Black Holes at LHC?

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Abstract. Strategies for identifying speculative mini black hole events (due to large extra dimensions) at future colliders are reviewed. Estimates for production cross sections, Hawking radiation, di-jet suppression and multi-mono-jet emission are surveyed. We further report on a class of effective entropy formulas that could lead to the formation of a final black hole remnant state, BHR. Such BHRs could be both electrically charged and uncharged. Charged BHRs should be observable by single stiff charged tracks in the detectors. Collinear hadronic jets with a large missing transverse momentum are presented as new observable signal for electrically neutral black holes.

1. Introduction

Black holes have received an ever growing attention, since their first prediction from the Schwarzschild solution [1]. Just recently it was conjectured that in the presence of additional compactified large extra dimensions (LXDs) [2] black holes (BH) might even be produced in future colliders [3, 4, 5, 6] like the Large Hadron Collider (LHC). Measuring black hole physics in the laboratory would give a unique key to test our understanding of Planck-scale physics and quantum gravity. Here we review the status of this field of research in view of its possible impact on the first year of p-p running at the LHC, including the implications of the possible existence of black hole remnants [7, 8, 9, 10, 11, 12, 13, 14, 15, 16, 17, 18, 19, 20, 21, 22, 23, 24, 25, 26].

2. Hierarchy-problem and large extra dimensions

There exist several models which go beyond the Standard Model (SM) by assuming extra spatial dimensions [2, 27]. These models provide a solution to the so-called hierarchy problem by the statement that the huge Planck-scale, as derived from Newton’s gravitational constant $G_N$, is due to the higher dimensional geometry of space-time, and therefore just an ”effective mirror” of the true fundamental scale ($M_f$) of gravity. This fundamental scale might be as low as a few TeV. Although, these models can partly be
motivated by String Theory [28], a phenomenologist’s point of view, of studying effective theories of some unknown deeper theory (not necessarily String Theory) is also justified.

In the further discussion, the model suggested by Arkani-Hamed, Dimopoulos and Dvali [2] is used. In this model the $d$ extra space-like dimensions are compactified on tori with radii $R$. Gravitons are allowed to propagate freely in the $(3+d)+1$-dimensional bulk while all SM particles are confined to our 3+1-dimensional sub-manifold (brane). The fundamental mass $M_f$ and the Planck mass $m_{Pl}$ are then related by

$$m_{Pl}^2 = M_f^{d+2} R^d.$$  

This equation allows to estimate the radius $R$ of these extra dimensions. For two extra dimensions and $M_f \sim \text{TeV}$, $R$ can be as large as 2 mm. For a constant $M_f$ a higher number of extra dimensions corresponds to a smaller compactification radius $R$. For recent updates on parameter constraints on $d$ and $M_f$ see e.g. Ref. [29].

3. Black holes at the large hadron collider?

At distances smaller than the size of the extra dimensions the Schwarzschild radius [30] is given by

$$R_{d+1}^H = \frac{2}{d+1} \left( \frac{1}{M_f} \right)^{d+1} \frac{M}{M_f}.$$  

This radius is much larger than the Schwarzschild radius corresponding to the same BH mass in 3+1 dimensions. From the Hoop conjecture [31] one assumes the formation of a black hole as soon the impact parameter of two colliding particles is smaller than the corresponding Schwarzschild radius. Accordingly, this minimal impact parameter rises enormously in the extra-dimensional setup. The straightforward approximation of the LXD-black hole production cross section can be made by taking the classical geometric cross section

$$\sigma(M) \approx \pi R_H^2,$$  

which only contains the fundamental scale as a coupling constant. Although, this classical cross section has been under debate [32, 33, 34], semi-classical considerations, which take into account that only a fraction of the initial energy can be captured behind the Schwarzschild-horizon, yield form factors of order one [35]. Also angular momentum considerations change the results only by a factors order one [36] and the naive classical result remains even valid in String Theory [37]. The differential cross section in proton-proton collisions is then given by summation over all possible parton interactions and integration over the momentum fractions, where the kinematic relation $x_1 x_2 s = \hat{s} = M^2$ has to be fulfilled. This yields

$$\frac{d\sigma}{dM} = \sum_{A_1, B_2} \int_0^1 dx_1 \frac{2\sqrt{\hat{s}}}{x_1 s} f_A(x_1, \hat{s}) f_B(x_2, \hat{s}) \sigma(M, d).$$  

The particle distribution functions for $f_A$ and $f_B$ are tabulated e.g. in the CTEQ-tables [38]. A numerical evaluation of this expression results in the differential cross section
as shown in Fig. 1 (left). Most of the black holes have masses close to the production threshold. This is due to the fact that even in high energetic collisions, the proton contains a high number of small $x$ gluons which dominate the scattering process. It is now straightforward to compute the total cross section and the production rate by integration over Eq. (4), see Fig. 1.

Figure 1. The left plot shows the number of black holes produced in three months at the LHC as a function of the varying mass scale $M_f$. This is done under the assumption of a pp (PbPb) peak luminosity of $10^{34} \text{cm}^{-2}\text{s}^{-1}$ $(0.5 \cdot 10^{27} \text{cm}^{-2}\text{s}^{-1})$ at an invariant energy of 14 ATeV (5 ATeV). The right plot shows the number of black holes produced in three months under the assumption of a pp (PbPb) peak luminosity of $10^{34} \text{cm}^{-2}\text{s}^{-1}$ $(0.5 \cdot 10^{27} \text{cm}^{-2}\text{s}^{-1})$ as a function of the invariant energy $\sqrt{s}$. In both cases, the curves for various $d$ differ from the above depicted ones by less than a factor 10.

Thus, cross sections like Eq. (3) lead to the exciting prediction that if large extra dimensions do actually exist, a large number (up to $10^9$ per year) of black holes will be produced in future colliders [3, 6, 16, 17, 18, 19, 20, 21, 22, 23, 39, 40, 41, 42, 43, 44, 45, 46, 47, 48] and should in fact, be daily produced in ultra high energetic cosmic ray events [49, 50].

4. Black hole evaporation process

As exciting the sole production of microscopical black holes in collider experiments is, to relate it to experiment the evaporation process of the black hole is unknown. This evaporation process is often classified in three phases. In the balding phase, the newly formed black hole radiates away its angular momentum by gravitational radiation. The second phase is the Hawking phase, where it is assumed to enter the semi-classical regime of quantum theory on the background of curved space-time. According to the Hawking law, the black hole emits radiation that is distributed by the thermal spectrum

$$\varepsilon = \frac{\Omega_{(3)}}{(2\pi)^3} \int \frac{\omega^3 d\omega}{\exp[S(M) - S(M - \omega)] + s},$$

(5)
where $\omega^3/(\exp[S(M) - S(M - \omega)] + s) = n(\omega, M)$ is the spectral density and $s = 0$ (or $s = \pm 1$) is the Maxwell-Boltzmann, Fermi-Dirac, Bose-Einstein factor. This is true up to grey body factors up to the order of one \[51\]. As long the BH mass $M$ is much bigger than the fundamental mass $M_f$ the difference in the BH entropies $S(M)$ can be approximated by a derivative leading to the Hawking temperature $T_H$: $S(M) - S(M - \omega) \approx (\partial S)/(\partial M)\omega = ((\omega))/T_H$. As soon as the BH mass approaches the fundamental mass $M \approx M_f$, this temperature would exceed the actual mass of the black hole. This reflects the fact that the BH entered the regime of quantum gravity, in which no predictive theory is known and the BH’s behavior and fate is unclear, so we rely on the rough, intuitive estimates of such speculative scenarios. In a numerical approach on could either assume that the BH performs a prompt final decay into $2 - 6$ particles which carry the BH’s charge, momentum and other quantum numbers \[52, 53\], or that a remnant (BHR) is left over.

The idea of a remnant has been put forward to cure the information loss problem. This remnant idea is supported by arguments employing the uncertainty relation \[7, 8, 9\], by introducing corrections to the BH-Lagrangian \[12, 13\], by the consideration of axionic charge \[14\], by leading order quantum gravity considerations \[15\], or by quantum hair \[54\] arguments. These arguments are mostly made for $3 + 1$ dimensions, but also apply for cases where $d > 0$. A rough intuitive modeling of the formation of a black hole remnant with a mass $M_R \geq M_f$ can be done by imposing the condition

$$M - \omega \geq M_R \quad ,$$

on any single particle emission \[24, 25\]. The spectral density with such a condition is plotted as the dotted line in Fig. 2 left. It is also possible to soften the rough condition \[6\] and to impose that the spectral density smoothly approaches the remnant mass $M_R$. Therefore it has to fulfill

$$\lim_{\omega \to M - M_R} n(\omega, M) = 0 \quad \text{and} \quad \lim_{\omega \to M - M_R} \partial_\omega (n(\omega, M)\omega^3) = \text{finite} \quad .$$

If one demands that for $M \gg M_R$ Hawking’s result is recovered, one finds for $s = 0$ that the entropy can be expressed in terms of a Laurent series:

$$S(M) = \frac{d + 1}{d + 2} \left( \frac{M - M_R}{M_f} \right)^{\frac{d+1}{d+2}} + \frac{1}{M_f} \int_\epsilon^\infty \sum_{n=0}^\infty a_n \left( \frac{M_f}{x} \right)^{n+1} ~dx \quad ,$$

where $\epsilon$ is an infinitesimal positive number and $a_i$ are the coefficients of the Laurent series. In Fig. 2 left, the spectral densities for several of those cases with non zero coefficients $a_0$ and $a_1$, are plotted. The spectral densities may allow for a more realistic simulation of the decay of a microscopic BH into a stable BHR.

5. Signatures for black hole formation at the LHC through di-jet suppression and production of multiple mono-jets

One of the first signatures of BH formation suggested was the suppression of hadronic di-jet events above the BH production threshold (at $2E_T > M_f$) energy \[18, 39, 46\],
as can be seen in Fig. 3. Here, the expected standard model cross section for jet production is shown as a full line for pp interactions at $\sqrt{s} = 14$ TeV. The dashed line and the dashed-dotted line depict the expected cut-off behavior if black hole formation is included [18]. The Hawking radiation from the decay of the black hole will be emitted predominantly around transverse momenta of $\sim 50 - 500$ GeV and can therefore not mask the high $p_T$ cut-off from the black hole formation. However, particles originating from the Hawking radiation in the $p_T$ range below the $\sim 1$ TeV cut-off should cause multiple mono-jets (see e.g. Fig. 2 right).

Figure 2. Left figure: Normalized spectral densities from Eq. (5) with $M_R = 4$TeV, the condition (6) gives the dotted line, the modified entropy (8) with $a_0 = 2$ (denoted by $a_0$) gives the dashed line, and $a_1 = 1$ gives the dashed-dotted line, where all other coefficients $a_i = 0$. Right figure: Transverse momentum distribution of a single BH event at the LHC with an initial energy of 2 TeV and a BHR mass of 1 TeV and $p_T > 10$GeV. The dashed line represents the BHR transverse momentum which, in the case of a neutral BHR, would be not visible in the detector [55].

6. Signatures for black hole remnants

The formation of stable BHRs would provide interesting new signatures that allow for the identification of such a BHR event at future colliders: Electrically charged BHRs would leave a stiff ionizing track in the detector. This would allow to identify the BHR [26] and measure it’s mass directly.

Neutral BHRs could be identified e.g. by the $p_t$ distributions, multiplicities, and angular correlations [25, 26] of the Hawking evaporated SM particles. Here we propose a new signal for uncharged BHRs, namely the search for events with $\sim$TeV missing energy plus a quenched high $p_T$ hadron spectrum in the same event. Here the BHR carries a major fraction of the total energy. While many extensions of the standard model predict missing energy signatures, here the spray of awayside hadronic Hawking-jets, above a 10 GeV $p_T$ cut off, shows a clear focussing, see Fig. 2 right. Such events constitute, according to our simulation a significant fraction of the BHR events. As most BHs are expected to be produced close the the production threshold, $M_{BH} \sim M_f$, the total event
structure would then be dominated by this particular BHR event topology.

![Figure 3.](image_url)

**Figure 3.** Differential cross section for the production of hard di-jets with high transverse momenta. The dashed line is for two extra dimensions and the dashed-dotted line is for six extra dimensions, both for $M_f = 1\text{TeV}$ [57].

### 7. Summary

We have surveyed observable consequences of recent speculations of abundant black hole formation, as a consequence of large extra dimensions, which were suggested as a possible solution of the hierarchy problem. Such a scenario, suppression of hard (TeV) di-jets above the BH formation threshold should be observed at the LHC. Most BHs are expected to be produced close to the production threshold. Rare high mass BHs ought to decay rapidly by multiple hard mono jets, due to Hawking radiation. Speculations about the formation of BH remnants can be tested experimentally at the LHC: Charged stable BHRs would leave single stiff tracks in the LHC detectors, e.g. ALICE, ATLAS, and CMS. Uncharged BHRs with their very small reaction cross sections could be observed by searching for events with $\sim 1\text{ TeV}$ missing energy and quenching of the high $p_T$ hadron spectra.

Naturally, to date the dynamics of the quantum gravitational process of the BH formation is far from being understood. Recently, it has been suggested that the bremsstrahlung due to collapse of galactic, and microscopic black holes might be so strong that BHs are not formed at all in a finite time in the frame of a distant observer [56]. Possibly, for the microscopic black hole with large extra dimensions to be studied at the LHC this could lead to strong non equilibrium radiation into the forward - backward direction. This non thermal quantum radiation might be similar to the thermal radiation with an effective, angular dependent temperature.
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