Black hole production at the LHC

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Abstract

In the TeV gravity scenarios, black holes are expected to be produced at the Large Hadron Collider (LHC) in CERN. In this article, we review the current status of the theoretical studies on this issue. After a brief overview, we explain our studies on the apparent horizon (AH) formation in high-energy particle collisions.

1 Introduction

Almost a decade ago, scenarios in which the Planck energy M_p could be $O(\text{TeV})$ were proposed [1]. In these scenarios, our 3-dimensional space is a brane floating in large extra dimensions, and gauge particles and interactions are confined on the brane. Since the TeV scale energy will be reached by the Large Hadron Collider (LHC) in CERN, we have a possibility to observe quantum gravity phenomena by experiments. Specifically, in the collision with the energy much higher than the Planck scale, the black hole production is expected [2]. Since the LHC is planned to begin operation in 2008, the black hole production at the LHC is a very timely topic. In this article, we review the theoretical studies on this issue. We give a brief overview in the next section. In Sec. 3, we focus attention to our studies on the apparent horizon (AH) formation in high-energy particle collisions.

2 Brief overview

The LHC is designed so that protons collide with the center-of-mass energy 14 TeV. In the collisions, the partons interact with each other and black holes could be produced in these processes. If a black hole is produced, it emits mainly the gravitational wave and become a stationary higher-dimensional Kerr black hole (the balding phase). Then, the black hole will evaporate by the Hawking radiation (evaporation). The particles emitted in this process can be observed by the detectors such as the ATLAS. In the final phase of evaporation, the quantum gravity effects may become important (the Planck phase). Let us look at these issues one by one.

2.1 Production rate

The black holes with mass (few)M_p are expected to exist, since its gravitational radius is larger than the Planck length. Then the trans-Planckian collision is expected to cause the gravitational collapse if the impact parameter is smaller than the gravitational radius $r_h(\sqrt{\tau s})$ of the parton-pair system. Thus the parton-parton cross section for the black hole production is estimated as $\sigma_{ij\to bh}(\tau s) \sim \pi[r_h(\sqrt{\tau s})]^2$. In order to obtain the proton-proton cross section for the black hole production, one should multiply the parton distribution functions and take the sum over all possible parton pairs:

$$\sigma_{pp\to bh}(\tau_m, s) = \sum_{ij} \int_{\tau_m}^{1} d\tau \int_{\tau}^{1} \frac{dx}{x} f_i(x) f_j(\tau/x) \sigma_{ij\to bh}(\tau s). \tag{1}$$

Based on this calculation, the black hole production rate is expected to be 1Hz in the most optimistic estimate [2]. We remark that the production rate depends on the effect of balding and the black hole threshold mass. Also, the value of $\sigma_{ij\to bh}$ should be estimated by a direct calculation. The topics in Sec. 3 are related to these issues.

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2.2 Balding phase

Once a black hole is produced, it decays through several phases. The first phase is the so-called balding phase. In this phase, the produced black hole emits gauge and gravitational radiations and eventually becomes a stationary higher-dimensional Kerr black hole. The gravitational radiation is expected to be larger than the gauge radiation. The characteristic time scale is estimated from the quasinormal frequency as $t_{\text{balding}} \sim M_p^{-1}(M/M_p)^{1/(D-3)}$, where D is the spacetime dimensionality.

Since the radiations carry part of the system energy and angular momentum, the final mass and angular momentum of the black hole is determined by the amount of the radiations. For this reason, the study of the balding phase is important in order to estimate the distribution of the mass and angular momentum of produced black holes. However, because of the highly nonlinear nature of high-energy particle systems, the study of this process is very difficult even numerically. So far there are no reliable estimates of the amount of radiations, although several attempts have been made including the interesting one by Pretorius [3].

2.3 Evaporation

The produced black hole evaporates by the Hawking radiation. The evaporation phase is further divided into two phases: the spin-down phase and the Schwarzschild phase. In the spin-down phase, the angular momentum of the black hole is extracted by emission of spin particles. After that, the black hole is Schwarzschild-like and the emission becomes almost isotropic. The characteristic time scale is estimated as $t_{\text{evaporation}} \sim M_p^{-1}(M/M_p)^{(D-1)/(D-3)}$, which is larger than t_{balding} for $M \gg M_p$. The energy spectrum of emitted particles are almost thermal and the temperature is $T_H = (D-3)/4\pi r_h(M)$. Since the number of brane fields is much larger than that of the bulk fields, the black hole radiates mainly on the brane [4] (though there are several subsequent discussions on this issue).

The emitted particles can be detected at the LHC. If the 10TeV mass black hole is produced, the signals have the following features: (i) $\sim$ 50 quanta with energy 150-200 GeV; (ii) Large transverse momentum; (iii) $\sim$ 10% hard leptons and $\sim$ 2% hard photons. The S/N ratio of lepton and photon events is very large, and it makes the detection easier. In fact, the ATLAS group demonstrated that the detection of black hole events is relatively easy by constructing the event generator [5].

We comment on the studies of the greybody factors. Because of the curvature scattering, part of the emitted particles is absorbed by the black hole and the spectrum differs from that of the black body. These effects were studied by many authors. The greybody factors of the Schwarzschild black hole were numerically calculated for both brane fields and bulk gravitons [6]. The greybody factors of the Kerr black hole were studied by full numerical calculations for brane fields [7]. Thanks to their studies, the temporal evolution of the evaporation can be calculated quite accurately. The recently constructed event generator takes account of the effects of these greybody factors [8]. Note that the greybody factor of the Kerr black hole for bulk gravitons is left as a remaining problem.

2.4 Planck phase

As the black hole evaporates, the mass decreases and becomes close to the Planck mass M_p. In this phase, the quantum gravity effects may become important. Currently there are no reliable predictions for this phase since we have no theory of quantum gravity. Rather, we can able to learn the dynamics of quantum gravity from the experiments. This opens up an interesting possibility to construct the quantum gravity theory based on the experiments. If this is the case, we might be able to resolve e.g. the information loss problem.

3 Studies on the apparent horizon formation

Now, we turn to the studies on the apparent horizon (AH) formation in high-energy particle collisions by ourselves. Motivation for our studies is as follows. In Sec. 2.1, the parton-parton cross section for the black hole production is assumed to be $\sigma_{ij\to bh} = \pi[r_h(2p)]^2$, where p denotes the energy of each incoming particle. Since this is just the order estimate, the realistic cross section will be $\sigma_{ij\to bh} = F_{ij}(D)\pi[r_h(2p)]^2$, where $F_{ij}(D)$ depends on the characters of the incoming particles such as charges and spins as well as the dimensionality D. It is necessary to obtain the reliable cross sections by direct calculations.

The AH is defined as a closed $(D-2)$-dimensional spacelike surface whose outgoing null geodesic congruence has zero expansion. Assuming the cosmic censorship, the AH existence is the sufficient condition for the black hole formation when the null energy condition is satisfied. Therefore, the AH is a good indicator for the black hole formation. We studied the AH formation in the grazing collision of Aichelburg-Sexl (AS) particles [9, 10]. The charge effect and the effects of spin and duration were discussed in [11] and [12], respectively. We briefly review these studies one by one.

3.1 Aichelburg-Sexl particle collision

In [9, 10], we studied the AH formation in the collision of AS particles with the impact parameter b, using the $(D \geq 4)$-dimensional general relativity. By using the AS particles, we ignored charges and spins of incoming particles, the brane tension and the structure of extra dimensions. By numerically calculating the cross section $\sigma_{\rm AH}$ for the AH formation, we found a lower bound on $\sigma_{ij\to bh}$.

The AS particle is a simple massless pointlike particle whose metric for $D \geq 5$ is

$$ds^2 = -dudv + \sum_i dx_i^2 + \Phi(r)\delta(u)du^2, \quad \Phi(r) = \frac{16\pi Gp}{(D-4)\Omega_{D-3}r^{D-4}}, \tag{2}$$

where $r := \sqrt{\sum_i x_i^2}$ and the particle is located at $r = 0$. The gravitational field is distributed in the transverse plane to the motion, and it propagates at the speed of light along $u = 0$. We can set up the collision of two AS particles by just combining two metrics, since they do not interact before the collision. In this spacetime, the two incoming waves propagate along $u = 0$ and $v = 0$, and collide at $u = v = 0$. The locations of particles in the transvese plane are $x_i = (\pm b, 0, ..., 0)$, where b is the impact parameter.

The equation and the boundary conditions for determining the AH on the slice $u \leq 0 = v$ and $v \leq 0 = u$ were derived by Eardley and Giddings, and they solved the AH analytically in the case $D = 4$ [13]. Unfortunately, their method could not be applied to the higher-dimensional cases, and myself and Nambu [9] developed a numerical code to solve this problem. In Ref. [10], myself and Rychkov improved this result by solving the AH on a different slice, $u \geq 0 = v$ and $v \geq 0 = u$. The results of these two works are summarized as follows:

D	4	5	6	7	8	9	10	11
$\sigma_{\rm YN}/\pi r_h^2(2p)$ [9]	0.65	1.08	1.34	1.52	1.64	1.74	1.82	1.88
$\sigma_{\rm YR}/\pi r_h^2(2p)$ [10]	0.71	1.54	2.15	2.52	2.77	2.95	3.09	3.20

These values give the reliable lower bounds on $\sigma_{ij\to bh}$ for the case of AS particle collisions. In addition, using the area theorem, we could find the lower bound $M_{\rm AH}$ on the mass of final state of the produced black hole $M_{\rm BH}$ by calculating the AH area (i.e. $M_{\rm BH} > M_{\rm AH}$). $M_{\rm AH}$ has the tendency to decrease as the impact parameter b and the dimensionality D are increased. Our results were used in e.g. [14] in order to improve the estimate of the black hole production rate at the LHC. Specifically, they compared the two cases $M_{\rm BH} = 2p$ and $M_{\rm BH} = M_{\rm AH}$. The result is that the two estimates of the black hole production rate differ by a factor 10^3–10^6, indicating the importance of the studies on the balding phase.

3.2 Charge effect

In [11], myself and Mann discussed the effect of electric charge on the AH formation. In that paper, we ignored the confinement of electromagnetic fields on the brane. Namely, using the higher-dimensional classical Einstein-Maxwell theory, we introduced the charged version of the AS particle as the particle model as the first step. We studied only the head-on collision cases for simplicity.

The metric of the charged AS particle is similar to Eq. (2), but the function $\Phi(r)$ has the correction term due to the charge:

$$\Phi(r) = \frac{16\pi Gp}{(D-4)\Omega_{D-3}r^{D-4}} - \frac{16\pi^2(2D-5)!!G\gamma q^2}{(D-3)(2D-7)(2D-4)!!r^{2D-7}}, \tag{3}$$

where q is the D-dimensional charge and γ is the Lorentz factor. Since the correction term is negative, it is expected that the charge makes the AH formaton difficult. In fact, we solved the AH analytically and found that the condition for the AH formation is roughly given as $\gamma q^2 \lesssim Gp^2$. This is rewritten as $\alpha C_{\rm b}^{D-4}(M_p/m)(M_p/p) \lesssim 1$ with the fine structure constant α, the brane thickness $C_{\rm b}$ in the unit of the Planck length, and the rest mass m. This condition cannot be satisfied at the LHC, and our result might indicate that the black hole production rate is highly suppressed by the charge effect. However, in the regime where the AH formation is prohibited in this model, the QED effects are found to be important by evaluating the so-called classical radius. Therefore, further improvement is required to obtain the definite conclusion.

3.3 Effects of spin and duration

In [12], myself, Zelnikov and Frolov discussed the effects of spin and duration on the AH formation using the gyraton model [15], which represents the gravitational field of a spinning radiation beam pulse. Although the gyraton is a classical model, it can be regarded as a toy model of the quantum wavepackets with spin. For simplicity, we considered only the head-on collision in four dimensions.

The gyraton metric is given by

$$ds^2 = -dudv + dr^2 + r^2 d\phi^2 - 8Gp\chi_p(u)\log r du^2 + 4GJ\chi_j(u)dud\phi, \tag{4}$$

where J is the angular momentum (spin) and the last term causes the repulsive gravitational field around the center. $\chi_p(u)$ and $\chi_j(u)$ are the functions normalized as $\int \chi_p(u)du = \int \chi_j(u)du = 1$, which specify the energy and angular momentum distributions. The characteristic width of $\chi_p(u)$ and $\chi_j(u)$ is the duration L of the gyraton. Using this model, we studied the AH formation numerically, and found that the condition for the AH formation is roughly expressed as $L \simeq r_h(2p)$ and $J \lesssim 0.4pr_h(2p)$. By assuming L to be the Lorentz contracted proton size $\sim 1.5 \times 10^{-4}$fm and J to be $\hbar/2$, the above two conditions are satisfied at the LHC. Therefore the spin effects might not have such a significant effect for the black hole production rate, though it could be changed by a factor.

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