

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 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 hypothesis. Given the lack of evidence for a signal, we set 95% CL 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.

PACS numbers: 12.60.-i,13.85.Rm,14.70.Bh,14.80-j

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 multi-jet 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 sections, cross section times branching fraction times acceptance times efficiency, of the order of 1 pb and on excited-quark masses up to 460 GeV at the 95% confidence level [16].

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 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 vector-like 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 $u^* \rightarrow u\gamma$ and $u^* \rightarrow u\gamma$ 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 (PDFs) 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 PDFs [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 pile-up, 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 pile-up 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 accordion geometry. In front of the EMC, the inner detector allows an accurate reconstruction of tracks from the primary pp collision point and also from secondary vertices, permitting an efficient reconstruction of photon conversions in the inner detector up to a radius of 80 cm. For $|\eta| < 1.37$ [29], an iron/scintillator-tile calorimeter behind the EMC provides hadronic coverage. The endcap and forward regions, $1.5 < |\eta| < 4.9$, are instrumented with liquid-argon calorimeters for both electromagnetic and hadronic measurements. For further details relevant to photon identification and measurement, see Ref. [20].

For details relevant to jet detection and measurement, see Ref. [30]. Events are collected with a trigger requiring at least one photon candidate with transverse momentum (p_T) above 80 GeV. The integrated luminosity of the sample is $(2.11 \pm 0.08) \text{ fb}^{-1}$ [32, 33].

Events containing at least one photon and at least one jet are selected for analysis. Each event must have a primary vertex with at least five charged-particle tracks with $p_T > 400$ MeV. Multiple vertices can appear when pile-up interactions occur for the same bunch crossing. If more than one vertex is found, the primary vertex is taken as the vertex with the highest scalar sum p_T^2 of associated tracks. Photon candidates with $p_T > 85$ GeV and $|\eta| < 1.37$ and jet candidates with $p_T > 30$ GeV and $|\eta| < 2.8$ are used. These objects are identified using criteria that closely follow those applied in the isolated photon cross section measurement [20] and dijet resonance search [22]. Subleading photons or jets are allowed; when more than one photon or jet is found, the highest p_T candidates are selected to constitute the photon+jet pair.

Jets are reconstructed from clusters of calorimeter cells using the anti- k_t clustering algorithm [34] with radius parameter $R = 0.6$. Jet energies are corrected to the hadronic scale [30, 31]. Jet candidates are rejected in regions of the calorimeter where the jet energy is not yet measured in an optimal way. Candidates consistent with spurious calorimeter noise or energy spikes are also rejected.

Photon candidates are reconstructed from clusters in the electromagnetic calorimeter and tracking information provided by the inner detector. They satisfy standard ATLAS selection criteria that are designed to reject instrumental backgrounds from hadrons [20]. The photon candidates must meet p_T - and η -dependent requirements on hadronic leakage, shower shapes in the electromagnetic strip layer, and shower shapes in the second sampling layer of the electromagnetic calorimeter. Inner detector tracking information is used to reject electrons and to recover photons converted to e^+e^- pairs. Energy calibrations are applied to photon candidates to account for energy loss in front of the electromagnetic calorimeter and for both lateral and longitudinal leakage. Events are discarded if the leading photon appears in calorimeter cells affected by noise bursts or transient hardware problems.

These photon identification criteria reduce instrumental backgrounds to a negligible level, but much of the substantial background from secondary (jet fragmentation) photons remains. We reduce this background with requirements on nearby calorimeter activity. Associated ‘‘isolation’’ calorimeter energy near the photon candidate is calculated by summing the transverse momentum as measured in 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 pile-up 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 as also to be 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 $p_T > 30$ GeV to reduce the background from photons during fragmentation of final state quarks (fragmentation photons) and to reduce the systematic effects from leakage of nearby jet showers into the photon isolation energy measurement.

Additional reduction of 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 require $|\eta_\gamma - \eta_j| < 1.4$ between the photon and jet. The former criterion was chosen to avoid kinematic bias of the $m_{\gamma j}$ distribution due to inclusion of any η range where reconstruction efficiency is lower, such as the barrel-endcap transition region $1.37 < |\eta| < 1.52$. The latter was chosen by optimizing expected significance using the $|\eta_\gamma - \eta_j|$ 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*

$$f(x \equiv m_{\gamma j}/\sqrt{s}) = p_1(1-x)^{p_2}x^{-p_3-p_4 \ln x}. \quad (1)$$

The motivation for this function is discussed in Ref. [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 -value is 23%, indicating the data distribution is compatible with Eq. 1. The functional form also describes the leading-order PYTHIA direct photon prediction for comparable event statistics.

We search for statistical evidence of a resonance in this distribution using the BUMPHUNTER algorithm [39]. The algorithm operates on the binned $m_{\gamma j}$ distribution, comparing the background estimate with the data in mass intervals of varying contiguous bin multiplicities across the entire distribution. For each interval in the scan, it computes the significance of any excess found. The algorithm identifies the interval 784–1212 GeV, indicated by the vertical lines in Fig. 1, as the single most discrepant

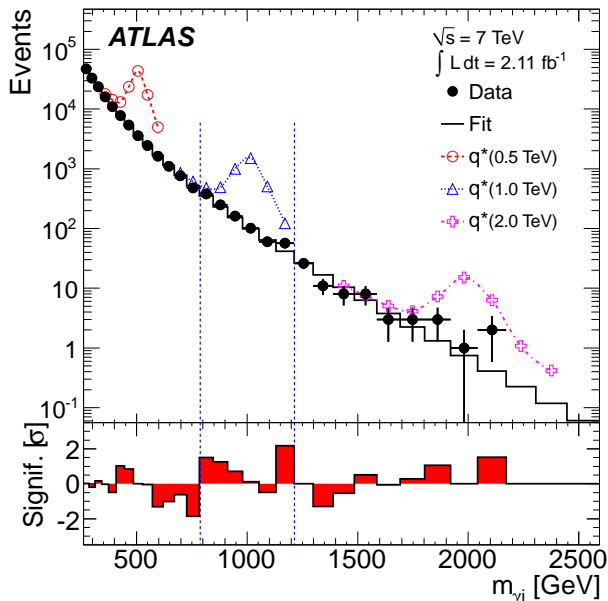


FIG. 1. Invariant mass of the photon+jet pair for events passing the final selection. Overlaid: the fitted background function integrated over each bin (stepped solid line), the most discrepant region identified by BUMPHUNTER (two dashed vertical lines), and three examples of excited-quark signals, normalized to luminosity, as described in the text. The bottom panel shows the statistical significance of the difference between data and background in each bin.

interval. The significance of the outcome is evaluated using the ensemble of possible outcomes for the significance of any region in the distribution in the background-only hypothesis, obtained by repeating the analysis on pseudodata drawn from the background function. Before including systematic uncertainties, the probability (p -value) of observing a background fluctuation at least as significant as the above, including the trials factor, or “look-elsewhere” effect, is 20%. Inclusion of systematic uncertainties renders the p -value similarly large.

Lacking evidence of any signal, we exclude two types of photon+jet signals: a generic signal with Gaussian distribution and arbitrary production cross section, and the excited-quark model. We compute Bayesian limits at 95% credibility level (CL) using a prior probability density that is constant for positive values of the signal production cross section and zero for unphysical, negative values, as described in Ref. [40]. We consider systematic uncertainties on expected signal yield due to imperfect knowledge of the detector: the integrated luminosity (3.7%), trigger efficiencies (<0.5%), and signal photon identification efficiencies (2.0%). The last of these consists of isolation (0.4%), pile-up interactions (0.5%), conversions (1.2%), simulation mismodeling (1.3%), and the extrapolation of the photon identification efficiency to high p_T (<0.3%). Uncertainties on photon energy scale

(0.5–1.5%), jet energy scale (2–4%), and jet energy resolution (5–15%) contribute through their effects on the signal distribution. These systematic uncertainties are treated as marginalized Gaussian nuisance parameters in the limit calculation.

We also evaluate two systematic uncertainties on the background estimate. To account for the statistical uncertainties on the background fit parameters, we repeatedly fit the background function to pseudodata for each bin drawn from Poisson distributions. The mean of the Poisson distribution for a given bin corresponds to the number of entries actually observed in that bin in the data. We then take the variation in the fit predictions for a given bin, 0.5% of the background at low mass to almost 10% of the background at 2 TeV, as indicative of the systematic uncertainty. We treat this bin-by-bin uncertainty in the limit as fully correlated, using a single nuisance parameter that scales the entire background distribution.

While our function can describe the $m_{\gamma j}$ shape for direct photon production, as modeled in the PYTHIA direct photon+jet simulation, the function need not remain a good description of the full distribution after including 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 σ times branching fraction B times acceptance A times efficiency ϵ , of a potential signal as a function of the central mass of each signal template. We take the signal lineshape 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 q^* mass. Also shown are $\pm 1\sigma$ and $\pm 2\sigma$ 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].

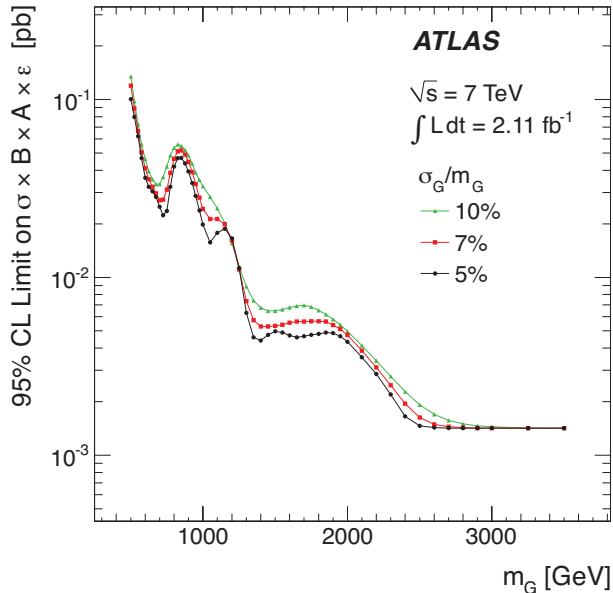


FIG. 2. The 95% CL upper limits on $\sigma \times B \times A \times \epsilon$ for a hypothetical signal with Gaussian $m_{\gamma j}$ distribution decaying to a photon and a jet as a function of the signal mass, m_G , for three values of the relative Gaussian width σ_G/m_G and taking into account systematic uncertainties.

In conclusion, the photon+jet mass distribution measured in 2.11 fb^{-1} of pp collision data collected at $\sqrt{s} = 7 \text{ TeV}$ 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 Gaussian-lineshape and excited-quark signal using Bayesian statistics. The limits on Gaussian resonances, for example, exclude 2 TeV resonances with effective cross sections near 5 fb. We also exclude the excited-quark model in the photon+jet final state for masses up to 2.46 TeV. The limits reported here on resonant production of new particles in the photon+jet final state are the most stringent limits set to date in this channel.

Acknowledgements

We thank CERN for the very successful operation of the LHC, as well as the support staff from our institutions without whom ATLAS could not be operated efficiently.

We acknowledge the support of ANPCyT, Argentina; YerPhI, Armenia; ARC, Australia; BMWF, Austria; ANAS, Azerbaijan; SSTC, Belarus; CNPq and FAPESP,

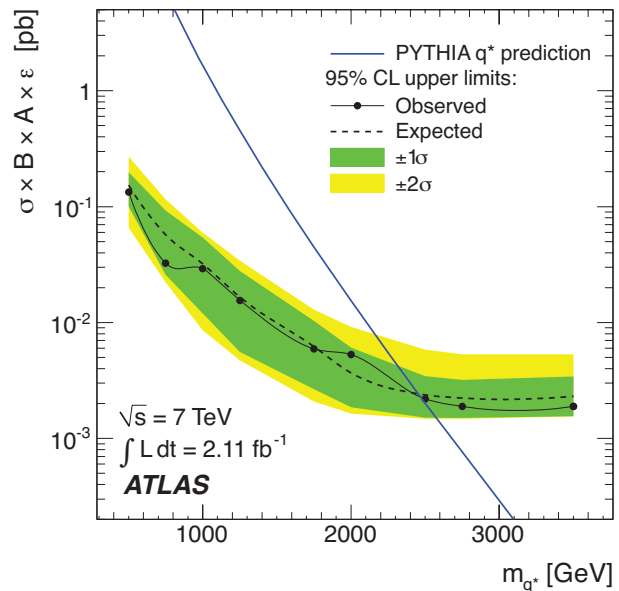


FIG. 3. The 95% CL upper limits on $\sigma \times B \times A \times \epsilon$ for excited quarks decaying to a photon and a jet as a function of the signal mass, m_{q^*} , for the PYTHIA q^* prediction and taking into account systematic uncertainties.

Brazil; NSERC, NRC and CFI, Canada; CERN; CONICYT, Chile; CAS, MOST and NSFC, China; COLCIENCIAS, Colombia; MSMT CR, MPO CR and VSC CR, Czech Republic; DNRf, DNSRC and Lundbeck Foundation, Denmark; ARTEMIS, European Union; IN2P3-CNRS, CEA-DSM/IRFU, France; GNAS, Georgia; BMBF, DFG, HGF, MPG and AvH Foundation, Germany; GSRT, Greece; ISF, MINERVA, GIF, DIP and Benoziyo Center, Israel; INFN, Italy; MEXT and JSPS, Japan; CNRST, Morocco; FOM and NWO, Netherlands; RCN, Norway; MNiSW, Poland; GRICES and FCT, Portugal; MERYs (MECTS), Romania; MES of Russia and ROSATOM, Russian Federation; JINR; MSTd, Serbia; MSSR, Slovakia; ARRS and MVZT, Slovenia; DST/NRF, South Africa; MICINN, Spain; SRC and Wallenberg Foundation, Sweden; SER, SNSF and Cantons of Bern and Geneva, Switzerland; NSC, Taiwan; TAEK, Turkey; STFC, the Royal Society and Leverhulme Trust, United Kingdom; DOE and NSF, United States of America.

The crucial computing support from all WLCG partners is acknowledged gratefully, in particular from CERN and the ATLAS Tier-1 facilities at TRIUMF (Canada), NDGF (Denmark, Norway, Sweden), CC-IN2P3 (France), KIT/GridKA (Germany), INFN-CNAF (Italy), NL-T1 (Netherlands), PIC (Spain), ASGC (Taiwan), RAL (UK) and BNL (USA) and in the Tier-2 facilities worldwide.

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