\bar{t}+W$, $t\bar{t}+Z$, $t\bar{t}+W+\text{jet}$, $t\bar{t}+Z+\text{jet}$, $t\bar{t}+W^\pm W^\mp$, $W^\pm W^\pm+2$ jets were generated with MADGRAPH [29], and showered and hadronised with PYTHIA. These are normalised to LO theoretical calculations [29].

4 Object reconstruction

Electrons are found by a calorimeter-seeded reconstruction algorithm and are matched to a track. They are required to satisfy $E_T = E_{\text{cluster}}/\cosh(\eta_{\text{track}}) > 25$ GeV (where ‘cluster’ refers to the calorimeter electron cluster) in a pseudorapidity range $|\eta_{\text{cluster}}| < 2.47$ but excluding the transition region between the barrel and endcap calorimeters covering $1.37 < |\eta_{\text{cluster}}| < 1.52$. We require a ‘tight’ electron selection [30]. Electrons must also satisfy calorimeter isolation: the difference between the transverse energy deposited inside a cone of size $\Delta R = \sqrt{\Delta\phi^2 + \Delta\eta^2} = 0.2$ around the electron direction and the electron transverse energy has to be lower than 3.5 GeV.

Muons are found with an algorithm which requires that tracks reconstructed in the muon spectrometer match a track in the inner detector [31]. We apply a loose cosmic ray rejection by removing all back-to-back muon pairs ($\Delta\phi(\mu_1, \mu_2) > 3.1$) whose transverse impact parameter with respect to the beam spot is greater than 0.5 mm. Muon candidates must satisfy $p_T > 20$ GeV and $|\eta| < 2.5$. We also require that the muons are isolated. An η - ϕ cone of $\Delta R = 0.3$ about the muon direction must contain less than 4 GeV of additional energy in the calorimeter and less than 4 GeV from additional tracks. Finally, we remove all muons within an η - ϕ cone of $\Delta R = 0.4$ of any jet with $p_T > 20$ GeV.

Jets [32] are reconstructed from topological clusters of calorimeter energy deposits [33] using the anti- k_t algorithm [34] with a radius parameter equal to 0.4. A jet energy scale (JES) correction is applied to account for the energy response and non-uniformity of the EM and hadronic calorimeters. Jets are required to satisfy $p_T > 20$ GeV and $|\eta| < 2.5$. Jets overlapping with selected electrons within an η - ϕ cone of $\Delta R = 0.2$ are removed. During part of the data-taking period, data from a small portion of the LAr electromagnetic calorimeter was not read out due to a technical problem; this results in a signal efficiency loss of 10-15%, depending on jet multiplicity.

Missing transverse momentum (E_T^{miss}) is constructed from the vector sum of topological calorimeter cluster deposits, projected in the transverse plane [35]. Deposits associated with selected jets or electrons are corrected to the energy scale appropriate for jets or electrons, respectively. Muons are included in the E_T^{miss} calculation after a correction for the muon contribution to calorimeter energy deposits. All other energy deposits with $|\eta| < 4.5$ and not associated with leptons or jets contribute to the calculation of E_T^{miss} .

5 Event selection

In the mass range considered, where $m_{b'} > m_t + m_W$, each b' is assumed to decay exclusively to a top quark and a W boson, giving a signature of $t\bar{t}$ with two additional W bosons, as shown in figure 2. The signature for same-sign top-quark production is similar to $t\bar{t}$, but with two positive leptons in the final state from top-quark decay due to the asymmetric

charge of the pp collisions. In this analysis, the final state for both signatures must contain at least one lepton pair with the same electric charge, plus missing transverse momentum from neutrinos, and a large jet multiplicity.

Events are selected that satisfy the following requirements:

- Events must contain a primary vertex, consistent with the beam spot position, determined with at least five tracks, each with $p_T > 0.4$ GeV;
- Events must contain at least two leptons with the same electric charge, each within $|\eta| < 2.5$. Muons must have $p_T > 20$ GeV and electrons must have $E_T > 25$ GeV. In events with more than one same-sign pair, the pairs are sorted according to the leading lepton p_T , then by the subleading lepton p_T . The first pair is chosen;
- In the ee or $\mu\mu$ channel, the invariant mass of the two leptons must exceed 15 GeV and not be in the Z -boson mass window: $|m_{\ell\ell} - m_Z| > 10$ GeV;
- Events must contain at least two jets, each with $p_T > 20$ GeV and $|\eta| < 2.5$;
- The magnitude of the missing transverse momentum must be greater than 40 GeV;
- Three signal regions are defined, as follows.
 - For a heavy down-type quark, and for same-sign top quarks produced from high-mass Z' exchange, the scalar sum H_T of the transverse energy of the selected leptons and jets must exceed 350 GeV. This cut has been optimised in order to reach the maximum sensitivity with $m_{b'}$ = 400 GeV (close to previous exclusion limits) and for same-sign top quarks produced from high-mass Z' exchange. Including both lepton charge configurations, we refer to this as the ‘heavy-quark signal region’.
 - When applied to searches for same-sign top-quarks, the events are required to satisfy all the requirements of the heavy-quark signal region, but including only events with positively-charged leptons, as the pp initial state of the LHC gives predominantly positively-charged top quarks; we refer to this as the ‘same-sign top-quark signal region’.
 - For same-sign top quarks produced from low-mass Z' exchange, the signal region is optimised by requiring positively-charged leptons, $H_T > 150$ GeV and invariant mass of the lepton pair $m_{\ell\ell} > 100$ GeV; we refer to this as the ‘low-mass Z' boson signal region’.

The efficiencies of the event selection for heavy-quark and same-sign top-quark events are given in table 1.

6 Standard model backgrounds

In the SM, events with the same-sign dilepton signature are due to three categories of processes:

Heavy-quark and same-sign top-quark signal regions		
	$\ell^+\ell^+$ and $\ell^-\ell^-$	
$b'_{m_{b'}=350 \text{ GeV}}$	2.0%	
$b'_{m_{b'}=450 \text{ GeV}}$	2.5%	
$b'_{m_{b'}=550 \text{ GeV}}$	2.7%	
	$\ell^+\ell^+$	$\ell^-\ell^-$
tt_{LL}	0.7%	negligible
tt_{LR}	0.8%	negligible
tt_{RR}	0.8%	negligible
Low-mass Z' boson signal region		
$tt_{RR,m_{Z'}=100 \text{ GeV}}$	0.7%	negligible
$tt_{RR,m_{Z'}=150 \text{ GeV}}$	0.8%	negligible
$tt_{RR,m_{Z'}=200 \text{ GeV}}$	1.0%	negligible

Table 1. Efficiencies of the event selection for heavy-quark and same-sign top-quark events in the heavy-quark signal region (two same-sign leptons, at least two jets, and $E_T^{\text{miss}} > 40 \text{ GeV}$ and $H_T > 350 \text{ GeV}$) as well as efficiencies of the event selection for same-sign top-quark events via a low-mass Z' boson in the low-mass Z' boson signal region (two same-sign leptons, at least two jets, $E_T^{\text{miss}} > 40 \text{ GeV}$, $H_T > 150 \text{ GeV}$ and $m_{\ell\ell} > 100 \text{ GeV}$). Efficiencies are relative to the total cross section, and so include the effect of branching ratios (4.5% for tt and 9% for b' , without including $W \rightarrow \tau\nu$ contributions) as well as acceptance. Statistical uncertainty is 0.01% for tt and 0.05% for b' .

- those in which one lepton originates from a jet or from a photon conversion,
- those with an opposite-sign dilepton pair in which the reconstructed charge of one lepton is mismeasured, and
- those that originate from a pair of Z/W gauge bosons.

The diboson contribution is estimated using simulated samples, and the remaining backgrounds are estimated by extrapolation from control samples selected in the data as described in the following sections.

6.1 Backgrounds with leptons originating from jets or photons

A significant SM background source is due to events in which one of the two leptons comes from the decay of a W or Z boson (called ‘real’ below) and the second is a ‘fake’ lepton, a jet or photon misreconstructed as an isolated lepton. Here ‘fake’ is used to indicate both non-prompt leptons and misidentified π^0 s, conversions, etc.

The dominant fake-lepton mechanism is the semi-leptonic decay of a b - or c -hadron, in which a muon survives the isolation requirements. In the case of electrons, the three mechanisms are b - or c -hadron decay, light flavour jets with a leading π^0 overlapping with a charged particle, and conversion of photons. Processes that contribute are opposite-sign top-quark pair production, production of W bosons in association with jets and multi-jet production.

The ‘matrix method’ [36] is applied to estimate the fraction of events in the signal regions that contains at least one fake lepton. A selection is defined to isolate lepton-like jets and used to count the number of observed dilepton events with zero, one or two selected leptons (‘L’) together with two, one or zero lepton-like jets (‘J’), respectively ($N_{JJ}, N_{LJ}, N_{JL}, N_{LL}$). The categories N_{LJ} and N_{JL} are distinguished by p_T -ordering.

Two probabilities are defined and measured: r and f , the probabilities that real or fake leptons, respectively, which satisfy the lepton-like jet selection also satisfy the final lepton selection requirements. Using r and f , linear expressions are obtained for the observed yields as a function of the number of events with zero, one and two real leptons (‘R’) together with two, one and zero fake leptons (‘F’), respectively ($N_{FF}, N_{RF}, N_{FR}, N_{RR}$, respectively). These linear expressions form a matrix that is inverted in order to extract the real and fake content of the selected dilepton event sample. The categories N_{RF} and N_{FR} are distinguished by p_T -ordering.

For muons, lepton-like jets are found by removing the three isolation requirements: calorimeter, track and jet isolation as described above. For electrons, lepton-like jets are found by removing the requirement on the electron isolation and the quality of the associated ID track.

The probability for real leptons r is measured in samples of opposite-sign dielectron and dimuon events, with one selected lepton and one lepton-like jet, which are dominated by $Z \rightarrow \ell\ell$ decays. The requirement $86 \text{ GeV} < m_{\ell+\ell^-} < 96 \text{ GeV}$ is applied to achieve a high purity.

The corresponding probability for fake leptons f is measured in data from a sample of single-lepton candidate events dominated by multi-jet production, where contributions from real leptons are suppressed using kinematic requirements. The probability f is found to decrease significantly with rising lepton p_T or event H_T , and is therefore parameterised in these variables [37].

The value of the probability f is found to be substantially different in samples with and without a large heavy-flavour contribution. If the heavy-flavour fraction in the signal region is different from the control region, using the value of f from the control region would lead to a biased estimate of the fake-lepton contribution in the signal regions. Instead, individual jets are assigned either a heavy-flavour probability (f_{HF}) or a light-flavour probability (f_{LF}) based on a standard heavy-flavour tagging algorithm which identifies jets with tracks which have large impact parameter significance [38]. This algorithm correctly identifies 90% of heavy-flavour jets and misidentifies 50% of light-flavour jets in $t\bar{t}$ simulated events. The probability f_{HF} is measured in samples of heavy-flavour jets, selected using the same tagging algorithm with a stricter requirement. The probability f_{LF} is measured in a sample of jets constructed by requiring small impact parameter significance.

6.2 Background from charge misidentification

Events in which a pair of opposite-sign leptons are produced may be reconstructed as a pair of same-sign leptons if a lepton charge is misidentified. This is referred to as ‘charge flip’ in the plots and the tables.

For electrons, the dominant mechanism is hard bremsstrahlung, producing a photon which carries a large fraction of the electron momentum and then converts asymmetrically, giving most of its momentum to an electron of the opposite charge. Processes susceptible to this effect are those with opposite-sign electrons, such as $Z/\gamma^* \rightarrow e^+e^-$ (including $Z/\gamma^* \rightarrow \tau^+\tau^- \rightarrow e^+e^- + 4\nu$) and $t\bar{t}$ dileptonic decays with at least one electron. For both electrons and muons, misidentification of the charge may occur due to misreconstruction of the ID track. For muons, the requirement that the measured charges in the ID and MS agree reduces this to negligible levels in the range of p_T found in the sample.

The charge-flip rate for electrons is derived as a function of electron η from the rate of same-sign and opposite-sign electron pairs in events with $m_{\ell\ell} \in [81, 101]$ GeV. This rate is then applied to events with an opposite-sign ee or $e\mu$ pair to model the charge-flip contribution to the same-sign sample.

A fraction of the charge-flip electron background is included in the data-driven estimate of the fake lepton events described above. However, studies of Z events show that electron charge-flips are well modeled using the weighted opposite-sign lepton pair events as described here. To avoid double counting, the overlap is removed from the fake-lepton background prediction. The charge-flip overlap fraction is measured by normalizing the prediction to the observed same-sign dilepton peak from $Z \rightarrow e^+e^-$ processes in events with $m_{\ell\ell} \in [81, 101]$ GeV and found to be $(23 \pm 3)\%$.

6.3 Backgrounds from processes with two electroweak bosons

True same-sign dilepton events are produced from SM diboson processes such as WZ or ZZ production. With a total cross section to same-sign leptons equal to 0.7 pb, small with respect to the expected b' or same-sign top-quark production, SM diboson events are a rare but irreducible background to new physics sources, since events with more than two leptons are not excluded by the selection. This category includes events from the processes $t\bar{t} + W$, $t\bar{t} + Z$, $t\bar{t} + W + \text{jet}$, $t\bar{t} + Z + \text{jet}$, $t\bar{t} + W^\pm W^\mp$, and $W^\pm W^\pm + 2$ jets, which together contribute 12-29% of the diboson background. The contribution to the selected sample is estimated using simulated events, as described above, and referred to as ‘real’ in plots and tables.

6.4 Background control regions

To validate the modeling of the SM backgrounds, two control regions are examined. Control regions are orthogonal to signal regions and defined by selections which suppress possible signal contributions.

The first control region inverts the charge selection, requiring a pair of opposite-sign leptons, at least two reconstructed jets and missing transverse momentum greater than 40 GeV. This region validates the lepton efficiencies and the modeling of the missing transverse momentum and H_T . Figure 3 shows the observed and expected missing transverse momentum and H_T distributions, which are in good agreement within uncertainties.

The second control region is used to validate modeling of the same-sign background sources, but in events with no reconstructed jets. Figure 4 shows the observed and expected missing transverse momentum and H_T distributions, which are in good agreement within uncertainties.

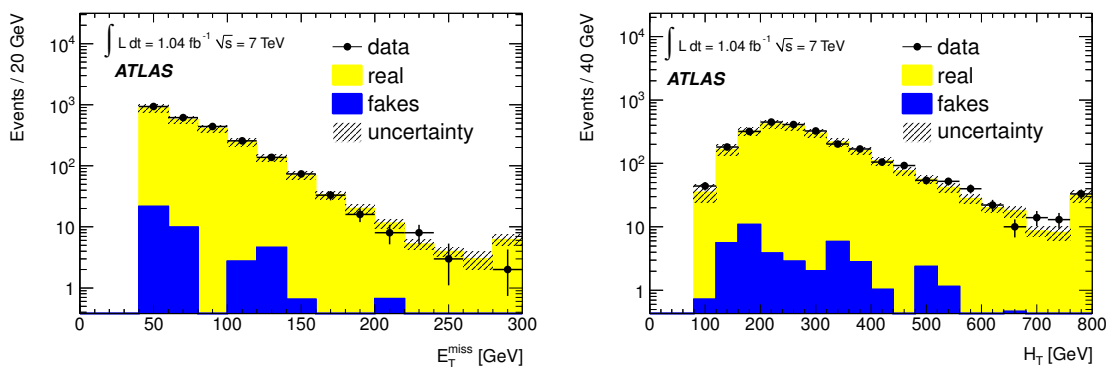


Figure 3. Comparison of observed data and expected SM backgrounds in events with a pair of opposite-sign leptons, at least two reconstructed jets and missing transverse momentum greater than 40 GeV. Distribution of missing transverse momentum (left) and H_T (right). Uncertainties (hatched) are systematic and statistical. The last bin includes overflow events.

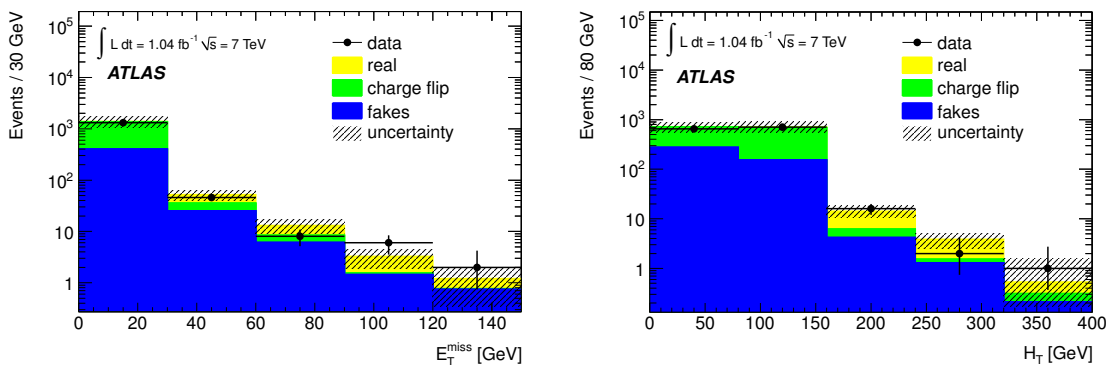


Figure 4. Comparison of observed data and expected SM backgrounds in events with a pair of same-sign leptons and no reconstructed jets; the invariant mass requirement is not made here. Distribution of missing transverse momentum (left) and H_T (right). Uncertainties (hatched) are systematic and statistical. The last bin includes overflow events.

7 Systematic uncertainties

Several sources of systematic uncertainties have been considered, and their estimates are summarised below.

- Object calibration and resolutions: Uncertainties in the jet [32] and lepton efficiency, energy or momentum calibration, and resolution lead to systematic uncertainties on the signal and background acceptances. There is also some uncertainty in estimating the effect of problems with the LAr calorimeter readout as described above. These uncertainties are summarised in table 2 for signal and background separately.
- Fake-lepton background: A 20%-70% uncertainty on the estimate of the fake lepton background is estimated from a combination of two sources. First, we vary the heavy-flavour tagging threshold defined in section 5 to modify the heavy-flavour iden-

tification efficiency within its uncertainties; the difference in the estimated fake-lepton background is taken as an uncertainty. Second, we compare the fake probability f measured from the simulated multijet samples to probabilities measured in $t\bar{t}$ and W boson+jets simulated samples; the difference in the probabilities is propagated to the fake-lepton background estimate.

- Charge-flip background: the uncertainty on the overall scale of the charge-flip background in the signal regions is derived from a comparison of the charge-flip rate extracted by several methods. All techniques use dielectron events with dilepton invariant mass close to the Z boson mass. The primary technique uses a maximum likelihood fit to extract the charge-flip rates in different kinematic regions simultaneously. An alternative method, tag-and-probe, identifies a tag electron in the low pseudorapidity region which satisfies strict track-matching requirements to ensure a negligible charge-flip rate; the probe electron is used to measure the charge-flip rate. In a third method, the rates for each region are derived from electron pairs in that region. The difference in the method results is used to estimate the systematic uncertainty, which is found to be 30% – 100%, increasing as a function of lepton $|\eta|$ and p_T .
- Uncertainties affecting the Monte Carlo backgrounds and signals: luminosity and Monte Carlo cross sections. The uncertainty on the measured luminosity from van der Meer scans was estimated to be 3.7% [10, 11]. Uncertainties on Monte Carlo cross sections depend on the process. The main source of systematic uncertainty on the production cross section originates from the diboson contribution. This uncertainty, which is nearly 100%, is estimated from the difference between the nominal sample described above and an alternative sample which uses HERWIG to model the generation and emission of hard partons.
- Initial and final state QCD radiation: parameters describing the level of radiation in the simulation are varied over a range consistent with experimental data [39]. In the signal regions, the corresponding uncertainty on the acceptance is 12.3% for the $t\bar{t}$ signal and 6.8% for the b' signal.
- Parton Distribution Functions: the uncertainty is evaluated using a range of current PDF sets [39]. In the signal regions, the uncertainty on the acceptance is 2.0% for both the $t\bar{t}$ and b' signals.

8 Results

Due to the charge of the initial state in pp collisions, the SM and same-sign top-quark expectation for positively- and negatively-charged pairs are not equal. This makes the negatively-charged pairs a control region for the same-sign top-quark signal. In both cases, the observed number of events agrees well with the SM expectation within uncertainties. Heavy down-type quarks are expected in both the positively- and negatively-charged samples.

Source	Uncertainty on tt acceptance (%)	Uncertainty on b' acceptance (%)	Uncertainty on background acceptance (%)
Jet energy scale	+1.7, -2.3	+0.5, -0.5	+7.1, -5.5
Jet energy resolution	+0.7, -0.8	+0.7, -0.8	+4.1, -4.2
Jet reconstruction efficiency	+0.1, -0.1	+0.1, -0.1	+0.1, -0.1
Electron energy scale	+0.5, -0.7	+0.2, -0.3	+1.1, -1.2
Electron energy resolution	+0.1, -0.3	+0.1, -0.1	+0.8, -0.8
Electron efficiency	+3.5, -4.2	+3.3, -4.9	+1.8, -2.0
Muon energy scale	+0.1, -0.1	+0.1, -0.1	+0.1, -0.1
Muon energy resolution	+0.2, -0.3	+0.1, -0.2	+0.6, -0.7
Muon efficiency	+4.7, -5.8	+4.3, -5.2	+2.3, -3.0
Missing transverse momentum	+0.8, -0.8	+0.8, -0.8	+0.9, -0.9
LAr calorimeter readout	+2.0, -3.0	+2.0, -3.0	+1.0, -2.0

Table 2. Sources of systematic uncertainties related to jet and lepton energy or momentum calibration and resolution, and their contributions to the uncertainty on signal (tt and b') and background acceptance. Lepton efficiencies include trigger, reconstruction and identification terms.

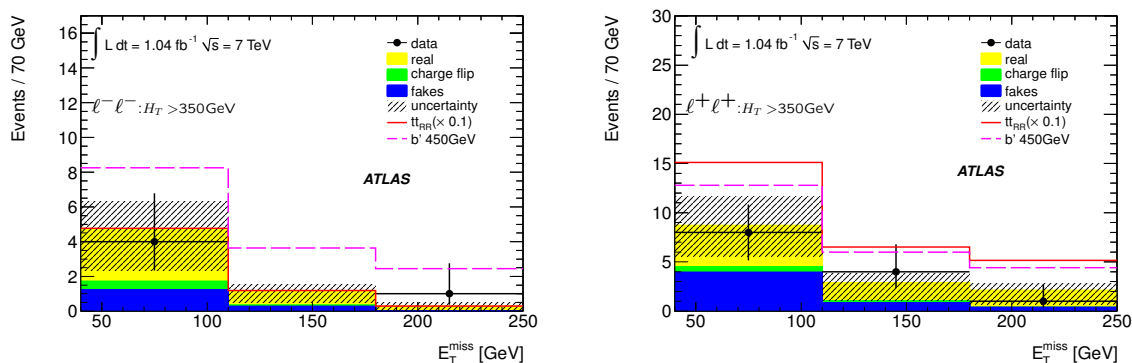


Figure 5. E_T^{miss} distribution: comparison of observed data and expected SM backgrounds for events with a pair of same-sign leptons, at least two reconstructed jets, $E_T^{\text{miss}} > 40$ GeV and $H_T > 350$ GeV. Left are negatively-charged lepton pairs, right are positively-charged lepton pairs. Uncertainties (hatched) are systematic and statistical. The last bin includes overflow events. tt_{RR} (scaled by 0.1 and assuming $C/\Lambda^2 = 1/\text{TeV}^2$, see eq. (9.1)) and b' signals include both signal and background.

In each of the three signal regions, the largest source of SM background is due to diboson production, followed by the fake lepton background. In table 3 (table 4) the expected and observed yields are shown for events with two negatively (positively) charged leptons in the heavy-quark signal region. The positive-lepton sample is the same-sign top-quark signal region. The distributions of E_T^{miss} and H_T are shown in figures 5 and 6.

	e^-e^-	$\mu^-\mu^-$	$e^-\mu^-$
Fake	$0.2 \pm 0.3 \pm 0.1$	$0.7 \pm 0.3_{-0.3}^{+0.6}$	$0.5 \pm 0.2_{-0.3}^{+0.7}$
Charge flip	$0.3 \pm 0.1_{-0.1}^{+0.3}$	$0 \pm 0_{-0.0}^{+0.1}$	$0.3 \pm 0.1_{-0.1}^{+0.2}$
Real	$0.8 \pm 0_{-0.6}^{+0.3}$	$1.0 \pm 0_{-0.6}^{+0.4}$	$2.3 \pm 0_{-1.9}^{+0.8}$
Total	$1.4 \pm 0.3_{-0.6}^{+0.4}$	$1.7 \pm 0.3 \pm 0.7$	$3.1 \pm 0.2_{-1.9}^{+1.1}$
Data	1	2	2
tt_{LL}	$0.2 \pm 0 \pm 0.1$	$0.2 \pm 0 \pm 0.1$	$0.5 \pm 0 \pm 0.3$
tt_{LR}	$0.02 \pm 0 \pm 0.01$	$0.001 \pm 0_{-0.001}^{+0.01}$	$0.02 \pm 0 \pm 0.02$
tt_{RR}	$0.5 \pm 0 \pm 0.3$	$0.1 \pm 0 \pm 0.2$	$0.8 \pm 0 \pm 0.3$
b' 450 GeV	$1.8 \pm 0 \pm 0.3$	$2.1 \pm 0 \pm 0.3$	$4.3 \pm 0 \pm 0.5$

Table 3. Predicted number of SM background events and observed data with two negatively-charged leptons, at least two jets, $E_T^{\text{miss}} > 40$ GeV and $H_T > 350$ GeV. Uncertainties are statistical followed by systematic. The expected contribution from same-sign top-quark pairs is shown (assuming $C/\Lambda^2 = 1/\text{TeV}^2$, see eq. (9.1)) as well as from a 450 GeV b' .

	e^+e^+	$\mu^+\mu^+$	$e^+\mu^+$
Fake	$0.8 \pm 0.6_{-0.4}^{+0.2}$	$1.0 \pm 0.3_{-0.4}^{+0.6}$	$3.3 \pm 1.1_{-1.4}^{+1.6}$
Charge flip	$0.3 \pm 0.1_{-0.1}^{+0.3}$	$0 \pm 0_{-0.0}^{+0.1}$	$0.4 \pm 0.1_{-0.1}^{+0.3}$
Real	$1.9 \pm 0_{-1.5}^{+0.7}$	$1.6 \pm 0_{-0.9}^{+0.7}$	$4.4 \pm 0_{-3.1}^{+1.3}$
Total	$3.0 \pm 0.6_{-1.5}^{+0.8}$	$2.6 \pm 0.3_{-1.1}^{+0.9}$	$8.1 \pm 1.1_{-3.4}^{+2.2}$
Data	2	1	10
tt_{LL}	$30.1 \pm 0 \pm 5.0$	$30.4 \pm 0 \pm 4.8$	$64.2 \pm 0 \pm 10.3$
tt_{LR}	$3.8 \pm 0 \pm 0.6$	$4.2 \pm 0 \pm 0.7$	$8.3 \pm 0 \pm 1.3$
tt_{RR}	$35.5 \pm 0 \pm 6.0$	$29.5 \pm 0 \pm 4.6$	$65.7 \pm 0 \pm 10.4$
b' 450 GeV	$1.8 \pm 0 \pm 0.3$	$2.7 \pm 0 \pm 0.4$	$5.0 \pm 0 \pm 0.7$

Table 4. Predicted number of SM background events and observed data with two positively-charged leptons, at least two jets, $E_T^{\text{miss}} > 40$ GeV and $H_T > 350$ GeV. Uncertainties are statistical followed by systematic. The expected contribution from same-sign top-quark pairs is shown (assuming $C/\Lambda^2 = 1/\text{TeV}^2$, see eq. (9.1)) as well as from a 450 GeV b' .

In the signal region tuned for same-sign top quarks due to low-mass Z' exchange, the expected and observed yields are shown for events with two negatively (positively) charged leptons in table 5 (table 6). The distribution of E_T^{miss} and H_T are shown in figures 7 and 8.

9 Interpretation of the results

Since the data are consistent with the Standard Model expectations, the analysis sets limits on the production of two processes producing same-sign dilepton signals from new physics sources. For each model, upper limits at 95% confidence level on the cross sections of the hypothetical processes are derived using the CL_s method [40, 41]. In both cases,

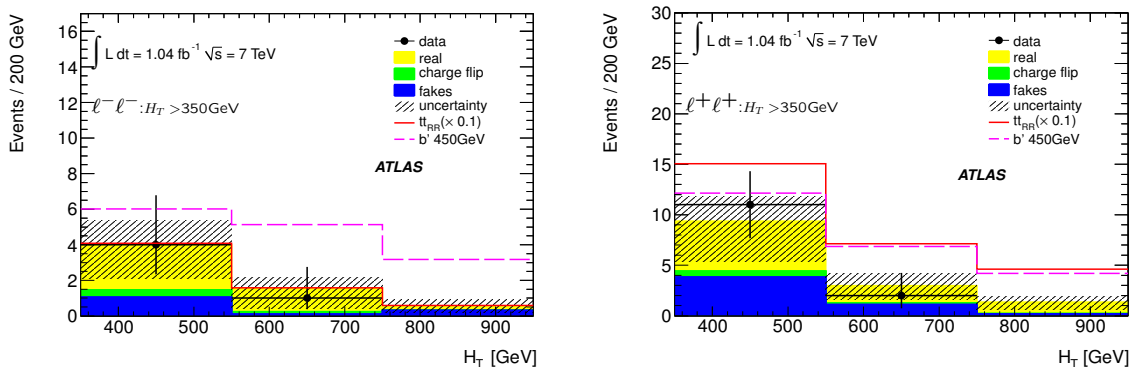


Figure 6. H_T distribution: comparison of observed data and expected SM backgrounds for events with a pair of same-sign leptons, at least two reconstructed jets, $E_T^{\text{miss}} > 40$ GeV and $H_T > 350$ GeV. Left are negatively-charged lepton pairs, right are positively-charged lepton pairs. Uncertainties (hatched) are systematic and statistical. The last bin includes overflow events. tt_{RR} (scaled by 0.1 and assuming $C/\Lambda^2 = 1/\text{TeV}^2$, see eq. (9.1)) and b' signals include both signal and background.

	e^-e^-	$\mu^-\mu^-$	$e^-\mu^-$
Fake	$0.2 \pm 0.4 \pm 0.1$	$0.8 \pm 0.4_{-0.3}^{+0.4}$	$0.4 \pm 0.3_{-0.1}^{+1.0}$
Charge flip	$0.7 \pm 0.1_{-0.2}^{+0.7}$	$0.2 \pm 0 \pm 0.2$	$0.5 \pm 0.1_{-0.1}^{+0.5}$
Real	$1.5 \pm 0_{-1.0}^{+0.6}$	$1.4 \pm 0_{-0.8}^{+0.5}$	$2.9 \pm 0_{-1.8}^{+0.8}$
Total	$2.4 \pm 0.4_{-1.1}^{+0.9}$	$2.4 \pm 0.4_{-0.8}^{+0.6}$	$3.9 \pm 0.3_{-1.8}^{+1.4}$
Data	1	3	1
$tt_{RR, m_{Z'}=100\text{GeV}}$	$0.01 \pm 0 \pm 0.01$	$0.01 \pm 0 \pm 0.01$	$0.01 \pm 0 \pm 0.01$
$tt_{RR, m_{Z'}=150\text{GeV}}$	$0.02 \pm 0 \pm 0.01$	$0.02 \pm 0 \pm 0.01$	$0.03 \pm 0 \pm 0.01$
$tt_{RR, m_{Z'}=200\text{GeV}}$	$0.01 \pm 0 \pm 0.01$	$0.01 \pm 0 \pm 0.01$	$0.06 \pm 0 \pm 0.02$

Table 5. Predicted number of SM background events and observed data with two negatively-charged leptons, at least two jets, $E_T^{\text{miss}} > 40$ GeV, $H_T > 150$ GeV and $m_{\ell\ell} > 100$ GeV. Uncertainties are statistical followed by systematic. The expected contribution from same-sign top-quark pairs with low-mass Z' exchange is shown, using a fixed value $C/\Lambda^2 = -1 \text{ TeV}^{-2}$, where $\Lambda = m_{Z'}$ in each case, see eq. (9.1).

we use a single-bin counting experiment, fitting the data to extract the most likely signal cross section. Systematic uncertainties are included as variations in the expected signal and background yields, which are fluctuated in the ensembles used to generate the CLs distributions.

9.1 Same-sign top-quark production

We calculate upper limits on the cross section of same-sign top-quark pair production using only the positively-charged lepton pairs. Modeling tt production in terms of effective four-fermion operators, the expected 95% confidence level limits on $\sigma(pp \rightarrow tt)$ are shown in table 7 for the three possible chirality combinations of the tt pair, which influence the

	e^+e^+	$\mu^+\mu^+$	$e^+\mu^+$
Fake	$0.5 \pm 0.4^{+0.1}_{-0.2}$	$1.6 \pm 0.5^{+1.2}_{-1.3}$	$3.1 \pm 1.0^{+2.2}_{-1.5}$
Charge flip	$0.6 \pm 0.1^{+0.6}_{-0.2}$	$0 \pm 0^{+0.1}_{-0.0}$	$0.9 \pm 0.1^{+0.6}_{-0.2}$
Real	$1.9 \pm 0^{+0.7}_{-1.1}$	$2.1 \pm 0^{+0.8}_{-0.7}$	$5.6 \pm 0^{+1.6}_{-3.5}$
Total	$3.0 \pm 0.4^{+0.9}_{-1.2}$	$3.7 \pm 0.5 \pm 1.5$	$9.6 \pm 1.0^{+2.8}_{-3.8}$
Data	3	4	8
$tt_{RR,m_{Z'}=100\text{GeV}}$	$0.24 \pm 0 \pm 0.04$	$0.36 \pm 0 \pm 0.06$	$0.6 \pm 0 \pm 0.1$
$tt_{RR,m_{Z'}=150\text{GeV}}$	$0.6 \pm 0 \pm 0.1$	$0.9 \pm 0 \pm 0.2$	$1.5 \pm 0 \pm 0.3$
$tt_{RR,m_{Z'}=200\text{GeV}}$	$1.1 \pm 0 \pm 0.2$	$1.7 \pm 0 \pm 0.3$	$3.2 \pm 0 \pm 0.6$

Table 6. Predicted number of SM background events and observed data with two positively-charged leptons, at least two jets, $E_T^{\text{miss}} > 40$ GeV, $H_T > 150$ GeV and $m_{\ell\ell} > 100$ GeV. Uncertainties are statistical followed by systematic. The expected contribution from same-sign top-quark pairs with low-mass Z' exchange is shown, using a fixed value of the coupling $C/\Lambda^2 = -1 \text{ TeV}^{-2}$, where $\Lambda = m_{Z'}$ in each case, see eq. (9.1).

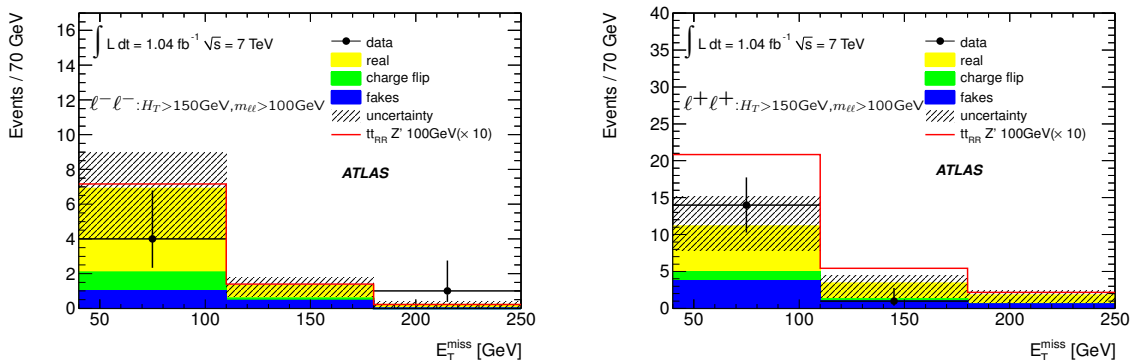


Figure 7. E_T^{miss} distribution: comparison of observed data and expected SM backgrounds for events with a pair of same-sign leptons, at least two reconstructed jets, $E_T^{\text{miss}} > 40$ GeV, $H_T > 150$ GeV and $m_{\ell\ell} > 100$ GeV. Left are negatively-charged lepton pairs, right are positively-charged lepton pairs. Uncertainties (hatched) are systematic and statistical. The last bin includes overflow events. tt_{RR} from Z' 100 GeV ($\times 10$) signal histogram includes both signal and background.

efficiency primarily through the lepton transverse momentum. In table 8 the limits are given for a model with a light flavour-changing Z' boson with right-handed couplings, and three values of its mass. These limits supersede those on this process previously reported by ATLAS [42]. The limits reported here are more stringent than those of ref. [42] due to the use of both electrons and muons, and an event selection optimized for same-sign top-quark pair production including a jet multiplicity requirement. Ref. [42] used a more inclusive selection examining a range of new physics models.

The cross-section limits in table 7 can be directly translated into limits on coefficients of effective operators corresponding to each pair of chiralities. There are five independent dimension-six four-fermion operators mediating $uu \rightarrow tt$ [16], with four possible structures.

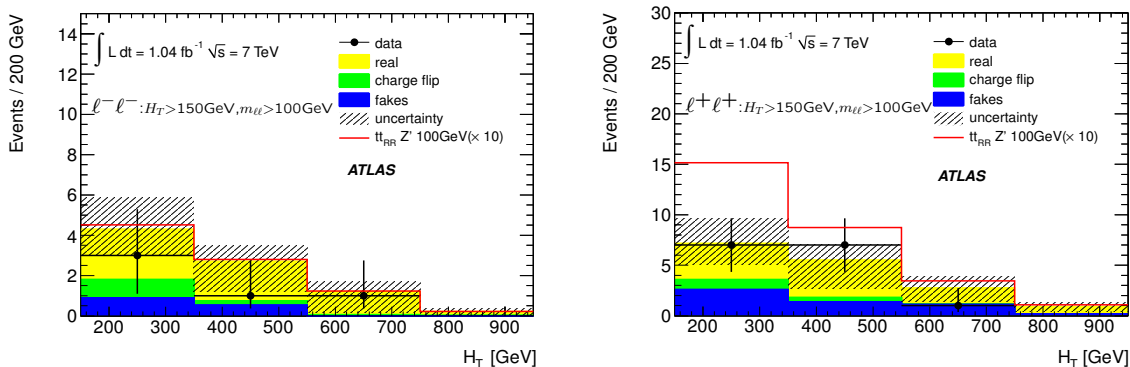


Figure 8. H_T distributions: comparison of observed data and expected SM backgrounds for events with a pair of same-sign leptons, at least two reconstructed jets, $E_T^{\text{miss}} > 40$ GeV, $H_T > 150$ GeV and $m_{\ell\ell} > 100$ GeV. Left are negatively-charged lepton pairs, right are positively-charged lepton pairs. Uncertainties (hatched) are systematic and statistical. The last bin includes overflow events. tt_{RR} from Z' 100 GeV ($\times 10$) signal histogram includes both signal and background.

Chirality config.	Median expected limit, σ	68% range limit, σ	Observed limit, σ	Observed limit, C
LL	$\sigma < 1.8$ pb	1.1-3.2 pb	$\sigma < 1.7$ pb	$C_{LL}/\Lambda^2 < 0.35 \text{ TeV}^{-2}$
LR	$\sigma < 1.7$ pb	1.0-3.0 pb	$\sigma < 1.7$ pb	$C_{RL}/\Lambda^2, C'_{LR}/\Lambda^2 < 0.98 \text{ TeV}^{-2}$
RR	$\sigma < 1.7$ pb	1.0-3.0 pb	$\sigma < 1.7$ pb	$C_{RR}/\Lambda^2 < 0.35 \text{ TeV}^{-2}$

Table 7. Expected and observed upper limits on same-sign top-quark cross section at 95% confidence level. The uncertainties for the expected limits describe a range which includes 68% of pseudo-experiments drawn from the background-only hypothesis. A dileptonic decay branching ratio of 10.6% has been taken into account, so that the limits are directly on $\sigma(pp \rightarrow tt)$. The observed limit on the coefficients $C_{LL}, C_{LR} = C'_{RL}, C_{RR}$ of the effective operator is also indicated.

Z' mass	Median expected limit, σ	68% range limit, σ	Observed limit, σ
100 GeV	$\sigma < 2.1$ pb	1.4-3.3 pb	$\sigma < 2.0$ pb
150 GeV	$\sigma < 1.7$ pb	1.0-2.8 pb	$\sigma < 1.6$ pb
200 GeV	$\sigma < 1.5$ pb	0.9-2.3 pb	$\sigma < 1.4$ pb

Table 8. Expected and observed upper limits on same-sign top-quark production from low mass Z' cross sections at 95% confidence level. The uncertainties for the expected limits describe a range which includes 68% of pseudo-experiments drawn from the background-only hypothesis. A dileptonic decay branching ratio of 10.6% has been taken into account.

The resulting Lagrangian relevant for tt production reads

$$\begin{aligned}
 \mathcal{L}_{4F} = & \frac{1}{2} \frac{C_{LL}}{\Lambda^2} (\bar{u}_L \gamma^\mu t_L) (\bar{u}_L \gamma_\mu t_L) + \frac{1}{2} \frac{C_{RR}}{\Lambda^2} (\bar{u}_R \gamma^\mu t_R) (\bar{u}_R \gamma_\mu t_R) \\
 & - \frac{1}{2} \frac{C_{LR}}{\Lambda^2} (\bar{u}_L \gamma^\mu t_L) (\bar{u}_R \gamma_\mu t_R) - \frac{1}{2} \frac{C'_{LR}}{\Lambda^2} (\bar{u}_{La} \gamma^\mu t_{Lb}) (\bar{u}_{Rb} \gamma_\mu t_{Ra}) + \text{h.c.}, \quad (9.1)
 \end{aligned}$$

where the subindices a, b in the last term indicate the colour contractions. The limits on operator coefficients are the most relevant for a comparison between different experiments,

Label	Spin	Quantum numbers	Limit	Mass Limit
\mathcal{B}_μ	1	$(1, 1)_0$	$ g_{13} /\Lambda < 0.57 \text{ TeV}^{-1}$	1.7 TeV
\mathcal{W}_μ	1	$(1, 3)_0$	$ g_{13} /\Lambda < 0.57 \text{ TeV}^{-1}$	1.7 TeV
\mathcal{G}_μ	1	$(8, 1)_0$	$ g_{13} /\Lambda < 0.99 \text{ TeV}^{-1}$	1.0 TeV
\mathcal{H}_μ	1	$(8, 3)_0$	$ g_{13} /\Lambda < 0.99 \text{ TeV}^{-1}$	1.0 TeV
\mathcal{Q}_μ^5	1	$(3, 2)_{-\frac{5}{6}}$	$ g_{11}g_{33} /\Lambda^2 < 0.34 \text{ TeV}^{-2}$	1.7 TeV
\mathcal{Y}_μ^5	1	$(\bar{6}, 2)_{-\frac{5}{6}}$	$ g_{11}g_{33} /\Lambda^2 < 0.63 \text{ TeV}^{-2}$	1.3 TeV
ϕ	0	$(1, 2)_{-\frac{1}{2}}$	$ g_{13}^u g_{31}^u /\Lambda^2 < 0.92 \text{ TeV}^{-2}$	1.1 TeV
Φ	0	$(8, 2)_{-\frac{1}{2}}$	$ g_{13}^u g_{31}^u /\Lambda^2 < 1.8 \text{ TeV}^{-2}$	0.8 TeV
Ω^4	0	$(\bar{6}, 1)_{-\frac{4}{3}}$	$ g_{11}g_{33} /\Lambda^2 < 0.33 \text{ TeV}^{-2}$	1.8 TeV
Σ	0	$(\bar{6}, 3)_{-\frac{1}{3}}$	$ g_{11}g_{33} /\Lambda^2 < 0.16 \text{ TeV}^{-2}$	2.5 TeV

Table 9. Lower (upper) limits at 95% confidence level on the masses (couplings) for generic heavy vector bosons and scalars which mediate the production of same-sign top-quark pairs. A theoretical uncertainty due to variations of the Q^2 scale gives a 5% uncertainty on the limits of the couplings g . Quantum numbers are defined in the text.

because the production cross sections themselves depend on the type of particles being collided and their centre-of-mass energy. These limits improve on those reported by the CMS Collaboration, $C_{RR}/\Lambda^2 < 2.7 \text{ TeV}^{-2}$ [43] using 35 pb^{-1} of 2010 data.

Constraints can also be placed on generic classes of models with new particles mediating same-sign top-quark production at the tree level. These new particles can be classified according to their quantum numbers under the SM group $SU(3)_C \times SU(2)_L \times U(1)_Y$. In table 9 limits are given for different types of particles, using the notation of ref. [17]; the quantum numbers $(C, I)_Y$ refer to the transformation properties under the SM group, where C is the colour (octet, sextet, triplet or singlet); I the weak isospin (triplet, doublet or singlet) and Y is the hypercharge. The couplings labeled as g_{13} involve a flavour change between the up and top quark, whereas g_{11} , g_{33} are flavour-diagonal couplings of the new particle to the up and top quarks, respectively; for \mathcal{B}_μ and \mathcal{G}_μ vector bosons $|g_{13}| \equiv (|g_{13}^q|^2 + |g_{13}^u|^2)^{1/2}$, where g_{13}^q is left-handed and g_{13}^u is right-handed. In particular, limits are placed on new colour-sextet scalars and vector bosons produced in the s -channel [6, 7], as well as on heavy flavour-changing scalars and vector bosons. The last column gives the mass limits for unit couplings. Notice that for larger couplings the mass limits are more stringent, and conversely for smaller couplings the mass limits are looser.

Limits for neutral colour singlets (\mathcal{B}_μ) are of interest because the exchange of a t -channel Z' boson, corresponding to \mathcal{B}_μ in table 9, has been proposed as a possible mechanism which could increase the value of the forward-backward production asymmetry A_{FB} in $t\bar{t}$ production at the Tevatron. CDF and D0 have reported measurements [2, 3] of this asymmetry which lie above the Standard Model expectation. In the simplest realisation of this idea, the Z' boson is real and leads to same-sign top-quark pair production [1, 44].

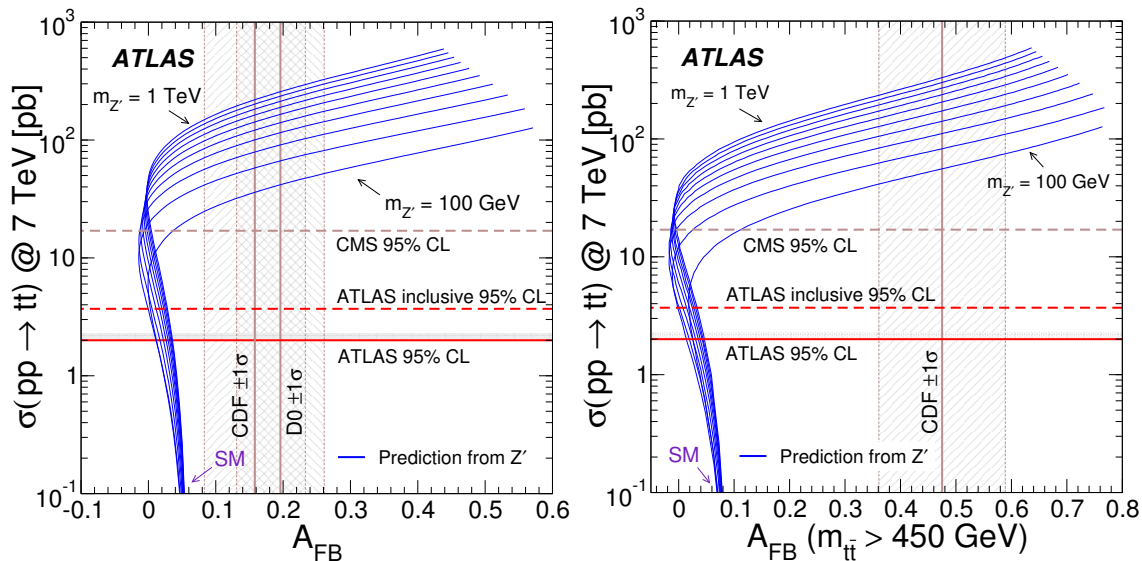


Figure 9. Allowed regions for the new physics contributions to the inclusive (left) and high-mass (right) A_{FB} at Tevatron, and the $t\bar{t}$ cross section at LHC. Limits from this analysis are the solid horizontal lines. The measurements of A_{FB} from CDF and D0 are shown as vertical lines with bands representing the uncertainties.

For a given mass and coupling of the new Z' boson, its contribution to the A_{FB} at the Tevatron and the $t\bar{t}$ cross section at the LHC are related. Figure 9 shows the contributions to the inclusive (left) and high-mass (right) A_{FB} from the exchange of a Z' boson with right-handed couplings, versus the same-sign top-quark pair cross sections at the LHC. They have been obtained following the method outlined in ref. [45].

For each curve in figure 9, corresponding to a different Z' boson mass ranging between 100 GeV and 1 TeV from bottom to top, the lower end (out of scale) corresponds to vanishing coupling $g_{13} = 0$. The shape of the curves is due to the interference of the Z' with the $t\bar{t}$ production amplitude, which gives a negative contribution to the forward-backward production asymmetry, while the quadratic Z' contribution increases it. As the coupling is increased from zero, the contribution to the forward-backward asymmetry is first negative and then becomes positive at larger couplings.

The solid horizontal line represents the 95% CL limit on same-sign top-quark production obtained from this analysis, taken as the most conservative one in tables 7 and 8. For comparison, limits from previous analyses [42, 43] are also shown. Previous ATLAS limits [42] already exclude the possibility of any positive contributions to either the inclusive or the high-mass A_{FB} in $t\bar{t}$ production in minimal models with a single, real Z' boson. Still, these constraints can be evaded in non-minimal models [46] which involve more than one Z' boson so as to partially cancel their contribution to same-sign top quark production. The tighter constraints reported here narrow the parameter space for such cancellations.

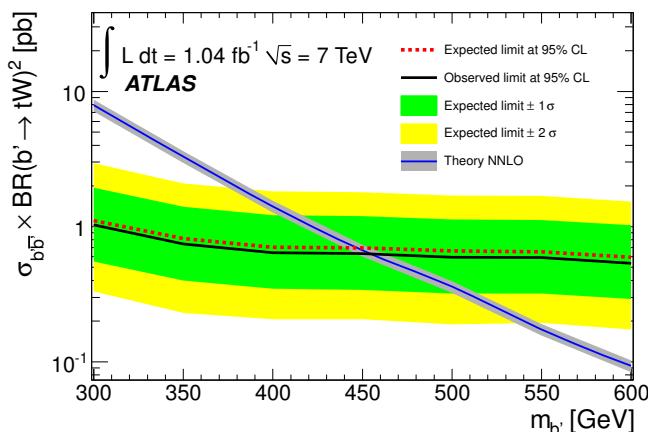


Figure 10. 95% confidence level exclusion limits on cross section times branching ratio for $b'\bar{b}'$ production with decay $b' \rightarrow tW$.

9.2 Heavy down-type quarks

The second process investigated is pair production of chiral down-type charge $-1/3$ quarks b' with decay $b'\bar{b}' \rightarrow W^-tW^+\bar{t}$. The branching ratio for $b' \rightarrow Wt$ is assumed to be unity for fourth-generation quarks b' if $m_{b'} > m_t + m_W$ or for other heavy quark models such as exotic isodoublets $(T_B)_{L,R}$ coupling predominantly to the third generation [5]. The cross section for strong pair production is the same in both cases. The observed and expected cross-section limits for $b'\bar{b}'$ production are shown in figure 10. The intersection of the limit with the theoretical cross-section calculation at next-to-next-to-leading order in QCD yields a lower bound of 450 GeV on the new quark mass.

10 Conclusion

A search is presented for anomalous same-sign top-quark production and heavy fourth-generation down-type quark production in events with two isolated leptons (e or μ) having the same electric charge, large missing transverse momentum, and at least two jets. The data are selected from events collected from pp collisions at $\sqrt{s} = 7 \text{ TeV}$ by the ATLAS detector and correspond to an integrated luminosity of 1.04 fb^{-1} . The observed data are consistent with expectations from Standard Model processes. Upper limits are set at 95% confidence level on the cross section of new sources of same-sign top-quark pair production via a heavy mediator at 1.7 pb for each chirality. For light Z' mediators, limits range from 1.4-2.0 pb depending on the Z' mass. These limits are translated into limits on coefficients of effective operators which mediate $uu \rightarrow tt$ production, and an interpretation is presented for the case of a flavor-changing Z' boson, which has been proposed as an explanation for the measurement of the top-quark pair production forward-backward asymmetry at the Tevatron. In addition, limits are set on the production of heavy down-type quarks. A lower limit of 450 GeV is set at 95% confidence level on the mass of fourth-generation down-type quarks. This is the strongest limit in the same-sign lepton channel, complementing a stronger limit in the single-lepton channel [14], which has a larger branching ratio but significantly higher background levels.

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