LOW-SCALE GRAVITY BLACK HOLES at LHC

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We search for extra dimensions by looking for black holes at LHC. Theoretical investigations provide the basis for the collider experiments. We use black hole generators to simulate the experimental signatures (colour, charge, spectrum of emitted particles, missing transverse energy) of black holes at LHC in models with TeV scale quantum gravity, rotation, fermion splitting, brane tension and Hawking radiation. We implement the extra-dimensional simulations at the CMS data analysis and test further beyond standard models of black holes too.

1 Introduction

1.1 Quantum gravity and accelerator physics
Quantum gravity is becoming a testable theory with the Large Hadron Collider program starting soon at CERN. We can obtain bounds from collider experiments. One considers graviton interference effects at the LHC. In extra-dimensional models the Planck scale can be as low as the TeV scale which is going to be accessible for the LHC. Quantum gravity can affect the decay modes of particles with mass in the TeV range. In hadron/lepton scatterings and decays the cross sections and branching ratios receive a contribution from quantum gravity in extra-dimensional models. We can consider limits from cosmology and astrophysics as well, e.g. cosmic rays and supernovae. Of particular interest is particle astrophysics, evidence from astronomical observations for extra dimensions.

1.2 Cosmic rays and supernovae – cosmic rays are Nature’s free collider
Supernova cores emit large fluxes of Kaluza – Klein gravitons producing a cosmic background which by radiative decays provides a diffuse gamma-ray background. The cooling limit from the SN 1987A neutrino burst puts a bound on the radius of extra dimensions.

Cosmic neutrinos produce black holes, and the energy loss from graviton mediated interactions cannot explain cosmic ray events above a limit. Black holes are produced in observable collisions of elementary particles if extra dimensions exist. Leading to giant air showers, the Auger Observatory will probe the Planck mass up to 4 TeV and may observe hundreds of black holes (Anchordoqui et al. 2002).

1.3 Quantum black holes
Quantum black holes provide limits on gravity as well, the transitions in their energy spectra (quasi-normal modes) depend on the parameters of space-times around the black holes, e.g. in string theories.
Alternatives to the hierarchy problem (Planck scale of $10^{19} \text{ GeV}$, electro-weak scale of 240 GeV) are supersymmetry (fundamental theory at $M_{\text{Pl}}$, EW derived from radiative corrections) and extra dimensions (EW scale fundamental, $M_{\text{Pl}}$ derived). In the latter, matter is confined in 4D while gravity propagates in all dimensions and is weak as the compact space dimensions are large compared to the EW scale (Arkani-Hamed, Dimopoulos, Dvali, 1998).

While there is a large variety of stringy black holes (Youm, 1999) we consider brane world models of black hole generators BlackMax (Dai et al. 2007) and Charybdis (Harris et al. 2003). While the latter has no rotation, BlackMax generates rotating black holes in split fermion models (Arkani-Hamed, Schmaltz 2000, fermions live on separate branes) and models with brane tension. We simulate the experimental signatures of black holes formed at the LHC and the particle decay. We interface BlackMax for CMS analysis.

Further models of Dvali (copies of standard model, non-integer extra dimensions) suggest black hole detection is even more likely (with somewhat different particle decay) and provide explanations for astrophysical dark matter.

### 2.1 BlackMax simulations, analysis

We have studied rotating and non-rotating blackholes and extra-dimensional scenarios with branes of various dimensions, fermion splitting dimensions and tension. The hoop conjecture assumes a black hole forms if the impact parameter of colliding particles is less than two times the gravitational radius corresponding to their COM energy.

We examine non-rotating models of BlackMax for comparison with Charybdis, 3 models with 5, 3 and 3 extra dimensions, Planck mass of 2, 2 and 5 TeV, and minimum black hole mass of 4, 5 and 7 TeV, respectively. The center-of-mass energy of protons at LHC is taken 14 TeV.

BlackMax controls mass loss, momentum loss, angular momentum loss, angular momentum suppression, charge suppression and colour suppression. In Charybdis-I these loss factors are treated differently (keep the colour minimum, etc).

For the Giudice – Wells (PDG, particle data group) definition of Planck mass the cross sections are $2 \times 10^{-10}$ b, $2 \times 10^{-11}$ b and $8 \times 10^{-14}$ b in BlackMax for the 3 models, respectively. (Rates are the number of events (per given interval) per total number of black holes multiplied by cross section of black holes and integrated luminosity.)

PDG gives higher multiplicities in higher dimensions than the Dimopoulos – Landsberg definition of Planck mass. For the BlackMax – Charybdis comparison we use Dimopoulos Planck mass and BlackMax-II (beta version, with baryon and lepton number conservation).

We find that the mass function of microscopic black holes is “universal”, that is, the initial distribution of black hole mass per event (normalized to the total number of events) is almost the same for the three models examined. We plot $M - M_{\text{min}}$ vs. log $N$ (per event) and they are almost identical straight lines with slopes very close. Here we used the Dimopoulos Planck mass (and 60000 events) but models with rotation and brane tension give similar mass functions too.

We have studied the distribution of black hole colours and charges as well.

The multiplicity (average number of emitted particles per black hole) in model 2 (for PDG Planck mass) is distributed as 4.5 quarks, 1 lepton, 1 gluon, 0.5 gauge boson $W,Z$, less than 0.1 for Higgs bosons, for photons and gravitons.

As we expect quarks/jets dominate, and charged antileptons are more abundant due to their positive charge.

Due to equipartition the average energy of emitted particles shows an opposite tendency to their multiplicity with parameters (e.g. black hole mass). Rotating models have higher energies and lower multiplicities.
2.2 Pseudorapidity

We characterise the angular distribution by the pseudorapidity and compare various beyond standard models to the standard by the ratio of integrated pseudorapidity between [0.5, 1] and [0, 0.5]. Values for various extra-dimensional black holes differ from the QCD value.

The $\eta$ ratios for quarks, anti-quarks, charged leptons, anti-leptons, electrons, muons, photons in all models are significantly lower than the asymptotic QCD value.

$\eta$ is also used as angular cut for detector acceptance (\(< 2.5\) for leptons, \(< 5\) for jets, quarks, W,Z).

2.3 Electrons/positrons, muons/anti-muons, photons

We study electrons, muons and photons (anti-particles are included for the experiment).

The energy distributions of emitted particles show the expected spectrum shape.

The distribution of transverse momentum of leptons and antileptons can be used as they are easy to identify.

3 Transverse momentum

The distribution of transverse momentum is an important distribution to distinguish extra-dimensional and super-symmetric scenarios from the standard model. The standard model cuts off for low values of $p_T$ and the mean value for single top quarks is 66 GeV. Our extra-dimensional models have values an order of magnitude larger.

The extra-dimensional models have even higher transverse momentum tails than super-symmetric/SUGRA models as in SUSY the missing particle, the neutralino does not interact strongly (no high-$p_T$ tail). In the extra-dimensional models the higher the dimension and the number of split dimensions the higher $p_T$ tail we get.

The distributions for electrons and muons are not significantly different.
3.1 Standard and beyond standard models

Apart from the MET, SUSY models tend to give higher multiplicities than extra-dimensional (but not always, e.g. $qq_R \Rightarrow q\chi_0$).

We calculate the standard model background by Pythia. We consider $pp \Rightarrow q\bar{q}$, $pp \Rightarrow t\bar{t}$ and plot the distribution of transverse momentum $p_T$ of top quarks ($t+\bar{t}$) emitted in the standard model.

4 Graviton emission and MET

One can use the missing transverse energy MET (reconstructed from the energy deposits in the calorimeter and the reconstructed muon tracks) to distinguish among various gravity models. In addition to the neutrino emission the gravitons contribute to the missing energy.

BlackMax-I has graviton emission in the Hawking radiation phase and BlackMax-II has gravitons in the final burst too. Charybdis-I considers only neutrinos for MET as graviton emission is not included even for non-rotating black holes.

The MET from neutrinos is higher for extra-dimensional scenarios than for super-symmetry.

5 Comparison of BlackMax with Charybdis

The cross sections for BlackMax (I,II) and Charybdis-I are significantly different. In addition Yoshino – Rychkov suppression in BlackMax-II decreases the cross sections by several orders of magnitude.

For the varying cross sections we compare BlackMax-II with Charybdis-I by normalizing to the total number of black hole events (60000 for Dimopoulos Planck mass).

We find that the relative distributions of initial black hole mass are in remarkable agreement in BlackMax and Charybdis. That is because the mass loss mechanism does not affect the initial mass distribution. We have found a universal (exponential) mass function for the three models as well.

In the following figures we show model 1 in BlackMax and Charybdis. Model 1 is also experimentally the most accessible as it has the lowest minimum black hole mass.

BlackMax gives higher multiplicities and correspondingly lower transverse momentum and energy than Charybdis. The MET is higher in BlackMax with gravitons.
Figure 3: The relative distributions of pseudorapidity $\eta$ of all particles (left) and electrons + positrons (right) emitted from black holes in model 1 in BlackMax and Charybdis (blue).

Figure 4: The relative distributions of transverse momentum $p_T$ [GeV] of all particles (left) and electrons + positrons (right) emitted from black holes in model 1 in BlackMax and Charybdis.

Figure 5: The relative distributions (spectrum) of energy $E$ [GeV] of all particles (left) and electrons + positrons (right) emitted from black holes in model 1 in BlackMax and Charybdis.
Figure 6: The relative distributions of missing transverse energy MET [GeV] including gravitons in model 1 in BlackMax and Charybdis (red)(left) and the distribution of transverse momentum $p_T$ [GeV] of top quarks ($t + \bar{t}$) emitted in the standard model (right).

References

6. C.M. Harris, P. Richardson, B.R. Webber, JHEP0308,033(2003)