Probing TeV Gravity with the ATLAS Detector

Victor Lendermann (on behalf of the ATLAS Collaboration)
Kirchhoff-Institut für Physik, Universität Heidelberg,
Im Neuenheimer Feld 227, 69120 Heidelberg, Germany
E-mail: victor@kip.uni-heidelberg.de

Abstract. Models with compactified extra space dimensions offer a new way to address outstanding problems in and beyond the Standard Model. In these models, the strength of gravity is strongly increased at small distances, which opens up the possibility of observing quantum gravity effects in the TeV energy range reachable by the LHC. One of the most spectacular phenomena would be the production of microscopic black holes. Searches for black holes are foreseen in the ATLAS experiment with the start-up of data taking in 2009. We present feasibility studies for the triggering, selection and reconstruction of the black hole event topologies, the black hole discovery potential and their identification.

1. Introduction

The unification of all fundamental interactions is a major goal for modern particle physics. An outstanding challenge for unified theories is the huge difference between the electroweak energy scale, $M_{\text{EW}} \simeq 100 \text{GeV}$, and the Planck scale, $M_{\text{Pl}} \simeq 10^{19} \text{GeV}$ at which the gravitational interaction becomes strong.

A class of approaches addressing this hierarchy problem is based on the hypothesis of compactified extra space dimensions. In ADD models [1–3] additional flat extra dimensions are postulated, while RS [4, 5] models invoke a single warped extra dimension. The observed weakness of gravity is due to the gravitational field being allowed to expand into the higher-dimensional space (bulk), while the Standard Model (SM) particles are confined to our familiar three-dimensional space (3-brane). Such models are in particular motivated by string theory.

In extra-dimensional models, the $D$-dimensional Planck scale $M_D$ is the fundamental scale from which the Planck scale in four dimensions is derived. The relationship between the two scales is determined by the volume of the extra dimensions in ADD models or by the warp factor in RS models. For large extra dimensions or a strongly warped extra dimension, the fundamental scale of gravity can be very low. Current experimental limits allow the fundamental scale of gravity to be as low as about 1 TeV (see [6] for review). The constraints have been set by tabletop experiments, particle accelerator experiments, astrophysical observations and cosmological considerations, and cosmic ray measurements.

The gravity scale in the TeV range would open up a rich phenomenology at the LHC. Real graviton production and virtual graviton exchange in $pp$ collisions are examples of perturbatively calculable processes predicted in the models with extra dimensions [7]. In addition, non-perturbative effects, most notably the production of black holes (BH), are considered (see [8, 9] for review). The discovery and study of such processes at the LHC will not only test general relativity and probe extra dimensions, but would also open a path to understanding quantum
gravity. In the following, feasibility studies for the triggering, selection and reconstruction of
the black hole event topologies, the black hole discovery potential and their identification with
the ATLAS detector are presented. Details of this work can be found in Ref. [10].

2. Black Hole Production and Decay

If two particles, e.g. two partons in a pp interaction, pass within a distance smaller than the
event horizon defined by their total centre-of-mass energy, the particles will be trapped behind
the horizon and a black hole may form. In general, black hole formation in higher dimensions
has a complicated dependence on both the gravitation field of the brane and the geometry of
the extra dimensions.

A complete quantitative description of black hole production requires the theory of quantum
gravity. Lacking such a theory, we can only consider a semi-classical picture for black holes with
mass $M_{BH}$ substantially heavier than the fundamental Planck scale in higher dimensions. In
this regime, the brane’s gravitational field should be negligible and its only effect is to bind the
black hole to the brane.

We also assume the geometrical scales of the extra dimensions to be large compared to $1/M_{D}$,
so that there is a wide regime in which the geometry of the extra dimensions plays no essential
role, and the ADD and RS models can be treated indistinguishably. Thus, we may consider
the high-energy collision of the particles and the resulting black hole formation to be in $D$
-dimensional flat spacetime [11]. For a particular amount of available energy, a range of black
hole masses will result depending on the impact parameter of the particle collision.

Since the black hole is not an ordinary particle of the Standard Model and its correct
quantum theoretical treatment is unknown, it is treated as a quasi-stable state with a long
enough lifetime, which is produced and decays according to a semi-classical formalism. There
is no exact prediction for the minimum mass of black holes for which this formalism is valid.
Based on current lower limits on the fundamental scale and basic theoretical considerations [12],
substantial production of semi-classical black holes at $M_{BH} \lesssim 5$ TeV seems unlikely. Hence, the
minimum mass of a black hole is set at 5 TeV or more in the present study. The black hole
produced may have any gauge or spin quantum numbers.

Discussions of semi-classical black hole production at colliders postulate a black disc form
for the cross section $\sigma \approx \pi r_{h}^2$, where $r_{h}$ is the horizon radius of the black hole formed in the
parton scattering process [13–16]. This approximation can be modified by a number of effects
depending on mass, angular momentum, electric charge, colour, and finite size of the incoming
particles. The current results, though far from complete, indicate that the simple geometric cross
section is correct if multiplied by a formation factor of order unity [17]. A striking feature of the
black disc cross section is its rise with the centre-of-mass energy which distinguishes black hole
production from any perturbative process. However, at hadron colliders the rising parton cross
section folded with parton distribution functions (PDF) still results in a falling cross section in
hadron interactions.

Black hole production and decay can be qualitatively thought of as evolving according to a
series of distinct phases. In the first phase, the gravitational field of the relativistic particles
producing the black hole is approximately localized to narrow longitudinal shock waves which
interact non-linearly by shearing and focusing, and space-time within the future light-cone of the
collision becomes highly curved. A complex-shaped event horizon forms which quickly collapses
down to a more regular-shaped apparent horizon by the emission of gravitational waves into the
bulk space. According to the no-hair theorem [18], the resulting asymmetry and moments due to
the violent production process are radiated away by gravitons into the bulk until a Kerr-Newman
stationary solution is formed, which is characterized by only its mass, angular momentum and
local gauge charges.

Black holes are expected to be produced in high angular momentum states from particle
collisions above the Planck scale. It is anticipated that they will spin-down very rapidly to a Reissner-Nordström static solution by the emission of high-spin state particles.

Following the spin-down phase, thermal Hawking radiation [19] is thought to be emitted by black holes due to quantum effects. This phase is the most well studied. A black hole of a particular mass is characterized by a Hawking temperature $T_H$ and as the decay progresses the black hole mass falls and the temperature rises. Grey-body factors modify the spectrum of emitted particles from that of a perfect thermal black body [20]. They quantify the probability of transmission of the particles through the curved space-time outside the horizon. At high energies, the shape of the spectrum is like that of a black body, while at low energies the behaviour of the grey-body factors is spin-dependent and also depends on the number of dimensions.

The Hawking radiation allows black holes to lose mass; they are expected to evaporate, shrink, and ultimately vanish. The final fate of the black hole is unknown since quantum gravity will become important as the black hole mass approaches the Planck scale. The black hole can not decay down to nothing without the loss of information [18]. The possibility of a final black hole remnant with mass of the order of the Planck scale has been studied [21]. Either this remnant is charged and ionizing like a particle, in which case it will need to be detected, or more likely [22], it will be neutral and possibly not detectable.

Since gravitons propagate into the bulk, it is possible for the black hole to pick up a recoil transverse to the brane direction. If the brane tension is insufficient to bind the black hole to the brane, we might anticipate that the black hole could leave the brane, resulting in a large missing energy signature [23].

Baryon and lepton numbers do not have to be conserved in black hole decays. However, violation of quantum number conservation in the gravitational interaction imposes severe lower bounds on the fundamental gravity scale, far beyond the range accessible at the LHC [24].

3. Black Hole Monte Carlo Simulations

For the present study, events are generated by the Monte Carlo (MC) program CHARYBDIS [25, 26] and passed through the full simulation of the ATLAS detector. Event samples were produced for different number of extra dimensions in the ADD framework, setting the fundamental gravity scale\(^1\) to $M_D = 1\, \text{TeV}$ and requiring the minimum black hole mass to be at least 5\, TeV.

The generator models mainly the Hawking radiation phase, ignoring the horizon formation, balding and spin-down effects. The Hawking evaporation process is treated as a democratic decay into all SM particles with equal probabilities assigned to each degree of freedom taking into account polarization, charge and colour. The emitted charge is chosen to minimise the magnitude of the black hole charge. The particles are treated as massless, including the gauge bosons, Higgs boson and heavy quarks. The energies are assigned to the decay particles according to the Hawking temperature $T_H$ taking spin statistics factors into account. $T_H$ is updated after each emission, and the decay is assumed to be quasi-stationary, i.e. the black hole comes into equilibrium at each new temperature before the next particle is emitted. Although black holes may lose a significant fraction of their mass via graviton radiation into the bulk, gravitons are not included in the present model, such that missing energy comes only from neutrinos.

The evaporation phase ends when the chosen energy for the emitted particle is ruled out by the kinematics of a two-body decay. At this point an isotropic two-body phase-space decay is performed. In our simulation, the decay is performed totally to Standard Model particles and no stable exotic remnants remain.

\(^{1}\) Dimopoulos–Landsberg convention for $M_D$ is used: $M_D^{D-2} = 1/G_D$, where $G_D$ is the $D$-dimensional Newton gravity constant.
Figure 1. (left) Multiplicity of reconstructed objects for four black hole samples: three samples with black hole masses $M_{BH} > 5 \text{ TeV}$ and with $n = 2$ (black), 4 (red) and 7 (green) extra dimensions, as well as one sample with $n = 2$ and $M_{BH} > 8 \text{ TeV}$. All samples are simulated with the gravity scale of $M_D = 1 \text{ TeV}$; (right) Event aplanarity for two black hole samples with $M_{BH} > 5 \text{ TeV}$ and $n = 2$ (green) and $n = 7$ (black), as well as for QCD dijet (magenta), $t\bar{t}$ (violet), $Z + \text{jet}$ (orange) and $W + \text{jet}$ (cyan) backgrounds.

4. Black Hole Search Strategy

4.1. Basic Event Properties and Backgrounds

The high mass scale, and the thermal nature of the decay process result in black hole events being characterised by a large number of high-$p_T$ final state particles, including all SM fields.

Black hole signatures can be faked by a number of SM backgrounds. The dominant ones are states with high multiplicity or high energy jets. In this study we use QCD dijet samples generated using PYTHIA 6.4 [29], $t\bar{t}$ event samples generated using MC@NLO [30, 31], as well as vector boson plus jets signals generated using ALPGEN [32].

For a given black hole mass and a fixed fundamental scale $M_D$ (in Dimopoulos–Landsberg convention) the Hawking temperature is higher for larger number of extra dimensions $n$. Higher temperature means higher energy emissions, with the consequence that the energy is shared between fewer particles. This significantly affects the multiplicity and event shape distributions (Fig. 1), leading to QCD-jet-like event shapes for high $n$. This strong dependence on the model parameters hampers the seemingly natural usage of event shape variables for separation of black hole events from SM backgrounds.

4.2. Triggering on Black Holes

The ATLAS trigger and data-acquisition system consists of three levels of online event selection: level-1, level-2 and event filter [33]. Each subsequent trigger level refines the decisions made at the previous level and may apply additional selection criteria. From the initial bunch-crossing rate of 40 MHz, only 50–200 Hz may be selected for permanent storage. The level-1 trigger is implemented using dedicated electronics, while the higher level triggers are software implementations running on a computer cluster.

Although black holes may decay to all the SM particles, jets are expected to carry a dominant fraction of the visible decay energy and hence provide a good option for triggering black hole events. The abundance of highly energetic jets in Hawking radiation results from the large number of quark degrees of freedom and from the temperature of Hawking radiation [14, 15]. The total efficiency of the single-jet trigger for black hole events is demonstrated in Fig. 2 for a simulated dataset with two extra-dimensions, $M_D = 1 \text{ TeV}$, $M_{BH} > 5 \text{ TeV}$. Setting this trigger threshold at 400 GeV will provide greater than 99% efficiency at all trigger levels. The Standard
Model process trigger rate at this threshold is expected to be less than 0.1 Hz while running at a luminosity of the $10^{31}\,\text{cm}^{-2}\text{s}^{-1}$, which should allow this trigger to run without prescaling even significantly below this threshold.

Alternatively, a trigger based on the scalar sum of transverse energies of all recorded decay products ("sum-$E_T$ trigger") is considered. No simulation of this trigger was available in the samples used in this study.

Based on experience of previous collider experiments, one may expect detector hardware problems at the beginning of data taking. In particular, noisy channels in the calorimeter or trigger electronics may cause high trigger rates for the single-jet trigger and for the sum-$E_T$ trigger, such that even the highest threshold triggers have to be prescaled. In such cases, a multijet (3- or 4-jet) trigger is considered for use and is expected to provide a high trigger efficiency for black holes.

4.3. Offline Analysis Strategy

Two complementary methods to select black hole events are studied. Both methods show similar performance but differ in sensitivity to systematic uncertainties.

In the first method, a minimum scalar sum of the transverse momenta of all reconstructed objects, $\sum |p_T| > 2.5\,\text{TeV}$ is required to reject backgrounds. Figure 3 demonstrates good background discrimination and high signal efficiency for all black hole samples. This requirement is relatively unaffected by changes in the number of extra dimensions $n$. A further requirement of at least one lepton ($e$ or $\mu$) with $p_T > 50\,\text{GeV}$ should strongly suppress the remaining QCD background while still maintaining a significant signal efficiency. Figure 4 shows the distribution of the reconstructed invariant masses of black holes after applying the above requirements.

In the second method, at least four objects with $p_T > 200\,\text{GeV}$ are required. Figure 5a shows as an example the $p_T$ distributions of the 4th-leading object. The signal is characterized by larger $p_T$ than the backgrounds. In addition a requirement of at least one lepton with $p_T > 200\,\text{GeV}$ is imposed, in order to suppress remaining QCD backgrounds. The corresponding lepton $p_T$ distribution, plotted after the requirement of four high $p_T$ objects, is shown in Fig. 5b.

4.4. Discovery Reach

Producing a robust discovery potential for black hole events is difficult, because the semi-classical assumptions that allow us to model them are valid only well above the Planck scale. It is anticipated that events at the Planck mass would not resemble black hole events nor pass the signal selection, being of low multiplicity and energy, but that as the energy rises above that, the number of black holes produced will increase. Therefore we calculate discovery bounds conservatively by introducing an artificial cutoff on the minimum black hole mass in generated samples. The discovery reach as a function of the mass threshold for the semi-classical black
Figure 3. $\sum |p_T|$ distributions for (left) black hole samples and (right) backgrounds (QCD dijet, $t\bar{t}$ and $W/Z + \text{jet}$), along with one signal sample for reference.

Figure 4. Black hole mass distribution with requirements $\sum |p_T| > 2.5 \text{ TeV}$ and lepton $p_T > 50 \text{ GeV}$ for the signal sample with $n = 2$ and $M_{BH} > 5 \text{ TeV}$, and for backgrounds.

Figure 5. Event selection variables for the black hole sample with $n = 2$ and $M_{BH} > 5 \text{ TeV}$ and for backgrounds: (left) $p_T$ distribution of 4th-leading object out of all selected objects; (right) $p_T$ distribution of the leading lepton (electron or muon) after requiring at least four reconstructed objects with $p_T > 200 \text{ GeV}$.

Hole production using the $\sum |p_T|$ and lepton cuts is shown in Fig. 6. 5 TeV black holes can be discovered with only a few pb$^{-1}$ of data, while a 1 fb$^{-1}$ of data would allow discovery of black holes with a threshold of 8 TeV.

4.5. Black Hole Identification
Several methods of identifying black holes and distinguishing them from other signatures of new physics were proposed [14, 15, 34, 35]. Their performance is to be studied in future with detailed
One approach focuses on a distinct property of black holes, the democratic decay to all SM particles, modified by phase space factors and grey-body factors. A measurement of relative production rates of different particle types in black holes decays may provide a strong hint for black holes if the ratios of the different rates would correspond to the democratic decay expectation.

Another approach is to extract the parton cross section from the $pp$ cross section for the process under study and check its dependence on the parton-parton centre-of-mass energy. For black holes, a rising cross section is expected which is a distinct feature of this non-perturbative process. However, such an extraction may be difficult to realise, as it requires on one hand a precise measurement of the differential cross section with a good resolution of the black hole mass reconstruction, and on the other hand a good theoretical understanding of black hole production. In particular, the applicability of the standard factorisation ansatz to this non-perturbative process is not yet proven, and thus the fraction of the parton energy available for black hole formation is unknown. Furthermore a good knowledge of PDFs is required in the regime where corrections due to gravitational interactions may affect the PDF evolution.

A further assessment of event properties may be obtained by studying global event shape variables. This may also provide information on the model parameters, such as the number of extra dimensions.

In the present work the distribution of missing transverse energy $E_T^{\text{miss}}$ is studied. Black holes are characterised by a very long $E_T^{\text{miss}}$ tail extending up to several TeV, as shown in Fig. 7. Note, that CHARYBDIS does not include graviton emission, and thus probably underestimates the $E_T^{\text{miss}}$ contribution. This property of black holes is hard to reproduce in other new physics scenarios. For example, $R$-parity conserving supersymmetric models often predict relatively high $E_T^{\text{miss}}$ values ($\sim 300$ GeV) associated with the loss of two undetected massive neutralinos from every event. However, very few produce many events with values as high as those estimated conservatively in black hole events, since models with suitably heavy neutralinos must necessarily have small cross-sections.

### 5. Plans for the First LHC Data

For the first phase of LHC running it is planned to collect $\gtrsim 100 \text{pb}^{-1}$ of $pp$ scattering data at the reduced centre-of-mass energy of 10 TeV. Considering the lower bounds on the fundamental gravity scale of $\sim 1$ TeV and the requirement of a minimum mass for semi-classical black hole production $M_{\text{BH}} \gtrsim 5 M_D$, the potential for the discovery of such black holes in the first data is very limited. However, if the fundamental gravity scale is indeed in the LHC energy reach, we may expect non-perturbative gravity effects to appear already in the first data. Therefore, the ATLAS strategy for the first data is to search for any events characterised by high multiplicity...
and/or high total scalar $p_T$ of the decay products.

An alternative approach for searches of low gravity scale effects is based on the consideration [12] that such effects may first be observed in contact interactions leading to the enhancement of the dijet and dilepton spectra at high invariant masses. The search strategy for such signals is similar to that used for compositeness searches (see e.g. [36]). A detailed study of such signatures may allow us to distinguish among black hole type effects and other possible effects of new physics.

6. Conclusions and Outlook

The ATLAS detector at the LHC provides an unprecedented opportunity to search for extra spatial dimensions and to investigate the production of hypothetic microscopic black holes. The search strategy for semi-classical black holes has been developed including triggering and offline signal selection. For a fundamental gravity scale of 1 TeV and a black hole mass threshold of 5 TeV, a discovery is possible with a few pb$^{-1}$ of $pp$ data at 14 TeV, whereas $\sim$1 fb$^{-1}$ would be sufficient for a threshold of 8 TeV. At present, new versions of several MC generators are being developed which should allow more sophisticated simulations of black hole production and decays [27, 28]. However, the uncertainty of model predictions for the energy range near the fundamental gravity scale remains the major limiting factor for a more precise understanding of black hole physics.

References

[1] N. Arkani-Hamed, S. Dimopoulos and G. Dvali, Phys. Lett. B 429 (1998) 263; arXiv:hep-ph/9803315.
[2] I. Antoniadis et al., Phys. Lett. B 436 (1998) 257; arXiv:hep-ph/9804398.
[3] N. Arkani-Hamed, S. Dimopoulos and G. Dvali, Phys. Rev. D 59 (1999) 086004; arXiv:hep-ph/9807344.
[4] L. Randall and R. Sundrum, Phys. Rev. Lett. 83 (1999) 2370; arXiv:hep-ph/9905221.
[5] L. Randall and R. Sundrum, Phys. Rev. Lett. 83 (1999) 4690; arXiv:hep-th/9906064.
[6] C. Amsler et al. [PDG], Phys. Lett. B 667 (2008) 1.
[7] L. Benucci, these proceedings.
[8] P. Kanti, Int. J. Mod. Phys. A 19 (2004) 4899; arXiv:hep-ph/0402168.
[9] G. L. Landsberg, J. Phys. G 32 (2006) R337; arXiv:hep-ph/0607297.
[10] G. Aad et al. [ATLAS Collaboration], arXiv:0901.0512.
[11] R. C. Myers and M. J. Perry, Ann. Phys. 172 (1986) 304.
[12] P. Meade and L. Randall, JHEP 0805 (2008) 003; arXiv:0708.3017 [hep-ph].
[13] T. Banks and W. Fischler, arXiv:hep-th/9906038.
[14] S. Dimopoulos and G. Landsberg, Phys. Rev. Lett. 87 (2001) 161602; arXiv:hep-ph/0106295.
[15] S. B. Giddings and S. Thomas, Phys. Rev. D 65 (2002) 056010; arXiv:hep-ph/0106219.
[16] K. Cheung, Phys. Rev. Lett. **88** (2002) 221602; arXiv:hep-ph/0110163.
[17] D. M. Gingrich, Int. J. Mod. Phys. A **21** (2006) 6653; arXiv:hep-ph/0609055.
[18] S. W. Hawking, Phys. Rev. D **72** (2005) 084013; arXiv:hep-th/0507171.
[19] S. W. Hawking, Commun. Math. Phys. **43** (1975) 199.
[20] D. N. Page, Phys. Rev. D **13** (1976) 198.
[21] B. Koch, M. Bleicher and S. Hossenfelder, JHEP **0510** (2005) 053; arXiv:hep-ph/0507138.
[22] A. Casher and N. Raz, arXiv:0705.0444.
[23] D. M. Gingrich, JHEP **0711** (2007) 064; arXiv:0706.0623.
[24] V. Berezinsky and M. Narayan, Phys. Rev. D **75** (2007) 105001; arXiv:0705.0945.
[25] C. M. Harris, P. Richardson and B. R. Webber, JHEP **0308** (2003) 033; arXiv:hep-ph/0307305.
[26] D. M. Gingrich, arXiv:hep-ph/0610219.
[27] D. C. Dai et al., Phys. Rev. D **77** (2008) 076007; arXiv:0711.3012.
[28] M. Casals, S. R. Dolan, J. Frost, J. R. Gaunt, M. A. Parker, M. O. P. Sampaio and B. R. Webber, in preparation.
[29] T. Sjöstrand, S. Mrenna and P. Skands, JHEP **0605** (2006) 026; arXiv:hep-ph/0603175.
[30] S. Frixione and B. R. Webber, JHEP **0206** (2002) 029; arXiv:hep-ph/0204244.
[31] S. Frixione, P. Nason and B. R. Webber, JHEP **0308** (2003) 007; arXiv:hep-ph/0305252.
[32] M. L. Mangano et al., JHEP **0307** (2003) 001; arXiv:hep-ph/0206293.
[33] G. Aad et al. [ATLAS Collaboration], JINST **3** (2008) S08003, Chapt. 8.
[34] C. M. Harris et al., JHEP **0505** (2005) 053; arXiv:hep-ph/0411022.
[35] A. Roy and M. Cavaglia, Phys. Rev. D **77** (2008) 064029; arXiv:0801.3281.
[36] S. Ferrag, J. Phys. Conf. Ser. **110** (2008) 072010, ATL-PHYS-CONF-2008-005.