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Search for light resonances decaying to boosted quark pairs and produced in association with a photon or a jet in proton–proton collisions at $\sqrt{s} = 13$ TeV with the ATLAS detector

The ATLAS Collaboration

This Letter presents a search for new light resonances decaying to pairs of quarks and produced in association with a high-p_{T} photon or jet. The dataset consists of proton–proton collisions with an integrated luminosity of 36.1 fb^{-1} at a centre-of-mass energy of $\sqrt{s} = 13$ TeV recorded by the ATLAS detector at the Large Hadron Collider. Resonance candidates are identified as massive large-radius jets with substructure consistent with a particle decaying into a quark pair. The mass spectrum of the candidates is examined for local excesses above background. No evidence of a new resonance is observed in the data, which are used to exclude the production of a lepto-phobic axial-vector Z' boson. These results improve upon the limits on light dijet resonances obtained at lower centre-of-mass energies.

1 Introduction

Searches for resonance peaks in the invariant mass spectrum of hadrons are an essential part of the physics programme at the energy frontier. Many theoretical models predict resonances [1–3] with significant couplings to quarks and gluons, including resonances which also couple to dark-matter particles [4–7]. At the Large Hadron Collider (LHC), the ability to discover or exclude such hadronic resonances has been extended into the TeV range, although no evidence of statistically significant excesses has been seen [8, 9].

Sensitivity to light resonances is reduced by the immense background rates that would saturate the trigger and data acquisition systems. The recording of collision data typically requires placing thresholds of several hundred GeV on the transverse momentum ($p_{\mathrm{T}}^{\mathrm{min}}$) of at least one jet, which translates to approximate thresholds on mass of $m \approx 2p_{\mathrm{T}}^{\mathrm{min}}$. Consequently, recent searches for dijet resonances have poor sensitivity for masses well below 1 TeV. This limitation can be avoided by recording only a summary of the jet information needed for performing a resonance search in the dijet mass spectrum. This strategy is called "trigger-object-level analysis" in ATLAS [10] and "data scouting" in CMS [11], and has set limits for resonance masses in the range 500–800 GeV [11].

In this Letter, a search using an alternative approach [4, 12] is performed, in order to cover even lower resonance masses. The trigger threshold limitations are reduced by examining data where the light resonance is boosted in the transverse direction[1] via recoil from high transverse momentum (p_{T}) initial-state radiation (ISR) of a photon or jet. Requiring a hard ISR object in the final state comes at the cost of reduced signal production rates, but allows highly efficient triggering at masses much lower than when triggering directly on the resonance decay products. The search is performed for resonance masses from 100 GeV to 220 GeV, a range in which the resonance is boosted and its decay products are collimated, such that the resonance mass can be calculated from the mass of a large-radius jet. In this regime, the use of jet substructure methods strongly suppresses the background, making it a crucial component for the search sensitivity. In addition, current datasets are the largest collected, allowing the sensitivity to rare processes to be extended beyond that of earlier studies.

Recently, CMS reported results of applying a similar technique [13] to exclude a light Z' boson with Standard Model (SM) coupling values (g_q) exceeding 0.1 to 0.25 in the mass range 50–300 GeV.

2 ATLAS detector

The ATLAS experiment [14] at the LHC is a multi-purpose particle detector with a forward-backward symmetric cylindrical geometry with layers of tracking, calorimeter, and muon detectors over nearly the entire solid angle around the proton–proton (pp) collision point. The inner detector (ID) consists of a high-granularity silicon pixel detector, including an insertable B-layer [15], and a silicon microstrip tracker, together providing precision tracking in the pseudorapidity range $|\eta| < 2.5$. Complementary, a transition radiation tracker provides tracking and electron identification information for $|\eta| < 2.0$. The ID

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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 upwards. Cylindrical coordinates (r, ϕ) are used in the transverse plane, ϕ being the azimuthal angle around the z-axis. The pseudorapidity is defined in terms of the polar angle θ as $\eta = -\ln\tan(\theta/2)$. It is equivalent to the rapidity for massless particles. Angular distance is measured in units of $\Delta R \equiv \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2}$.

is surrounded by a 2 T superconducting solenoid. Lead/liquid-argon (LAr) sampling calorimeters provide electromagnetic (EM) energy measurements with high granularity, covering the region $|\eta| < 3.2$. A hadron (steel/scintillator-tile) calorimeter covers the central pseudorapidity range ($|\eta| < 1.7$). The end-cap and forward regions are instrumented with copper/LAr calorimeters ($1.7 < |\eta| < 3.2$) and LAr calorimeters with copper and tungsten absorbers, providing EM and hadronic energy measurements covering the region $|\eta| \leq 4.9$. The muon spectrometer consists of precision tracking chambers covering the region $|\eta| \leq 2.7$. The first-level trigger is implemented in hardware and uses a subset of the detector information to reduce the accepted rate to 100 kHz. This hardware trigger [16] is followed by a software-based trigger that reduces the rate of recorded events to 1 kHz.

3 Data and simulation samples

The data were collected in pp collisions at $\sqrt{s} = 13$ TeV during 2015 and 2016. Collision events are recorded with two triggers. The first selects events with at least one photon candidate that has an online transverse energy $E_{\mathrm{T}} > 140$ GeV and passes the "loose" identification requirements based on the shower shapes in the EM and hadronic calorimeters [16]. The second trigger selects events with at least one jet candidate with online $E_{\mathrm{T}} > 380$ GeV formed from clusters of energy deposits in the calorimeters [17] by the anti-k_t algorithm [18, 19] with radius parameter $R = 0.4$, implemented in the FastJet package [20].

Only data satisfying beam, detector and data-quality criteria are considered [21]. The data used correspond to an integrated luminosity of 36.1 fb^{-1}. The uncertainty in the integrated luminosity is 2.1%; it is derived following a methodology similar to that detailed in Ref. [22].

Samples of simulated events are used to characterise the hypothetical resonances as well as to study the kinematic distributions of background processes. These samples are not used to estimate the background contributions, except when validating the data-driven background estimate (described in Section 5).

Background samples were simulated using the SHERPA 2.1.1 event generator [23]. Processes containing a photon with associated jets were generated in several bins of photon p_{T}. The matrix elements were calculated at leading order (LO) with up to three partons for photon $p_{\mathrm{T}} < 70$ GeV or four partons for higher photon p_{T}. Multijet background samples were generated at LO in several bins of leading-jet p_{T}. Samples of W+jets, Z+jets, $W+\gamma$ and $Z+\gamma$ events were simulated in bins of W/Z-boson p_{T}. Matrix elements were calculated at LO, and the cross sections were corrected at next-to-leading order (NLO) using K-factors derived from corresponding samples with leptonic vector-boson decays generated at NLO. All the above background samples were merged with the SHERPA parton shower [24] using the ME+PS@LO prescription [25]. The CT10 set of parton distribution functions (PDFs) [26] were used in conjunction with the dedicated parton shower tuning developed by the SHERPA authors.

As a benchmark signal, samples with a Z' resonance with only hadronic couplings were generated as in Refs. [27–29]. This Z' has axial-vector couplings to quarks. The coupling of the Z' to quarks, g_q, is set to be universal in quark flavour. A set of samples was generated with $m_{Z'}$ between 100 and 220 GeV and with $g_q = 0.5$, using the MADGRAPH_AMC@NLO generator [30] with the NNPDF2.3 LO PDF [31] and the A14 set of tuned parameters (tune) [32]. Parton showers were produced in PYTHIA 8.186 [33]. The total width $\Gamma_{Z'}$ for the $g_q = 0.5$ samples is negligible compared to the experimental resolution, which is about 10% of the boson mass. Interference of this benchmark model with the Standard Model Z boson is assumed to be negligible. For efficient population of the kinematic phase space, a photon (jet) with $p_{\mathrm{T}} \geq$ 100 GeV (350 GeV) was required in the generation phase.

The response of the detector to particles was modelled with a full ATLAS detector simulation [34] based on GEANT4 [35]. All simulated events were overlaid with additional pp interactions (pile-up) simulated with the soft strong-interaction processes of PYTHIA 8.186 [33] using the A2 tune [36] and the MSTW2008LO PDF set [37]. The simulated events were reconstructed in the same way as the data, and were reweighted such that the distribution of the expected number of pp interactions per bunch crossing matches that seen in data.

4 Event reconstruction and event selection

Events are required to have a reconstructed primary vertex, defined as a vertex with at least two reconstructed tracks with $p_{\mathrm{T}} > 400$ MeV each and with the largest sum of track p_{T}^2.

Photons are reconstructed from clusters of energy deposits in the electromagnetic calorimeter. The photon energy scale is corrected using events with $Z \rightarrow e^+e^-$ decays in data [38]. Identification requirements are applied to reduce the contamination from π^0 or other neutral hadrons decaying into photons. The photon identification is based on the profile of the energy deposits in the first and second layers of the electromagnetic calorimeter. Photons used in the event selection must satisfy the "tight" identification and isolation criteria defined in Ref. [39], and must have $|\eta| < 2.37$, excluding the EM calorimeter's barrel/end-cap transition region of $1.37 < |\eta| < 1.52$. The efficiency of the photon selection is roughly 95% for photons with $E_{\mathrm{T}} > 150$ GeV.

Two non-exclusive categories of jet candidates are built from clusters of energy deposits in the calorimeters [17] and are distinguished by the radius parameter used in the anti-k_t algorithm. Jets with a radius parameter $R = 1.0$ are referred to as *large-R* jets, denoted by J and required to have $|\eta| < 2.0$, whereas jets with a radius parameter $R = 0.4$ are referred to as *narrow* jets, denoted as j and are required to have $|\eta| < 2.4$. To mitigate the effects of pile-up and soft radiation, the large-R jets are trimmed [40]. Trimming takes the original constituents of the jet and reclusters them using the k_t algorithm [41] with a smaller radius parameter, R_{subjet}, to produce a collection of subjets. These subjets are discarded if they carry less than a specific fraction (f_{cut}) of the original jet p_{T}. The trimming parameters optimised for this search are $R_{\mathrm{subjet}} = 0.2$ and $f_{\mathrm{cut}} = 5\%$ [42].

The energies of selected narrow jets are corrected for contributions from pile-up interactions [43]. A correction used to calibrate jet energy measurements to the scale of the constituent particles of the jet [44] is then applied. Narrow jets with 25 GeV $< p_{\mathrm{T}} <$ 60 GeV are required to originate from the primary vertex as determined by a jet vertex tagger [43] that relies on tracks associated with the jets.

Quality requirements are applied to photon candidates to identify those arising from instrumental problems or non-collision background [45], and events containing such candidates are rejected. In addition, quality requirements are applied to remove events containing jets misreconstructed from detector noise or out-of-time energy deposits in the calorimeter from cosmic rays or other non-collision sources [46].

The production cross sections of the signal models considered in this search are many orders of magnitude lower than the background cross sections. In order to enhance the sensitivity to the signal, jet substructure techniques are used to identify the expected two-body quark-pair signal-like events within a single large-R jet. One of the commonly used jet substructure variables is τ_{21} [47], defined as the ratio τ_2/τ_1. The variable τ_N is a measure of how consistent a given jet's constituents are with being fully aligned along N or more axes; thus τ_{21} is a useful discriminant for differentiating between a two-particle jet from the decay of a boosted resonance and a single-particle jet. However, τ_{21} is correlated with the reconstructed large-R

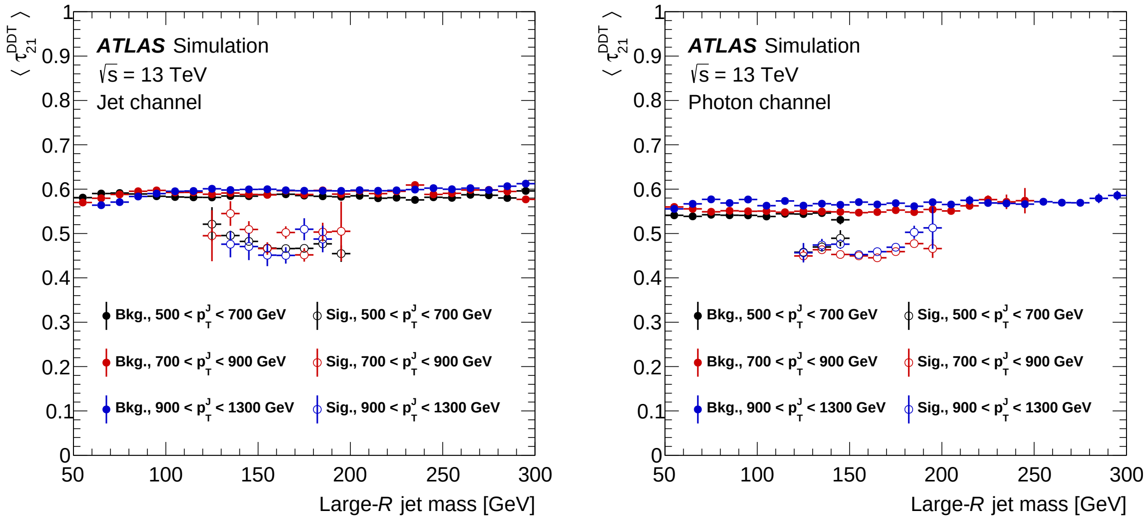

Figure 1: Mean value of τ_{21}^{DDT} as a function of the large-R jet mass, for various ranges of large-R jet transverse momentum, for cases where the ISR object is a jet (left) and a photon (right).

jet mass m_J. Any selection requirement on τ_{21} leads to a selection of jets from the leading background processes with efficiency strongly dependent on the jet mass, and modifies the final jet mass distribution in a way that makes it difficult to model using a simple functional approach, effectively increasing the systematic uncertainties and weakening the overall sensitivity. To avoid this, the designed decorrelated tagger (DDT) method [48, 49] is used to decorrelate τ_{21} from the reconstructed jet mass. The variable ρ^{DDT} is defined as

$$\rho^{\mathrm{DDT}} \equiv \log\left(\frac{m_J^2}{p_{\mathrm{T}}^J \times \mu}\right),$$

where $\mu \equiv 1$ GeV is an arbitrary scale parameter. For $\rho^{\mathrm{DDT}} \gtrsim 1$, there is a linear relationship between ρ^{DDT} and the mean value of τ_{21}. This allows the definition of τ_{21}^{DDT} [48, 49], a linearly corrected version of τ_{21}, which has mean values that are independent of the mass of the jet, as seen in Figure 1 for various ranges of large-R p_{T}^J.

Selected events are required to have at least one large-R jet, the resonance candidate, and at least one narrow jet or photon with azimuthal angular separation of at least $\Delta\phi = \pi/2$ from the resonance candidate. The ISR jet is the leading narrow jet with $p_{\mathrm{T}}^j > 420$ GeV, while the ISR photon is the leading photon with $p_{\mathrm{T}}^\gamma > 155$ GeV.

In the signal region (SR), the large-R jet must satisfy $p_{\mathrm{T}}^J > 200$ GeV in the photon channel and $p_{\mathrm{T}}^J > 450$ GeV in the jet channel, $p_{\mathrm{T}}^J > 2 \times m_J$ to ensure sufficient collimation of the quark pairs from signal resonances so as to avoid edge effects of using a fixed-cone jet algorithm, $\tau_{21}^{\mathrm{DDT}} < 0.50$ to suppress backgrounds and $\rho^{\mathrm{DDT}} > 1.5$. The τ_{21}^{DDT} requirement was chosen by maximising the expected signal significance. The ρ^{DDT} constraint ensures that the τ_{21}^{DDT} variable is linear relative to ρ^{DDT}. If multiple jets satisfy these requirements, the jet with the lower τ_{21}^{DDT} from the two leading large-R jets is selected.

5 Background estimation and systematic uncertainties

The dominant backgrounds in the jet and photon channels are due to multi-jet production and inclusive γ production, respectively. The inclusive γ background is dominated by γ+jets and also includes multi-jet processes being misidentified with the same topology. In both channels, there is a sub-leading contribution from production of a jet or photon in association with a hadronically decaying electroweak gauge boson, V, where V represents a W or Z boson.

In the dominant backgrounds, the boosted phase space relevant to this search is not well described by Monte Carlo programs. Therefore, a data-driven technique is used to model the expected background in the signal region via a transfer-factor method which extrapolates from a control region (CR), defined by inverting the jet substructure requirement to $\tau_{21}^{\mathrm{DDT}} > 0.50$.

The multi-jet and inclusive γ background estimates are constructed in bins of candidate resonance mass. In each bin, the estimate is calculated as $(N_{\mathrm{CR}} - N_V)$ multiplied by the transfer factor, where N_{CR} is the number of events in the CR and N_V is the expected contribution from production with an associated vector boson estimated from simulated samples with cross sections computed at NLO precision in the strong coupling. The transfer factor (TF) is the expected ratio of events which pass the τ_{21}^{DDT} requirement to events which fail, measured using data with $m_J < (0.8 \times m_{Z'})$ or $m_J > (1.2 \times m_{Z'})$, to avoid potential contamination from a signal near $m_{Z'}$. The TF is parameterised in terms of two kinematic quantities, $\log(p_{\mathrm{T}}^J/\mu)$ and ρ^{DDT}; it is implemented as a two-dimensional histogram, smoothed and interpolated into the signal region using a Gaussian process regression [50] using a squared exponential or "Gaussian kernel" with a characteristic length scale $\ell \propto 1/\sigma$ for a Gaussian width σ.

Residual contamination from signal events which leak into the control region is accounted for in the statistical analysis as follows: the background estimate and its uncertainty are validated by constructing an interpolation using data with $m_J < (0.7 \times m_{Z'})$ or $m_J > (1.3 \times m_{Z'})$, which is then compared to the data observed in a validation region (VR) in which $m_J \in [0.7, 0.8]m_{Z'}$ or $m_J \in [1.2, 1.3]m_{Z'}$. Where appropriate, the uncertainty in the data-driven background is increased to match the mean observed deviation of the background estimate from the data in the VR. This uncertainty inflation is added explicitly to account for the case where the background estimate is based on fewer events in the control region. This, however, does not change the nominal background estimate. For the ISR jet channel, the scale factor in the background uncertainty is found to be consistent with 1, while for the ISR γ channel the scale factor ranges from 1 to 2 across the values of $m_{Z'}$. The difference in the scale factors across channels comes from the number of data events: the ISR jet channel has 10 times more events than the ISR γ channel, which exposes subtle structures in the TF profile because the error bars are smaller. This leads to smaller optimal length scales in the GP fit, which in turn leads to larger uncertainties in the interpolation.

As a cross-check, the TF method is applied to a candidate mass range near the W and Z boson masses: the signal region's mass range is set as a ±20% window around 85 GeV ([68,102] GeV), and the validation region as a ±30% window around the same mass, but with the SR removed ([59.5,68] GeV and [102,110.5] GeV). Figure 2 shows distributions of the large-R jet mass for data and the resulting background estimate. The latter is found to agree with the data within uncertainties. The SM prediction for W and Z production is scaled with the NLO cross section using NLO K-factors, as described in Section 3. The best-fit signal strength relative to the SM prediction for W and Z production, $\hat{\mu} = \sigma/\sigma_{W/Z}$, is $\hat{\mu} = 0.93 \pm 0.03$ (stat) $\pm$ 0.24 (syst) in the ISR jet channel and $\hat{\mu} = 1.07 \pm 0.13$ (stat) $\pm$ 0.35 (syst) in the ISR γ channel, consistent with the SM predictions. This result shows that the TF method works well.

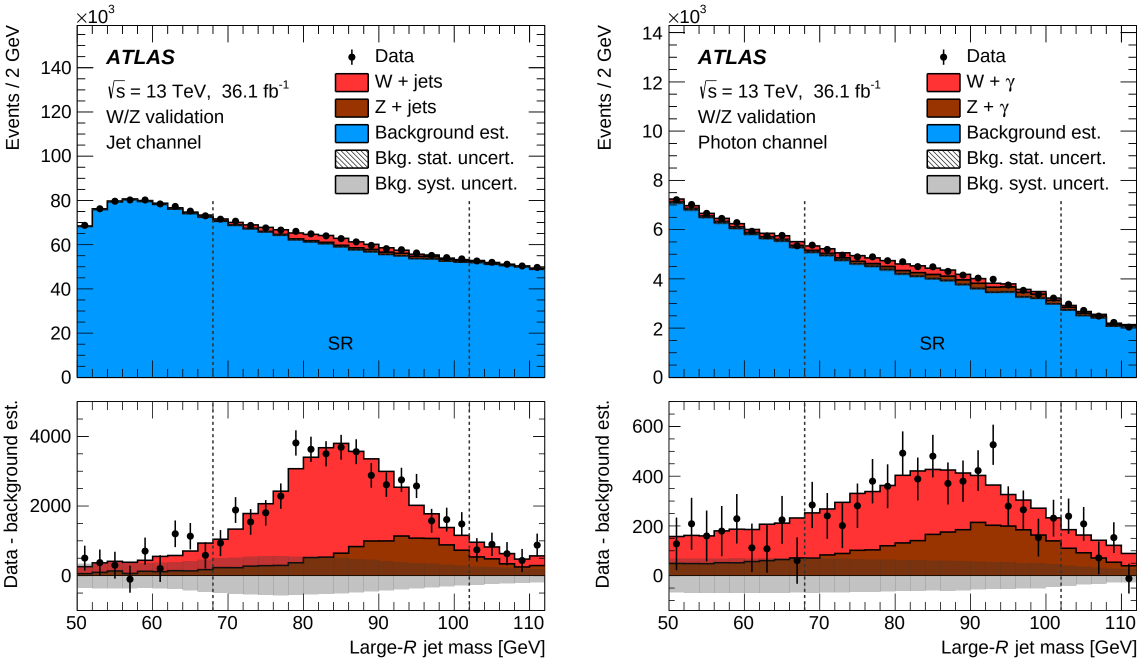

Figure 2: Top: distribution of large-R jet mass near the W and Z boson masses, as a validation of background estimate using the transfer factor described in the text. The vertical dashed lines indicate the signal region (SR) surrounding the target W and Z boson masses. Bottom: residual between data and the estimated background. The distributions are shown for both the (left) jet and (right) photon channels. The contributions from the W and Z backgrounds have been scaled by their best-fit values, as described in the text. In the top panel, the statistical uncertainty is too small to be visible; in the bottom panel it is incorporated into the error bars on the data.

The largest systematic uncertainty is due to the estimate of the dominant background using the TF method. The Gaussian process regression provides a measure of the uncertainty in the interpolation through the posterior distribution in the kernel-induced transfer factor function space, conditioned on the measurement of the ratio of numbers of events in the signal and control regions ($N_{\mathrm{SR}}/N_{\mathrm{CR}}$) [50]. This uncertainty is tuned using the validation region defined above. The final uncertainty is approximately 1% of the total multi-jet or inclusive photon background estimate.

Additional systematic uncertainties stem from the use of simulated samples for the vector-boson associated backgrounds as well as the hypothetical signals. The largest sources of systematic uncertainty in each channel arise from uncertainties in the calibration and resolution of the large-R jet energy and mass, as well as the modelling of τ_{21}^{DDT}; individually these uncertainties range up to 10% relative to the signal, but together these uncertainties are less than 1% of the background estimate in the signal region. Additional, smaller systematic uncertainties are due to the uncertainty in the parton distribution functions and integrated luminosity.

6 Results

The observed distributions of the large-R jet mass are compared with the background estimates in Figure 3 and Figure 4 for two representative Z' mass values for the ISR jet and ISR γ channels, respectively. The

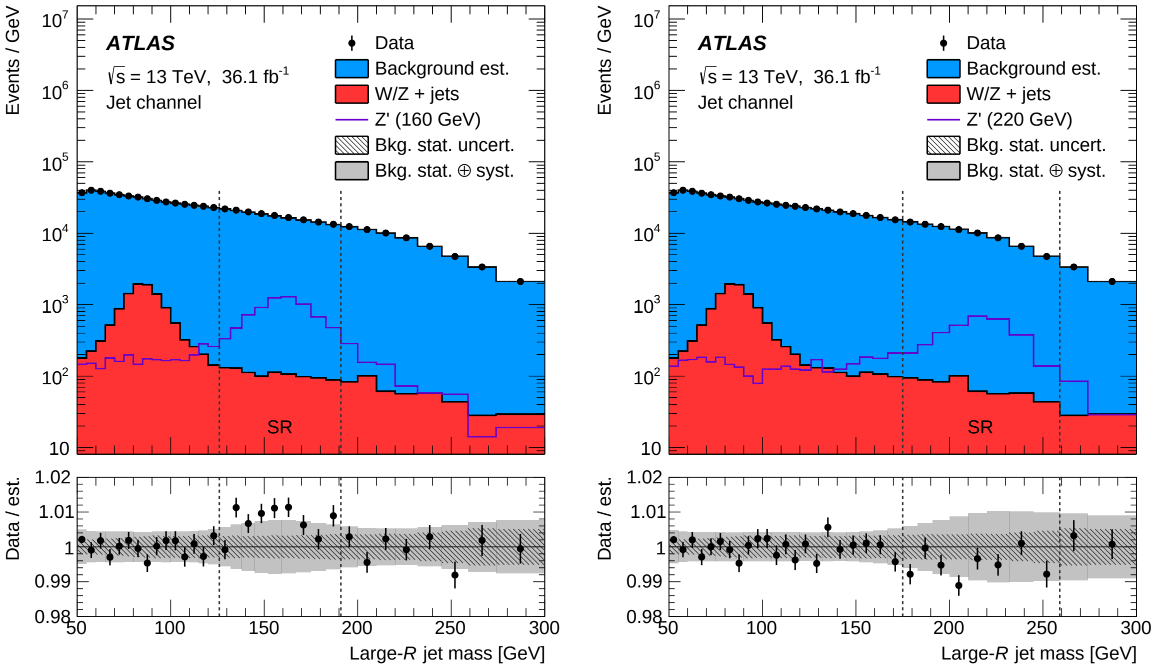

Figure 3: Top: distribution of large-R jet mass in the jet channel for $m_{Z'}$ = 160 GeV (left) and 220 GeV (right). The vertical dashed lines indicate the signal region (SR) surrounding the target Z' mass. The signal is generated with $g_q = 0.5$. Bottom: ratio of data to the estimated background. The background estimate is different for each signal mass hypothesis; more details are given in the text.

slope in the data and background distributions changes for a large-R jet mass around 225 GeV (100 GeV) for Figure 3 (Figure 4), due to the boosted topology requirement, $p_{\mathrm{T}}^{J} > 2 \times m_J$. The beginning of this effect is determined by the p_{T}^{J} requirements of 450 GeV and 200 GeV for the ISR jet and ISR γ channels, respectively. The observed distributions of the large-R jet mass are well reproduced by the estimated background contributions.

A binned likelihood fit to the large-R jet mass distribution is performed in each mass-dependent signal region in both the ISR jet and γ channels, accounting for potential signal contamination in the control region used to define the TF. The largest excess is observed in the ISR jet signal region centred at 150 GeV. Performing a signal-plus-background fit with a Z' model assumption, the local significance in this region is found to be 2.5σ, corresponding to a global significance of 1.1σ, where the look-elsewhere effect [51] is calculated with respect to the entire mass window examined. The largest positive deviation from the expected background in the ISR γ channel is seen in the signal region centred at 140 GeV, with local (global) significance of 2.2σ (0.8σ).

Upper limits are derived at 95% confidence level on the Z' production cross section times acceptance as a function of the Z' mass between 100 and 220 GeV using profile-likelihood-ratio tests [52] with the CL$_{\mathrm{s}}$ method [53], shown in Figure 5.

The acceptance accounts for all selection criteria except for the requirement on τ_{21}^{DDT}; it can vary significantly for various theoretical models, yet can be well estimated without detailed detector simulation. For the Z’ signal model considered in this paper, acceptance values vary from 0.10% to 0.06% in the ISR jet channel and from 4.0% to 1.0% in the ISR γ channel, in the mass range between 100 and 220 GeV. The

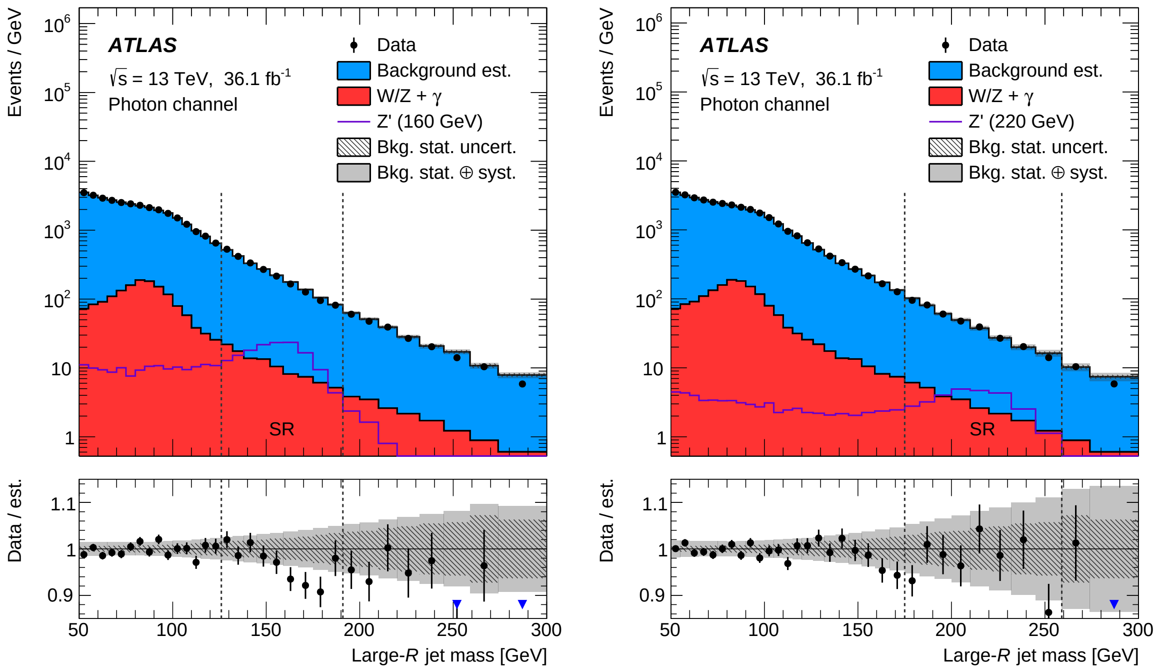

Figure 4: Top: distribution of large-R jet mass in the photon channel for $m_{Z'}$ = 160 GeV (left) and 220 GeV (right). The vertical dashed lines indicate the signal region (SR) surrounding the target Z' mass. The signal is generated with g_q = 0.5. Bottom: ratio of data to the estimated background. The background estimate is different for each signal mass hypothesis; more details are given in the text.

efficiency of the τ_{21}^{DDT} requirement is less model dependent but more dependent on accurate modelling of the τ_{21}^{DDT} variable in simulated samples. The acceptance times efficiency varies between 0.07%–0.04% (2.6%–0.5%) for the ISR jet (ISR γ) channel over the 100–220 GeV mass interval.

The observed and expected limits on the coupling g_q are shown in Figure 6, for the combination of the ISR jet and ISR γ channels. In the combination, the nuisance parameters corresponding to luminosity and large-R jet energy scale and resolution uncertainties are fully correlated between channels, while the background uncertainties are uncorrelated. The largest deviation is for the 140 GeV signal hypothesis, corresponding to 2.4σ local and 1.2σ global significances.

The effects of systematic uncertainties are studied for hypothesised signals using the signal-strength parameter μ. The relative uncertainties in the best-fit μ value from the leading sources of systematic uncertainty are shown in Table 1 for $m_{Z'}$ = 160 and 220 GeV. The TF systematic uncertainty has the largest impact on the sensitivity, accounting for 90% (88%) of the total impact for the 160 (220) GeV signal hypothesis. The second biggest impact is due to uncertainties associated with large-R jets. The data's statistical uncertainty accounts for about 10% of the total impact at both mass points considered.

Table 1: The source and relative size of each of the largest uncertainties in the best-fit signal-strength parameter μ of hypothesised signal production of Z' with $m_{Z'} = 160$ GeV and $m_{Z'} = 220$ GeV.

Uncertainty source	$\Delta\mu/\mu$ [%]	
	$m_{Z'} = 160$ GeV	$m_{Z'} = 220$ GeV
Transfer factor	90	88
Large-R jet	25	17
Total systematic uncertainty	93	91
Statistical uncertainty	10	11

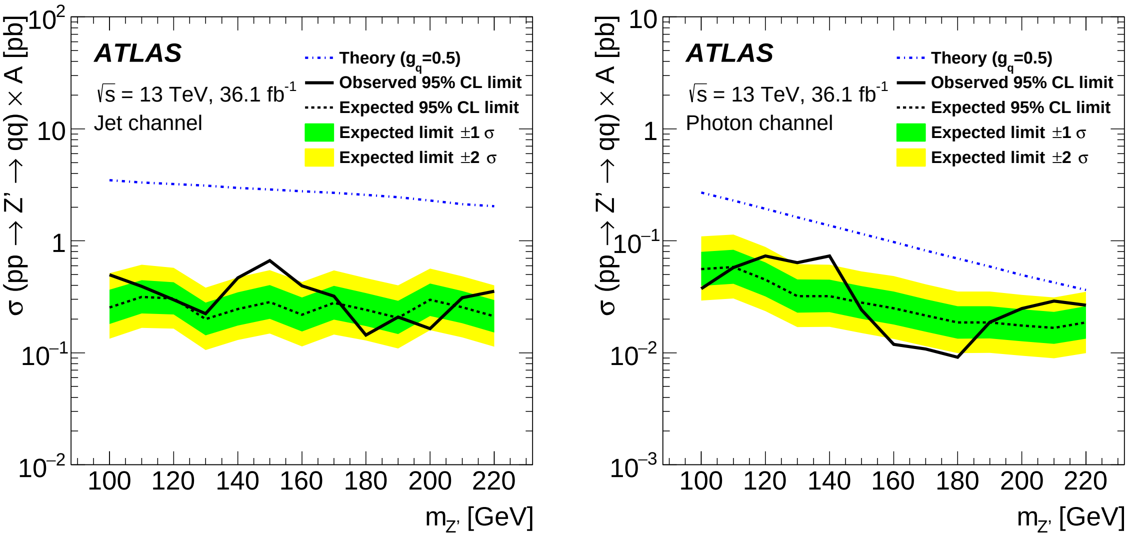

Figure 5: Observed and expected limits at 95% confidence level on the Z' production cross section (σ) times kinematic acceptance (A, see text for details) in the ISR jet channel (left) and the ISR γ channel (right).

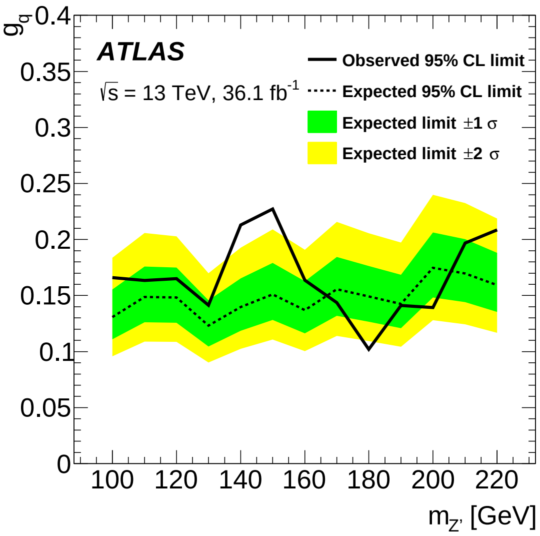

Figure 6: Observed and expected limits at 95% confidence level on the coupling (g_q), for the combination of the ISR jet and ISR γ channels.

7 Conclusion

In summary, a search for new light resonances decaying into pairs of quarks and produced in association with a high-p_{T} photon or jet is presented.The search is based on 36.1 fb^{-1} of 13 TeV pp collisions recorded by the ATLAS detector at the LHC. Resonance candidates are identified as massive large-radius jets with substructure consistent with a quark pair. The mass spectrum of the candidates is examined for local excesses above a data-derived estimate of a smoothly falling background. No evidence of anomalous phenomena is observed in the data, and limits are presented on the cross section and couplings of a leptophobic axial-vector Z' benchmark model. Upper limits at 95% confidence level on production cross sections times acceptance are 0.50 pb (0.04 pb) for a 100 GeV signal hypothesis, and 0.35 pb (0.03 pb) for a 220 GeV signal hypothesis in the ISR jet (ISR γ) channels. The observed upper limits on the coupling g_q are 0.17 for $m_{Z'}$ = 100 GeV and 0.21 for $m_{Z'}$ = 220 GeV, when combining ISR jet and ISR γ channels.

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