Interaction of a TeV Scale Black Hole with the Quark-Gluon Plasma at LHC

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If the fundamental Planck scale is near a TeV, then parton collisions with high enough center-of-mass energy should produce black holes. The production rate for such black holes has been extensively studied for the case of a proton-proton collision at $\sqrt{s} = 14$ TeV and for a lead-lead collision at $\sqrt{s} = 5.5$ TeV at LHC. As the parton energy density is much higher at lead-lead collisions than in pp collisions at LHC, one natural question is whether the produced black holes will be able to absorb the partons formed in the lead-lead collisions and eventually ‘eat’ the quark-gluon plasma formed at LHC. In this paper, we make a quantitative analysis of this possibility and find that since the energy density of partons formed in lead-lead collisions at LHC is about 500 GeV/fm$^3$, the rate of absorption for one of these black holes is much smaller than the rate of evaporation. Hence, we argue that black holes formed in such collisions will decay very quickly, and will not absorb very many nearby partons. More precisely, we show that for the black hole mass to increase via parton absorption at the LHC the typical energy density of quarks and gluons should be of the order of $10^{10}$ GeV/fm$^3$. As LHC will not be able to produce such a high energy density partonic system, the black hole will not be able to absorb a sufficient number of nearby partons before it decays. The typical life time of the black hole formed at LHC is found to be a small fraction of a fm/c.

I. INTRODUCTION

There is now a huge literature devoted to the possibility that the scale of quantum gravity could be as low as a TeV [1]. If this is true, then quantum gravity and perhaps even string theory effects will become relevant in collider experiments. For example, there are many discussions on graviton and radion production and processes related to them at LHC [2,3]. One of the most exciting aspects of this TeV scale gravity will be the production of black holes in particle accelerators. These ‘brane-world’ black holes will be our first window into the extra dimensions of space predicted by string theory, and required by the brane-world scenarios that provide for a low energy Planck scale [1]. While the exact metrics describing black holes in brane-world scenarios are unknown, considerable work on this issue is underway [4]. Furthermore, even without the exact metrics it is possible to make estimates based on crude information. In particular, it is well-understood that when the mass of the black hole is greater than the Planck scale, the gravitational field of the brane can be neglected; furthermore, as long as the size of the black hole is small compared to the characteristic length scales, then a brane-world black hole may be regarded, to very good approximation, as simply a higher-dimensional black hole in flat space. Using these approximations, in a number of recent papers people have studied the production of microscopic black holes in proton-proton (pp) and lead-lead (PbPb) collisions at LHC and cosmic ray events [5–16], [17], [18–20].

The evolution of a black hole after its formation is governed by two competing effects: 1) absorption of nearby particles by the black hole and 2) evaporation of the black hole. Many papers have been written for the case of primordial black holes within the braneworld scenarios [21]. In this paper we will study the case of the black holes formed at LHC. In addition to any black holes formed at LHC in pp or PbPb collisions, there will be many more standard model particles formed, in particular a huge number of quarks and gluons. The energy density of the quarks and gluons formed in a pp collision is not very large and hence the absorption of partons by the black hole is very small. However, the energy density of the partons formed in the PbPb collisions at LHC (at $\sqrt{s} = 5.5$ TeV per nucleon) is large. This is because a huge number of partons are formed in PbPb collisions (equivalent to 208-208 pp collisions) in a small volume. Therefore one needs to determine if a black hole can absorb a sufficient amount of partons after its formation in PbPb collisions to eventually ‘eat’ the quark-gluon plasma. In this paper we will analyze the evolution of the black hole at LHC by incorporating the absorption of partons by the black hole and the decay of the black hole simultaneously.

The paper is organized as follows: In section II we present the calculation of the black hole mass evolution at LHC. In section III we present a perturbative QCD calculation to determine the energy density of the partons formed in PbPb collisions at LHC. In section IV and V we present our main results and conclusions respectively.

II. EVOLUTION OF A TEV SCALE BLACK HOLE AT LHC

The absorption rate of the black hole is proportional to the surface area of the black hole and to the energy density of the mass less gluons produced at LHC [22]. The
Effective black hole radius $r_{\text{eff}}$ for capturing particles is given by [23]:

$$
    r_{\text{eff}} = \frac{1}{M_P} \left( \frac{M_{BH}}{M_P} \right)^{1/4}
$$

where $M_P$ is the TeV scale Planck mass, $M_{BH}$ is the black hole mass and $d$ is the number of extra dimensions. The effective radius in various numbers of extra dimensions is given as shown:

- For $d = 2$:
  $$
  r_{\text{eff}} = 1.6 \frac{1}{M_P} \left( \frac{M_{BH}}{M_P} \right)^{1/4}
  $$
- For $d = 4$:
  $$
  r_{\text{eff}} = 2.63 \frac{1}{M_P} \left( \frac{M_{BH}}{M_P} \right)^{1/4}
  $$
- For $d = 7$:
  $$
  r_{\text{eff}} = 3.77 \frac{1}{M_P} \left( \frac{M_{BH}}{M_P} \right)^{1/4}
  $$

The cross section for the particle absorption by the black hole is given by:

$$
    \sigma = \pi r_{\text{eff}}^2.
$$

Using this absorption cross section the accretion rate of the black hole mass becomes [22]:

$$
    \frac{dM_{BH}}{d\tau}|_{\text{accr}} = F \pi r_{\text{eff}}^2 \epsilon(\tau),
$$

where $\epsilon(\tau)$ is the energy density of the mass less gluons produced at LHC. As gluons are the dominant part of the total parton production at LHC (more than 80 percent) we will consider the absorption of the gluons in this paper for simplicity. The energy density $\epsilon(\tau)$ of the gluons formed in PbPb collisions at LHC will be calculated in the next section by using perturbative QCD. For an upper limit on our estimates on the accretion rate we will take $F = 1$ in our calculation. This value might be lower indicating less accretion [22]. As we are interested in the maximum accretion we will use $F = 1$ in this paper.

Now we consider the evaporation rate of the black hole at LHC. It is known that the evaporation is much faster for smaller mass black holes [24] and hence the rate of evaporation of the TeV scale black hole at LHC is much higher. We use the recent calculations of black hole radiation in the context of TeV scale physics [21,24,25] which yields the evaporation rate:

$$
    \frac{dM_{BH}}{d\tau}|_{\text{eva}} = - \sum \Gamma_s g_s^{s} \frac{\pi^2}{120} \frac{A_{3+d} T_{BH}^{4+d}}{\left( \frac{d+5}{2} \right) \left( \frac{d+3}{2} \right) !} \frac{1}{r_{\text{eff}}^{4+d}}
$$

where

$$
    T_{BH} = \frac{d+1}{4\pi r_{BH}}
$$

and the area in the extra dimension is given by:

$$
    A_{3+d} = \left( \frac{3+d}{2} \right) \frac{\pi^{d+3}}{(d+3)/2!} r_{BH}^{2+d}
$$

As the change in Stefan-Boltzmann constant is very weakly dependent on the number of extra dimension [24] we have used the four dimensional value equals $\frac{\pi^2}{120}$ in the above. In the equation (5) $g_{eff}$ corresponds to the effective degrees of freedom of the standard model particles into which the black hole evaporates. The effective number of degrees of freedom is given by: $g_{eff} = g_{bos} + \frac{7}{2} g_{ferm}$. In this paper we will assume that a black hole radiates mainly to the mass less particles (electrons and positrons, muons and anti-muons, photons, neutrinos, gluons and up, down, strange quarks) for which $g_{eff} = 46$ with $g_{eff} = 18$ for spin $s = 1$ and 28 for $s = 1/2$. $\Gamma_s$ is the dimensionless grey body factor which we take the same value as in [23] in the geometric optics approximations. There has been recent progress on grey body factors in extra dimensions [26]. In the above equation is the sum of fermions and bosons. For thermodynamics to be a reasonable approximation one requires $M_{BH} >> M_P$ [23], which will be true for the ratio being $\geq 3$.

The net change of the black hole mass is therefore:

$$
    \frac{dM_{BH}(\tau)}{d\tau} = \frac{dM_{BH}(\tau)}{d\tau}|_{\text{accr}} + \frac{dM_{BH}(\tau)}{d\tau}|_{\text{eva}}
$$

which gives:

$$
    \frac{dM_{BH}(\tau)}{d\tau} = \pi r_{\text{eff}}^2 (\tau) \epsilon(\tau) - \frac{\Gamma_s g_s^{s} f_d}{7680} \frac{1}{r_{\text{eff}}^{4+d}}
$$

where $f_d$ = $\frac{(d+3)(d+1)}{4\pi^2 \Gamma((d+5)/2)}$. We get $f_2 = 9.45$, $f_4 = 30$ and $f_7 = 210$. By using the relation between $r_{\text{eff}}$ and the black hole mass $M_{BH}$ we obtain, from the above equation:

$$
    \frac{dM_{BH}(\tau)}{d\tau} = F_d(\tau) M_{BH}^2(\tau) - \frac{B_d}{M_{BH}(\tau)}
$$

This equation has to be solved numerically once we know the gluon energy density $\epsilon(\tau)$ at LHC. In the above equation

$$
    F_d = \epsilon(\tau) C_d
$$

\[ B_d = \frac{\Gamma_s g_s^{s} f_d}{7680 C_d} \quad \text{with} \]

\[ C_d = \frac{d+3}{(d+1) M_P^2} \left[ \frac{2^{d+3}(d-3)/2(d+3) \Gamma((d+5)/2)}{2(d+2) M_P} \right]^{4+d} \]

We now just need to determine the gluon energy density at LHC by using perturbative QCD methods.
III. GLUON ENERGY DENSITY AT LHC

Now let us determine the energy density of the mass less gluons formed in PbPb collisions at LHC. We use perturbative QCD methods to determine the gluon energy density produced at LHC. In the lowest order of pQCD calculations the cross section for gluon-minijet production in pp collisions is given by [27–29]:

\[
\sigma_{\text{jet}} = \int dp_T dy_1 dy_2 \frac{2\pi p_T}{s} \sum_{ijkl} x_1 f_{i/A}(x_1, p_T^2)
\]

\[
x_2 f_{j/A}(x_2, p_T^2) \hat{\sigma}_{ij-kl}(\hat{s}, \hat{t}, \hat{u}).
\]

(13)

The jet cross section can be related to the total number of minijets formed in PbPb collisions at LHC:

\[
N_{\text{jet}} = T(0) \int dp_T dy_1 dy_2 \frac{2\pi p_T}{s} \sum_{ijkl} x_1 f_{i/A}(x_1, p_T^2)
\]

\[
x_2 f_{j/A}(x_2, p_T^2) \hat{\sigma}_{ij-kl}(\hat{s}, \hat{t}, \hat{u}),
\]

(14)

where \(T(0) = 9A^2/8\pi R_A^2\) is the nuclear geometrical factor for head-on PbPb collisions (for a nucleus with a sharp surface). Here \(R_A = 1.2A^{1/3}\) fm is the nuclear radius. \(\hat{\sigma}_{ij-kl}\) denotes the elementary pQCD parton parton cross sections, which are given by:

\[
\hat{\sigma}_{gg-qq} = \frac{\alpha_s^2}{\hat{s}}(\hat{s}^2 + \hat{u}^2)[\frac{1}{\hat{t}^2} - \frac{4}{9\hat{u}\hat{t}}],
\]

(15)

\[
\hat{\sigma}_{gg-gg} = \frac{9\alpha_s^2}{2\hat{s}}[3 - \frac{\hat{u}}{\hat{s}^2} - \frac{\hat{s}}{\hat{t}^2} - \frac{\hat{u}}{\hat{u}^2}],
\]

(16)

As gluons are the dominant part of the parton production at LHC we have considered the above two partonic type collisions. The kinematic relations are given by:

\[
\hat{s} = x_1 x_2 s = 4p_T^2 \cosh^2\left(\frac{y_1 - y_2}{2}\right).
\]

(17)

The momentum rapidities \(y_1, y_2\) and the momentum fractions \(x_1, x_2\) are related by:

\[
x_1 = p_T (e^{y_1} + e^{y_2})/\sqrt{s}, \quad x_2 = p_T (e^{-y_1} + e^{-y_2})/\sqrt{s}.
\]

(18)

We use the saturation argument to fix the minimum momentum scale at the which the pQCD is applicable to be 2 GeV at LHC [30]. The partonic structure functions \(f_{i,j/A}\) used in Eq. (13) are GRV98 [31] for the proton structure function and EKS98 [32] for nuclear shadowing effects.

The total transverse energy \(< E_T^{\text{tot}} >\) produced in nuclear collisions is given by:

\[
<E_T^{\text{tot}} > = T(0) \int dp_T dy_1 dy_2 \frac{2\pi p_T}{s} \sum_{ijkl} x_1 f_{i/A}(x_1, p_T^2)
\]

\[
x_2 f_{j/A}(x_2, p_T^2) \hat{\sigma}_{ij-kl}(\hat{s}, \hat{t}, \hat{u}).
\]

(19)

The above pQCD formula has the information in the momentum space via \(p_T\) and \(y\) (the momentum rapidity) distribution. In order to obtain energy density we need to supply additional information about coordinate distribution. For an expanding system the minijet number distribution eq. (14) can be related to the phase-space distribution function via [33]:

\[
\frac{d^3 N_{\text{jet}}}{\pi dy dp_T} = g_c \int f(x, p) p^\mu d\sigma^\mu
\]

(20)

where \(g_c = 16\) is the product of spin and color degrees of freedom,

\[
d\sigma^\mu = 2\pi R^2_A \tau d\eta(cosh(\eta, 0, 0, \sinh \eta)),
\]

(21)

and

\[
p^\mu = (p_T \cos \phi, p_T \cos \phi, p_T \sin \phi, p_T \sin \phi),
\]

(22)

for an 1+1 dimension expanding system. Using the above relations we get at the initial time \(\tau_0 = (1/p_0)\):

\[
\frac{dN_{\text{jet}}}{\pi dy dp_T} = g_c \pi R^2_A \tau_0 \int d\eta p_T \cosh(\eta - \tilde{y}) f(p_T, \eta, \tau_0),
\]

(23)

where we assume a transverse isotropy at the early stage.

We take a boost non-invariant distribution function in the following. We assume a Gaussian coordinate rapidity \(\eta (>1/2\ln(1+\tau/\tau^2))\) distribution of the form [29]

\[
f(p_T, \eta, \tau_0) = f(p_T, \tau_0) e^{-\frac{(\eta - \tilde{y})^2}{4\tau^2(p_T)}},
\]

(24)

where \(f(p_T, \tau_0)\) is obtained from \(\frac{dN_{\text{jet}}}{dy dp_T}\) by using pQCD from eq. (14). Using the above form in eq. (23) we get:

\[
\frac{dN_{\text{jet}}}{dy dp_T} = g_c 2\pi R^2_A \tau_0 p_T^2 f(p_T, \tau_0) \int_{-\infty}^{\infty} d\eta \cos(\eta - \tilde{y}) \times e^{-\frac{(\eta - \tilde{y})^2}{4\tau^2(p_T)}},
\]

(25)

which gives:

\[
\frac{dN_{\text{jet}}}{dy dp_T} = g_c 2\pi \sqrt{\pi R^2_A \tau_0 p_T^2} f(p_T, \tau_0) \sigma(p_T) e^{\sigma^2(p_T)/4},
\]

(26)

From the above equation we get:

\[
f(p_T, \tau) = \frac{dN_{\text{jet}}}{dy dp_T} \frac{g_c 2\pi \sqrt{\pi R^2_A \tau_0 p_T^2} \sigma(p_T) e^{\sigma^2(p_T)/4}}
\]

(27)

which gives a boost non-invariant initial phase-space gluon distribution function:
Using the above boost non-invariant gluon distribution function the initial minijet energy density is given by:

$$\epsilon(\tau_0, \eta) = g_C \int d\Gamma(p^u a_u)^2 f(p_T, \eta, y, \tau_0) = g_C \int d^2 p_T p_T^2 \int dy \cosh^2(\eta - y) \left( e^{(\eta - y)^2/\sigma^2} / \sqrt{\pi \sigma^2} \right)$$

(29)

Before we calculate the initial gluonic energy density at LHC we would like to find out the values of the unknown parameter $\sigma^2$ appearing in the above equation. We will fix this unknown parameter by equating the first moment of the distribution function with the pQCD predicted $E_T$ distribution as given by eq. (19). We have

$$\int dp_T \int dy \frac{dE_T^{{\text{jet}}}}{dy dp_T} = 2g_C \pi^2 R_A^2 \tau_0 \int dp_T \int dy \frac{\mathcal{T}^2}{\sigma^2} f(p_T, y)$$

(28)

IV. RESULTS AND DISCUSSIONS

In this section we will present the results for the evolution of the black hole mass at LHC by taking both accretion and radiation into account. The accretion rate depends on the energy density of the gluons (see eq. (11)) which is a function of time. The energy density of the gluons at LHC decreases as a function of time. This is because of the fast expansion of the system, which acquires more volume. In our numerical calculation we will assume a maximum energy density at all time which is the energy density obtained at initial collision, as described in the last section. Thus our results will overestimate the effect of accretion and thus underestimate the critical energy density. However the expansion time is at a fm/c scale which is slow compared to the vaporization time scale at LHC. We solve the eq. (11) numerically with the gluon energy density obtained in the last section. The time evolution of a black hole of mass 3 TeV is shown in Fig.1. The Planck mass is chosen to be 1 TeV. Different curves are for different numbers of extra dimensions. Solid, dotted and dashed lines correspond to $d=2$, 4 and 7 respectively. It can be seen that the decay of a 3 TeV mass black hole is almost instantaneous at LHC even if one takes into account the absorption of partons with energy density of 517 GeV/fm$^3$. The black hole of mass 3 TeV (with Planck mass equals to 1 TeV) decays within a fraction of a fm/c. The partons in the QGP phase hadronize in a hadronization time scale which is more than a fm/c. Hence a 3 TeV mass black hole completely evaporates before any of the hadrons are formed at LHC.

Now let us study the evolution of a heavier black hole, say 5 TeV, at LHC. As stated earlier a heavier mass black hole will evaporate slower. This is because the temperature of the black hole is inversely proportional to its mass. The evolution of a 5 TeV mass black hole at LHC is shown in Fig. 2. We have used a Planck mass equals to 1 TeV. In comparison to Fig. 1 the decay time of the 5 TeV black hole mass is slightly enhanced when compared to the case when the mass of the black hole is 3 TeV, but it is still instantaneous in comparison to hadronization scale which is more than a fm/c. This suggests that a typical black hole formed at LHC evaporates instantaneously and can not eat sufficient matter.

In Fig. 3 we have shown the results of the time evolution of the 5 TeV mass black hole but with Planck mass equals to 2 TeV. As can be seen from the figure the evaporation is much faster than the earlier two cases, considered in Fig. 1 and 2. This is because as the Planck mass is increased the Schwarzschild radius is decreased. Due to the decrease in the Schwarzschild radius the effective cross section for absorption of matter by the black hole is decreased. Hence the evolution of the black hole mass decreases much faster as we increase the Planck mass which can be seen from Fig. 3.

In the following we will present estimates of the minimum energy density of the matter we would need in order for a TeV scale black hole to swallow quark-gluon matter at LHC. In order for a black hole to increase its mass, one must have:

$$\frac{dM_{BH}}{d\tau} > 0.$$  (31)

Hence from eq. (10) we get the minimum required energy density ($\epsilon_{\text{min}}$) of the partonic matter to be:

$$\epsilon_{\text{min}} = \frac{\sum \Gamma_s g_{\text{eff}} f_{\text{p}}}{7680 \pi^2 \epsilon_{\text{eff}}}$$  (32)

From the above equation we get for $M_{\rho} = 1$ TeV:

1) Case with the number of extra dimensions $d=2$:

$$\epsilon_{\text{min}} = 4.2 \times 10^{10} \text{ GeV/fm}^3 \quad \text{for} \quad M_{BH} = 3 \text{ TeV}$$

$$\epsilon_{\text{min}} = 2.1 \times 10^{10} \text{ GeV/fm}^3 \quad \text{for} \quad M_{BH} = 5 \text{ TeV},$$

2) Case with the number of extra dimensions $d=4$:
\[ \epsilon_{\text{min}} = 3.2 \times 10^{10} \text{ GeV/fm}^3 \quad \text{for} \quad M_{\text{BH}} = 3 \text{ TeV} \]
\[ \epsilon_{\text{min}} = 2.2 \times 10^{10} \text{ GeV/fm}^3 \quad \text{for} \quad M_{\text{BH}} = 5 \text{ TeV}, \]

3) Case with the number of extra dimensions \(d=7:\)
\[ \epsilon_{\text{min}} = 7.5 \times 10^{10} \text{ GeV/fm}^3 \quad \text{for} \quad M_{\text{BH}} = 3 \text{ TeV} \]
\[ \epsilon_{\text{min}} = 5.8 \times 10^{10} \text{ GeV/fm}^3 \quad \text{for} \quad M_{\text{BH}} = 5 \text{ TeV}. \]

It can be seen that the minimum energy density required for different values of \(M_{\text{BH}}\) and for different values of number of extra dimension is much higher than the energy density obtained at LHC. Note that these numbers are obtained for \(M_P = 1 \text{ TeV}\). For higher values of \(M_P\) these numbers will be further increased. Creation of such astronomically high values of energy density is beyond the reach of any accelerator experiment. This means that black holes created in high energy hadronic colliders at LHC will not swallow the matter nearby.

V. CONCLUSIONS

If the fundamental Planck scale is near a TeV, then parton collisions with high enough center-of-mass energy should produce black holes. The production rate for such black holes has been extensively studied for the case of a proton-proton collision at \(\sqrt{s} = 14 \text{ TeV}\) and for a lead-lead collision at \(\sqrt{s} = 5.5 \text{ TeV}\) at LHC. As the parton energy density is much higher at lead-lead collisions than in pp collisions at LHC, it is necessary to check if the produced black hole will be able to absorb the partons formed in the lead-lead collisions and eventually consume much of the quark-gluon plasma formed at LHC. In this paper, we have made a quantitative analysis of this possibility and found that as the energy density of partons formed in lead-lead collisions at LHC is about 500 GeV/fm\(^3\), the rate of absorption of these black holes is much smaller than the rate of evaporation. Hence black holes formed in such collisions evaporate much too quickly to absorb the partons nearby. For the black hole mass to increase via parton absorption at the LHC the typical energy density of quarks and gluons should be of the order of \(10^{10} \text{ GeV/fm}^3\). As LHC will not be able to produce such a high energy density partonic system, the black hole will not be able to absorb sufficient nearby partons before it decays. The typical life time of the black hole formed at LHC is found to be a small fraction of a fm/c.

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Black Hole Evolution at LHC

FIG. 1: Evolution of black hole of mass equals to 3 TeV at LHC. The Planck mass equals to 1 TeV.

FIG. 2: Evolution of black hole of mass equals to 5 TeV at LHC. The Planck mass equals to 1 TeV.

FIG. 3: Evolution of black hole of mass equals to 5 TeV at LHC. The Planck mass equals to 2 TeV.