Physics Letters B 672 (2009) 71–76

Contents lists available at ScienceDirect

Physics Letters B

www.elsevier.com/locate/physletb

# Exclusion of black hole disaster scenarios at the LHC

Benjamin Koch [a,b,*], Marcus Bleicher [b], Horst Stöcker [b,c,d]

[a] *Pontificia Universidad Católica de Chile, Av. Vicuña Mackenna 4860, Santiago, Chile*
[b] *Institut für Theoretische Physik, Johann Wolfgang Goethe - Universität, Max-von-Laue-Strasse 1, D-60438 Frankfurt am Main, Germany*
[c] *Frankfurt Institute for Advanced Studies (FIAS), Ruth-Moufang-Strasse 1, D-60438 Frankfurt am Main, Germany*
[d] *GSI - Helmholtzzentrum für Schwerionenforschung GmbH, Planckstrasse 1, D-64291 Darmstadt, Germany*

ARTICLE INFO

*Article history:*
Received 26 July 2008
Received in revised form 28 November 2008
Accepted 6 January 2009
Available online 9 January 2009
Editor: T. Yanagida

*Keywords:*
Extra dimensions
Black holes
LHC

ABSTRACT

The upcoming high energy experiments at the LHC are one of the most outstanding efforts for a better understanding of nature. It is associated with great hopes in the physics community. But there is also some fear in the public, that the conjectured production of mini black holes might lead to a dangerous chain reaction. In this Letter we summarize the most straightforward arguments that are necessary to rule out such doomsday scenarios.



## 1. Motivation

As an explanation for the large hierarchy between the Planck scale and the electroweak scale some authors postulated the existence of additional spatial dimensions [1–5]. One exciting consequence of such theories is that they allow for the production of black holes in highly energetic particle collisions [6–13]. It was further conjectured that black holes could have a stable final state. This lead to a public discussion whether such mini black holes once they are produced at the large hadron collider (LHC) could be growing dangerously inside the earth [14]. There is to our knowledge no scientific work that predicts that the remnants (if they exist) of such mini black holes (if they exist) could be stable at masses far above the Planck scale $M_f$. However, given the public alarm over the subject, we want to go further and also exclude danger from scenarios which are to the present understanding of the physics of mini black holes not well motivated. A number of counter arguments disfavor such disaster scenarios. Recently those arguments have been summarized and discussed by a group [15] who comes to the conclusion that "there is no risk of any significance whatsoever from such black holes". In this Letter we independently present a short coherent argument why there is no risk due to mini black holes from TeV particle collisions. First we look at the logically possible black hole evolution paths. After this we show for every endpoint of the paths, why mini black holes cannot be dangerously growing. For this we use arguments which are already present in [15], but we also bring forward new arguments such as the influence of a strongly growing black hole mass on the escape velocity of the mini black hole.

## 2. Black holes in large extra dimensions

High energy experiments like those at the large hadron collider (LHC) play a crucial role for a better understanding of the fundamental laws of physics. One hope is that those experiments can discriminate between several approaches that try to extend the physical framework of the standard model [9,16–22]. In some models [1–5] it was conjectured that the hierarchy problem between the Planck scale, $m_{\text{Planck}} \approx 10^{19}$ GeV, and the electroweak scale, $m_{\text{EW}} \approx 100$ GeV, can be solved by postulating the existence of additional spatial dimensions. In Refs. [1–3] this is done by assuming that the (d) additional spatial dimensions are compactified on a small radius $R$ and further demanding that all known Standard Model particles exist on a $(3+1)$-dimensional sub-manifold (3-brane). They find that the fundamental mass $M_f$ and the Planck mass $m_{\text{Planck}}$ are related by

$$m_{\text{Planck}}^2 = M_f^{d+2} R^d. \tag{1}$$

Within this approach it is possible to have a fundamental gravitational scale of $M_f \sim 1$ TeV. The huge hierarchy between $m_{\text{EW}}$ and $m_{\text{Planck}}$ would then come as a result of our "ignorance" regarding extra spatial dimensions. Due to the comparatively low fundamental scale $M_f \sim$ TeV and the hoop conjecture [23], it might

* Corresponding author at: Institut für Theoretische Physik, Johann Wolfgang Goethe - Universität, Max-von-Laue-Strasse 1, D-60438 Frankfurt am Main, Germany.
*E-mail address:* bkoch@fis.puc.cl (B. Koch).

0370-2693/$ – see front matter © 2009 Published by Elsevier B.V.
doi:10.1016/j.physletb.2009.01.003

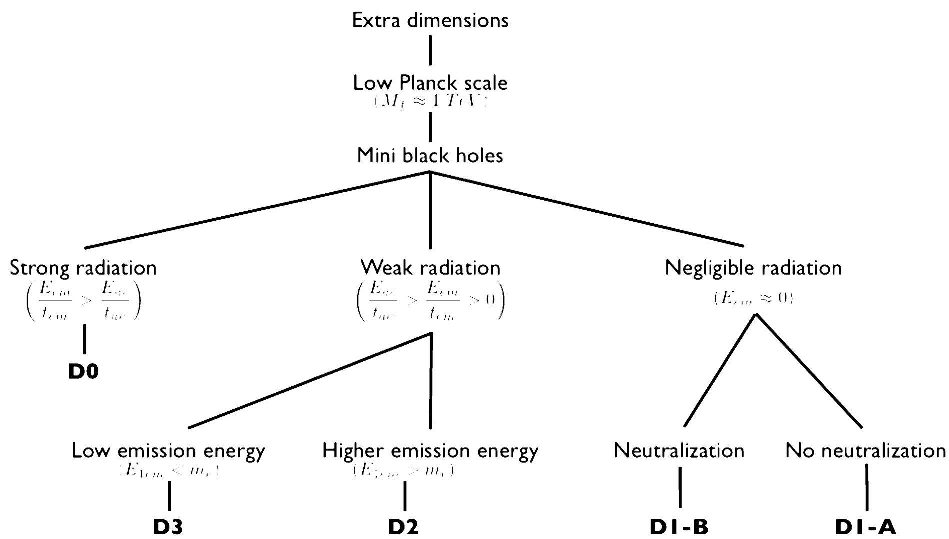


**Fig. 1.** Possible black hole evolution paths.

be possible to produce mini black holes with masses of approximately 1 TeV in future colliders [6–13]. This can only be the case when the invariant scattering energy $\sqrt{s}$ reaches the relevant energy scale $M_f$. The higher dimensional Schwarzschild radius [8,24] of these black holes is given by

$$R_H^{d+1} = \frac{16\pi(2\pi)^d}{(d+2)A_{d+2}}\left(\frac{1}{M_f}\right)^{d+1}\frac{M}{M_f}, \qquad (2)$$

where $A_{d+2}$ is the area of the $(d+2)$-dimensional unit sphere

$$A_{d+2} = \frac{2\pi^{(3+d)/2}}{\Gamma(\frac{3+d}{2})}. \qquad (3)$$

A semi-classical approximation for the mini black hole production cross section is given by

$$\sigma(M) \approx \pi R_H^2 \xi(\sqrt{s} - M_f), \qquad (4)$$

where the function $\xi$ ensures that black holes are only produced above the $M_f$ threshold. The function $\xi$ is one for $\sqrt{s} \gg M_f$ and zero for $\sqrt{s} \approx M_f$. In many simulations $\xi$ is replaced by a theta function. The validity of this approximation has been debated in [25–35] and the observable formation of an event horizon has been questioned [36,37]. However, other improved calculations including the diffuseness of the scattering particles (as opposed to point particles) and the angular momentum of the collision (as opposed to head on collisions) as well as string inspired arguments only lead to modifications of (4) which are of the order of one [38–41]. This would open up a unique possibility of studying gravitational effects at very small distance scales in the laboratory. Such observations of gravitational physics at the tiny scales of the quantum world may provide access to the presently biggest question of theoretical physics: A unified description of quantum physics and gravity.

At the same time there is a growing concern in the public. "Could such monstrous objects like mini black holes (once they are produced at LHC) eat up the entire world?" This question is controversially discussed in blogs and online-video-portals [14]. Similar anxieties (with strangelets instead of black holes) have already been stirred up when the previous generation of collider was built [42]. Fears of possibly dangerous mini black holes have been augmented by the idea of a quasi stable black hole final state. A quasi stable black hole final state has been frequently studied in the literature [43–68] which partially refer to astrophysical black holes and partially refer to mini black holes. Instead of ignoring this concern we take it serious and try to discuss the issue without provoking an emotional palaver. We explain from theoretical arguments why such a disaster is generally believed to be impossible. But we even go one step further and discuss the question: "What if the theory is wrong?" We show that even if the current theories are wrong, there is no danger as long as the "true theory" is not completely unphysical [69]. By mostly using arguments that are based on black hole production in highly energetic cosmic rays [70], a recent and extensive study on the (im) possibility of dangerous mini black holes has been given in [15]. However, in this Letter we want to concentrate on a short but convincing argument.

## 3. Possible black hole evolution paths

The logical structure of the assumptions that are relevant for this study is shown in Fig. 1. We will now discuss the tree structure in Fig. 1 step by step. Every branch of the tree ends with a discussion (D0–D3) which can be found in the next section. In those discussions we explain with either theoretical or experimental arguments why the discussed branch cannot have any disastrous consequences. Therefore, we define the average energy ($E_{em}$) as the energy which is emitted in the rest frame of the mini black hole in the average time scale ($t_{em}$). The corresponding definition for accretion gives the average energy ($E_{ac}$) as the energy which is accreted in the rest frame of the mini black hole in the average time scale ($t_{ac}$). If not explicitly stated otherwise, accretion times and energies are those for relativistic mini black holes from highly energetic cosmic rays. In order to open up the possibility of producing mini black holes in a 14 TeV collider, one has to assume the existence of extra dimensions with a fundamental mass scale in the ∼TeV range. Next one has to assume that quantum gravity effects do not spoil the conjecture that classical closed trapped surfaces lead to the formation of a black hole event horizon. If all this is given then the mini black hole could in principle follow three different paths in its further development. First, it could emit highly energetic radiation ($E_{em}$) in a short time scale ($t_{em}$) such that a comparison to the accretion energy ($E_{ac}$) and accretion time ($t_{ac}$) shows a net emission ($E_{em}/t_{em} > E_{ac}/t_{ac}$). This is what most theoreticians predict and it would be the case for both, the balding phase and the Hawking phase. In the tree Fig. 1 this possibility is denoted as "*Strong radiation*". As discussed in (D0) such a black hole cannot cause any danger.

Secondly, the mini black hole might (in contradiction to Hawking's calculation) not emit any radiation which is caused by the curvature of spacetime. In the tree this possibility is denoted as "*Negligible radiation*". In this case it consumes everything it encounters on its trajectory. By this it should acquire some net charge. As discussed in (D1-A) mini black holes with this property are ruled out by highly energetic cosmic ray observations. One could further assume that the acquired net charge is radiated away without loosing a significant amount of energy. This case is discussed in (D1-B) for two complementary scenarios which both show that high energy cosmic ray observations rule out any danger from such mini black holes.

The third possibility is a relatively weak radiating black hole (eventually forming a black hole remnant). This means that the mini black hole eats in average more matter than it emits $E_{ac}/t_{ac} > E_{em}/t_{em} > 0$, it is therefore labeled by "*Weak radiation*". In this case one can distinguish between the two cases where the emission energy per particle ($E_{1em}$) in the rest frame of the mini black hole is either larger or smaller than the electron mass ($m_e$). As shown in the discussions (D2) and (D3), both cases inevitably lead to a stopping of mini black holes from cosmic rays which rules out any danger from the concerning scenarios.

Please note that the structure of the different evolution paths is held in such a way that it cannot be mistrusted by arguments that refer to a possibly different radiation mechanism. For instance also a conjectured neutralization of the black holes via a Schwinger mechanism is covered by discussion (D1-B).

## 4. Discussions

*D0: The black hole temperature*

Most theoretical models for large extra dimensions predict that the mini black holes emit highly energetic radiation in a very short time scale. The temperature of this radiation was derived from the quantum theory in curved spacetime [71,72]. This so-called Hawking temperature is inversely proportional to the radius of the black hole [8]

$$T_H = \frac{d+1}{4\pi R_H}. \tag{5}$$

Using the Stefan Boltzmann law for higher dimensions, the decay rate of a mini black hole in the canonical picture is

$$\frac{dM}{dt} \approx -c\frac{d+1}{4R_H^2}. \tag{6}$$

Comparing this decay rate to typical growth rates at the early stage of the mini black hole evolution [15] one finds for instance for $M = 10M_f = 10^4$ GeV that the decay rate (6) exceeds the growth rate for any number of dimensions by more than thirty orders of magnitude. From this estimate it is clear that such mini black holes that are produced on the earth can never grow.

*D1-A: The black hole charge*

In this discussion we rely on the logical imperative that those mini black holes that originate from the collapse of charged particles or that swallow charged particles also have effectively some charge. If the average time for the emission of a single particle in the rest frame of the black hole ($t_{1em}$) is of the same order of magnitude or even bigger than the average time ($t_{ac}$) between accretion events ($t_{1em} \gtrsim t_{ac}$) one can make a simple random walk approximation for the black hole charge. In this approximation, the charge that a black hole inherits from the accreted or collapsed matter is

$$|Q_e| = \frac{\sum_i |q_i| t_i}{\sum_k t_k}, \tag{7}$$

where $q_i$ is the charge of the black hole at each step of its evolution and $t_i$ is the duration of this step of the evolution. If the black hole charge changes randomly at any step of the evolution it scales like ($\sqrt{n}$) where ($n$) is the number of steps. But even in the unlikely case that the black hole always tends to neutralize in the following step after obtaining the charge $|q_i| \geqslant 1/3$ (for a quark), this still results in an effective charge $|Q_e| \geqslant 1/6$, if the neutralization time scale is at least of the same order of magnitude as the accretion time scale. If such black holes would be produced at the highest center of mass energy at the LHC ($\sqrt{s_{NN}} = 14$ TeV), then black holes must have been produced in the whole past life time of the earth and the sun from highly energetic cosmic ray events (having an even higher center of mass energy of up to $\sqrt{s_{NN}} = 400$ TeV). However, there is one difference between the black holes from cosmic rays and those in the laboratory: The black holes in the laboratory might have a very low kinetic energy (i.e. velocity) in the rest frame of the earth, while the black holes from cosmic rays always have at least a momentum of

$$p \geqslant \frac{M^2}{2m_p}\left(1 \pm \mathcal{O}\left(\frac{m_p}{M}\right)\right), \tag{8}$$

where $m_p$ is the mass of a proton. This means that a black hole from a cosmic ray with a rest-mass of $\sim$1 TeV has a kinetic energy of at least $\sim 0.5 \times 10^6$ GeV. The kinetic energy loss of a black hole with an effective electrical charge $|Q_e|$ and a mass $M$ can be calculated with the help of the Bethe–Bloch formula

$$\frac{dE}{dx} = \frac{\kappa}{A_0}\frac{|Q_e|^2 Z}{\beta^2}\left(\frac{1}{2}\log\left(2m_e\frac{\beta^2 T_m}{I^2(1-\beta^2)}\right)\right), \tag{9}$$

where ($\beta = \sqrt{1 - M^2/(M^2 + E_{kin}^2)}$), ($Z$) is the average charge of the target, ($T_m = 2m_e\beta^2/(1-\beta^2)1/(1 + 2m_e/(M\sqrt{1-\beta^2}) + m_e^2/M^2)$), ($I$) is the average electronic excitation levels of the target, ($m_e$) is the electron mass, and ($\kappa/A_0$) is the standard energy loss parameter of the target. The resulting curves from Eq. (9) have a minimum at relatively low kinetic energies and a logarithmic growth for higher energies. It is also clear that a higher effective charge also means a higher energy loss since the energy loss is ($\sim |Q_e|^2$). By only taking the minimum energy loss of those curves one finds that ($\sim$1 TeV) black holes can be stopped in the earth if they effectively carry ($Q_e > 0.4$) elementary charges. The whole argument can be extended by replacing the earth by the sun which shows that mini black holes from cosmic rays with an effective charge of ($Q_e > 0.04$) would be stopped in the sun. Since the expected effective charge is ($|Q_e| \geqslant 1/6$), we can conclude that the existence of our solar system proofs that mini black holes cannot be dangerous because they would have already been produced and stopped inside the earth (sun) without causing any damage. The magnetic field of the sun is a million times smaller than the magnetic field of a white dwarf. Since not even the magnetic fields of white dwarfs manage to deflect highly energetic cosmic rays [15], the sun can be used for this kind of argument. Although this argument is sufficient to rule out dangerous charged black holes we want to mention that it underestimates the true stopping power by far. Especially taking into account the dense core of the sun and the process of pair creation in the Bethe–Bloch formula increases the effect by at least three orders of magnitude [15].

*D1-B: Neutralization without significant energy loss*

In this discussion we refer to scenario where it is assumed that black hole radiation is only present if the black hole is charged. This very special scenario of black hole evolution has been put forward by the assumption that a black hole only radiates if it is charged [73,74] and the Hawking radiation is strongly suppressed. Such a behavior was motivated by postulating a Schwinger mechanism and a coincidental suppression of Hawking or Unruh radiation. This scenario seems to be especially tuned to make the microscopical black holes grow without being slowed down by electromagnetic interactions. However, as explained in [15] such a scenario is highly doubtable. The reason is that there is no known mechanism to shut off the quantum effects responsible for Hawking radiation, but still leave intact either the quantum effects responsible for Schwinger discharge, or some other neutralization mechanism that acts to discharge the black holes. Since the time scale of such a neutralization due to a Schwinger process is supposably extremely short ($\sim R_H/c$), the discussion (D1-B) of an effectively charged black hole that gets slowed down by electromagnetic interactions cannot be applied. Therefore, the only possible process to slow down such a mini black hole is the accretion slow down. We explicitly consider two straightforward equations to describe the growth of the black hole (which originates from a highly energetic cosmic ray collision) propagating through an aggregation of matter. Both equations can be seen as complementary simplifications of a realistic description. We applying those growth equations and their effect due to accretion slow down to different astronomical objects and find that cosmic ray arguments also exclude any danger from those mini black holes.

For the first equation it is assumed that the accretion process for a mini black hole who has some overlap with the wave function of a nucleon is dominated by the strong interaction. Remember that the nucleon radius $r_p$ is much larger than the black hole radius $r_H$. As soon as some colored part of the nucleon is trapped inside of the black hole, all subsequent dynamics could be dictated by the strong interaction between the remaining nucleon color charges and the trapped color charges. Thus, in this first approximation we assume that the possible (color neutral) final states of a black hole - nucleon system after such an encounter are only determined by strong dynamics while the effects of the black hole rapidity and of the black hole surface are neglected. Those strongly interacting but color neutral final states (with a neutralized Black hole BH) for an initial black hole - proton system could be $(\mathrm{BH}+p^+ \to \{\mathrm{BH}+e^+, \mathrm{BH}+\pi^+, \mathrm{BH}+\pi^+ + \pi^0, \ldots, \mathrm{BH}+X\})$. In order to be most pessimistic about the braking efficiency of the reaction one has to assume that no momentum is transferred to the final state $(X)$. In this case the mini black hole grows in mass if the rest mass of $(X)$ is smaller than the rest mass of the nucleon. This effect of the strong dynamics can be parameterized by claiming that a black hole can accrete some fraction $(1>\alpha>0)$ of a nucleon when it propagates through it. For this kind of accretion the mass growth $(dM)$ after propagating a distance $(dx)$ in a star with average density $(\rho)$ is at least

$$\frac{dM_1(x)}{dx} = \pi (r_p + R_H)^2 \rho\alpha \geqslant \alpha\pi r_p^2 \rho \quad \Rightarrow \quad M_1(x) \geqslant x\pi r_p^2 \rho\alpha + M_f. \tag{10}$$

This solution is independent of the number of extra dimensions $d$ and valid within its assumptions as long as the black hole radius is much smaller than the nucleon radius (for $d \geqslant 1$ this means $M_1 < 5\times 10^9$ GeV). The subscript in $(M_1)$ refers to the fact that this is evolution scenario number one. The approximation (10) is tuned to represent the subsequent accretion of a nucleus, but it neglects a possible rapidity and area dependence of the black hole accretion. In this sense it can be seen as complementary to the following more standard accretion estimate, which neglects the strong dynamics but takes into account the geometric area of the black hole.

The second equation is more intuitive than (10) and it is also the basis of the discussion in [15]. Here it is assumed that the black hole consumes and keeps all matter and energy that passes its trajectory. In this case one can estimate the black hole growth rate to be proportional to the black holes surface area

$$A(M) = 4\pi \left(\frac{16\pi (2\pi)^d}{(d+2)A_{d+2}}\right)^{2/(d+1)} \frac{1}{M_f^2}\left(\frac{M}{M_f}\right)^{2/(d+1)}. \tag{11}$$

With the area (11) and the density of the matter $(\rho)$, the growth rate is at least

$$\frac{dM_2(x)}{dx} = \rho A(M_2). \tag{12}$$

The subscript in $(M_2)$ refers to the fact that this is evolution scenario number two. Eq. (12) suggests that for $(d>1)$ the growth rate due to thermal motion inside of the earth would be too slow to do any harm within the lifetime of the earth. However, for low black hole velocities (as they would be possible at LHC) Eq. (12) has to be corrected by taking additional effects such as Bondi accretion into account. It turns out that only for $d>6$ the growth rate due to thermal motion inside of the earth would be too slow to do any harm within the lifetime of the earth [15]. Therefore, we have to study the cases $d \leqslant 6$ of (12). Also this second estimate has its weakness because it does not take into account any effects due to strong interactions inside a nucleon. A further weakness is that it does not respect the consistency condition due microgravity experiments that confirm a $(3+1)$-dimensional behavior down to the micrometer scale, but it stays pretty robust for high black hole rapidity. Even though the growth equations (10), (12) only apply in certain limits, we use them as complementary ends of more elaborate approximations [15].

Now we apply the growth equations (10), (12) to the accretion slow down, which is the only mechanism of slowing down the neutralizing mini black holes of this discussion after they are produced in cosmic rays. As mentioned in [15], the accretion slow down does in the worst case of "perfect accretion" not lead to any momentum transfer. However, one can use the relativistic relation between the black hole rest mass $M_i$, energy $E_i$, and velocity $v_i$

$$E_i = \frac{M_i}{\sqrt{1-\frac{v_i^2}{c^2}}}, \tag{13}$$

where the index $(i=1)$ refers to scenario (10) and the index $(i=2)$ refers to scenario (12). Now one can solve this equation for the velocity $(v_i)$ and use the relativistic energy-momentum relation $(E_i^2 = M_i^2 + p^2)$ which gives

$$v_i \approx c\sqrt{1-\frac{M_i^2}{M_i^2+p^2}}. \tag{14}$$

The momentum $(p)$ of the mini black hole in the case of "perfect accretion" does not change during the accretion and is therefore the momentum it inherits from its production due to an highly energetic cosmic ray event. Close to the production threshold of $(M_f \approx 1$ TeV) this momentum as seen from the laboratory frame is $(p \approx M_f^2/(2m_p))$, where $(m_p)$ is the proton mass. Thus, the velocity of the mini black hole after propagating through a star (planet) with radius $(r)$ reads

$$v_i \approx c\sqrt{1-\frac{M_i^2(2r)}{M_i^2(2r)+M_f^4/(2m_p)^2}}. \tag{15}$$

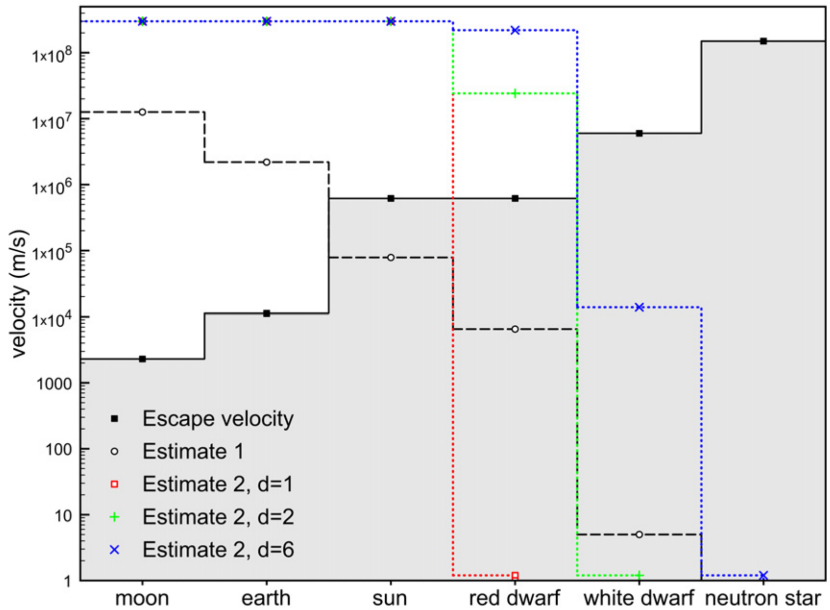


**Fig. 2.** Escape velocity compared to the velocity of an originally TeV black hole after propagating through the moon, the earth, the sun, a red dwarf, a white dwarf, or a neutron star according to equations (10) ≡ Estimate 1, (12) ≡ Estimate 2. In Eq. (10) $\alpha$ was set to one. For Eq. (12) the cases $d = \{1, 2, 6\}$ are plotted, the remaining cases $d = \{3, 4, 5\}$ lie between those curves. For the radii and densities average values were taken.

This equation shows that even in the case of "perfect accretion" without momentum transfer, the mini black hole velocity can decrease due to its mass growth which was not taken into account by [15]. Please note that this decrease of the black hole velocity is solely an effect of the growing black hole mass while other speed diminishing interactions (that in most scenarios play a dominant role) are not even taken into account. Those velocities are compared to according escape velocities in Fig. 2. As can bee seen in Fig. 2, Eq. (10) already leads to a contradiction with the existence of stars like the sun and their corresponding escape velocities. The next exclusion comes for Eq. (12) with ($d = 1$) and the existence of red dwarfs. Fig. 2 further shows that for Eq. (12) with ($6 \geqslant d > 1$) there is a contradiction to the existence of white dwarfs and the corresponding escape velocities. Thus, one can say that the existence of old ($> 1gyr$) white dwarfs is in contradiction to dangerous black holes that behave according to Eqs. (10) or (12). The result would be even clearer for neutron stars but not all neutron stars can be used as an argument because the ultra highly energetic cosmic rays undergo deflection and deceleration in the large magnetic fields that exist around neutron stars [15]. However, the flux of high energy cosmic rays that reach a white dwarf is in any model high enough to produce at least more than thirty-five mini black holes with $M_f > 14$ TeV per Myr [15]. For Eq. (10) the argument with the white dwarfs works as long as the fraction $\alpha$ is bigger than $1 \times 10^{-7}$. This limit is obtained by varying $\alpha$ in Eqs. (10), (15) and comparing the result to the escape velocity of a white dwarf. But what happens when the fraction is smaller than $1 \times 10^{-7}$? In this case one can look at the growth rate of a mini black hole with a thermal velocity of $\sim 10^3$ m/s. It turns out that in this case it takes 1.4 billion years for a thermal mini black hole until it has grown to he size of a proton, which is comparable to the age of the universe. Thus, we have shown that for each of the growth estimates (10), (15) the existence of white dwarfs is in contradiction with the possibility of dangerous mini black holes.

*D2: Higher emission energy*

There are two conditions to be fulfilled before arriving at this scenario. Which are ($E_{ac}/t_{ac} > E_{em}/t_{em} = E_{1em}/t_{1em}$) and ($E_{1em} > m_e$), where all magnitudes are defined in the rest frame of a mini black holes originating from a cosmic ray event and ($E_{1em}, t_{1em}$) are the average values per single emission. Combining the two conditions and solving for the emission time ($t_{1em}$) gives

$$t_{1em} > t_{ac} \frac{m_e}{E_{ac}}. \tag{16}$$

We will now show that this condition cannot be fulfilled by a self neutralizing mini black hole without leading to electromagnetic stopping. The minimal accretion energy for a highly energetic nucleon black hole collision can be calculated like in Eq. (12) from the product of the proton radius, the minimal black hole area (which is at $M = M_f$), and the proton density. This gives for one extra dimension ($E_{ac}(M = M_f, d = 1) \approx 1.6 \times 10^{-3}$ GeV) and it is slightly bigger for ($d > 1$) until for six extra dimensions it is ($E_{ac}(M = M_f, d = 6) \approx 4.7 \times 10^{-3}$ GeV). Here one can read off a lower bound for the accreted energy per event ($E_{ac} > 1.6 \times 10^{-3}$ GeV). With this lower bound one finds

$$t_{1em} > 0.3 t_{ac}, \tag{17}$$

which shows that the emission time has to be at least of the same order of magnitude as the accretion time. The accretion time scale $t_{ac}$ is determined from the mean distance $l_p$ (Lorentz contracted) which a mini black hole has to travel in the sun until it encounters a nucleon as $t_{ac} = (l_p/c)(2m_p/M_f) \approx 10^{-22}$ s. However, as discussed in (D1-A) an emission time scale which is comparable or bigger than the accretion time scale means that electromagnetic stopping has to take place. Therefore, the condition (16) inevitable leads to electromagnetic stopping of mini black holes from cosmic rays which rules out any danger from this scenario.

*D3: Low emission energy*

In this discussion it is assumed that the mini black hole emits less energy per emission than the electron mass $E_{1em} < m_e \approx 511$ keV. Since the electron is the lightest charged particle, there is no way, the black hole can neutralize, once it has obtained some charge due to its production or due to a subsequent accretion. Therefore, the above condition inevitable leads to electromagnetic stopping of mini black holes from cosmic rays (like discussed in D1-A) which rules out any danger from this scenario.

## 5. Summary

In this Letter we reviewed the framework for the conjectured production of mini black holes at the LHC and we have motivated the necessity of analyzing the possible danger that could come with the production of mini black holes. After this we discussed the (logically) possible black hole evolution paths. Then we discussed every single outcome of those paths (D0–D3) and showed that none of them can lead to a black hole disaster at the LHC.

## Acknowledgements

This work was supported by GSI. The authors thank Michelangelo Mangano for fruitful discussions and his helpful comments. We also acknowledge discussion with Rainer Plaga.

## References

[1] N. Arkani-Hamed, S. Dimopoulos, G.R. Dvali, Phys. Lett. B 429 (1998) 263, hep-ph/9803315.
[2] I. Antoniadis, N. Arkani-Hamed, S. Dimopoulos, G.R. Dvali, Phys. Lett. B 436 (1998) 257, hep-ph/9804398.
[3] N. Arkani-Hamed, S. Dimopoulos, G.R. Dvali, Phys. Rev. D 59 (1999) 086004, hep-ph/9807344.
[4] L. Randall, R. Sundrum, Phys. Rev. Lett. 83 (1999) 3370, hep-ph/9905221.
[5] L. Randall, R. Sundrum, Phys. Rev. Lett. 83 (1999) 4690, hep-th/9906064.
[6] T. Banks, W. Fischler, hep-th/9906038.
[7] S.B. Giddings, E. Katz, J. Math. Phys. 42 (2001) 3082, hep-th/0009176.
[8] S.B. Giddings, S.D. Thomas, Phys. Rev. D 65 (2002) 056010, hep-ph/0106219.
[9] S. Dimopoulos, G.L. Landsberg, Phys. Rev. Lett. 87 (2001) 161602, hep-ph/0106295.
[10] S. Hossenfelder, S. Hofmann, M. Bleicher, H. Stoecker, Phys. Rev. D 66 (2002) 101502, hep-ph/0109085.
[11] M. Bleicher, S. Hofmann, S. Hossenfelder, H. Stoecker, Phys. Lett. B 548 (2002) 73, hep-ph/0112186.
[12] A.V. Kotwal, C. Hays, Phys. Rev. D 66 (2002) 116005, hep-ph/0206055.
[13] S.B. Giddings, V.S. Rychkov, Phys. Rev. D 70 (2004) 104026, hep-th/0409131.
[14] http://backreaction.blogspot.com/2008/04/black-holes-at-lhc-again.html; http://www.youtube.com/watch?v=z7yZ5LEL5es; http://www.youtube.com/watch?v=ozjq80IF9dg; http://www.youtube.com/watch?v=BXzugu39pKM.
[15] S.B. Giddings, M.L. Mangano, Phys. Rev. D 78 (2008) 035009, arXiv: 0806.3381 [hep-ph]; S.B. Giddings, M.L. Mangano, arXiv: 0808.4087 [hep-ph].
[16] H. Bachacou, I. Hinchliffe, F.E. Paige, Phys. Rev. D 62 (2000) 015009, hep-ph/9907518.
[17] V.A. Khoze, A.D. Martin, M.G. Ryskin, Eur. Phys. J. C 23 (2002) 311, hep-ph/0111078.
[18] S. Dimopoulos, R. Emparan, Phys. Lett. B 526 (2002) 393, hep-ph/0108060.
[19] G. Weiglein, et al., LHC/LC Study Group, Phys. Rep. 426 (2006) 47, hep-ph/0410364.
[20] N. Arkani-Hamed, S. Dimopoulos, JHEP 0506 (2005) 073, hep-th/0405159.
[21] B. Lillie, L. Randall, L.T. Wang, JHEP 0709 (2007) 074, hep-ph/0701166.
[22] K. Cheung, W.Y. Keung, T.C. Yuan, Phys. Rev. Lett. 99 (2007) 051803, arXiv: 0704.2588 [hep-ph].
[23] K.S. Thorne, in: J. Klauder (Ed.), Magic Without Magic, W.H. Freeman, San Francisco, 1972, pp. 231–258.
[24] R.C. Myers, M.J. Perry, Ann. Phys. 172 (1986) 304.
[25] M.B. Voloshin, Phys. Lett. B 524 (2002) 376, hep-ph/0111099; M.B. Voloshin, Phys. Lett. B 605 (2005) 426, Erratum.
[26] M.B. Voloshin, Phys. Lett. B 518 (2001) 137, hep-ph/0107119.
[27] S.B. Giddings, hep-ph/0110127.
[28] T.G. Rizzo, hep-ph/0111230.
[29] A. Jevicki, J. Thaler, Phys. Rev. D 66 (2002) 024041, hep-th/0203172.
[30] D.M. Eardley, S.B. Giddings, Phys. Rev. D 66 (2002) 044011, gr-qc/0201034.
[31] V.S. Rychkov, Phys. Rev. D 70 (2004) 044003, hep-ph/0401116.
[32] V.S. Rychkov, hep-th/0410295.
[33] K. Kang, H. Nastase, Phys. Rev. D 71 (2005) 124035, hep-th/0409099.
[34] T.G. Rizzo, Class. Quantum Grav. 23 (2006) 4263, hep-ph/0601029.
[35] T.G. Rizzo, JHEP 0609 (2006) 021, hep-ph/0606051.
[36] T. Vachaspati, D. Stojkovic, L.M. Krauss, Phys. Rev. D 76 (2007) 024005, gr-qc/0609024.
[37] T. Vachaspati, D. Stojkovic, Phys. Lett. B 663 (2008) 107, gr-qc/0701096.
[38] H. Yoshino, Y. Nambu, Phys. Rev. D 67 (2003) 024009, gr-qc/0209003.
[39] S.N. Solodukhin, Phys. Lett. B 533 (2002) 153, hep-ph/0201248.
[40] D. Ida, K.y. Oda, S.C. Park, Phys. Rev. D 67 (2003) 064025, hep-th/0212108; D. Ida, K.y. Oda, S.C. Park, Phys. Rev. D 69 (2004) 049901, Erratum.
[41] G.T. Horowitz, J. Polchinski, Phys. Rev. D 66 (2002) 103512, hep-th/0206228.
[42] A. Dar, A. De Rujula, U.W. Heinz, Phys. Lett. B 470 (1999) 142, hep-ph/9910471.
[43] B. Whitt, Phys. Rev. D 32 (1985) 379.
[44] Y. Aharonov, A. Casher, S. Nussinov, Phys. Lett. B 191 (1987) 51.
[45] G.W. Gibbons, K.i. Maeda, Nucl. Phys. B 298 (1988) 741.
[46] B. Whitt, Phys. Rev. D 38 (1988) 3000.
[47] M.J. Bowick, S.B. Giddings, J.A. Harvey, G.T. Horowitz, A. Strominger, Phys. Rev. Lett. 61 (1988) 2823.
[48] C.G. Callan, R.C. Myers, M.J. Perry, Nucl. Phys. B 311 (1989) 673.
[49] R.C. Myers, J.Z. Simon, Phys. Rev. D 38 (1988) 2434.
[50] S.R. Coleman, J. Preskill, F. Wilczek, Mod. Phys. Lett. A 6 (1991) 1631.
[51] K.M. Lee, V.P. Nair, E.J. Weinberg, Phys. Rev. Lett. 68 (1992) 1100, hep-th/9111045.
[52] T. Banks, A. Dabholkar, M.R. Douglas, M. O'Loughlin, Phys. Rev. D 45 (1992) 3607, hep-th/9201061.
[53] J.D. Barrow, E.J. Copeland, A.R. Liddle, Phys. Rev. D 46 (1992) 645.
[54] T. Banks, M. O'Loughlin, A. Strominger, Phys. Rev. D 47 (1993) 4476, hep-th/9211030.
[55] K.I. Maeda, T. Tachizawa, T. Torii, T. Maki, Phys. Rev. Lett. 72 (1994) 450, gr-qc/9310015.
[56] S.B. Giddings, Phys. Rev. D 49 (1994) 4078, hep-th/9310101.
[57] A. Bonanno, M. Reuter, Phys. Rev. D 62 (2000) 043008, hep-th/0002196.
[58] R.J. Adler, P. Chen, D.I. Santiago, Gen. Relativ. Gravit. 33 (2001) 2101, gr-qc/0106080.
[59] S. Alexeyev, A. Barrau, G. Boudoul, O. Khovanskaya, M. Sazhin, Class. Quantum Grav. 19 (2002) 4431, gr-qc/0201069.
[60] J.G. Baker, M. Campanelli, C.O. Lousto, R. Takahashi, Phys. Rev. D 69 (2004) 027505, astro-ph/0305287.
[61] S. Hossenfelder, M. Bleicher, S. Hofmann, H. Stoecker, A.V. Kotwal, Phys. Lett. B 566 (2003) 233, hep-ph/0302247.
[62] B. Koch, M. Bleicher, S. Hossenfelder, JHEP 0510 (2005) 053, hep-ph/0507138.
[63] S. Hossenfelder, B. Koch, M. Bleicher, hep-ph/0507140.
[64] T.J. Humanic, B. Koch, H. Stoecker, Int. J. Mod. Phys. E 16 (2007) 841, hep-ph/0607097.
[65] H. Ghaffarnejad, Phys. Rev. D 75 (2007) 084009.
[66] X. Li, Phys. Lett. B 647 (2007) 207.
[67] B. Koch, arXiv: 0707.4644 [hep-ph].
[68] P. Nicolini, arXiv: 0807.1939 [hep-th].
[69] N. Arkani Hamed, Asking a Judge to Save the World, and Maybe a Whole Lot More, New York Times, Sciene, 1999, March 29.
[70] A. Ringwald, H. Tu, Phys. Lett. B 525 (2002) 135, hep-ph/0111042.
[71] S.W. Hawking, Commun. Math. Phys. 43 (1975) 199; S.W. Hawking, Commun. Math. Phys. 46 (1976) 206, Erratum.
[72] S.W. Hawking, D.N. Page, Commun. Math. Phys. 87 (1983) 577.
[73] R. Plaga, Private communication, 2008.
[74] R. Plaga, arXiv: 0808.1415 [hep-ph].