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Search for new resonances in photon and jet final states using CMS data

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Searching for new resonances is one of the ways at the Large Hadron Collider to look for new physics beyond the standard model (BSM), put forward by many theoretical models. Such BSM models predict for instance the existence of substructure of quarks and the quantum black holes, with their signature manifesting in different final states in proton-proton collisions at the LHC. A search for a resonance in the γ+jet final state is performed using the CMS collision data at a center-of-mass energy of 13 TeV corresponding to luminosity of 138 fb^{-1}. If the resonance exists, the signal would appear as a bump over the invariant mass distribution of the known standard model (SM) background processes. The SM background estimation is performed using data and exclusion limits are set on the model parameters in the absence of a signal in the data.

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1. Introduction

This document reports the search for resonances in events with photon and jet final states using proton-proton (pp) collision data by the CMS experiment [1] corresponding to an integrated luminosity of 138 fb^{-1}. The search could answer one of the open question of the Standard Model, why there are only three families of fermions defined in the model. Many theoretical models [2], [3] describes there is some underlying structure of the quarks and the quarks could exist in a excited state. The composite model used in this study assumes compositeness scale less than LHC energy ($\Lambda < \sqrt{s}$) and mass scale of excited quarks $M_{q^\star} = \Lambda$ with gauge interactions dominating over contact interactions in this regime.

In addition, we also consider models by Arkani-Hamed, Dimopoulos and Dvali (ADD) [5] and Randall-Sundrum (RS1) [6] for the existence of Quantum Black Holes (QBH). The models predict the fundamental Planck scale (M_D) can be as low as TeV in the $4 + n$ spacetime dimensions (where n is the number of extra dimensions), and thus QBH could be produced at the LHC. The maximum allowed mass of QBH is set to be either $3M_D$ or LHC center-of-mass energy $\sqrt{s}$, whichever is smaller. With QBHs produced between M_{th} and the maximum mass, the invariant masses of QBH production resembles to a resonance shape due to continuous falling spectrum. In this document, we are presenting a search for QBH predicted by the models ADD and RS1 decaying to γ+jet final state. The ADD model consider $n = 6$ extra flat dimensions [5] and RS1 model considers $n = 1$ extra dimension with a warped geometry [6].

2. Event Selection

The photons with transverse momentum $p_T^\gamma > 240$ GeV in the pseudorapidity (η) region of the detector $|\eta| < 1.44$ are considered as the possible photons candidates. Among these selected candidates, the highest photon which passes the identification criteria and isolation requirements is chosen as final photon candidate in an event. The jets are reconstructed using the anti-algorithm with distance parameter of 0.4 (AK4) [7]. The reconstructed AK4 jets passing identification criteria, and with $\Delta R = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2} < 1.1$ between them, are clustered together to capture the final state radiation (FSR) and thereby improving the γ+jet mass resolution. These clustered jets are named as wide-jets. The leading wide-jet with $p_T > 170$, and in the tracker region of the detector ($|\eta| < 2.4$) is considered as the final jet candidate for further data analysis. The photons should be well separated from wide-jets with $\Delta R > 1.1$, and to further suppress the t-channel background processes $|\Delta\eta(\gamma,\text{wide-jet})| < 1.5$ is applied. Additionally, a tagger condition [8] is applied to differentiate the heavy flavor ($b^\star$) jets from light jets ($q^\star \sim u^\star, d^\star$). All the selections applied are optimized based on the upper cross-section limits using the Monte-Carlo (MC) simulations. In order to avoid turn-on region due to the kinematic selections, events with m$_{\gamma+jet} > 0.76$ TeV are considered only, where m$_{\gamma+jet}$ represents the mass of photon and wide-jet system.

3. Analysis Strategy

The search for resonance is performed by looking for a bump over the invariant distribution of the γ+jet system. In the absence of any significant deviation from data over the SM, an upper limit on the cross-section and a lower limit on the mass of the signal resonance are set. The background is estimated by fitting the γ+jet mass distribution with an analytical function $\frac{d\sigma}{dm_{\gamma j}} = \frac{p_0(1-m_{\gamma j}/\sqrt{s})^{p_1}}{(m_{\gamma j}/\sqrt{s})^{p_2+p_3 \log(m_{\gamma j}/\sqrt{s})}}$, where p_0, p_1, p_2, and p_3 are the nuisance parameters describing the background distribution [9], [10]. Fig. 1 shows the fitted invariant mass distribution with the polynomial function defined. In order to evaluate any possible bias due to the choice of functional form, alternative functions are also considered and the bias is found to be negligible compared to the statistical uncertainty of the fit. The functions chosen for background estimation and performing bias studies is based on F-Test [11] and goodness-of-fit (gof) test with their p-value significance found to be greater than 0.05.

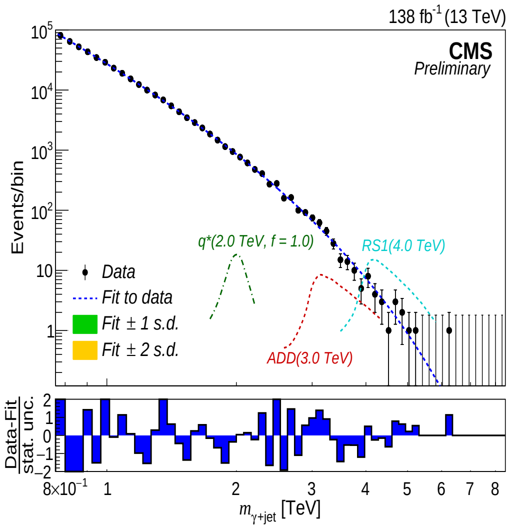

Figure 1: Fits to the γ+jet invariant mass distribution in data for q* and QBH signals. The bottom panel shows the ratio of the difference between the data and the background prediction, and the statistical uncertainty of fit. The yellow and green bands represent the 68% and 95% confidence level statistical uncertainties in the fit.

4. Results and Summary

No significant deviations from data is observed and 95% upper confidence exclusion limits (CL) [13], [14] are set on the product of cross-section (σ) and branching fraction (B) of the signal. The exclusion limits for $q^\star$ and $b^\star$ for all three coupling multipliers f = 0.1, 0.5 and 1.0 are shown in Fig. 2 and Fig. 3, respectively. The observed exclusion limit on $M_{q^\star}$ is found to be 6.0, 5.4 and 2.4 TeV for coupling strength f = 1.0, 0.5 and 0.1, respectively. Similarly, the observed exclusion limit on $b^\star$ is set to 2.15 and 1.6 TeV for the coupling strength f =1.0 and 0.5, while for f = 0.1 the analysis could not reach the required sensitivity. However, for the $b^\star$ signal search an additional interpretation of $b^\star$ produced via contact interactions (CI) [12] decaying to photon and jet is also considered. The observed limits on $b^\star$ when combining both processes of $b^\star$ produced via gauge and CI are set to be 3.8 TeV, as shown in Fig. 3 (upper left). The QBH signal with the ADD (RS1) model with n = 6(1) extra dimensions are excluded up to the mass 7.5 (5.2) TeV, as shown in Fig. 4. More details on the results can be found in Ref. [15].

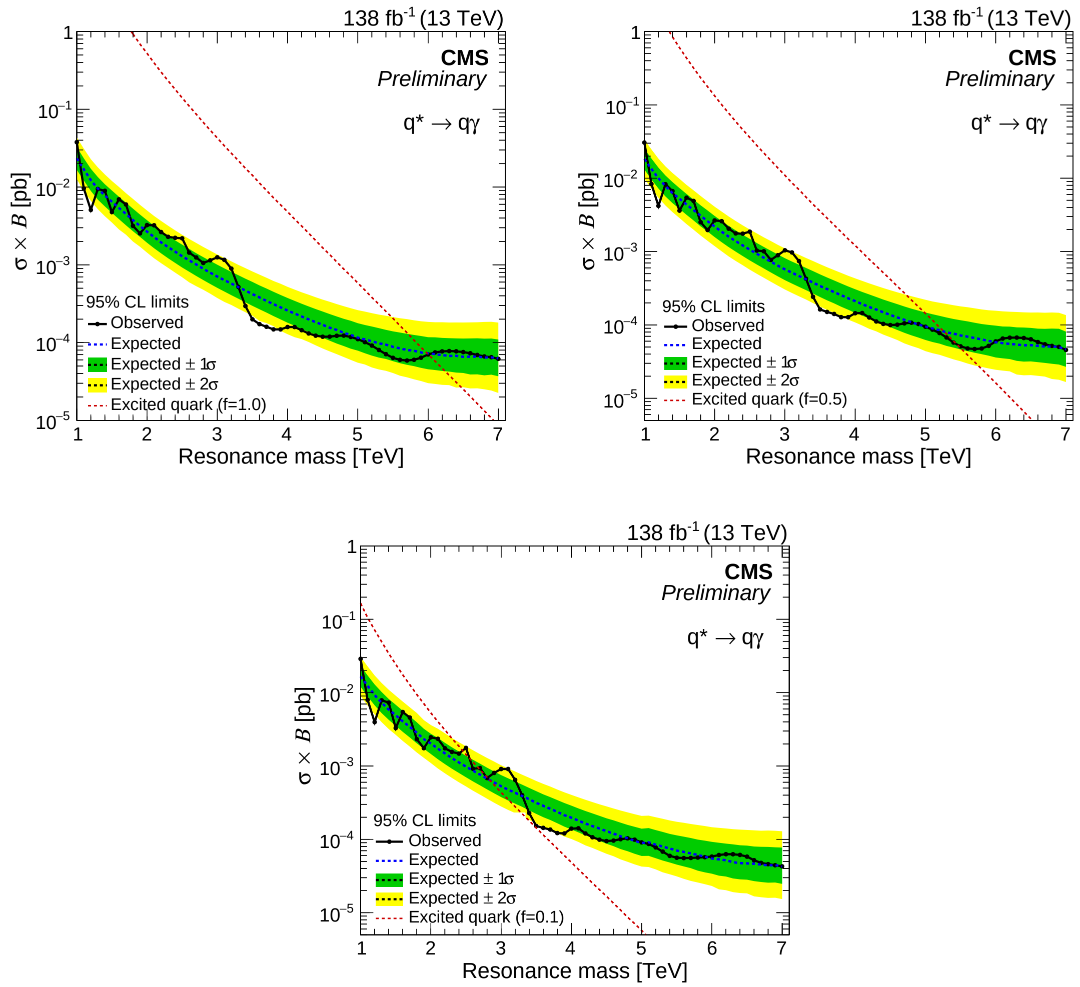

Figure 2: The expected (dashed) and observed (solid) 95% upper limits on $\sigma \times B$, as functions of the $q^{\star}$ signal mass for coupling strength $f = 1.0$ (upper left), $f = 0.5$ (upper right), and $f = 0.1$ (lower). The green (inner) and yellow bands (outer) correspond to 1 and 2 standard deviation uncertainties in the expected limit, respectively. The limits are compared with the theoretical predictions for $q^{\star}$ production for the corresponding coupling strengths.

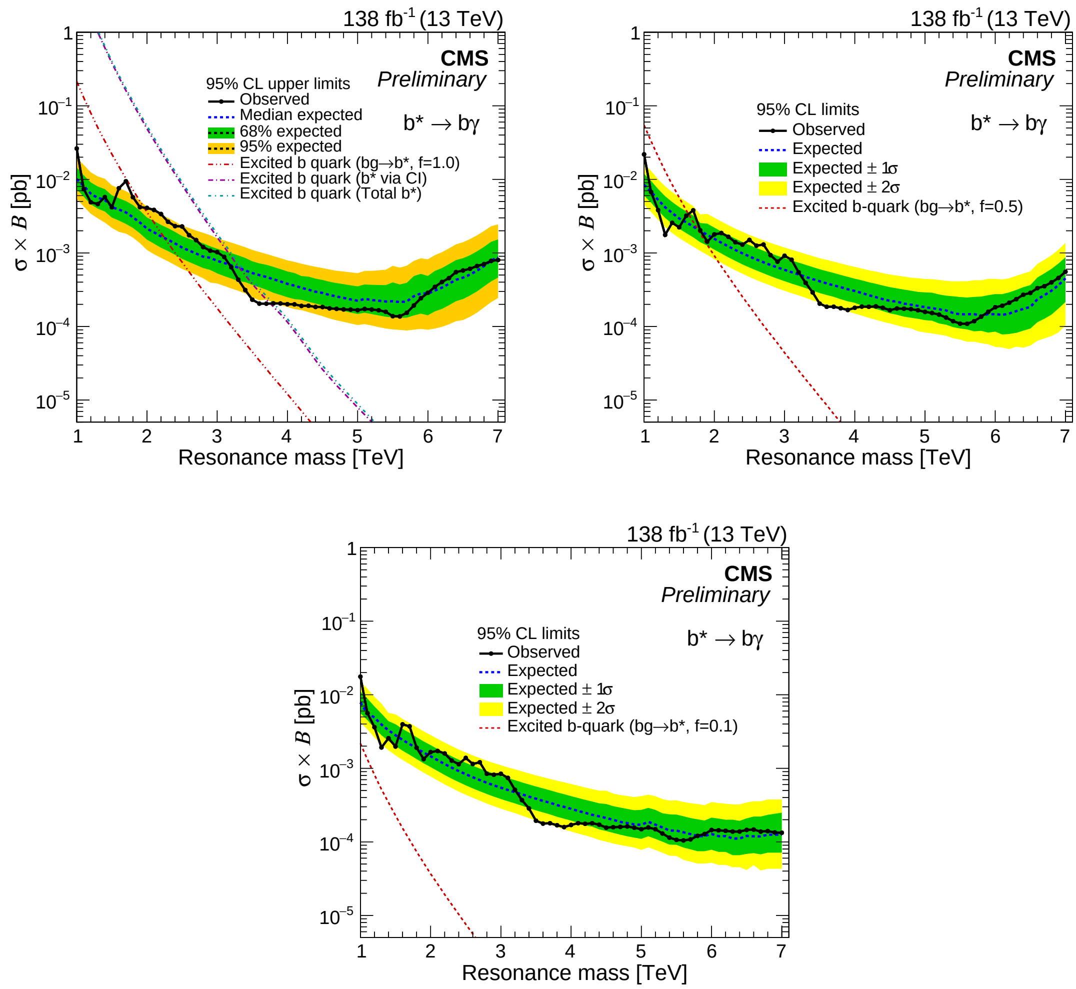

Figure 3: The expected (dashed) and observed (solid) 95% upper limits on $\sigma \times B$, as functions of the $q^\star$ signal mass for coupling strength $f = 1.0$ (upper left), $f = 0.5$ (upper right), and $f = 0.1$ (lower). The green (inner) and yellow bands (outer) correspond to 1 and 2 standard deviation uncertainties in the expected limit, respectively. The limits are compared with the theoretical predictions for $b^\star$ production for the corresponding coupling strengths.

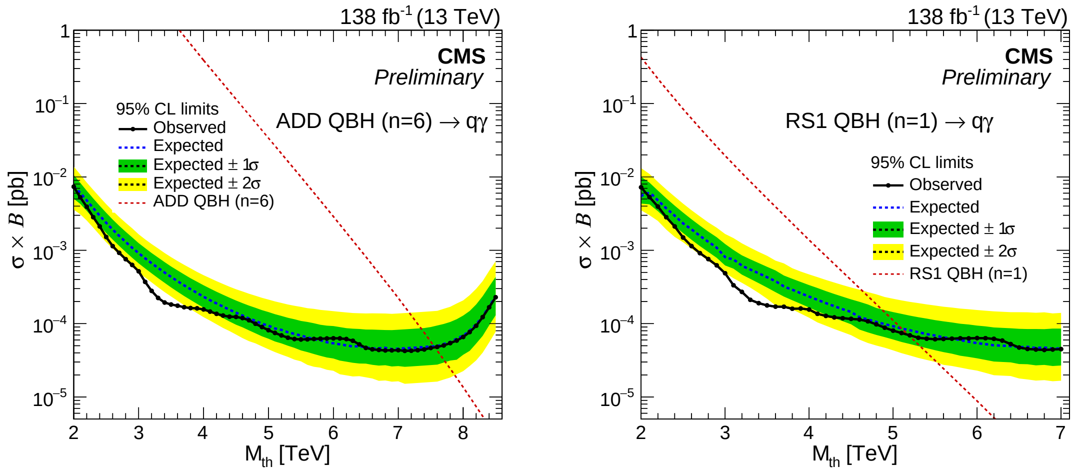

Figure 4: The expected (dashed) and observed (solid) 95% upper limit on $\sigma \times B$ for the ADD ($n = 6$) and RS1 ($n = 1$) models, as a function of the minimum black hole mass on the left and right, respectively. The green (inner) and yellow bands (outer) correspond to 1 and 2 standard deviation uncertainties in the expected limit. The limits are compared with the theoretical predictions for QBH production for ADD ($n = 6$) and RS1 ($n = 1$) models.

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