EUROPEAN ORGANISATION FOR NUCLEAR RESEARCH (CERN)

Submitted to: Phys. Lett. B.

CERN-EP-2024-261
22nd November 2024

Search for Higgs boson decays into a Z boson and a light hadronically decaying resonance in 140 fb^{-1} of 13 TeV pp collisions with the ATLAS detector

The ATLAS Collaboration

A search for decays of the Higgs boson into a Z boson and a light resonance, with a mass of 0.5–3.5 GeV, is performed using the full 140 fb^{-1} dataset of 13 TeV proton–proton collisions recorded by the ATLAS detector during Run 2 of the LHC. Leptonic decays of the Z boson and hadronic decays of the light resonance are considered. The resonance can be interpreted as a J/ψ or η_c meson, an axion-like particle, or a light pseudoscalar in two-Higgs-doublet models. Due to its low mass, it would be produced with high boost and reconstructed as a single small-radius jet of hadrons. A neural network is used to correct the Monte Carlo simulation of the background in a data-driven way. Two additional neural networks are used to distinguish signal from background. A binned profile-likelihood fit is performed on the final-state invariant mass distribution. No significant excess of events relative to the expected background is observed, and upper limits at 95% confidence level are set on the Higgs boson's branching fraction to a Z boson and a light resonance. The exclusion limit is $\sim$10% for the lower masses, and increases for higher masses. Upper limits on the effective coupling $C^{\mathrm{eff}}_{ZH}/\Lambda$ of an axion-like particle to a Higgs boson and Z boson are also set at 95% confidence level, and range from 0.9 to 2 TeV^{-1}.

Contents

1 Introduction

Since its discovery in 2012 [1, 2], the Higgs boson has been studied intensively by the ATLAS and CMS experiments at the CERN Large Hadron Collider (LHC) [3]. So far, all of its measured properties have been found to be consistent with the predictions of the Standard Model (SM) [4, 5]. The expected value in the SM for the total decay-width of the Higgs boson is 4.1 MeV [6]. However, the limited precision of the measurement ($4.5^{+3.0}_{-2.5}$ MeV [7], $3.2^{+2.4}_{-1.7}$ MeV [8]) still allows significant contributions from 'beyond the SM' (BSM) decays. Because the decay width is so small, even a small coupling to a non-SM particle could result in new decay modes with large branching fractions. These decays are very interesting because several models predict additional particles that address limitations of the SM, for example the nature of dark matter or the strong CP problem. The most restrictive upper limits at 95% confidence level (CL) on the Higgs branching fractions to invisible or undetected decays are 13% [4] and 11% [9], respectively.

One of the simplest extensions of the SM is the two-Higgs-doublet model (2HDM) [10, 11], which introduces a second Higgs doublet, allowing the presence of additional lighter Higgs bosons. For some parameter values in both the 2HDM and the 2HDM with an additional singlet (2HDM+S) [12, 13], the additional particles can have large couplings to the observed Higgs boson. The two Higgs doublets in these models are also needed to generate the fermion and boson masses in the Minimal Supersymmetric Standard Model (MSSM) [14] and next-to-MSSM (NMSSM) [15]. The extension of the MSSM to the NMSSM with this additional scalar field can solve the μ-problem of the MSSM [16], and greatly reduces the fine-tuning and little-hierarchy problems.

Axions and axion-like particles (ALPs) are other well-known light resonances predicted by theoretical models [17, 18]. Axions were initially introduced to address the strong CP problem [19], but ALPs are of much wider interest. They are one of the leading dark-matter candidates [20] and could also explain the observed tension between the theoretical prediction and the measured magnetic moment of the muon [21].

There has recently been increasing interest in light-resonance (a) decays of the Higgs boson. Both ATLAS and CMS have published several results, most of them focusing on masses of $\mathcal{O}$(1-10 GeV), pairs of a-resonances ($H \to aa$), and leptonic/photonic decays of the a-resonance [22–24].

However, in both the 2HDM(+S) and axion models certain assumptions can lead to dominant decay modes that are hadronic. For instance, in the type-II 2HDM+S, assuming $\tan\beta = 1$, the branching fraction $\mathcal{B}(a \to gg)$ exceeds 85% for masses up to 3 GeV [25]. Similarly, for an ALP with Wilson coefficients equal to 1, the branching fraction for decays into gluons is almost 100% for masses greater than 3 GeV, and decays into pions are significant for masses up to 1 GeV [18].

A light scalar resonance, with a mass of up to a few GeV, originating from a Higgs boson decay can be also interpreted within the SM. For example, $c\bar{c}$ mesons such as η_c and J/ψ (Q) have masses ~3 GeV and decay mostly into hadrons, with $\mathcal{B} \sim 85\%$. However, their production through $H \to ZQ$ is suppressed and the expected branching fractions are of the order of 10^{-5} and 10^{-6} for η_c and J/ψ respectively [26].

This analysis focuses on the $H \to Za$ decay, utilizing leptonic decays of the Z boson for event triggering [27]. It specifically targets a low-mass (≤4 GeV) hadronically decaying a-resonance from the $H \to Za$ process. It supersedes the initial version of the analysis published in 2020 [28], and aims to address the primary limitation of that study: the background modelling uncertainty. The present analysis incorporates a novel neural-network approach to improve the background modelling, leading to significantly stronger exclusion limits, and includes several additional methodological upgrades. Moreover, an axion interpretation is included, resulting in the exclusion of a range of Higgs-Z-a effective coupling values.

2 ATLAS detector

The ATLAS experiment [29] at the LHC is a multipurpose particle detector with a forward–backward symmetric cylindrical geometry and a near 4π coverage in solid angle.[1] It consists of an inner tracking detector surrounded by a thin superconducting solenoid providing a 2 T axial magnetic field, electromagnetic and hadronic calorimeters, and a muon spectrometer. The inner tracking detector covers the pseudorapidity range $|\eta| < 2.5$. It consists of silicon pixel, silicon microstrip, and transition radiation tracking detectors. Lead/liquid-argon (LAr) sampling calorimeters provide electromagnetic (EM) energy measurements with high granularity within the region $|\eta| < 3.2$. A steel/scintillator-tile hadronic calorimeter covers the central pseudorapidity range ($|\eta| < 1.7$). The endcap and forward regions are instrumented with LAr calorimeters for EM and hadronic energy measurements up to $|\eta| = 4.9$. The muon spectrometer surrounds the calorimeters and is based on three large superconducting air-core toroidal magnets with eight coils each. The field integral of the toroids ranges between 2.0 and 6.0 T m across most of the detector. The muon spectrometer includes a system of precision tracking chambers up to $|\eta| = 2.7$ and fast detectors for triggering up to $|\eta| = 2.4$. The luminosity is measured mainly by the LUCID–2 [30] detector, which is located close to the beampipe. A two-level trigger system is used to select events [31]. 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

---

[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 $\Delta R \equiv \sqrt{(\Delta y)^2 + (\Delta\phi)^2}$.

on average depending on the data-taking conditions. A software suite [32] 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

This search uses the entire Run 2 proton–proton (pp) collision dataset recorded by the ATLAS detector at the LHC between 2015 and 2018. The dataset corresponds to an integrated luminosity of 140 fb^{-1} [33] at a pp centre-of-mass energy of $\sqrt{s}$ = 13 TeV. The data are required to satisfy criteria that ensure that the detector was in good operating condition [34].

Samples of Monte Carlo (MC) simulated signal events ($gg \to H \to Za \to \ell\ell gg$ or $\ell\ell q\bar{q}$) are generated via the gluon–gluon fusion (ggF) process using Powheg Box v2 [35–37] and the PDF4LHC15nnlo next-to-next-to-leading-order (NNLO) parton distribution function (PDF) set [38]. The simulation achieves NNLO accuracy for arbitrary inclusive $gg \to H$ observables by reweighting the Higgs boson rapidity spectrum in H_J−MiNLO [39–41] to that in HNNLO [42]. The samples are normalized to match the total Higgs boson production cross-section of 55.6 pb (for a mass of 125.09 GeV) at $\sqrt{s}$ = 13 TeV [42] because the event acceptance for ggF production is similar to that for other Higgs boson production processes.

Particle decays, hadronization, parton showers and the underlying event in the signal samples are modelled with Pythia 8.212 [43] and EvtGen 1.6.0 [44], using a set of tuned parameters called the A14 tune [45] and the NNPDF23lo PDF set [46]. The branching fractions of the a resonance are determined using the Pythia 8 MSSM scenario with two Higgs doublets, which predicts $a \to gg$ to be the dominant decay mode until $a \to c\bar{c}$ becomes kinematically accessible. The signal MC samples used in this analysis have a-resonance masses covering the range 0.5–4 GeV. The Z boson is required to decay into a pair of electrons, muons, or τ-leptons. Two dedicated samples with η_c or J/ψ decays ($H \to Z\eta_c$ or ZJ/ψ) are also simulated using Pythia 8. An alternative set of signal samples where Herwig 7.1 [47] is used to model the parton shower and hadronization is produced to estimate the uncertainties associated with the modelling of the $a \to$hadrons decay.

The background in this analysis is dominated by Z + jets events. It is modelled in the same way as the signal samples, using Powheg and Pythia+EvtGen for event generation and showering. The CTEQ6L1 PDF set [48] and the AZNLO tune of Pythia 8 are used. The Z + jets events can also be modelled with Sherpa 2.2.1 [49], using the NNPDF3.0nnlo PDF set [50] for the modelling of the hard interaction and parton shower. In this case, the inclusive production cross-sections are known to NNLO in QCD [51]. The Powheg sample is chosen because it is larger than the Sherpa sample. Only samples with $Z \to ee$ or $Z \to \mu\mu$ decays are considered. An additional ~5% contribution from $Z \to \tau\tau$ decays is effectively taken into account by including the Z boson's transverse momentum among the background reweighting variables, as described in Section 5.

The ZZ and ZW processes constitute small (<1%) backgrounds in this analysis. They are modelled with Sherpa 2.2.1, using the NNPDF3.0nnlo PDF set. The $t\bar{t}$ process also produces a small (<1%) background in this analysis. For the $t\bar{t}$ background, the hard interaction is modelled using Powheg, while the decay, hadronization, parton shower and underlying event are modelled using Pythia 8 and EvtGen. The above-mentioned processes constitute the total background in this analysis.

The simulated event samples also include a GEANT4-based simulation of the ATLAS detector and its response [52, 53], and the effect of other pp interactions in either the bunch crossing containing the hard interaction or neighbouring ones.

4 Event selection

The low-mass signal resonance is highly boosted due to the relatively large kinetic energy imparted to it because of the sizeable mass difference between the Higgs boson and Z boson. It is therefore reconstructed as a single small-radius ($R = 0.4$) jet using particle flow objects [54] as input to the anti-k_t algorithm [55, 56].

Jets are calibrated such that the average detector-level jet energy scale (JES) matches that of the corresponding particle-level jets, using a combination of simulation-based and in situ techniques [57]. They are required to have $p_{\mathrm{T}} > 20$ GeV and $|\eta| < 2.5$, and satisfy a jet cleaning requirement [58]. To reject jets from pile-up interactions, jets with $p_{\mathrm{T}} < 60$ GeV and $|\eta| < 2.4$ are required to pass a *Tight* 'jet vertex tagger' [59] requirement.

Jet substructure variables are built using tracks matched to the calorimeter jet by ghost association [60]. In this method the tracks are included in the jet clustering process with negligible energy so that they do not influence the jet's kinematic properties. These tracks must have $p_{\mathrm{T}} > 500$ MeV and $|\eta| < 2.5$, and satisfy loose quality criteria and track-to-vertex matching requirements [61] to reject fake tracks from the reconstruction and tracks from pile-up, respectively.

Electron candidates are reconstructed by matching tracks in the inner detector to topological energy clusters in the electromagnetic calorimeter [62]. Muons are reconstructed using tracks in the muon spectrometer, matched to tracks in the inner detector if available [63]. Electrons and muons are required to satisfy *Loose* identification and *Loose* isolation criteria, to have transverse momentum $p_{\mathrm{T}} > 18$ GeV, and at least one must have $p_{\mathrm{T}} > 27$ GeV and be reconstructed within $|\eta| < 2.47$ (e) or $|\eta| < 2.7$ (μ) (but electrons within $1.37 < |\eta| < 1.52$ are excluded). An inner-detector track associated with an electron (muon) must have a transverse impact parameter significance $d_0/\sigma_{d_0} < 5\,(3)$ relative to the beamline, and a longitudinal impact parameter z_0 satisfying $|z_0 \sin(\theta)| < 0.5$ mm. An overlap removal procedure resolves cases in which multiple electrons, muons or jets are reconstructed from the same detector signature.

Events are selected by a combination of single-electron or single-muon triggers for each data-taking period [64–66], and the lepton reconstructed online by the trigger is required to be within $\Delta R = 0.1$ of an offline reconstructed lepton. Events are required to have at least one reconstructed primary interaction vertex [67]. At least two same-flavour opposite-charge electrons or muons are required to pass this selection, and have an invariant mass compatible with the mass of the Z boson: $81 < m_{\ell\ell} < 101$ GeV. If multiple same-flavour opposite-sign lepton pairs fulfil this requirement, the pairing with an invariant mass closest to that of the Z boson is chosen. A small fraction of the $Z \to \tau^+\tau^-$ decays can pass the selection if the two τ-leptons decay to leptons of the same flavour. Higgs boson candidates are reconstructed from the lepton pair and jet system ($\ell\ell j$), which is required to have an invariant mass passing a loose preselection requirement: $m_{\ell\ell j} < 250$ GeV. If multiple jets satisfy these requirements, the jet with the highest p_{T} is selected. The jet is required to have at least two ghost-associated tracks.

5 Background reweighting

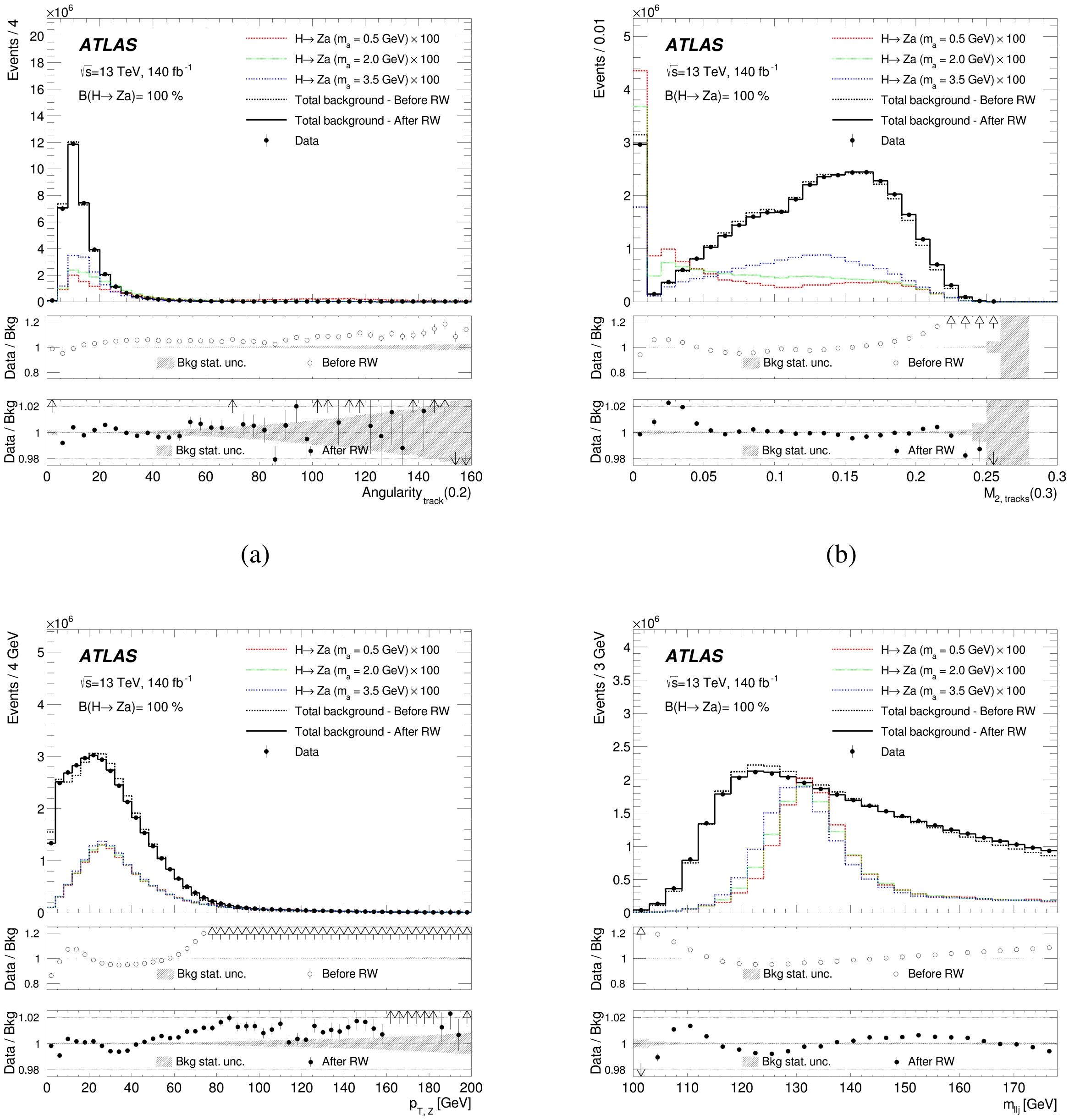
Neither Powheg nor Sherpa model the main $Z+$jets accurately enough. A classifier ($C(x)$) is known to be able to approximate the density ratio of two datasets when trained to distinguish between them, $p_1(x)/p_2(x) \approx C(x)/(1 - C(x))$ [68]. In line with this approach, a neural network (NN) is trained to estimate the multidimensional density ratio of the total-background to data, with the goal of simultaneously improving the modelling of jet substructure and event kinematic variables. Its output is transformed into an additional weight for each MC event in order to equalize the two density functions. Events falling in the region $120 < m_{\ell\ell j} < 140$ GeV, where the most of the signal is expected, are excluded from the training. Any signal contamination outside this region is negligible. The NN is able to reweight events in the excluded region effectively.

The training variables consist of event kinematic variables (final-state invariant mass and transverse momentum, and dilepton and jet transverse momenta) and jet substructure variables. Seven dimensionless variables, constructed from the jet's ghost-associated tracks, are chosen to capitalize on the presence of a narrow jet or two-pronged substructure in the jet's track system: the number of tracks; the ratio of the p_{T} of the highest-p_{T} track to the p_{T} of the track system; the angular separation ΔR between the highest-p_{T} track and the jet axis; N-subjettiness τ_N [69] (with $N = 2$, exclusive-k_t-subjet axes with radius parameters of 0.2, and a jet-axis radius parameter of 0.4), which is an effective discriminating variable for tagging boosted objects; angularity ($\tilde{\tau}_{-2}$) [70], which quantifies how the energy of the jet is distributed relative to the jet axis; and U_1 (with $\beta = 0.7$) and M_2 (with $\beta = 0.3$), which are modified energy correlation functions [71] designed for quark–gluon discrimination and to target two-pronged substructure, respectively.

The reweighting NN is a simple feed-forward network designed and trained using Keras [72]. The hyperparameter optimization uses a mixture of various methods. First, an exponential loss function for log-likelihood-ratio estimation [73] is used along with a hyperbolic tangent function ($8 \tanh x$) which limits the maximum output of the last neuron. Second, the ReLU neuron activation function, typically suggested for feed-forward NNs, is used. For the loss minimizer, stochastic gradient descent was chosen over adaptive moment estimation (Adam) because it provides more flexibility to tune its internal parameters. The number of layers (3), the number of neurons per layer (100), the learning rate (0.11), the decay rate (0.001), the momentum (0.975) and the batch size (200) are chosen via probabilistic Bayesian optimization. The goal of Bayesian optimization is to minimize the error function $f(x)$, which is a measure of the algorithm's mismodelling as a function of the hyperparameters. The set of hyperparameters is chosen with the use of Bayesian statistics for the prior and the observations. The optimization is implemented with the *Hyperopt* library and the Tree-structured Parzen Estimator algorithm [74]. This strategy reaches optimal performance significantly more quickly than other approaches such as random or grid searches. The training ends when the validation loss stops improving (with 10-epoch patience) and the epoch with the best value is chosen (epoch 50). Finally, the events are reweighted with an appropriate factor arising from the NN output. The final-state invariant mass and three other variables used in the reweighting are shown in Figure 1.

6 Signal–to–background discrimination

After the initial event selection, two NNs are used to further suppress the background. First, a *regression* NN is used to estimate the mass of the a-resonance, and second, a *classification* NN is used to discriminate between signal and background. The reconstructed jet mass has quite poor resolution for such low-energy jets and it cannot inform the classifier where a specific event lies in the hadronic resonance mass spectrum.



(a) (b)

(c) (d)

Figure 1: The (a) angularity, (b) modified energy correlation function, (c) Z boson transverse momentum, and (d) invariant mass of the lepton pair plus jet system, for data, background (pre- and post-reweighting) and three $H \to Za$ signal hypotheses (for $a \to q\bar{q}/gg$ inclusively). Events are required to pass the complete event selection but not the classification NN requirement. The background normalization is set equal to that of the data for events passing the preselection and being in the $m_{\ell\ell j}$ 100–180 GeV region. The signal normalization assumes the SM Higgs boson inclusive production cross-section, $\mathcal{B}(H \to Za) = 100\%$, and it is scaled up by a factor of 100. The error bars (hatched regions) represent the data (MC) sample's statistical uncertainty in the histograms and the ratio plots. Vertical arrows indicate data points that fall outside the displayed y-axis range.

Therefore, the regression NN is trained with the seven jet substructure variables to estimate the mass of the resonance (two of the variables are shown in Figures 1(a) and 1(b)). Its output in Figure 2(a) differentiates between the various signal hypotheses significantly better than the jet mass. It is then provided along with the values of the same seven variables to the classification NN. The regression-NN strategy is preferable to other commonly used approaches (e.g. a parameterized NN using the generator-level resonance mass) as it allows the analysis to be conducted with a single classification NN and a single background model, without a significant decrease in performance.

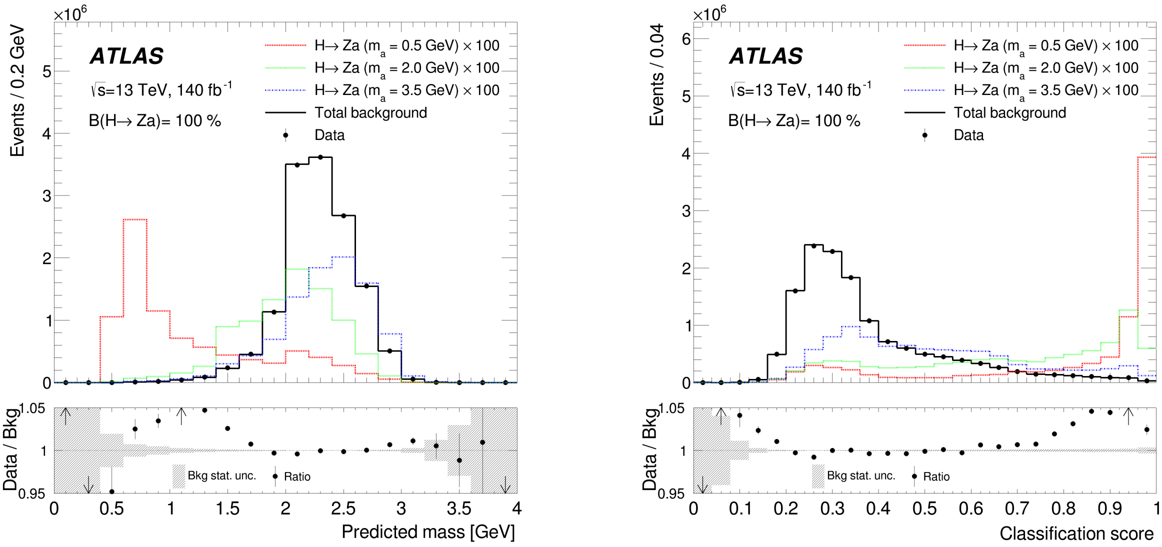
The regression NN is trained on nine different signal-hypothesis samples ranging from 0.5 to 4 GeV in steps of 0.5 GeV. The classification NN is trained with all the signal hypotheses against the total background. Both the quark and gluon decay modes are included and their relative contributions come from the MSSM scenario mentioned in Section 3. The fraction of gg decays varies from 97% to 6% for masses of 0.5 to 4 GeV and the $q\bar{q}$ decay fraction varies correspondingly from 0% to 56%. The hyperparameter optimization follows the same methodology as used for the reweighting, encompassing typically suggested functions, self-optimizing algorithms and Bayesian optimization. Both the NN performance and the level of MC–data agreement (χ^2 test) for the output distributions are taken into account to select the best set. The optimized hyperparameter values for the regression / classification NN are as follows: number of layers (4 / 3), number of neurons per layer (35 / 10), neuron activation function (ReLU / ReLU), output function (linear / sigmoid), loss function (Huber / binary cross-entropy), loss minimizer (Adam / Adam), batch size (160 / 100), regularization (R2, 10^{-11} / R2, 10^{-10}) and epochs (50 / 29). Figure 2 shows the regression and classification NN output variables for the reweighted background, the data and three signal hypotheses.

Although the NNs are trained with a mixture of $a \to gg$ and $a \to q\bar{q}$ decays (with different branching fractions), their performance is generally similar for the two cases. Their performance is poorer for the higher masses, where a-resonance decays tend to have higher track multiplicity, making the hadronic decay appear similar to background jets. This is reflected in the distributions of jet substructure training variables, which are indeed very similar for higher-mass signals and background in Figures 1(a) and 1(b). The $a \to c\bar{c}$ decay mode becomes dominant in the 4 GeV sample, leading to quite different kinematics and much poorer NN performance. Consequently, the 4 GeV $a \to q\bar{q}$ case is omitted from the final results.

A single threshold requirement is placed on the classification NN's output variable to reject background events for all signal hypotheses. The threshold value is chosen to be 0.93, which rejects 99.3% of the background for a signal efficiency of more than 30% for $m_a = 0.5$ GeV, ~10% for $m_a = 2$ GeV, and ~3% for $m_a = 3.5$ GeV. Although this threshold value is not optimal for the higher masses, it allows a single background model to be used. Events passing the classification NN selection populate the signal region (SR). The MC expected yields for the reweighted background, three signal hypotheses and the data in the SR are shown in Figure 3(a).

7 Statistical model

A measure of the signal strength is extracted for each given signal hypothesis using a binned maximum-likelihood fit [75] to the distribution of the final-state invariant mass $m_{\ell\ell j}$ in the range 100–178 GeV, as shown in Figure 3(b). The signal strength is translated to $\mathcal{B}(H \to Za)$ assuming $\mathcal{B}(a \to gg) = 100\%$ or $\mathcal{B}(a \to q\bar{q}) = 100\%$. Systematic uncertainties are included in the fit as nuisance parameters which modify the signal and background model and they are implemented as Gaussian constraints on the nominal values.



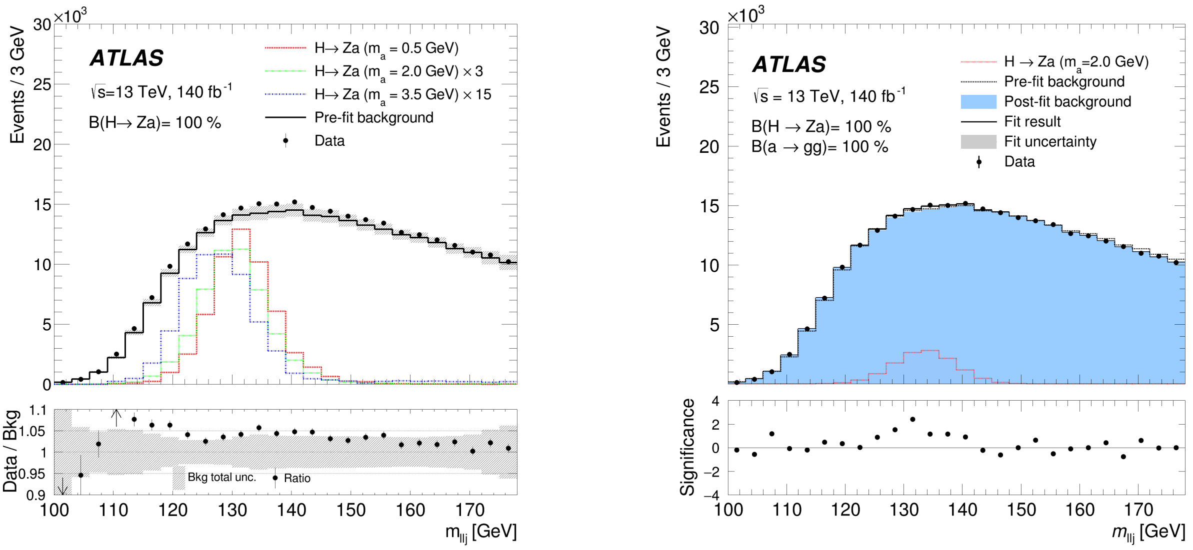
(a)

(b)

Figure 2: The (a) regression and (b) classification NN output variables for data, reweighted background, and three $H \to Za$ signal hypotheses ($a \to q\bar{q}/gg$ inclusively). Events are required to pass the complete event selection, including a $120 < m_{\ell\ell j} < 140$ GeV requirement, but not the classification NN output variable requirement. The background normalization is set equal to that of the data for events passing the preselection and being in the $m_{\ell\ell j}$ 100–180 GeV region. The signal normalization assumes the SM Higgs boson inclusive production cross-section, $\mathcal{B}(H \to Za) = 100\%$, and it is scaled up by a factor of 100. The error bars (hatched regions) represent the data (MC) sample's statistical uncertainty in the histograms and the ratio plots. Vertical arrows indicate data points that fall outside the displayed y-axis range.

The signal model is produced from a simple Gaussian fit with mean μ and width σ of the MC-simulated $m_{\ell\ell j}$ distribution. Different (μ, σ) values are obtained for each mass point and decay mode ($a \to gg/q\bar{q}$). The signal's mean (μ) shifts from 125 GeV for $m_a = 4$ GeV to 131.5 GeV for $m_a = 0.5$ GeV. This mass dependence is expected, as higher masses result in less collimated jets, causing some energy to fall outside the jet cone. Additionally, the jet calibration is not optimized for such low energies, contributing to the shift in the mean. A mean value around 1 GeV higher is observed for $a \to gg$ decays. The signal's width (σ) of 5.0–5.5 GeV varies little with the decay mode or m_a value. For the background the reweighted MC shape is used.

Systematic uncertainties are the dominant source of uncertainty for this analysis. For the signal, both the theory and experimental uncertainties are considered. The experimental uncertainties come from the jet reconstruction, and the lepton reconstruction, identification, isolation and track-to-vertex matching, as well as from the pile-up distribution and the triggering. The jet uncertainties (energy scale and resolution) are found to have the largest effect. The experimental uncertainties are expected to mostly affect the signal distribution (Gaussian μ and σ) and they result in a combined uncertainty of about 1.0 GeV for both μ and σ ($\Delta\mu = 1.1$ GeV and $\Delta\sigma = 0.7$ GeV). Theory uncertainties in parton showering and hadronization are estimated by comparing the nominal Pythia MC signal samples with alternative Herwig samples. The Herwig samples are produced separately for $a \to gg$ and $a \to q\bar{q}$, but only for masses greater than 2 GeV due to Herwig technical specifications. The uncertainties are extrapolated to the lower masses. They affect the Gaussian mean (μ), resulting in $\Delta\mu = 0.5$–2.5 GeV, but their effect on the Gaussian width is minor. In



(a) (b)

Figure 3: Invariant mass of the lepton pair plus jet system for data, reweighted background, and various signal hypotheses. Events are required to pass the complete event selection (preselection and classification NN requirement). In (a) the pre-fit background distribution is shown along with three $H \rightarrow Za$ signal hypotheses coming from the pure MC sample ($a \rightarrow q\bar{q}/gg$ inclusively). The background normalization is set equal to that of the data for events passing the preselection and being in the region 100–180 GeV. In (b) the background shape and normalization come from the fit to the data. The signal includes only gg decays, its shape comes from the fit, and it is normalized to $\mathcal{B}(H \rightarrow Za) = 100\%$. The error bars represent the data sample's statistical uncertainty and the grey bands represent the full background model uncertainty, (a) before the fit (assuming all the uncertainties are uncorrelated) and (b) after the fit. The lower panels show (a) the ratio of the data to the pre-fit background prediction and (b) the per-bin signal significance with respect to the post-fit background, $(N_{\text{data}} - N_{\text{bkg}}) \big/ \sqrt{\sigma^2_{\text{data}} + \sigma^2_{\text{bkg}}}$. The post-fit background uncertainty is calculated from a fit under the background-only hypothesis. Vertical arrows indicate data points that fall outside the displayed y-axis range.

general, the effect on μ tends to decrease for higher masses and it is ~1 GeV larger for gg decays than for $q\bar{q}$ decays. More importantly, the theory uncertainties affect the classification NN's efficiency, which leads to a quite large uncertainty in the expected number of events, about 60% for $a \rightarrow gg$ and about 25% for $a \rightarrow q\bar{q}$. This is the most significant uncertainty for this analysis, and it is due to Pythia generally decaying the a-resonance with lower multiplicity than Herwig. The NN is particularly effective in identifying two-track jets, and these are more common in the Pythia samples. For η_c and J/ψ uncertainties from the $m_a = 3.0$ GeV model are used. In addition, a total Higgs boson production cross-section uncertainty of $^{+5.6\%}_{-7.4\%}$ is included [6].

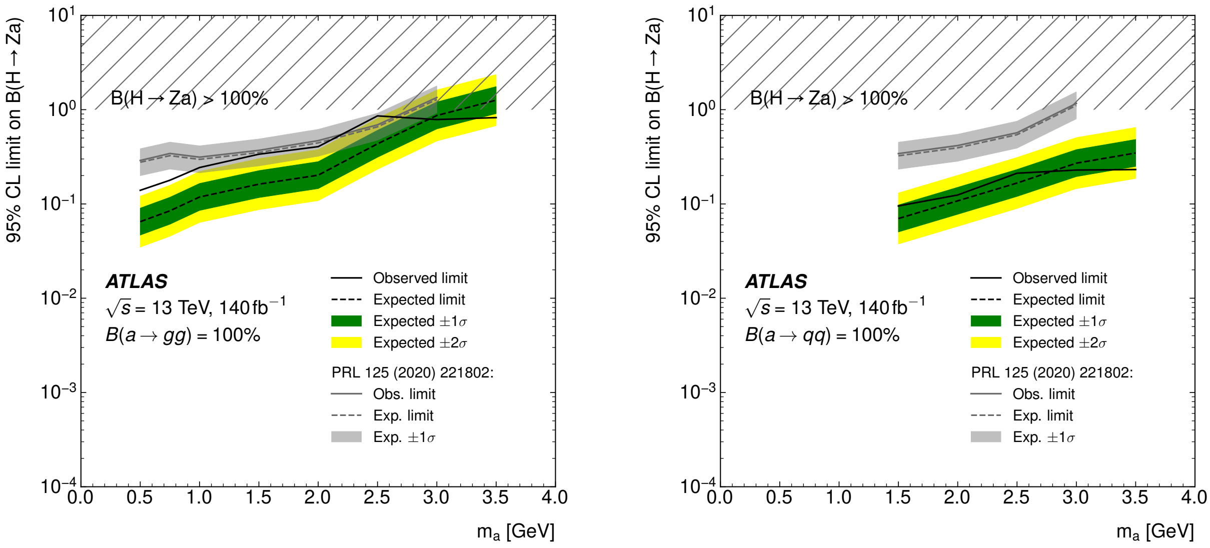
Five kinds of uncertainties incorporate all the possible reweighting performance, experimental and theory uncertainties in the background modelling. All of them are included in the fit as alternative shapes for the background distribution. For the NN performance, two uncertainties are considered. The first is estimated from a control region (CR) that includes the same number of background events as the SR. It is defined by changing the classification NN requirement from >0.93 (SR) to 0.883–0.93. For any reasonable $H \rightarrow Za$ branching fraction (<20%), the resulting signal contamination has a negligible effect in the shape of the systematic distribution produced in the CR. The ratio of data events to MC events in this region is used to derive a shape systematic uncertainty. The second is estimated using a bootstrapping method. Ten replicas of the original MC and data event samples are created by weighting each event with a random Poisson($\mu = 1$) number. For each replica a reweighting NN is trained, and a systematic uncertainty distribution is built from the bin-by-bin standard deviations in the SR. The main sources of experimental uncertainty are the jet energy scale and resolution. MC samples are produced with corresponding scale and resolution variations, their predictions are reweighted using the nominal model, and the resulting shape differences are used. Other experimental uncertainties, such as tracking uncertainties, are found to be insignificant. The effect of theory uncertainties in the parton showering and hadronization are estimated by using the alternative SHERPA $Z+$jets sample. A second reweighting NN is trained using this sample, with the same input variables and training procedure as for the nominal POWHEG sample. The ratio of the distributions in the SR is used as an additional systematic uncertainty. The MC statistical uncertainty is also taken into account.

Finally, a luminosity uncertainty is included. The uncertainty in the combined 2015–2018 integrated luminosity is 0.83% [33], obtained using the LUCID-2 detector [30] for the primary luminosity measurements, complemented by measurements using the inner detector and calorimeters.

8 Results and interpretations

Hypotheses with signal mean greater than ~130 GeV (corresponding to $m_a = 0.5-2.5$ GeV and $a \to gg$) accommodate the slight excess of events observed in data for $m_{\ell\ell j}$ around 135 GeV and create a potential small signal as shown in Figure 3(b). Conversely, if the signal mean is lower, the data are more compatible with the background only hypothesis. The largest local significance is $\sim 1.5\sigma$ and it is observed for $m_a = 0.5$ GeV in the $a \to gg$ scenario. Upper limits at 95% CL are set on $\mathcal{B}(H \to Za)$ for the various signal hypotheses, using the profile-likelihood test statistic [75] and the CL_S technique [76]. The observed and expected upper limits for $a \to gg$ and $a \to q\bar{q}$ are shown in Figure 4, in comparison to the limits from Ref. [28]. For $a \to q\bar{q}$, only decays to the heaviest possible quarks are considered. The slight excess around 135 GeV mentioned above, causes the observed limits to be higher than the expected limits for cases where the signal mean is greater than ~130 GeV. The expected limits are generally more restrictive for $a \to q\bar{q}$ because of the lower signal theory uncertainty.

Limits are also set on $H \to Z\eta_c$ and $H \to ZJ/\psi$ decays; however, the analysis has limited sensitivity for these cases and cannot exclude any physical branching fraction (it excludes $\mathcal{B}(H \to Z\eta_c) > 1.2$ and $\mathcal{B}(H \to ZJ/\psi) > 1.4$). Finally, ALP decay rates can be obtained by assuming the effective Wilson coefficients (determining the coupling strength to various particles) are equal to 1 [18]. For ALP masses of 0.5–1 GeV the 3π decay mode is one of the leading ones. However, the analysis is not sensitive to the $3\pi^0$ decay mode, due to the lack of inner-detector tracks. For $\mathcal{B}(a \to \pi^+\pi^-\pi^0) = 0.10$ (0.20) and $m_a = 0.5$ GeV (1 GeV), the upper limit on $\mathcal{B}(H \to Za)$ is 0.45 (0.81). This can be used to exclude values of the effective coupling $C_{ZH}^{\text{eff}}/\Lambda$ of the candidate axion to the Higgs and Z bosons. At 95% CL, $C_{ZH}^{\text{eff}}/\Lambda < 2.0$ TeV^{-1} for $m_a = 0.5$ GeV and $C_{ZH}^{\text{eff}}/\Lambda < 0.89$ TeV^{-1} for $m_a = 1$ GeV.



(a)

(b)

Figure 4: Observed 95% CL upper limits on $\mathcal{B}(H \to Za)$ for (a) $\mathcal{B}(a \to gg) = 100\%$ and (b) $\mathcal{B}(a \to q\bar{q}) = 100\%$, and the expectation under the background-only hypothesis together with its $\pm 1\sigma$ and $\pm 2\sigma$ intervals. The weaker limits from the previous version of the analysis [28] are also shown. Linear interpolation is used to set limits between the mass points for which MC signal samples were generated.

9 Conclusions

A search for Higgs boson decays into a Z boson and a light resonance of mass 0.5–3.5 GeV is performed using 140 fb^{-1} of proton—proton collisions at $\sqrt{s} = 13$ TeV recorded by the ATLAS detector at the LHC. The search considers leptonic decays of the Z boson and hadronic decays of the light resonance that are collimated into a single small-radius jet. Separate neural networks are used to improve the modelling of the simulated background, and to discriminate signal from background. A binned profile-likelihood fit is performed on the invariant mass of the dilepton-plus-jet system. No significant excess above the Standard Model background prediction is found and upper limits at 95% confidence level are set on the branching fraction for $H \to Za$, where a is a light pseudoscalar, as a function of its mass m_a, separately for the $a \to gg$ and $a \to q\bar{q}$ scenarios. Compared to a previous ATLAS search using the same dataset, the innovative techniques used in this analysis allow to improve the branching fraction limits by a factor of up to two (three) in the case of $a \to gg$ ($a \to q\bar{q}$). Upper limits are also set on the branching fractions for $H \to Z\eta_c$ and $H \to ZJ/\psi$, and on the effective coupling of an axion-like particle to the Higgs boson and Z boson ($C^{\text{eff}}_{ZH}/\Lambda$).

Acknowledgements

We thank CERN for the very successful operation of the LHC and its injectors, as well as the support staff at CERN and at our institutions worldwide without whom ATLAS could not be operated efficiently.

The crucial computing support from all WLCG partners is acknowledged gratefully, in particular from CERN, the ATLAS Tier-1 facilities at TRIUMF/SFU (Canada), NDGF (Denmark, Norway, Sweden), CC-IN2P3 (France), KIT/GridKA (Germany), INFN-CNAF (Italy), NL-T1 (Netherlands), PIC (Spain), RAL (UK) and BNL (USA), the Tier-2 facilities worldwide and large non-WLCG resource providers. Major contributors of computing resources are listed in Ref. [77].

We gratefully acknowledge the support of ANPCyT, Argentina; YerPhI, Armenia; ARC, Australia; BMWFW and FWF, Austria; ANAS, Azerbaijan; CNPq and FAPESP, Brazil; NSERC, NRC and CFI, Canada; CERN; ANID, Chile; CAS, MOST and NSFC, China; Minciencias, Colombia; MEYS CR, Czech Republic; DNRF and DNSRC, Denmark; IN2P3-CNRS and CEA-DRF/IRFU, France; SRNSFG, Georgia; BMBF, HGF and MPG, Germany; GSRI, Greece; RGC and Hong Kong SAR, China; ICHEP and Academy of Sciences and Humanities, Israel; INFN, Italy; MEXT and JSPS, Japan; CNRST, Morocco; NWO, Netherlands; RCN, Norway; MNiSW, Poland; FCT, Portugal; MNE/IFA, Romania; MSTDI, Serbia; MSSR, Slovakia; ARIS and MVZI, Slovenia; DSI/NRF, South Africa; MICIU/AEI, Spain; SRC and Wallenberg Foundation, Sweden; SERI, SNSF and Cantons of Bern and Geneva, Switzerland; NSTC, Taipei; TENMAK, Türkiye; STFC/UKRI, United Kingdom; DOE and NSF, United States of America.

Individual groups and members have received support from BCKDF, CANARIE, CRC and DRAC, Canada; CERN-CZ, FORTE and PRIMUS, Czech Republic; COST, ERC, ERDF, Horizon 2020, ICSC-NextGenerationEU and Marie Skłodowska-Curie Actions, European Union; Investissements d'Avenir Labex, Investissements d'Avenir Idex and ANR, France; DFG and AvH Foundation, Germany; Herakleitos, Thales and Aristeia programmes co-financed by EU-ESF and the Greek NSRF, Greece; BSF-NSF and MINERVA, Israel; NCN and NAWA, Poland; La Caixa Banking Foundation, CERCA Programme Generalitat de Catalunya and PROMETEO and GenT Programmes Generalitat Valenciana, Spain; Göran Gustafssons Stiftelse, Sweden; The Royal Society and Leverhulme Trust, United Kingdom.

In addition, individual members wish to acknowledge support from Armenia: Yerevan Physics Institute (FAPERJ); CERN: European Organization for Nuclear Research (CERN PJAS); Chile: Agencia Nacional de Investigación y Desarrollo (FONDECYT 1230812, FONDECYT 1230987, FONDECYT 1240864); China: Chinese Ministry of Science and Technology (MOST-2023YFA1605700), National Natural Science Foundation of China (NSFC - 12175119, NSFC 12275265, NSFC-12075060); Czech Republic: Czech Science Foundation (GACR - 24-11373S), Ministry of Education Youth and Sports (FORTE CZ.02.01.01/00/22_008/0004632), PRIMUS Research Programme (PRIMUS/21/SCI/017); EU: H2020 European Research Council (ERC - 101002463); European Union: European Research Council (ERC - 948254, ERC 101089007), European Union, Future Artificial Intelligence Research (FAIR-NextGenerationEU PE00000013), Italian Center for High Performance Computing, Big Data and Quantum Computing (ICSC, NextGenerationEU); France: Agence Nationale de la Recherche (ANR-20-CE31-0013, ANR-21-CE31-0013, ANR-21-CE31-0022, ANR-22-EDIR-0002); Germany: Baden-Württemberg Stiftung (BW Stiftung-Postdoc Eliteprogramme), Deutsche Forschungsgemeinschaft (DFG - 469666862, DFG - CR 312/5-2); Italy: Istituto Nazionale di Fisica Nucleare (ICSC, NextGenerationEU), Ministero dell'Università e della Ricerca (PRIN - 20223N7F8K - PNRR M4.C2.1.1); Japan: Japan Society for the Promotion of Science (JSPS KAKENHI JP22H01227, JSPS KAKENHI JP22H04944, JSPS KAKENHI JP22KK0227, JSPS KAKENHI JP23KK0245); Netherlands: Netherlands Organisation for Scientific Research (NWO Veni 2020 - VI.Veni.202.179); Norway: Research Council of Norway (RCN-314472); Poland: Ministry of Science and Higher Education (IDUB AGH, POB8, D4 no 9722), Polish National Agency for Academic Exchange (PPN/PPO/2020/1/00002/U/00001), Polish National Science Centre (NCN 2021/42/E/ST2/00350, NCN OPUS 2023/51/B/ST2/02507, NCN OPUS nr 2022/47/B/ST2/03059, NCN UMO-2019/34/E/ST2/00393, NCN & H2020 MSCA 945339, UMO-2020/37/B/ST2/01043, UMO-2021/40/C/ST2/00187, UMO-2022/47/O/ST2/00148, UMO-2023/49/B/ST2/04085, UMO-2023/51/B/ST2/00920); Slovenia: Slovenian Research Agency (ARIS grant J1-3010); Spain: Generalitat Valenciana (Artemisa, FEDER, IDIFEDER/2018/048), Ministry of Science and Innovation (MCIN & NextGenEU PCI2022-135018-2, MICIN & FEDER PID2021-125273NB, RYC2019-028510-I, RYC2020-030254-I, RYC2021-031273-I, RYC2022-038164-I); Sweden: Carl Trygger Foundation (Carl Trygger Foundation CTS 22:2312), Swedish Research Council (Swedish Research Council 2023-04654, VR 2018-00482, VR 2022-03845, VR 2022-04683, VR 2023-03403, VR grant 2021-03651), Knut and Alice Wallenberg Foundation (KAW 2018.0458, KAW 2019.0447, KAW 2022.0358); Switzerland: Swiss National Science Foundation (SNSF - PCEFP2_194658); United Kingdom: Leverhulme Trust (Leverhulme Trust RPG-2020-004), Royal Society (NIF-R1-231091); United States of America: U.S. Department of Energy (ECA DE-AC02-76SF00515), Neubauer Family Foundation.

References

[1] ATLAS Collaboration, *Observation of a new particle in the search for the Standard Model Higgs boson with the ATLAS detector at the LHC*, Phys. Lett. B **716** (2012) 1, arXiv: `1207.7214 [hep-ex]`.

[2] CMS Collaboration, *Observation of a new boson at a mass of 125 GeV with the CMS experiment at the LHC*, Phys. Lett. B **716** (2012) 30, arXiv: `1207.7235 [hep-ex]`.

[3] L. Evans and P. Bryant, *LHC Machine*, JINST **3** (2008) S08001.

[4] ATLAS Collaboration, *A detailed map of Higgs boson interactions by the ATLAS experiment ten years after the discovery*, Nature **607** (2022) 52, arXiv: `2207.00092 [hep-ex]`, Erratum: Nature **612** (2022) E24.

[5] CMS Collaboration, *A portrait of the Higgs boson by the CMS experiment ten years after the discovery*, Nature **607** (2022) 60, arXiv: `2207.00043 [hep-ex]`, Erratum: Nature **623** (2023) E4.

[6] D. de Florian et al., *Handbook of LHC Higgs Cross Sections: 4. Deciphering the Nature of the Higgs Sector*, (2017), arXiv: `1610.07922 [hep-ph]`.

[7] ATLAS Collaboration, *Evidence of off-shell Higgs boson production from ZZ leptonic decay channels and constraints on its total width with the ATLAS detector*, Phys. Lett. B **846** (2023) 138223, arXiv: `2304.01532 [hep-ex]`, Erratum: Phys. Lett. B **854** (2024) 138734.

[8] CMS Collaboration, *Measurement of the Higgs boson width and evidence of its off-shell contributions to ZZ production*, Nature Phys. **18** (2022) 1329, arXiv: `2202.06923 [hep-ex]`.

[9] ATLAS Collaboration, *Combination of searches for invisible decays of the Higgs boson using* $139\, fb^{-1}$ *of proton–proton collision data at* $\sqrt{s} = 13$ *TeV collected with the ATLAS experiment*, Phys. Lett. B **842** (2023) 137963, arXiv: `2301.10731 [hep-ex]`.

[10] G. C. Branco et al., *Theory and phenomenology of two-Higgs-doublet models*, Phys. Rept. **516** (2012) 1, arXiv: `1106.0034 [hep-ph]`.

[11] J. F. Gunion and H. E. Haber, *The CP conserving two-Higgs-doublet model: The approach to the decoupling limit*, Phys. Rev. D **67** (2003) 075019, arXiv: `hep-ph/0207010`.

[12] M. Muhlleitner, M. O. P. Sampaio, R. Santos and J. Wittbrodt, *The N2HDM under theoretical and experimental scrutiny*, JHEP **03** (2017) 094, arXiv: `1612.01309 [hep-ph]`.

[13] C.-Y. Chen, M. Freid and M. Sher, *Next-to-minimal two Higgs doublet model*, Phys. Rev. D **89** (2014) 075009, arXiv: `1312.3949 [hep-ph]`.

[14] C. Csaki, *The Minimal supersymmetric standard model (MSSM)*, Mod. Phys. Lett. A **11** (1996) 599, arXiv: `hep-ph/9606414`.

[15] M. Maniatis, *The Next-to-minimal Supersymmetric Extension Of The Standard Model Reviewed*, Int. J. Mod. Phys. A **25** (2010) 3505, arXiv: `0906.0777 [hep-ph]`.

[16] K. S. Babu and Y. Mimura, *Solving the mu problem in gauge mediated supersymmetry breaking models with flavor symmetry*, (2001), arXiv: `hep-ph/0101046 [hep-ph]`.

[17] K. Baker et al., *The quest for axions and other new light particles*, Annalen Phys. **525** (2013) A93, arXiv: `1306.2841 [hep-ph]`.

[18] M. Bauer, M. Neubert and A. Thamm, *Collider probes of axion-like particles*, JHEP **12** (2017) 044, arXiv: `1708.00443 [hep-ph]`.

[19] R. D. Peccei and H. R. Quinn, CP *Conservation in the Presence of Pseudoparticles*, Phys. Rev. Lett. **38** (1977) 1440.

[20] A. Chatrchyan, C. Eröncel, M. Koschnitzke and G. Servant, *ALP dark matter with non-periodic potentials: parametric resonance, halo formation and gravitational signatures*, JCAP **10** (2023) 068, arXiv: `2305.03756 [hep-ph]`.

[21] M. A. Buen-Abad, J. Fan, M. Reece and C. Sun, *Challenges for an axion explanation of the muon g-2 measurement*, JHEP **09** (2021) 101, arXiv: `2104.03267 [hep-ph]`.

[22] CMS Collaboration, *Search for an exotic decay of the Higgs boson into a Z boson and a pseudoscalar particle in proton–proton collisions at* $\sqrt{s} = 13$ *TeV*, Phys. Lett. B **852** (2023) 138582, arXiv: `2311.00130 [hep-ex]`.

[23] ATLAS Collaboration, *Search for short- and long-lived axion-like particles in* $H \to aa \to 4\gamma$ *decays with the ATLAS experiment at the LHC*, Eur. Phys. J. C **84** (2023) 742, arXiv: `2312.03306 [hep-ex]`.

[24] ATLAS Collaboration, *Search for Higgs boson decays to beyond-the-Standard-Model light bosons in four-lepton events with the ATLAS detector at* $\sqrt{s} = 13$ *TeV*, JHEP **06** (2018) 166, arXiv: `1802.03388 [hep-ex]`.

[25] D. Curtin et al., *Exotic decays of the 125 GeV Higgs boson*, Phys. Rev. D **90** (2014) 075004, arXiv: `1312.4992 [hep-ph]`.

[26] G. Isidori, A. V. Manohar and M. Trott, *Probing the nature of the Higgs-like Boson via* $h \to V\mathcal{F}$ *decays*, Phys. Lett. B **728** (2014) 131, arXiv: `1305.0663 [hep-ph]`.

[27] ATLAS Collaboration, *Search for the decay of the Higgs boson to a Z boson and a light pseudoscalar particle decaying to two photons*, Phys. Lett. B **850** (2023) 138536, arXiv: `2312.01942 [hep-ex]`.

[28] ATLAS Collaboration, *Search for Higgs Boson Decays into a Z Boson and a Light Hadronically Decaying Resonance Using* 13 *TeV* pp *Collision Data from the ATLAS Detector*, Phys. Rev. Lett. **125** (2020) 221802, arXiv: `2004.01678 [hep-ex]`.

[29] ATLAS Collaboration, *The ATLAS Experiment at the CERN Large Hadron Collider*, JINST **3** (2008) S08003.

[30] G. Avoni et al., *The new LUCID-2 detector for luminosity measurement and monitoring in ATLAS*, JINST **13** (2018) P07017.

[31] ATLAS Collaboration, *Performance of the ATLAS trigger system in 2015*, Eur. Phys. J. C **77** (2017) 317, arXiv: `1611.09661 [hep-ex]`.

[32] ATLAS Collaboration, *Software and computing for Run 3 of the ATLAS experiment at the LHC*, (2024), arXiv: `2404.06335 [hep-ex]`.

[33] ATLAS Collaboration, *Luminosity determination in pp collisions at $\sqrt{s} = 13$ TeV using the ATLAS detector at the LHC*, Eur. Phys. J. C **83** (2023) 982, arXiv: `2212.09379 [hep-ex]`.

[34] ATLAS Collaboration, *ATLAS data quality operations and performance for 2015–2018 data-taking*, JINST **15** (2020) P04003, arXiv: `1911.04632 [physics.ins-det]`.

[35] P. Nason, *A New method for combining NLO QCD with shower Monte Carlo algorithms*, JHEP **11** (2004) 040, arXiv: `hep-ph/0409146 [hep-ph]`.

[36] S. Frixione, P. Nason and C. Oleari, *Matching NLO QCD computations with Parton Shower simulations: the POWHEG method*, JHEP **11** (2007) 070, arXiv: `0709.2092 [hep-ph]`.

[37] S. Alioli, P. Nason, C. Oleari and E. Re, *A general framework for implementing NLO calculations in shower Monte Carlo programs: the POWHEG BOX*, JHEP **06** (2010) 043, arXiv: `1002.2581 [hep-ph]`.

[38] J. Butterworth et al., *PDF4LHC recommendations for LHC Run II*, J. Phys. G **43** (2016) 023001, arXiv: `1510.03865 [hep-ph]`.

[39] K. Hamilton, P. Nason, C. Oleari and G. Zanderighi, *Merging H/W/Z + 0 and 1 jet at NLO with no merging scale: a path to parton shower + NNLO matching*, JHEP **05** (2013) 082, arXiv: `1212.4504 [hep-ph]`.

[40] K. Hamilton, P. Nason and G. Zanderighi, *MINLO: multi-scale improved NLO*, JHEP **10** (2012) 155, arXiv: `1206.3572 [hep-ph]`.

[41] J. M. Campbell et al., *NLO Higgs boson production plus one and two jets using the POWHEG BOX, MadGraph4 and MCFM*, JHEP **07** (2012) 092, arXiv: `1202.5475 [hep-ph]`.

[42] S. Catani and M. Grazzini, *Next-to-Next-to-Leading-Order Subtraction Formalism in Hadron Collisions and its Application to Higgs-Boson Production at the Large Hadron Collider*, Phys. Rev. Lett. **98** (2007) 222002, arXiv: `hep-ph/0703012`.

[43] T. Sjöstrand et al., *An introduction to PYTHIA 8.2*, Comput. Phys. Commun. **191** (2015) 159, arXiv: `1410.3012 [hep-ph]`.

[44] D. J. Lange, *The EvtGen particle decay simulation package*, Nucl. Instrum. Meth. A **462** (2001) 152.

[45] ATLAS Collaboration, *ATLAS Pythia 8 tunes to 7 TeV data*, ATL-PHYS-PUB-2014-021, 2014, URL: `https://cds.cern.ch/record/1966419`.

[46] NNPDF Collaboration, R. D. Ball et al., *Parton distributions with LHC data*, Nucl. Phys. B **867** (2013) 244, arXiv: `1207.1303 [hep-ph]`.

[47] J. Bellm et al., *Herwig 7.1 Release Note*, (2017), arXiv: `1705.06919 [hep-ph]`.

[48] J. Pumplin et al., *New Generation of Parton Distributions with Uncertainties from Global QCD Analysis*, JHEP **07** (2002) 012, arXiv: `hep-ph/0201195`.

[49] E. Bothmann et al., *Event generation with Sherpa 2.2*, SciPost Phys. **7** (2019) 034, arXiv: `1905.09127 [hep-ph]`.

[50] NNPDF Collaboration, R. D. Ball et al., *Parton distributions for the LHC run II*, JHEP **04** (2015) 040, arXiv: `1410.8849 [hep-ph]`.

[51] C. Anastasiou, L. Dixon, K. Melnikov and F. Petriello, *High-precision QCD at hadron colliders: Electroweak gauge boson rapidity distributions at next-to-next-to leading order*, Phys. Rev. D **69** (2004) 094008, arXiv: `hep-ph/0312266 [hep-ph]`.

[52] S. Agostinelli et al., *GEANT4 – a simulation toolkit*, Nucl. Instrum. Meth. A **506** (2003) 250.

[53] ATLAS Collaboration, *The ATLAS Simulation Infrastructure*, Eur. Phys. J. C **70** (2010) 823, arXiv: `1005.4568 [physics.ins-det]`.

[54] ATLAS Collaboration, *Jet reconstruction and performance using particle flow with the ATLAS Detector*, Eur. Phys. J. C **77** (2017) 466, arXiv: `1703.10485 [hep-ex]`.

[55] M. Cacciari, G. P. Salam and G. Soyez, *The anti-k_t jet clustering algorithm*, JHEP **04** (2008) 063, arXiv: `0802.1189 [hep-ph]`.

[56] M. Cacciari, G. P. Salam and G. Soyez, *FastJet user manual*, Eur. Phys. J. C **72** (2012) 1896, arXiv: `1111.6097 [hep-ph]`.

[57] ATLAS Collaboration, *Jet energy scale and resolution measured in proton–proton collisions at $\sqrt{s} = 13$ TeV with the ATLAS detector*, Eur. Phys. J. C **81** (2021) 689, arXiv: `2007.02645 [hep-ex]`.

[58] ATLAS Collaboration, *Selection of jets produced in 13TeV proton-proton collisions with the ATLAS detector*, tech. rep. ATLAS-CONF-2015-029, CERN, 2015, URL: `https://cds.cern.ch/record/2037702`.

[59] ATLAS Collaboration, *Performance of pile-up mitigation techniques for jets in pp collisions at $\sqrt{s} = 8$ TeV using the ATLAS detector*, Eur. Phys. J. C **76** (2016) 581, arXiv: `1510.03823 [hep-ex]`.

[60] M. Cacciari and G. P. Salam, *Pileup subtraction using jet areas*, Phys. Lett. B **659** (2008) 119, arXiv: `0707.1378 [hep-ph]`.

[61] ATLAS Collaboration, *Performance of the ATLAS track reconstruction algorithms in dense environments in LHC Run 2*, Eur. Phys. J. C **77** (2017) 673, arXiv: `1704.07983 [hep-ex]`.

[62] ATLAS Collaboration, *Electron and photon performance measurements with the ATLAS detector using the 2015–2017 LHC proton–proton collision data*, JINST **14** (2019) P12006, arXiv: `1908.00005 [hep-ex]`.

[63] ATLAS Collaboration, *Muon reconstruction and identification efficiency in ATLAS using the full Run 2 pp collision data set at $\sqrt{s} = 13$ TeV*, Eur. Phys. J. C **81** (2021) 578, arXiv: `2012.00578 [hep-ex]`.

[64] ATLAS Collaboration, *Performance of electron and photon triggers in ATLAS during LHC Run 2*, Eur. Phys. J. C **80** (2020) 47, arXiv: `1909.00761 [hep-ex]`.

[65] ATLAS Collaboration, *Performance of the ATLAS muon triggers in Run 2*, JINST **15** (2020) P09015, arXiv: `2004.13447 [physics.ins-det]`.

[66] ATLAS Collaboration,
The ATLAS inner detector trigger performance in pp collisions at 13 *TeV during LHC Run 2*,
Eur. Phys. J. C **82** (2022) 206, arXiv: `2107.02485 [hep-ex]`.

[67] ATLAS Collaboration, *Vertex Reconstruction Performance of the ATLAS Detector at* $\sqrt{s}$ = 13 *TeV*,
ATL-PHYS-PUB-2015-026, 2015, URL: `https://cds.cern.ch/record/2037717`.

[68] K. Cranmer, J. Pavez and G. Louppe,
Approximating Likelihood Ratios with Calibrated Discriminative Classifiers, 2016,
arXiv: `1506.02169 [stat.AP]`.

[69] J. Thaler and K. Van Tilburg, *Identifying Boosted Objects with N-subjettiness*, JHEP **03** (2011) 015,
arXiv: `1011.2268 [hep-ph]`.

[70] L. G. Almeida et al., *Substructure of high-p_T jets at the LHC*, Phys. Rev. D **79** (2009) 074017,
arXiv: `0807.0234 [hep-ph]`.

[71] I. Moult, L. Necib and J. Thaler, *New angles on energy correlation functions*, JHEP **12** (2016) 153,
arXiv: `1609.07483 [hep-ph]`.

[72] F. Chollet et al., *Keras*, `https://keras.io`, 2015.

[73] G. V. Moustakides and K. Basioti,
Training Neural Networks for Likelihood/Density Ratio Estimation, 2019,
arXiv: `1911.00405 [eess.SP]`.

[74] J. Bergstra, D. Yamins and D. D. Cox, *Making a Science of Model Search*, 2012,
arXiv: `1209.5111 [cs.CV]`.

[75] G. Cowan, K. Cranmer, E. Gross and O. Vitells,
Asymptotic formulae for likelihood-based tests of new physics, Eur. Phys. J. C **71** (2011) 1554,
arXiv: `1007.1727 [physics.data-an]`, Erratum: Eur. Phys. J. C **73** (2013) 2501.

[76] A. L. Read, *Presentation of search results: the CL_S technique*, J. Phys. G **28** (2002) 2693.

[77] ATLAS Collaboration, *ATLAS Computing Acknowledgements*, ATL-SOFT-PUB-2023-001, 2023,
URL: `https://cds.cern.ch/record/2869272`.

The ATLAS Collaboration

G. Aad[105], E. Aakvaag[17], B. Abbott[124], S. Abdelhameed[120a], K. Abeling[57], N.J. Abicht[51], S.H. Abidi[30], M. Aboelela[46], A. Aboulhorma[36e], H. Abramowicz[156], Y. Abulaiti[121], B.S. Acharya[71a,71b,m], A. Ackermann[65a], C. Adam Bourdarios[4], L. Adamczyk[88a], S.V. Addepalli[148], M.J. Addison[104], J. Adelman[119], A. Adiguzel[22c], T. Adye[138], A.A. Affolder[140], Y. Afik[41], M.N. Agaras[13], A. Aggarwal[103], C. Agheorghiesei[28c], F. Ahmadov[40,ab], S. Ahuja[98], X. Ai[64e], G. Aielli[78a,78b], A. Aikot[168], M. Ait Tamlihat[36e], B. Aitbenchikh[36a], M. Akbiyik[103], T.P.A. Åkesson[101], A.V. Akimov[150], D. Akiyama[173], N.N. Akolkar[25], S. Aktas[22a], K. Al Khoury[43], G.L. Alberghi[24b], J. Albert[170], P. Albicocco[55], G.L. Albouy[62], S. Alderweireldt[54], Z.L. Alegria[125], M. Aleksa[37], I.N. Aleksandrov[40], C. Alexa[28b], T. Alexopoulos[10], F. Alfonsi[24b], M. Algren[58], M. Alhroob[172], B. Ali[136], H.M.J. Ali[94,v], S. Ali[32], S.W. Alibocus[95], M. Aliev[34c], G. Alimonti[73a], W. Alkakhi[57], C. Allaire[68], B.M.M. Allbrooke[151], J.S. Allen[104], J.F. Allen[54], C.A. Allendes Flores[141f], P.P. Allport[21], A. Aloisio[74a,74b], F. Alonso[93], C. Alpigiani[143], Z.M.K. Alsolami[94], M. Alvarez Estevez[102], A. Alvarez Fernandez[103], M. Alves Cardoso[58], M.G. Alviggi[74a,74b], M. Aly[104], Y. Amaral Coutinho[85b], A. Ambler[107], C. Amelung[37], M. Amerl[104], C.G. Ames[112], D. Amidei[109], B. Amini[56], K.J. Amirie[159], S.P. Amor Dos Santos[134a], K.R. Amos[168], D. Amperiadou[157], S. An[86], V. Ananiev[129], C. Anastopoulos[144], T. Andeen[11], J.K. Anders[37], A.C. Anderson[61], A. Andreazza[73a,73b], S. Angelidakis[9], A. Angerami[43], A.V. Anisenkov[39], A. Annovi[76a], C. Antel[58], E. Antipov[150], M. Antonelli[55], F. Anulli[77a], M. Aoki[86], T. Aoki[158], M.A. Aparo[151], L. Aperio Bella[50], C. Appelt[156], A. Apyan[27], S.J. Arbiol Val[89], C. Arcangeletti[55], A.T.H. Arce[53], J-F. Arguin[111], S. Argyropoulos[157], J.-H. Arling[50], O. Arnaez[4], H. Arnold[150], G. Artoni[77a,77b], H. Asada[114], K. Asai[122], S. Asai[158], N.A. Asbah[37], R.A. Ashby Pickering[172], K. Assamagan[30], R. Astalos[29a], K.S.V. Astrand[101], S. Atashi[163], R.J. Atkin[34a], H. Atmani[36f], P.A. Atmasiddha[132], K. Augsten[136], A.D. Auriol[21], V.A. Austrup[104], G. Avolio[37], K. Axiotis[58], G. Azuelos[111,af], D. Babal[29b], H. Bachacou[139], K. Bachas[157,q], A. Bachiu[35], E. Bachmann[52], A. Badea[41], T.M. Baer[109], P. Bagnaia[77a,77b], M. Bahmani[19], D. Bahner[56], K. Bai[127], J.T. Baines[138], L. Baines[97], O.K. Baker[177], E. Bakos[16], D. Bakshi Gupta[8], L.E. Balabram Filho[85b], V. Balakrishnan[124], R. Balasubramanian[4], E.M. Baldin[39], P. Balek[88a], E. Ballabene[24b,24a], F. Balli[139], L.M. Baltes[65a], W.K. Balunas[33], J. Balz[103], I. Bamwidhi[120b], E. Banas[89], M. Bandieramonte[133], A. Bandyopadhyay[25], S. Bansal[25], L. Barak[156], M. Barakat[50], E.L. Barberio[108], D. Barberis[59b,59a], M. Barbero[105], M.Z. Barel[118], T. Barillari[113], M-S. Barisits[37], T. Barklow[148], P. Baron[126], D.A. Baron Moreno[104], A. Baroncelli[64a], A.J. Barr[130], J.D. Barr[99], F. Barreiro[102], J. Barreiro Guimarães da Costa[14], M.G. Barros Teixeira[134a], S. Barsov[39], F. Bartels[65a], R. Bartoldus[148], A.E. Barton[94], P. Bartos[29a], A. Basan[103], M. Baselga[51], S. Bashiri[89], A. Bassalat[68,b], M.J. Basso[160a], S. Bataju[46], R. Bate[169], R.L. Bates[61], S. Batlamous[102], B. Batool[146], M. Battaglia[140], D. Battulga[19], M. Bauce[77a,77b], M. Bauer[81], P. Bauer[25], L.T. Bazzano Hurrell[31], J.B. Beacham[53], T. Beau[131], J.Y. Beaucamp[93], P.H. Beauchemin[162], P. Bechtle[25], H.P. Beck[20,p], K. Becker[172], A.J. Beddall[84], V.A. Bednyakov[40], C.P. Bee[150], L.J. Beemster[16], T.A. Beermann[37], M. Begalli[85d], M. Begel[30], J.K. Behr[50], J.F. Beirer[37], F. Beisiegel[25], M. Belfkir[120b], G. Bella[156], L. Bellagamba[24b], A. Bellerive[35], P. Bellos[21], K. Beloborodov[39], D. Benchekroun[36a], F. Bendebba[36a], Y. Benhammou[156],

K.C. Benkendorfer[63], L. Beresford[50], M. Beretta[55], E. Bergeaas Kuutmann[166], N. Berger[4], B. Bergmann[136], J. Beringer[18a], G. Bernardi[5], C. Bernius[148], F.U. Bernlochner[25], F. Bernon[37], A. Berrocal Guardia[13], T. Berry[98], P. Berta[137], A. Berthold[52], S. Bethke[113], A. Betti[77a,77b], A.J. Bevan[97], N.K. Bhalla[56], S. Bharthuar[113], S. Bhatta[150], D.S. Bhattacharya[171], P. Bhattarai[148], Z.M. Bhatti[121], K.D. Bhide[56], V.S. Bhopatkar[125], R.M. Bianchi[133], G. Bianco[24b,24a], O. Biebel[112], M. Biglietti[79a], C.S. Billingsley[46], Y. Bimgdi[36f], M. Bindi[57], A. Bingham[176], A. Bingul[22b], C. Bini[77a,77b], G.A. Bird[33], M. Birman[174], M. Biros[137], S. Biryukov[151], T. Bisanz[51], E. Bisceglie[45b,45a], J.P. Biswal[138], D. Biswas[146], I. Bloch[50], A. Blue[61], U. Blumenschein[97], J. Blumenthal[103], V.S. Bobrovnikov[39], M. Boehler[56], B. Boehm[171], D. Bogavac[37], A.G. Bogdanchikov[39], L.S. Boggia[131], C. Bohm[49a], V. Boisvert[98], P. Bokan[37], T. Bold[88a], M. Bomben[5], M. Bona[97], M. Boonekamp[139], A.G. Borbély[61], I.S. Bordulev[39], G. Borissov[94], D. Bortoletto[130], D. Boscherini[24b], M. Bosman[13], K. Bouaouda[36a], N. Bouchhar[168], L. Boudet[4], J. Boudreau[133], E.V. Bouhova-Thacker[94], D. Boumediene[42], R. Bouquet[59b,59a], A. Boveia[123], J. Boyd[37], D. Boye[30], I.R. Boyko[40], L. Bozianu[58], J. Bracinik[21], N. Brahimi[4], G. Brandt[176], O. Brandt[33], B. Brau[106], J.E. Brau[127], R. Brener[174], L. Brenner[118], R. Brenner[166], S. Bressler[174], G. Brianti[80a,80b], D. Britton[61], D. Britzger[113], I. Brock[25], R. Brock[110], G. Brooijmans[43], A.J. Brooks[70], E.M. Brooks[160b], E. Brost[30], L.M. Brown[170], L.E. Bruce[63], T.L. Bruckler[130], P.A. Bruckman de Renstrom[89], B. Brüers[50], A. Bruni[24b], G. Bruni[24b], D. Brunner[49a,49b], M. Bruschi[24b], N. Bruscino[77a,77b], T. Buanes[17], Q. Buat[143], D. Buchin[113], A.G. Buckley[61], O. Bulekov[39], B.A. Bullard[148], S. Burdin[95], C.D. Burgard[51], A.M. Burger[37], B. Burghgrave[8], O. Burlayenko[56], J. Burleson[167], J.T.P. Burr[33], J.C. Burzynski[147], E.L. Busch[43], V. Büscher[103], P.J. Bussey[61], J.M. Butler[26], C.M. Buttar[61], J.M. Butterworth[99], W. Buttinger[138], C.J. Buxo Vazquez[110], A.R. Buzykaev[39], S. Cabrera Urbán[168], L. Cadamuro[68], D. Caforio[60], H. Cai[133], Y. Cai[14,115c], Y. Cai[115a], V.M.M. Cairo[37], O. Cakir[3a], N. Calace[37], P. Calafiura[18a], G. Calderini[131], P. Calfayan[35], G. Callea[61], L.P. Caloba[85b], D. Calvet[42], S. Calvet[42], R. Camacho Toro[131], S. Camarda[37], D. Camarero Munoz[27], P. Camarri[78a,78b], M.T. Camerlingo[74a,74b], D. Cameron[37], C. Camincher[170], M. Campanelli[99], A. Camplani[44], V. Canale[74a,74b], A.C. Canbay[3a], E. Canonero[98], J. Cantero[168], Y. Cao[167], F. Capocasa[27], M. Capua[45b,45a], A. Carbone[73a,73b], R. Cardarelli[78a], J.C.J. Cardenas[8], M.P. Cardiff[27], G. Carducci[45b,45a], T. Carli[37], G. Carlino[74a], J.I. Carlotto[13], B.T. Carlson[133,r], E.M. Carlson[170,160a], J. Carmignani[95], L. Carminati[73a,73b], A. Carnelli[139], M. Carnesale[37], S. Caron[117], E. Carquin[141f], I.B. Carr[108], S. Carrá[73a], G. Carratta[24b,24a], A.M. Carroll[127], M.P. Casado[13,i], M. Caspar[50], F.L. Castillo[4], L. Castillo Garcia[13], V. Castillo Gimenez[168], N.F. Castro[134a,134e], A. Catinaccio[37], J.R. Catmore[129], T. Cavaliere[4], V. Cavaliere[30], L.J. Caviedes Betancourt[23b], Y.C. Cekmecelioglu[50], E. Celebi[84], S. Cella[37], V. Cepaitis[58], K. Cerny[126], A.S. Cerqueira[85a], A. Cerri[151], L. Cerrito[78a,78b], F. Cerutti[18a], B. Cervato[146], A. Cervelli[24b], G. Cesarini[55], S.A. Cetin[84], P.M. Chabrillat[131], D. Chakraborty[119], J. Chan[18a], W.Y. Chan[158], J.D. Chapman[33], E. Chapon[139], B. Chargeishvili[154b], D.G. Charlton[21], M. Chatterjee[20], C. Chauhan[137], Y. Che[115a], S. Chekanov[6], S.V. Chekulaev[160a], G.A. Chelkov[40,a], A. Chen[109], B. Chen[156], B. Chen[170], H. Chen[115a], H. Chen[30], J. Chen[64c], J. Chen[147], M. Chen[130], S. Chen[90], S.J. Chen[115a], X. Chen[64c], X. Chen[15,ae], Y. Chen[64a], C.L. Cheng[175], H.C. Cheng[66a], S. Cheong[148], A. Cheplakov[40], E. Cheremushkina[50], E. Cherepanova[118], R. Cherkaoui El Moursli[36e], E. Cheu[7], K. Cheung[67], L. Chevalier[139], V. Chiarella[55], G. Chiarelli[76a], N. Chiedde[105], G. Chiodini[72a], A.S. Chisholm[21], A. Chitan[28b], M. Chitishvili[168], M.V. Chizhov[40,s], K. Choi[11], Y. Chou[143], E.Y.S. Chow[117], K.L. Chu[174], M.C. Chu[66a], X. Chu[14,115c], Z. Chubinidze[55], J. Chudoba[135], J.J. Chwastowski[89], D. Cieri[113], K.M. Ciesla[88a], V. Cindro[96], A. Ciocio[18a], F. Cirotto[74a,74b], Z.H. Citron[174], M. Citterio[73a], D.A. Ciubotaru[28b], A. Clark[58], P.J. Clark[54], N. Clarke Hall[99], C. Clarry[159], J.M. Clavijo Columbie[50], S.E. Clawson[50], C. Clement[49a,49b], Y. Coadou[105], M. Cobal[71a,71c], A. Coccaro[59b], R.F. Coelho Barrue[134a], R. Coelho Lopes De Sa[106], S. Coelli[73a], L.S. Colangeli[159], B. Cole[43], J. Collot[62], P. Conde Muiño[134a,134g], M.P. Connell[34c], S.H. Connell[34c], E.I. Conroy[130], F. Conventi[74a,ag], H.G. Cooke[21], A.M. Cooper-Sarkar[130], F.A. Corchia[24b,24a], A. Cordeiro Oudot Choi[131], L.D. Corpe[42], M. Corradi[77a,77b], F. Corriveau[107,aa], A. Cortes-Gonzalez[19], M.J. Costa[168], F. Costanza[4], D. Costanzo[144], B.M. Cote[123], J. Couthures[4], G. Cowan[98], K. Cranmer[175], L. Cremer[51], D. Cremonini[24b,24a], S. Crépé-Renaudin[62], F. Crescioli[131], M. Cristinziani[146], M. Cristoforetti[80a,80b], V. Croft[118], J.E. Crosby[125], G. Crosetti[45b,45a], A. Cueto[102], H. Cui[99], Z. Cui[7], W.R. Cunningham[61], F. Curcio[168], J.R. Curran[54], P. Czodrowski[37], M.J. Da Cunha Sargedas De Sousa[59b,59a], J.V. Da Fonseca Pinto[85b], C. Da Via[104], W. Dabrowski[88a], T. Dado[37], S. Dahbi[153], T. Dai[109], D. Dal Santo[20], C. Dallapiccola[106], M. Dam[44], G. D'amen[30], V. D'Amico[112], J. Damp[103], J.R. Dandoy[35], D. Dannheim[37], M. Danninger[147], V. Dao[150], G. Darbo[59b], S.J. Das[30], F. Dattola[50], S. D'Auria[73a,73b], A. D'Avanzo[74a,74b], C. David[34a], T. Davidek[137], I. Dawson[97], H.A. Day-hall[136], K. De[8], C. De Almeida Rossi[159], R. De Asmundis[74a], N. De Biase[50], S. De Castro[24b,24a], N. De Groot[117], P. de Jong[118], H. De la Torre[119], A. De Maria[115a], A. De Salvo[77a], U. De Sanctis[78a,78b], F. De Santis[72a,72b], A. De Santo[151], J.B. De Vivie De Regie[62], J. Debevc[96], D.V. Dedovich[40], J. Degens[95], A.M. Deiana[46], F. Del Corso[24b,24a], J. Del Peso[102], L. Delagrange[131], F. Deliot[139], C.M. Delitzsch[51], M. Della Pietra[74a,74b], D. Della Volpe[58], A. Dell'Acqua[37], L. Dell'Asta[73a,73b], M. Delmastro[4], C.C. Delogu[103], P.A. Delsart[62], S. Demers[177], M. Demichev[40], S.P. Denisov[39], H. Denizli[22a], L. D'Eramo[42], D. Derendarz[89], F. Derue[131], P. Dervan[95], K. Desch[25], C. Deutsch[25], F.A. Di Bello[59b,59a], A. Di Ciaccio[78a,78b], L. Di Ciaccio[4], A. Di Domenico[77a,77b], C. Di Donato[74a,74b], A. Di Girolamo[37], G. Di Gregorio[37], A. Di Luca[80a,80b], B. Di Micco[79a,79b], R. Di Nardo[79a,79b], K.F. Di Petrillo[41], M. Diamantopoulou[35], F.A. Dias[118], T. Dias Do Vale[147], M.A. Diaz[141a,141b], A.R. Didenko[40], M. Didenko[168], E.B. Diehl[109], S. Díez Cornell[50], C. Diez Pardos[146], C. Dimitriadi[166], A. Dimitrievska[21], J. Dingfelder[25], T. Dingley[130], I-M. Dinu[28b], S.J. Dittmeier[65b], F. Dittus[37], M. Divisek[137], B. Dixit[95], F. Djama[105], T. Djobava[154b], C. Doglioni[104,101], A. Dohnalova[29a], Z. Dolezal[137], K. Domijan[88a], K.M. Dona[41], M. Donadelli[85d], B. Dong[110], J. Donini[42], A. D'Onofrio[74a,74b], M. D'Onofrio[95], J. Dopke[138], A. Doria[74a], N. Dos Santos Fernandes[134a], P. Dougan[104], M.T. Dova[93], A.T. Doyle[61], M.A. Draguet[130], M.P. Drescher[57], E. Dreyer[174], I. Drivas-koulouris[10], M. Drnevich[121], M. Drozdova[58], D. Du[64a], T.A. du Pree[118], F. Dubinin[39], M. Dubovsky[29a], E. Duchovni[174], G. Duckeck[112], O.A. Ducu[28b], D. Duda[54], A. Dudarev[37], E.R. Duden[27], M. D'uffizi[104], L. Duflot[68], M. Dührssen[37], I. Duminica[28g], A.E. Dumitriu[28b], M. Dunford[65a], S. Dungs[51], K. Dunne[49a,49b], A. Duperrin[105], H. Duran Yildiz[3a], M. Düren[60], A. Durglishvili[154b], D. Duvnjak[35], B.L. Dwyer[119], G.I. Dyckes[18a], M. Dyndal[88a], B.S. Dziedzic[37], Z.O. Earnshaw[151], G.H. Eberwein[130], B. Eckerova[29a], S. Eggebrecht[57], E. Egidio Purcino De Souza[85e], L.F. Ehrke[58], G. Eigen[17], K. Einsweiler[18a], T. Ekelof[166], P.A. Ekman[101], S. El Farkh[36b], Y. El Ghazali[64a], H. El Jarrari[37], A. El Moussaouy[36a], V. Ellajosyula[166], M. Ellert[166], F. Ellinghaus[176], N. Ellis[37], J. Elmsheuser[30], M. Elsawy[120a], M. Elsing[37], D. Emeliyanov[138], Y. Enari[86], I. Ene[18a], S. Epari[13], P.A. Erland[89], D. Ernani Martins Neto[89], M. Errenst[176], M. Escalier[68],

C. Escobar[168], E. Etzion[156], G. Evans[134a,134b], H. Evans[70], L.S. Evans[98], A. Ezhilov[39],
S. Ezzarqtouni[36a], F. Fabbri[24b,24a], L. Fabbri[24b,24a], G. Facini[99], V. Fadeyev[140],
R.M. Fakhrutdinov[39], D. Fakoudis[103], S. Falciano[77a], L.F. Falda Ulhoa Coelho[134a],
F. Fallavollita[113], G. Falsetti[45b,45a], J. Faltova[137], C. Fan[167], K.Y. Fan[66b], Y. Fan[14],
Y. Fang[14,115c], M. Fanti[73a,73b], M. Faraj[71a,71b], Z. Farazpay[100], A. Farbin[8], A. Farilla[79a],
T. Farooque[110], J.N. Farr[177], S.M. Farrington[138,54], F. Fassi[36e], D. Fassouliotis[9],
M. Faucci Giannelli[78a,78b], W.J. Fawcett[33], L. Fayard[68], P. Federic[137], P. Federicova[135],
O.L. Fedin[39,a], M. Feickert[175], L. Feligioni[105], D.E. Fellers[127], C. Feng[64b], Z. Feng[118],
M.J. Fenton[163], L. Ferencz[50], R.A.M. Ferguson[94], P. Fernandez Martinez[69],
M.J.V. Fernoux[105], J. Ferrando[94], A. Ferrari[166], P. Ferrari[118,117], R. Ferrari[75a], D. Ferrere[58],
C. Ferretti[109], M.P. Fewell[1], D. Fiacco[77a,77b], F. Fiedler[103], P. Fiedler[136], S. Filimonov[39],
A. Filipčič[96], E.K. Filmer[160a], F. Filthaut[117], M.C.N. Fiolhais[134a,134c,c], L. Fiorini[168],
W.C. Fisher[110], T. Fitschen[104], P.M. Fitzhugh[139], I. Fleck[146], P. Fleischmann[109], T. Flick[176],
M. Flores[34d,ac], L.R. Flores Castillo[66a], L. Flores Sanz De Acedo[37], F.M. Follega[80a,80b],
N. Fomin[33], J.H. Foo[159], A. Formica[139], A.C. Forti[104], E. Fortin[37], A.W. Fortman[18a],
M.G. Foti[18a], L. Fountas[9,j], D. Fournier[68], H. Fox[94], P. Francavilla[76a,76b], S. Francescato[63],
S. Franchellucci[58], M. Franchini[24b,24a], S. Franchino[65a], D. Francis[37], L. Franco[117],
V. Franco Lima[37], L. Franconi[50], M. Franklin[63], G. Frattari[27], Y.Y. Frid[156], J. Friend[61],
N. Fritzsche[37], A. Froch[58], D. Froidevaux[37], J.A. Frost[130], Y. Fu[64a],
S. Fuenzalida Garrido[141f], M. Fujimoto[105], K.Y. Fung[66a], E. Furtado De Simas Filho[85e],
M. Furukawa[158], J. Fuster[168], A. Gaa[57], A. Gabrielli[24b,24a], A. Gabrielli[159], P. Gadow[37],
G. Gagliardi[59b,59a], L.G. Gagnon[18a], S. Gaid[165], S. Galantzan[156], J. Gallagher[1],
E.J. Gallas[130], A.L. Gallen[166], B.J. Gallop[138], K.K. Gan[123], S. Ganguly[158], Y. Gao[54],
F.M. Garay Walls[141a,141b], B. Garcia[30], C. García[168], A. Garcia Alonso[118],
A.G. Garcia Caffaro[177], J.E. García Navarro[168], M. Garcia-Sciveres[18a], G.L. Gardner[132],
R.W. Gardner[41], N. Garelli[162], R.B. Garg[148], J.M. Gargan[54], C.A. Garner[159], C.M. Garvey[34a],
V.K. Gassmann[162], G. Gaudio[75a], V. Gautam[13], P. Gauzzi[77a,77b], J. Gavranovic[96],
I.L. Gavrilenko[39], A. Gavrilyuk[39], C. Gay[169], G. Gaycken[127], E.N. Gazis[10], A.A. Geanta[28b],
A. Gekow[123], C. Gemme[59b], M.H. Genest[62], A.D. Gentry[116], S. George[98], W.F. George[21],
T. Geralis[48], A.A. Gerwin[124], P. Gessinger-Befurt[37], M.E. Geyik[176], M. Ghani[172],
K. Ghorbanian[97], A. Ghosal[146], A. Ghosh[163], A. Ghosh[7], B. Giacobbe[24b], S. Giagu[77a,77b],
T. Giani[118], A. Giannini[64a], S.M. Gibson[98], M. Gignac[140], D.T. Gil[88b], A.K. Gilbert[88a],
B.J. Gilbert[43], D. Gillberg[35], G. Gilles[118], L. Ginabat[131], D.M. Gingrich[2,af],
M.P. Giordani[71a,71c], P.F. Giraud[139], G. Giugliarelli[71a,71c], D. Giugni[73a], F. Giuli[78a,78b],
I. Gkialas[9,j], L.K. Gladilin[39], C. Glasman[102], G.R. Gledhill[127], G. Glemža[50], M. Glisic[127],
I. Gnesi[45b], Y. Go[30], M. Goblirsch-Kolb[37], B. Gocke[51], D. Godin[111], B. Gokturk[22a],
S. Goldfarb[108], T. Golling[58], M.G.D. Gololo[34g], D. Golubkov[39], J.P. Gombas[110],
A. Gomes[134a,134b], G. Gomes Da Silva[146], A.J. Gomez Delegido[168], R. Gonçalo[134a],
L. Gonella[21], A. Gongadze[154c], F. Gonnella[21], J.L. Gonski[148], R.Y. González Andana[54],
S. González de la Hoz[168], R. Gonzalez Lopez[95], C. Gonzalez Renteria[18a],
M.V. Gonzalez Rodrigues[50], R. Gonzalez Suarez[166], S. Gonzalez-Sevilla[58], L. Goossens[37],
B. Gorini[37], E. Gorini[72a,72b], A. Gorišek[96], T.C. Gosart[132], A.T. Goshaw[53], M.I. Gostkin[40],
S. Goswami[125], C.A. Gottardo[37], S.A. Gotz[112], M. Gouighri[36b], V. Goumarre[50],
A.G. Goussiou[143], N. Govender[34c], R.P. Grabarczyk[130], I. Grabowska-Bold[88a], K. Graham[35],
E. Gramstad[129], S. Grancagnolo[72a,72b], C.M. Grant[1,139], P.M. Gravila[28f], F.G. Gravili[72a,72b],
H.M. Gray[18a], M. Greco[72a,72b], M.J. Green[1], C. Grefe[25], A.S. Grefsrud[17], I.M. Gregor[50],
K.T. Greif[163], P. Grenier[148], S.G. Grewe[113], A.A. Grillo[140], K. Grimm[32], S. Grinstein[13,w],

J.-F. Grivaz[68], E. Gross[174], J. Grosse-Knetter[57], L. Guan[109], J.G.R. Guerrero Rojas[168], G. Guerrieri[37], R. Gugel[103], J.A.M. Guhit[109], A. Guida[19], E. Guilloton[172], S. Guindon[37], F. Guo[14,115c], J. Guo[64c], L. Guo[50], L. Guo[14,u], Y. Guo[109], A. Gupta[51], R. Gupta[133], S. Gurbuz[25], S.S. Gurdasani[56], G. Gustavino[77a,77b], P. Gutierrez[124], L.F. Gutierrez Zagazeta[132], M. Gutsche[52], C. Gutschow[99], C. Gwenlan[130], C.B. Gwilliam[95], E.S. Haaland[129], A. Haas[121], M. Habedank[61], C. Haber[18a], H.K. Hadavand[8], A. Hadef[52], A.I. Hagan[94], J.J. Hahn[146], E.H. Haines[99], M. Haleem[171], J. Haley[125], G.D. Hallewell[105], L. Halser[20], K. Hamano[170], M. Hamer[25], E.J. Hampshire[98], J. Han[64b], L. Han[115a], L. Han[64a], S. Han[18a], Y.F. Han[159], K. Hanagaki[86], M. Hance[140], D.A. Hangal[43], H. Hanif[147], M.D. Hank[132], J.B. Hansen[44], P.H. Hansen[44], D. Harada[58], T. Harenberg[176], S. Harkusha[178], M.L. Harris[106], Y.T. Harris[25], J. Harrison[13], N.M. Harrison[123], P.F. Harrison[172], N.M. Hartman[113], N.M. Hartmann[112], R.Z. Hasan[98,138], Y. Hasegawa[145], F. Haslbeck[130], S. Hassan[17], R. Hauser[110], C.M. Hawkes[21], R.J. Hawkings[37], Y. Hayashi[158], D. Hayden[110], C. Hayes[109], R.L. Hayes[118], C.P. Hays[130], J.M. Hays[97], H.S. Hayward[95], F. He[64a], M. He[14,115c], Y. He[50], Y. He[99], N.B. Heatley[97], V. Hedberg[101], A.L. Heggelund[129], C. Heidegger[56], K.K. Heidegger[56], J. Heilman[35], S. Heim[50], T. Heim[18a], J.G. Heinlein[132], J.J. Heinrich[127], L. Heinrich[113,ad], J. Hejbal[135], A. Held[175], S. Hellesund[17], C.M. Helling[169], S. Hellman[49a,49b], R.C.W. Henderson[94], L. Henkelmann[33], A.M. Henriques Correia[37], H. Herde[101], Y. Hernández Jiménez[150], L.M. Herrmann[25], T. Herrmann[52], G. Herten[56], R. Hertenberger[112], L. Hervas[37], M.E. Hesping[103], N.P. Hessey[160a], J. Hessler[113], M. Hidaoui[36b], N. Hidic[137], E. Hill[159], S.J. Hillier[21], J.R. Hinds[110], F. Hinterkeuser[25], M. Hirose[128], S. Hirose[161], D. Hirschbuehl[176], T.G. Hitchings[104], B. Hiti[96], J. Hobbs[150], R. Hobincu[28e], N. Hod[174], M.C. Hodgkinson[144], B.H. Hodkinson[130], A. Hoecker[37], D.D. Hofer[109], J. Hofer[168], T. Holm[25], M. Holzbock[37], L.B.A.H. Hommels[33], B.P. Honan[104], J.J. Hong[70], J. Hong[64c], T.M. Hong[133], B.H. Hooberman[167], W.H. Hopkins[6], M.C. Hoppesch[167], Y. Horii[114], M.E. Horstmann[113], S. Hou[153], M.R. Housenga[167], A.S. Howard[96], J. Howarth[61], J. Hoya[6], M. Hrabovsky[126], A. Hrynevich[50], T. Hryn'ova[4], P.J. Hsu[67], S.-C. Hsu[143], T. Hsu[68], M. Hu[18a], Q. Hu[64a], S. Huang[33], X. Huang[14,115c], Y. Huang[144], Y. Huang[103], Y. Huang[14], Z. Huang[104], Z. Hubacek[136], M. Huebner[25], F. Huegging[25], T.B. Huffman[130], M. Hufnagel Maranha De Faria[85a], C.A. Hugli[50], M. Huhtinen[37], S.K. Huiberts[17], R. Hulsken[107], N. Huseynov[12,g], J. Huston[110], J. Huth[63], R. Hyneman[7], G. Iacobucci[58], G. Iakovidis[30], L. Iconomidou-Fayard[68], J.P. Iddon[37], P. Iengo[74a,74b], R. Iguchi[158], Y. Iiyama[158], T. Iizawa[130], Y. Ikegami[86], D. Iliadis[157], N. Ilic[159], H. Imam[85c], G. Inacio Goncalves[85d], T. Ingebretsen Carlson[49a,49b], J.M. Inglis[97], G. Introzzi[75a,75b], M. Iodice[79a], V. Ippolito[77a,77b], R.K. Irwin[95], M. Ishino[158], W. Islam[175], C. Issever[19], S. Istin[22a,ak], H. Ito[173], R. Iuppa[80a,80b], A. Ivina[174], J.M. Izen[47], V. Izzo[74a], P. Jacka[135], P. Jackson[1], C.S. Jagfeld[112], G. Jain[160a], P. Jain[50], K. Jakobs[56], T. Jakoubek[174], J. Jamieson[61], W. Jang[158], M. Javurkova[106], P. Jawahar[104], L. Jeanty[127], J. Jejelava[154a], P. Jenni[56,f], C.E. Jessiman[35], C. Jia[64b], H. Jia[169], J. Jia[150], X. Jia[14,115c], Z. Jia[115a], C. Jiang[54], S. Jiggins[50], J. Jimenez Pena[13], S. Jin[115a], A. Jinaru[28b], O. Jinnouchi[142], P. Johansson[144], K.A. Johns[7], J.W. Johnson[140], F.A. Jolly[50], D.M. Jones[151], E. Jones[50], K.S. Jones[8], P. Jones[33], R.W.L. Jones[94], T.J. Jones[95], H.L. Joos[57,37], R. Joshi[123], J. Jovicevic[16], X. Ju[18a], J.J. Junggeburth[37], T. Junkermann[65a], A. Juste Rozas[13,w], M.K. Juzek[89], S. Kabana[141e], A. Kaczmarska[89], M. Kado[113], H. Kagan[123], M. Kagan[148], A. Kahn[132], C. Kahra[103], T. Kaji[158], E. Kajomovitz[155], N. Kakati[174], I. Kalaitzidou[56], C.W. Kalderon[30], N.J. Kang[140], D. Kar[34g], K. Karava[130], M.J. Kareem[160b], E. Karentzos[25],

O. Karkout[118], S.N. Karpov[40], Z.M. Karpova[40], V. Kartvelishvili[94], A.N. Karyukhin[39], E. Kasimi[157], J. Katzy[50], S. Kaur[35], K. Kawade[145], M.P. Kawale[124], C. Kawamoto[90], T. Kawamoto[64a], E.F. Kay[37], F.I. Kaya[162], S. Kazakos[110], V.F. Kazanin[39], Y. Ke[150], J.M. Keaveney[34a], R. Keeler[170], G.V. Kehris[63], J.S. Keller[35], J.J. Kempster[151], O. Kepka[135], J. Kerr[160b], B.P. Kerridge[138], S. Kersten[176], B.P. Kerševan[96], L. Keszeghova[29a], S. Ketabchi Haghighat[159], R.A. Khan[133], A. Khanov[125], A.G. Kharlamov[39], T. Kharlamova[39], E.E. Khoda[143], M. Kholodenko[134a], T.J. Khoo[19], G. Khoriauli[171], J. Khubua[154b,*], Y.A.R. Khwaira[131], B. Kibirige[34g], D. Kim[6], D.W. Kim[49a,49b], Y.K. Kim[41], N. Kimura[99], M.K. Kingston[57], A. Kirchhoff[57], C. Kirfel[25], F. Kirfel[25], J. Kirk[138], A.E. Kiryunin[113], S. Kita[161], C. Kitsaki[10], O. Kivernyk[25], M. Klassen[162], C. Klein[35], L. Klein[171], M.H. Klein[46], S.B. Klein[58], U. Klein[95], A. Klimentov[30], T. Klioutchnikova[37], P. Kluit[118], S. Kluth[113], E. Kneringer[81], T.M. Knight[159], A. Knue[51], D. Kobylianskii[174], S.F. Koch[130], M. Kocian[148], P. Kodyš[137], D.M. Koeck[127], P.T. Koenig[25], T. Koffas[35], O. Kolay[52], I. Koletsou[4], T. Komarek[89], K. Köneke[57], A.X.Y. Kong[1], T. Kono[122], N. Konstantinidis[99], P. Kontaxakis[58], B. Konya[101], R. Kopeliansky[43], S. Koperny[88a], K. Korcyl[89], K. Kordas[157,e], A. Korn[99], S. Korn[57], I. Korolkov[13], N. Korotkova[39], B. Kortman[118], O. Kortner[113], S. Kortner[113], W.H. Kostecka[119], V.V. Kostyukhin[146], A. Kotsokechagia[37], A. Kotwal[53], A. Koulouris[37], A. Kourkoumeli-Charalampidi[75a,75b], C. Kourkoumelis[9], E. Kourlitis[113,ad], O. Kovanda[127], R. Kowalewski[170], W. Kozanecki[127], A.S. Kozhin[39], V.A. Kramarenko[39], G. Kramberger[96], P. Kramer[25], M.W. Krasny[131], A. Krasznahorkay[37], A.C. Kraus[119], J.W. Kraus[176], J.A. Kremer[50], T. Kresse[52], L. Kretschmann[176], J. Kretzschmar[95], K. Kreul[19], P. Krieger[159], K. Krizka[21], K. Kroeninger[51], H. Kroha[113], J. Kroll[135], J. Kroll[132], K.S. Krowpman[110], U. Kruchonak[40], H. Krüger[25], N. Krumnack[83], M.C. Kruse[53], O. Kuchinskaia[39], S. Kuday[3a], S. Kuehn[37], R. Kuesters[56], T. Kuhl[50], V. Kukhtin[40], Y. Kulchitsky[40], S. Kuleshov[141d,141b], M. Kumar[34g], N. Kumari[50], P. Kumari[160b], A. Kupco[135], T. Kupfer[51], A. Kupich[39], O. Kuprash[56], H. Kurashige[87], L.L. Kurchaninov[160a], O. Kurdysh[68], Y.A. Kurochkin[38], A. Kurova[39], M. Kuze[142], A.K. Kvam[106], J. Kvita[126], T. Kwan[107], N.G. Kyriacou[109], L.A.O. Laatu[105], C. Lacasta[168], F. Lacava[77a,77b], H. Lacker[19], D. Lacour[131], N.N. Lad[99], E. Ladygin[40], A. Lafarge[42], B. Laforge[131], T. Lagouri[177], F.Z. Lahbabi[36a], S. Lai[57], J.E. Lambert[170], S. Lammers[70], W. Lampl[7], C. Lampoudis[157,e], G. Lamprinoudis[103], A.N. Lancaster[119], E. Lançon[30], U. Landgraf[56], M.P.J. Landon[97], V.S. Lang[56], O.K.B. Langrekken[129], A.J. Lankford[163], F. Lanni[37], K. Lantzsch[25], A. Lanza[75a], M. Lanzac Berrocal[168], J.F. Laporte[139], T. Lari[73a], F. Lasagni Manghi[24b], M. Lassnig[37], V. Latonova[135], S.D. Lawlor[144], Z. Lawrence[104], R. Lazaridou[172], M. Lazzaroni[73a,73b], H.D.M. Le[110], E.M. Le Boulicaut[177], L.T. Le Pottier[18a], B. Leban[24b,24a], A. Lebedev[83], M. LeBlanc[104], F. Ledroit-Guillon[62], S.C. Lee[153], S. Lee[49a,49b], T.F. Lee[95], L.L. Leeuw[34c,ai], M. Lefebvre[170], C. Leggett[18a], G. Lehmann Miotto[37], M. Leigh[58], W.A. Leight[106], W. Leinonen[117], A. Leisos[157,t], M.A.L. Leite[85c], C.E. Leitgeb[19], R. Leitner[137], K.J.C. Leney[46], T. Lenz[25], S. Leone[76a], C. Leonidopoulos[54], A. Leopold[149], R. Les[110], C.G. Lester[33], M. Levchenko[39], J. Levêque[4], L.J. Levinson[174], G. Levrini[24b,24a], M.P. Lewicki[89], C. Lewis[143], D.J. Lewis[4], L. Lewitt[144], A. Li[30], B. Li[64b], C. Li[109], C-Q. Li[113], H. Li[64a], H. Li[64b], H. Li[115a], H. Li[15], H. Li[64b], J. Li[64c], K. Li[14], L. Li[64c], M. Li[14,115c], R. Li[177], S. Li[14,115c], S. Li[64d,64c,d], T. Li[5], X. Li[107], Z. Li[158], Z. Li[14,115c], Z. Li[64a], S. Liang[14,115c], Z. Liang[14], M. Liberatore[139], B. Liberti[78a], K. Lie[66c], J. Lieber Marin[85e], H. Lien[70], H. Lin[109], K. Lin[110], L. Linden[112], R.E. Lindley[7], J.H. Lindon[2], J. Ling[63], E. Lipeles[132], A. Lipniacka[17], A. Lister[169], J.D. Little[70], B. Liu[14], B.X. Liu[115b], D. Liu[64d,64c], E.H.L. Liu[21], J.B. Liu[64a], J.K.K. Liu[33], K. Liu[64d], K. Liu[64d,64c], M. Liu[64a], M.Y. Liu[64a], P. Liu[14], Q. Liu[64d,143,64c], X. Liu[64a], X. Liu[64b], Y. Liu[115b,115c], Y.L. Liu[64b], Y.W. Liu[64a], S.L. Lloyd[97], E.M. Lobodzinska[50], P. Loch[7], E. Lodhi[159], T. Lohse[19], K. Lohwasser[144], E. Loiacono[50], J.D. Lomas[21], J.D. Long[43], I. Longarini[163], R. Longo[167], I. Lopez Paz[69], A. Lopez Solis[50], N.A. Lopez-canelas[7], N. Lorenzo Martinez[4], A.M. Lory[112], M. Losada[120a], G. Löschcke Centeno[151], O. Loseva[39], X. Lou[49a,49b], X. Lou[14,115c], A. Lounis[68], P.A. Love[94], G. Lu[14,115c], M. Lu[68], S. Lu[132], Y.J. Lu[153], H.J. Lubatti[143], C. Luci[77a,77b], F.L. Lucio Alves[115a], F. Luehring[70], O. Lukianchuk[68], B.S. Lunday[132], O. Lundberg[149], B. Lund-Jensen[149,*], N.A. Luongo[6], M.S. Lutz[37], A.B. Lux[26], D. Lynn[30], R. Lysak[135], E. Lytken[101], V. Lyubushkin[40], T. Lyubushkina[40], M.M. Lyukova[150], M.Firdaus M. Soberi[54], H. Ma[30], K. Ma[64a], L.L. Ma[64b], W. Ma[64a], Y. Ma[125], J.C. MacDonald[103], P.C. Machado De Abreu Farias[85e], R. Madar[42], T. Madula[99], J. Maeda[87], T. Maeno[30], P.T. Mafa[34c,k], H. Maguire[144], V. Maiboroda[139], A. Maio[134a,134b,134d], K. Maj[88a], O. Majersky[50], S. Majewski[127], N. Makovec[68], V. Maksimovic[16], B. Malaescu[131], Pa. Malecki[89], V.P. Maleev[39], F. Malek[62,o], M. Mali[96], D. Malito[98], U. Mallik[82,*], S. Maltezos[10], S. Malyukov[40], J. Mamuzic[13], G. Mancini[55], M.N. Mancini[27], G. Manco[75a,75b], J.P. Mandalia[97], S.S. Mandarry[151], I. Mandić[96], L. Manhaes de Andrade Filho[85a], I.M. Maniatis[174], J. Manjarres Ramos[92], D.C. Mankad[174], A. Mann[112], S. Manzoni[37], L. Mao[64c], X. Mapekula[34c], A. Marantis[157,t], G. Marchiori[5], M. Marcisovsky[135], C. Marcon[73a], M. Marinescu[21], S. Marium[50], M. Marjanovic[124], A. Markhoos[56], M. Markovitch[68], M.K. Maroun[106], E.J. Marshall[94], Z. Marshall[18a], S. Marti-Garcia[168], J. Martin[99], T.A. Martin[138], V.J. Martin[54], B. Martin dit Latour[17], L. Martinelli[77a,77b], M. Martinez[13,w], P. Martinez Agullo[168], V.I. Martinez Outschoorn[106], P. Martinez Suarez[13], S. Martin-Haugh[138], G. Martinovicova[137], V.S. Martoiu[28b], A.C. Martyniuk[99], A. Marzin[37], D. Mascione[80a,80b], L. Masetti[103], J. Masik[104], A.L. Maslennikov[39], S.L. Mason[43], P. Massarotti[74a,74b], P. Mastrandrea[76a,76b], A. Mastroberardino[45b,45a], T. Masubuchi[128], T.T. Mathew[127], T. Mathisen[166], J. Matousek[137], D.M. Mattern[51], J. Maurer[28b], T. Maurin[61], A.J. Maury[68], B. Maček[96], D.A. Maximov[39], A.E. May[104], R. Mazini[34g], I. Maznas[119], M. Mazza[110], S.M. Mazza[140], E. Mazzeo[73a,73b], J.P. Mc Gowan[170], S.P. Mc Kee[109], C.A. Mc Lean[6], C.C. McCracken[169], E.F. McDonald[108], A.E. McDougall[118], L.F. Mcelhinney[94], J.A. Mcfayden[151], R.P. McGovern[132], R.P. Mckenzie[34g], T.C. Mclachlan[50], D.J. Mclaughlin[99], S.J. McMahon[138], C.M. Mcpartland[95], R.A. McPherson[170,aa], S. Mehlhase[112], A. Mehta[95], D. Melini[168], B.R. Mellado Garcia[34g], A.H. Melo[57], F. Meloni[50], A.M. Mendes Jacques Da Costa[104], H.Y. Meng[159], L. Meng[94], S. Menke[113], M. Mentink[37], E. Meoni[45b,45a], G. Mercado[119], S. Merianos[157], C. Merlassino[71a,71c], L. Merola[74a,74b], C. Meroni[73a,73b], J. Metcalfe[6], A.S. Mete[6], E. Meuser[103], C. Meyer[70], J-P. Meyer[139], R.P. Middleton[138], L. Mijović[54], G. Mikenberg[174], M. Mikestikova[135], M. Mikuž[96], H. Mildner[103], A. Milic[37], D.W. Miller[41], E.H. Miller[148], L.S. Miller[35], A. Milov[174], D.A. Milstead[49a,49b], T. Min[115a], A.A. Minaenko[39], I.A. Minashvili[154b], A.I. Mincer[121], B. Mindur[88a], M. Mineev[40], Y. Mino[90], L.M. Mir[13], M. Miralles Lopez[61], M. Mironova[18a], M.C. Missio[117], A. Mitra[172], V.A. Mitsou[168], Y. Mitsumori[114], O. Miu[159], P.S. Miyagawa[97], T. Mkrtchyan[65a], M. Mlinarevic[99], T. Mlinarevic[99], M. Mlynarikova[37], S. Mobius[20], P. Mogg[112], M.H. Mohamed Farook[116], A.F. Mohammed[14,115c], S. Mohapatra[43], G. Mokgatitswane[34g], L. Moleri[174], B. Mondal[146], S. Mondal[136], K. Mönig[50], E. Monnier[105], L. Monsonis Romero[168], J. Montejo Berlingen[13], A. Montella[49a,49b], M. Montella[123], F. Montereali[79a,79b], F. Monticelli[93], S. Monzani[71a,71c], A. Morancho Tarda[44], N. Morange[68], A.L. Moreira De Carvalho[50], M. Moreno Llácer[168], C. Moreno Martinez[58],

J.M. Moreno Perez[23b], P. Morettini[59b], S. Morgenstern[37], M. Morii[63], M. Morinaga[158],
M. Moritsu[91], F. Morodei[77a,77b], P. Moschovakos[37], B. Moser[130], M. Mosidze[154b],
T. Moskalets[46], P. Moskvitina[117], J. Moss[32,l], P. Moszkowicz[88a], A. Moussa[36d],
Y. Moyal[174], E.J.W. Moyse[106], O. Mtintsilana[34g], S. Muanza[105], J. Mueller[133],
D. Muenstermann[94], R. Müller[37], G.A. Mullier[166], A.J. Mullin[33], J.J. Mullin[132], A.E. Mulski[63],
D.P. Mungo[159], D. Munoz Perez[168], F.J. Munoz Sanchez[104], M. Murin[104], W.J. Murray[172,138],
M. Muškinja[96], C. Mwewa[30], A.G. Myagkov[39,a], A.J. Myers[8], G. Myers[109], M. Myska[136],
B.P. Nachman[18a], K. Nagai[130], K. Nagano[86], R. Nagasaka[158], J.L. Nagle[30,ah], E. Nagy[105],
A.M. Nairz[37], Y. Nakahama[86], K. Nakamura[86], K. Nakkalil[5], H. Nanjo[128],
E.A. Narayanan[46], Y. Narukawa[158], I. Naryshkin[39], L. Nasella[73a,73b], S. Nasri[120b],
C. Nass[25], G. Navarro[23a], J. Navarro-Gonzalez[168], A. Nayaz[19], P.Y. Nechaeva[39],
S. Nechaeva[24b,24a], F. Nechansky[135], L. Nedic[130], T.J. Neep[21], A. Negri[75a,75b],
M. Negrini[24b], C. Nellist[118], C. Nelson[107], K. Nelson[109], S. Nemecek[135], M. Nessi[37,h],
M.S. Neubauer[167], F. Neuhaus[103], J. Neundorf[50], J. Newell[95], P.R. Newman[21], C.W. Ng[133],
Y.W.Y. Ng[50], B. Ngair[120a], H.D.N. Nguyen[111], R.B. Nickerson[130], R. Nicolaidou[139],
J. Nielsen[140], M. Niemeyer[57], J. Niermann[37], N. Nikiforou[37], V. Nikolaenko[39,a],
I. Nikolic-Audit[131], K. Nikolopoulos[21], P. Nilsson[30], I. Ninca[50], G. Ninio[156], A. Nisati[77a],
N. Nishu[2], R. Nisius[113], N. Nitika[71a,71c], J-E. Nitschke[52], E.K. Nkadimeng[34g], T. Nobe[158],
T. Nommensen[152], M.B. Norfolk[144], B.J. Norman[35], M. Noury[36a], J. Novak[96], T. Novak[96],
L. Novotny[136], R. Novotny[116], L. Nozka[126], K. Ntekas[163], N.M.J. Nunes De Moura Junior[85b],
J. Ocariz[131], A. Ochi[87], I. Ochoa[134a], S. Oerdek[50,x], J.T. Offermann[41], A. Ogrodnik[137],
A. Oh[104], C.C. Ohm[149], H. Oide[86], R. Oishi[158], M.L. Ojeda[37], Y. Okumura[158],
L.F. Oleiro Seabra[134a], I. Oleksiyuk[58], S.A. Olivares Pino[141d], G. Oliveira Correa[13],
D. Oliveira Damazio[30], J.L. Oliver[163], Ö.O. Öncel[56], A.P. O'Neill[20], A. Onofre[134a,134e],
P.U.E. Onyisi[11], M.J. Oreglia[41], D. Orestano[79a,79b], N. Orlando[13], R.S. Orr[159],
L.M. Osojnak[132], Y. Osumi[114], G. Otero y Garzon[31], H. Otono[91], P.S. Ott[65a], G.J. Ottino[18a],
M. Ouchrif[36d], F. Ould-Saada[129], T. Ovsiannikova[143], M. Owen[61], R.E. Owen[138],
V.E. Ozcan[22a], F. Ozturk[89], N. Ozturk[8], S. Ozturk[84], H.A. Pacey[130], A. Pacheco Pages[13],
C. Padilla Aranda[13], G. Padovano[77a,77b], S. Pagan Griso[18a], G. Palacino[70], A. Palazzo[72a,72b],
J. Pampel[25], J. Pan[177], T. Pan[66a], D.K. Panchal[11], C.E. Pandini[118],
J.G. Panduro Vazquez[138], H.D. Pandya[1], H. Pang[139], P. Pani[50], G. Panizzo[71a,71c],
L. Panwar[131], L. Paolozzi[58], S. Parajuli[167], A. Paramonov[6], C. Paraskevopoulos[55],
D. Paredes Hernandez[66b], A. Pareti[75a,75b], K.R. Park[43], T.H. Park[159], M.A. Parker[33],
F. Parodi[59b,59a], V.A. Parrish[54], J.A. Parsons[43], U. Parzefall[56], B. Pascual Dias[111],
L. Pascual Dominguez[102], E. Pasqualucci[77a], S. Passaggio[59b], F. Pastore[98], P. Patel[89],
U.M. Patel[53], J.R. Pater[104], T. Pauly[37], F. Pauwels[137], C.I. Pazos[162], M. Pedersen[129],
R. Pedro[134a], S.V. Peleganchuk[39], O. Penc[37], E.A. Pender[54], S. Peng[15], G.D. Penn[177],
K.E. Penski[112], M. Penzin[39], B.S. Peralva[85d], A.P. Pereira Peixoto[143], L. Pereira Sanchez[148],
D.V. Perepelitsa[30,ah], G. Perera[106], E. Perez Codina[160a], M. Perganti[10], H. Pernegger[37],
S. Perrella[77a,77b], O. Perrin[42], K. Peters[50], R.F.Y. Peters[104], B.A. Petersen[37],
T.C. Petersen[44], E. Petit[105], V. Petousis[136], C. Petridou[157,e], T. Petru[137], A. Petrukhin[146],
M. Pettee[18a], A. Petukhov[84], K. Petukhova[37], R. Pezoa[141f], L. Pezzotti[37], G. Pezzullo[177],
A.J. Pfleger[37], T.M. Pham[175], T. Pham[108], P.W. Phillips[138], G. Piacquadio[150], E. Pianori[18a],
F. Piazza[127], R. Piegaia[31], D. Pietreanu[28b], A.D. Pilkington[104], M. Pinamonti[71a,71c],
J.L. Pinfold[2], B.C. Pinheiro Pereira[134a], J. Pinol Bel[13], A.E. Pinto Pinoargote[139,139],
L. Pintucci[71a,71c], K.M. Piper[151], A. Pirttikoski[58], D.A. Pizzi[35], L. Pizzimento[66b],
A. Pizzini[118], M.-A. Pleier[30], V. Pleskot[137], E. Plotnikova[40], G. Poddar[97], R. Poettgen[101],

L. Poggioli[131], S. Polacek[137], G. Polesello[75a], A. Poley[147,160a], A. Polini[24b], C.S. Pollard[172],
Z.B. Pollock[123], E. Pompa Pacchi[124], N.I. Pond[99], D. Ponomarenko[70], L. Pontecorvo[37],
S. Popa[28a], G.A. Popeneciu[28d], A. Poreba[37], D.M. Portillo Quintero[160a], S. Pospisil[136],
M.A. Postill[144], P. Postolache[28c], K. Potamianos[172], P.A. Potepa[88a], I.N. Potrap[40],
C.J. Potter[33], H. Potti[152], J. Poveda[168], M.E. Pozo Astigarraga[37], A. Prades Ibanez[78a,78b],
J. Pretel[170], D. Price[104], M. Primavera[72a], L. Primomo[71a,71c], M.A. Principe Martin[102],
R. Privara[126], T. Procter[61], M.L. Proffitt[143], N. Proklova[132], K. Prokofiev[66c], G. Proto[113],
J. Proudfoot[6], M. Przybycien[88a], W.W. Przygoda[88b], A. Psallidas[48], J.E. Puddefoot[144],
D. Pudzha[56], D. Pyatiizbyantseva[39], J. Qian[109], R. Qian[110], D. Qichen[104], Y. Qin[13],
T. Qiu[54], A. Quadt[57], M. Queitsch-Maitland[104], G. Quetant[58], R.P. Quinn[169],
G. Rabanal Bolanos[63], D. Rafanoharana[56], F. Raffaeli[78a,78b], F. Ragusa[73a,73b], J.L. Rainbolt[41],
J.A. Raine[58], S. Rajagopalan[30], E. Ramakoti[39], L. Rambelli[59b,59a], I.A. Ramirez-Berend[35],
K. Ran[50,115c], D.S. Rankin[132], N.P. Rapheeha[34g], H. Rasheed[28b], V. Raskina[131],
D.F. Rassloff[65a], A. Rastogi[18a], S. Rave[103], S. Ravera[59b,59a], B. Ravina[57], I. Ravinovich[174],
M. Raymond[37], A.L. Read[129], N.P. Readioff[144], D.M. Rebuzzi[75a,75b], G. Redlinger[30],
A.S. Reed[113], K. Reeves[27], J.A. Reidelsturz[176], D. Reikher[127], A. Rej[51], C. Rembser[37],
H. Ren[64a], M. Renda[28b], F. Renner[50], A.G. Rennie[163], A.L. Rescia[50], S. Resconi[73a],
M. Ressegotti[59b,59a], S. Rettie[37], W.F. Rettie[35], J.G. Reyes Rivera[110], E. Reynolds[18a],
O.L. Rezanova[39], P. Reznicek[137], H. Riani[36d], N. Ribaric[53], E. Ricci[80a,80b], R. Richter[113],
S. Richter[49a,49b], E. Richter-Was[88b], M. Ridel[131], S. Ridouani[36d], P. Rieck[121], P. Riedler[37],
E.M. Riefel[49a,49b], J.O. Rieger[118], M. Rijssenbeek[150], M. Rimoldi[37], L. Rinaldi[24b,24a],
P. Rincke[57,166], T.T. Rinn[30], M.P. Rinnagel[112], G. Ripellino[166], I. Riu[13],
J.C. Rivera Vergara[170], F. Rizatdinova[125], E. Rizvi[97], B.R. Roberts[18a], S.S. Roberts[140],
S.H. Robertson[107,aa], D. Robinson[33], M. Robles Manzano[103], A. Robson[61], A. Rocchi[78a,78b],
C. Roda[76a,76b], S. Rodriguez Bosca[37], Y. Rodriguez Garcia[23a], A.M. Rodríguez Vera[119],
S. Roe[37], J.T. Roemer[37], O. Røhne[129], R.A. Rojas[106], C.P.A. Roland[131], J. Roloff[30],
A. Romaniouk[81], E. Romano[75a,75b], M. Romano[24b], A.C. Romero Hernandez[167],
N. Rompotis[95], L. Roos[131], S. Rosati[77a], B.J. Rosser[41], E. Rossi[130], E. Rossi[74a,74b],
L.P. Rossi[63], L. Rossini[56], R. Rosten[123], M. Rotaru[28b], B. Rottler[56], C. Rougier[92],
D. Rousseau[68], D. Rousso[50], A. Roy[167], S. Roy-Garand[159], A. Rozanov[105],
Z.M.A. Rozario[61], Y. Rozen[155], A. Rubio Jimenez[168], V.H. Ruelas Rivera[19], T.A. Ruggeri[1],
A. Ruggiero[130], A. Ruiz-Martinez[168], A. Rummler[37], Z. Rurikova[56], N.A. Rusakovich[40],
H.L. Russell[170], G. Russo[77a,77b], J.P. Rutherfoord[7], S. Rutherford Colmenares[33], M. Rybar[137],
E.B. Rye[129], A. Ryzhov[46], J.A. Sabater Iglesias[58], H.F-W. Sadrozinski[140], F. Safai Tehrani[77a],
B. Safarzadeh Samani[138], S. Saha[1], M. Sahinsoy[84], A. Saibel[168], M. Saimpert[139],
M. Saito[158], T. Saito[158], A. Sala[73a,73b], D. Salamani[37], A. Salnikov[148], J. Salt[168],
A. Salvador Salas[156], D. Salvatore[45b,45a], F. Salvatore[151], A. Salzburger[37], D. Sammel[56],
E. Sampson[94], D. Sampsonidis[157,e], D. Sampsonidou[127], J. Sánchez[168],
V. Sanchez Sebastian[168], H. Sandaker[129], C.O. Sander[50], J.A. Sandesara[106], M. Sandhoff[176],
C. Sandoval[23b], L. Sanfilippo[65a], D.P.C. Sankey[138], T. Sano[90], A. Sansoni[55], L. Santi[37,77b],
C. Santoni[42], H. Santos[134a,134b], A. Santra[174], E. Sanzani[24b,24a], K.A. Saoucha[165],
J.G. Saraiva[134a,134d], J. Sardain[7], O. Sasaki[86], K. Sato[161], C. Sauer[37], E. Sauvan[4],
P. Savard[159,af], R. Sawada[158], C. Sawyer[138], L. Sawyer[100], C. Sbarra[24b], A. Sbrizzi[24b,24a],
T. Scanlon[99], J. Schaarschmidt[143], U. Schäfer[103], A.C. Schaffer[68,46], D. Schaile[112],
R.D. Schamberger[150], C. Scharf[19], M.M. Schefer[20], V.A. Schegelsky[39], D. Scheirich[137],
M. Schernau[141e], C. Scheulen[58], C. Schiavi[59b,59a], M. Schioppa[45b,45a], B. Schlag[148],
S. Schlenker[37], J. Schmeing[176], M.A. Schmidt[176], K. Schmieden[103], C. Schmitt[103],

N. Schmitt[103], S. Schmitt[50], L. Schoeffel[139], A. Schoening[65b], P.G. Scholer[35], E. Schopf[130], M. Schott[25], J. Schovancova[37], S. Schramm[58], T. Schroer[58], H-C. Schultz-Coulon[65a], M. Schumacher[56], B.A. Schumm[140], Ph. Schune[139], H.R. Schwartz[140], A. Schwartzman[148], T.A. Schwarz[109], Ph. Schwemling[139], R. Schwienhorst[110], F.G. Sciacca[20], A. Sciandra[30], G. Sciolla[27], F. Scuri[76a], C.D. Sebastiani[95], K. Sedlaczek[119], S.C. Seidel[116], A. Seiden[140], B.D. Seidlitz[43], C. Seitz[50], J.M. Seixas[85b], G. Sekhniaidze[74a], L. Selem[62], N. Semprini-Cesari[24b,24a], A. Semushin[178,39], D. Sengupta[58], V. Senthilkumar[168], L. Serin[68], M. Sessa[78a,78b], H. Severini[124], F. Sforza[59b,59a], A. Sfyrla[58], Q. Sha[14], E. Shabalina[57], H. Shaddix[119], A.H. Shah[33], R. Shaheen[149], J.D. Shahinian[132], D. Shaked Renous[174], L.Y. Shan[14], M. Shapiro[18a], A. Sharma[37], A.S. Sharma[169], P. Sharma[30], P.B. Shatalov[39], K. Shaw[151], S.M. Shaw[104], Q. Shen[64c], D.J. Sheppard[147], P. Sherwood[99], L. Shi[99], X. Shi[14], S. Shimizu[86], C.O. Shimmin[177], I.P.J. Shipsey[130,*], S. Shirabe[91], M. Shiyakova[40,y], M.J. Shochet[41], D.R. Shope[129], B. Shrestha[124], S. Shrestha[123,aj], I. Shreyber[39], M.J. Shroff[170], P. Sicho[135], A.M. Sickles[167], E. Sideras Haddad[34g,164], A.C. Sidley[118], A. Sidoti[24b], F. Siegert[52], Dj. Sijacki[16], F. Sili[93], J.M. Silva[54], I. Silva Ferreira[85b], M.V. Silva Oliveira[30], S.B. Silverstein[49a], S. Simion[68], R. Simoniello[37], E.L. Simpson[104], H. Simpson[151], L.R. Simpson[109], S. Simsek[84], S. Sindhu[57], P. Sinervo[159], S. Singh[30], S. Sinha[50], S. Sinha[104], M. Sioli[24b,24a], I. Siral[37], E. Sitnikova[50], J. Sjölin[49a,49b], A. Skaf[57], E. Skorda[21], P. Skubic[124], M. Slawinska[89], I. Slazyk[17], V. Smakhtin[174], B.H. Smart[138], S.Yu. Smirnov[39], Y. Smirnov[39], L.N. Smirnova[39,a], O. Smirnova[101], A.C. Smith[43], D.R. Smith[163], E.A. Smith[41], J.L. Smith[104], R. Smith[148], H. Smitmanns[103], M. Smizanska[94], K. Smolek[136], A.A. Snesarev[39], H.L. Snoek[118], S. Snyder[30], R. Sobie[170,aa], A. Soffer[156], C.A. Solans Sanchez[37], E.Yu. Soldatov[39], U. Soldevila[168], A.A. Solodkov[39], S. Solomon[27], A. Soloshenko[40], K. Solovieva[56], O.V. Solovyanov[42], P. Sommer[52], A. Sonay[13], W.Y. Song[160b], A. Sopczak[136], A.L. Sopio[54], F. Sopkova[29b], J.D. Sorenson[116], I.R. Sotarriva Alvarez[142], V. Sothilingam[65a], O.J. Soto Sandoval[141c,141b], S. Sottocornola[70], R. Soualah[165], Z. Soumaimi[36e], D. South[50], N. Soybelman[174], S. Spagnolo[72a,72b], M. Spalla[113], D. Sperlich[56], G. Spigo[37], B. Spisso[74a,74b], D.P. Spiteri[61], M. Spousta[137], E.J. Staats[35], R. Stamen[65a], A. Stampekis[21], E. Stanecka[89], W. Stanek-Maslouska[50], M.V. Stange[52], B. Stanislaus[18a], M.M. Stanitzki[50], B. Stapf[50], E.A. Starchenko[39], G.H. Stark[140], J. Stark[92], P. Staroba[135], P. Starovoitov[165], S. Stärz[107], R. Staszewski[89], G. Stavropoulos[48], A. Stefl[37], P. Steinberg[30], B. Stelzer[147,160a], H.J. Stelzer[133], O. Stelzer-Chilton[160a], H. Stenzel[60], T.J. Stevenson[151], G.A. Stewart[37], J.R. Stewart[125], M.C. Stockton[37], G. Stoicea[28b], M. Stolarski[134a], S. Stonjek[113], A. Straessner[52], J. Strandberg[149], S. Strandberg[49a,49b], M. Stratmann[176], M. Strauss[124], T. Strebler[105], P. Strizenec[29b], R. Ströhmer[171], D.M. Strom[127], R. Stroynowski[46], A. Strubig[49a,49b], S.A. Stucci[30], B. Stugu[17], J. Stupak[124], N.A. Styles[50], D. Su[148], S. Su[64a], W. Su[64d], X. Su[64a], D. Suchy[29a], K. Sugizaki[158], V.V. Sulin[39], M.J. Sullivan[95], D.M.S. Sultan[130], L. Sultanaliyeva[39], S. Sultansoy[3b], S. Sun[175], W. Sun[14], O. Sunneborn Gudnadottir[166], N. Sur[105], M.R. Sutton[151], H. Suzuki[161], M. Svatos[135], M. Swiatlowski[160a], T. Swirski[171], I. Sykora[29a], M. Sykora[137], T. Sykora[137], D. Ta[103], K. Tackmann[50,x], A. Taffard[163], R. Tafirout[160a], J.S. Tafoya Vargas[68], Y. Takubo[86], M. Talby[105], A.A. Talyshev[39], K.C. Tam[66b], N.M. Tamir[156], A. Tanaka[158], J. Tanaka[158], R. Tanaka[68], M. Tanasini[150], Z. Tao[169], S. Tapia Araya[141f], S. Tapprogge[103], A. Tarek Abouelfadl Mohamed[110], S. Tarem[155], K. Tariq[14], G. Tarna[28b], G.F. Tartarelli[73a], M.J. Tartarin[92], P. Tas[137], M. Tasevsky[135], E. Tassi[45b,45a], A.C. Tate[167], G. Tateno[158], Y. Tayalati[36e,z], G.N. Taylor[108], W. Taylor[160b], P. Teixeira-Dias[98], J.J. Teoh[159],

K. Terashi[158], J. Terron[102], S. Terzo[13], M. Testa[55], R.J. Teuscher[159,aa], A. Thaler[81],
O. Theiner[58], T. Theveneaux-Pelzer[105], O. Thielmann[176], D.W. Thomas[98], J.P. Thomas[21],
E.A. Thompson[18a], P.D. Thompson[21], E. Thomson[132], R.E. Thornberry[46], C. Tian[64a],
Y. Tian[58], V. Tikhomirov[39,a], Yu.A. Tikhonov[39], S. Timoshenko[39], D. Timoshyn[137],
E.X.L. Ting[1], P. Tipton[177], A. Tishelman-Charny[30], S.H. Tlou[34g], K. Todome[142],
S. Todorova-Nova[137], S. Todt[52], L. Toffolin[71a,71c], M. Togawa[86], J. Tojo[91], S. Tokár[29a],
K. Tokushuku[86], O. Toldaiev[70], G. Tolkachev[105], M. Tomoto[86,114], L. Tompkins[148,n],
E. Torrence[127], H. Torres[92], E. Torró Pastor[168], M. Toscani[31], C. Tosciri[41], M. Tost[11],
D.R. Tovey[144], I.S. Trandafir[28b], T. Trefzger[171], A. Tricoli[30], I.M. Trigger[160a],
S. Trincaz-Duvoid[131], D.A. Trischuk[27], B. Trocmé[62], A. Tropina[40], L. Truong[34c],
M. Trzebinski[89], A. Trzupek[89], F. Tsai[150], M. Tsai[109], A. Tsiamis[157], P.V. Tsiareshka[40],
S. Tsigaridas[160a], A. Tsirigotis[157,t], V. Tsiskaridze[159], E.G. Tskhadadze[154a], M. Tsopoulou[157],
Y. Tsujikawa[90], I.I. Tsukerman[39], V. Tsulaia[18a], S. Tsuno[86], K. Tsuri[122], D. Tsybychev[150],
Y. Tu[66b], A. Tudorache[28b], V. Tudorache[28b], A.N. Tuna[63], S. Turchikhin[59b,59a],
I. Turk Cakir[3a], R. Turra[73a], T. Turtuvshin[40], P.M. Tuts[43], S. Tzamarias[157,e], E. Tzovara[103],
F. Ukegawa[161], P.A. Ulloa Poblete[141c,141b], E.N. Umaka[30], G. Unal[37], A. Undrus[30],
G. Unel[163], J. Urban[29b], P. Urrejola[141a], G. Usai[8], R. Ushioda[142], M. Usman[111],
F. Ustuner[54], Z. Uysal[84], V. Vacek[136], B. Vachon[107], T. Vafeiadis[37], A. Vaitkus[99],
C. Valderanis[112], E. Valdes Santurio[49a,49b], M. Valente[160a], S. Valentinetti[24b,24a], A. Valero[168],
E. Valiente Moreno[168], A. Vallier[92], J.A. Valls Ferrer[168], D.R. Van Arneman[118],
T.R. Van Daalen[143], A. Van Der Graaf[51], P. Van Gemmeren[6], M. Van Rijnbach[37],
S. Van Stroud[99], I. Van Vulpen[118], P. Vana[137], M. Vanadia[78a,78b], U.M. Vande Voorde[149],
W. Vandelli[37], E.R. Vandewall[125], D. Vannicola[156], L. Vannoli[55], R. Vari[77a], E.W. Varnes[7],
C. Varni[18b], D. Varouchas[68], L. Varriale[168], K.E. Varvell[152], M.E. Vasile[28b], L. Vaslin[86],
A. Vasyukov[40], L.M. Vaughan[125], R. Vavricka[103], T. Vazquez Schroeder[37], J. Veatch[32],
V. Vecchio[104], M.J. Veen[106], I. Veliscek[30], L.M. Veloce[159], F. Veloso[134a,134c],
S. Veneziano[77a], A. Ventura[72a,72b], S. Ventura Gonzalez[139], A. Verbytskyi[113],
M. Verducci[76a,76b], C. Vergis[97], M. Verissimo De Araujo[85b], W. Verkerke[118],
J.C. Vermeulen[118], C. Vernieri[148], M. Vessella[163], M.C. Vetterli[147,af], A. Vgenopoulos[103],
N. Viaux Maira[141f], T. Vickey[144], O.E. Vickey Boeriu[144], G.H.A. Viehhauser[130], L. Vigani[65b],
M. Vigl[113], M. Villa[24b,24a], M. Villaplana Perez[168], E.M. Villhauer[54], E. Vilucchi[55],
M.G. Vincter[35], A. Visibile[118], C. Vittori[37], I. Vivarelli[24b,24a], E. Voevodina[113], F. Vogel[112],
J.C. Voigt[52], P. Vokac[136], Yu. Volkotrub[88b], E. Von Toerne[25], B. Vormwald[37],
V. Vorobel[137], K. Vorobev[39], M. Vos[168], K. Voss[146], M. Vozak[118], L. Vozdecky[124],
N. Vranjes[16], M. Vranjes Milosavljevic[16], M. Vreeswijk[118], N.K. Vu[64d,64c], R. Vuillermet[37],
O. Vujinovic[103], I. Vukotic[41], I.K. Vyas[35], S. Wada[161], C. Wagner[148], J.M. Wagner[18a],
W. Wagner[176], S. Wahdan[176], H. Wahlberg[93], C.H. Waits[124], J. Walder[138], R. Walker[112],
W. Walkowiak[146], A. Wall[132], E.J. Wallin[101], T. Wamorkar[18a], A.Z. Wang[140], C. Wang[103],
C. Wang[11], H. Wang[18a], J. Wang[66c], P. Wang[104], P. Wang[99], R. Wang[63], R. Wang[6],
S.M. Wang[153], S. Wang[14], T. Wang[64a], W.T. Wang[82], W. Wang[14], X. Wang[167],
X. Wang[64c], Y. Wang[64d], Y. Wang[115a], Y. Wang[64a], Z. Wang[109], Z. Wang[64d,53,64c],
Z. Wang[109], A. Warburton[107], R.J. Ward[21], N. Warrack[61], S. Waterhouse[98], A.T. Watson[21],
H. Watson[54], M.F. Watson[21], E. Watton[61,138], G. Watts[143], B.M. Waugh[99], J.M. Webb[56],
C. Weber[30], H.A. Weber[19], M.S. Weber[20], S.M. Weber[65a], C. Wei[64a], Y. Wei[56],
A.R. Weidberg[130], E.J. Weik[121], J. Weingarten[51], C. Weiser[56], C.J. Wells[50], T. Wenaus[30],
B. Wendland[51], T. Wengler[37], N.S. Wenke[113], N. Wermes[25], M. Wessels[65a], A.M. Wharton[94],
A.S. White[63], A. White[8], M.J. White[1], D. Whiteson[163], L. Wickremasinghe[128],

W. Wiedenmann[175], M. Wielers[138], C. Wiglesworth[44], D.J. Wilbern[124], H.G. Wilkens[37], J.J.H. Wilkinson[33], D.M. Williams[43], H.H. Williams[132], S. Williams[33], S. Willocq[106], B.J. Wilson[104], D.J. Wilson[104], P.J. Windischhofer[41], F.I. Winkel[31], F. Winklmeier[127], B.T. Winter[56], M. Wittgen[148], M. Wobisch[100], T. Wojtkowski[62], Z. Wolffs[118], J. Wollrath[37], M.W. Wolter[89], H. Wolters[134a,134c], M.C. Wong[140], E.L. Woodward[43], S.D. Worm[50], B.K. Wosiek[89], K.W. Woźniak[89], S. Wozniewski[57], K. Wraight[61], C. Wu[21], M. Wu[115b], M. Wu[117], S.L. Wu[175], X. Wu[58], X. Wu[64a], Y. Wu[64a], Z. Wu[4], J. Wuerzinger[113,ad], T.R. Wyatt[104], B.M. Wynne[54], S. Xella[44], L. Xia[115a], M. Xia[15], M. Xie[64a], A. Xiong[127], J. Xiong[18a], D. Xu[14], H. Xu[64a], L. Xu[64a], R. Xu[132], T. Xu[109], Y. Xu[143], Z. Xu[54], Z. Xu[115a], B. Yabsley[152], S. Yacoob[34a], Y. Yamaguchi[86], E. Yamashita[158], H. Yamauchi[161], T. Yamazaki[18a], Y. Yamazaki[87], S. Yan[61], Z. Yan[106], H.J. Yang[64c,64d], H.T. Yang[64a], S. Yang[64a], T. Yang[66c], X. Yang[37], X. Yang[14], Y. Yang[46], Y. Yang[64a], W-M. Yao[18a], H. Ye[57], J. Ye[14], S. Ye[30], X. Ye[64a], Y. Yeh[99], I. Yeletskikh[40], B. Yeo[18b], M.R. Yexley[99], T.P. Yildirim[130], P. Yin[43], K. Yorita[173], S. Younas[28b], C.J.S. Young[37], C. Young[148], C. Yu[14,115c], Y. Yu[64a], J. Yuan[14,115c], M. Yuan[109], R. Yuan[64d,64c], L. Yue[99], M. Zaazoua[64a], B. Zabinski[89], I. Zahir[36a], E. Zaid[54], Z.K. Zak[89], T. Zakareishvili[168], S. Zambito[58], J.A. Zamora Saa[141d,141b], J. Zang[158], D. Zanzi[56], R. Zanzottera[73a,73b], O. Zaplatilek[136], C. Zeitnitz[176], H. Zeng[14], J.C. Zeng[167], D.T. Zenger Jr[27], O. Zenin[39], T. Ženiš[29a], S. Zenz[97], S. Zerradi[36a], D. Zerwas[68], M. Zhai[14,115c], D.F. Zhang[144], J. Zhang[64b], J. Zhang[6], K. Zhang[14,115c], L. Zhang[64a], L. Zhang[115a], P. Zhang[14,115c], R. Zhang[175], S. Zhang[109], S. Zhang[92], T. Zhang[158], X. Zhang[64c], Y. Zhang[143], Y. Zhang[99], Y. Zhang[115a], Z. Zhang[18a], Z. Zhang[64b], Z. Zhang[68], H. Zhao[143], T. Zhao[64b], Y. Zhao[140], Z. Zhao[64a], Z. Zhao[64a], A. Zhemchugov[40], J. Zheng[115a], K. Zheng[167], X. Zheng[64a], Z. Zheng[148], D. Zhong[167], B. Zhou[109], H. Zhou[7], N. Zhou[64c], Y. Zhou[15], Y. Zhou[115a], Y. Zhou[7], C.G. Zhu[64b], J. Zhu[109], X. Zhu[64d], Y. Zhu[64c], Y. Zhu[64a], X. Zhuang[14], K. Zhukov[70], N.I. Zimine[40], J. Zinsser[65b], M. Ziolkowski[146], L. Živković[16], A. Zoccoli[24b,24a], K. Zoch[63], T.G. Zorbas[144], O. Zormpa[48], W. Zou[43], L. Zwalinski[37].

[1] Department of Physics, University of Adelaide, Adelaide; Australia.
[2] Department of Physics, University of Alberta, Edmonton AB; Canada.
[3] (a)Department of Physics, Ankara University, Ankara;(b)Division of Physics, TOBB University of Economics and Technology, Ankara; Türkiye.
[4] LAPP, Université Savoie Mont Blanc, CNRS/IN2P3, Annecy; France.
[5] APC, Université Paris Cité, CNRS/IN2P3, Paris; France.
[6] High Energy Physics Division, Argonne National Laboratory, Argonne IL; United States of America.
[7] Department of Physics, University of Arizona, Tucson AZ; United States of America.
[8] Department of Physics, University of Texas at Arlington, Arlington TX; United States of America.
[9] Physics Department, National and Kapodistrian University of Athens, Athens; Greece.
[10] Physics Department, National Technical University of Athens, Zografou; Greece.
[11] Department of Physics, University of Texas at Austin, Austin TX; United States of America.
[12] Institute of Physics, Azerbaijan Academy of Sciences, Baku; Azerbaijan.
[13] Institut de Física d'Altes Energies (IFAE), Barcelona Institute of Science and Technology, Barcelona; Spain.
[14] Institute of High Energy Physics, Chinese Academy of Sciences, Beijing; China.
[15] Physics Department, Tsinghua University, Beijing; China.
[16] Institute of Physics, University of Belgrade, Belgrade; Serbia.
[17] Department for Physics and Technology, University of Bergen, Bergen; Norway.

[18](a)Physics Division, Lawrence Berkeley National Laboratory, Berkeley CA;(b)University of California, Berkeley CA; United States of America.
[19]Institut für Physik, Humboldt Universität zu Berlin, Berlin; Germany.
[20]Albert Einstein Center for Fundamental Physics and Laboratory for High Energy Physics, University of Bern, Bern; Switzerland.
[21]School of Physics and Astronomy, University of Birmingham, Birmingham; United Kingdom.
[22](a)Department of Physics, Bogazici University, Istanbul;(b)Department of Physics Engineering, Gaziantep University, Gaziantep;(c)Department of Physics, Istanbul University, Istanbul; Türkiye.
[23](a)Facultad de Ciencias y Centro de Investigaciónes, Universidad Antonio Nariño, Bogotá;(b)Departamento de Física, Universidad Nacional de Colombia, Bogotá; Colombia.
[24](a)Dipartimento di Fisica e Astronomia A. Righi, Università di Bologna, Bologna;(b)INFN Sezione di Bologna; Italy.
[25]Physikalisches Institut, Universität Bonn, Bonn; Germany.
[26]Department of Physics, Boston University, Boston MA; United States of America.
[27]Department of Physics, Brandeis University, Waltham MA; United States of America.
[28](a)Transilvania University of Brasov, Brasov;(b)Horia Hulubei National Institute of Physics and Nuclear Engineering, Bucharest;(c)Department of Physics, Alexandru Ioan Cuza University of Iasi, Iasi;(d)National Institute for Research and Development of Isotopic and Molecular Technologies, Physics Department, Cluj-Napoca;(e)National University of Science and Technology Politechnica, Bucharest;(f)West University in Timisoara, Timisoara;(g)Faculty of Physics, University of Bucharest, Bucharest; Romania.
[29](a)Faculty of Mathematics, Physics and Informatics, Comenius University, Bratislava;(b)Department of Subnuclear Physics, Institute of Experimental Physics of the Slovak Academy of Sciences, Kosice; Slovak Republic.
[30]Physics Department, Brookhaven National Laboratory, Upton NY; United States of America.
[31]Universidad de Buenos Aires, Facultad de Ciencias Exactas y Naturales, Departamento de Física, y CONICET, Instituto de Física de Buenos Aires (IFIBA), Buenos Aires; Argentina.
[32]California State University, CA; United States of America.
[33]Cavendish Laboratory, University of Cambridge, Cambridge; United Kingdom.
[34](a)Department of Physics, University of Cape Town, Cape Town;(b)iThemba Labs, Western Cape;(c)Department of Mechanical Engineering Science, University of Johannesburg, Johannesburg;(d)National Institute of Physics, University of the Philippines Diliman (Philippines);(e)University of South Africa, Department of Physics, Pretoria;(f)University of Zululand, KwaDlangezwa;(g)School of Physics, University of the Witwatersrand, Johannesburg; South Africa.
[35]Department of Physics, Carleton University, Ottawa ON; Canada.
[36](a)Faculté des Sciences Ain Chock, 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.
[37]CERN, Geneva; Switzerland.
[38]Affiliated with an institute formerly covered by a cooperation agreement with CERN.
[39]Affiliated with an institute covered by a cooperation agreement with CERN.
[40]Affiliated with an international laboratory covered by a cooperation agreement with CERN.
[41]Enrico Fermi Institute, University of Chicago, Chicago IL; United States of America.
[42]LPC, Université Clermont Auvergne, CNRS/IN2P3, Clermont-Ferrand; France.
[43]Nevis Laboratory, Columbia University, Irvington NY; United States of America.
[44]Niels Bohr Institute, University of Copenhagen, Copenhagen; Denmark.

[45](a)Dipartimento di Fisica, Università della Calabria, Rende;(b)INFN Gruppo Collegato di Cosenza, Laboratori Nazionali di Frascati; Italy.
[46]Physics Department, Southern Methodist University, Dallas TX; United States of America.
[47]Physics Department, University of Texas at Dallas, Richardson TX; United States of America.
[48]National Centre for Scientific Research "Demokritos", Agia Paraskevi; Greece.
[49](a)Department of Physics, Stockholm University;(b)Oskar Klein Centre, Stockholm; Sweden.
[50]Deutsches Elektronen-Synchrotron DESY, Hamburg and Zeuthen; Germany.
[51]Fakultät Physik , Technische Universität Dortmund, Dortmund; Germany.
[52]Institut für Kern- und Teilchenphysik, Technische Universität Dresden, Dresden; Germany.
[53]Department of Physics, Duke University, Durham NC; United States of America.
[54]SUPA - School of Physics and Astronomy, University of Edinburgh, Edinburgh; United Kingdom.
[55]INFN e Laboratori Nazionali di Frascati, Frascati; Italy.
[56]Physikalisches Institut, Albert-Ludwigs-Universität Freiburg, Freiburg; Germany.
[57]II. Physikalisches Institut, Georg-August-Universität Göttingen, Göttingen; Germany.
[58]Département de Physique Nucléaire et Corpusculaire, Université de Genève, Genève; Switzerland.
[59](a)Dipartimento di Fisica, Università di Genova, Genova;(b)INFN Sezione di Genova; Italy.
[60]II. Physikalisches Institut, Justus-Liebig-Universität Giessen, Giessen; Germany.
[61]SUPA - School of Physics and Astronomy, University of Glasgow, Glasgow; United Kingdom.
[62]LPSC, Université Grenoble Alpes, CNRS/IN2P3, Grenoble INP, Grenoble; France.
[63]Laboratory for Particle Physics and Cosmology, Harvard University, Cambridge MA; United States of America.
[64](a)Department of Modern Physics and State Key Laboratory of Particle Detection and Electronics, University of Science and Technology of China, Hefei;(b)Institute of Frontier and Interdisciplinary Science and Key Laboratory of Particle Physics and Particle Irradiation (MOE), Shandong University, Qingdao;(c)School of Physics and Astronomy, Shanghai Jiao Tong University, Key Laboratory for Particle Astrophysics and Cosmology (MOE), SKLPPC, Shanghai;(d)Tsung-Dao Lee Institute, Shanghai;(e)School of Physics, Zhengzhou University; China.
[65](a)Kirchhoff-Institut für Physik, Ruprecht-Karls-Universität Heidelberg, Heidelberg;(b)Physikalisches Institut, Ruprecht-Karls-Universität Heidelberg, Heidelberg; Germany.
[66](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.
[67]Department of Physics, National Tsing Hua University, Hsinchu; Taiwan.
[68]IJCLab, Université Paris-Saclay, CNRS/IN2P3, 91405, Orsay; France.
[69]Centro Nacional de Microelectrónica (IMB-CNM-CSIC), Barcelona; Spain.
[70]Department of Physics, Indiana University, Bloomington IN; United States of America.
[71](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.
[72](a)INFN Sezione di Lecce;(b)Dipartimento di Matematica e Fisica, Università del Salento, Lecce; Italy.
[73](a)INFN Sezione di Milano;(b)Dipartimento di Fisica, Università di Milano, Milano; Italy.
[74](a)INFN Sezione di Napoli;(b)Dipartimento di Fisica, Università di Napoli, Napoli; Italy.
[75](a)INFN Sezione di Pavia;(b)Dipartimento di Fisica, Università di Pavia, Pavia; Italy.
[76](a)INFN Sezione di Pisa;(b)Dipartimento di Fisica E. Fermi, Università di Pisa, Pisa; Italy.
[77](a)INFN Sezione di Roma;(b)Dipartimento di Fisica, Sapienza Università di Roma, Roma; Italy.
[78](a)INFN Sezione di Roma Tor Vergata;(b)Dipartimento di Fisica, Università di Roma Tor Vergata, Roma; Italy.
[79](a)INFN Sezione di Roma Tre;(b)Dipartimento di Matematica e Fisica, Università Roma Tre, Roma;

Italy.
[80](a)INFN-TIFPA;(b)Università degli Studi di Trento, Trento; Italy.
[81]Universität Innsbruck, Department of Astro and Particle Physics, Innsbruck; Austria.
[82]University of Iowa, Iowa City IA; United States of America.
[83]Department of Physics and Astronomy, Iowa State University, Ames IA; United States of America.
[84]Istinye University, Sariyer, Istanbul; Türkiye.
[85](a)Departamento de Engenharia Elétrica, Universidade Federal de Juiz de Fora (UFJF), Juiz de Fora;(b)Universidade Federal do Rio De Janeiro COPPE/EE/IF, Rio de Janeiro;(c)Instituto de Física, Universidade de São Paulo, São Paulo;(d)Rio de Janeiro State University, Rio de Janeiro;(e)Federal University of Bahia, Bahia; Brazil.
[86]KEK, High Energy Accelerator Research Organization, Tsukuba; Japan.
[87]Graduate School of Science, Kobe University, Kobe; Japan.
[88](a)AGH University of Krakow, Faculty of Physics and Applied Computer Science, Krakow;(b)Marian Smoluchowski Institute of Physics, Jagiellonian University, Krakow; Poland.
[89]Institute of Nuclear Physics Polish Academy of Sciences, Krakow; Poland.
[90]Faculty of Science, Kyoto University, Kyoto; Japan.
[91]Research Center for Advanced Particle Physics and Department of Physics, Kyushu University, Fukuoka ; Japan.
[92]L2IT, Université de Toulouse, CNRS/IN2P3, UPS, Toulouse; France.
[93]Instituto de Física La Plata, Universidad Nacional de La Plata and CONICET, La Plata; Argentina.
[94]Physics Department, Lancaster University, Lancaster; United Kingdom.
[95]Oliver Lodge Laboratory, University of Liverpool, Liverpool; United Kingdom.
[96]Department of Experimental Particle Physics, Jožef Stefan Institute and Department of Physics, University of Ljubljana, Ljubljana; Slovenia.
[97]School of Physics and Astronomy, Queen Mary University of London, London; United Kingdom.
[98]Department of Physics, Royal Holloway University of London, Egham; United Kingdom.
[99]Department of Physics and Astronomy, University College London, London; United Kingdom.
[100]Louisiana Tech University, Ruston LA; United States of America.
[101]Fysiska institutionen, Lunds universitet, Lund; Sweden.
[102]Departamento de Física Teorica C-15 and CIAFF, Universidad Autónoma de Madrid, Madrid; Spain.
[103]Institut für Physik, Universität Mainz, Mainz; Germany.
[104]School of Physics and Astronomy, University of Manchester, Manchester; United Kingdom.
[105]CPPM, Aix-Marseille Université, CNRS/IN2P3, Marseille; France.
[106]Department of Physics, University of Massachusetts, Amherst MA; United States of America.
[107]Department of Physics, McGill University, Montreal QC; Canada.
[108]School of Physics, University of Melbourne, Victoria; Australia.
[109]Department of Physics, University of Michigan, Ann Arbor MI; United States of America.
[110]Department of Physics and Astronomy, Michigan State University, East Lansing MI; United States of America.
[111]Group of Particle Physics, University of Montreal, Montreal QC; Canada.
[112]Fakultät für Physik, Ludwig-Maximilians-Universität München, München; Germany.
[113]Max-Planck-Institut für Physik (Werner-Heisenberg-Institut), München; Germany.
[114]Graduate School of Science and Kobayashi-Maskawa Institute, Nagoya University, Nagoya; Japan.
[115](a)Department of Physics, Nanjing University, Nanjing;(b)School of Science, Shenzhen Campus of Sun Yat-sen University;(c)University of Chinese Academy of Science (UCAS), Beijing; China.
[116]Department of Physics and Astronomy, University of New Mexico, Albuquerque NM; United States of America.

[117]Institute for Mathematics, Astrophysics and Particle Physics, Radboud University/Nikhef, Nijmegen; Netherlands.
[118]Nikhef National Institute for Subatomic Physics and University of Amsterdam, Amsterdam; Netherlands.
[119]Department of Physics, Northern Illinois University, DeKalb IL; United States of America.
[120](a)New York University Abu Dhabi, Abu Dhabi;(b)United Arab Emirates University, Al Ain; United Arab Emirates.
[121]Department of Physics, New York University, New York NY; United States of America.
[122]Ochanomizu University, Otsuka, Bunkyo-ku, Tokyo; Japan.
[123]Ohio State University, Columbus OH; United States of America.
[124]Homer L. Dodge Department of Physics and Astronomy, University of Oklahoma, Norman OK; United States of America.
[125]Department of Physics, Oklahoma State University, Stillwater OK; United States of America.
[126]Palacký University, Joint Laboratory of Optics, Olomouc; Czech Republic.
[127]Institute for Fundamental Science, University of Oregon, Eugene, OR; United States of America.
[128]Graduate School of Science, Osaka University, Osaka; Japan.
[129]Department of Physics, University of Oslo, Oslo; Norway.
[130]Department of Physics, Oxford University, Oxford; United Kingdom.
[131]LPNHE, Sorbonne Université, Université Paris Cité, CNRS/IN2P3, Paris; France.
[132]Department of Physics, University of Pennsylvania, Philadelphia PA; United States of America.
[133]Department of Physics and Astronomy, University of Pittsburgh, Pittsburgh PA; United States of America.
[134](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.
[135]Institute of Physics of the Czech Academy of Sciences, Prague; Czech Republic.
[136]Czech Technical University in Prague, Prague; Czech Republic.
[137]Charles University, Faculty of Mathematics and Physics, Prague; Czech Republic.
[138]Particle Physics Department, Rutherford Appleton Laboratory, Didcot; United Kingdom.
[139]IRFU, CEA, Université Paris-Saclay, Gif-sur-Yvette; France.
[140]Santa Cruz Institute for Particle Physics, University of California Santa Cruz, Santa Cruz CA; United States of America.
[141](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.
[142]Department of Physics, Institute of Science, Tokyo; Japan.
[143]Department of Physics, University of Washington, Seattle WA; United States of America.
[144]Department of Physics and Astronomy, University of Sheffield, Sheffield; United Kingdom.
[145]Department of Physics, Shinshu University, Nagano; Japan.
[146]Department Physik, Universität Siegen, Siegen; Germany.
[147]Department of Physics, Simon Fraser University, Burnaby BC; Canada.

[148]SLAC National Accelerator Laboratory, Stanford CA; United States of America.
[149]Department of Physics, Royal Institute of Technology, Stockholm; Sweden.
[150]Departments of Physics and Astronomy, Stony Brook University, Stony Brook NY; United States of America.
[151]Department of Physics and Astronomy, University of Sussex, Brighton; United Kingdom.
[152]School of Physics, University of Sydney, Sydney; Australia.
[153]Institute of Physics, Academia Sinica, Taipei; Taiwan.
[154](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.
[155]Department of Physics, Technion, Israel Institute of Technology, Haifa; Israel.
[156]Raymond and Beverly Sackler School of Physics and Astronomy, Tel Aviv University, Tel Aviv; Israel.
[157]Department of Physics, Aristotle University of Thessaloniki, Thessaloniki; Greece.
[158]International Center for Elementary Particle Physics and Department of Physics, University of Tokyo, Tokyo; Japan.
[159]Department of Physics, University of Toronto, Toronto ON; Canada.
[160](a)TRIUMF, Vancouver BC;(b)Department of Physics and Astronomy, York University, Toronto ON; Canada.
[161]Division of Physics and Tomonaga Center for the History of the Universe, Faculty of Pure and Applied Sciences, University of Tsukuba, Tsukuba; Japan.
[162]Department of Physics and Astronomy, Tufts University, Medford MA; United States of America.
[163]Department of Physics and Astronomy, University of California Irvine, Irvine CA; United States of America.
[164]University of West Attica, Athens; Greece.
[165]University of Sharjah, Sharjah; United Arab Emirates.
[166]Department of Physics and Astronomy, University of Uppsala, Uppsala; Sweden.
[167]Department of Physics, University of Illinois, Urbana IL; United States of America.
[168]Instituto de Física Corpuscular (IFIC), Centro Mixto Universidad de Valencia - CSIC, Valencia; Spain.
[169]Department of Physics, University of British Columbia, Vancouver BC; Canada.
[170]Department of Physics and Astronomy, University of Victoria, Victoria BC; Canada.
[171]Fakultät für Physik und Astronomie, Julius-Maximilians-Universität Würzburg, Würzburg; Germany.
[172]Department of Physics, University of Warwick, Coventry; United Kingdom.
[173]Waseda University, Tokyo; Japan.
[174]Department of Particle Physics and Astrophysics, Weizmann Institute of Science, Rehovot; Israel.
[175]Department of Physics, University of Wisconsin, Madison WI; United States of America.
[176]Fakultät für Mathematik und Naturwissenschaften, Fachgruppe Physik, Bergische Universität Wuppertal, Wuppertal; Germany.
[177]Department of Physics, Yale University, New Haven CT; United States of America.
[178]Yerevan Physics Institute, Yerevan; Armenia.
[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 CERN, Geneva; Switzerland.
[g] Also at CMD-AC UNEC Research Center, Azerbaijan State University of Economics (UNEC); Azerbaijan.

[h] Also at Département de Physique Nucléaire et Corpusculaire, Université de Genève, Genève; Switzerland.
[i] Also at Departament de Fisica de la Universitat Autonoma de Barcelona, Barcelona; Spain.
[j] Also at Department of Financial and Management Engineering, University of the Aegean, Chios; Greece.
[k] Also at Department of Mathematical Sciences, University of South Africa, Johannesburg; South Africa.
[l] Also at Department of Physics, California State University, Sacramento; United States of America.
[m] Also at Department of Physics, King's College London, London; United Kingdom.
[n] Also at Department of Physics, Stanford University, Stanford CA; United States of America.
[o] Also at Department of Physics, Stellenbosch University; South Africa.
[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 Henan University; China.
[v] Also at Imam Mohammad Ibn Saud Islamic University; Saudi Arabia.
[w] Also at Institucio Catalana de Recerca i Estudis Avancats, ICREA, Barcelona; Spain.
[x] Also at Institut für Experimentalphysik, Universität Hamburg, Hamburg; Germany.
[y] Also at Institute for Nuclear Research and Nuclear Energy (INRNE) of the Bulgarian Academy of Sciences, Sofia; Bulgaria.
[z] Also at Institute of Applied Physics, Mohammed VI Polytechnic University, Ben Guerir; Morocco.
[aa] Also at Institute of Particle Physics (IPP); Canada.
[ab] Also at Institute of Physics, Azerbaijan Academy of Sciences, Baku; Azerbaijan.
[ac] Also at National Institute of Physics, University of the Philippines Diliman (Philippines); Philippines.
[ad] Also at Technical University of Munich, Munich; Germany.
[ae] Also at The Collaborative Innovation Center of Quantum Matter (CICQM), Beijing; China.
[af] Also at TRIUMF, Vancouver BC; Canada.
[ag] Also at Università di Napoli Parthenope, Napoli; Italy.
[ah] Also at University of Colorado Boulder, Department of Physics, Colorado; United States of America.
[ai] Also at University of the Western Cape; South Africa.
[aj] Also at Washington College, Chestertown, MD; United States of America.
[ak] Also at Yeditepe University, Physics Department, Istanbul; Türkiye.
* Deceased