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Physics Letters, Section B: Nuclear, Elementary Particle and High-Energy Physics, 728(1)

0370-2693

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2014

10.1016/j.physletb.2013.12.029

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Peer reviewed
Search for new phenomena in photon + jet events collected in proton–proton collisions at \( \sqrt{s} = 8 \) TeV with the ATLAS detector

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**A R T I C L E I N F O**

**Article history:**
Received 13 September 2013
Received in revised form 26 November 2013
Accepted 9 December 2013
Available online 14 December 2013
Editor: H. Weerts

**A B S T R A C T**

This Letter describes a model-independent search for the production of new resonances in photon + jet (\( \gamma + \) jet) events using 20 fb\(^{-1}\) of proton–proton LHC data recorded with the ATLAS detector at a centre-of-mass energy of \( \sqrt{s} = 8 \) TeV. The \( \gamma + \) jet mass distribution is compared to a background model fit from data; no significant deviation from the background-only hypothesis is found. Limits are set at 95% credibility level on generic Gaussian-shaped signals and two benchmark phenomena beyond the Standard Model: non-thermal quantum black holes and excited quarks. Non-thermal quantum black holes are excluded below masses of 4.6 TeV and excited quarks are excluded below masses of 3.5 TeV.

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1. Introduction

Several exotic production mechanisms have been proposed that produce massive photon + jet (\( \gamma + \) jet) final states. They include non-thermal quantum black holes (QBHs) [1–3], excited quarks [4–6], quirks [7–9], Regge excitations of string theory [10–12], and topological pions [13]. Of the past searches [14–18], the only LHC search for this signature was done using proton–proton (pp) collision data obtained at a centre-of-mass energy of \( \sqrt{s} = 7 \) TeV with the ATLAS detector. It found no evidence of new physics and placed upper limits on the visible signal.

This Letter describes a model-independent search for s-channel \( \gamma + \) jet production, improved over the earlier search. It presents the first limits on QBHs decaying to the \( \gamma + \) jet final state and places new limits both on excited quarks and on generic Gaussian-shaped sources which describe other narrow resonant signals such as topological pions. Sensitivity to such signals has been improved compared to the previous search through a combination of an order-of-magnitude larger data sample (20.3 fb\(^{-1}\)), a higher centre-of-mass energy (\( \sqrt{s} = 8 \) TeV), reduced background uncertainties, and improved selection criteria at high invariant mass.

The Standard Model (SM) of particle physics lacks a mechanism whereby pp collisions produce resonances that subsequently decay to a \( \gamma + \) jet final state. Direct \( \gamma + \) jet production can occur at tree level via Compton scattering of a quark and a gluon, or through quark–antiquark annihilation. The former process accounts for most of the direct \( \gamma + \) jet production. Events with a high transverse momentum photon and one or more jets can also arise from radiation off final-state quarks, or from dijet or multi-jet processes, where secondary photons, referred to as fragmentation photons, are produced during fragmentation of the hard-scattered quarks or gluons [19–22]. The \( \gamma + \) jet invariant mass (\( m_{\gamma j} \)) distribution resulting from this mixture of processes is smooth and rapidly falling, and is therefore well suited to revealing high-mass resonances decaying to \( \gamma + \) jet.

The \( m_{\gamma j} \) distribution is used to search for a peak over the SM background, estimated by fitting a smoothly falling function to the \( m_{\gamma j} \) distribution in the region \( m_{\gamma j} > 426 \) GeV. In the absence of a signal, Bayes’ theorem is used to set limits on Gaussian-shaped signals and on two benchmark models: QBHs and excited quarks.

Models with extra dimensions, such as the Arkani-Hamed-Dimopoulos-Dvali (ADD) model [23,24], solve the mass hierarchy problem of the SM by lowering the fundamental scale of quantum gravity (\( M_D \)) to a few TeV. Consequently, the LHC could produce quantum black holes with masses at or above \( M_D \) [25,26]. QBHs produced near \( M_D \) would evaporate faster than they thermalize, decaying into a few particles rather than high-multiplicity final states [23]. Regardless of the number of extra dimensions n, such a signal would appear as a local excess above the steeply falling \( m_{\gamma j} \) distribution near the threshold mass (\( M_{th} \)) and would fall exponentially at higher masses. Searches performed by the CMS Collaboration for QBHs with high-multiplicity energetic final states yielded limits in the range of 4.3–6.2 TeV, for \( n = 1–6 \) and different model assumptions [27]. This Letter assumes \( M_{th} = M_D \) and \( n = 6 \), where the cross-section times branching fraction for QBH production and decay to \( \gamma + \) jet final states at \( M_{th} = 1.3 \) and 5 TeV is 200, 0.3 and \( 6 \times 10^{-5} \) pb, respectively [3]. For decays to dijet final...
mitting an efficient reconstruction of photon conversions in the upward. Cylindrical coordinates
primary
ner detector allows an accurate reconstruction of tracks from the are used in photon identification. Upstream of the EMC, the in-
three additional, differently segmented, layers; only the first two
netic calorimeter (EMC). The EMC has a pre-sampler layer and
ments. Events for this analysis were collected with a trigger requir-
calorimeters for both the electromagnetic and hadronic measure-
ons states at these same threshold masses, the rates are larger by fac-
tors of 11, 39 and 125.

Excited-quark (q∗) states, which the ATLAS and CMS exper-
iments have also sought in dijet final states [28–30], could be
produced via the fusion of a gluon with a quark. The model is
defined by one parameter, the excited-quark mass mqq∗, with the
compositeness scale set to mqq∗. Only gauge interactions are con-
sidered with the SU(3), SU(2), and U(1) coupling multipliers fixed to
f3 = f = f′ = 1 [5]. This results in branching fractions for q∗ → qg
and q∗ → qF of 0.85 (0.85) and 0.02 (0.005), respectively, for q = u
(q = d). The leading-order cross-sections times branching fractions
combining all flavours of excited quarks for mqq∗ = 1.3 and 5 TeV
are 4, 2 × 10−3 and 3 × 10−6 pb, respectively.

Factorization and renormalization scale uncertainties are not
used for either signal type, for comparison with earlier analy-
6. Signal and background simulation samples

To cross-check the data-driven background estimates, the SM
prompt photon processes are simulated with PYTHIA 8.165 [31]
and SHERPA 1.4.0 [32]. The PYTHIA and SHERPA prompt photon
samples use CTEQ6L1 [33] and CT10 [34] leading-order and next-
to-leading-order parton distribution functions (PDFs), respectively.
The simulated samples of QHBs are obtained from the QHB1.05
The simulated q∗ signal samples are generated with the excited-
quark model in PYTHIA 8.165. Both signal generators use the
MSTW2008LO [36] leading-order PDF set with the AU2 underlying-
event tune [37]. Additional inelastic pp interactions, termed pileup,
are included in the event simulation by overlaying simulated
minimum bias events with an average of 20 interactions per
bunch crossing. All the above Monte Carlo (MC) simulated samples
are produced using the ATLAS full GEANT4 [38] detector simul-
ator [39]. Supplementary studies of the background shape are also
performed with the next-to-leading-order JETPHOX 1.3.0 genera-
tor [19–21] at parton level using CT10 PDFs.

3. The ATLAS detector

A detailed description of the detector is available in Ref. [40],
and the event selection is similar to that described in Ref. [18].

Photons are detected by a lead–liquid-argon sampling electromag-
netic calorimeter (EMC). The EMC has a pre-sampler layer and
two additional, differently segmented, layers; only the first two
are used in photon identification. Upstream of the EMC, the in-
ner detector allows an accurate reconstruction of tracks from the
primary pp collision point and also from secondary vertices, per-
mitting an efficient reconstruction of photon conversions in the
inner detector. For |η| < 1.371 an iron–scintillator tile calorimeter
behind the EMC provides hadronic coverage. The endcap and for-
ward regions, 1.5 < |η| < 4.9, are instrumented with liquid-argon
calorimeters for both the electromagnetic and hadronic measure-
ments. Events for this analysis were collected with a trigger requir-
ing at least one photon candidate with transverse momentum (pT)
above 120 GeV [41]. The integrated luminosity of the data sample2
is (20.3 ± 0.6) fb−1.

4. Event selection

Each event is required to contain a primary vertex with at least
two tracks each with pT > 400 MeV. If more than one vertex is
found, the primary vertex is defined as the one with the highest
scalar sum ∑pT of associated tracks.

Jets are reconstructed from clusters of calorimeter cells [43],
using the anti-kT clustering algorithm [44] with radius parameter
R = 0.6. The effects on jet energies due to multiple pp collisions
in the same or in neighbouring bunch crossings are accounted for
by a jet-area-based correction [45,46]. Jet energies are calibrated
to the hadronic energy scale using corrections from MC simula-
tion and the combination of several in situ techniques applied to
data [47]. Events are discarded if the leading (highest-pT) jet is
affected by noise or hardware problems in the detector, or is iden-
tified as arising from non-collision backgrounds. Only jets with
|η| < 2.8 are considered further.

Photon candidates are reconstructed from clusters in the elec-
tromagnetic calorimeter and tracking information provided by the
inner detector. Inner detector tracking information is used to re-
ject electrons and to recover photons converted to e+e− pairs [48].
Photon candidates satisfy standard ATLAS selection criteria that are
designed to reject backgrounds from hadrons [49]. The photon can-
didates must meet η-dependent requirements on hadronic leakage
and shower shapes in the first two sampling layers of the elec-
tromagnetic calorimeter. Energy calibrations are applied to photon
candidates to account for energy loss upstream of the electro-
magnetic calorimeter and for both lateral and longitudinal shower
leakage. The simulation is corrected for differences between data
and MC events for each photon shower shape variable. Events are
discarded if the leading photon is reconstructed using calorimeter
cells affected by noise bursts or transient hardware problems.

These photon identification criteria reduce instrumental back-
grounds to a negligible level, but some background from fragmen-
tation photons and hadronic jets remains. This background is
further reduced by requirements on nearby calorimeter activity.
Energy deposited in the calorimeter near the photon candidate,
Ejet |pT|, must be no larger than 0.011 pT + 3.65 GeV, a criterion
that provides constant efficiency for all pileup conditions and over
the entire pT range explored. This transverse isolation energy is
calculated by summing the energy as measured in electromagnetic
and hadronic calorimeter cells inside a cone of radius ΔR =
√(Δη)2 + (Δφ)2 = 0.4 centred on the photon cluster, but exclud-
ing the energy of the photon cluster itself, and is corrected on an
event-by-event basis for the ambient energy density due to pileup
and the underlying event, as well as energy leakage from the pho-
ton cluster into the cone. Additionally, the photon is required to
have angular separation of ΔR(γ, jet) > 1.0 between the leading
photon and all other jets with pT > 30 GeV, with the exception of
a required photon-matched jet. Such photon-matched jets arise
from the fact that photon energy deposits in the calorimeter are
also reconstructed as jets. To further suppress background from
fragmentation photons, where the angular separation between the
photon and the corresponding photon-matched jet can be large,
the leading photon candidate is required to have exactly one re-
constructed jet with ΔR(γ, jet) < 0.1. This photon-matched jet is
not considered in any other selection criteria, including those re-
lated to photon isolation.

1 ATLAS uses a right-handed coordinate system with its origin at the nominal in-
teraction point (IP) in the centre of the detector and the z-axis along the beam pipe.
The x-axis points from the IP to the centre of the LHC ring, and the y-axis points
upward. Cylindrical coordinates (r, φ) are used in the transverse plane, φ being the
azimuthal angle around the beam pipe. The pseudorapidity is defined in terms of
the polar angle θ at η = −ln(tan(θ/2)).

2 The systematic uncertainty on the luminosity is derived, following the same
methodology as that detailed in Ref. [42], from a preliminary calibration of the lu-
minosity scale derived from beam-separation scans performed in November 2012.
Events containing at least one photon candidate and at least one jet candidate, each with $p_T > 125$ GeV, are selected for final analysis. The photon trigger is fully efficient for these events. In the events where more than one photon or jet is found, the highest-$p_T$ candidates are selected to constitute the photon and jet pair to compute $m_{\gamma\gamma}$.

The sensitivity of the search is improved by requirements on photon and jet pseudorapidities. Dijet production rates increase with jet absolute pseudorapidity whereas rates for an $s$-channel signal would diminish. Photons are required to be in the barrel calorimeter, $|\eta_{\gamma}| < 1.37$, and the distance between the photon and jet, $\Delta\eta = |\eta_{\gamma} - \eta_{\gamma}|$, must be less than 1.6. The latter requirement was chosen by optimizing the expected significance of signals, using the $\Delta\eta$ distribution found in QBH and excited-quark signal simulations, with respect to the SM background as predicted by the PYTHIA prompt photon simulation.

The acceptance of the event selection is about 60%. It is calculated using parton-level quantities by imposing the kinematic selection criteria (photon/jet $|\eta|$, photon/jet $p_T$, $\Delta\eta$, $\Delta R$). All other selections, which in general correspond to event and object quality criteria, were used to calculate the efficiency based on the events included in the acceptance. The efficiency falls from 83% to 72% for masses from 1 TeV to 6 TeV for QBH signals and from 85% to 80% for excited-quark signals over the same mass range. There are 285 356 events in the data sample after all event selections. The highest $m_{\gamma\gamma}$ value observed is 2.57 TeV.

5. Background estimation

The combined SM and instrumental background to the search is determined by fitting the $m_{\gamma\gamma}$ distribution to the four-parameter ansatz function [50],

$$f(x) = \frac{p_1(1-x)^{p_2}}{\Gamma(p_3+p_4\ln x)}.$$  \hspace{1cm} \hspace{1cm} (1)

The functional form has been tested with PYTHIA and SHERPA prompt photon simulations and next-to-leading-order JETPHOX predictions with comparable sample size. Two additional control samples in the data are also defined to further validate the functional form. The first control sample is defined by reversing two of the photon identification criteria, $|\eta_{\gamma}|$, $p_T$, $\Delta\eta$, $\Delta R$. All other selections, which in general correspond to event and object quality criteria, were used to calculate the efficiency based on the events included in the acceptance. The efficiency falls from 83% to 72% for masses from 1 TeV to 6 TeV for QBH signals and from 85% to 80% for excited-quark signals over the same mass range. There are 285 356 events in the data sample after all event selections. The highest $m_{\gamma\gamma}$ value observed is 2.57 TeV.

6. Results

6.1. Search results

The search region is defined to be $m_{\gamma\gamma} > 426$ GeV, which is the lower edge of the first bin for which biases due to kinematic and trigger threshold effects are negligible. The $\gamma +$ jet search is sensitive to new resonances in the region between 426 GeV and 1 TeV, where the statistics of dijet searches are limited by the higher hadronic trigger thresholds. The BUMPHunter algorithm [52] is used to search for statistical evidence of a resonance. The algorithm operates on the binned $m_{\gamma\gamma}$ distribution, comparing the background estimate with the data in mass intervals of varying numbers of adjacent bins across the entire distribution. For each interval in the scan, it computes the significance of any excess found. The significance of the outcome is evaluated using the ensemble of possible outcomes in any part of the distribution under the background-only hypothesis, obtained by repeating the analysis on pseudo-data drawn from the background function. The algorithm identifies the two-bin interval 785–916 GeV as the single most discrepant interval. Before including systematic uncertainties, the $p$-value is 61%, including the trials factor, or “look-elsewhere” effect. Thus, the excess is not significant and the data are consistent with a smoothly falling background.

6.2. Limit results

In the absence of any signal, three types of $\gamma +$ jet signals are explored: a generic Gaussian-shaped signal with an arbitrary production cross-section, resulting from resonances with varying intrinsic widths convolved with the detector resolution; the QBH model; and the excited-quark model. For each signal mass considered, the fit to the observed mass distribution is repeated with the sum of the four-parameter background function (Eq. (1)) and a signal template with a normalization determined during the fit. Bayesian limits at the 95% Cl are computed as described in Ref. [28] using a prior probability density that is constant for positive values of the signal production cross-section and zero for unphysical, negative values.

Systematic uncertainties affecting the limits on production of new signals are evaluated. The signal yield is subject to systematic uncertainties on the integrated luminosity (2.8%), photon isolation efficiency (1.2%), trigger efficiency (0.5%), and photon identification efficiencies (1.5%). The last of these includes extrapolation to
At 3 TeV, the new limit improves the earlier ATLAS result in this channel by an order of magnitude. The sizes of the systematic uncertainties are similar for through their effects on the shape and yield of the signal distribution. The mean of the Poisson distribution for a given bin corresponds to the number of entries actually observed in that bin in the data. The variations in the fit predictions for a given bin, 1% of the background at 1 TeV to about 20% of the background at 3 TeV, are taken as indicative of the systematic uncertainty. This bin-by-bin uncertainty is treated in the limit as fully correlated, using a single nuisance parameter that scales the entire background contribution due to the absence of observed events. At 1 TeV and beyond the highest-mass event recorded, 2.57 TeV, the limits begin to converge due to the PDF uncertainties were examined and found to be negligible. To account for the statistical uncertainties on the background fit parameters, the background function is repeatedly fit to pseudodata for which the content of each bin is 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. The variations in the fit predictions for a given bin, and a jet, as a function of the threshold mass \(M_{th}\), assuming \(M_0 = M_3\) and \(n = 6\). The limits take into account statistical and systematic uncertainties. Points along the solid black line indicate the mass of the signal where the limit is computed. The black short dashed line is the central value of the expected limit. Also shown are the ±1σ and ±2σ uncertainty bands indicating the underlying distribution of possible limit outcomes under the background-only hypothesis. The predicted visible cross-section for QBHs is shown as the long dashed line.

The limit on the visible cross-section in the excited-quark model as a function of the q* mass, assumed to be the same for \(u^*\) and \(d^*\), is shown in Fig. 4. The rise in the expected and observed limits at high \(m_{q^*}\) is due to the increased fraction of off-shell production of the q*, which alters the signal distribution to lower masses with a wider peak. The observed (expected) lower limit on the excited-quark mass is found to be 3.5 (3.4) TeV, at 95% CL. With a much lower branching fraction than the dijet channel but also smaller backgrounds, this result improves on the present exclusion limits in the dijet final state: 3.32 TeV from CMS with...
5 fb$^{-1}$ of data at $\sqrt{s} = 7$ TeV [30], and 2.83 TeV from ATLAS with 4.8 fb$^{-1}$ [28] of data at $\sqrt{s} = 7$ TeV. The uncertainty on the $q^*$ theoretical cross-section arising from PDF uncertainties moves the uppermost excluded mass by 0.9%.

7. Conclusions

In conclusion, the $\gamma + jet$ mass distribution measured in 20.3 fb$^{-1}$ of pp collision data, collected at $\sqrt{s} = 8$ TeV by the ATLAS experiment at the LHC, is well described by the background model and no evidence for new phenomena is found. Limits at 95% CL using Bayesian statistics are presented for signal processes and excited quarks. The limits on Gaussian-shaped resonances exclude 4 TeV resonances with visible cross-sections near 0.1 fb. Non-thermal quantum black hole and excited-quark models with a $\gamma + jet$ final state are excluded for masses up to 4.6 TeV and 1.5 TeV, respectively. The limits reported here on the production of new resonances in the $\gamma + jet$ final state are the most stringent limits set to date in this channel.

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.

Acknowledgements

We acknowledge the support of ANPCyT, Argentina; YerPhI, Armenia; ARC, Australia; BMWF and FWF, Austria; ANAS, Azerbaijan; SSTC, Belarus; CNPq and FAPESP, Brazil; NSERC, NRC and CI, Canada; CERN; CONICYT, Chile; CAS, MOST and NSFC, China; COLCIENCIAS, Colombia; MPT, CERN; MSMT, CR; MPO CR and VSC CR, Czech Republic; DLR, DMSN and Lundbeck Foundation, Denmark; EPLANET, ERC and NSRF, European Union; IN2P3-CNRS, CEA-DSM/IRFU, France; GNSF, Georgia; BMF, DFG, HGF, MPG and AvH Foundation, Germany; GSRT and NSRF, Greece; ISF, MINERVA, GIF, DIP and Benoziyo Center, Israel; INFN, Italy; MEXT and JSPS, Japan; CNRST, Morocco; FOM and NWO, Netherlands; BRF and RCN, Norway; MNISW, Poland; GRCs and FCT, Portugal; MERSY (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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