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Black hole production at the CERN LHC: String balls and black holes from pp and lead-lead collisions

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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 at the CERN LHC has been extensively studied for the case of a proton-proton collision. In this paper, we extend this analysis to a lead-lead collision at LHC. We find that the cross section for small black holes which may in principle be produced in such a collision is either enhanced or suppressed, depending upon the black hole mass. For example, for black holes with a mass around 3 TeV we find that the differential black hole production cross section, $d\sigma/dM$, in a typical lead-lead collision is up to 90 times larger than that for black holes produced in a typical proton-proton collision. We also discuss the cross sections for ''string ball'' production in these collisions. For string balls of mass about 1 (2) TeV, we find that the differential production cross section in a typical lead-lead collision may be enhanced by a factor up to 3300 (850) times that of a proton-proton collision at LHC.

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I. INTRODUCTION

It is now generally accepted that the scale of quantum gravity *could be* as low as a TeV [1]. If this is true, then we stand on the threshold of an exciting revolution in our understanding of quantum gravity and perhaps even string theory. One of the most exciting aspects of this revolution 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 several brane-world scenarios that provide for a low energy planck scale [1]. While the exact metrics describing black holes in brane-world scenarios are still largely unknown, considerable work on this issue is underway [2]. Furthermore, even without the exact metrics it is of course 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) collisions and cosmic ray events [3–16].

The principle aim of this paper is to extend the analysis of black hole production to include collisions involving heavy nuclei, such as lead or gold at very high energy. We also estimate the string ball production cross section both at a pp and PbPb collision at the CERN Large Hadron Collider (LHC). String balls are lighter than black holes and hence they should be produced in larger amounts at LHC.

At present the Relativistic Heavy Ion Collider (RHIC) at BNL collide two gold nuclei (to produce the ''quark-gluon plasma'' [17]) at $\sqrt{s^{NN}}=200$ GeV, which is insufficient to create any black hole of TeV scale mass. This is because to create a black hole of mass M_{BH} the minimum center of mass energy of two colliding partons must be greater than M_{BH} which is not the case at the RHIC energy. However, in future LHC will collide two lead nuclei at $\sqrt{s^{NN}}=5.5$ TeV. The total center of mass energy of this system is $5.5\times 208 = 1144$ TeV which is much larger than the 14 TeV at a pp collision at LHC. Hence, it is expected that many more black holes of mass less than 5.5 TeV will be produced in a Pb-Pb collision than in a pp collision.

Intuitively, this looks straightforward: A proton is a collection of partons, i.e., quarks and gluons. At high enough energy, a pp collision may cause some of the partons to have a high enough center-of-mass energy to form a black hole. Lead (at rest) consists of many protons and neutrons, and therefore at high energy collisions this system is just a larger aggregate of partons. Thus, we would expect to produce more small black holes in a lead-lead collision at $\sqrt{s^{NN}} = 5.5$ TeV at LHC. An interesting feature of a PbPb collision is that the string ball production is much more dominant than that in a pp collision.

Of course, one should address one point here: As the energy of the colliding partons is increased, the size of the black hole which is created may become large and it may absorb nearby partons. For a typical black hole formed at LHC ($M\sim$TeV) the rate at which the black hole can absorb nearby partons depends on the energy density of the quarks and gluons at LHC. The typical energy density of the quarks and gluons formed in PbPb collisions at LHC is of the order of 1000 GeV/fm^3 [21]. It follows that the absorption is not very large for a TeV scale black hole at LHC [22]. This is because the rate of evaporation for a TeV scale black hole is very large [23]. In PbPb collisions at LHC the evaporation rate of a black hole is much larger than the absorption rate, and hence a black hole will evaporate nearly instantaneously after its formation. In order for the black hole mass to be stable against decay, the energy density of the partons has to be very much larger than the achievable energy density of the partons at LHC. These issues will be addressed elsewhere [22].

II. BLACK HOLE AND STRING BALL PRODUCTION IN *pp* AND PbPb COLLISIONS

The black hole (string ball) production cross section $\sigma_{BH}(\sigma_{SB})$ at high energy hadronic collisions at zero impact parameter is given by [4]

$$\frac{d\sigma^{AB\to BH(SB)+X}(s)}{dM^2}=\sum_{ab}\int_\tau^1 dx_a\int_{\tau/x_a}^1 dx_b \times f_{a/A}(x_a,Q^2)f_{b/B}(x_b,Q^2) \times\hat{\sigma}^{ab\to BH(SB)}(\hat{s})\,\delta(\hat{s}-M^2). \quad (1)$$

In the above expression $x_a(x_b)$ is the longitudinal momentum fraction of the parton inside the hadron A(B) and $\tau=M^2/s$, with $\sqrt{s}$ being the NN center of mass energy. Energy-momentum conservation implies $\hat{s}=x_a x_b s=M^2$, where M is the mass of the black hole or string ball. Using the above relation we get

$$\sigma^{AB\to BH(SB)+X}(s)=\sum_{ab}\frac{1}{s}\int_{M^2>M^2_{min}} dM^2\int_\tau^1\frac{dx_a}{x_a} \times f_{a/A}(x_a,Q^2)f_{b/B}(\tau/x_a,Q^2) \times\hat{\sigma}^{ab\to BH(SB)}(\hat{s}). \quad (2)$$

$Q^2=M^2$ is the scale at which the parton distribution function is measured. M_{min} is the minimum mass of the black hole (string ball) above which the total cross section is computed. Σ_{ab} represents sum over all partonic combinations [5]. The black hole (string ball) production cross sections in a binary partonic collision are given by [4,18]

$$\hat{\sigma}^{ab\to BH}(\hat{s})=\frac{1}{M_P^2}\left[\frac{M_{BH}}{M_P}\left(\frac{8\Gamma\left(\frac{n+3}{2}\right)}{n+2}\right)\right]^{2/(n+1)}$$

$$\hat{\sigma}^{ab\to SB}(\hat{s})=\frac{1}{M_s^2}\quad \text{for}\quad M_s/g_s<M_{SB}<M_s/g_s^2$$

$$\hat{\sigma}^{ab\to SB}(\hat{s})=\frac{g_s^2M_{SB}^2}{M_s^4}\quad \text{for}\quad M_s<M_{SB}<M_s/g_s \quad (3)$$

where g_s is the string coupling strength, and M_s, M_P, M_{SB} and M_{BH} are the string mass scale, Planck mass scale, string ball mass and black hole mass respectively. n denotes the number of extra spatial dimensions.

For nuclear collisions at very high energy the calculation is similar to that of the minijet production in AA collisions at RHIC and LHC [20]. The parton distribution function inside a large nucleus is given by

$$R_{a/A}(x_a,Q^2)=\frac{f_{a/A}(x_a,Q^2)}{Af_{a/N}(x_a,Q^2)} \quad (4)$$

where $f_{a/A}(x_a,Q^2)$ and $f_{a/N}(x_a,Q^2)$ are the parton distribution functions inside the free nucleus and free nucleon respectively. The NMC and EMC experiments show that $R_{a/A}(x_a,Q^2)\neq 1$ for all values of x. In fact there is a strong shadowing effect $[R_{a/A}(x_a,Q^2)<1]$ for much smaller values of x $(x\ll 0.01)$. However, for black hole (string ball) production the shadowing effects should not be important. This is because we assume a minimum mass for the black hole (string ball) ~ 1 TeV, and we probe the minimum value of x at $x_{min}=M^2/s=1/(5.5\times 5.5)=0.033$ where there are no shadowing effects. Also the present parametrizations [24,25] for the ratio function $R_A(x,Q^2)$ do not cover the Q^2 range up to 1 TeV^2. For this reason we will consider the unshadowed parton distribution function $R_A(x,Q^2)=1$ in this paper, as there is no shadowing for $x_{min}=0.033$ at the TeV mass scale domain of black hole (string ball) production. One also does not have to worry about the saturation of parton distribution functions in PbPb collisions at LHC. This is because saturation happens at a very low value of x (equivalent to $Q\sim 2$ GeV at $\sqrt{s^{NN}}=5.5$ TeV PbPb collisions [26]) which is much less than our minimum value $x_{min}=0.033$. Hence for black hole (or string ball) production of TeV mass scale one does not need to worry about both shadowing and saturation at LHC.

III. BLACK HOLE AND STRING BALL PRODUCTION CROSS SECTIONS AT LHC: A COMPARISON WITH *pp* COLLISIONS

In this section we compute the cross sections for black hole (string ball) production at LHC for a PbPb and *pp* collision. We use the recent parton distribution function set CTEQ6M [27] in our calculation which is the more advanced version of CTEQ5 [28]. The scale Q at which the parton distribution is determined in our study lies within the allowed range for this PDF set. For black hole production we take $n=4$ throughout our calculation. The dependence of cross section on n is very weak [4]. In Fig. 1(a) we present the differential cross section for black hole production in a pp collision and in Fig. 1(b) we present the corresponding results for a PbPb collision at LHC. Clearly, the cross section for black hole production at lower mass is much enhanced in a PbPb collision over that in a pp collision: The differential cross section is approximately 3300 (90) times larger for black holes of mass 1 (3) TeV. Of course, the GR approximation fails at a mass scale that is typically larger than the Planck scale, since the minimum mass at which a black hole

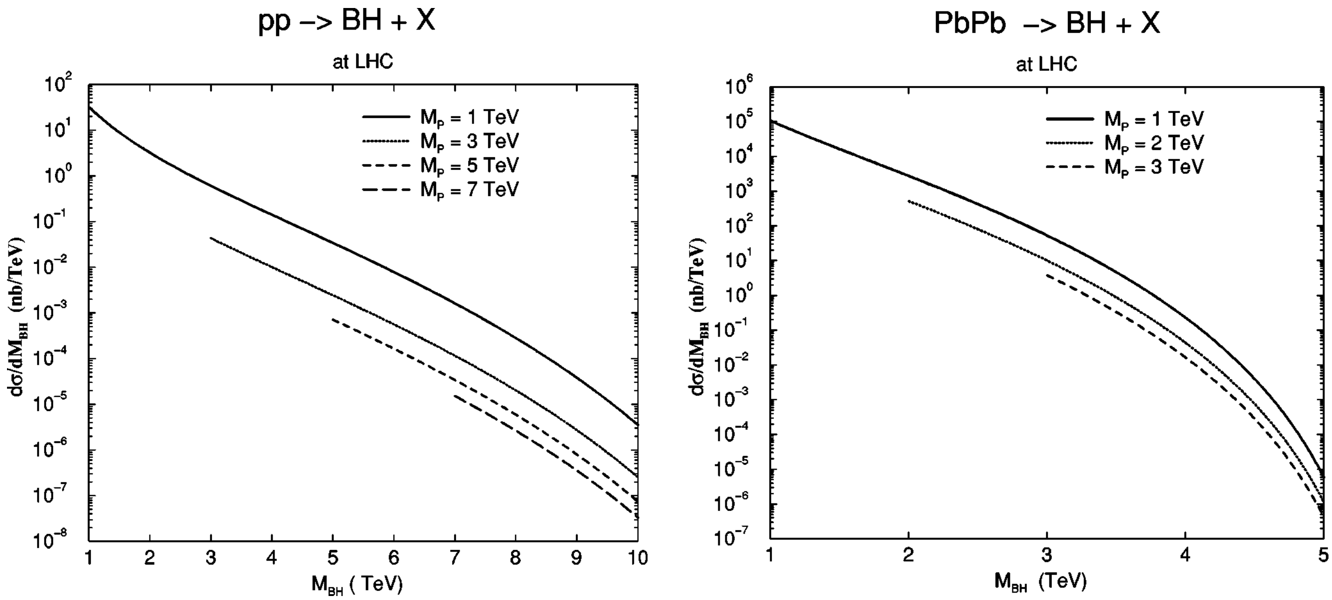

FIG. 1. (a) The differential cross section for black hole production $d\sigma/dM_{BH}$ in a pp collision at $\sqrt{s}^{NN}=14$ TeV at LHC. (b) The differential cross section for black hole production $d\sigma/dM_{BH}$ in a PbPb collision at $\sqrt{s}^{NN}=5.5$ TeV at LHC.

can be treated general-relativistically is around M_s/g_s^2, and in order to trust perturbative string theory the string coupling must be less than 1. Thus, it is unclear that it even makes sense to talk about black holes with a mass scale right at the string scale of 1 TeV, unless of course we are actually at strong coupling—a point to which we shall return in the conclusions.

On the other hand, the cross section is much smaller for higher mass black hole production in PbPb collisions because the maximum center of mass energy available in a binary parton collision is 5.5 TeV. As a pp collision is at 14 TeV c.m. energy, more larger mass black holes are produced at this experiment. If one is trying to produce black holes with masses ~ 5 TeV then pp collisions at LHC constitute a good black hole production factory.

In string theory, it is now well understood [18] that in the lower mass range it does not make sense to talk about black holes, but instead we encounter new and exotic objects known as ''string balls.'' Crudely, these are highly excited, long strings which decay through evaporation at the Hagedorn temperature. We will present the results for the string ball production cross section using Eq. (1) along with the

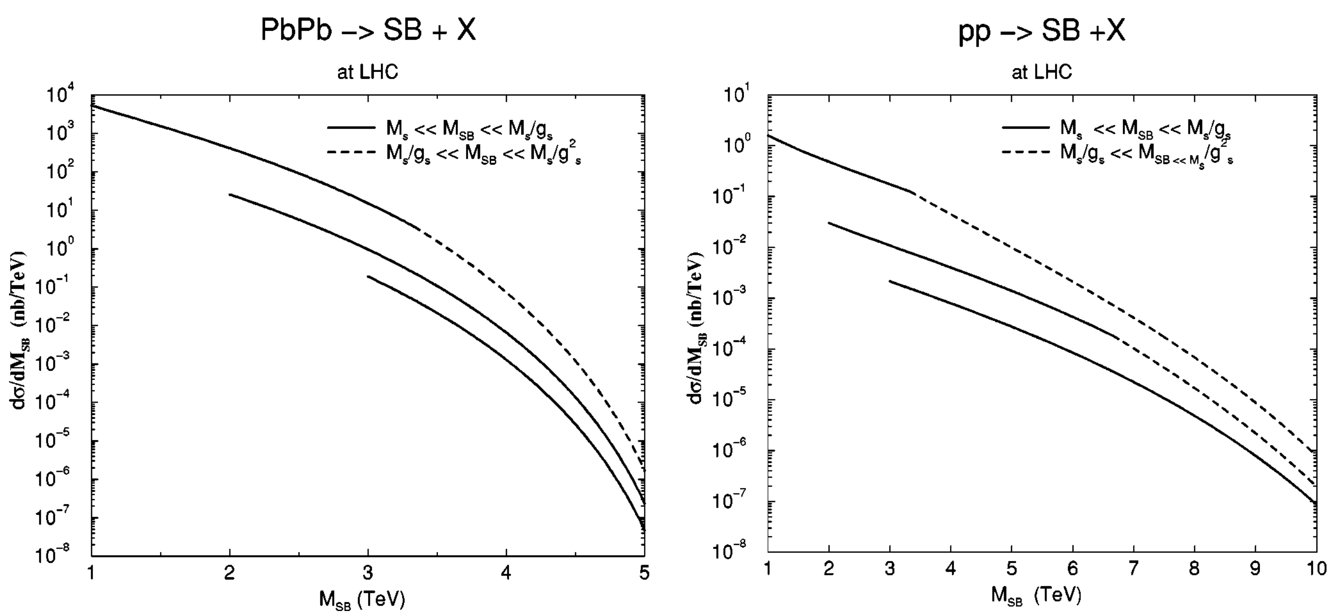

FIG. 2. (a) The differential cross section for string ball production $d\sigma/dM_{SB}$ in a pp collision at $\sqrt{s}^{NN}=14$ TeV at LHC. Three curves correspond to three different values of M_s used, as discussed in the text. $g_s=0.3$ is used in the calculation. (b) The differential cross section for string ball production $d\sigma/dM_{SB}$ in a PbPb collision at $\sqrt{s}^{NN}=5.5$ TeV at LHC. Other parameters are the same as in (a).

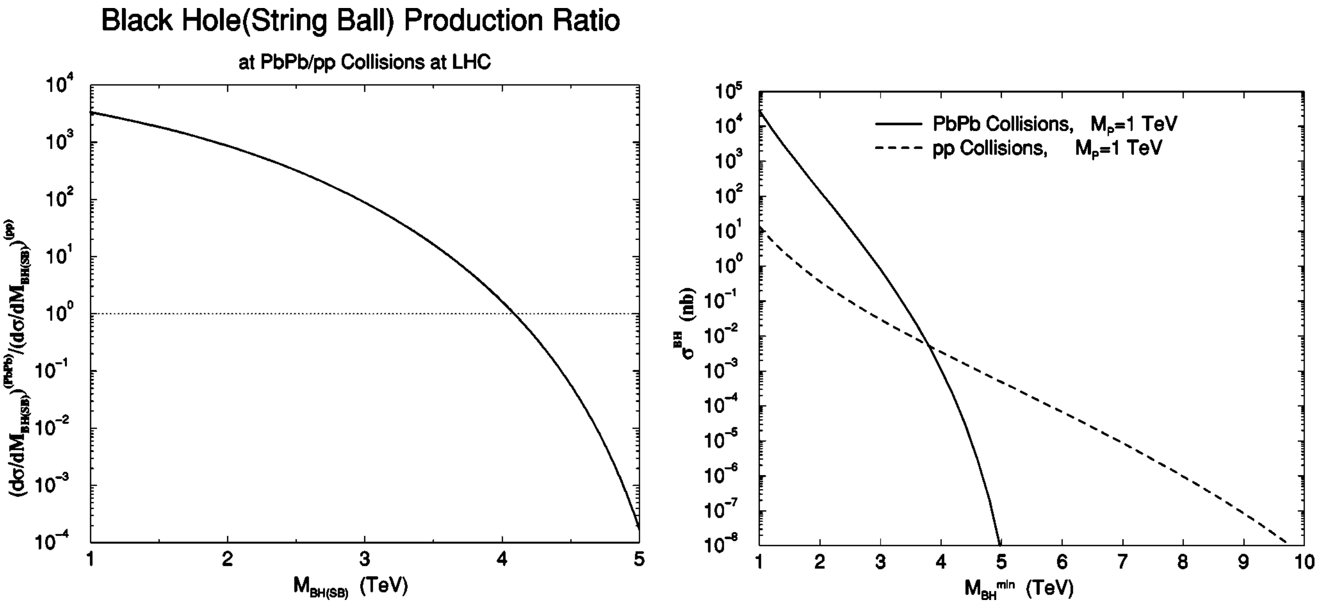

FIG. 3. (a) Ratio of the black hole (string ball) production in a PbPb/pp collision at LHC as a function of black hole (string ball) mass. (b) The total cross section for black hole production in a pp collision at $\sqrt{s^{NN}}=14$ TeV at LHC and in a PbPb collision at $\sqrt{s^{NN}}=5.5$ TeV at LHC.

second and third expressions of Eq. (3). In Fig. 2a(2b) we present the differential cross sections for string ball production for pp (PbPb) colliisons at LHC. We have chosen $g_s=0.3$ in our calculations. In Fig. 2 the upper (middle(lower)) line corresponds to $M_s=1(2(3))$ TeV respectively. For any other values of g_s^2 our results can be multiplied by an appropriate factor which is evident from third expression of Eq. (3). It should be mentioned that for weak string coupling $g_s \ll 1$ the string ball production cross section decreases and there is no black hole production as is evident from the fact that more black holes are produced in the strong coupling limit. We also note that the differential cross section for string ball production is approximately 3300, 850, 90 times larger for string balls of mass 1, 2, 3 TeV respectively in a PbPb collision than in a pp collision at LHC. The ratio of the differential cross sections for black hole production in a PbPb collision to that in a pp collision at LHC is the same as that of string ball production. This is plotted in Fig. 3a as a function of string ball (black hole) mass. Finally we predict the total cross section from Eq. (2) by doing a Monte Carlo integration. We find that the cross sections are about 14, respectively 28000 (nb), in a *pp*, respectively PbPb, collision which produces at least 1 TeV black holes. In Fig. 3b we present the total black hole production cross section in pp and PbPb collisions at LHC above different values of minimum black hole mass with $M_P=1$ TeV. Note that the σ^{PbPb} we obtain here is not simply equal to A^2 times σ^{pp}, since the PbPb collisions are at $\sqrt{s^{NN}}=5.5$ TeV, whereas the *pp* collisions are at $\sqrt{s^{NN}}=14$ TeV.

IV. CONCLUSION

If the fundamental planck scale is near a TeV, then parton collisions with high enough center-of-mass energy should produce black holes and string balls. Black hole production in a pp collision at LHC has been extensively studied in the literature. In this paper we have calculated the cross sections for black hole and string ball production at LHC in a PbPb collision at $\sqrt{s^{NN}}=5.5$ TeV. We have also computed the string ball production cross section for a pp collision at $\sqrt{s^{NN}}$ $=$ 14 TeV at LHC. We find that the cross section of small black holes which may in principle be produced in such collisions is either enhanced or suppressed, depending upon the black hole mass. For example, for black holes with a mass around 3 TeV we find that a typical lead-lead collision may produce up to 90 times the $d\sigma/dM$ of such black holes that would be produced in a typical proton-proton collision. For string balls of mass about 1, 2, 3 TeV we find that a typical lead-lead collision may produce up to 3300, 850, 90 times the $d\sigma/dM$ of such string balls that would be produced in a proton-proton collisions at LHC.

The key mass scale in this story is the minimum mass, M_s/g_s^2, at which it makes sense to talk about a black hole, and at which we see the transition to string balls. Obviously, this mass scale depends explicitly upon the string coupling. Furthermore, it has the intriguing property that we *lower* the mass scale for black holes as we run to stronger coupling. This is particularly interesting from the vantage point of recent ideas which are emerging in string cosmology. In particular, it has been suggested that several problems, including even the famous cosmological constant problem, may be resolved in scenarios where the dilaton or string coupling *runs to infinity* [19]. In such a scenario, it is clear that the string ball picture must break down, since we are in the strongly coupled regime or "M theory." Indeed, if string theory is strongly coupled, the window for string balls presumably disappears, and all massive "string" states will be black holes. This means that it may be possible to place strong experimental contraints on these cosmological models with a runaway dilaton, if we do *not* see black holes in collider experiments. Research on this and related issues is currently underway.

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[1] N. Arkani-Hamed, S. Dimopoulos, and G. Dvali, Phys. Lett. B **429**, 263 (1998); I. Antoniadis, N. Arkani-Hamed, S. Dimopoulos, and G. Dvali, *ibid.* **436**, 257 (1998); L. Randall and R. Sundrum, Phys. Rev. Lett. **83**, 3370 (1999); **83**, 4690 (1999).

[2] A. Chamblin, S.W. Hawking, and H.S. Reall, Phys. Rev. D **61**, 065007 (2000); R. Emparan, G.T. Horowitz, and R.C. Myers, J. High Energy Phys. **01**, 007 (2000); N. Dadhich, R. Maartens, P. Papadopoulos, and V. Rezania, Phys. Lett. B **487**, 1 (2000); A. Chamblin, H. Reall, H. Shinkai, and T. Shiromizu, Phys. Rev. D **63**, 064015 (2001); P. Kanti and K. Tamvakis, *ibid.* **65**, 084010 (2002); C. Germani and R. Maartens, *ibid.* **64**, 124010 (2001); I. Giannakis and H. Ren, *ibid.* **63**, 125017 (2001); R. Casadio and L. Mazzacurati, ‘‘Bulk shape of brane-world black holes,’’ gr-qc/0205129.

[3] T. Banks and W. Fischler, ‘‘A Model for High Energy Scattering in Quantum Gravity,’’ hep-th/9906038.

[4] S. Dimopoulos and G. Landsberg, Phys. Rev. Lett. **87**, 161602 (2001).

[5] S.B. Giddings and S. Thomas, Phys. Rev. D **65**, 056010 (2002).

[6] S.B. Giddings, in Proceedings of the APS/DPF/DPB Summer Study on the Future of Particle Physics, Snowmass, 2001, edited by R. Davidson and C. Quigg, hep-ph/0110127.

[7] D.M. Eardley and S.B. Giddings, Phys. Rev. D **66**, 044011 (2002).

[8] L. Anchordoqui and H. Goldberg, Phys. Rev. D **65**, 047502 (2002).

[9] R. Casadio and B. Harms, ‘‘Can black holes and naked singularities be detected in accelerators?,’’ hep-th/0110255.

[10] K. Cheung, Phys. Rev. D **66**, 036007 (2002); Phys. Rev. Lett. **88**, 221602 (2002); K. Cheung and Chung-Hsien Chou, Phys. Rev. D **66**, 036008 (2002).

[11] Y. Uehara, Mod. Phys. Lett. A **17**, 1551 (2002).

[12] Seong Chan Park and H.S. Song, ‘‘Production of Spinning Black Holes at colliders,’’ hep-ph/0111069.

[13] M. Bleicher, S. Hofmann, S. Hossenfelder, and H. Stöcker, ‘‘Black Hole Production in Large Extra Dimensions at the Tevatron: New Limit on the Fundamental Scale of Gravity,’’ hep-ph/0112186; S. Hossenfelder, S. Hofmann, M. Bleicher, and H. Stöcker, Phys. Rev. D **66**, 101502(R) (2002).

[14] J.L. Feng and A.D. Shapere, Phys. Rev. Lett. **88**, 021303 (2002).

[15] R. Emparan, M. Masip, and R. Rattazzi, Phys. Rev. D **65**, 064023 (2002).

[16] A. Ringwald and H. Tu, Phys. Lett. B **525**, 135 (2002).

[17] K. Geiger and J.I. Kapusta, Phys. Rev. D **47**, 4905 (1993); Phys. Rev. Lett. **70**, 1920 (1993); G.C. Nayak, J. High Energy Phys. **02**, 005 (1998); Phys. Lett. B **442**, 427 (1998).

[18] S. Dimopoulos and R. Emparan, Phys. Lett. B **526**, 393 (2002).

[19] T. Damour, F. Piazza, and G. Veneziano, Phys. Rev. Lett. **89**, 081601 (2002); A. Chamblin and N. Lambert, Phys. Rev. D **65**, 066002 (2002).

[20] K.J. Eskola, K. Kajantie, and J. Lindfors, Nucl. Phys. **B323**, 37 (1989); K.J. Eskola and K. Kajantie, Z. Phys. C **75**, 515 (1997); K.J. Eskola and M. Gyulassy, Phys. Rev. C **47**, 2329 (1993).

[21] G.C. Nayak *et al.*, Nucl. Phys. **A687**, 457 (2001); K.J. Eskola, *ibid.* **A702**, 249 (2002) and references therein.

[22] A. Chamblin, F. Cooper, and G. C. Nayak, ‘‘Interaction of microscopic black holes with the quark-gluon plasma’’ (in preparation).

[23] R. Guedens, D. Clancy, and A.R. Liddle, Phys. Rev. D **66**, 043513 (2002) and references therein.

[24] K.J. Eskola *et al.*, Nucl. Phys. **B351**, 351 (1998); Eur. Phys. J. C **9**, 61 (1999).

[25] M. Hirai, S. Kumano, and M. Miyama, Phys. Rev. D **64**, 034003 (2001).

[26] A.H. Mueller, Nucl. Phys. **B572**, 227 (2000); K.J. Eskola *et al.*, *ibid.* **B570**, 379 (2000); L. McLerran and R. Venugopalan, Phys. Rev. D **49**, 2233 (1994); **49**, 3352 (1994); **50**, 2225 (1994).

[27] J. Pumplin *et al.*, J. High Energy Phys. **07**, 012 (2002).

[28] H.L. Lai *et al.*, Eur. Phys. J. C **12**, 375 (2000).