Production of Spinning Black Holes at colliders

Seong Chan Park* and H. S. Song†

Center for Theoretical Physics and School of Physics, Seoul National University, Seoul 151-742, Korea

Abstract

When the Planck scale is as low as TeV scale, there will be chances to produce Black holes (BH’s) at future colliders. Generally, BH’s produced via pariticle collisions could have non-zero angular momentum. We estimate the production cross section of spinning and non-spinning BH’s for future colliders. Although the production cross section for the rotating BH is much suppressed by angular momentum dependent factor, the total cross section could be $\sim 2 - 3$ times enhanced for the case of $\delta = 4 - 6$.

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*schan@mulli.snu.ac.kr

†hssong@physs.snu.ac.kr
**Introduction.**—Some of the most intriguing phenomena of the TeV-scale gravity [1], [2] is the production of Black holes (BH’s) at the future colliders like Large Hadronic Collider (LHC) of the CERN [3], [4] (see also [5] as earlier study on the properties of black holes in the large extra dimensions/TeV-scale gravity scenario) and at the atmosphere by cosmic rays [6].

The mass of the BH, $M_{BH}$, produced at LHC could be larger than the $D$-dimensional gravity scale, $M_D$, which is related with four dimensional Planck scale, $M_P$, as $M_D^{\delta+2} R^\delta = M_P^2$, where $D = 4 + \delta$ and $R$ is the size of extra dimensions.

When $M_D \sim \mathcal{O}(1)$ TeV, the size of the extra dimensions is much larger than the Schwarzschild radius, $R_S$, of $D$-dimensional BH of mass $M_{BH} \sim M_D$:

$$R_{BH} \sim \frac{1}{M_D} \left( \frac{M_{BH}}{M_D} \right)^{1/(\delta+1)} \ll R. \tag{1}$$

Since the Compton wavelength of the BH($L_{BH}$) is smaller than $R_{BH}$ when $M_D < M_{BH}$, the following relation is assumed to be valid for our interests:

$$L_{BH} < R_{BH} \ll R. \tag{2}$$

In Ref. [3] and [4], the production cross section of BH via particle collisions were estimated by semi-classical arguments. Semi-classical approximation is strictly valid when $L_{BH} \ll R_{BH}$ and as $M_{BH}$ approaches $M_D$ unknown stringy effects might be important.

As a first try to estimate, they just considered the case for the non-spinning, non-charged BH production. It is important to note that such tiny black holes could be generated only provided their electric charge is zero, otherwise they would be naked singularities [7]. In the contrary, any object which is produced via fusion process of colliding particles could have angular momentum or spin. Non-spinning case could occur only when the orbital and internal angular momenta are exactly cancelled. We may imagine the case of exactly head-on collision of initial particles for the production of non-spinning BH.

The main objective of this letter is re-estimation of the the spinning and non-spinning BH production cross section for the improved estimation. We will point out that even
though the spinning BH production cross section is suppressed, the total cross section for the spinning and non-spinning BHs could be much enhanced. That means we may have bigger chance to see the BH at our future lab experiments.

Non-spinning BH production.– We first review the production process of non-spinning BHs. Classically speaking, BH can be formed when and only when the energy $M$ is compacted into a region whose circumference in every direction is less than $2\pi R_{BH}$. $R_{BH}$ is Schwarzschild radius of BH which is determined by mass ($M$), angular momentum ($J$) and possibly (electric) charge ($Q$). From the above classical argument, we deduce the simple picture of BH production at particle collision as following. Consider two partons with the center of mass (CM) energy $\sqrt{s} = M_{BH}$ moving in opposite directions. When the impact parameter ($b$) is less than the Schwarzschild radius, the particles effectively inject the critical mass of BH in the radius. Then a BH is formed and almost stationary in the CM frame. From this semi-classical arguments, we could find the geometrical approximation for the cross section for producing a BH of mass $M_{BH}$ as

$$\sigma(M_{BH}) \approx \pi R_{BH}^2.$$  \hspace{1cm} (3)

The Schwarzschild radius for the non-spinning BH is given by \([10]\)

$$R_{BH}(J = 0) = \frac{1}{\sqrt{\pi} M_D} \left( \frac{M_{BH}}{M_D} \frac{8\Gamma(\frac{4+3}{2})}{\delta + 2} \right)^{\frac{1}{\delta + 1}},$$  \hspace{1cm} (4)

so the larger $M_{BH}$ provides the larger $R_S$. From the above expression for the parton level cross sections, we can obtain the total cross section by convoluting parton distribution function (PDF) for the initial partons:

$$\frac{d\sigma(pp \to BH + X)}{dM_{BH}} = \frac{2M_{BH}}{s} \sum_{a,b} \int_{M_{ab}/s}^1 f_a(x_a) f_b(x_a, \frac{M_{BH}^2}{x_a s}) \sigma(ab \to BH)|_{s=M_{BH}^2}. $$  \hspace{1cm} (5)

There are several uncertainties in this semi-classical estimation.

Firstly, there could be quantum probability that BH is produced even when $b > R_S$. However, as Voloshin argued in Ref. [8], this probability might be exponentially suppressed by Euclidean BH action (see also Ref. [4]).
Secondly, as $M_{\text{BH}}$ approaches $M_P$ (or $M_D$ for $D$-dimensional BH), BH becomes stringy. Unfortunately we do not have enough information of this unknown stringy correction, yet. In this study, we simply ignore such uncertainties.

**Spinning BH production.** – Now, let us consider the case with the spinning BH. In the Ref. [10], the rotating BH solution in $4+\delta$ dimensional space-time is obtained. The rotating BH generally has inner and outer horizons. They are described not only by $M_{\text{BH}}$ but also by the angular momentum of the BH parametrized by dimensionless parameter $a$ like

$$R_{\text{BH}}(J) = \frac{1}{\sqrt{\pi M_D}} \left( \frac{M_{\text{BH}}}{M_D} \right) \frac{1}{1 + a^2} \frac{8\Gamma\left(\frac{\delta+3}{2}\right)}{\delta + 2} \frac{1}{\delta + 1} R_S(J = 0),$$

(6)

where $a \equiv \frac{(\delta+2)J}{2M_{\text{BH}}R_{\text{BH}}}$ and $J$ is the angular momentum of BH.

For the produced BH from the particle collision, the angular momentum of the BH is allowed upto $(M_{\text{BH}}R_{\text{BH}})$ at the classical limit. The range of the $a$ parameter is given as

$$0 \leq a \leq \frac{(\delta + 2)}{2}.$$  

(7)

As we will show below, the upper bound for the angular momentum does not much affect the estimation of total cross section.

To estimate the BH production cross section for rotating BH, we assume that the semi-classical reasoning for the non-rotating BH might be still valid for rotating BH. Semi-classical reasoning suggests that, if the impact parameter is less than the size of BH given in Eq.(6), a BH with the mass $M_{\text{BH}}$ and angular momentum $J$ forms. The total cross section can be estimated and is of order

$$\sigma(M_{\text{BH}}) = \sum_J \hat{\sigma}(J)$$

$$= \frac{\delta+2}{\sum_{a=0}^{\delta+2} \left( \frac{1}{1 + a^2} \right)^{\delta+1} \hat{\sigma}(J = 0)}$$

(8)

at the parton level.

We see that the production cross section for the large angular momentum is a bit suppressed by the angular momentum dependent factor. In Fig.1, we plotted the ratio of
\[ R \equiv \hat{\sigma}(J) / \hat{\sigma}(0) \text{ with respect to } J \text{ (or } a \text{) at the parton level.} \]

Solid (black) line and dashed (red) line describe the cases with \( \delta = 4 \) and \( \delta = 6 \), respectively. The higher spin states of BH is seen to be quite suppressed and we can understand this suppression from the \( a \) dependent factor \( \left( \frac{1}{1+a^2} \right)^{\frac{\delta+1}{\delta-1}} \). This factor is originally introduced to describe the radius of spinning BH. With the factor the radius of the spinning BH is smaller than that of non-spinning BH for the same energy and the geometrical cross section is also suppressed since \( \sigma \sim R_S^2 \).

The total cross section could be obtained after convoluting about parton distribution fuction. With the geometrical arguments, the spin dependent part of the BH production cross section could be factored out. We found that the total cross section of spinning and non-spinning BH production process is about \( \sim 2 \) and \( \sim 3 \) times larger than that of only non-spinning BH production process for \( \delta = 4 \) and \( \delta = 6 \), respectively.

**Decay of spinning BH.** – Produced BH might decay primarily via Hawking radiation. Hence with the large extra dimension, we may have chance to test the Hawking’s speculative BH thermodynamics \[11\]. There are some known properties of BH radiation for the BH located on the brane. BH acts as a point radiator and emit mostly s-waves since the wavelength of the thermal radiation of Hawking temperature is larger than the size of the BH \[3\]. BHs radiate mainly on the brane since there are much more particles on the brane than in the bulk \[12\]. Typically, TeV-scale BHs is belived to decay very fastly \( (\sim 10^{-25} \text{ sec.}) \) (however there are very different estimation based on canonical and micro-canonical pictures of BH \[7\].)

Hawking radiation is thermal process which is governed by Hawking temperature, which is given as

\[ T_H = \frac{(\delta + 1) + (\delta - 1)a^2}{4\pi(1 + a^2)} \frac{1}{R_{BH}}, \]

Since \( T_H \propto 1/R_{BH} \), we see that the rotating BH has a bit larger Hawking temperature than non-rotating one. BH decay occurs in several stages: ‘balding phase’, ‘spin-down phase’, ‘Schwarzschild phase’, and ‘Planck phase’ \[4\]. Through the balding phase, BH will settle down to a symmetrical rotating BH by emitting gauge and gravitational radiation. Then
by emitting quanta with non-zero angular momenta BH will lose its spin. In Schwarzschild phase, BH is non-rotating or Schwarzschild BH. After the Schwarzschild phase, the BH mass is much reduced and the complex stringy effects will be important. This is Planck phase. In principle, we can measure the energy spectrum of the radiation from the BH and by reconstructing Wien’s displacement law, we may have chance to test Hawking’s law for rotating and non-rotating BH.

Summary and Conclusion.– In this letter, we study the spinning and non-spinning BH production at particle collider based on the semi-classical arguments. We point out that from the angular momentum dependence of the size of BH, geometrical cross section for the rotating BH production process is much suppressed. However the total cross section obtained by summing rotating and non-rotating BH production cross sections could be $\sim 2-3$ times enhanced at the parton level. Rotating BH might decay by Hawking radiation by several steps. Its temperature is a bit higher than that of non-rotating BH with same mass.

In this study, we just consider the case when the BH is produced on the rigid brane. However, crucial modification is expected when the fluctuation of the brane is considered, especially in the decay process of the BH which occurs mainly on the brane. Still there remains stringy corrections to our estimation and we are waiting for the further study. Acknowledgments.– The work was supported in part by the BK21 program and in part by the Korea Research Foundation(KRF-2000-D00077).
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FIG. 1. The ratio $R \equiv \hat{\sigma}(J)/\hat{\sigma}(0)$ plotted w.r.t the parameter $a \equiv \frac{(\delta+2)J}{2M_{BH}R_{BH}}$. Solid (black) line and dashed (red) line denotes $\delta = 4$ and $\delta = 6$, respectively. Higher spin states for BH are quite suppressed.