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Constraints on the Higgs boson self-coupling from single- and double-Higgs production with the ATLAS detector using pp collisions at $\sqrt{s} = 13$ TeV

The ATLAS Collaboration *

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ABSTRACT

Constraints on the Higgs boson self-coupling are set by combining double-Higgs boson analyses in the $b\bar{b}b\bar{b}$, $b\bar{b}\tau^+\tau^-$ and $b\bar{b}\gamma\gamma$ decay channels with single-Higgs boson analyses targeting the $\gamma\gamma$, ZZ^*, WW^*, $\tau^+\tau^-$ and $b\bar{b}$ decay channels. The data used in these analyses were recorded by the ATLAS detector at the LHC in proton–proton collisions at $\sqrt{s} = 13$ TeV and correspond to an integrated luminosity of 126–139 fb^{-1}. The combination of the double-Higgs analyses sets an upper limit of $\mu_{HH} < 2.4$ at 95% confidence level on the double-Higgs production cross-section normalised to its Standard Model prediction. Combining the single-Higgs and double-Higgs analyses, with the assumption that new physics affects only the Higgs boson self-coupling (λ_{HHH}), values outside the interval $-0.4 < \kappa_\lambda = (\lambda_{HHH}/\lambda^{\mathrm{SM}}_{HHH}) < 6.3$ are excluded at 95% confidence level. The combined single-Higgs and double-Higgs analyses provide results with fewer assumptions, by adding in the fit more coupling modifiers introduced to account for the Higgs boson interactions with the other Standard Model particles. In this relaxed scenario, the constraint becomes $-1.4 < \kappa_\lambda < 6.1$ at 95% CL.

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1. Introduction

Since the discovery of the Higgs boson by the ATLAS and CMS collaborations [1,2] at the Large Hadron Collider (LHC) [3], a major goal of the physics programme of the LHC experiments has been to measure its properties and determine whether they correspond to those predicted by the Standard Model (SM) of particle physics [4–7] or involve new phenomena beyond those described by this theory. One of the most intriguing and interesting characteristics of the SM is that the gauge electroweak (EW) symmetry is broken spontaneously by the non-trivial structure of the Higgs boson [8–13] potential, related to its self-interaction. In the SM, this mechanism allows elementary particles to acquire their mass, while preserving perturbative unitarity up to very high energies. The Higgs boson potential also plays a fundamental role in understanding the stability of our universe [14].

The Higgs boson self-interactions are characterised by the trilinear self-coupling λ_{HHH}. In the SM, the Higgs boson self-coupling can be predicted at lowest order from the values of the Higgs boson mass m_H [15] and the Fermi constant G_F [16]: $\lambda_{HHH} = (m_H^2 G_\mathrm{F})/\sqrt{2}$.

At the LHC the Higgs boson self-interaction is directly accessible via the production of Higgs boson pairs (here referred to as double-Higgs production). In this Letter the three most sensitive double-Higgs decay channels, $b\bar{b}\gamma\gamma$, $b\bar{b}\tau^+\tau^-$, and $b\bar{b}b\bar{b}$ [17–19], are combined using the complete dataset collected by ATLAS at $\sqrt{s} = 13$ TeV in the data-taking period 2015–2018, corresponding to an integrated luminosity of 126–139 fb^{-1}. This combination is used to place constraints on the double-Higgs production cross-section and on the Higgs boson self-coupling. Results are reported in terms of the coupling modifier κ_λ defined as the ratio of the Higgs boson self-coupling to its SM value, $\kappa_\lambda = \lambda_{HHH}/\lambda^{\mathrm{SM}}_{HHH}$.

The Higgs boson self-interaction also contributes to other processes via sizeable next-to-leading-order (NLO) EW corrections. In particular, it has been shown [20–25] that the single Higgs boson (here referred to as single-Higgs) production cross-sections and branching ratios are also modified if the Higgs boson self-coupling deviates from the SM prediction.

More stringent constraints on κ_λ are also reported in this Letter from combinations of the recent ATLAS single-Higgs results [26] based on the full Run 2 data set from the $\gamma\gamma$, ZZ^*, WW^*, $\tau^+\tau^-$ and $b\bar{b}$ decay channels with the above mentioned double-Higgs results. The single-Higgs measurements of the simplified template cross-sections (STXS) and the double-Higgs results have been parameterised to take into account the impact of κ_λ and the other coupling modifiers. This more comprehensive combination makes it possible to perform tests of κ_λ relaxing the assumptions about Higgs boson interactions with the other SM particles.

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

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A previous ATLAS combination of searches for non-resonant and resonant HH pair production was performed on a partial Run 2 dataset, using up to 36.1 fb^{-1} of data [27]. The combined observed (expected) upper limit on non-resonant HH production at 95% confidence level (CL) was 6.9 (10) times the predicted SM cross-section. When varying the Higgs boson trilinear self-coupling from its SM value, the allowed range of the self-coupling modifier κ_λ was observed (expected) to be $-5.0 \leq \kappa_\lambda \leq 12.0$ ($-5.8 \leq \kappa_\lambda \leq 12.0$). The CMS Collaboration also published a combination of HH searches using its full Run 2 dataset, up to 138 fb^{-1} of data [28]. The CMS combined observed (expected) upper limit on non-resonant HH production at 95% CL is 3.4 (2.5) times the predicted Standard Model cross-section, and the observed allowed range of the self-coupling modifier κ_λ is $-1.24 \leq \kappa_\lambda \leq 6.49$.

2. Theoretical framework

A simplified way to test the validity of the SM in the Higgs sector is provided by the so called 'kappa framework' [29,30]. In this framework, the couplings of the Higgs boson to the other SM particles involved at leading order (LO) in perturbation theory for the process under study are dressed with scaling factors κ_m. In this simplified approach, based on several assumptions described in Section 10.2 of Ref. [29], production and decay yields are scaled by powers of the corresponding coupling modifier κ_m defined as the ratio of the coupling between the particle m and the Higgs boson to its SM value. Any significant deviation of a measured κ_m from unity would indicate the presence of physics beyond the SM in the tested interaction. In this work, only the coupling modifiers κ_t, κ_b, κ_τ, and κ_V are considered for single-Higgs interactions (in addition to the κ_λ modifier that impacts the NLO EW corrections as described in the following). They describe the modifications of the SM Higgs boson coupling to up-type quarks, to down-type quarks, to leptons and to vector bosons V ($V = W$ or Z) respectively. In this parameterisation the interactions between the Higgs boson and the gluons and photons are resolved in terms of the coupling modifiers of the SM particles that enter the loop-level diagrams. New particles contributing to these diagrams are not considered. The total width of the Higgs boson is also parameterised in terms of the coupling modifiers of the individual SM particles, assuming no beyond-the-SM contributions. For double-Higgs production the coupling modifiers κ_λ, κ_t, κ_V and κ_{2V} are considered. The last of these is related to the $VVHH$ interaction vertex, which can be tested in double-Higgs vector-boson fusion (VBF) production (VBF HH) as described in the following.

Double-Higgs production is directly sensitive to the Higgs boson self-coupling, starting at the lowest order in perturbation theory. In the SM, the gluon–gluon fusion process (ggF HH) accounts for more than 90% of the Higgs boson pair-production $pp \to HH$ cross-section. The next most abundant process is VBF HH production, while very small contributions are expected from double-Higgs production in association with a vector boson (VHH) and in association with top-quarks ($t\bar{t}\,HH$). An overview of double-Higgs production at the LHC can be found in Ref. [31].

At lowest order in perturbation theory, the ggF HH process proceeds via two amplitudes: the first ($\mathcal{A}_1$) represented by diagram (a) in Fig. 1, and the second ($\mathcal{A}_2$) represented by diagram (b). The $\mathcal{A}_1$ amplitude is proportional to the square of the Higgs boson coupling to the top-quark, which scales as κ_t^2, and the $\mathcal{A}_2$ amplitude is proportional to the product of κ_t and the Higgs boson self-coupling modifier κ_λ.

In the SM, the interference between these two amplitudes is destructive and yields an overall cross-section of $\sigma^{\mathrm{SM}}_{\mathrm{ggF}}(pp \to HH) = 31.0^{+2.1}_{-7.2}$ fb at $\sqrt{s} = 13$ TeV, calculated at NLO in QCD with the measured value of the top-quark mass and corrected to next-to-next-to-leading order (NNLO) including finite top-quark mass effects [30,32–41]. The large negative uncertainty originates from the scheme and scale choice of the virtual top-quark mass [41]. Deviations of the ggF HH cross-section from the SM prediction can therefore be parameterised in terms of the two coupling modifiers κ_λ and κ_t following the prescription described in Refs. [30,34–40]. Higher-order QCD corrections do not add further $t\bar{t}H$ or HHH vertices to the diagrams shown in Fig. 1, implying that this parameterisation is applicable to any order in QCD (i.e. also when the amplitudes $\mathcal{A}_1$ and $\mathcal{A}_2$ are modified to include their higher-order QCD corrections). Signal samples for ggF double-Higgs production can be obtained from simulated samples that are generated at different values of these couplings and then combined using morphing techniques, as described in Ref. [27]. Detailed validation studies of this procedure can be found in Ref. [42]. In the SM, the b-quark loop contribution to the ggF HH cross-section is negligible [30,43–45], so its contribution is not included in this analysis.

The second most abundant SM double-Higgs process is VBF HH production, with a predicted SM cross-section of 1.72 ± 0.04 fb at 13 TeV [46–48]. At LO in perturbation theory, this process depends on several diagrams that involve the interaction of the Higgs boson with the W or Z vector bosons as shown in Fig. 1. The three representative diagrams that enter the total amplitude of the VBF HH process can be parameterised with different combinations of the κ_λ, κ_V and κ_{2V} coupling modifiers [49]. The first diagram, shown in Fig. 1(c), is proportional to κ_V and κ_λ, the second, shown in Fig. 1(d), to κ_V^2 and the last one, shown in Fig. 1(e) and related to the quartic interaction vertex $VVHH$, to κ_{2V}. The VBF HH production process can therefore be parameterised using six terms derived from the square of the amplitude described above, which scales as a polynomial of κ_λ, κ_V and κ_{2V}. The parameterisation of the signal samples, in terms of yields and kinematic properties, for the double-Higgs VBF process as a function of these coupling modifiers is performed using a set of six independent samples generated for different values of κ_λ, κ_V and κ_{2V}. The values of κ_λ, κ_V, and κ_{2V} for these six samples were chosen to obtain good statistical precision in the region of parameter space where this analysis is sensitive. The validity of this parameterisation was checked with additional VBF signal samples generated with different values of these coupling modifiers.

The ggF HH process is sensitive to the sign of κ_λ relative to the top-quark couplings because of interference between different amplitudes whose leading-order Feynman diagrams are depicted in Fig. 1. Similarly, the VBF HH process provides sensitivity to the relative sign between κ_{2V} and κ_V.

A complementary approach to study the Higgs boson self-coupling is to use single-Higgs processes, as proposed in Refs. [20–25]. These processes do not depend on λ_{HHH} at LO, but the Higgs boson self-coupling contributes to the calculation of the complete NLO EW corrections. In particular, λ_{HHH} contributes to NLO EW corrections via Higgs boson self-energy loop corrections and via additional diagrams, examples of which are shown in Fig. 2. Therefore, an indirect constraint on κ_λ can be extracted by comparing precise measurements of single-Higgs production and decay yields with the SM predictions corrected for the λ_{HHH}-dependent NLO EW effects. A framework for a global fit to constrain the Higgs boson self-coupling and the other coupling modifiers κ_m was proposed in Refs. [20,21]; the model-dependent assumptions of this parameterisation are described in the same references. In the current work, inclusive production cross-sections, decay branching ratios and differential cross-sections are exploited to increase the sensitivity of the single-Higgs analyses to κ_λ and κ_m. The differential information is encoded through the simplified template cross-section (STXS) framework described in Section III.3 of Ref. [50]. The signal yield in a specific decay channel and STXS bin is then proportional to:

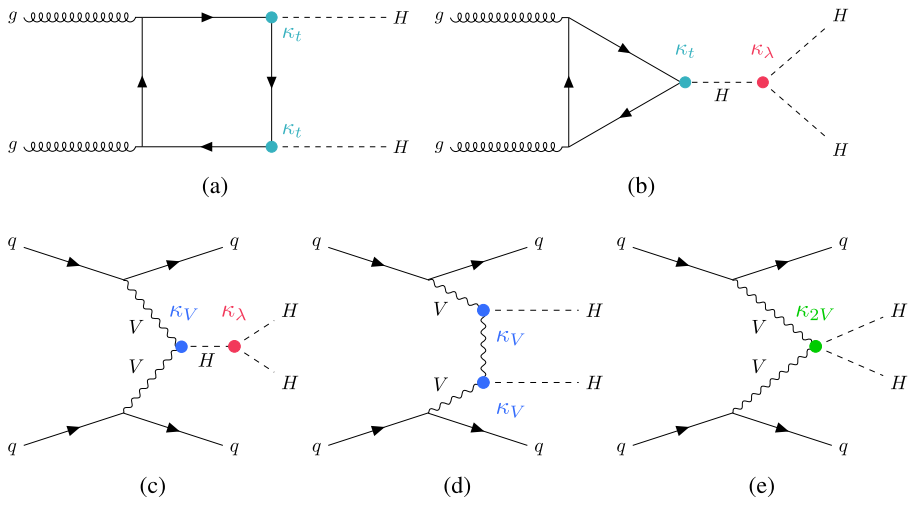

Fig. 1. Examples of leading-order Feynman diagrams for Higgs boson pair production: for ggF production, diagram (a) is proportional to the square of the top-quark Yukawa coupling, while diagram (b) is proportional to the product of the top-quark Yukawa coupling and the Higgs boson self-coupling. For VBF production, diagram (c) is proportional to the product of the coupling of the Higgs boson to the vector bosons and the self-coupling, diagram (d) to the square of the coupling to the vector bosons, and diagram (e) to the interaction between two vectors bosons and two Higgs bosons.

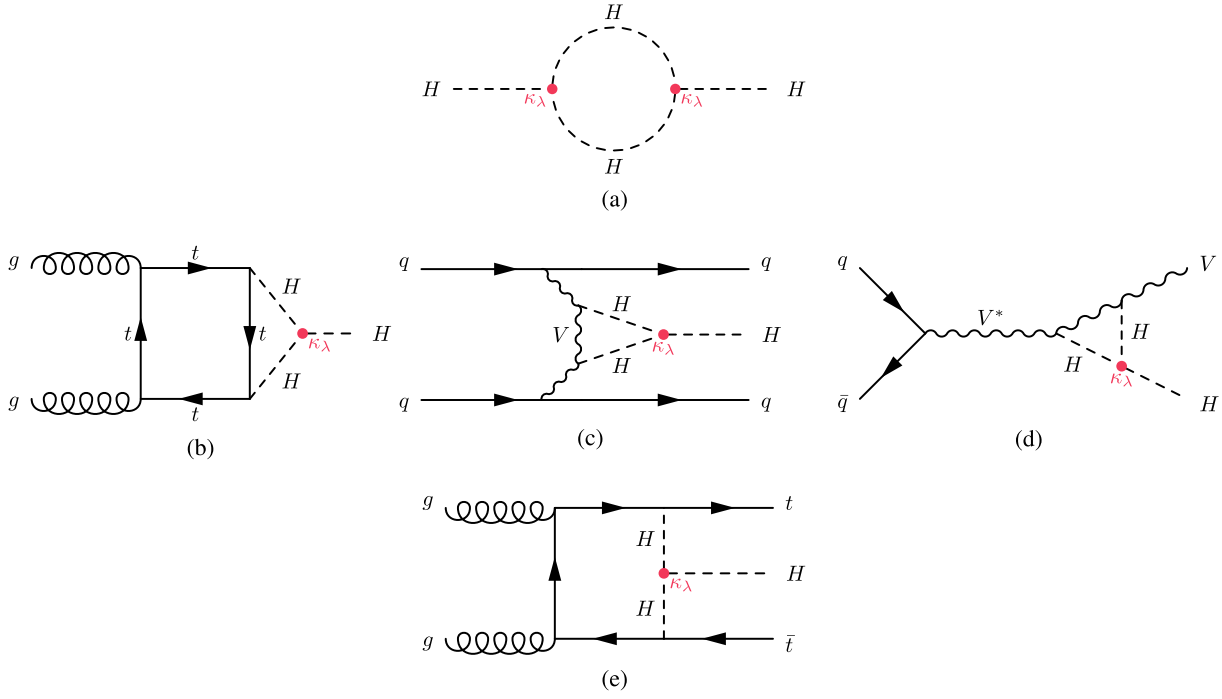

Fig. 2. Examples of one-loop λ_{HHH}-dependent diagrams for (a) the Higgs boson self-energy, and for single-Higgs production in the (b) ggF, (c) VBF, (d) VH, and (e) $t\bar{t}H$ modes. The self-coupling vertex is indicated by the filled circle.

$$n_{i,f}^{\text{signal}}(\kappa_\lambda,\kappa_m) \propto \mu_i(\kappa_\lambda,\kappa_m) \times \mu_f(\kappa_\lambda,\kappa_m) \times \sigma_{\text{SM},i} \times \mathcal{B}_{\text{SM},f} \times (\epsilon \times A)_{if} \,,$$

where μ_i and μ_f describe respectively the multiplicative corrections to the expected SM Higgs boson production cross-sections in an STXS bin ($\sigma_{\text{SM},i}$) and each decay-channel branching ratio ($\mathcal{B}_{\text{SM},f}$) as a function of the values of the Higgs boson self-coupling modifier κ_λ and the LO-inspired modifiers κ_m. The $(\epsilon \times A)_{if}$ coefficients take into account the analysis efficiency times acceptance in each production and decay mode.

The functional dependence of $\mu_i(\kappa_\lambda,\kappa_m)$ and $\mu_f(\kappa_\lambda,\kappa_m)$ on κ_λ and κ_m varies according to the production mode, the decay channel and, more strongly for the VH and $t\bar{t}H$ production modes, on the STXS bin. A detailed description of the cross-section and decay-rate dependence on κ_λ is given in Refs. [51,52]. The STXS information from the VBF, WH, ZH and $t\bar{t}H$ production modes is exploited here to constrain κ_λ and κ_m. For the ggF production mode, only the inclusive cross-section dependence on κ_λ is currently available and it was used in this study, while the STXS bin dependence was not considered.

Conversely, the κ_λ-modifier can affect the Higgs boson production kinematics and thus modify the analysis efficiency times acceptance in a given STXS bin. This residual dependence was evaluated and found to be negligible for single-Higgs processes, as described in Ref. [51]. Thus the single-Higgs selection acceptances and efficiencies are assumed to be constant as a function of κ_λ in each STXS bin. A detailed description of the parameterisation of the single-Higgs processes as a function of the κ_λ cou-

Table 1
Integrated luminosity of the dataset used for each input channel in the combination. The last column provides references to publications describing each channel in detail.

Analysis channel	Integrated luminosity [fb^{-1}]	Ref.
$HH \to b\bar{b}\gamma\gamma$	139	[17]
$HH \to b\bar{b}\tau^+\tau^-$	139	[18]
$HH \to b\bar{b}b\bar{b}$	126	[19]
$H \to \gamma\gamma$	139	[58]
$H \to ZZ^* \to 4\ell$	139	[59]
$H \to \tau^+\tau^-$	139	[60]
$H \to WW^* \to e\nu\mu\nu$ (ggF,VBF)	139	[61]
$H \to b\bar{b}$ (VH)	139	[62]
$H \to b\bar{b}$ (VBF)	126	[63]
$H \to b\bar{b}$ ($t\bar{t}H$)	139	[64]

pling modifiers used in this Letter can be found in Ref. [52]. The model under discussion does not allow for any new physics beyond that encoded in the aforementioned κ_λ and κ_m parameters. The dependence of the decay branching ratios and the Higgs boson self-energy on κ_λ is also taken into account for the double-Higgs analyses when combining them with the single-Higgs results.

A Higgs boson mass value of $m_H = 125.09 \pm 0.24$ GeV [15] is used for all results presented in this Letter.

3. Data samples and combined analyses

The results, presented in Sections 5 and 6, are obtained using the full Run 2 dataset collected by the ATLAS experiment [53–55] from LHC 13 TeV pp collisions in the 2015–2018 data-taking period. The integrated luminosity corresponds to 126–139 fb^{-1}, depending on the trigger selection. A two-level trigger system [56] is used to select events. An extensive software suite [57] is used in the reconstruction and analysis of collision and simulated data, in detector operations, and in the trigger and data acquisition systems of the experiment.

Each input analysis used in the combination is summarised in Table 1. Details about the individual analyses can be found in the references reported in the same table. Each analysis separates the selected events into different kinematic and topological regions, called categories.

4. Statistical model and systematic uncertainty correlations

The statistical treatment used in this Letter follows the procedures described in Refs. [65,66]. The results are obtained from a likelihood function $L(\vec{\alpha}, \vec{\theta})$, where $\vec{\alpha}$ represents the vector of the parameters of interest (POI) of the model and $\vec{\theta}$ is a set of nuisance parameters, including the systematic uncertainty contributions and background parameters that are constrained by sidebands or control regions in data. The global likelihood function $L(\vec{\alpha}, \vec{\theta})$ is obtained as the product of the likelihoods of each input analysis. These are, in turn, products of likelihoods computed in the single analysis categories. The results presented in the following sections are based on the profile-likelihood-ratio test statistic $\Lambda(\vec{\alpha}, \vec{\theta})$, and 68% as well as 95% CL intervals are derived in the asymptotic approximation [67]. The CL$_s$ approach [68] is only used to derive the cross-section upper limits shown in Section 5.

To derive the expected results, Asimov datasets [67] are produced with all the nuisance parameters set to the values derived from the fit to the data and the parameters of interest fixed to the values corresponding to the hypothesis mentioned in the text.

The basic assumption in performing a statistical combination by using the product of the likelihoods is that the analyses being combined are statistically independent. For this reason the event samples used in the single-Higgs and double-Higgs analyses were checked for overlaps. The overlap among the single-Higgs analyses was checked previously in the combination published in Ref. [26] and found to be negligible. The event overlap among the three double-Higgs analyses combined for the first time for this result was studied and found to be significantly smaller than 0.1%. These analyses are therefore treated as statistically independent. As a last step, the overlap of event samples between the single-Higgs and double-Higgs analyses, which are combined for the first time in this Letter, was investigated. For most of the categories, this overlap is significantly below the 1% level in either the single-Higgs or the double-Higgs channel, and can therefore be neglected. The only exception is the overlap between the $H \to \tau^+\tau^-$ and $HH \to b\bar{b}\tau^+\tau^-$ channels, mainly due to the $t\bar{t}H$ categories in the $H \to \tau^+\tau^-$ analysis, which is found to be at the 4% level in the double-Higgs signal regions. The $t\bar{t}H$ categories in the $H \to \tau^+\tau^-$ channel were removed from the combination used to produce the results presented in the following sections.

A complete discussion of the sources of systematic uncertainty considered in the individual analyses is provided in the publications referenced in Table 1. The correlation model adopted for the systematic uncertainties within the single-Higgs combination is described in detail in Ref. [26].

For this Letter, additional correlations of systematic uncertainties between the double-Higgs analyses and between the single-Higgs and double-Higgs combinations were investigated and implemented as needed. In both cases, systematic uncertainties related to the data-taking conditions, such as those associated with pile-up mis-modelling and the integrated luminosity, are considered to be fully correlated among the input searches. Uncertainties related to physics objects used by multiple searches are treated as correlated where appropriate: experimental uncertainties that are related to the same physics object but determined with different methodologies or implemented with different parameterisations are treated as uncorrelated. Theoretical uncertainties of simulated signal and background processes, such as the single-Higgs and double-Higgs production cross-sections, QCD scale, and proton parton distribution functions are treated as correlated where relevant. The experimental uncertainty of the Higgs boson mass measurement [15] is treated as correlated where relevant. Signal theory uncertainties of the single-Higgs and double-Higgs production modes (e.g., missing higher-order QCD corrections, parton shower, parton distribution functions, etc.) are treated as uncorrelated, while the systematic uncertainties of the decay branching ratios are treated as correlated. For the systematic uncertainties that are constrained significantly in the fit to data, the impact of treating them as correlated or uncorrelated in the combined fit was checked. In general, the impact of these different correlation schemes on the exclusion limits is found to be very small, below the 2% level. Since choosing to treat them as uncorrelated gives slightly larger uncertainties for the parameter of interest, this approach was chosen for the results presented in the following sections.

For the double-Higgs analyses, the most important uncertainties are related to background estimates from data-driven methodologies (derived from data sidebands or control regions) and are therefore not correlated with the single-Higgs analyses. The change of the correlation scheme was found to have a negligible impact on the combined double-Higgs results, except for the theoretical uncertainties of the ggF HH cross-section, where assuming a correlation loosens the limits on the signal strength by 7% and this is therefore adopted.

5. Double-Higgs combination results

The double-Higgs boson analyses in the $b\bar{b}b\bar{b}$, $b\bar{b}\tau^+\tau^-$ and $b\bar{b}\gamma\gamma$ decay channels referenced in Table 1 are combined in order to place constraints on the production cross-section and the Higgs

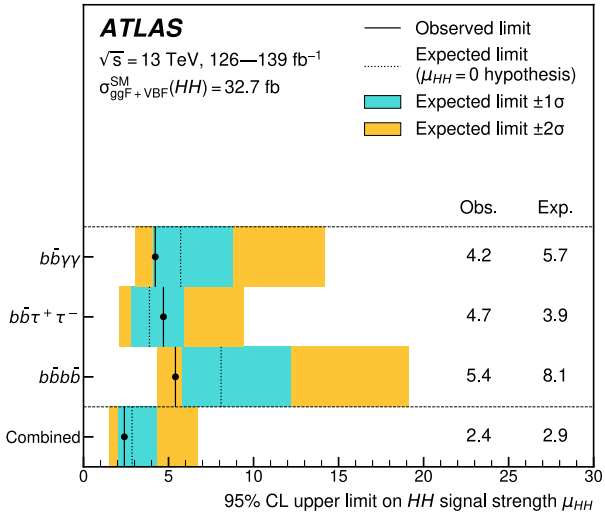

Fig. 3. Observed and expected 95% CL upper limits on the signal strength for double-Higgs production from the $b\bar{b}b\bar{b}$, $b\bar{b}\tau^+\tau^-$ and $b\bar{b}\gamma\gamma$ decay channels, and their statistical combination. The value $m_H = 125.09$ GeV is assumed when deriving the predicted SM cross-section. The expected limit and the corresponding error bands are derived assuming the absence of the HH process and with all nuisance parameters profiled to the observed data.

boson's self-coupling. First, the value of the signal strength μ_{HH}, defined as the ratio of the double-Higgs production cross-section, including only the ggF HH and VBF HH processes, to its SM prediction of 32.7 fb [30–40,46] is determined. To produce this result the ratio of the ggF HH to VBF HH production cross-sections and the relative kinematic distributions are assumed to be as predicted by the SM, and the other minor production modes are neglected.

This combination yields an observed 95% CL upper limit on μ_{HH} of 2.4, with an expected upper limit of 2.9 in the absence of HH production and 4.0 expected in the SM case. The limits on the signal strength obtained from the individual channels and their combination are shown in Fig. 3. The best-fit value obtained from the fit to the data is $\mu_{HH} = -0.7 \pm 1.3$, which is compatible with the SM prediction of unity, with a p-value of 0.2. From the same combination, a 95% CL upper limit on $\sigma(pp \to HH)$ of 73 fb is derived (where only ggF HH and VBF HH processes are considered), compared with an expected limit of 85 fb assuming no HH production. When deriving the cross-section limits the theoretical uncertainties on the predicted cross-sections are not included. The cross-section limit as a function of the coupling modifier is shown in Fig. 4(a). The signal acceptance of the double-Higgs analyses has a strong dependence on the value of κ_λ (mainly due to its impact on the m_{HH} distribution), determining the shapes of the exclusion limit curve shown in Fig. 4(a).

Constraints on the coupling modifiers are obtained by using the values of the test statistic as a function of κ_λ in the asymptotic approximation and including the theoretical uncertainty of the cross-section predictions. The κ_λ parameterisation of NLO EW corrections in the Higgs boson decay and self-energy, as well as in single-Higgs backgrounds, is included when deriving these results, although its impact on the constraints is negligible. With these assumptions, the observed (expected) constraints at 95% CL are $-0.6 < \kappa_\lambda < 6.6$ $(-2.1 < \kappa_\lambda < 7.8)$. The expected constraint is derived using the SM assumption. More results with different assumptions about the other coupling modifiers are given in Section 6.

The combined double-Higgs channels are also sensitive to the VBF HH process, and hence to the $HHVV$ quartic interaction. The 95% CL observed VBF HH cross-section upper limit as a function of κ_{2V} is shown in Fig. 4(b). Constraints are derived directly from the test statistic value parameterised as a function of κ_{2V}. An observed (expected) 95% CL constraint of $0.1 < \kappa_{2V} < 2.0$ $(0.0 < \kappa_{2V} < 2.1)$ is obtained, fixing all other coupling modifiers to unity and with the expected values derived under the SM hypothesis.

6. Single- and double-Higgs combination results

Following the prescriptions described in Section 2 the double-Higgs and single-Higgs analyses summarised in Table 1 are combined to derive constraints on κ_λ. Several fits to data are performed with different assumptions about the coupling modifiers to other SM particles.

At first, only possible deviations of κ_λ from its SM value are considered, assuming that all other Higgs boson interactions proceed as predicted by the SM. The values of twice the negative-logarithm of the profile likelihood ratio $(-2\ln\Lambda)$ as a function of κ_λ are shown in Fig. 5 for the single-Higgs and double-Higgs analyses, and their combination.

The combined observed (expected) constraints obtained under this hypothesis are $-0.4 < \kappa_\lambda < 6.3$ $(-1.9 < \kappa_\lambda < 7.6)$ at 95% CL. All the expected constraints reported in this section are derived from an Asimov dataset generated for the SM assumption that corresponds to all coupling modifiers equal to unity. The result is driven by the double-Higgs combination as can be seen in Fig. 5. The expected test statistic $(-2\ln\Lambda)$ curve in Fig. 5(b) exhibits a 'two-minima-like' structure due to the quadratic dependence of the observed signal yields on the parameter of interest κ_λ (partially resolved by the m_{HH} kinematic information used in the fit). The observed curve is more parabolic because the best-fit value of κ_λ is close to the value where the predicted double-Higgs cross-section, shown in Fig. 4(a), reaches its minimum.

The main advantage of adding the single-Higgs analyses is the possibility of relaxing assumptions about modifiers for couplings to other SM particles. First, the assumption about the Higgs boson to top-quark coupling modifier, κ_t, can be released. Thanks to the strong constraints on κ_t from the single-Higgs measurements, the constraints on κ_λ obtained from a fit with a floating value of κ_t are almost as strong as those obtained with its value fixed to unity, as reported in Table 2. Two-dimensional contours of $-2\ln\Lambda$ in the κ_λ–κ_t plane are shown in Fig. 6. All other coupling modifiers are fixed to unity in this fit.

The most generic model allows all of the coupling modifiers κ_λ, κ_t, κ_b, κ_τ, and κ_V implemented in this parameterisation to float freely in the fit. The exception is κ_{2V}, which is fixed to unity since there is no complete parameterisation of single-Higgs NLO EW corrections as a function of this coupling modifier. A recent work [69], shows that a consistent parameterisation of the κ_V and κ_{2V} coupling modifiers seems to be possible, though the sensitivity of single-H processes to κ_{2V} is shown to be very small.

In the combination of the single-Higgs and double-Higgs analyses, an observed (expected) exclusion of $-1.4 < \kappa_\lambda < 6.1$ $(-2.2 < \kappa_\lambda < 7.7)$ is obtained at 95% CL in this less model-dependent fit. The values of all the other coupling modifiers agree with the SM prediction within uncertainties. The values of the test statistic as a function of κ_λ for this generic model are also shown in Fig. 5. It was checked that for a generic model in which κ_{2V} also floats freely in the double-Higgs parameterisation, the observed exclusion constraints on κ_λ weaken by less than 5%. In this approach, the $VVHH$ vertex is parameterised in terms of the κ_{2V} coupling modifier for the VBF HH process but the single-Higgs NLO EW corrections are not.

7. Conclusion

Single- and double-Higgs boson analyses based on the complete LHC Run 2 dataset of 13 TeV proton–proton collisions collected with the ATLAS detector are combined to investigate the Higgs

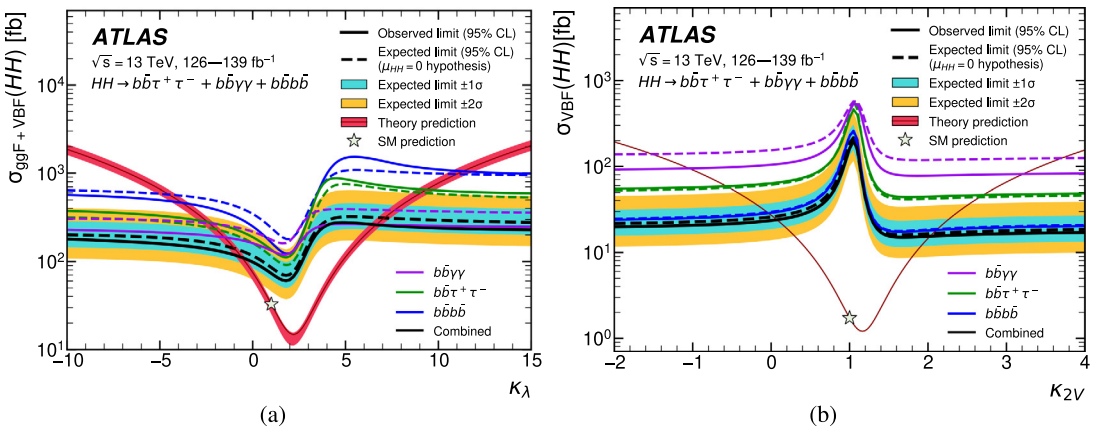

Fig. 4. Observed and expected 95% CL exclusion limits on the production cross-sections of (a) the combined ggF HH and VBF HH processes as a function of κ_λ and (b) the VBF HH process as a function of κ_{2V}, for the three double-Higgs search channels and their combination. The expected limits assume no HH production or no VBF HH production respectively. The red line shows (a) the theory prediction for the combined ggF HH and VBF HH cross-section as a function of κ_λ where all parameters and couplings are set to their SM values except for κ_λ, and (b) the predicted VBF HH cross-section as a function of κ_{2V}. The bands surrounding the red cross-section lines indicate the theoretical uncertainty on the predicted cross-section. The uncertainty band in (b) is smaller than the width of the plotted line.

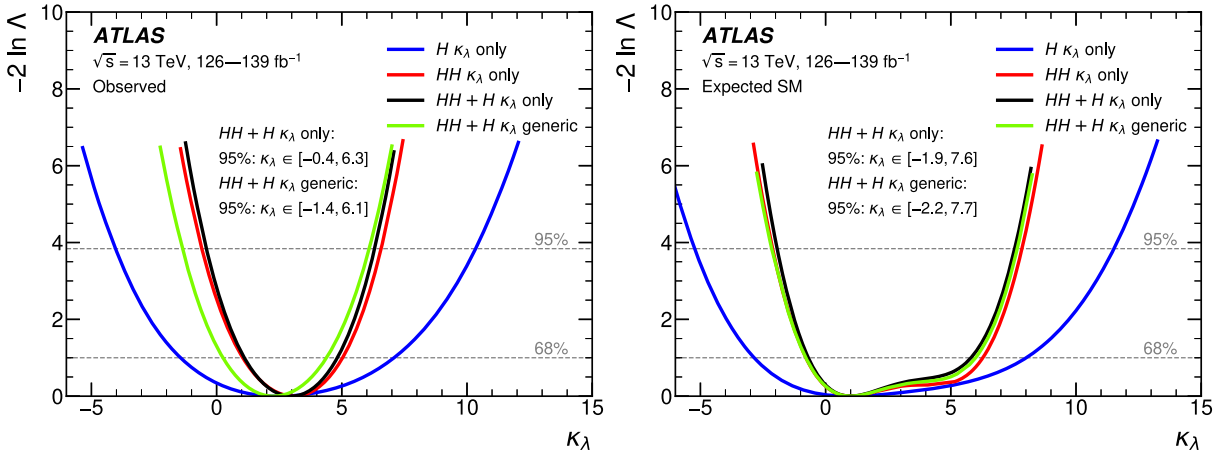

Fig. 5. Observed (a) and expected (b) values of the test statistic $(-2\ln\Lambda)$, as a function of the κ_λ parameter for the single-Higgs (blue) and double-Higgs (red) analyses, and their combination (black) derived from the combined single-Higgs and double-Higgs analyses, with all other coupling modifiers fixed to unity. The combined result for the generic model (free floating κ_t, κ_b, κ_V and κ_τ) is also superimposed (green curve). The observed best-fit value of κ_λ for the generic model is shifted slightly relative to the other models because of its correlation with the best-fit values of the κ_b, κ_t and κ_τ parameters, which are slightly below, but compatible with unity.

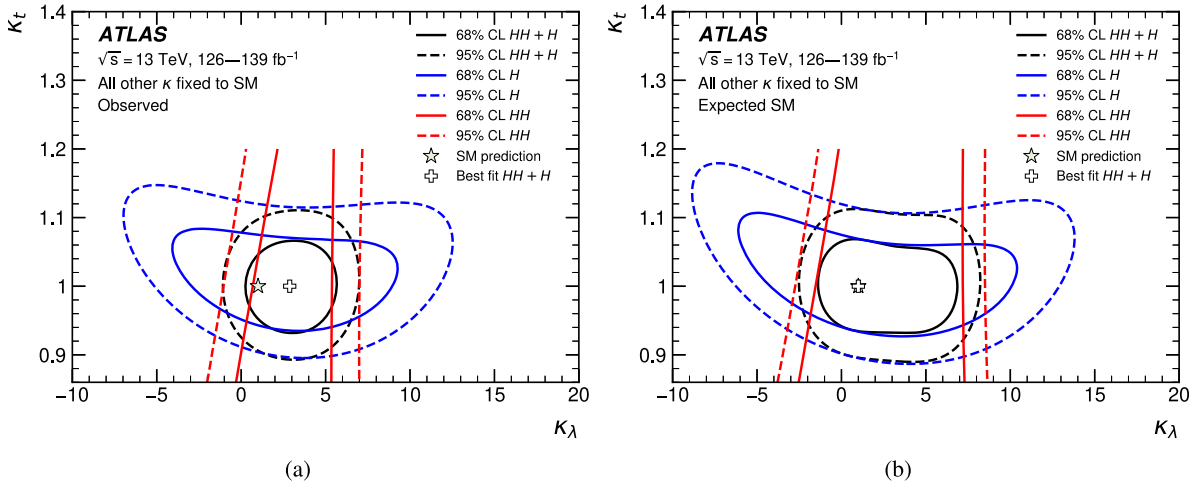

Fig. 6. Observed (a) and expected (b) constraints in the κ_λ–κ_t plane from single-Higgs (blue) and double-Higgs (red) analyses, and their combination (black). The solid (dashed) lines show the 68% (95%) CL contours. The double-Higgs contours are shown for values of κ_t smaller than 1.2. The observed constraint for the single- and double-Higgs combination for κ_t values below unity is slightly less stringent than that for the single-Higgs fit alone due to the slightly higher best-fit value for this coupling modifier.

Table 2
Summary of κ_λ observed and expected constraints and corresponding observed best-fit values with their uncertainties. In the first column, the coupling modifiers that are free floating in addition to κ_λ in the corresponding fit are reported. The uncertainties on κ_λ are extracted from the test statistic curves, which are not expected to follow Gaussian distributions.

Combination assumption	Obs. 95% CL	Exp. 95% CL	Obs. value$^{+1\sigma}_{-1\sigma}$
HH combination	$-0.6 < \kappa_\lambda < 6.6$	$-2.1 < \kappa_\lambda < 7.8$	$\kappa_\lambda = 3.1^{+1.9}_{-2.0}$
Single-H combination	$-4.0 < \kappa_\lambda < 10.3$	$-5.2 < \kappa_\lambda < 11.5$	$\kappa_\lambda = 2.5^{+4.6}_{-3.9}$
HH+H combination	$-0.4 < \kappa_\lambda < 6.3$	$-1.9 < \kappa_\lambda < 7.6$	$\kappa_\lambda = 3.0^{+1.8}_{-1.9}$
HH+H combination, κ_t floating	$-0.4 < \kappa_\lambda < 6.3$	$-1.9 < \kappa_\lambda < 7.6$	$\kappa_\lambda = 3.0^{+1.8}_{-1.9}$
HH+H combination, κ_t, κ_V, κ_b, κ_τ floating	$-1.4 < \kappa_\lambda < 6.1$	$-2.2 < \kappa_\lambda < 7.7$	$\kappa_\lambda = 2.3^{+2.1}_{-2.0}$

boson self-interaction and shed more light on the Higgs boson potential, the source of EW symmetry breaking in the SM.

Using the three most sensitive double-Higgs decay channels, $b\bar{b}b\bar{b}$, $bb\tau^+\tau^-$ and $bb\gamma\gamma$, an observed (expected) upper limit of 2.4 (2.9) at 95% CL is set on the double-Higgs signal strength, defined as the sum of the ggF HH and VBF HH production cross-sections normalised to its SM prediction. These processes are directly sensitive to the Higgs boson self-coupling. This combination can also be used to set a constraint of $-0.6 < \kappa_\lambda < 6.6$ at 95% CL on the Higgs boson self-coupling modifier, assuming that the other Higgs boson interactions are as predicted by the SM.

Using the VBF HH process, a constraint on the κ_{2V} coupling modifier of $0.1 < \kappa_{2V} < 2.0$ is also derived at 95% CL, assuming all other Higgs boson interactions are as predicted by the SM.

The measurements from the three double-Higgs decay channels are combined with single-Higgs boson cross-section measurements from the $\gamma\gamma$, ZZ^*, WW^*, $\tau^+\tau^-$ and $b\bar{b}$ decay channels to derive constraints on κ_λ that are either more stringent or less model-dependent. Using this combination and assuming that κ_λ is the only source of physics beyond the SM, values of κ_λ outside the range $-0.4 < \kappa_\lambda < 6.3$ are excluded at 95% CL, with an expected excluded range of $-1.9 < \kappa_\lambda < 7.6$. If assumptions about the other coupling modifiers, κ_t, κ_b κ_τ, and κ_V, are relaxed, this constraint becomes $-1.4 < \kappa_\lambda < 6.1$ at 95% CL, where the expected interval under the SM assumption is $-2.2 < \kappa_\lambda < 7.7$. This constraint on the Higgs boson self-coupling is not quite as strong but less model-dependent. This study provides the most stringent constraints on Higgs boson self-interactions to date.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: ATLAS Collaboration reports financial support was provided by CERN.

Data availability

The authors are unable or have chosen not to specify which data has been used.

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Sykora [132], D. Ta [99], K. Tackmann [48,w], A. Taffard [159], R. Tafirout [155a], J.S. Tafoya Vargas [66], R.H.M. Taibah [126], R. Takashima [87], K. Takeda [83], E.P. Takeva [52], Y. Takubo [82], M. Talby [101], A.A. Talyshev [37], K.C. Tam [64b], N.M. Tamir [150], A. Tanaka [152], J. Tanaka [152], R. Tanaka [66], M. Tanasini [57b,57a], J. Tang [62c], Z. Tao [163], S. Tapia Araya [80], S. Tapprogge [99], A. Tarek Abouelfadl Mohamed [106], S. Tarem [149], K. Tariq [62b], G. Tarna [101,27b], G.F. Tartarelli [70a], P. Tas [132], M. Tasevsky [130], E. Tassi [43b,43a], A.C. Tate [161], G. Tateno [152], Y. Tayalati [35e], G.N. Taylor [104], W. Taylor [155b], H. Teagle [91], A.S. Tee [169], R. Teixeira De Lima [142], P. Teixeira-Dias [94], J.J. Teoh [154], K. Terashi [152], J. Terron [98], S. Terzo [13], M. Testa [53], R.J. Teuscher [154,x], A. Thaler [78], O. Theiner [56], N. Themistokleous [52], T. Theveneaux-Pelzer [18], O. Thielmann [170], D.W. Thomas [94], J.P. Thomas [20], E.A. Thompson [48], P.D. Thompson [20], E. Thomson [127], E.J. Thorpe [93], Y. Tian [55], V. Tikhomirov [37,a], Yu.A. Tikhonov [37], S. Timoshenko [37], E.X.L. Ting [1], P. Tipton [171], S. Tisserant [101], S.H. Tlou [33g], A. Tnourji [40], K. Todome [23b,23a], S. Todorova-Nova [132], S. Todt [50], M. Togawa [82], J. Tojo [88], S. Tokár [28a], K. Tokushuku [82], R. Tombs [32], M. Tomoto [82,110], L. Tompkins [142], K.W. Topolnicki [84b], P. Tornambe [102], E. Torrence [122], H. Torres [50], E. Torró Pastor [162], M. Toscani [30], C. Tosciri [39], M. Tost [11], D.R. Tovey [138], A. Traeet [16], I.S. Trandafir [27b], T. Trefzger [165], A. Tricoli [29], I.M. Trigger [155a], S. Trincaz-Duvoid [126], D.A. Trischuk [26], B. Trocmé [60], A. Trofymov [66], C. Troncon [70a], L. Truong [33c], M. Trzebinski [85], A. Trzupek [85], F. Tsai [144], M. Tsai [105], A. Tsiamis [151,f], P.V. Tsiareshka [37], S. Tsigaridas [155a], A. Tsirigotis [151,u], V. Tsiskaridze [144], E.G. Tskhadadze [148a], M. Tsopoulou [151,f], Y. Tsujikawa [86], I.I. Tsukerman [37], V. Tsulaia [17a], S. Tsuno [82], O. Tsur [149], D. Tsybychev [144], Y. Tu [64b], A. Tudorache [27b], V. Tudorache [27b], A.N. Tuna [36], S. Turchikhin [38], I. Turk Cakir [3a], R. Turra [70a], T. Turtuvshin [38,y], P.M. Tuts [41], S. Tzamarias [151,f], P. Tzanis [10], E. Tzovara [99], K. Uchida [152], F. Ukegawa [156], P.A. Ulloa Poblete [136c], E.N. Umaka [80], G. Unal [36], M. Unal [11], A. Undrus [29], G. Unel [159], J. Urban [28b], P. Urquijo [104], G. Usai [8], R. Ushioda [153], M. Usman [107], Z. Uysal [21b], L. Vacavant [101], V. Vacek [131], B. Vachon [103], K.O.H. Vadla [124], T. Vafeiadis [36], A. Vaitkus [95], C. Valderanis [108], E. Valdes Santurio [47a,47b], M. Valente [155a], S. Valentinetti [23b,23a], A. Valero [162], A. Vallier [101], J.A. Valls Ferrer [162], T.R. Van Daalen [137], P. Van Gemmeren [6], M. Van Rijnbach [124,36], S. Van Stroud [95], I. Van Vulpen [113], M. Vanadia [75a,75b], W. Vandelli [36], M. Vandenbroucke [134], E.R. Vandewall [120], D. Vannicola [150], L. Vannoli [57b,57a], R. Vari [74a], E.W. Varnes [7], C. Varni [17a], T. Varol [147], D. Varouchas [66], L. Varriale [162], K.E. Varvell [146], M.E. Vasile [27b], L. Vaslin [40], G.A. Vasquez [164], F. Vazeille [40], T. Vazquez Schroeder [36], J. Veatch [31], V. Vecchio [100], M.J. Veen [102], I. Veliscek [125], L.M. Veloce [154],

F. Veloso [129a,129c], S. Veneziano [74a], A. Ventura [69a,69b], A. Verbytskyi [109], M. Verducci [73a,73b], C. Vergis [24], M. Verissimo De Araujo [81b], W. Verkerke [113], J.C. Vermeulen [113], C. Vernieri [142], P.J. Verschuuren [94], M. Vessella [102], M.C. Vetterli [141,ae], A. Vgenopoulos [151,f], N. Viaux Maira [136f], T. Vickey [138], O.E. Vickey Boeriu [138], G.H.A. Viehhauser [125], L. Vigani [63b], M. Villa [23b,23a], M. Villaplana Perez [162], E.M. Villhauer [52], E. Vilucchi [53], M.G. Vincter [34], G.S. Virdee [20], A. Vishwakarma [52], C. Vittori [23b,23a], I. Vivarelli [145], V. Vladimirov [166], E. Voevodina [109], F. Vogel [108], P. Vokac [131], J. Von Ahnen [48], E. Von Toerne [24], B. Vormwald [36], V. Vorobel [132], K. Vorobev [37], M. Vos [162], J.H. Vossebeld [91], M. Vozak [113], L. Vozdecky [93], N. Vranjes [15], M. Vranjes Milosavljevic [15], M. Vreeswijk [113], R. Vuillermet [36], O. Vujinovic [99], I. Vukotic [39], S. Wada [156], C. Wagner [102], W. Wagner [170], S. Wahdan [170], H. Wahlberg [89], R. Wakasa [156], M. Wakida [110], V.M. Walbrecht [109], J. Walder [133], R. Walker [108], W. Walkowiak [140], A.M. Wang [61], A.Z. Wang [169], C. Wang [62a], C. Wang [62c], H. Wang [17a], J. Wang [64a], R.-J. Wang [99], R. Wang [61], R. Wang [6], S.M. Wang [147], S. Wang [62b], T. Wang [62a], W.T. Wang [79], X. Wang [14c], X. Wang [161], X. Wang [62c], Y. Wang [62d], Y. Wang [14c], Z. Wang [105], Z. Wang [62d,51,62c], Z. Wang [105], A. Warburton [103], R.J. Ward [20], N. Warrack [59], A.T. Watson [20], H. Watson [59], M.F. Watson [20], G. Watts [137], B.M. Waugh [95], A.F. Webb [11], C. Weber [29], H.A. Weber [18], M.S. Weber [19], S.M. Weber [63a], C. Wei [62a], Y. Wei [125], A.R. Weidberg [125], J. Weingarten [49], M. Weirich [99], C. Weiser [54], C.J. Wells [48], T. Wenaus [29], B. Wendland [49], T. Wengler [36], N.S. Wenke [109], N. Wermes [24], M. Wessels [63a], K. Whalen [122], A.M. Wharton [90], A.S. White [61], A. White [8], M.J. White [1], D. Whiteson [159], L. Wickremasinghe [123], W. Wiedenmann [169], C. Wiel [50], M. Wielers [133], N. Wieseotte [99], C. Wiglesworth [42], L.A.M. Wiik-Fuchs [54], D.J. Wilbern [119], H.G. Wilkens [36], D.M. Williams [41], H.H. Williams [127], S. Williams [32], S. Willocq [102], P.J. Windischhofer [125], F. Winklmeier [122], B.T. Winter [54], J.K. Winter [100], M. Wittgen [142], M. Wobisch [96], R. Wölker [125], J. Wollrath [159], M.W. Wolter [85], H. Wolters [129a,129c], V.W.S. Wong [163], A.F. Wongel [48], S.D. Worm [48], B.K. Wosiek [85], K.W. Woźniak [85], K. Wraight [59], J. Wu [14a,14d], M. Wu [64a], M. Wu [112], S.L. Wu [169], X. Wu [56], Y. Wu [62a], Z. Wu [134,62a], J. Wuerzinger [125], T.R. Wyatt [100], B.M. Wynne [52], S. Xella [42], L. Xia [14c], M. Xia [14b], J. Xiang [64c], X. Xiao [105], M. Xie [62a], X. Xie [62a], S. Xin [14a,14d], J. Xiong [17a], I. Xiotidis [145], D. Xu [14a], H. Xu [62a], H. Xu [62a], L. Xu [62a], R. Xu [127], T. Xu [105], W. Xu [105], Y. Xu [14b], Z. Xu [62b], Z. Xu [14a], B. Yabsley [146], S. Yacoob [33a], N. Yamaguchi [88], Y. Yamaguchi [153], H. Yamauchi [156], T. Yamazaki [17a], Y. Yamazaki [83], J. Yan [62c], S. Yan [125], Z. Yan [25], H.J. Yang [62c,62d], H.T. Yang [62a], S. Yang [62a], T. Yang [64c], X. Yang [62a], X. Yang [14a], Y. Yang [44], Z. Yang [62a,105], W-M. Yao [17a], Y.C. Yap [48], H. Ye [14c], H. Ye [55], J. Ye [44], S. Ye [29], X. Ye [62a], Y. Yeh [95], I. Yeletskikh [38], B.K. Yeo [17a], M.R. Yexley [90], P. Yin [41], K. Yorita [167], S. Younas [27b], C.J.S. Young [54], C. Young [142], M. Yuan [105], R. Yuan [62b,l], L. Yue [95], X. Yue [63a], M. Zaazoua [35e], B. Zabinski [85], E. Zaid [52], T. Zakareishvili [148b], N. Zakharchuk [34], S. Zambito [56], J.A. Zamora Saa [136d,136b], J. Zang [152], D. Zanzi [54], O. Zaplatilek [131], S.V. Zeißner [49], C. Zeitnitz [170], J.C. Zeng [161], D.T. Zenger Jr [26], O. Zenin [37], T. Ženiš [28a], S. Zenz [93], S. Zerradi [35a], D. Zerwas [66], B. Zhang [14c], D.F. Zhang [138], G. Zhang [14b], J. Zhang [62b], J. Zhang [6], K. Zhang [14a,14d], L. Zhang [14c], P. Zhang [14a,14d], R. Zhang [169], S. Zhang [105], T. Zhang [152], X. Zhang [62c], X. Zhang [62b], Y. Zhang [62c,5], Z. Zhang [17a], Z. Zhang [66], H. Zhao [137], P. Zhao [51], T. Zhao [62b], Y. Zhao [135], Z. Zhao [62a], A. Zhemchugov [38], X. Zheng [62a], Z. Zheng [142], D. Zhong [161], B. Zhou [105], C. Zhou [169], H. Zhou [7], N. Zhou [62c], Y. Zhou [7], C.G. Zhu [62b], C. Zhu [14a,14d], H.L. Zhu [62a], H. Zhu [14a], J. Zhu [105], Y. Zhu [62c], Y. Zhu [62a], X. Zhuang [14a], K. Zhukov [37], V. Zhulanov [37], N.I. Zimine [38], J. Zinsser [63b], M. Ziolkowski [140], L. Živković [15], A. Zoccoli [23b,23a], K. Zoch [56], T.G. Zorbas [138], O. Zormpa [46], W. Zou [41], L. Zwalinski [36]

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

[17] [(a)] Physics Division, Lawrence Berkeley National Laboratory, Berkeley CA; [(b)] University of California, Berkeley CA; United States of America
[18] Institut für Physik, Humboldt Universität zu Berlin, Berlin; Germany
[19] Albert Einstein Center for Fundamental Physics and Laboratory for High Energy Physics, University of Bern, Bern; Switzerland
[20] School of Physics and Astronomy, University of Birmingham, Birmingham; United Kingdom
[21] [(a)] Department of Physics, Bogazici University, Istanbul; [(b)] Department of Physics Engineering, Gaziantep University, Gaziantep; [(c)] Department of Physics, Istanbul University, Istanbul; [(d)] Istinye University, Sariyer, Istanbul; Türkiye
[22] [(a)] Facultad de Ciencias y Centro de Investigaciónes, Universidad Antonio Nariño, Bogotá; [(b)] Departamento de Física, Universidad Nacional de Colombia, Bogotá; Colombia
[23] [(a)] Dipartimento di Fisica e Astronomia A. Righi, Università di Bologna, Bologna; [(b)] INFN Sezione di Bologna; Italy
[24] Physikalisches Institut, Universität Bonn, Bonn; Germany
[25] Department of Physics, Boston University, Boston MA; United States of America
[26] Department of Physics, Brandeis University, Waltham MA; United States of America
[27] [(a)] Transilvania University of Brasov, Brasov; [(b)] Horia Hulubei National Institute of Physics and Nuclear Engineering, Bucharest; [(c)] Department of Physics, Alexandru Ioan Cuza University of Iasi, Iasi; [(d)] National Institute for Research and Development of Isotopic and Molecular Technologies, Physics Department, Cluj-Napoca; [(e)] University Politehnica Bucharest, Bucharest; [(f)] West University in Timisoara, Timisoara; [(g)] Faculty of Physics, University of Bucharest, Bucharest; Romania
[28] [(a)] Faculty of Mathematics, Physics and Informatics, Comenius University, Bratislava; [(b)] Department of Subnuclear Physics, Institute of Experimental Physics of the Slovak Academy of Sciences, Kosice; Slovak Republic
[29] Physics Department, Brookhaven National Laboratory, Upton NY; United States of America
[30] Universidad de Buenos Aires, Facultad de Ciencias Exactas y Naturales, Departamento de Física, y CONICET, Instituto de Física de Buenos Aires (IFIBA), Buenos Aires; Argentina
[31] California State University, CA; United States of America
[32] Cavendish Laboratory, University of Cambridge, Cambridge; United Kingdom
[33] [(a)] Department of Physics, University of Cape Town, Cape Town; [(b)] iThemba Labs, Western Cape; [(c)] Department of Mechanical Engineering Science, University of Johannesburg, Johannesburg; [(d)] National Institute of Physics, University of the Philippines Diliman (Philippines); [(e)] University of South Africa, Department of Physics, Pretoria; [(f)] University of Zululand, KwaDlangezwa; [(g)] School of Physics, University of the Witwatersrand, Johannesburg; South Africa
[34] Department of Physics, Carleton University, Ottawa ON; Canada
[35] [(a)] Faculté des Sciences Ain Chock, Réseau Universitaire de Physique des Hautes Energies - Université Hassan II, Casablanca; [(b)] Faculté des Sciences, Université Ibn-Tofail, Kénitra; [(c)] Faculté des Sciences Semlalia, Université Cadi Ayyad, LPHEA, Marrakech; [(d)] LPMR, Faculté des Sciences, Université Mohamed Premier, Oujda; [(e)] Faculté des sciences, Université Mohammed V, Rabat; [(f)] Institute of Applied Physics, Mohammed VI Polytechnic University, Ben Guerir; Morocco
[36] CERN, Geneva; Switzerland
[37] Affiliated with an institute covered by a cooperation agreement with CERN
[38] Affiliated with an international laboratory covered by a cooperation agreement with CERN
[39] Enrico Fermi Institute, University of Chicago, Chicago IL; United States of America
[40] LPC, Université Clermont Auvergne, CNRS/IN2P3, Clermont-Ferrand; France
[41] Nevis Laboratory, Columbia University, Irvington NY; United States of America
[42] Niels Bohr Institute, University of Copenhagen, Copenhagen; Denmark
[43] [(a)] Dipartimento di Fisica, Università della Calabria, Rende; [(b)] INFN Gruppo Collegato di Cosenza, Laboratori Nazionali di Frascati; Italy
[44] Physics Department, Southern Methodist University, Dallas TX; United States of America
[45] Physics Department, University of Texas at Dallas, Richardson TX; United States of America
[46] National Centre for Scientific Research "Demokritos", Agia Paraskevi; Greece
[47] [(a)] Department of Physics, Stockholm University; [(b)] Oskar Klein Centre, Stockholm; Sweden
[48] Deutsches Elektronen-Synchrotron DESY, Hamburg and Zeuthen; Germany
[49] Fakultät Physik, Technische Universität Dortmund, Dortmund; Germany
[50] Institut für Kern- und Teilchenphysik, Technische Universität Dresden, Dresden; Germany
[51] Department of Physics, Duke University, Durham NC; United States of America
[52] SUPA - School of Physics and Astronomy, University of Edinburgh, Edinburgh; United Kingdom
[53] INFN e Laboratori Nazionali di Frascati, Frascati; Italy
[54] Physikalisches Institut, Albert-Ludwigs-Universität Freiburg, Freiburg; Germany
[55] II. Physikalisches Institut, Georg-August-Universität Göttingen, Göttingen; Germany
[56] Département de Physique Nucléaire et Corpusculaire, Université de Genève, Genève; Switzerland
[57] [(a)] Dipartimento di Fisica, Università di Genova, Genova; [(b)] INFN Sezione di Genova; Italy
[58] II. Physikalisches Institut, Justus-Liebig-Universität Giessen, Giessen; Germany
[59] SUPA - School of Physics and Astronomy, University of Glasgow, Glasgow; United Kingdom
[60] LPSC, Université Grenoble Alpes, CNRS/IN2P3, Grenoble INP, Grenoble; France
[61] Laboratory for Particle Physics and Cosmology, Harvard University, Cambridge MA; United States of America
[62] [(a)] Department of Modern Physics and State Key Laboratory of Particle Detection and Electronics, University of Science and Technology of China, Hefei; [(b)] Institute of Frontier and Interdisciplinary Science and Key Laboratory of Particle Physics and Particle Irradiation (MOE), Shandong University, Qingdao; [(c)] School of Physics and Astronomy, Shanghai Jiao Tong University, Key Laboratory for Particle Astrophysics and Cosmology (MOE), SKLPPC, Shanghai; [(d)] Tsung-Dao Lee Institute, Shanghai; China
[63] [(a)] Kirchhoff-Institut für Physik, Ruprecht-Karls-Universität Heidelberg, Heidelberg; [(b)] Physikalisches Institut, Ruprecht-Karls-Universität Heidelberg, Heidelberg; Germany
[64] [(a)] Department of Physics, Chinese University of Hong Kong, Shatin, N.T., Hong Kong; [(b)] Department of Physics, University of Hong Kong, Hong Kong; [(c)] Department of Physics and Institute for Advanced Study, Hong Kong University of Science and Technology, Clear Water Bay, Kowloon, Hong Kong; China
[65] Department of Physics, National Tsing Hua University, Hsinchu; Taiwan
[66] IJCLab, Université Paris-Saclay, CNRS/IN2P3, 91405, Orsay; France
[67] Department of Physics, Indiana University, Bloomington IN; United States of America
[68] [(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
[69] [(a)] INFN Sezione di Lecce; [(b)] Dipartimento di Matematica e Fisica, Università del Salento, Lecce; Italy
[70] [(a)] INFN Sezione di Milano; [(b)] Dipartimento di Fisica, Università di Milano, Milano; Italy
[71] [(a)] INFN Sezione di Napoli; [(b)] Dipartimento di Fisica, Università di Napoli, Napoli; Italy
[72] [(a)] INFN Sezione di Pavia; [(b)] Dipartimento di Fisica, Università di Pavia, Pavia; Italy
[73] [(a)] INFN Sezione di Pisa; [(b)] Dipartimento di Fisica E. Fermi, Università di Pisa, Pisa; Italy
[74] [(a)] INFN Sezione di Roma; [(b)] Dipartimento di Fisica, Sapienza Università di Roma, Roma; Italy
[75] [(a)] INFN Sezione di Roma Tor Vergata; [(b)] Dipartimento di Fisica, Università di Roma Tor Vergata, Roma; Italy
[76] [(a)] INFN Sezione di Roma Tre; [(b)] Dipartimento di Matematica e Fisica, Università Roma Tre, Roma; Italy
[77] [(a)] INFN-TIFPA; [(b)] Università degli Studi di Trento, Trento; Italy
[78] Universität Innsbruck, Department of Astro and Particle Physics, Innsbruck; Austria
[79] University of Iowa, Iowa City IA; United States of America
[80] Department of Physics and Astronomy, Iowa State University, Ames IA; United States of America
[81] [(a)] Departamento de Engenharia Elétrica, Universidade Federal de Juiz de Fora (UFJF), Juiz de Fora; [(b)] Universidade Federal do Rio De Janeiro COPPE/EE/IF, Rio de Janeiro; [(c)] Instituto de Física, Universidade de São Paulo, São Paulo; [(d)] Rio de Janeiro State University, Rio de Janeiro; Brazil
[82] KEK, High Energy Accelerator Research Organization, Tsukuba; Japan
[83] Graduate School of Science, Kobe University, Kobe; Japan

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

[158] United Arab Emirates University, Al Ain; United Arab Emirates
[159] Department of Physics and Astronomy, University of California Irvine, Irvine CA; United States of America
[160] Department of Physics and Astronomy, University of Uppsala, Uppsala; Sweden
[161] Department of Physics, University of Illinois, Urbana IL; United States of America
[162] Instituto de Física Corpuscular (IFIC), Centro Mixto Universidad de Valencia - CSIC, Valencia; Spain
[163] Department of Physics, University of British Columbia, Vancouver BC; Canada
[164] Department of Physics and Astronomy, University of Victoria, Victoria BC; Canada
[165] Fakultät für Physik und Astronomie, Julius-Maximilians-Universität Würzburg, Würzburg; Germany
[166] Department of Physics, University of Warwick, Coventry; United Kingdom
[167] Waseda University, Tokyo; Japan
[168] Department of Particle Physics and Astrophysics, Weizmann Institute of Science, Rehovot; Israel
[169] Department of Physics, University of Wisconsin, Madison WI; United States of America
[170] Fakultät für Mathematik und Naturwissenschaften, Fachgruppe Physik, Bergische Universität Wuppertal, Wuppertal; Germany
[171] Department of Physics, Yale University, New Haven CT; United States of America

[a] Also affiliated with an institute covered by a cooperation agreement with CERN.
[b] Also at An-Najah National University, Nablus; Palestine.
[c] Also at Borough of Manhattan Community College, City University of New York, New York NY; United States of America.
[d] Also at Bruno Kessler Foundation, Trento; Italy.
[e] Also at Center for High Energy Physics, Peking University; China.
[f] Also at Center for Interdisciplinary Research and Innovation (CIRI-AUTH), Thessaloniki; Greece.
[g] Also at Centro Studi e Ricerche Enrico Fermi; Italy.
[h] Also at CERN, Geneva; Switzerland.
[i] Also at Département de Physique Nucléaire et Corpusculaire, Université de Genève, Genève; Switzerland.
[j] Also at Departament de Fisica de la Universitat Autonoma de Barcelona, Barcelona; Spain.
[k] Also at Department of Financial and Management Engineering, University of the Aegean, Chios; Greece.
[l] Also at Department of Physics and Astronomy, Michigan State University, East Lansing MI; United States of America.
[m] Also at Department of Physics and Astronomy, University of Louisville, Louisville, KY; United States of America.
[n] Also at Department of Physics, Ben Gurion University of the Negev, Beer Sheva; Israel.
[o] Also at Department of Physics, California State University, East Bay; United States of America.
[p] Also at Department of Physics, California State University, Sacramento; United States of America.
[q] Also at Department of Physics, King's College London, London; United Kingdom.
[r] Also at Department of Physics, University of Fribourg, Fribourg; Switzerland.
[s] Also at Department of Physics, University of Thessaly; Greece.
[t] Also at Department of Physics, Westmont College, Santa Barbara; United States of America.
[u] Also at Hellenic Open University, Patras; Greece.
[v] Also at Institucio Catalana de Recerca i Estudis Avancats, ICREA, Barcelona; Spain.
[w] Also at Institut für Experimentalphysik, Universität Hamburg, Hamburg; Germany.
[x] Also at Institute of Particle Physics (IPP); Canada.
[y] Also at Institute of Physics and Technology, Ulaanbaatar; Mongolia.
[z] Also at Institute of Physics, Azerbaijan Academy of Sciences, Baku; Azerbaijan.
[aa] Also at Institute of Theoretical Physics, Ilia State University, Tbilisi; Georgia.
[ab] Also at Lawrence Livermore National Laboratory, Livermore; United States of America.
[ac] Also at RWTH Aachen University, III. Physikalisches Institut A, Aachen; Germany.
[ad] Also at The Collaborative Innovation Center of Quantum Matter (CICQM), Beijing; China.
[ae] Also at TRIUMF, Vancouver BC; Canada.
[af] Also at Università di Napoli Parthenope, Napoli; Italy.
[ag] Also at University of Chinese Academy of Sciences (UCAS), Beijing; China.
[ah] Also at University of Colorado Boulder, Department of Physics, Colorado; United States of America.
[ai] Also at Washington College, Maryland; United States of America.
[aj] Also at Yeditepe University, Physics Department, Istanbul; Türkiye.
[*] Deceased.