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Quantum black holes at LHC

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Summary. — I present a review of the state of the art of quantum black holes and of their possible phenomenology at the LHC following X. Calmet, S. D. H. Hsu and W. Gong, *Phys. Lett. B*, **668** (2008) 20-23. By quantum black holes I mean black holes of mass and Schwarzchild radius of the order of the quantum gravity scale, far below the semi-classical regime. These black holes inherit $SU(3)$ and $U(1)$ charges from their parton progenitors and decays in two-particles final states. The model is based on a minimal assumption: the conservation of local gauge charges, while no constraint is imposed on global symmetries. It is possible to identify in that way some interesting signature for quantum black holes decaying in two-particles back-to-back final states such as jet + hard photon, jet + missing energy, jet + charged lepton and two charged leptons with different flavor. The phenomenology depends strongly on the symmetries imposed in the model.

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1. – Introduction

When gravitational effects become relevant, one of the most interesting results is the possible generation of black holes. It is known that gravity become important only if the energy of the system is bigger than the Planck mass. M_p is defined by dimensional analysis as $M_p = \sqrt{\hbar c/G} = 1.2 \cdot 10^{19}\,\mathrm{GeV}/c^2$ and at this scale of energy it is impossible to detect any gravitational effect in particle physics experiment. Anyhow a lot of models [1-3] have been built in order to allow M_p to be smaller, and in particular at the order of the TeV, *i.e.* at the electroweak symmetry-breaking region. The main goal of this models is to solve or maybe just to rephrase the hierarchy problem. We can think about extradimensional models in which M_p is an effective 4-*dimensional* low-energy scale function of a fundamental parameter M_* and some geometrical parameter, *e.g.*, the

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extradimensional volume V_D. Another model recently proposed [3] considers the Newton constant G as a running constant. G is known from direct measurements only up to energy of the order of 10^{-3} eV corresponding to distances around 10^{-4} m, so that hypothesis can be made on its high-energy behavior. In this contest, if the Planck mass is in the TeV region at the scale of energy of LHC, gravitational effects can play an important role also in elementary particle collisions and mini black holes can eventually be created. Let me stress that some lower bound has already been set on the magnitude of M_p for different models, and we always find them in the TeV region [4-6].

2. – Black holes in elementary particle collision

It has been believed that collisions where the center-of-mass energy substantially exceeds the Planck mass would produce black holes. This statement can be thought as an extrapolation of Kip Thorne's hoop conjecture and leads to the naive estimate that the cross-section for black-holes production is roughly given by

$$\hat{\sigma}(pp > BH) = \pi R_s^2\big(\sqrt{s}\,\big),$$

where $R_s = 2G\sqrt{s}/c^2$ is the Schwarzchild radius corresponding to the center-of-mass energy $\sqrt{s}$.

To better understand this process, Eardley and Giddings [7] formally proved the formation of a closed trapped surface when the collision happens in a region of weak curvature. The cross-section is again proportional to πR_s^2 up to a numerical factor depending on the number of dimensions. For four-dimensional models this factor is given by $F(4) = 0.64$. As one can read from Schwarzchild radius expression, the cross-section is proportional to Newton constant G, so that, if at LHC range of energy M_p is small enough, black-hole production can become observable.

Eardley-Giddings construction is based on shock waves collision and it is only valid in the limit of highly boosted massless particles. The idea [8] is that the gravitational field of a rapidly moving particle is dilated in the orthogonal direction to the particle motion and compressed in the direction of the motion, showing the same physical behavior as the electromagnetic field. By causality, two colliding particles will not be able to influence each other until they enter the trapped region.

This horizon formation is proved only in a weak curvature region, where quantum gravity effects are small. For that reason the construction is valid in the thermal or classical regime for which $M_{\mathrm{BH}} \gg M_p$, and can be extended in the so-called semi-classical regime in which M_{BH} can be up to 5 times bigger than M_p [9]. Naively we can guess that the black-hole mass is just the center-of-mass energy of the two partons. Anyhow, as we can see in [10], at LHC this condition can hardly be reached, even in the case of $M_p = 1\,\mathrm{TeV}$. Two are the main reasons. The first one is the Parton Distribution Functions effect: even if the parton cross-section grows with energy, PDFs make the total cross-section rapidly fall to zero. The second one is related to the fact that the black-hole mass would depend on the impact parameter, so that not all the the partonic center-of-mass energy is available for the black hole. This effect is the so-called inelasticity [11, 10].

Since at LHC dominate black holes with small masses (near M_p), it is possible to extrapolate the quantum regime from the thermal one, as shown in [12]. If in the semi-classical regime black holes evaporate in many particles final states, where the number of particles is proportional to the mass, in the quantum regime there is just enough energy to create a black hole at rest and it will decay in two particles back to back.

The decay modes of a black hole will be for sure strongly dependent on the quantum gravity model, so that one is forced to make some assumption to impose some constraint. Following [12] it is possible to work only with symmetries, imposing minimal conditions to keep phenomenology free. The central assumption in this discussion [12] is that quantum black holes preserve QCD and $U(1)$ charges since local gauge symmetries are not violated by gravity. No similar hypothesis is made on global charges. For that reason, quantum black holes are defined by three quantities: mass, spin and gauge charges. The fact that QBHs carry color charge is not in contradiction with confinement, since the typical length scale of QCD, *i.e.* a Fermi, is much larger than the size of the QBH. The formation and decay of QBH is a short-distance process and hadronization occurs only subsequently.

Even Lorentz symmetry can be left free to include models like strings that allow Lorentz violation. Another principle to consider is the democracy of gravity. This basically means that gravity couples universally and does not distinguish flavors. For that reason, to have the cross-section for the decay in a specific final state, it is enough to divide the total cross-section for the black-hole production by the total number of possible final states allowed by the conservation of gauge charges.

3. – Black holes at LHC

Since black holes can be classified under their $SU(3)_c$ and $U(1)_{em}$ representations, it is interesting to study the color representations relevant at LHC.

– $3 \times \bar{3} = 8 + 1$

– $3 \times 3 = 6 + \bar{3}$

– $3 \times 8 = 3 + \bar{6} + 15$

– $8 \times 8 = 1_s + 8_s + 8_a + 10 + \bar{10}_a + 27_s$

With these results we can already understand the most interesting phenomenology. The first line says that a black hole generated after the collision of a quark and antiquark can be an octet or a singlet under color. If we take the singlet, it can decay on every couple of particle-antiparticle, *e.g.*, gluon-gluon, quark-antiquark, and also lepton-antilepton. Now, since gravity is democratic and does not distinguish flavors, the two leptons can have different flavor. In this case a signal can be $e^+ \; \mu^-$ back to back. In the second line black holes generated in the collision of two quarks have representation $\bar{3}$. A possible decay can be lepton-antiquark back to back, or if we allow Lorentz to be violated, antiquark-vector boson.

Similar signatures can be found in the other cases. We can affirm that some of the most interesting signals for a black-hole decay can involve flavor violation or lepton number violation. These kinds of signature are the most promising ones, since the standard model background is very small, while for processes involving 2 jets the QCD background is too large.

Some estimates for the cross-section of processes mediated by quantum black holes have already been done. For example, in [12] the authors compare cross-sections calculated in different models: ADD for 5, 6 and 7 extra dimensions, RS and CHR. The last one [3] allows M_p to be small also in 4 dimensions with the help of a large hidden sector coupling just gravitationally to the Standard Model. The orders of magnitude of the cross-section calculated are in the range 10^3–10^4 fb.

This model has been implemented in MadGraph as an effective model describing four-particles interaction mediated by a non-propagating auxiliary field. We will be able to produce events soon.

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