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Search for boosted low-mass resonances decaying into hadrons produced in association with a photon in pp collisions at $\sqrt{s} = 13$ TeV with the ATLAS detector

The ATLAS Collaboration

Many extensions of the Standard Model, including those with dark matter particles, propose new mediator particles that decay into hadrons. This paper presents a search for such low mass narrow resonances decaying into hadrons using 140 fb^{-1} of proton–proton collision data recorded with the ATLAS detector at a centre-of-mass energy of 13 TeV. The resonances are searched for in the invariant mass spectrum of large-radius jets with two-pronged substructure that are recoiling against an energetic photon from initial state radiation, which is used as a trigger to circumvent limitations on the maximum data recording rate. This technique enables the search for boosted hadronically decaying resonances in the mass range 20–100 GeV hitherto unprobed by the ATLAS Collaboration. The observed data are found to agree with Standard Model predictions and 95% confidence level upper limits are set on the coupling of a hypothetical new spin-1 Z' resonance with Standard Model quarks as a function of the assumed Z'-boson mass in the range between 20 and 200 GeV.

1 Introduction

Many extensions of the Standard Model (SM) predict new mediator particles that couple to SM particles. A particular class of spin-1 mediators are referred to as Z'. These Z' mediators appear in dark matter models [1, 2] among many others [3–9]. The minimal requirement for a Z' resonance to be produced in the s-channel at the LHC is a $Z'q\bar{q}$ coupling, which in turn predicts resonances decaying into hadronic but not necessarily leptonic final states. The first searches for hadronically decaying resonances at hadron colliders were carried out at the SPS by the UA1 [10, 11] and UA2 [12, 13] Collaborations. The invariant mass reach was extended by the CDF [14] and D0 [15] Collaborations at the Tevatron, and by the ATLAS [16–18] and CMS [19, 20] Collaborations at the LHC. However, with the increase of the centre-of-mass energy and instantaneous luminosity, the sensitivity to light hadronically decaying resonances with small production cross sections is significantly hampered by the high QCD multijet production cross section, which results in an event rate many orders of magnitude above the data recording bandwidth of the experiment. This limitation has been partially addressed by performing searches using online reconstruction algorithms run at the trigger level [21, 22]. Another technique is to use initial-state radiation (ISR) [23] to avoid reliance on single-jet triggers with transverse momentum (p_T) thresholds of around 0.5 TeV, which has been extensively used at the LHC [24–28].

This paper presents a search for hadronically decaying resonances in the challenging invariant mass range between 20 and 100 GeV that was hitherto unexplored by the ATLAS Collaboration. The search uses 140 fb^{-1} of pp collisions recorded by the ATLAS detector between 2015 and 2018 at a centre-of-mass energy of $\sqrt{s}$ = 13 TeV. The bandwidth and QCD background limitations are overcome by using a single-photon trigger with a transverse momentum threshold of p_T > 140 GeV. The search strategy selects ISR photons from the $q\bar{q} \rightarrow Z' \rightarrow q\bar{q}$ process, resulting in a final state with hadronic activity from the $Z' \rightarrow q\bar{q}$ decay recoiling against an energetic photon in the plane perpendicular to the beamline. The leading-order Feynman diagram for the $q\bar{q} \rightarrow \gamma + Z' \rightarrow \gamma + q\bar{q}$ process is shown in Figure 1(a).

The Lorentz boost of the Z' boson brings an increased collimation of the $Z' \rightarrow q\bar{q}$ decay products with decreasing $m_{Z'}$, resulting in a very dense and experimentally challenging jet topology for $m_{Z'} \lesssim 50$ GeV. This challenge is overcome by using the track-assisted reclustered (TAR) jet reconstruction technique [29] that combines information from the tracker and the calorimeters, and was first employed in Ref. [30]. The decay products of the Z' resonance are reconstructed as a single large-radius jet. The signal is searched for as a resonance in the spectrum of the invariant mass of the large-radius jet (m_J) over the background expected from SM processes.

The dominant backgrounds are non-resonant in m_J and arise from QCD multijet production in association with either a photon (see Figure 1(b)) or a jet misidentified as a photon. In both cases, QCD jets can pass the selection for a boosted massive Z' resonance decaying into a pair of quarks due to rare fluctuations in parton showering and hadronisation folded with detector response. Both background sources are estimated from data using signal-depleted control regions (CR) after validating the methodology with Monte Carlo (MC) simulations. Resonant backgrounds arise from SM production of $\gamma+V$ ($V = W, Z$), with $V \rightarrow q\bar{q}$ (see Figure 1(c)). Another resonant background arises from SM top-antitop-quark ($t\bar{t}$) production or associated production of a top-quark and a W boson (tW), where one of the two W bosons in the event decays into a quark pair and the other W boson decays into an electron and a neutrino, with the former being misidentified as a photon. All resonant backgrounds are estimated using MC simulations. The correct modelling of the m_J distribution in resonant processes is verified in a dedicated CR enriched in $t\bar{t}$ events. The results are interpreted within the framework of a dark matter model with a Z' mediator in the mass range between 20 and 200 GeV that decays into a pair of quarks [1, 2]. The lower limit of the search
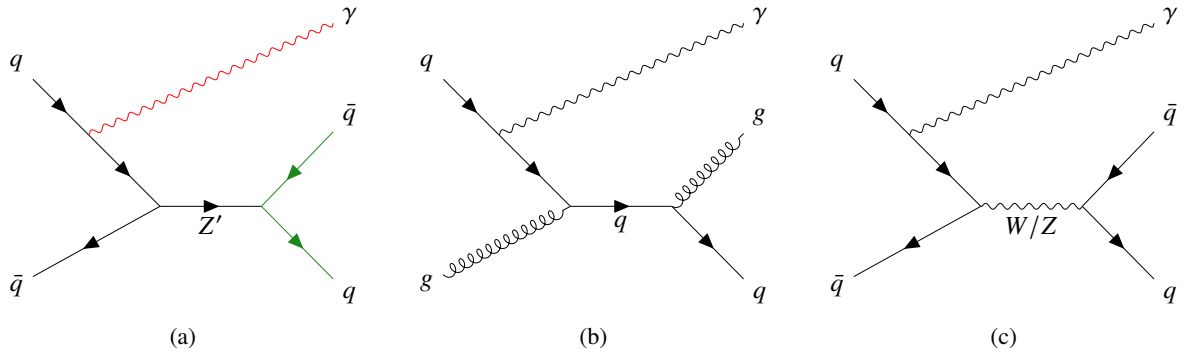
Figure 1: Representative leading-order Feynman diagrams for (a) the $q\bar{q} \rightarrow \gamma + Z' \rightarrow \gamma + q\bar{q}$ process, (b) the non-resonant background from multijet production in association with a photon, and (c) the dominant resonant background from $\gamma+V$, where $V \rightarrow q\bar{q}$ and $V = W, Z$.

range is chosen to avoid the non-trivial effects on the acceptance of the search, while the upper limit is in the region where other searches by the ATLAS Collaboration dominate the sensitivity [16–18, 21, 24, 25, 31].

2 ATLAS detector

The ATLAS experiment [32] at the LHC is a multipurpose particle detector with a forward–backward symmetric cylindrical geometry and a near 4π coverage in solid angle.[1] It consists of an inner tracking detector surrounded by a thin superconducting solenoid providing a 2 T axial magnetic field, electromagnetic and hadronic calorimeters, and a muon spectrometer. The inner tracking detector covers the pseudorapidity range $|\eta| < 2.5$. It consists of silicon pixel, silicon microstrip, and transition radiation tracking detectors. Lead/liquid-argon (LAr) sampling calorimeters provide electromagnetic (EM) energy measurements with high granularity within the region $|\eta| < 3.2$. A steel/scintillator-tile hadronic calorimeter covers the central pseudorapidity range ($|\eta| < 1.7$). The endcap and forward regions are instrumented with LAr calorimeters for EM and hadronic energy measurements up to $|\eta| = 4.9$. The muon spectrometer surrounds the calorimeters and is based on three large superconducting air-core toroidal magnets with eight coils each. The field integral of the toroids ranges between 2.0 and 6.0 T m across most of the detector. The muon spectrometer includes a system of precision tracking chambers up to $|\eta| = 2.7$ and fast detectors for triggering up to $|\eta| = 2.4$. The luminosity is measured mainly by the LUCID–2 [33] detector, which is located close to the beampipe. A two-level trigger system is used to select events [34]. The first-level trigger is implemented in hardware and uses a subset of the detector information to accept events at a rate below 100 kHz. This is followed by a software-based trigger that reduces the accepted event rate to 1 kHz on average depending on the data-taking conditions. A software suite [35] is used in data simulation, in the reconstruction and analysis of real and simulated data, in detector operations, and in the trigger and data acquisition systems of the experiment.

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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. Polar 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 $\eta = -\ln\tan(\theta/2)$ and is equal to the rapidity $y = \frac{1}{2}\ln\left(\frac{E+p_z c}{E-p_z c}\right)$ in the relativistic limit. Angular distance is measured in units of $\Delta R \equiv \sqrt{(\Delta y)^2 + (\Delta \phi)^2}$.

3 Data and simulated event samples

This analysis is performed using data from proton–proton (pp) collisions at $\sqrt{s}$ = 13 TeV at the LHC, collected during 2015–2018 with the ATLAS detector. The total integrated luminosity of this data sample is 140 fb^{-1} [36], obtained using the LUCID-2 detector for the primary luminosity measurements. Data in this analysis are required to satisfy standard quality requirements [37].

SM background processes and the Z' signal are simulated using MC event generators. A detailed simulation of the ATLAS detector [38] based on the GEANT4 [39] package is used to simulate the detector response for all MC event samples. Contributions from additional pp interactions (pile-up) are simulated with the PYTHIA 8.186 [40] event generator using the NNPDF2.3LO parton distribution function (PDF) set [41] and corrected to match the spectrum of the average number of pp collisions per bunch-crossing in the data. Parton shower simulations with PYTHIA use the A14 set of tuned parameters [42] with the NNPDF2.3LO PDF set [41] and EvtGen [43] is used to model the decays of heavy-flavour hadrons. All simulations using the SHERPA event generator employ its internal parton shower model.

Prompt single-photon production was simulated with SHERPA 2.2.1 [44]. The parton-level process was generated at leading order (LO) in QCD for up to three additional partons, using the CT10NLO PDF set [45], and matched to the parton shower using the MEPS@LO prescription [46]. Photons from the matrix elements were required to be isolated according to a smooth-cone hadronic isolation criterion [47] with $\delta_0 = 0.3$, $\epsilon_\gamma = 0.025$ and $n = 2$. Multijet production was simulated using PYTHIA 8.230 [48, 49] with the NNPDF2.3LO PDF set with LO matrix elements for dijet production matched to the parton shower. The renormalisation and factorisation scales were set to the geometric mean of the squared transverse masses of the two outgoing particles in the matrix element. The $\gamma+V$ processes were simulated with SHERPA 2.2.11 using the NNPDF3.0NNLO PDF set [50]. The perturbative calculations for $\gamma+V$ were performed at next-to-leading order (NLO) in QCD for up to one additional parton and LO for up to three additional partons, and matched to the parton shower [51, 52] using the MEPS@NLO prescription. The matrix elements use the narrow-width approximation for the V bosons. Backgrounds from $t\bar{t}$ and single-top-quark production were generated at NLO in QCD with POWHEG BOX v2 [53–56] using the NNPDF3.0NLO PDF set [50] and interfaced to PYTHIA 8.230 for parton showering and hadronisation. The diagram removal scheme [57] was used to remove interference and overlap between tW and $t\bar{t}$ production. The $t\bar{t}$ samples are normalized using calculations at NNLO in QCD including next-to-next-to-leading logarithmic corrections for soft-gluon radiation [58–64]. The single-top-quark processes are normalized to cross sections at NLO in QCD from HATHOR v2.1 [65, 66]. The backgrounds from QCD V+jets production that are relevant for the top-quark control region defined in Section 5 were simulated with MADGRAPH5_AMC@NLO 2.2.2 [67], using LO-accurate matrix elements with up to four final-state partons. The matrix-element calculation employed the NNPDF3.0NLO set of PDFs, and was interfaced to PYTHIA 8.186. The overlap between matrix element and parton shower emissions was removed using the CKKW-L merging procedure [68, 69]. The V+jets samples were normalised to a next-to-next-to-leading-order prediction in QCD [70].

The signal model [1, 71, 72] features a vector resonance Z' with the $Z'q\bar{q}$ coupling g_q set to 0.2 (with $q = u, d, s, c, b$), which results in a Z' width well below the detector resolution. The signal was simulated generating $\gamma + Z'$ events at LO in QCD with MADGRAPH5_AMC@NLO v2.9.2 using the NNPDF3.0NLO PDF set and interfaced to PYTHIA 8.244. The rates for all decay modes except $Z' \rightarrow q\bar{q}$ were set to 0, and the interference between the Z' and the SM Z boson was neglected [1, 2]. The translation of the results to other g_q values is done following Ref. [73]. The mass of the hypothesised Z' resonance ranged between 20 GeV and 200 GeV.

4 Event reconstruction

At least one pp collision vertex, reconstructed from at least two ID tracks, is required in the event [74]. The vertex whose associated tracks give the highest sum of squared transverse momentum is designated the primary vertex (PV). The ID tracks must have at least seven hits and satisfy $p_T > 0.5$ GeV and $|\eta| < 2.5$ requirements [75, 76]. Their transverse and longitudinal impact parameters relative to the PV must satisfy $|d_0| < 2$ mm and $|z_0 \sin(\theta)| < 3$ mm, respectively.

Photon candidates are reconstructed from three-dimensional topological clusters of energy deposits (topoclusters) in the electromagnetic calorimeter [77]. The contamination from neutral hadrons is reduced using the energy deposition profile in the first two calorimeter layers. 'Tight' criteria as defined in Ref. [78] are applied for photon identification and isolation. Photons are required to have $p_T > 10$ GeV and to fall within $|\eta| < 1.37$ or $1.52 < |\eta| < 2.37$, thus avoiding the transition region between the barrel and endcap calorimeters.

Jets are formed with the anti-k_t algorithm [79, 80]. Jets with a radius parameter value of $R = 0.2$ are used in the overall reconstruction of the event. These $R = 0.2$ jets are built from topoclusters in the calorimeter that are corrected using the local cell signal weighting (LCW) method [81]. In addition, jets with $R = 0.4$ are used in the identification of b-hadron decays. These $R = 0.4$ jets are clustered from topoclusters and tracks with a particle flow algorithm that subtracts contributions due to charged particles from topoclusters [82]. A multivariate algorithm is used to identify $R = 0.4$ jets containing b-hadrons (b-tagging) with an average efficiency of 85% [83]. Corrections for pile-up [84] and to the energy scale and resolution [85] are applied to both jet definitions. Jets with $R = 0.2$ ($R = 0.4$) are required to have $p_T > 25$ GeV and $|\eta| < 2.2$ (2.5). $R = 0.4$ jets with $p_T < 60$ GeV and $|\eta| < 2.4$ are identified as originating from the PV using associated tracks [86]. No such procedure is applied to $R = 0.2$ jets since they are only used in association with tracks.

The TAR technique [29] is used to reconstruct the $Z' \to q\bar{q}$ decay in the challenging boosted low-mass phase space for the first time. This technique improves the resolution of jet substructure observables by combining tracking and calorimeter measurements. The TAR jets are formed from ID tracks and $R = 0.2$ jets as follows. The calibrated $R = 0.2$ jets are reclustered into larger jets with $R = 1.0$ using trimming parameters optimized for ATLAS [87]. ID tracks are associated to the $R = 0.2$ subjets of the reclustered jet. The p_T of each associated track is then rescaled by a common factor so the magnitude of the vector p_T sum of the associated tracks equals the p_T of the $R = 0.2$ jet. These rescaled tracks are used to calculate TAR jet observables, e.g., the jet mass m_J.

Resonance candidate $R = 1.0$ TAR jets are selected to be central ($|\eta| < 2$), have sufficient transverse momentum to balance the ISR photon ($p_{T,J} > 150$ GeV), and be collimated ($2m_J / p_{T,J} < 1$). They must be separated from the highest-p_T photon in the event by $\Delta\phi > \pi/2$, and isolated from any photon with $p_T^\gamma / p_T^J > 0.1$ by $\Delta R \geq 1.2$. TAR jets consisting of fewer than three rescaled tracks are rejected, since the substructure variable D_2 introduced in Section 5 is ill-defined for such jets [88].

Muons are reconstructed by matching a track or track segment found in the muon spectrometer to an ID track. Muons must satisfy the 'Medium' requirements in Ref. [89] and have $p_T > 25$ GeV and $|\eta| < 2.5$. Muons must be isolated using the 'Loose' criteria in Ref. [89], which limits the total energy observed in tracks and calorimeter deposits near the (extrapolated) muon track.

5 Event selection and analysis strategy

The signal is characterised by hadronic activity from the $Z' \to q\bar{q}$ decay produced back-to-back in azimuth to an isolated prompt energetic photon, which is used to trigger the event [90]. To ensure the trigger is fully efficient, the transverse momentum of the leading photon p_T^γ is required to be greater than $150\,\text{GeV}$. At least one TAR jet is required. To reduce the non-resonant background contribution, events are rejected if any $R = 0.2$ jet within $\Delta R \leq 1.2$ of the leading TAR jet (but not reclustered into it) has a p_T greater than p_T^γ. Similarly, events where the leading TAR jet has $\rho \equiv \log(m_J^2/p_{T,J}^2) \leq -5.4$ are rejected to improve the modelling of non-resonant backgrounds at the low end of the m_J spectrum using the data-driven approach, which will be described later in this Section. This selection has a negligible effect on the signal acceptance in the targeted $m_{Z'}$ range.

The internal energy distribution in TAR jets from signal events is consistent with a two-prong $Z' \to q\bar{q}$ decay, while TAR jets from non-resonant backgrounds are compatible with a one-prong decay. This difference is characterised using the D_2 observable [88], which was found to be powerful at discriminating between one- and two-prong jets [91]. The D_2 variable is defined using ratios of energy correlation functions that explore the substructure of a jet using an angular-weighted sum over the momenta of its constituents. The values of D_2 for two-prong jets are typically smaller than those for one-prong jets. Figure 2(a) shows a comparison of the distribution of the D_2 observable between non-resonant background processes in three mass ranges and the resonant backgrounds.

The D_2 observable is correlated with m_J. To eliminate the shaping of m_J resulting from the D_2 selection, a decorrelated observable [92–96] is defined as

$$D_2^{\text{DDT}}(\rho, p_T) = D_2 - D_2^{13\%}(\rho, p_T), \tag{1}$$

where 'DDT' stands for 'Designed Decorrelated Tagger'. Here, $D_2^{13\%}$ is the 13% quantile, i.e., the value of D_2 that splits the non-resonant background MC sample into two subsamples of 87% and 13%. Hence, a selection of $D_2^{\text{DDT}}(\rho, p_T) < 0$ has a fixed efficiency of 13% in non-resonant background MC samples, irrespective of the mass or p_T of the jet. The quantile value of 13% was chosen by optimising the overall analysis sensitivity following the $S/\sqrt{B}$ metric, where S and B are the expected numbers of signal and background events, respectively, and by minimising the magnitude of the variations in the initial $D_2^{13\%}(\rho, p_T)$ distribution for non-resonant background events.

The final $D_2^{13\%}(\rho, p_T)$ map is obtained by smoothing its initial distribution by convolution with a two-dimensional Gaussian kernel [97]. The parameters of the smoothing procedure like the binning of the initial $D_2^{13\%}(\rho, p_T)$ distribution and the kernel widths in ρ and p_T dimensions are optimised by minimising the Jensen-Shannon distance [98–100] between the m_J distributions for non-resonant background MC samples before and after the $D_2^{\text{DDT}}(\rho, p_T) < 0$ selection. In addition to D_2, six other jet substructure observables capable of discriminating between one- and two-prong jets [91], including τ_{21} used in a similar previous ATLAS search [24], were explored following the procedure above. The D_2 variable was chosen since it minimises the shaping of the m_J distribution following the Jensen-Shannon distance metric.

Figure 2(b) shows the final $D_2^{13\%}(\rho, p_T)$ map after smoothing. In the following, the 'tagged' sample enriched in signal and two-prong resonant backgrounds is defined by the criterion $D_2^{\text{DDT}} < 0$, while the complementary 'anti-tagged' sample is enriched in non-resonant backgrounds.

Ideally, the shape of the m_J distribution of non-resonant background should be identical in the tagged and anti-tagged samples. In practice, the accuracy is limited by statistical and theoretical uncertainties on
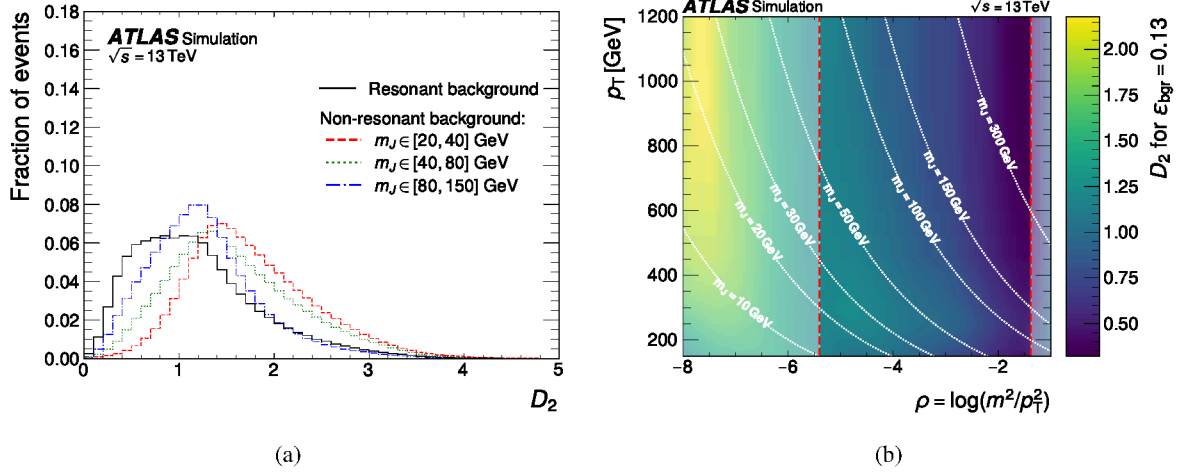
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Figure 2: (a) Distribution of the D_2 observable [88] in MC simulations of non-resonant background processes in three different mass ranges (broken lines) compared to the resonant backgrounds (solid line). (b) The 13% quantile of the D_2 observable in the simulated non-resonant background sample. The contours of constant m_J are indicated by white dashed lines. White-shaded areas separated by vertical broken lines indicate the phase space that the $\rho < -5.4$ and $2m_J/p_{T,J} > 1$ selections reject.

the modelling of non-resonant backgrounds in MC simulations. Hence, this background distribution is estimated using data. This is done by modifying the non-resonant background contribution taken from the anti-tagged region in data by an m_J-dependent correction $\kappa_{D_2^{\mathrm{DDT}}}(m_J)$ that is applied to the initial D_2^{DDT} efficiency of 13% as determined in simulations. Typically, the $\kappa_{D_2^{\mathrm{DDT}}}(m_J)$ provides a percent-level correction to the nominal tagging efficiency. In order to reduce the impact of statistical fluctuations, $\kappa_{D_2^{\mathrm{DDT}}}$ is parameterized in m_J by a Bernstein polynomial [101] of order five. In addition to providing an orthonormal basis, Bernstein polynomials bestow the advantage of strictly positive coefficients that are easily interpretable. The order of the Bernstein polynomial was optimised using pseudoexperiments requiring that a spurious signal bias be smaller than one-third of the statistical uncertainty, and considering the χ^2 probability, and the goodness-of-fit in data. The six Bernstein coefficients of $\kappa_{D_2^{\mathrm{DDT}}}$ are determined in the simultaneous fit to data described in Section 6.

The data sample is further split into the central and forward regions defined by $|\eta_\gamma| \leq 1.3$ and $|\eta_\gamma| > 1.3$, respectively. Together with the split into tagged and anti-tagged categories, this defines four analysis regions in total: 'central tagged', 'forward tagged', 'central anti-tagged', and 'forward anti-tagged', where the former two are enriched in resonant processes due to the $D_2^{\mathrm{DDT}} < 0$ selection. The central tagged analysis region is then defined as the signal region (SR), since signal tends to be more central for such quark-induced processes with energetic ISR photons. The other three analysis regions are referred to as control regions (CR).

To minimize biases due to a potential signal contamination in the forward tagged CR and other CRs, a single $\kappa_{D_2^{\mathrm{DDT}}}(m_J)$ correction is determined and applied in all four regions in a simultaneous fit procedure discussed in Section 6. In all CRs, the signal contamination never exceeds three permille. Hence, the signal significance, defined as $S/\sqrt{B}$ in the m_J region around the $m_{Z'}$ candidate mass, is at least two times smaller in the CRs compared to the SR, at the level of sensitivity of this analysis. A systematic uncertainty on the assumption that $\kappa_{D_2^{\mathrm{DDT}}}(m_J)$ is identical in the central and forward regions is estimated as described

in Section 6.

The resonant background processes ($\gamma+V$, tW and $t\bar{t}$) and the signal are modelled using MC simulations. The efficiency of the D_2^{DDT} selection in MC simulations is calibrated using $W \to q\bar{q}'$ decays. This is done using a dedicated top CR (denoted 'top CR'), which targets the semi-muonic decay of $t\bar{t}$ pairs and hence requires a single energetic muon trigger and exactly one isolated muon with $p_T \geq 30\,\text{GeV}$. At least three $R = 0.4$ jets must be present, of which at least two should be b-tagged. At least one b-tagged jet must fall within $\Delta R < 1.5$ from the muon to select for collimated $t \to bW$ decays. Furthermore, at least one TAR jet passing all SR selections except for D_2^{DDT} must be present. TAR jets must be separated by $\Delta R \geq 1.05$ from muons and by $\Delta R \geq 1.45$ from b-tagged jets.

The fiducial on-shell $W \to qq'$ production rate is extracted in the top CR using a parametrised fit to the W-boson candidate mass spectrum, where the contribution from W bosons is captured by a Gaussian distribution, while the background is described by a second order polynomial. The efficiency of the D_2^{DDT} selection $\varepsilon_{D_2^{\text{DDT}}}^{\text{res}}$ for resonant W-boson production is then determined as the ratio of the fiducial on-shell W-boson production rates after and before applying the $D_2^{\text{DDT}} < 0$ requirement. The ratio

$$\mathcal{R}_{D_2^{\text{DDT}}} = \frac{\varepsilon_{D_2^{\text{DDT}},\text{data}}^{\text{res}}}{\varepsilon_{D_2^{\text{DDT}},\text{MC}}^{\text{res}}}$$

is then used to calibrate the tagging efficiency in MC simulations of resonant processes. The calibration factor is measured to be $\mathcal{R}_{D_2^{\text{DDT}}} = 0.971 \pm 0.026$. Its value and the corresponding uncertainty is propagated to the signal extraction fit described in Section 6.

6 Statistical analysis and systematic uncertainties

The resonant $Z' \to q\bar{q}$ signal is extracted via a simultaneous maximum-likelihood fit [102, 103] to the binned m_J distributions in the SR and the three CR categories, but not the top CR. This fit considers signal and resonant background predictions from MC simulations scaled to their theoretical cross sections and calibrated for the D_2^{DDT} selection efficiency determined in the top CR. The width of the bins in m_J is chosen as about one-third of the experimental resolution on $m_{Z'}$ while keeping the statistical uncertainties per bin approximately constant. The expected yields ν_i for the Poisson probability density in a given m_J bin i are given as

$$\nu_{\text{SR},i}(\mu, \theta) = \mu \cdot \nu_{\text{SR,sig},i}(\theta) + \sum_{\text{res. bkg.}} \nu_{\text{SR,bkg},i}(\theta) + \frac{13\%}{1 - 13\%} \kappa_{D_2^{\text{DDT}},i} \cdot \nu_{\text{central},i} \tag{2}$$

for the SR and

$$\nu_{\text{caCR},i}(\mu, \theta) = \mu \cdot \nu_{\text{caCR,sig},i}(\theta) + \sum_{\text{res. bkg}} \nu_{\text{caCR,bkg},i}(\theta) + \nu_{\text{central},i} \tag{3}$$

in the central anti-tagged CR labelled as 'caCR'. Here, μ is the signal strength, i.e. a factor multiplying the expected signal yields, θ is the vector of nuisance parameters representing systematic uncertainties and the $\mathcal{R}_{D_2^{\text{DDT}}}$ calibration, 'sig' labels the signal and 'res. bkg' the resonant background processes. The values $\nu_{\text{central},i}$ approximate the yield of the non-resonant background in the central anti-tagged CR. The relevant difference between Eqs. (2) and (3) is the transfer factor $\frac{13\%}{1-13\%} \kappa_{D_2^{\text{DDT}},i}$ that considers the non-resonant background tagging efficiency in data. The probability densities in the forward tagged and anti-tagged

CRs are defined in analogy to Eqs. (2) and (3), respectively, using the same $\frac{13\%}{1-13\%}\kappa_{D_2^{\mathrm{DDT}},i}$ transfer factor. Hence, the non-resonant background contribution is simultaneously fit in the SR and the three CRs through a common set of the Bernstein coefficients for the $\kappa_{D_2^{\mathrm{DDT}}}(m_J)$ correction.

The uncertainty in the non-resonant background estimate represents the dominant systematic uncertainty in this analysis, contributing between 80% and 90% of the total systematic uncertainty, depending on the $m_{Z'}$ hypothesis. This uncertainty estimate considers three different sources, which are described below.

First, a systematic uncertainty on the assumption that $\kappa_{D_2^{\mathrm{DDT}}}(m_J)$ is identical in the central and forward regions is explicitly considered in the simultaneous maximum-likelihood fit procedure through Eqs. (2) and (3) and their counterparts for the forward CRs. Since the central and forward regions use the same $\kappa_{D_2^{\mathrm{DDT}}}$ correction factor and hence the same Bernstein coefficients, any tensions between the data in the tagged central and forward regions and the estimates obtained from the corresponding untagged regions will result in an increased uncertainty in the fitting procedure. This source of systematic uncertainty explicitly accounts for statistical limitations due to a finite number of data and MC events, and contributes more than 90% of the uncertainty on the non-resonant background estimate.

Second, a systematic uncertainty accounting for a potential spurious signal bias as a function of m_J is considered. This bias is evaluated through a multiplicative nuisance parameter on the signal yield in fits to pseudoexperiments derived from Asimov data. The corresponding uncertainty is below one percent of the uncertainty on the non-resonant background estimate.

Third, a systematic uncertainty related to the extrapolation between the forward and central regions is evaluated. This uncertainty accounts for localised fluctuations in tagged region data on scales that are comparable to the m_J resolution. This uncertainty is derived from the net difference between observed data and the pre-fit background prediction. If this net difference is larger than $\sqrt{B}$ in a given m_J bin, a systematic uncertainty is added to this bin. Only the tagged forward control region is used to determine the net difference in order to minimise any impact from signal that may potentially be present. This systematic uncertainty is applied in the central and forward regions, per m_J bin and it is taken as uncorrelated across bins. It contributes a few percent of the uncertainty in the non-resonant background estimate.

The systematic uncertainties related to MC simulations are parameterized as nuisance parameters with Gaussian or log-normal prior probabilities, are profiled and used to constrain the template shapes and the normalisations varied in the fit. The leading sources of systematic uncertainty related to MC simulations originate from the theoretical modelling of signal events. Among those uncertainties are: the choice of the factorisation and renormalisation scales, the choice of PDFs, and the uncertainty on the strong coupling constant α_{s}. Sub-leading sources of systematic uncertainties that affect both signal and background events modelled using MC simulations are related to the energy scale and resolution of $R = 0.2$ and $R = 0.4$ jets [85]. Other, typically negligible sources of systematic uncertainty are related to the identification and reconstruction of photons [77], the finite number of MC events, and the measured integrated luminosity [36]. Overall, this search is limited by statistical uncertainties in the data, which typically range between 20% and 50% of the theoretical cross section for the $Z' \to q\bar{q}$ process, depending on $m_{Z'}$.

7 Results

The distributions of m_J in the SR and the central anti-tagged CR and are shown in Figure 3 after the fit to data under the background-only hypothesis. The statistical weight of the anti-tagged CRs is significantly higher than that of the tagged regions since they have seven times the yield. Hence, the excursion of the data points from the background prediction relative to the total statistical plus systematic uncertainty in the
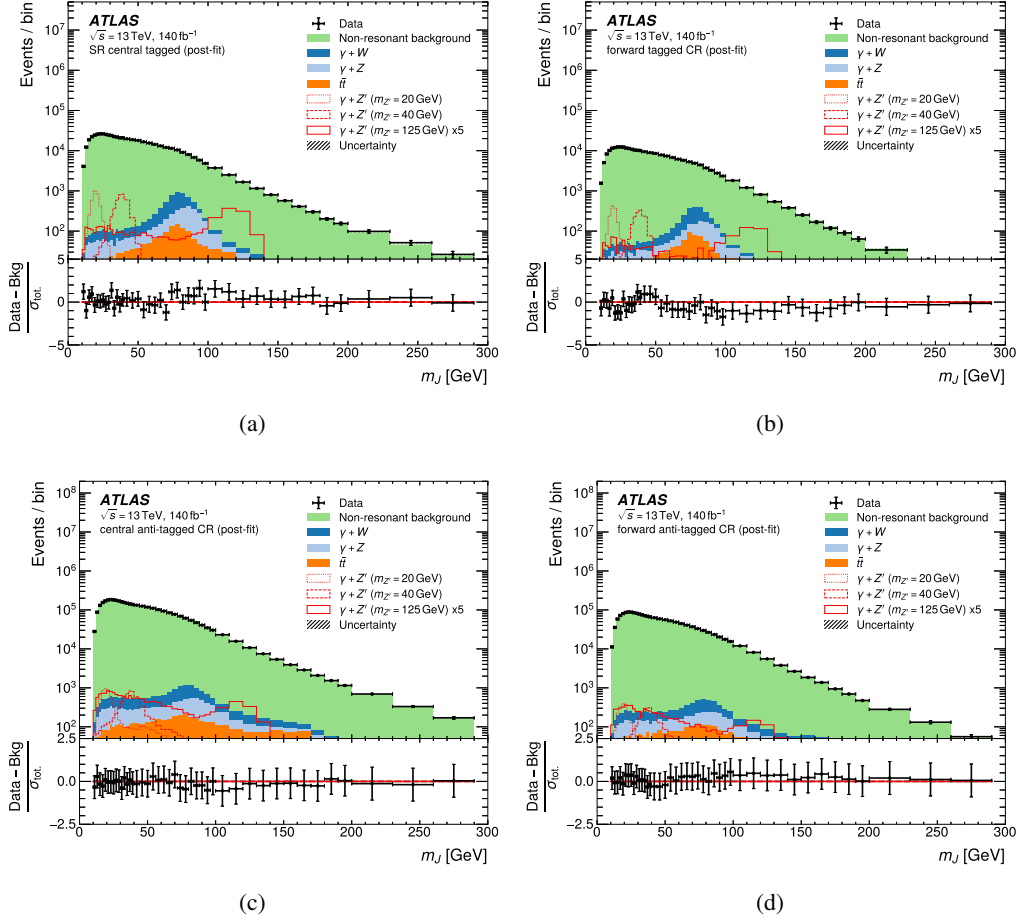
Figure 3: Invariant mass m_J of the resonance candidates in the (a) SR, i.e., central tagged region, (b) forward tagged CR, (c) central anti-tagged CR, and (d) forward anti-tagged CR, after the fit to data under the background-only hypothesis. The total systematic uncertainty is shown as the hatched band. Three representative $\gamma + Z$ signal distributions are overlaid as red lines. The signal is shown for $g_q = 0.2$ with production cross sections of 309 fb, 143 fb, and 34.2 fb for $m'_Z = 20, 50,$ and 125 GeV, respectively.

anti-tagged CRs is much smaller than in the tagged regions. For the same reason, the relative contribution of the systematic uncertainty, shown as a hatched band, appears larger in the anti-tagged CRs due to the smaller total uncertainty compared to the tagged regions. Figure 4 shows the corresponding $\kappa_{D_2^{\text{DDT}}}(m_J)$ correction after the fit to data under the background-only hypothesis alongside observed ratios of tagged over anti-tagged events in the central and forward regions. No significant deviation from SM predictions is observed.

In absence of a significant excess, the results are interpreted in Figure 5 as exclusion limits at 95% confidence level (CL) on the g_q coupling strength with the CL_s formalism [104] using a profile likelihood ratio [105] as test statistic. In the range $m_{Z'} < 100$ GeV, hitherto unprobed by ATLAS, g_q couplings as small as 0.1 are excluded.
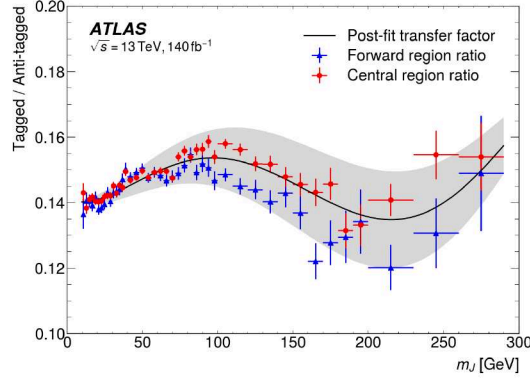
Figure 4: The distribution of the transfer factor $\frac{13\%}{1-13\%}\kappa_{D_2^{\mathrm{DDT}}}(m_J)$ after the fit to data under the background-only hypothesis. The corresponding uncertainty band is shown as a shaded area. Also shown are the observed ratios of tagged over anti-tagged events in the central (red circles) and forward (blue triangles) regions, where the prior expected contributions from resonant backgrounds have been subtracted and the uncertainties are purely statistical.
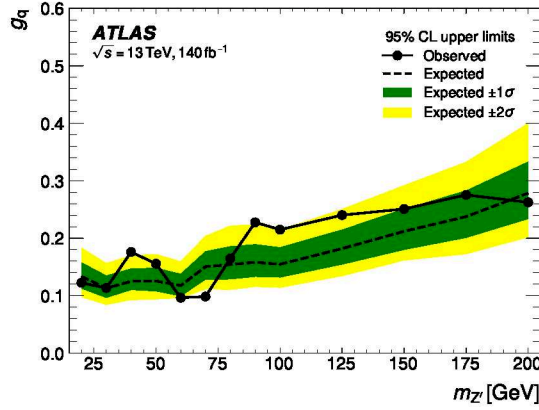
Figure 5: Observed (expected) upper exclusion limits at 95% CL on the coupling strength g_q of a new vector Z' particle decaying to a $q\bar{q}$ pair for the LHC DM WG benchmark signal model from Refs. [1, 71, 72] where decay rates for all decay modes except $Z' \rightarrow q\bar{q}$ are set to 0, and the interference between the Z' and the SM Z boson is neglected. The expected $\pm 1\sigma$ ($\pm 2\sigma$) interval around the expected limit is shown as the filled green (yellow) band.

8 Conclusion

This paper presents a search for light hadronically decaying resonances using 140 fb^{-1} of pp collision data at $\sqrt{s} = 13$ TeV recorded by the ATLAS detector at the LHC. To avoid bandwidth limitations, events are triggered using energetic photons radiated from the initial state, and a search for resonances is performed on the invariant mass of the recoiling hadronic system. A track-assisted reclustered jet reconstruction method that combines information from the tracker and the calorimeters is used to reconstruct these boosted hadronically decaying resonances. A data-driven method is used to estimate the non-resonant background from the Standard Model production of a photon in association with jets and QCD multijet production with a jet misidentified as a photon. These techniques allow a search for new hadronically decaying resonances with invariant masses from 20 to 100 GeV for the first time in ATLAS. No evidence for new resonances is found. The results are interpreted within the framework of a dark matter model with a Z' mediator, i.e., the

$q\bar{q} \rightarrow \gamma + Z' \rightarrow \gamma + q\bar{q}$ process, and probe previously uncharted parameter space for the $Z'q\bar{q}$ coupling g_q for masses $20 < m_{Z'} < 200$ GeV, excluding g_q couplings down to 0.1.

Acknowledgements

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G. Aad [104], E. Aakvaag [17], B. Abbott [123], S. Abdelhameed [119a], K. Abeling [56], N.J. Abicht [50], S.H. Abidi [30], M. Aboelela [45], A. Aboulhorma [36e], H. Abramowicz [154], H. Abreu [153], Y. Abulaiti [120], B.S. Acharya [70a,70b,l], A. Ackermann [64a], C. Adam Bourdarios [4], L. Adamczyk [87a], S.V. Addepalli [27], M.J. Addison [103], J. Adelman [118], A. Adiguzel [22c], T. Adye [137], A.A. Affolder [139], Y. Afik [40], M.N. Agaras [13], J. Agarwala [74a,74b], A. Aggarwal [102], C. Agheorghiesei [28c], F. Ahmadov [39,x], W.S. Ahmed [106], S. Ahuja [97], X. Ai [63e], G. Aielli [77a,77b], A. Aikot [166], M. Ait Tamlihat [36e], B. Aitbenchikh [36a], M. Akbiyik [102], T.P.A. Åkesson [100], A.V. Akimov [38], D. Akiyama [171], N.N. Akolkar [25], S. Aktas [22a], K. Al Khoury [42], G.L. Alberghi [24b], J. Albert [168], P. Albicocco [54], G.L. Albouy [61], S. Alderweireldt [53], Z.L. Alegria [124], M. Aleksa [37], I.N. Aleksandrov [39], C. Alexa [28b], T. Alexopoulos [10], F. Alfonsi [24b], M. Algren [57], M. Alhroob [170], B. Ali [135], H.M.J. Ali [93], S. Ali [32], S.W. Alibocus [94], M. Aliev [34c], G. Alimonti [72a], W. Alkakhi [56], C. Allaire [67], B.M.M. Allbrooke [149], J.F. Allen [53], C.A. Allendes Flores [140f], P.P. Allport [21], A. Aloisio [73a,73b], F. Alonso [92], C. Alpigiani [141], Z.M.K. Alsolami [93], M. Alvarez Estevez [101], A. Alvarez Fernandez [102], M. Alves Cardoso [57], M.G. Alviggi [73a,73b], M. Aly [103], Y. Amaral Coutinho [84b], A. Ambler [106], C. Amelung[37], M. Amerl [103], C.G. Ames [111], D. Amidei [108], K.J. Amirie [158], S.P. Amor Dos Santos [133a], K.R. Amos [166], D. Amperiadou [155], S. An[85], V. Ananiev [128], C. Anastopoulos [142], T. Andeen [11], J.K. Anders [37], A.C. Anderson [60], S.Y. Andrean [48a,48b], A. Andreazza [72a,72b], S. Angelidakis [9], A. Angerami [42], A.V. Anisenkov [38], A. Annovi [75a], C. Antel [57], E. Antipov [148], M. Antonelli [54], F. Anulli [76a], M. Aoki [85], T. Aoki [156], M.A. Aparo [149], L. Aperio Bella [49], C. Appelt [19], A. Apyan [27], S.J. Arbiol Val [88], C. Arcangeletti [54], A.T.H. Arce [52], J-F. Arguin [110], S. Argyropoulos [55], J.-H. Arling [49], O. Arnaez [4], H. Arnold [148], G. Artoni [76a,76b], H. Asada [113], K. Asai [121], S. Asai [156], N.A. Asbah [37], K. Assamagan [30], R. Astalos [29a], K.S.V. Astrand [100], S. Atashi [162], R.J. Atkin [34a], M. Atkinson[165], H. Atmani[36f], P.A. Atmasiddha [131], K. Augsten [135], S. Auricchio [73a,73b], A.D. Auriol [21], V.A. Austrup [103], G. Avolio [37], K. Axiotis [57], G. Azuelos [110,ac], D. Babal [29b], H. Bachacou [138], K. Bachas [155,p], A. Bachiu [35], F. Backman [48a,48b], A. Badea [40], T.M. Baer [108], P. Bagnaia [76a,76b], M. Bahmani [19], D. Bahner [55], K. Bai [126], J.T. Baines [137], L. Baines [96], O.K. Baker [175], E. Bakos [16], D. Bakshi Gupta [8], L.E. Balabram Filho [84b], V. Balakrishnan [123], R. Balasubramanian [117], E.M. Baldin [38], P. Balek [87a], E. Ballabene [24b,24a], F. Balli [138], L.M. Baltes [64a], W.K. Balunas [33], J. Balz [102], I. Bamwidhi [119b], E. Banas [88], M. Bandieramonte [132], A. Bandyopadhyay [25], S. Bansal [25], L. Barak [154], M. Barakat [49], E.L. Barberio [107], D. Barberis [58b,58a], M. Barbero [104], M.Z. Barel [117], T. Barillari [112], M-S. Barisits [37], T. Barklow [146], P. Baron [125], D.A. Baron Moreno [103], A. Baroncelli [63a], A.J. Barr [129], J.D. Barr [98], F. Barreiro [101], J. Barreiro Guimarães da Costa [14], U. Barron [154], M.G. Barros Teixeira [133a], S. Barsov [38], F. Bartels [64a], R. Bartoldus [146], A.E. Barton [93], P. Bartos [29a], A. Basan [102], M. Baselga [50], A. Bassalat [67,b], M.J. Basso [159a], S. Bataju [45], R. Bate [167], R.L. Bates [60], S. Batlamous[101], B. Batool [144], M. Battaglia [139], D. Battulga [19], M. Bauce [76a,76b], M. Bauer [80], P. Bauer [25], L.T. Bazzano Hurrell [31], J.B. Beacham [52], T. Beau [130], J.Y. Beaucamp [92], P.H. Beauchemin [161], P. Bechtle [25], H.P. Beck [20,o], K. Becker [170], A.J. Beddall [83], V.A. Bednyakov [39], C.P. Bee [148], L.J. Beemster [16], T.A. Beermann [37], M. Begalli [84d], M. Begel [30], A. Behera [148], J.K. Behr [49], J.F. Beirer [37], F. Beisiegel [25], M. Belfkir [119b], G. Bella [154], L. Bellagamba [24b], A. Bellerive [35], P. Bellos [21], K. Beloborodov [38], D. Benchekroun [36a], F. Bendebba [36a], Y. Benhammou [154],

K.C. Benkendorfer [62], L. Beresford [49], M. Beretta [54], E. Bergeaas Kuutmann [164], N. Berger [4], B. Bergmann [135], J. Beringer [18a], G. Bernardi [5], C. Bernius [146], F.U. Bernlochner [25], F. Bernon [37,104], A. Berrocal Guardia [13], T. Berry [97], P. Berta [136], A. Berthold [51], S. Bethke [112], A. Betti [76a,76b], A.J. Bevan [96], N.K. Bhalla [55], S. Bhatta [148], D.S. Bhattacharya [169], P. Bhattarai [146], K.D. Bhide [55], V.S. Bhopatkar [124], R.M. Bianchi [132], G. Bianco [24b,24a], O. Biebel [111], R. Bielski [126], M. Biglietti [78a], C.S. Billingsley [45], M. Bindi [56], A. Bingul [22b], C. Bini [76a,76b], G.A. Bird [33], M. Birman [172], M. Biros [136], S. Biryukov [149], T. Bisanz [50], E. Bisceglie [44b,44a], J.P. Biswal [137], D. Biswas [144], I. Bloch [49], A. Blue [60], U. Blumenschein [96], J. Blumenthal [102], V.S. Bobrovnikov [38], M. Boehler [55], B. Boehm [169], D. Bogavac [37], A.G. Bogdanchikov [38], L.S. Boggia [130], C. Bohm [48a], V. Boisvert [97], P. Bokan [37], T. Bold [87a], M. Bomben [5], M. Bona [96], M. Boonekamp [138], C.D. Booth [97], A.G. Borbély [60], I.S. Bordulev [38], G. Borissov [93], D. Bortoletto [129], D. Boscherini [24b], M. Bosman [13], J.D. Bossio Sola [37], K. Bouaouda [36a], N. Bouchhar [166], L. Boudet [4], J. Boudreau [132], E.V. Bouhova-Thacker [93], D. Boumediene [41], R. Bouquet [58b,58a], A. Boveia [122], J. Boyd [37], D. Boye [30], I.R. Boyko [39], L. Bozianu [57], J. Bracinik [21], N. Brahimi [4], G. Brandt [174], O. Brandt [33], F. Braren [49], B. Brau [105], J.E. Brau [126], R. Brener [172], L. Brenner [117], R. Brenner [164], S. Bressler [172], G. Brianti [79a,79b], D. Britton [60], D. Britzger [112], I. Brock [25], G. Brooijmans [42], E.M. Brooks [159b], E. Brost [30], L.M. Brown [168], L.E. Bruce [62], T.L. Bruckler [129], P.A. Bruckman de Renstrom [88], B. Brüers [49], A. Bruni [24b], G. Bruni [24b], M. Bruschi [24b], N. Bruscino [76a,76b], T. Buanes [17], Q. Buat [141], D. Buchin [112], A.G. Buckley [60], O. Bulekov [38], B.A. Bullard [146], S. Burdin [94], C.D. Burgard [50], A.M. Burger [37], B. Burghgrave [8], O. Burlayenko [55], J. Burleson [165], J.T.P. Burr [33], J.C. Burzynski [145], E.L. Busch [42], V. Büscher [102], P.J. Bussey [60], J.M. Butler [26], C.M. Buttar [60], J.M. Butterworth [98], W. Buttinger [137], C.J. Buxo Vazquez [109], A.R. Buzykaev [38], S. Cabrera Urbán [166], L. Cadamuro [67], D. Caforio [59], H. Cai [132], Y. Cai [14,114c], Y. Cai [114a], V.M.M. Cairo [37], O. Cakir [3a], N. Calace [37], P. Calafiura [18a], G. Calderini [130], P. Calfayan [69], G. Callea [60], L.P. Caloba [84b], D. Calvet [41], S. Calvet [41], M. Calvetti [75a,75b], R. Camacho Toro [130], S. Camarda [37], D. Camarero Munoz [27], P. Camarri [77a,77b], M.T. Camerlingo [73a,73b], D. Cameron [37], C. Camincher [168], M. Campanelli [98], A. Camplani [43], V. Canale [73a,73b], A.C. Canbay [3a], E. Canonero [97], J. Cantero [166], Y. Cao [165], F. Capocasa [27], M. Capua [44b,44a], A. Carbone [72a,72b], R. Cardarelli [77a], J.C.J. Cardenas [8], G. Carducci [44b,44a], T. Carli [37], G. Carlino [73a], J.I. Carlotto [13], B.T. Carlson [132,q], E.M. Carlson [168,159a], J. Carmignani [94], L. Carminati [72a,72b], A. Carnelli [138], M. Carnesale [76a,76b], S. Caron [116], E. Carquin [140f], S. Carrá [72a], G. Carratta [24b,24a], A.M. Carroll [126], T.M. Carter [53], M.P. Casado [13,i], M. Caspar [49], F.L. Castillo [4], L. Castillo Garcia [13], V. Castillo Gimenez [166], N.F. Castro [133a,133e], A. Catinaccio [37], J.R. Catmore [128], T. Cavaliere [4], V. Cavaliere [30], N. Cavalli [24b,24a], L.J. Caviedes Betancourt [23b], Y.C. Cekmecelioglu [49], E. Celebi [83], S. Cella [37], F. Celli [129], M.S. Centonze [71a,71b], V. Cepaitis [57], K. Cerny [125], A.S. Cerqueira [84a], A. Cerri [149], L. Cerrito [77a,77b], F. Cerutti [18a], B. Cervato [144], A. Cervelli [24b], G. Cesarini [54], S.A. Cetin [83], D. Chakraborty [118], J. Chan [18a], W.Y. Chan [156], J.D. Chapman [33], E. Chapon [138], B. Chargeishvili [152b], D.G. Charlton [21], M. Chatterjee [20], C. Chauhan [136], Y. Che [114a], S. Chekanov [6], S.V. Chekulaev [159a], G.A. Chelkov [39,a], A. Chen [108], B. Chen [154], B. Chen [168], H. Chen [114a], H. Chen [30], J. Chen [63c], J. Chen [145], M. Chen [129], S. Chen [156], S.J. Chen [114a], X. Chen [63c], X. Chen [15,ab], Y. Chen [63a], C.L. Cheng [173], H.C. Cheng [65a], S. Cheong [146], A. Cheplakov [39], E. Cheremushkina [49], E. Cherepanova [117], R. Cherkaoui El Moursli [36e], E. Cheu [7], K. Cheung [66], L. Chevalier [138], V. Chiarella [54], G. Chiarelli [75a], N. Chiedde [104], G. Chiodini [71a], A.S. Chisholm [21], A. Chitan [28b], M. Chitishvili [166], M.V. Chizhov [39],

K. Choi [11], Y. Chou [141], E.Y.S. Chow [116], K.L. Chu [172], M.C. Chu [65a], X. Chu [14,114c],
Z. Chubinidze [54], J. Chudoba [134], J.J. Chwastowski [88], D. Cieri [112], K.M. Ciesla [87a],
V. Cindro [95], A. Ciocio [18a], F. Cirotto [73a,73b], Z.H. Citron [172], M. Citterio [72a], D.A. Ciubotaru[28b],
A. Clark [57], P.J. Clark [53], N. Clarke Hall [98], C. Clarry [158], J.M. Clavijo Columbie [49],
S.E. Clawson [49], C. Clement [48a,48b], Y. Coadou [104], M. Cobal [70a,70c], A. Coccaro [58b],
R.F. Coelho Barrue [133a], R. Coelho Lopes De Sa [105], S. Coelli [72a], B. Cole [42], J. Collot [61],
P. Conde Muiño [133a,133g], M.P. Connell [34c], S.H. Connell [34c], E.I. Conroy [129], F. Conventi [73a,ad],
H.G. Cooke [21], A.M. Cooper-Sarkar [129], F.A. Corchia [24b,24a], A. Cordeiro Oudot Choi [130],
L.D. Corpe [41], M. Corradi [76a,76b], F. Corriveau [106,w], A. Cortes-Gonzalez [19], M.J. Costa [166],
F. Costanza [4], D. Costanzo [142], B.M. Cote [122], J. Couthures[4], G. Cowan [97], K. Cranmer [173],
D. Cremonini [24b,24a], S. Crépé-Renaudin [61], F. Crescioli [130], M. Cristinziani [144],
M. Cristoforetti [79a,79b], V. Croft [117], J.E. Crosby [124], G. Crosetti [44b,44a], A. Cueto [101], H. Cui[98],
Z. Cui [7], W.R. Cunningham [60], F. Curcio [166], J.R. Curran [53], P. Czodrowski [37],
M.J. Da Cunha Sargedas De Sousa [58b,58a], J.V. Da Fonseca Pinto [84b], C. Da Via [103],
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R. De Asmundis [73a], N. De Biase [49], S. De Castro [24b,24a], N. De Groot [116], P. de Jong [117],
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A. De Santo [149], J.B. De Vivie De Regie [61], J. Debevc [95], D.V. Dedovich[39], J. Degens [94],
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C.M. Delitzsch [50], M. Della Pietra [73a,73b], D. Della Volpe [57], A. Dell'Acqua [37],
L. Dell'Asta [72a,72b], M. Delmastro [4], P.A. Delsart [61], S. Demers [175], M. Demichev [39],
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C. Deutsch [25], F.A. Di Bello [58b,58a], A. Di Ciaccio [77a,77b], L. Di Ciaccio [4],
A. Di Domenico [76a,76b], C. Di Donato [73a,73b], A. Di Girolamo [37], G. Di Gregorio [37],
A. Di Luca [79a,79b], B. Di Micco [78a,78b], R. Di Nardo [78a,78b], K.F. Di Petrillo [40],
M. Diamantopoulou [35], F.A. Dias [117], T. Dias Do Vale [145], M.A. Diaz [140a,140b],
F.G. Diaz Capriles [25], A.R. Didenko[39], M. Didenko [166], E.B. Diehl [108], S. Díez Cornell [49],
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I-M. Dinu [28b], S.J. Dittmeier [64b], F. Dittus [37], M. Divisek [136], F. Djama [104], T. Djobava [152b],
C. Doglioni [103,100], A. Dohnalova [29a], J. Dolejsi [136], Z. Dolezal [136], K. Domijan [87a],
K.M. Dona [40], M. Donadelli [84d], B. Dong [109], J. Donini [41], A. D'Onofrio [73a,73b],
M. D'Onofrio [94], J. Dopke [137], A. Doria [73a], N. Dos Santos Fernandes [133a], P. Dougan [103],
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E. Duchovni [172], G. Duckeck [111], O.A. Ducu [28b], D. Duda [53], A. Dudarev [37], E.R. Duden [27],
M. D'uffizi [103], L. Duflot [67], M. Dührssen [37], I. Duminica [28g], A.E. Dumitriu [28b],
M. Dunford [64a], S. Dungs [50], K. Dunne [48a,48b], A. Duperrin [104], H. Duran Yildiz [3a],
M. Düren [59], A. Durglishvili [152b], B.L. Dwyer [118], G.I. Dyckes [18a], M. Dyndal [87a],
B.S. Dziedzic [37], Z.O. Earnshaw [149], G.H. Eberwein [129], B. Eckerova [29a], S. Eggebrecht [56],
E. Egidio Purcino De Souza [84e], L.F. Ehrke [57], G. Eigen [17], K. Einsweiler [18a], T. Ekelof [164],
P.A. Ekman [100], S. El Farkh [36b], Y. El Ghazali [63a], H. El Jarrari [37], A. El Moussaouy [36a],
V. Ellajosyula [164], M. Ellert [164], F. Ellinghaus [174], N. Ellis [37], J. Elmsheuser [30], M. Elsawy [119a],
M. Elsing [37], D. Emeliyanov [137], Y. Enari [85], I. Ene [18a], S. Epari [13], P.A. Erland [88],
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
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M.G. Vincter [35], A. Visibile[117], C. Vittori [37], I. Vivarelli [24b,24a], E. Voevodina [112], F. Vogel [111],

J.C. Voigt [51], P. Vokac [135], Yu. Volkotrub [87b], J. Von Ahnen [49], E. Von Toerne [25],

B. Vormwald [37], V. Vorobel [136], K. Vorobev [38], M. Vos [166], K. Voss [144], M. Vozak [117],

L. Vozdecky [123], N. Vranjes [16], M. Vranjes Milosavljevic [16], M. Vreeswijk [117], N.K. Vu [63d,63c],

R. Vuillermet [37], O. Vujinovic [102], I. Vukotic [40], S. Wada [160], C. Wagner[105], J.M. Wagner [18a],

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A. Wall [131], E.J. Wallin [100], T. Wamorkar [6], A.Z. Wang [139], C. Wang [102], C. Wang [11],

H. Wang [18a], J. Wang [65c], P. Wang [98], R. Wang [62], R. Wang [6], S.M. Wang [151], S. Wang [63b],

S. Wang [14], T. Wang [63a], W.T. Wang [81], W. Wang [14], X. Wang [114a], X. Wang [165],

X. Wang [63c], Y. Wang [63d], Y. Wang [114a], Y. Wang[63a], Z. Wang [108], Z. Wang [63d,52,63c],

Z. Wang [108], A. Warburton [106], R.J. Ward [21], N. Warrack [60], S. Waterhouse [97], A.T. Watson [21],

H. Watson [60], M.F. Watson [21], E. Watton [60,137], G. Watts [141], B.M. Waugh [98], J.M. Webb [55],

C. Weber [30], H.A. Weber [19], M.S. Weber [20], S.M. Weber [64a], C. Wei [63a], Y. Wei [55],

A.R. Weidberg [129], E.J. Weik [120], J. Weingarten [50], C. Weiser [55], C.J. Wells [49], T. Wenaus [30],

B. Wendland [50], T. Wengler [37], N.S. Wenke[112], N. Wermes [25], M. Wessels [64a], A.M. Wharton [93],

A.S. White [62], A. White [8], M.J. White [1], D. Whiteson [162], L. Wickremasinghe [127],

W. Wiedenmann [173], M. Wielers [137], C. Wiglesworth [43], D.J. Wilbern[123], H.G. Wilkens [37],

J.J.H. Wilkinson [33], D.M. Williams [42], H.H. Williams[131], S. Williams [33], S. Willocq [105],

B.J. Wilson [103], P.J. Windischhofer [40], F.I. Winkel [31], F. Winklmeier [126], B.T. Winter [55],

J.K. Winter [103], M. Wittgen[146], M. Wobisch [99], T. Wojtkowski[61], Z. Wolffs [117], J. Wollrath[162], M.W. Wolter [88], H. Wolters [133a,133c], M.C. Wong[139], E.L. Woodward [42], S.D. Worm [49], B.K. Wosiek [88], K.W. Woźniak [88], S. Wozniewski [56], K. Wraight [60], C. Wu [21], M. Wu [114b], M. Wu [116], S.L. Wu [173], X. Wu [57], Y. Wu [63a], Z. Wu [4], J. Wuerzinger [112,aa], T.R. Wyatt [103], B.M. Wynne [53], S. Xella [43], L. Xia [114a], M. Xia [15], M. Xie [63a], S. Xin [14,114c], A. Xiong [126], J. Xiong [18a], D. Xu [14], H. Xu [63a], L. Xu [63a], R. Xu [131], T. Xu [108], Y. Xu [15], Z. Xu [53], Z. Xu[114a], B. Yabsley [150], S. Yacoob [34a], Y. Yamaguchi [157], E. Yamashita [156], H. Yamauchi [160], T. Yamazaki [18a], Y. Yamazaki [86], J. Yan[63c], S. Yan [60], Z. Yan [105], H.J. Yang [63c,63d], H.T. Yang [63a], S. Yang [63a], T. Yang [65c], X. Yang [37], X. Yang [14], Y. Yang [45], Y. Yang[63a], Z. Yang [63a], W-M. Yao [18a], H. Ye [114a], H. Ye [56], J. Ye [14], S. Ye [30], X. Ye [63a], Y. Yeh [98], I. Yeletskikh [39], B.K. Yeo [18b], M.R. Yexley [98], T.P. Yildirim [129], P. Yin [42], K. Yorita [171], S. Younas [28b], C.J.S. Young [37], C. Young [146], C. Yu [14,114c], Y. Yu [63a], J. Yuan [14,114c], M. Yuan [108], R. Yuan [63d,63c], L. Yue [98], M. Zaazoua [63a], B. Zabinski [88], E. Zaid[53], Z.K. Zak [88], T. Zakareishvili [166], S. Zambito [57], J.A. Zamora Saa [140d,140b], J. Zang [156], D. Zanzi [55], O. Zaplatilek [135], C. Zeitnitz [174], H. Zeng [14], J.C. Zeng [165], D.T. Zenger Jr [27], O. Zenin [38], T. Ženiš [29a], S. Zenz [96], S. Zerradi [36a], D. Zerwas [67], M. Zhai [14,114c], D.F. Zhang [142], J. Zhang [63b], J. Zhang [6], K. Zhang [14,114c], L. Zhang [63a], L. Zhang [114a], P. Zhang [14,114c], R. Zhang [173], S. Zhang [108], S. Zhang [91], T. Zhang [156], X. Zhang [63c], X. Zhang [63b], Y. Zhang [63c], Y. Zhang [98], Y. Zhang [114a], Z. Zhang [18a], Z. Zhang [63b], Z. Zhang [67], H. Zhao [141], T. Zhao [63b], Y. Zhao [139], Z. Zhao [63a], Z. Zhao [63a], A. Zhemchugov [39], J. Zheng [114a], K. Zheng [165], X. Zheng [63a], Z. Zheng [146], D. Zhong [165], B. Zhou [108], H. Zhou [7], N. Zhou [63c], Y. Zhou[15], Y. Zhou [114a], Y. Zhou[7], C.G. Zhu [63b], J. Zhu [108], X. Zhu[63d], Y. Zhu [63c], Y. Zhu [63a], X. Zhuang [14], K. Zhukov [69], N.I. Zimine [39], J. Zinsser [64b], M. Ziolkowski [144], L. Živković [16], A. Zoccoli [24b,24a], K. Zoch [62], T.G. Zorbas [142], O. Zormpa [47], W. Zou [42], L. Zwalinski [37].

[1]Department of Physics, University of Adelaide, Adelaide; Australia.

[2]Department of Physics, University of Alberta, Edmonton AB; Canada.

[3][a]Department of Physics, Ankara University, Ankara;[b]Division of Physics, TOBB University of Economics and Technology, Ankara; Türkiye.

[4]LAPP, Université Savoie Mont Blanc, CNRS/IN2P3, Annecy; France.

[5]APC, Université Paris Cité, CNRS/IN2P3, Paris; France.

[6]High Energy Physics Division, Argonne National Laboratory, Argonne IL; United States of America.

[7]Department of Physics, University of Arizona, Tucson AZ; United States of America.

[8]Department of Physics, University of Texas at Arlington, Arlington TX; United States of America.

[9]Physics Department, National and Kapodistrian University of Athens, Athens; Greece.

[10]Physics Department, National Technical University of Athens, Zografou; Greece.

[11]Department of Physics, University of Texas at Austin, Austin TX; United States of America.

[12]Institute of Physics, Azerbaijan Academy of Sciences, Baku; Azerbaijan.

[13]Institut de Física d'Altes Energies (IFAE), Barcelona Institute of Science and Technology, Barcelona; Spain.

[14]Institute of High Energy Physics, Chinese Academy of Sciences, Beijing; China.

[15]Physics Department, Tsinghua University, Beijing; China.

[16]Institute of Physics, University of Belgrade, Belgrade; Serbia.

[17]Department for Physics and Technology, University of Bergen, Bergen; Norway.

[18][a]Physics Division, Lawrence Berkeley National Laboratory, Berkeley CA;[b]University of California, Berkeley CA; United States of America.

[19]Institut für Physik, Humboldt Universität zu Berlin, Berlin; Germany.

[20]Albert Einstein Center for Fundamental Physics and Laboratory for High Energy Physics, University of Bern, Bern; Switzerland.

[21]School of Physics and Astronomy, University of Birmingham, Birmingham; United Kingdom.

[22][a]Department of Physics, Bogazici University, Istanbul;[b]Department of Physics Engineering, Gaziantep University, Gaziantep;[c]Department of Physics, Istanbul University, Istanbul; Türkiye.

[23][a]Facultad de Ciencias y Centro de Investigaciónes, Universidad Antonio Nariño, Bogotá;[b]Departamento de Física, Universidad Nacional de Colombia, Bogotá; Colombia.

[24][a]Dipartimento di Fisica e Astronomia A. Righi, Università di Bologna, Bologna;[b]INFN Sezione di Bologna; Italy.

[25]Physikalisches Institut, Universität Bonn, Bonn; Germany.

[26]Department of Physics, Boston University, Boston MA; United States of America.

[27]Department of Physics, Brandeis University, Waltham MA; United States of America.

[28][a]Transilvania University of Brasov, Brasov;[b]Horia Hulubei National Institute of Physics and Nuclear Engineering, Bucharest;[c]Department of Physics, Alexandru Ioan Cuza University of Iasi, Iasi;[d]National Institute for Research and Development of Isotopic and Molecular Technologies, Physics Department, Cluj-Napoca;[e]National University of Science and Technology Politechnica, Bucharest;[f]West University in Timisoara, Timisoara;[g]Faculty of Physics, University of Bucharest, Bucharest; Romania.

[29][a]Faculty of Mathematics, Physics and Informatics, Comenius University, Bratislava;[b]Department of Subnuclear Physics, Institute of Experimental Physics of the Slovak Academy of Sciences, Kosice; Slovak Republic.

[30]Physics Department, Brookhaven National Laboratory, Upton NY; United States of America.

[31]Universidad de Buenos Aires, Facultad de Ciencias Exactas y Naturales, Departamento de Física, y CONICET, Instituto de Física de Buenos Aires (IFIBA), Buenos Aires; Argentina.

[32]California State University, CA; United States of America.

[33]Cavendish Laboratory, University of Cambridge, Cambridge; United Kingdom.

[34][a]Department of Physics, University of Cape Town, Cape Town;[b]iThemba Labs, Western Cape;[c]Department of Mechanical Engineering Science, University of Johannesburg, Johannesburg;[d]National Institute of Physics, University of the Philippines Diliman (Philippines);[e]University of South Africa, Department of Physics, Pretoria;[f]University of Zululand, KwaDlangezwa;[g]School of Physics, University of the Witwatersrand, Johannesburg; South Africa.

[35]Department of Physics, Carleton University, Ottawa ON; Canada.

[36][a]Faculté des Sciences Ain Chock, Réseau Universitaire de Physique des Hautes Energies - Université Hassan II, Casablanca;[b]Faculté des Sciences, Université Ibn-Tofail, Kénitra;[c]Faculté des Sciences Semlalia, Université Cadi Ayyad, LPHEA-Marrakech;[d]LPMR, Faculté des Sciences, Université Mohamed Premier, Oujda;[e]Faculté des sciences, Université Mohammed V, Rabat;[f]Institute of Applied Physics, Mohammed VI Polytechnic University, Ben Guerir; Morocco.

[37]CERN, Geneva; Switzerland.

[38]Affiliated with an institute covered by a cooperation agreement with CERN.

[39]Affiliated with an international laboratory covered by a cooperation agreement with CERN.

[40]Enrico Fermi Institute, University of Chicago, Chicago IL; United States of America.

[41]LPC, Université Clermont Auvergne, CNRS/IN2P3, Clermont-Ferrand; France.

[42]Nevis Laboratory, Columbia University, Irvington NY; United States of America.

[43]Niels Bohr Institute, University of Copenhagen, Copenhagen; Denmark.

[44][a]Dipartimento di Fisica, Università della Calabria, Rende;[b]INFN Gruppo Collegato di Cosenza, Laboratori Nazionali di Frascati; Italy.

[45]Physics Department, Southern Methodist University, Dallas TX; United States of America.

[46]Physics Department, University of Texas at Dallas, Richardson TX; United States of America.

[47]National Centre for Scientific Research "Demokritos", Agia Paraskevi; Greece.

[48][a]Department of Physics, Stockholm University;[b]Oskar Klein Centre, Stockholm; Sweden.

[49]Deutsches Elektronen-Synchrotron DESY, Hamburg and Zeuthen; Germany.

[50]Fakultät Physik , Technische Universität Dortmund, Dortmund; Germany.

[51]Institut für Kern- und Teilchenphysik, Technische Universität Dresden, Dresden; Germany.

[52]Department of Physics, Duke University, Durham NC; United States of America.

[53]SUPA - School of Physics and Astronomy, University of Edinburgh, Edinburgh; United Kingdom.

[54]INFN e Laboratori Nazionali di Frascati, Frascati; Italy.

[55]Physikalisches Institut, Albert-Ludwigs-Universität Freiburg, Freiburg; Germany.

[56]II. Physikalisches Institut, Georg-August-Universität Göttingen, Göttingen; Germany.

[57]Département de Physique Nucléaire et Corpusculaire, Université de Genève, Genève; Switzerland.

[58][a]Dipartimento di Fisica, Università di Genova, Genova;[b]INFN Sezione di Genova; Italy.

[59]II. Physikalisches Institut, Justus-Liebig-Universität Giessen, Giessen; Germany.

[60]SUPA - School of Physics and Astronomy, University of Glasgow, Glasgow; United Kingdom.

[61]LPSC, Université Grenoble Alpes, CNRS/IN2P3, Grenoble INP, Grenoble; France.

[62]Laboratory for Particle Physics and Cosmology, Harvard University, Cambridge MA; United States of America.

[63][a]Department of Modern Physics and State Key Laboratory of Particle Detection and Electronics, University of Science and Technology of China, Hefei;[b]Institute of Frontier and Interdisciplinary Science and Key Laboratory of Particle Physics and Particle Irradiation (MOE), Shandong University, Qingdao;[c]School of Physics and Astronomy, Shanghai Jiao Tong University, Key Laboratory for Particle Astrophysics and Cosmology (MOE), SKLPPC, Shanghai;[d]Tsung-Dao Lee Institute, Shanghai;[e]School of Physics and Microelectronics, Zhengzhou University; China.

[64][a]Kirchhoff-Institut für Physik, Ruprecht-Karls-Universität Heidelberg, Heidelberg;[b]Physikalisches Institut, Ruprecht-Karls-Universität Heidelberg, Heidelberg; Germany.

[65][a]Department of Physics, Chinese University of Hong Kong, Shatin, N.T., Hong Kong;[b]Department of Physics, University of Hong Kong, Hong Kong;[c]Department of Physics and Institute for Advanced Study, Hong Kong University of Science and Technology, Clear Water Bay, Kowloon, Hong Kong; China.

[66]Department of Physics, National Tsing Hua University, Hsinchu; Taiwan.

[67]IJCLab, Université Paris-Saclay, CNRS/IN2P3, 91405, Orsay; France.

[68]Centro Nacional de Microelectrónica (IMB-CNM-CSIC), Barcelona; Spain.

[69]Department of Physics, Indiana University, Bloomington IN; United States of America.

[70][a]INFN Gruppo Collegato di Udine, Sezione di Trieste, Udine;[b]ICTP, Trieste;[c]Dipartimento Politecnico di Ingegneria e Architettura, Università di Udine, Udine; Italy.

[71][a]INFN Sezione di Lecce;[b]Dipartimento di Matematica e Fisica, Università del Salento, Lecce; Italy.

[72][a]INFN Sezione di Milano;[b]Dipartimento di Fisica, Università di Milano, Milano; Italy.

[73][a]INFN Sezione di Napoli;[b]Dipartimento di Fisica, Università di Napoli, Napoli; Italy.

[74][a]INFN Sezione di Pavia;[b]Dipartimento di Fisica, Università di Pavia, Pavia; Italy.

[75][a]INFN Sezione di Pisa;[b]Dipartimento di Fisica E. Fermi, Università di Pisa, Pisa; Italy.

[76][a]INFN Sezione di Roma;[b]Dipartimento di Fisica, Sapienza Università di Roma, Roma; Italy.

[77][a]INFN Sezione di Roma Tor Vergata;[b]Dipartimento di Fisica, Università di Roma Tor Vergata, Roma; Italy.

[78][a]INFN Sezione di Roma Tre;[b]Dipartimento di Matematica e Fisica, Università Roma Tre, Roma; Italy.

[79][a]INFN-TIFPA;[b]Università degli Studi di Trento, Trento; Italy.

[80]Universität Innsbruck, Department of Astro and Particle Physics, Innsbruck; Austria.

[81]University of Iowa, Iowa City IA; United States of America.

[82]Department of Physics and Astronomy, Iowa State University, Ames IA; United States of America.

[83]Istinye University, Sariyer, Istanbul; Türkiye.

[84][(a)]Departamento de Engenharia Elétrica, Universidade Federal de Juiz de Fora (UFJF), Juiz de Fora;[(b)]Universidade Federal do Rio De Janeiro COPPE/EE/IF, Rio de Janeiro;[(c)]Instituto de Física, Universidade de São Paulo, São Paulo;[(d)]Rio de Janeiro State University, Rio de Janeiro;[(e)]Federal University of Bahia, Bahia; Brazil.

[85]KEK, High Energy Accelerator Research Organization, Tsukuba; Japan.

[86]Graduate School of Science, Kobe University, Kobe; Japan.

[87][(a)]AGH University of Krakow, Faculty of Physics and Applied Computer Science, Krakow;[(b)]Marian Smoluchowski Institute of Physics, Jagiellonian University, Krakow; Poland.

[88]Institute of Nuclear Physics Polish Academy of Sciences, Krakow; Poland.

[89]Faculty of Science, Kyoto University, Kyoto; Japan.

[90]Research Center for Advanced Particle Physics and Department of Physics, Kyushu University, Fukuoka ; Japan.

[91]L2IT, Université de Toulouse, CNRS/IN2P3, UPS, Toulouse; France.

[92]Instituto de Física La Plata, Universidad Nacional de La Plata and CONICET, La Plata; Argentina.

[93]Physics Department, Lancaster University, Lancaster; United Kingdom.

[94]Oliver Lodge Laboratory, University of Liverpool, Liverpool; United Kingdom.

[95]Department of Experimental Particle Physics, Jožef Stefan Institute and Department of Physics, University of Ljubljana, Ljubljana; Slovenia.

[96]School of Physics and Astronomy, Queen Mary University of London, London; United Kingdom.

[97]Department of Physics, Royal Holloway University of London, Egham; United Kingdom.

[98]Department of Physics and Astronomy, University College London, London; United Kingdom.

[99]Louisiana Tech University, Ruston LA; United States of America.

[100]Fysiska institutionen, Lunds universitet, Lund; Sweden.

[101]Departamento de Física Teorica C-15 and CIAFF, Universidad Autónoma de Madrid, Madrid; Spain.

[102]Institut für Physik, Universität Mainz, Mainz; Germany.

[103]School of Physics and Astronomy, University of Manchester, Manchester; United Kingdom.

[104]CPPM, Aix-Marseille Université, CNRS/IN2P3, Marseille; France.

[105]Department of Physics, University of Massachusetts, Amherst MA; United States of America.

[106]Department of Physics, McGill University, Montreal QC; Canada.

[107]School of Physics, University of Melbourne, Victoria; Australia.

[108]Department of Physics, University of Michigan, Ann Arbor MI; United States of America.

[109]Department of Physics and Astronomy, Michigan State University, East Lansing MI; United States of America.

[110]Group of Particle Physics, University of Montreal, Montreal QC; Canada.

[111]Fakultät für Physik, Ludwig-Maximilians-Universität München, München; Germany.

[112]Max-Planck-Institut für Physik (Werner-Heisenberg-Institut), München; Germany.

[113]Graduate School of Science and Kobayashi-Maskawa Institute, Nagoya University, Nagoya; Japan.

[114][(a)]Department of Physics, Nanjing University, Nanjing;[(b)]School of Science, Shenzhen Campus of Sun Yat-sen University;[(c)]University of Chinese Academy of Science (UCAS), Beijing; China.

[115]Department of Physics and Astronomy, University of New Mexico, Albuquerque NM; United States of America.

[116]Institute for Mathematics, Astrophysics and Particle Physics, Radboud University/Nikhef, Nijmegen; Netherlands.

[117]Nikhef National Institute for Subatomic Physics and University of Amsterdam, Amsterdam;

Netherlands.

[118]Department of Physics, Northern Illinois University, DeKalb IL; United States of America.

[119](a)New York University Abu Dhabi, Abu Dhabi;(b)United Arab Emirates University, Al Ain; United Arab Emirates.

[120]Department of Physics, New York University, New York NY; United States of America.

[121]Ochanomizu University, Otsuka, Bunkyo-ku, Tokyo; Japan.

[122]Ohio State University, Columbus OH; United States of America.

[123]Homer L. Dodge Department of Physics and Astronomy, University of Oklahoma, Norman OK; United States of America.

[124]Department of Physics, Oklahoma State University, Stillwater OK; United States of America.

[125]Palacký University, Joint Laboratory of Optics, Olomouc; Czech Republic.

[126]Institute for Fundamental Science, University of Oregon, Eugene, OR; United States of America.

[127]Graduate School of Science, Osaka University, Osaka; Japan.

[128]Department of Physics, University of Oslo, Oslo; Norway.

[129]Department of Physics, Oxford University, Oxford; United Kingdom.

[130]LPNHE, Sorbonne Université, Université Paris Cité, CNRS/IN2P3, Paris; France.

[131]Department of Physics, University of Pennsylvania, Philadelphia PA; United States of America.

[132]Department of Physics and Astronomy, University of Pittsburgh, Pittsburgh PA; United States of America.

[133](a)Laboratório de Instrumentação e Física Experimental de Partículas - LIP, Lisboa;(b)Departamento de Física, Faculdade de Ciências, Universidade de Lisboa, Lisboa;(c)Departamento de Física, Universidade de Coimbra, Coimbra;(d)Centro de Física Nuclear da Universidade de Lisboa, Lisboa;(e)Departamento de Física, Universidade do Minho, Braga;(f)Departamento de Física Teórica y del Cosmos, Universidad de Granada, Granada (Spain);(g)Departamento de Física, Instituto Superior Técnico, Universidade de Lisboa, Lisboa; Portugal.

[134]Institute of Physics of the Czech Academy of Sciences, Prague; Czech Republic.

[135]Czech Technical University in Prague, Prague; Czech Republic.

[136]Charles University, Faculty of Mathematics and Physics, Prague; Czech Republic.

[137]Particle Physics Department, Rutherford Appleton Laboratory, Didcot; United Kingdom.

[138]IRFU, CEA, Université Paris-Saclay, Gif-sur-Yvette; France.

[139]Santa Cruz Institute for Particle Physics, University of California Santa Cruz, Santa Cruz CA; United States of America.

[140](a)Departamento de Física, Pontificia Universidad Católica de Chile, Santiago;(b)Millennium Institute for Subatomic physics at high energy frontier (SAPHIR), Santiago;(c)Instituto de Investigación Multidisciplinario en Ciencia y Tecnología, y Departamento de Física, Universidad de La Serena;(d)Universidad Andres Bello, Department of Physics, Santiago;(e)Instituto de Alta Investigación, Universidad de Tarapacá, Arica;(f)Departamento de Física, Universidad Técnica Federico Santa María, Valparaíso; Chile.

[141]Department of Physics, University of Washington, Seattle WA; United States of America.

[142]Department of Physics and Astronomy, University of Sheffield, Sheffield; United Kingdom.

[143]Department of Physics, Shinshu University, Nagano; Japan.

[144]Department Physik, Universität Siegen, Siegen; Germany.

[145]Department of Physics, Simon Fraser University, Burnaby BC; Canada.

[146]SLAC National Accelerator Laboratory, Stanford CA; United States of America.

[147]Department of Physics, Royal Institute of Technology, Stockholm; Sweden.

[148]Departments of Physics and Astronomy, Stony Brook University, Stony Brook NY; United States of America.

[149]Department of Physics and Astronomy, University of Sussex, Brighton; United Kingdom.

[150]School of Physics, University of Sydney, Sydney; Australia.

[151]Institute of Physics, Academia Sinica, Taipei; Taiwan.

[152][(a)]E. Andronikashvili Institute of Physics, Iv. Javakhishvili Tbilisi State University, Tbilisi;[(b)]High Energy Physics Institute, Tbilisi State University, Tbilisi;[(c)]University of Georgia, Tbilisi; Georgia.

[153]Department of Physics, Technion, Israel Institute of Technology, Haifa; Israel.

[154]Raymond and Beverly Sackler School of Physics and Astronomy, Tel Aviv University, Tel Aviv; Israel.

[155]Department of Physics, Aristotle University of Thessaloniki, Thessaloniki; Greece.

[156]International Center for Elementary Particle Physics and Department of Physics, University of Tokyo, Tokyo; Japan.

[157]Department of Physics, Tokyo Institute of Technology, Tokyo; Japan.

[158]Department of Physics, University of Toronto, Toronto ON; Canada.

[159][(a)]TRIUMF, Vancouver BC;[(b)]Department of Physics and Astronomy, York University, Toronto ON; Canada.

[160]Division of Physics and Tomonaga Center for the History of the Universe, Faculty of Pure and Applied Sciences, University of Tsukuba, Tsukuba; Japan.

[161]Department of Physics and Astronomy, Tufts University, Medford MA; United States of America.

[162]Department of Physics and Astronomy, University of California Irvine, Irvine CA; United States of America.

[163]University of Sharjah, Sharjah; United Arab Emirates.

[164]Department of Physics and Astronomy, University of Uppsala, Uppsala; Sweden.

[165]Department of Physics, University of Illinois, Urbana IL; United States of America.

[166]Instituto de Física Corpuscular (IFIC), Centro Mixto Universidad de Valencia - CSIC, Valencia; Spain.

[167]Department of Physics, University of British Columbia, Vancouver BC; Canada.

[168]Department of Physics and Astronomy, University of Victoria, Victoria BC; Canada.

[169]Fakultät für Physik und Astronomie, Julius-Maximilians-Universität Würzburg, Würzburg; Germany.

[170]Department of Physics, University of Warwick, Coventry; United Kingdom.

[171]Waseda University, Tokyo; Japan.

[172]Department of Particle Physics and Astrophysics, Weizmann Institute of Science, Rehovot; Israel.

[173]Department of Physics, University of Wisconsin, Madison WI; United States of America.

[174]Fakultät für Mathematik und Naturwissenschaften, Fachgruppe Physik, Bergische Universität Wuppertal, Wuppertal; Germany.

[175]Department of Physics, Yale University, New Haven CT; United States of America.

[a] Also Affiliated with an institute covered by a cooperation agreement with CERN.

[b] Also at An-Najah National University, Nablus; Palestine.

[c] Also at Borough of Manhattan Community College, City University of New York, New York NY; United States of America.

[d] Also at Center for Interdisciplinary Research and Innovation (CIRI-AUTH), Thessaloniki; Greece.

[e] Also at Centro Studi e Ricerche Enrico Fermi; Italy.

[f] Also at CERN, Geneva; Switzerland.

[g] Also at CMD-AC UNEC Research Center, Azerbaijan State University of Economics (UNEC); Azerbaijan.

[h] Also at Département de Physique Nucléaire et Corpusculaire, Université de Genève, Genève; Switzerland.

[i] Also at Departament de Fisica de la Universitat Autonoma de Barcelona, Barcelona; Spain.

[j] Also at Department of Financial and Management Engineering, University of the Aegean, Chios; Greece.

[k] Also at Department of Physics, California State University, Sacramento; United States of America.

[l] Also at Department of Physics, King's College London, London; United Kingdom.

[m] Also at Department of Physics, Stanford University, Stanford CA; United States of America.

[n] Also at Department of Physics, Stellenbosch University; South Africa.

[o] Also at Department of Physics, University of Fribourg, Fribourg; Switzerland.

[p] Also at Department of Physics, University of Thessaly; Greece.

[q] Also at Department of Physics, Westmont College, Santa Barbara; United States of America.

[r] Also at Hellenic Open University, Patras; Greece.

[s] Also at Institucio Catalana de Recerca i Estudis Avancats, ICREA, Barcelona; Spain.

[t] Also at Institut für Experimentalphysik, Universität Hamburg, Hamburg; Germany.

[u] Also at Institute for Nuclear Research and Nuclear Energy (INRNE) of the Bulgarian Academy of Sciences, Sofia; Bulgaria.

[v] Also at Institute of Applied Physics, Mohammed VI Polytechnic University, Ben Guerir; Morocco.

[w] Also at Institute of Particle Physics (IPP); Canada.

[x] Also at Institute of Physics, Azerbaijan Academy of Sciences, Baku; Azerbaijan.

[y] Also at Institute of Theoretical Physics, Ilia State University, Tbilisi; Georgia.

[z] Also at National Institute of Physics, University of the Philippines Diliman (Philippines); Philippines.

[aa] Also at Technical University of Munich, Munich; Germany.

[ab] Also at The Collaborative Innovation Center of Quantum Matter (CICQM), Beijing; China.

[ac] Also at TRIUMF, Vancouver BC; Canada.

[ad] Also at Università di Napoli Parthenope, Napoli; Italy.

[ae] Also at University of Colorado Boulder, Department of Physics, Colorado; United States of America.

[af] Also at Washington College, Chestertown, MD; United States of America.

[ag] Also at Yeditepe University, Physics Department, Istanbul; Türkiye.

[*] Deceased