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Search for black holes and other new phenomena in high-multiplicity final states in proton–proton collisions at $\sqrt{s} = 13\,\text{TeV}$

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ABSTRACT

A search for new physics in energetic, high-multiplicity final states has been performed using proton–proton collision data collected with the CMS detector at a center-of-mass energy of 13 TeV and corresponding to an integrated luminosity of $2.3\,\text{fb}^{-1}$. The standard model background, dominated by multijet production, is determined exclusively from control regions in data. No statistically significant excess of events is observed. Model-independent limits on the product of the cross section and the acceptance of a new physics signal in these final states are set and further interpreted in terms of limits on the production of black holes. Semiclassical black holes and string balls with masses as high as 9.5 TeV, and quantum black holes with masses as high as 9.0 TeV are excluded by this search in the context of models with extra dimensions, thus significantly extending limits set at a center-of-mass energy of 8 TeV with the LHC Run 1 data.

1. Introduction

The standard model (SM) [1–3] of particle physics is a remarkably successful theory. However, several outstanding problems remain. One of these is the "hierarchy problem" [4], i.e., the vast separation between the electroweak energy scale and the scale at which gravity becomes strong. The latter, referred to as the "Planck scale" (M_{Pl}), is some 17 orders of magnitude greater than the former. There are various theoretical extensions of the SM that address the hierarchy problem, such as supersymmetry (SUSY) and models with extra dimensions.

In many of these models, high-multiplicity, energetic final states naturally occur. Strong single or pair production of various new physics signals result in multijet final states, often accompanied by energetic leptons and/or invisible particles resulting in transverse momentum (p_{T}) imbalance in the event. Examples include a large variety of SUSY signals, both with R-parity [5] conservation [6] and violation [7], and signals associated with technicolor models [8], axigluons [9], colorons [10–13], and various models with low-scale gravity.

In this Letter, we describe a model-independent search for new physics in high-multiplicity final states, and explicitly test the predictions of two possible solutions to the hierarchy problem. One of these solutions invokes a model with n large extra dimensions, colloquially known as the "ADD model", named after its proponents, Arkani-Hamed, Dimopoulos, and Dvali [14–16]. The other solution is based on the Randall–Sundrum model [17,18], called the "RS1 model". In this model a single, compact extra spatial dimension is warped, and the SM particles are localized on a TeV-scale brane, while gravity originates on the second, Planck brane, separated from the TeV brane in the extra dimension.

In the ADD model, the fundamental multidimensional Planck scale (M_{D}) is related to the "apparent" 3-dimensional Planck scale M_{Pl} as:

$$M_{\text{D}} = \frac{1}{r}\left(\frac{rM_{\text{Pl}}}{\sqrt{8\pi}}\right)^{\frac{2}{n+2}}, \quad (1)$$

where r is the compactification radius or the characteristic size of extra dimensions.

In the RS1 model, the analog of the ADD scale M_{D} is defined as a function of the exponential warp factor k and the compactification radius r:

$$M_{\text{D}} = \frac{M_{\text{Pl}}}{\sqrt{8\pi}} \mathrm{e}^{-\pi k r}. \quad (2)$$

In both models, M_{D} can be of order 1 TeV, thus eliminating the hierarchy of scales and alleviating the hierarchy problem.

At high-energy hadron colliders, such as the CERN LHC, if the collision energy exceeds M_{D}, both the ADD and RS1 models allow for the formation of microscopic black holes (BHs) [19–23].

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In the simplest scenario, microscopic BHs are produced when the distance of closest approach between two colliding particles is less than the Schwarzschild radius R_S, which for a BH in a $(3+n)$-dimensional space is given by [24]:

$$R_S = \frac{1}{\sqrt{\pi} M_D} \left[\frac{M_{BH}}{M_D} \left(\frac{8\Gamma(\frac{n+3}{2})}{n+2} \right) \right]^{\frac{1}{n+1}}, \tag{3}$$

where M_{BH} is the mass of the BH. The parton-level production cross section of such processes is expected to be simply πR_S^2 [19, 20]. In more complicated scenarios with energy loss during the formation of the BH horizon, the production cross section could significantly depart from this simple geometrical formula. Since the production of BHs is a threshold phenomenon, we assume a minimum mass threshold $M_{BH}^{min} \geq M_D$.

In the semiclassical case, corresponding to $M_{BH} \gg M_D$, BHs evaporate rapidly via Hawking radiation [25], with a lifetime of order 10^{-27} seconds. As gravity couples universally to the energy-momentum tensor and does not distinguish between various particle species, microscopic BHs decay democratically into all SM degrees of freedom, i.e., all SM particle species with all possible values of quantum numbers, such as spin, color, and charge. The final state is therefore populated by a variety of energetic particles, such as hadrons (jets), leptons, photons, and neutrinos. Due to the large number of color degrees of freedom, about 75% of the particles produced are expected to be quarks and gluons. The final state may contain significant transverse momentum imbalance from the presence of neutrinos, which constitute about 5% of the decay products. Other processes, such as the decay of W and Z bosons, or of heavy-flavor quarks, and the possible emission of gravitons or the formation of a noninteracting stable BH remnant, contribute to the transverse momentum imbalance as well.

The semiclassical approximation breaks down when the mass of the BH approaches M_D and the BH becomes a quantum object or a quantum black hole (QBH). These objects do not obey the usual BH thermodynamics and hence decay much more rapidly than their semiclassical counterparts. Their decays are characterized by the presence of only a few particles, e.g., a pair of jets [26–28]. These QBHs could also decay into lepton flavor violating final states, as preserving baryon number or lepton numbers separately is typically not a requirement of the decay process [26,27].

In addition to semiclassical BHs and QBHs, one could also explore stringy precursors of BHs, called "string balls" (SBs) [29]. Such objects, which arise in string theory, are highly excited, long, folded strings that form below the BH production threshold. Like semiclassical BHs, SBs evaporate thermally, but at a constant Hagedorn temperature [30] independent of the SB mass, and also produce a large number of energetic particles in the final state, with the composition similar to that for a semiclassical BH. String balls undergo a phase transition into ordinary semiclassical BHs when their mass reaches M_S/g_S^2 [29], where M_S and g_S are the string scale and the string coupling constant, respectively. For an SB mass between M_S/g_S and the BH transition, M_S/g_S^2, the parton-level cross section saturates at $\sigma \sim 1/M_S^2$, while for lighter SBs, it grows as $\sigma \sim g_S^2 M_{SB}^2/M_S^4$ [29].

While our choice of final states is inspired by the production of microscopic BHs, in this Letter we focus on a generic search (Section 8) that can be used to probe a large class of new-physics models. Consequently, our emphasis is on the exploration of a multiparticle final state with a model-independent search.

During Run 1 of the LHC, a number of searches for semiclassical and quantum BHs were performed at a center-of-mass energy of 8 TeV. A review of these results can be found in Ref. [31]. The limits on the minimum BH mass set by these searches lie in the 6 TeV range. With the increased LHC center-of-mass energy of 13 TeV, the BH phase space can be probed much more extensively, as was demonstrated in the recent ATLAS publications [32–34], which set BH mass limits reaching 9 TeV.

2. Analysis strategy

The most challenging aspect of the analysis presented in this Letter is accurately describing the QCD multijet background, since the BH signal leads to a broad excess in the S_T spectrum, rather than a narrow peak. Here, S_T is defined as the scalar sum of the transverse energies of jets, leptons, photons, as well as the missing transverse energy (E_T^{miss}, defined as the magnitude of the transverse momentum imbalance in an event, as detailed in Section 4):

$$S_T = \left(\sum_{i=1}^{N} E_{T,i} \right) + E_T^{miss}, \tag{4}$$

where N is the total number of final-state objects (excluding the E_T^{miss}), or the object multiplicity. For the QCD background, the final-state objects are almost exclusively jets and the E_T^{miss} is expected to be small, so the S_T variable is reduced to a scalar sum of the transverse momenta of the jets. The signal region for this search typically lies in the high-multiplicity regime where the QCD multijet background is dominated by higher-order effects. These effects have not been calculated for high-multiplicity final states, and therefore an accurate simulation of the QCD multijet background, pertinent to our signal region, does not yet exist.

This significant hurdle is mitigated by predicting the QCD multijet background directly from data using a new technique developed in Run 1 of the LHC [35–37]. Studies performed with simulated QCD multijet events and with data at low object multiplicities show that the shape of the S_T distribution above its turn-on threshold is approximately independent of the multiplicity of the final state. This observation is consistent with the development of the parton shower via nearly collinear emission, which approximately conserves the S_T value, up to the effects of additional jets falling below the kinematic threshold. For this reason one can predict the S_T spectrum of a multijet final state using samples of dijet or trijet events. This feature provides a powerful tool to predict the shape of the S_T spectrum at higher multiplicity using a low-multiplicity control region. The method has found wide applicability in various CMS searches, such as a search for stealth SUSY [38] and a search for multijet resonances [39]. An earlier CMS analysis [35] also considered other kinematic variables, such as the invariant mass or transverse invariant mass of the event. However, the multiplicity invariance is not exhibited by these variable to the degree shown by the S_T variable.

In this Letter we follow closely the methodology of Refs. [35–37] geared toward a multiparticle final state, dominated by QCD multijets in the case of semiclassical BHs, and toward a dijet final state for the QBHs. The variable S_T is the single discriminating variable used in the analysis, chosen for its robustness against variations in the BH evaporation model and its lack of sensitivity to the relative abundance of various particles produced. This variable encompasses the total transverse energy in an event and is therefore useful in discriminating between the signal and the background. There is a minimum transverse energy (E_T) threshold of 50 GeV [35] that each of the objects (including the E_T^{miss}) has to satisfy to be counted toward the definition of S_T. The exact choice of the E_T threshold is not particularly important; the 50 GeV threshold is chosen as it makes the analysis insensitive to additional interactions in the same or adjacent bunch crossings (pileup) and moderates the effect of initial-state radiation, which generally spoils the S_T invariance.

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