SEARCH FOR LOW SCALE GRAVITY SIGNATURES IN ATLAS

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Abstract. - At the LHC, the ATLAS detector may reveal signatures of extra dimensional models which predict quantum gravity at the TeV scale. One of the most dramatic consequences of such models is the copious production of micro black holes. Micro black holes can yield distinct signatures with large multiplicity and large energy release in the ATLAS detector. Extra dimensional models also predict the existence of Kaluza-Klein partners of SM gauge bosons, such as the excited graviton and gluon. These particles can be searched for in their two-body decays. The emerging final state particles are highly energetic, thus requiring novel reconstruction techniques, in particular in the heavy quark (t, b) channels. I will summarise the current status of the low scale gravity studies in ATLAS with example signatures.

1. Introduction

The unification of the gravitational force with other known forces has been a long standing aim in physics, as early as Nordström, Kaluza and Klein's work on extra spatial dimensions in the 1920's [1]. Their ideas re-emerged with new models during the late 1990's, after the hierarchy problem, namely the difference between the Planck scale ($M_{Pl} \sim 10^{19}$ GeV) which governs gravity and the electroweak scale ($M_{EW} \sim 10^2$ GeV), had motivated a number of extensions to the SM. Models allowing particles to propagate in additional dimensions were proposed to explain that gravity is only apparently weak and that the fundamental scale of gravity may actually be much smaller than otherwise expected. Since then, implications of such models have been searched for at currently operating colliders [1, 2].

In the simplest of such proposed models, the ADD Large Extra Dimension (LED) model ([3]), SM particles are confined on a spatial 3-D brane and the graviton, as the mediator of gravity, is allowed to propagate in n large, flat, compactified extra dimensions (ED). In the $(4+n)$-D world which corresponds to the fundamental Planck

scale ($M_{\text{Pl}(4+\text{n})}$), gravity is as strong as other gauge forces, however, it is weak at the Planck scale in 4-D. The relation between the two Planck scales is governed by the size R and number n, of extra dimensions: $M_{\text{Pl}}^2 \sim R^n M_{\text{Pl}(4+\text{n})}^{n+2}$. Table-top experiments testing gravitational inverse-square law lead to an upper bound of $R < 44$ μm, at 95% confidence level[1] [4, 5]. Assuming a Planck scale near the TeV range, R becomes as large as $\sim 10^{18}$ km for $n = 1$; this is clearly ruled out by the classical description of gravitational force. Having the fundamental scale of gravity as low as the TeV scale, these models also allow predictions for production and decay of micro-black holes at such energies.

LHC experiments, such as the general purpose detector ATLAS [6], can shed light on the nature of gravity, which, if at the TeV-scale, can manifest itself at the LHC in various distinct signatures. In particular, the gravitational field (or any other particle field allowed to propagate in the ED) is represented in 4-D as a series of Kaluza-Klein (KK) towers (excitations), giving rise to directly searchable final states at colliders.

In this note, we report on the potential of the ATLAS detector for revealing TeV-scale gravity signals with three possible signatures from different models with increasing signature complexities We start with exclusive new particle searches as resonances through their decays into dielectron and heavy dijet states and finish with inclusive searches for black holes in energetic multi-particle final states.

2. Search for KK Graviton Resonance Signal in the Dielectron Channel for a Warped ED Geometry

The feasibility of ATLAS detecting a Randall-Sundrum (RS) graviton resonance [7] in the dielectron channel has been studied using full detector simulation [8]. RS proposes a non-factorisable geometry in 5-D space, with the ED warped by an exponential factor $e^{-2kr_c\phi}$, where k is the curvature scale and r_c is the size of the 5th dimension.

The model predicts graviton resonances, each of which represents one KK excitation, decaying into any SM particles. The properties of the RS KK states are expressed in terms of a dimensionless coupling parameter, $c = \text{k}/\bar{M}_{\text{Pl}}$, the relative strength of k to the reduced Planck scale.

The strategy chosen for the RS KK graviton (G_{KK}) search is to scan for a resonance over the SM background in the dilepton invariant mass distribution. The selection of back-to-back, energetic ($p_{\text{T}} > 65$ GeV) electrons, with no charge requirement, in events which have been pre-selected by a single electron trigger, provides a very robust sample to reconstruct a resonance. Loose selection requirements on electron identification (described elsewhere [8]) guarantee a sufficient dielectron efficiency at high mass (66-54%, for 0.5-1.4 TeV G_{KK}) with optimised discovery reach for heavy G_{KK} while controlling backgrounds from irreducible (neutral DY) and reducible processes. The reducible QCD dijet background which may yield fake electrons have

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[1]Various indirect limits exist on ED from astrophysics and cosmology (such as supernova cooling and others) which are the most stringent. However, most bounds are only reliable as order of magnitude level estimates due to many large uncertainties.

been neglected in this version. Monte Carlo (MC) studies show that for $k/\bar{M}_{\mathrm{Pl}} <$ 0.06, the resonance peak is narrow compared to the experimental dilepton resolution.

The acceptance of the ATLAS detector to RS G_{KK} is determined by the electron track acceptance ($|\eta| < 2.5$). Fig. 1 shows the dielectron spectrum obtained by a parametrised fit to the expected SM background and an example G_{KK} reconstruction from MC simulation. The systematic errors have been estimated to be within the range 10-15%.

The signal region is defined by a mass window determined by the detector resolution. In the case of a 1 TeV G_{KK}, the total resolution is 7.9 GeV. The cross-section, including the branching ratio (BR), varies from about 200-20 fb, for a 0.5-1.4 TeV graviton, as calculated by PYTHIA [9]. For reach calculations, a flat 1.6 NLO correction factor (K-factor) has been applied. To evaluate the discovery potential, pseudo-experiments with null (SM-only) and test (Signal+ SM) simulated data are generated. Based on the dilepton mass distribution, the likelihoods are then calculated for each pseudo-experiment with both a null hypothesis and a test hypothesis, and the likelihood ratio is obtained. The confidence level is then evaluated using the likelihood ratio distribution for the null set that extends beyond the mean of the distribution for the test set ("extended maximum likelihood fitting"). The results are used to extract the discovery (5σ) and the evidence (3σ) potential of ATLAS as a function of G_{KK} mass for 1 fb^{-1} LHC data (Fig. 1). The $\sigma \cdot BR$ curves are further used to constrain the RS graviton mass as a function of $k/\bar{M}_{\mathrm{Pl}}$. For example, a 900 GeV G_{KK} can be discovered with 1 fb^{-1} of LHC data for $k/\bar{M}_{\mathrm{Pl}} = 0.01$. This number can be compared to the Tevatron reach which is of the same order in mass, but for an order of magnitude higher value of $k/\bar{M}_{\mathrm{Pl}}$, for similar integrated luminosity. The current most stringent limit comes from D0 in the dielectron+diphoton channel with 900 GeV for $k/\bar{M}_{\mathrm{Pl}} = 0.1$, with a similar reach from CDF based on about 1 fb^{-1} Tevatron data [10].

The spin-2 graviton resonances can also be distinguished from dilepton resonances predicted by other models thanks to the characteristic differential angular distribution at the centre of mass (CoM) frame nof the dielectrons [11], as in the searches at the Tevatron [12].

3. Search for KK Gluon Resonance Signal in Heavy Jet Pairs for a Flat Extra Dimension

Various ED models give rise to higher KK modes of SM particles in addition to gravitons. One particular signature arises from those that allow excited KK gluon modes (g_{KK}). These gluons couple to quarks of the SM. The fact that only hadronic decays are possible makes searches for g_{KK} more challenging than G_{KK} described above. KK gluons will be interesting to search for at the LHC, as the LHC will be a parton factory at high energies. Canonical feasibility studies with light dijet signatures were performed earlier for the ATLAS detector [13]. Here we concentrate
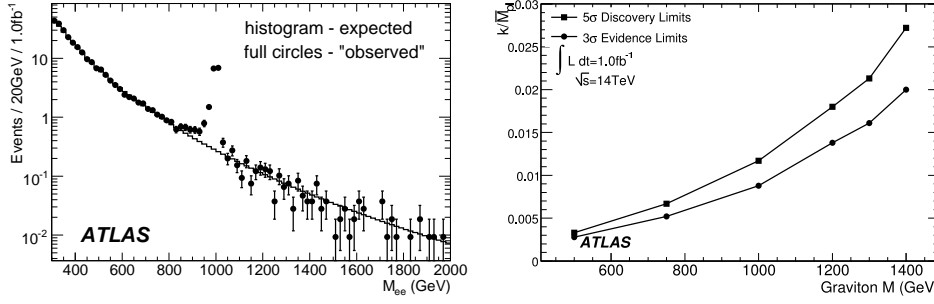
Figure 1: Left: Drell-Yan mass spectrum with (circles) and without (histogram) signal reconstructed from full simulation for a 1 TeV G_{KK} and $\mathrm{k}/\bar{M}_{\mathrm{Pl}} = 0.02$. Right: Discovery potential dependence on the coupling vs G_{KK} mass.

on heavy quark final states $(Q\bar{Q})$ coming from a g_{KK} decay, within the scope of TeV^{-1} ED model [14].

Models with TeV^{-1} ED [15] propose gauge coupling unification at a scale much lower than the GUT scale. In such a model, matter resides on a p-brane (p > 3), with chiral fermions confined to the ordinary 3-D world and SM gauge bosons allowed to propagate in the ED; all of which are internal to the p-brane. SM gauge bosons that propagate in the ED give rise to an infinite tower of associated KK states of increasing mass, with mass separations inversely proportional to R, the size of the extra dimension for a given n. In this model, g_{KK} couples only to quarks, with a factor of $\sqrt{2}$ relative to SM gluon couplings. KK gluons couple democratically to all quarks, meaning that, for a heavy g_{KK}, quark branching fractions can be taken as equal to each other.

Searches in heavy quark final states have been performed at the Tevatron (see, for example, [16]). The LHC, being a top quark factory due to the large phase space for top quark pair production and higher luminosity, will allow higher signal reach in the $t\bar{t}$ channel. Moreover, these top quarks will be heavily boosted and very energetic. Therefore, ATLAS will need novel jet reconstruction techniques at very large masses of KK gluons, for efficient signal detection.

An initial study of g_{KK} reconstruction from $t\bar{t}$ and $b\bar{b}$ channels has been performed at ATLAS using a fast detector simulation (ATLFAST [17]). The $t\bar{t}$ events have been selected in the semileptonic decay channel (one top quark decaying hadronically, the other decaying leptonically) to better control the background levels. A slowly-varying event selection efficiency of 30% and 12% have been obtained for g_{KK} masses up to (and including) 2 TeV for the $b\bar{b}$ and the $t\bar{t}$ channels respectively. For b-tagging efficiency, values extracted from an earlier tuning for high transverse momentum b-jets have been used. For the $b\bar{b}$ channel, a flat value of 10% is used for all g_{KK} masses; and for the $t\bar{t}$ channel, variable values have been applied. The b-tagging efficiency for b quarks coming from top decays is higher (the average transverse momentum of

such b-jets are smaller).

The production of g_{KK} is dominated by quark anti-quark annihilation leading to an s-channel resonance in the $Q\bar{Q}$ final states ($q\bar{q} \rightarrow g_{KK} \rightarrow Q\bar{Q}$), as the t-channel is suppressed due to parton distribution functions (pdf's). This gives way to resonance-like spectra for the signal, as opposed to, for example, light dijet background which also has a t-channel contribution and can lead to very forward jets yielding a broader signature. Fig. 2 shows the signal vs background mass distributions for a 1 TeV g_{KK} for which the production cross section is about 1100 pb. At this g_{KK} mass, the natural width of the resonance and experimental effects contribute approximately equally to the width of the mass peak. The main backgrounds for the $t\bar{t}$ final state are the irreducible SM $t\bar{t}$ and reducible W+jets. The levels of these backgrounds are low compared to the expected signal strength; therefore, a resonance may be detected in this channel. For the $b\bar{b}$ final state, SM light dijet production is another non-negligible background in addition to the irreducible and large SM $b\bar{b}$ background.

The g_{KK} discovery prospects in $Q\bar{Q}$ final states are obtained via a straightforward significance calculation in simple mass windows around the reference g_{KK} masses. Fig. 2 shows that discovery can be achieved in three years of high luminosity (10^{34} cm^{-1}s^{-1}). The 5σ g_{KK} mass reach for $t\bar{t}$ channel is 3.3 TeV with 300 fb^{-1} data at 14 TeV LHC CoM energy. Owing to the large background yields with large calculation uncertainties, it is unlikely that the $b\bar{b}$ channel can be used as the primary channel for g_{KK} evidence. However, both channels are complementary and any excess in one can be cross-checked by the other and by the light dijet channel data.

In the analysis described above, heavy jet reconstruction has not been optimised for very energetic and collimated heavy jets. Experimental techniques are being developed to efficiently reconstruct very energetic and boosted heavy jets in the ATLAS detector. They will allow improved reconstruction of high mass g_{KK} resonances[2].

4. Inclusive Searches for Black Holes for a Large Extra Dimensional Model

The possible existence of ED and a fundamental Planck scale at TeV energies has the appealing consequence that micro black holes (μ-BHs) may be produced at the LHC by trans-Planckian collisions of incoming partons [20]. Once the centre of mass energy of two colliding protons is much larger than $M_{Pl(4+n)}$, a semi-classical regime opens up, the quantum gravity effects can be ignored and a black hole can be created.

Within the ADD large extra dimension model [3], a $(4+n)$-D black hole can be formed when the impact parameter of two colliding partons is smaller than the Schwarzschild radius (R_s) corresponding to the CoM energy of the collision. For semi-classical TeV-range black holes, the R_s is extremely small ($< 10^{-50}$ m) and the Hawking temperature which determines the "evaporation" properties of the black

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[2]There is also ongoing feasibility work for a RS g_{KK} predicted to predominantly decay into $t\bar{t}$ [18]. Such a particle up to a mass of 800 GeV was recently ruled out at Tevatron [19].
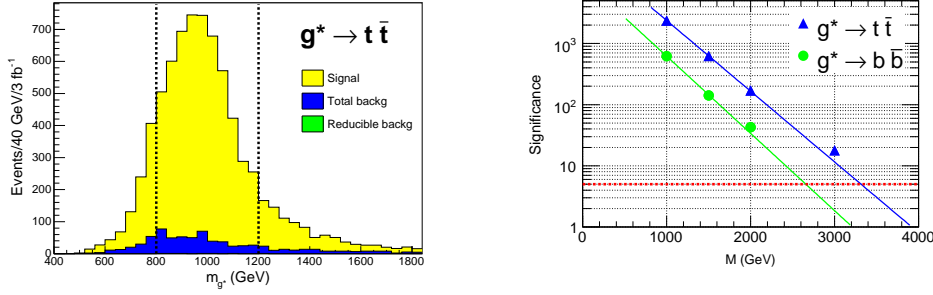
Figure 2: Left: Reconstructed mass peaks for a 1 TeV g_{KK} (denoted as g* in the figures) assuming $\mathcal{L} = 3$ fb^{-1}. Vertical dotted lines show the mass window used for significance calculation. Right: Significance as a function of mass for g_{KK} searches for $\mathcal{L} = 300$ fb^{-1}.

hole is high [21]. Therefore, the black holes that are expected to be produced at the LHC are often denoted as μ-BHs and are expected to have a lifetimes of the order of 10^{-26} seconds. Such μ-BHs can be modelled in Monte Carlo generators following their formation and decay evolution process. In the semi-classical approach, the production cross section of a μ-BH is given as πR_s^2: for the TeV-range black hole masses, this corresponds to pb-range cross sections at the LHC. This production rate is comparable to that of the main high Q^2 SM processes, making μ-BH searches at the LHC an appealing possibility.

ATLAS has employed two complementary search strategies to detect black holes [8]. Both searches follow an inclusive approach, making use of highly energetic multi-particle final states. The simulation of the μ-BH signal has been performed with CHARYBDIS, a dedicated event generator for black hole production at colliders, based on the semi-classical approximation, i.e., general relativistic (GR) black holes [22]. This imposes tight constraints on the minimum mass of the μ-BH (M_{BH}). For the current analysis, the minimum μ-BH mass studied has been set at 5 TeV, and the fundamental Planck scale[3] has been fixed at 1 TeV.

The black hole detection strategies at ATLAS take advantage of the distinct features of a μ-BH decay. In the semi-classical scheme, the μ-BH, once produced, evaporates democratically into all kinds of known particles yielding a high-multiplicity final state (> 10 energetic particles) and with a large total energy due to the large mass of the black hole. These features are not expected in SM processes. An inclusive selection, which exploits such features and is robust against variations in theory parameters which may have large uncertainties, retains most signal events while removing the backgrounds dominated by $t\bar{t}$, QCD and W+jets events.

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[3]There exists various definitions of Planck Scale. CHARYBDIS follows the definition [23] used by the PDG [1].

Method 1 imposes a minimum $\sum(p_T) > 2.5$ TeV (which can also be used as the trigger) and requires a lepton (e or μ) with at least 50 GeV p_T to remove most of the QCD background. Method 2 selects those events with 4 "objects" (any particles) passing $p_T > 200$ GeV threshold and an additional requirement of a lepton with the same p_T threshold. Signal acceptance for Method 1 is 0.46 (0.17) for n=2(7), for $M_{BH} > 5$ TeV. For Method 2, the acceptance is slightly lower at 0.34 (0.09) for n=2(7). Fig. 3 illustrates the signal event yield for reconstructed black holes with $M_{BH} > 5$ TeV, for n =2. The signal is significant in comparison to the expected SM backgrounds, after all the selection cuts for Method 1 have been applied.

If the semi-classical model estimates are valid, black holes can be discovered with a few pb^{-1} data above a 5 TeV μ-BH mass threshold, and 1 fb^{-1} data would allow a discovery with a threshold of 8 TeV. Fig. 3 shows the ATLAS experiment's black hole reach for the first method described above. Method 2 yields a less conservative potential at high mass as a result of the BH mass cut applied at the selection level. The search reach is mainly limited at the high mass by the falling production cross-section reflecting the falling parton luminosity due to pdf's. The theoretical and experimental uncertainties have been explored and their effects on the signal acceptance have been quantified. It has been observed that the largest uncertainties arise at high n, which is expected as this parameter affects the evolution of the μ-BH decay (the Hawking temperature of the black hole depends on n). Extracting model parameters (such as the number of ED and the temperature) has also been studied. However, due to large uncertainties in the model parameters and the necessity of measuring an accurate BH mass resolution, such a measurement would require more data, if and once a μ-BH were observed at ATLAS.

Distinguishing black hole signatures from other models have also been studied. For example, it has been shown that a significant tail of the event missing E_T spectrum in the TeV range can be used to separate BH production from Supersymmetric (SUSY) processes where a large missing E_T is also expected due to the lightest SUSY particle [24]. However, the separation power would depend highly on the description of the graviton emission process during the μ-BH decay.

Since the analysis described above was performed, various other approaches to μ-BH production have been formalised in an attempt to embed TeV-scale gravity effects into a realistic quantum theory. These include quantum black holes for quantum gravity effects near the Planck Scale [25] and string balls as highly excited string states in string theory [26]. The Quantum BH model is implemented in a recent generator program (BLACKMAX [27]) and predicts mostly very energetic low multiplicity dijet-type signatures. This type of signature is currently under study using ATLFAST simulation.

Recently, the LHC programme has been revised with the possibility of collecting about 100 pb^{-1} data at 10 TeV CoM energy for initial running. Given the current reach estimates for 14 TeV running, hints of GR black holes at the LHC might still be possible.
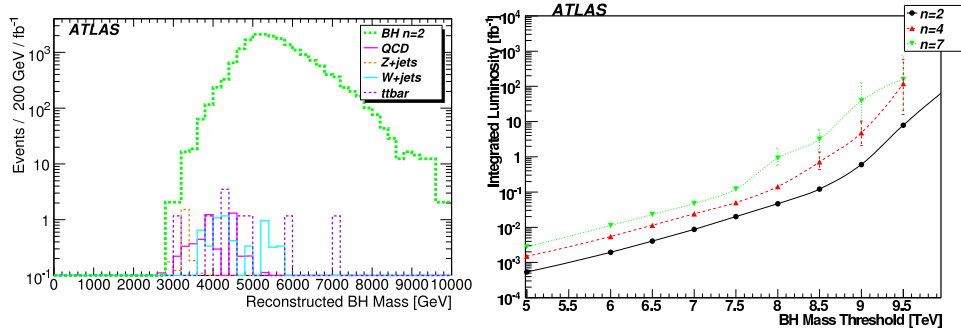
Figure 3: Left: Reconstructed μ-BH mass for a 5 TeV threshold and for two ED is shown overlaid with the backgrounds after all the selection requirements of Method 1. Right: Discovery potential as a function of μ-BH mass threshold for searches within the ADD model. Error bars correspond to statistical uncertainties.

5. Conclusion

The ATLAS experiment has a very rich TeV-scale gravity search programme and will be able to probe the existence of extra dimensions. Analyses are being optimised for observation of TeV-scale gravity effects. A quickly understood ATLAS detector may reveal hints of extra dimensions and quantum gravity within the first year of LHC running, depending on the model parameters. The absence of a signal will be used to constrain current models and their predictions.

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REFERENCES

[1] C. Amsler *et al.*, Physics Letters B 667, 1, 2008.
[2] M. Karagoz Unel, AIP Conf. Proc. 753, pp. 400-409, 2005, and references therein.
[3] N. Arkani-Hamed, S. Dimopoulos and G.R. Dvali, Phys. Rev. D59, 086004, 1999.
[4] D.J. Kapner *et al.*, Phys. Rev. Lett. 98, 021101, 2007.
[5] E.G. Adelberger, B.R Heckel and A.E. Nelson, Ann. Rev. Nucl. Part. Sci. 53, 77-121, 2003; arXiv:hep-ph/0307284.
[6] G. Aad *et al.*, ATLAS Collaboration, JINST 3 S08003, 2008.
[7] L. Randall and R. Sundrum, Phys. Rev. Lett. 83, 3370, 1999.
[8] G. Aad *et al.*, ATLAS Collaboration, arXiv:0901.0512, 2008.
[9] T. Sjöstrand *et al.*, Computer Phys. Commun. 135, 238, 2001.

[10] V.M. Abazov *et al.*, D0 collaboration, Phys. Rev. Lett. 100, 091802, 2008; T. Aaltonen *et al.*, CDF Collaboration, Phys. Rev. Lett. 99, 171802, 2007.

[11] B.C Allanach *et al.*, JHEP 0009 019, 2000; arXiv:hep-ph/0006114.

[12] A. Abulencia *et al.*, CDF Collaboration, Phys. Rev. Lett. 95, 252001, 2005.

[13] C. Balazs *et al.*, in Les Houches BSM Report, arXiv:hep-ph/0402295, 2004.

[14] L.March, E. Ros and B. Salvachua, ATL-PHYS-PUB-2006-002, 2006.

[15] K.R. Dienes, E. Dudas and T. Gherghetta, Nucl. Phys. B 537, 47, 1999.

[16] T. Aaltonen *et al.*, the CDF Collaboration, Phys. Rev. D 77, 051102(R), 2008.

[17] D.F.E. Richter-Was and L. Poggioli, ATL-PHYS-98-131, 1998.

[18] B. Lillie, R. Randall and L.Wang, JHEP 09, 074, 2007.

[19] M. Guchait, F. Mahmoudi and K. Sridhar, JHEP 0705 103, 2007.

[20] P. Kanti, Int. J. Mod. Phys A19, 4899-4951, 2004.

[21] S.W. Hawking, Commun. Math. Phys. 43, 199, 1975.

[22] C.M. Harris, P. Richardson and B.R. Webber, JHEP 08, 033, 2003.

[23] G.F. Giudice, R. Rattazzi and J.D. Wells, Nucl. Phys. B 544, 3-38, 1999.

[24] S.P. Martin, arXiv:hep-ph/9709356v5.

[25] R. Meade and L. Randall, JHEP 05, 003, 2008.

[26] D.M. Gingrich and K. Martell, arXiv:0808.2512.

[27] D. Dai *et al.*, Phys. Rev. D 77, 076007, 2008.