Mini Black Holes in the first year of the LHC

Discovery Through Di-Jet Suppression, Mono-Jet Emission and ionising tracks in ALICE

H. Stöcker[1,2]

[1] FIAS- Frankfurt Institute for Advanced Studies
D–60438 Frankfurt am Main, Germany

[2] Institut für Theoretische Physik, Johann Wolfgang Goethe - Universität
D–60438 Frankfurt am Main, Germany

E-mail: stoecker@fias.uni-frankfurt.de

Abstract. The experimental signatures of TeV-mass black hole (BH) formation in heavy ion collisions at the LHC is examined. We find that the black hole production results in a complete disappearance of all very high p_T (> 500 GeV) back-to-back correlated di-jets of total mass $M > M_f \sim 1$TeV. We show that the subsequent Hawking-decay produces multiple hard mono-jets and discuss their detection. We study the possibility of cold black hole remnant (BHR) formation of mass $\sim M_f$ and the experimental distinguishability of scenarios with BHRs and those with complete black hole decay. Due to the rather moderate luminosity in the first year of LHC running the least chance for the observation of BHs or BHRs at this early stage will be by ionizing tracks in the ALICE TPC. Finally we point out that stable BHRs would be interesting candidates for energy production by conversion of mass to Hawking radiation.

1. Introduction

Frankfurt-born astronomer Karl Schwarzschild discovered the first analytic solution of the General Theory of Relativity [1]. He laid the ground for studies of some of the most fascinating and mysterious objects in the universe: the black holes. Recently, it was conjectured that black holes (BH) do also reach into the regime of particle physics: In the presence of additional compactified large extra dimensions (LXDs), it seems possible to produce tiny black holes in colliders such as the Large Hadron Collider (LHC), at the European Center for Nuclear Research, CERN. This would allow for tests of Planck-scale physics and of the onset of quantum gravity - in the laboratory! Understanding black hole physics is a key to the phenomenology of these new effects beyond the Standard Model (SM).

During the last decade, several models [2, 3, 4] using extra dimensions as an additional assumption to the quantum field theories of the Standard Model (SM) have been proposed. The most intriguing feature of these models is that they provide a solution to the so-called hierarchy problem by identifying the "observed" huge Planck-scale as a geometrical feature of the space-time, while the true fundamental scale of gravity M_f may be as low as 1 TeV. The setup of these effective models is partly motivated by String Theory. The question whether our space-time has additional dimensions is well-founded on its own and worth the effort of examination.

In our further discussion, we use the model proposed by Arkani-Hamed, Dimopoulos and Dvali [3], proposing d extra space-like dimensions without curvature, each of them compactified to a certain radius R. Here all SM particles are confined to our 3+1-dimensional brane, while gravitons are allowed to propagate freely in the (3+d)+1-dimensional bulk. The Planck mass m_{Pl} and the fundamental mass M_f are related by

$$m_{Pl}^2 = M_f^{d+2} R^d \quad . \tag{1}$$

The radius R of these extra dimensions can be estimated using Eq.(1). For d equaling 2 to 7 and $M_f \sim$ TeV, R extends from 2 mm to $\sim$ 10 fm. Therefore, the inverse compactification radius $1/R$ lies in energy range eV to MeV, respectively. The case $d = 1$ is excluded: It would result in an extra dimension about the size of the solar system. For recent updates on constraints on the parameters d and M_f see e.g. Ref. [5].

2. Estimates of LXD-black hole formation cross sections at the LHC

The most exciting signature of LXDs is the possibility of black hole production in colliders [6, 7, 8, 9, 10, 11, 12, 13, 14, 15, 16, 17, 18, 19, 20, 21, 22, 23, 24, 25, 26, 27] and in ultra high energetic cosmic ray events [28, 29]: At distances below the size of the extra dimensions the Schwarzschild radius [30] is given by

$$R_H^{d+1} = \frac{2}{d+1} \left(\frac{1}{M_f}\right)^{d+1} \frac{M}{M_f} \quad . \tag{2}$$

This radius is much larger than the corresponding radius in 3+1 dimensions. Accordingly, the impact parameter at which colliding particles form a black hole via the Hoop conjecture [31] rises enormously in the extra-dimensional setup. The LXD-black hole production cross section can be approximated by the classical geometric cross section

$$\sigma(M) \approx \pi R_H^2 \quad , \tag{3}$$

which only contains the fundamental scale as a coupling constant.

This classical cross section has been under debate [32, 33, 34]: Semi-classical considerations yield form factors of order one [35], which take into account that only a fraction of the initial energy can be captured behind the Schwarzschild-horizon. Angular momentum considerations change the results by a factor of two [36]. Nevertheless, the naive classical result remains valid also in String Theory [37].

Stronger modifications to the BH cross section are expected from recent calculations introducing a minimal length scale, suggested by String Theory and Loop Quantum Gravity alike. Via the use of a model implementing a Generalized Uncertainty Principle (GUP), one can show that a minimal length scale leads to a reduction of the density of states in momentum space at high energies. The squeezing of the momentum states not only reduces the black hole cross section, but also Standard Model cross sections involving high momentum transfer [21], see Fig. 1.

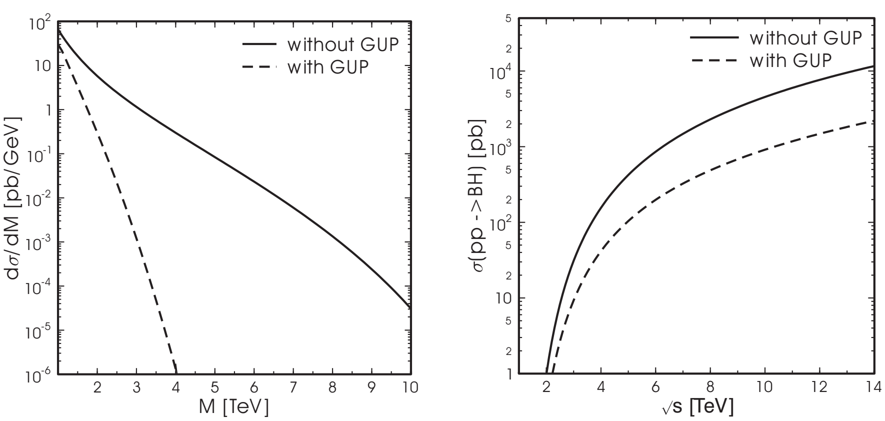

Figure 1. The left plot shows the differential cross section for black hole production in p-p collisions at $\sqrt{s} = 14$TeV (LHC) for $M_f = 1$ TeV. The right plot shows the integrated cross section for BH production as a function of the collision energy $\sqrt{s}$. In both cases, the curves for various d differ only slightly from the above depicted ones. The dashed curves show calculations including the minimal length (via a Generalized Uncertainty Principle (GUP)) [21, 23].

Setting $M_f \sim 1$ TeV and $d = 2 - 7$ one finds cross-sections of $\sigma \sim 400$ pb$-$10 nb. Using the geometrical cross section formula, it is now possible to compute the differential cross section $\mathrm{d}\sigma/\mathrm{d}M$ for p-p collisions with an invariant energy $\sqrt{s}$. This cross section is given by the summation over all possible parton interactions and integration over the momentum fractions x_i, where the kinematic relation $x_1 x_2 s = \hat{s} = M^2$ has to be fulfilled. This yields the expression

$$\frac{\mathrm{d}\sigma}{\mathrm{d}M} = \sum_{A,B} \int_0^1 \mathrm{d}x_1 \frac{2\sqrt{\hat{s}}}{x_1 s} f_A(x_1, \hat{s}) f_B(x_2, \hat{s}) \sigma(M, d). \tag{4}$$

A numerical evaluation [23] using the CTEQ4-parton distributions $f_i(x, Q)$ results in the cross section displayed in Figure 1.

One can see that independent of the specific scenario, most of the black holes created have masses close to the production threshold. This is due to the fact that the parton distribution functions $f_i(x_i)$ are strongly peaked at small values of the momentum fractions x_i.

At the LHC up to 10^9 black holes may be created per year with the estimated full LHC luminosity of $L = 10^{34}\mathrm{cm}^{-2}\mathrm{s}^{-1}$ at $\sqrt{s} = 14$ TeV: Depending on the specific scenario, about ten black holes per second could be created [7]. In the first year of running this rate will be thousand fold lower. LXD-black hole production would have dramatic consequences for future collider physics: Once the collision energy crosses the threshold for black hole production, no further information about the structure of matter at small scales can be extracted - this would be "*the end of short distance physics*" [9].

3. Suppression of high mass correlated di-jet signals in heavy ion collisions

The above findings led to a high number of publications on the topic of TeV-mass black holes at colliders [7, 8, 9, 10, 11, 17, 19, 20, 24, 25, 38, 39, 41, 43, 48, 49, 50, 52, 53], for hadronic collisions as well as for heavy ion collisions [19, 24, 40]: At the same center of mass energy, the number of black holes in a heavy ion event compared to a hadronic event is increased by about thousandfold due to the scaling with the number of binary collisions [40].

The first, cleanest signal for LXD-black hole formation in Pb-Pb collisions is the complete suppression of high energy back-to-back-correlated di-jets with $M > M_f$: two very high energy partons which usually define the di-jets in the Standard Model, each having an energy of $\sim$ one-half M_f (i.e. $p_T \geq 500$ GeV), now end up inside the black hole [19, 20, 24, 41] instead of being observable in the detector. Di-jets with $E_{di-jet} > M_f$ cannot be emitted.

4. Hard, isotropic multiple mono-jet emission as a signal for hot LXD-black hole hawking-evaporation

Once produced, the black holes may undergo an evaporation process [42] whose thermal properties carry information about the parameters M_f and d. An analysis of the evaporation will therefore offer the possibility to extract knowledge about the topology of space time and the underlying theory.

To understand the signature caused by black hole decay, we have to examine the Hawking evaporation process in detail: The evaporation rate $\mathrm{d}M/\mathrm{d}t$ can be computed for an arbitrary number of dimensions using the thermodynamics of black holes. The Hawking-temperature (T) depends on the black hole radius

$$T = \frac{1+d}{4\pi}\frac{1}{R_H} \quad , \tag{5}$$

which is given by Eq. (2). The smaller the black hole, the larger its temperature.

Integrating the thermodynamic identity $\mathrm{d}S/\mathrm{d}M = 1/T$ over M yields the entropy

$$S(M) = 2\pi\frac{d+1}{d+2}\left(M_f R_H\right)^{d+2} \quad . \tag{6}$$

With rising temperature, the emission of a particle will have a non-negligible influence on the total energy of the black hole. This problem can appropriately be addressed by including the back-reaction of the emitted quanta as derived in Ref. [44, 45]. It is found that in the regime of interest, when M is of order M_f, the number density for a single particle micro state $n(\omega)$ is modified and now given by the change of the black hole's entropy:

$$n(\omega) = \frac{\exp[S(M-\omega)]}{\exp[S(M)]} \quad . \tag{7}$$

From this, using the evaporation rate we obtain

$$\frac{\mathrm{d}M}{\mathrm{d}t} = \frac{\Omega_{(3)}^2}{(2\pi)^3} R_H^2 \int_0^M \frac{\omega^3\,\mathrm{d}\omega}{\exp\left[\mathrm{S(M-\omega) - S(M)}\right]} \quad , \tag{8}$$

where $\Omega_{(3)}$ is the 3-dimensional unit sphere.

One observes that the evaporation process of the black holes slows down in its late stages [11, 12] ‡, and may even come to a complete stop, thus, stable black hole remnants may be formed [12, 24, 25, 46, 53].

The above discussion allows for the following observations:

- Typical temperatures for LXD-black holes with $M_{BH} \gg M_f$, e.g. $5-10$ TeV, are several hundred GeV. This high temperature results in a very short lifetime. The black hole will decay close to the primary interaction region and thus its decay products can be observed in collider detectors.
- Most of the SM particles of the black body radiation are emitted with ~ 100 GeV average energy, which leads to multiple high energy mono-jets with much higher multiplicity than in Standard Model processes [24].
- The total number of emitted jets can be estimated to be of order 10. Because of the thermal characteristics of the decay, the pattern will be nearly isotropic, with a high sphericity of the event.

Although the high mass BHs might give the cleanest signatures, one has to keep in mind that in the first year of LHC running one has to search for BHs or BHRs in the low mass region (slightly above 1TeV) as the rather moderate luminosity will only allow

‡ In a 3-dimensional theory this enhanced lifetime can also be obtained from a renormalization group approach [46].

for the production of a small number of those objects which have most likely masses just above the production threshold.

Ideally, the energy distribution of the decay products allows for a determination of the temperature (by fitting the energy spectrum to the predicted shape) as well as of the total mass of the BH (by summing up all energies). This then will allow for a reconstruction of the fundamental scale $M_{\rm f}$ and the number of extra dimensions.

Several experimental groups have included LXD-black hole searches into their research programs for physics beyond the Standard Model, in particular the ALICE, ATLAS and CMS collaborations at the LHC [48]. PYTHIA 6.2 [49] with the CHARYBDIS [50] event generator allows for a simulation of black hole events and data reconstruction from the decay products. Such analysis has been summarized in Refs. [48, 51, 52]. If only low mass BHRs are produced, however, these signals dont exist. Therefore one has to search for the stable ($M = 1$TeV) ionizionizinging track of the BHR in the ALICE TPC.

5. Formation of stable black hole remnants and single track detection in the ALICE-TPC

To obtain predictions for collider experiments, one has to produce numerical simulations incorporating black hole events. These simulations have been performed but have so far assumed mostly that the black holes decay completely into Standard Model particles. As already pointed out, however, there are equally strong indications that the black holes do NOT evaporate completely, but rather leave a meta-stable black hole remnant (BHR) [11, 12, 13, 24, 25, 46, 53].

If BHRs are formed, they can carry charge and may thus not only be reconstructed via decay products, but can rather directly be observed: Charged BHRs should appear in the ALICE detector at the LHC as a magnetically very stiff charged (small curvature) track. As shown in Fig. 2, the mass of a charged BHR can be reconstructed within the ALICE time of flight and spatial resolution [48].

6. Black hole remnants as interesting candidates for energy production by conversion of mass to Hawking radiation

If stable BHRs really exist one could not only study them with various experimental setups but also use them as catalyzers to capture and convert, in accordance with $E = mc^2$, high intensity beams of low energy baryons (p,n, nuclei), of mass ~ 1 AGeV, into photonic, leptonic and light mesonic Hawking radiation, thus serving as a source of energy with 90% efficiency (as only neutrinos and gravitons would escape the detector/reactor). If BHRs (Stable Remnants) are made available by the LHC or the NLC and can be used to convert mass in energy, then the total 2050 yearly world energy consumption of roughly 10^{21} Joule can be covered by just ~ 10 tons of arbitrary material, converted to radiation by the Hawking process via $m = E/c^2 = 10^{21}\mathrm{J}/(3{\cdot}10^8\mathrm{m/s})^2 = 10^4$

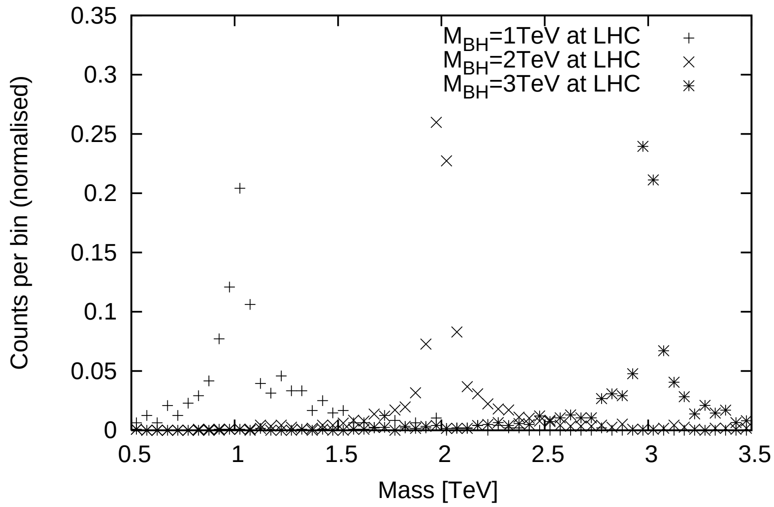

Figure 2. Reconstructed BHR masses in p-p reactions at $\sqrt{s} = 14$ TeV from ALICE (TOF 56 ps) resolution for $M_{\rm BH} = 1, 2, 3$ TeV[27, 48].

kg [55].

7. Conclusion

The LHC will provide exciting discovery potential way beyond supersymmetric extensions of the Standard Model. Still one has to keep in mind that the LHC will run in the first year with rather moderate luminosity. Hence we first must focus on the dominant part of the production cross section for BHs, which is just slightly above the production threshold. The most prominent signatures in this regime are a complete suppression of back-to-back correlated di-jets, the production of mono-jets with energies < 1TeV and the possibility of the formation of stable black hole remnants. We have shown how signatures in the ALICE TPC chamber can be used to identify BHRs with masses of ≈ 1TeV in the first year of LHC running, even at rather moderate luminosities.

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