Black Hole Production in TeV-Scale Gravity, and the Future of High Energy Physics

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If the Planck scale is near a TeV, black hole production should be possible at colliders, as well as by cosmic rays. I begin with a review of the two approaches to TeV-scale gravity, large extra dimensions and warped compactification, presented in a unified framework. Then properties of such black holes and estimates of their production rates are given, and consequences for the future of high-energy experimental physics are discussed.

1. Introduction

The two most important – and mysterious – scales in physics are the Planck scale, $G_N^{-1/2} \simeq 10^{19}$ GeV, and the weak scale, $G_F^{-1/2} \simeq 300$ GeV. The hierarchy problem is the problem of explaining the large disparity between these scales. In traditional scenarios, the Planck scale is fundamental, and the weak scale is derived from it via some dynamical mechanism. However, we have recently begun exploring an alternative viewpoint: *the weak scale is the fundamental scale of nature, and the four-dimensional Planck scale is to be derived from that.* Ingredients in constructing such a scenario include large or warped extra dimensions, propagation of matter and gauge degrees of freedom on brane worlds, and a *fundamental* Planck scale of $\mathcal{O}(TeV)$. I will use the generic name "TeV-scale gravity" (TeVG) for these scenarios.

If the fundamental Planck scale is $\mathcal{O}(TeV)$, we are at the threshold of a phenomenally exciting period in experimental physics. In particular, we might hope to observe experimentally strings, branes, Kaluza-Klein modes from the extra dimensions, and other quantum gravity phenomena. But most remarkably – and largely independent of one's beliefs about the ultimate nature of quantum gravity – we would be able to produce black holes[1, 2, 3]. Their production should be copious and would have outstanding signatures. It also appears to signal the end of our long quest to understand physics at shorter distances.

In these proceedings I'll review some of these developments. I'll begin with a rapid review of TeV-scale gravity scenarios and their associated theoretical challenges. This review will present the two scenarios for TeVG – large extra dimensions and warped compactification – in a unified framework perhaps not widely appreciated. I'll then discuss black holes in these scenarios, and their production in accelerators. High energy cosmic rays also may have sufficient energy to produce black holes, and I'll next summarize the corresponding expectations. This is followed by a discussion of the consequences of black hole production for the future of high energy physics. Lastly, following the HEPAP charge, I'll briefly address the implications of these possibilities for our future strategy in experimental physics. I've tried to include references necessary for clarity; more complete references can be found in [2].

2. TeV scale gravity

Conventional compactification scenarios are now widely familiar. We imagine that in addition to the four spacetime dimensions we see, with coordinates x^μ, there are $D-4$ unseen dimensions with coordinates y^m. The full D-dimensional metric takes the form

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

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where the characteristic size of the extra dimensions is $\mathcal{O}(l_{Planck})$, explaining their invisibility.

There is an important generalization of this that respects the (approximate) 4d Poincaré invariance that we observe in nature: the scale of the four-dimensional metric may vary depending on location in the extra dimension,

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

for some function $A(y)$. Such a metric is known as a *warped metric*, and the factor $\exp\{2A\}$, which can alternately be thought of as giving a position-dependent red shift, is known as a *warp factor*.

Given such a warped compactification, we would like to understand the observed strength of 4d gravity. Suppose that fundamental physics has an effective action

$$S = \frac{1}{8\pi G_D} \int d^D x \sqrt{-g} \, \frac{1}{2}\mathcal{R} + \int d^D x \sqrt{-g}\mathcal{L} \tag{3}$$

where G_D is the gravitational constant, $\mathcal{R}$ is the curvature scalar, and $\mathcal{L}$ is the lagrangian for non-gravitational fields. For the Planck mass we will use a convention useful in comparing to experimental bounds[4] (for further discussion comparing conventions see the appendix):

$$M_p^{D-2} = \frac{(2\pi)^{D-4}}{4\pi G_D} \, . \tag{4}$$

If the metric (2) satisfies the equations of motion derived from (3), then four-dimensional metric fluctuations, with metric of the form

$$ds^2 = e^{2A(y)}g_{\mu\nu}(x)dx^\mu dx^\nu + g_{mn}(y)dy^m dy^n \, , \tag{5}$$

are governed by the 4d action

$$S_4 = \frac{M_4^2}{4} \int d^4 x \sqrt{-g_4(x)}\mathcal{R}_4 \tag{6}$$

with the four- and D-dimensional Planck masses related by

$$\frac{M_4^2}{M_p^2} = M_p^{D-4} \int \frac{d^{D-4}y}{(2\pi)^{D-4}} \sqrt{g_{D-4}}e^{2A} \equiv M_p^{D-4}V_w \, . \tag{7}$$

This equation defines the "warped volume" V_w.

Eq. (7) is key to understanding the relationship between different scenarios. There are two obvious possibilities:

1. Conventional small-scale compactification: $M_p \sim M_4 \sim 10^{19}GeV$, and $V_w \sim 1/M_p^{D-4}$.

2. TeV-scale gravity scenario: $M_p \sim 1$ TeV, which then requires $V_w \gg 1/M_p^{D-4}$.

There are two basic kinds of schemes to achieve a large warped volume. The first is the scenario of Arkani-Hamed, Dimopoulos, and Dvali[5], which imagines negligible warping, $e^A \approx 1$, and simply large volume, $M_p^{D-4}V_{D-4} \gg 1$. The size of the extra dimensions then ranges from $\mathcal{O}(mm)$ for $D = 6$ to $\mathcal{O}(10\,fm)$ for $D = 10$. However, gauge interactions have been well tested, with no evidence of extra dimensions, to around 100 GeV. These statements can be reconciled by noting that string theory provides a natural mechanism for gauge interactions to operate in a lower-dimensional arena: they can propagate on a D-brane. So the picture is that of large extra dimensions in which only gravity propagates, and a typically three-dimensional D-brane on which fermions and gauge bosons propagate.

The second scheme is based on large warp factor, with gauge and matter fields propagating on branes as in the ADD scenario[5]. A general class of string solutions with requisite warp factor have been found in [6] and were discussed in Kachru's talk; toy models with some of the basic features appear in the work of Randall and Sundrum[7]. See fig. 1.

Specifically, the gravitational action in (3) has a "symmetry" corresponding to a global choice of scale:

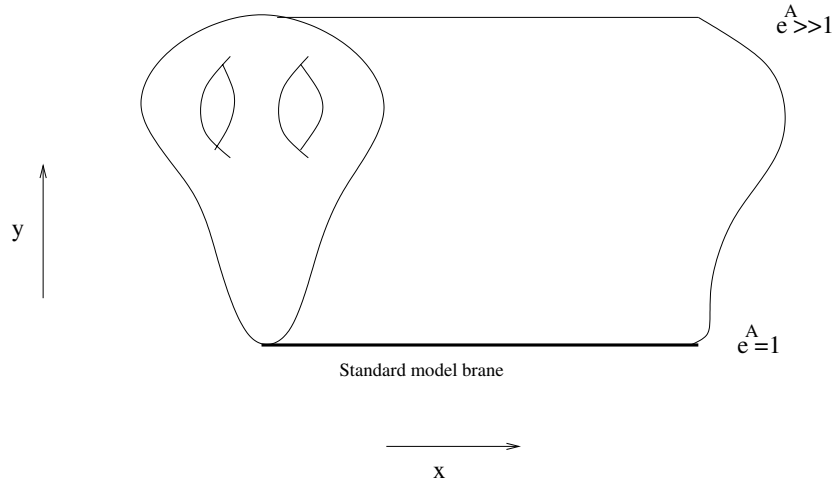$$g \to \lambda^2 g \; ; \; M_p \to M_p/\lambda \tag{8}$$

Figure 1: Schematic of a warped compactification.

where g is the full D-dimensional metric, and with corresponding scalings of the matter fields and other dimensionful parameters. Since $g_{\mu\nu} = e^{2A}\eta_{\mu\nu}$, this may be used to set $e^A = 1$ at the brane where the standard model propagates. A large e^A elsewhere in the compact dimensions can then yield a large warped volume. This is precisely what happens in [6]. These models also break supersymmetry, and have vanishing cosmological constant at tree-level. They differ from the ADD models[5] in several important respects[8], most notably their Kaluza-Klein spectrum.

Clearly a critical question regards the likelihood that TeV-scale gravity is realized, in one of the above scenarios or in a completely different manner, in nature. The scenarios based on brane worlds and large/warped extra dimensions do face several challenges:

1. How does one obtain the standard model gauge group, $SU(3){\times}SU(2){\times}U(1)$, and the correct matter representations?

2. Why does such a model reproduce the relationship between the coupling constants that in traditional SUSY/GUT scenarios emerges from coupling unification?

3. Why is the proton stable?

4. How is the correct scale produced for neutrino masses?

5. What stabilizes moduli, such as the size of the extra dimensions?

6. What is the role of supersymmetry – is it for example in protecting the largeness of the extra-dimensions or warp factor? How is it broken?

7. How do we obtain a small cosmological constant?

Several of these are equally problematical for conventional SUSY/GUT scenarios, *e.g.* based on small-scale string compactification. However, so far TeVG scenarios face additional theoretical challenges such as 1)-4), and to some degree 6). There are, however, ideas that begin to address these, and moreover the space of of such models has been less explored than SUSY/GUT scenarios. It may be that further exploration reveals more natural solutions to these problems.

3. Black holes in brane-world scenarios

If TeV-scale gravity is realized in nature, production of black holes should be possible for $\sqrt{s} \gg 1$ TeV. Let's briefly consider their properties. We use two approximations. The first is that we initially assume that black hole radii are small as compared to the radii and curvature radii of the extra dimensions, and the scale on which the warp factor varies:
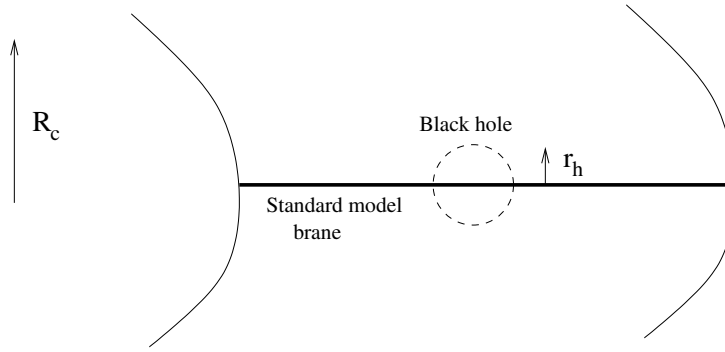
$$r_h \ll R_c , \qquad (9)$$

Figure 2: Shown is a black hole on a brane in a compactification with large or warped extra dimensions. We consider the approximation where the black hole size is small as compared to characteristic geometrical scales.

where R_c denotes a characteristic geometrical scale; see fig. 2. Secondly, the standard model brane has a tension and thus a gravitational field. However, we will consider black holes with masses typically larger than the tension, and so neglect the effects of this gravitational field[1]. These approximations mean we effectively consider black holes in D-dimensional flat spacetime. Furthermore, as we'll discuss, we are interested in spinning solutions. These higher dimensional spinning black hole solutions were given by Myers and Perry in [9], and are parametrized by their mass M and spin J. Other parameters are given in terms of these in [9]. In the $J = 0$ limit they take the form

$$r_h(M,J) \xrightarrow{J \to 0} 2 \left[\frac{\pi^{\frac{D-7}{2}} \Gamma\left(\frac{D-1}{2}\right)}{(D-2)} \frac{M}{M_p^{D-2}} \right]^{1/(D-3)} , \qquad (10)$$

for the radius,

$$T_H \xrightarrow{J \to 0} \frac{D-3}{4\pi r_h} \qquad (11)$$

for the Hawking temperature, and

$$S_{BH} = \xrightarrow{J \to 0} \frac{\pi^{(D-1)/2}}{2\Gamma\left(\frac{D-1}{2}\right)} \frac{r_h^{D-2}}{G_D} \qquad (12)$$

for the entropy.

A critical question is at what mass is the black hole description valid. In our conventions, the experimental bounds on the Planck mass in ADD scenarios from absence of missing energy signatures[4, 10, 11] are $M_p > 1.1$ TeV - .8 TeV for $D = 6 - 10$. Similar bounds appear in the RS toy models for warped compactifications[12]. In order to neglect quantum or classical (*e.g.* string) effects that strongly modify solutions, we must consider black holes at higher masses. The dominant quantum effect is the Hawking radiation, and criteria for this to be small include a lifetime long as compared to M^{-1}, or validity of the statistical description for the black hole. The latter is more stringent, and since S_{BH} parameterizes the number of degrees of freedom of the black hole, becomes

$$1 \gg \frac{1}{\sqrt{S_{BH}}} . \qquad (13)$$

For $M = 5M_p$, $1/\sqrt{S_{BH}} \sim 1/5$, and for $M = 10M_p$, $1/\sqrt{S_{BH}} \sim 1/8$, so we only trust a black hole description beginning in this range.

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[1] The authors of [5] neglect this effect entirely.

Classical modifications to gravity, such as string theory, can also be important. String effects are relevant for $M \sim g_s^{-7/4} M_p$, where g_s is the string coupling, and thus depend on the value of the coupling. Weaker couplings imply higher thresholds for black hole behavior. However, the string correspondence principle[13] states that the black hole spectrum matches onto the string spectrum for r_h of order the string scale, suggesting that a black hole description is essentially valid until this point.

4. Black hole production at accelerators

The energy frontier is at hadron machines, and in hadron scattering the black hole cross section is found from the partonic cross section for partons i and j to form a black hole:

$$\sigma_{pp \to bh}(M_{min}, s) = \sum_{ij} \int_{\tau_m}^1 d\tau \int_\tau^1 \frac{dx}{x} f_i(x) f_j(\tau/x) \sigma_{ij \to bh}(\tau s) . \qquad (14)$$

Here $\sqrt{s}$ is the collider center of mass energy, x and τ/x are the parton momentum fractions, and f_i are the parton distribution functions. Studies should include the parameter M_{min} corresponding to the minimum mass for a valid black hole description, and we define $\tau_m = M_{min}^2/s$.

To estimate the parton-level cross section, consider partons scattering at center of mass energy $\sqrt{s}$ and impact parameter b. A longstanding conjecture in relativity is Thorne's hoop conjecture[14], which states that horizons form when and only when a mass M is compacted into a region whose circumference in every direction is less than $2\pi r_h(M)$. This conjecture implies that the cross-section for black hole production is

$$\sigma_{ij \to bh}(s) \sim \pi r_h^2(\sqrt{s}) . \qquad (15)$$

Can we believe this conjecture? High-energy gravitational scattering has been studied at the classical level in four dimensions; in the symmetrical case of zero impact parameter, Penrose[15] has found an apparent horizon of area $\mathcal{A} = 8\pi s$, implying that a black hole of mass $M > \sqrt{s/2}$ forms. d'Eath and Payne[16, 17, 18] extended these results, arguing using a perturbative analysis that a black hole of mass $M \sim .84\sqrt{s}$ forms. The fact that big black holes form in on-axis collisions strongly indicates that black holes should form for impact parameters $b \lesssim r_h$, but clearly further study, which may have to be numerical, is desired.

The question of quantum corrections is also addressed by the presence of a large horizon. This in particular suggests that the curvature at the horizon is small. In the absence of strong curvature, a semiclassical treatment of gravity should be valid. The semiclassical approximation only appears to fail near the center of the black hole, long after a black hole has formed. These points can be illustrated in four dimensions by imagining a collision of partons with CM energy equal to the rest mass of the sun; here we'd expect a horizon of radius ~ 1 km to form, with weak curvature at the horizon. This buttresses the argument for (15).

The estimate (15) has been criticized by Voloshin in [19], where two objections are raised. The first is a suggestion that the calculation of the rate should include the exponential of minus the euclidean black hole action. However, this seems clearly incorrect: as described above, black hole formation is a *classically allowed* (in fact compulsory!) process. One ordinarily encounters the euclidean action only when studying amplitudes for quantum processes that are classically forbidden. The second objection involves an application of CPT to argue that since the decay $BH \to ij$ is small (thermally suppressed), the amplitude $ij \to BH$ should be small. This however neglects the fact that the black hole should have a number of distinct states. We can label these as α, and the statement that $\alpha \to ij$ is small CPT conjugates to the statement that $\bar{i}\bar{j} \to \bar{\alpha}$ is small. This does not mean that $ij \to \alpha$ is small; in particular, in classical gravity, the time reverse of a black hole is a white hole which is a very different state. Application of such state-counting arguments clearly requires an improved understanding of the description of the internal states of a black hole.

Another important point is that typically black holes are produced with large spin. This is because the cross-section is dominated by large impact parameters, so typically $J \sim r_h M$. This complicates study of the formation process, and in particular indications from other examples of

gravitational collapse with high angular momentum suggest the possibility of added complexities such as initially toroidal horizons[2]. The differential cross-section can be parametrized as

$$\frac{d\sigma_{ij}(s)}{dJdM} = F(s,J,M)\pi r_h^2 , \tag{16}$$

where further effort is required to compute the function F. However, we believe that the total cross-section can be approximated by (15).

We therefore estimate rates using (15) and the CTEQ5 structure functions[20][3]. The result is impressive. For example, assume a Planck mass $M_p = 1$ TeV, and consider LHC with $\sqrt{s} = 14$ TeV. If the minimum mass to produce true black holes is $M_{min} = 5$ TeV, they are produced with cross-section $\sim 2.4 \times 10^5$ fb and thus at a rate ~ 1 Hz. If 10 TeV is required to make a black hole, the cross section and rate are still respectable at 10 fb and 3/day. Looking further into the possible future, if VLHC were built at $\sqrt{s} = 100$ TeV and luminosity $100 fb^{-1}/yr$, 10 TeV black holes would be produced at $\sim kHz$ rates, and 50 TeV black holes at $\sim .5$ Hz. Notice that the cross section grows as

$$\sigma \sim s^{\frac{1}{D-3}} . \tag{17}$$

Thus at sufficiently high energies colliders inevitably become black hole factories, and ultimately black hole production becomes a dominant process. The critical question, depending on the value of the Planck scale, is what energy reach we require to begin to see these stunning developments. It is amusing to note that if we're lucky, colliders could beat LIGO to observation of black hole formation.

5. Black hole decays and signatures

Once produced, black holes decay primarily via Hawking radiation, and should yield events that stand out in detectors. These decays and their signatures were surveyed in Scott Thomas' talk, and are discussed in detail in [2], but I'll briefly summarize some of the most notable points here.

Black hole decay occurs in several stages, with different characteristic time-scales and energy spectra. When a black hole first forms in a high-energy collision, the horizon will be highly asymmetrical, and could even be topologically non-trivial. The black hole will then settle down to a symmetrical rotating black hole by emitting gauge and gravitational radiation. In the course of this emission, the horizon can only grow, by the area theorem. Since the final state of this phase is a black hole with no hair, we refer to this as the *balding* phase. The duration of this phase is expected to be $\mathcal{O}(r_h)$, and the characteristic frequency of the radiation emitted should be $\mathcal{O}(1/r_h)$. Based on the estimates of [16, 17, 18], in a head on collision one expects about 16% of CM energy of the partons to be emitted this way, with the likelihood of greater emission from balding at larger impact parameters.

The next phase is *spin down*. The black hole Hawking radiates, first shedding its angular momentum by preferentially emitting quanta with angular momenta $l \sim 1$. These quanta will have characteristic energies given by the Hawking temperature T_H at the time they are emitted. This process has been treated in detail for four-dimensional black holes by Page [21, 22]. Rough estimates based on this suggest that 25% of the black hole's energy is radiated in this phase, although Page's calculations should be redone in the higher-dimensional context.

Spin down leaves behind a Schwarzschild black hole, which then continues to Hawking radiate through what we call the *Schwarzschild phase*. Here again at a given instant quanta are emitted with a thermal spectrum at $\sim T_H$. As the black hole decays its temperature increases according to (11). The total spectrum of the decay products can be obtained by integrating the thermal spectrum over this evolution.

Once the black hole reaches a mass $M \sim M_p$, Hawking's calculations fail. We call this phase the *Planck phase*. One expects the final decay of the Planck phase to result in emission of a few quanta with energies $\mathcal{O}(M_p)$.

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[2]I thank Scott Hughes for conversations on this point.
[3]We thank T. Rizzo for performing these estimates.

These decays should be quite spectacular. In particular, black hole events should produce a large number, of order $S_{BH} \gtrsim 25$, of hard quanta, with energies approaching a sizeable fraction of 1 TeV. In particular, a substantial fraction of the beam energy is thereby deposited in visible transverse energy, in an event with high sphericity. Based on [21, 22], one can estimate that the ratio of hadronic to leptonic activity is around 5:1. (A more careful estimate based on a higher-dimensional version of the analysis of [21, 22] should be done.) Furthermore, it should ultimately be possible to determine the black hole spin axis by observing the characteristic dipole pattern from the spin-down phase. More detailed discussion of black hole signatures can be found in [2].

6. Black holes from cosmic rays

Physicists be warned: journalists regularly read our electronic archives! After [2] appeared, a journalist almost immediately asked me the question, what if Hawking's calculations are wrong, and black holes don't evaporate? Of course, we certainly believe that Hawking's calculations are correct, if not to the last detail, and furthermore on general quantum grounds black holes should decay – they are massive states with no conserved quantities to stabilize them. But further assurances are welcome.

For energies accessible in the foreseeable future, an answer comes from cosmic rays, which are observed up to lab energies 10^{11} GeV. They collide with protons in the atmosphere, and therefore probe CM energies up to $\sqrt{s} \sim 400$ TeV. So if accelerators can investigate black hole production, black holes are already being produced in the atmosphere; if this weren't a safe thing to do, we wouldn't be here to talk about it.

We might hope to observe these events at cosmic-ray observatories, and thus need rates. At ultra-high energies, it is uncertain what fraction of cosmic-ray primaries are nucleons versus heavy nuclei such as iron, and other constituents have not been conclusively ruled out. The most optimistic case for producing black holes is nucleons; otherwise the following estimates have to be readjusted to account for the distribution of the energy between the constituents of a nucleus. (This reduces the effective flux at a given pp CM energy.) Suppose for example $M_p = 1$ TeV and the black hole threshold is 10 TeV, and consider the cosmic ray flux at $\sqrt{s} \sim 40$ TeV (thus $E_{lab} \sim 10^{18} eV$). The results of [2] show that with these parameters the branching ratio for $pp \to BH$ is $\sim 3 \times 10^{-9}$, resulting in roughly 100 black holes produced over the surface of the earth in a year. The rates are too small to be observed because pp collisions are dominated by QCD processes.

This suggests that we consider cosmic rays with small standard-model cross sections, in particular neutrinos[23, 24, 25]. The ultra-high-energy neutrino flux is not known, but *if* the ultra-high energy cosmic ray primaries are dominantly protons, a lower bound is believed to follow from the observation that these protons should scatter off the microwave background, resonantly producing pions and hence neutrinos[26, 27, 28]. This is the physics behind the GZK bound. There may be other fluxes in addition to these Greisen neutrinos, due to active galactic nuclei or gamma ray bursts (for summaries, see [29, 30, 31]).

The cross section for $\nu p \to BH$ can also be estimated from (15) and the structure functions from an expression analogous to (14). This results[23, 24, 25] in cross-sections $\sigma \sim 10^6$ pb for $\sqrt{s} \sim 100$ TeV in the optimistic case of $M_p = 1$ TeV and minimum black hole mass 5 TeV.

The Greisen flux peaks at $\sqrt{s} \sim 100$ TeV, and combined with the above cross section, yields an estimated production rate

$$R \sim \frac{\text{several black holes}}{(\text{year})(km^3(we))} \tag{18}$$

where we denotes water equivalent. This appears above the threshold of detectability by the Hires Fly's Eye experiment, with acceptance $1 km^3(we)$, or the Auger detector, presently under construction, with acceptance $1 km^3(we)$ for its ground array; for the latter, such estimates give 6–17 events/yr for $D = 5$–10^4. (Some discussion of possible signatures of such events appears in [32].) Note, however, some caveats. First, there could well be a mild numerical suppression in

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[4]Note that [24] sets the Planck mass to 1 TeV in the conventions of [3], which in $D = 10$ corresponds to roughly

(15); for example, a factor $\mathcal{O}(1/10)$ is very significant in the cosmic ray context, but not in that of collider production. Second, the presence of a Greisen neutrino flux at this level relies on the assumption that charged cosmic ray primaries are protons, not nuclei.

Other planned detectors may be able to improve on this. The proposed upgrade to AMANDA, Icecube, instruments $1km^3(we)$ but faces issues in resolving ultra-high energy events; OWL/AirWatch has potential reach to $6 \times 10^4 km^3(we)$. And, of course, other components to the neutrino flux enhance the odds; for example, some models[33] of active galactic nuclei predict fluxes 10^5 times the Greisen flux, peaking around $\sqrt{s} = 10$ TeV.

It is also worth point out that if the Planck scale is beyond the reach of LHC or a linear collider, $M_p \gtrsim 6$ TeV, black hole events might nonetheless be observed in cosmic ray experiments with sufficient acceptance.

7. Consequences for high energy physics

We do not know the ultimate theory of quantum gravity, although a good guess is string theory. However, one thing seems clear: once we reach the threshold to produce black holes, it will be very difficult and likely impossible to probe shorter distances via high energy scattering.

Of course, the black-hole threshold is above the Planck mass, and it's widely believed that sub-planckian distances can't make sense in quantum gravity. But suppose that nevertheless shorter-distance physics did exist. Black hole production would then render it invisible. This is because we need to perform scattering at energies $\gg M_p$ in order to see such physics. However, at these energies, a large black hole will form, and cloak any hard process behind the horizon. All we see is that a black hole forms, and then evaporates via Hawking decay. For larger energies, we just get larger black holes. This is directly related to ideas about the infrared/ultraviolet connection that have been widely discussed in the theoretical literature.

Black hole production therefore represents the end of short distance physics. Fortunately, it is not the end of high energy physics. As we go to higher energies, the black holes that we make get larger and extend further into the extra dimensions. At some point they get large enough to run into other features of the extra dimensions. For example, they might encounter the finite radius of one of the dimensions, or finite curvature radii, or bump into other branes in the extra dimensions. As the black holes become large enough to detect these features, their cross-sections, decay rates, and decay spectra change. For example, once a black hole has a radius larger than that of one of the extra dimensions, or larger than a curvature radius in the extra dimensions, the effective dimension in the production cross-section (17) changes. By measuring kinks in the cross-section at larger energies, one can explore the extra dimensions. So high energy experiments will be used to study the geography of the extra dimensions.

8. Strategies for the future

If nature realizes TeV-scale gravity, we are at the threshold of a phenomenally exciting period of physics. We will finally be able to experimentally address the puzzles of quantum gravity, and we should start making black holes, close the frontier of short-distance physics, and instead begin exploration of the terra incognita of extra dimensions. At the same time experimental physics may reveal exciting discoveries such as strings, branes, or other exotica of a fundamental theory of gravity. What are the odds that gravity is realized this way, and what should we do to be sure we don't miss out on such a discovery?

An amusing exercise has been polling some (~ 10) of my fellow theorists to see what odds they would assign to the various possibilities once we understand the physics of the TeV scale. They were given the following four choices, and the range of odds given were: TeV-scale gravity 0-25%, SUSY 25-100%, just the standard model 0-30%, and none of the above (or other) 5-65%.

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three times the experimental bounds[4] – see appendix. Feng and Shapere also consider minimum black hole masses as low as 1 TeV, which in our conventions correspond to $M \sim M_p/3$ – far out of the range $M \gtrsim 5M_p$ where the black hole approximation is valid. The preceding improved estimate, provided by J. Feng, was recomputed with $M_p = 1$ TeV and $M_{min} = 5$ TeV.

Present theoretical wisdom clearly holds that the most likely discoveries at the TeV scale are the Higgs and supersymmetry. The case for this is buttressed by various indirect arguments, such as the apparent unification of couplings. If we review the theoretical issues for TeV-scale gravity scenarios discussed in section II, with our present state of knowledge it does appear more difficult for TeV-scale gravity to fit nature than supersymmetric grand unification to do so – though they both confront theoretical obstacles.

There are counterpoints to this. First, TeV-scale gravity is much younger and less explored – it may become more attractive if we gain deeper insight that leads to resolution of some of its difficulties. Secondly, let me define an index, along the lines of Gross' talk in the evening sessions, that may serve as a guide towards the importance of investigating a given scenario:

$$I = (\text{probability}) \cdot (\text{impact of discovery}) . \tag{19}$$

While the probabilities that people assign to TeV-scale gravity are substantially lower than just supersymmetry (and of course they are not mutually exclusive), the impact of discovering strong gravity at the TeV scale would be far greater.

What do we need to do to discover or rule out TeV-scale gravity? On the experimental side, LHC should give a bound[4, 34] $M_p \gtrsim 6$ TeV, and a linear collider would not appear to reach beyond[34]. On the theoretical side, the possibility that $M_p > 6$ TeV seems like a definite possibility, but clearly more theoretical understanding of these scenarios is needed.

So what is a reasonable experimental course of action? Since supersymmetry is the best bet and a linear collider will likely be crucial in exploring it, building a linear collider seems like a good next step, and supplies an alternative approach to placing bounds on TeVG[34]. However, the much more spectacular scenario of strong gravitational physics (or something more bizarre) lying somewhere not far above a TeV is a definite possibility. We should hedge our bets, certainly by continued theoretical exploration of these scenarios. But more importantly, we should actively continue to pursue long range plans that will allow us to push the energy frontier beyond that explored by LHC.

Acknowledgments

: Appendix A Comparison of Conventions

In this proceedings and [2] we normalize M_p in a convention useful in quoting experimental bounds[4]. In these conventions, the D-dimensional Newton constant and the Planck mass are related by

$$M_p^{D-2} = \frac{(2\pi)^{D-4}}{4\pi G_D} . \tag{A1}$$

At least two other conventions exist. For example, bounds quoted in the *Linear Collider physics resource book*[34] are quoted for M_D in the convention of [10]:

$$M_D^{D-2} = \frac{(2\pi)^{D-4}}{8\pi G_D} . \tag{A2}$$

Thus

$$M_p = 2^{\frac{1}{D-2}} M_D , \tag{A3}$$

a small relative correction.

The paper by Dimopoulos and Landsberg [3] uses somewhat different conventions,

$$M_{DL}^{D-2} = \frac{1}{G_D} . \tag{A4}$$

Therefore the relation between the Planck masses in our two normalizations is

$$M_p^{D-2} = 2^{D-6}\pi^{D-5}M_{DL}^{D-2} \ . \tag{A5}$$

In $D = 6$ the difference is not great, $M_p = 1.3M_{DL}$, but in $D = 10$ the difference results in a substantial factor: $M_p = 2.9M_{DL}$.

Appendix: References

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