Physics Letters B 728 (2014) 562–578

Contents lists available at ScienceDirect

Physics Letters B

www.elsevier.com/locate/physletb

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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ARTICLE INFO

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

ABSTRACT

This Letter describes a model-independent search for the production of new resonances in photon + jet (γ + 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 γ + 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.

1. Introduction

Several exotic production mechanisms have been proposed that produce massive photon + jet (γ + 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 cross-section in the range 1.5–100 fb and excluded excited-quark masses up to 2.46 TeV at the 95% credibility level (CL) [18]. The present Letter describes a model-independent search for s-channel γ + jet production, improved over the earlier search. It presents the first limits on QBHs decaying to the γ + 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 γ + jet final state. Direct γ + 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 γ + 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 γ + 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 γ + 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–Dimopoulous–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 [2,3]. Regardless of the number of extra dimensions n, such a signal would appear as a local excess over 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 $M_{\text{th}} = M_D$ and $n = 6$, where the cross-section times branching fraction for QBH production and decay to γ + jet final states at $M_{\text{th}} = 1, 3$ and 5 TeV is 200, 0.3 and 6×10^{-5} pb, respectively [3]. For decays to dijet final

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http://dx.doi.org/10.1016/j.physletb.2013.12.029

states at these same threshold masses, the rates are larger by factors of 11, 39 and 125.

Excited-quark (q^*) states, which the ATLAS and CMS experiments 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 m_{q^*}, with the compositeness scale set to m_{q^*}. Only gauge interactions are considered with the SU(3), SU(2), and U(1) coupling multipliers fixed to $f_s = f = f' = 1$ [5]. This results in branching fractions for $q^* \to qg$ and $q^* \to q\gamma$ 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 $m_{q^*} = 1, 3$ 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 analyses [18,28,29].

2. 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 QBHs are obtained from the QBH 1.05 generator [35] followed by parton showering using PYTHIA 8.165. 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 simulation [39]. Supplementary studies of the background shape are also performed with the next-to-leading-order JETPHOX 1.3.0 generator [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 electromagnetic calorimeter (EMC). The EMC has a pre-sampler layer and three additional, differently segmented, layers; only the first two are used in photon identification. Upstream 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. For $|\eta| < 1.37$ [1] 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 the electromagnetic and hadronic measurements. Events for this analysis were collected with a trigger requiring at least one photon candidate with transverse momentum (p_T) above 120 GeV [41]. The integrated luminosity of the data sample[2] 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 $p_T > 400$ MeV. If more than one vertex is found, the primary vertex is defined as the one with the highest scalar summed p_T^2 of associated tracks.

Jets are reconstructed from clusters of calorimeter cells [43], using the anti-k_t 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 simulation and the combination of several in situ techniques applied to data [47]. Events are discarded if the leading (highest-p_T) jet is affected by noise or hardware problems in the detector, or is identified as arising from non-collision backgrounds. Only jets with $|\eta_j| < 2.8$ are considered further.

Photon candidates are reconstructed from clusters in the electromagnetic calorimeter and tracking information provided by the inner detector. Inner detector tracking information is used to reject 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 candidates must meet η-dependent requirements on hadronic leakage and shower shapes in the first two sampling layers of the electromagnetic calorimeter. Energy calibrations are applied to photon candidates to account for energy loss upstream of the electromagnetic 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 backgrounds to a negligible level, but some background from fragmentation 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, E_T^{isol}, must be no larger than $0.011\ p_T^\gamma + 3.65$ GeV, a criterion that provides constant efficiency for all pileup conditions and over the entire p_T 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 $\Delta R = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2} = 0.4$ centred on the photon cluster, but excluding 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 photon cluster into the cone. Additionally, the photon is required to have angular separation of $\Delta R(\gamma, \text{jet}) > 1.0$ between the leading photon and all other jets with $p_T > 30$ 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 reconstructed jet with $\Delta R(\gamma, \text{jet}) < 0.1$. This photon-matched jet is not considered in any other selection criteria, including those related to photon isolation.

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[1] ATLAS uses a right-handed coordinate system with its origin at the nominal interaction 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 as $\eta = -\ln\tan(\theta/2)$.

[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 luminosity 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 $p_{\mathrm{T}} > 125$ 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 $m_{\gamma j}$.

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, $\Delta\eta = |\eta_\gamma - \eta_j|$, 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}, $\Delta\eta$, ΔR). 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 $m_{\gamma j}$ value observed is 2.57 TeV.

5. Background estimation

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

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

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, ΔE and E_{ratio} [49], that compare the lateral shower shapes of single photons in the first layer of the calorimeter to those of jets with high electromagnetic energy fraction and low particle multiplicity, typical for meson decays. This sample has a similar $m_{\gamma j}$ shape to the dominant background, SM γ + jet events. The second control sample is defined by reversing the photon isolation criterion, $E_{\mathrm{T}}^{\mathrm{isol}}$. This control sample is enriched in the second largest background, dijet events in which a jet has passed the photon identification cuts.

Fig. 1 shows the resulting distribution of the γ + jet invariant mass. The bin widths are chosen to be twice the mass resolution at the centre of each bin. The relative resolution is about 4% of $m_{\gamma j}$ at 1 TeV, improving to about 3% at 2 TeV. 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 [51]. The fit quality is quantified using a negative log-likelihood test statistic. The probability of the fit quality to be at least as good as the observed fit (p-value) is 74%, indicating that the data are consistent with the functional form.

6. Results

6.1. Search results

The search region is defined to be $m_{\gamma j} > 426$ GeV, which is the lower edge of the first bin for which biases due to kinematic and trigger threshold effects are negligible. The γ + 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 $m_{\gamma j}$ 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 pseudodata 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.

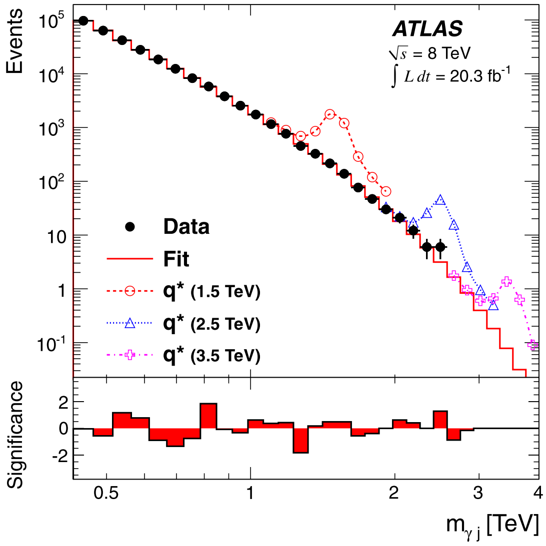

Fig. 1. Invariant mass of the γ + jet pair for events passing the final selections. The bin widths are chosen to be twice the mass resolution at the centre of each bin. Overlaid is the fitted background function integrated over each bin (solid line), with three examples of q^* signals, as described in the text. For better visibility the q^* signals are only drawn for $m_{\gamma j}$ within ±25% of the nominal signal mass. The bottom panel shows the statistical significance of the difference between data and background in each bin.

6.2. Limit results

In the absence of any signal, three types of γ + 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

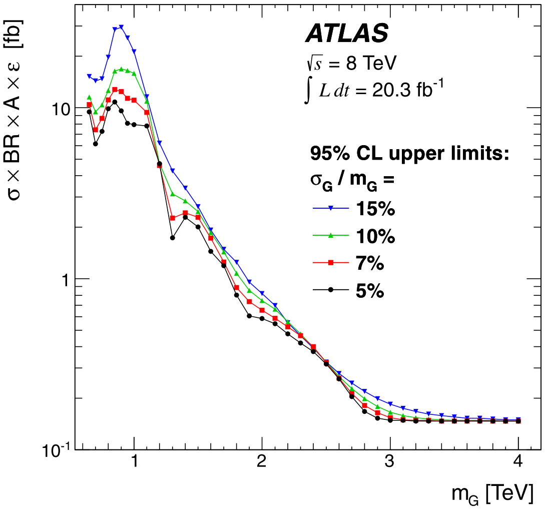

Fig. 2. The 95% CL upper limits on $\sigma \times BR \times A \times \varepsilon$ for a hypothetical signal with a Gaussian-shaped $m_{\gamma j}$ distribution as a function of the signal mass m_{G} for four values of the relative width $\sigma_{\mathrm{G}}/m_{\mathrm{G}}$.

high p_{T} (0.1%) and pileup effects (0.1%). Uncertainties on the jet and photon energy scale contribute 1.0–1.5% and 0.3%, respectively, through their effects on the shape and yield of the signal distribution. The sizes of the systematic uncertainties are similar for the q^* and QBH signals. These systematic uncertainties are treated as marginalized nuisance parameters in the limit calculation. Systematic uncertainties on the value and shape of the signal acceptance 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, 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 distribution. Several other fit functions from Ref. [50] were tested, and a negligible systematic uncertainty was found.

Fig. 2 shows the model-independent limits on the visible cross-section, defined as the product of the cross-section (σ) times branching fraction (BR) times acceptance (A) times efficiency (ε), of a potential signal as a function of the mass of each signal template, and includes the systematic uncertainties discussed above. The signal line shape is modelled as a Gaussian distribution, with one of four relative widths: $\sigma_{\mathrm{G}}/m_{\mathrm{G}} = 5\%, 7\%, 10\%$, and 15%, where σ_{G} (m_{G}) is the width (mean mass) of the Gaussian. The differences between the limits for different widths are driven by the increased sensitivity to local fluctuations for the narrower signals. Beyond the highest-mass event recorded, 2.57 TeV, the limits begin to converge due to the absence of observed events. At 1 TeV and 4 TeV the limits are 8 fb and 0.1 fb, respectively, for $\sigma_{\mathrm{G}}/m_{\mathrm{G}} = 5\%$. At 3 TeV, the new limit improves the earlier ATLAS result in this channel by an order of magnitude.

The limit on the visible cross-section in the QBH model is shown in Fig. 3 as a function of M_{th}. The observed (expected) lower limit on the QBH mass threshold is found to be 4.6 (4.6) TeV, at 95% CL. The uncertainty on the QBH theoretical cross-section arising from PDF uncertainties moves the uppermost excluded mass by 0.2%.

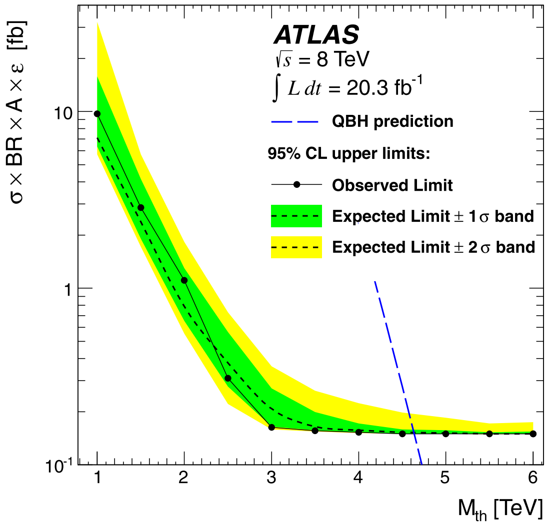

Fig. 3. The 95% CL upper limits on $\sigma \times BR \times A \times \varepsilon$ for QBHs decaying to a photon and a jet, as a function of the threshold mass M_{th}, assuming $M_D = M_{\mathrm{th}}$ and $n = 6$. The limits take into account statistical and systematic uncertainties. Points along the 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 $\pm 1\sigma$ and $\pm 2\sigma$ 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.

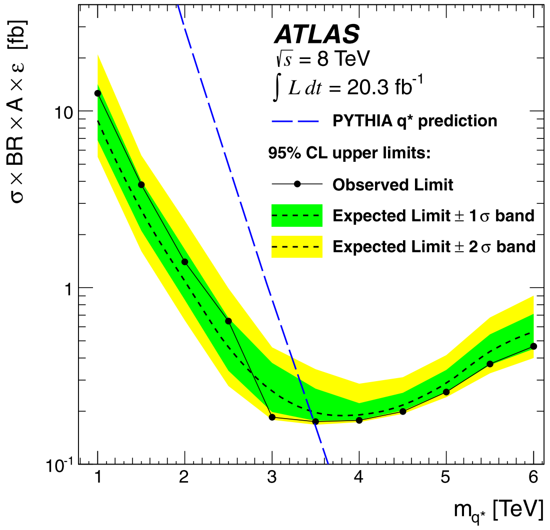

Fig. 4. The 95% CL upper limits on $\sigma \times BR \times A \times \varepsilon$ for excited quarks decaying to a photon and a jet, as a function of the signal mass m_{q^*}. The limits take into account statistical and systematic uncertainties. Points along the solid black line indicate the mass of the signal where the limit is computed. The black short dashed line is the central value of the expected limit. Also shown are the $\pm 1\sigma$ and $\pm 2\sigma$ uncertainty bands indicating the underlying distribution of possible limit outcomes under the background-only hypothesis. The long dashed line shows the predicted visible cross-section for excited-quark production from PYTHIA.

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 γ + 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 yielding a Gaussian line shape, non-thermal quantum black holes, 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 γ + jet final state are excluded for masses up to 4.6 TeV and 3.5 TeV, respectively. The limits reported here on the production of new resonances in the γ + 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 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; EPLANET, ERC and NSRF, European Union; IN2P3-CNRS, CEA-DSM/IRFU, France; GNSF, Georgia; BMBF, 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; 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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