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Letter

Search for the $Z\gamma$ decay mode of new high-mass resonances in pp collisions at $\sqrt{s} = 13$ TeV with the ATLAS detector

The ATLAS Collaboration *

A R T I C L E I N F O

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A B S T R A C T

This letter presents a search for narrow, high-mass resonances in the $Z\gamma$ final state with the Z boson decaying into a pair of electrons or muons. The $\sqrt{s} = 13$ TeV pp collision data were recorded by the ATLAS detector at the CERN Large Hadron Collider and have an integrated luminosity of 140 fb^{-1}. The data are found to be in agreement with the Standard Model background expectation. Upper limits are set on the resonance production cross section times the decay branching ratio into $Z\gamma$. For spin-0 resonances produced via gluon–gluon fusion, the observed limits at 95% confidence level vary between 65.5 fb and 0.6 fb, while for spin-2 resonances produced via gluon–gluon fusion (or quark–antiquark initial states) limits vary between 77.4 (76.1) fb and 0.6 (0.5) fb, for the mass range from 220 GeV to 3400 GeV.

1. Introduction

Theories beyond the Standard Model (BSM theories) predict the existence of new heavy bosons (X) as additional gauge fields or by expanding the Higgs sector [1–3]. High-energy proton–proton (pp) collisions at the CERN Large Hadron Collider (LHC) could produce high-mass bosons with masses up to several TeV, allowing a wide range of BSM scenarios to be tested. This letter targets narrow spin-0 and spin-2 high-mass resonances that decay into the $Z\gamma$ final state, with the Z boson decaying into an electron or muon pair. The $Z(\rightarrow \ell\ell)\gamma$ final state, where $\ell = e$ or μ, can be fully reconstructed with high efficiency and the invariant mass can be measured with good resolution. In addition, lepton and photon signatures lead to relatively small backgrounds from general hadronic final-state decays.

The ATLAS [4,5] and CMS [6] collaborations have searched for heavy $Z\gamma$ resonances. The ATLAS Collaboration has used 36.1 fb^{-1} of 13 TeV pp collision data to search for spin-0 and spin-2 high-mass resonances via the $Z(\rightarrow \ell\ell)\gamma$ final state. For the spin-0 resonance, the observed upper limits set on the production cross section times branching ratio, $\sigma(pp \rightarrow X) \cdot \mathcal{B}(X \rightarrow Z\gamma)$, vary between 88 fb and 2.8 fb at 95% confidence level in the mass range from 0.25 TeV to 2.4 TeV [7]. In addition to the search in the leptonic final state, a search for hadronic Z boson decays [8] was also published by the ATLAS Collaboration using a dataset with an integrated luminosity of 139 fb^{-1}. Upper limits from 10 fb to 0.05 fb were set in the mass range from 1.0 TeV to 6.8 TeV. A similar analysis was carried out by the CMS Collaboration with an integrated luminosity of 35.9 fb^{-1}. The Z boson was studied in both the leptonic and hadronic decay modes. The results from these channels were combined, and for narrow spin-0 resonances with masses between 0.35 TeV and 4.0 TeV, the upper limits ranged from 50 fb to 0.3 fb [9]. In all these searches, the data were found to agree with the Standard Model (SM) background expectation.

An improved search for high-mass $Z\gamma$ resonances is presented in this letter. For bosons with masses of around a TeV or above, a highly boosted Z boson is produced, where the leptons from the Z boson decay are highly collimated. Due to this boost, the energy deposits from the two electrons in $Z \rightarrow ee$ decays are very close together, with an angular separation of around 0.2 rad for higher signal masses, which affects the reconstruction of individual electrons. Consequently, the use of conventional electron identification requirements causes a significant loss of signal efficiency (around 20% for a resonance mass of 3400 GeV). In addition, due to the closeness of the two electrons, about 20% of the electrons are not reconstructed properly but instead classified as photons. Such challenges are addressed by developing a customized electron identification algorithm based on multivariate analysis (MVA) techniques. The main background in this analysis is non-resonant production of a Z boson with a photon. In addition, a smaller contribution comes from the production of a Z boson together with a hadronic jet, when the jet is incorrectly identified as a photon. The search is based on 13 TeV pp collision data recorded by the ATLAS detector at the LHC from 2015 to 2018, with a total integrated luminosity of 140 fb^{-1}. This is much larger than the dataset used in the previous ATLAS search in the $Z(\rightarrow \ell\ell)\gamma$ decay channel [7] and to-

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* E-mail address: atlas.publications@cern.ch.

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gether with better electron identification performance, the search range is widened to cover masses from 220 GeV to 3400 GeV.

2. ATLAS detector and data sample

The ATLAS detector [4,5] at the LHC is a multipurpose particle detector with a front-to-back symmetric cylindrical geometry and solid angle coverage close to 4π.[1] It consists of an inner tracking detector surrounded by a thin superconducting solenoid, electromagnetic (EM) 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 (TRT) detectors. Lead/liquid-argon (LAr) sampling calorimeters provide electromagnetic energy measurements with high granularity. A hadron calorimeter covers the central pseudorapidity range ($|\eta| < 1.7$). The endcap and forward regions are instrumented with LAr calorimeters for both the 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 chambers for tracking and fast detectors for triggering.

A two-level trigger system [10] was used during the data taking. The first-level trigger (L1) is implemented in hardware and uses a subset of the detector information. This is followed by a high-level software-based trigger that runs an algorithm similar to that in the offline reconstruction software, reducing the event rate from a maximum L1 rate of 100 kHz to approximately 1 kHz.

The trigger used in this search selects events with one or two electrons or muons, or a high-energy photon. During the highest instantaneous luminosity period, the minimum transverse momentum (p_{T}) threshold was 26 GeV for the single-electron trigger and 17 GeV for each electron in the dielectron trigger. The threshold for the single-muon trigger was also 26 GeV, while asymmetric p_{T} thresholds of 22 GeV and 8 GeV were used for the dimuon trigger. The lowest transverse energy threshold for a single photon was 140 GeV. Higher-threshold triggers with looser lepton identification criteria complement these lowest-threshold triggers. In the signal region chosen for the analysis, the trigger efficiencies range from 94% to 100% for simulated events with a spin-0 or spin-2 resonance having a mass between 220 GeV and 3400 GeV. After applying data quality requirements, the dataset of $\sqrt{s} = 13$ TeV pp collisions used in this search has an integrated luminosity of 140 fb^{-1} [11]. The average number of pp interactions per beam crossing (pile-up) ranged from ∼13 in 2015 to ∼39 in 2018. The peak instantaneous luminosity was 2×10^{34} $\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$.

An extensive software suite [12] 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.

3. Event simulation

Samples of Monte Carlo (MC) simulated events are used to optimize the search strategy, evaluate the selection efficiency and study the different background contributions. The generated samples of signal events were processed with a detailed ATLAS detector simulation [13] based on GEANT4 [14]. The POWHEG BOX v1 [15–18] generator and CT10 PDF set [19] were used to simulate gluon–gluon fusion (ggF) production of spin-0 resonances with masses of 200, 300, 500, 1000, 1500, 2000, 2500, 3000, and 3500 GeV and an intrinsic width of 4 MeV. This is much smaller than the experimental resolution (see Section 5) and is referred to as the narrow-width assumption. Spin-2 resonances with masses of 200, 250, 300, 500, 750, 1000, 1500, 2000, 2500, 3000, and 3500 GeV and an intrinsic width of 4 MeV were simulated for gluon–gluon and quark–antiquark initial states. These event samples were simulated at leading order (LO) in QCD in the Higgs Characterisation Model [20] with MADGRAPH5_AMC@NLO 2.3.3 [21]. For the high-mass spin-0 (spin-2) resonances, the parton showering, hadronization and multi-parton interactions were simulated with PYTHIA 8.186 [22] using the AZNLO (A14) set of tuned parameters and the CTEQ6L1 [23] (NNPDF2.3 [24]) PDF set. Interference between the resonant signal and the non-resonant background is neglected because of the assumed narrow width of the resonance.

The SM $Z+\gamma$ process was simulated using the SHERPA 2.2.2 [25] generator. The matrix elements were calculated using the COMIX [26] and OPENLOOPS 1.3.1 [27] generators. For real emission of up to three partons at LO in QCD, the matrix elements were merged with the SHERPA parton shower [28] using the MEPS@LO prescription [29]. In addition, the NNPDF3.0NNLO PDF set was used in conjunction with dedicated parton shower tuning developed by the SHERPA authors. To study the background model in detail, a large sample of $Z+\gamma$ events was simulated using fast simulation of the calorimeter response [30]. The subdominant background process, $Z+$jets production, is modelled by using a control region enhanced in data events with jets misidentified as photons.

4. Object and event selections

Events containing at least one primary vertex candidate formed by reconstructed tracks with $p_{\mathrm{T}} > 500$ MeV are selected. The primary vertex candidate with the largest sum of the squared transverse momenta ($\sum p_{\mathrm{T}}^2$) of the associated tracks is considered to be the primary vertex of the interaction of interest. The $X \to Z(\to \ell\ell)\gamma$ candidate events are selected by requiring two same-flavour opposite-charge leptons to form a Z boson candidate, and at least one photon candidate.

Muon candidates are reconstructed by combining tracks in the inner tracking detector with tracks in the muon spectrometer. They are required to satisfy $p_{\mathrm{T}} > 10$ GeV and $|\eta| < 2.7$. Muons must meet the *Medium* identification criteria [31]. Electron and photon candidates are reconstructed from clusters of energy deposits in the EM calorimeter cells. Electron candidates must have a matching track reconstructed in the inner tracking detector and $p_{\mathrm{T}} > 10$ GeV, and be within the fiducial region of $|\eta| < 2.47$, excluding the EM calorimeter barrel/endcap transition region of $1.37 < |\eta| < 1.52$ [32].

In the high-mass $X \to Z\gamma$ search, the energy deposits from the two electrons are very close together in the EM calorimeter, causing significant signal efficiency losses when using *Loose* identification criteria [32]. In addition, the sub-leading electron is often misreconstructed as a photon. This identification challenge is addressed by developing a dedicated MVA-based identification (MVA ID) criterion using a set of shower shape and track-based variables. The calorimeter shower shape variables used are R_η, R_{had}, R_ϕ, ΔE_s and E_{ratio}. The track-based variables considered are E/p, eProbabilityHT, $\Delta\eta_1$, d_0, $n_{\mathrm{innermost}}$, n_{Pixel} and n_{Si}. The aforementioned variables are also used to develop standard electron identification criteria for the ATLAS Collaboration and are described in detail in Table 1 of Ref. [32]. Additionally, n_{TRT}, defined as the number of hits in the TRT detector, and the $\Delta\phi_{\mathrm{rescaled}}$ variables, defined as the $\Delta\phi$ between the energy cluster and associated track in the presampler and the calorimeter's first, second and third layers after rescaling the EM energy deposits, are used in the MVA ID development. All these input variables were chosen because of their separation power when comparing $m_X = 5$ TeV signal MC events to background sideband data excluding events with dielectron invariant mass within

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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 $\eta = -\ln\tan(\theta/2)$. Angular distance is measured in units of $\Delta R \equiv \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2}$.

±15 GeV of the Z boson mass, $m_Z = 91.2$ GeV. The background in the sideband region includes both real and misreconstructed electrons. The MVA method is based on a Gradient Boosting Decision Tree (GBDT) architecture provided by the XGBoost software library [33] and the training is carried out on electrons in the signal and background events. Good separation between signal and background is obtained with an optimal cut-point which corresponds to 99% signal efficiency and 76% background rejection. Among all training variables, the most discriminating shower shape and additional track-based variables are E_{ratio} and $\Delta\phi_{\mathrm{rescaled2}}$, respectively. The MVA ID is combined with the *Loose* identification criterion by using a logical OR to cover the whole explored mass range, and this is named Mixed ID. Compared to the *Loose* identification, the Mixed ID improves the identification efficiency of signal events by 6.2% to 12.7% across the full range of resonance masses. In order to form the Z boson candidate, electrons misreconstructed as a photon candidate are also selected. Similarly to electron candidates, they are required to have $p_{\mathrm{T}} > 50$ GeV and be within $|\eta| < 2.47$, excluding the region of $1.37 < |\eta| < 1.52$. They are also required to have at least one track with an angular distance $\Delta R < 0.1$ from the photon.

A track-based isolation requirement [31,32] is applied to the electrons and muons to make sure they are isolated from additional activity in the detector. Electron and muon candidates are also required to be associated with the primary vertex by requiring the longitudinal impact parameter, z_0, to satisfy $|z_0 \sin\theta| < 0.5$ mm, where θ is the polar angle of the track. The significance of the transverse impact parameter d_0, calculated with respect to the measured beam-line position, must satisfy $|d_0/\sigma_{d_0}| < 3\,(5)$ for muons (electrons) where σ_{d_0} is the uncertainty in d_0.

The Z boson candidates are reconstructed from two same-flavour opposite-sign lepton candidates. For events where one of the electrons is misreconstructed as a photon, additional criteria are applied to increase the selection efficiency of the real electron and to reduce other photon backgrounds, which are determined from MC information. The angular distance between the selected electron and photon, ΔR, must be less than 1.0. In addition, the relative difference between the transverse momenta of the two objects must be greater than 5%, which suppresses the selection of objects that come from the same electron. If multiple Z candidates are reconstructed in the same event, the one with mass closest to the Z pole, $m_Z = 91.2$ GeV, is chosen. Corrections are applied to the four-momenta of the leptons to improve the resolution of signal events. In particular, muon momenta are corrected for collinear final-state radiation (FSR) effects [34], and lepton (both electron and muon) four-momenta are corrected using a Z boson mass constraint [35]. The Z mass constraint improves the $\ell\ell\gamma$ mass resolution significantly. This is especially so in the muon channel, where the resolution improves by 8% for the lowest resonance mass and by up to 70% for larger masses, where the precision of the momentum measurement decreases with increasing muon transverse momentum. The corrected dilepton invariant mass is required to be within ±15 GeV of the Z boson mass.

Photon candidates are required to have $p_{\mathrm{T}} > 15$ GeV and pseudorapidity within the regions $|\eta| < 1.37$ or $1.52 < |\eta| < 2.37$. The *Tight* identification [32] and *Loose* isolation criteria are also applied. The $Z(\ell\ell)\gamma$ candidate is reconstructed from the selected Z boson and the photon with the largest transverse momentum. The selected lepton pair and photon are required to match the trigger object(s) used to select the event, with the lepton p_{T} requirement(s) being slightly higher than the trigger threshold(s).

To resolve potential ambiguities due to a single detector response being assigned to two objects by the reconstruction algorithm, an overlap removal procedure is applied. For electrons, if the leading object has $p_{\mathrm{T}} < 500$ GeV, other electron energy clusters closer than $|\Delta\eta| = 0.075$ and $|\Delta\phi| = 0.125$ are removed. If the leading electron has $p_{\mathrm{T}} > 500$ GeV, other electron energy clusters closer than $|\Delta\eta| = 0.05$ and $|\Delta\phi| = 0.05$ are removed. If an electron candidate's track is closer than $\Delta R = 0.02$ to a muon candidate's track, the electron is rejected. Photon candidates within $\Delta R = 0.3$ of the selected lepton pair are rejected; this suppresses the FSR $Z + \gamma$ events and additional possible contributions from photons misidentified as electrons. If an electron is misreconstructed as a photon because of its closeness to another electron, no overlap removal is applied.

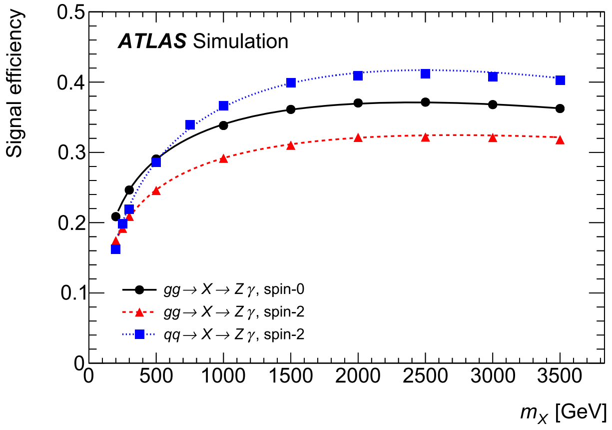

Fig. 1. Efficiency of $X \to Z\gamma$ final-state reconstruction and selection (including kinematic acceptance) as a function of resonance mass m_X for spin-0 resonances generated via gluon–gluon fusion, and for spin-2 resonances generated from gluon–gluon and quark–antiquark initial states. The markers show the efficiencies for simulated events, while the curves indicate the parameterizations used in the analysis. The efficiencies are for $X \to Z\gamma$ where the Z boson decays into ee, $\mu\mu$ or $\tau\tau$.

In order to further reduce the non-resonant $Z + \gamma$ background contamination, a requirement $p_{\mathrm{T}}/m_{Z\gamma} > 0.2$ is placed on transverse momentum of the photon candidate relative to the invariant mass of the final-state particles, $m_{Z\gamma}$, where the latter must satisfy $200 < m_{Z\gamma} < 3500$ GeV. The full analysis selections are summarized in Table 1.

The signal efficiency is defined as the ratio of the number of events satisfying all selection criteria (as described above) to the total number of events expected from the process $pp \to X \to Z\gamma$, where the Z boson decays into ee, $\mu\mu$ or $\tau\tau$. The efficiency is parameterized as a function of the resonance mass to interpolate efficiencies in the mass intervals between the simulated samples. This is done using the sum of a first-order polynomial and a logarithmic function, $\varepsilon = a + b \cdot m_X + c \cdot \ln(m_X + d)$, where a, b, c and d are free parameters in the fit. Fig. 1 shows the reconstruction and selection efficiency for simulated spin-0 and spin-2 resonance events as a function of m_X. The efficiencies for spin-0 and spin-2 resonances produced via the gluon–gluon fusion process and spin-2 resonances originating from quark–antiquark initial states are parameterized separately. The efficiencies range from 22% to 36% over the mass range from 220 GeV to 3400 GeV for spin-0 resonances produced by gluon–gluon fusion. Differences in the production and decay of the spin-0 and spin-2 resonances result in significantly different transverse momentum and pseudorapidity distributions of the final-state Z bosons and photons, leading to the differences between the detection efficiency curves shown in Fig. 1.

5. Signal and background modelling

Analytic models are used to extract the signal and background yields from the $m_{Z\gamma}$ distribution of the data. Simulated signal samples are used to determine the parameters describing the signal shapes. The models used to describe the background shapes are chosen by studying the simulated background samples, and the values of free parameters are obtained by fitting the models to the data.

The signal mass distribution of the $Z\gamma$ final states is well modelled by a double-sided Crystal Ball (DSCB) function (a Gaussian function with a power-law tail on each side) [36,37]. The Gaussian component of the signal distribution is described by the peak position μ_{CB} and width σ_{CB}.

Table 1
Object and event selections for the analysis.

Selection	Muon	Electron	Electron as photon	Photon
p_{T}	> 10 GeV	> 10 GeV	> 50 GeV	> 15 GeV
$\|\eta\|$	< 2.7	< 2.47 Exclude [1.37, 1.52]	< 2.47 Exclude [1.37, 1.52]	< 2.37 Exclude [1.37, 1.52]
$\|d_0\|/\sigma_{d_0}$	< 3	< 5		
$\|z_0 \sin\theta\|$	< 0.5 mm	< 0.5 mm		
Identification	*Medium*	Mixed	MVA	*Tight*
Isolation	Track-based *Tight*	Track-based *Tight*		*Loose*
$\Delta R(\mathrm{track}, \gamma)$			< 0.1	
ee or $\mu\mu$ pair $e\gamma$ pair	≥ 2, opposite charge		$\Delta R(e, \gamma) < 1$ $\|p_{\mathrm{T}}^{e} - p_{\mathrm{T}}^{\gamma}\|/p_{\mathrm{T}}^{e \text{ or } \gamma} > 5\%$	
Categorization	lepton pair closest to $m_Z = 91.2$ GeV, decide if electron channel or muon channel			
Event selections	$\|m_{\ell\ell}^{\mathrm{corrected}} - m_Z\| < 15$ GeV, $m_Z = 91.2$ GeV Trigger match, overlap removal $p_{\mathrm{T}}^{\gamma}/m_{Z\gamma} > 0.2$; signal region: $200 < m_{Z\gamma} < 3500$ GeV			

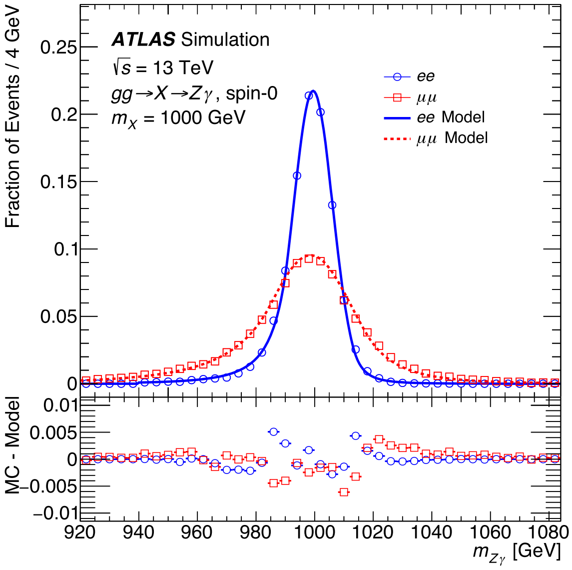

Fig. 2. Differential distributions of the invariant mass $m_{Z\gamma}$ of the spin-0 resonance with $m_X = 1000$ GeV produced by the gluon–gluon fusion process. The markers show the distributions of the simulated events. The solid and dashed lines are the fitted models in the $ee\gamma$ and $\mu\mu\gamma$ channels, respectively. The mass resolution in the muon channel is compatible to that in the electron channel when $m_X < 300$ GeV.

For the interpolation of the DSCB signal shape parameters as a function of m_X, all simulated signal events are fitted simultaneously to parameterize the signal shapes for mass points m_X between simulated samples. A set of polynomials whose coefficients are determined during the fitting process are used to interpolate signal shape parameters as a function of m_X. The parameterization is carried out separately for each of the three models considered, i.e. spin-0 and spin-2 resonances produced via gluon–gluon fusion and spin-2 resonances from quark–antiquark initial states, and for $Z \to ee$ and $Z \to \mu\mu$ final states. The $m_{Z\gamma}$ distributions of the spin-0 resonance at $m_X = 1000$ GeV are shown in Fig. 2. The simulated signal events and the fitted parametric models agree well, with differences below 5 per mille. Good quality fits are also obtained for all other resonance models.

The background consists mainly of non-resonant associated production of a Z boson and a photon (irreducible background) and Z + jet events where the jet is misidentified as a photon (reducible background). Their relative contributions are determined by a simultaneous binned fit to the calorimeter isolation distribution of the photon candidate in the signal region and in a control region enriched in Z + jets background. The control region is defined by requiring the photon candidate to fail the *Tight* identification but pass a modified loose identification [32]. The calorimeter isolation distributions of the photon in the signal and control regions are determined by the simulated non-resonant $Z + \gamma$ samples, while the distributions of the misidentified jet are determined in the fit and assumed to be the same in the signal and control regions. The composition is estimated separately in the $Z \to ee$ and $Z \to \mu\mu$ final states. In the electron (muon) channel, the ratio of $Z + \gamma$ events to all background events is 0.919 (0.908). Besides estimating the $Z + \gamma$ event fraction inclusively in the full mass region, it is also evaluated as a function of $m_{Z\gamma}$. The fractions are relatively stable, with the largest variation being 5%. Only simulated $Z + \gamma$ samples are used to construct the total background model to reduce the statistical fluctuations from the limited number of data-derived Z + jet events, which are obtained by requiring the photon candidate to satisfy the *Loose*, but not the *Tight*, identification criterion. To account for the contribution from Z + jet events, the ratio of Z + jet to $Z + \gamma$ events is fitted as an exponential function of $m_{Z\gamma}$. The functional form is chosen to have the minimum spurious signal described below. The total background is obtained after multiplying the $Z + \gamma$ distribution in MC simulation by this exponential function to estimate the Z + jet contribution. The fit uncertainty of the ratio is propagated to the total background as well. The background distribution falls smoothly as a function of $m_{Z\gamma}$.

The analytic background models are chosen so as to reduce the bias in the extracted signal yield and also by limiting the number of free parameters in the fits to avoid a reduction in sensitivity [38]. For each analysis category, the bias (also known as the "spurious signal") is estimated as a function of m_X by fitting the $m_{Z\gamma}$ distribution of the background, obtained as described above, with signal-plus-background models. The spurious signal is required to be less than 50% of the expected statistical uncertainty of the signal yield. The function with the fewest free parameters is selected if this requirement is satisfied by two or more of the functions considered. The Dijet function[2] is selected for both the electron and muon channels. The envelope of the spurious signal is used to define a systematic uncertainty of the background modelling, parameterized as an exponential function of $m_{Z\gamma}$. For the $Z \to ee$

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[2] The Dijet function is defined as $f_{\mathrm{bkg}}(x; b, a_0) = N(1-x)^b x^{a_0}$, where $x = m_{Z\gamma}/\sqrt{s}$, N is the normalization factor, and b and a_0 are free parameters in each fit.

($Z \to \mu\mu$) final state, the spurious signal ranges from 10.2 (10.7) events at 220 GeV to 0.003 (0.007) events at 3400 GeV. Signal models for different-spin resonances are tested in the fits, and the parameterized spurious-signal uncertainties derived with spin-0 resonance samples are the most conservative. If the purity of the $Z+\gamma$ sample is varied by $\pm 5\%$, or the fitted ratio of $Z+$ jet to $Z+\gamma$ events as a function of $m_{Z\gamma}$ is varied by $\pm 1\sigma$ of the error, the Dijet function is still selected for both channels. This indicates that the search relies on the parameterization of the $m_{Z\gamma}$ distribution, but only mildly on the background composition.

6. Systematic uncertainties

The dominant systematic uncertainty is the spurious signal defined as the bias induced in the signal yield by the choice of a particular background model. Its evaluation is described in Section 5, where it is found be as large as 10.2 events in the electron channel and 10.7 events in the muon channel.

The uncertainty in the combined 2015–2018 integrated luminosity is 0.83% [11], obtained using the LUCID-2 detector [39] for the primary luminosity measurements, complemented by measurements using the inner detector and calorimeters. The systematic uncertainties impacting the signal modelling come from the muon momentum scale and resolution, and the electron and photon energy scales and resolutions. Their impact on the peak position (μ_{CB}) and width (σ_{CB}) of the simulated signal distribution is estimated from the relative changes in the fitted $m_{Z\gamma}$ signal distribution when varying the momentum or energy scales and resolutions by their uncertainties. The muon momentum scale and resolution systematic uncertainties are determined from $Z \to \mu\mu$ and $J/\psi \to \mu\mu$ events using the techniques described in Ref. [40]. The muon momentum scale uncertainty and the sagitta bias [41] lead to a μ_{CB} uncertainty of up to 0.023%, while both the muon spectrometer and muon identification contribute to the muon momentum resolution and lead to uncertainties in σ_{CB} of up to 1.9% and 1.8% respectively. The systematic uncertainties in the electron and photon energy scale and resolution follow those in Refs. [42,43]. The overall energy scale factors and their uncertainties were determined using $Z \to ee$ events collected during 2015 and 2016. Compared to Ref. [43], several systematic uncertainties were re-evaluated with the 13 TeV data, including uncertainties related to the observed LAr cell non-linearity, the detector material simulation, the intercalibration of the first and second layers of the calorimeter, and the pedestal corrections. The electron/photon energy resolution uncertainties produce an uncertainty in σ_{CB} varying from 2.5% to 10% in the muon channel and from 7% to 60% in the electron channel. The variation in μ_{CB} due to the electron and photon energy scale systematic uncertainty is less than 0.4% for the muon channel and less than 0.7% for the electron channel. The systematic uncertainties in the signal efficiency due to the reconstruction, identification, isolation and trigger efficiencies for leptons and photons are estimated in simulation from the relative change in the signal efficiency when each of those efficiencies is varied by its uncertainty. The photon triggers, identification and isolation contribute a total systematic uncertainty of up to 1.5% (1.7%) to the signal efficiency in the muon (electron) channel. The electron reconstruction, identification, isolation and trigger contribute a systematic uncertainty of up to 4% to the signal efficiency in the electron channel. In the muon channel, the signal efficiency systematic uncertainties from the muon triggers, reconstruction and isolation are estimated to not exceed 1%, 6% and 1.2%, respectively. All these systematic uncertainties affecting the signal efficiency are estimated using spin-0 resonance samples only and are also used in the spin-2 resonance results. To check whether a bias could be introduced by this uncertainty assignment, the largest systematic uncertainty in the signal efficiency (i.e. the muon reconstruction efficiency) is also estimated using spin-2 resonance samples. The estimates of this systematic uncertainty from the spin-0 and spin-2 resonance samples are compatible within the statistical uncertainty. An “extra smearing” muon p_{T} uncertainty accounts for the impact of the poorly measured resolution of high-p_{T} muons (usually > 300 GeV) which satisfy the *Medium*, but not the *HighPt* [31], identification criterion. The impact on the $m_{\mu\mu\gamma}$ resolution is estimated to be 2.4%. The systematic uncertainty due to electron charge misidentification is evaluated using $Z \to ee$ events and found to be negligible.

Table 2
The main sources of systematic uncertainty for the $X \to Z\gamma$ search. The gluon–gluon fusion spin-0 signal samples produced for m_X = 220–3400 GeV are used to evaluate the systematic uncertainty. The uncertainty ranges span the variations among different categories and different m_X resonance masses. The uncertainty due to the spurious signal is reported as an absolute number of events. In the table, “ID” for photons and electrons refers to identification efficiency uncertainties, “ISO” refers to isolation efficiency uncertainties, “TRIG” refers to trigger efficiency uncertainties, “RECO” refers to muon reconstruction efficiency uncertainty and “TTVA” refers to muon track-to-vertex-association efficiency uncertainty.

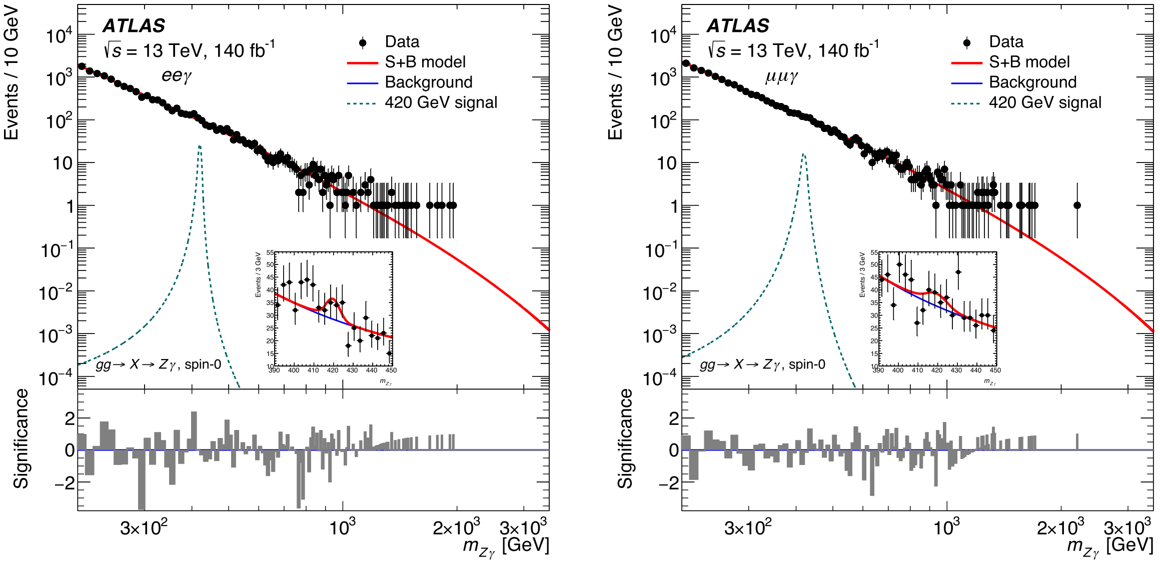
Category	$\mu\mu\gamma$	$ee\gamma$
Luminosity	0.83%	
Signal Efficiency		
Photon ID/ISO/TRIG efficiency	1.0% – 1.5%	1.0% – 1.7%
Muon ISO efficiency	1.0% – 1.2%	–
Muon RECO efficiency	0.22% – 6%	–
Muon TTVA efficiency	0.14% – 0.23%	–
Muon TRIG efficiency	0.6% – 1.0%	–
Electron ID/ISO/RECO/TRIG efficiency	–	2.9% – 4%
MVA/Mixed electron ID efficiency	–	1.0% – 1.1%
Pile-up	< 0.016%	–
Signal modelling effect on μ_{CB}		
Electron and photon energy scale	0.33% – 0.4%	0.15% – 0.7%
Muon momentum scale/sagitta bias	< 0.023%	–
Signal modelling effect on σ_{CB}		
Electron and photon energy resolution	2.5% – 10%	7% – 60%
Muon ID resolution	0.4% – 1.8%	–
Muon MS resolution	0.6% – 1.9%	–
Extra smearing of muon p_{T}	2.4%	–
Background modelling (in number of events)		
Spurious signal	0.01 – 10.7	0.003 – 10.2

The uncertainty due to the MVA and Mixed electron identifications applied to the reconstructed electrons in this high-mass analysis is evaluated by applying the tag-and-probe method to the $Z \to ee$ data and MC samples. Events where the electrons have an angular separation $\Delta R(e,e) < 0.5$ are used to imitate the case where the electrons are very close to each other, as in the high-mass resonance analysis. Due to the $\Delta R(e,e)$ requirement, the $Z \to ee$ event yield is limited and thus an inclusive p_{T} bin is defined in the EM calorimeter barrel and endcap region. The efficiencies are evaluated for electrons with $\Delta R(e,e) < 0.5$ in an inclusive p_{T} region between 27 and 3000 GeV and the barrel ($|\eta| < 1.37$) and endcap ($1.52 < |\eta| < 2.47$) regions. The systematic uncertainty due to the MVA ID and its mixture with the *Loose* ID is estimated to vary between 1.0% and 1.1% for resonance masses between 220 GeV and 3400 GeV.

Table 2 summarizes the estimated systematic uncertainties for the $X \to Z\gamma$ search in the ee and $\mu\mu$ channels and the mass range m_X = 220–3400 GeV.

7. Results

An unbinned profile-likelihood-ratio fit method [44] is used to estimate the heavy-resonance production cross section times the branching ratio of the $X \to Z\gamma$ decay, $\sigma(pp \to X) \cdot \mathcal{B}(X \to Z\gamma)$, in the mass range between 220 GeV and 3400 GeV. In the likelihood function, the expected number of signal events N_{sig} is defined as $N_{\mathrm{sig}} = L \times \sigma(pp \to X) \times \mathcal{B}\big(X \to Z(\to ee, \mu\mu \text{ or } \tau\tau)\gamma\big) \times \varepsilon$, where L is the integrated luminosity and ε is the parameterized signal efficiency as a function of



(a)

(b)

Fig. 3. The $Z\gamma$ invariant mass distributions of data events satisfying the high-mass selection for the (a) $ee\gamma$ and (b) $\mu\mu\gamma$ channels. The points with error bars represent the data and statistical uncertainty. The background component (solid blue line in the inset) and spin-0 signal component (dashed dark cyan line) of the signal + background unbinned fit (solid red line) to data are displayed. The bottom panel of each figure shows the significance, which is defined as the residual of the data with respect to the fitted background component divided by the statistical uncertainty of the data. The lower mass region is expanded and displayed in the two inset plots, where an excess with a combined local significance of 2.3σ at 420 GeV can be seen.

m_X. The invariant mass ($m_{Z\gamma}$) distributions of data events in both the $ee\gamma$ and $\mu\mu\gamma$ channels are fitted simultaneously with the signal-plus-background models and are shown in Fig. 3. The highest-mass $ee\gamma$ and $\mu\mu\gamma$ events in the data are at 2.0 TeV and 2.2 TeV, respectively. No significant excess relative to the background-only hypothesis is seen. For spin-0 heavy resonances, the largest excess is observed at 420 GeV with a local significance of 2.3 standard deviations after combining the $ee\gamma$ and $\mu\mu\gamma$ channel distributions shown in Fig. 3. The individual significances at the same m_X value are 2.1σ and 1.1σ in the electron and muon channels respectively.

The probability of compatibility between the data and the expected background plus signal is examined for increasing values of the signal cross section, and a modified frequentist (CL$_s$) approach [45] is used to set an upper limit on the cross section. The limit at 95% confidence level (CL) is determined by identifying the signal cross section for which the CL$_s$ value is equal to 0.05. The observed (expected) cross-section limits for m_X up to 1850 (900) GeV are derived using closed-form asymptotic formulae [44]. At higher m_X values the asymptotic formulae underestimate the observed (expected) limits by 5% to 17% (1.4% to 29%) because of the smaller number of events, and ensemble tests with sampling distributions generated using pseudo-experiments are used instead. Fig. 4 shows the observed and expected upper limits as a function of m_X for a spin-0 resonance signal produced via gluon–gluon fusion, using the combined data from the $ee\gamma$ and $\mu\mu\gamma$ channels. The observed (expected) limits range from 65.5 fb to 0.6 fb (43.3 fb to 0.6 fb). The search is limited by the statistical uncertainty of the selected data events in the $m_{Z\gamma}$ distribution. The dominant systematic uncertainty is the spurious-signal uncertainty, which has at most a 12% impact on the asymptotic expected upper limit on $\sigma(pp \to X) \cdot \mathcal{B}(X \to Z\gamma)$.

The results are also interpreted in terms of spin-2 resonances (for both the ggX and $q\bar{q}X$ processes) in the same mass range as the nominal spin-0 resonances. As shown in Fig. 5, the observed (expected) limits range from 77.4 fb to 0.6 fb (50.8 fb to 0.6 fb) for a ggX spin-2 resonance and from 76.1 fb to 0.5 fb (50.3 fb to 0.5 fb) for a $q\bar{q}X$ spin-2 resonance. Table 3 summarizes the observed (expected) upper limits on $\sigma(pp \to X) \cdot \mathcal{B}(X \to Z\gamma)$ for spin-0 and spin-2 heavy-resonance masses from 220 GeV to 3400 GeV.

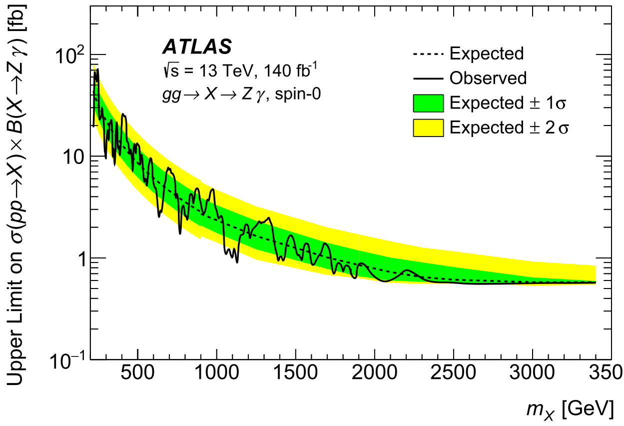


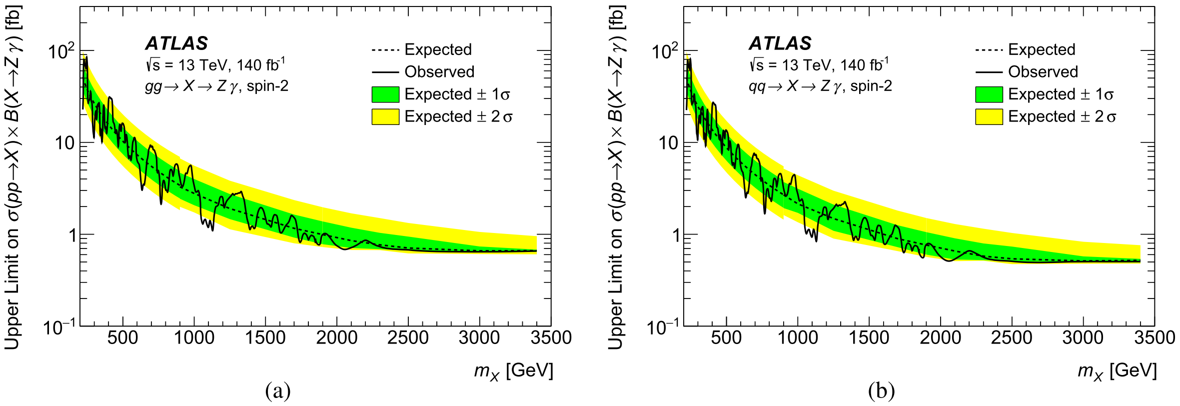
Fig. 4. Observed (solid line) and expected (dashed line) 95% CL upper limits on the production cross section times branching ratio of a narrow-width spin-0 resonance X produced from gluon–gluon initial states and decaying into a Z boson and a photon, $\sigma(pp \to X) \cdot \mathcal{B}(X \to Z\gamma)$, as a function of the resonance mass m_X. Observed (expected) results are derived from ensemble tests for $m_X >$ 1850 (900) GeV and from asymptotic formulae for lower m_X values. The green and yellow bands correspond to the $\pm1\sigma$ and $\pm2\sigma$ intervals for the expected upper limits. The limits are shown in the m_X range from 220 GeV to 3400 GeV and are obtained from the combined $ee\gamma$ and $\mu\mu\gamma$ channels.

8. Conclusion

A search for new resonances decaying into the $Z(\to \ell\ell)\gamma$ final state in the mass range between 220 GeV and 3400 GeV has been performed using 140 fb^{-1} of $\sqrt{s} = 13$ TeV pp collision data recorded with the ATLAS detector at the LHC. The observed data are in agreement with the smoothly falling background predicted by the SM. No evidence of $X \to Z\gamma$ decay is observed, and upper limits are set on $\sigma(pp \to X) \cdot \mathcal{B}(X \to Z\gamma)$ as a function of m_X. The results are presented using spin-0 and spin-2 interpretations. For spin-0 resonances, the observed limits vary between 65.5 fb and 0.6 fb. The cross-section limits vary between 77.4 (76.1) fb and 0.6 (0.5) fb for spin-2 resonances produced from

Table 3
The observed (expected) upper limits on $\sigma(pp \to X) \cdot \mathcal{B}(X \to Z\gamma)$ for spin-0 and spin-2 heavy resonances at 95% CL. The value of m_X varies from 220 GeV to 3400 GeV.

95% CL upper limits on $\sigma(pp \to X) \cdot \mathcal{B}(X \to Z\gamma)$	Observed	Expected
ggX spin-0	65.5 fb – 0.6 fb	43.3 fb – 0.6 fb
ggX spin-2	77.4 fb – 0.6 fb	50.8 fb – 0.6 fb
$q\bar{q}X$ spin-2	76.1 fb – 0.5 fb	50.3 fb – 0.5 fb



(a) (b)

Fig. 5. Observed (solid line) and expected (dashed line) 95% CL limits on the production cross section times branching ratio of a narrow-width spin-2 resonance X produced from (a) gluon–gluon initial states and (b) $q\bar{q}$ initial states and decaying into a Z boson and a photon, $\sigma(pp \to X) \cdot \mathcal{B}(X \to Z\gamma)$, as a function of the resonance mass m_X. Observed (expected) results are derived from ensemble tests for $m_X > 1850\,(900)$ GeV and from asymptotic formulae for lower m_X values. The green and yellow bands correspond to the $\pm 1\sigma$ and $\pm 2\sigma$ intervals for the expected upper limit respectively. The limits are shown in the m_X range from 220 GeV to 3400 GeV and are obtained from the combined $ee\gamma$ and $\mu\mu\gamma$ channels.

gluon–gluon (quark–antiquark) initial states. These results improve the expected upper limit on $\sigma(pp \to X) \cdot \mathcal{B}(X \to Z\gamma)$ for a spin-0 resonance by a factor of 1.9 to 4 in the m_X range of 250 GeV to 2400 GeV covered by a previous ATLAS search. In addition, this search extends the covered mass range to 3400 GeV by using the higher integrated luminosity of the full Run 2 dataset as well as an MVA electron identification technique. Compared to a resonance search by ATLAS using hadronic decays of the Z boson and the full Run 2 dataset, this search probes lower m_X values, down to 220 GeV, and has better sensitivity up to 2300 GeV.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

The data for this manuscript are not available. The values in the plots and tables associated to this article are stored in HEPDATA (https://hepdata.cedar.ac.uk)

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S. Schlenker[36], J. Schmeing[171], M.A. Schmidt[171], K. Schmieden[100], C. Schmitt[100], S. Schmitt[48], L. Schoeffel[135], A. Schoening[63b], P.G. Scholer[54], E. Schopf[126], M. Schott[100], J. Schovancova[36], S. Schramm[56], F. Schroeder[171], T. Schroer[56], H-C. Schultz-Coulon[63a], M. Schumacher[54], B.A. Schumm[136], Ph. Schune[135], A.J. Schuy[138], H.R. Schwartz[136], A. Schwartzman[143], T.A. Schwarz[106], Ph. Schwemling[135], R. Schwienhorst[107], A. Sciandra[136], G. Sciolla[26], F. Scuri[74a], C.D. Sebastiani[92], K. Sedlaczek[115], P. Seema[18], S.C. Seidel[112], A. Seiden[136], B.D. Seidlitz[41], C. Seitz[48], J.M. Seixas[83b], G. Sekhniaidze[72a], S.J. Sekula[44], L. Selem[60], N. Semprini-Cesari[23b,23a], D. Sengupta[56], V. Senthilkumar[163], L. Serin[66], L. Serkin[69a,69b], M. Sessa[76a,76b], H. Severini[120], F. Sforza[57b,57a], A. Sfyrla[56], E. Shabalina[55], R. Shaheen[144], J.D. Shahinian[128], D. Shaked Renous[169], L.Y. Shan[14a], M. Shapiro[17a], A. Sharma[36], A.S. Sharma[164], P. Sharma[80], S. Sharma[48], P.B. Shatalov[37], K. Shaw[146], S.M. Shaw[101], A. Shcherbakova[37], Q. Shen[62c,5], P. Sherwood[96], L. Shi[96], X. Shi[14a], C.O. Shimmin[172], J.D. Shinner[95], I.P.J. Shipsey[126], S. Shirabe[56,h], M. Shiyakova[38,u], J. Shlomi[169], M.J. Shochet[39], J. Shojaii[105], D.R. Shope[125], B. Shrestha[120], S. Shrestha[119,aj], E.M. Shrif[33g], M.J. Shroff[165], P. Sicho[131], A.M. Sickles[162], E. Sideras Haddad[33g], A. Sidoti[23b], F. Siegert[50], Dj. Sijacki[15], R. Sikora[86a], F. Sili[90], J.M. Silva[20], M.V. Silva Oliveira[29], S.B. Silverstein[47a], S. Simion[66], R. Simoniello[36], E.L. Simpson[59], H. Simpson[146], L.R. Simpson[106], N.D. Simpson[98], S. Simsek[82], S. Sindhu[55], P. Sinervo[155], S. Singh[155], S. Sinha[48], S. Sinha[101], M. Sioli[23b,23a], I. Siral[36], E. Sitnikova[48], S.Yu. Sivoklokov[37,*], J. Sjölin[47a,47b], A. Skaf[55], E. Skorda[20], P. Skubic[120], M. Slawinska[87], V. Smakhtin[169], B.H. Smart[134], J. Smiesko[36], S.Yu. Smirnov[37], Y. Smirnov[37], L.N. Smirnova[37,a], O. Smirnova[98], A.C. Smith[41], E.A. Smith[39], H.A. Smith[126], J.L. Smith[92], R. Smith[143], M. Smizanska[91], K. Smolek[132], A.A. Snesarev[37], S.R. Snider[155], H.L. Snoek[114], S. Snyder[29], R. Sobie[165,w], A. Soffer[151], C.A. Solans Sanchez[36], E.Yu. Soldatov[37], U. Soldevila[163], A.A. Solodkov[37], S. Solomon[26], A. Soloshenko[38], K. Solovieva[54], O.V. Solovyanov[40], V. Solovyev[37], P. Sommer[36], A. Sonay[13], W.Y. Song[156b], J.M. Sonneveld[114], A. Sopczak[132], A.L. Sopio[96], F. Sopkova[28b], V. Sothilingam[63a], S. Sottocornola[68], R. Soualah[116b], Z. Soumaimi[35e], D. South[48], N. Soybelman[169], S. Spagnolo[70a,70b], M. Spalla[110], D. Sperlich[54], G. Spigo[36], S. Spinali[91], D.P. Spiteri[59], M. Spousta[133], E.J. Staats[34], A. Stabile[71a,71b], R. Stamen[63a], A. Stampekis[20], M. Standke[24], E. Stanecka[87], M.V. Stange[50], B. Stanislaus[17a], M.M. Stanitzki[48], B. Stapf[48], E.A. Starchenko[37], G.H. Stark[136], J. Stark[102,aa], D.M. Starko[156b], P. Staroba[131], P. Starovoitov[63a], S. Stärz[104], R. Staszewski[87], G. Stavropoulos[46], J. Steentoft[161], P. Steinberg[29], B. Stelzer[142,156a], H.J. Stelzer[129], O. Stelzer-Chilton[156a], H. Stenzel[58], T.J. Stevenson[146], G.A. Stewart[36], J.R. Stewart[121], M.C. Stockton[36], G. Stoicea[27b], M. Stolarski[130a], S. Stonjek[110], A. Straessner[50], J. Strandberg[144], S. Strandberg[47a,47b], M. Stratmann[171], M. Strauss[120], T. Strebler[102], P. Strizenec[28b], R. Ströhmer[166], D.M. Strom[123], L.R. Strom[48], R. Stroynowski[44], A. Strubig[47a,47b], S.A. Stucci[29], B. Stugu[16], J. Stupak[120], N.A. Styles[48], D. Su[143], S. Su[62a], W. Su[62d], X. Su[62a,66], K. Sugizaki[153], V.V. Sulin[37], M.J. Sullivan[92], D.M.S. Sultan[78a,78b], L. Sultanaliyeva[37], S. Sultansoy[3b], T. Sumida[88], S. Sun[106], S. Sun[170], O. Sunneborn Gudnadottir[161], N. Sur[102], M.R. Sutton[146], H. Suzuki[157], M. Svatos[131], M. Swiatlowski[156a], T. Swirski[166], I. Sykora[28a], M. Sykora[133], T. Sykora[133], D. Ta[100], K. Tackmann[48,t], A. Taffard[160], R. Tafirout[156a], J.S. Tafoya Vargas[66], E.P. Takeva[52], Y. Takubo[84], M. Talby[102], A.A. Talyshev[37], K.C. Tam[64b], N.M. Tamir[151], A. Tanaka[153],

J. Tanaka[153], R. Tanaka[66], M. Tanasini[57b,57a], Z. Tao[164], S. Tapia Araya[137f], S. Tapprogge[100], A. Tarek Abouelfadl Mohamed[107], S. Tarem[150], K. Tariq[14a], G. Tarna[102,27b], G.F. Tartarelli[71a], P. Tas[133], M. Tasevsky[131], E. Tassi[43b,43a], A.C. Tate[162], G. Tateno[153], Y. Tayalati[35e,v], G.N. Taylor[105], W. Taylor[156b], H. Teagle[92], A.S. Tee[170], R. Teixeira De Lima[143], P. Teixeira-Dias[95], J.J. Teoh[155], K. Terashi[153], J. Terron[99], S. Terzo[13], M. Testa[53], R.J. Teuscher[155,w], A. Thaler[79], O. Theiner[56], N. Themistokleous[52], T. Theveneaux-Pelzer[102], O. Thielmann[171], D.W. Thomas[95], J.P. Thomas[20], E.A. Thompson[17a], P.D. Thompson[20], E. Thomson[128], Y. Tian[55], V. Tikhomirov[37,a], Yu.A. Tikhonov[37], S. Timoshenko[37], D. Timoshyn[133], E.X.L. Ting[1], P. Tipton[172], S.H. Tlou[33g], A. Tnourji[40], K. Todome[154], S. Todorova-Nova[133], S. Todt[50], M. Togawa[84], J. Tojo[89], S. Tokár[28a], K. Tokushuku[84], O. Toldaiev[68], R. Tombs[32], M. Tomoto[84,111], L. Tompkins[143,n], K.W. Topolnicki[86b], E. Torrence[123], H. Torres[102,aa], E. Torró Pastor[163], M. Toscani[30], C. Tosciri[39], M. Tost[11], D.R. Tovey[139], A. Traeet[16], I.S. Trandafir[27b], T. Trefzger[166], A. Tricoli[29], I.M. Trigger[156a], S. Trincaz-Duvoid[127], D.A. Trischuk[26], B. Trocmé[60], C. Troncon[71a], L. Truong[33c], M. Trzebinski[87], A. Trzupek[87], F. Tsai[145], M. Tsai[106], A. Tsiamis[152,e], P.V. Tsiareshka[37], S. Tsigaridas[156a], A. Tsirigotis[152,r], V. Tsiskaridze[155], E.G. Tskhadadze[149a], M. Tsopoulou[152,e], Y. Tsujikawa[88], I.I. Tsukerman[37], V. Tsulaia[17a], S. Tsuno[84], O. Tsur[150], K. Tsuri[118], D. Tsybychev[145], Y. Tu[64b], A. Tudorache[27b], V. Tudorache[27b], A.N. Tuna[36], S. Turchikhin[57b,57a], I. Turk Cakir[3a], R. Turra[71a], T. Turtuvshin[38,x], P.M. Tuts[41], S. Tzamarias[152,e], P. Tzanis[10], E. Tzovara[100], F. Ukegawa[157], P.A. Ulloa Poblete[137c,137b], E.N. Umaka[29], G. Unal[36], M. Unal[11], A. Undrus[29], G. Unel[160], J. Urban[28b], P. Urquijo[105], G. Usai[8], R. Ushioda[154], M. Usman[108], Z. Uysal[21b], L. Vacavant[102], V. Vacek[132], B. Vachon[104], K.O.H. Vadla[125], T. Vafeiadis[36], A. Vaitkus[96], C. Valderanis[109], E. Valdes Santurio[47a,47b], M. Valente[156a], S. Valentinetti[23b,23a], A. Valero[163], E. Valiente Moreno[163], A. Vallier[102,aa], J.A. Valls Ferrer[163], D.R. Van Arneman[114], T.R. Van Daalen[138], A. Van Der Graaf[49], P. Van Gemmeren[6], M. Van Rijnbach[125,36], S. Van Stroud[96], I. Van Vulpen[114], M. Vanadia[76a,76b], W. Vandelli[36], M. Vandenbroucke[135], E.R. Vandewall[121], D. Vannicola[151], L. Vannoli[57b,57a], R. Vari[75a], E.W. Varnes[7], C. Varni[17b], T. Varol[148], D. Varouchas[66], L. Varriale[163], K.E. Varvell[147], M.E. Vasile[27b], L. Vaslin[40], G.A. Vasquez[165], A. Vasyukov[38], F. Vazeille[40], T. Vazquez Schroeder[36], J. Veatch[31], V. Vecchio[101], M.J. Veen[103], I. Veliscek[126], L.M. Veloce[155], F. Veloso[130a,130c], S. Veneziano[75a], A. Ventura[70a,70b], S. Ventura Gonzalez[135], A. Verbytskyi[110], M. Verducci[74a,74b], C. Vergis[24], M. Verissimo De Araujo[83b], W. Verkerke[114], J.C. Vermeulen[114], C. Vernieri[143], M. Vessella[103], M.C. Vetterli[142,ag], A. Vgenopoulos[152,e], N. Viaux Maira[137f], T. Vickey[139], O.E. Vickey Boeriu[139], G.H.A. Viehhauser[126], L. Vigani[63b], M. Villa[23b,23a], M. Villaplana Perez[163], E.M. Villhauer[52], E. Vilucchi[53], M.G. Vincter[34], G.S. Virdee[20], A. Vishwakarma[52], A. Visibile[114], C. Vittori[36], I. Vivarelli[146], E. Voevodina[110], F. Vogel[109], P. Vokac[132], Yu. Volkotrub[86a], J. Von Ahnen[48], E. Von Toerne[24], B. Vormwald[36], V. Vorobel[133], K. Vorobev[37], M. Vos[163], K. Voss[141], J.H. Vossebeld[92], M. Vozak[114], L. Vozdecky[94], N. Vranjes[15], M. Vranjes Milosavljevic[15], M. Vreeswijk[114], R. Vuillermet[36], O. Vujinovic[100], I. Vukotic[39], S. Wada[157], C. Wagner[103], J.M. Wagner[17a], W. Wagner[171], S. Wahdan[171], H. Wahlberg[90], M. Wakida[111], J. Walder[134], R. Walker[109], W. Walkowiak[141], A. Wall[128], T. Wamorkar[6], A.Z. Wang[170], C. Wang[100], C. Wang[62c], H. Wang[17a], J. Wang[64a], R.-J. Wang[100], R. Wang[61], R. Wang[6], S.M. Wang[148], S. Wang[62b], T. Wang[62a], W.T. Wang[80],

W. Wang[14a], X. Wang[14c], X. Wang[162], X. Wang[62c], Y. Wang[62d], Y. Wang[14c], Z. Wang[106], Z. Wang[62d,51,62c], Z. Wang[106], A. Warburton[104], R.J. Ward[20], N. Warrack[59], A.T. Watson[20], H. Watson[59], M.F. Watson[20], E. Watton[59,134], G. Watts[138], B.M. Waugh[96], C. Weber[29], H.A. Weber[18], M.S. Weber[19], S.M. Weber[63a], C. Wei[62a], Y. Wei[126], A.R. Weidberg[126], E.J. Weik[117], J. Weingarten[49], M. Weirich[100], C. Weiser[54], C.J. Wells[48], T. Wenaus[29], B. Wendland[49], T. Wengler[36], N.S. Wenke[110], N. Wermes[24], M. Wessels[63a], A.M. Wharton[91], A.S. White[61], A. White[8], M.J. White[1], D. Whiteson[160], L. Wickremasinghe[124], W. Wiedenmann[170], C. Wiel[50], M. Wielers[134], C. Wiglesworth[42], D.J. Wilbern[120], H.G. Wilkens[36], D.M. Williams[41], H.H. Williams[128], S. Williams[32], S. Willocq[103], B.J. Wilson[101], P.J. Windischhofer[39], F.I. Winkel[30], F. Winklmeier[123], B.T. Winter[54], J.K. Winter[101], M. Wittgen[143], M. Wobisch[97], Z. Wolffs[114], J. Wollrath[160], M.W. Wolter[87], H. Wolters[130a,130c], A.F. Wongel[48], S.D. Worm[48], B.K. Wosiek[87], K.W. Woźniak[87], S. Wozniewski[55], K. Wraight[59], C. Wu[20], J. Wu[14a,14e], M. Wu[64a], M. Wu[113], S.L. Wu[170], X. Wu[56], Y. Wu[62a], Z. Wu[135], J. Wuerzinger[110,ae], T.R. Wyatt[101], B.M. Wynne[52], S. Xella[42], L. Xia[14c], M. Xia[14b], J. Xiang[64c], M. Xie[62a], X. Xie[62a], S. Xin[14a,14e], A. Xiong[123], J. Xiong[17a], D. Xu[14a], H. Xu[62a], L. Xu[62a], R. Xu[128], T. Xu[106], Y. Xu[14b], Z. Xu[52], Z. Xu[14a], B. Yabsley[147], S. Yacoob[33a], Y. Yamaguchi[154], E. Yamashita[153], H. Yamauchi[157], T. Yamazaki[17a], Y. Yamazaki[85], J. Yan[62c], S. Yan[126], Z. Yan[25], H.J. Yang[62c,62d], H.T. Yang[62a], S. Yang[62a], T. Yang[64c], X. Yang[62a], X. Yang[14a], Y. Yang[44], Y. Yang[62a], Z. Yang[62a], W-M. Yao[17a], Y.C. Yap[48], H. Ye[14c], H. Ye[55], J. Ye[14a], S. Ye[29], X. Ye[62a], Y. Yeh[96], I. Yeletskikh[38], B.K. Yeo[17b], M.R. Yexley[96], P. Yin[41], K. Yorita[168], S. Younas[27b], C.J.S. Young[36], C. Young[143], C. Yu[14a,14e], Y. Yu[62a], M. Yuan[106], R. Yuan[62b], L. Yue[96], M. Zaazoua[62a], B. Zabinski[87], E. Zaid[52], T. Zakareishvili[149b], N. Zakharchuk[34], S. Zambito[56], J.A. Zamora Saa[137d,137b], J. Zang[153], D. Zanzi[54], O. Zaplatilek[132], C. Zeitnitz[171], H. Zeng[14a], J.C. Zeng[162], D.T. Zenger Jr[26], O. Zenin[37], T. Ženiš[28a], S. Zenz[94], S. Zerradi[35a], D. Zerwas[66], M. Zhai[14a,14e], B. Zhang[14c], D.F. Zhang[139], J. Zhang[62b], J. Zhang[6], K. Zhang[14a,14e], L. Zhang[14c], P. Zhang[14a,14e], R. Zhang[170], S. Zhang[106], T. Zhang[153], X. Zhang[62c], X. Zhang[62b], Y. Zhang[62c,5], Y. Zhang[96], Z. Zhang[17a], Z. Zhang[66], H. Zhao[138], P. Zhao[51], T. Zhao[62b], Y. Zhao[136], Z. Zhao[62a], A. Zhemchugov[38], J. Zheng[14c], K. Zheng[162], X. Zheng[62a], Z. Zheng[143], D. Zhong[162], B. Zhou[106], H. Zhou[7], N. Zhou[62c], Y. Zhou[7], C.G. Zhu[62b], J. Zhu[106], Y. Zhu[62c], Y. Zhu[62a], X. Zhuang[14a], K. Zhukov[37], V. Zhulanov[37], N.I. Zimine[38], J. Zinsser[63b], M. Ziolkowski[141], L. Živković[15], A. Zoccoli[23b,23a], K. Zoch[61], T.G. Zorbas[139], O. Zormpa[46], W. Zou[41], L. Zwalinski[36]

[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] *(a) Institute of High Energy Physics, Chinese Academy of Sciences, Beijing; (b) Physics Department, Tsinghua University, Beijing; (c) Department of Physics, Nanjing University, Nanjing; (d) School of Science, Shenzhen Campus of Sun Yat-sen University; (e) University of Chinese Academy of Science (UCAS), Beijing; China*
[15] *Institute of Physics, University of Belgrade, Belgrade; Serbia*
[16] *Department for Physics and Technology, University of Bergen, Bergen; Norway*
[17] *(a) Physics Division, Lawrence Berkeley National Laboratory, Berkeley CA; (b) University of California, Berkeley CA; United States of America*
[18] *Institut für Physik, Humboldt Universität zu Berlin, Berlin; Germany*

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

[20] *School of Physics and Astronomy, University of Birmingham, Birmingham; United Kingdom*

[21] *(a) Department of Physics, Bogazici University, Istanbul; (b) Department of Physics Engineering, Gaziantep University, Gaziantep; (c) Department of Physics, Istanbul University, Istanbul; Türkiye*

[22] *(a) Facultad de Ciencias y Centro de Investigaciónes, Universidad Antonio Nariño, Bogotá; (b) Departamento de Física, Universidad Nacional de Colombia, Bogotá; Colombia*

[23] *(a) Dipartimento di Fisica e Astronomia A. Righi, Università di Bologna, Bologna; (b) INFN Sezione di Bologna; Italy*

[24] *Physikalisches Institut, Universität Bonn, Bonn; Germany*

[25] *Department of Physics, Boston University, Boston MA; United States of America*

[26] *Department of Physics, Brandeis University, Waltham MA; United States of America*

[27] *(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) University Politehnica Bucharest, Bucharest; (f) West University in Timisoara, Timisoara; (g) Faculty of Physics, University of Bucharest, Bucharest; Romania*

[28] *(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*

[29] *Physics Department, Brookhaven National Laboratory, Upton NY; United States of America*

[30] *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*

[31] *California State University, CA; United States of America*

[32] *Cavendish Laboratory, University of Cambridge, Cambridge; United Kingdom*

[33] *(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*

[34] *Department of Physics, Carleton University, Ottawa ON; Canada*

[35] *(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*

[36] *CERN, Geneva; Switzerland*

[37] *Affiliated with an institute covered by a cooperation agreement with CERN*

[38] *Affiliated with an international laboratory covered by a cooperation agreement with CERN*

[39] *Enrico Fermi Institute, University of Chicago, Chicago IL; United States of America*

[40] *LPC, Université Clermont Auvergne, CNRS/IN2P3, Clermont-Ferrand; France*

[41] *Nevis Laboratory, Columbia University, Irvington NY; United States of America*

[42] *Niels Bohr Institute, University of Copenhagen, Copenhagen; Denmark*

[43] *(a) Dipartimento di Fisica, Università della Calabria, Rende; (b) INFN Gruppo Collegato di Cosenza, Laboratori Nazionali di Frascati; Italy*

[44] *Physics Department, Southern Methodist University, Dallas TX; United States of America*

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

[46] *National Centre for Scientific Research "Demokritos", Agia Paraskevi; Greece*

[47] *(a) Department of Physics, Stockholm University; (b) Oskar Klein Centre, Stockholm; Sweden*

[48] *Deutsches Elektronen-Synchrotron DESY, Hamburg and Zeuthen; Germany*

[49] *Fakultät Physik, Technische Universität Dortmund, Dortmund; Germany*

[50] *Institut für Kern- und Teilchenphysik, Technische Universität Dresden, Dresden; Germany*

[51] *Department of Physics, Duke University, Durham NC; United States of America*

[52] *SUPA - School of Physics and Astronomy, University of Edinburgh, Edinburgh; United Kingdom*

[53] *INFN e Laboratori Nazionali di Frascati, Frascati; Italy*

[54] *Physikalisches Institut, Albert-Ludwigs-Universität Freiburg, Freiburg; Germany*

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

[56] *Département de Physique Nucléaire et Corpusculaire, Université de Genève, Genève; Switzerland*

[57] *(a) Dipartimento di Fisica, Università di Genova, Genova; (b) INFN Sezione di Genova; Italy*

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

[59] *SUPA - School of Physics and Astronomy, University of Glasgow, Glasgow; United Kingdom*

[60] *LPSC, Université Grenoble Alpes, CNRS/IN2P3, Grenoble INP, Grenoble; France*

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

[62] *(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; China*

[63] *(a) Kirchhoff-Institut für Physik, Ruprecht-Karls-Universität Heidelberg, Heidelberg; (b) Physikalisches Institut, Ruprecht-Karls-Universität Heidelberg, Heidelberg; Germany*

[64] *(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*

[65] *Department of Physics, National Tsing Hua University, Hsinchu; Taiwan*

[66] *IJCLab, Université Paris-Saclay, CNRS/IN2P3, 91405, Orsay; France*

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

[68] *Department of Physics, Indiana University, Bloomington IN; United States of America*

[69] *(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*

[70] *(a) INFN Sezione di Lecce; (b) Dipartimento di Matematica e Fisica, Università del Salento, Lecce; Italy*

[71] *(a) INFN Sezione di Milano; (b) Dipartimento di Fisica, Università di Milano, Milano; Italy*

[72] *(a) INFN Sezione di Napoli; (b) Dipartimento di Fisica, Università di Napoli, Napoli; Italy*

[73] *(a) INFN Sezione di Pavia; (b) Dipartimento di Fisica, Università di Pavia, Pavia; Italy*

[74] *(a) INFN Sezione di Pisa; (b) Dipartimento di Fisica E. Fermi, Università di Pisa, Pisa; Italy*

[75] *(a) INFN Sezione di Roma; (b) Dipartimento di Fisica, Sapienza Università di Roma, Roma; Italy*

[76] *(a) INFN Sezione di Roma Tor Vergata; (b) Dipartimento di Fisica, Università di Roma Tor Vergata, Roma; Italy*

[77] *(a) INFN Sezione di Roma Tre; (b) Dipartimento di Matematica e Fisica, Università Roma Tre, Roma; Italy*

[78] *(a) INFN-TIFPA; (b) Università degli Studi di Trento, Trento; Italy*

[79] *Universität Innsbruck, Department of Astro and Particle Physics, Innsbruck; Austria*

[80] *University of Iowa, Iowa City IA; United States of America*

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

[82] *Istinye University, Sariyer, Istanbul; Türkiye*

[83] *(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; Brazil*

[84] *KEK, High Energy Accelerator Research Organization, Tsukuba; Japan*

[85] *Graduate School of Science, Kobe University, Kobe; Japan*

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

[87] *Institute of Nuclear Physics Polish Academy of Sciences, Krakow; Poland*

[88] *Faculty of Science, Kyoto University, Kyoto; Japan*
[89] *Research Center for Advanced Particle Physics and Department of Physics, Kyushu University, Fukuoka; Japan*
[90] *Instituto de Física La Plata, Universidad Nacional de La Plata and CONICET, La Plata; Argentina*
[91] *Physics Department, Lancaster University, Lancaster; United Kingdom*
[92] *Oliver Lodge Laboratory, University of Liverpool, Liverpool; United Kingdom*
[93] *Department of Experimental Particle Physics, Jožef Stefan Institute and Department of Physics, University of Ljubljana, Ljubljana; Slovenia*
[94] *School of Physics and Astronomy, Queen Mary University of London, London; United Kingdom*
[95] *Department of Physics, Royal Holloway University of London, Egham; United Kingdom*
[96] *Department of Physics and Astronomy, University College London, London; United Kingdom*
[97] *Louisiana Tech University, Ruston LA; United States of America*
[98] *Fysiska institutionen, Lunds universitet, Lund; Sweden*
[99] *Departamento de Física Teorica C-15 and CIAFF, Universidad Autónoma de Madrid, Madrid; Spain*
[100] *Institut für Physik, Universität Mainz, Mainz; Germany*
[101] *School of Physics and Astronomy, University of Manchester, Manchester; United Kingdom*
[102] *CPPM, Aix-Marseille Université, CNRS/IN2P3, Marseille; France*
[103] *Department of Physics, University of Massachusetts, Amherst MA; United States of America*
[104] *Department of Physics, McGill University, Montreal QC; Canada*
[105] *School of Physics, University of Melbourne, Victoria; Australia*
[106] *Department of Physics, University of Michigan, Ann Arbor MI; United States of America*
[107] *Department of Physics and Astronomy, Michigan State University, East Lansing MI; United States of America*
[108] *Group of Particle Physics, University of Montreal, Montreal QC; Canada*
[109] *Fakultät für Physik, Ludwig-Maximilians-Universität München, München; Germany*
[110] *Max-Planck-Institut für Physik (Werner-Heisenberg-Institut), München; Germany*
[111] *Graduate School of Science and Kobayashi-Maskawa Institute, Nagoya University, Nagoya; Japan*
[112] *Department of Physics and Astronomy, University of New Mexico, Albuquerque NM; United States of America*
[113] *Institute for Mathematics, Astrophysics and Particle Physics, Radboud University/Nikhef, Nijmegen; Netherlands*
[114] *Nikhef National Institute for Subatomic Physics and University of Amsterdam, Amsterdam; Netherlands*
[115] *Department of Physics, Northern Illinois University, DeKalb IL; United States of America*
[116] (a) *New York University Abu Dhabi, Abu Dhabi;* (b) *University of Sharjah, Sharjah; United Arab Emirates*
[117] *Department of Physics, New York University, New York NY; United States of America*
[118] *Ochanomizu University, Otsuka, Bunkyo-ku, Tokyo; Japan*
[119] *Ohio State University, Columbus OH; United States of America*
[120] *Homer L. Dodge Department of Physics and Astronomy, University of Oklahoma, Norman OK; United States of America*
[121] *Department of Physics, Oklahoma State University, Stillwater OK; United States of America*
[122] *Palacký University, Joint Laboratory of Optics, Olomouc; Czech Republic*
[123] *Institute for Fundamental Science, University of Oregon, Eugene, OR; United States of America*
[124] *Graduate School of Science, Osaka University, Osaka; Japan*
[125] *Department of Physics, University of Oslo, Oslo; Norway*
[126] *Department of Physics, Oxford University, Oxford; United Kingdom*
[127] *LPNHE, Sorbonne Université, Université Paris Cité, CNRS/IN2P3, Paris; France*
[128] *Department of Physics, University of Pennsylvania, Philadelphia PA; United States of America*
[129] *Department of Physics and Astronomy, University of Pittsburgh, Pittsburgh PA; United States of America*
[130] (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*
[131] *Institute of Physics of the Czech Academy of Sciences, Prague; Czech Republic*
[132] *Czech Technical University in Prague, Prague; Czech Republic*
[133] *Charles University, Faculty of Mathematics and Physics, Prague; Czech Republic*
[134] *Particle Physics Department, Rutherford Appleton Laboratory, Didcot; United Kingdom*
[135] *IRFU, CEA, Université Paris-Saclay, Gif-sur-Yvette; France*
[136] *Santa Cruz Institute for Particle Physics, University of California Santa Cruz, Santa Cruz CA; United States of America*
[137] (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*
[138] *Department of Physics, University of Washington, Seattle WA; United States of America*
[139] *Department of Physics and Astronomy, University of Sheffield, Sheffield; United Kingdom*
[140] *Department of Physics, Shinshu University, Nagano; Japan*
[141] *Department Physik, Universität Siegen, Siegen; Germany*
[142] *Department of Physics, Simon Fraser University, Burnaby BC; Canada*
[143] *SLAC National Accelerator Laboratory, Stanford CA; United States of America*
[144] *Department of Physics, Royal Institute of Technology, Stockholm; Sweden*
[145] *Departments of Physics and Astronomy, Stony Brook University, Stony Brook NY; United States of America*
[146] *Department of Physics and Astronomy, University of Sussex, Brighton; United Kingdom*
[147] *School of Physics, University of Sydney, Sydney; Australia*
[148] *Institute of Physics, Academia Sinica, Taipei; Taiwan*
[149] (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*
[150] *Department of Physics, Technion, Israel Institute of Technology, Haifa; Israel*
[151] *Raymond and Beverly Sackler School of Physics and Astronomy, Tel Aviv University, Tel Aviv; Israel*
[152] *Department of Physics, Aristotle University of Thessaloniki, Thessaloniki; Greece*
[153] *International Center for Elementary Particle Physics and Department of Physics, University of Tokyo, Tokyo; Japan*
[154] *Department of Physics, Tokyo Institute of Technology, Tokyo; Japan*
[155] *Department of Physics, University of Toronto, Toronto ON; Canada*
[156] (a) *TRIUMF, Vancouver BC;* (b) *Department of Physics and Astronomy, York University, Toronto ON; Canada*
[157] *Division of Physics and Tomonaga Center for the History of the Universe, Faculty of Pure and Applied Sciences, University of Tsukuba, Tsukuba; Japan*
[158] *Department of Physics and Astronomy, Tufts University, Medford MA; United States of America*
[159] *United Arab Emirates University, Al Ain; United Arab Emirates*
[160] *Department of Physics and Astronomy, University of California Irvine, Irvine CA; United States of America*
[161] *Department of Physics and Astronomy, University of Uppsala, Uppsala; Sweden*
[162] *Department of Physics, University of Illinois, Urbana IL; United States of America*

[163] *Instituto de Física Corpuscular (IFIC), Centro Mixto Universidad de Valencia - CSIC, Valencia; Spain*
[164] *Department of Physics, University of British Columbia, Vancouver BC; Canada*
[165] *Department of Physics and Astronomy, University of Victoria, Victoria BC; Canada*
[166] *Fakultät für Physik und Astronomie, Julius-Maximilians-Universität Würzburg, Würzburg; Germany*
[167] *Department of Physics, University of Warwick, Coventry; United Kingdom*
[168] *Waseda University, Tokyo; Japan*
[169] *Department of Particle Physics and Astrophysics, Weizmann Institute of Science, Rehovot; Israel*
[170] *Department of Physics, University of Wisconsin, Madison WI; United States of America*
[171] *Fakultät für Mathematik und Naturwissenschaften, Fachgruppe Physik, Bergische Universität Wuppertal, Wuppertal; Germany*
[172] *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 High Energy Physics, Peking University; China.
[e] Also at Center for Interdisciplinary Research and Innovation (CIRI-AUTH), Thessaloniki; Greece.
[f] Also at Centro Studi e Ricerche Enrico Fermi; Italy.
[g] Also at CERN, Geneva; Switzerland.
[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, Ben Gurion University of the Negev, Beer Sheva; Israel.
[l] Also at Department of Physics, California State University, Sacramento; United States of America.
[m] Also at Department of Physics, King's College London, London; United Kingdom.
[n] Also at Department of Physics, Stanford University, Stanford CA; United States of America.
[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 and Technology, Ulaanbaatar; Mongolia.
[y] Also at Institute of Physics, Azerbaijan Academy of Sciences, Baku; Azerbaijan.
[z] Also at Institute of Theoretical Physics, Ilia State University, Tbilisi; Georgia.
[aa] Also at L2IT, Université de Toulouse, CNRS/IN2P3, UPS, Toulouse; France.
[ab] Also at Lawrence Livermore National Laboratory, Livermore; United States of America.
[ac] Also at National Institute of Physics, University of the Philippines Diliman (Philippines); Philippines.
[ad] Also at Ochanomizu University, Otsuka, Bunkyo-ku, Tokyo; Japan.
[ae] Also at Technical University of Munich, Munich; Germany.
[af] Also at The Collaborative Innovation Center of Quantum Matter (CICQM), Beijing; China.
[ag] Also at TRIUMF, Vancouver BC; Canada.
[ah] Also at Università di Napoli Parthenope, Napoli; Italy.
[ai] Also at University of Colorado Boulder, Department of Physics, Colorado; United States of America.
[aj] Also at Washington College, Chestertown, MD; United States of America.
[ak] Also at Yeditepe University, Physics Department, Istanbul; Türkiye.
[*] Deceased.