Black Holes in the Lab?

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Abstract

If TeV-scale gravity describes nature, black holes will be produced in particle accelerators, perhaps even with impressive rates at the Large Hadron Collider. Their decays, largely via the Hawking process, will be spectacular. Black holes also would be produced in cosmic ray collisions with our atmosphere, and their showers may be observable. Such a scenario means the end of our quest to understand the world at shorter distances, but may represent the beginning of the exploration of extra dimensions.

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Black holes are perhaps the most profoundly mysterious objects in physics. We have long pondered what happens at the core of a black hole. The answer likely involves radically new physics, including breakdown of space and time, and is still beyond the reach of current approaches to quantum gravity such as string theory. Moreover, Hawking's discovery of black hole radiance[1] and proposal that black holes violate quantum mechanics[2] has led us to the sharp paradox of black hole information, which drives at the very heart of the problem of reconciling quantum mechanics and gravity. There is no clear way out:[2] information loss associated with breakdown of quantum mechanics apparently leads to disastrous violations of energy conservation; information cannot escape a black hole without violating locality; and the third alternative, black hole remnants, lead to catastrophic instabilities. String theorists have recently investigated the second alternative, via holography, but the jury is still out as no one has managed to understand how holographic theories can reproduce the approximately local physics that we see in our everyday world.

Experimental clues to the physics of black hole decay would be welcome. Unfortunately, manufacture of microscopic black holes apparently requires scattering energies above the four-dimensional Planck mass, $M_4 \sim 10^{19}$ GeV, placing this possibility far in our future.

However, recently there has been a revolution in thinking about the relationship between the Planck scale and the weak scale, $M_W \sim 1\text{TeV}$. The longstanding "hierarchy problem" is to explain the large ratio of these; one would naturally expect $M_W \sim M_4$. The new idea is that the weak scale and the *fundamental* Planck scale, M_P, are indeed the same size, but four-dimensional gravity is weak (hence M_4 is large) due to dilution of gravity in large or warped extra dimensions.

Specifically, for a general Poincaré-invariant metric

$$ds^2 = e^{2A(y)} dx^{\mu 2} + g_{mn}(y) dy^m dy^n \ , \tag{1}$$

where x^μ are the four dimensions we see, y^m are the extra n dimensions, and the function $A(y)$ is the *warp factor*, M_4 is given by

$$\frac{M_4^2}{M_P^2} = M_P^n \int d^n y \sqrt{g} e^{2A} \ . \tag{2}$$

Either large volume or large A produce a big ratio between M_P and the observed Planck scale. The hierarchy problem morphs into that of explaining why the extra dimensions are large, or highly warped. For $n = 2$–6 their size ranges from $mm - fm$. This presents a conflict with precision measurements of the gauge forces which have now reached the scale of $10^{-3} fm$, but we are saved by the brane world idea, which follows naturally from string theory: gauge forces, corresponding to open strings, propagate on a brane within the extra dimensions, whereas gravity, which is always transmitted by closed strings, propagates in all of the dimensions. Such scenarios go by the name "TeV-scale gravity."

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[2] For reviews, see [3, 4, 5, 6].

If TeV-scale gravity describes nature, the consequences are astounding. We will begin to explore quantum gravity, and possibly string theory, at accelerators in the relatively near future. Indeed, model independent bounds based on present experiments merely indicate $M_P \gtrsim 800\mathrm{GeV}$; TeV-scale gravity could be the physics of the Large Hadron Collider (LHC).

The most generic and spectacular result of such a scenario would be the production of black holes in particle accelerators[7, 8]. LHC will collide protons, which are aggregates of partons (quarks and gluons). If $M_P \sim \mathcal{O}(TeV)$, then parton collisions with significantly higher center-of-mass energy E should produce black holes; we consider $E \gtrsim 5M_P$, such that the Bekenstein-Hawking entropy $S_{BH} \gtrsim 25$ (for $n = 6$) in order to ensure that these are close to having a classical description. In TeV-gravity/brane world scenarios, there are two other important approximations. The first is that the gravitational field of the brane can be neglected, and is valid for black holes heavy compared to M_P, and the second is to consider black holes small as compared to the scales of the extra dimensions. We may then effectively discuss black holes in $4 + n$ dimensional flat space, as studied in [9].

The first question in these scenarios concerns the production rate for black holes. Two ingredients are needed: the parton density in a proton, which is approximately known, and the cross-section for two partons to form a black hole, which is not. This cross-section may, however, be estimated. Arguments along the lines of Thorne's hoop conjecture indicate that a black hole forms when partons collide at impact parameter b that is less than the Schwarzschild radius r_h corresponding to E. This would suggest a parton-parton cross-section of the form

$$\sigma \sim r_h^2(E) \sim E^{\frac{1}{n+1}} \ . \tag{3}$$

However, until now the high-energy gravitational collision problem has been little studied. In 1974, Penrose[10] argued that black holes form in zero impact parameter collisions, and this work was extended by D'Eath and Payne[11, 12, 13], but the problem at non-zero b had not been systematically treated. In [14], Doug Eardley and I recently revisited this problem, and in particular showed that in four dimensions, a trapped surface forms in collisions with impact parameter $b \lesssim 1.6E$, very close to the naïve expectation of $b \lesssim 2E$. Furthermore, in higher dimensions we reduced the problem of finding a trapped surface to a higher-dimensional analog of the Plateau problem, which we expect to have a solution – work on this continues.

Using the estimate (3), one readily finds an impressive result: for $M_P \sim 1$ TeV, the LHC will produce black holes with masses larger than $5M_P$ at the rate of about one per second[7, 8]. This would qualify LHC to be called a black hole factory.

Black holes will then decay leaving spectacular signatures. The first stage of their decay is purely classical, and involves the rather asymmetric initial black hole settling down to a hairless spinning black hole, radiating its multipole moments. We call this stage "balding." An important open problem is to determine how much energy is left in the black hole at the end of this stage; rough estimates based on the size of the initial trapped surface – which can only grow – and extrapolation of [11, 12, 13] suggest that this energy is around $15 - 40\%$ of the initial energy E. We hope that improvement of numerical relativity or perturbation methods eventually give us a better characterization of this stage.

Hawking's calculation then becomes relevant. As in the decay of four-dimensional black holes, one expects the black hole to first shed its spin, radiating particles preferentially in the equatorial plane, in a "spin-down" phase. Extrapolation of Page's four-dimensional results[15, 16] suggest a mass loss of perhaps 25% in spin-down. An important problem is to redo Page's analysis in the higher-dimensional setting.

Spin-down leaves a Schwarzschild black hole which continues to evaporate through the "Schwarzschild phase." The instantaneous energy distribution is thermal, and may be integrated to find an overall spectrum. This phase should represent perhaps 75% of the black hole decay energy.

When the black hole reaches the Planck size, we confront the profound mystery we began with: what effects govern the final decay, what do they tell us about the nature of quantum gravity, and what happens to information? Exploration of this "Planck phase" is beyond present theoretical technology, which makes the prospect of experimental results all the more tantalizing.

Products of these stages should stand out in accelerators[7, 8]. In particular, a black hole should produce of order S_{BH} energetic primary particles – leptons, quarks, gluons, *etc.* – in its Schwarzschild phase. These will be radiated roughly isotropically, with characteristic spectra and species ratios, as predicted by Hawking's calculations and numerical extensions. These events should not be masked by backgrounds from any known extrapolation of the standard model – they are very unique.

This scenario has other interesting consequences. First, we know that cosmic rays hit our atmosphere with center-of-mass energies exceeding energies accessible at LHC: if TeV-scale gravity is correct, black hole events have peppered our upper atmosphere throughout earth's history. If ultrahigh-energy neutrino cosmic ray fluxes are sufficiently strong, these events may even be observable in the next round of cosmic ray observatories[17, 18, 19, 20, 21].

It also appears likely that, through the AdS/CFT correspondence, relativists might tell particle theorists something about QCD. I have recently argued[22] that black hole formation or other strong gravity effects in anti-de Sitter space are dual to the physics that saturates the Froissart bound for hadron cross-sections

$$\sigma \sim \ln^2 E \ . \tag{4}$$

Important questions remain regarding the structure and stability of such black holes.

Finally, consequences for the future of high energy physics are profound. Humanity has pursued a longstanding quest to understand physics at shorter and shorter distances. In quantum gravity we don't know that distances shorter than the Planck scale exist, but this is a question that should be addressed experimentally. However, once we start making black holes this appears impossible. Any attempt at collisions that can probe shorter distances will be cloaked inside an event horizon, and all that will be seen in our detectors is the products of the black hole decay – there is apparently no way to directly observe the short-distance physics taking place inside the black hole. Black hole production represents the end of short-distance physics. However, it doesn't necessarily spell a dismal future for high-energy experiments. As we produce bigger black holes, they reach off the brane that is our world and offer us a way to explore the geometry and other features of the extra dimensions. High energy physics can become the study of the geography of extra dimensions.

References

[1] S. W. Hawking, "Particle Creation By Black Holes," Commun. Math. Phys. **43**, 199 (1975).

[2] S. W. Hawking, "Breakdown Of Predictability In Gravitational Collapse," Phys. Rev. D **14**, 2460 (1976).

[3] S. B. Giddings, "The Black hole information paradox," arXiv:hep-th/9508151.

[4] A. Strominger, "Les Houches lectures on black holes," arXiv:hep-th/9501071.

[5] S. B. Giddings, "Quantum mechanics of black holes," arXiv:hep-th/9412138.

[6] G. 't Hooft, "Black Holes, Hawking Radiation, And The Information Paradox," Nucl. Phys. Proc. Suppl. **43**, 1 (1995).

[7] S. B. Giddings and S. Thomas, "High energy colliders as black hole factories: The end of short distance physics," Phys. Rev. D **65**, 056010 (2002) [arXiv:hep-ph/0106219].

[8] S. Dimopoulos and G. Landsberg, "Black holes at the LHC," Phys. Rev. Lett. **87**, 161602 (2001) [arXiv:hep-ph/0106295].

[9] R. C. Myers and M. J. Perry, "Black Holes In Higher Dimensional Space-Times," Annals Phys. **172**, 304 (1986).

[10] R.Penrose *unpublished* (1974).

[11] P. D. D'Eath and P. N. Payne, "Gravitational Radiation In High Speed Black Hole Collisions. 1. Perturbation Treatment Of The Axisymmetric Speed Of Light Collision," Phys. Rev. D **46**, 658 (1992).

[12] P. D. D'Eath and P. N. Payne, "Gravitational Radiation In High Speed Black Hole Collisions. 2. Reduction To Two Independent Variables And Calculation Of The Second Order News Function," Phys. Rev. D **46**, 675 (1992).

[13] P. D. D'Eath and P. N. Payne, "Gravitational Radiation In High Speed Black Hole Collisions. 3. Results And Conclusions," Phys. Rev. D **46**, 694 (1992).

[14] D. M. Eardley and S. B. Giddings, "Classical black hole production in high-energy collisions," arXiv:gr-qc/0201034.

[15] D. N. Page, "Particle Emission Rates From A Black Hole: Massless Particles From An Uncharged, Nonrotating Hole," Phys. Rev. D **13**, 198 (1976).

[16] D. N. Page, "Particle Emission Rates From A Black Hole. II. Massless Particles From A Rotating Hole," Phys. Rev. D **14**, 3260 (1976).

[17] J. L. Feng and A. D. Shapere, "Black hole production by cosmic rays," arXiv:hep-ph/0109106.

[18] L. Anchordoqui and H. Goldberg, "Experimental signature for black hole production in neutrino air showers," arXiv:hep-ph/0109242.

[19] R. Emparan, M. Masip and R. Rattazzi, "Cosmic rays as probes of large extra dimensions and TeV gravity," arXiv:hep-ph/0109287.

[20] S. B. Giddings, "Black hole production in TeV-scale gravity, and the future of high energy physics," in *Proc. of the APS/DPF/DPB Summer Study on the Future of Particle Physics (Snowmass 2001)* ed. R. Davidson and C. Quigg, arXiv:hep-ph/0110127.

[21] A. Ringwald and H. Tu, "Collider versus cosmic ray sensitivity to black hole production," Phys. Lett. B **525**, 135 (2002) [arXiv:hep-ph/0111042].

[22] S. B. Giddings, "High energy QCD scattering, the shape of gravity on an IR brane, and the Froissart bound," arXiv:hep-th/0203004.