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A search for $t\bar{t}$ resonances with the ATLAS detector in 2.05 fb^{-1} of proton-proton collisions at $\sqrt{s} = 7$ TeV

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Abstract A search for top quark pair resonances in final states containing at least one electron or muon has been performed with the ATLAS experiment at the CERN Large Hadron Collider. The search uses a data sample corresponding to an integrated luminosity of 2.05 fb^{-1}, which was recorded in 2011 at a proton-proton centre-of-mass energy of 7 TeV. No evidence for a resonance is found and limits are set on the production cross-section times branching ratio to $t\bar{t}$ for narrow and wide resonances. For narrow Z' bosons, the observed 95 % Bayesian credibility level limits range from 9.3 pb to 0.95 pb for masses in the range of $m_{Z'} = 500$ GeV to $m_{Z'} = 1300$ GeV. The corresponding excluded mass region for a leptophobic topcolour Z' boson (Kaluza-Klein gluon excitation in the Randall-Sundrum model) is $m_{Z'} < 880$ GeV ($m_{g_{\mathrm{KK}}} < 1130$ GeV).

1 Introduction

The Standard Model of particle physics (SM) is believed to be an effective theory valid up to energies in the TeV range. Since particle masses are central to the breaking of the electroweak symmetry, final states that involve the heaviest of the particles presumed to be elementary, the top quark, offer particular promise in searches for new physics. This Article describes searches for new heavy particles decaying to top quark pairs ($t\bar{t}$) using the ATLAS detector [1] at the CERN Large Hadron Collider (LHC). Multiple final state topologies containing at least one lepton (electron or muon) are considered, in which the lepton is expected to originate from the decay of one of the W bosons produced in the top quark decays. In events with one lepton—the lepton plus jets ($\ell +$ jets) channel—the reconstructed $t\bar{t}$ mass spectrum is used to search for a signal. In events with two leptons—the dilepton channel—the effective mass is used. Both variables are defined in Sect. 8.

The benchmark model used to quantify the experimental sensitivity to narrow resonances is a topcolour Z' boson [2] arising in models of strong electroweak symmetry breaking through top quark condensation [3]. The specific model used is the leptophobic scenario, model IV in Ref. [2] with $f_1 = 1$ and $f_2 = 0$ and a width of 1.2 % of the Z' boson mass. The model used for wide resonances is a Kaluza-Klein (KK) gluon g_{KK}, which appears in Randall-Sundrum (RS) models in which particles are located in a warped dimension [4–7]. The left-handed (g_L) and right-handed (g_R) couplings to quarks take the conventional RS values [5]: $g_L = g_R = -0.2g_s$ for light quarks including charm, where $g_s = \sqrt{4\pi\alpha_s}$; $g_L = 1.0g_s$, $g_R = -0.2g_s$ for bottom quarks; and $g_L = 1.0g_s$, $g_R = 4.0g_s$ for the top quark. In this case, the resonance width is 15.3 % of its mass, larger than the detector resolution.

Previous searches for $t\bar{t}$ resonances were most recently carried out by the CDF [8–12] and D0 [13, 14] collaborations at Run II of the Fermilab Tevatron Collider, and by the CMS collaboration [15] at the LHC. No evidence for new particles was uncovered and 95 % confidence level limits were set on the mass of a leptophobic topcolour Z' boson [16] at $m_{Z'} > 900$ GeV [11] as well as on the coupling strength of a heavy colour-octet vector particle.

2 The ATLAS detector

The ATLAS detector [1] is designed to measure the properties of particles produced in proton-proton (pp) interactions with excellent precision. Its cylindrical geometry, with axis aligned with the proton beams, is augmented by two endcap sections. This results in almost complete 4π solid angle coverage. The Inner Detector (ID) covers pseudorapidities[1] of $|\eta| < 2.5$ and consists of layers of silicon

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[1] ATLAS uses a right-handed coordinate system with its origin at the nominal interaction point (IP) in the centre of the detector and the z-

pixel and strip detectors and a straw-tube transition radiation tracker. It is embedded in the bore of a 2 T superconducting solenoidal magnet to allow precise measurement of charged particle momenta. This system is surrounded by a hermetic calorimeter system consisting of finely segmented sampling calorimeters using lead/liquid-argon for the detection of electromagnetic (EM) showers up to $|\eta| < 3.2$, and copper or tungsten/liquid-argon for hadronic showers for $1.5 < |\eta| < 4.9$. In the central region ($|\eta| < 1.7$), an iron/scintillator hadronic calorimeter is used. Outside the calorimeters, the muon spectrometer incorporates multiple layers of trigger and tracking chambers within an air-core toroidal magnetic field, enabling an independent, precise measurement of muon track momenta.

3 Data sample

The data were collected with the ATLAS detector at the CERN LHC in 2011 using single-lepton triggers with transverse momentum thresholds at 20 GeV or 22 GeV for electrons and 18 GeV for muons. These triggers use similar, but looser selection criteria than the offline reconstruction and reach their efficiency plateaus at 25 GeV (electrons) and 20 GeV (muons).

Only data where all subsystems were operational are used. Applying these requirements to pp collision data recorded with stable beam conditions between March and August 2011 at $\sqrt{s} = 7$ TeV results in a data sample of $2.05 \pm 0.08\ \text{fb}^{-1}$ [17, 18].

4 Simulated samples

The irreducible SM $t\bar{t}$ background is simulated using MC@NLO v3.41 [19, 20] with `CTEQ6.6` [21] parton distribution functions (PDFs), interfaced to HERWIG v6.5 [22] for the parton shower and hadronization steps and JIMMY [23] to model effects due to the underlying event and multiple parton interactions. The top quark mass is set to 172.5 GeV and only events in which at least one of the W bosons decays leptonically are generated. The inclusive cross-section of 165 pb is taken from approximate next-to-next-to-leading-order (NNLO) calculations [24]. Electroweak single top quark production is simulated using the same programs, and cross-sections are based on approximate NNLO calculations: 65 pb (t-channel) [25], 4.6 pb (s-channel) [26] and 15.7 pb (Wt process) [27]. Samples produced with different parameter settings or other Monte Carlo (MC) event generators are used to evaluate the systematic uncertainties due to the top quark mass, modelling of the shape of the $t\bar{t}$ mass distribution (POWHEG [28]), the parton shower model (POWHEG+ HERWIG compared to POWHEG + PYTHIA [29]), and initial- and final-state radiation effects (using ACERMC [30]). These last uncertainties are considered both separately and in a correlated way.

Production of a W or Z boson plus jets with leptonic vector boson decays is simulated with ALPGEN v2.13 [31] and `CTEQ6L1` [32] PDFs in exclusive bins of parton multiplicity for multiplicities lower than five, and inclusively above that. For the Z boson plus jets sample, Z-photon interference is included and events are required to have a dilepton invariant mass in the range $10 < m_{\ell\ell} < 2000$ GeV. The events are processed by HERWIG and JIMMY, and matrix-element–parton-shower matching is performed with the MLM [33] method. The inclusive samples are initially normalized to the NNLO cross-sections [34, 35], and in addition later corrected using data as described in Sect. 7.2 and Sect. 7.3.

Diboson samples for the $\ell +$ jets channel are produced using HERWIG v6.5 with JIMMY and `MRST2007LO`* [36] PDFs with JIMMY. A filter requires the presence of one lepton with $p_{\mathrm{T}} > 10$ GeV and pseudorapidity $|\eta| < 2.8$. The cross-sections used for these filtered samples are 11.8 pb for WW production, 3.4 pb for WZ production, and 0.98 pb for ZZ production. These values are multiplied with "K-factors" of 1.52, 1.58 and 1.20, corresponding to the ratio of the next-to-leading-order (NLO) and leading-order (LO) calculations, and obtained using the MCFM [37, 38] generator. Additional diboson samples for the dilepton channel are simulated using ALPGEN v2.13 with `CTEQ6L1` PDFs and interfaced with HERWIG and JIMMY.

Signal samples for Z' bosons decaying to $t\bar{t}$ are generated using PYTHIA v6.421 with `CTEQ6L1` PDFs allowing all top quark decay modes. Cross-sections for the Z' boson samples are evaluated with an updated calculation [39] to which a K-factor of 1.3 is applied [40]. Samples of KK gluons are generated with MADGRAPH v4.4.51 [41], and showered with PYTHIA without taking into account interference with SM $t\bar{t}$ production, and the cross-sections are recalculated using PYTHIA v8.1 [42]. In both cases, `CTEQ6L1` PDFs are used. The resulting cross-sections are given in Table 1.

After event generation, all samples are processed by a GEANT4-based [43] simulation of the ATLAS detector [44] and reconstructed using the same software as used for data. All simulated samples include the effects due to multiple pp interactions per bunch-crossing, and events are reweighted so that the data and simulated sample instantaneous luminosity profiles match.

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axis along the beam pipe. The x-axis points from the IP to the centre 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 $\eta = -\ln\tan(\theta/2)$.

Table 1 Cross-sections times branching ratios for the resonant signal processes obtained using the generator and PDF combinations described in the text. The KK gluon (Z') cross-sections are given at LO (LO × 1.3)

Signal mass [GeV]	$\sigma \times \mathrm{BR}(Z'/g_{\mathrm{KK}} \to t\bar{t})$ [pb]	
	Topcolour Z'	g_{KK}
500 GeV	19.6	81.2
600 GeV	10.3	39.4
700 GeV	5.6	20.8
800 GeV	3.2	11.6
900 GeV	1.9	6.8
1000 GeV	1.2	4.1
1200 GeV	0.46	1.7
1400 GeV	0.19	0.73
1600 GeV	0.086	0.35
1800 GeV	0.039	0.18
2000 GeV	0.018	0.095

5 Object reconstruction

Electron candidates must have an EM shower shape consistent with expectations based on simulation, test-beam and $Z \to ee$ events in data, and must have a matching track in the ID [45]. They are required to have transverse momentum $p_{\mathrm{T}} > 25$ GeV and $|\eta_{\mathrm{cluster}}| < 2.47$, where η_{cluster} is the pseudorapidity of the calorimeter cluster associated to the candidate. Candidates in the calorimeter transition region at $1.37 < |\eta_{\mathrm{cluster}}| < 1.52$ are excluded.

Muon candidates are reconstructed from track segments in the various layers of the muon chambers, and matched with tracks found in the ID. The final candidates are refitted using the complete track information from both detector systems, and required to satisfy $p_{\mathrm{T}} > 25$ GeV and $|\eta| < 2.5$. Additionally, muons are required to be separated by $\Delta R > 0.4$ from any jet with $p_{\mathrm{T}} > 20$ GeV.

The leptons in each event are required to be isolated [46] to reduce the background due to non-prompt leptons, e.g. from decays of hadrons (including heavy flavour) produced in jets. For electrons, the calorimeter isolation transverse energy in a cone in η-ϕ space of radius $\Delta R = 0.2$ around the electron position[2] is required to be less than 3.5 GeV. The core of the electron energy deposition is excluded and the sum is corrected for transverse shower leakage and pile-up from additional pp collisions. For muons, the calorimeter isolation transverse energy, corrected for muon energy deposition, in a cone of $\Delta R = 0.3$ is required to be less than 4.0 GeV. The scalar sum of track transverse momenta in a cone of $\Delta R = 0.3$ around but excluding the muon track is also required to be less than 4.0 GeV.

Jets are reconstructed with the anti-k_t algorithm [47, 48] with radius parameter $R = 0.4$ from topological clusters [49] of energy deposits in the calorimeters, calibrated at the EM energy scale appropriate for the energy deposited by electrons or photons. These jets are then calibrated to the hadronic energy scale, using a p_{T}- and η-dependent correction factor [49] obtained from simulation, test-beam and collision data. The uncertainty on this correction factor is determined from control samples in data. Jets must have $p_{\mathrm{T}} > 20$ GeV and $|\eta| < 4.5$. If the closest object to an electron candidate is a jet with a separation $\Delta R < 0.2$ the jet is removed in order to avoid double-counting of electrons as jets. While the topological clusters are taken to be massless, jets are composed of many of these, and their spatial distribution within the jet cone leads to an invariant mass [50].

Jets originating from b-quarks are selected by exploiting the long lifetimes of bottom hadrons (about 1.5 ps) leading to typical flight paths before decay of a few millimeters, which are observable in the detector. A multivariate b-tagging algorithm [51] is used in this analysis at an operating point yielding, in simulated $t\bar{t}$ events, an average 60 % b-tagging efficiency and a light quark jet rejection factor of 345.

The missing transverse momentum ($E_{\mathrm{T}}^{\mathrm{miss}}$) is constructed [52] from the vector sum of all calorimeter cells contained in topological clusters. Calorimeter cells are associated with a parent physics object in a chosen order: electrons, jets and muons, such that a cell is uniquely associated to a single physics object. Cells belonging to electrons are calibrated at the electron energy scale, but omitting the out-of-cluster correction to avoid double cell-energy counting, while cells belonging to jets are taken at the corrected energy scale used for jets. Finally, the p_{T} of muons passing selection requirements is included, and the contributions from any calorimeter cells associated to the muons are subtracted. The remaining energy clusters not associated to electrons or jets are included at the EM scale.

For all reconstructed objects in simulation, scaling factors are applied to compensate for the difference in reconstruction efficiencies between data and simulation. The uncertainties on these scaling factors are used to determine the corresponding systematic uncertainties.

6 Event selection

After the event has been accepted by the trigger, it is required to have at least one offline-reconstructed primary vertex with at least five tracks with $p_{\mathrm{T}} > 0.4$ GeV, and it is discarded if any jet with $p_{\mathrm{T}} > 20$ GeV is identified as out-of-time activity or calorimeter noise [49].

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[2] The radius ΔR between the object axis and the edge of the object cone is defined as $\Delta R = \sqrt{(\Delta\phi)^2 + (\Delta\eta)^2}$.

6.1 ℓ + jets channel

The event must contain exactly one isolated lepton, and events where an electron shares an inner detector track with a non-isolated muon, or with a second lepton with $p_{\mathrm{T}} > 15$ GeV, are rejected. The total $t\bar{t}$ event fraction is enhanced by applying the following event-level cuts. In the electron channel, $E_{\mathrm{T}}^{\mathrm{miss}}$ must be larger than 35 GeV and $m_{\mathrm{T}} > 25$ GeV, where m_{T} is the lepton-$E_{\mathrm{T}}^{\mathrm{miss}}$ transverse mass;[3] in the muon channel, $E_{\mathrm{T}}^{\mathrm{miss}} > 20$ GeV and $E_{\mathrm{T}}^{\mathrm{miss}} + m_{\mathrm{T}} > 60$ GeV are required. If one of the jets has mass $m_j > 60$ GeV, the event must contain at least three jets with $p_{\mathrm{T}} > 25$ GeV and $|\eta| < 2.5$; if not, at least four jets satisfying the same p_{T} and η criteria must be present. The leading jet must have $p_{\mathrm{T}} > 60$ GeV, and at least one of the jets must be tagged as a b-jet. The requirement on the number of jets is relaxed when one jet has $m_j > 60$ GeV since for top quarks with significant boost the decay products are collimated, and multiple quarks from top quark or W boson decay can be reconstructed as a single, massive jet. This subsample represents approximately 0.3 % of the selected event sample. The total signal acceptance times branching ratio to $t\bar{t}$ is 7.4 % for a topcolour Z' boson of mass $m_{Z'} = 800$ GeV and 7.3 % for a KK-gluon of mass $m_{g_{\mathrm{KK}}} = 1300$ GeV.

6.2 Dilepton channel

The event selection follows that used in a recent ATLAS $t\bar{t}$ production cross-section measurement [53]. Candidate events are required to have two isolated leptons of opposite charge and two or more jets with $p_{\mathrm{T}} > 25$ GeV. In order to suppress the Z plus jets background, ee and $\mu\mu$ events are required to have an invariant dilepton mass outside the Z boson mass window, defined as $|m_Z - m_{\ell\ell}| < 10$ GeV, and $E_{\mathrm{T}}^{\mathrm{miss}} > 40$ GeV. An additional cut $m_{\ell\ell} > 10$ GeV is applied to the data in order to conform with the lower $m_{\ell\ell}$ cut-off in the Z plus jets simulation and to reduce backgrounds from meson resonances. In the $e\mu$ channel the non-$t\bar{t}$ background is suppressed by requiring the scalar sum of the transverse momenta of the identified leptons and jets to be larger than 130 GeV. The total signal acceptance times branching ratio to $t\bar{t}$ is 1.3 % for a topcolour Z' boson of mass $m_{Z'} = 800$ GeV and 1.5 % for a KK-gluon of mass $m_{g_{\mathrm{KK}}} = 1100$ GeV.

7 Data-driven background modelling

For the dominant background sources, $t\bar{t}$ and single top production, W plus jets in the ℓ + jets channel and Z plus jets in the dilepton channel, the simulated samples are corrected based on measurements in data. The multijet background is determined directly from data. All other backgrounds are taken without modification from simulation.

7.1 SM $t\bar{t}$ and single top modelling

As discussed in Sect. 4, the SM $t\bar{t}$ and single top backgrounds are simulated using the MC@NLO generator with `CTEQ6.6` PDFs. To investigate the impact of the choice of PDFs on modelling of this dominant background, the events are re-weighted to `MSTW2008nlo` [54] PDFs and the data are compared to the background expectation for angular variables: jet and lepton rapidities, and azimuthal angles between these objects and $E_{\mathrm{T}}^{\mathrm{miss}}$. Since the use of `MSTW2008nlo` leads to better agreement in these angular variables, samples re-weighted to these PDFs are used in the analysis. Distributions obtained with `CTEQ6.6` PDFs are used to estimate the systematic uncertainty associated with this shape modelling.

7.2 W plus jets corrections

For the ℓ + jets channel, the W plus jets background is determined using the ALPGEN samples described in Sect. 4, with data-driven corrections.

The flavour composition is determined from data based on the tagged fraction of W plus one- and two-jet events [55], and the known b-tagging efficiencies, measured using various techniques involving jets containing muons [56]. The MC predictions for different flavour contributions are scaled accordingly, adjusting the "light parton" scale factor to keep the untagged W plus two jets normalization unchanged. The $Wb\bar{b}$ and $Wc\bar{c}$ components are scaled by a factor 1.63, the Wc component by a factor 1.11, and the "light parton" component by a factor 0.83. The flavour composition uncertainty of the W plus jets background is estimated by varying these scaling factors by their uncertainties (13 % for $Wb\bar{b}$ and $Wc\bar{c}$, 9 % for Wc).

Normalization factors are derived based on the charge asymmetry in W boson production at the LHC [57]:

$$(N_{W^+} + N_{W^-})^{\mathrm{exp}} = \left(\frac{r_{\mathrm{MC}} + 1}{r_{\mathrm{MC}} - 1}\right)(N_{W^+} - N_{W^-})^{\mathrm{data}}$$

where N_{W^+} and N_{W^-} are the number of events with W^+ and W^- bosons, $r_{\mathrm{MC}} = N_{W^+}/N_{W^-}$, and the superscripts "exp" and "data" denote expected and data events, respectively. The difference $(N_{W^+} - N_{W^-})^{\mathrm{data}}$ and ratio r_{MC} are extracted from data and simulation, respectively, as a function of the number of b-tags and the number of reconstructed jets passing the selection cuts. The background contamination in the W boson samples extracted from data is verified to be charge-symmetric within uncertainties, and cancels in

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[3] The transverse mass is defined by the formula $m_{\mathrm{T}} = \sqrt{2p_{\mathrm{T}}^{\ell}E_{\mathrm{T}}^{\mathrm{miss}}(1-\cos\Delta\phi)}$, where p_{T}^{ℓ} is the lepton p_{T} and $\Delta\phi$ is the azimuthal angle between the lepton and $E_{\mathrm{T}}^{\mathrm{miss}}$.

the difference. In the tagged four-jet bin, an overall normalization factor for the simulated samples of 0.91 (0.81) is required in the electron (muon) channel to match the data-driven prediction. The overall normalization uncertainty on the W plus jets background is set at 48 %, based on an uncorrelated, 24 %–per-jet uncertainty with respect to the inclusive W boson production cross-section [58].

7.3 Z plus jets corrections

Even though the event selection in the dilepton channel includes cuts to reject Z plus jets events, a small fraction of events in the $E_{\mathrm{T}}^{\mathrm{miss}}$ tails and dilepton invariant mass sidebands remain. To estimate this background contribution, the number of Drell-Yan events is measured in a data control sample orthogonal to the signal sample [53]. The control sample consists of events with at least two jets, a dilepton invariant mass inside the Z boson mass window, and $E_{\mathrm{T}}^{\mathrm{miss}} > 40$ GeV.

A small contamination in the control sample from non-Z-boson processes is subtracted from data using simulation. A scale factor is then derived based on ALPGEN Z plus jets samples to extrapolate the data-to-MC differences measured in the control region (CR) into the signal region (SR):

$$N_{Z+\mathrm{jets}}^{\mathrm{SR}} = \frac{(\mathrm{Data}^{\mathrm{CR}} - \mathrm{MC}_{\mathrm{other}}^{\mathrm{CR}})}{\mathrm{MC}_{N_{Z+\mathrm{jets}}}^{\mathrm{CR}}} \mathrm{MC}_{N_{Z+\mathrm{jets}}}^{\mathrm{SR}}$$

where $\mathrm{MC}_{N_{Z+\mathrm{jets}}}^{\mathrm{SR/CR}}$ represents the expected number of events in the signal and control regions, respectively. $\mathrm{MC}_{\mathrm{other}}^{\mathrm{CR}}$ is the number of events from non-Z contamination in the control region. $\mathrm{Data}^{\mathrm{CR}}$ is the observed number of events in the control region. The Z plus jets background normalization prediction from the simulation is thus scaled by the ratio of data to simulated events in the control region. In the $\ell+$jets channel the background from Z plus jets production is small and evaluated directly from the simulation.

7.4 Multijet background estimation

Jets, including those containing a leptonically decaying bottom or charmed hadron, can fake the isolated lepton signature produced by vector boson decays. Multijet events can thus contain objects that pass the lepton selection but are not leptons from vector boson decays, and contribute to the selected events. In the $\ell+$jets channel, the multijet background expectation and kinematic distributions are determined using the method described below. It models the multijet background with a data-driven template, which is normalized in the multijet-dominated low $E_{\mathrm{T}}^{\mathrm{miss}}$ region. Since the multijet background in the b-tagged samples is dominated by true, non-prompt leptons from heavy flavour quark decays in both electron and muon samples, the template is used for both samples.

Events for the template are selected from a jet-triggered sample where exactly one jet with a high electromagnetic fraction (between 0.8 and 0.95) is present. This jet, which in addition must have at least four tracks to reduce the contribution from photon conversions, is used to model the lepton candidate. Events in which a good electron candidate is present are rejected, yielding a sample highly enriched in multijet background with kinematic characteristics very similar to the multijet events that do pass all the lepton selection cuts.

To determine the normalization of the multijet background, the data-driven multijet template and the simulated $t\bar{t}$, single top, W plus jets and Z plus jets background samples are fitted to the data using the full $E_{\mathrm{T}}^{\mathrm{miss}}$ spectrum, i.e. applying all selections except the $E_{\mathrm{T}}^{\mathrm{miss}}$ cut. Other contributions are negligible after all selection cuts. For MC samples, each bin is allowed to vary according to a Gaussian distribution centred at the bin height, with 10 % RMS to account for their own modelling uncertainties. The multijet background and signal $E_{\mathrm{T}}^{\mathrm{miss}}$ spectra are sufficiently different so that fitting the multijet contribution to the full distribution will not mask a potential signal. The multijet template is determined before b-tagging to reduce statistical fluctuations. The kinematic distributions in both tagged and untagged samples have been verified to agree in shape within the available statistics in data.

In the dilepton channel, the small multijet background contribution is estimated from data using the Matrix Method [59], which accounts for small backgrounds with both one (W plus jets background) and two objects (multijet background) mimicking leptons from vector boson decays.

8 Mass reconstruction

8.1 $\ell+$jets channel

To reconstruct the $t\bar{t}$ invariant mass, the neutrino's longitudinal momentum (p_z) is determined by imposing the W boson mass constraint. If the discriminant of the quadratic equation is negative, a situation usually due to $E_{\mathrm{T}}^{\mathrm{miss}}$ resolution effects, the smallest changes to the $E_{\mathrm{T}}^{\mathrm{miss}}$ x and y components that lead to a null discriminant are applied [60], leading to an improved resolution for those two components. If there are two solutions, the smallest p_z solution is chosen.

Different mass reconstruction algorithms are used for the samples with or without a jet with $m_j > 60$ GeV. In the sample without such a jet, the dominant source of long, non-Gaussian tails in the mass resolution is the inclusion of a jet from initial- or final-state radiation in place of one of the jets directly related to a top quark decay product. To reduce this contribution, the four leading jets with $p_{\mathrm{T}} > 20$ GeV and $|\eta| < 2.5$ are considered, and a jet is excluded if its

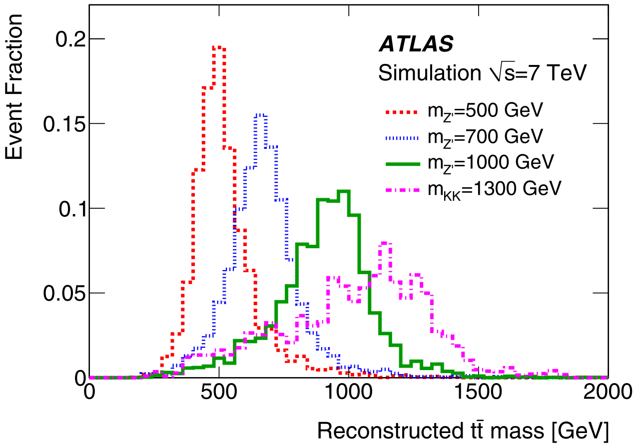


Fig. 1 Reconstructed $t\bar{t}$ pair invariant mass in simulation for four resonance masses: $m_{Z'} = 500$, 700, 1000 and $m_{g_{\mathrm{KK}}} = 1300$ GeV

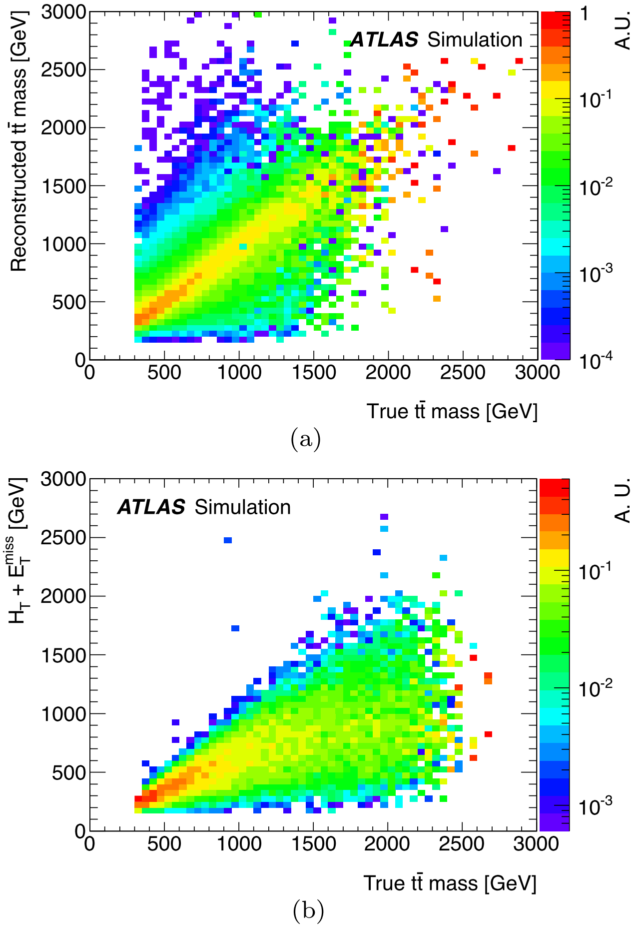
angular distance to the lepton or closest jet satisfies $\Delta R > 2.5 - 0.015 \times (m_j/\mathrm{GeV})$. If more than one jet satisfies this condition, the jet with the largest ΔR is excluded. If a jet was discarded and more than three jets remain, the procedure is iterated. Then $m_{t\bar{t}}$ is reconstructed from the lepton, $E_{\mathrm{T}}^{\mathrm{miss}}$ and the leading four jets, or three jets if only three remain. The ΔR cut removes jets that are well-separated from the rest of the activity in the event. Furthermore, by requiring only three jets in the mass reconstruction, the method allows one of the jets from top quark decay to be outside the detector acceptance, or merged with another jet.

For events with high $t\bar{t}$ mass, the top quark and W boson momenta can be large enough for some of the decay products to be merged into a single jet, in which case using the four highest p_{T} jets often leads to a significant overestimation of $m_{t\bar{t}}$, causing a substantial contribution to the very high mass tail. To mitigate this, if one of the jets has mass $m_j > 60$ GeV, it is combined with the jet closest to it (in ΔR) with $p_{\mathrm{T}} > 20$ GeV to form the hadronic top quark candidate, and the other top quark is formed by combining the reconstructed leptonic W boson candidate with, among those remaining, the jet with $p_{\mathrm{T}} > 20$ GeV closest to it.

The mass resolution obtained from simulation is shown in Fig. 1 using a few signal masses, and the correlation between true and reconstructed $t\bar{t}$ mass ($m_{t\bar{t}}$) is shown in Fig. 2(a).

8.2 Dilepton channel

The dilepton channel is kinematically underconstrained due to the presence of two undetected neutrinos. The effective mass is correlated with $m_{t\bar{t}}$ and is defined as $H_{\mathrm{T}} + E_{\mathrm{T}}^{\mathrm{miss}}$, where H_{T} is the scalar sum of transverse momenta of the leptons and the two leading jets. The correlation between true $t\bar{t}$ mass and reconstructed $H_{\mathrm{T}} + E_{\mathrm{T}}^{\mathrm{miss}}$ is shown in Fig. 2(b).



(a)

(b)

Fig. 2 (**a**) Reconstructed versus true $t\bar{t}$ pair invariant mass in the $\ell+$jets channel and (**b**) effective mass ($H_{\mathrm{T}} + E_{\mathrm{T}}^{\mathrm{miss}}$) versus true $t\bar{t}$ invariant mass in the dilepton channel. The spectrum is normalized to unity for each bin in the true $t\bar{t}$ mass to show the correlation over a large mass range better

9 Systematic uncertainties

Since the search for resonances is done using binned $m_{t\bar{t}}$ and $H_{\mathrm{T}} + E_{\mathrm{T}}^{\mathrm{miss}}$ distributions, two categories of systematic uncertainties are considered: uncertainties in the normalization of the expected event yield, which do not impact the shapes of the different contributions, and uncertainties affecting the shape of the $m_{t\bar{t}}$ or effective mass distributions, which can also impact the event yields.

Systematic uncertainties that affect only the normalization of the different backgrounds come from the uncertainty on the integrated luminosity (3.7 %); the lepton trigger and reconstruction efficiencies ($\leq$1.5 %); and background normalizations: $t\bar{t}$ ($^{+7.0}_{-9.6}$ % [24]), single top (10 %), diboson (5 %), W or Z plus jets in the $\ell+$jets channel (48 %), Z plus jets in the dilepton channel (12 %), W plus jets and multijet in the dilepton channel (76 %), multijet in the $\ell+$jets channel (50 %).

The dominant uncertainties that affect both yields and shape in the $\ell+$jets channel arise from the b-tagging efficiency [56], with 13 % (17 %) variation in the background ($m_{Z'} = 800$ GeV signal) yields, jet energy scale including pile-up effects, 15 % (4 %) [49], and modelling of initial- and final-state radiation, 7 % (6 %). The first two have been determined from data by comparing results from different methods and/or data samples, while the last has been estimated from MC simulations in which the relevant parameters were varied [61].

The largest shape uncertainties in the dilepton channel arise from the modelling of initial- and final-state radiation, with 1.0 % (5.1 %) variation in the background ($m_{g_{\mathrm{KK}}} = 1000$ GeV signal) yields, the jet energy scale 2.5 % (3.0 %) and PDFs 3.7 % (0.6 %).

Other uncertainties arising from MC modelling as well as object identification and momentum measurements have smaller impact. These include the following: jet energy resolution and reconstruction efficiency, muon p_{T} resolution, electron energy scale and energy resolution, $E_{\mathrm{T}}^{\mathrm{miss}}$ measurement, $m_{t\bar{t}}$ shape (as evaluated by comparison of POWHEG with MC@NLO), parton shower and fragmentation (PYTHIA versus HERWIG), W plus jets shape (evaluated by varying ALPGEN generation parameters), W plus jets composition (from the uncertainty in Wc and $Wc\bar{c} + Wb\bar{b}$ fractions), mis-modelling of the multijet background shape, as well as potential effects due to mis-modelling of pile-up effects.

10 Comparison of data and background expectation

Tables 2 and 3 compare the predicted and observed event yields after applying the event selection cuts described in Sect. 6 for the $\ell+$jets and dilepton channels, respectively.

Table 2 Number of expected and observed events for the e and $\mu+$jets channels after applying all selection cuts described in Sect. 6. The uncertainties given are the normalization uncertainties as described in Sect. 9. Statistical uncertainties on these numbers are small

	Electron channel	Muon channel
$t\bar{t}$	7830 ± 750	10000 ± 960
Single top	470 ± 50	570 ± 60
W plus jets	1120 ± 540	1450 ± 700
Z plus jets	85 ± 40	90 ± 45
Diboson	18 ± 1	18 ± 1
Multijet	340 ± 170	470 ± 240
Total expected	9860 ± 940	12600 ± 1210
Data observed	9622	12706
$m_{g_{Z'}} = 800$ GeV	200	224
$m_{g_{\mathrm{KK}}} = 1300$ GeV	59	65

Table 3 Number of expected and observed events in the dilepton channel after applying all selection cuts described in Sect. 6. The uncertainties shown are all normalization uncertainties as described in Sect. 9. Statistical uncertainties on these numbers are small

	Dilepton channel
$t\bar{t}$	4020 ± 470
Single top	210 ± 30
Z plus jets	570 ± 70
Diboson	185 ± 30
W plus jets and Multijet	190 ± 145
Total expected	5200 ± 500
Data observed	5304
$m_{g_{Z'}} = 800$ GeV	77
$m_{g_{\mathrm{KK}}} = 1100$ GeV	75

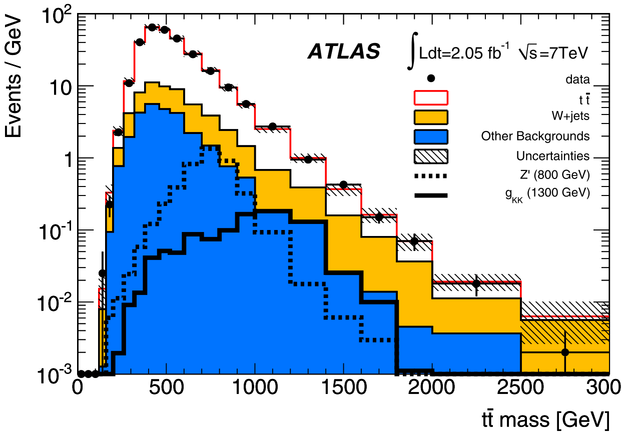


Fig. 3 Reconstructed $t\bar{t}$ mass in the $\ell+$jets channel after all cuts, with the expectation from SM background and two signal masses, a Z' boson with $m_{Z'} = 800$ GeV and a KK gluon with $m_{g_{\mathrm{KK}}} = 1300$ GeV. The electron and muon channels have been added together and all events beyond the range of the histogram have been added to the last bin. "Other backgrounds" includes single top, Z plus jets, diboson and multijet production. The hatched area shows the background normalization uncertainties

The reconstructed $m_{t\bar{t}}$ distribution is shown for data and background expectation as well as two signal masses in Fig. 3. Figure 4 shows the $H_{\mathrm{T}} + E_{\mathrm{T}}^{\mathrm{miss}}$ distribution for data and SM expectation together with a hypothetical KK-gluon signal with a mass of 1100 GeV for comparison. (The dilepton channel has very limited sensitivity to topcolour Z' bosons.) In both the $\ell+$jets and dilepton channels good agreement is found between data and expected background in the event yields as well as the shapes of kinematic distributions.

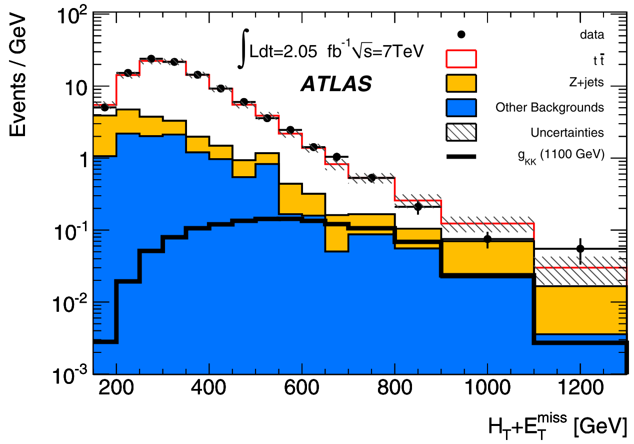
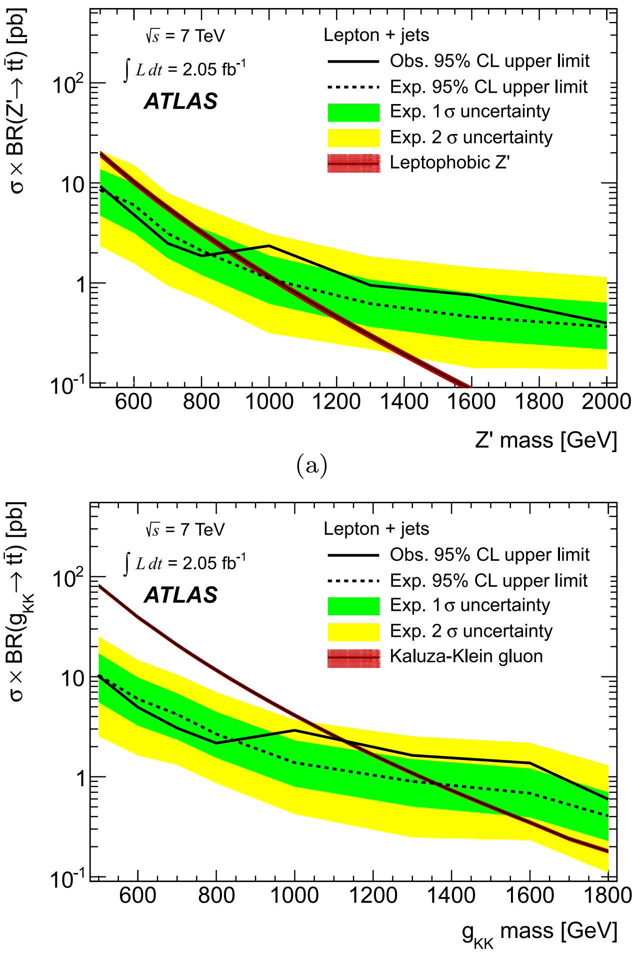


Fig. 4 The $H_T + E_T^{\text{miss}}$ distribution after all selection requirements in the dilepton channel with a KK-gluon signal of mass $m_{g_{KK}} = 1100$ GeV for comparison. "Other backgrounds" includes single top, diboson, W plus jets, and multijet production. The hatched area shows the background normalization uncertainties

11 Results

The results of this search are obtained by comparing the $m_{t\bar{t}}$ and $H_T + E_T^{\text{miss}}$ distributions with background-only and signal-plus-background hypotheses. The significance of a potential signal is summarized by a p-value, the probability of observing, in the absence of signal, an excess at least as signal-like as the one observed in data. The outcome of the search is ranked using the BUMPHUNTER [62] algorithm for the $\ell +$jets channel and a likelihood ratio test statistic for the dilepton channel. No significant deviations from SM expectations are observed.

Given the absence of a signal, upper limits are set on cross-section times branching ratio ($\sigma \times$ BR) as a function of mass using a Bayesian approach [63]. For the limit setting, the $\ell +$jets channel uses variable-size binning, with bins ranging in size from 40 GeV to 500 GeV bins for narrow resonances, and 80 GeV to 500 GeV for Kaluza-Klein gluons. These values are close to the mass resolution while limiting bin-by-bin statistical fluctuations. Mass values below 500 GeV, i.e. the $t\bar{t}$ threshold region, are not considered. A single bin contains all events with $m_{t\bar{t}} > 2.5$ TeV. In the dilepton channel variable-sized bins are used with bins ranging in size from 50 GeV to 200 GeV to maximize sensitivity while limiting bin-by-bin statistical fluctuations. The last bin contains all events with $H_T + E_T^{\text{miss}} > 1.1$ TeV.



(a)

(b)

Fig. 5 Observed (*solid line*) and expected (*dashed line*) 95 % CL upper limits on (**a**) $\sigma \times \text{BR}(Z' \to t\bar{t})$ and (**b**) $\sigma \times \text{BR}(g_{KK} \to t\bar{t})$ for the $\ell +$jets channel. The inner and outer bands show the range in which the limit is expected to lie in 68 % and 95 % of pseudo-experiments, respectively, and the *bold lines* correspond to the predicted cross-section times branching ratio in the leptophobic topcolour and RS models. The bands around the signal cross-section curves represent the effect of the PDF uncertainty on the prediction

The likelihood function is defined as the product of the Poisson probabilities over all bins of the reconstructed $t\bar{t}$ invariant mass or $H_T + E_T^{\text{miss}}$ distribution in the $\ell +$jets or dilepton channel, respectively. The Poisson probability in each bin is evaluated for the observed number of data events given the background and signal template expectation. The total signal acceptance as a function of mass is propagated into the expectation. To calculate a likelihood for combined channels, the likelihoods of the individual channels are multiplied.

The posterior probability density is calculated using Bayes' theorem, with a flat positive prior in the signal cross-section which is found to be a good approximation of the reference prior [64]. Systematic uncertainties are incorporated using nuisance parameters that smear the parameters of the Poisson probability in each bin. For each systematic uncertainty a Gaussian prior controls the probability for a given deviation of the parameter from the nominal value. The 95 % credibility level (CL) upper limit on the signal cross-section times branching ratio is identified with the 95 % point of the posterior probability. The expected limits are determined by using the background expectation instead of the data in the limit computation, and the one and two standard-deviation

Table 4 Expected and observed 95 % CL upper limits on $\sigma \times \mathrm{BR}(Z' \to t\bar{t})$ for the $\ell +$jets channel

Mass [GeV]	Z' Exp. [pb]	Z' Obs. [pb]
500	8.5	9.3
600	6.0	4.8
700	3.1	2.5
800	2.1	1.9
1000	1.1	2.4
1300	0.62	0.95
1600	0.46	0.76
2000	0.37	0.40

Table 5 Expected and observed 95 % CL upper limits on $\sigma \times \mathrm{BR}(g_{\mathrm{KK}} \to t\bar{t})$

Mass [GeV]	g_{KK} Exp. [pb]	g_{KK} Obs. [pb]
$\ell +$jets channel		
500	10.3	10.1
600	6.0	5.0
700	4.2	3.1
800	2.7	2.2
1000	1.4	2.9
1300	0.90	1.6
1600	0.68	1.4
1800	0.41	0.60
Dilepton channel		
500	17.0	19.6
600	11.3	18.5
700	7.6	11.7
800	5.7	7.6
1000	3.2	3.4
1300	2.7	2.3
1600	2.8	2.9
1800	3.1	3.4

bands around these limits are determined from the distribution of limits in pseudo-experiments.

Systematic uncertainties degrade the expected cross-section limits by a factor ranging from 3.0 at low mass to 1.5 at high mass. Of the 32 systematic uncertainties considered, none contribute individually more than 15 % of the degradation.

For the $\ell +$jets channel the 95 % CL observed limits on narrow and wide resonances are shown in Fig. 5, together with the predicted cross-section times branching ratio for the models considered and the expected limits. Numerical values are given in Tables 4 and 5. The observed (expected) 95 % CL limit on $\sigma \times \mathrm{BR}(Z' \to t\bar{t})$ ranges from 9.3 (8.5) pb at $m_{Z'} = 500$ GeV to 0.95 (0.62) pb at $m_{Z'} = 1300$ GeV.

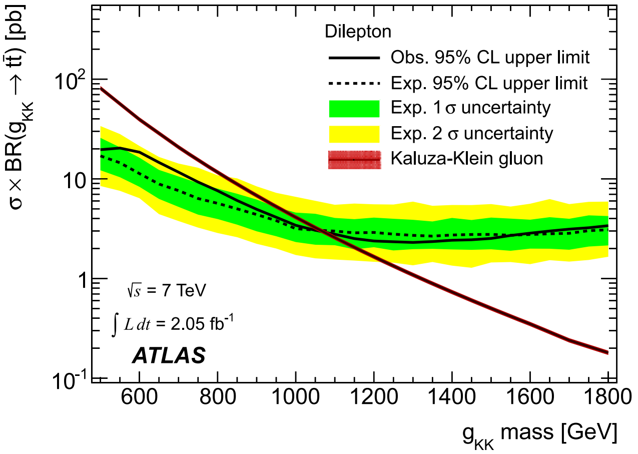


Fig. 6 Observed (*solid line*) and expected (*dashed line*) 95 % CL upper limits on $\sigma \times \mathrm{BR}(g_{\mathrm{KK}} \to t\bar{t})$ for the dilepton channel. The inner and outer bands show the range in which the limit is expected to lie in 68 % and 95 % of pseudo-experiments, respectively, and the *bold line* corresponds to the predicted cross-section times branching ratio for the RS model. The band around the signal cross-section curve represents the effect of the PDF uncertainty on the prediction

The mass range 500 GeV $< m_{Z'} <$ 880 GeV is excluded at 95 % CL. The expected mass exclusion is 500 GeV $< m_{Z'} <$ 1010 GeV.[4] The observed (expected) 95 % CL limit on $\sigma \times \mathrm{BR}(g_{\mathrm{KK}} \to t\bar{t})$ ranges from 10.1 (10.3) pb at $m_{g_{\mathrm{KK}}} = 500$ GeV to 1.6 (0.9) pb at $m_{g_{\mathrm{KK}}} = 1300$ GeV. g_{KK} resonances with mass between 500 GeV and 1130 GeV are excluded at 95 % CL, while the expected mass exclusion is 500 GeV $< m_{g_{\mathrm{KK}}} <$ 1360 GeV.

For the dilepton channel, the 95 % CL limits on the g_{KK} resonance are shown in Fig. 6 with numerical values summarized in Table 5. The observed (expected) 95 % CL limit on $\sigma \times \mathrm{BR}(g_{\mathrm{KK}} \to t\bar{t})$ ranges from 19.6 (17.0) pb at $m_{g_{\mathrm{KK}}} = 500$ GeV to 2.3 (2.7) pb at $m_{g_{\mathrm{KK}}} = 1300$ GeV. This result excludes g_{KK} resonances with masses between 500 GeV and 1080 GeV at 95 % CL while the expected mass exclusion is 500 GeV $< m_{g_{\mathrm{KK}}} <$ 1070 GeV. No limit is set on $m_{Z'}$ in the dilepton channel.

Combining the $\ell +$jets and dilepton channels does not lead to a significant improvement in the limits. However, the dilepton channel, with different background composition and systematics, provides an important and largely independent cross-check of the result.

12 Summary

A search for top quark pair resonances in the $\ell +$jets and dilepton final states has been performed with the ATLAS

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[4] For comparison with the Tevatron, the observed (expected) 95 % CL exclusion limit is 500 GeV $< m_{Z'} <$ 860 (930) GeV when using the old LO cross-section calculation [2].

experiment at the LHC. The search uses a data sample corresponding to an integrated luminosity of 2.05 fb^{-1}, recorded at a proton-proton centre-of-mass energy of 7 TeV. The data are found to be consistent with Standard Model background expectations. Using the reconstructed $t\bar{t}$ mass ($H_{\mathrm{T}} + E_{\mathrm{T}}^{\mathrm{miss}}$) spectrum in the $\ell +$ jets (dilepton) channel, limits are set on the production cross-section times branching ratio to $t\bar{t}$ for narrow and wide resonances. In the narrow Z' benchmark model, observed 95 % CL limits range from 9.3 pb at $m = 500$ GeV to 0.95 pb at $m = 1300$ GeV, and a leptophobic topcolour Z' boson with 500 GeV $< m_{Z'} <$ 880 GeV is excluded at 95 % CL. In the wide resonance benchmark model, Randall-Sundrum Kaluza-Klein gluons are excluded at 95 % CL with masses between 500 GeV and 1130 GeV.

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