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Search for Production of Resonant States in the Photon-Jet Mass Distribution
Using pp Collisions at $\sqrt{s} = 7$ TeV Collected by the ATLAS Detector

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This Letter describes a model-independent search for the production of new resonant states in photon + jet events in 2.11 fb$^{-1}$ of proton-proton collisions at $\sqrt{s} = 7$ TeV. We compare the photon + jet mass distribution to a background model derived from data and find consistency with the background-only hypothesis. Given the lack of evidence for a signal, we set 95% credibility level limits on generic Gaussian-shaped signals and on a benchmark excited-quark ($q^*$) model, excluding 2 TeV Gaussian resonances with cross section times branching fraction times acceptance times efficiency near 5 fb and excluding $q^*$ masses below 2.46 TeV, respectively.

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In the standard model (SM), proton-proton (pp) collisions do not produce photon + jet pairs through a resonance. Direct photon + jet production occurs at tree level via Compton scattering of a quark and a gluon or through quark-antiquark annihilation, the former accounting for the majority of direct photon + jet production at all center-of-mass energies. Events with a high transverse momentum photon and one or more jets can also arise from radiation off final-state quarks or from multijet processes where dijet or higher-order events produce secondary photons during fragmentation of the hard-scatter quarks and gluons [1–4]. The photon + jet invariant mass ($m_{\gamma j}$) [5] distribution resulting from this mixture of processes is smooth and rapidly falling, constituting a promising place to look for resonances.

Despite many possible exotic production mechanisms such as excited quarks [6,7], quirks [8–10], Regge excitations of string theory [11–14], and topological pions [15], the most recent searches for photon + jet resonances were published a decade ago [16–19]. The previous most sensitive search for new phenomena in the photon + jet final state places limits on effective signal cross section, cross section times branching fraction times acceptance times efficiency near 5 fb and excluding $q^*$ masses below 2.46 TeV, respectively.

This Letter describes a general search for resonant s-channel photon + jet production in 2.11 fb$^{-1}$ of pp collisions at a center-of-mass energy $\sqrt{s} = 7$ TeV with the ATLAS detector. It follows earlier measurements of isolated photon differential cross sections at the Large Hadron Collider (LHC) [20,21]. The entire $m_{\gamma j}$ distribution is fit to a smooth function to obtain the background to this search. We look for evidence of a narrow resonance, not much wider than the detector mass resolution. This search extends the method used in the search for resonant dijet production [22] to handle the more diverse mixture of processes contributing to the $m_{\gamma j}$ distribution. In the absence of a signal, we use Bayes’ theorem to set limits on Gaussian-shaped resonances and on a benchmark excited-quark ($q^*$) model [6,7].

In the excited-quark model studied here, the LHC could produce single $q^*$ states with vectorlike couplings to the W and Z gauge bosons via the absorption of a gluon by a quark. As in Ref. [7], we define the model by one parameter, the excited-quark mass $m_{q^*}$, setting the compositeness scale equal to $m_{q^*}$ and SU(3), SU(2), and U(1) coupling multipliers $f_s = f = f' = 1$. At $m_{q^*} = 2.5$ TeV, this gives branching fractions for $u^* \to ug$ and $u^* \to uy$ of 0.85 and 0.02, respectively. The corresponding branching fractions for $d^*$ quarks are 0.85 and 0.005, respectively. We do not make any further assumptions about higher-order corrections or the excited-quark dynamics and neglect scale uncertainties and uncertainties on parton distribution functions in order to provide a convenient benchmark process for theoretical reinterpretation.

We simulate the SM direct photon processes and the $q^*$ model with PYTHIA 6.4.25 [23] using the AMBT1 tune [24], MSTW2007 parton distribution functions [25], and a GEANT4-based detector simulation [26,27]. Supplementary studies of the background shape function are performed with next-to-leading-order JETPHOX 1.3.0 [1,2]. Additional inelastic pp interactions, termed pileup, are included in the event simulation, distributed so as to reproduce the number of collisions per bunch crossing in the data. The mean number of pileup interactions is approximately 6.

A detailed description of the detector is available in Ref. [28]. Photons are detected by a lead–liquid-argon sampling electromagnetic calorimeter (EMC) with an

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When more than one photon or jet is found, the highest criteria that closely follow those applied in the isolated j
Ref. [30]. Events are collected with a trigger requiring at photon identification and measurement, see Ref. [20]. For details relevant with liquid-argon calorimeters for both electromagnetic and hadronic measurements. For further details relevant behind the EMC provides hadronic coverage. The endcap
Ref. [31,32]. For details relevant to photon candidates to account for energy loss in the electromagnetic and hadronic calorimeter cells inside a cone of radius \( \Delta R = \sqrt{\Delta \eta^2 + (\Delta \phi)^2} = 0.4 \) centered on the photon cluster, but excluding the energy of the photon cluster itself. The isolation energy is corrected on an event-by-event basis for the ambient energy density due to pileup and the underlying event. This isolation energy is required to be less than 7 GeV.

The photon deposits energy in the electromagnetic calorimeter in such a way that it is also reconstructed as a jet. Jets within \( \Delta R < 0.2 \) of the photon are therefore not considered in this analysis. We require an angular separation \( \Delta R(\gamma, \text{jet}) > 0.6 \) between the signal photon and all jets with \( p_T > 30 \text{ GeV} \) to reduce the background from photons during fragmentation of final-state quarks (fragmentation photons) and to reduce the systematic effects from the leakage of nearby jet showers into the photon isolation energy measurement.

An additional reduction of the fragmentation photon background is achieved by requirements on the photon and jet pseudorapidities. Dijet production rates increase with jet pseudorapidity whereas rates for our assumed \( s \)-channel signal would diminish. We restrict the analysis to photons in the barrel calorimeter, \( |\eta| < 1.37 \), and to require \( |\eta_{\gamma} - \eta_{\text{jet}}| < 1.4 \) between the photon and jet. The former condition was chosen to avoid kinematic bias of the \( m_{\gamma j} \) distribution due to the inclusion of any \( \eta \) range where reconstruction efficiency is lower, such as the barrel-endcap transition region \( 1.37 < |\eta| < 1.52 \). The latter was chosen by optimizing the expected significance using the \( |\eta_{\gamma} - \eta_{\text{jet}}| \) distributions found in excited-quark signal simulation and background-dominated control data selected as in the nominal analysis but inverting the photon isolation requirement. This control sample is also used to check the background estimate.

After the above selections, Fig. 1 shows the distribution of the \( m_{\gamma j} \) invariant mass in bins equal to the mass resolution. The \( m_{\gamma j} \) resolution is about 4% at 600 GeV, improving to 3% at 2 TeV. We determine the combined SM and instrumental background to the search by fitting this distribution to the four-parameter ansatz,

\[
f(x \equiv m_{\gamma j}/\sqrt{s}) = p_1 (1 - x)^{p_2} x^{-p_3} e^{-p_4 x}.
\]

The motivation for this function is discussed in Refs. [16,35–37]. The fit result is also shown in Fig. 1. The bottom panel of the figure shows the statistical significance of the difference between data and the fit in each bin [38]. With a negative log-likelihood test statistic, the \( p \)
FIG. 1 (color online). Invariant mass of the photon + jet pair for events passing the final selection. Overlaid: The fitted background function integrated over each bin (stepped solid line), the most discrepant region identified by BUMPHUNTER (two dashed vertical lines), and three examples of excited-quark signals, normalized to luminosity, as described in the text. The bottom panel shows the statistical significance of the difference between data and background in each bin.

The leading-order PYTHIA direct photon prediction implemented in JETPHOX, which includes the next-to-leading-order nonisolated and fragmentation photon events. For example, the function describes the next-to-leading-order prediction implemented in JETPHOX, which includes the fragmentation photon contributions, for some viable choices of theory parameters but not for others.

The second background systematic uncertainty accounts for any unmodeled features of fragmentation photon events in our isolated photon sample. We fit the background function to the $m_{\gamma j}$ distribution in the control data selected with the inverted isolation requirement, then measure for each $m_{\gamma j}$ bin the magnitude of any deviation from the fit, and assign the ratio of the deviation to the fit expectation as a parametrization bias systematic uncertainty. To extrapolate this uncertainty to large $m_{\gamma j}$ where few control data exist, we fit the tail $m_{\gamma j} > 1$ TeV with a two-degree polynomial.

Figure 2 shows the model-independent limits on the effective cross section, cross section $\sigma$ times branching fraction $B$ times acceptance $A$ times efficiency $\epsilon$, of a potential signal as a function of the central mass of each signal template. We take the signal line shape to be a Gaussian distribution with one of three widths, $\sigma_G/m_G = 5\%, 7\%$, and $10\%$ of the central mass of the
Gaussian. The limit weakens as the width increases and the peak becomes less distinct. For example, for a 1 TeV signal the limit for a width of 10% is 1.6 times the limit for a width of 5%.

The limit on the effective cross section in the excited-quark model is shown in Fig. 3 as a function of the photon mass. Also shown are uncertainty bands indicating the underlying distribution of possible limit outcomes in the background-only hypothesis. The solid line indicates the prediction from the PYTHIA excited-quark implementation. We exclude such excited quarks with masses below 2.46 TeV at 95% CL, complementing the more stringent exclusion below 2.99 TeV on this specific q⁻ model in the dijet final state [22].

In conclusion, the photon + jet mass distribution measured in 2.11 fb⁻¹ of pp collision data collected at √s = 7 TeV by the ATLAS Collaboration has been examined for narrow resonances. The observed distribution extends up to masses of about 2 TeV. It is well described by a smooth function fitted to it and assumed to represent the SM expectation. No evidence for the production of resonances is found. We set limits at 95% CL on the Gaussian line shape and excited-quark model in the photon + jet final state for masses up to 2.46 TeV. The limits reported here on the resonant production of new particles in the photon + jet final state are the most stringent limits set to date in this channel.

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The invariant mass $m_{\gamma j}$ is defined as $\sqrt{(E_\gamma^2 + E_j^2) - (p_\gamma^2 + p_j^2)}$, where $E$ and $p$ denote the energy and momentum, respectively, of the photon and the jet.


ATLAS uses a right-handed coordinate system with the z axis along the beam pipe. The x axis points to the center of the LHC ring, and the y axis points upward. Cylindrical coordinates $(r, \phi)$ are used in the transverse plane, with azimuthal angle $\phi$. The pseudorapidity is defined in terms of the polar angle $\theta$ as $\eta = -\ln\tan(\theta/2)$. The transverse momentum and energy are defined as $p_T = p \sin \theta$ and $E_T = E \sin \theta$, respectively.
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