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Search for excited quarks in the γ + jet final state in proton–proton collisions at $\sqrt{s} = 8$ TeV

CMS Collaboration *

CERN, Switzerland

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A search for excited quarks decaying into the γ + jet final state is presented. The analysis is based on data corresponding to an integrated luminosity of 19.7 fb^{-1} collected by the CMS experiment in proton–proton collisions at $\sqrt{s} = 8$ TeV at the LHC. Events with photons and jets with high transverse momenta are selected and the γ + jet invariant mass distribution is studied to search for a resonance peak. The 95% confidence level upper limits on the product of cross section and branching fraction are evaluated as a function of the excited quark mass. Limits on excited quarks are presented as a function of their mass and coupling strength; masses below 3.5 TeV are excluded at 95% confidence level for unit couplings to their standard model partners.

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1. Introduction

The standard model (SM) of strong and electroweak interactions is a theory that successfully describes a wide range of phenomena in particle physics. Despite its immense success, the theory leaves many questions unanswered, which suggests that the SM may be an effective, low-energy approximation of a more fundamental theory. Many proposals for physics beyond the SM are based on the assumption that quarks are composite objects. The most compelling evidence of quark substructure would be provided by the discovery of an excited state of a quark. An excited quark ($q^\star$) may couple to an ordinary quark and a gauge boson via gauge interactions given by the Lagrangian [1–3]:

$$\mathcal{L}_{\text{int}} = \frac{1}{2\Lambda}\bar{q}^*_R\sigma^{\mu\nu}\left[g_s f_s \frac{\lambda_a}{2} G^a_{\mu\nu} + g f \frac{\tau}{2} W_{\mu\nu} + g' f' \frac{Y}{2} B_{\mu\nu}\right] q_L + \text{h.c.}, \tag{1}$$

where $q^\star_R$ is the excited quark field, $\sigma_{\mu\nu}$ is the Pauli spin matrix, q_L is the quark field, $G^a_{\mu\nu}$, $W_{\mu\nu}$ and $B_{\mu\nu}$ are the field-strength tensors of the SU(3), SU(2) and U(1) gauge fields, λ_a, τ, Y are the corresponding gauge structure constants and g_s, g, g' are the gauge coupling constants. The compositeness scale, Λ, is the typical energy scale of these interactions, and f_s, f, f' are unknown dimensionless constants determined by the compositeness dynamics, which represent the strengths of the excited quark couplings to the SM partners and are usually assumed to be of order unity. In proton–proton collisions, the production and decay of excited quarks, could occur via either gauge or contact interactions [2]. The production of $q^\star$ via gauge interactions would proceed through quark–gluon (qg) annihilation. In this analysis, which assumes gauge interactions, excited quarks would then decay into a quark and a gauge boson (γ, g, W, Z) and appear as resonances in the invariant mass distribution of the decay products. Many searches for excited quarks have been performed in various decay channels [4–13], but no evidence of their existence has been found to date.

This Letter presents the first search by the CMS experiment for a resonance peak in the γ + jet final state. The data set used in this study was collected in 2012 in proton–proton collisions at the CERN LHC at a center-of-mass energy of $\sqrt{s} = 8$ TeV and corresponds to an integrated luminosity of 19.7 fb^{-1}.

Only spin-1/2, mass degenerate excited states of the first generation quarks, $q^\star(= u^\star, d^\star)$, which would be expected to be predominantly produced in pp collisions, are considered [2,3]. We focus on the scenario where the compositeness scale is the same as the mass of the excited quark, i.e., $\Lambda = M_{q^\star}$ and assume that f_s, f, and f' have the same value, denoted by f.

The dominant background for this search is SM γ + jet production. This process is an irreducible background, which is produced at leading order (LO) through quark–gluon Compton scattering ($qg \to q\gamma$) and quark–antiquark annihilation ($q\bar{q} \to g\gamma$).

* *E-mail address:* cms-publication-committee-chair@cern.ch.

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The second-largest background is from quantum chromodynamics (QCD) dijet and multijet production, where one of the jets with high transverse momentum p_T^{jet} mimics an isolated photon. This background falls rapidly with the photon transverse momentum p_T^{γ} as compared to the γ + jet background. The electroweak production of $W/Z + \gamma$ would yield similar final states, but owing to their small cross section, these backgrounds are negligible.

2. CMS detector

The CMS experiment uses a right-handed coordinate system, with the origin at the nominal interaction point, the x axis pointing to the center of the LHC, the y axis pointing up (perpendicular to the LHC plane), and the z axis along the counterclockwise-beam direction. The polar angle θ is measured from the positive z axis and the azimuthal angle ϕ is measured in the x–y plane. The central feature of the CMS apparatus is a superconducting solenoid of 6 m internal diameter, providing a magnetic field of 3.8 T. Within the superconducting solenoid volume are a silicon pixel and strip tracker, a lead tungstate crystal electromagnetic calorimeter (ECAL), and a brass/scintillator sampling hadron calorimeter (HCAL). The ECAL consists of nearly 76 000 crystals and provides coverage in pseudorapidity up to $|\eta| < 1.48$ in the barrel region and $1.48 < |\eta| < 3.0$ in the two endcap regions, where pseudorapidity is defined as $\eta = -\ln[\tan(\theta/2)]$. Each crystal subtends an area of 0.0174×0.0174 in the η–ϕ plane in the barrel region. In the region $|\eta| < 1.74$, the HCAL cells have widths of 0.087 in pseudorapidity and 0.087 in azimuth. In the η–ϕ plane, and for $|\eta| < 1.48$, the HCAL cells map on to 5×5 ECAL crystals arrays to form calorimeter towers projecting radially outwards from close to the nominal interaction point. At larger values of $|\eta|$, the size of the towers increases and the matching ECAL arrays contain fewer crystals. A detailed description of the CMS detector can be found elsewhere [14].

The CMS experiment uses a two-tier trigger system consisting of the first-level (L1) trigger and High Level Trigger (HLT). The L1 trigger, which is comprised of custom electronics, reduces the readout rate from the bunch crossing frequency of approximately 20 MHz to below 100 kHz. The HLT is a software-based trigger system that makes use of information from all sub-detectors, including the tracker, to further decrease the event rate to about 400 Hz. Only those events passing the L1 trigger are considered by the HLT. In the HLT the photon trigger uses the same clustering algorithms as are used by the offline photon reconstruction. Events used in this analysis passed a trigger that required at least one photon with transverse energy greater than 150 GeV. The trigger is fully efficient for offline reconstructed photons with p_T greater than 170 GeV.

3. Event selection

Each event is required to have at least one primary vertex reconstructed within $|z| < 24$ cm from the center of the detector and with a transverse distance less than 2 cm from the z-axis. The event reconstruction is performed using a particle-flow algorithm [15,16], which reconstructs and identifies individual particles using an optimized combination of information from all subdetectors. Photons are identified as energy clusters in the ECAL. These energy clusters are merged to form superclusters that are 5 crystals wide in η, centered around the most energetic crystal, and have a variable width in ϕ. The energy of charged hadrons is determined from a combination of the track momentum and the corresponding ECAL and HCAL energy, corrected for the combined response function of the calorimeters. The energy of neutral hadrons is obtained from the corresponding corrected ECAL and HCAL energies. For each event, hadronic jets are formed from these reconstructed particles with the infrared- and collinear-safe anti-k_T algorithm [17], using a distance parameter $\Delta R = 0.5$, where $\Delta R = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2}$ and $\Delta\eta$ and $\Delta\phi$ are the pseudorapidity and azimuthal angle difference between the jet axis and the particle direction. Jet energy corrections are applied to every jet to establish a uniform calorimetric response in η and a more precise absolute response in p_T^{jet}. Jet energy scale (JES) corrections are derived from Monte Carlo (MC) simulations, and a residual correction is derived from data [18].

Events are required to have at least one photon in the barrel region that has $p_T^{\gamma} > 170$ GeV. Photons (which can include those from π^0 decays or from electron bremsstrahlung) are identified as objects associated with ECAL energy clusters not linked to the extrapolation of any charged-particle trajectory to the ECAL. They are further required to have an ECAL shower energy profile consistent with that of a photon. The photon with the highest p_T (leading) in the event is selected as the photon candidate. The photon candidates must also satisfy the following isolation criteria: (a) the energy deposited in the single HCAL tower closest to the supercluster position, inside a cone of $\Delta R = 0.15$ centered on the photon direction, must be less than 5% of the energy deposited in that ECAL supercluster; (b) the total p_T of photons within a cone of $\Delta R = 0.3$, excluding strips of width $\Delta\eta = 0.015$ on each side of the supercluster, must be less than $0.5\ \text{GeV} + 0.005 p_T^{\gamma}$; (c) the total p_T of all charged hadrons within a hollow cone of $0.02 < \Delta R < 0.3$ about the supercluster must be less than 0.7 GeV; (d) the total p_T of all neutral hadrons within a cone of $\Delta R = 0.3$ must be less than $0.4\ \text{GeV} + 0.04 p_T^{\gamma}$. These isolation variables are corrected for the presence of additional reconstructed vertices associated with extra interactions in the same bunch crossing (pileup) by subtracting the average energy calculated from the typical energy density in the event, as computed using the FastJet package [19]. The signal efficiency is found to be ∼70% for the photon identification and isolation selection criteria. Anomalous calorimeter signals [20], caused by isolated large noise in the detector could be reconstructed as photon candidates. A selection is therefore applied on the shower shape variables to largely remove such photon candidates from the event. In addition, to reduce the anomalous calorimeter noise signals [21], the ECAL crystals with energy greater than 1 GeV are required to be within a 5 ns window relative to the supercluster time.

The leading jet separated from the photon candidate by $\Delta R > 0.5$ and satisfying particle flow based jet identification criteria [22] is selected as the jet candidate. The jet identification criteria include requirements on the number of constituents and on the fraction of the jet energy held by each constituent type. The jet candidate is required to be within the pseudorapidity region $|\eta^{jet}| < 3.0$ and must have a transverse momentum $p_T^{jet} > 170$ GeV. The invariant mass of γ + jet is calculated using the leading photon and jet candidates and is given by $M_{\gamma,\text{jet}} = \sqrt{(E^{\gamma} + E^{jet})^2 - (\vec{p}^{\gamma} + \vec{p}^{jet})^2}$, where E and $\vec{p}$ denote the energy and momentum, respectively, of the photon and of the jet.

The production of excited quarks via the expected s-channel process would result in an isotropic distribution of final-state objects. All backgrounds are produced predominantly through t-channel processes and have an angular distribution that is strongly peaked in the forward or backward direction. Therefore, to reduce these backgrounds while retaining high signal acceptance, the leading photon and jet candidates are required to satisfy $|\Delta\eta(\gamma, \text{jet})| < 2.0$. To ensure the back-to-back topology expected in a two body final state, $|\Delta\phi(\gamma, \text{jet})| > 1.5$ is required between the photon and jet candidates. The above-mentioned thresholds for $|\Delta\eta|$, $|\Delta\phi|$, and $|\eta^{jet}|$ selection were chosen to optimize the search

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