Resonance search for quark excitation with the CMS experiment

Varun Sharma
Department of Physics & Astrophysics, University of Delhi, Delhi-110062, India

Abstract

A search for excited quarks ($q^\star$) decaying into a $\gamma + \text{jet}$ final state in pp collisions at $\sqrt{s} = 8$ TeV is presented. The search is done with the data taken by the CMS experiment at the CERN LHC and corresponds to an integrated luminosity of 19.7 fb$^{-1}$. We find no deviation from the standard model predictions and evaluate the 95% CL upper limits on cross section times branching fraction as a function of excited quark mass ($M_{q^\star}$). Limits on excited quarks are presented as a function of their mass and coupling strength; masses below 3.5 TeV are excluded at 95% CL for unit couplings to their standard model partners.

Keywords: CMS, physics, photon, jet, excited quarks

1. Introduction

The standard model (SM) of particle physics has emerged as the most successful theory, with experimental results being consistently in agreement with its predictions, especially after the discovery of a Higgs boson in proton-proton collisions at the CERN LHC. Still it is conceivable that the SM is just an effective theory and that above a certain energy scale new physics emerges, as it falls short of providing the answer to several mysteries that particle physics seeks to unravel. Among several proposals, suggested by theorists, the compositeness model [1] in which both the quarks and leptons are composed of fundamental entities called preons, attempts to explain the mass hierarchy and the observed patterns within different generations of fermions. The effective Lagrangian which describes the coupling of excited fermions states with SM partners via gauge interactions is given by,

$$\mathcal{L}_{\text{int}} = \frac{1}{2\Lambda} q^\star R G_{\mu\nu} \left[ g_s f_s \frac{\Lambda_s}{2} G_{\mu\nu}^\tau + g f \frac{\tau W_{\mu\nu} + g' f' \frac{Y}{2} B_{\mu\nu}}{2} q_L + \text{h.c.} \right],$$  \hfill (1)

where $\Lambda$ is the compositeness scale, $G_{\mu\nu}^\alpha$, $W_{\mu\nu}$ and $B_{\mu\nu}$ are the field-strength tensors of the SU(3), SU(2) and U(1) gauge fields, with corresponding gauge structure constants, $\lambda_s$, $\tau$, $Y$ and gauge coupling constants $g_s$, $g$, $g'$. Coupling multipliers to SU(3), SU(2) and U(1) field-strength tensors are given by $f_s$, $f$, $f'$, respectively.

The proceeding reports the search for a resonance peak in the $\gamma + \text{jet}$ final state by the CMS experiment [2] using data collected in proton-proton collisions at the CERN LHC at $\sqrt{s} = 8$ TeV and corresponding to an integrated luminosity of 19.7 fb$^{-1}$ [3].

This study takes into account only spin-1/2, mass degenerate excited states of first generation quarks, $q^\star(=u^\star, d^\star)$. The compositeness scale is considered same as the mass of the excited quark, i.e., $\Lambda = M_{q^\star}$, along with the assumption that $f_s$, $f$, and $f'$ have the same value, denoted by $f$.

The dominant background for this search is the SM $\gamma$+jet production, which is irreducible and includes both quark-gluon Compton scattering ($qg \rightarrow q\gamma$) and quark-antiquark annihilation ($q\bar{q} \rightarrow \gamma\gamma$). The second-largest background is from QCD the dijet and multijet production, where one of the jets mimics an isolated photon, followed by small contribution from electroweak production of $W/Z+\gamma$ processes.
2. Object reconstruction and event selection

Jet in an event is reconstructed using particle-flow technique, which consists of reconstructing and identifying muons, electrons, photons, charged and neutral hadrons with an optimized combination of all sub-detector information. These particles are clustered into jets using the anti-$k_t$ algorithm with a distance parameter of 0.5. Photons are identified as energy clusters in the electromagnetic calorimeter (ECAL). These clusters are grouped to form superclusters that are 5 crystals wide in $\eta$, centered about the most energetic crystal, and have a variable width in $\phi$.

Events selected by CMS two-tier trigger system which also includes presence of at least one photon with transverse energy greater that 150 GeV are used for analysis. Each event is required to have at least one primary vertex reconstructed within longitudinal coordinate of the vertex, $|z| < 24$ cm; and the spatial separation in transverse plane from the beam position $\rho$ should not exceed 2 cm.

Photon candidates are selected by requiring the ratio of the energy deposited in the closest HCAL tower to that of the ECAL to be less than 0.05 and the spatial distribution of energy from the EM shower to be consistent with that expected for a photon. It should also satisfy the stringent photon isolation requirement based on the PF algorithm, which include:

- the scalar sum $P_T$ of photons within a cone of $\Delta R < 0.3$ excluding a strip in $\eta$ of 0.015 about the supercluster must be less than 0.5 GeV + 0.005 $P_T^\gamma$;
- 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;
- the total $P_T$ of all neutral hadrons within a cone of $\Delta R = 0.3$ must be less than 0.4 GeV + 0.04 $P_T^\gamma$.

These isolation variables are corrected for the presence of additional vertices associated with extra interactions in the same bunch crossing by subtracting the average energy evaluated from the typical energy density in the event. Events are required to have at least one photon in the barrel region, i.e., $|\eta^\gamma| < 1.44$, with $P_T^\gamma > 170$ GeV. The highest $P_T$ jet (leading) should be separated from the photon candidate by $\Delta R > 0.5$ and satisfying particle flow based jet identification criteria is selected as the jet candidate. The jet candidate is required to be within the pseudorapidity region $|\eta^\text{jet}| < 3.0$ and must have $P_T^\text{jet} > 170$ GeV.

To retain high signal acceptance and reduce QCD dijet background, the leading photon and jet candidates are required to satisfy $|\Delta \eta(\gamma, \text{jet})| < 2.0$. To ensure 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. A selection on the mass, $M_{\gamma,\text{jet}} > 560$ GeV, is applied to avoid the kinematical turn-on region associated with the various selection requirements. The acceptance ($A$) $\times$ efficiency ($e$) for full event selection of $q^* \rightarrow q\gamma$ signal for resonance mass of 1 TeV is shown in Table 1.

<table>
<thead>
<tr>
<th>Selection criteria</th>
<th>$A \times e$ (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Photon identification &amp; isolation</td>
<td>70.2</td>
</tr>
<tr>
<td>$P_T^\gamma &gt; 170$ GeV</td>
<td>67.2</td>
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<tr>
<td>$</td>
<td>\eta^\gamma</td>
</tr>
<tr>
<td>$P_T^\text{jet} &gt; 170$ GeV</td>
<td>63.6</td>
</tr>
<tr>
<td>$</td>
<td>\eta^\text{jet}</td>
</tr>
<tr>
<td>$</td>
<td>\Delta \phi(\gamma, \text{jet})</td>
</tr>
<tr>
<td>$</td>
<td>\Delta \eta(\gamma, \text{jet})</td>
</tr>
<tr>
<td>$M_{\gamma,\text{jet}} &gt; 560$ GeV</td>
<td>54.2</td>
</tr>
</tbody>
</table>

Table 1: The acceptance times efficiency for event selection of $q^* \rightarrow q\gamma$ signal for resonance mass of 1 TeV.

3. Signal and background modeling

The expected signal from excited quarks, backgrounds from $\gamma$+jet and dijet MC predictions are generated using PYTHIA6.426, while electroweak backgrounds are taken from the MadGraph event generator. A K-factor of 1.3 is used to scale the PYTHIA $\gamma$ + jet and dijet production to account for the next-to-leading contributions. The generated events are processed with a full detector simulation based on GEANT4. The MC prediction is normalized to the integrated luminosity of the data sample. The invariant mass distribution of the $\gamma$ + jet events in the collected data and for simulated events, after applying all the selection, are shown in Fig. 1.
4. Results

The sources of systematic uncertainties affecting only signal are listed in Table 2. The uncertainty associated with JER and PER translate into a 5% relative uncertainty in the mass resolution, while effects of JES and PES uncertainties are estimated to be 0.5-0.7% (as a function of $\gamma$ + jet mass) and 0.7%, respectively. For the background shape uncertainty, the background parameters are marginalized with a flat prior.

A Bayesian formalism using a binned likelihood with a uniform prior for the signal cross section is used for estimating the 95% confidence level (CL) upper limit on the cross section. Log-normal prior distribution functions are used to model the systematic uncertainties which are treated as nuisance parameters to evaluate the limits.

The 95% CL upper limits on $\sigma \times B$ as a function of $M_{q^*}$ is shown in Fig. 2. A lower bound of 3.5 (2.9) TeV on the mass of excited quarks is obtained for $f = 1.0 (0.5)$ by comparing the observed limits with the leading order theoretical predictions. The results shown in Fig. 3 presents limits on the excited quark mass as a function of compositeness scale.

5. Summary

A search for excited quarks in the $\gamma +$ jet final state in the proton-proton collision data set at $\sqrt{s} = 8$ TeV has been presented. The data are found to be consistent with the predictions of the standard model and upper limits are placed on $\sigma \times B$ for $q^*$ production in the $\gamma +$ jet final state.