Black holes (quantum gravity) cheat-sheet

Douglas M. Gingrich
University of Alberta & TRIUMF

February 22, 2019

Types of black holes

You typically hear three types of black holes mentioned: classical, semi-classical, and quantum. A classical black hole is the type you find in undergraduate textbooks on general relativity. Since textbook gravity is a classical theory, these are referred to as classical black holes. They do not decay, and are not searched for at the LHC.

Hawking, and others, used quantum field theory to describe particle creation and annihilation near the black hole event horizon and showed that black holes can decay (or more properly evaporate). This is a semi-classical theory as the remaining properties of the back hole are still treated classically. Such black holes are often called semi-classical and are the type of black holes associated with astronomical observations. We will refer to them as general relativistic (GR) black holes to avoid the common confusion of using the word classical when semi-classical was really meant. The evaporation rate is very low for astronomical black holes of huge mass because their temperature is low. However, if you scale these astronomical objects down to TeV-scale masses, they are very hot and evaporate essentially instantaneously.

Quantum black holes (QBHs) are postulated to be the objects in a regime in which the GR description breaks down and a quantum description of the object becomes essential. In essence, any black hole produced at the LHC would need a quantum description at some point in its lifetime, even if it could initially be described as a GR black hole.

There are other gravitational object, such as string balls, which ATLAS and CMS have searched for, but I restrict this brief to GR black holes and QBHs.

Model considerations

There is no first-principles theory for black hole production and decay at the LHC. We just have models embedded in theoretical paradigms. The models are no-perturbative, and one can not draw Feynman diagrams or describe observables using a perturbative-series expansion. The models usually add a new gravitational term to the standard model Lagrangian which gives rises to the beyond-standard-model effects. If the gravitational term dominates, black holes are not influenced by QCD effect. The usual hypothesis is that the LHC creates a regime in which gravity is very strong and the other interactions can be ignored.

Black hold production is the same for GR black holes and QBHs, which is based on a conjecture that if an amount of energy can be brought into a volume that can be enclosed by a circumference given by its gravitational radius, a black hole will form. For our purposes, the gravitational radius can also be called the event horizon radius. Simplifying assumptions can be made so that event horizon radius become the Schwarzschild radius, or other commonly occurring event horizons found in GR textbooks.

The energies available at the LHC are not high enough to form the typical black holes we are familiar with because the Planck scale $M_{\mathrm{Pl}} \sim 10^{16}$ TeV is huge; or in other words, gravity is too weak. This is why gravity is typically not part of the standard model. To make black holes interesting to the LHC experiments, we need a mechanism to lower the gravity scale M_{Pl} to a lower (TeV) gravity scale $\bar{M}$. We then argue that $\bar{M}$ is the fundamental scale of gravity and that M_{Pl} is derived from it. There are three popular ways to lower the Planck scale: postulating several large extra dimensions (ADD), postulating a few (usually just one) curved extra dimensions (Randall-Sundrum), or postulating a large number of particle species in a hidden sector that interacts only gravitationally (Dvali). The later model has not yet receive much experimental attention.

Since black holes are non-perturbative macroscopic objects they should be produced above or near the Planck scale: $M \gtrsim \bar{M}$. The consequence being that they have not yet been observed because our energies are not high enough.

Model parameters

All the models essentially use a classical black-disk cross section for production. This is proportional to the gravitational radius squared. The gravitational radius is a function of mass M depending on the Planck scale $\bar{M}$ and extra number of dimensions n (or total number of dimensions $D = n + 4$). In both models we require $M > \bar{M}$. In the ADD model $\bar{M} = M_D$ and $n > 1$, while in the Randall-Sundrum model $\bar{M} = \tilde{M}$ and $n = 1$.

A note about QCD and parton distributions functions. We have no idea of the gravitational content of the proton. So we model the partons in the proton the same as other QCD processes using parton distribution functions (PDFs). But in reality, gravity would be strong and important. So one should not dwell too much on the PDF type, the scale used, etc. since it's all fiction. Within ATLAS, the QCD scale used for QBHs is taken to be the inverse gravitational radius, while for GR black holes the mass is historically used. Currently both ATLAS and CMS pick CTEQ6L1 as the PDF set since it has better extrapolated behaviour to high x than other more popular PDFs. The difference in cross sections due to different PDF sets can be large. Indeed, some PDF sets give negative values, discontinuities, and bump-like structure at high x. CTEQ6L1 does not suffer from these pathologies up to our highest-mass events, so far.

For the decays, the models are totally different depending on if a GR black hole or QBHs are being described; GR black holes are only considered in the ADD model. GR black holes evaporate and have a temperature. This temperature variable is not independent but depends on M_D and n. The GR black hole searches typically require the evaporation to three or more objects. When the GR black hole mass is reduced from evaporation down to M_D, a hypothetical remnant is formed which just decays. There are several choices for this decay and this choice is usually considered as part of the model definition. We usually consider a low-multiplicity remnant decay and a high-multiplicity remnant decay. This is the main difference between the `CHARYBDIS2` and `BlackMax` event generators, which are typically used for GR black hole simulation.

For QBH decays, we restrict the decay to two particles. The `BlackMax` generator picks the decay particle types the same way it decides on the particle types in Hawking evaporation of GR black holes. The `QBH` generator picks the decays based on conservation laws and the number of degrees of freedom (i.e. quantum numbers of the possible different decay particles); somewhat similar to particle decays.

Remember: gravity is a separate term in the Lagrangian and need not conserve global quantum numbers like baryon and lepton number as the standard model Lagrangian accidentally conserves. However, the existing models do enforce local quantum number conservation like colour charge and electric charge, and total angular momentum.

In short, we typically fix several model parameter values or definitions, and call it the model, except for three parameters: M_D, n, and M_{th}. For GR black hole searches in ATLAS, we typically choose $n = 2, 4, 6$ and work only in the two dimensional parameter space (M_{th}, M_D). For QBH searches, we typically choose $n = 1$ (Randall-Sundrum) and $n = 6$ (ADD). In addition, ATLAS fixes $M_{\mathrm{th}} = M_D$, and works in a one parameter space M_{th}. CMS typically do not make this requirement but work in the two parameters space.

Experimental search parameters

The LHC experiments use a different search variable depending on the type of black hole being searched for. GR black holes are searched for in the H_{T} spectrum of all particles in the event after selections, while QBHs are searched for in the invariant two-body mass spectrum. Note that H_{T} is not a variable in the model nor has it a direct analytical, or even numerical, relationship to a single parameter of the model.

Presentation of results

For GR black holes, upper limits are set on the visible cross section versus H_{T}. These are so-called model independent limits as they do not involve the signal in the calculation. Model-dependent limits are set on the two-dimensional parameter space (M_D,M_{th}) for fixed values of n; often for both low- and high-multiplicity remnant models.

For QBHs, only model-dependent upper limits are set on cross section times acceptance versus M_{th}. The intersection of this limit curve with the model cross section times acceptance curve gives the lower limit on the threshold production mass M_{th}.

Frequently asked questions

- Why $n = 6$? Super-string theory is formulated in $n = 6$ extra dimensions. The calculations for GR black holes have only been carried out up to $n = 6$.

- Is M_D the same Planck scale as limits are set on in mono-jet and mono-photon searches? Yes. The Kaluza-Klein theory is perturbative ADD used for mono-jet and mono-photon, and black holes are non-perturbative ADD.