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ABSTRACT

A search for the $Z\gamma$ decay of the Higgs boson, with Z boson decays into pairs of electrons or muons is presented. The analysis uses proton–proton collision data at $\sqrt{s}$ = 13 TeV corresponding to an integrated luminosity of 139 fb^{-1} recorded by the ATLAS detector at the Large Hadron Collider. The observed data are consistent with the expected background with a p-value of 1.3%. An upper limit at 95% confidence level on the production cross-section times the branching ratio for $pp \to H \to Z\gamma$ is set at 3.6 times the Standard Model prediction while 2.6 times is expected in the presence of the Standard Model Higgs boson. The best-fit value for the signal yield normalised to the Standard Model prediction is $2.0^{+1.0}_{-0.9}$ where the statistical component of the uncertainty is dominant.

1. Introduction

A new boson [1,2] was discovered in 2012 by the ATLAS and CMS Collaborations. The observed properties of the particle, such as its couplings to Standard Model (SM) elementary particles, its spin and its parity, are so far consistent with the predictions for a SM Higgs boson (H) [3–7]. The mass of this boson was determined by the ATLAS and CMS Collaborations to be $m_H = 125.09 \pm 0.21(\text{stat}) \pm 0.11(\text{syst})$ GeV using the LHC Run 1 data set [8]. Subsequent measurements, by both collaborations during the LHC Run 2, are published [9–11] and are consistent with this value.

The SM Higgs boson can decay into $Z\gamma$ through loop diagrams and the branching ratio is predicted to be $B(H \to Z\gamma) = (1.54 \pm 0.09) \times 10^{-3}$ at $m_H = 125.09$ GeV [12]. It can differ from the SM value for several scenarios beyond the SM, for example, if the Higgs boson were a neutral scalar of different origin [13,14], or a composite state [15]. Different branching ratios are also expected for models with additional colourless charged scalars, leptons or vector bosons that couple to the Higgs boson, due to their contributions via loop corrections [16–18].

Final states where the Z boson decays into electron or muon pairs can be efficiently triggered and clearly distinguished from background events produced in pp collisions. In addition, the $Z(\to \ell\ell)\gamma$ ($\ell = e$ or μ) final state can be reconstructed completely with good invariant mass resolution and relatively small backgrounds.

Previous searches for the $H \to Z(\to \ell\ell)\gamma$ decay by the ATLAS and CMS Collaborations use the full pp data sets collected at $\sqrt{s} = 7$ and 8 TeV [19,20] and partial data sets collected at 13 TeV [21,22]. In all cases, no significant excess of events above the expected background is observed around the Higgs boson mass. Prior to the present study, the ATLAS Collaboration reported an observed (expected assuming the presence of a SM Higgs boson signal) upper limit on the production cross-section times branching ratio for $pp \to H \to Z\gamma$ of 6.6 (5.2) times the SM prediction at 95% confidence level for a Higgs boson with $m_H = 125.09$ GeV using a sample corresponding to an integrated luminosity of 36.1 fb^{-1} [21]. The CMS Collaboration reported an observed (expected assuming the presence of a SM Higgs boson signal) upper limit of 7.4 (6.0) times the SM prediction for a Higgs boson with $m_H = 125$ GeV using a sample corresponding to an integrated luminosity of 35.9 fb^{-1} [22].

An updated search for decays of the Higgs boson into $Z\gamma$ with the Z boson decaying into electron or muon pairs is detailed in this letter. The search uses pp collision data recorded at $\sqrt{s} = 13$ TeV with the ATLAS detector at the LHC from 2015 to 2018, corresponding to a total integrated luminosity of 139 fb^{-1}. There are important improvements in this analysis compared with the previous one [21], including an increase in the size of the data set, an improved event categorisation, and optimised lepton and photon identification criteria. Events with at least one photon and two electrons or muons of opposite charge are classified into six mutually exclusive categories which are designed to enhance the sensitivity to the presence of the SM Higgs boson decaying into $Z\gamma$. The dominant background is the irreducible non-resonant production of Z bosons together with photons. A simultaneous fit to the reconstructed $Z\gamma$ invariant mass distributions in all the categories is performed to extract the overall $H \to Z\gamma$ signal yield.

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Table 1
Higgs boson MC samples produced with Powheg-Box v2 with the techniques used to generate the event and their precision in α_s for the event generation (gen.). The version of Pythia 8 and the PDF set used for modelling the Higgs bosons decay, parton shower, hadronisation and the underlying event are listed. The precision of the total cross-section used in the sample normalisation is also reported. The cross-section of the $q\bar{q} \to ZH$ sample is normalised to take into account contributions from both $q\bar{q} \to ZH$ and $gg \to ZH$.

Process	Technique	Pythia 8 version & tune	PDF set	QCD (gen.)	Normalisation
ggF	NNLOPS [90,91] & MiNLO [92–98]	8.186, AZNLO [87]	NNPDF30 [75,76]	NNLO	NNNLO (QCD), NLO (EW) [33–44]
VBF	Powheg [67–71]	8.186, AZNLO	NNPDF30	NLO	NNLO (QCD), NLO (EW) [45–47]
$q\bar{q} \to VH$	MiNLO [98–100]	8.186, AZNLO	NNPDF30	NLO	NNLO (QCD), NLO (EW) [48–55]
$t\bar{t}H$	Powheg	8.230, A14 [86]	NNPDF23 [29]	NLO	NNLO (QCD), NLO (EW) [56–59]

2. ATLAS detector and data sample

The ATLAS detector [23,24] 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 (ID) surrounded by a thin superconducting solenoid, electromagnetic (EM) and hadronic calorimeters, and a muon spectrometer (MS) incorporating three large air-core toroidal magnets with eight coils each.

A two-level trigger system [25] was used during the $\sqrt{s} =$ 13 TeV data-taking period. The first-level trigger (L1) is implemented in hardware and uses a subset of the detector information. This is followed by a software-based high-level trigger which runs algorithms similar to those in the offline reconstruction software, reducing the event rate to approximately 1 kHz from the maximum L1 rate of 100 kHz.

The events were collected with triggers requiring either one or two electrons or muons in the event. Due to the increasing luminosity, the transverse momentum (p_{T}) thresholds were increased slightly during the data-taking periods. At the highest instantaneous luminosity recorded, the lowest p_{T} threshold for the single-muon trigger was 26 GeV. For the dimuon trigger, asymmetric p_{T} thresholds of 22 GeV and 8 GeV were used. The p_{T} threshold was 26 GeV for the single-electron trigger and 17 GeV for both electrons in the dielectron trigger. These lowest-threshold triggers were complemented by triggers with higher thresholds but looser lepton identification criteria. For $H \to Z\gamma$ events that pass the full analysis selection, described in Section 4, the trigger selection is 95.6% efficient for the $ee\gamma$ final state and 92.2% efficient for the $\mu\mu\gamma$ final state. The trigger efficiency has been measured to an accuracy better than 2%. After applying trigger and data quality requirements, the integrated luminosity of the data used in this search corresponds to 139 ± 2.4 fb^{-1}. The average number of pp interactions per bunch crossing (pile-up) ranged from about 13 in 2015 to about 39 in 2018, with a peak instantaneous luminosity of 2×10^{34} cm^{-2} s^{-1}.

3. Simulation samples

Simulated Monte Carlo (MC) events of the signal and dominant backgrounds are used to optimise the search strategy. The generated MC events, unless stated otherwise, were processed with the detailed ATLAS detector simulation [26] based on Geant4 [27]. The effects of pile-up were modelled by overlaying simulated inelastic pp events over the original hard-scattering event. The pile-up events were generated with Pythia 8.186 [28] using the NNPDF2.3LO set of parton distribution functions (PDFs) [29] and the A3 parameter tune [30]. The MC events were weighted to reproduce the distribution of the number of interactions per bunch crossing observed in the data.

In order to improve the description of the data, simulated events were corrected to ensure that the efficiencies for the reconstruction and identification of objects match those measured in data. The corrections include those applied to trigger, reconstruction, identification and isolation efficiencies for electrons and muons, identification and selection efficiencies for photons, and selection efficiency for jets [31,32]. Similarly, momentum and energy scale and resolution corrections for simulated objects were also taken into account.

The mass of the Higgs boson for all simulated samples was chosen to be $m_H = 125$ GeV and the corresponding width is $\Gamma_H = 4.1$ MeV [12]. The samples were normalised with the latest available theoretical calculations of the corresponding SM production cross-sections at $m_H = 125.09$ GeV via gluon–gluon fusion (ggF) [12,33–44], via vector-boson fusion (VBF) [12,45–47], in association with a vector boson (VH, where V is a W or a Z boson) [12,48–55] and with a top-quark pair ($t\bar{t}H$) [12,56–59]. The branching ratio is calculated at leading order in QCD [12,60–63] and it has been shown that higher order QCD corrections have a small impact on the estimated coupling strength [64–66].

The production of the SM Higgs boson was modelled with the Powheg-Box v2 Monte Carlo event generator [67–71], as described in Ref. [72] and summarised in Table 1. Pythia 8 [28] was used to simulate the $H \to Z\gamma$ decay as well as to provide parton showering, hadronisation and the underlying event. Other Higgs boson production processes are not considered as their contributions to the total Higgs boson production cross-section are of the order of 0.1% or less. All four production modes of the Higgs boson considered contribute to the signal in this analysis and their relative yields were fixed to the SM predictions. Contributions from $H \to \mu\mu$ (where the reconstructed photon originates from QED final-state radiation) were evaluated using samples produced in the same manner and are considered as a potential background in this analysis. The impact of interference between Higgs bosons decays with the same final-state signature ($H \to \gamma^*\gamma$, $\gamma^* \to e^+e^-/\mu^+\mu^-$ and $H \to \mu\mu$) is expected to be negligible in the Standard Model [73] and is neglected.

Additional samples of Higgs bosons produced by gluon–gluon fusion are used for studies of theoretical uncertainties. A sample with multiple parton interactions disabled is used to study the uncertainties in the signal acceptance related to the modelling of non-perturbative quantum chromodynamics (QCD) effects. A sample generated with MadGraph5_aMC@NLO [74] using the NNPDF30 PDF [75,76] set, which includes up to two jets at next-to-leading-order (NLO) accuracy in QCD using the FxFx merging scheme [74,77], is used to study the ggF acceptance in the analysis categories.

The background in this analysis originates mainly from non-resonant production of a Z boson and a photon ($Z\gamma$), with a

[1] The ATLAS experiment uses a right-handed coordinate system with its origin at the nominal interaction point (IP) in the centre of the detector and the z-axis along the beam pipe. The x-axis points from the IP to the centre of the LHC ring, and the y-axis points upward. Polar coordinates (r, ϕ) are used in the transverse plane. The polar angle (θ) is measured from the positive z-axis and the azimuthal angle (ϕ) is measured from the positive x-axis in the transverse plane. The pseudorapidity is defined in as $\eta = -\ln\tan(\theta/2)$. Angular distance is measured in units of $\Delta R = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2}$.

smaller contribution from the production of Z bosons in association with jets ($Z +$ jets), with one jet misidentified as a photon.

A large sample of background $Z\gamma$ events was simulated with the Sherpa v2.2.2 [78] generator using a fast simulation of the calorimeter response [79]. It was produced at NLO precision in QCD for up to one additional parton and leading-order (LO) accuracy in QCD for up to three additional partons using the NNPDF3.0nnlo PDF set [76]. The matrix elements were matched and merged with the Sherpa parton shower [80,81] using the MEPS@LO prescription [82–85].

The electroweak production of $Z\gamma jj$ with jets originating from the fragmentation of partons arising from electroweak vertices is also considered. It was generated at LO accuracy in QCD using MadGraph5_aMC@NLO 2.3.3 with no additional partons in the final state, which is orthogonal to the $Z\gamma$ simulation with Sherpa. The NNPDF30 LO PDF set [76] was used for the generation of the events, and the hadronisation, parton shower and the underlying event of the events was modelled using Pythia 8.212 with the A14 parameter tune [86].

The background originating from $Z +$ jets is estimated using a data-driven technique which is validated using a sample simulated with the Powheg-Box v1 MC generator [68–70] at NLO accuracy in QCD. It was interfaced to Pythia 8.186 for the modelling of the parton shower, hadronisation and the underlying event with parameters set according to the AZNLO tune [87]. The CT10 PDF set [88] was used for the hard-scattering processes, whereas the CTEQ6L1 PDF set [89] was used for the parton shower.

4. Event selection, reconstruction and categorisation

Events are required to have at least one photon candidate and at least two same-flavour opposite-charge leptons, ($\ell = e, \mu$), associated with a primary vertex candidate. This primary vertex candidate is reconstructed from charged particles (tracks) in the ID with transverse momentum $p_{\mathrm{T}} > 500$ MeV, and is defined to be the one with the largest sum of the squared transverse momenta of the associated tracks.

Muon candidates are required to have a high-quality track in the ID or the MS, satisfy the *medium* identification criteria, be within $|\eta| < 2.7$ and have $p_{\mathrm{T}} > 10$ GeV [32]. Electron and photon candidates are reconstructed from topological clusters of energy deposits in the EM calorimeter, and in the case of an electron, a track in the ID matched to the cluster [31,101]. Electron and photon candidates in the transition region between the barrel and endcap EM calorimeters, $1.37 < |\eta| < 1.52$, are excluded. Electrons are required to satisfy *loose* likelihood-based identification criteria [31], have $p_{\mathrm{T}} > 10$ GeV and be within $|\eta| < 2.47$, while photon candidates are required to satisfy $p_{\mathrm{T}} > 10$ GeV, $|\eta| < 2.37$ and the *tight* identification criteria. Compared with the previous ATLAS publication [21] the electron identification criteria is looser, improving signal acceptance, and the photon identification has been updated to improve efficiency in the transverse momentum range 10 GeV − 35 GeV. The lepton and photon candidates are also required to be isolated from additional activity in the tracking detector and in the calorimeters. Contributions to the energy deposited in the calorimeters originating from the underlying events and pile-up are corrected for on an event-by-event basis using the method described in Refs. [102–104].

In order to ensure that muon and electron candidates originate from the primary vertex, it is required that the longitudinal impact parameter, Δz_0, computed relative to the primary vertex position, satisfies $|\Delta z_0 \cdot \sin\theta| < 0.5$ mm, where θ is the polar angle of the track. Additionally, to suppress leptons from heavy-flavour decays the significance of the transverse impact parameter d_0 calculated relative 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 obtained from the track fit.

Jets are reconstructed from topological clusters [105] using the anti-k_t algorithm [106] with a radius parameter of 0.4. They are required to have $p_{\mathrm{T}} > 25$ GeV and $|\eta| < 4.4$. Jets produced in pile-up interactions are suppressed by requiring that those with $p_{\mathrm{T}} < 60$ GeV and $|\eta| < 2.4$ pass a selection based on a jet vertex tagging algorithm [107], which is 92% efficient for jets originating from the hard interaction.

An overlap removal procedure is applied to the selected lepton, photon and jet candidates. If two electrons share the same track, or the separation between two electron energy clusters satisfies $|\Delta\eta| < 0.075$ and $|\Delta\phi| < 0.125$, then only the highest-p_{T} electron is retained. Electron candidates that fall within $\Delta R = 0.02$ of a selected muon candidate are also discarded. In order to suppress the events arising from QED final-state radiation (FSR), photon candidates within a $\Delta R = 0.3$ cone around the leptons of the Z boson candidate are rejected. Jet–lepton and jet–photon overlap removal are also performed by removing the jet if its axis is within a cone of size $\Delta R = 0.2$ around one of the leptons or the photon.

The Z boson candidates are reconstructed from two same-flavour opposite-charge leptons satisfying the selection criteria. The leptons of the Z boson candidate are additionally required to be consistent with being accepted by at least one of the triggers that the event passed. It is required that the p_{T} of the leptons that are associated with the single-lepton or dilepton triggers is 1 GeV above the trigger threshold. The invariant mass of the Z boson candidates is required to be between 50 GeV and 101 GeV before applying the mass resolution improvements described in the following.

The resolution of the invariant mass of the $Z \to \mu\mu$ candidates is improved by 3% by correcting the muon momenta for collinear FSR ($\Delta R < 0.15$), using all photons identified in the EM calorimeter [72]. A constrained kinematic fit is applied to the dilepton invariant mass [108] for all Z boson candidates. This fit uses a line shape modelled by a Breit-Wigner distribution using the world average values for Z bosons mass and width [109] and a single Gaussian to model the lepton momentum response. It improves the mass resolution by 14% for the Higgs boson candidates with electrons in the final state and by 10% for final states with muons when combined with the FSR correction.

After the FSR correction and applying the kinematic fit, Z boson candidates are required to have an invariant mass within 10 GeV of the Z boson mass, $m_Z = 91.2$ GeV. If an event has multiple Z boson candidates which pass all requirements, the candidate with the mass closest to the Z boson mass is chosen. Fewer than 1% of the simulated signal events that pass the final $H \to Z\gamma$ selection have more than two leptons (dominated by events produced via VH and $t\bar{t}H$) and less than 0.1% of the signal events have a Z boson candidate that does not match a true Z boson.

The Higgs boson candidate is reconstructed from the Z boson candidate and the highest-p_{T} photon candidate in the event. The invariant mass of the final-state particles, $m_{Z\gamma}$ after correction for FSR and by the kinematic fit, is required to satisfy $105 \text{ GeV} < m_{Z\gamma} < 160$ GeV. Finally, to reduce background contamination and simplify the background modelling, an additional requirement is placed on the transverse momentum of the photon such that $p_{\mathrm{T}}^{\gamma}/m_{Z\gamma} > 0.12$.

For SM $H \to Z(\to \ell\ell)\gamma$ events, the reconstruction and selection efficiency (including kinematic acceptance) is 20.4% varying by a maximum of 2% depending on the production mode.

In order to improve the sensitivity to a $H \to Z\gamma$ signal, the selected events are classified into six mutually exclusive categories with different expected signal-to-background ratios and mass resolutions. Categories are defined according to the lepton flavour and event kinematics. Additionally, a boosted decision tree (BDT)

Table 2
The number of data events selected in each category and in the $Z\gamma$ mass range of 105–160 GeV. In addition, the following numbers are given: the expected number of Higgs boson signal events in an interval around the peak position for a signal of $m_H = 125.09$ GeV containing 68% of the SM signal (S_{68}), the mass resolution quantified by the width of the S_{68} interval (w_{68}) defined by the difference between the 84th and the 16th percentile of the signal mass distribution, the background in the S_{68} interval (B_{68}) is estimated from fits to the data using the background models described in Section 5, the observed number of events in the S_{68} interval (N_{68}), the expected signal-to-background ratio in the S_{68} window (S_{68}/B_{68}), and the expected significance estimate defined as $S_{68}/\sqrt{S_{68}+B_{68}}$. The final row of the table displays the expected number of events for an analysis performed in a single inclusive category calculated by summing the number of events in each individual category.

Category	Events	S_{68}	B_{68}	N_{68}	w_{68} [GeV]	S_{68}/B_{68} $[10^{-2}]$	$S_{68}/\sqrt{S_{68}+B_{68}}$
VBF-enriched	194	2.7	16.7	17	3.7	16.2	0.60
High relative p_T	2276	7.6	108.5	118	3.7	7.0	0.70
High p_{Tt} ee	5567	9.9	474.7	498	3.8	2.1	0.45
Low p_{Tt} ee	76 679	34.5	6418.6	6505	4.1	0.5	0.43
High p_{Tt} $\mu\mu$	6979	12.0	634.4	632	3.9	1.9	0.47
Low p_{Tt} $\mu\mu$	100 876	43.5	8506.9	8491	4.0	0.5	0.47
Inclusive	192 571	110.2	16159.8	16261	4.0	0.7	0.86

trained to separate VBF signal events from other Higgs boson production modes and backgrounds is used to define a category of events with at least two jets. If there are more than two jets in an event, the two highest-p_T jets are used. The kinematic variables used in the categorisation and as input to the BDT, which have been extended with respect to the Ref. [21], are:

- The p_T of the highest-p_T jet, p_T^{j1}.
- The pseudorapidity difference between the two jets, $\Delta\eta_{jj}$.
- The minimum ΔR between the Z boson or photon candidate and either of the two jets, $\Delta R^{\text{min}}_{\gamma \text{ or } Z,j}$.
- The invariant mass of the two jets, m_{jj}.
- The absolute value of the difference between the pseudorapidity of the $Z\gamma$ system and the average pseudorapidity of the two jets, $\left(|\eta_{Z\gamma} - (\eta_{j1}+\eta_{j2})/2|\right)$ [110].
- The azimuthal separation between the $Z\gamma$ system and the system formed by the two jets, $\Delta\Phi_{Z\gamma,jj}$.
- The azimuthal angle between the dilepton system and the photon, $\Delta\Phi_{Z,\gamma}$.
- The component, p_{Tt}, of the transverse momentum of the $Z\gamma$ system, that is perpendicular to the difference of the 3-momenta of the Z boson and the photon candidate ($p_{Tt} = |\vec{p}_T^{Z\gamma} \times \hat{t}|$, where $\hat{t} = (\vec{p}_T^{Z} - \vec{p}_T^{\gamma})/|\vec{p}_T^{Z} - \vec{p}_T^{\gamma}|$). This quantity is strongly correlated with the transverse momentum of the $Z\gamma$ system, but has better experimental resolution [111,112].

Events with two or more jets with $\Delta\eta_{jj} > 2$ that have a BDT output score larger than 0.87 are classified into a *VBF-enriched* category. Of the remaining events, those that satisfy the requirement on $p_T^{\gamma}/m_{Z\gamma} > 0.4$ are classified into a *High relative* p_T category while the others are separated into four categories depending on the lepton flavour and a cut at $p_{Tt} = 40$ GeV. The boundaries of the categories are selected to maximise the expected signal significance.

VBF events are estimated to constitute 72% of the signal in the *VBF-enriched category*. The *High relative* p_T and *High* p_{Tt} categories are expected to be enriched in VBF, *VH* and $t\bar{t}H$ events as these production modes have on average higher Higgs boson p_T than ggF production. Because the continuum $Z\gamma$ background has on average lower Higgs boson candidate p_T than the signal, the signal-to-background ratio is expected to be higher in these categories than in the other categories, as shown in Table 2. The table also summarises the observed number of events in data in the $Z\gamma$ mass range of 105-160 GeV and the expected number of signal (S_{68}) and background (B_{68}) events in a $m_{Z\gamma}$ window containing 68% of the expected signal. In addition the width of the window containing 68% of the SM signal (w_{68}), which quantifies the mass resolution and is defined as the difference between the 84th and the 16th percentile of the signal mass distribution, is reported. B_{68} is estimated from fits to the data using the background models described in Section 5. The categorisation improves the expected sensitivity, which is defined as $S_{68}/\sqrt{S_{68}+B_{68}}$, by approximately 50%.

5. Signal and background modelling

The signal and background yields are extracted from a fit to the $m_{Z\gamma}$ distribution observed in data by assuming parametric models for both the signal and backgrounds. For the signal, the expected acceptance and parameters that describe the shape are obtained from simulated signal samples in the same manner as Ref. [21]. For the background, the models are chosen using simulated background samples and the values of their parameters are determined by a fit to the mass spectra measured in data.

The signal mass distribution for the Higgs boson decay into $Z\gamma$ is well modelled by a double-sided Crystal Ball (DSCB) function (a Gaussian function with power-law tails on both sides) [113,114]. The peak position and width of the Gaussian component are represented by μ_{CB} and σ_{CB}, respectively. The parameters of the DSCB are determined in each category by performing a maximum-likelihood fit to the signal MC samples.

The parametric model used to describe the background $m_{Z\gamma}$ distribution is selected using a template that is constructed from the simulated $Z\gamma$ and electroweak $Z\gamma jj$ events, and a $Z+$jets contribution derived from data. The simulated $Z\gamma$ events use a fast simulation of the calorimeter response which has been confirmed to produce a $m_{Z\gamma}$ distribution compatible, in each category, with $Z\gamma$ events simulated with the detailed simulation. The shape of the $m_{Z\gamma}$ distribution for $Z+$jets events is constructed for each category from a data control region defined by requiring the photon candidate to not satisfy the tight identification criteria but still pass a looser identification criteria. To smooth the statistical fluctuations of the $m_{Z\gamma}$ distribution for $Z+$jets events, an analytic function is fitted to the ratio of the $m_{Z\gamma}$ distributions for $Z+$jets and $Z\gamma$ events, in the $m_{Z\gamma}$ range of 105–160 GeV. The smoothed $m_{Z\gamma}$ distribution for $Z+$jets events is constructed by multiplying the $Z\gamma$ distribution by the fitted ratio. The $Z+$jets and $Z\gamma$ distributions have similar shapes, allowing a parametric function to be used to fit the ratio.[2] The uncertainty in the fitted ratio is found to have negligible impact on the background template.

The background composition in each category is determined using data and confirms the dominance of the $Z\gamma$ process over other backgrounds where jets are misidentified as photons. A two-dimensional sideband technique [21,115] based on the track and calorimeter isolation of the photon candidate and whether the

[2] The functional form used is $(1-x^{1/3})^{f_0} x^{p_0+p_1 \log(x)}$ where $x = m_{Z\gamma}/\sqrt{s}$ ($\sqrt{s}$ = 13 TeV) where f_i and p_i are the free parameters of the model.

Table 3
The selected background function and fit range in each analysis category.

Category	Function Type	Fit range [GeV]
VBF-enriched	Second-order power function	110–155
High relative p_{T}	Second-order exponential polynomial	105–155
ee high p_{Tt}	Second-order Bernstein polynomial	115–145
ee low p_{Tt}	Second-order exponential polynomial	115–160
$\mu\mu$ high p_{Tt}	Third-order Bernstein polynomial	115–160
$\mu\mu$ low p_{Tt}	Third-order Bernstein polynomial	115–160

photon candidate satisfies the tight or the looser identification criteria is performed in each category. The fraction of $Z\gamma$ events with genuine photons (including the $Z\gamma jj$ contribution), inclusive over categories, is $0.78^{+0.04}_{-0.09}$.

To construct the final background template for each category, the normalisation of the electroweak $Z\gamma jj$ events is based on the predicted cross-section while the combined $Z\gamma$ and $Z+$jets distribution is normalised to the number of data events in that category after subtracting the expected number of electroweak $Z\gamma jj$ events. The background template is treated as a representative Asimov dataset [116] when choosing the functional form used to model it.

The functional form used to model the background is selected from the following families of functions: Bernstein polynomials, exponential polynomial functions ($\mathrm{e}^{(\Sigma_{i=0}^{N} p_i m_{Z\gamma}^{i})}$), a sum of power functions ($\Sigma_{i=1}^{N} f_i m_{Z\gamma}^{p_i}$), and a class of functions given by $(1-x^{1/3})^f x^{\Sigma_{i=0}^{N} p_i \log(x)^i}$ where $x = m_{Z\gamma}/\sqrt{s}$ ($\sqrt{s} = 13$ TeV) where f_i and p_i are the free parameters of the models. The choice of analytical model of the background and the $m_{Z\gamma}$ range used for the final fit is optimised in each category using the background template mentioned earlier. The optimisation procedure, which has been updated when compared to Ref. [21], includes a limit on the amount of bias in the extracted signal yield (also referred to as spurious signal) and a requirement on the fit quality, and it prefers models with fewer free parameters to maximise the statistical sensitivity to the expected signal. For each category used in the analysis, the bias due to the spurious signal is estimated by performing a signal-plus-background fit to the $m_{Z\gamma}$ background-only distribution estimated as explained above, with m_H varied between 123 GeV and 127 GeV. The maximum number of signal events derived from these fits in each category constitutes the spurious-signal systematic uncertainty. A requirement that the spurious signal be less than 50% of the expected statistical uncertainty in the signal yield is applied when selecting the background modelling function. Stricter requirements on the spurious signal are not possible due to the statistical uncertainty in the $m_{Z\gamma}$ background template. In addition, the χ^2 probability of the background-only fit is required to be larger than 1%. The fit range is optimised in each analysis category by varying the lower and upper bounds in 5 GeV steps within the ranges 105–115 GeV and 140–160 GeV, respectively. The optimal fit range and function are selected to achieve the highest signal significance while fitting the expected mass distribution of background plus SM signal. The significance evaluation also includes the spurious-signal systematic uncertainty. The selected background functional form and fit range in each category are detailed in Table 3.

6. Systematic uncertainties

The dominant experimental uncertainty in the signal yield is the spurious signal from the choice of background model. The spurious signal corresponds to as much as 50% of the statistical error in the expected signal yield per category, due to a limited number of simulated background events. It introduces a 28% systematic uncertainty in the signal strength, defined as the ratio of the observed to expected signal yield; however, it only increases the total uncertainty in the expected signal strength by 5.6% because of the large statistical uncertainty. The contribution from $H \to \mu\mu$ is estimated using simulated events and amounts to about 1.7% inclusively, and up to 3.3% in individual categories. An uncertainty in this contribution taken from the latest ATLAS measurement [117] results in an uncertainty of 2.1% in the expected signal yield. The combined uncertainty in the signal yield in any category due to the reconstruction, identification, isolation, and trigger efficiency measurements [31,32] is no more than 2.6%, 2.4% and 1.6% for photons, electrons and muons, respectively. Pile-up also affects the lepton and photon identification efficiency but contributes a negligible amount to the uncertainty (0.2%). The uncertainty in the combined 2015–2018 integrated luminosity is 1.7% [118,119].

The theoretical uncertainties in the predicted signal yield originate from uncertainties in the predicted branching ratio (5.7%) [12] as well as from uncertainties in the modelling of the production cross-section and kinematics of the Higgs boson due to missing higher-order QCD calculations (5.3%), that are dominated by uncertainties in the QCD renormalisation and factorisation scales (5.2%). Smaller effects originate from the parton shower modelling uncertainty (1.3%), PDFs (2.5%) and α_{s} (1.9%). The uncertainties in the Higgs boson event kinematics due to missing higher-order QCD calculations impact the distribution of signal events amongst the analysis categories. They are evaluated using an extension of the Stewart–Tackmann method [12,120], based on inputs from Refs. [121–123]. Details of how the uncertainty in the acceptance of ggF events in the VBF-enriched category and all other categories is evaluated can be found in Refs. [124] and [21], respectively. Additionally, to account for the uncertainties in the modelling of jet kinematics in ggF events the category acceptance is compared with the acceptance derived from the MadGraph5_aMC@NLO sample. The Higgs boson and jet kinematics particularly affect the ggF signal acceptance in the VBF-enriched category (37%) and High relative p_{T} category (21%). The effect of parton shower modelling, PDFs and α_{s} on the distribution of signal events amongst the analysis categories is less than 11%, 1% and 2%, respectively. The expected signal yield in the VBF category is also affected (14%) by the jet energy scale, jet energy resolution and vertex tagging efficiency [125].

The uncertainty in the modelling of the signal shape varies between analysis channels. The uncertainty in the mass resolution (σ_{CB}) is dominated by the uncertainty in the electron and photon energy resolution ($< 3.4\%$) and in the muon momentum resolution ($< 3.6\%$). The uncertainty in the signal position (μ_{CB}) from the uncertainty in electron, photon and muon calibration ($< 0.15\%$) is less than the uncertainty in the assumed Higgs boson mass of 0.19% [8]. The impact of the signal model uncertainty on the signal strength is less than 2%.

7. Results

A profile-likelihood-ratio test statistic [116] is used to search for a localised excess of events above the expected background by performing a fit to the $m_{Z\gamma}$ spectra in the various categories. In the same manner as was done in previous searches for $H \to Z\gamma$ [21], the likelihood is built from the product of Poisson probability terms across all categories with two contributions: non-resonant background, and Higgs boson signal. The likelihood includes terms for the systematic uncertainties discussed in Section 6 implemented as nuisance parameters. The nuisance parameters describe the systematic uncertainties, which are parameterised as Gaussian or log-normal priors and are correlated across analysis categories where appropriate. Upper limits are set on the Higgs boson production cross-section at 95% confidence level (CL) using the modified frequentist formalism [126]. The results are derived using closed-form asymptotic formulae [116].

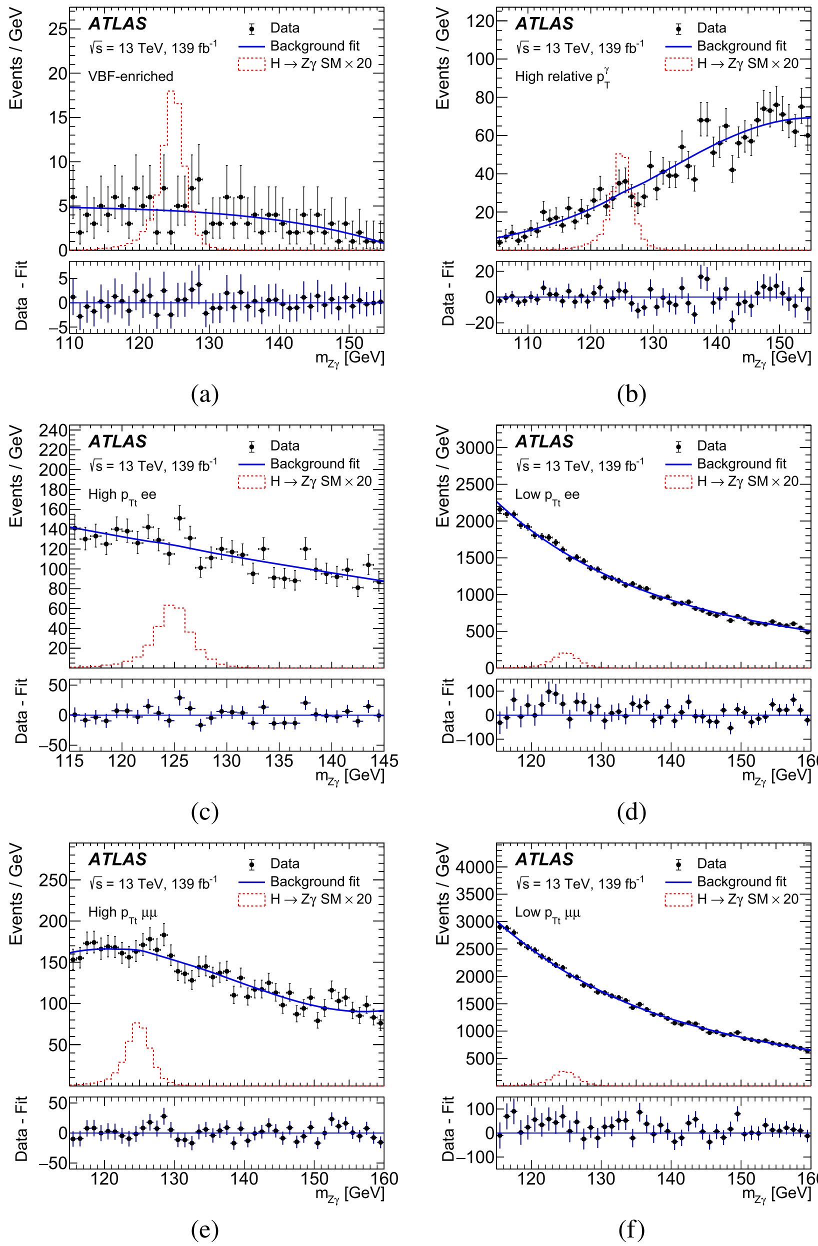

Fig. 1. The $Z\gamma$ invariant mass ($m_{Z\gamma}$) distributions of events satisfying the $H \to Z\gamma$ selection in data for the six event categories: (a) VBF-enriched, (b) High relative p_T^γ, (c) High p_{Tt} ee, (d) Low p_{Tt} ee, (e) High p_{Tt} $\mu\mu$, and (f) Low p_{Tt} $\mu\mu$. The black points represent data. The error bars represent only the statistical uncertainty of the data. The solid blue lines show the background-only fits to the data, performed independently in each category. The dashed red histogram corresponds to the expected signal for a SM Higgs boson with $m_H = 125$ GeV decaying into $Z\gamma$ multiplied by a factor of 20. The bottom part of the figures shows the residuals of the data with respect to the background-only fit.

The invariant mass distributions of the $Z\gamma$ events for the various categories are shown in Fig. 1 with the background-only fit superimposed. The expected Higgs boson signal normalised to 20 times the SM prediction for $m_H = 125$ GeV is also shown. At $m_H = 125.09$ GeV, the observed (expected with a SM Higgs boson) p-value under the background hypothesis is 1.3% (12.3%), which corresponds to a significance of 2.2σ (1.2σ). A weighted sum of all categories with the fitted signal-plus-background model superimposed is shown in Fig. 2. The events are weighted by $\ln(1 + S_{68}/B_{68})$, where S_{68} and B_{68} are defined in Section 4.

The best-fit value for the $H \to Z\gamma$ signal strength, defined as the ratio of the observed to the predicted SM signal yield, is found to be $2.0 \pm 0.9(\text{stat.})^{+0.4}_{-0.3}(\text{syst.}) = 2.0^{+1.0}_{-0.9}(\text{tot.})$ with an expected value of $1.0 \pm 0.8(\text{stat.}) \pm 0.3(\text{syst.})$ assuming the presence of the SM Higgs boson. The measured signal strength amongst all categories are compatible within their total uncertainties. The largest measured signal strength is $4.7^{+3.0}_{-2.7}(\text{tot.})$ in the High p_{Tt} ee category. The total uncertainty is dominated by the statistical component from the data. The systematic component of the total uncertainty is dominated by the spurious-signal uncertainties.

The observed 95% CL limit on the $H \to Z\gamma$ signal strength is found to be 3.6 times the SM prediction compared with an expected value of 1.7 (2.6) assuming no (SM) Higgs boson decays into $Z\gamma$. The observed upper limit on $\sigma(pp \to H) \cdot B(H \to Z\gamma)$ is 305 fb at 95% CL. Assuming the SM Higgs boson production cross-section, the upper limit at 95% CL on $B(H \to Z\gamma)$ is found to be 0.55%.

This result represents an improvement of about a factor of 2.4 in expected sensitivity compared with the previous ATLAS publication [21]. Of this improvement, a factor of approximately two is

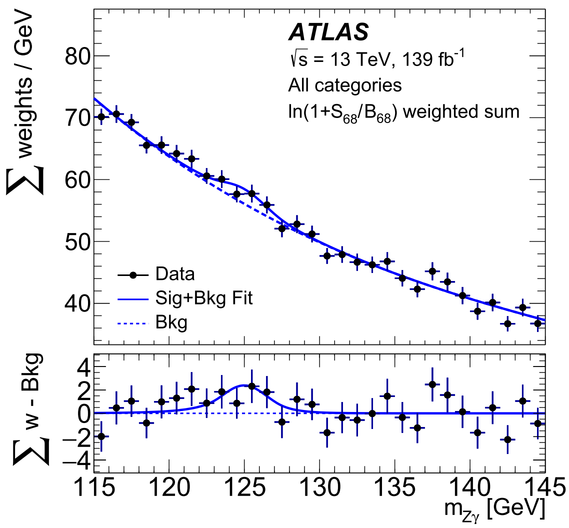

Fig. 2. Weighted $Z\gamma$ invariant mass ($m_{Z\gamma}$) distribution of events satisfying the $H \to Z\gamma$ selection in data. The black points represent data. The error bars represent only the statistical uncertainty of the data. Events are weighted by $\ln(1 + S_{68}/B_{68})$, where S_{68} and B_{68} are the expected signal and background events in a $m_{Z\gamma}$ window containing 68% of the expected signal. The solid blue curve shows the combined fitted signal-plus-background model when fitting all analysis categories simultaneously, the dashed line shows the model of the background component.

due to the larger analysed dataset and the additional 20% improvement can be attributed to the improvements in the analysis.

8. Conclusion

A search for $Z\gamma$ decays of the SM Higgs boson in 139 fb^{-1} of pp collisions at $\sqrt{s} = 13$ TeV is performed with the ATLAS experiment at the LHC. The observed data are consistent with the expected background with a p-value of 1.3%, while the expected p-value in the presence of a SM Higgs boson is 12.3%. These p-values correspond to a significance of 2.2 and 1.2 standard deviations, respectively. The observed 95% CL upper limit on the $\sigma(pp \to H) \cdot B(H \to Z\gamma)$ is 3.6 times the SM prediction for a Higgs boson mass of 125.09 GeV. The expected limit on $\sigma(pp \to H) \cdot B(H \to Z\gamma)$ assuming either no Higgs boson decay into $Z\gamma$ or the presence of the SM Higgs boson decay is 1.7 and 2.6 times the SM prediction, respectively. The best-fit value for the signal yield normalised to the SM prediction is $2.0^{+1.0}_{-0.9}$ where the statistical component of the uncertainty is dominant.

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.

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The ATLAS Collaboration

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Clement [45a,45b], Y. Coadou [102], M. Cobal [67a,67c], A. Coccaro [55b], J. Cochran [79], R. Coelho Lopes De Sa [103], H. Cohen [160], A.E.C. Coimbra [36], B. Cole [39], A.P. Colijn [120], J. Collot [58], P. Conde Muiño [139a,139h], S.H. Connell [33c], I.A. Connelly [57], S. Constantinescu [27b], F. Conventi [70a,am], A.M. Cooper-Sarkar [134], F. Cormier [174], K.J.R. Cormier [166], L.D. Corpe [95], M. Corradi [73a,73b], E.E. Corrigan [97], F. Corriveau [104,ab], M.J. Costa [173], F. Costanza [5], D. Costanzo [148], G. Cowan [94], J.W. Cowley [32], J. Crane [101], K. Cranmer [125], R.A. Creager [136], S. Crépé-Renaudin [58], F. Crescioli [135], M. Cristinziani [24], V. Croft [169], G. Crosetti [41b,41a], A. Cueto [5], T. Cuhadar Donszelmann [170], H. Cui [15a,15d], A.R. Cukierman [152], W.R. Cunningham [57], S. Czekierda [85], P. Czodrowski [36], M.M. Czurylo [61b], M.J. Da Cunha Sargedas De Sousa [60b], J.V. Da Fonseca Pinto [81b], C. Da Via [101], W. Dabrowski [84a], F. Dachs [36], T. Dado [47], S. Dahbi [33e], T. Dai [106], C. Dallapiccola [103], M. Dam [40], G. D'amen [29], V. D'Amico [75a,75b], J. Damp [100], J.R. Dandoy [136], M.F. Daneri [30], M. Danninger [151], V. Dao [36], G. Darbo [55b], O. Dartsi [5], A. Dattagupta [131], T. Daubney [46], S. D'Auria [69a,69b], C. David [167b], T. Davidek [142], D.R. Davis [49], I. Dawson [148], K. De [8], R. De Asmundis [70a], M. De Beurs [120], S. De Castro [23b,23a], N. De Groot [119], P. de Jong [120], H. De la Torre [107], A. De Maria [15c], D. De Pedis [73a], A. De Salvo [73a], U. De Sanctis [74a,74b], M. De Santis [74a,74b], A. De Santo [155], J.B. De Vivie De Regie [65], C. Debenedetti [145], D.V. Dedovich [80], A.M. Deiana [42], J. Del Peso [99], Y. Delabat Diaz [46], D. Delgove [65], F. Deliot [144], C.M. Delitzsch [7], M. Della Pietra [70a,70b], D. Della Volpe [54], A. Dell'Acqua [36], L. Dell'Asta [74a,74b], M. Delmastro [5], C. Delporte [65], P.A. Delsart [58], D.A. DeMarco [166], S. Demers [182], M. Demichev [80], G. Demontigny [110], S.P. Denisov [123], L. D'Eramo [121], D. Derendarz [85], J.E. Derkaoui [35d], F. Derue [135], P. Dervan [91], K. Desch [24], K. Dette [166], C. Deutsch [24], M.R. Devesa [30], P.O. Deviveiros [36], F.A. Di Bello [73a,73b], A. Di Ciaccio [74a,74b], L. Di Ciaccio [5], W.K. Di Clemente [136], C. Di Donato [70a,70b], A. Di Girolamo [36], G. Di Gregorio [72a,72b], B. Di Micco [75a,75b], R. Di Nardo [75a,75b], K.F. Di Petrillo [59], R. Di Sipio [166], C. Diaconu [102], F.A. Dias [120], T. Dias Do Vale [139a], M.A. Diaz [146a], F.G. Diaz Capriles [24], J. Dickinson [18], M. Didenko [165], E.B. Diehl [106], J. Dietrich [19], S. Díez Cornell [46], C. Diez Pardos [150], A. Dimitrievska [18], W. Ding [15b], J. Dingfelder [24], S.J. Dittmeier [61b], F. Dittus [36], F. Djama [102], T. Djobava [158b], J.I. Djuvsland [17], M.A.B. Do Vale [81c], M. Dobre [27b], D. Dodsworth [26], C. Doglioni [97], J. Dolejsi [142], Z. Dolezal [142], M. 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A. Dubreuil [54], E. Duchovni [179], G. Duckeck [114], O.A. Ducu [36], D. Duda [115], A. Dudarev [36], A.C. Dudder [100], E.M. Duffield [18], M. D'uffizi [101], L. Duflot [65], M. Dührssen [36], C. Dülsen [181], M. Dumancic [179], A.E. Dumitriu [27b], M. Dunford [61a], A. Duperrin [102], H. Duran Yildiz [4a], M. Düren [56], A. Durglishvili [158b], D. Duschinger [48], B. Dutta [46], D. Duvnjak [1], G.I. Dyckes [136], M. Dyndal [36], S. Dysch [101], B.S. Dziedzic [85], M.G. Eggleston [49], T. Eifert [8], G. Eigen [17], K. Einsweiler [18], T. Ekelof [171], H. El Jarrari [35e], V. Ellajosyula [171], M. Ellert [171], F. Ellinghaus [181], A.A. Elliot [93], N. Ellis [36], J. Elmsheuser [29], M. Elsing [36], D. Emeliyanov [143], A. Emerman [39], Y. Enari [162], M.B. Epland [49], J. Erdmann [47], A. Ereditato [20], P.A. Erland [85], M. Errenst [181], M. Escalier [65], C. Escobar [173], O. Estrada Pastor [173], E. Etzion [160], H. Evans [66], M.O. Evans [155], A. Ezhilov [137], F. 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Gorini [36], E. Gorini [68a,68b], A. Gorišek [92], A.T. Goshaw [49], M.I. Gostkin [80], C.A. Gottardo [119], M. Gouighri [35b], A.G. Goussiou [147], N. Govender [33c], C. Goy [5], I. Grabowska-Bold [84a], E.C. Graham [91], J. Gramling [170], E. Gramstad [133], S. Grancagnolo [19], M. Grandi [155], V. Gratchev [137], P.M. Gravila [27f], F.G. Gravili [68a,68b], C. Gray [57], H.M. Gray [18], C. Grefe [24], K. Gregersen [97], I.M. Gregor [46], P. Grenier [152], K. Grevtsov [46], C. Grieco [14], N.A. Grieser [128], A.A. Grillo [145], K. Grimm [31,k], S. Grinstein [14,w], J.-F. Grivaz [65], S. Groh [100], E. Gross [179], J. Grosse-Knetter [53], Z.J. Grout [95], C. Grud [106], A. Grummer [118], J.C. Grundy [134], L. Guan [106], W. Guan [180], C. Gubbels [174], J. Guenther [36], A. Guerguichon [65], J.G.R. Guerrero Rojas [173], F. Guescini [115], D. Guest [170], R. Gugel [100], A. Guida [46], T. Guillemin [5], S. Guindon [36], U. Gul [57], J. Guo [60c], W. Guo [106], Y. Guo [60a], Z. Guo [102], R. Gupta [46], S. Gurbuz [12c], G. Gustavino [128], M. Guth [52], P. Gutierrez [128], C. Gutschow [95], C. Guyot [144], C. Gwenlan [134], C.B. Gwilliam [91], E.S. Haaland [133], A. Haas [125], C. Haber [18], H.K. Hadavand [8], A. Hadef [60a], M. Haleem [176], J. Haley [129], J.J. Hall [148], G. Halladjian [107], G.D. Hallewell [102], K. Hamano [175],

H. Hamdaoui [35e], M. Hamer [24], G.N. Hamity [50], K. Han [60a,v], L. Han [60a], S. Han [18], Y.F. Han [166], K. Hanagaki [82,t], M. Hance [145], D.M. Handl [114], M.D. Hank [37], R. Hankache [135], E. Hansen [97], J.B. Hansen [40], J.D. Hansen [40], M.C. Hansen [24], P.H. Hansen [40], E.C. Hanson [101], K. Hara [168], T. Harenberg [181], S. Harkusha [108], P.F. Harrison [177], N.M. Hartman [152], N.M. Hartmann [114], Y. Hasegawa [149], A. Hasib [50], S. Hassani [144], S. Haug [20], R. Hauser [107], L.B. Havener [39], M. Havranek [141], C.M. Hawkes [21], R.J. Hawkings [36], S. Hayashida [117], D. Hayden [107], C. Hayes [106], R.L. Hayes [174], C.P. Hays [134], J.M. Hays [93], H.S. Hayward [91], S.J. Haywood [143], F. He [60a], Y. He [164], M.P. Heath [50], V. Hedberg [97], S. Heer [24], A.L. Heggelund [133], C. Heidegger [52], K.K. Heidegger [52], W.D. Heidorn [79], J. Heilman [34], S. Heim [46], T. Heim [18], B. Heinemann [46,aj], J.G. Heinlein [136], J.J. Heinrich [131], L. Heinrich [36], J. Hejbal [140], L. Helary [46], A. Held [125], S. Hellesund [133], C.M. Helling [145], S. Hellman [45a,45b], C. Helsens [36], R.C.W. Henderson [90], Y. Heng [180], L. Henkelmann [32], A.M. Henriques Correia [36], H. Herde [26], Y. Hernández Jiménez [33e], H. Herr [100], M.G. Herrmann [114], T. Herrmann [48], G. Herten [52], R. Hertenberger [114], L. Hervas [36], T.C. Herwig [136], G.G. Hesketh [95], N.P. Hessey [167a], H. Hibi [83], A. Higashida [162], S. Higashino [82], E. Higón-Rodriguez [173], K. Hildebrand [37], J.C. Hill [32], K.K. Hill [29], K.H. Hiller [46], S.J. Hillier [21], M. Hils [48], I. Hinchliffe [18], F. Hinterkeuser [24], M. Hirose [132], S. Hirose [52], D. Hirschbuehl [181], B. Hiti [92], O. Hladik [140], D.R. Hlaluku [33e], J. Hobbs [154], N. Hod [179], M.C. Hodgkinson [148], A. Hoecker [36], D. Hohn [52], D. Hohov [65], T. Holm [24], T.R. Holmes [37], M. Holzbock [114], L.B.A.H. Hommels [32], T.M. Hong [138], J.C. Honig [52], A. Hönle [115], B.H. Hooberman [172], W.H. Hopkins [6], Y. Horii [117], P. Horn [48], L.A. Horyn [37], S. Hou [157], A. Hoummada [35a], J. Howarth [57], J. Hoya [89], M. Hrabovsky [130], J. Hrdinka [77], J. Hrivnac [65], A. Hrynevich [109], T. Hryn'ova [5], P.J. Hsu [64], S.-C. Hsu [147], Q. Hu [29], S. Hu [60c], Y.F. Hu [15a,15d,an], D.P. Huang [95], Y. Huang [60a], Y. Huang [15a], Z. Hubacek [141], F. Hubaut [102], M. Huebner [24], F. Huegging [24], T.B. Huffman [134], M. Huhtinen [36], R. Hulsken [58], R.F.H. Hunter [34], P. Huo [154], N. Huseynov [80,ac], J. Huston [107], J. Huth [59], R. Hyneman [152], S. Hyrych [28a], G. Iacobucci [54], G. Iakovidis [29], I. Ibragimov [150], L. Iconomidou-Fayard [65], P. Iengo [36], R. Ignazzi [40], O. Igonkina [120,y,*], R. Iguchi [162], T. Iizawa [54], Y. Ikegami [82], M. Ikeno [82], N. Ilic [119,166,ab], F. Iltzsche [48], H. Imam [35a], G. Introzzi [71a,71b], M. Iodice [75a], K. Iordanidou [167a], V. Ippolito [73a,73b], M.F. Isacson [171], M. Ishino [162], W. Islam [129], C. Issever [19,46], S. Istin [159], F. Ito [168], J.M. Iturbe Ponce [63a], R. Iuppa [76a,76b], A. Ivina [179], H. Iwasaki [82], J.M. Izen [43], V. Izzo [70a], P. Jacka [140], P. Jackson [1], R.M. Jacobs [46], B.P. Jaeger [151], V. Jain [2], G. Jäkel [181], K.B. Jakobi [100], K. Jakobs [52], T. Jakoubek [179], J. Jamieson [57], K.W. Janas [84a], R. Jansky [54], M. Janus [53], P.A. Janus [84a], G. Jarlskog [97], A.E. Jaspan [91], N. Javadov [80,ac], T. Javůrek [36], M. Javurkova [103], F. Jeanneau [144], L. Jeanty [131], J. Jejelava [158a], P. Jenni [52,c], N. Jeong [46], S. Jézéquel [5], H. Ji [180], J. Jia [154], H. Jiang [79], Y. Jiang [60a], Z. Jiang [152], S. Jiggins [52], F.A. Jimenez Morales [38], J. Jimenez Pena [115], S. Jin [15c], A. Jinaru [27b], O. Jinnouchi [164], H. Jivan [33e], P. Johansson [148], K.A. Johns [7], C.A. Johnson [66], R.W.L. Jones [90], S.D. Jones [155], T.J. Jones [91], J. Jongmanns [61a], J. Jovicevic [36], X. Ju [18], J.J. 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Khandoga [144], A. Khanov [129], A.G. Kharlamov [122b,122a], T. Kharlamova [122b,122a], E.E. Khoda [174], A. Khodinov [165], T.J. Khoo [54], G. Khoriauli [176], E. Khramov [80], J. Khubua [158b], S. Kido [83], M. Kiehn [36], C.R. Kilby [94], E. Kim [164], Y.K. Kim [37], N. Kimura [95], A. Kirchhoff [53], D. Kirchmeier [48], J. Kirk [143], A.E. Kiryunin [115], T. Kishimoto [162], D.P. Kisliuk [166], V. Kitali [46], C. Kitsaki [10], O. Kivernyk [24], T. Klapdor-Kleingrothaus [52], M. Klassen [61a], C. Klein [34], M.H. Klein [106], M. Klein [91], U. Klein [91], K. Kleinknecht [100], P. Klimek [121], A. Klimentov [29], T. Klingl [24], T. Klioutchnikova [36], F.F. Klitzner [114], P. Kluit [120], S. Kluth [115], E. Kneringer [77], E.B.F.G. Knoops [102], A. Knue [52], D. Kobayashi [88], M. Kobel [48], M. Kocian [152], T. Kodama [162], P. Kodys [142], D.M. Koeck [155], P.T. Koenig [24], T. Koffas [34], N.M. Köhler [36], M. Kolb [144], I. Koletsou [5], T. Komarek [130], T. Kondo [82], K. 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V.V. Kostyukhin [148,165], A. Kotsokechagia [65], A. Kotwal [49], A. Koulouris [10],
A. Kourkoumeli-Charalampidi [71a,71b], C. Kourkoumelis [9], E. Kourlitis [6], V. Kouskoura [29], R. Kowalewski [175],
W. Kozanecki [101], A.S. Kozhin [123], V.A. Kramarenko [113], G. Kramberger [92], D. Krasnopevtsev [60a],
M.W. Krasny [135], A. Krasznahorkay [36], D. Krauss [115], J.A. Kremer [100], J. Kretzschmar [91], P. Krieger [166],
F. Krieter [114], A. Krishnan [61b], M. Krivos [142], K. Krizka [18], K. Kroeninger [47], H. Kroha [115], J. Kroll [140],
J. Kroll [136], K.S. Krowpman [107], U. Kruchonak [80], H. Krüger [24], N. Krumnack [79], M.C. Kruse [49],
J.A. Krzysiak [85], A. Kubota [164], O. Kuchinskaia [165], S. Kuday [4b], J.T. Kuechler [46], S. Kuehn [36], T. Kuhl [46],
V. Kukhtin [80], Y. Kulchitsky [108,ae], S. Kuleshov [146b], Y.P. Kulinich [172], M. Kuna [58], T. Kunigo [86], A. Kupco [140],
T. Kupfer [47], O. Kuprash [52], H. Kurashige [83], L.L. Kurchaninov [167a], Y.A. Kurochkin [108], A. Kurova [112],
M.G. Kurth [15a,15d], E.S. Kuwertz [36], M. Kuze [164], A.K. Kvam [147], J. Kvita [130], T. Kwan [104], F. La Ruffa [41b,41a],
C. Lacasta [173], F. Lacava [73a,73b], D.P.J. Lack [101], H. Lacker [19], D. Lacour [135], E. Ladygin [80], R. Lafaye [5],
B. Laforge [135], T. Lagouri [146c], S. Lai [53], I.K. Lakomiec [84a], J.E. Lambert [128], S. Lammers [66], W. Lampl [7],
C. Lampoudis [161], E. Lançon [29], U. Landgraf [52], M.P.J. Landon [93], M.C. Lanfermann [54], V.S. Lang [52],
J.C. Lange [53], R.J. Langenberg [103], A.J. Lankford [170], F. Lanni [29], K. Lantzsch [24], A. Lanza [71a],
A. Lapertosa [55b,55a], J.F. Laporte [144], T. Lari [69a], F. Lasagni Manghi [23b,23a], M. Lassnig [36], T.S. Lau [63a],
A. Laudrain [65], A. Laurier [34], M. Lavorgna [70a,70b], S.D. Lawlor [94], M. Lazzaroni [69a,69b], B. Le [101],
E. Le Guirriec [102], A. Lebedev [79], M. LeBlanc [7], T. LeCompte [6], F. Ledroit-Guillon [58], A.C.A. Lee [95],
C.A. Lee [29], G.R. Lee [17], L. Lee [59], S.C. Lee [157], S. Lee [79], B. Lefebvre [167a], H.P. Lefebvre [94], M. Lefebvre [175],
C. Leggett [18], K. Lehmann [151], N. Lehmann [20], G. Lehmann Miotto [36], W.A. Leight [46], A. Leisos [161,u],
M.A.L. Leite [81d], C.E. Leitgeb [114], R. Leitner [142], D. Lellouch [179,*], K.J.C. Leney [42], T. Lenz [24], S. Leone [72a],
C. Leonidopoulos [50], A. Leopold [135], C. Leroy [110], R. Les [107], C.G. Lester [32], M. Levchenko [137], J. Levêque [5],
D. Levin [106], L.J. Levinson [179], D.J. Lewis [21], B. Li [15b], B. Li [106], C-Q. Li [60a], F. Li [60c], H. Li [60a], H. Li [60b], J. Li [60c],
K. Li [147], L. Li [60c], M. Li [15a,15d], Q. Li [15a,15d], Q.Y. Li [60a], S. Li [60d,60c], X. Li [46], Y. Li [46], Z. Li [60b], Z. Li [134],
Z. Li [104], Z. Liang [15a], M. Liberatore [46], B. Liberti [74a], A. Liblong [166], K. Lie [63c], S. Lim [29], C.Y. Lin [32],
K. Lin [107], R.A. Linck [66], R.E. Lindley [7], J.H. Lindon [21], A. Linss [46], A.L. Lionti [54], E. Lipeles [136],
A. Lipniacka [17], T.M. Liss [172,ak], A. Lister [174], J.D. Little [8], B. Liu [79], B.L. Liu [6], H.B. Liu [29], J.B. Liu [60a],
J.K.K. Liu [37], K. Liu [60d], M. Liu [60a], P. Liu [15a], X. Liu [60a], Y. Liu [46], Y. Liu [15a,15d], Y.L. Liu [106], Y.W. Liu [60a],
M. Livan [71a,71b], A. Lleres [58], J. Llorente Merino [151], S.L. Lloyd [93], C.Y. Lo [63b], E.M. Lobodzinska [46], P. Loch [7],
S. Loffredo [74a,74b], T. Lohse [19], K. Lohwasser [148], M. Lokajicek [140], J.D. Long [172], R.E. Long [90],
I. Longarini [73a,73b], L. Longo [36], K.A. Looper [127], I. Lopez Paz [101], A. Lopez Solis [148], J. Lorenz [114],
N. Lorenzo Martinez [5], A.M. Lory [114], P.J. Lösel [114], A. Lösle [52], X. Lou [46], X. Lou [15a], A. Lounis [65], J. Love [6],
P.A. Love [90], J.J. Lozano Bahilo [173], M. Lu [60a], Y.J. Lu [64], H.J. Lubatti [147], C. Luci [73a,73b], F.L. Lucio Alves [15c],
A. Lucotte [58], F. Luehring [66], I. Luise [135], L. Luminari [73a], B. Lund-Jensen [153], M.S. Lutz [160], D. Lynn [29],
H. Lyons [91], R. Lysak [140], E. Lytken [97], F. Lyu [15a], V. Lyubushkin [80], T. Lyubushkina [80], H. Ma [29], L.L. Ma [60b],
Y. Ma [95], D.M. Mac Donell [175], G. Maccarrone [51], A. Macchiolo [115], C.M. Macdonald [148], J.C. MacDonald [148],
J. Machado Miguens [136], D. Madaffari [173], R. Madar [38], W.F. Mader [48], M. Madugoda Ralalage Don [129],
N. Madysa [48], J. Maeda [83], T. Maeno [29], M. Maerker [48], V. Magerl [52], N. Magini [79], J. Magro [67a,67c,q],
D.J. Mahon [39], C. Maidantchik [81b], T. Maier [114], A. Maio [139a,139b,139d], K. Maj [84a], O. Majersky [28a],
S. Majewski [131], Y. Makida [82], N. Makovec [65], B. Malaescu [135], Pa. Malecki [85], V.P. Maleev [137], F. Malek [58],
D. Malito [41b,41a], U. Mallik [78], D. Malon [6], C. Malone [32], S. Maltezos [10], S. Malyukov [80], J. Mamuzic [173],
G. Mancini [70a,70b], I. Mandić [92], L. Manhaes de Andrade Filho [81a], I.M. Maniatis [161], J. Manjarres Ramos [48],
K.H. Mankinen [97], A. Mann [114], A. Manousos [77], B. Mansoulie [144], I. Manthos [161], S. Manzoni [120],
A. Marantis [161], G. Marceca [30], L. Marchese [134], G. Marchiori [135], M. Marcisovsky [140], L. Marcoccia [74a,74b],
C. Marcon [97], C.A. Marin Tobon [36], M. Marjanovic [128], Z. Marshall [18], M.U.F. Martensson [171],
S. Marti-Garcia [173], C.B. Martin [127], T.A. Martin [177], V.J. Martin [50], B. Martin dit Latour [17],
L. Martinelli [75a,75b], M. Martinez [14,w], P. Martinez Agullo [173], V.I. Martinez Outschoorn [103],
S. Martin-Haugh [143], V.S. Martoiu [27b], A.C. Martyniuk [95], A. Marzin [36], S.R. Maschek [115], L. Masetti [100],
T. Mashimo [162], R. Mashinistov [111], J. Masik [101], A.L. Maslennikov [122b,122a], L. Massa [23b,23a],
P. Massarotti [70a,70b], P. Mastrandrea [72a,72b], A. Mastroberardino [41b,41a], T. Masubuchi [162], D. Matakias [29],
A. Matic [114], N. Matsuzawa [162], P. Mättig [24], J. Maurer [27b], B. Maček [92], D.A. Maximov [122b,122a],
R. Mazini [157], I. Maznas [161], S.M. Mazza [145], J.P. Mc Gowan [104], S.P. Mc Kee [106], T.G. McCarthy [115],
W.P. McCormack [18], E.F. McDonald [105], J.A. Mcfayden [36], G. Mchedlidze [158b], M.A. McKay [42],
K.D. McLean [175], S.J. McMahon [143], P.C. McNamara [105], C.J. McNicol [177], R.A. McPherson [175,ab],

J.E. Mdhluli [33e], Z.A. Meadows [103], S. Meehan [36], T. Megy [38], S. Mehlhase [114], A. Mehta [91], B. Meirose [43], D. Melini [159], B.R. Mellado Garcia [33e], J.D. Mellenthin [53], M. Melo [28a], F. Meloni [46], A. Melzer [24], E.D. Mendes Gouveia [139a,139e], L. Meng [36], X.T. Meng [106], S. Menke [115], E. Meoni [41b,41a], S. Mergelmeyer [19], S.A.M. Merkt [138], C. Merlassino [134], P. Mermod [54], L. Merola [70a,70b], C. Meroni [69a], G. Merz [106], O. Meshkov [113,111], J.K.R. Meshreki [150], J. Metcalfe [6], A.S. Mete [6], C. Meyer [66], J-P. Meyer [144], M. Michetti [19], R.P. Middleton [143], L. Mijović [50], G. Mikenberg [179], M. Mikestikova [140], M. Mikuž [92], H. Mildner [148], A. Milic [166], C.D. Milke [42], D.W. Miller [37], A. Milov [179], D.A. Milstead [45a,45b], R.A. Mina [152], A.A. Minaenko [123], I.A. Minashvili [158b], A.I. Mincer [125], B. Mindur [84a], M. Mineev [80], Y. Minegishi [162], L.M. Mir [14], M. Mironova [134], A. Mirto [68a,68b], K.P. Mistry [136], T. Mitani [178], J. Mitrevski [114], V.A. Mitsou [173], M. Mittal [60c], O. Miu [166], A. Miucci [20], P.S. Miyagawa [93], A. Mizukami [82], J.U. Mjörnmark [97], T. Mkrtchyan [61a], M. Mlynarikova [142], T. Moa [45a,45b], S. Mobius [53], K. Mochizuki [110], P. Mogg [114], S. Mohapatra [39], R. Moles-Valls [24], K. Mönig [46], E. Monnier [102], A. Montalbano [151], J. Montejo Berlingen [36], M. Montella [95], F. Monticelli [89], S. Monzani [69a], N. Morange [65], A.L. Moreira De Carvalho [139a], D. Moreno [22a], M. Moreno Llácer [173], C. Moreno Martinez [14], P. Morettini [55b], M. Morgenstern [159], S. Morgenstern [48], D. Mori [151], M. Morii [59], M. Morinaga [178], V. Morisbak [133], A.K. Morley [36], G. Mornacchi [36], A.P. Morris [95], L. Morvaj [154], P. Moschovakos [36], B. Moser [120], M. Mosidze [158b], T. Moskalets [144], J. Moss [31,m], E.J.W. Moyse [103], S. Muanza [102], J. Mueller [138], R.S.P. Mueller [114], D. Muenstermann [90], G.A. Mullier [97], D.P. Mungo [69a,69b], J.L. Munoz Martinez [14], F.J. Munoz Sanchez [101], P. Murin [28b], W.J. Murray [177,143], A. Murrone [69a,69b], J.M. Muse [128], M. Muškinja [18], C. Mwewa [33a], A.G. Myagkov [123,ag], A.A. Myers [138], G. Myers [66], J. Myers [131], M. Myska [141], B.P. Nachman [18], O. Nackenhorst [47], A. Nag Nag [48], K. Nagai [134], K. Nagano [82], Y. Nagasaka [62], J.L. Nagle [29], E. Nagy [102], A.M. Nairz [36], Y. Nakahama [117], K. Nakamura [82], T. Nakamura [162], H. Nanjo [132], F. Napolitano [61a], R.F. Naranjo Garcia [46], R. Narayan [42], I. Naryshkin [137], T. Naumann [46], G. Navarro [22a], P.Y. Nechaeva [111], F. Nechansky [46], T.J. Neep [21], A. Negri [71a,71b], M. Negrini [23b], C. Nellist [119], C. Nelson [104], M.E. Nelson [45a,45b], S. Nemecek [140], M. Nessi [36,e], M.S. Neubauer [172], F. Neuhaus [100], M. Neumann [181], R. Newhouse [174], P.R. Newman [21], C.W. Ng [138], Y.S. Ng [19], Y.W.Y. Ng [170], B. Ngair [35e], H.D.N. Nguyen [102], T. Nguyen Manh [110], E. Nibigira [38], R.B. Nickerson [134], R. Nicolaidou [144], D.S. Nielsen [40], J. Nielsen [145], M. Niemeyer [53], N. Nikiforou [11], V. Nikolaenko [123,ag], I. Nikolic-Audit [135], K. Nikolopoulos [21], P. Nilsson [29], H.R. Nindhito [54], Y. Ninomiya [82], A. Nisati [73a], N. Nishu [60c], R. Nisius [115], I. Nitsche [47], T. Nitta [178], T. Nobe [162], D.L. Noel [32], Y. Noguchi [86], I. Nomidis [135], M.A. Nomura [29], M. Nordberg [36], J. Novak [92], T. Novak [92], O. Novgorodova [48], R. Novotny [141], L. Nozka [130], K. Ntekas [170], E. Nurse [95], F.G. Oakham [34,al], H. Oberlack [115], J. Ocariz [135], A. Ochi [83], I. Ochoa [39], J.P. Ochoa-Ricoux [146a], K. O'Connor [26], S. Oda [88], S. Odaka [82], S. Oerdek [53], A. Ogrodnik [84a], A. Oh [101], C.C. Ohm [153], H. Oide [164], M.L. Ojeda [166], H. Okawa [168], Y. Okazaki [86], M.W. O'Keefe [91], Y. Okumura [162], T. Okuyama [82], A. Olariu [27b], L.F. Oleiro Seabra [139a], S.A. Olivares Pino [146a], D. Oliveira Damazio [29], J.L. Oliver [1], M.J.R. Olsson [170], A. Olszewski [85], J. Olszowska [85], Ö.O. Öncel [24], D.C. O'Neil [151], A.P. O'neill [134], A. Onofre [139a,139e], P.U.E. Onyisi [11], H. Oppen [133], R.G. Oreamuno Madriz [121], M.J. Oreglia [37], G.E. Orellana [89], D. Orestano [75a,75b], N. Orlando [14], R.S. Orr [166], V. O'Shea [57], R. Ospanov [60a], G. Otero y Garzon [30], H. Otono [88], P.S. Ott [61a], G.J. Ottino [18], M. Ouchrif [35d], J. Ouellette [29], F. Ould-Saada [133], A. Ouraou [144], Q. Ouyang [15a], M. Owen [57], R.E. Owen [143], V.E. Ozcan [12c], N. Ozturk [8], J. Pacalt [130], H.A. Pacey [32], K. Pachal [49], A. Pacheco Pages [14], C. Padilla Aranda [14], S. Pagan Griso [18], G. Palacino [66], S. Palazzo [50], S. Palestini [36], M. Palka [84b], P. Palni [84a], C.E. Pandini [54], J.G. Panduro Vazquez [94], P. Pani [46], G. Panizzo [67a,67c], L. Paolozzi [54], C. Papadatos [110], K. Papageorgiou [9,g], S. Parajuli [42], A. Paramonov [6], C. Paraskevopoulos [10], D. Paredes Hernandez [63b], S.R. Paredes Saenz [134], B. Parida [179], T.H. Park [166], A.J. Parker [31], M.A. Parker [32], F. Parodi [55b,55a], E.W. Parrish [121], J.A. Parsons [39], U. Parzefall [52], L. Pascual Dominguez [135], V.R. Pascuzzi [18], J.M.P. Pasner [145], F. Pasquali [120], E. Pasqualucci [73a], S. Passaggio [55b], F. Pastore [94], P. Pasuwan [45a,45b], S. Pataraia [100], J.R. Pater [101], A. Pathak [180,i], J. Patton [91], T. Pauly [36], J. Pearkes [152], B. Pearson [115], M. Pedersen [133], L. Pedraza Diaz [119], R. Pedro [139a], T. Peiffer [53], S.V. Peleganchuk [122b,122a], O. Penc [140], H. Peng [60a], B.S. Peralva [81a], M.M. Perego [65], A.P. Pereira Peixoto [139a], L. Pereira Sanchez [45a,45b], D.V. Perepelitsa [29], E. Perez Codina [167a], F. Peri [19], L. Perini [69a,69b], H. Pernegger [36], S. Perrella [36], A. Perrevoort [120], K. Peters [46], R.F.Y. Peters [101], B.A. Petersen [36], T.C. Petersen [40], E. Petit [102], V. Petousis [141], A. Petridis [1], C. Petridou [161], P. Petroff [65], F. Petrucci [75a,75b], M. Pettee [182], N.E. Pettersson [103], K. Petukhova [142], A. Peyaud [144], R. Pezoa [146d],

L. Pezzotti [71a,71b], T. Pham [105], F.H. Phillips [107], P.W. Phillips [143], M.W. Phipps [172], G. Piacquadio [154], E. Pianori [18], A. Picazio [103], R.H. Pickles [101], R. Piegaia [30], D. Pietreanu [27b], J.E. Pilcher [37], A.D. Pilkington [101], M. Pinamonti [67a,67c], J.L. Pinfold [3], C. Pitman Donaldson [95], M. Pitt [160], L. Pizzimento [74a,74b], A. Pizzini [120], M.-A. Pleier [29], V. Plesanovs [52], V. Pleskot [142], E. Plotnikova [80], P. Podberezko [122b,122a], R. Poettgen [97], R. Poggi [54], L. Poggioli [135], I. Pogrebnyak [107], D. Pohl [24], I. Pokharel [53], G. Polesello [71a], A. Poley [151,167a], A. Policicchio [73a,73b], R. Polifka [142], A. Polini [23b], C.S. Pollard [46], V. Polychronakos [29], D. Ponomarenko [112], L. Pontecorvo [36], S. Popa [27a], G.A. Popeneciu [27d], L. Portales [5], D.M. Portillo Quintero [58], S. Pospisil [141], K. Potamianos [46], I.N. Potrap [80], C.J. Potter [32], H. Potti [11], T. Poulsen [97], J. Poveda [173], T.D. Powell [148], G. Pownall [46], M.E. Pozo Astigarraga [36], P. Pralavorio [102], S. Prell [79], D. Price [101], M. Primavera [68a], M.L. Proffitt [147], N. Proklova [112], K. Prokofiev [63c], F. Prokoshin [80], S. Protopopescu [29], J. Proudfoot [6], M. Przybycien [84a], D. Pudzha [137], A. Puri [172], P. Puzo [65], D. Pyatiizbyantseva [112], J. Qian [106], Y. Qin [101], A. Quadt [53], M. Queitsch-Maitland [36], M. Racko [28a], F. Ragusa [69a,69b], G. Rahal [98], J.A. Raine [54], S. Rajagopalan [29], A. Ramirez Morales [93], K. Ran [15a,15d], D.M. Rauch [46], F. Rauscher [114], S. Rave [100], B. Ravina [148], I. Ravinovich [179], J.H. Rawling [101], M. Raymond [36], A.L. Read [133], N.P. Readioff [148], M. Reale [68a,68b], D.M. Rebuzzi [71a,71b], G. Redlinger [29], K. Reeves [43], J. Reichert [136], D. Reikher [160], A. Reiss [100], A. Rej [150], C. Rembser [36], A. Renardi [46], M. Renda [27b], M.B. Rendel [115], A.G. Rennie [57], S. Resconi [69a], E.D. Resseguie [18], S. 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Simsek [12b], P. Sinervo [166], V. Sinetckii [113], S. Singh [151], M. Sioli [23b,23a], I. Siral [131], S.Yu. Sivoklokov [113], J. Sjölin [45a,45b], A. Skaf [53], E. Skorda [97], P. Skubic [128], M. Slawinska [85], K. Sliwa [169], R. Slovak [142], V. Smakhtin [179], B.H. Smart [143], J. Smiesko [28b], N. Smirnov [112], S.Yu. Smirnov [112], Y. Smirnov [112], L.N. Smirnova [113,r], O. Smirnova [97], E.A. Smith [37], H.A. Smith [134], M. Smizanska [90], K. Smolek [141], A. Smykiewicz [85], A.A. Snesarev [111], H.L. Snoek [120], I.M. Snyder [131], S. Snyder [29], R. Sobie [175,ab], A. Soffer [160], A. Søgaard [50], F. Sohns [53], C.A. Solans Sanchez [36], E.Yu. Soldatov [112], U. Soldevila [173], A.A. Solodkov [123], A. Soloshenko [80], O.V. Solovyanov [123], V. Solovyev [137], P. Sommer [148], H. Son [169], W. Song [143], W.Y. Song [167b], A. Sopczak [141], A.L. Sopio [95], F. Sopkova [28b], S. Sottocornola [71a,71b], R. Soualah [67a,67c], A.M. Soukharev [122b,122a], D. South [46], S. 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Tayalati [35e], A.J. Taylor [50], G.N. Taylor [105], W. Taylor [167b], H. Teagle [91], A.S. Tee [90], R. Teixeira De Lima [152], P. Teixeira-Dias [94], H. Ten Kate [36], J.J. Teoh [120], S. Terada [82], K. Terashi [162], J. Terron [99], S. Terzo [14], M. Testa [51], R.J. Teuscher [166,ab], S.J. Thais [182], N. Themistokleous [50], T. Theveneaux-Pelzer [46], F. Thiele [40], D.W. Thomas [94], J.O. Thomas [42], J.P. Thomas [21], E.A. Thompson [46], P.D. Thompson [21], E. Thomson [136], E.J. Thorpe [93], R.E. Ticse Torres [53], V.O. Tikhomirov [111,ah], Yu.A. Tikhonov [122b,122a], S. Timoshenko [112], P. Tipton [182], S. Tisserant [102], K. Todome [23b,23a], S. Todorova-Nova [142], S. Todt [48], J. Tojo [88], S. Tokár [28a], K. Tokushuku [82], E. Tolley [127], R. Tombs [32], K.G. Tomiwa [33e], M. Tomoto [117], L. Tompkins [152], P. Tornambe [103], E. Torrence [131], H. Torres [48], E. Torró Pastor [147], C. Tosciri [134], J. Toth [102,aa], D.R. Tovey [148], A. Traeet [17], C.J. Treado [125], T. Trefzger [176], F. Tresoldi [155], A. Tricoli [29], I.M. Trigger [167a], S. Trincaz-Duvoid [135], D.A. Trischuk [174], W. Trischuk [166], B. Trocmé [58], A. Trofymov [65], C. Troncon [69a], F. Trovato [155], L. Truong [33c], M. Trzebinski [85], A. Trzupek [85], F. Tsai [46], J.C-L. Tseng [134], P.V. Tsiareshka [108,ae], A. Tsirigotis [161,u], V. Tsiskaridze [154], E.G. Tskhadadze [158a], M. Tsopoulou [161], I.I. Tsukerman [124], V. Tsulaia [18], S. Tsuno [82], D. Tsybychev [154], Y. Tu [63b], A. Tudorache [27b], V. Tudorache [27b], T.T. Tulbure [27a], A.N. Tuna [59], S. Turchikhin [80], D. Turgeman [179], I. Turk Cakir [4b,s], R.J. Turner [21], R. Turra [69a], P.M. Tuts [39], S. Tzamarias [161], E. Tzovara [100], K. Uchida [162], F. Ukegawa [168], G. Unal [36], M. Unal [11], A. Undrus [29], G. Unel [170], F.C. Ungaro [105], Y. Unno [82], K. Uno [162], J. Urban [28b], P. Urquijo [105], G. Usai [8], Z. Uysal [12d], V. Vacek [141], B. Vachon [104], K.O.H. Vadla [133], T. 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T. Vazquez Schroeder [36], J. Veatch [53], V. Vecchio [101], M.J. Veen [120], L.M. Veloce [166], F. Veloso [139a,139c],
S. Veneziano [73a], A. Ventura [68a,68b], A. Verbytskyi [115], V. Vercesi [71a], M. Verducci [72a,72b],
C.M. Vergel Infante [79], C. Vergis [24], W. Verkerke [120], A.T. Vermeulen [120], J.C. Vermeulen [120], C. Vernieri [152],
M.C. Vetterli [151,al], N. Viaux Maira [146d], T. Vickey [148], O.E. Vickey Boeriu [148], G.H.A. Viehhauser [134],
L. Vigani [61b], M. Villa [23b,23a], M. Villaplana Perez [3], E.M. Villhauer [50], E. Vilucchi [51], M.G. Vincter [34],
G.S. Virdee [21], A. Vishwakarma [50], C. Vittori [23b,23a], I. Vivarelli [155], M. Vogel [181], P. Vokac [141],
S.E. von Buddenbrock [33e], E. Von Toerne [24], V. Vorobel [142], K. Vorobev [112], M. Vos [173], J.H. Vossebeld [91],
M. Vozak [101], N. Vranjes [16], M. Vranjes Milosavljevic [16], V. Vrba [141], M. Vreeswijk [120], R. Vuillermet [36],
I. Vukotic [37], S. Wada [168], P. Wagner [24], W. Wagner [181], J. Wagner-Kuhr [114], S. Wahdan [181], H. Wahlberg [89],
R. Wakasa [168], V.M. Walbrecht [115], J. Walder [143], R. Walker [114], S.D. Walker [94], W. Walkowiak [150],
V. Wallangen [45a,45b], A.M. Wang [59], A.Z. Wang [180], C. Wang [60a], C. Wang [60c], F. Wang [180], H. Wang [18],
H. Wang [3], J. Wang [63a], P. Wang [42], Q. Wang [128], R.-J. Wang [100], R. Wang [60a], R. Wang [6], S.M. Wang [157],
W.T. Wang [60a], W. Wang [15c], W.X. Wang [60a], Y. Wang [60a], Z. Wang [106], C. Wanotayaroj [46], A. Warburton [104],
C.P. Ward [32], D.R. Wardrope [95], N. Warrack [57], A.T. Watson [21], M.F. Watson [21], G. Watts [147], B.M. Waugh [95],
A.F. Webb [11], C. Weber [29], M.S. Weber [20], S.A. Weber [34], S.M. Weber [61a], A.R. Weidberg [134],
J. Weingarten [47], M. Weirich [100], C. Weiser [52], P.S. Wells [36], T. Wenaus [29], B. Wendland [47], T. Wengler [36],
S. Wenig [36], N. Wermes [24], M. Wessels [61a], T.D. Weston [20], K. Whalen [131], A.M. Wharton [90], A.S. White [106],
A. White [8], M.J. White [1], D. Whiteson [170], B.W. Whitmore [90], W. Wiedenmann [180], C. Wiel [48],
M. Wielers [143], N. Wieseotte [100], C. Wiglesworth [40], L.A.M. Wiik-Fuchs [52], H.G. Wilkens [36], L.J. Wilkins [94],
H.H. Williams [136], S. Williams [32], S. Willocq [103], P.J. Windischhofer [134], I. Wingerter-Seez [5], E. Winkels [155],
F. Winklmeier [131], B.T. Winter [52], M. Wittgen [152], M. Wobisch [96], A. Wolf [100], R. Wölker [134], J. Wollrath [52],
M.W. Wolter [85], H. Wolters [139a,139c], V.W.S. Wong [174], N.L. Woods [145], S.D. Worm [46], B.K. Wosiek [85],
K.W. Woźniak [85], K. Wraight [57], S.L. Wu [180], X. Wu [54], Y. Wu [60a], J. Wuerzinger [134], T.R. Wyatt [101],
B.M. Wynne [50], S. Xella [40], L. Xia [177], J. Xiang [63c], X. Xiao [106], X. Xie [60a], I. Xiotidis [155], D. Xu [15a], H. Xu [60a],
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D.P. Yallup [95], N. Yamaguchi [88], Y. Yamaguchi [164], A. Yamamoto [82], M. Yamatani [162], T. Yamazaki [162],
Y. Yamazaki [83], J. Yan [60c], Z. Yan [25], H.J. Yang [60c,60d], H.T. Yang [18], S. Yang [60a], T. Yang [63c], X. Yang [60b,58],
Y. Yang [162], Z. Yang [60a], W-M. Yao [18], Y.C. Yap [46], Y. Yasu [82], E. Yatsenko [60c], H. Ye [15c], J. Ye [42], S. Ye [29],
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J. Zahreddine [135], A.M. Zaitsev [123,ag], T. Zakareishvili [158b], N. Zakharchuk [34], S. Zambito [36], D. Zanzi [36],
D.R. Zaripovas [57], S.V. Zeißner [47], C. Zeitnitz [181], G. Zemaityte [134], J.C. Zeng [172], O. Zenin [123], T. Ženiš [28a],
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