Search for TeV-scale gravity signatures in final states with leptons and jets with the ATLAS detector at $\sqrt{s} = 7$ TeV


DOI
10.1016/j.physletb.2012.08.009

Publication date
2012

Document Version
Final published version

Published in
Physics Letters B

Citation for published version (APA):

General rights
It is not permitted to download or to forward/distribute the text or part of it without the consent of the author(s) and/or copyright holder(s), other than for strictly personal, individual use, unless the work is under an open content license (like Creative Commons).
Search for TeV-scale gravity signatures in final states with leptons and jets with the ATLAS detector at $\sqrt{s} = 7$ TeV

ATLAS Collaboration

1. Introduction

Models proposing extra spatial dimensions address the mass hierarchy problem, the origin of the sixteen orders of magnitude separation between the electroweak and Planck scales. These allow the gravitational field to propagate into the $(n+4)$ dimensions, where $n$ is the number of extra spatial dimensions, while Standard Model (SM) fields are constrained to lie in our four-dimensional brane. Consequently, the resulting Planck scale in $(n+4)$ dimensions, $M_{\text{P}}$, is greatly diminished compared to the four-dimensional analogue, $M_{\text{P}4}$, and should be near the other fundamental scale, the electroweak scale, if the hierarchy problem is to be addressed. Such low-scale gravity models allow the existence of gravitational states such as black holes and, within the context of weakly-coupled string theory, string balls, that could be produced with appreciable cross sections at the Large Hadron Collider (LHC).

Two such extra-dimensional scenarios are the Randall–Sundrum models [1] and the large, flat extra-dimensional ADD models [2,3]. In the large extra dimension scenario, there are a number $n > 1$ of additional flat extra dimensions, and $M_D$ is determined by the volume and shape of the extra dimensions. Within the context of this model, experimental lower limits on the value of $M_D$ have been obtained from experiments at LEP [4] and the Tevatron [5,6], as well as at ATLAS [7,8] and CMS [9], by searching for production of the heavy Kaluza–Klein gravitons associated with the extra dimensions. The most stringent limits [7] come from the LHC analyses that search for non-interacting gravitons recoiling against a single jet (monojet) and large missing transverse energy, and range from $M_D > 2.0$ TeV, for $n = 6$, to $M_D > 3.2$ TeV, for $n = 2$. Due to the greatly enhanced strength of gravitational interactions at short distances, or high energies, the formation of gravitational states such as black holes or string balls at the LHC is another signature of extra-dimensional models.

Large extra dimensions can be embedded into weakly-coupled string theory [10,11]. In these models, black holes end their Hawking evaporation phase when their mass reaches a critical value $M_S/g_s^2$, also known as the correspondence point, where $M_S$ and $g_s$ are the string scale and coupling constant, respectively. At this point they transform into high-entropy string states – string balls – which, in turn, continue to decay thermally. The semi-classical approximations used in the modelling of black hole production are valid only for partonic centre-of-mass energies well above $M_D$, motivating the use of a minimal threshold $M_{\text{TH}}$ to remove contributions where the modelling is not reliable. The resulting black hole mass distribution ranges from this threshold up to $\sqrt{s}$. The precise mass value above which the production of such high multiplicity states is feasible is uncertain. A conservative interpretation [12,13] is that $M_{\text{TH}} > 3M_S$ for string balls and $M_{\text{TH}} > 5M_D$ for black holes.

Thermal radiation is thought to be emitted by black holes due to quantum effects [14]. A black hole, in $(n+4)$ dimensions, of given mass and angular momentum is characterised by a Hawking temperature, which is higher for a lighter, or more strongly rotating, black hole. Grey-body factors modify the spectrum of emitted particles from that of a perfect thermal black body [15], by quantifying the transmission probability through the curved space–time outside the horizon; these emissivities depend upon particle spin, $n$ and the properties of the black hole. All Standard Model particles are emitted.

As the black hole mass approaches the Planck scale and few further emissions are expected, quantum effects become important and classical evaporation is no longer a suitable description. The
remaining black hole remnant is decayed to a small number of SM particles.\(^3\)

Were black hole states\(^2\) to be produced at the LHC, they would decay to final states with a relatively high multiplicity of high-\(p_T\) particles, most commonly jets. While the multiplicity is generally high, the exact spectrum is rather model dependent: for example, the inclusion of black hole rotation leads to a somewhat lower multiplicity of higher energy emissions\([16]\). One of the few more robust predictions of these models is the expectation that particles are produced approximately according to their degrees of freedom, (with some modification by the relative emissivities). This is the “democratic” or “universal” coupling of gravity. Thus, the probability for the production of a leptonic final state varies primarily with the emission multiplicity, which depends upon model parameters and the remnant state treatment. Nonetheless, this multiplicity dependence is much reduced compared to using the multiplicity directly, for even low multiplicity decays will frequently contain a lepton. Hence, these models predict the existence of at least one high-\(p_T\) lepton\(^2\) in a significant fraction (\(\sim 15\%\)–50\%) of final states for black holes or string balls with \(M_D\) and \(M_{\text{ch}}\) values in the range accessible to LHC experiments and not already excluded. The largest theoretical uncertainties in the modelling of these states are the limited knowledge of gravitational radiation and the resultant cross section during the formation phase, and the uncertainties of the decay process as the black hole mass approaches \(M_D\), especially the treatment of the remnant state.

Searches for these gravitational states have previously been performed by investigating final states with multiple high-\(p_T\) objects\([17]\), high-\(p_T\) jets only, and in dimuon events\([8]\). This analysis searches for an excess of multi-object events produced at high \(\sum p_T\), defined as the scalar sum of \(p_T\) of the reconstructed objects selected (hadronic jets, electrons and muons). Only events containing at least one isolated electron or muon are selected. While jets should dominate the decays of black holes, the rate for lepton production is anticipated to be smaller, as noted above. Additionally, the requirement of a high-\(p_T\) lepton significantly reduces the dominant multi-jet background, whilst maintaining a high efficiency for black hole events.

This search considers final states with three or more selected objects (leptons or jets), and consequently is not sensitive to two-body final states, as predicted in so-called quantum black hole states\([18]\). Results for two-body final states can be found in Ref.\([19]\).

2. The ATLAS detector

The ATLAS detector\([20]\) is a multipurpose particle physics apparatus with a forward–backward symmetric cylindrical geometry and nearly \(4\pi\) coverage in solid angle.\(^4\) The layout of the detector is dominated by four superconducting magnet systems, which comprise a thin solenoid surrounding inner tracking detectors and three large toroids, each consisting of eight coils. The inner detector consists of a silicon pixel detector, a silicon microstrip detector (SCT) and a transition radiation tracker (TRT). In the pseudorapidity region \(|\eta| < 3.2\), high-granularity liquid-argon (LAr) electromagnetic (EM) sampling calorimeters are used. An iron-scintillator tile calorimeter provides coverage for hadronic showers over \(|\eta| < 1.7\). The end-cap and forward regions, spanning \(1.5 < |\eta| < 4.9\), are instrumented with LAr calorimetry for both EM and hadronic measurements. The muon spectrometer surrounds these, and comprises a system of precision tracking chambers, and detectors for triggering.

3. Trigger and data selection

The data used in this analysis were recorded between March and July in 2011, with the LHC operating at a centre-of-mass energy of 7 TeV. The integrated luminosity is 1.04 fb\(^{-1}\), with an uncertainty of 3.7%\([21,22]\).

Events are required to pass either a single electron or a single muon trigger, for the electron and muon channels, respectively. The electron (muon) trigger threshold lies at transverse energy, \(E_T = 20\text{ GeV}\ (p_T = 18\text{ GeV})\). The trigger efficiencies reach the plateau region for lepton transverse momenta values substantially below the minimum analysis threshold of 40 GeV, with typical trigger efficiencies for leptons selected for offline analysis of: 96% for electrons\([23]\), 75% for muons with \(|\eta| < 1.05\) and 88% for muons with \(1.05 < |\eta| < 2.0\)\([24]\).

4. Monte Carlo simulation

Monte Carlo (MC) simulated event samples are used to develop and validate the analysis procedure, to help estimate the SM backgrounds in the signal region and to investigate specific signal models. Jets produced via QCD processes are generated with \textsc{pythia}\([25]\), using the MRST2007LO\(^*\) modified leading-order parton distribution functions (PDF)\([26]\), which are used with all leading-order (LO) Monte Carlo generators. The production of top quark pairs and of single top quarks is simulated with \textsc{alpgen}\([29]\), using the CTQG6L1 PDFs\([30]\), and events generated with \textsc{sherpa}\([31]\) are used to assess the systematic uncertainty associated with the choice of MC generator. Diboson (WW, ZZ) production is simulated with \textsc{herwig}\([32]\). Fragmentation and hadronisation for the \textsc{alpgen} and MC@NLO samples are performed with \textsc{herwig}, using \textsc{jimmy}\([33]\) for the underlying event. All MC samples are produced using a specific ATLAS parameter tune\([34]\) and the ATLAS full \textsc{geant4}\([35]\) detector simulation\([36]\). The MC samples are produced with a simulation of multiple interactions per LHC bunch crossing (pile-up). Different pile-up conditions as a function of the LHC instantaneous luminosity are taken into account by reweighting MC events according to the number of interactions observed in the data, which has a mean of about six.

Signal samples are generated with \textsc{charybdis}\([16]\) and \textsc{blackmax}\([37,38]\) generators. The shower evolution and hadronisation uses \textsc{pythia}, with the CTEQ6.6 PDF sets using the black hole mass as the QCD scale. No radiation losses in the formation phase are modelled. The \textsc{charybdis} samples are generated with both low and high multiplicity remnants, whilst the \textsc{blackmax} samples use the final burst remnant model, which gives high multiplicity remnant states\([37]\). The high multiplicity options of both generators produce concordant distributions. Samples are generated for both rotating and non-rotating black holes for six extra dimensions. Focus is placed on models with six extra dimensions due to the less stringent limits on \(M_D\). String ball samples are produced with \textsc{charybdis} for both rotating and non-rotating cases, for six extra dimensions.
dimensions, and a string coupling, $g_s$, of 0.4. For each benchmark model, samples are generated with $M_H$ ($M_s$ for string ball models) varying from 0.5–2.5 TeV and $M_{1H}$ from 3–5 TeV.

5. Object reconstruction

Electrons are reconstructed from clusters in the electromagnetic calorimeter matched to a track in the inner detector [23]. A set of electron identification criteria based on the calorimeter shower shape, track quality and track matching with the calorimeter cluster are described in Ref. [39] and are referred to as “loose”, “medium” and “tight”. Electrons are required to have $p_T > 40$ GeV, $|\eta| < 2.47$ and to pass the “medium” electron definition. Electron candidates are required to be isolated: the sum of the transverse energy deposited within a cone of size $\Delta R < 0.2$ around the electron candidate (corrected for transverse shower leakage and pile-up from additional $pp$ collisions) is required to be less than 10% of the electron $p_T$. Electrons with a distance to the closest jet of $0.2 < \Delta R < 0.4$ are discarded, where $\Delta R = \sqrt{(\Delta \eta)^2 + (\Delta \phi)^2}$. Muon candidates are selected from a combined track in the muon spectrometer and in the inner detector. Muons are required to have $p_T > 40$ GeV. Muon candidates are required to have an associated inner detector track with sufficient hits in the pixel, SCT and TRT detectors to ensure a good measurement. Additional requirements are made on the muon system hits in order to guarantee the best possible resolution at high $p_T$: muon candidates must have hits in at least three precision layers and no hits in detector regions with more limited alignment precision. These requirements effectively restrict the muon acceptance to the barrel region ($|\eta| < 1.0$) and a portion of the end-cap region ($1.3 < |\eta| < 2.0$) [40]. Muons with a distance to the closest jet of $\Delta R > 0.4$ are discarded. In order to reject muons resulting from cosmic rays, requirements are placed on the distance of each muon track from a reconstructed primary vertex (PV): $|z_0| < 1$ mm and $|d_0| < 0.2$ mm, where $z_0$ and $d_0$ are the impact parameters of each muon in the longitudinal and transverse planes, respectively. Muons must be isolated: the $p_T$ sum of tracks within a cone of $\Delta R < 0.3$ around the muon candidate is required to be less than 5% of the muon $p_T$.

Jets are reconstructed using the anti-$k_t$ jet clustering algorithm [41] with a distance parameter $R$ of 0.4. The inputs to the jet algorithm are clusters seeded from calorimeter cells with energy deposits significantly above the measured noise [42]. Jets are corrected for effects from calorimeter non-compensation and inhomogeneities through the use of $p_T$- and $\eta$-dependent calibration factors based on Monte Carlo corrections validated with test-beam and collision data [43]. This calibration corresponds to the scale that would be obtained applying the jet algorithm to stable particles at the primary collision vertex. Selected jets are required to have $p_T > 40$ GeV and $|\eta| < 2.8$. Events with jets failing jet quality criteria against noise and non-collision backgrounds are rejected [44]. Jets within a distance $\Delta R < 0.2$ of a selected electron are also rejected.

6. Event selection

Events are required to have a reconstructed primary vertex associated with at least five tracks. During the data-taking period considered, a readout failure in the LAr barrel calorimeter resulted in a small “dead” region, in which up to 30% of the incident jet energy may be lost. Should any of the four leading jets with $p_T > 40$ GeV fall into this region, the event is vetoed. This is applied consistently to all data and Monte Carlo events, and results in a loss of signal efficiency of $\sim 15$–20% for the models considered. Additionally, electrons incident on this region are discarded. Selected events contain at least one high-$p_T$ ($> 40$ GeV) isolated lepton. Two statistically independent samples are defined by separating events for which the leading lepton (that of highest $p_T$) is an electron (muon) into an electron (muon) channel sample.

High multiplicity final states of interest can be separated from Standard Model background events using the quantity:

$$\sum_{i=\text{objects}} p_T = \sum_{i=\text{objects}} p_{T,i}$$

which is the scalar sum of the transverse momenta of the selected final state reconstructed objects (leptons and jets), described in Section 5. The signal, containing multiple high-$p_T$ leptons and jets, manifests itself at high $\sum p_T$.

The missing transverse momentum $E_t^{\text{miss}}$ is defined as the opposite of the vectorial $p_T$ sum of reconstructed objects in the event, comprising selected leptons, jets with $p_T > 20$ GeV, any additional identified non-isolated muons, and calorimeter clusters not belonging to any of the aforementioned object types. Although $E_t^{\text{miss}}$ is not considered as an object in this analysis, it is used in the definitions of regions for background estimation.

Prefeature requirements are used to select a sample of events with similar kinematics and composition to the signal regions for this search, described later in this section, but with lower $p_T$ thresholds for selected objects. Events are required to have at least three selected objects passing the 40 GeV $p_T$ threshold, with at least one lepton, and have a moderate requirement of $\sum p_T > 300$ GeV. Additionally, the electron channel requires the leading electron to pass the “tight” selection. Fig. 1 shows the transverse momentum of the leading lepton after event preselection for electron and muon channels, where the background distributions have been normalised to be in agreement with data in selected control regions, as described in Section 7.

For the signal region, the $\sum p_T$, lepton and jet $p_T$ requirements are raised further. Events are required to contain at least three reconstructed objects with $p_T > 100$ GeV, at least one of which must be a lepton. These events are required to have a minimum $\sum p_T > 700$ GeV. To determine limits on the cross section for the signal production of these final states, this threshold is varied between 700 and 1500 GeV. In making exclusion contours in the $M_2$–$M_{1H}$ plane, using the benchmark models described in Section 4, a single signal region is used, defined by a $\sum p_T > 1500$ GeV requirement.

7. Background estimation

The backgrounds are estimated using a combination of data-driven and MC-based techniques. The dominant Standard Model sources of background are: $W +$ jets, $Z/\gamma^* +$ jets, $t\bar{t}$ and other non-$t\bar{t}$ multi-jet processes, subsequently referred to as multi-jet events. In $W +$ jets, $Z/\gamma^* +$ jets and $t\bar{t}$ processes, events are produced with real leptons, and associated additional high-$p_T$ jets. In multi-jet events, reconstructed high-$p_T$ leptons are present either due to the production of a real lepton within a jet, via semileptonic quark decays (dominantly heavy flavour decays), or due to a jet being misreconstructed from calorimeter clusters as a high-$p_T$ electron. These are denoted as fake leptons while those originating from $t\bar{t}$-leptons or heavy gauge bosons are referred to as prompt leptons.

The contribution to the muon channel signal region from multi-jets is predicted to be negligible by MC simulations, cross-checked with data using a non-isolated muon sample with the yield extrapolated to the signal region criteria. The multi-jet contribution to the electron channel is estimated using a data-driven matrix method, described in detail in Ref. [45]. Using the signal region definition, a multi-jet enhanced region is defined by loosening the electron identification criterion used in the event selection from “tight” to “medium”.

\[ \sum_{t=\text{objects}} p_T = \sum_{t=\text{objects}} p_{T,t} \]
The numbers of data events in this looser electron sample which pass \((N_{\text{pass}})\) and fail \((N_{\text{fail}})\) the final, tighter lepton selection criteria are counted. \(N_{\text{prompt}}\) and \(N_{\text{fake}}\) are defined as the numbers of events for which the electrons are prompt and fake, respectively. The following relationships hold:

\[
N_{\text{pass}} = \epsilon_{\text{prompt}} N_{\text{prompt}} + \epsilon_{\text{fake}} N_{\text{fake}},
\]

\[
N_{\text{fail}} = (1 - \epsilon_{\text{prompt}}) N_{\text{prompt}} + (1 - \epsilon_{\text{fake}}) N_{\text{fake}}.
\]

Simultaneous solution of these two equations gives a prediction for the number of events in data in the signal region which are events with fake leptons:

\[
N_{\text{fake}} = \frac{N_{\text{pass}} - (1 - \epsilon_{\text{prompt}} - 1/\epsilon_{\text{prompt}}) N_{\text{pass}}}{1/\epsilon_{\text{fake}} - 1/\epsilon_{\text{prompt}}}. 
\]

The efficiency \(\epsilon_{\text{fake}}\) is determined from a multi-jet dominated data control region defined by \(300 < \sum p_T < 700\) GeV and \(E_T^{\text{miss}} < 15\) GeV, in which events must have at least three reconstructed objects passing preselection criteria, in the electron channel. This region is also considered with the electron criterion loosened to “medium”. The efficiency for identifying fakes as prompt electrons is measured as the fraction of these events which also pass the tighter electron identification requirement. The MC simulations are used to correct the efficiency for the small fraction (~10%) of prompt leptons. No dependence on lepton \(p_T\), \(\sum p_T\) or the choice of maximum \(E_T^{\text{miss}}\) used to define the control region is observed.

The efficiency \(\epsilon_{\text{prompt}}\) is evaluated in a second control region, again containing at least three preselected objects, but with at least two opposite-sign electrons satisfying \(80 < m_{\ell\ell} < 100\) GeV, where \(m_{\ell\ell}\) denotes the dilepton invariant mass. The efficiency for identifying prompt electrons is obtained through the ratio of “medium–medium” to “medium–tight” events in this high purity control region.

The numbers of \(Z/\gamma^* + J\) jets events in the signal region for each channel are estimated by measuring the ratio of the number of events in data to that in MC simulation in a control region with: two opposite-sign leptons (two electrons or two muons) with \(80 < m_{\ell\ell} < 100\) GeV, at least three preselected objects and \(300 < \sum p_T < 700\) GeV. This ratio is a scaling factor that is then used to rescale the pure MC prediction (normalised to the next-to-next-to-leading order (NNLO) cross section) in the signal region. The factors derived agree with unity to within the experimental uncertainty.

The numbers of \(W +\) jets and \(t\bar{t}\) events in the signal region are estimated in a similar fashion, by defining a control region containing events with: exactly one electron (or muon, separately), with \(40 < m_T < 100\) GeV, where \(m_T\) is the transverse mass, calculated from the lepton transverse momentum vector, \(p_T^e\), and the missing transverse momentum vector, \(p_T^{\text{miss}}\):

\[
m_T = \sqrt{2 \cdot p_T^e \cdot E_T^{\text{miss}} \cdot (1 - \cos(\Delta \phi(p_T^e, p_T^{\text{miss}}}))}.
\]

with \(30 < E_T^{\text{miss}} < 60\) GeV, at least three preselected objects and \(300 < \sum p_T < 700\) GeV. Due to their similar behaviour in \(\sum p_T\), \(W +\) jets and \(t\bar{t}\) events are treated as a single background; a scaling factor is derived and used to rescale the pure MC prediction (normalised to the NNLO cross section) in the signal region. The factors derived are consistent with unity to within the experimental uncertainty.

8. Systematic uncertainties

In this analysis, the dominant sources of systematic uncertainty on the estimated background event rates are: choice of the control regions used to derive the background estimates (for the multi-jet and \(Z +\) jets backgrounds), MC modelling uncertainties assessed using alternative samples produced with different generators (for the \(Z +\) jets, \(W +\) jets and \(t\bar{t}\) backgrounds) and the jet energy scale (JES). Other uncertainties include those on the jet energy resolution (JER), lepton reconstruction and identification, PDF uncertainties, the finite size of event samples in the control regions and the uncertainties in the effects of initial and final-state radiation. For the \(Z +\) jets, \(W +\) jets and \(t\bar{t}\) backgrounds the use of a control region in data to renormalise the MC predictions, as described in Section 7, mitigates the effects of most of the systematic
uncertainties, which act primarily to vary the overall magnitude of the predicted backgrounds, rather than their shapes. For the background estimates of $Z$ + jets, $W$ + jets and $t\bar{t}$ processes, the dominant uncertainties are those associated with the extrapolation of the background shape to the signal region, followed by the jet energy scale. The sizes of the systematic uncertainties described above vary, depending on the channel and on the $p_T$ range of the signal region, but are typically 15–20%, except for the highest $p_T$ bins in which the MC event samples are smaller leading to larger statistical fluctuations. These are summarised in Tables 1 and 2.

The JES and JER uncertainties are applied to Monte Carlo simulated jets, and are propagated throughout the analysis to assess their effect. The JES uncertainties applied were measured using the complete 2010 dataset and the techniques described in Ref. [44]. The JER measured with 2010 data [44] is applied to all Monte Carlo simulated jets, with the difference between the nominal and recalibrated values taken as the systematic uncertainty. Additional contributions are added to both of these uncertainties to account for the effect of high luminosity pile-up in the 2011 run. The effect of pile-up on other analysis-level distributions was investigated and found to be negligible, as expected from the high-$p_T$ objects populating the signal region.

9. Results and interpretation

The observed and predicted event yields, following the estimations described in Section 7, are given in Tables 1 and 2, as a function of minimum $\sum p_T$. The distribution of $\sum p_T$ is shown in Fig. 2, along with the distribution of the highest-$p_T$ lepton or jet. The SM background estimates are in good agreement with the observed data, for all choices of $\sum p_T$ threshold. No excess is observed beyond the Standard Model expectation; $p$-values for the background-only hypothesis in the signal regions are in the range 0.43–0.47. Therefore, model-independent exclusion limits are determined on the fiducial cross section for non-SM production of these final states, $\sigma(pp \to X)$, as a function of minimum $\sum p_T$.

The translation from an upper limit on the number of events to a fiducial cross section requires knowledge of the mapping (or, equivalently, the selection efficiency), $\epsilon_{\text{fid}}$, from the true signal production in the fiducial region to that reconstructed. The true fiducial region for the electron (muon) channel is defined from simulated events with final states that pass the following requirements at generator level: the leading lepton is a prompt electron (muon) within the experimental acceptance described in Section 5, with $p_T > 100$ GeV and separated from jets with $p_T > 20$ GeV by $\Delta R(\text{lepton,jet}) > 0.4$; at least two additional jets or isolated leptons with $p_T > 100$ GeV are present and $\sum p_T$ is above the respective signal region threshold. Jets are defined using the anti-$k_T$ algorithm with $R = 0.4$ on stable particles.

For the models considered, $\epsilon_{\text{fid}}$ varies, and averages 63% for the electron channel, and 44% for the muon channel. The full range of $\epsilon_{\text{fid}}$ is 57–67% for the electron channel and 39–50% for the muon channel.

Under the assumption of equal a priori signal model production of electrons and muons, a combined limit can also be calculated: this is a limit on the fiducial cross section for all final states with at least one lepton ($e$ or $\mu$), for which $\epsilon_{\text{fid}}$ averages 57%, with a range from 50–61%.

For the derivation of the upper limits on the fiducial cross section, the lowest observed efficiency for each channel is used, for all signal regions. The corresponding observed and expected upper limits on the fiducial cross-section $\sigma(pp \to X)$ at 95% confidence level are displayed in Fig. 3 and Table 3. These exclusion regions are obtained using the CLs prescription [46]. For $\sum p_T > 1.5$ TeV, the observed (expected) 95% C.L. upper limit on the non-Standard Model fiducial cross section is 16.7 fb (20.4 fb) for final states containing at least one electron or muon.

The expected and observed limits in the muon channel are slightly more stringent, due to the lower level of the SM background, in spite of the smaller efficiency and acceptance for the signal.

For the models considered, the total signal acceptance is highly model-dependent, driven primarily by the fraction of events containing a lepton in the final states, and averages about 10% and 5% for the (mutually exclusive) electron and muon channels respectively. It is lowest for the low multiplicity, low mass states (small values of $M_{TH}/M_D$ or $M_{TH}$ and $M_D$) that are theoretically or experimentally disfavoured.

The observed number of data events in the signal region (for $\sum p_T > 1500$ GeV) along with the background expectations are used to obtain exclusion contours in the plane of $M_D$ and $M_{TH}$ for several benchmark-model gravitational states. No theoretical uncertainty on signal prediction is assessed; that is, the exclusion limits are set for the exact benchmark models as implemented in the BLACKMAX and CHARYBDIS generators. In deriving the exclusion contours, the uncertainty in the integrated luminosity and the statistical and experimental systematic uncertainties in the signal acceptances are included, and are found to be less than 10%.
Fig. 2. The distributions of $\sum p_T$ (a), (b) and leading object $p_T$ (c), (d) for the signal region in the electron (left) and muon (right) channels. The background processes are shown according to their data-derived estimates. The lower panels show the ratio of the data to the expected background (points) and the uncertainty (shaded band). The shaded band in each panel indicates the uncertainty on the expectation from the finite size of event samples, jet and lepton energy scales and resolutions. Two representative signal distributions are overlaid for comparison purposes. The signal labelled “Black Hole” is a non-rotating black hole sample with $n = 6$, $M_D = 0.8$ TeV and $M_{TH} = 4$ TeV. The signal labelled “String Ball” is a rotating string ball sample with $n = 6$, $M_D = 1.26$ TeV, $M_S = 1$ TeV and $M_{TH} = 3$ TeV. The final histogram bin shows the integral of all events with $\sum p_T \geq 2900$ GeV (a), (b) or $p_T \geq 1100$ GeV (c), (d).

in total. Some of the theoretical uncertainties, such as the effects of black hole rotation, or spin, are discussed in Section 1. One of the more significant theoretical uncertainties is that associated with the decay of the state as its mass approaches $M_D$. A common prescription is to end thermal emissions at a mass close to $M_{D}$, at which point the state decays immediately to a remnant state, the multiplicity of which is uncertain. The efficiency of the event selection for searches for strong gravitational states could differ significantly according to the remnant model choice, particularly for samples in which a limited number of Hawking emissions are anticipated, motivating the consideration of multiple remnant models. The requirement of only three high-$p_T$ objects for this analysis mitigates the dependence of the selection efficiency, and resulting cross section limits, on the modelling of the remnant decays.

The 95% exclusion contours in the $M_D-M_{TH}$ plane ($M_S-M_{TH}$ plane for string balls) for different models are obtained using the CLs prescription. Fig. 4 shows exclusion contours for rotating black hole benchmark models with high- and low-multiplicity remnant decays. Their comparison allows an assessment of the effect of this modelling uncertainty on the analysis, which is inevitably greatest in the regime of low $M_{TH}/M_D$. Limits for rotating and non-rotating string ball models are shown in Fig. 5. The behaviour of the contours observed at high values of $M_{TH}/M_S$ is due to a step decrease in the gradient of the string ball cross section, $d\sigma_{SB}/dM_S$ above a value of $M_{TH} = M_S/g_S^2$. The string ball models illustrated were simulated using a high-multiplicity remnant model.

10. Summary

A search for microscopic black holes and string ball states in ATLAS using a total integrated luminosity of 1.04 fb$^{-1}$ was presented. The search has considered final states with three or more high transverse momentum objects, at least one of which was required to be a lepton (electron or muon). No deviation from
the Standard Model was observed in either the electron or the muon channels. Consequently, limits are set on TeV-scale gravity models, interpreted in a two-dimensional parameter grid of benchmark models in the $M_D$–$M_{TH}$ plane. Upper limits, at 95% C.L., are set on the fiducial cross-sections for new physics production of high-$\sum p_T$ multi-object final states containing a high-$p_T$ (>100 GeV) isolated lepton within the experimental acceptance. For final states with $\sum p_T > 1.5$ TeV, a limit of 16.7 fb is set.

**Acknowledgements**

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; BMWF, Austria; ANAS, Azerbaijan; STC, Belarus; CNPq and FAPESP, 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; DNRF, DNSRC and Lundbeck Foundation, Denmark; EPLANET and ERC, European Union; IN2P3-CNRS, CEA-DSM/IRFU, France; GNAS, Georgia; BMBF, DFG, MPG and AvH Foundation, Germany; GSRT, Greece; IF, MINERVA, GIF, DIP and Benoziyo Center, Israel; INFN, Italy; MEXT and JSPS, Japan; CNRST, Morocco; FOM and NWO, Netherlands; RCN, Norway; MNiSW, Poland; GRICES and FCT, Portugal; MERSYS (MECTS), Romania; MES of Russia and ROSATOM, Russian Federation; JINR; MSTD, Serbia; MSSR, Slovakia; ARRS and MVZT, Slovenia; DST/NRF, South Africa; MICINN, 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.
Fig. 5. The exclusion limit in the $M_{TH}$–$M_S$ plane, with electron and muon channels combined, for non-rotating (a) and rotating (b) string balls with six extra dimensions. The solid (dashed) line shows the observed (expected) 95% C.L. limits, with the dark and light bands illustrating the expected $1\sigma$ and $2\sigma$ variations of the expected limits. The dotted lines indicate constant $k = M_{TH}/M_S$. All samples were produced with the CHARYBDIS generator, using a high multiplicity remnant state.

Open access

This article is published Open Access at sciencedirect.com. It is distributed under the terms of the Creative Commons Attribution License 3.0, which permits unrestricted use, distribution, and reproduction in any medium, provided the original authors and source are credited.

References


ATLAS Collaboration


1 University of Albany, Albany, NY, United States
2 Department of Physics, University of Alberta, Edmonton, AB, Canada
3 (a) Department of Physics, Ankara University, Ankara; (b) Department of Physics, Dumlupinari University, Kayseri; (c) Department of Physics, Gazi University, Ankara; (d) Division of Physics, TOBB University of Economics and Technology, Ankara; (e) Turkish Atomic Energy Authority, Ankara, Turkey
4 LAPP, CNRS/IN2P3 and Université de Savoie, Annecy-le-Vieux, France
5 High Energy Physics Division, Argonne National Laboratory, Argonne, IL, United States
6 Department of Physics, University of Arizona, Tucson, AZ, United States
7 Department of Physics, The University of Texas at Arlington, Arlington, TX, United States
8 Physics Department, University of Athens, Athens, Greece
9 Physics Department, National Technical University of Athens, Zografou, Greece
10 Institute of Physics, Azerbaijan Academy of Sciences, Baka, Azerbaijan
11 Institut de Física d'Altes Energies and Departament de Física de la Universitat Autònoma de Barcelona and ICREA, Barcelona, Spain
12 (a) Institute of Physics, University of Belgrade, Belgrade; (b) Vinca Institute of Nuclear Sciences, University of Belgrade, Belgrade, Serbia
13 Department for Physics and Technology, University of Bergen, Bergen, Norway
14 Physics Division, Lawrence Berkeley National Laboratory and University of California, Berkeley, CA, United States
15 Department of Physics, Humboldt University, Berlin, Germany
16 Albert Einstein Center for Fundamental Physics and Laboratory for High Energy Physics, University of Bern, Bern, Switzerland
17 School of Physics and Astronomy, University of Birmingham, Birmingham, United Kingdom
18 (a) Department of Physics, Bogazici University, Istanbul; (b) Division of Physics, Dogus University, Istanbul; (c) Department of Physics Engineering, Gaziantep University, Gaziantep;
19 (a) Department of Physics, Institut für Experimentelle Physik IV, Technische Universität Dortmund, Dortmund, Germany
20 (a) INFN Sezione di Bologna; (b) Dipartimento di Fisica, Università di Bologna, Bologna, Italy
21 Physical Institute, University of Bern, Bern, Switzerland
22 Department of Physics, Boston University, Boston, MA, United States
23 Department of Physics, Brandeis University, Waltham, MA, United States
24 (a) Universidad Federal do Rio de Janeiro CPPE/EE/IF, Rio de Janeiro; (b) Federal University of Juiz de Fora (UFJF), Juiz de Fora; (c) Federal University of Sao Joao del Rei (UFSJ), Sao Joao del Rei; (d) Instituto de Física, Universidade de Sao Paulo, Sao Paulo, Brazil
25 Physics Department, Brookhaven National Laboratory, Upton, NY, United States
26 (a) National Institute of Physics and Nuclear Engineering, Bucharest; (b) University Politehnica Bucharest, Bucharest; (c) West University in Timisoara, Timisoara, Romania
27 Departamento de Física, Universidad de Buenos Aires, Buenos Aires, Argentina
28 Cavendish Laboratory, University of Cambridge, Cambridge, United Kingdom
29 Department of Physics, Carleton University, Ottawa, ON, Canada
30 CERN, Geneva, Switzerland
31 (a) Enrico Fermi Institute, University of Chicago, Chicago, IL, United States
32 (a) Departamento de Física, Pontificia Universidad Católica de Chile, Santiago; (b) Departamento de Física, Universidad Técnica Federico Santa María, Valparaíso, Chile
33 (a) Institute of High Energy Physics, Chinese Academy of Sciences, Beijing; (b) Department of Modern Physics, University of Science and Technology of China, Anhui; (c) Department of Physics, Nanjing University, Nanjing; (d) School of Physics, Shandong University, Shandong, China
34 Laboratoire de Physique Corpusculaire, Clermont Université and Université Blaise Pascal and CNRS/IN2P3, Aubiere, France
35 Nevis Laboratory, Columbia University, Irvington, NY, United States
36 (a) Niels Bohr Institute, University of Copenhagen, Copenhagen, Denmark
37 INFN Gruppo Collegato di Cosenza; (b) Dipartimento di Fisica, Università della Calabria, Arcavacata di Rende, Italy
38 AGH University of Science and Technology, Faculty of Physics and Applied Computer Science, Krakow, Poland
39 The Henryk Niewodniczanski Institute of Nuclear Physics, Polish Academy of Sciences, Krakow, Poland
40 Physics Department, Southern Methodist University, Dallas, TX, United States
41 Physics Department, University of Texas at Dallas, Richardson, TX, United States
42 DESY, Hamburg and Zeuthen, Germany
43 Institut für Experimentelle Physik IV, Technische Universität Dortmund, Dortmund, Germany
44 Institut für Kern- and Teilchenphysik, Technical University Dresden, Dresden, Germany
45 Department of Physics, Duke University, Durham, NC, United States
46 SUPA – School of Physics and Astronomy, University of Edinburgh, Edinburgh, United Kingdom
47 Fachhochschule Wiener Neustadt, Johannes Gutenbergstrasse 3 2700 Wiener Neustadt, Austria
48 INFN Laboratori Nazionali di Frascati, Frascati, Italy
49 Fakultät für Mathematik und Physik, Albert-Ludwigs-Universität, Freiburg i.Br., Germany
50 Section de Physique, Université de Genève, Geneva, Switzerland
51 (a) INFN Sezione di Genova; (b) Dipartimento di Fisica, Università di Genova, Genova, Italy
52 I.E.Andronikashvili Institute of Physics, Tbilisi State University, Tbilisi; (b) High Energy Physics Institute, Tbilisi State University, Tbilisi, Georgia
53 Il Physikalisches Institut, Justus-Liebig-Universität Gießen, Gießen, Germany
54 SUPA – School of Physics and Astronomy, University of Glasgow, Glasgow, United Kingdom
55 Il Physikalisches Institut, Georg-August-Universität, Göttingen, Germany
56 Laboratoire de Physique Subatomique et de Cosmologie, Université Joseph Fourier and CNRS/IN2P3 and Institut National Polytechnique de Grenoble, Grenoble, France
57 Department of Physics, Hampton University, Hampton, VA, United States
58 Laboratory for Particle Physics and Cosmology, Harvard University, Cambridge, MA, United States
59 (a) Kirchhoff-Institut für Physik, Ruprecht-Karls-Universität Heidelberg, Heidelberg; (b) Physikalisches Institut, Ruprecht-Karls-Universität Heidelberg, Heidelberg; (c) ZITI Institut für technische Informatik, Ruprecht-Karls-Universität Heidelberg, Mannheim, Germany
60 Faculty of Applied Information Science, Hiroshima Institute of Technology, Hiroshima, Japan
61 Department of Physics, Indiana University, Bloomington, IN, United States
62 Institut für Astro- und Teilchenphysik, Leopold-Franzens-Universität, Innsbruck, Austria
63 University of Iowa, Iowa City, IA, United States
64 Department of Physics and Astronomy, Iowa State University, Ames, IA, United States
65 Joint Institute for Nuclear Research, JINR Dubna, Dubna, Russia
66 KEK, High Energy Accelerator Research Organization, Tsukuba, Japan
67 Graduate School of Science, Kobe University, Kobe, Japan