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Search for a new scalar decaying into new spin-1 bosons in four-lepton final states with the ATLAS detector

The ATLAS Collaboration

A search is conducted for a new scalar boson S, with a mass distinct from that of the Higgs boson, decaying into four leptons ($\ell = e, \mu$) via an intermediate state containing two on-shell, promptly decaying new spin-1 bosons Z_d: $S \to Z_\mathrm{d}Z_\mathrm{d} \to 4\ell$, where the Z_d boson has a mass between 15 and 300 GeV, and the S boson has a mass between either 30 and 115 GeV or 130 and 800 GeV. The search uses proton–proton collision data collected with the ATLAS detector at the Large Hadron Collider with an integrated luminosity of 139 fb^{-1} at a centre-of-mass energy of $\sqrt{s}$ = 13 TeV. No significant excess above the Standard Model background expectation is observed. Upper limits at 95% confidence level are set on the production cross-section times branching ratio, $\sigma(gg \to S) \times \mathcal{B}(S \to Z_\mathrm{d}Z_\mathrm{d} \to 4\ell)$, as a function of the mass of both particles, m_S and $m_{Z\mathrm{d}}$.

1 Introduction

Notwithstanding its spectacular successes, the Standard Model (SM) is incomplete. In particular, the nature of dark matter is unknown. A potential framework for extending the SM to include dark matter is the Hidden Abelian Higgs Model (HAHM) [1–6], which posits a 'hidden' or 'dark' sector of particles and fields, including a field with a $U(1)_{\mathrm{d}}$ dark gauge symmetry mixing kinetically with the SM $U(1)_{\mathrm{Y}}$ hypercharge gauge field with some coupling strength ϵ. This results in an additional scalar S along with a new gauge boson Z_{d} or 'dark photon'. The scalar S mixes with the SM Higgs boson with coupling κ, so all processes that can produce a SM Higgs boson also produce an S boson. Hence, the dominant production process for S in proton–proton (pp) collisions would be gluon–gluon fusion. The decays of the Z_{d} boson are determined by the gauge couplings and are independent of the mixings for $\epsilon, \kappa \ll 1$; the branching ratio of the Z_{d} boson into electron or muon pairs would therefore be around 10% to 15% over the Z_{d} boson mass range $1\,\mathrm{GeV} < m_{Z_{\mathrm{d}}} < 60\,\mathrm{GeV}$ [1].

Previous studies [7–12] have searched for a resonantly produced SM Higgs boson mixing with a new scalar decaying into a $Z_{\mathrm{d}}Z_{\mathrm{d}}$ or a ZZ_{d} pair, with each Z_{d} or Z boson decaying into a pair of electrons or muons ($\ell \equiv e, \mu$) with opposite electric charge. Other similar searches, including searches for pairs of light bosons decaying into muons, τ-leptons, photons, and/or jets, as well as searches for a single light boson decaying into a pair of muons, using both $\sqrt{s} = 8\,\mathrm{TeV}$ and $\sqrt{s} = 13\,\mathrm{TeV}$ data, were performed at the Large Hadron Collider (LHC) by the ATLAS [13–17], CMS [18–21], and LHCb [22] experiments. Further searches for a SM Higgs boson decaying into undetected particles are reported in Refs. [23, 24]. The present work extends the previous ATLAS $H \to Z_{\mathrm{d}}Z_{\mathrm{d}} \to 4\ell$ search [7], where the additional scalar S decaying into the $Z_{\mathrm{d}}Z_{\mathrm{d}}$ pair, $S \to Z_{\mathrm{d}}Z_{\mathrm{d}} \to 4\ell$, has a mass distinct from that of the SM Higgs boson. The search reported here makes no use of information about any possible jets or missing transverse energy, and so may also be sensitive to other signal processes that may produce extra particles in addition to four leptons.

2 The ATLAS detector

The ATLAS experiment [25] at the LHC is a multipurpose particle detector with a forward–backward symmetric cylindrical geometry and a near 4π coverage in solid angle.[1] It consists of an inner tracking detector surrounded by a thin superconducting solenoid providing a 2 T axial magnetic field, electromagnetic and hadronic calorimeters, and a muon spectrometer. The inner tracking detector covers the pseudorapidity range $|\eta| < 2.5$. It consists of silicon pixel, silicon microstrip, and transition radiation tracking detectors. Lead/liquid-argon (LAr) sampling calorimeters provide electromagnetic (EM) energy measurements with high granularity within the region $|\eta| < 3.2$. A steel/scintillator-tile hadronic calorimeter covers the central pseudorapidity range ($|\eta| < 1.7$). The endcap and forward regions are instrumented with LAr calorimeters for EM and hadronic energy measurements up to $|\eta| = 4.9$. The muon spectrometer surrounds the calorimeters and is based on three large superconducting air-core toroidal magnets with eight coils each. The field integral of the toroids ranges between 2.0 and 6.0 T m across most of the detector. The muon spectrometer includes a system of precision tracking chambers up to $|\eta| = 2.7$ and fast detectors

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

for triggering up to $|\eta| = 2.4$. The luminosity is measured mainly by the LUCID–2 [26] detector, which is located close to the beampipe. A two-level trigger system is used to select events [27]. The first-level trigger is implemented in hardware and uses a subset of the detector information to accept events at a rate below 100 kHz. This is followed by a software-based trigger that reduces the accepted event rate to 1 kHz on average depending on the data-taking conditions. A software suite [28] 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 Data and simulated event samples

The data used in this search were recorded during the 2015–2018 LHC run with pp collisions at $\sqrt{s} = 13$ TeV. After requiring that all detector systems were operational [29] without excess calorimeter noise [30], this corresponds to an integrated luminosity of 139 fb^{-1} [31]. Events were selected by triggers requiring either one or two electron or muon candidates [32–34]. The trigger thresholds on transverse momentum p_{T} range from $p_{\mathrm{T}} > 7$ GeV to $p_{\mathrm{T}} > 60$ GeV, depending on lepton multiplicity and flavour. In either case, the trigger efficiency is above 95% relative to the offline signal event selection criteria. Collision events are selected by requiring an identified primary vertex with at least two tracks [35] and at least four lepton candidates satisfying the requirements given in Section 4.

The expected contribution of the $S \to Z_{\mathrm{d}}Z_{\mathrm{d}} \to 4\ell$ ($\ell = e, \mu$) signal is determined from Monte Carlo (MC) simulations. Samples for this process are produced according to the HAHM implementation [36] for the gluon–gluon fusion production process at leading order (LO) using MadGraph5_aMC@NLO 2.2.2 [37] with the mixing parameters ϵ and κ both set to 10^{-4} so that decays of the Z_{d} boson are prompt [1]. Parton showers and decays are simulated using Pythia 8.186 [38], along with EvtGen 1.2.0 [39] to decay heavy-flavour hadrons. The NNPDF2.3lo [40] set of parton distribution functions (PDFs) and the A14 tune [41] are used. The width of the scalar S is taken to vary with mass in the same way as the SM Higgs boson [42]. The signal samples cover different m_S and $m_{Z_{\mathrm{d}}}$ mass hypotheses, in two regions. In the first region, there are 32 samples with 30 GeV $< m_S <$ 110 GeV and 15 GeV $< m_{Z_{\mathrm{d}}} <$ 48 GeV, and in the second there are 49 samples with 150 GeV $< m_S <$ 800 GeV and 15 GeV $< m_{Z_{\mathrm{d}}} <$ 300 GeV. In both cases, $m_S > 2m_{Z_{\mathrm{d}}}$. Detector effects are included using a Geant4 [43] simulation of the ATLAS detector [44]. The effects of additional pp collisions in the same or a neighbouring bunch crossing (pile-up) are included in the simulation.

Most background processes are estimated by using MC simulations, which consider $\ell = e, \mu, \tau$, and thus include leptonic τ-lepton decays. The samples used are identical to those of Ref. [7] and are briefly summarized here. The non-resonant $q\bar{q} \to ZZ^* \to 4\ell$ and $gg \to ZZ^* \to 4\ell$ background processes are simulated using Sherpa 2.2.2 [45–51] at next-to-leading order (NLO) for up to one additional parton and at LO for up to three additional partons. The $H \to ZZ^* \to 4\ell$ background is simulated with Powheg Box v2 [52–56] for the gluon–gluon fusion, vector–boson fusion, and $t\bar{t}H$ processes, with Pythia 8.186 for the VH process, and with MadGraph5_aMC@NLO for the $b\bar{b}H$ process. Higher-order electroweak processes, including triboson production (VVV) and vector–boson scattering (VBS), are simulated using Sherpa 2.2.2, while the process $t\bar{t} + (Z \to \ell\ell)$ is simulated with Sherpa 2.2.0. Other, reducible, backgrounds have fewer than four prompt leptons in the final state, but can be accepted by the event selection if there are additional leptons from, for example, heavy-flavour decay or jets misidentified as leptons. Backgrounds due to Z + jets and $t\bar{t}$ processes are estimated from data (see Section 5), but the method also requires simulations of these processes; the Z + jets process is simulated with Sherpa 2.2.1,

while the $t\bar{t}$ process is simulated with Powheg Box v2. The WZ process was generated with Powheg Box at NLO. For processes simulated with MadGraph5_aMC@NLO and Powheg Box v2, Pythia is used to simulate parton showers and decays along with EvtGen. For the portion of the $gg \to ZZ^* \to 4\ell$ sample with $m_{4\ell} > 130\,\text{GeV}$ (corresponding to a few percent of the total estimated background) and the VVV samples, detector effects are included using a fast simulation [44], of just the calorimeter response [57] component, which relies on a parameterization. All other samples use the full Geant4 simulation.

In addition to the backgrounds mentioned above, numerous other simulated background processes were checked, including $t\bar{t}$ associated with a diboson pair, VH with the Higgs boson decaying into two W bosons, $Z\Upsilon$, tH, tWH, and $q\bar{q} \to ZZ^*$ at low p_{T}. The contributions from these backgrounds were lower than 0.02 events, so they were not included in the further background calculations.

4 Event selection

After reconstruction, electrons and muons are identified using the standard ATLAS 'Loose' criteria [58, 59], defined to maximize the reconstruction and identification efficiencies while still providing good-quality candidates. Electron candidates must satisfy $p_{\text{T}} > 7\,\text{GeV}$, $|\eta| < 2.47$, and must also have an additional associated hit in the innermost layer of the silicon detector. Longitudinal and transverse impact parameters with respect to the primary vertex must satisfy $|z_0 \sin\theta| < 0.5\,\text{mm}$ and $|d_0|/\sigma_{d_0} < 5$. Muon candidates must satisfy $p_{\text{T}} > 5\,\text{GeV}$ and $|\eta| < 2.5$, except that 'calorimeter-tagged' (CT) muons, identified by matching an inner-detector (ID) track (with no corresponding track in the muon system) with a deposit in the calorimeter consistent with a minimum-ionizing particle, must instead satisfy $p_{\text{T}} > 15\,\text{GeV}$. Except for 'stand-alone' (SA) muons lacking a matching ID track, muon candidates must also have impact parameters satisfying $|z_0 \sin\theta| < 0.5\,\text{mm}$, $|d_0| < 1\,\text{mm}$, and $|d_0|/\sigma_{d_0} < 3$. Quadruplets are then formed from two same-flavour, opposite-sign lepton pairs: either $4e$, $2e2\mu$, or 4μ. A quadruplet may contain no more than one CT or SA muon. In the case of four same-flavour leptons, two quadruplets are formed, one for each possible pairing. If there are more than four leptons then there may be additional quadruplets, depending on the flavours and signs of the leptons.

Leptons must be isolated from other deposits in the calorimeter or ID tracks [58, 59]. This rejects backgrounds in which leptons arise from the decay of heavy-flavour hadrons, or in which jets are misidentified as leptons [60]. For each lepton, the sum of the transverse energies of topological clusters [61] within a cone of $\Delta R = 0.2$ around it (excluding energy attributed to the lepton itself) must be less than 20% of its p_{T} for electrons, and less than 30% of its p_{T} for muons. The transverse momenta of tracks in a cone around the lepton are also summed, and must be less than 15% of its p_{T}. The radius of the cone depends on the momentum of the lepton. For electrons, it is $\Delta R = \min(0.2, 10\,\text{GeV}/p_{\text{T}})$, while for muons it is $\Delta R = \min(0.3, 10\,\text{GeV}/p_{\text{T}})$. In both cases, tracks and energy clusters attributed to other leptons in the quadruplet are excluded from the sums.

For each possible quadruplet, the invariant masses of the two pairs are denoted m_{ab} and m_{cd}, where $m_{ab} > m_{cd}$. If all four leptons have the same flavour, then the alternative pairing $m_{ad,bc}$ can be defined taking the positively charged lepton of the m_{ab} pair and the negatively charged lepton of the m_{cd} pair to make m_{ad} and the remaining two leptons to make m_{bc}.[2]

[2] These $m_{ab,cd}$ variables are distinct from the $m_{12,34}$ variables used in Ref. [7], which were chosen such that $|m_{12} - m_Z| < |m_{34} - m_Z|$. For $m_{4\ell} < 2m_Z$, $m_{ab,cd} = m_{12,34}$. For larger $m_{4\ell}$, either $m_{ab,cd} = m_{12,34}$ or $m_{ab,cd} = m_{34,12}$.

Each quadruplet must contain all the leptons corresponding to at least one of the triggers satisfied by the event. The three highest-p_{T} leptons must satisfy $p_{\mathrm{T}\ell_1} > 20\,\mathrm{GeV}$, $p_{\mathrm{T}\ell_2} > 15\,\mathrm{GeV}$, and $p_{\mathrm{T}\ell_3} > 10\,\mathrm{GeV}$. To remove poorly-measured leptons and electrons from bremsstrahlung, all pairs of same-flavour leptons in the quadruplet must satisfy a separation requirement of $\Delta R(\ell, \ell') > 0.1$, while different-flavour pairs must satisfy $\Delta R(\ell, \ell') > 0.2$. At least one quadruplet per event is required. If more than one quadruplet passes these requirements, the one with the smallest mass difference between the two pairs, $\Delta m_{\ell\ell} = |m_{ab} - m_{cd}|$, is chosen.

All dilepton pair masses m_{ab}, m_{cd}, m_{ad}, and m_{bc} must be larger than 11.105 GeV, corresponding to $m_{\Upsilon(3S)} + 0.75\,\mathrm{GeV}$, where $m_{\Upsilon(3S)}$ is taken to be 10.355 GeV [62]. This removes events where the alternate pairing may be consistent with ZZ^* decay as well as events with lepton pairs consistent with J/ψ or Υ decay.

Two signal regions are defined, each considering a scalar S with a mass different from that of the SM Higgs boson. The lower mass signal region (SR1) requires $m_{4\ell} < 115\,\mathrm{GeV}$ and, to reject background from Z bosons, either $m_{ab} < 50\,\mathrm{GeV}$ or $m_{ab} > 106\,\mathrm{GeV}$ (this is the complement of one of the signal region requirements from the $H \to ZZ_{\mathrm{d}} \to 4\ell$ search in Ref. [7], and was chosen to avoid overlap with that search). The higher mass signal region (SR2) requires $m_{4\ell} > 130\,\mathrm{GeV}$, and $|m_{ab,cd} - m_Z| > 8\,\mathrm{GeV}$ and $|m_{ad,bc} - m_Z| > 4\,\mathrm{GeV}$, where the latter requirement on the alternative pairing applies only to the $4e$ and 4μ events. These pair mass requirements were set to optimize the expected significance.

Consistency between m_{ab} and m_{cd} is enforced by requiring $m_{cd}/m_{ab} > 0.85 - 0.1125 f(m_{ab})$, where the modulating function f decreases monotonically from $f(m_{ab} \leq 10\,\mathrm{GeV}) = 1$ to $f(m_{ab} \geq 50\,\mathrm{GeV}) = 0$. It is the result of re-optimizing the analysis to allow for larger Z_{d} widths at lower lepton-pair invariant masses, where the background is low, and is fully described in Ref. [7].

Finally, if E'_{ab} is defined as the energy of the ab dilepton pair in the rest frame of the four-lepton system, then

$$\frac{E'_{ab}}{m_{4\ell}} = \frac{1}{2}\left(1 + \frac{m_{ab}^2 - m_{cd}^2}{m_{4\ell}^2}\right).$$

The additional requirement $|E'_{ab}/m_{4\ell} - 0.5| < 0.008$ reduces the dominant ZZ^* background by about a factor of 1.5, while reducing the efficiency for the signal by less than five percent over most of the $(m_S, m_{Z_{\mathrm{d}}})$ range.

5 Background estimation

Backgrounds with four prompt leptons are estimated directly from simulation (see Section 3). The dominant background, comprising 90%–95% of the total, is the non-resonant process $ZZ^* \to 4\ell$. As described in Ref. [7], the prediction of this background was verified using background-dominated validation regions. The background from SM Higgs boson production is effectively suppressed by the requirement that the overall invariant mass $m_{4\ell}$ not be consistent with that of the SM Higgs boson. Other processes with four prompt leptons include $t\bar{t}Z \to 4\ell + X$ and processes with three gauge bosons and are found to be small in comparison with the dominant ZZ^* background. The reducible background due to WZ production is similarly small.

Contributions from Z + jets and $t\bar{t}$ (including $t\bar{t}Z$ decays with fewer than four leptons) processes to the signal regions are estimated from data. They are estimated separately but with similar techniques. In both

cases, the event sample is enlarged by relaxing the requirements on isolation and impact parameters for two of the lepton candidates. For the $t\bar{t}$ background, the two candidates with largest p_{T} must satisfy the nominal requirements. For the Z + jets background, the two candidates in the pair with invariant mass closest to that of the Z boson must satisfy the nominal requirements. In both cases, events are then classified into four regions based on the requirements satisfied by the other two candidates:

- Region A: The remaining two candidates both satisfy isolation and impact parameter requirements.
- Region B: The remaining two candidates both satisfy the isolation requirement, but at least one does not satisfy the impact parameter requirement.
- Region C: The remaining two candidates both satisfy the impact parameter requirement, but at least one does not satisfy the isolation requirement.
- Region D: All other events.

To obtain adequate statistics, event selections are applied only as far as the quarkonia veto, and the electron identification is also relaxed. Backgrounds other than the one being estimated are subtracted from the event counts in regions B, C, and D, using estimates from simulation. The number of background events in the signal region A can then be estimated as $N_{\mathrm{A}} = \epsilon_{\mathrm{sel}} N_{\mathrm{B}} N_{\mathrm{C}} / N_{\mathrm{D}}$, where ϵ_{sel} is the efficiency of the remaining selections as determined from simulation. This assumes that the isolation and impact parameter requirements are uncorrelated. This is nearly the case for the $4e$ and $2e2\mu$ final states (correlation coefficient $r < 0.01$), but they are more correlated for the 4μ final state ($r \approx 0.4$). The effect of the correlation is taken into account as a systematic uncertainty assigned to the yields of the Z + jets and $t\bar{t}$ backgrounds.

6 Systematic uncertainties

The uncertainty in the integrated luminosity is 1.7% [31], obtained using the LUCID-2 detector [26]. Uncertainties in the yields and efficiencies of simulated samples due to pile-up arise from differences between the predicted and measured inelastic cross-sections and from the reweighting procedure. These uncertainties are approximately 1%.

The efficiency for events to satisfy the selection depends on the triggering, reconstruction, identification, and isolation efficiencies for leptons, as well as the determination of their momentum scale. Tag-and-probe techniques are applied to dilepton resonances, including $Z \to \ell^+\ell^-$, $J/\psi \to \ell^+\ell^-$, and $\Upsilon \to \mu^+\mu^-$, to measure the efficiencies as well as momentum scales and resolutions for electrons and muons. This leads to corrections to account for differences between data and simulation along with an estimate of the residual uncertainty [58, 59]. As there are four leptons in the final state, small single-lepton uncertainties can result in larger uncertainties in the final yields and efficiencies for simulated samples, up to 17%, dominated by the uncertainties on the electron reconstruction and identification efficiencies.

Uncertainties in the modelling of the simulated signal and background processes are estimated by varying the PDFs according to the prescription of Ref. [63] and the factorization and renormalization scales up and down by a factor of two. For the signal process, the resulting yield uncertainties are taken from the results for gluon–gluon fusion production of Ref. [64] and vary from 10%–19% depending on m_S, dominated by the uncertainty from factorization and renormalization scale variations. For the dominant $ZZ^* \to 4\ell$ background, these same sources result in an uncertainty in the yield of about 6%. Additionally, for this sample, the matrix element matching scale is varied from the nominal value of 20 GeV to 15 GeV and 30 GeV; the resummation scale is varied up and down by a factor of four; and the alternate recoil scheme

Table 1: Expected event yields of the SM background processes and observed data in the two signal regions SR1 and SR2. The first uncertainty is the statistical component of the total uncertainty and the second the systematic component.

Process	Yield (± stat. ± syst.)	
	SR1	SR2
$ZZ^* \to 4\ell$	$30.9 \pm 0.5 \pm 3.2$	$62.0 \pm 0.5 \pm 7.9$
$H \to ZZ^* \to 4\ell$	$0.61 \pm 0.01 \pm 0.04$	$0.22 \pm 0.01 \pm 0.03$
WZ	$0.06 \pm 0.04 \pm 0.03$	$0.42 \pm 0.10 \pm 0.05$
VVV	$0.06 \pm 0.01 \pm 0.01$	$0.78 \pm 0.02 \pm 0.14$
$t\bar{t}$	$0.33 \pm <0.01 \pm 0.31$	$0.78 \pm 0.01 \pm 0.46$
Z + jets	$0.70 \pm 0.01 \pm 0.72$	$2.53 \pm <0.01 \pm 1.08$
Total	$32.6 \pm 0.5 \pm 3.3$	$66.8 \pm 0.6 \pm 8.0$
Data	36	55

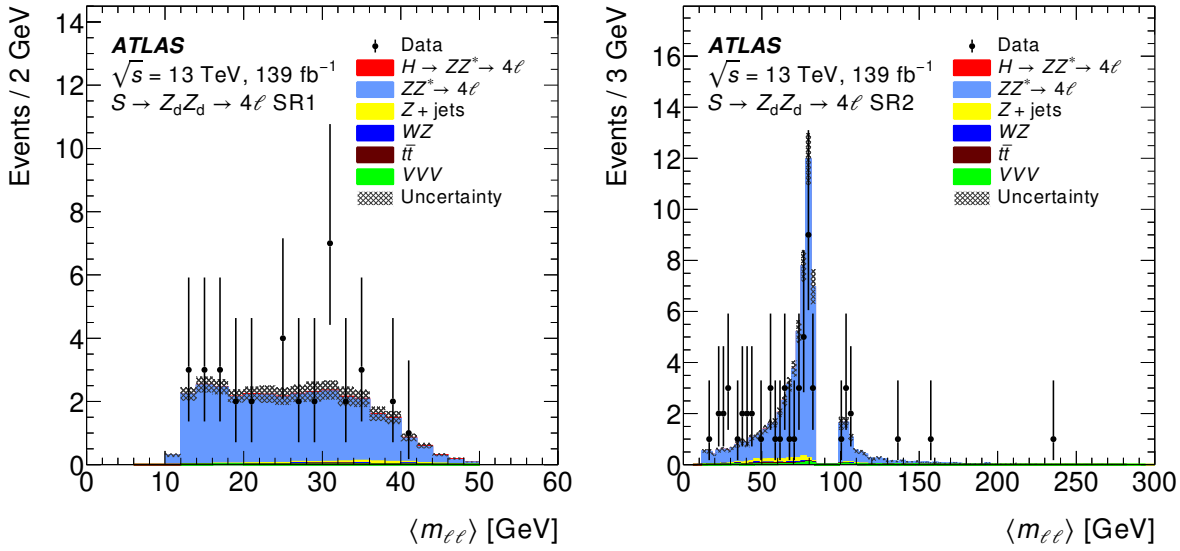
of Ref. [65] (SHERPA parameter `CSS_KIN_SCHEME=1`) is compared. This results in an uncertainty in the yield of 6% in SR1 and 12% in SR2, dominated by the matrix element matching scale. The uncertainty in the yield for the $H \to ZZ^* \to 4\ell$ process is about 9% [66]. The uncertainty in the data-driven Z + jets/$t\bar{t}$ background estimate is 50%–100%.

7 Results

Table 1 reports the observed and expected yields in the signal regions. In SR1 ($m_{4\ell} < 115$ GeV), 36 events are observed with an estimated background of 32.6 ± 3.3, while in SR2 ($m_{4\ell} > 130$ GeV), there are 55 events with an estimated background of 66.8 ± 8.0. The distributions of $\langle m_{\ell\ell} \rangle = \frac{1}{2}(m_{ab} + m_{cd})$ for both signal regions are shown in Figure 1, while Figure 2 shows the overall invariant mass $m_{4\ell}$, which can also be interpreted as the mass of the scalar candidate. The selected events are represented in the $(m_{4\ell}, \langle m_{\ell\ell} \rangle)$ plane in Figure 3, while the estimated background and an example signal shape in SR1 are shown in Figure 4.

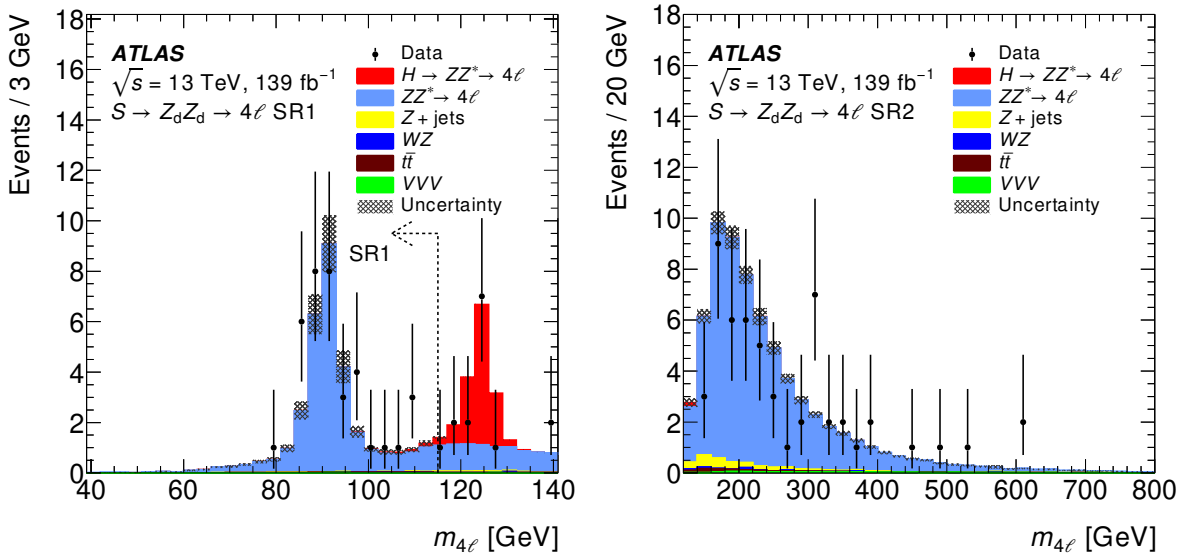
A two-dimensional interpolation procedure is used to obtain the shape of the $\langle m_{\ell\ell} \rangle$ distribution for the predicted signal at any point on the (m_S, m_{Z_d}) plane. For each generated signal MC sample, the $\langle m_{\ell\ell} \rangle$ distribution is fit. In SR1, these distributions are fit well by Gaussians, with three parameters. However, in SR2, the distributions are observed to be asymmetric, and a double-sided Crystal Ball distribution [67] is used instead, with seven parameters. For this interpolation, the S boson production cross-section and decay branching ratios are factored out, with the cross-section taken from Ref. [64] and the branching ratio set to one. Each fit parameter is then interpolated separately using the thin plate spline method [68–70], with the regularization parameter set to zero so that the interpolation passes smoothly through each control point.

Exclusion limits on $\sigma(gg \to S) \times \mathcal{B}(S \to Z_d Z_d \to 4\ell)$ are set using frequentist significance testing of a statistic derived from a profile likelihood ratio that considers the data, the background model, and the signal model distributions for various hypothesized (m_S, m_{Z_d}) points [71–73]. To reduce the resources required, events are binned coarsely in $m_{4\ell}$ and limits set independently within each $m_{4\ell}$ bin as a function of $\langle m_{\ell\ell} \rangle$. Bins with a width of 1 GeV are used for $\langle m_{\ell\ell} \rangle$. In SR1 there are eight equal-sized bins in $m_{4\ell}$ in the range of 30 GeV to 110 GeV, and for SR2, there are 14 equal-sized bins in the range of 125 GeV to 825 GeV.



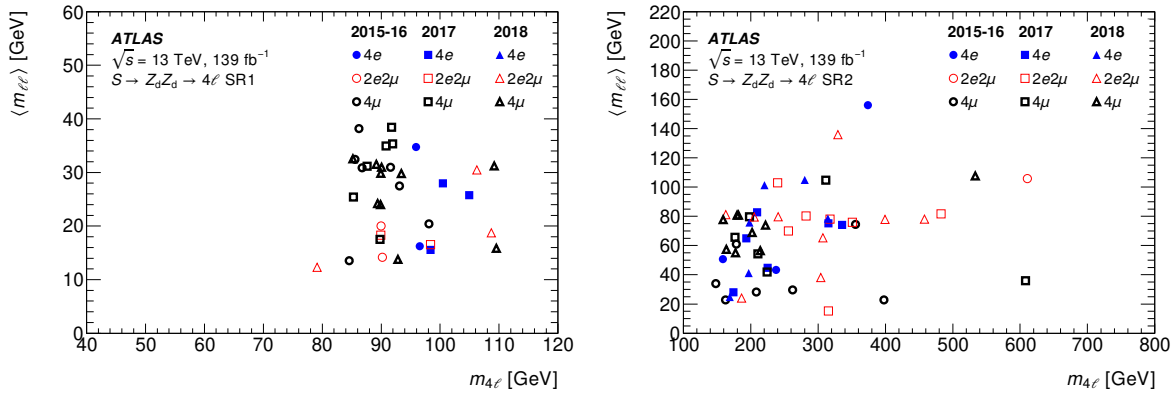
(a) (b)

Figure 1: Distributions of the average dilepton mass $\langle m_{\ell\ell} \rangle = \frac{1}{2}(m_{ab} + m_{cd})$ for the two signal regions (a) SR1 and (b) SR2. The hatched bands show the uncertainty in the background prediction. The uncertainties on the data points are asymmetric Poisson errors (Eqs. (40.76a) and (40.76b) of Ref. [62]).



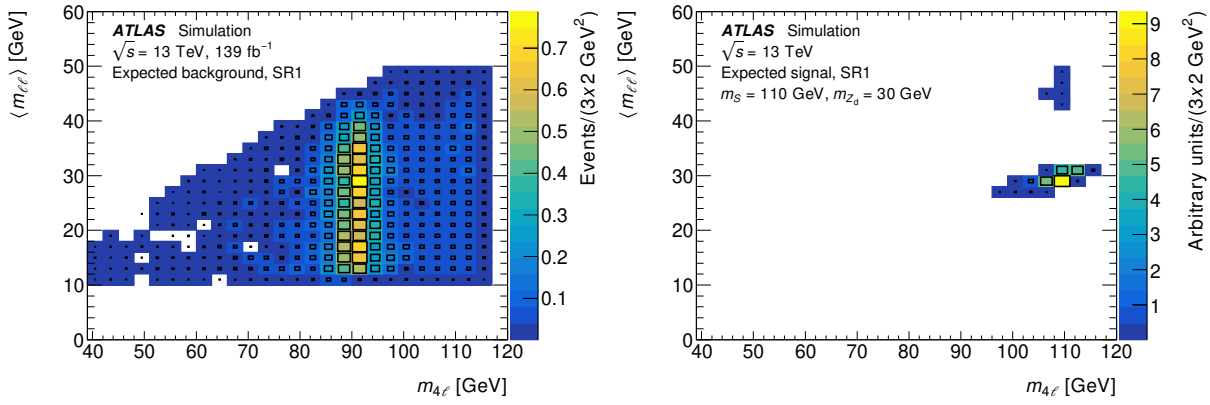
(a) (b)

Figure 2: Distributions of the total invariant mass $m_{4\ell}$ for the two signal regions (a) SR1 and (b) SR2. In (a), the requirement $m_{4\ell} < 115$ GeV is not applied, but is shown by the arrow. The hatched bands show the uncertainty in the background prediction; however, in (b), background uncertainties are not shown for $m_{4\ell} > 115$ GeV. The uncertainties on the data points are asymmetric Poisson errors (Eqs. (40.76a) and (40.76b) of Ref. [62]).



(a) (b)

Figure 3: Events selected in signal regions (a) SR1 and (b) SR2, represented in the $(m_{4\ell}, \langle m_{\ell\ell} \rangle)$ plane. The points are differentiated by final state ($4e$, $2e2\mu$, and 4μ) and by data-taking period (2015–2016, 2017, and 2018).



(a) (b)

Figure 4: (a) Estimated background and (b) expected signal shape for $(m_S, m_{Z_d}) = (110\,\text{GeV}, 30\,\text{GeV})$ in SR1 in the $(m_{4\ell}, \langle m_{\ell\ell} \rangle)$ plane, using both histograms and box representations. The signal normalization is arbitrary.

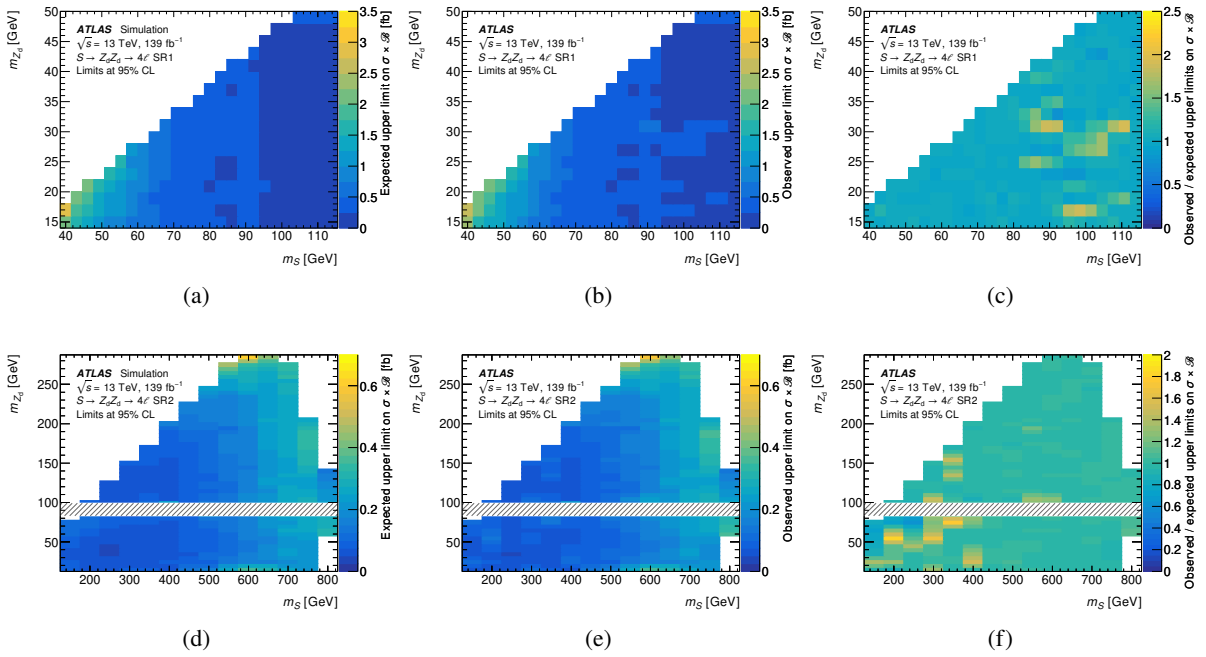
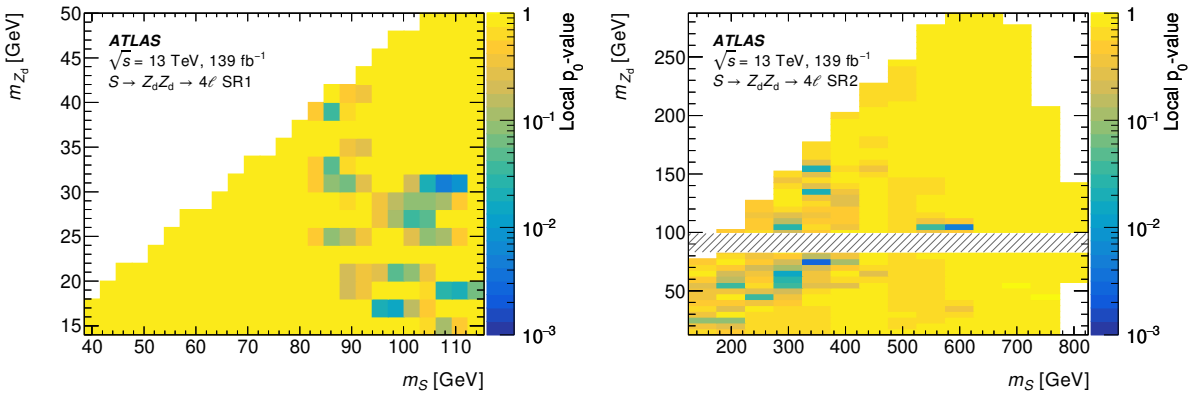


Figure 5: 95% CL expected and observed limits on the total cross-section times branching ratio $\sigma(gg \to S) \times \mathcal{B}(S \to Z_\mathrm{d}Z_\mathrm{d} \to 4\ell)$. (a) SR1 expected limit; (b) SR1 observed limit; (c) ratio of observed to expected limits in SR1; (d) SR2 expected limit; (e) SR2 observed limit; (f) ratio of observed to expected limits in SR2. The horizontal bands in the SR2 figures show the region excluded by the Z boson veto requirement, $|m_{ab,cd} - m_Z| > 8\,\mathrm{GeV}$.

Only signal MC events with $m_{4\ell}$ within one bin width of the generated m_S value are used to form the signal model distributions for this calculation. Limits are evaluated as described in Refs. [7–9] (using the `HypoTestInverter` component of the RooStats toolkit [74] and evaluating the test statistic distributions with MC pseudoexperiments taking into account both statistical and systematic uncertainties), resulting in $\mathrm{CL_s}$ frequentist upper limits at 95% confidence level (CL) on $\sigma(gg \to S) \times \mathcal{B}(S \to Z_\mathrm{d}Z_\mathrm{d} \to 4\ell)$ as a function of the m_{Z_d} parameter in each $m_{4\ell}$ bin. Expected and observed limits and their ratios are shown in Figures 5(a) to 5(c) for SR1 and Figures 5(d) to 5(f) for SR2. The corresponding one-dimensional local p_0-values are shown in Figures 6(a) and 6(b). In SR1, the point with the smallest p_0-value is at $(m_S, m_{Z_\mathrm{d}}) = (110\,\mathrm{GeV}, 30\,\mathrm{GeV})$ with a local significance of 2.7σ, while in SR2 the smallest p_0-value is at $(m_S, m_{Z_\mathrm{d}}) = (350\,\mathrm{GeV}, 75\,\mathrm{GeV})$ with a local significance of 2.8σ. The local significance can be converted to a global significance by including the look-elsewhere effect using MC pseudo experiments as outlined in Ref. [75]. For SR2, the largest global significance is 0.5σ.

The local significance of the deviation in SR1 is re-evaluated using the same frequentist significance testing as described above but applied in the two-dimensional $(m_{4\ell}, \langle m_{\ell\ell}\rangle)$ plane with a binning of $\Delta m_{4\ell} \times \Delta\langle m_{\ell\ell}\rangle = 3\,\mathrm{GeV} \times 1\,\mathrm{GeV}$. The evaluation is done in a narrow window scanned over the plane with size set to contain at least 99% of the expected signal. The resulting local p_0-value still corresponds to a significance of 2.7σ but for the mass point $(m_S, m_{Z_\mathrm{d}}) = (109\,\mathrm{GeV}, 31\,\mathrm{GeV})$. Converting this to a global significance yields 1.6σ.



(a) (b)

Figure 6: Local p_0-values in the $(m_{4\ell}, \langle m_{\ell\ell} \rangle)$ plane for (a) SR1 and (b) SR2, evaluated in slices in $m_{4\ell}$. The horizontal band in the SR2 figure shows the region excluded by the Z boson veto requirement, $|m_{ab,cd} - m_Z| > 8$ GeV.

8 Conclusions

A search is presented for the decay of a new scalar S into two new spin-1 particles $S \to Z_d Z_d$, with each Z_d boson decaying into a pair of electrons or muons, yielding an inclusive four-lepton final state. It is conducted in the plane of the reconstructed four-lepton mass and the average dilepton mass of the $Z_d \to \ell\ell$ candidates, and it uses 139 fb^{-1} of pp collision data at $\sqrt{s} = 13$ TeV recorded by the ATLAS experiment at the LHC during the period 2015–2018. Two different signal regions are studied, corresponding to 30 GeV $< m_S <$ 115 GeV and 130 GeV $< m_S <$ 800 GeV. The data are found to be consistent with the Standard Model background expectation, and 95% CL upper limits are set on the total cross-section times branching ratio $\sigma(gg \to S) \times \mathcal{B}(S \to Z_d Z_d \to 4\ell)$ as a function of m_S and m_{Z_d}. In the first signal region, the limits range from 0.14 fb to 3.1 fb and in the second, from 0.05 fb to 0.60 fb. These represent stringent constraints on the dark sector described by the Hidden Abelian Higgs Model, and also apply to similar models resulting in a four-lepton final state.

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The ATLAS Collaboration

G. Aad [102], B. Abbott [120], K. Abeling [55], N.J. Abicht [49], S.H. Abidi [29], A. Aboulhorma [35e], H. Abramowicz [152], H. Abreu [151], Y. Abulaiti [117], A.C. Abusleme Hoffman [137a], B.S. Acharya [69a,69b,n], C. Adam Bourdarios [4], L. Adamczyk [86a], L. Adamek [155], S.V. Addepalli [26], M.J. Addison [101], J. Adelman [115], A. Adiguzel [21c], T. Adye [134], A.A. Affolder [136], Y. Afik [36], M.N. Agaras [13], J. Agarwala [73a,73b], A. Aggarwal [100], C. Agheorghiesei [27c], A. Ahmad [36], F. Ahmadov [38,aa], W.S. Ahmed [104], S. Ahuja [95], X. Ai [62a], G. Aielli [76a,76b], A. Aikot [163], M. Ait Tamlihat [35e], B. Aitbenchikh [35a], I. Aizenberg [169], M. Akbiyik [100], T.P.A. Åkesson [98], A.V. Akimov [37], D. Akiyama [168], N.N. Akolkar [24], K. Al Khoury [41], G.L. Alberghi [23b], J. Albert [165], P. Albicocco [53], G.L. Albouy [60], S. Alderweireldt [52], M. Aleksa [36], I.N. Aleksandrov [38], C. Alexa [27b], T. Alexopoulos [10], A. Alfonsi [114], F. Alfonsi [23b], M. Algren [56], M. Alhroob [120], B. Ali [132], H.M.J. Ali [91], S. Ali [149], S.W. Alibocus [92], M. Aliev [146], G. Alimonti [71a], W. Alkakhi [55], C. Allaire [66], B.M.M. Allbrooke [147], J.F. Allen [52], C.A. Allendes Flores [137f], P.P. Allport [20], A. Aloisio [72a,72b], F. Alonso [90], C. Alpigiani [139], M. Alvarez Estevez [99], A. Alvarez Fernandez [100], M. Alves Cardoso [56], M.G. Alviggi [72a,72b], M. Aly [101], Y. Amaral Coutinho [83b], A. Ambler [104], C. Amelung[36], M. Amerl [101], C.G. Ames [109], D. Amidei [106], S.P. Amor Dos Santos [130a], K.R. Amos [163], V. Ananiev [125], C. Anastopoulos [140], T. Andeen [11], J.K. Anders [36], S.Y. Andrean [47a,47b], A. Andreazza [71a,71b], S. Angelidakis [9], A. Angerami [41,ad], A.V. Anisenkov [37], A. Annovi [74a], C. Antel [56], M.T. Anthony [140], E. Antipov [146], M. Antonelli [53], D.J.A. Antrim [17a], F. Anulli [75a], M. Aoki [84], T. Aoki [154], J.A. Aparisi Pozo [163], M.A. Aparo [147], L. Aperio Bella [48], C. Appelt [18], A. Apyan [26], N. Aranzabal [36], C. Arcangeletti [53], A.T.H. Arce [51], E. Arena [92], J-F. Arguin [108], S. Argyropoulos [54], J.-H. Arling [48], O. Arnaez [4], H. Arnold [114], Z.P. Arrubarrena Tame[109], G. Artoni [75a,75b], H. Asada [111], K. Asai [118], S. Asai [154], N.A. Asbah [61], J. Assahsah [35d], K. Assamagan [29], R. Astalos [28a], S. Atashi [160], R.J. Atkin [33a], M. Atkinson[162], N.B. Atlay [18], H. Atmani[62b], P.A. Atmasiddha [106], K. Augsten [132], S. Auricchio [72a,72b], A.D. Auriol [20], V.A. Austrup [101], G. Avolio [36], K. Axiotis [56], G. Azuelos [108,ah], D. Babal [28b], H. Bachacou [135], K. Bachas [153,q], A. Bachiu [34], F. Backman [47a,47b], A. Badea [61], P. Bagnaia [75a,75b], M. Bahmani [18], A.J. Bailey [163], V.R. Bailey [162], J.T. Baines [134], L. Baines [94], C. Bakalis [10], O.K. Baker [172], E. Bakos [15], D. Bakshi Gupta [8], V. Balakrishnan [120], R. Balasubramanian [114], E.M. Baldin [37], P. Balek [86a], E. Ballabene [23b,23a], F. Balli [135], L.M. Baltes [63a], W.K. Balunas [32], J. Balz [100], E. Banas [87], M. Bandieramonte [129], A. Bandyopadhyay [24], S. Bansal [24], L. Barak [152], M. Barakat [48], E.L. Barberio [105], D. Barberis [57b,57a], M. Barbero [102], G. Barbour[96], K.N. Barends [33a], T. Barillari [110], M-S. Barisits [36], T. Barklow [144], P. Baron [122], D.A. Baron Moreno [101], A. Baroncelli [62a], G. Barone [29], A.J. Barr [126], J.D. Barr [96], L. Barranco Navarro [47a,47b], F. Barreiro [99], J. Barreiro Guimarães da Costa [14a], U. Barron [152], M.G. Barros Teixeira [130a], S. Barsov [37], F. Bartels [63a], R. Bartoldus [144], A.E. Barton [91], P. Bartos [28a], A. Basan [100], M. Baselga [49], A. Bassalat [66,b], M.J. Basso [156a], C.R. Basson [101], R.L. Bates [59], S. Batlamous[35e], J.R. Batley [32], B. Batool [142], M. Battaglia [136], D. Battulga [18], M. Bauce [75a,75b], M. Bauer [36], P. Bauer [24], L.T. Bazzano Hurrell [30], J.B. Beacham [51], T. Beau [127], P.H. Beauchemin [158], F. Becherer [54], P. Bechtle [24], H.P. Beck [19,p], K. Becker [167], A.J. Beddall [82], V.A. Bednyakov [38], C.P. Bee [146], L.J. Beemster [15], T.A. Beermann [36], M. Begalli [83d], M. Begel [29], A. Behera [146], J.K. Behr [48], J.F. Beirer [55], F. Beisiegel [24], M. Belfkir [159], G. Bella [152], L. Bellagamba [23b], A. Bellerive [34], P. Bellos [20],

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R. Cherkaoui El Moursli [35e], E. Cheu [7], K. Cheung [65], L. Chevalier [135], V. Chiarella [53], G. Chiarelli [74a], N. Chiedde [102], G. Chiodini [70a], A.S. Chisholm [20], A. Chitan [27b], M. Chitishvili [163], M.V. Chizhov [38,s], K. Choi [11], A.R. Chomont [75a,75b], Y. Chou [103], E.Y.S. Chow [114], T. Chowdhury [33g], K.L. Chu [169], M.C. Chu [64a], X. Chu [14a,14e], J. Chudoba [131], J.J. Chwastowski [87], D. Cieri [110], K.M. Ciesla [86a], V. Cindro [93], A. Ciocio [17a], F. Cirotto [72a,72b], Z.H. Citron [169,l], M. Citterio [71a], D.A. Ciubotaru [27b], B.M. Ciungu [155], A. Clark [56], P.J. Clark [52], J.M. Clavijo Columbie [48], S.E. Clawson [48], C. Clement [47a,47b], J. Clercx [48], L. Clissa [23b,23a], Y. Coadou [102], M. Cobal [69a,69c], A. Coccaro [57b], R.F. Coelho Barrue [130a], R. Coelho Lopes De Sa [103], S. Coelli [71a], H. Cohen [152], A.E.C. Coimbra [71a,71b], B. Cole [41], J. Collot [60], P. Conde Muiño [130a,130g], M.P. Connell [33c], S.H. Connell [33c], I.A. Connelly [59], E.I. Conroy [126], F. Conventi [72a,ai], H.G. Cooke [20], A.M. Cooper-Sarkar [126], A. Cordeiro Oudot Choi [127], F. Cormier [164], L.D. Corpe [40], M. Corradi [75a,75b], F. Corriveau [104,y], A. Cortes-Gonzalez [18], M.J. Costa [163], F. Costanza [4], D. Costanzo [140], B.M. Cote [119], G. Cowan [95], K. Cranmer [170], D. Cremonini [23b,23a], S. Crépé-Renaudin [60], F. Crescioli [127], M. Cristinziani [142], M. Cristoforetti [78a,78b], V. Croft [114], J.E. Crosby [121], G. Crosetti [43b,43a], A. Cueto [99], T. Cuhadar Donszelmann [160], H. Cui [14a,14e], Z. Cui [7], W.R. Cunningham [59], F. Curcio [43b,43a], P. Czodrowski [36], M.M. Czurylo [63b], M.J. Da Cunha Sargedas De Sousa [57b,57a], J.V. Da Fonseca Pinto [83b], C. Da Via [101], W. Dabrowski [86a], T. Dado [49], S. Dahbi [33g], T. Dai [106], D. Dal Santo [19], C. Dallapiccola [103], M. Dam [42], G. D'amen [29], V. D'Amico [109], J. Damp [100], J.R. Dandoy [128], M.F. Daneri [30], M. Danninger [143], V. Dao [36], G. Darbo [57b], S. Darmora [6], S.J. Das [29,aj], S. D'Auria [71a,71b], C. David [156b], T. Davidek [133], B. Davis-Purcell [34], I. Dawson [94], H.A. Day-hall [132], K. De [8], R. De Asmundis [72a], N. De Biase [48], S. De Castro [23b,23a], N. De Groot [113], P. de Jong [114], H. De la Torre [107], A. De Maria [14c], A. De Salvo [75a], U. De Sanctis [76a,76b], A. De Santo [147], J.B. De Vivie De Regie [60], D.V. Dedovich [38], J. Degens [114], A.M. Deiana [44], F. Del Corso [23b,23a], J. Del Peso [99], F. Del Rio [63a], F. Deliot [135], C.M. Delitzsch [49], M. Della Pietra [72a,72b], D. Della Volpe [56], A. Dell'Acqua [36], L. Dell'Asta [71a,71b], M. Delmastro [4], P.A. Delsart [60], S. Demers [172], M. Demichev [38], S.P. Denisov [37], L. D'Eramo [40], D. Derendarz [87], F. Derue [127], P. Dervan [92], K. Desch [24], C. Deutsch [24], F.A. Di Bello [57b,57a], A. Di Ciaccio [76a,76b], L. Di Ciaccio [4], A. Di Domenico [75a,75b], C. Di Donato [72a,72b], A. Di Girolamo [36], G. Di Gregorio [5], A. Di Luca [78a,78b], B. Di Micco [77a,77b], R. Di Nardo [77a,77b], C. Diaconu [102], M. Diamantopoulou [34], F.A. Dias [114], T. Dias Do Vale [143], M.A. Diaz [137a,137b], F.G. Diaz Capriles [24], M. Didenko [163], E.B. Diehl [106], L. Diehl [54], S. Díez Cornell [48], C. Diez Pardos [142], C. Dimitriadi [161,24,161], A. Dimitrievska [17a], J. Dingfelder [24], I-M. Dinu [27b], S.J. Dittmeier [63b], F. Dittus [36], F. Djama [102], T. Djobava [150b], J.I. Djuvsland [16], C. Doglioni [101,98], J. Dolejsi [133], Z. Dolezal [133], M. Donadelli [83c], B. Dong [107], J. Donini [40], A. D'Onofrio [77a,77b], M. D'Onofrio [92], J. Dopke [134], A. Doria [72a], N. Dos Santos Fernandes [130a], M.T. Dova [90], A.T. Doyle [59], M.A. Draguet [126], E. Dreyer [169], I. Drivas-koulouris [10], A.S. Drobac [158], M. Drozdova [56], D. Du [62a], T.A. du Pree [114], F. Dubinin [37], M. Dubovsky [28a], E. Duchovni [169], G. Duckeck [109], O.A. Ducu [27b], D. Duda [52], A. Dudarev [36], E.R. Duden [26], M. D'uffizi [101], L. Duflot [66], M. Dührssen [36], C. Dülsen [171], A.E. Dumitriu [27b], M. Dunford [63a], S. Dungs [49], K. Dunne [47a,47b], A. Duperrin [102], H. Duran Yildiz [3a], M. Düren [58], A. Durglishvili [150b], B.L. Dwyer [115], G.I. Dyckes [17a], M. Dyndal [86a], S. Dysch [101], B.S. Dziedzic [87], Z.O. Earnshaw [147], G.H. Eberwein [126], B. Eckerova [28a], S. Eggebrecht [55], M.G. Eggleston [51], E. Egidio Purcino De Souza [127], L.F. Ehrke [56], G. Eigen [16], K. Einsweiler [17a], T. Ekelof [161], P.A. Ekman [98], S. El Farkh [35b], Y. El Ghazali [35b], H. El Jarrari [35e,149], A. El Moussaouy [35a], V. Ellajosyula [161], M. Ellert [161], F. Ellinghaus [171], A.A. Elliot [94],

N. Ellis [36], J. Elmsheuser [29], M. Elsing [36], D. Emeliyanov [134], Y. Enari [154], I. Ene [17a], S. Epari [13], J. Erdmann [49], P.A. Erland [87], M. Errenst [171], M. Escalier [66], C. Escobar [163], E. Etzion [152], G. Evans [130a], H. Evans [68], L.S. Evans [95], M.O. Evans [147], A. Ezhilov [37], S. Ezzarqtouni [35a], F. Fabbri [59], L. Fabbri [23b,23a], G. Facini [96], V. Fadeyev [136], R.M. Fakhrutdinov [37], S. Falciano [75a], L.F. Falda Ulhoa Coelho [36], P.J. Falke [24], J. Faltova [133], C. Fan [162], Y. Fan [14a], Y. Fang [14a,14e], M. Fanti [71a,71b], M. Faraj [69a,69b], Z. Farazpay [97], A. Farbin [8], A. Farilla [77a], T. Farooque [107], S.M. Farrington [52], F. Fassi [35e], D. Fassouliotis [9], M. Faucci Giannelli [76a,76b], W.J. Fawcett [32], L. Fayard [66], P. Federic [133], P. Federicova [131], O.L. Fedin [37,a], G. Fedotov [37], M. Feickert [170], L. Feligioni [102], D.E. Fellers [123], C. Feng [62b], M. Feng [14b], Z. Feng [114], M.J. Fenton [160], A.B. Fenyuk [37], L. Ferencz [48], R.A.M. Ferguson [91], S.I. Fernandez Luengo [137f], M.J.V. Fernoux [102], J. Ferrando [48], A. Ferrari [161], P. Ferrari [114,113], R. Ferrari [73a], D. Ferrere [56], C. Ferretti [106], F. Fiedler [100], A. Filipčič [93], E.K. Filmer [1], F. Filthaut [113], M.C.N. Fiolhais [130a,130c,c], L. Fiorini [163], W.C. Fisher [107], T. Fitschen [101], P.M. Fitzhugh [135], I. Fleck [142], P. Fleischmann [106], T. Flick [171], L. Flores [128], M. Flores [33d,ae], L.R. Flores Castillo [64a], L. Flores Sanz De Acedo [36], F.M. Follega [78a,78b], N. Fomin [16], J.H. Foo [155], B.C. Forland [68], A. Formica [135], A.C. Forti [101], E. Fortin [36], A.W. Fortman [61], M.G. Foti [17a], L. Fountas [9,j], D. Fournier [66], H. Fox [91], P. Francavilla [74a,74b], S. Francescato [61], S. Franchellucci [56], M. Franchini [23b,23a], S. Franchino [63a], D. Francis [36], L. Franco [113], L. Franconi [48], M. Franklin [61], G. Frattari [26], A.C. Freegard [94], W.S. Freund [83b], Y.Y. Frid [152], J. Friend [59], N. Fritzsche [50], A. Froch [54], D. Froidevaux [36], J.A. Frost [126], Y. Fu [62a], M. Fujimoto [118], E. Fullana Torregrosa [163,*], K.Y. Fung [64a], E. Furtado De Simas Filho [83b], M. Furukawa [154], J. Fuster [163], A. Gabrielli [23b,23a], A. Gabrielli [155], P. Gadow [36], G. Gagliardi [57b,57a], L.G. Gagnon [17a], E.J. Gallas [126], B.J. Gallop [134], K.K. Gan [119], S. Ganguly [154], J. Gao [62a], Y. Gao [52], F.M. Garay Walls [137a,137b], B. Garcia [29], C. García [163], A. Garcia Alonso [114], A.G. Garcia Caffaro [172], J.E. García Navarro [163], M. Garcia-Sciveres [17a], G.L. Gardner [128], R.W. Gardner [39], N. Garelli [158], D. Garg [80], R.B. Garg [144,o], J.M. Gargan [52], C.A. Garner [155], S.J. Gasiorowski [139], P. Gaspar [83b], G. Gaudio [73a], V. Gautam [13], P. Gauzzi [75a,75b], I.L. Gavrilenko [37], A. Gavrilyuk [37], C. Gay [164], G. Gaycken [48], E.N. Gazis [10], A.A. Geanta [27b], C.M. Gee [136], C. Gemme [57b], M.H. Genest [60], S. Gentile [75a,75b], S. George [95], W.F. George [20], T. Geralis [46], P. Gessinger-Befurt [36], M.E. Geyik [171], M. Ghani [167], M. Ghneimat [142], K. Ghorbanian [94], A. Ghosal [142], A. Ghosh [160], A. Ghosh [7], B. Giacobbe [23b], S. Giagu [75a,75b], T. Giani [114], P. Giannetti [74a], A. Giannini [62a], S.M. Gibson [95], M. Gignac [136], D.T. Gil [86b], A.K. Gilbert [86a], B.J. Gilbert [41], D. Gillberg [34], G. Gilles [114], N.E.K. Gillwald [48], L. Ginabat [127], D.M. Gingrich [2,ah], M.P. Giordani [69a,69c], P.F. Giraud [135], G. Giugliarelli [69a,69c], D. Giugni [71a], F. Giuli [36], I. Gkialas [9,j], L.K. Gladilin [37], C. Glasman [99], G.R. Gledhill [123], G. Glemža [48], M. Glisic [123], I. Gnesi [43b,f], Y. Go [29,aj], M. Goblirsch-Kolb [36], B. Gocke [49], D. Godin [108], B. Gokturk [21a], S. Goldfarb [105], T. Golling [56], M.G.D. Gololo [33g], D. Golubkov [37], J.P. Gombas [107], A. Gomes [130a,130b], G. Gomes Da Silva [142], A.J. Gomez Delegido [163], R. Gonçalo [130a,130c], G. Gonella [123], L. Gonella [20], A. Gongadze [150c], F. Gonnella [20], J.L. Gonski [41], R.Y. González Andana [52], S. González de la Hoz [163], S. Gonzalez Fernandez [13], R. Gonzalez Lopez [92], C. Gonzalez Renteria [17a], M.V. Gonzalez Rodrigues [48], R. Gonzalez Suarez [161], S. Gonzalez-Sevilla [56], G.R. Gonzalvo Rodriguez [163], L. Goossens [36], B. Gorini [36], E. Gorini [70a,70b], A. Gorišek [93], T.C. Gosart [128], A.T. Goshaw [51], M.I. Gostkin [38], S. Goswami [121], C.A. Gottardo [36], S.A. Gotz [109], M. Gouighri [35b], V. Goumarre [48], A.G. Goussiou [139], N. Govender [33c], I. Grabowska-Bold [86a], K. Graham [34], E. Gramstad [125], S. Grancagnolo [70a,70b], M. Grandi [147], C.M. Grant [1,135], P.M. Gravila [27f], F.G. Gravili [70a,70b], H.M. Gray [17a], M. Greco [70a,70b], C. Grefe [24], I.M. Gregor [48], P. Grenier [144], C. Grieco [13],

A.A. Grillo[136], K. Grimm[31], S. Grinstein[13,u], J.-F. Grivaz[66], E. Gross[169], J. Grosse-Knetter[55], C. Grud[106], J.C. Grundy[126], L. Guan[106], W. Guan[29], C. Gubbels[164], J.G.R. Guerrero Rojas[163], G. Guerrieri[69a,69c], F. Guescini[110], R. Gugel[100], J.A.M. Guhit[106], A. Guida[18], T. Guillemin[4], E. Guilloton[167,134], S. Guindon[36], F. Guo[14a,14e], J. Guo[62c], L. Guo[48], Y. Guo[106], R. Gupta[48], S. Gurbuz[24], S.S. Gurdasani[54], G. Gustavino[36], M. Guth[56], P. Gutierrez[120], L.F. Gutierrez Zagazeta[128], C. Gutschow[96], C. Gwenlan[126], C.B. Gwilliam[92], E.S. Haaland[125], A. Haas[117], M. Habedank[48], C. Haber[17a], H.K. Hadavand[8], A. Hadef[100], S. Hadzic[110], J.J. Hahn[142], E.H. Haines[96], M. Haleem[166], J. Haley[121], J.J. Hall[140], G.D. Hallewell[102], L. Halser[19], K. Hamano[165], H. Hamdaoui[35e], M. Hamer[24], G.N. Hamity[52], E.J. Hampshire[95], J. Han[62b], K. Han[62a], L. Han[14c], L. Han[62a], S. Han[17a], Y.F. Han[155], K. Hanagaki[84], M. Hance[136], D.A. Hangal[41,ad], H. Hanif[143], M.D. Hank[128], R. Hankache[101], J.B. Hansen[42], J.D. Hansen[42], P.H. Hansen[42], K. Hara[157], D. Harada[56], T. Harenberg[171], S. Harkusha[37], M.L. Harris[103], Y.T. Harris[126], J. Harrison[13], N.M. Harrison[119], P.F. Harrison[167], N.M. Hartman[110], N.M. Hartmann[109], Y. Hasegawa[141], A. Hasib[52], S. Haug[19], R. Hauser[107], C.M. Hawkes[20], R.J. Hawkings[36], Y. Hayashi[154], S. Hayashida[111], D. Hayden[107], C. Hayes[106], R.L. Hayes[114], C.P. Hays[126], J.M. Hays[94], H.S. Hayward[92], F. He[62a], M. He[14a,14e], Y. He[138], Y. He[127], N.B. Heatley[94], V. Hedberg[98], A.L. Heggelund[125], N.D. Hehir[94,*], C. Heidegger[54], K.K. Heidegger[54], W.D. Heidorn[81], J. Heilman[34], S. Heim[48], T. Heim[17a], J.G. Heinlein[128], J.J. Heinrich[123], L. Heinrich[110,af], J. Hejbal[131], L. Helary[48], A. Held[170], S. Hellesund[16], C.M. Helling[164], S. Hellman[47a,47b], R.C.W. Henderson[91], L. Henkelmann[32], A.M. Henriques Correia[36], H. Herde[98], Y. Hernández Jiménez[146], L.M. Herrmann[24], T. Herrmann[50], G. Herten[54], R. Hertenberger[109], L. Hervas[36], M.E. Hesping[100], N.P. Hessey[156a], H. Hibi[85], S.J. Hillier[20], J.R. Hinds[107], F. Hinterkeuser[24], M. Hirose[124], S. Hirose[157], D. Hirschbuehl[171], T.G. Hitchings[101], B. Hiti[93], J. Hobbs[146], R. Hobincu[27e], N. Hod[169], M.C. Hodgkinson[140], B.H. Hodkinson[32], A. Hoecker[36], J. Hofer[48], T. Holm[24], M. Holzbock[110], L.B.A.H. Hommels[32], B.P. Honan[101], J. Hong[62c], T.M. Hong[129], B.H. Hooberman[162], W.H. Hopkins[6], Y. Horii[111], S. Hou[149], A.S. Howard[93], J. Howarth[59], J. Hoya[6], M. Hrabovsky[122], A. Hrynevich[48], T. Hryn'ova[4], P.J. Hsu[65], S.-C. Hsu[139], Q. Hu[41], Y.F. Hu[14a,14e], S. Huang[64b], X. Huang[14c], Y. Huang[140], Y. Huang[14a], Z. Huang[101], Z. Hubacek[132], M. Huebner[24], F. Huegging[24], T.B. Huffman[126], C.A. Hugli[48], M. Huhtinen[36], S.K. Huiberts[16], R. Hulsken[104], N. Huseynov[12], J. Huston[107], J. Huth[61], R. Hyneman[144], G. Iacobucci[56], G. Iakovidis[29], I. Ibragimov[142], L. Iconomidou-Fayard[66], P. Iengo[72a,72b], R. Iguchi[154], T. Iizawa[84], Y. Ikegami[84], N. Ilic[155], H. Imam[35a], M. Ince Lezki[56], T. Ingebretsen Carlson[47a,47b], G. Introzzi[73a,73b], M. Iodice[77a], V. Ippolito[75a,75b], R.K. Irwin[92], M. Ishino[154], W. Islam[170], C. Issever[18,48], S. Istin[21a,al], H. Ito[168], J.M. Iturbe Ponce[64a], R. Iuppa[78a,78b], A. Ivina[169], J.M. Izen[45], V. Izzo[72a], P. Jacka[131,132], P. Jackson[1], R.M. Jacobs[48], B.P. Jaeger[143], C.S. Jagfeld[109], P. Jain[54], G. Jäkel[171], K. Jakobs[54], T. Jakoubek[169], J. Jamieson[59], K.W. Janas[86a], A.E. Jaspan[92], M. Javurkova[103], F. Jeanneau[135], L. Jeanty[123], J. Jejelava[150a,ab], P. Jenni[54,g], C.E. Jessiman[34], S. Jézéquel[4], C. Jia[62b], J. Jia[146], X. Jia[61], X. Jia[14a,14e], Z. Jia[14c], Y. Jiang[62a], S. Jiggins[48], J. Jimenez Pena[13], S. Jin[14c], A. Jinaru[27b], O. Jinnouchi[138], P. Johansson[140], K.A. Johns[7], J.W. Johnson[136], D.M. Jones[32], E. Jones[48], P. Jones[32], R.W.L. Jones[91], T.J. Jones[92], R. Joshi[119], J. Jovicevic[15], X. Ju[17a], J.J. Junggeburth[36], T. Junkermann[63a], A. Juste Rozas[13,u], M.K. Juzek[87], S. Kabana[137e], A. Kaczmarska[87], M. Kado[110], H. Kagan[119], M. Kagan[144], A. Kahn[41], A. Kahn[128], C. Kahra[100], T. Kaji[168], E. Kajomovitz[151], N. Kakati[169], I. Kalaitzidou[54], C.W. Kalderon[29], A. Kamenshchikov[155], S. Kanayama[138], N.J. Kang[136], D. Kar[33g], K. Karava[126], M.J. Kareem[156b], E. Karentzos[54],

I. Karkanias [153], O. Karkout [114], S.N. Karpov [38], Z.M. Karpova [38], V. Kartvelishvili [91], A.N. Karyukhin [37], E. Kasimi [153], J. Katzy [48], S. Kaur [34], K. Kawade [141], M.P. Kawale [120], T. Kawamoto [135], E.F. Kay [36], F.I. Kaya [158], S. Kazakos [107], V.F. Kazanin [37], Y. Ke [146], J.M. Keaveney [33a], R. Keeler [165], G.V. Kehris [61], J.S. Keller [34], A.S. Kelly[96], J.J. Kempster [147], K.E. Kennedy [41], P.D. Kennedy [100], O. Kepka [131], B.P. Kerridge [167], S. Kersten [171], B.P. Kerševan [93], S. Keshri [66], L. Keszeghova [28a], S. Ketabchi Haghighat [155], M. Khandoga [127], A. Khanov [121], A.G. Kharlamov [37], T. Kharlamova [37], E.E. Khoda [139], T.J. Khoo [18], G. Khoriauli [166], J. Khubua [150b,*], Y.A.R. Khwaira [66], A. Kilgallon [123], D.W. Kim [47a,47b], Y.K. Kim [39], N. Kimura [96], A. Kirchhoff [55], C. Kirfel [24], F. Kirfel [24], J. Kirk [134], A.E. Kiryunin [110], C. Kitsaki [10], O. Kivernyk [24], M. Klassen [63a], C. Klein [34], L. Klein [166], M.H. Klein [106], M. Klein [92,*], S.B. Klein [56], U. Klein [92], P. Klimek [36], A. Klimentov [29], T. Klioutchnikova [36], P. Kluit [114], S. Kluth [110], E. Kneringer [79], T.M. Knight [155], A. Knue [54], R. Kobayashi [88], D. Kobylianskii [169], S.F. Koch [126], M. Kocian [144], P. Kodyš [133], D.M. Koeck [123], P.T. Koenig [24], T. Koffas [34], M. Kolb [135], I. Koletsou [4], T. Komarek [122], K. Köneke [54], A.X.Y. Kong [1], T. Kono [118], N. Konstantinidis [96], B. Konya [98], R. Kopeliansky [68], S. Koperny [86a], K. Korcyl [87], K. Kordas [153,e], G. Koren [152], A. Korn [96], S. Korn [55], I. Korolkov [13], N. Korotkova [37], B. Kortman [114], O. Kortner [110], S. Kortner [110], W.H. Kostecka [115], V.V. Kostyukhin [142], A. Kotsokechagia [135], A. Kotwal [51], A. Koulouris [36], A. Kourkoumeli-Charalampidi [73a,73b], C. Kourkoumelis [9], E. Kourlitis [110,af], O. Kovanda [147], R. Kowalewski [165], W. Kozanecki [135], A.S. Kozhin [37], V.A. Kramarenko [37], G. Kramberger [93], P. Kramer [100], M.W. Krasny [127], A. Krasznahorkay [36], J.W. Kraus [171], J.A. Kremer [100], T. Kresse [50], J. Kretzschmar [92], K. Kreul [18], P. Krieger [155], S. Krishnamurthy [103], M. Krivos [133], K. Krizka [20], K. Kroeninger [49], H. Kroha [110], J. Kroll [131], J. Kroll [128], K.S. Krowpman [107], U. Kruchonak [38], H. Krüger [24], N. Krumnack[81], M.C. Kruse [51], J.A. Krzysiak [87], O. Kuchinskaia [37], S. Kuday [3a], S. Kuehn [36], R. Kuesters [54], T. Kuhl [48], V. Kukhtin [38], Y. Kulchitsky [37,a], S. Kuleshov [137d,137b], M. Kumar [33g], N. Kumari [48], A. Kupco [131], T. Kupfer[49], A. Kupich [37], O. Kuprash [54], H. Kurashige [85], L.L. Kurchaninov [156a], O. Kurdysh [66], Y.A. Kurochkin [37], A. Kurova [37], M. Kuze [138], A.K. Kvam [103], J. Kvita [122], T. Kwan [104], N.G. Kyriacou [106], L.A.O. Laatu [102], C. Lacasta [163], F. Lacava [75a,75b], H. Lacker [18], D. Lacour [127], N.N. Lad [96], E. Ladygin [38], B. Laforge [127], T. Lagouri [137e], S. Lai [55], I.K. Lakomiec [86a], N. Lalloue [60], J.E. Lambert [165], S. Lammers [68], W. Lampl [7], C. Lampoudis [153,e], A.N. Lancaster [115], E. Lançon [29], U. Landgraf [54], M.P.J. Landon [94], V.S. Lang [54], R.J. Langenberg [103], O.K.B. Langrekken [125], A.J. Lankford [160], F. Lanni [36], K. Lantzsch [24], A. Lanza [73a], A. Lapertosa [57b,57a], J.F. Laporte [135], T. Lari [71a], F. Lasagni Manghi [23b], M. Lassnig [36], V. Latonova [131], A. Laudrain [100], A. Laurier [151], S.D. Lawlor [95], Z. Lawrence [101], M. Lazzaroni [71a,71b], B. Le[101], E.M. Le Boulicaut [51], B. Leban [93], A. Lebedev [81], M. LeBlanc [36], F. Ledroit-Guillon [60], A.C.A. Lee[96], S.C. Lee [149], S. Lee [47a,47b], T.F. Lee [92], L.L. Leeuw [33c], H.P. Lefebvre [95], M. Lefebvre [165], C. Leggett [17a], G. Lehmann Miotto [36], M. Leigh [56], W.A. Leight [103], W. Leinonen [113], A. Leisos [153,t], M.A.L. Leite [83c], C.E. Leitgeb [48], R. Leitner [133], K.J.C. Leney [44], T. Lenz [24], S. Leone [74a], C. Leonidopoulos [52], A. Leopold [145], C. Leroy [108], R. Les [107], C.G. Lester [32], M. Levchenko [37], J. Levêque [4], D. Levin [106], L.J. Levinson [169], M.P. Lewicki [87], D.J. Lewis [4], A. Li [5], B. Li [62b], C. Li[62a], C-Q. Li [62c], H. Li [62a], H. Li [62b], H. Li [14c], H. Li [62b], K. Li [139], L. Li [62c], M. Li [14a,14e], Q.Y. Li [62a], S. Li [14a,14e], S. Li [62d,62c,d], T. Li [5], X. Li [104], Z. Li [126], Z. Li [104], Z. Li [92], Z. Li [14a,14e], S. Liang [14a,14e], Z. Liang [14a], M. Liberatore [135], B. Liberti [76a], K. Lie [64c], J. Lieber Marin [83b], H. Lien [68], K. Lin [107], R.E. Lindley [7], J.H. Lindon [2], E. Lipeles [128], A. Lipniacka [16], A. Lister [164], J.D. Little [4], B. Liu [14a], B.X. Liu [143],

D. Liu[62d,62c], J.B. Liu[62a], J.K.K. Liu[32], K. Liu[62d,62c], M. Liu[62a], M.Y. Liu[62a], P. Liu[14a], Q. Liu[62d,139,62c], X. Liu[62a], Y. Liu[14d,14e], Y.L. Liu[62b], Y.W. Liu[62a], J. Llorente Merino[143], S.L. Lloyd[94], E.M. Lobodzinska[48], P. Loch[7], S. Loffredo[76a,76b], T. Lohse[18], K. Lohwasser[140], E. Loiacono[48], M. Lokajicek[131,*], J.D. Lomas[20], J.D. Long[162], I. Longarini[160], L. Longo[70a,70b], R. Longo[162], I. Lopez Paz[67], A. Lopez Solis[48], J. Lorenz[109], N. Lorenzo Martinez[4], A.M. Lory[109], G. Löschcke Centeno[147], O. Loseva[37], X. Lou[47a,47b], X. Lou[14a,14e], A. Lounis[66], J. Love[6], P.A. Love[91], G. Lu[14a,14e], M. Lu[80], S. Lu[128], Y.J. Lu[65], H.J. Lubatti[139], C. Luci[75a,75b], F.L. Lucio Alves[14c], A. Lucotte[60], F. Luehring[68], I. Luise[146], O. Lukianchuk[66], O. Lundberg[145], B. Lund-Jensen[145,*], N.A. Luongo[123], M.S. Lutz[152], D. Lynn[29], H. Lyons[92], R. Lysak[131], E. Lytken[98], V. Lyubushkin[38], T. Lyubushkina[38], M.M. Lyukova[146], H. Ma[29], K. Ma[62a], L.L. Ma[62b], Y. Ma[121], D.M. Mac Donell[165], G. Maccarrone[53], J.C. MacDonald[100], R. Madar[40], W.F. Mader[50], J. Maeda[85], T. Maeno[29], M. Maerker[50], H. Maguire[140], V. Maiboroda[135], A. Maio[130a,130b,130d], K. Maj[86a], O. Majersky[48], S. Majewski[123], N. Makovec[66], V. Maksimovic[15], B. Malaescu[127], Pa. Malecki[87], V.P. Maleev[37], F. Malek[60], M. Mali[93], D. Malito[95], U. Mallik[80,*], S. Maltezos[10], S. Malyukov[38], J. Mamuzic[13], G. Mancini[53], G. Manco[73a,73b], J.P. Mandalia[94], I. Mandić[93], L. Manhaes de Andrade Filho[83a], I.M. Maniatis[169], J. Manjarres Ramos[102,ac], D.C. Mankad[169], A. Mann[109], B. Mansoulie[135], S. Manzoni[36], A. Marantis[153,t], G. Marchiori[5], M. Marcisovsky[131], C. Marcon[71a], M. Marinescu[20], M. Marjanovic[120], E.J. Marshall[91], Z. Marshall[17a], S. Marti-Garcia[163], T.A. Martin[167], V.J. Martin[52], B. Martin dit Latour[16], L. Martinelli[75a,75b], M. Martinez[13,u], P. Martinez Agullo[163], V.I. Martinez Outschoorn[103], P. Martinez Suarez[13], S. Martin-Haugh[134], V.S. Martoiu[27b], A.C. Martyniuk[96], A. Marzin[36], D. Mascione[78a,78b], L. Masetti[100], T. Mashimo[154], J. Masik[101], A.L. Maslennikov[37], L. Massa[23b], P. Massarotti[72a,72b], P. Mastrandrea[74a,74b], A. Mastroberardino[43b,43a], T. Masubuchi[154], T. Mathisen[161], J. Matousek[133], N. Matsuzawa[154], J. Maurer[27b], B. Maček[93], D.A. Maximov[37], R. Mazini[149], I. Maznas[153], M. Mazza[107], S.M. Mazza[136], E. Mazzeo[71a,71b], C. Mc Ginn[29], J.P. Mc Gowan[104], S.P. Mc Kee[106], E.F. McDonald[105], A.E. McDougall[114], J.A. Mcfayden[147], R.P. McGovern[128], G. Mchedlidze[150b], R.P. Mckenzie[33g], T.C. Mclachlan[48], D.J. Mclaughlin[96], K.D. McLean[165], S.J. McMahon[134], P.C. McNamara[105], C.M. Mcpartland[92], R.A. McPherson[165,y], S. Mehlhase[109], A. Mehta[92], D. Melini[151], B.R. Mellado Garcia[33g], A.H. Melo[55], F. Meloni[48], A.M. Mendes Jacques Da Costa[101], H.Y. Meng[155], L. Meng[91], S. Menke[110], M. Mentink[36], E. Meoni[43b,43a], C. Merlassino[126], L. Merola[72a,72b], C. Meroni[71a,71b], G. Merz[106], O. Meshkov[37], J. Metcalfe[6], A.S. Mete[6], C. Meyer[68], J-P. Meyer[135], R.P. Middleton[134], L. Mijović[52], G. Mikenberg[169], M. Mikestikova[131], M. Mikuž[93], H. Mildner[100], A. Milic[36], C.D. Milke[44], D.W. Miller[39], L.S. Miller[34], A. Milov[169], D.A. Milstead[47a,47b], T. Min[14c], A.A. Minaenko[37], I.A. Minashvili[150b], L. Mince[59], A.I. Mincer[117], B. Mindur[86a], M. Mineev[38], Y. Mino[88], L.M. Mir[13], M. Miralles Lopez[163], M. Mironova[17a], A. Mishima[154], M.C. Missio[113], T. Mitani[168], A. Mitra[167], V.A. Mitsou[163], O. Miu[155], P.S. Miyagawa[94], Y. Miyazaki[89], A. Mizukami[84], T. Mkrtchyan[63a], M. Mlinarevic[96], T. Mlinarevic[96], M. Mlynarikova[36], S. Mobius[19], K. Mochizuki[108], P. Moder[48], P. Mogg[109], A.F. Mohammed[14a,14e], S. Mohapatra[41], G. Mokgatitswane[33g], L. Moleri[169], B. Mondal[142], S. Mondal[132], K. Mönig[48], E. Monnier[102], L. Monsonis Romero[163], J. Montejo Berlingen[13,84], M. Montella[119], F. Montereali[77a,77b], F. Monticelli[90], S. Monzani[69a,69c], N. Morange[66], A.L. Moreira De Carvalho[130a], M. Moreno Llácer[163], C. Moreno Martinez[56], P. Morettini[57b], S. Morgenstern[36], M. Morii[61], M. Morinaga[154], A.K. Morley[36], F. Morodei[75a,75b],

L. Morvaj[36], P. Moschovakos[36], B. Moser[36], M. Mosidze[150b], T. Moskalets[54], P. Moskvitina[113], J. Moss[31,m], E.J.W. Moyse[103], O. Mtintsilana[33g], S. Muanza[102], J. Mueller[129], D. Muenstermann[91], R. Müller[19], G.A. Mullier[161], A.J. Mullin[32], J.J. Mullin[128], D.P. Mungo[155], D. Munoz Perez[163], F.J. Munoz Sanchez[101], M. Murin[101], W.J. Murray[167,134], A. Murrone[71a,71b], J.M. Muse[120], M. Muškinja[17a], C. Mwewa[29], A.G. Myagkov[37,a], A.J. Myers[8], A.A. Myers[129], G. Myers[68], M. Myska[132], B.P. Nachman[17a], O. Nackenhorst[49], A. Nag[50], K. Nagai[126], K. Nagano[84], J.L. Nagle[29,aj], E. Nagy[102], A.M. Nairz[36], Y. Nakahama[84], K. Nakamura[84], K. Nakkalil[5], H. Nanjo[124], R. Narayan[44], E.A. Narayanan[112], I. Naryshkin[37], M. Naseri[34], S. Nasri[159], C. Nass[24], G. Navarro[22a], J. Navarro-Gonzalez[163], R. Nayak[152], A. Nayaz[18], P.Y. Nechaeva[37], F. Nechansky[48], L. Nedic[126], T.J. Neep[20], A. Negri[73a,73b], M. Negrini[23b], C. Nellist[114], C. Nelson[104], K. Nelson[106], S. Nemecek[131], M. Nessi[36,h], M.S. Neubauer[162], F. Neuhaus[100], J. Neundorf[48], R. Newhouse[164], P.R. Newman[20], C.W. Ng[129], Y.W.Y. Ng[48], B. Ngair[35e], H.D.N. Nguyen[108], R.B. Nickerson[126], R. Nicolaidou[135], J. Nielsen[136], M. Niemeyer[55], J. Niermann[55,36], N. Nikiforou[36], V. Nikolaenko[37,a], I. Nikolic-Audit[127], K. Nikolopoulos[20], P. Nilsson[29], I. Ninca[48], H.R. Nindhito[56], G. Ninio[152], A. Nisati[75a], N. Nishu[2], R. Nisius[110], J-E. Nitschke[50], E.K. Nkadimeng[33g], S.J. Noacco Rosende[90], T. Nobe[154], D.L. Noel[32], T. Nommensen[148], M.B. Norfolk[140], R.R.B. Norisam[96], B.J. Norman[34], J. Novak[93], T. Novak[48], L. Novotny[132], R. Novotny[112], L. Nozka[122], K. Ntekas[160], N.M.J. Nunes De Moura Junior[83b], E. Nurse[96], J. Ocariz[127], A. Ochi[85], I. Ochoa[130a], S. Oerdek[48,v], J.T. Offermann[39], A. Ogrodnik[133], A. Oh[101], C.C. Ohm[145], H. Oide[84], R. Oishi[154], M.L. Ojeda[48], Y. Okazaki[88], M.W. O'Keefe[92], Y. Okumura[154], L.F. Oleiro Seabra[130a], S.A. Olivares Pino[137d], D. Oliveira Damazio[29], D. Oliveira Goncalves[83a], J.L. Oliver[160], A. Olszewski[87], Ö.O. Öncel[54], D.C. O'Neil[143], A.P. O'Neill[19], A. Onofre[130a,130e], P.U.E. Onyisi[11], M.J. Oreglia[39], G.E. Orellana[90], D. Orestano[77a,77b], N. Orlando[13], R.S. Orr[155], V. O'Shea[59], L.M. Osojnak[128], R. Ospanov[62a], G. Otero y Garzon[30], H. Otono[89], P.S. Ott[63a], G.J. Ottino[17a], M. Ouchrif[35d], J. Ouellette[29], F. Ould-Saada[125], M. Owen[59], R.E. Owen[134], K.Y. Oyulmaz[21a], V.E. Ozcan[21a], N. Ozturk[8], S. Ozturk[82], H.A. Pacey[32], A. Pacheco Pages[13], C. Padilla Aranda[13], G. Padovano[75a,75b], S. Pagan Griso[17a], G. Palacino[68], A. Palazzo[70a,70b], S. Palestini[36], J. Pan[172], T. Pan[64a], D.K. Panchal[11], C.E. Pandini[114], J.G. Panduro Vazquez[95], H.D. Pandya[1], H. Pang[14b], P. Pani[48], G. Panizzo[69a,69c], L. Paolozzi[56], C. Papadatos[108], S. Parajuli[44], A. Paramonov[6], C. Paraskevopoulos[10], D. Paredes Hernandez[64b], T.H. Park[155], M.A. Parker[32], F. Parodi[57b,57a], E.W. Parrish[115], V.A. Parrish[52], J.A. Parsons[41], U. Parzefall[54], B. Pascual Dias[108], L. Pascual Dominguez[152], F. Pasquali[114], E. Pasqualucci[75a], S. Passaggio[57b], F. Pastore[95], P. Pasuwan[47a,47b], P. Patel[87], U.M. Patel[51], J.R. Pater[101], T. Pauly[36], J. Pearkes[144], M. Pedersen[125], R. Pedro[130a], S.V. Peleganchuk[37], O. Penc[36], E.A. Pender[52], H. Peng[62a], K.E. Penski[109], M. Penzin[37], B.S. Peralva[83d], A.P. Pereira Peixoto[60], L. Pereira Sanchez[47a,47b], D.V. Perepelitsa[29,aj], E. Perez Codina[156a], M. Perganti[10], L. Perini[71a,71b,*], H. Pernegger[36], O. Perrin[40], K. Peters[48], R.F.Y. Peters[101], B.A. Petersen[36], T.C. Petersen[42], E. Petit[102], V. Petousis[132], C. Petridou[153,e], A. Petrukhin[142], M. Pettee[17a], N.E. Pettersson[36], A. Petukhov[37], K. Petukhova[133], A. Peyaud[135], R. Pezoa[137f], L. Pezzotti[36], G. Pezzullo[172], T.M. Pham[170], T. Pham[105], P.W. Phillips[134], G. Piacquadio[146], E. Pianori[17a], F. Piazza[71a,71b], R. Piegaia[30], D. Pietreanu[27b], A.D. Pilkington[101], M. Pinamonti[69a,69c], J.L. Pinfold[2], B.C. Pinheiro Pereira[130a], A.E. Pinto Pinoargote[135], L. Pintucci[69a,69c], K.M. Piper[147], A. Pirttikoski[56], C. Pitman Donaldson[96], D.A. Pizzi[34], L. Pizzimento[64b], A. Pizzini[114], M.-A. Pleier[29], V. Plesanovs[54], V. Pleskot[133], E. Plotnikova[38], G. Poddar[4],

R. Poettgen[98], L. Poggioli[127], I. Pokharel[55], S. Polacek[133], G. Polesello[73a], A. Poley[143,156a], R. Polifka[132], A. Polini[23b], C.S. Pollard[167], Z.B. Pollock[119], V. Polychronakos[29], E. Pompa Pacchi[75a,75b], D. Ponomarenko[113], L. Pontecorvo[36], S. Popa[27a], G.A. Popeneciu[27d], A. Poreba[36], D.M. Portillo Quintero[156a], S. Pospisil[132], M.A. Postill[140], P. Postolache[27c], K. Potamianos[167], P.A. Potepa[86a], I.N. Potrap[38], C.J. Potter[32], H. Potti[1], T. Poulsen[48], J. Poveda[163], M.E. Pozo Astigarraga[36], A. Prades Ibanez[163], J. Pretel[54], D. Price[101], M. Primavera[70a], M.A. Principe Martin[99], R. Privara[122], T. Procter[59], M.L. Proffitt[139], N. Proklova[128], K. Prokofiev[64c], G. Proto[110], S. Protopopescu[29], J. Proudfoot[6], M. Przybycien[86a], W.W. Przygoda[86b], J.E. Puddefoot[140], D. Pudzha[37], D. Pyatiizbyantseva[37], J. Qian[106], D. Qichen[101], Y. Qin[101], T. Qiu[52], A. Quadt[55], M. Queitsch-Maitland[101], G. Quetant[56], R.P. Quinn[164], G. Rabanal Bolanos[61], D. Rafanoharana[54], F. Ragusa[71a,71b], J.L. Rainbolt[39], J.A. Raine[56], S. Rajagopalan[29], E. Ramakoti[37], K. Ran[48,14e], N.P. Rapheeha[33g], H. Rasheed[27b], V. Raskina[127], D.F. Rassloff[63a], S. Rave[100], B. Ravina[55], I. Ravinovich[169], M. Raymond[36], A.L. Read[125], N.P. Readioff[140], D.M. Rebuzzi[73a,73b], G. Redlinger[29], A.S. Reed[110], K. Reeves[26], J.A. Reidelsturz[171], D. Reikher[152], A. Rej[142], C. Rembser[36], A. Renardi[48], M. Renda[27b], M.B. Rendel[110], F. Renner[48], A.G. Rennie[160], A.L. Rescia[48], S. Resconi[71a], M. Ressegotti[57b,57a], S. Rettie[36], J.G. Reyes Rivera[107], B. Reynolds[119], E. Reynolds[17a], O.L. Rezanova[37], P. Reznicek[133], N. Ribaric[91], E. Ricci[78a,78b], R. Richter[110], S. Richter[47a,47b], E. Richter-Was[86b], M. Ridel[127], S. Ridouani[35d], P. Rieck[117], P. Riedler[36], M. Rijssenbeek[146], A. Rimoldi[73a,73b], M. Rimoldi[48], L. Rinaldi[23b,23a], T.T. Rinn[29], M.P. Rinnagel[109], G. Ripellino[161], I. Riu[13], P. Rivadeneira[48], J.C. Rivera Vergara[165], F. Rizatdinova[121], E. Rizvi[94], B.A. Roberts[167], B.R. Roberts[17a], S.H. Robertson[104,y], D. Robinson[32], C.M. Robles Gajardo[137f], M. Robles Manzano[100], A. Robson[59], A. Rocchi[76a,76b], C. Roda[74a,74b], S. Rodriguez Bosca[63a], Y. Rodriguez Garcia[22a], A. Rodriguez Rodriguez[54], A.M. Rodríguez Vera[156b], S. Roe[36], J.T. Roemer[160], A.R. Roepe-Gier[136], J. Roggel[171], O. Røhne[125], R.A. Rojas[103], C.P.A. Roland[68], J. Roloff[29], A. Romaniouk[37], E. Romano[73a,73b], M. Romano[23b], A.C. Romero Hernandez[162], N. Rompotis[92], L. Roos[127], S. Rosati[75a], B.J. Rosser[39], E. Rossi[126], E. Rossi[72a,72b], L.P. Rossi[57b], L. Rossini[54], R. Rosten[119], M. Rotaru[27b], B. Rottler[54], C. Rougier[102,ac], D. Rousseau[66], D. Rousso[32], A. Roy[162], S. Roy-Garand[155], A. Rozanov[102], Y. Rozen[151], X. Ruan[33g], A. Rubio Jimenez[163], A.J. Ruby[92], V.H. Ruelas Rivera[18], T.A. Ruggeri[1], A. Ruggiero[126], A. Ruiz-Martinez[163], A. Rummler[36], Z. Rurikova[54], N.A. Rusakovich[38], H.L. Russell[165], G. Russo[75a,75b], J.P. Rutherfoord[7], S. Rutherford Colmenares[32], K. Rybacki[91], M. Rybar[133], E.B. Rye[125], A. Ryzhov[44], J.A. Sabater Iglesias[56], P. Sabatini[163], L. Sabetta[75a,75b], H.F-W. Sadrozinski[136], F. Safai Tehrani[75a], B. Safarzadeh Samani[147], M. Safdari[144], S. Saha[165], M. Sahinsoy[110], M. Saimpert[135], M. Saito[154], T. Saito[154], D. Salamani[36], A. Salnikov[144], J. Salt[163], A. Salvador Salas[13], D. Salvatore[43b,43a], F. Salvatore[147], A. Salzburger[36], D. Sammel[54], D. Sampsonidis[153,e], D. Sampsonidou[123], J. Sánchez[163], A. Sanchez Pineda[4], V. Sanchez Sebastian[163], H. Sandaker[125], C.O. Sander[48], J.A. Sandesara[103], M. Sandhoff[171], C. Sandoval[22b], D.P.C. Sankey[134], T. Sano[88], A. Sansoni[53], L. Santi[75a,75b], C. Santoni[40], H. Santos[130a,130b], S.N. Santpur[17a], A. Santra[169], K.A. Saoucha[140], J.G. Saraiva[130a,130d], J. Sardain[7], O. Sasaki[84], K. Sato[157], C. Sauer[63b], F. Sauerburger[54], E. Sauvan[4], P. Savard[155,ah], R. Sawada[154], C. Sawyer[134], L. Sawyer[97], I. Sayago Galvan[163], C. Sbarra[23b], A. Sbrizzi[23b,23a], T. Scanlon[96], J. Schaarschmidt[139], P. Schacht[110], D. Schaefer[39], U. Schäfer[100], A.C. Schaffer[66,44], D. Schaile[109], R.D. Schamberger[146], C. Scharf[18], M.M. Schefer[19], V.A. Schegelsky[37], D. Scheirich[133], F. Schenck[18], M. Schernau[160], C. Scheulen[55], C. Schiavi[57b,57a], E.J. Schioppa[70a,70b],

M. Schioppa[43b,43a], B. Schlag[144], K.E. Schleicher[54], 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[139], H.R. Schwartz[136], A. Schwartzman[144], 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[145], 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[147], S.M. Shaw[101], A. Shcherbakova[37], Q. Shen[62c,5], P. Sherwood[96], L. Shi[96], X. Shi[14a], C.O. Shimmin[172], Y. Shimogama[168], J.D. Shinner[95], I.P.J. Shipsey[126,*], S. Shirabe[56,h], M. Shiyakova[38,w], J. Shlomi[169], M.J. Shochet[39], J. Shojaii[105], D.R. Shope[125], B. Shrestha[120], S. Shrestha[119,ak], 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[147], 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[144], M. Smizanska[91], K. Smolek[132], A.A. Snesarev[37], S.R. Snider[155], H.L. Snoek[114], S. Snyder[29], R. Sobie[165,y], A. Soffer[152], 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], M. Spina[147], 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,ac], 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[143,156a], H.J. Stelzer[129], O. Stelzer-Chilton[156a], H. Stenzel[58], T.J. Stevenson[147], 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[145], S. Strandberg[47a,47b], 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[144], S. Su[62a], W. Su[62d], X. Su[62a,66], K. Sugizaki[154], 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[147], 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,v], 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[152], A. Tanaka[154], J. Tanaka[154], R. Tanaka[66], M. Tanasini[57b,57a], Z. Tao[164], S. Tapia Araya[137f], S. Tapprogge[100],

A. Tarek Abouelfadl Mohamed [107], S. Tarem [151], 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 [154], Y. Tayalati [35e,x], G.N. Taylor [105], W. Taylor [156b], H. Teagle[92], A.S. Tee [170], R. Teixeira De Lima [144], P. Teixeira-Dias [95], J.J. Teoh [155], K. Terashi [154], J. Terron [99], S. Terzo [13], M. Testa [53], R.J. Teuscher [155,y], 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 [23b,23a], 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 [144,o], K.W. Topolnicki [86b], E. Torrence [123], H. Torres [102,ac], E. Torró Pastor [163], M. Toscani [30], C. Tosciri [39], M. Tost [11], D.R. Tovey [140], 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 [146], M. Tsai [106], A. Tsiamis [153,e], P.V. Tsiareshka[37], S. Tsigaridas [156a], A. Tsirigotis [153,t], V. Tsiskaridze [155], E.G. Tskhadadze [150a], M. Tsopoulou [153,e], Y. Tsujikawa [88], I.I. Tsukerman [37], V. Tsulaia [17a], S. Tsuno [84], O. Tsur[151], K. Tsuri [118], D. Tsybychev [146], Y. Tu [64b], A. Tudorache [27b], V. Tudorache [27b], A.N. Tuna [36], S. Turchikhin [38], I. Turk Cakir [3a], R. Turra [71a], T. Turtuvshin [38,z], P.M. Tuts [41], S. Tzamarias [153,e], P. Tzanis [10], E. Tzovara [100], K. Uchida[154], 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 [138], 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,ac], J.A. Valls Ferrer [163], D.R. Van Arneman [114], T.R. Van Daalen [139], 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 [152], L. Vannoli [57b,57a], R. Vari [75a], E.W. Varnes [7], C. Varni [17b], T. Varol [149], D. Varouchas [66], L. Varriale [163], K.E. Varvell [148], 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], A. Verbytskyi [110], M. Verducci [74a,74b], C. Vergis [24], M. Verissimo De Araujo [83b], W. Verkerke [114], J.C. Vermeulen [114], C. Vernieri [144], M. Vessella [103], M.C. Vetterli [143,ah], A. Vgenopoulos [153,e], N. Viaux Maira [137f], T. Vickey [140], O.E. Vickey Boeriu [140], 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 [147], V. Vladimirov[167], E. Voevodina [110], F. Vogel [109], P. Vokac [132], J. Von Ahnen [48], E. Von Toerne [24], B. Vormwald [36], V. Vorobel [133], K. Vorobev [37], M. Vos [163], K. Voss [142], J.H. Vossebeld [92], M. Vozak [114], L. Vozdecky [94], N. Vranjes [15], M. Vranjes Milosavljevic [15], M. Vreeswijk [114], N.K. Vu [62d,62c], 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], R. Wakasa [157], M. Wakida [111], J. Walder [134], R. Walker [109], W. Walkowiak [142], 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 [149], 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 [139], 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], K. Whalen [123], 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[144], M. Wobisch [97], Z. Wolffs [114], R. Wölker [126], 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,af], T.R. Wyatt [101], B.M. Wynne [52], S. Xella [42], L. Xia [14c], M. Xia [14b], J. Xiang [64c], X. Xiao [106], M. Xie [62a], X. Xie [62a], S. Xin [14a,14e], 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 [148], S. Yacoob [33a], N. Yamaguchi [89], Y. Yamaguchi [138], E. Yamashita [154], 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 [44], S. Ye [29], X. Ye [62a], Y. Yeh [96], I. Yeletskikh [38], B. Yeo [17b], M.R. Yexley [96], P. Yin [41], K. Yorita [168], S. Younas [27b], C.J.S. Young [36], C. Young [144], Y. Yu [62a], M. Yuan [106], R. Yuan [62b,k], L. Yue [96], M. Zaazoua [62a], B. Zabinski [87], E. Zaid[52], T. Zakareishvili [150b], N. Zakharchuk [34], S. Zambito [56], J.A. Zamora Saa [137d,137b], J. Zang [154], 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 [140], 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 [154], X. Zhang [62c], X. Zhang [62b], Y. Zhang [62c,5], Y. Zhang [96], Z. Zhang [17a], Z. Zhang [66], H. Zhao [139], 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 [144], 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 [142], L. Živković [15], A. Zoccoli [23b,23a], K. Zoch [56], T.G. Zorbas [140], 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)National University of Science and Technology Politechnica, 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, Université Hassan II de 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, Institute of Science, Tokyo; Japan.
[139]Department of Physics, University of Washington, Seattle WA; United States of America.
[140]Department of Physics and Astronomy, University of Sheffield, Sheffield; United Kingdom.
[141]Department of Physics, Shinshu University, Nagano; Japan.
[142]Department Physik, Universität Siegen, Siegen; Germany.
[143]Department of Physics, Simon Fraser University, Burnaby BC; Canada.

[144]SLAC National Accelerator Laboratory, Stanford CA; United States of America.
[145]Department of Physics, Royal Institute of Technology, Stockholm; Sweden.
[146]Departments of Physics and Astronomy, Stony Brook University, Stony Brook NY; United States of America.
[147]Department of Physics and Astronomy, University of Sussex, Brighton; United Kingdom.
[148]School of Physics, University of Sydney, Sydney; Australia.
[149]Institute of Physics, Academia Sinica, Taipei; Taiwan.
[150(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.
[151]Department of Physics, Technion, Israel Institute of Technology, Haifa; Israel.
[152]Raymond and Beverly Sackler School of Physics and Astronomy, Tel Aviv University, Tel Aviv; Israel.
[153]Department of Physics, Aristotle University of Thessaloniki, Thessaloniki; Greece.
[154]International Center for Elementary Particle Physics and Department of Physics, University of Tokyo, 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 and Astronomy, Michigan State University, East Lansing MI; United States of America.
[l] Also at Department of Physics, Ben Gurion University of the Negev, Beer Sheva; Israel.
[m] Also at Department of Physics, California State University, Sacramento; United States of America.
[n] Also at Department of Physics, King's College London, London; United Kingdom.
[o] Also at Department of Physics, Stanford University, Stanford CA; United States of America.
[p] Also at Department of Physics, University of Fribourg, Fribourg; Switzerland.
[q] Also at Department of Physics, University of Thessaly; Greece.
[r] Also at Department of Physics, Westmont College, Santa Barbara; United States of America.
[s] Also at Faculty of Physics, Sofia University, 'St. Kliment Ohridski', Sofia; Bulgaria.
[t] Also at Hellenic Open University, Patras; Greece.
[u] Also at Institucio Catalana de Recerca i Estudis Avancats, ICREA, Barcelona; Spain.
[v] Also at Institut für Experimentalphysik, Universität Hamburg, Hamburg; Germany.
[w] Also at Institute for Nuclear Research and Nuclear Energy (INRNE) of the Bulgarian Academy of Sciences, Sofia; Bulgaria.
[x] Also at Institute of Applied Physics, Mohammed VI Polytechnic University, Ben Guerir; Morocco.
[y] Also at Institute of Particle Physics (IPP); Canada.
[z] Also at Institute of Physics and Technology, Mongolian Academy of Sciences, Ulaanbaatar; Mongolia.
[aa] Also at Institute of Physics, Azerbaijan Academy of Sciences, Baku; Azerbaijan.
[ab] Also at Institute of Theoretical Physics, Ilia State University, Tbilisi; Georgia.
[ac] Also at L2IT, Université de Toulouse, CNRS/IN2P3, UPS, Toulouse; France.
[ad] Also at Lawrence Livermore National Laboratory, Livermore; United States of America.
[ae] Also at National Institute of Physics, University of the Philippines Diliman (Philippines); Philippines.
[af] Also at Technical University of Munich, Munich; Germany.
[ag] Also at The Collaborative Innovation Center of Quantum Matter (CICQM), Beijing; China.
[ah] Also at TRIUMF, Vancouver BC; Canada.
[ai] Also at Università di Napoli Parthenope, Napoli; Italy.
[aj] Also at University of Colorado Boulder, Department of Physics, Colorado; United States of America.
[ak] Also at Washington College, Chestertown, MD; United States of America.
[al] Also at Yeditepe University, Physics Department, Istanbul; Türkiye.
[*] Deceased