News about TeV-scale black holes

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Collider produced black holes are the most exciting prediction from models with large extra dimensions. These black holes exist in an extreme region, in which gravity meets quantum field theory, particle physics, and thermodynamics. An investigation of the formation and decay processes can therefore provide us with important insights about the underlying theory and open a window to the understanding of Physics at the Planck scale. The production and the evaporation of TeV-scale black holes yields distinct signatures that have been examined closely during the last years, with analytical approaches as well as by use of numerical simulations. I present new results for the LHC, which take into account that, instead of a final decay, a black hole remnant can be left.

1. Black Holes in High Energy Collisions

High energetic particle collisions will eventually lead to strong gravitational interactions and result in the formation of a black hole's horizon. In the presence of large additional compactified dimensions [1], it could be possible that the threshold for black hole production lies within the accessible range for future experiments. In the context of models with such extra dimensions, the black hole production is predicted to drastically change high energy physics at the LHC. These effective models are string-inspired [2–4] extensions to the Standard Model in the overlap region between 'top-down' and 'bottom-up' approaches.

The possible production of TeV-scale black holes at the LHC is surely one of the most exciting predictions of physics beyond the Standard Model and has received a great amount of interest during the last years. For reviews on the subject the interested reader is referred to [5].

Due to their Hawking-radiation, these black holes have an high temperature of some 100 GeV and decay very fast into $\sim 10-25$ thermally distributed particles of the Standard Model (before fragmentation), which yields a signature unlike all other new predicted effects. The black hole's evaporation process connects quantum gravity with quantum field theory and particle physics, and is a promising way towards the understanding of Planck scale physics.

Black holes are a fascinating field of research which features an interplay between General Relativity, thermodynamics, quantum field theory, and recently also particle physics. The investigation of black holes objects would allow us to test Planck scale effects and

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the onset of quantum gravity. The understanding of the black holes properties thus is a key knowledge to the phenomenology of physics beyond the Standard Model.

Recently, the production of black holes has been incorporated into detailed numerical simulations of black hole events at the LHC and their detection [6]. These important investigations allow us to reconstruct initial parameters of the model from observed data.

So far these simulations have assumed that the black hole decays in its final phase completely into some few particles of the Standard Model. However, from the theoretical point of view, there are strong indications that the black hole does not evaporate completely, but leaves a stable black hole remnant. In a recent work, we included this possibility into the numerical simulation and examined the consequences for the observables of the black hole event [7].

2. Signatures of Black Hole Relics

We have parameterized the modifications to the black hole evaporation arising from the presence of a remnant mass and included these modifications in a numerical simulation for black hole events at the LHC, for details see [7]. The relevant parameter is the mass of the remnant, $M_{\rm R}$ that we assume to be close by the new fundamental scale $M_{\rm f}$.

In the regime of interest here, when the mass of the black hole, M, is of order $M_{\rm f}$, the emission rate for a single particle microstate has to take into account the backreaction on the black hole and is given by

$$n(\omega) = \frac{\exp[S(M-\omega)]}{\exp[S(M)]} \quad . \tag{1}$$

where S is the black hole's entropy.

For the spectral energy density we then use this particle spectrum and integrate over the momentum space. From this one obtains the evaporation rate with the Stefan-Boltzmann law to

$$\frac{{\rm d}M}{{\rm d}t} = \frac{\Omega^2_{(3)}}{(2\pi)^3} R_H^2 \int_0^{M-M_{\rm r}} \frac{\omega^3 \, {\rm d}\omega}{\exp[S(M-\omega)-S(M)]+s} \quad . \tag{2}$$

where R_H is the Schwarzschild-radius of the black hole and typically of order $1/M_{\rm f}$, and s labels the spin-statistic of the emitted radiation. The appearance of the remnant as a smallest possible mass is captured in the upper integration bound.

For the present examination we have initialized a sample of 50,000 events of black hole remnants in a proton-proton collision at $\sqrt{s} = 14$ TeV. All plots are for $d = 2$ since a higher number of extra dimensions leads to variations by less than 5%. The produced black hole remnants are strongly peaked around central rapidities, making them potentially accessible to the CMS and ATLAS experiments.

Figure 1 shows the transverse momentum, p_T, of the decay products as it results from the modified evaporation rate Eq. (2) before fragmentation. One clearly sees the additional contribution from the final decay which causes a bump in the spectrum that is absent in the case of a remnant formation. An examination of the sampled data shows that after fragmentation, this bump is slightly washed out but still present. However, from the rapidity distribution and the fact that the black hole event is spherical, a part

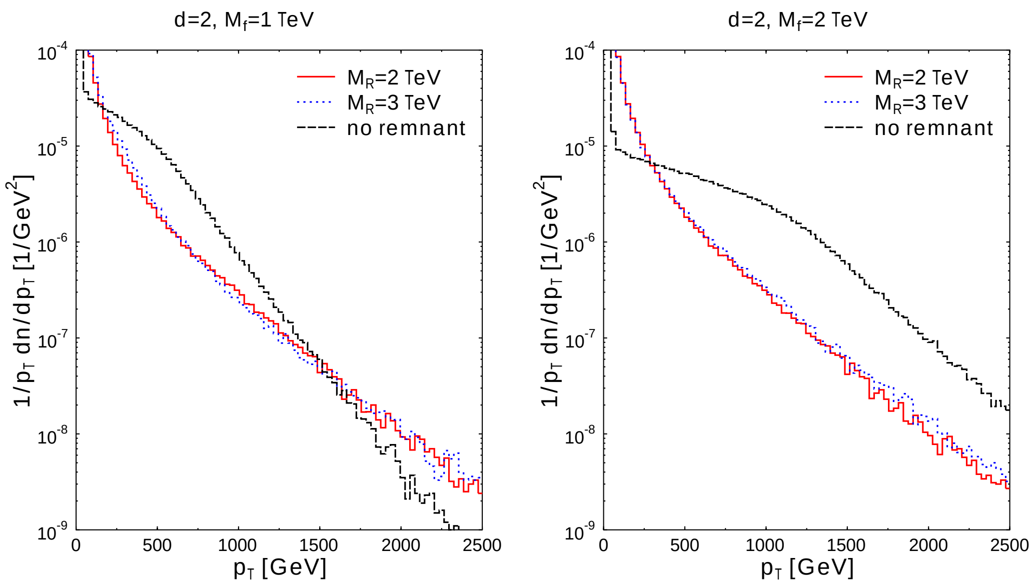

Figure 1. Transverse momentum distribution of initially emitted particles (before the fragmentation of the emitted partons) with final (two body) decay in contrast to the formation of a black hole remnant.

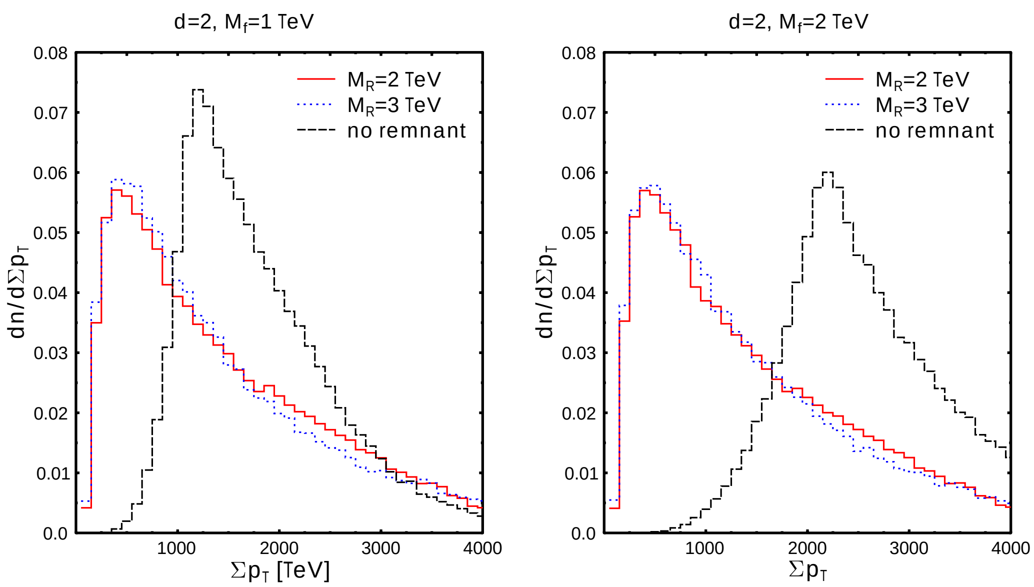

Figure 2. The total sum of the transverse momenta of the decay products.

of the high p_T-particles will be at large y and thus be not available in the detector. We therefore want to mention that one has to include the experimental acceptance in detail if one wants to compare to experimental observables.

Figure 2 shows the sum over the transverse momenta of the black hole's decay products. To interpret this observable one might think of the black hole event as a multijet with total Σp_T. As is evident, the formation of a remnant lowers the total p_T by about $M_{\rm R}$. This also means that the signatures of the black hole as previously analyzed are dominated by the assumed final and not by the Hawking phase.

An examination of the total multiplicities of the event shows that the formation a black hole remnant increases the multiplicity due to the additional low energetic particles that are emitted in the late stages instead of a final decay with $2-5$ particles.

It is interesting to note that the dependence on $M_{\rm f}$ is dominated by those on $M_{\rm R}$, making the remnant mass the primary observable.

3. Conclusions

We examined the formation of black hole remnants in proton proton collision in contrast to a final decay and found the total multiplicity of the event to be lowered by ~ 100 and the missing transverse momentum to be increased. We have shown that the formation of black hole remnants in high energy collisions would yield signatures that differ significantly from the total decay of black holes.

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