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Search for strong gravity in multijet final states produced in pp collisions at $\sqrt{s} = 13$ TeV using the ATLAS detector at the LHC

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Abstract: A search is conducted for new physics in multijet final states using 3.6 inverse femtobarns of data from proton-proton collisions at $\sqrt{s} = 13$ TeV taken at the CERN Large Hadron Collider with the ATLAS detector. Events are selected containing at least three jets with scalar sum of jet transverse momenta (H_T) greater than 1 TeV. No excess is seen at large H_T and limits are presented on new physics: models which produce final states containing at least three jets and having cross sections larger than 1.6 fb with $H_T > 5.8$ TeV are excluded. Limits are also given in terms of new physics models of strong gravity that hypothesize additional space-time dimensions.

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Contents

1 Introduction

Many models of gravity postulate a fundamental gravitational scale comparable to the electroweak scale, hence allowing the production of non-perturbative gravitational states, such as micro black holes and string balls (highly excited string states) at Large Hadron Collider (LHC) collision energies [1–4]. If black holes or string balls with masses much higher than this fundamental gravitational scale are produced at the LHC, they behave as classical thermal states and decay to a relatively large number of high transverse momentum (p_{T}) particles. One of the predictions of these models is that particles are emitted from black holes at rates which primarily depend on the number of Standard Model (SM) degrees of freedom (number of charge, spin, flavour, and colour states). Spin-dependent effects, such as the Fermi-Dirac and Bose-Einstein distributions in statistical mechanics, and gravitational transmission factors (also dependent on spin) are less important. Several searches were carried out using data from Run-1 at the LHC at centre-of-mass energies of 7 and 8 TeV by ATLAS [5–9] and CMS [10–12]. The analysis described here follows the method of a similar ATLAS analysis using 8 TeV data [5]. The increase in the LHC energy to 13 TeV in Run-2 brings a large increase in the sensitivity compared to Run-1; for the data set used here the increase is of the order of 50% in the energy scale being probed. Another analysis looking at dijet final states [13] is also sensitive to new physics of the type discussed here.

Identification of high-p_{T}, high-multiplicity final states resulting from the decay of high-mass objects is accomplished by studying the scalar sum of the jet p_{T} (H_{T}). A low-H_{T} control region is defined. New physics of the type considered in this paper cannot contribute significantly in this region as it is excluded by the previous searches. A fit-based technique is used to extrapolate from the control region to a high-H_{T} signal region to estimate the amount of the SM background. The observation is compared to the background-only expectation determined by the fit-based method. In the absence of significant deviations from the background-only expectation, 95% Confidence Level (CL) limits on micro black hole and string-ball production are set. The limits are given in terms of parameters used in the CHARYBDIS2 1.0.4 [14] model.

The production and decay of black holes and string balls lead to final states distinguished by a high multiplicity of high-p_{T} particles, consisting mostly of jets arising from quark and gluon emission. Since black-hole decay is considered to be a stochastic process, different numbers of particles, and consequently jets, are emitted from black holes with identical kinematic distributions. This motivates the search in inclusive jet multiplicity slices, rather than optimizing a potential signal-to-background for a particular exclusive jet multiplicity.

The analysis is not optimized for any particular model. However, for the purpose of comparison to other searches both within ATLAS and between the LHC experiments, CHARYBDIS2 1.0.4 is used. For the micro black holes the number of extra dimensions in the model is fixed to be two, four or six, the black hole is required to be rotating, and the limits are presented as a function of the fundamental Planck scale (M_{D}) and the mass threshold (M_{th}). In the case of string balls, limits are presented as functions of M_{th}, the string scale (M_{S}) and the string coupling (g_{S}).

2 ATLAS detector

The ATLAS detector [15] covers almost the whole solid angle around the collision point with layers of tracking detectors, calorimeters and muon chambers. For the measurements presented in this note, the calorimeters are of particular importance. The inner detector, immersed in a magnetic field provided by a solenoidal magnet, has full coverage in ϕ and covers the pseudorapidity[1] range $|\eta| < 2.5$. It consists of a silicon pixel detector, a silicon microstrip detector and a transition radiation straw-tube tracker. The innermost pixel layer, the insertable B-layer, was added between Run-1 and Run-2 of the LHC, at a radius of 33 mm around a new, thinner, beam pipe. In the pseudorapidity region $|\eta| < 3.2$, high granularity liquid-argon (LAr) electromagnetic (EM) sampling calorimeters are used. An iron-scintillator tile calorimeter provides hadronic coverage 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 calorimeters, and comprises a system of precision tracking chambers for muon reconstruction up to $|\eta| = 2.7$ and trigger detectors with three large toroids, each consisting of eight coils providing magnetic fields for the muon detectors.

[1] ATLAS uses a right-handed coordinate system with its origin at the nominal interaction point in the centre of the detector and the z-axis along the beam direction. The x-axis points toward 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 z-axis. The pseudorapidity η is defined in terms of the polar angle θ by $\eta \equiv -\ln[\tan(\theta/2)]$.

3 Event selection

The data used here were recorded in 2015, with the LHC operating at a centre-of-mass energy of $\sqrt{s} = 13$ TeV. All detector elements are required to be fully operational, except for the insertable B-layer of pixels which was not operating for a small subset of the data. Data corresponding to a total integrated luminosity of 3.6 fb^{-1} are used in this analysis measured with an uncertainty of 9%. This is derived following the same methodology as that detailed in ref. [16], from a preliminary calibration of the luminosity scale using a pair of x–y beam-separation scans performed in June 2015.

The ATLAS detector has a two-level trigger system: the level-1 hardware stage and the high-level trigger software stage. The events used in this search are selected using a high-H_{T} trigger, which requires at least one jet of hadrons with $p_{\mathrm{T}} > 200$ GeV, and a high scalar sum of transverse momentum of all the jets in the events, $H_{\mathrm{T}} > 0.85$ TeV. In this analysis, a requirement of $H_{\mathrm{T}} > 1$ TeV is applied, for which the trigger is fully efficient. All jets included in the computation of H_{T} are required to satisfy $p_{\mathrm{T}} > 50$ GeV and $|\eta| < 2.8$.

Events are required to have a primary vertex with at least two associated tracks with p_{T} above 0.4 GeV. The primary vertex assigned to the hard-scattering collision is the one with the highest $\sum_{\mathrm{track}} p_{\mathrm{T}}^2$, where the scalar sum of track p_{T}^2 is taken over all tracks associated with that vertex.

Since black holes and string balls are expected to decay predominantly to quarks and gluons, the search is simplified by considering only jets. The analysis uses jets of hadrons, as well as misidentified jets arising from photons, electrons, and taus. Using the hadronic energy calibration instead of the dedicated calibration developed for these objects leads to small energy shifts. Since particles of these types are expected to occur in less than 0.6% of the signal events in the data sample (as determined from simulation studies), such calibration effects do not contribute significantly to the resolution of H_{T}.

The anti-k_t algorithm [17] is used for jet clustering, with a radius parameter $R = 0.4$. The inputs to the jet reconstruction are three-dimensional clusters comprised of energy deposits in the calorimeters [18]. This method first clusters together topologically connected calorimeter cells and then classifies these clusters as either electromagnetic or hadronic. The four-momenta corresponding to these clusters are calibrated for the response to incident hadrons using the procedures described in refs. [19, 20]. The agreement between data and simulation is further improved by the application of a residual correction derived in situ at lower collision energies [21] which was validated for use at 13 TeV through additional extrapolation uncertainties [22].

While a data-driven method is used to estimate the background, simulated events are used to establish, test and validate the methodology of the analysis. Therefore, simulation is not required to accurately describe the background, but it should be sufficiently similar that the strategy can be tested before applying it to data. Multijet events constitute the dominant background in the search region, with small contributions from top-quark pair-production ($t\bar{t}$), γ + jets; W + jets, Z + jets, single-top quark, and diboson background contributions are negligible.

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The baseline multijet sample of inclusive jets is generated using PYTHIA 8.186 [23] implementing leading order (LO) perturbative QCD matrix elements with NNPDF23_ lo_ as_ 0130_ qed parton distribution functions (PDFs) [24] for $2 \to 2$ processes and p_{T}-ordered parton showers calculated in a leading-logarithmic approximation with the ATLAS A14 set of tuned parameters (tune) [25]. A reasonable agreement in the shape of the H_{T} distribution was observed in Run-1 for different inclusive jet multiplicity categories [5]. All Monte-Carlo (MC) simulated background samples are passed through a full GEANT4 [26] simulation of the ATLAS detector [27]. Signal samples are generated from the CHARYBDIS2 1.0.4 MC event generator, which is run with leading-order PDF CTEQ6L1 [28] and uses the PYTHIA 8.210 generator for fragmentation with the ATLAS A14 tune. The most important parameters that have significant effects on micro black hole production are the number of extra dimensions, the (4+n)-dimensional Planck scale M_{D} and the black hole mass threshold M_{th}. Signal samples are generated on a grid of M_{D} and M_{th} for $n = 2$, 4 and 6. In the case of string-ball production two sets of samples are produced; one as a function of M_{th} and the string scale M_{S} for fixed value $g_{\mathrm{S}} = 0.6$ of the string coupling, and one as a function of g_{S} and M_{th} for $M_{\mathrm{S}} = 3$ TeV. The signal samples are passed through a fast detector simulation AtlFast-II [29]. All simulated signal and background samples are reconstructed using the same software as the data.

4 Analysis strategy

The search is performed by examining the H_{T} distribution for several inclusive jet multiplicities. For each multiplicity, three regions of H_{T} are used: control ($C < H_{\mathrm{T}} < V$), validation ($V < H_{\mathrm{T}} < S$) and signal ($H_{\mathrm{T}} > S$). Data in the control region are fitted to an empirical function which is then extrapolated to predict the event rate in the validation and signal regions in the absence of new physics. The boundaries of these regions (C, V and S) depend on the integrated luminosity of the data sample used and inclusive jet multiplicity requirement. The following criteria must be satisfied: the lower boundary of the control region (C) should be sufficiently large that the shape of the H_{T} distribution near the boundary is not distorted by event selection effects; contamination from a possible signal due to new physics in the control region must be small for all possible signals not excluded by prior results. There should be some background events in the validation region whose lower boundary is deterined by V, with a small signal to background ratio from signals that are not excluded by a previous analysis, so that the background extrapolation can be checked. The signal region is defined so that the background extrapolation uncertainty relative to the background prediction is small: the boundary S is chosen so that the (pseudo-experiment-based, see below) background extrapolation uncertainty is approximately 0.5 events for $H_{\mathrm{T}} \geq S$.

A large increase in sensitivity to new physics is expected in Run-2 primarily due to the increase in centre-of-mass energy. A data set of a few fb^{-1} has such a large range of sensitivity that significant signal contamination in the control and validation regions is possible. Therefore, a bootstrap approach is adopted and data sets are examined whose size increases by approximately a factor of ten at each step, starting with a sample whose sensitivity is slightly beyond the Run-1 limit; simulation studies indicate an initial integrated luminosity of up to 10 pb^{-1} would be free of signal contamination. This will ensure that if a search in one step sees no new physics, the possible contributions of signal to the control and validation regions of the next step are small. For each data set the boundaries of the regions are determined as follows. Simulations are normalized to data in the normalization region, which is 1.5 TeV$< H_\mathrm{T} <$ 2.9 TeV. First, the lower boundary of the validation region, V, is chosen from this normalized MC simulation so that at least 20 events are expected for $S > H_\mathrm{T} > V$. This will allow a quantitative comparison of the data and expectation in the validation region to check that the extrapolation procedure is working properly. The lower boundary of the control region (C) is determined by requiring that the fit functions applied to MC-pseudo-data have a reduced χ^2 distribution peaked near one and then choosing C to minimize the pseudo-experiment-based uncertainty. Finally, the lower boundary of the signal region, S, is chosen so that the extrapolation uncertainty is approximately 0.5 events for $H_\mathrm{T} > S$.

The total data set used corresponds to an integrated luminosity of 3.6 fb^{-1}. A four-step bootstrap is adopted using exclusive data sets, for which 6.5 pb^{-1} is used in the first step, 74 pb^{-1} in the second, 0.44 fb^{-1} in the third and the remaining 3.0 fb^{-1} is used in the last step. The observed H_T distribution is shown in figure 1 for 6.5 pb^{-1}. A comparison is made with MC simulation for illustration. The MC simulation was normalized to the data in the normalization region independently in each jet multiplicity (n_jet) sample. Lines delimiting the control, validation and signal regions are shown. Before normalization the ratio Data/MC is approximately 0.74. The example signal ($M_\mathrm{D} = 2.5$ TeV, $M_\mathrm{th} = 6.0$ TeV) shown is just beyond the limit obtained from the Run-1 8 TeV analysis. Any possible signal must therefore be smaller than this. The H_T distribution expected from this signal is such that any contamination in the control and validation regions is negligible. In addition, the contamination in the control region is negligible for all signals that this data set (6.5 pb^{-1}) is sensitive to. Possible contamination in the validation region is less than 10% for signals not excluded by the Run-1 analysis. It can be seen from figure 1 that data sets with high jet multiplicity contain rather few events. This first-step analysis therefore uses only the data sample with jet multiplicity, $n_\mathrm{jet} \geq 3$.

The observed H_T distribution from the 74 pb^{-1} sample used in the second step is shown in figure 2 where comparison is made with MC simulation for illustration. The MC simulation was normalized to the data in the normalization region independently in each n_jet sample. Before normalization the ratio data/MC increases with jet multiplicity from 0.74 to 0.87. This variation is not unexpected since the MC simulation is leading order in QCD. Signal samples ($M_\mathrm{D} = 3$ TeV, $M_\mathrm{th} = 7.5$ TeV) are superimposed on data in figure 2 which correspond approximately to those just beyond the sensitivity of the first-step analysis. The logic of the previous paragraph applied here shows that the bootstrap approach is protected against signal contamination if data sets increasing by a factor of ten in integrated luminosity are used.

The observed H_T distribution from the 0.44 fb^{-1} sample used in the third step is shown in figure 3 where comparison is made with MC simulation for illustration. The MC simulation was normalized to the data in the normalization region independently in

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each $n_{\rm jet}$ sample. Before normalization the ratio Data/MC increases with jet multiplicity from 0.78 to 0.84. Signal samples ($M_{\rm D}$ = 4.5 TeV, $M_{\rm th}$ = 8 TeV) are superimposed on data in figure 3 which correspond approximately to those just beyond the sensitivity of the second-step analysis.

Finally the observed $H_{\rm T}$ distribution from the 3.0 fb^{-1} sample used in the fourth step is shown in figure 4, again comparison is made with MC simulation for illustration. The MC simulation was normalized to the data in the normalization region independently in each $n_{\rm jet}$ sample. Before normalization the ratio Data/MC increases with jet multiplicity from 0.73 to 0.77. The ratio Data/MC is found to be consistent for all four exclusive data samples within statistical and luminosity uncertainties. Signal samples ($M_{\rm D}$ = 2.5 TeV, $M_{\rm th}$ = 9.0 TeV) are superimposed on data in figure 4 which correspond approximately to those just beyond the sensitivity of the third-step analysis.

As already mentioned, in order to estimate the number of background events in the validation and signal regions, a data-driven method is used. Data in the control region are fitted to an empirical function which is then used to extrapolate to higher $H_{\rm T}$. The analytic functions considered for this analysis and the allowed ranges of parameters in the fit are summarized in table 1. Function 1 is the baseline function used to fit background for the Run-1 result [5]. Functions 2–10 are the alternative background functions considered or motivated by the Run-1 analysis. These functions are found to fit the $H_{\rm T}$ distribution of multijet Monte Carlo samples well and were also used to describe dijet or multijet mass or $H_{\rm T}$ distributions in many previous searches [30–33].

The 10 functions shown in table 1 are found to fit pseudo-data generated from the simulated multijet sample very well. The difference in fit result between these functions is statistically small and the simulated sample does not have a precision to identify which function is intrinsically better than the rest. Therefore, the choice of the baseline function is not critical. To select a baseline function in an unbiased manner, the following procedure is applied. Data corresponding to 1000 pseudo-experiments (PEs) drawn from samples of the simulated background are used to evaluate the functions and to assess their ability to obtain a good fit and to correctly predict the event rates in the validation and signal regions. Functions are required to converge in the control region and decrease monotonically with $H_{\rm T}$ in the signal region for 95% or more of pseudo-experiments. Provided these criteria are met, functions are ranked based on the goodness of their extrapolation in the validation region based on the statistical uncertainty and potential bias of their extrapolation. The top-ranked function is selected as the baseline function. Any function which satisfies these criteria but whose extrapolation does not agree with the data in the validation region within 95% confidence level is rejected and its result is not used to obtain the signal region background uncertainty estimate.

The procedure of ranking and selecting background functions as well as the procedure of determining the control, validation, and signal region boundaries is repeated for each step used in the bootstrap process and for analyses with different $n_{\rm jet}$ requirements.

Figure 5 shows fits to the data in the control region and their extrapolation into the signal and validation regions for $n_{\rm jet} \geq 3$ and the data set corresponding to the first step in the bootstrap. Function 4 is the baseline while functions 1, 9 and 10 pass the goodness

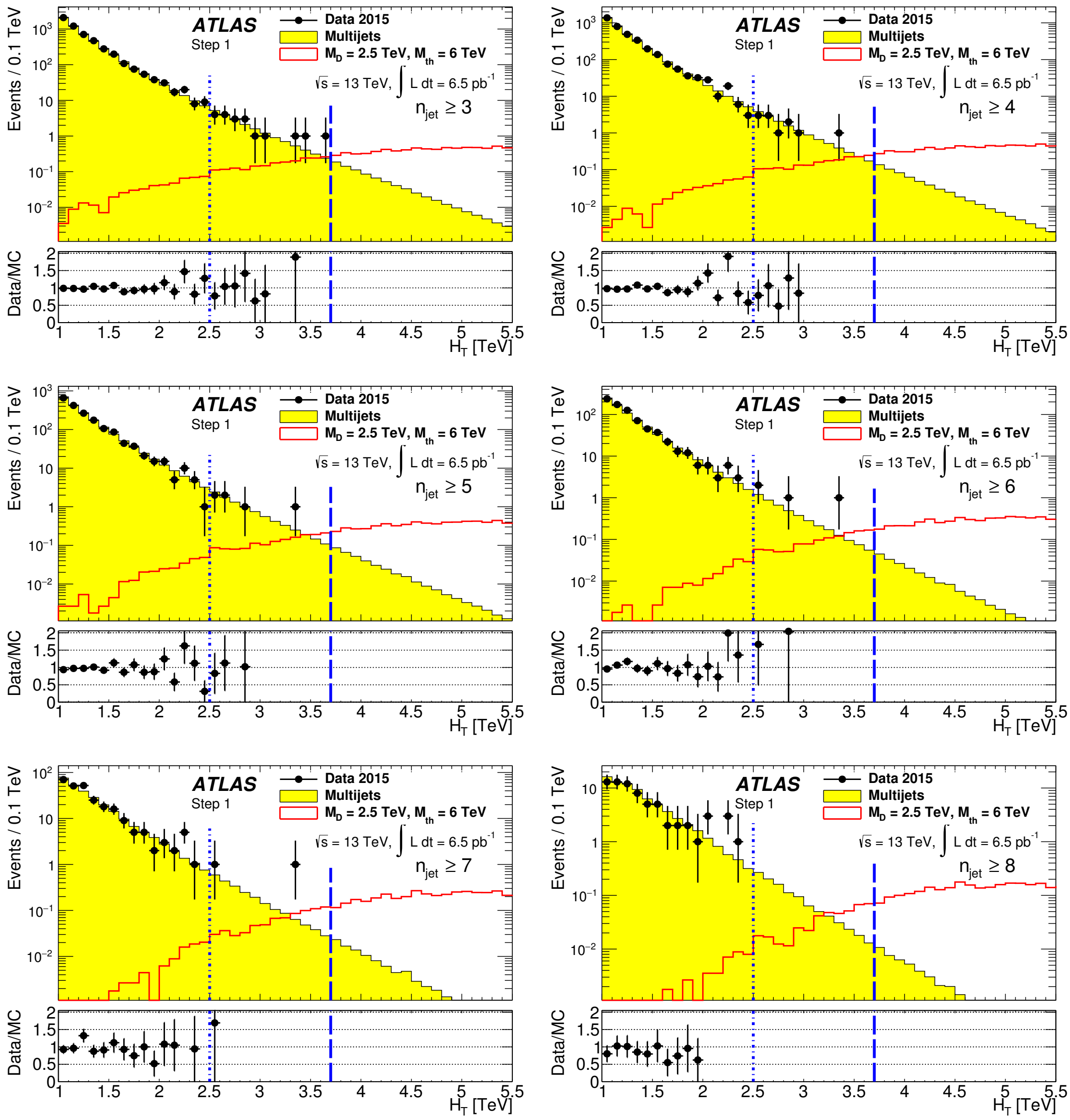

Figure 1. Data and MC simulation comparison for the distributions of the scalar sum of jet transverse momenta H_{T} in different inclusive n_{jet} bins for the 6.5 pb^{-1} data sample. The black hole signal with $M_{\mathrm{D}} = 2.5$ TeV, $M_{\mathrm{th}} = 6.0$ TeV is superimposed with the data and background MC simulation sample. The MC is normalized to data in the normalization region. The vertical dashed-dotted line marks the boundary between control region and validation region, and the dashed line marks the boundary between validation region and signal region. The boundaries shown correspond to those determined for the $n_{\mathrm{jet}} \geq 3$ case.

of fit and monotonicity tests. The baseline is used to predict rates in the signal region and the others are used to assess systematic uncertainties. As will be quantified below, but is already clear from this figure, there is no evidence for a discrepancy in the signal and validation regions between the data and the remaining extrapolations.

Figure 6 shows the comparison for the 74 pb^{-1} data set which corresponds to the second step. Here the functions 1, 3, 4, 5, 6, 9, and 10 in table 1 are qualified for all jet

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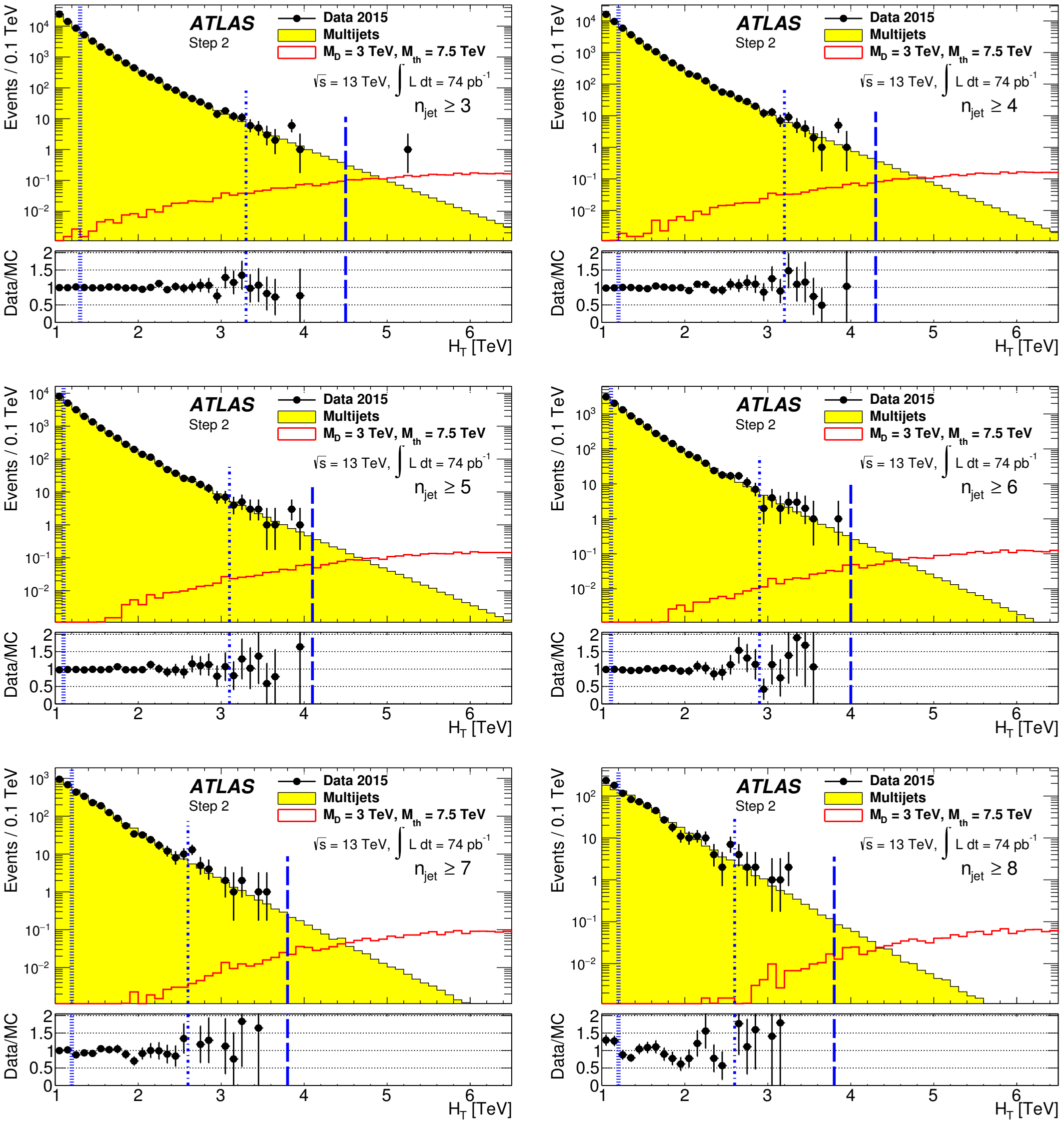

Figure 2. Data and MC simulation comparison for H_{T} distributions in different inclusive n_{jet} bins for the 74 pb^{-1} data sample. The black hole signal with $M_{\mathrm{D}} = 3$ TeV, $M_{\mathrm{th}} = 7.5$ TeV is superimposed with the data and background MC. The MC simulation was normalized to data in the normalization region. The vertical dotted line marks the lower boundary of the control region, the vertical dashed-dotted line marks the boundary between control region and validation region, and the vertical dashed line marks the boundary between validation region and signal region. These boundaries are determined for each n_{jet} sample separately.

multiplicities with function 10 being the baseline. Additionally, function 8 is qualified for $n_{\mathrm{jet}} \geq 4$ to $n_{\mathrm{jet}} \geq 7$, function 7 for $n_{\mathrm{jet}} \geq 6$ and $n_{\mathrm{jet}} \geq 7$, and function 2 for $n_{\mathrm{jet}} \geq 6$. Figure 7 shows the comparison for the 0.44 fb^{-1} data set which corresponds to the third step. Here all the functions are qualified for all jet multiplicities with 10 being the baseline. Finally, figure 8 shows the comparison for the 3.0 fb^{-1} data set which corresponds to the fourth step. Here all functions are qualified for all jet multiplicities less than eight. For $n_{\mathrm{jet}} \geq 8$ all functions except 7 and 8 are qualified. Function 10 is the baseline for all jet

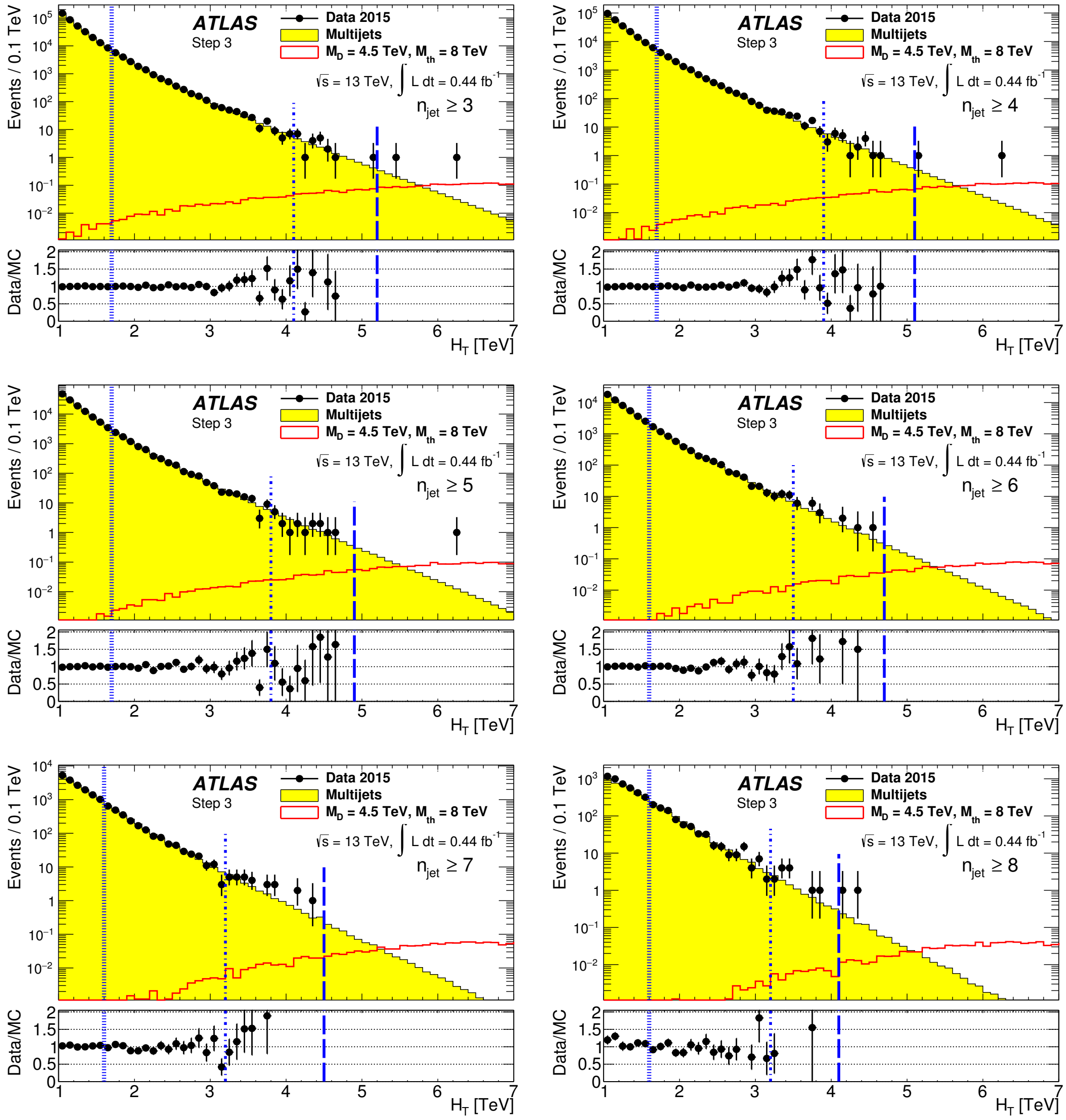

Figure 3. Data and MC simulation comparison for H_{T} distributions in different inclusive n_{jet} bins for the 0.44 fb^{-1} data sample. The black hole signal with $M_{\mathrm{D}} = 4.5$ TeV, $M_{\mathrm{th}} = 8$ TeV is superimposed with the data and background MC. The MC simulation is normalized to data in the normalization region. The vertical dotted line marks the lower boundary of the control region, the vertical dashed-dotted line marks the boundary between control region and validation region, and the vertical dashed line marks the boundary between validation region and signal region. These boundaries are determined for each n_{jet} sample separately.

multiplicities except $n_{\mathrm{jet}} \geq 3$ where function 5 is the baseline and $n_{\mathrm{jet}} \geq 7$ where function 4 is baseline.

5 Uncertainties

There are two components of uncertainty on the background projections: a statistical component arising from data fluctuations in the control region and a systematic component

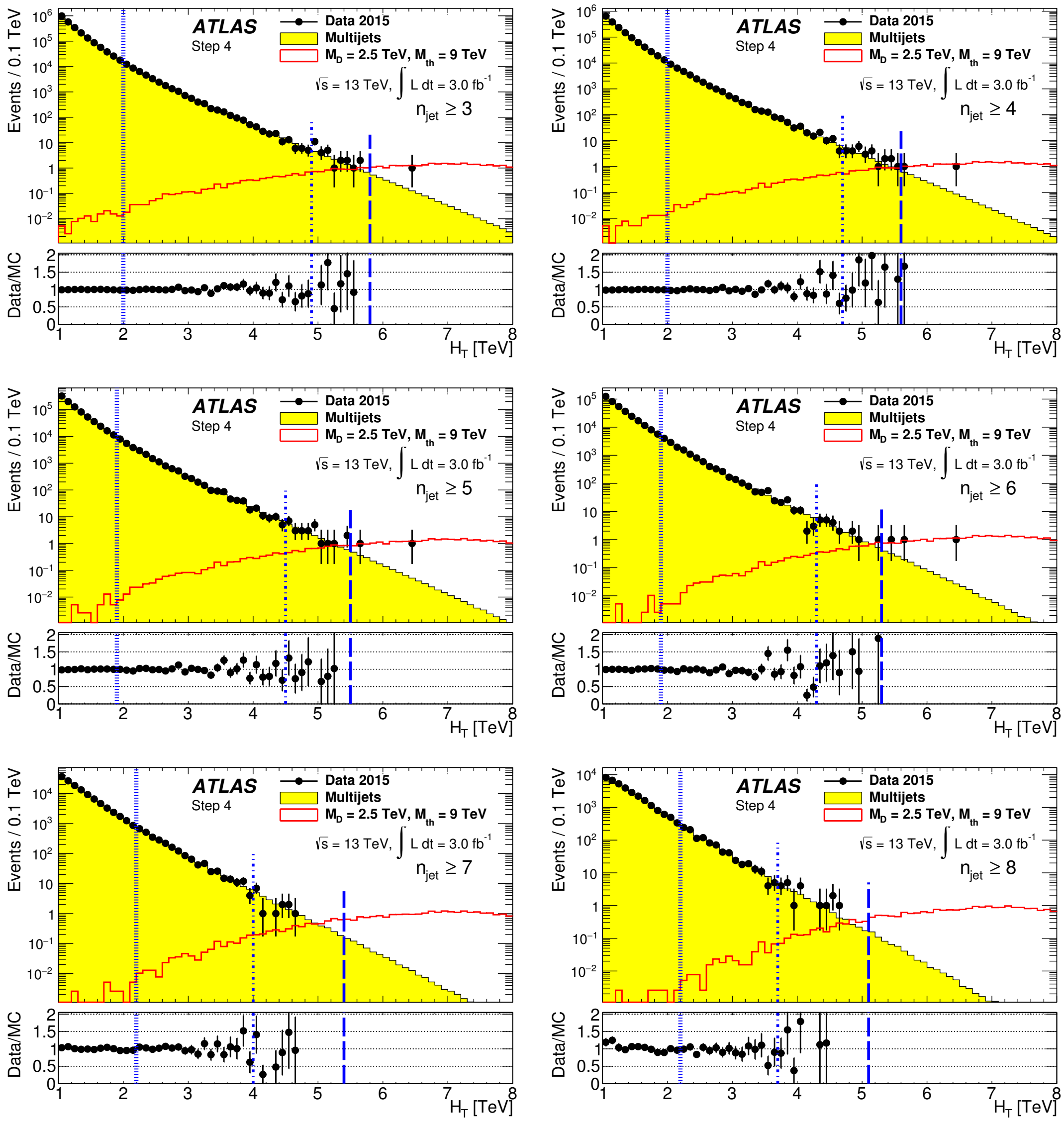

Figure 4. Data and MC simulation comparison for H_{T} distributions in different inclusive n_{jet} bins for the 3.0 fb^{-1} data sample. The black hole signal with $M_{\mathrm{D}} = 2.5$ TeV, $M_{\mathrm{th}} = 9.0$ TeV is superimposed with the data and background MC. The MC simulation is normalized to data in the normalization region. The vertical dotted line marks the lower boundary of the control region, the vertical dashed-dotted line marks the boundary between control region and validation region, and the vertical dashed line marks the boundary between validation region and signal region. These boundaries are determined for each n_{jet} sample separately.

associated with the choice and extrapolation of the empirical fitting functions. In a pseudo-experiment based approach, the statistical component and the extrapolation uncertainty of the baseline fitting function are estimated from the width and median value of the difference between the extrapolations obtained from pseudo-experiments using the baseline function and the actual values in the validation and signal regions of the H_{T} distribution. In a data-driven approach, the maximal difference in the background projection between the baseline

	Functional form	p_1	p_2
1	$f_1(x) = \frac{p_0(1-x)^{p_1}}{x^{p_2}}$	(0,+∞)	(0,+∞)
2	$f_2(x) = p_0(1-x)^{p_1} e^{p_2 x^2}$	(0,+∞)	(-∞ ,+∞)
3	$f_3(x) = p_0(1-x)^{p_1} x^{p_2 x}$	(0,+∞)	(-∞ ,+∞)
4	$f_4(x) = p_0(1-x)^{p_1} x^{p_2 \ln x}$	(0,+∞)	(-∞ ,+∞)
5	$f_5(x) = p_0(1-x)^{p_1}(1+x)^{p_2 x}$	(0,+∞)	(0,+∞)
6	$f_6(x) = p_0(1-x)^{p_1}(1+x)^{p_2 \ln x}$	(0,+∞)	(0,+∞)
7	$f_7(x) = \frac{p_0}{x}(1-x)^{[p_1 - p_2 \ln x]}$	(0,+∞)	(0,+∞)
8	$f_8(x) = \frac{p_0}{x^2}(1-x)^{[p_1 - p_2 \ln x]}$	(0,+∞)	(0,+∞)
9	$f_9(x) = \frac{p_0(1-x^{1/3})^{p_1}}{x^{p_2}}$	(0,+∞)	(0,+∞)
10	$f_{10}(x) = p_0(1-x^{1/3})^{p_1} x^{p_2 \ln x}$	(0,+∞)	(-∞ ,+∞)

Table 1. Analytic functions considered in this analysis where $x = H_{\mathrm{T}}/\sqrt{s}$. p_0 is a normalization constant. p_1 and p_2 are free parameters in a fit, and their allowed floating ranges are shown in the last two columns.

function and qualified alternative function is used to estimate the uncertainty associated with the choice of fitting function. The estimated uncertainties are shown in tables 2, 3, 4 and 5 where they are indicated by (PE) and (DD) based on the approach used.

In order to convert a limit on the number of events in the signal region to a limit on a physics model, simulated signals are needed. This simulation is used to determine the number of signal events after event selection and therefore depends on the uncertainties in that determination. The uncertainty on the expected signal yield includes a luminosity uncertainty of 9% and jet energy scale and resolution uncertainties, which ranges from 1 to 4% depending on the signal models. The latter are critical as they impact the signal selection efficiency.

6 Results

Tables 2, 3, 4 and 5 show the predicted number of background events in the validation and signal regions in the data sets corresponding to each step of the analysis. The first step analysis is shown only for events with $n_{\mathrm{jet}} \geq 3$: no useful limit can be obtained for higher multiplicities using this 6.5 pb^{-1} data set as there is insufficient data.

In the case of the second step and $n_{\mathrm{jet}} \geq 3$, function 5 is excluded at 95% CL by the observed validation region yield, and the remaining qualified functions (10, 1, 4, 9, 6 and 3) are validated. These are shown in figure 6. For the remaining multiplicities all qualified functions are consistent with data in the validation region and are used to obtain signal region estimates.

Whether or not any given function can succeed in providing a satisfactory fit depends on the data in the control regions whose boundaries depend on the total luminosity used

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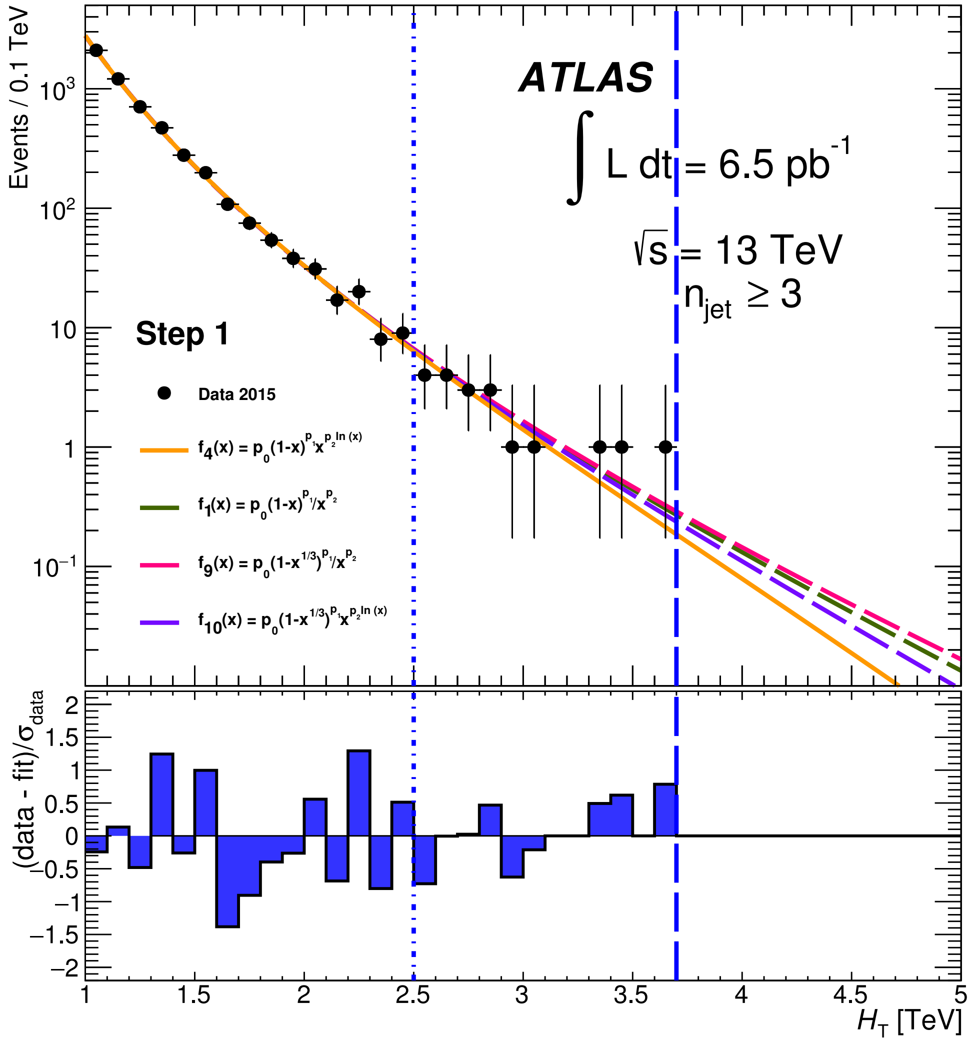

Figure 5. The data in 1.0 TeV $< H_T <$ 2.5 TeV for $n_{\text{jet}} \geq 3$ are fitted by the baseline function (solid), and three alternative functions (dashed). The fitted functions are extrapolated to the validation region and signal region. The control, validation and signal regions are delimited by the vertical lines. The bottom section of the figure shows the residual significance defined as the ratio of the difference between fit and data over the statistical uncertainty of data, where the fit prediction is taken from the baseline function.

in that step. For the fourth step and $n_{\text{jet}} \geq 8$, functions 1, 2, 3 4, 5, 6, 9, and 10 are qualified; all the functions are qualified for the remaining jet multiplicities. Function 10 is the baseline in all cases except in $n_{\text{jet}} \geq 3$ where function 10 as well as functions 1 and 4 are excluded in the validation region. The remaining functions (5, 6, 9, 3, 8, 7, 2) are validated, and function 5 becomes the baseline. In other cases, all functions are validated. These are shown in figure 8. For the remaining multiplicities all validated functions are consistent with data in the validation region and are used to obtain signal region estimates.

As can be seen from tables 2 to 5, the predicted and observed number of events in the validation regions are in agreement. Since there is no excess in the signal region in any given

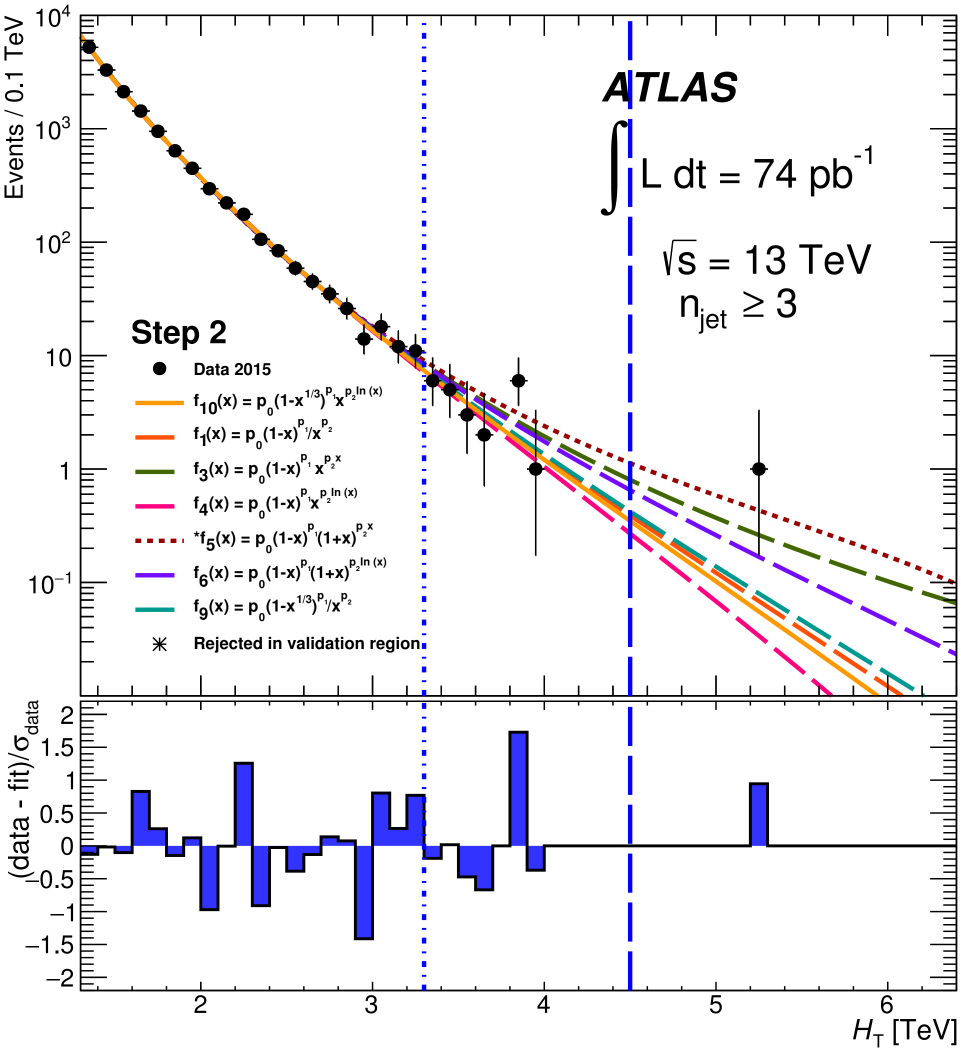

Figure 6. The data in 1.2 TeV $< H_T <$ 3.3 TeV for $n_{\rm jet} \geq 3$ are fitted by the baseline function (solid), and six alternative functions (dashed). The fitted functions are extrapolated to the validation region and signal region. The control, validation and signal regions are delimited by the vertical lines. The function indicated by an asterisk is rejected at 95% CL by the data in the validation region. The bottom section of the figure shows the residual significance defined as the ratio of the difference between fit and data over the statistical uncertainty of data, where the fit prediction is taken from the baseline function.

step, there can be no significant signal contributions to the control and validation regions for the subsequent steps and limits can be set using the last step where the observation is consistent with the absence of signal. The p-values of a background-only hypothesis of all the predictions in the signal and validation regions of all the validation functions are larger than 0.1. The model-dependent 95% CL limit is shown in figure 9 as a function of $M_{\rm D}$ and $M_{\rm th}$ for classical rotating black holes with $n = 2, 4, 6$ simulated with CHARYBDIS2, using the $n_{\rm jet} \geq 3$ result for the data set with $3.0\,{\rm fb}^{-1}$. This jet multiplicity yields the best expected limit for the models under test. Limits are shown for classical black holes

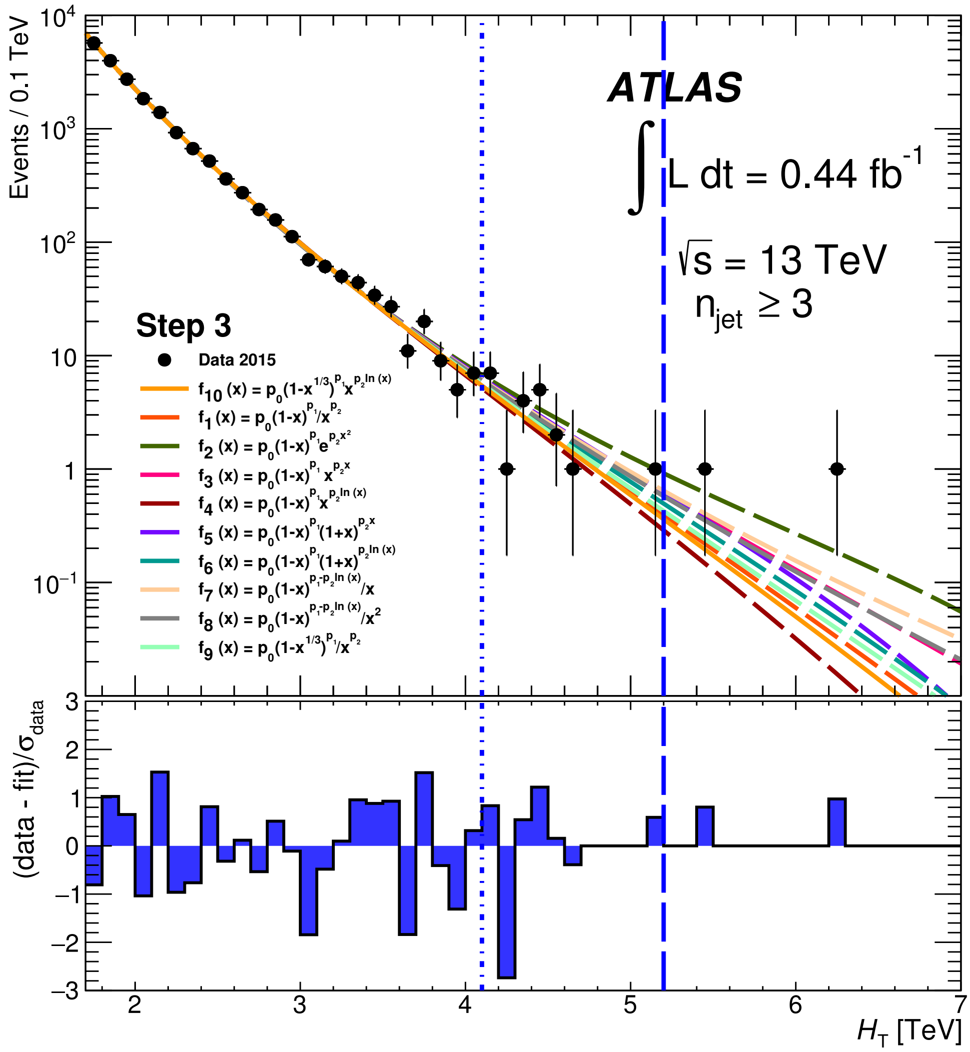

Figure 7. The data in 1.7 TeV $< H_\mathrm{T} <$ 4.1 TeV for $n_\mathrm{jet} \geq 3$ are fitted by the baseline function (solid), and nine alternative functions (dashed). The fitted functions are extrapolated to the validation region and signal region. The control, validation and signal regions are delimited by the vertical lines. The bottom section of the figure shows the residual significance defined as the ratio of the difference between fit and data over the statistical uncertainty of data, where the fit prediction is taken from the baseline function.

with $n = 2, 4$ and 6. For the purpose of comparing sensitivity with other LHC searches for strong gravity, the interpretation is extended to parameter space where the M_th and M_D are comparable. The expected limit significantly exceeds the sensitivity reached by the Run-1 ATLAS search [5]. The production of a rotating black hole with n = 6 is excluded, for M_th up to 9.0 TeV–9.7 TeV, depending on the M_D. The evolution of the limits with luminosity is shown in figure 10 where a comparison with the Run-1 limit as well as the uncertainty on the final expected limit is shown.

An interpretation in terms of the string ball model with six extra dimensions is shown in figure 11. Limits are shown as a function of M_th and g_S for constant M_S and as a function of M_th and M_S for fixed g_S.

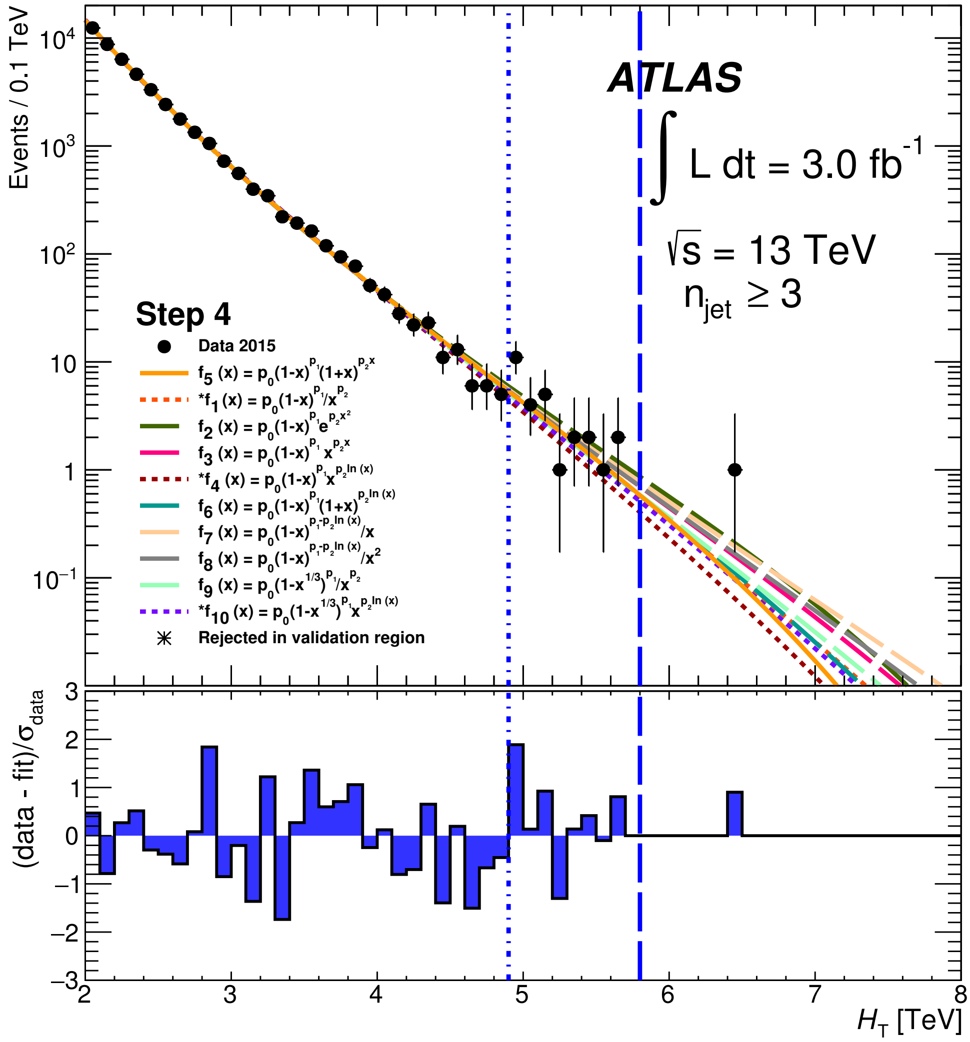

Figure 8. The data in 2.0 TeV $< H_\mathrm{T} <$ 4.9 TeV for $n_\mathrm{jet} \geq 3$ are fitted by the baseline function (solid), and nine alternative functions (dashed). The fitted functions are extrapolated to the validation region and signal region. The control, validation and signal regions are delimited by the vertical lines. The three functions indicated by asterisks are rejected at 95% CL by the data in the validation region. The bottom section of the figure shows the residual significance defined as the ratio of the difference between fit and data over the statistical uncertainty of data, where the fit prediction is taken from the baseline function.

$n_\mathrm{jet} \geq$	VR (obs)	VR (exp)	SR (obs)	SR (exp)
3	19	20.4 ± 4.4 (PE) ± 2.6 (DD)	0	0.65 ± 0.46 (PE) ± 0.64 (DD)

Table 2. The expected and observed number of events in the validation region (VR) and signal region (SR) are shown for $n_\mathrm{jet} \geq 3$ in the 6.5 pb^{-1} data set. The uncertainties on the predicted rates are shown. They are obtained from the pseudo-experiment based approach (PE) and the data-driven approach (DD).

$n_{\text{jet}} \geq$	VR (obs)	VR (exp)	SR (obs)	SR (exp)
3	23	27.1 ± 3.7 (PE) ± 9.6 (DD)	1	1.42 ± 0.41 (PE) $^{+4.3}_{-1.42}$ (DD)
4	27	25.4 ± 3.2 (PE) ± 15.5 (DD)	0	1.62 ± 0.46 (PE) $^{+9.2}_{-1.62}$ (DD)
5	21	18.9 ± 2.9 (PE) ± 9.9 (DD)	0	1.32 ± 0.48 (PE) $^{+5.1}_{-1.32}$ (DD)
6	18	20.7 ± 3.3 (PE) ± 10.4 (DD)	0	1.19 ± 0.48 (PE) $^{+13.3}_{-1.19}$ (DD)
7	29	22.2 ± 3.7 (PE) ± 7.0 (DD)	0	0.81 ± 0.36 (PE) ± 0.60 (DD)

Table 3. The expected and observed number of events in the validation region (VR) and signal region (SR) are shown for five overlapping inclusive jet multiplicity bins in the 74 pb^{-1} data set. The uncertainties on the predicted rates are shown. They are obtained from the pseudo-experiment based approach (PE) and the data-driven approach (DD).

$n_{\text{jet}} \geq$	VR (obs)	VR (exp)	SR (obs)	SR (exp)
3	21	20.4 ± 2.7 (PE) ± 10.5 (DD)	2	1.46 ± 0.42 (PE) $^{+4.37}_{-1.46}$ (DD)
4	23	29.9 ± 3.9 (PE) ± 8.1 (DD)	2	1.95 ± 0.46 (PE) $^{+4.06}_{-1.95}$ (DD)
5	17	21.4 ± 3.4 (PE) ± 7.1 (DD)	1	1.56 ± 0.51 (PE) $^{+3.47}_{-1.56}$ (DD)
6	19	28.3 ± 4.3 (PE) ± 6.3 (DD)	0	1.44 ± 0.40 (PE) $^{+2.13}_{-1.44}$ (DD)
7	28	24.7 ± 3.8 (PE) ± 4.5 (DD)	0	0.96 ± 0.39 (PE) $^{+1.74}_{-0.96}$ (DD)
8	25	31.8 ± 4.7 (PE) ± 1.4 (DD)	2	2.86 ± 0.40 (PE) ± 0.70 (DD)

Table 4. The expected and observed number of events in the validation region (VR) and signal region (SR) are shown for six overlapping inclusive jet multiplicity bins in the 0.44 fb^{-1} data set. The uncertainties on the predicted rates are shown. They are obtained from the pseudo-experiment based approach (PE) and the data-driven approach (DD).

$n_{\text{jet}} \geq$	VR (obs)	VR (exp)	SR (obs)	SR (exp)
3	28	19.5 ± 3.6 (PE) ± 4.1 (DD)	1	2.10 ± 0.51 (PE) ± 1.78 (DD)
4	27	20.8 ± 2.3 (PE) ± 6.4 (DD)	2	2.36 ± 0.52 (PE) ± 2.12 (DD)
5	26	22.3 ± 2.6 (PE) ± 6.8 (DD)	2	1.95 ± 0.45 (PE) $^{+2.10}_{-1.95}$ (DD)
6	20	20.3 ± 2.9 (PE) ± 5.4 (DD)	3	1.82 ± 0.49 (PE) $^{+1.91}_{-1.82}$ (DD)
7	14	20.7 ± 4.1 (PE) ± 1.7 (DD)	0	0.53 ± 0.36 (PE) ± 0.22 (DD)
8	19	18.2 ± 4.9 (PE) ± 3.5 (DD)	0	0.43 ± 0.36 (PE) ± 0.26 (DD)

Table 5. The expected and observed number of events in the validation region (VR) and signal region (SR) are shown for six overlapping inclusive jet multiplicity bins in the 3.0 fb^{-1} data set. The uncertainties on the predicted rates are shown. They are obtained from the pseudo-experiment based approach (PE) and the data-driven approach (DD).

The limits can be re-expressed in terms of a limit on the cross section to produce new physics with a minimum H_{T} requirement ($H_{\text{T}}^{\text{min}}$) as a function of n_{jet} with the kinematic restriction that each jet must satisfy $p_{\text{T}} > 50$ GeV and $|\eta| < 2.8$ and that at least one jet must have $p_{\text{T}} > 200$ GeV. In order to do this the efficiency for detecting events satisfying this kinematic requirement must be known. This efficiency is model-dependent. A conservative estimate was obtained by taking the minimal efficiency from signal models whose

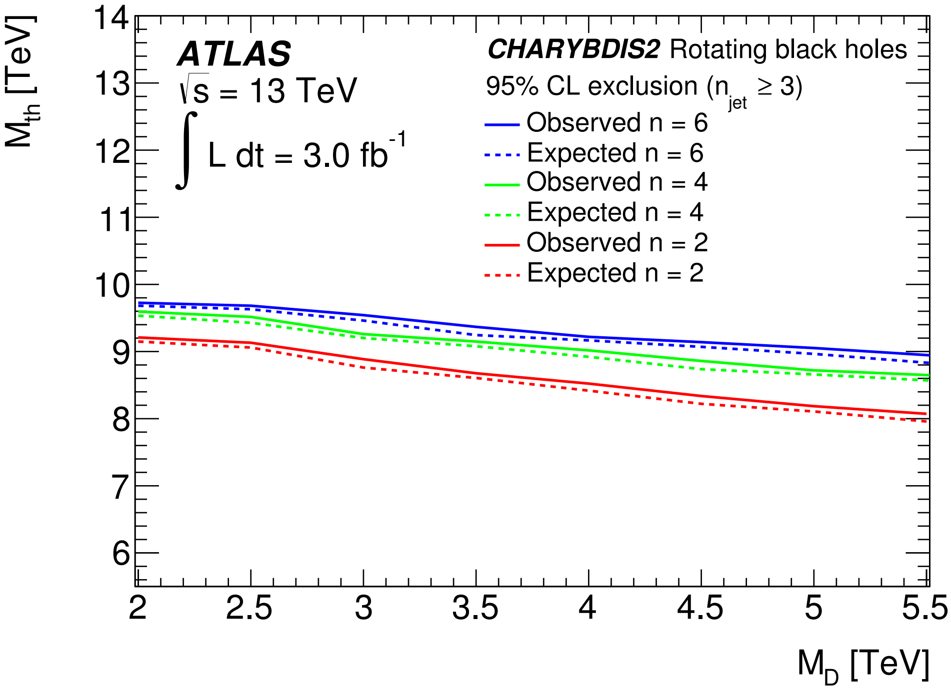

Figure 9. The observed and expected 95% CL exclusion limits on rotating black holes with different numbers of extra dimensions ($n = 2, 4, 6$) in the $M_{\mathrm{D}} - M_{\mathrm{th}}$ grid. The results are based on the analysis of 3.0 fb^{-1} of integrated luminosity. The region below the lines is excluded.

$n_{\mathrm{jet}} \geq$	$H_{\mathrm{T}} > H_{\mathrm{T}}^{\mathrm{min}}$ (TeV)	Expected limit (fb)	Observed limit (fb)
3	5.8	$1.63^{+0.70}_{-0.57}$	1.33
4	5.6	$1.77^{+0.70}_{-0.57}$	1.77
5	5.5	$1.56^{+0.73}_{-0.50}$	1.75
6	5.3	$1.52^{+0.69}_{-0.50}$	2.15
7	5.4	$1.02^{+0.36}_{-0.0}$	1.02
8	5.1	$1.01^{+0.29}_{-0.0}$	1.01

Table 6. The expected and observed limits on the inclusive cross section in femtobarns for production of events as a function of n_{jet} and the minimum value of H_{T} . The limits are derived from results of the 3.0 fb^{-1} analysis so $H_{\mathrm{T}}^{\mathrm{min}}$ corresponds to the value of S for the last analysis step.

predicted rates lie within ± 10% of the observed limits. The minimum efficiency is found to be 0.98. The resulting limit on the cross section is shown in table 6 which shows the expected limits together with their uncertainties, and the observed limits.

7 Conclusion

A search for signals of strong gravity in multijet final states was performed using 3.6 fb^{-1} of proton-proton data taken at 13 TeV from the Large Hadron Collider using the ATLAS detector. Distributions of events as a function of the scalar sum of the transverse momenta

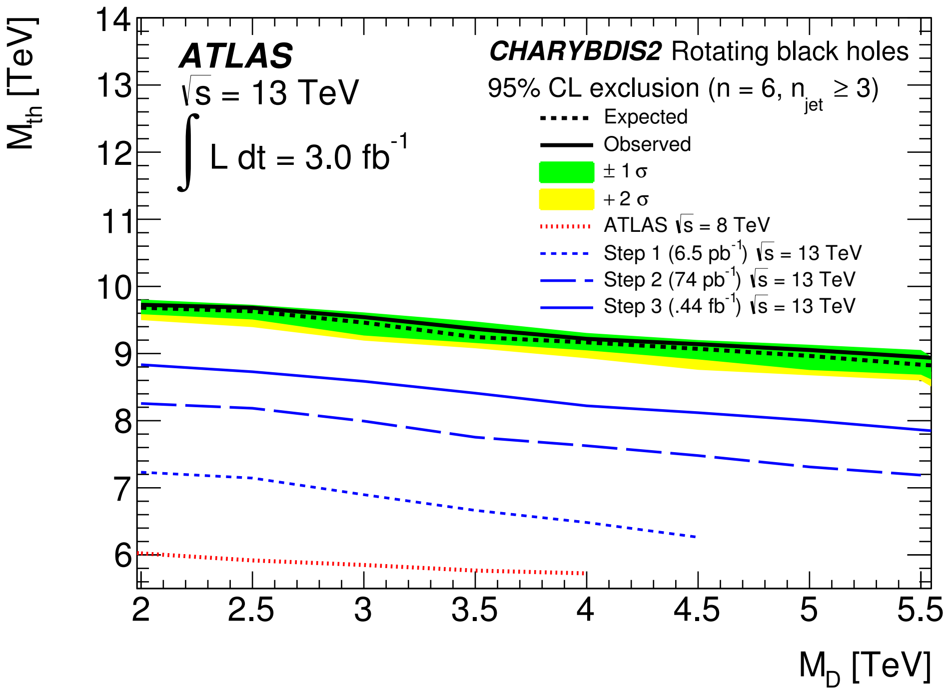

Figure 10. The observed and expected limits on rotating black holes with $n = 6$ in the $M_\mathrm{D} - M_\mathrm{th}$ grid, from the analysis with an integrated luminosity of 3.0 fb^{-1}. The 95% CL expected limit is shown as the black dashed line, and limits corresponding to the $\pm$ 1 σ and + 2 σ variations of the background expectation are shown as the green and yellow bands, respectively. The 95% CL observed limit is shown as the black solid line. The -2 σ band is not shown as it almost completely overlaps with the -1 σ band. The blue dashed lines corresponds to the observed limits from the first, second and third step analyses. The red dotted line corresponds to the limit from Run-1 ATLAS multijet search [5].

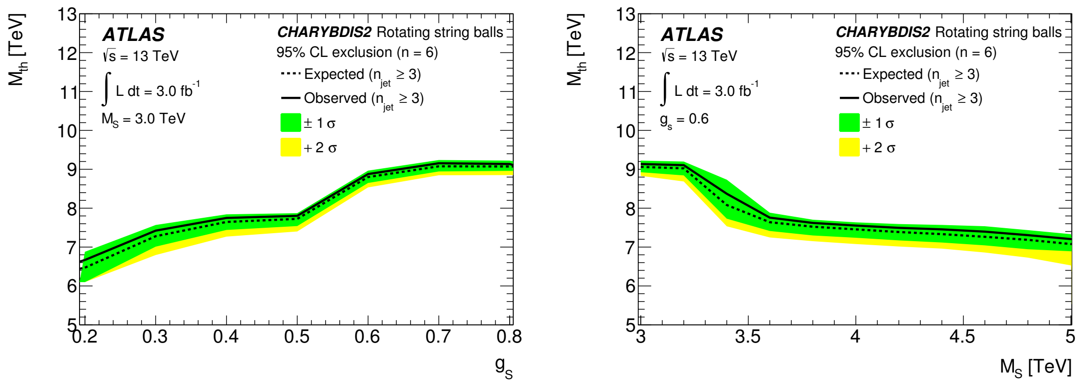

Figure 11. The expected and observed limits on the string ball model with $n = 6$, from the analysis with an integrated luminosity of 3.0 fb^{-1}. The left plot shows the 95% CL limit as a function of g_S and M_th (solid line). The dashed line shows the expected limit; the limits corresponding to the $\pm$ 1 σ and + 2 σ variations of the background expectation are shown as the green and yellow bands, respectively. The right plot shows the limits as a function of M_th and M_S for $g_\mathrm{S} = 0.6$. The -2 σ band is not shown as it almost completely overlaps with the -1 σ band.

of jets were examined. No evidence for deviations from Standard Model expectations at large H_T has been seen. In the CHARYBDIS2 1.0.4 model exclusions are shown as a function of M_D and M_{th}. The production of a rotating black hole with $n = 6$ is excluded, for M_{th} up to 9.0 TeV–9.7 TeV, depending on the M_D. Limits on parameters in the string-ball model are also set. These extend significantly the limits from the 8 TeV LHC analyses.

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