Black Hole Production Rates at the LHC: Still Large

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We examine the rates for the production of black holes(BH) at the LHC in light of the exponential suppression of the geometric cross section estimate proposed by Voloshin. We show that these rates will still be quite large over a reasonable range of model parameters. While BH production may not be the dominant process, its unique signature will ensure observability over conventional backgrounds.

Theories with extra dimensions and a low effective Planck scale(M_*) offer the exciting possibility that the production rate of black holes(BH) somewhat more massive than M_* can be quite large at future colliders. For example, cross sections of order 100 pb at the LHC[1], and even larger ones at the VLHC, have been advertised in the analyses presented by Giddings and Thomas(GT) and by Dimopoulos and Landsberg(DL). Although in practice the actual production cross section critically depends on the BH mass, the exact value of M_* and the number of extra dimensions, following the analysis of the authors in Ref.[1], one finds very large rates over almost all of the interesting parameter space. These earlier analyses and discussions of the production of BH at colliders have been extended for the Snowmass proceedings by several authors[2].

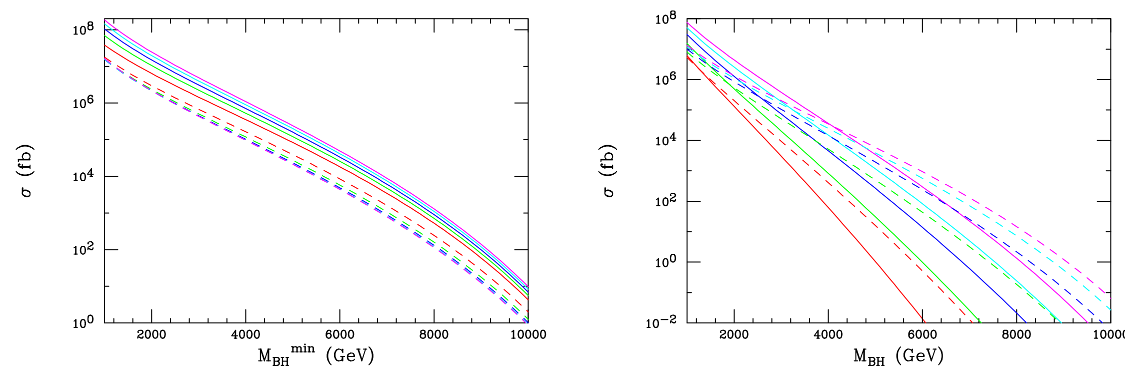

Figure 1: (Left)Cross section for the production of BH more massive than M_{BH}^{min} at the LHC assuming $M_* = 1$ TeV for $\delta = 2(3,4,5,6)$ extra dimensions corresponding to the red(green,blue,cyan,magenta) curves. The solid(dashed) curves are the results from the work by Giddings and Thomas(Dimopoulos and Landsberg). (Right)Same as on the left but now including the effects of the Voloshin damping factor. We observe that large cross sections are possible over a reasonable range of the model parameters. We identify M_* with either M_{GT} or M_{DL} for the appropriate set of curves.

The basic idea behind the original collider BH papers is as follows: we consider the collision of two high energy Standard Model(SM) partons which are confined to a 3-brane, as they are in both the models of Arkani-Hamed, Dimopoulos and Dvali(ADD)[3] and Randall and Sundrum(RS)[4]. In addition, we imagine that gravity is free to propagate in δ extra dimensions with the $4+\delta$ dimensional Planck scale assumed to be $M_* \sim 1$ TeV. The curvature of the space is assumed to be small compared to the energy scales involved in the collision so that quantum gravity effects can be neglected. When these partons have a center of mass energy in excess of $\sim M_*$ and the impact parameter for the collision is less than the Schwarzschild radius, R_S, associated with this center of mass energy, a $4+\delta$-dimensional BH is formed with reasonably high efficiency. The subprocess cross section for the production of a non-spinning BH is thus essentially geometric

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for *each* pair of partons:

$$\hat{\sigma} \simeq \pi R_S^2\,; \tag{1}$$

where we note that R_S scales as

$$R_S \sim \Big[\frac{M_{BH}}{M_*^{\;2+\delta}}\Big]^{\frac{1}{1+\delta}}\,, \tag{2}$$

apart from an overall δ- and *author-dependent* numerical factor. This is due to the different expressions for the $4+\delta$ dimensional Schwarzschild radius used by the two sets of original authors GT and DL. Explicitly there are two different relationships employed between the $4+\delta$-dimensional Planck masses, $M_{GT,DL}$, and the associated Newton's constant, $G_{4+\delta}$: $M_{DL}^{2+\delta} = G_{4+\delta}^{-1}$, while $M_{GT}^{2+\delta} = (2\pi)^\delta/4\pi G_{4+\delta}$. Depending on how the input parameters are chosen, this numerical factor can turn out to be relatively important since it leads to a very different δ dependence for the BH production cross section in the two cases. In the DL case the δ-dependence of the numerical coefficient is rather weak whereas is it somewhat stronger in the GT analysis. For the same input value of M_{BH} one finds the ratio of the cross sections obtained by the two sets of authors to be

$$\frac{\hat{\sigma}_{GT}}{\hat{\sigma}_{DL}} = \Big[\frac{(2\pi)^\delta}{(4\pi)}\Big]^{\frac{2}{1+\delta}}\;\Big[\frac{M_{DL}^2}{M_{GT}^2}\Big]^{\frac{2+\delta}{1+\delta}}\,, \tag{3}$$

which is always greater than unity for $\delta \geq 2$ and grows as δ increases *if* one assumes $M_* = M_{GT} = M_{DL}$ as an input. When the differences in the definitions of the Planck scale are accounted for both cross sections lead to the *same* numerical result.

The approximate geometric subprocess cross section expression is claimed to hold by GT and DL when the ratio M_{BH}/M_* is "large", *i.e.*, when the system can be treated semi-classically and quantum gravitational effects are small; one may debate just what "large" really means, but it most likely means "at least a few". Certainly when M_{BH}/M_* is near unity one might expect stringy effects to become important and even the finite extent of the incoming partons associated with this stringy-ness would need to be considered.

In order to obtain the actual cross section at a collider one takes the geometric parton-level result, folds in the appropriate parton densities and integrates over the relevant kinematic variables. The resulting total cross section for BH with masses $\geq M_{BH}^{min}$ is then given by the expression

$$\sigma = \int_{M_{BH}^{min\;2}/s}^{1} d\tau \int_\tau^1 \frac{dx}{x}\sum_{ab} f_a(x) f_b(\tau/x)\;\hat{\sigma}(M_{BH})\,, \tag{4}$$

where we have summed over all possible pairs of initial state partons with their associated densities $f_i(x)$.

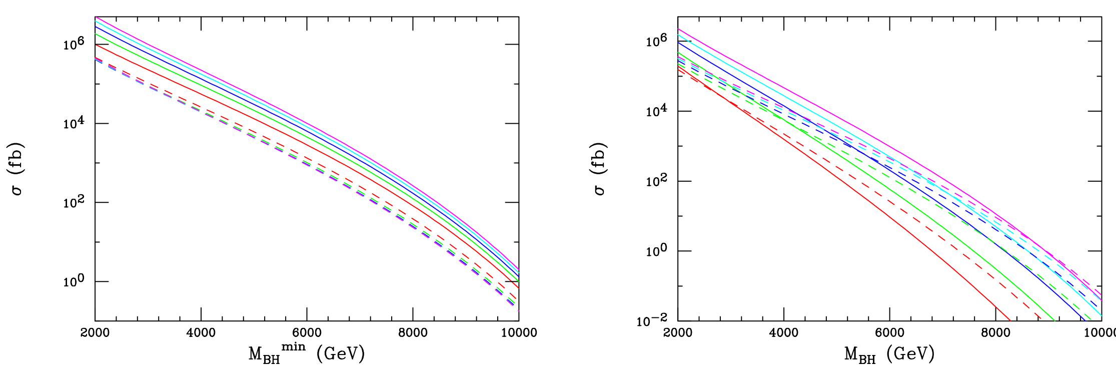

Figure 2: Same as the last figure but now for a larger value of the fundamental Planck scale, $M_* = 2$ TeV.

Voloshin has recently argued that an additional exponential suppression factor, S, is also present which seriously damps the pure geometric cross section for this process[5] even in the semi-classical case, *i.e.*, we should rescale $\hat{\sigma} \to S\hat{\sigma}$ in the equations above. Here S is given by

$$S = exp[-4\pi R_S M_{BH}/(1+\delta)(2+\delta)] \sim exp\Big[-C\Big(\frac{M_{BH}}{M_*}\Big)^{\frac{2+\delta}{1+\delta}}\Big]\,, \tag{5}$$

where C is a relatively small, though δ-dependent, constant. While this possibility remains controversial, and strong arguments have been made on either side of the argument, for purposes of this discussion we will assume this suppression is indeed present. (However, we warn the reader that the jury is still out on this issue. In either case we anxiously await the resolution of this important argument.) If Voloshin's criticisms of the geometrical cross section are valid one worries that the resulting exponentially suppressed rates for heavy BH production will possibly be too small to be observable at the LHC; as we will see below this need not be so.

Just how do the suppressed and unsuppressed cross sections at the LHC compare? As can be seen in Fig. 1 for the case $M_* = 1$ TeV, the unsuppressed rates for BH production at the LHC are quite large over a wide range of masses and numbers of extra dimensions using either set of authors' cross section expressions. (In this figure and the others below we appropriately identify M_* as either M_{GT} or M_{DL} depending on which set of predictions are being discussed.) Note that the results of Giddings and Thomas are always larger than those of Dimopoulos and Landsberg due to the different definitions used for the Planck scale and that the difference between the two sets of predictions increases as δ increases as discussed above. We also see that Fig. 1 shows the effects of the suppression predicted by Voloshin in the two cases. From these results we make the important observation that for at least for some ranges of parameters BH will still be produced at rates that are large enough to be observable at the LHC *even when the Voloshin suppression is active*. For example, assuming that $M_{BH}^{min} = 5$ TeV, we see that it is quite easy to have cross sections in the 100-1000 fb range. Although this is not a huge cross section the associated rates at the LHC will be quite large given an integrated luminosity of order 100 fb^{-1}/yr. Note that the suppression factor modifies the two sets of predictions in quite different manners due to the two different expressions used for R_S. Since $(R_S)_{GT} > (R_S)_{DL}$ for all $\delta \geq 2$, assuming the same input values for M_{GT} and M_{DL}, the GT results are found to be more suppressed than are those of DL.

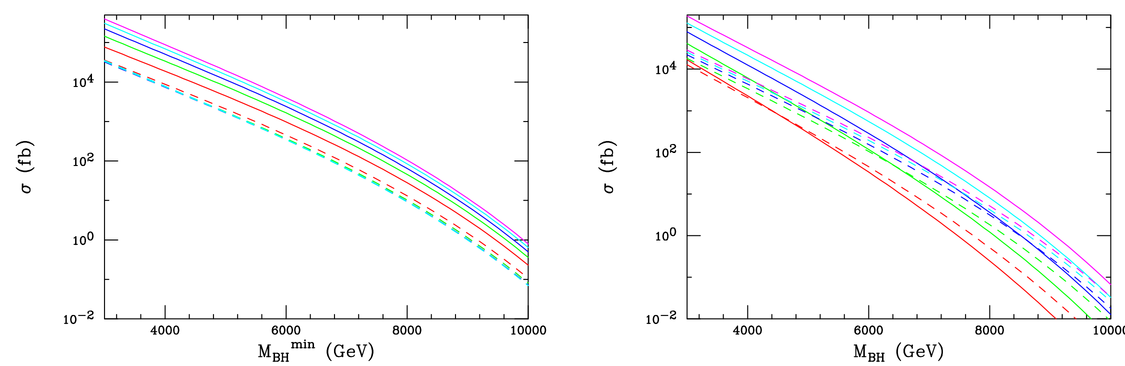

Figure 3: Same as the last figure but now for $M_* = 3$ TeV.

What happens as we vary M_*? Figs. 2 and 3 show the effects of increasing M_* from 1 TeV to 2 and 3 TeV. As expected the unsuppressed rates for any fixed value of M_{BH} decreases but we also see that the Voloshin suppression becomes less effective. This is also to be expected since the ratio M_{BH}/M_* in the exponent of the factor S has been decreased for fixed M_{BH}. Again we see that for BH in the 5-6 TeV range it is relatively likely that the production cross section can quite easily be in excess of 100 fb.

We remind the reader that once produced these BH essentially decay semi-classically, mostly on the brane, via Hawking radiation into a reasonably large number $\simeq 25$ or more final state partons in a highly spherical pattern. Hadrons will dominate over leptons by a factor of order 5-10 for such final states. These unusual signatures would not be missed at either hadron or lepton colliders. (We note that an alternative decay scenario has been advocated by Casadio and Harms[6].) These features are sufficiently unique that BH production above conventional backgrounds should be observable at the LHC even if the cross sections are substantially smaller than the original estimates.

We have examined the production of BH at the LHC assuming that the exponential suppression of the geometric cross section predicted by Voloshin is realized. We have found that even when this suppression is significant the resulting rates are still quite large for a wide range of model parameters given an integrated luminosity of order 100 fb^{-1}.

References

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