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Produkce černých děr na urychlovači LHC

Black holes production at the LHC

Summary

The Large Hadron Collider recently put into operation in the European Organisation for Nuclear Research (CERN) accelerates protons to unprecedently high collision energy. One of the more exotic new effects which could be discovered by the facility are microscopic black holes. They require, however, that gravity propagates in additional spatial dimensions to the usual three ones. These extra dimensions must be compact on a length scale which is large in comparison to the Planck length. Even if such conditions were realistic, the created black holes would quickly evaporate. It is demonstrated that even if created they pose no danger for the stability of the surrounding matter.

Shrnutí

Urychlovač LHC, uvedený nedávno do provozu v Evropské organizaci pro jaderný výzkum (CERN), urychluje protony na doposud nejvyšší dosaženou energii. Jedním z exotičtějších jevů, které by na tomto zařízení mohly být pozorovány, jsou mikroskopické černé díry. Pro jejich produkci je však nutné aby se gravitace šířila více než třemi prostorovými rozměry. Tyto přidané rozměry pak musí být kompaktní na délkové škále, která je mnohem větší než Planckova délka. I kdyby byli požadované podmínky realizovány v přírodě, produkované černé díry by se rychle rozpadly. Rovněž se dá prokázat, že i kdyby ve srážkách protonů černé díry vznikaly, nepředstavují žádné riziko pro stabilitu hmoty ve svém okolí.

Klíčová slova:
LHC, černé díry, velké přidané rozměry, Hawkingovo záření, bezpečnost LHC

Keywords:
LHC, black holes, large extra dimensions, Hawking radiation, LHC safety

Contents

1 Introduction

With the commisioning of the Large Hadron Collider (LHC), general public has become sensitive to topics that connected the machine with potential exotic observables and scenarios. Creation of miniature black holes was among the most frequently reviewed, together with arguments why it should or should not be dangerous for the existence of our Universe. Our Faculty has strong involvement in the research programme of the LHC: we have quite active grups involved in ALICE and ATLAS collaborations (see e.g. [1]). Therefore, such questions concern us and we may be asked about some aspects of them anytime by people outside the field. It is the aim of this lecture to review the conditions for creation of microscopic black holes at the LHC as well as explain the mechanisms of their production and decay.

Formally, to create a black hole is rather simple. It is just necessary to confine mass or its energy equivalent *within* the Schwarzschild radius [2]. For the mass of the Sun the Schwarzschild radius is 2.9 km, for the Earth it is 8.8 mm. Clearly, these numbers are far below the actual sizes of these bodies. Thus neither of them is a black hole. Let us look at microscopic processes. If we take 1 TeV as a typical scale for LHC experiments, such energy would have to be confined within 10^{-50} m in order to create a microscopic black hole. This is, however, 15 orders of magnitude below the Planck length scale where quantum gravity effects are expected to be imporant and the classical picture used in this argument cannot be applied.

The possibility for the creation of black holes in collider experiments at the energies of a few TeV arises with widening the space-time by additional spatial dimensions in which gravity can propagate [3, 4]. Since we observe that gravity acts in only three spatial dimensions, the additional ones would have to be compactified on a length scale below our current experience with the gravitational force. The concept of (large) extra dimensions was inspired by the string theory and designed in order to provide an alternative explanation to the hierarchy problem. The latter rests in the fact that there is a gigantic gap between the largest energy scale of the standard model—namely that of electroweak phase transition at about 100 GeV—and the fundamental Planck scale of 10^{19} GeV.

In this lecture we shortly introduce the idea of large extra dimensions and mention experimental tests which put limits on the allowed parameter space. Then, after a brief review of the elementary black hole physics, we show how black holes can appear at TeV energies when we allow for large extra dimensions. After this, the rate of production in current experiments is estimated. Finally, we explain that even if the black holes were produced, they immediately evaporate. In any case, their existence is safe from the viewpoint of the stability of the environment, as can be deduced from the fact that reactions potentially producing black holes run continuously in the interactions of cosmic rays with cosmic bodies (including Earth).

2 Large Extra Dimensions

The hierarchy problem of high energy physics has motivated many efforts towards its solution. The aim is to explain the huge discrepancy between the electroweak scale $\mathcal{O}(100\,\mathrm{GeV})$ set by the expectation value of the Higgs field, and the next bigger scale given by the Planck mass

$$M_{\mathrm{Pl}} = \sqrt{\frac{\hbar c}{G}} = 1.22 \times 10^{19}\,\mathrm{GeV}/c^2$$

where G is the gravitational constant

$$\begin{aligned} G &= 6.674\,28(78) \times 10^{-11}\,\mathrm{m}^2\mathrm{kg}^{-1}\mathrm{s}^{-2} \\ &= 6.708\,81(67) \times 10^{-39}\,\hbar c\,(\mathrm{GeV}/c^2)^{-2}\,. \end{aligned}$$

This issue has been among the main motivations for the formulation of supersymmetric and technicolor models. Keeping in mind the focus of this lecture we shall, however, review a different kind of explanation: the Large Extra Dimensions.

The idea is to unify the fundamental Planck scale with the electroweak one by setting the former down to the TeV level. How does this work? Notice that the Planck mass is related to size of the gravitational constant G

$$G = \frac{\hbar c}{M_{\mathrm{Pl}}^2}\,.$$

Thus lowering M_{Pl} down to a new fundamental scale M_f which we want to identify with the electroweak scale would give a larger value of the gravitational constant. This could be accommodated under the assumption that on short distances gravity spreads in more than three spatial dimensions. At large distances we must recover the inverse squared distance dependence of the field, that is in accord with three spatial dimensions and dictated by observations. Such behaviour is achieved if the extra dimensions are compact on some length scale R_c which is smaller than the length over which gravity is known to exhibit the r^{-2} dependence.

Additional spatial dimensions carry with them the possibility of exciting so called Kaluza-Klein (KK) modes [5, 6]. The simplest example of this behaviour is constructed with a massless scalar field $\phi(x_\mu, z)$ which is defined in one temporal and 3+1 spatial dimensions; the extra dimension is parametrised here by the coordinate z. It thus obeys the Klein-Gordon equation in 5 dimensions

$$\Box_5 \phi(x_\mu, z) = \Box_4 \phi(x_\mu, z) - \frac{\partial^2}{\partial z^2} \phi(x_\mu, z) = 0\,, \tag{1}$$

where $\Box_n$ is the d'Alembert operator in n dimensions. Since the added dimension is compact, we can decompose the field into Fourier modes

$$\phi(x_\mu, z) = \sum_{k=-\infty}^{\infty} \phi^{(k)}(x_\mu)\, \exp\left(\frac{i\,k\,z}{R_c}\right)\,, \tag{2}$$

where R_c is the scale on which the fifth dimension is compactified. Inserting this decomposition into the Klein-Gordon equation yields a series of equations for all Fourier modes in only four coordinates

$$\left(\Box_4 - \frac{k^2}{R_c^2}\right) \phi^{(k)}(x_\mu) = 0\,. \tag{3}$$

We observe that the obtained tower of *Kaluza-Klein modes* represents massive fields with masses $\hbar k / c R_c$. Only the zeroth mode is massless. If the compactification scale is small enough, the effective masses may be far beyond the reach of experiments. But if R_c increases, it may be realistic to excite some of the KK modes. The situation with graviton field is more complex since the tensorial field upon its Fourier decomposition leads to tensorial, vectorial, and scalar KK towers.

Now we are ready to illustrate how the effective inverse squared distance law of the gravitational field comes to place for long distances. Formally, the theory of gravity in any dimensions is specified by the Einstein-Hilbert action. If we now limit ourselves for the sake of brevity to the zeroth KK modes of the gravity, we can integrate out the d additional compact dimensions, so schematically

$$\frac{c^{d-1} M_f^{2+d}}{16\,\pi\,\hbar^{d+1}} \int d^4x \int_0^{2\pi} d^d z\, \sqrt{-g}\, R \to \frac{c^{d-1} M_f^{2+d} V_d}{16\,\pi\,\hbar^{d+1}} \int d^4x\, \sqrt{-g_4}\, R_4\,, \tag{4}$$

where g and g_4 are the determinants of the metric in 4+d and 4 dimensions, respectively, and R and R_4 are corresponding scalar curvatures. We have introduced the d-dimensional volume of the integrated extra dimensions

$$V_d = (2\pi R_c)^d\,.$$

On the right hand side we have an expression that is formally identical to the Einstein-Hilbert action in the 3+1 space time, if we identify

$$M_{\rm Pl}^2 = \left(\frac{c}{\hbar}\right)^d M_f^{2+d} (2\pi R_c)^d\,. \tag{5}$$

Even without going to Einstein-Hilbert action this can be understood from considering the gravitational potential. Recall that for a pointlike central mass in any number dimensions n it has to fulfill Poisson's equation

$$\triangle_n \Phi(x) = \delta^{(n)}(x)\,. \tag{6}$$

From this follows the $1/r^{1+d}$ dependence of the potential for a pointlike source in 3+d spatial dimensions. If the fundamental mass scale is M_f then for distances much shorter than typical size of the extra dimensions, $r \ll R_c$, we have

$$\Phi(r) = -\frac{\hbar c}{M_f^2} \left(\frac{\hbar}{c\,M_f}\right)^d \frac{M}{r^{1+d}}\,, \tag{7}$$

where M is the central gravitating mass. For distances much larger than the compactification scale $r \gg R_c$ the potential is proportional to

$$\Phi(r) \propto -\frac{\hbar c}{M_f^2} \left(\frac{\hbar}{2\pi\, c\, M_f\, R_c}\right)^d \frac{M}{r}\,, \tag{8}$$

where we have added the factor 2π in order to be consistent with the integration of Einstein-Hilbert action. We see that the standard Newtonian solution is recovered if we set the Planck mass according to eq. (5). If we now set the fundamental scale M_f to 1 TeV, just because we desire that it is reachable by the LHC experiments, eq. (5) allows us to determine the size of compactification R_c for any given d ($d > 0$)

$$R_c = \frac{\hbar}{2\pi\, c\, M_f} \left(\frac{M_{\rm Pl}}{M_f} \right)^{2/d} . \tag{9}$$

For one extra spatial dimension ($d = 1$) this gives $R_c = \mathcal{O}(10^{13}\,\mathrm{m})$, which is by about a factor of 100 more than the size of the solar system. Obviously, on this scale gravity does obey the inverse squared distance law and thus $d = 1$ is ruled out.

For two extra spatial dimensions this gives about millimeter scale and may be lowered slightly by increasing M_f. Larger d's put the R_f size below 0.1 μm.

Hence, in order to test the large extra dimensions hypothesis it becomes essential to measure gravitational field on very small distances. Such experiments have been performed by the Eöt-wash group at the University of Washington with the help of torsion balance [7], i.e. in a similar manner as the classical setup by lord Cavendish. The current limitation is set to $R_c \ll 0.44\,\mu$m [8]. For $d = 2$, from eq. (9) this sets a lower limit on the fundamental mass scale to $M_f \geq 3.2\,\mathrm{TeV}/c^2$ [8]. Thus it seems, that with a bit of luck the LHC could be sensitive to large extra dimensions, but this requires $d \geq 2$.

3 Black holes in arbitrary dimensions

According to General Relativity, gravity is expressed as a curvature of the space-time. The metric obeys Einstein's equation

$$R_{\mu\nu} - \frac{1}{2} g_{\mu\nu} R = -\frac{8\,\pi\, G}{c^4}\, T_{\mu\nu} \, . \tag{10}$$

Here, $g_{\mu\nu}$ is the metric tensor and $R_{\mu\nu}$ is the Ricci tensor which is obtained from the Riemannian curvature tensor by contraction

$$R_{\mu\nu} = R^{\gamma}{}_{\mu\nu\gamma} \, .$$

The curvature tensor is obtained from the metric tensor via Christoffel symbols $\Gamma^{\alpha}_{\beta\gamma}$

$$\begin{aligned} R^{\alpha}{}_{\beta\gamma\delta} &= \Gamma^{\alpha}_{\beta\delta,\gamma} - \Gamma^{\alpha}_{\beta\gamma,\delta} + \Gamma^{\alpha}_{\mu\gamma}\Gamma^{\mu}_{\beta\delta} - \Gamma^{\alpha}_{\mu\delta}\Gamma^{\mu}_{\beta\gamma} \, , \\ \Gamma^{\alpha}_{\beta\gamma} &= \frac{1}{2} g^{\delta\alpha} \left(g_{\delta\beta,\gamma} + g_{\delta\gamma,\beta} - g_{\beta\gamma,\delta} \right) \, , \end{aligned}$$

and the subscripts following the commas denote differentiation with respect to the corresponding coordinate. Scalar curvature is the contraction of the Ricci tensor

$$R = R^{\mu}{}_{\mu}\,.$$

As follows from Einstein's equation, the curvature is given by the local energy and momentum density, which is expressed via the energy-momentum tensor $T_{\mu\nu}$. The metric *around* a spherically distributed mass M in *three* spatial and one temporal dimension is given by a solution of eq. (10) due to Schwarzschild [2]

$$\mathrm{d}s^2 = g_{\mu\nu}\,\mathrm{d}x^{\mu}\mathrm{d}x^{\nu} = \gamma_3(r)\,\mathrm{d}(ct)^2 - \gamma_3^{-1}(r)\,\mathrm{d}r^2 - r^2\mathrm{d}\Omega_3^2\,, \tag{11}$$

with

$$\gamma_3(r) = \left(1 - \frac{2GM}{c^2 r}\right) = \left(1 - \frac{R_{3H}}{r}\right)\,. \tag{12}$$

Here, for spatial dimensions we use spherical coordinates with the solid angle element on unit sphere

$$\mathrm{d}\Omega_3^2 = \mathrm{d}\theta^2 + \sin^2\theta\,\mathrm{d}\phi^2\,.$$

In expression (12) we introduced the Schwarzschild radius

$$R_{3H} = \frac{2GM}{c^2} = \frac{2\hbar M}{cM_{\mathrm{Pl}}^2}\,. \tag{13}$$

In the second equality we have expressed the Schwarzschild radius with the help of the Planck mass. From eq. (11) we see that the metric exhibits a singularity as $r \to R_{3H}$. Here we have the event horizon. Recall that $\gamma_3(r)$ gives the relativistic potential Φ and the field strength

$$\Phi_3(r) = \frac{c^2}{2}\ln\gamma_3(r) \tag{14}$$

$$\boldsymbol{g} = \boldsymbol{g}(r) = \nabla\Phi_3(r)\,. \tag{15}$$

In case of three dimensions we recover for large $r \gg R_{3H}$

$$g(r) = |\boldsymbol{g}(r)| \approx G\frac{M}{r^2}\,. \tag{16}$$

Let us now turn to the general case with $(3+d)$ spatial dimensions. Einstein's equation keeps the form (10) but the energy-momentum tensor changes the dimension. Since the curvature has dimension L^{-1}, the dimension of G must be $L^{3+d}M^{-1}T^{-2}$. The equation can again be solved for central field outside the generating energy and the (3+d)-dimensional metric is [9]

$$\mathrm{d}s^2 = g_{\mu\nu}\,\mathrm{d}x^\mu \mathrm{d}x^\nu = \gamma(r)\,\mathrm{d}(ct)^2 - \gamma^{-1}(r)\,\mathrm{d}r^2 - r^2 \mathrm{d}\Omega_d^2\,, \tag{17}$$

with

$$\gamma(r) = \left(1 - \frac{8\pi\Gamma\left(\frac{d+3}{2}\right) GM}{(d+2)\pi^{(d+3)/2} c^2 r^{d+1}}\right) = \left(1 - \left(\frac{R_H}{r}\right)^{d+1}\right) . \tag{18}$$

The Schwarzschild radius in (3+d) dimensions thus takes he form

$$R_H = \left(\frac{8\pi\Gamma\left(\frac{3+d}{2}\right) GM}{(d+2)\pi^{(d+3)/2} c^2}\right)^{\frac{1}{d+1}} , \tag{19}$$

where $\Gamma\left(\frac{d+3}{2}\right)$ is the Gamma function. Again, it is possible to calculate the gravitational potential and the field via eqs. (14) and (15). For $r \gg R_H$ one arrives at

$$\Phi = \frac{c^2}{2} \ln \gamma \approx -\frac{c^2}{2}\left(\frac{R_H}{r}\right)^{d+1} \tag{20}$$

$$g(r) \approx \frac{(d+1)c^2}{2}\left(\frac{R_H}{r}\right)^{d+1} \frac{1}{r} . \tag{21}$$

Now let us make contact with the large extra dimensions hypothesis. We require that this potential is equal to eq. (7)

$$\frac{c^2}{2}\left(\frac{R_H}{r}\right)^{d+1} \stackrel{!}{=} \frac{\hbar c}{M_f^2}\left(\frac{\hbar}{c\,M_f}\right)^{d} \frac{M}{r^{1+d}} \tag{22}$$

and from this we obtain

$$R_H^{1+d} = 2\left(\frac{\hbar}{c\,M_f}\right)^{d+1} \frac{M}{M_f} . \tag{23}$$

This puts the Schwarzschild radius into connection with the new large fundamental mass scale.

4 Production of black holes in colliders

Having derived the Schwarzschild radius for arbitrary dimensions we are now in position to estimate the cross section of microscopic black hole production and the production rate at the LHC. In principle, a microscopic object must be treated within a quantum theory. However, since microscopic black holes do not appear in the Standard Model and their quantum theoretical treatment is not known, yet, we fall back to a semiclassical approach. The cross section for production of a microscopic black hole with a mass M will be estimated simply from the circular area with the radius R_H [10]

$$\hat{\sigma}(M) \approx \pi R_H^2 \, \Theta(M - M_f) \,, \tag{24}$$

where the Heaviside function $\Theta(M - M_f)$ cuts off black hole production for masses below the fundamental scale M_f. If we choose $M_f = 1$ TeV/c^2 and two extra dimensions, then $\sigma(1\,\text{TeV})$ is about a nanobarn. This is the cross section for parton-parton interaction.

In order to determine the differential cross section $d\sigma/dM$ in proton-proton collisions one must convolute the parton cross section with parton distribution functions and sum over all possible parton pairs within the two protons. Parton distribution functions $f_i(x, \hat{s})$ parametrize the probability to find parton i (quark or gluon) carrying the fraction x of the total proton momentum. They depend on the energy scale of the process $\hat{s}$. With the help of the parton distribution functions the differential cross section is calculated as [10]

$$\frac{d\sigma}{dM} = \sum_{i,j} \int_0^1 dx_1 \, \frac{2\sqrt{\hat{s}}}{x_1 s} \, f_i(x_1, \hat{s}) \, f_j(x_2, \hat{s}) \, \hat{\sigma}(M) \,, \tag{25}$$

where the summation goes over all possible combinations of partons that can lead to black hole formation and the integration runs over all momentum fractions. The other momentum fraction, x_2, is not integrated as it is constrained by the total energy

$$x_1 \, x_2 \, s = \hat{s} = M^2 \,, \tag{26}$$

where s is the square of the centre of mass energy of the proton-proton system. From this $x_2 = M^2/x_1 s$.

For practical evaluation, the parton distribution functions can be taken from the CTEQ parametrization [11] and the integral can be calculated.

The total cross section for production of black holes with masses above M_f is finally obtained by integrating $d\sigma/dM$.

When this estimate is multiplied with the integrated luminosity, one can deduce the number of black holes to be expected. With the projected luminosity at the LHC at $\sqrt{s} = 14$ TeV, which is $L = 10^{33}$ cm^{-2}s^{-1}, we arrive at the order of 10^9 black holes per year. Note however, that with increasing fundamental mass scale the cross section drops exponentially. As M_f approaches 10 TeV/c^2, we expect about 1 black hole per year.

5 The fate of microscopic black holes

Considerations concerning the entropy content of matter falling into a black hole lead to a conclusion that black holes must posses entropy which is proportional to the area of the event horizon [12]. In accordance with thermodynamic relations, the black hole then emits black body radiation with a temperature that is inversely proportional to the mass [13]

$$T_H = \frac{\hbar c^3}{G\, k_B} \frac{1}{8\, \pi\, M} \, . \tag{27}$$

Here, T_H is called the Hawking temperature. More generally, in 3+d spatial dimensions the temperature is determined as

$$T_H = \frac{\hbar c}{4\pi k_B} \left. \frac{\partial \gamma(r)}{\partial r} \right|_{r=R_H} \tag{28}$$

and from this via inserting eq. (18) for $\gamma(r)$ we obtain the relation for the Hawking temperature

$$T_H = \frac{1+d}{4\pi} \frac{\hbar c}{k_B} \frac{1}{R_H} = \frac{1+d}{4\pi\, 2^{1/(d+1)}} \frac{c^2 M_f}{k_B} \left(\frac{M_f}{M} \right)^{\frac{1}{d+1}} \, . \tag{29}$$

It is important to realise that the temperature is *inversely* proportional to the mass of the black hole at the power of $1/(d{+}1)$. A simple insertion of $M = 1$ TeV/c^2 in two extra dimensions yields the Hawking temperature of several hundred GeV divided by k_B or, equivalently, thousands of trillions Kelvin.

Note that the intensity of radiation per area would *increase* if the mass of the black hole drops, because smaller black holes have higher temperatures.

Thus we expect that the most microscopic black holes radiate strongly and get rid of all their energy extremely fast. The specific signature would be blackbody radiation with a temperture of a few hundred GeV/k_B. For a black hole with the mass of a few TeV/c^2 this practically means a few jet-like structures which are not accompanied by an associated jet in the opposite azimuth.

Microscopically, the mechanism of radiation follows from very basic principle of quantum theory [13]. Particle-antiparticle pairs must be continuously created and annihilated everywhere in space. In the vicinity of the event horizon some particles may fall into the black hole and their partner then escapes as radiation.

Yet another reasoning that black holes must be vulnerable to decays is at hand if they are produced in collisions of quarks and gluons. In such a case the black holes would not carry any quantum number that is not present in the incident partons and they can decay via the same channel as they were produced [14]. The decay rate would be directly related to the production rate.

These are very general arguments which hold also in more than three dimensions. Nevertheless, in order to make the statement about safety of the LHC yet stronger, studies were done which assume that the above is not true and *stable* black holes can be created, even though it dramatically violates some basic rules of quantum physics [15, 16]. The relevant comparison is with the results of cosmic rays interactions with cosmic bodies. The only difference to the collisions at the LHC is that the latter would produce black holes basically at rest while the black holes would move very fast in case of cosmic ray interactions. One must therefore study the stopping power of cosmic bodies.

First of all, one must assume that the black holes are electrically neutral. If they were charged, which is actually natural to expect given that they can be produced in interactions of quarks, they would be easily captured within stars and/or planets once they were produced on their surfaces or in the atmosphere. No macroscopic effect has been observed so far, however. This leads to the conclusion, that if existent, they are either neutral or cause no effect even if they are stopped.

Various scenarios of mass accreation by neutral black holes stopped within a planet or star have been scrutinized in [15]. In models with three or more extra dimensions the compactification scale must be small and this terminates the black hole growth while it is still microscopic. Thus the only possibility is that there are two extra dimensions. Recall that one large extra dimension is ruled out by observations since the compactification length would be of astronomical scale.

However, even if such possibility was open, black holes would be produced and stopped in interactions of cosmic rays with compact stars like white dwarfs and neutron stars. If they would have macroscopic effects, they would have lead to destructions which end in an explosive release of large amount of energy. The time scale for such destructions would be much shorter than the observed lifetime of these cosmic bodies [15].

We can conclude, therefore, that the speculation that disastrous scenario is to be expected due to black hole creation at the LHC can be firmly rejected. First of all, this rejection is based on very fundamental processes which must be present if black holes were created. But even beyond that, our confidence can rest on the observed stability of compact stars.

6 Concluding remarks

In this lecture I reviewed a very exotic scenario of an LHC collision. In spite of its extreme strangeness, general public sometimes seem to take it as granted. The reason seems to be that such scenario is bizarre enough and the general belief is that physics of the microworld must be very strange. While, of course, the judgement about the validity of the theory is based on observations, let me here just summarize the main assumptions that must be valid in order for the black holes to be produced:

- Gravity must propagate in more than three spatial dimensions.
- The extra dimensions must be compactified on a length scale that leads to a new fundamental mass scale of a few TeV.

If these conditions are both fulfilled, then LHC might be in position to create microscopic black holes.

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