Title
Search for invisible particles produced in association with single-top-quarks in proton-proton collisions at √s = 8 Tev with the ATLAS detector

Permalink
https://escholarship.org/uc/item/7gd458zb

Journal
European Physical Journal C, 75(2)

ISSN
1434-6044

Authors
Aad, G
Abbott, B
Abdallah, J
et al.

Publication Date
2015

DOI
10.1140/epjc/s10052-014-3233-4

License
CC BY 4.0

Peer reviewed
Search for invisible particles produced in association with single-top-quarks in proton–proton collisions at $\sqrt{s} = 8$ TeV with the ATLAS detector

ATLAS Collaboration

CERN, 1211 Geneva 23, Switzerland

1 Introduction

Many theories beyond the standard model (BSM) predict enhanced production of events with large missing energy in association with a single reconstructed object. Such events have been searched for at the large hadron collider (LHC), when the single object is either a photon [1,2], a jet [3,4], or a $W$ or $Z$ boson [5,6].

This paper presents a search for singly produced top quarks in association with significant missing energy, corresponding to the associated production of one or several undetected neutral particles, and without any other reconstructed object. These neutral particles can be either stable and/or weakly interacting with ordinary matter – providing an interesting interpretation in terms of dark-matter candidates – or long-lived and decaying outside of the detector. The observation of such final states, commonly referred to as monotop events, would be evidence for new phenomena. Moreover, processes involving top quarks are sensitive to BSM physics, due to the large mass of this standard model (SM) particle which is close to the electroweak symmetry-breaking scale.

No such process is possible in the SM at tree level: the direct production of a top quark and a $Z$ boson decaying into a pair of neutrinos, without any additional quark, is suppressed by the Glashow–Iliopoulos–Maiani mechanism [7].

This search is performed with the ATLAS detector [8] in $pp$ collisions at $\sqrt{s} = 8$ TeV with the data collected in 2012 at the LHC and corresponding to an integrated luminosity of 20.3 fb$^{-1}$. The ATLAS detector covers the pseudorapidity range $|\eta| < 4.9$ and the full azimuthal angle $\phi$. It consists of an inner tracking detector covering the pseudorapidity range $|\eta| < 2.5$ surrounded by a superconducting solenoid, electromagnetic and hadronic calorimeters, and an external muon spectrometer with large superconducting toroidal magnets.

The search is based on the analysis of top-quark events where the $W$ boson from the top quark decays into a lepton and a neutrino. Previous results of a search for monotop production, exploiting the case of fully hadronic top-quark decays, have been published by the CDF Collaboration using $p\bar{p}$ collision data at $\sqrt{s} = 1.96$ TeV, corresponding to an integrated luminosity of 7.7 fb$^{-1}$ [9], and more recently by the CMS Collaboration using $pp$ collision data at $\sqrt{s} = 8$ TeV, corresponding to an integrated luminosity of 19.7 fb$^{-1}$ [10].

1 The ATLAS experiment uses a right-handed coordinate system with its origin at the nominal interaction point (IP) in the centre of the detector and the $z$-axis along the beam pipe. The $x$-axis points from the IP to the centre of the LHC ring, and the $y$-axis points upwards. Cylindrical coordinates ($r, \phi$) are used in the transverse plane, $\phi$ being the azimuthal angle around the beam pipe. The pseudorapidity is defined in terms of the polar angle $\theta$ as $\eta = -\ln\tan(\theta/2)$. 

\textit{DOI 10.1140/epjc/s10052-014-3233-4}


Received: 21 October 2014 / Accepted: 15 December 2014 / Published online: 18 February 2015

© CERN for the benefit of the ATLAS collaboration 2015. This article is published with open access at Springerlink.com
2 Signal models

Many theoretical models predicting the production of monotop events in hadron colliders have been proposed. In a first class of theories, a charged resonance is produced by down-type antiquark fusion and decays into a top quark and a neutral particle, as in SU(5) models [11], in R-parity-violating SUSY [12] or in hylogenesis models [13,14]. In a second class of theories, the monoprot final state is produced through a non-resonant process, as in R-parity-conserving SUSY [15], or in models where an interaction of a gluon with an up-type quark allows production of a set of invisible particles via a $u\rightarrow t$ or $c\rightarrow t$ coupling [16–19].

Because of the variety of these theories, effective models [20,21] are used for the search reported in this paper. Furthermore, as minimal extensions of the SM, the effective models tested in this search are required to respect the electroweak gauge structure [22]. The possibilities for monotop production in $pp$ collisions considered are thus:

- Resonant production of a $+2/3$ charged spin-0 boson, $S$, decaying into a right-handed top quark and a neutral, colour singlet, spin-1/2 fermion, $f_{\text{met}}$;
- Non-resonant production of a neutral, colour singlet, spin-1 boson, $v_{\text{met}}$, in association with a right-handed top quark.

The Feynman diagrams for monotop production in the resonant and non-resonant models are shown in Fig. 1. Each of these effective models corresponds to one of the two classes of BSM theories detailed above.

A detailed study of the phenomenology of the resonant model is available in Ref. [23]. The interaction Lagrangians of the resonant and non-resonants models are given in Eqs. (1) and (2), respectively.

$$\mathcal{L}_{\text{res}} = \epsilon^{\alpha\beta\gamma}\varphi_{a}d_{\alpha}^{ij}d_{\beta}^{ij} + \varphi \bar{u}_{R}^{k} (a_{\text{res}}^{1/2}) \chi + \text{h.c.}$$  \hspace{1cm} (1)

$$\mathcal{L}_{\text{non-res}} = (a_{\text{non-res}})_{ij} V_{\gamma} \bar{f}_{R}^{j} y^{\mu} u_{R}^{i} + \text{h.c.}$$  \hspace{1cm} (2)

The fields $\varphi$, $\chi$, and $V_{\mu}$ correspond to the $S$, $f_{\text{met}}$, and $v_{\text{met}}$ exotic particles, respectively, the field $\bar{f}$ ($\bar{d}$) represents an up-type (down-type) quark, $(a_{\text{res}}^{0})_{ij}$, $(a_{\text{res}}^{1/2})$, and $(a_{\text{non-res}})_{ij}$ are the coupling matrices in the quark-flavour space, the indices $i$, $j$, $k$, represent the quark-generation number, and $\epsilon^{\alpha\beta\gamma}$ is the fully antisymmetric tensor, the indices $\alpha$, $\beta$, and $\gamma$ being the colour indices. The superscript $^c$ denotes the charge conjugation. The number of free parameters is reduced by assuming $(a_{\text{res}}^{0})_{12} = (a_{\text{res}}^{0})_{21} = (a_{\text{res}}^{1/2}) = a_{\text{res}}$ for the resonant model and $(a_{\text{non-res}})_{13} = (a_{\text{non-res}})_{31} = a_{\text{non-res}}$ for the non-resonant model, all other elements of these coupling matrices being equal to 0. For each model, the coupling parameter $a_{\text{res}}$ or $a_{\text{non-res}}$ and the masses of the exotic particles are independent.

The choice of model parameters – the effective couplings and the masses of the particles – is driven by phenomenological considerations: the particles $f_{\text{met}}$ and $v_{\text{met}}$ in the resonant and non-resonant models, respectively, are required to have missing transverse momentum as an experimental signature. For the resonant model, in which the $f_{\text{met}}$ fermion can decay into a five-body final state, Ref. [23] suggests that for $m(S) = 500$ GeV and an effective coupling of $a_{\text{res}} = 0.2$, the decay length of $f_{\text{met}}$ is large enough to be considered as invisible for the detector, as long as $m(f_{\text{met}})$ is below 100 GeV. For the non-resonant model, in which the $v_{\text{met}}$ boson can decay into a two-body final state either through a tree-level or a loop-induced interaction, Ref. [22] assumes that the $v_{\text{met}}$ boson decays into a set of invisible particles which can be dark-matter candidates. This assumption follows the spirit of several BSM models [16–18]. Hence, the $v_{\text{met}}$ particle in the non-resonant model can be considered to be an invisible spin-1 state with mass $m(v_{\text{met}})$. Studies of possible direct and indirect constraints on monotop model parameter values using experimental signatures other than monotop processes are discussed in Refs. [22,23].
3 Data and Monte Carlo samples

The data used for this analysis are selected from the recorded data streams using single-electron and single-muon triggers [24]. Stringent detector and data quality criteria are applied offline, resulting in a data sample corresponding to an integrated luminosity of 20.3 ± 0.6 fb⁻¹ [25].

The single-parton cross-sections are obtained from 5f FFN [49] PDF sets, added in quadrature to the scale energy of√s. The parton distribution function (PDF) set MSTW2008LO [32,33] is used. Resonant signal samples are modelled using Pythia v1.5.11 [26] using FeynRules [27–29] and interfaced with PYTHIA v8.175 [30,31] for parton showering and hadronisation. The parton distribution function (PDF) set AcerMC v8.175 [30,31] is used. The invisible state Wc is also included in the analysis using Alpgen +jets events. The parton showering, the hadronisation, and the underlying event are modelled using PYTHIA v6.426 [30].

The t£ cross-section for pp collisions at a centre-of-mass energy of √s = 8 TeV is αt£ = 253 _13 ±15 pb for a top-quark mass of 172.5 GeV. It has been calculated at next-to-next-to-leading order (NNLO) in QCD including resummation of next-to-next-to-leading logarithmic (NNLL) soft gluon terms [41–46] with the program Top++ v2.0 [47]. The PDF and αs uncertainties were calculated using the PDF4LHC prescription [48] with the MSTW2008 68% CL NNLO [32,33], CT10 NNLO [36,37] and NNPDF2.3 5f FFN [49] PDF sets, added in quadrature to the scale uncertainty. The single-top cross-sections are obtained from approximate NNLO calculations: 87.8 ±3.9 pb (t-channel), 22.4 ±1.5 pb (Wt process) and 5.6±0.2 pb (s-channel) [50–52].

The ALPGEN LO generator v2.14 [53] is used with PYTHIA v6.426 to generate events with a W boson produced in association with light or heavy quarks (W+light-quarks, W+bb, W+c+c, W+c+c) and Z+jets events. The ALPGEN matrix elements include diagrams with up to five additional partons.

To remove overlaps between the n and n + 1 parton samples the MLM matching scheme [54] is used. Double counting between the W+n parton samples and samples with associated heavy-quark pair production is removed utilising an overlap removal based on a ∆R = (|Δη|)² + (Δφ)² matching criterion. Diboson samples (WW, ZZ, and WZ) where at least one of the bosons decays leptonically are modelled by HERWIG v6.52 [55]. The single-boson and diboson simulation samples are normalised to the production cross-sections calculated at NNLO [56,57] and NLO [58], respectively.

After event generation, all signal and background samples are passed through the full simulation of the ATLAS detector [59] based on GEANT4 [60] and reconstructed using the same procedure as for collision data. All Monte Carlo (MC) samples are simulated with pile-up ² and re-weighted to have the same distribution of the mean number of interactions per bunch-crossing as in the data sample (20.7 on average).

4 Selection and background estimation

The experimental signature of the monotop events is one isolated charged lepton (electron or muon) from the W decay, large missing transverse momentum, and one jet identified as likely to have originated from a b-quark (b-tagged).

Electrons are identified as energy clusters in the electromagnetic calorimeter matched to reconstructed tracks in the inner detector [61–63]. Electron candidates are required to be isolated from other objects in the event and from hadronic activity to reduce the contamination by mis-reconstructed hadrons, electrons from heavy-flavour decays, and photon conversions. Muons are reconstructed using information from the muon spectrometer and the inner detector [64]. An isolation criterion [65] is applied to reduce the contribution of muons from heavy-flavour decays. The reconstructed charged lepton is required to have a transverse momentum pT ≥ 30 GeV to ensure a constant trigger efficiency and to have |η| < 2.5 for muons and |η| < 2.47 for electrons (for the latter, the electromagnetic calorimeter barrel–endcap transition region 1.37 < |η| < 1.52 is excluded).

Jets are reconstructed using the anti-kt algorithm [66] with a radius parameter R = 0.4 and calibrated to the hadronic energy scale [67]. Jets are required to have pT > 25 GeV and |η| < 2.5. To suppress jets from in-time pileup, at least 50% of the scalar pT sum of the tracks associated with a jet is required to be from tracks associated with the primary vertex. This jet vertex fraction requirement is applied only for jets with pT < 50 GeV and |η| < 2.4.

Exactly one jet is selected, and is required to be b-tagged. The b-tagging techniques are based on properties specific to extra proton–proton interactions from the same and previous bunch-crossings.
This analysis requires events to have calorimeter cells and is further refined with object-level correlation associated with topological clusters of energy deposits in light-quark selection efficiency of 0.2 %, as obtained in simulated events. The chosen working point corresponds to a b-tagging efficiency of 57 % and a light-quark selection efficiency of 0.2 %, as obtained in simulated t\bar{t} events.

The missing transverse momentum (with magnitude \( E_{\text{T}}^{\text{miss}} \)) is the negative vector sum of the transverse momentum associated with topological clusters of energy deposits in calorimeter cells and is further refined with object-level corrections from identified electrons, muons, and jets [69, 70]. This analysis requires events to have \( E_{\text{T}}^{\text{miss}} \) larger than 35 GeV to reduce the multijet background.

The main background to this final-state selection are t\bar{t} pairs where both top quarks decay semi-leptonically, \( t \rightarrow \ell b \nu \), with large \( E_{\text{T}}^{\text{miss}} \) due to one lepton and one jet not being reconstructed, and W+jets production, particularly with jets from heavy-flavour quarks. The background from multijet production due to misidentification as leptons is reduced by imposing a requirement on the sum of the \( E_{\text{T}}^{\text{miss}} \) and the transverse mass of the lepton–\( E_{\text{T}}^{\text{miss}} \) system: \( m_T(\ell, E_{\text{T}}^{\text{miss}}) + E_{\text{T}}^{\text{miss}} > 60 \text{ GeV} \). The distributions of kinematic variables and their normalisation for the multijet background are estimated with a data-driven matrix method [71]. All remaining background processes (t\bar{t}, singletop, W+jets, Z+jets and diboson production) are modelled using simulated samples and are scaled to the theory predictions described in Sect. 3. Possible contributions from t\bar{t}Z and t\bar{t}Z processes [72] in the \( Z \rightarrow \nu \nu \) decay mode are found to be negligible.

A counting experiment approach is followed. The monopole signal is prominent in regions of the phase space characterised by high \( m_T(\ell, E_{\text{T}}^{\text{miss}}) \) values, as suggested by Refs. [18, 21]. Hence, in addition to the pre-selection described previously, a criterion requiring \( m_T(\ell, E_{\text{T}}^{\text{miss}}) > 150 \text{ GeV} \) is used to define the signal region. In order to improve the sensitivity of the search, an optimisation of the event selection is performed with simulated data, using well-modelled variables. The lepton and the b-tagged jet are closer to each other when originating from the decay of a top quark than in the case of W+jets and multijet background events. Hence, a criterion imposing the rejection of events with large values of the difference in azimuth between the lepton and the b-tagged jet \( |\Delta \phi(\ell, b)| \) is tested, together with increased \( m_T(\ell, E_{\text{T}}^{\text{miss}}) \) threshold values. Figure 2 shows the distributions of these two variables for the expected background contribution, and for two mass hypotheses considered for each signal model. For each set of cuts on \( m_T(\ell, E_{\text{T}}^{\text{miss}}) \) and \( |\Delta \phi(\ell, b)| \), the sensitivity is estimated by calculating the expected limit on the production cross-section with the procedure described in Sect. 6 including the systematic uncertainties detailed in Sect. 5. The optimisation was performed using one mass hypothesis \( m(f_{\text{met}}) = 100 \text{ GeV} \) for the resonant model, for which the kinematic distributions have only small variations in the studied mass range. For the non-resonant model, characterised by larger variations of the kinematic distributions with \( v_{\text{met}} \), four signal mass hypotheses were studied: \( m(v_{\text{met}}) = 0, 100, 300, \) and 600 GeV. The resulting best-performing selections, for the tested mass hypotheses, are:

- **SRI (resonant model optimisation):**
  \[ m_T(\ell, E_{\text{T}}^{\text{miss}}) > 210 \text{ GeV} \text{ and } |\Delta \phi(\ell, b)| < 1.2 \]
- **SRII (non-resonant model optimisation):**
  \[ m_T(\ell, E_{\text{T}}^{\text{miss}}) > 250 \text{ GeV} \text{ and } |\Delta \phi(\ell, b)| < 1.4 \]
the sub-leading jet satisfies a b-tagging criterion with an efficiency of 80 %, the sub-leading jet satisfies \( p_T < 50 \) GeV, and the events must satisfy \( m_T(T, E_T^{\text{miss}}) > 150 \) GeV and \( |\Delta \phi(T, b)| < 1.8 \) in addition to the pre-selection criteria. The distributions of \( m_T(T, E_T^{\text{miss}}) \) and of \( |\Delta \phi(T, b)| \) in the three control regions are depicted in Fig. 4. Reasonable agreement between the data and the predicted background estimate is found.

5 Systematic uncertainties

The impact of systematic uncertainties is considered on the yields of individual background and signal processes. The main systematic uncertainties are those related to the jet energy scale, the b-tagging efficiency, the effect of the choice of PDF on signal and background acceptance, the effect of the choice of MC generator and of additional radiation on \( t\bar{t} \) modelling, and the effect of the limited size of the samples.

5.1 Sample size

Due to the stringent kinematic cuts in the signal regions, the impact of the limited size of the data and simulated samples on the signal and background estimates is a significant source of systematic uncertainty. For the \( Z+jets, \) multijet, and single-top-quark \( s-\) and \( t-\)channel processes, the expected event yield is zero in both channels, for the SRI and SRII selections, respectively. In such cases, a 68 % confidence level (CL) upper limit on the yields is calculated, assuming a Poisson distribution, and is taken into account in the limit-setting procedure. This upper limit represents at most 10 % of the background contribution.

For the other processes, which have non-negligible contributions, the effect of the limited sample size on expected signal (background) yields varies between 2 and 5 % (2 and 9 %).

5.2 Object modelling

The effect of the uncertainty on the jet energy scale [67] is a change in the signal (background) event yields of 1–5 % (9–10 %), depending on the channel and on the signal region. The impact of the jet energy resolution uncertainty, evaluated by smearing the jet energy in the simulation [73], is a 2–3 % (1–2 %) effect on the signal (background) rates. The systematic uncertainty associated with the efficiency of the cut on the jet vertex fraction results in yield variations of 2–3 % (2–6 %) in the signal (background). Uncertainties on b-tagging efficiency and mistagging rates are estimated from data [68]; the effect on signal and background yields is 3–5 %. The jet reconstruction efficiency uncertainty has an effect below 1 %, except for the background in the SRII region (up to 3 %).

Smaller uncertainties arise from the lepton trigger, reconstruction, and identification efficiencies (up to 1 %) and from lepton energy scale and resolution (up to 1 % for signal and between 1 and 3 % for background). The systematic uncertainties related to leptons and jets are propagated to the \( E_T^{\text{miss}} \). In addition, uncertainties on the estimation of the contributions of calorimeter energy deposits not associated with any reconstructed objects have an effect below 1 % (up to 4 %) on expected signal (background) contribution.

5.3 Signal and background acceptance modelling

The uncertainties on the signal and background acceptance due to the choice of PDF are estimated using the
Fig. 4 Distributions of (left) $m_T(l, E_{\text{miss}})$ and of (right) $\Delta \phi(l, b)$ in (top) the CR1, (middle) the CR2, and (bottom) the CR3 control region, for the electron and muon channels combined. The distributions observed in data, depicted with the points, are compared with the predicted background contributions. In the CR2 and CR3 regions, the negligible multijet contribution is not shown, and neither is the $Z + \text{jets}$ contribution in the CR3 region. The multijet background is normalised by the data-driven method, and the other backgrounds are normalised to their theoretical cross-sections. The error bands correspond to the uncertainties due to the statistical uncertainty of the sample added in quadrature with a conservative 50% normalisation uncertainty on the multijet contribution, and with the $W + \text{jets}$ and $t\bar{t}$ cross-section uncertainties. The ratios of the observed distributions to the predicted background distributions are shown in the lower frame.
The dependence of the $t\bar{t}$ process on the generator and parton showering simulation is evaluated by comparing the nominal sample produced with POWHEG+PYTHIA with three samples generated using the CT10 PDF, one sample produced with POWHEG-BOX v1.2r129, one sample using the ALPGEN LO multileg generator v2.14 [53], and one sample produced using MC@NLO v4.06 [75,76]. HERWIG v6.52 [55] is used for parton showering and hadronisation and JIMMY v4.31 [77] for the underlying event. The largest variation, representing 5–11 % of the total background yield, arises from the comparison with the ALPGEN+HERWIG sample. For $Wt$ production, the nominal POWHEG+PYTHIA sample is compared with a sample produced with MC@NLO v4.06, leading to a variation of 4–6 % on the total background yield. Furthermore, the uncertainty associated with the NLO calculation schemes for the $Wt$ process is evaluated by comparing the nominal sample generated with the diagram subtraction (DS) scheme [78]; this uncertainty is 3–5 % on the total background yield.

The dependence of the $t\bar{t}$ event rate on additional radiation is evaluated using a $t\bar{t}$ sample generated with the ACERMC LO generator v3.8 [38,39], with the CTEQ6L1 PDF set [40], and coupled with PYTHIA v6.426. The PYTHIA parameters are varied in a manner consistent with a measurement of $t\bar{t}$ production with additional jet activity [79]. The related variation in the total background is around 5 % (9 %) in the SRI (SRII) region.

5.4 Background normalisation

Theoretical uncertainties are $-5.9/5.1$ % for the inclusive $t\bar{t}$ cross-section [41–47], and 6.8 % for the $Wt$-channel cross-section [51]. An uncertainty of 24.5 % on diboson and $W$+light-quarks rates is also assigned. These estimates come from the uncertainty on the inclusive diboson and $W$-boson production cross-sections [57] (5 and 4 %, respectively) and from a conservative assessment based on a prediction for the ratio of the event rate with $n + 1$ jets to the event rate with $n$ jets [80,81], resulting in 24 % per additional jet, added in quadrature. A 50 % uncertainty, as evaluated in Ref. [82], is assigned to the $W+bb, W+cc$, and $W+cc$ rates.

5.5 Luminosity

The uncertainty on the integrated luminosity is 2.8 % [25], affecting the signal estimates as well as the simulated backgrounds.

6 Results and interpretation

Figure 5 shows the distributions of $E_T^{\text{miss}}$ in the SRI and SRII signal regions, comparing the data to the expected signal and background contributions. The expected resonant (non-

![Fig. 5 Distributions of $E_T^{\text{miss}}$ in the (left) SRI and (right) SRII signal regions, for the electron and muon channels combined. The distributions observed in data, depicted with the points, are compared with the predicted background contributions, shown stacked together with the expected resonant (non-resonant) signal contribution for the $m(f_{\text{res}}) = 100$ GeV and $m(S) = 500$ GeV ($m(V_{\text{max}}) = 700$ GeV) hypothesis. The expected backgrounds are normalised to their theoretical cross-sections, and the expected resonant (non-resonant) signal is normalised to the theoretical cross-section corresponding to $\delta_{\text{unc}} = 0.1$. The error bands on the expected backgrounds correspond to the uncertainties due to all systematic sources added in quadrature. The first (last) bin includes underflows (overflows). The ratios of the observed distributions to the predicted background distributions are shown in the lower frame.](image-url)
The expected contribution of resonant (non-resonant) signal corresponding to the lowest and highest mass hypotheses considered in this analysis and of SM backgrounds are given. The first quoted uncertainty gives the uncertainty due to statistics. The second one gives the uncertainties due to all other systematic effects, symmetrised, regrouped, and summed quadratically, without taking into account possible anticorrelations between systematic uncertainties and between processes, for the purpose of this table.

Table 1 reports the expected event yields for the background and signal processes and the observed event yields in the SRI and SRII signal regions. As no excess is observed in data, 95% CL upper limits on the signal production cross-sections are set with the CLs procedure \[83,84\]. A log-likelihood ratio (LLR) is used as the test statistic, defined as the ratio of the signal-plus-background hypothesis to the background-only hypothesis. For a given hypothesis, the combined likelihood is the product of the likelihoods for the two channels considered (electron and muon), each resulting from the product of a Poisson distribution representing the statistical fluctuations of the expected total event yield, and of Gaussian distributions representing the effect of the systematic uncertainties. Pseudo-experiments are generated for both hypotheses, taking into account correlations across channels and processes. The fraction of pseudo-experiments for the observed (background median) LLR threshold is set to the observed (background median) LLR.

Figure 6 shows the expected and observed 95% CL limits on the cross section times branching ratio as a function of the mass of \(v_{\text{met}}\) and \(m_{\text{met}}\), respectively. The predicted signal cross-sections for different coupling strengths are also shown.
of the mass of the invisible state, for each of the two signal models. In the case of the resonant model, cross-sections corresponding to an effective coupling strength $a_{\text{res}} = 0.2$ are excluded in the whole mass range, but not cross-sections corresponding to $a_{\text{res}} = 0.1$. For the non-resonant model, cross-sections corresponding to $a_{\text{non-res}} = 0.1$ (0.2, 0.3) are excluded up to $m(v_{\text{met}}) = 432$ GeV (657 GeV, 796 GeV).

The cross-sections are proportional to the square of the effective coupling. Thus, a 95% CL upper limit on $a_{\text{res}}$ and $a_{\text{non-res}}$ as a function of the mass of the invisible states is extracted. The results are shown in Fig. 7. This upper limit is set assuming that the coupling has no effect on the signal acceptance modelling. In the case of the resonant model, in which the increase of the resonance width with increasing coupling strength changes the signal kinematics, this assumption is validated by using two dedicated simulated samples produced with $a_{\text{res}} = 0.5$ and $a_{\text{res}} = 1.0$ instead of $a_{\text{res}} = 0.2$. These two hypotheses are excluded at 95% CL with the same limit-setting procedure. Since the kinematic distributions are similar in the whole $m(f_{\text{met}})$ range, this assumption is valid for all values of the $f_{\text{met}}$ mass. Tables 2 and 3 give the expected and observed 95% CL upper limits on the effective coupling as a function of the mass of the invisible state, for the resonant and non-resonant model, respectively.

### Table 2

<table>
<thead>
<tr>
<th>$m(f_{\text{met}})$ (GeV)</th>
<th>95% CL upper limit on $a_{\text{res}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Expected</td>
</tr>
<tr>
<td>0</td>
<td>0.13</td>
</tr>
<tr>
<td>20</td>
<td>0.13</td>
</tr>
<tr>
<td>40</td>
<td>0.13</td>
</tr>
<tr>
<td>60</td>
<td>0.13</td>
</tr>
<tr>
<td>80</td>
<td>0.14</td>
</tr>
<tr>
<td>100</td>
<td>0.15</td>
</tr>
</tbody>
</table>

### Table 3

<table>
<thead>
<tr>
<th>$m(v_{\text{met}})$ (GeV)</th>
<th>95% CL upper limit on $a_{\text{non-res}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Expected</td>
</tr>
<tr>
<td>0</td>
<td>0.03</td>
</tr>
<tr>
<td>25</td>
<td>0.013</td>
</tr>
<tr>
<td>50</td>
<td>0.022</td>
</tr>
<tr>
<td>75</td>
<td>0.027</td>
</tr>
<tr>
<td>100</td>
<td>0.031</td>
</tr>
<tr>
<td>125</td>
<td>0.034</td>
</tr>
<tr>
<td>150</td>
<td>0.038</td>
</tr>
<tr>
<td>200</td>
<td>0.044</td>
</tr>
<tr>
<td>250</td>
<td>0.055</td>
</tr>
<tr>
<td>300</td>
<td>0.066</td>
</tr>
<tr>
<td>400</td>
<td>0.093</td>
</tr>
<tr>
<td>500</td>
<td>0.13</td>
</tr>
<tr>
<td>600</td>
<td>0.18</td>
</tr>
<tr>
<td>700</td>
<td>0.24</td>
</tr>
<tr>
<td>800</td>
<td>0.32</td>
</tr>
<tr>
<td>900</td>
<td>0.41</td>
</tr>
<tr>
<td>1,000</td>
<td>0.52</td>
</tr>
</tbody>
</table>

### 7 Summary and conclusion

Monotop events are searched for in the $\sqrt{s} = 8$ TeV $pp$ collision data collected in 2012 by the ATLAS experiment at the LHC corresponding to an integrated luminosity of 20.3 fb$^{-1}$. Two classes of signal models are studied, producing right-
handed top quarks together with exotic neutral particles giving rise to missing energy. The semi-leptonic decay mode of the top quark is exploited: events with one isolated electron or muon and one b-tagged jet are selected. No significant deviation from the standard model predictions is observed. Upper limits on the signal cross-sections and on the corresponding effective couplings are set at 95 % CL using the CL$_{s}$ method. In the case of the production of a 500 GeV spin-0 resonance, effective coupling strengths above $\alpha_{\text{res}} = 0.15$ are excluded for a mass of the invisible spin-1/2 state between 0 and 100 GeV. In the case of non-resonant production, effective coupling strengths above $\alpha_{\text{non-res}} = 0.1, 0.2$, and 0.3 are excluded for a mass of the invisible spin-1 state up to 432, 657, and 796 GeV, respectively. The observed 95 % CL limits are compatible with the expectations.

Acknowledgments  We thank CERN for the very successful operation of the LHC, as well as the support staff from our institutions without whom ATLAS could not be operated efficiently. We acknowledge the support of ANPCyT, Argentina; YerPhI, Armenia; ARC, Australia; BMWFW and FWF, Austria; ANAS, Azerbaijan; SSTC, Belarus; CNPq and FAPERJ, Brazil; NSERC, NRC and CFI, Canada; CERN, CONICYT, Chile; CAS, MOST and NSFC, China; COLCIENCIAS, Colombia; MSMT CR, MPO CR and VSC CR, Czech Republic; CSC, DAFNE, DNSRC and Lundbeck Foundation, Denmark; EPLANET, ERC and NSRF, European Union; IN2P3-CNRS, CEA-DSM/IRFU, France; GNSF, Georgia; BMBF, DFG, MPG and AvH Foundation, Germany; GSRT and NSRF, Greece; ISF, MINEH, GIF, I-CORE and Benoziyo Center, Israel; INFN, Italy; MEXT and JSPS, Japan; CNRST, Morocco; FOM and NWO, Netherlands; BRF and RCN, Norway; MNISW and NCN, Poland; GRICES and FCT, Portugal; MINE/IFA, Romania; MES of Russia and ROSATOM, Russian Federation; JINR, MSTD, Serbia; MSSR, Slovakia; ARRS and MIZŠ, Slovenia; DST/NRF, South Africa; MINECO, Spain; SRC and Wallenberg Foundation, Sweden; SER, SNSF and Cantons of Bern and Geneva, Switzerland; NSC, Taiwan; TAEK, Turkey; STFC, the Royal Society and Leverhulme Trust, United Kingdom; DOE and NSF, United States of America. The crucial computing support from all WLCG partners is acknowledged gratefully, in particular from CERN and the ATLAS Tier-1 facilities at TRIUMF (Canada), NDGF (Denmark, Norway, Sweden), CC-IN2P3 (France), KIT/GridKA (Germany), INFN-CNAF (Italy), NL-T1 (Netherlands), PIC (Spain), ASGC (Taiwan), RAL (UK) and BNL (USA) and in the Tier-2 facilities worldwide.

Open Access  This article is distributed under the terms of the Creative Commons Attribution License which permits any use, distribution, and reproduction in any medium, provided the original author(s) and the source are credited. Funded by SCOAP$^3$/License Version CC BY 4.0.

References


4. CMS Collaboration, Search for dark matter, extra dimensions, and unparticles in monojet events in proton–proton collisions at $\sqrt{s} = 8$ TeV. arXiv:1408.3583 [hep-ex]


(a) Faculté des Sciences Ain Chock, Réseau Universitaire de Physique des Hautes Energies-Université Hassan II, Casablanca, Morocco; (b) Centre National de l’Energie des Sciences Techniques Nucleaires, Rabat, Morocco; (c) Faculté des Sciences Semlalia, Université Cadi Ayyad, LPHEA-Marrakech, Marrakech, Morocco; (d) Faculté des Sciences, Université Mohamed Premier and LPTPM, Oujda, Morocco; (e) Faculté des Sciences, Université Mohammed V-Agdal, Rabat, Morocco

DSM/IRFU (Institut de Recherches sur les Lois Fondamentales de l’Univers), CEA Saclay (Commissariat à l’Energie Atomique et aux Energies Alternatives), Gif-sur-Yvette, France

138 Santa Cruz Institute for Particle Physics, University of California Santa Cruz, Santa Cruz, CA, USA

139 Department of Physics, University of Washington, Seattle, WA, USA

140 Department of Physics and Astronomy, University of Sheffield, Sheffield, UK

141 Department of Physics, Shinshu University, Nagano, Japan

142 Fachbereich Physik, Universität Siegen, Siegen, Germany

143 Department of Physics, Simon Fraser University, Burnaby, BC, Canada

144 SLAC National Accelerator Laboratory, Stanford, CA, USA

145 (a) Faculty of Mathematics, Physics and Informatics, Comenius University, Bratislava, Slovak Republic; (b) Department of Subnuclear Physics, Institute of Experimental Physics of the Slovak Academy of Sciences, Kosice, Slovak Republic

146 (a) Department of Physics, University of Cape Town, Cape Town, South Africa; (b) Department of Physics, University of Johannesburg, Johannesburg, South Africa; (c) School of Physics, University of the Witwatersrand, Johannesburg, South Africa

147 (a) Department of Physics, Stockholm University, Stockholm, Sweden; (b) The Oskar Klein Centre, Stockholm, Sweden

148 Physics Department, Royal Institute of Technology, Stockholm, Sweden

149 Departments of Physics and Astronomy and Chemistry, Stony Brook University, Stony Brook, NY, USA

150 Department of Physics and Astronomy, University of Sussex, Brighton, UK

151 School of Physics, University of Sydney, Sydney, Australia

152 Department of Physics, Stockholm University, Stockholm, Sweden; (b) The Oskar Klein Centre, Stockholm, Sweden

153 Department of Pure and Applied Sciences, University of Tsukuba, Tsukuba, Japan

154 Department of Physics and Astronomy, Tufts University, Medford, MA, USA

155 Centro de Investigaciones, Universidad Antonio Narino, Bogota, Colombia

156 Department of Physics and Astronomy, University of California Irvine, Irvine, CA, USA

157 (a) INFN Gruppo Collegato di Udine, Sezione di Trieste, Udine, Italy; (b) ICTP, Trieste, Italy; (c) Dipartimento di Chimica, Fisica e Ambiente, Università di Udine, Udine, Italy

158 Department of Physics, University of Illinois, Urbana, IL, USA

159 Department of Physics and Astronomy, University of Uppsala, Uppsala, Sweden

160 (a) TRIUMF, Vancouver, BC, Canada; (b) Department of Physics and Astronomy, York University, Toronto, ON, Canada

161 Faculty of Pure and Applied Sciences, University of Tsukuba, Tsukuba, Japan

162 Department of Physics and Astronomy, Tufts University, Medford, MA, USA

163 Centro de Investigaciones, Universidad Antonio Narino, Bogota, Colombia

164 Department of Physics and Astronomy, University of California Irvine, Irvine, CA, USA

165 (a) INFN Gruppo Collegato di Udine, Sezione di Trieste, Udine, Italy; (b) ICTP, Trieste, Italy; (c) Dipartimento di Chimica, Fisica e Ambiente, Università di Udine, Udine, Italy

166 Department of Physics, University of Illinois, Urbana, IL, USA

167 Department of Physics and Astronomy, University of Uppsala, Uppsala, Sweden

168 Instituto de Física Corpuscular (IFIC) and Departamento de Física Atómica, Molecular y Nuclear and Departamento de Ingeniería Electrónica and Instituto de Microelectrónica de Barcelona (IMB-CN), University of Valencia and CSIC, Valencia, Spain

169 Department of Physics, University of British Columbia, Vancouver, BC, Canada

170 Department of Physics and Astronomy, University of Victoria, Victoria, BC, Canada

171 Department of Physics, University of Warwick, Coventry, UK

172 Waseda University, Tokyo, Japan

173 Department of Particle Physics, The Weizmann Institute of Science, Rehovot, Israel

174 Department of Physics, University of Wisconsin, Madison, WI, USA

175 Fakultät für Physik und Astronomie, Julius-Maximilians-Universität, Würzburg, Germany

176 Fachbereich C Physik, Bergische Universität Wuppertal, Wuppertal, Germany

177 Department of Physics, Yale University, New Haven, CT, USA