

# 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

ATLAS Collaboration; Newman, Paul

DOI:

[10.1016/j.physletb.2023.137745](https://doi.org/10.1016/j.physletb.2023.137745)

License:

Creative Commons: Attribution (CC BY)

*Document Version*

Version created as part of publication process; publisher's layout; not normally made publicly available

*Citation for published version (Harvard):*

ATLAS Collaboration & Newman, P 2023, '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', *Physics Letters B*.  
<https://doi.org/10.1016/j.physletb.2023.137745>

[Link to publication on Research at Birmingham portal](#)

## General rights

Unless a licence is specified above, all rights (including copyright and moral rights) in this document are retained by the authors and/or the copyright holders. The express permission of the copyright holder must be obtained for any use of this material other than for purposes permitted by law.

- Users may freely distribute the URL that is used to identify this publication.
- Users may download and/or print one copy of the publication from the University of Birmingham research portal for the purpose of private study or non-commercial research.
- User may use extracts from the document in line with the concept of 'fair dealing' under the Copyright, Designs and Patents Act 1988 (?)
- Users may not further distribute the material nor use it for the purposes of commercial gain.

Where a licence is displayed above, please note the terms and conditions of the licence govern your use of this document.

When citing, please reference the published version.

## Take down policy

While the University of Birmingham exercises care and attention in making items available there are rare occasions when an item has been uploaded in error or has been deemed to be commercially or otherwise sensitive.

If you believe that this is the case for this document, please contact [UBIRA@lists.bham.ac.uk](mailto:UBIRA@lists.bham.ac.uk) providing details and we will remove access to the work immediately and investigate.

# Journal Pre-proof

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

PII: S0370-2693(23)00079-5  
DOI: <https://doi.org/10.1016/j.physletb.2023.137745>  
Reference: PLB 137745

To appear in: *Physics Letters B*

Received date: 7 November 2022  
Revised date: 23 January 2023  
Accepted date: 31 January 2023

Please cite this article as: The ATLAS Collaboration, 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, *Physics Letters B*, 137745, doi: <https://doi.org/10.1016/j.physletb.2023.137745>.

This is a PDF file of an article that has undergone enhancements after acceptance, such as the addition of a cover page and metadata, and formatting for readability, but it is not yet the definitive version of record. This version will undergo additional copyediting, typesetting and review before it is published in its final form, but we are providing this version to give early visibility of the article. Please note that, during the production process, errors may be discovered which could affect the content, and all legal disclaimers that apply to the journal pertain.

© 2023 Published by Elsevier.



EUROPEAN ORGANISATION FOR NUCLEAR RESEARCH (CERN)



Submitted to: Phys. Lett. B.



CERN-EP-2022-149

5th June 2023

# 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

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<sup>-1</sup>. 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 ( $\lambda_{HHH}$ ), values outside the interval  $-0.4 < \kappa_\lambda = (\lambda_{HHH}/\lambda_{HHH}^{\text{SM}}) < 6.3$  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.

## 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  $\lambda_{HHH}$ . 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]:  $\lambda_{HHH} = (m_H^2 G_F)/\sqrt{2}$ .

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  $\text{fb}^{-1}$ . 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  $\kappa_\lambda$  defined as the ratio of the Higgs boson self-coupling to its SM value,  $\kappa_\lambda = \lambda_{HHH}/\lambda_{HHH}^{\text{SM}}$ .

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  $\kappa_\lambda$  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  $\kappa_\lambda$  and the other coupling modifiers. This more comprehensive combination makes it possible to perform tests of  $\kappa_\lambda$  relaxing the assumptions about Higgs boson interactions with the other SM particles.

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  $\text{fb}^{-1}$  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  $\kappa_\lambda$  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  $\text{fb}^{-1}$  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  $\kappa_\lambda$  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  $\kappa_m$ . 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  $\kappa_m$  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  $\kappa_m$  from unity would indicate the presence of physics beyond the SM in the tested interaction. In this work, only the coupling modifiers  $\kappa_t$ ,  $\kappa_b$ ,  $\kappa_\tau$ , and  $\kappa_V$  are considered for single-Higgs interactions (in addition to the  $\kappa_\lambda$  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  $\kappa_\lambda$ ,  $\kappa_t$ ,  $\kappa_V$  and  $\kappa_{2V}$  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  $pp \rightarrow HH$  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 Figure 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  $\kappa_t^2$ , and the  $\mathcal{A}_2$  amplitude is proportional to the product of  $\kappa_t$  and the Higgs boson self-coupling modifier  $\kappa_\lambda$ .

In the SM, the interference between these two amplitudes is destructive and yields an overall cross-section of  $\sigma_{\text{ggF}}^{\text{SM}}(pp \rightarrow HH) = 31.0_{-7.2}^{+2.1}$  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  $\kappa_\lambda$  and  $\kappa_t$  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 Figure 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.

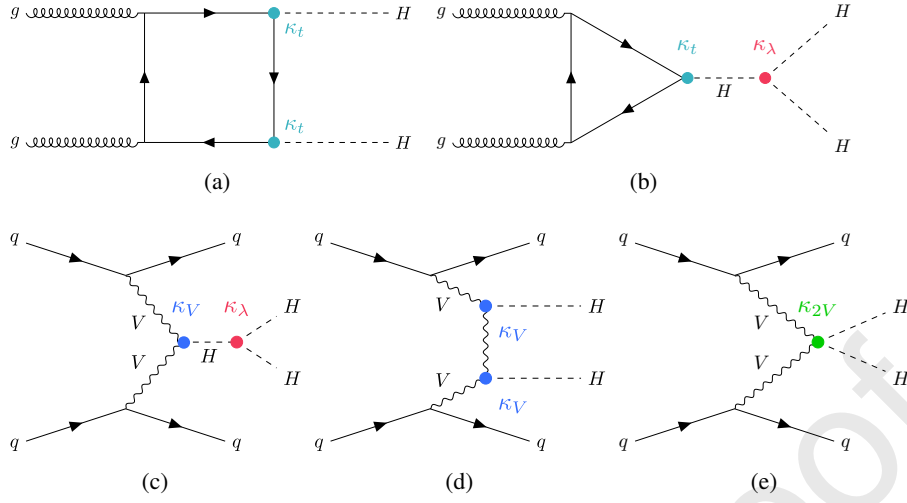


Figure 1: Examples of leading-order Feynman diagrams for Higgs boson pair production: for ggF production, diagram (a) is proportional to the square of the top-quark Yukawa coupling, while diagram (b) is proportional to the product of the top-quark Yukawa coupling and the Higgs boson self-coupling. For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

The second most abundant SM double-Higgs process is VBF  $HH$  production, with a predicted SM cross-section of  $1.72 \pm 0.04$  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 Figure 1. The three representative diagrams that enter the total amplitude of the VBF  $HH$  process can be parameterised with different combinations of the  $\kappa_\lambda$ ,  $\kappa_V$  and  $\kappa_{2V}$  coupling modifiers [49]. The first diagram, shown in Figure 1(c), is proportional to  $\kappa_V$  and  $\kappa_\lambda$ , the second, shown in Figure 1(d), to  $\kappa_V^2$  and the last one, shown in Figure 1(e) and related to the quartic interaction vertex  $VVHH$ , to  $\kappa_{2V}$ . 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  $\kappa_\lambda$ ,  $\kappa_V$  and  $\kappa_{2V}$ . 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  $\kappa_\lambda$ ,  $\kappa_V$  and  $\kappa_{2V}$ . The values of  $\kappa_\lambda$ ,  $\kappa_V$ , and  $\kappa_{2V}$  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  $\kappa_\lambda$  relative to the top-quark couplings because of interference between different amplitudes whose leading-order Feynman diagrams are depicted in Figure 1. Similarly, the VBF  $HH$  process provides sensitivity to the relative sign between  $\kappa_{2V}$  and  $\kappa_V$ .

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  $\lambda_{HHH}$  at LO, but the Higgs boson self-coupling contributes to the calculation of the complete NLO EW corrections. In particular,  $\lambda_{HHH}$  contributes to NLO EW corrections via Higgs boson self-energy loop corrections and via additional diagrams, examples of which are shown in Figure 2. Therefore, an indirect constraint on  $\kappa_\lambda$  can be extracted by comparing precise measurements of single-Higgs production and decay yields with the

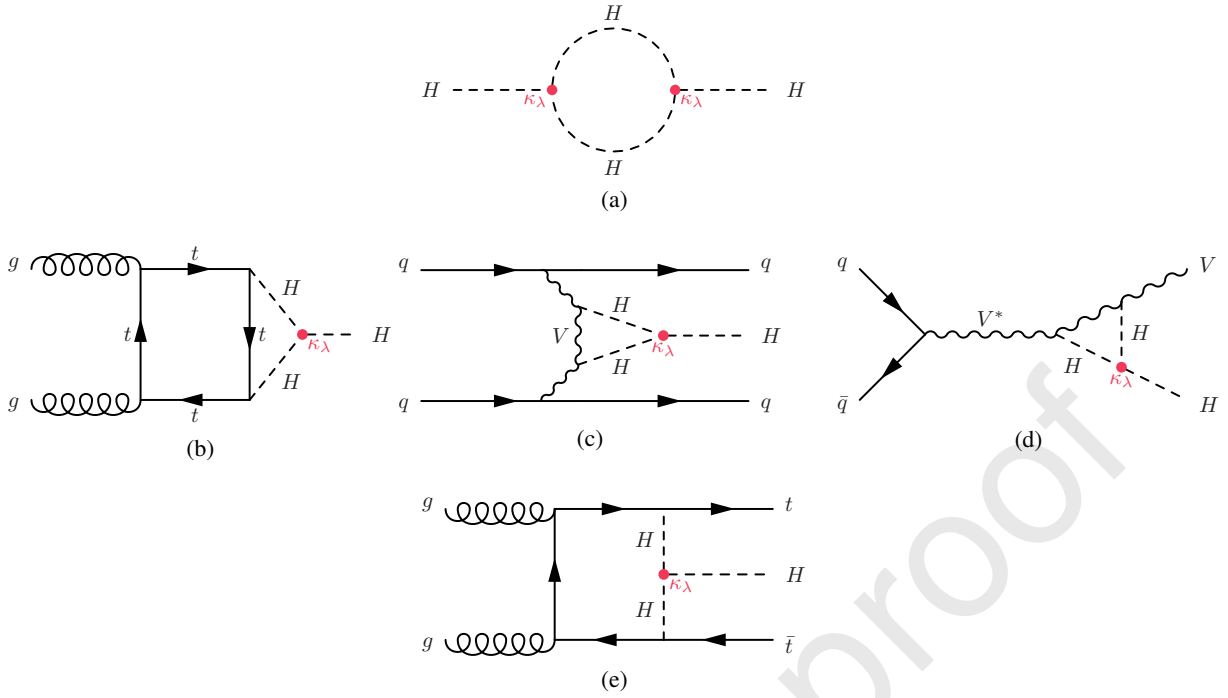


Figure 2: Examples of one-loop  $\lambda_{HHH}$ -dependent diagrams for (a) the Higgs boson self-energy, and for single-Higgs production in the (b) ggF, (c) VBF, (d)  $VH$ , and (e)  $t\bar{t}H$  modes. The self-coupling vertex is indicated by the filled circle.

SM predictions corrected for the  $\lambda_{HHH}$ -dependent NLO EW effects. A framework for a global fit to constrain the Higgs boson self-coupling and the other coupling modifiers  $\kappa_m$  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  $\kappa_\lambda$  and  $\kappa_m$ . 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:

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

where  $\mu_i$  and  $\mu_f$  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  $\kappa_\lambda$  and the LO-inspired modifiers  $\kappa_m$ . 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  $\kappa_\lambda$  and  $\kappa_m$  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  $\kappa_\lambda$  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  $\kappa_\lambda$  and  $\kappa_m$ . For the ggF production mode, only the inclusive cross-section dependence on  $\kappa_\lambda$  is currently available and it was used in this study, while the STXS bin dependence was not considered.



Conversely, the  $\kappa_\lambda$ -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  $\kappa_\lambda$  in each STXS bin. A detailed description of the parameterisation of the single-Higgs processes as a function of the  $\kappa_\lambda$  coupling 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  $\kappa_\lambda$  and  $\kappa_m$  parameters. The dependence of the decay branching ratios and the Higgs boson self-energy on  $\kappa_\lambda$  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<sup>-1</sup>, 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.

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



## 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  $H \rightarrow \tau^+\tau^-$  and  $HH \rightarrow b\bar{b}\tau^+\tau^-$  channels, mainly due to the  $t\bar{t}H$  categories in the  $H \rightarrow \tau^+\tau^-$  analysis, which is found to be at the 4% level in the double-Higgs signal regions. The  $t\bar{t}H$  categories in the  $H \rightarrow \tau^+\tau^-$  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 boson's self-coupling. First, the value of the signal strength  $\mu_{HH}$ , 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  $\mu_{HH}$  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 Figure 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  $\sigma(pp \rightarrow HH)$  of 73 fb (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 Figure 4(a). The signal acceptance of the double-Higgs analyses has a strong dependence on the value of  $\kappa_\lambda$  (mainly due to its impact on the  $m_{HH}$  distribution), determining the shapes of the exclusion limit curve shown in Figure 4(a).

Constraints on the coupling modifiers are obtained by using the values of the test statistic as a function of  $\kappa_\lambda$  in the asymptotic approximation and including the theoretical uncertainty of the cross-section predictions. The  $\kappa_\lambda$  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  $\kappa_{2V}$  is shown in Figure 4(b). Constraints are derived directly from the test statistic value parameterised as a function of  $\kappa_{2V}$ . 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.

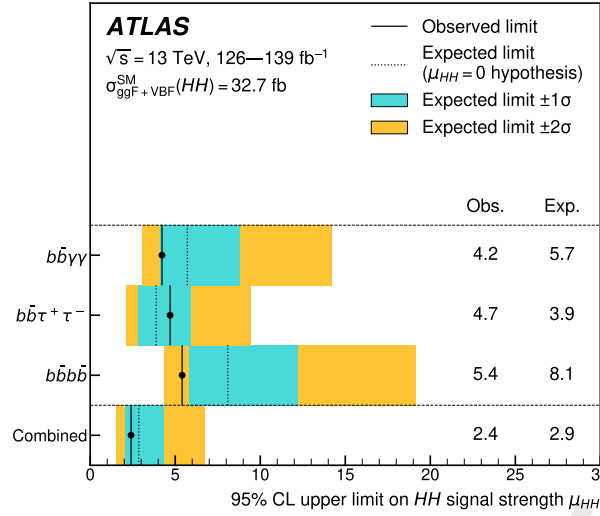


Figure 3: Observed and expected 95% CL upper limits on the signal strength for double-Higgs production from the  $b\bar{b}b\bar{b}$ ,  $b\bar{b}\tau^+\tau^-$  and  $b\bar{b}\gamma\gamma$  decay channels, and their statistical combination. The value  $m_H = 125.09$  GeV is assumed when deriving the predicted 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.

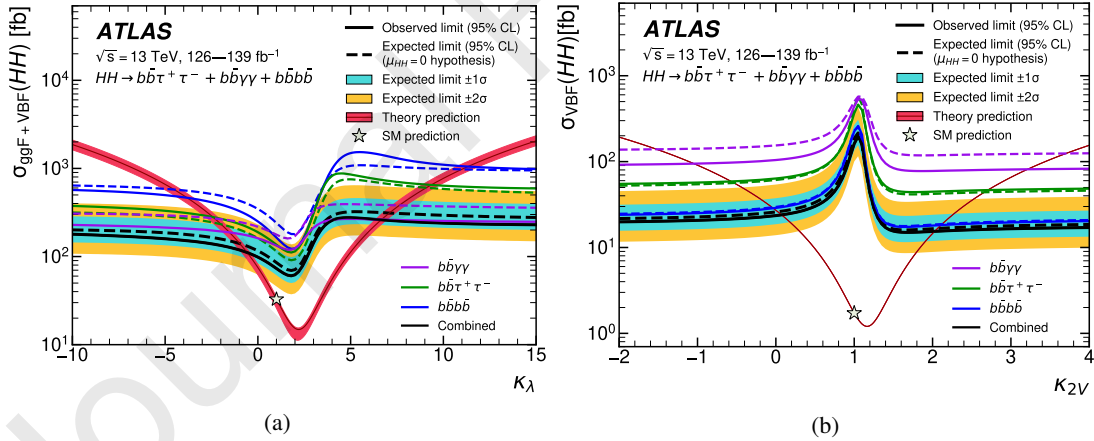


Figure 4: Observed and expected 95% CL exclusion limits on the production cross-sections of (a) the combined ggF  $HH$  and VBF  $HH$  processes as a function of  $\kappa_\lambda$  and (b) the VBF  $HH$  process as a function of  $\kappa_{2V}$ , for the three double-Higgs search channels and their combination. 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  $\kappa_\lambda$  where all parameters and couplings are set to their SM values except for  $\kappa_\lambda$ , and (b) the predicted VBF  $HH$  cross-section as a function of  $\kappa_{2V}$ . 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.

## 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  $\kappa_\lambda$ . Several fits to data are performed with different assumptions about the coupling modifiers to other SM particles.

At first, only possible deviations of  $\kappa_\lambda$  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  $\kappa_\lambda$  are shown in Figure 5 for the single-Higgs and double-Higgs analyses, and their combination.

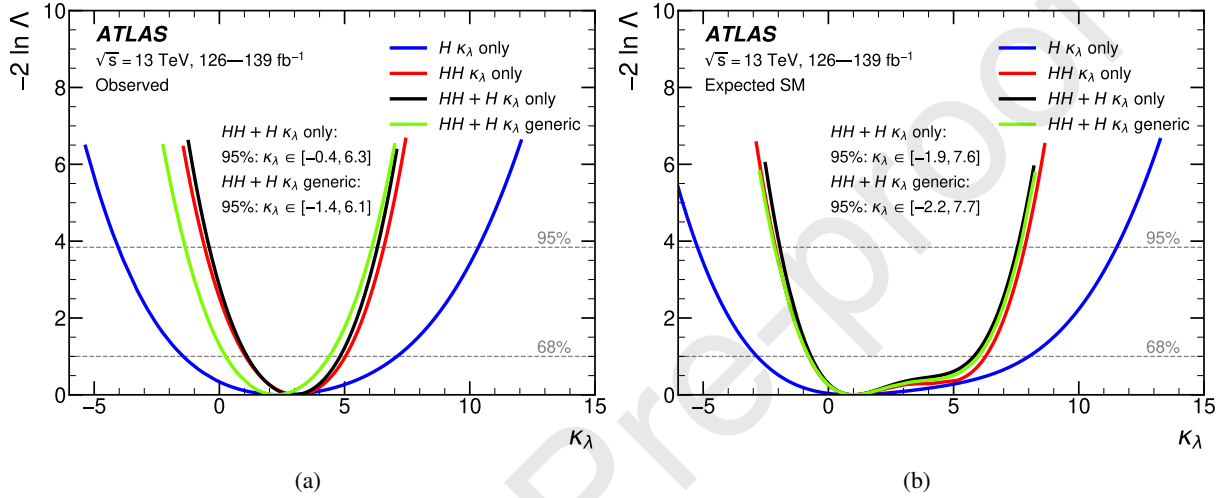


Figure 5: Observed (a) and expected (b) values of the test statistic ( $-2 \ln \Lambda$ ), as a function of the  $\kappa_\lambda$  parameter for the single-Higgs (blue) and double-Higgs (red) analyses, and their combination (black) derived from the combined single-Higgs and double-Higgs analyses, with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

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 Figure 5. The expected test statistic ( $-2 \ln \Lambda$ ) curve in Figure 5(b) exhibits a ‘two-minima-like’ structure due to the quadratic dependence of the observed signal yields on the parameter of interest  $\kappa_\lambda$  (partially resolved by the  $m_{HH}$  kinematic information used in the fit). The observed curve is more parabolic because the best-fit value of  $\kappa_\lambda$  is close to the value where the predicted double-Higgs cross-section, shown in Figure 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,  $\kappa_t$ , can be released. Thanks to the strong constraints on  $\kappa_t$  from the single-Higgs measurements, the constraints on  $\kappa_\lambda$  obtained from a fit with a floating value of  $\kappa_t$  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  $\kappa_\lambda$ - $\kappa_t$  plane are shown in Figure 6. All other coupling modifiers are fixed to unity in this fit.

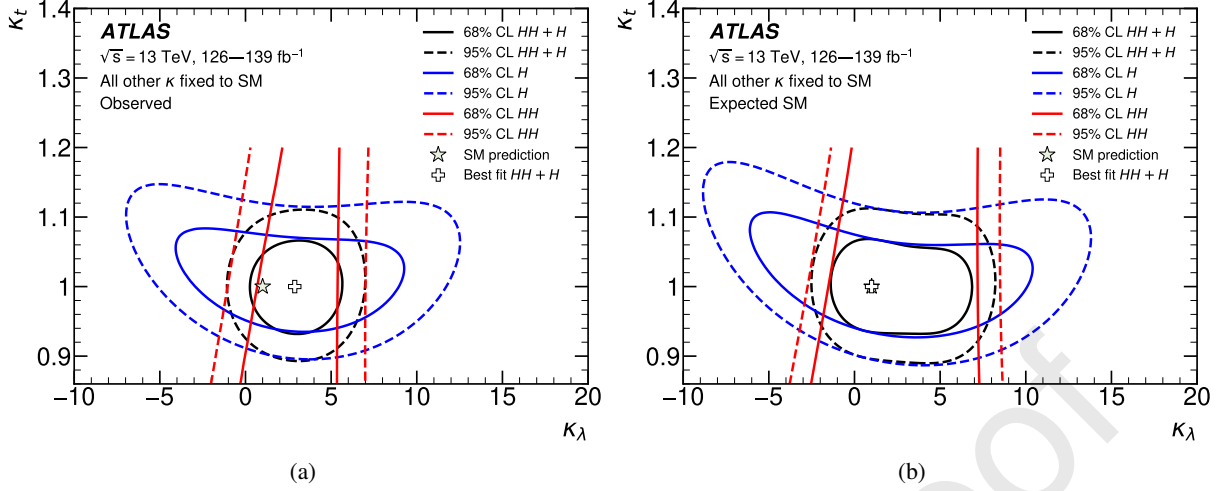


Figure 6: Observed (a) and expected (b) constraints in the  $\kappa_\lambda$ - $\kappa_t$  plane from single-Higgs (blue) and double-Higgs (red) analyses, and their combination (black). The solid (dashed) lines show the 68% (95%) CL contours. The double-Higgs contours are shown for values of  $\kappa_t$  smaller than 1.2. The observed constraint for the single- and double-Higgs combination for  $\kappa_t$  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.

The most generic model allows all of the coupling modifiers  $\kappa_\lambda$ ,  $\kappa_t$ ,  $\kappa_b$ ,  $\kappa_\tau$ , and  $\kappa_V$  implemented in this parameterisation to float freely in the fit. The exception is  $\kappa_{2V}$ , 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  $\kappa_V$  and  $\kappa_{2V}$  coupling modifiers seems to be possible, though the sensitivity of single-H processes to  $\kappa_{2V}$  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  $\kappa_\lambda$  for this generic model are also shown in Figure 5. It was checked that for a generic model in which  $\kappa_{2V}$  also floats freely in the double-Higgs parameterisation, the observed exclusion constraints on  $\kappa_\lambda$  weaken by less than 5%. In this approach, the  $VVHH$  vertex is parameterised in terms of the  $\kappa_{2V}$  coupling modifier for the VBF  $HH$  process but the single-Higgs NLO EW corrections are not.

Table 2: Summary of  $\kappa_\lambda$  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  $\kappa_\lambda$  in the corresponding fit are reported. The uncertainties on  $\kappa_\lambda$  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, $\kappa_t$ floating	$-0.4 < \kappa_\lambda < 6.3$	$-1.9 < \kappa_\lambda < 7.6$	$\kappa_\lambda = 3.0^{+1.8}_{-1.9}$
$HH+H$ combination, $\kappa_t, \kappa_V, \kappa_b, \kappa_\tau$ floating	$-1.4 < \kappa_\lambda < 6.1$	$-2.2 < \kappa_\lambda < 7.7$	$\kappa_\lambda = 2.3^{+2.1}_{-2.0}$

## 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 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,  $b\bar{b}b\bar{b}$ ,  $b\bar{b}\tau^+\tau^-$  and  $b\bar{b}\gamma\gamma$ , 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  $\kappa_{2V}$  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  $\kappa_\lambda$  that are either more stringent or less model-dependent. Using this combination and assuming that  $\kappa_\lambda$  is the only source of physics beyond the SM, values of  $\kappa_\lambda$  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,  $\kappa_t$ ,  $\kappa_b$ ,  $\kappa_\tau$ , and  $\kappa_V$ , 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.

## 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] S. L. Glashow, *Partial-symmetries of weak interactions*, *Nucl. Phys.* **22** (1961) 579.
- [5] A. Salam, *Weak and Electromagnetic Interactions*, *Conf. Proc. C* **680519** (1968) Proceedings of the eighth Nobel symposium.
- [6] S. Weinberg, *A Model of Leptons*, *Phys. Rev. Lett.* **19** (1967) 1264.
- [7] G. 't Hooft and M. J. G. Veltman, *Regularization and Renormalization of Gauge Fields*, *Nucl. Phys. B* **44** (1972) 189.
- [8] F. Englert and R. Brout, *Broken Symmetry and the Mass of Gauge Vector Mesons*, *Phys. Rev. Lett.* **13** (1964) 321.
- [9] P. W. Higgs, *Broken symmetries, massless particles and gauge fields*, *Phys. Lett.* **12** (1964) 132.
- [10] P. W. Higgs, *Broken Symmetries and the Masses of Gauge Bosons*, *Phys. Rev. Lett.* **13** (1964) 508.
- [11] P. W. Higgs, *Spontaneous Symmetry Breakdown without Massless Bosons*, *Phys. Rev.* **145** (1966) 1156.
- [12] G. S. Guralnik, C. R. Hagen and T. W. B. Kibble, *Global Conservation Laws and Massless Particles*, *Phys. Rev. Lett.* **13** (1964) 585.
- [13] T. W. B. Kibble, *Symmetry Breaking in Non-Abelian Gauge Theories*, *Phys. Rev.* **155** (1967) 1554.
- [14] G. Degrandi et al., *Higgs mass and vacuum stability in the Standard Model at NNLO*, *JHEP* **08** (2012) 098, arXiv: 1205.6497.
- [15] ATLAS and CMS Collaborations, *Combined Measurement of the Higgs Boson Mass in pp Collisions at  $\sqrt{s} = 7$  and 8 TeV with the ATLAS and CMS Experiments*, *Phys. Rev. Lett.* **114** (2015) 191803, arXiv: 1503.07589 [hep-ex].
- [16] Particle Data Group, R. L. Workman et al., *Review of Particle Physics*, *PTEP* **2022** (2022) 083C01.
- [17] ATLAS Collaboration, *Search for Higgs boson pair production in the two bottom quarks plus two photons final state in pp collisions at  $\sqrt{s} = 13$  TeV with the ATLAS detector*, *Phys. Rev. D* **106** (2022) 052001, arXiv: 2112.11876 [hep-ex].
- [18] ATLAS Collaboration, *Search for resonant and non-resonant Higgs boson pair production in the  $b\bar{b}\tau^+\tau^-$  decay channel using 13 TeV pp collision data from the ATLAS detector*, (2022), arXiv: 2209.10910 [hep-ex].
- [19] ATLAS Collaboration, *Search for non-resonant pair production of Higgs bosons in the  $b\bar{b}b\bar{b}$  final state in pp collisions at  $\sqrt{s} = 13$  TeV with the ATLAS detector*, CERN-EP-2022-235, 2022.
- [20] G. Degrandi, P. P. Giardino, F. Maltoni and D. Pagani, *Probing the Higgs self coupling via single Higgs production at the LHC*, *JHEP* **12** (2016) 080, arXiv: 1607.04251 [hep-ph].
- [21] F. Maltoni, D. Pagani, A. Shivaji and X. Zhao, *Trilinear Higgs coupling determination via single-Higgs differential measurements at the LHC*, *Eur. Phys. J. C* **77** (2017) 887, arXiv: 1709.08649 [hep-ph].
- [22] S. Di Vita, C. Grojean, G. Panico, M. Riembau and T. Vantalón, *A global view on the Higgs self-coupling*, *JHEP* **09** (2017) 069, arXiv: 1704.01953 [hep-ph].



- [23] M. Gorbahn and U. Haisch, *Indirect probes of the trilinear Higgs coupling:  $gg \rightarrow h$  and  $h \rightarrow \gamma\gamma$* , *JHEP* **10** (2016) 094, arXiv: [1607.03773 \[hep-ph\]](#).
- [24] W. Bizon, M. Gorbahn, U. Haisch and G. Zanderighi, *Constraints on the trilinear Higgs coupling from vector boson fusion and associated Higgs production at the LHC*, *JHEP* **07** (2017) 083, arXiv: [1610.05771 \[hep-ph\]](#).
- [25] M. McCullough, *An Indirect Model-Dependent Probe of the Higgs Self-Coupling*, *Phys. Rev. D* **90** (2014) 015001, [Erratum: *Phys. Rev. D* **92** (2015) 039903], arXiv: [1312.3322 \[hep-ph\]](#).
- [26] 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 \[hep-ex\]](#).
- [27] ATLAS Collaboration, *Combination of searches for Higgs boson pairs in  $pp$  collisions at  $\sqrt{s} = 13$  TeV with the ATLAS detector*, *Phys. Lett. B* **800** (2020) 135103, arXiv: [1906.02025 \[hep-ex\]](#).
- [28] CMS Collaboration, *A portrait of the Higgs boson by the CMS experiment ten years after the discovery*, *Nature* **607** (2022) 60, arXiv: [2207.00043 \[hep-ex\]](#).
- [29] LHC Higgs Cross Section Working Group, S. Heinemeyer et al., *Handbook of LHC Higgs Cross Sections: 3. Higgs Properties*, CERN-2013-004 (CERN, Geneva, 2013), arXiv: [1307.1347 \[hep-ph\]](#).
- [30] LHC Higgs Cross Section Working Group, D. de Florian et al., *Handbook of LHC Higgs Cross Sections: 4. Deciphering the Nature of the Higgs Sector*, CERN-2017-002-M (2017), arXiv: [1610.07922 \[hep-ph\]](#).
- [31] B. Di Micco et al., *Higgs boson potential at colliders: Status and perspectives*, *Reviews in Physics* **5** (2020) 100045, arXiv: [1910.00012](#).
- [32] M. Grazzini et al., *Higgs boson pair production at NNLO with top quark mass effects*, *JHEP* **05** (2018) 059, arXiv: [1803.02463 \[hep-ph\]](#).
- [33] G. Heinrich, S. P. Jones, M. Kerner, G. Luisoni and L. Scyboz, *Probing the trilinear Higgs boson coupling in di-Higgs production at NLO QCD including parton shower effects*, *JHEP* **06** (2019) 066, arXiv: [1903.08137 \[hep-ph\]](#).
- [34] S. Dawson, S. Dittmaier and M. Spira, *Neutral Higgs boson pair production at hadron colliders: QCD corrections*, *Phys. Rev. D* **58** (1998) 115012, arXiv: [hep-ph/9805244 \[hep-ph\]](#).
- [35] S. Borowka et al., *Higgs Boson Pair Production in Gluon Fusion at Next-to-Leading Order with Full Top-Quark Mass Dependence*, *Phys. Rev. Lett.* **117** (2016) 012001, [Erratum: *Phys. Rev. Lett.* **117** (2016) 079901], arXiv: [1604.06447 \[hep-ph\]](#).
- [36] J. Baglio et al., *Gluon fusion into Higgs pairs at NLO QCD and the top mass scheme*, *Eur. Phys. J. C* **79** (2019) 459, arXiv: [1811.05692 \[hep-ph\]](#).
- [37] R. Bonciani, G. Degrossi, P. P. Giardino and R. Gröber, *Analytical Method for Next-to-Leading-Order QCD Corrections to Double-Higgs Production*, *Phys. Rev. Lett.* **121** (2018) 162003, arXiv: [1806.11564 \[hep-ph\]](#).

- [38] D. de Florian and J. Mazzitelli, *Higgs Boson Pair Production at Next-to-Next-to-Leading Order in QCD*, *Phys. Rev. Lett.* **111** (2013) 201801, arXiv: [1309.6594 \[hep-ph\]](#).
- [39] D. Y. Shao, C. S. Li, H. T. Li and J. Wang, *Threshold resummation effects in Higgs boson pair production at the LHC*, *JHEP* **07** (2013) 169, arXiv: [1301.1245 \[hep-ph\]](#).
- [40] D. de Florian and J. Mazzitelli, *Higgs pair production at next-to-next-to-leading logarithmic accuracy at the LHC*, *JHEP* **09** (2015) 053, arXiv: [1505.07122 \[hep-ph\]](#).
- [41] J. Baglio et al., *gg → HH: Combined uncertainties*, *Phys. Rev. D* **103** (2021) 056002, arXiv: [2008.11626](#).
- [42] ATLAS Collaboration, *Validation of signal Monte Carlo event generation in searches for Higgs boson pairs with the ATLAS detector*, ATL-PHYS-PUB-2019-007, 2019, URL: <https://cds.cern.ch/record/2665057>.
- [43] J. Baglio et al., *Higgs-pair production via gluon fusion at hadron colliders: NLO QCD corrections*, *JHEP* **2020** (2020), arXiv: [2003.03227](#).
- [44] S. Dawson, E. Furlan and I. Lewis, *Unravelling an extended quark sector through multiple Higgs production?*, *Phys. Rev. D* **87** (2013) 014007, arXiv: [1210.6663 \[hep-ph\]](#).
- [45] T. Plehn, M. Spira and P. M. Zerwas, *Pair production of neutral Higgs particles in gluon-gluon collisions*, *Nucl. Phys. B* **479** (1996) 46, [Erratum: *Nucl. Phys. B* 531,655(1998)], arXiv: [hep-ph/9603205 \[hep-ph\]](#).
- [46] F. A. Dreyer and A. Karlberg, *Vector-boson fusion Higgs pair production at N<sup>3</sup>LO*, *Phys. Rev. D* **98** (11 2018) 114016, arXiv: [1811.07906](#).
- [47] J. Baglio et al., *The measurement of the Higgs self-coupling at the LHC: theoretical status*, *JHEP* **04** (2013) 151, arXiv: [1212.5581](#).
- [48] L.-S. Ling et al., *NNLO QCD corrections to Higgs pair production via vector boson fusion at hadron colliders*, *Phys. Rev. D* **89** (2014) 073001, arXiv: [1401.7754](#).
- [49] F. Bishara, R. Contino and J. Rojo, *Higgs pair production in vector-boson fusion at the LHC and beyond*, *Eur. Phys. J. C* **77** (2017) 481, arXiv: [1611.03860 \[hep-ph\]](#).
- [50] J. R. Andersen et al., ‘Les Houches 2015: Physics at TeV Colliders Standard Model Working Group Report’, *9th Les Houches Workshop on Physics at TeV Colliders (PhysTeV 2015) Les Houches, France, June 1-19, 2015*, 2016, arXiv: [1605.04692 \[hep-ph\]](#).
- [51] ATLAS Collaboration, *Constraint of the Higgs boson self-coupling from Higgs boson differential production and decay measurements*, tech. rep. ATL-PHYS-PUB-2019-009, CERN, 2019, URL: <https://cds.cern.ch/record/2667570>.
- [52] LHC Higgs Cross Section Working Group, *Modelling of the single-Higgs simplified template cross-sections (STXS 1.2) for the determination of the Higgs boson trilinear self-coupling*, tech. rep. LHCHWG-2022-002, CERN, 2022, URL: <https://cds.cern.ch/record/2803606>.

- [53] ATLAS Collaboration, *The ATLAS Experiment at the CERN Large Hadron Collider*, *JINST* **3** (2008) S08003.
- [54] ATLAS Collaboration, *ATLAS Insertable B-Layer Technical Design Report*, 2010, URL: <https://cds.cern.ch/record/1291633>.
- [55] B. Abbott et al., *Production and integration of the ATLAS Insertable B-Layer*, *JINST* **13** (2018) T05008, arXiv: [1803.00844](https://arxiv.org/abs/1803.00844) [physics.ins-det].
- [56] ATLAS Collaboration, *Performance of the ATLAS trigger system in 2015*, *Eur. Phys. J. C* **77** (2017) 317, arXiv: [1611.09661](https://arxiv.org/abs/1611.09661) [hep-ex].
- [57] ATLAS Collaboration, *The ATLAS Collaboration Software and Firmware*, ATL-SOFT-PUB-2021-001, 2021, URL: <https://cds.cern.ch/record/2767187>.
- [58] ATLAS Collaboration, *Measurement of the properties of Higgs boson production at  $\sqrt{s} = 13$  TeV in the  $H \rightarrow \gamma\gamma$  channel using  $139 \text{ fb}^{-1}$  of  $pp$  collision data with the ATLAS experiment*, (2022), arXiv: [2207.00348](https://arxiv.org/abs/2207.00348) [hep-ex].
- [59] ATLAS Collaboration, *Higgs boson production cross-section measurements and their EFT interpretation in the  $4\ell$  decay channel at  $\sqrt{s} = 13$  TeV with the ATLAS detector*, *Eur. Phys. J. C* **80** (2020) 957, arXiv: [2004.03447](https://arxiv.org/abs/2004.03447) [hep-ex], Erratum: *Eur. Phys. J. C* **81** (2021) 29.
- [60] ATLAS Collaboration, *Measurements of Higgs boson production cross-sections in the  $H \rightarrow \tau^+\tau^-$  decay channel in  $pp$  collisions at  $\sqrt{s} = 13$  TeV with the ATLAS detector*, *JHEP* **08** (2022) 175, arXiv: [2201.08269](https://arxiv.org/abs/2201.08269) [hep-ex].
- [61] ATLAS Collaboration, *Measurements of Higgs boson production by gluon–gluon fusion and vector-boson fusion using  $H \rightarrow WW^* \rightarrow e\nu\mu\nu$  decays in  $pp$  collisions at  $\sqrt{s} = 13$  TeV with the ATLAS detector*, (2022), arXiv: [2207.00338](https://arxiv.org/abs/2207.00338) [hep-ex].
- [62] ATLAS Collaboration, *Measurements of  $WH$  and  $ZH$  production in the  $H \rightarrow b\bar{b}$  decay channel in  $pp$  collisions at 13 TeV with the ATLAS detector*, *Eur. Phys. J. C* **81** (2021) 178, arXiv: [2007.02873](https://arxiv.org/abs/2007.02873) [hep-ex].
- [63] ATLAS Collaboration, *Measurements of Higgs Bosons Decaying to Bottom Quarks from Vector Boson Fusion Production with the ATLAS Experiment at  $\sqrt{s} = 13$  TeV*, *Eur. Phys. J. C* **81** (2020) 537, arXiv: [2011.08280](https://arxiv.org/abs/2011.08280) [hep-ex].
- [64] ATLAS Collaboration, *Measurement of Higgs boson decay into  $b$ -quarks in associated production with a top-quark pair in  $pp$  collisions at  $\sqrt{s} = 13$  TeV with the ATLAS detector*, *JHEP* **06** (2022) 097, arXiv: [2111.06712](https://arxiv.org/abs/2111.06712) [hep-ex].
- [65] ATLAS and CMS Collaborations, *Measurements of the Higgs boson production and decay rates and constraints on its couplings from a combined ATLAS and CMS analysis of the LHC  $pp$  collision data at  $\sqrt{s} = 7$  and 8 TeV*, *JHEP* **08** (2016) 045, arXiv: [1606.02266](https://arxiv.org/abs/1606.02266) [hep-ex].
- [66] ATLAS Collaboration, *Combined measurements of Higgs boson production and decay using up to  $80 \text{ fb}^{-1}$  of proton–proton collision data at  $\sqrt{s} = 13$  TeV collected with the ATLAS experiment*, *Phys. Rev. D* **101** (2020) 012002, arXiv: [1909.02845](https://arxiv.org/abs/1909.02845) [hep-ex].

- [67] 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](#), [Erratum: [Eur. Phys. J. C \*\*73\*\* \(2013\) 2501](#)], arXiv: [1007.1727 \[physics.data-an\]](#).
- [68] A. L. Read, *Presentation of search results: the  $CL_s$  technique*, [J. Phys. G \*\*28\*\* \(2002\) 2693](#).
- [69] Anisha, O. Atkinson, A. Bhardwaj, C. Englert and P. Stylianou, *Quartic Gauge-Higgs couplings: Constraints and Future Directions*, (2022), arXiv: [2208.09334 \[hep-ph\]](#).
- [70] ATLAS Collaboration, *ATLAS Computing Acknowledgements*, ATL-SOFT-PUB-2021-003, URL: <https://cds.cern.ch/record/2776662>.

## ATLAS acknowledgments

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

We acknowledge the support of ANPCyT, Argentina; YerPhI, Armenia; ARC, Australia; BMWFW and FWF, Austria; ANAS, Azerbaijan; SSTC, Belarus; CNPq and FAPESP, Brazil; NSERC, NRC and CFI, Canada; CERN; ANID, Chile; CAS, MOST and NSFC, China; Minciencias, Colombia; MEYS CR, Czech Republic; D NRF 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; ISF and Benozzi Center, Israel; INFN, Italy; MEXT and JSPS, Japan; CNRST, Morocco; NWO, Netherlands; RCN, Norway; MEiN, Poland; FCT, Portugal; MNE/IFA, Romania; JINR; MES of Russia and NRC KI, Russian Federation; MESTD, Serbia; MSSR, Slovakia; ARRS and MIZŠ, Slovenia; DSI/NRF, South Africa; MICINN, Spain; SRC and Wallenberg Foundation, Sweden; SERI, SNSF and Cantons of Bern and Geneva, Switzerland; MOST, Taiwan; TENMAK, Türkiye; STFC, United Kingdom; DOE and NSF, United States of America. In addition, individual groups and members have received support from BCKDF, CANARIE, Compute Canada and CRC, Canada; COST, ERC, ERDF, Horizon 2020 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 GIF, Israel; Norwegian Financial Mechanism 2014-2021, Norway; 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.

The crucial computing support from all WLCG partners is acknowledged gratefully, in particular from CERN, the ATLAS Tier-1 facilities at TRIUMF (Canada), NDGF (Denmark, Norway, Sweden), CC-IN2P3 (France), KIT/GridKA (Germany), INFN-CNAF (Italy), NL-T1 (Netherlands), PIC (Spain), ASGC (Taiwan), 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. [70].

## The ATLAS Collaboration

G. Aad<sup>101</sup>, B. Abbott<sup>119</sup>, D.C. Abbott<sup>102</sup>, K. Abeling<sup>55</sup>, S.H. Abidi<sup>29</sup>, A. Abouhorma<sup>35e</sup>,  
H. Abramowicz<sup>150</sup>, H. Abreu<sup>149</sup>, Y. Abulaiti<sup>116</sup>, A.C. Abusleme Hoffman<sup>136a</sup>, B.S. Acharya<sup>68a,68b,q</sup>,  
B. Achkar<sup>55</sup>, C. Adam Bourdarios<sup>4</sup>, L. Adamczyk<sup>84a</sup>, L. Adamek<sup>154</sup>, S.V. Addepalli<sup>26</sup>, J. Adelman<sup>114</sup>,  
A. Adiguzel<sup>21c</sup>, S. Adorni<sup>56</sup>, T. Adye<sup>133</sup>, A.A. Affolder<sup>135</sup>, Y. Afik<sup>36</sup>, M.N. Agaras<sup>13</sup>, J. Agarwala<sup>72a,72b</sup>,  
A. Aggarwal<sup>99</sup>, C. Agheorghiesei<sup>27c</sup>, J.A. Aguilar-Saavedra<sup>129f</sup>, A. Ahmad<sup>36</sup>, F. Ahmadov<sup>38,z</sup>,  
W.S. Ahmed<sup>103</sup>, S. Ahuja<sup>94</sup>, X. Ai<sup>48</sup>, G. Aielli<sup>75a,75b</sup>, I. Aizenberg<sup>168</sup>, M. Akbiyik<sup>99</sup>, T.P.A. Åkesson<sup>97</sup>,  
A.V. Akimov<sup>37</sup>, K. Al Khoury<sup>41</sup>, G.L. Alberghi<sup>23b</sup>, J. Albert<sup>164</sup>, P. Albicocco<sup>53</sup>, S. Alderweireldt<sup>52</sup>,  
M. Aleksa<sup>36</sup>, I.N. Aleksandrov<sup>38</sup>, C. Alexa<sup>27b</sup>, T. Alexopoulos<sup>10</sup>, A. Alfonsi<sup>113</sup>, F. Alfonsi<sup>23b</sup>,  
M. Alhroob<sup>119</sup>, B. Ali<sup>131</sup>, S. Ali<sup>147</sup>, M. Aliev<sup>37</sup>, G. Alimonti<sup>70a</sup>, W. Alkakh<sup>55</sup>, C. Allaire<sup>66</sup>,  
B.M.M. Allbrooke<sup>145</sup>, P.P. Allport<sup>20</sup>, A. Aloisio<sup>71a,71b</sup>, F. Alonso<sup>89</sup>, C. Alpigiani<sup>137</sup>,  
E. Alunno Camelia<sup>75a,75b</sup>, M. Alvarez Estevez<sup>98</sup>, M.G. Alvigi<sup>71a,71b</sup>, M. Aly<sup>100</sup>, Y. Amaral Coutinho<sup>81b</sup>,  
A. Ambler<sup>103</sup>, C. Amelung<sup>36</sup>, M. Amerl<sup>1</sup>, C.G. Ames<sup>108</sup>, D. Amidei<sup>105</sup>, S.P. Amor Dos Santos<sup>129a</sup>,  
S. Amoroso<sup>48</sup>, K.R. Amos<sup>162</sup>, V. Ananiev<sup>124</sup>, C. Anastopoulos<sup>138</sup>, T. Andeen<sup>11</sup>, J.K. Anders<sup>36</sup>,  
S.Y. Andreev<sup>47a,47b</sup>, A. Andreazza<sup>70a,70b</sup>, S. Angelidakis<sup>9</sup>, A. Angerami<sup>41,ab</sup>, A.V. Anisenkov<sup>37</sup>,  
A. Annovi<sup>73a</sup>, C. Antel<sup>56</sup>, M.T. Anthony<sup>138</sup>, E. Antipov<sup>120</sup>, M. Antonelli<sup>53</sup>, D.J.A. Antrim<sup>17a</sup>, F. Anulli<sup>74a</sup>,  
M. Aoki<sup>82</sup>, T. Aoki<sup>152</sup>, J.A. Aparisi Pozo<sup>162</sup>, M.A. Aparo<sup>145</sup>, L. Aperio Bella<sup>48</sup>, C. Appelt<sup>18</sup>,  
N. Aranzabal<sup>36</sup>, V. Araujo Ferraz<sup>81a</sup>, C. Arcangeletti<sup>53</sup>, A.T.H. Arce<sup>51</sup>, E. Arena<sup>91</sup>, J-F. Arguin<sup>107</sup>,  
S. Argyropoulos<sup>54</sup>, J.-H. Arling<sup>48</sup>, A.J. Armbruster<sup>36</sup>, O. Arnaez<sup>154</sup>, H. Arnold<sup>113</sup>,  
Z.P. Arrubarrena Tame<sup>108</sup>, G. Artoni<sup>74a,74b</sup>, H. Asada<sup>110</sup>, K. Asai<sup>117</sup>, S. Asai<sup>152</sup>, N.A. Asbah<sup>61</sup>,  
J. Assahsah<sup>35d</sup>, K. Assamagan<sup>29</sup>, R. Astalos<sup>28a</sup>, R.J. Atkin<sup>33a</sup>, M. Atkinson<sup>161</sup>, N.B. Atlay<sup>18</sup>, H. Atmani<sup>62b</sup>,  
P.A. Atmasiddha<sup>105</sup>, K. Augsten<sup>131</sup>, S. Auricchio<sup>71a,71b</sup>, A.D. Auriol<sup>20</sup>, V.A. Austrup<sup>170</sup>, G. Avner<sup>149</sup>,  
G. Avolio<sup>36</sup>, K. Axiotis<sup>56</sup>, M.K. Ayoub<sup>14c</sup>, G. Azuelos<sup>107,ae</sup>, D. Babal<sup>28a</sup>, H. Bachacou<sup>134</sup>, K. Bachas<sup>151,s</sup>,  
A. Bachi<sup>34</sup>, F. Backman<sup>47a,47b</sup>, A. Badae<sup>61</sup>, P. Bagnaia<sup>74a,74b</sup>, M. Bahmani<sup>18</sup>, A.J. Bailey<sup>162</sup>,  
V.R. Bailey<sup>161</sup>, J.T. Baines<sup>133</sup>, C. Bakalis<sup>10</sup>, O.K. Baker<sup>171</sup>, P.J. Bakker<sup>113</sup>, E. Bakos<sup>15</sup>, D. Bakshi Gupta<sup>8</sup>,  
S. Balaji<sup>146</sup>, R. Balasubramanian<sup>113</sup>, E.M. Baldin<sup>37</sup>, P. Balek<sup>132</sup>, E. Ballabene<sup>70a,70b</sup>, F. Balli<sup>134</sup>,  
L.M. Baltes<sup>63a</sup>, W.K. Balunas<sup>32</sup>, J. Balz<sup>99</sup>, E. Banas<sup>85</sup>, M. Bandieramonte<sup>128</sup>, A. Bandyopadhyay<sup>24</sup>,  
S. Bansal<sup>24</sup>, L. Barak<sup>150</sup>, E.L. Barberio<sup>104</sup>, D. Barberis<sup>57b,57a</sup>, M. Barbero<sup>101</sup>, G. Barbour<sup>95</sup>,  
K.N. Barends<sup>33a</sup>, T. Barillari<sup>109</sup>, M-S. Barisits<sup>36</sup>, T. Barklow<sup>142</sup>, R.M. Barnett<sup>17a</sup>, P. Baron<sup>121</sup>,  
D.A. Baron Moreno<sup>100</sup>, A. Baroncelli<sup>62a</sup>, G. Barone<sup>29</sup>, A.J. Barr<sup>125</sup>, L. Barranco Navarro<sup>47a,47b</sup>,  
F. Barreiro<sup>98</sup>, J. Barreiro Guimarães da Costa<sup>14a</sup>, U. Barron<sup>150</sup>, M.G. Barros Teixeira<sup>129a</sup>, S. Barsov<sup>37</sup>,  
F. Bartels<sup>63a</sup>, R. Bartoldus<sup>142</sup>, A.E. Barton<sup>90</sup>, P. Bartos<sup>28a</sup>, A. Basalae<sup>48</sup>, A. Basan<sup>99</sup>, M. Baselga<sup>49</sup>,  
I. Bashta<sup>76a,76b</sup>, A. Bassalat<sup>66,b</sup>, M.J. Basso<sup>154</sup>, C.R. Basson<sup>100</sup>, R.L. Bates<sup>59</sup>, S. Batlamous<sup>35e</sup>,  
J.R. Batley<sup>32</sup>, B. Batool<sup>140</sup>, M. Battaglia<sup>135</sup>, D. Battulga<sup>18</sup>, M. Baue<sup>74a,74b</sup>, P. Bauer<sup>24</sup>, A. Bayirli<sup>21a</sup>,  
J.B. Beacham<sup>51</sup>, T. Beau<sup>126</sup>, P.H. Beauchemin<sup>157</sup>, F. Becherer<sup>54</sup>, P. Bechtel<sup>24</sup>, H.P. Beck<sup>19,r</sup>, K. Becker<sup>166</sup>,  
A.J. Beddall<sup>21d</sup>, V.A. Bednyakov<sup>38</sup>, C.P. Bee<sup>144</sup>, L.J. Beamster<sup>15</sup>, T.A. Beermann<sup>36</sup>, M. Begalli<sup>81d,81d</sup>,  
M. Begel<sup>29</sup>, A. Behera<sup>144</sup>, J.K. Behr<sup>48</sup>, C. Beirao Da Cruz E Silva<sup>36</sup>, J.F. Beirer<sup>55,36</sup>, F. Beisiegel<sup>24</sup>,  
M. Belfkir<sup>158</sup>, G. Bella<sup>150</sup>, L. Bellagamba<sup>23b</sup>, A. Bellerive<sup>34</sup>, P. Bellos<sup>20</sup>, K. Beloborodov<sup>37</sup>,  
K. Belotskiy<sup>37</sup>, N.L. Belyaev<sup>37</sup>, D. Bencheekroun<sup>35a</sup>, F. Bendebba<sup>35a</sup>, Y. Benhammou<sup>150</sup>, D.P. Benjamin<sup>29</sup>,  
M. Benoit<sup>29</sup>, J.R. Bensinger<sup>26</sup>, S. Bentvelsen<sup>113</sup>, L. Beresford<sup>36</sup>, M. Beretta<sup>53</sup>, D. Berge<sup>18</sup>,  
E. Bergeaas Kuutmann<sup>160</sup>, N. Berger<sup>4</sup>, B. Bergmann<sup>131</sup>, J. Beringer<sup>17a</sup>, S. Berlendis<sup>7</sup>, G. Bernardi<sup>5</sup>,  
C. Bernius<sup>142</sup>, F.U. Bernlochner<sup>24</sup>, T. Berry<sup>94</sup>, P. Berta<sup>132</sup>, A. Berthold<sup>50</sup>, I.A. Bertram<sup>90</sup>, S. Bethke<sup>109</sup>,  
A. Betti<sup>74a,74b</sup>, A.J. Bevan<sup>93</sup>, M. Bhamjee<sup>33c</sup>, S. Bhatta<sup>144</sup>, D.S. Bhattacharya<sup>165</sup>, P. Bhattarai<sup>26</sup>,  
V.S. Bhopatkar<sup>120</sup>, R. Bi<sup>29,ah</sup>, R.M. Bianchi<sup>128</sup>, O. Biebel<sup>108</sup>, R. Bielski<sup>122</sup>, M. Biglietti<sup>76a</sup>,  
T.R.V. Billoud<sup>131</sup>, M. Bindi<sup>55</sup>, A. Bingul<sup>21b</sup>, C. Bini<sup>74a,74b</sup>, S. Biondi<sup>23b,23a</sup>, A. Biondini<sup>91</sup>,

C.J. Birch-sykes<sup>100</sup>, G.A. Bird<sup>20,133</sup>, M. Birman<sup>168</sup>, T. Bisanz<sup>36</sup>, E. Bisceglie<sup>43b,43a</sup>, D. Biswas<sup>169,m</sup>, A. Bitadze<sup>100</sup>, K. Bjørke<sup>124</sup>, I. Bloch<sup>48</sup>, C. Blocker<sup>26</sup>, A. Blue<sup>59</sup>, U. Blumenschein<sup>93</sup>, J. Blumenthal<sup>99</sup>, G.J. Bobbink<sup>113</sup>, V.S. Bobrovnikov<sup>37</sup>, M. Boehler<sup>54</sup>, D. Bogavac<sup>36</sup>, A.G. Bogdanchikov<sup>37</sup>, C. Bohm<sup>47a</sup>, V. Boisvert<sup>94</sup>, P. Bokan<sup>48</sup>, T. Bold<sup>184a</sup>, M. Bomben<sup>5</sup>, M. Bona<sup>93</sup>, M. Boonekamp<sup>134</sup>, C.D. Booth<sup>94</sup>, A.G. Borbély<sup>59</sup>, H.M. Borecka-Bielska<sup>107</sup>, L.S. Borgna<sup>95</sup>, G. Borissov<sup>90</sup>, D. Bortoletto<sup>125</sup>, D. Boscherini<sup>23b</sup>, M. Bosman<sup>13</sup>, J.D. Bossio Sola<sup>36</sup>, K. Bouaouda<sup>35a</sup>, N. Bouchhar<sup>162</sup>, J. Boudreau<sup>128</sup>, E.V. Bouhova-Thacker<sup>90</sup>, D. Boumediene<sup>40</sup>, R. Bouquet<sup>5</sup>, A. Boveia<sup>118</sup>, J. Boyd<sup>36</sup>, D. Boye<sup>29</sup>, I.R. Boyko<sup>38</sup>, J. Bracinek<sup>20</sup>, N. Brahimi<sup>62d</sup>, G. Brandt<sup>170</sup>, O. Brandt<sup>32</sup>, F. Braren<sup>48</sup>, B. Brau<sup>102</sup>, J.E. Brau<sup>122</sup>, K. Brendlinger<sup>48</sup>, R. Brenner<sup>168</sup>, L. Brenner<sup>113</sup>, R. Brenner<sup>160</sup>, S. Bressler<sup>168</sup>, B. Brickwedde<sup>99</sup>, D. Britton<sup>59</sup>, D. Britzger<sup>109</sup>, I. Brock<sup>24</sup>, G. Brooijmans<sup>41</sup>, W.K. Brooks<sup>136f</sup>, E. Brost<sup>29</sup>, T.L. Bruckler<sup>125</sup>, P.A. Bruckman de Renstrom<sup>85</sup>, B. Brüers<sup>48</sup>, D. Bruncko<sup>28b,\*</sup>, A. Bruni<sup>23b</sup>, G. Bruni<sup>23b</sup>, M. Bruschi<sup>23b</sup>, N. Brusino<sup>74a,74b</sup>, L. Bryngemark<sup>142</sup>, T. Buanes<sup>16</sup>, Q. Buat<sup>137</sup>, P. Buchholz<sup>140</sup>, A.G. Buckley<sup>59</sup>, I.A. Budagov<sup>38,\*</sup>, M.K. Bugge<sup>124</sup>, O. Bulekov<sup>37</sup>, B.A. Bullard<sup>61</sup>, S. Burdin<sup>91</sup>, C.D. Burgard<sup>48</sup>, A.M. Burger<sup>40</sup>, B. Burghgrave<sup>8</sup>, J.T.P. Burr<sup>32</sup>, C.D. Burton<sup>11</sup>, J.C. Burzynski<sup>141</sup>, E.L. Busch<sup>41</sup>, V. Büscher<sup>99</sup>, P.J. Bussey<sup>59</sup>, J.M. Butler<sup>25</sup>, C.M. Buttar<sup>59</sup>, J.M. Butterworth<sup>95</sup>, W. Buttinger<sup>133</sup>, C.J. Buxo Vazquez<sup>106</sup>, A.R. Buzykaev<sup>37</sup>, G. Cabras<sup>23b</sup>, S. Cabrera Urbán<sup>162</sup>, D. Caforio<sup>58</sup>, H. Cai<sup>128</sup>, Y. Cai<sup>14a,14d</sup>, V.M.M. Cairo<sup>36</sup>, O. Cakir<sup>3a</sup>, N. Calace<sup>36</sup>, P. Calafiura<sup>17a</sup>, G. Calderini<sup>126</sup>, P. Calfayan<sup>67</sup>, G. Callea<sup>59</sup>, L.P. Caloba<sup>81b</sup>, D. Calvet<sup>40</sup>, S. Calvet<sup>40</sup>, T.P. Calvet<sup>101</sup>, M. Calvetti<sup>73a,73b</sup>, R. Camacho Toro<sup>126</sup>, S. Camarda<sup>36</sup>, D. Camarero Munoz<sup>26</sup>, P. Camarri<sup>75a,75b</sup>, M.T. Camerlingo<sup>76a,76b</sup>, D. Cameron<sup>124</sup>, C. Camincher<sup>164</sup>, M. Campanelli<sup>95</sup>, A. Camplani<sup>42</sup>, V. Canale<sup>71a,71b</sup>, A. Canesse<sup>103</sup>, M. Cano Bret<sup>79</sup>, J. Cantero<sup>162</sup>, Y. Cao<sup>161</sup>, F. Capocasa<sup>26</sup>, M. Capua<sup>43b,43a</sup>, A. Carbone<sup>70a,70b</sup>, R. Cardarelli<sup>75a</sup>, J.C.J. Cardenas<sup>8</sup>, F. Cardillo<sup>162</sup>, T. Carli<sup>36</sup>, G. Carlino<sup>71a</sup>, J.I. Carlotto<sup>13</sup>, B.T. Carlson<sup>128,t</sup>, E.M. Carlson<sup>164,155a</sup>, L. Carminati<sup>70a,70b</sup>, M. Carnesale<sup>74a,74b</sup>, S. Caron<sup>112</sup>, E. Carquin<sup>136f</sup>, S. Carrá<sup>70a,70b</sup>, G. Carratta<sup>23b,23a</sup>, F. Carrio Argos<sup>33g</sup>, J.W.S. Carter<sup>154</sup>, T.M. Carter<sup>52</sup>, M.P. Casado<sup>13,j</sup>, A.F. Casha<sup>154</sup>, E.G. Castiglia<sup>171</sup>, F.L. Castillo<sup>63a</sup>, L. Castillo Garcia<sup>13</sup>, V. Castillo Gimenez<sup>162</sup>, N.F. Castro<sup>129a,129e</sup>, A. Catinaccio<sup>36</sup>, J.R. Catmore<sup>124</sup>, V. Cavaliere<sup>29</sup>, N. Cavalli<sup>23b,23a</sup>, V. Cavasinni<sup>73a,73b</sup>, E. Celebi<sup>21a</sup>, F. Celli<sup>125</sup>, M.S. Centonze<sup>69a,69b</sup>, K. Cerny<sup>121</sup>, A.S. Cerqueira<sup>81a</sup>, A. Cerri<sup>145</sup>, L. Cerrito<sup>75a,75b</sup>, F. Cerutti<sup>17a</sup>, A. Cervelli<sup>23b</sup>, S.A. Cetin<sup>21d</sup>, Z. Chadi<sup>35a</sup>, D. Chakraborty<sup>114</sup>, M. Chala<sup>129f</sup>, J. Chan<sup>169</sup>, W.Y. Chan<sup>152</sup>, J.D. Chapman<sup>32</sup>, B. Chargeishvili<sup>148b</sup>, D.G. Charlton<sup>20</sup>, T.P. Charman<sup>93</sup>, M. Chatterjee<sup>19</sup>, S. Chekanov<sup>6</sup>, S.V. Chekulaev<sup>155a</sup>, G.A. Chelkov<sup>38,a</sup>, A. Chen<sup>105</sup>, B. Chen<sup>150</sup>, B. Chen<sup>164</sup>, H. Chen<sup>14c</sup>, H. Chen<sup>29</sup>, J. Chen<sup>62c</sup>, J. Chen<sup>26</sup>, S. Chen<sup>152</sup>, S.J. Chen<sup>14c</sup>, X. Chen<sup>62c</sup>, X. Chen<sup>14b,ad</sup>, Y. Chen<sup>62a</sup>, C.L. Cheng<sup>169</sup>, H.C. Cheng<sup>64a</sup>, S. Cheong<sup>142</sup>, A. Cheplakov<sup>38</sup>, E. Cheremushkina<sup>48</sup>, E. Cherepanova<sup>113</sup>, R. Cherkaoui El Moursli<sup>35e</sup>, E. Cheu<sup>7</sup>, K. Cheung<sup>65</sup>, L. Chevalier<sup>134</sup>, V. Chiarella<sup>53</sup>, G. Chiarelli<sup>73a</sup>, N. Chiedde<sup>101</sup>, G. Chiodini<sup>69a</sup>, A.S. Chisholm<sup>20</sup>, A. Chitan<sup>27b</sup>, M. Chitishvili<sup>162</sup>, Y.H. Chiu<sup>164</sup>, M.V. Chizhov<sup>38</sup>, K. Choi<sup>11</sup>, A.R. Chomont<sup>74a,74b</sup>, Y. Chou<sup>102</sup>, E.Y.S. Chow<sup>113</sup>, T. Chowdhury<sup>33g</sup>, L.D. Christopher<sup>33g</sup>, K.L. Chu<sup>64a</sup>, M.C. Chu<sup>64a</sup>, X. Chu<sup>14a,14d</sup>, J. Chudoba<sup>130</sup>, J.J. Chwastowski<sup>85</sup>, D. Cieri<sup>109</sup>, K.M. Ciesla<sup>84a</sup>, V. Cindro<sup>92</sup>, A. Ciocio<sup>17a</sup>, F. Ciroto<sup>71a,71b</sup>, Z.H. Citron<sup>168,n</sup>, M. Citterio<sup>70a</sup>, D.A. Ciubotaru<sup>27b</sup>, B.M. Ciungu<sup>154</sup>, A. Clark<sup>56</sup>, P.J. Clark<sup>52</sup>, J.M. Clavijo Columbie<sup>48</sup>, S.E. Clawson<sup>100</sup>, C. Clement<sup>47a,47b</sup>, J. Clercx<sup>48</sup>, L. Clissa<sup>23b,23a</sup>, Y. Coadou<sup>101</sup>, M. Cobal<sup>168a,68c</sup>, A. Coccaro<sup>57b</sup>, R.F. Coelho Barrue<sup>129a</sup>, R. Coelho Lopes De Sa<sup>102</sup>, S. Coelli<sup>70a</sup>, H. Cohen<sup>150</sup>, A.E.C. Coimbra<sup>70a,70b</sup>, B. Cole<sup>41</sup>, J. Collot<sup>60</sup>, P. Conde Muiño<sup>129a,129g</sup>, M.P. Connell<sup>33c</sup>, S.H. Connell<sup>33c</sup>, I.A. Connelly<sup>59</sup>, E.I. Conroy<sup>125</sup>, F. Conventi<sup>71a,af</sup>, H.G. Cooke<sup>20</sup>, A.M. Cooper-Sarkar<sup>125</sup>, F. Cormier<sup>163</sup>, L.D. Corpe<sup>36</sup>, M. Corradi<sup>74a,74b</sup>, E.E. Corrigan<sup>97</sup>, F. Corriveau<sup>103,x</sup>, A. Cortes-Gonzalez<sup>18</sup>, M.J. Costa<sup>162</sup>, F. Costanza<sup>4</sup>, D. Costanzo<sup>138</sup>, B.M. Cote<sup>118</sup>, G. Cowan<sup>94</sup>, J.W. Cowley<sup>32</sup>, K. Cranmer<sup>116</sup>, S. Crépe-Renaudin<sup>60</sup>, F. Crescioli<sup>126</sup>, M. Cristinziani<sup>140</sup>, M. Cristoforetti<sup>77a,77b,d</sup>, V. Croft<sup>157</sup>, G. Crosetti<sup>43b,43a</sup>, A. Cueto<sup>36</sup>, T. Cuhadar Donszelmann<sup>159</sup>, H. Cui<sup>14a,14d</sup>, Z. Cui<sup>7</sup>, A.R. Cukierman<sup>142</sup>, W.R. Cunningham<sup>59</sup>, F. Curcio<sup>43b,43a</sup>, P. Czodrowski<sup>36</sup>, M.M. Czurylo<sup>63b</sup>, M.J. Da Cunha Sargedas De Sousa<sup>62a</sup>,



J.V. Da Fonseca Pinto<sup>81b</sup>, C. Da Via<sup>100</sup>, W. Dabrowski<sup>84a</sup>, T. Dado<sup>49</sup>, S. Dahbi<sup>33g</sup>, T. Dai<sup>105</sup>, C. Dallapiccola<sup>102</sup>, M. Dam<sup>42</sup>, G. D'amen<sup>29</sup>, V. D'Amico<sup>108</sup>, J. Damp<sup>99</sup>, J.R. Dandoy<sup>127</sup>, M.F. Daneri<sup>30</sup>, M. Danninger<sup>141</sup>, V. Dao<sup>36</sup>, G. Darbo<sup>57b</sup>, S. Darmora<sup>6</sup>, S.J. Das<sup>29</sup>, S. D'Auria<sup>70a,70b</sup>, C. David<sup>155b</sup>, T. Davidek<sup>132</sup>, D.R. Davis<sup>51</sup>, B. Davis-Purcell<sup>34</sup>, I. Dawson<sup>93</sup>, K. De<sup>8</sup>, R. De Asmundis<sup>71a</sup>, M. De Beurs<sup>113</sup>, N. De Biase<sup>48</sup>, S. De Castro<sup>23b,23a</sup>, N. De Groot<sup>112</sup>, P. de Jong<sup>113</sup>, H. De la Torre<sup>106</sup>, A. De Maria<sup>14c</sup>, A. De Salvo<sup>74a</sup>, U. De Sanctis<sup>75a,75b</sup>, A. De Santo<sup>145</sup>, J.B. De Vivie De Regie<sup>60</sup>, D.V. Dedovich<sup>38</sup>, J. Degens<sup>113</sup>, A.M. Deiana<sup>44</sup>, F. Del Corso<sup>23b,23a</sup>, J. Del Peso<sup>98</sup>, F. Del Rio<sup>63a</sup>, F. Deliot<sup>134</sup>, C.M. Delitzsch<sup>49</sup>, M. Della Pietra<sup>71a,71b</sup>, D. Della Volpe<sup>56</sup>, A. Dell'Acqua<sup>36</sup>, L. Dell'Asta<sup>70a,70b</sup>, M. Delmastro<sup>4</sup>, P.A. Delsart<sup>60</sup>, S. Demers<sup>171</sup>, M. Demichev<sup>38</sup>, S.P. Denisov<sup>37</sup>, L. D'Eramo<sup>114</sup>, D. Derendarz<sup>85</sup>, F. Derue<sup>126</sup>, P. Dervan<sup>91</sup>, K. Desch<sup>24</sup>, K. Dette<sup>154</sup>, C. Deutsch<sup>24</sup>, P.O. Deviveiros<sup>36</sup>, F.A. Di Bello<sup>57b,57a</sup>, A. Di Ciaccio<sup>75a,75b</sup>, L. Di Ciaccio<sup>4</sup>, A. Di Domenico<sup>74a,74b</sup>, C. Di Donato<sup>71a,71b</sup>, A. Di Girolamo<sup>36</sup>, G. Di Gregorio<sup>5</sup>, A. Di Luca<sup>77a,77b</sup>, B. Di Micco<sup>76a,76b</sup>, R. Di Nardo<sup>76a,76b</sup>, C. Diaconu<sup>101</sup>, F.A. Dias<sup>113</sup>, T. Dias Do Vale<sup>141</sup>, M.A. Diaz<sup>136a,136b</sup>, F.G. Diaz Capriles<sup>24</sup>, M. Didenko<sup>162</sup>, E.B. Diehl<sup>105</sup>, L. Diehl<sup>54</sup>, S. Díez Cornell<sup>48</sup>, C. Diez Pardos<sup>140</sup>, C. Dimitriadi<sup>24,160</sup>, A. Dimitrievska<sup>17a</sup>, W. Ding<sup>14b</sup>, J. Dingfelder<sup>24</sup>, I.M. Dinu<sup>27b</sup>, S.J. Dittmeier<sup>63b</sup>, F. Dittus<sup>36</sup>, F. Djama<sup>101</sup>, T. Djobava<sup>148b</sup>, J.I. Djuvslund<sup>16</sup>, C. Doglioni<sup>100,97</sup>, J. Dolejsi<sup>132</sup>, Z. Dolezal<sup>132</sup>, M. Donadelli<sup>81c</sup>, B. Dong<sup>62c</sup>, J. Donini<sup>40</sup>, A. D'Onofrio<sup>14c</sup>, M. D'Onofrio<sup>91</sup>, J. Dopke<sup>133</sup>, A. Doria<sup>71a</sup>, M.T. Dova<sup>89</sup>, A.T. Doyle<sup>59</sup>, M.A. Draguet<sup>125</sup>, E. Drechsler<sup>141</sup>, E. Dreyer<sup>168</sup>, I. Drivas-koulouris<sup>10</sup>, A.S. Drobac<sup>157</sup>, M. Drozdova<sup>56</sup>, D. Du<sup>62a</sup>, T.A. du Pree<sup>113</sup>, F. Dubinin<sup>37</sup>, M. Dubovsky<sup>28a</sup>, E. Duchovni<sup>168</sup>, G. Duckeck<sup>108</sup>, O.A. Ducu<sup>27b</sup>, D. Duda<sup>109</sup>, A. Dudarev<sup>36</sup>, M. D'uffizi<sup>100</sup>, L. Dufflot<sup>66</sup>, M. Dührssen<sup>36</sup>, C. Dülsen<sup>170</sup>, A.E. Dumitriu<sup>27b</sup>, M. Dunford<sup>63a</sup>, S. Dungs<sup>49</sup>, K. Dunne<sup>47a,47b</sup>, A. Duperrin<sup>101</sup>, H. Duran Yildiz<sup>3a</sup>, M. Düren<sup>58</sup>, A. Durglishvili<sup>148b</sup>, B.L. Dwyer<sup>114</sup>, G.I. Dyckes<sup>17a</sup>, M. Dyndal<sup>84a</sup>, S. Dysch<sup>100</sup>, B.S. Dziedzic<sup>85</sup>, Z.O. Earnshaw<sup>145</sup>, B. Eckerova<sup>28a</sup>, M.G. Eggleston<sup>51</sup>, E. Egidio Purcino De Souza<sup>81b</sup>, L.F. Ehrke<sup>56</sup>, G. Eigen<sup>16</sup>, K. Einsweiler<sup>17a</sup>, T. Ekelof<sup>160</sup>, P.A. Ekman<sup>97</sup>, Y. El Ghazali<sup>35b</sup>, H. El Jarrari<sup>35e,147</sup>, A. El Moussaouy<sup>35a</sup>, V. Ellajosyula<sup>160</sup>, M. Ellert<sup>160</sup>, F. Ellinghaus<sup>170</sup>, A.A. Elliot<sup>93</sup>, N. Ellis<sup>36</sup>, J. Elmsheuser<sup>29</sup>, M. Elsing<sup>36</sup>, D. Emeljanov<sup>133</sup>, A. Emerman<sup>41</sup>, Y. Enari<sup>152</sup>, I. Ene<sup>17a</sup>, S. Epari<sup>13</sup>, J. Erdmann<sup>49,ac</sup>, A. Ereditato<sup>19</sup>, P.A. Erland<sup>85</sup>, M. Errenst<sup>170</sup>, M. Escalier<sup>66</sup>, C. Escobar<sup>162</sup>, E. Etzion<sup>150</sup>, G. Evans<sup>129a</sup>, H. Evans<sup>67</sup>, M.O. Evans<sup>145</sup>, A. Ezhilov<sup>37</sup>, S. Ezzarqtouni<sup>35a</sup>, F. Fabbri<sup>59</sup>, L. Fabbri<sup>23b,23a</sup>, G. Facini<sup>95</sup>, V. Fadeyev<sup>135</sup>, R.M. Fakhrtudinov<sup>37</sup>, S. Falciano<sup>74a</sup>, P.J. Falke<sup>24</sup>, S. Falke<sup>36</sup>, J. Faltova<sup>132</sup>, Y. Fan<sup>14a</sup>, Y. Fang<sup>14a,14d</sup>, G. Fanourakis<sup>46</sup>, M. Fanti<sup>70a,70b</sup>, M. Faraj<sup>68a,68b</sup>, Z. Farazpay<sup>96</sup>, A. Farbin<sup>8</sup>, A. Farilla<sup>76a</sup>, T. Farooque<sup>106</sup>, S.M. Farrington<sup>52</sup>, F. Fassi<sup>35e</sup>, D. Fassouliotis<sup>9</sup>, M. Faucci Giannelli<sup>75a,75b</sup>, W.J. Fawcett<sup>32</sup>, L. Fayard<sup>66</sup>, P. Federicova<sup>130</sup>, O.L. Fedin<sup>37a</sup>, G. Fedotov<sup>37</sup>, M. Feickert<sup>169</sup>, L. Feligioni<sup>101</sup>, A. Fell<sup>138</sup>, D.E. Fellers<sup>122</sup>, C. Feng<sup>62b</sup>, M. Feng<sup>14b</sup>, Z. Feng<sup>113</sup>, M.J. Fenton<sup>159</sup>, A.B. Fenyuk<sup>37</sup>, L. Ferencz<sup>48</sup>, J. Ferrando<sup>48</sup>, A. Ferrari<sup>160</sup>, P. Ferrari<sup>113,112</sup>, R. Ferrari<sup>72a</sup>, D. Ferrere<sup>56</sup>, C. Ferretti<sup>105</sup>, F. Fiedler<sup>99</sup>, A. Filipčić<sup>92</sup>, E.K. Filmer<sup>1</sup>, F. Filthaut<sup>112</sup>, M.C.N. Fiolhais<sup>129a,129c,c</sup>, L. Fiorini<sup>162</sup>, F. Fischer<sup>140</sup>, W.C. Fisher<sup>106</sup>, T. Fitschen<sup>100</sup>, I. Fleck<sup>140</sup>, P. Fleischmann<sup>105</sup>, T. Flick<sup>170</sup>, L. Flores<sup>127</sup>, M. Flores<sup>33d</sup>, L.R. Flores Castillo<sup>64a</sup>, F.M. Follega<sup>77a,77b</sup>, N. Fomin<sup>16</sup>, J.H. Foo<sup>154</sup>, B.C. Forland<sup>67</sup>, A. Formica<sup>134</sup>, A.C. Forti<sup>100</sup>, E. Fortin<sup>101</sup>, A.W. Fortman<sup>61</sup>, M.G. Foti<sup>17a</sup>, L. Fountas<sup>9</sup>, D. Fournier<sup>66</sup>, H. Fox<sup>90</sup>, P. Francavilla<sup>73a,73b</sup>, S. Francescato<sup>61</sup>, S. Franchellucci<sup>56</sup>, M. Franchini<sup>23b,23a</sup>, S. Franchino<sup>63a</sup>, D. Francis<sup>36</sup>, L. Franco<sup>112</sup>, L. Franconi<sup>19</sup>, M. Franklin<sup>61</sup>, G. Frattari<sup>26</sup>, A.C. Freegard<sup>93</sup>, P.M. Freeman<sup>20</sup>, W.S. Freund<sup>81b</sup>, N. Fritzsche<sup>50</sup>, A. Froch<sup>54</sup>, D. Froidevaux<sup>36</sup>, J.A. Frost<sup>125</sup>, Y. Fu<sup>62a</sup>, M. Fujimoto<sup>117</sup>, E. Fullana Torregrosa<sup>162,\*</sup>, J. Fuster<sup>162</sup>, A. Gabrielli<sup>23b,23a</sup>, A. Gabrielli<sup>154</sup>, P. Gadow<sup>48</sup>, G. Gagliardi<sup>57b,57a</sup>, L.G. Gagnon<sup>17a</sup>, G.E. Gallardo<sup>125</sup>, E.J. Gallas<sup>125</sup>, B.J. Gallop<sup>133</sup>, R. Gamboa Goni<sup>93</sup>, K.K. Gan<sup>118</sup>, S. Ganguly<sup>152</sup>, J. Gao<sup>62a</sup>, Y. Gao<sup>52</sup>, F.M. Garay Walls<sup>136a,136b</sup>, B. Garcia<sup>29,ah</sup>, C. García<sup>162</sup>, J.E. García Navarro<sup>162</sup>, J.A. García Pascual<sup>14a</sup>, M. Garcia-Sciveres<sup>17a</sup>, R.W. Gardner<sup>39</sup>, D. Garg<sup>79</sup>, R.B. Garg<sup>142</sup>, S. Gargiulo<sup>54</sup>, C.A. Garner<sup>154</sup>, V. Garonne<sup>29</sup>, S.J. Gasiorowski<sup>137</sup>, P. Gaspar<sup>81b</sup>, G. Gaudio<sup>72a</sup>, V. Gautam<sup>13</sup>, P. Gauzzi<sup>74a,74b</sup>, I.L. Gavrilenko<sup>37</sup>, A. Gavrilyuk<sup>37</sup>, C. Gay<sup>163</sup>, G. Gaycken<sup>48</sup>,

E.N. Gazis<sup>10</sup>, A.A. Geanta<sup>27b,27e</sup>, C.M. Gee<sup>135</sup>, J. Geisen<sup>97</sup>, M. Geisen<sup>99</sup>, C. Gemme<sup>57b</sup>, M.H. Genest<sup>60</sup>, S. Gentile<sup>74a,74b</sup>, S. George<sup>94</sup>, W.F. George<sup>20</sup>, T. Geralis<sup>46</sup>, L.O. Gerlach<sup>55</sup>, P. Gessinger-Befurt<sup>36</sup>, M. Ghasemi Bostanabad<sup>164</sup>, M. Ghneimat<sup>140</sup>, K. Ghorbanian<sup>93</sup>, A. Ghosal<sup>140</sup>, A. Ghosh<sup>159</sup>, A. Ghosh<sup>7</sup>, B. Giacobbe<sup>23b</sup>, S. Giagu<sup>74a,74b</sup>, N. Giangiacomi<sup>154</sup>, P. Giannetti<sup>73a</sup>, A. Giannini<sup>62a</sup>, S.M. Gibson<sup>94</sup>, M. Gignac<sup>135</sup>, D.T. Gil<sup>84b</sup>, A.K. Gilbert<sup>84a</sup>, B.J. Gilbert<sup>41</sup>, D. Gillberg<sup>34</sup>, G. Gilles<sup>113</sup>, N.E.K. Gillwald<sup>48</sup>, L. Ginabat<sup>126</sup>, D.M. Gingrich<sup>2,ae</sup>, M.P. Giordani<sup>68a,68c</sup>, P.F. Giraud<sup>134</sup>, G. Giugliarelli<sup>68a,68c</sup>, D. Giugni<sup>70a</sup>, F. Giuli<sup>36</sup>, I. Gkialas<sup>9,k</sup>, L.K. Gladilin<sup>37</sup>, C. Glasman<sup>98</sup>, G.R. Gledhill<sup>122</sup>, M. Glisic<sup>122</sup>, I. Gnesi<sup>43b,g</sup>, Y. Go<sup>29,ah</sup>, M. Goblirsch-Kolb<sup>26</sup>, B. Gocke<sup>49</sup>, D. Godin<sup>107</sup>, S. Goldfarb<sup>104</sup>, T. Golling<sup>56</sup>, M.G.D. Gololo<sup>33g</sup>, D. Golubkov<sup>37</sup>, J.P. Gombas<sup>106</sup>, A. Gomes<sup>129a,129b</sup>, G. Gomes Da Silva<sup>140</sup>, A.J. Gomez Delegido<sup>162</sup>, R. Goncalves Gama<sup>55</sup>, R. Gonçalo<sup>129a,129c</sup>, G. Gonella<sup>122</sup>, L. Gonella<sup>20</sup>, A. Gongadze<sup>38</sup>, F. Gonnella<sup>20</sup>, J.L. Gonski<sup>41</sup>, R.Y. González Andana<sup>52</sup>, S. González de la Hoz<sup>162</sup>, S. Gonzalez Fernandez<sup>13</sup>, R. Gonzalez Lopez<sup>91</sup>, C. Gonzalez Renteria<sup>17a</sup>, R. Gonzalez Suarez<sup>160</sup>, S. Gonzalez-Sevilla<sup>56</sup>, G.R. Gonzalvo Rodriguez<sup>162</sup>, L. Goossens<sup>36</sup>, N.A. Gorasia<sup>20</sup>, P.A. Gorbounov<sup>37</sup>, B. Gorini<sup>36</sup>, E. Gorini<sup>69a,69b</sup>, A. Gorišek<sup>92</sup>, A.T. Goshaw<sup>51</sup>, M.I. Gostkin<sup>38</sup>, C.A. Gottardo<sup>36</sup>, M. Goughri<sup>35b</sup>, V. Goumarre<sup>48</sup>, A.G. Goussiou<sup>137</sup>, N. Govender<sup>33c</sup>, C. Goy<sup>4</sup>, I. Grabowska-Bold<sup>84a</sup>, K. Graham<sup>34</sup>, E. Gramstad<sup>124</sup>, S. Grancagnolo<sup>18</sup>, M. Grandi<sup>145</sup>, V. Gratchev<sup>37,\*</sup>, P.M. Gravila<sup>27f</sup>, F.G. Gravili<sup>69a,69b</sup>, H.M. Gray<sup>17a</sup>, M. Greco<sup>69a,69b</sup>, C. Grefe<sup>24</sup>, I.M. Gregor<sup>48</sup>, P. Grenier<sup>142</sup>, C. Grieco<sup>13</sup>, A.A. Grillo<sup>135</sup>, K. Grimm<sup>31,o</sup>, S. Grinstein<sup>13,v</sup>, J.-F. Grivaz<sup>66</sup>, E. Gross<sup>168</sup>, J. Grosse-Knetter<sup>55</sup>, C. Grud<sup>105</sup>, A. Grummer<sup>111</sup>, J.C. Grundy<sup>125</sup>, L. Guan<sup>105</sup>, W. Guan<sup>169</sup>, C. Gubbels<sup>163</sup>, J.G.R. Guerrero Rojas<sup>162</sup>, G. Guerrieri<sup>68a,68b</sup>, F. Guescini<sup>109</sup>, R. Gugel<sup>99</sup>, J.A.M. Guhit<sup>105</sup>, A. Guida<sup>48</sup>, T. Guillemain<sup>4</sup>, E. Guilloton<sup>166,133</sup>, S. Guindon<sup>36</sup>, F. Guo<sup>14a,14d</sup>, J. Guo<sup>62c</sup>, L. Guo<sup>66</sup>, Y. Guo<sup>105</sup>, R. Gupta<sup>48</sup>, S. Gurbuz<sup>24</sup>, S.S. Gurdasani<sup>54</sup>, G. Gustavino<sup>36</sup>, M. Guth<sup>56</sup>, P. Gutierrez<sup>119</sup>, L.F. Gutierrez Zagazeta<sup>127</sup>, C. Gutschow<sup>95</sup>, C. Guyot<sup>134</sup>, C. Gwenlan<sup>125</sup>, C.B. Gwilliam<sup>91</sup>, E.S. Haaland<sup>124</sup>, A. Haas<sup>116</sup>, M. Habedank<sup>48</sup>, C. Haber<sup>17a</sup>, H.K. Hadavand<sup>8</sup>, A. Hader<sup>99</sup>, S. Hadzic<sup>109</sup>, E.H. Haines<sup>95</sup>, M. Haleem<sup>165</sup>, J. Haley<sup>120</sup>, J.J. Hall<sup>138</sup>, G.D. Hallewell<sup>101</sup>, L. Halser<sup>19</sup>, K. Hamano<sup>164</sup>, H. Hamdaoui<sup>35e</sup>, M. Hamer<sup>24</sup>, G.N. Hamity<sup>52</sup>, J. Han<sup>62b</sup>, K. Han<sup>62a</sup>, L. Han<sup>14c</sup>, L. Han<sup>62a</sup>, S. Han<sup>17a</sup>, Y.F. Han<sup>154</sup>, K. Hanagaki<sup>82</sup>, M. Hance<sup>135</sup>, D.A. Hangal<sup>41,ab</sup>, H. Hanif<sup>141</sup>, M.D. Hank<sup>39</sup>, R. Hankache<sup>100</sup>, J.B. Hansen<sup>42</sup>, J.D. Hansen<sup>42</sup>, P.H. Hansen<sup>42</sup>, K. Hara<sup>156</sup>, D. Harada<sup>56</sup>, T. Harenberg<sup>170</sup>, S. Harkusha<sup>37</sup>, Y.T. Harris<sup>125</sup>, N.M. Harrison<sup>118</sup>, P.F. Harrison<sup>166</sup>, N.M. Hartman<sup>142</sup>, N.M. Hartmann<sup>108</sup>, Y. Hasegawa<sup>139</sup>, A. Hasib<sup>52</sup>, S. Haug<sup>19</sup>, R. Hauser<sup>106</sup>, M. Havranek<sup>131</sup>, C.M. Hawkes<sup>20</sup>, R.J. Hawkins<sup>36</sup>, S. Hayashida<sup>110</sup>, D. Hayden<sup>106</sup>, C. Hayes<sup>105</sup>, R.L. Hayes<sup>163</sup>, C.P. Hays<sup>125</sup>, J.M. Hays<sup>93</sup>, H.S. Hayward<sup>91</sup>, F. He<sup>62a</sup>, M. He<sup>14a,14d</sup>, Y. He<sup>153</sup>, Y. He<sup>126</sup>, M.P. Heath<sup>52</sup>, V. Hedberg<sup>97</sup>, A.L. Heggelund<sup>124</sup>, N.D. Hehir<sup>93</sup>, C. Heidegger<sup>54</sup>, K.K. Heidegger<sup>54</sup>, W.D. Heidorn<sup>80</sup>, J. Heilman<sup>34</sup>, S. Heim<sup>48</sup>, T. Heim<sup>17a</sup>, J.G. Heinlein<sup>127</sup>, J.J. Heinrich<sup>122</sup>, L. Heinrich<sup>109</sup>, J. Hejbal<sup>130</sup>, L. Helary<sup>48</sup>, A. Held<sup>169</sup>, S. Hellesund<sup>124</sup>, C.M. Helling<sup>163</sup>, S. Hellman<sup>47a,47b</sup>, C. Helsens<sup>36</sup>, R.C.W. Henderson<sup>90</sup>, L. Henkelmann<sup>32</sup>, A.M. Henriques Correia<sup>36</sup>, H. Herde<sup>97</sup>, Y. Hernández Jiménez<sup>144</sup>, L.M. Herrmann<sup>24</sup>, M.G. Herrmann<sup>108</sup>, T. Herrmann<sup>50</sup>, G. Herten<sup>54</sup>, R. Hertenberger<sup>108</sup>, L. Hervas<sup>36</sup>, N.P. Hessey<sup>155a</sup>, H. Hibi<sup>83</sup>, E. Higón-Rodríguez<sup>162</sup>, S.J. Hillier<sup>20</sup>, I. Hinchliffe<sup>17a</sup>, F. Hinterkeuser<sup>24</sup>, M. Hirose<sup>123</sup>, S. Hirose<sup>156</sup>, D. Hirschbuehl<sup>170</sup>, T.G. Hitchings<sup>100</sup>, B. Hiti<sup>92</sup>, J. Hobbs<sup>144</sup>, R. Hobincu<sup>27e</sup>, N. Hod<sup>168</sup>, M.C. Hodgkinson<sup>138</sup>, B.H. Hodgkinson<sup>32</sup>, A. Hoecker<sup>36</sup>, J. Hofer<sup>48</sup>, D. Hohn<sup>54</sup>, T. Holm<sup>24</sup>, M. Holzbock<sup>109</sup>, L.B.A.H. Hommels<sup>32</sup>, B.P. Honan<sup>100</sup>, J. Hong<sup>62c</sup>, T.M. Hong<sup>128</sup>, J.C. Honig<sup>54</sup>, A. Hönle<sup>109</sup>, B.H. Hooberman<sup>161</sup>, W.H. Hopkins<sup>6</sup>, Y. Horii<sup>110</sup>, S. Hou<sup>147</sup>, A.S. Howard<sup>92</sup>, J. Howarth<sup>59</sup>, J. Hoya<sup>6</sup>, M. Hrabovsky<sup>121</sup>, A. Hrynevich<sup>48</sup>, T. Hryn'ova<sup>4</sup>, P.J. Hsu<sup>65</sup>, S.-C. Hsu<sup>137</sup>, Q. Hu<sup>41</sup>, Y.F. Hu<sup>14a,14d,ag</sup>, D.P. Huang<sup>95</sup>, S. Huang<sup>64b</sup>, X. Huang<sup>14c</sup>, Y. Huang<sup>62a</sup>, Y. Huang<sup>14a</sup>, Z. Huang<sup>100</sup>, Z. Hubacek<sup>131</sup>, M. Huebner<sup>24</sup>, F. Huegging<sup>24</sup>, T.B. Huffman<sup>125</sup>, M. Huhtinen<sup>36</sup>, S.K. Huiberts<sup>16</sup>, R. Hulskén<sup>103</sup>, N. Huseynov<sup>12,a</sup>, J. Huston<sup>106</sup>, J. Huth<sup>61</sup>, R. Hyneman<sup>142</sup>, S. Hyrych<sup>28a</sup>, G. Iacobucci<sup>56</sup>, G. Iakovidis<sup>29</sup>, I. Ibragimov<sup>140</sup>, L. Iconomidou-Fayard<sup>66</sup>, P. Iengo<sup>71a,71b</sup>, R. Iguchi<sup>152</sup>, T. Iizawa<sup>56</sup>, Y. Ikegami<sup>82</sup>, A. Ilg<sup>19</sup>, N. Ilic<sup>154</sup>, H. Imam<sup>35a</sup>, T. Ingebretsen Carlson<sup>47a,47b</sup>, G. Introzzi<sup>72a,72b</sup>,

M. Iodice<sup>76a</sup>, V. Ippolito<sup>74a,74b</sup>, M. Ishino<sup>152</sup>, W. Islam<sup>169</sup>, C. Issever<sup>18,48</sup>, S. Istin<sup>21a,aj</sup>, H. Ito<sup>167</sup>,  
 J.M. Iturbe Ponce<sup>64a</sup>, R. Iuppa<sup>77a,77b</sup>, A. Ivina<sup>168</sup>, J.M. Izen<sup>45</sup>, V. Izzo<sup>71a</sup>, P. Jacka<sup>130,131</sup>, P. Jackson<sup>1</sup>,  
 R.M. Jacobs<sup>48</sup>, B.P. Jaeger<sup>141</sup>, C.S. Jagfeld<sup>108</sup>, G. Jäkel<sup>170</sup>, K. Jakobs<sup>54</sup>, T. Jakoubek<sup>168</sup>, J. Jamieson<sup>59</sup>,  
 K.W. Janas<sup>84a</sup>, G. Jarlskog<sup>97</sup>, A.E. Jaspán<sup>91</sup>, M. Javurkova<sup>102</sup>, F. Jeanneau<sup>134</sup>, L. Jeanty<sup>122</sup>,  
 J. Jejelava<sup>148a,aa</sup>, P. Jenni<sup>54,h</sup>, C.E. Jessiman<sup>34</sup>, S. Jézéquel<sup>4</sup>, J. Jia<sup>144</sup>, X. Jia<sup>61</sup>, X. Jia<sup>14a,14d</sup>, Z. Jia<sup>14c</sup>,  
 Y. Jiang<sup>62a</sup>, S. Jiggins<sup>52</sup>, J. Jimenez Pena<sup>109</sup>, S. Jin<sup>14c</sup>, A. Jinaru<sup>27b</sup>, O. Jinnouchi<sup>153</sup>, P. Johansson<sup>138</sup>,  
 K.A. Johns<sup>7</sup>, D.M. Jones<sup>32</sup>, E. Jones<sup>166</sup>, P. Jones<sup>32</sup>, R.W.L. Jones<sup>90</sup>, T.J. Jones<sup>91</sup>, R. Joshi<sup>118</sup>,  
 J. Jovicevic<sup>15</sup>, X. Ju<sup>17a</sup>, J.J. Junggeburth<sup>36</sup>, A. Juste Rozas<sup>13,v</sup>, S. Kabana<sup>136e</sup>, A. Kaczmarek<sup>85</sup>,  
 M. Kado<sup>74a,74b</sup>, H. Kagan<sup>118</sup>, M. Kagan<sup>142</sup>, A. Kahn<sup>41</sup>, A. Kahn<sup>127</sup>, C. Kahra<sup>99</sup>, T. Kaji<sup>167</sup>,  
 E. Kajomovitz<sup>149</sup>, N. Kakati<sup>168</sup>, C.W. Kalderon<sup>29</sup>, A. Kamenshchikov<sup>154</sup>, S. Kanayama<sup>153</sup>, N.J. Kang<sup>135</sup>,  
 Y. Kano<sup>110</sup>, D. Kar<sup>33g</sup>, K. Karava<sup>125</sup>, M.J. Kareem<sup>155b</sup>, E. Karentzos<sup>54</sup>, I. Karkanas<sup>151,f</sup>, S.N. Karpov<sup>38</sup>,  
 Z.M. Karpova<sup>38</sup>, V. Kartvelishvili<sup>90</sup>, A.N. Karyukhin<sup>37</sup>, E. Kasimi<sup>151,f</sup>, C. Kato<sup>62d</sup>, J. Katzy<sup>48</sup>, S. Kaur<sup>34</sup>,  
 K. Kawade<sup>139</sup>, K. Kawagoe<sup>88</sup>, T. Kawamoto<sup>134</sup>, G. Kawamura<sup>55</sup>, E.F. Kay<sup>164</sup>, F.I. Kaya<sup>157</sup>, S. Kazakos<sup>13</sup>,  
 V.F. Kazanin<sup>37</sup>, Y. Ke<sup>144</sup>, J.M. Keaveney<sup>33a</sup>, R. Keeler<sup>164</sup>, G.V. Kehris<sup>61</sup>, J.S. Keller<sup>34</sup>, A.S. Kelly<sup>95</sup>,  
 D. Kelsey<sup>145</sup>, J.J. Kempster<sup>20</sup>, K.E. Kennedy<sup>41</sup>, P.D. Kennedy<sup>99</sup>, O. Kepka<sup>130</sup>, B.P. Kerridge<sup>166</sup>,  
 S. Kersten<sup>170</sup>, B.P. Kerševan<sup>92</sup>, S. Keshri<sup>66</sup>, L. Keszeghova<sup>28a</sup>, S. Ketabchi Haghighat<sup>154</sup>, M. Khandoga<sup>126</sup>,  
 A. Khanov<sup>120</sup>, A.G. Kharlamov<sup>37</sup>, T. Kharlamova<sup>37</sup>, E.E. Khoda<sup>137</sup>, T.J. Khoo<sup>18</sup>, G. Khoraiuli<sup>165</sup>,  
 J. Khubua<sup>148b</sup>, Y.A.R. Khwaira<sup>66</sup>, M. Kiehn<sup>36</sup>, A. Kilgallon<sup>122</sup>, D.W. Kim<sup>47a,47b</sup>, E. Kim<sup>153</sup>, Y.K. Kim<sup>39</sup>,  
 N. Kimura<sup>95</sup>, A. Kirchhoff<sup>55</sup>, D. Kirchmeier<sup>50</sup>, C. Kirfel<sup>24</sup>, J. Kirk<sup>133</sup>, A.E. Kiryunin<sup>109</sup>, T. Kishimoto<sup>152</sup>,  
 D.P. Kisliuk<sup>154</sup>, C. Kitsaki<sup>10</sup>, O. Kivernyk<sup>24</sup>, M. Klassen<sup>63a</sup>, C. Klein<sup>34</sup>, L. Klein<sup>165</sup>, M.H. Klein<sup>105</sup>,  
 M. Klein<sup>91</sup>, S.B. Klein<sup>56</sup>, U. Klein<sup>91</sup>, P. Klimek<sup>36</sup>, A. Klimentov<sup>29</sup>, F. Klimpel<sup>109</sup>, T. Klingl<sup>24</sup>,  
 T. Klioutchnikova<sup>36</sup>, F.F. Klitzner<sup>108</sup>, P. Kluit<sup>113</sup>, S. Kluth<sup>109</sup>, E. Kneringer<sup>78</sup>, T.M. Knight<sup>154</sup>, A. Knue<sup>54</sup>,  
 D. Kobayashi<sup>88</sup>, R. Kobayashi<sup>86</sup>, M. Kocian<sup>142</sup>, P. Kodys<sup>132</sup>, D.M. Koeck<sup>145</sup>, P.T. Koenig<sup>24</sup>, T. Koffas<sup>34</sup>,  
 M. Kolb<sup>134</sup>, I. Koletsou<sup>4</sup>, T. Komarek<sup>121</sup>, K. Köneke<sup>54</sup>, A.X.Y. Kong<sup>1</sup>, T. Kono<sup>117</sup>, N. Konstantinidis<sup>95</sup>,  
 B. Konya<sup>97</sup>, R. Kopeliansky<sup>67</sup>, S. Koperny<sup>84a</sup>, K. Korcyl<sup>85</sup>, K. Kordas<sup>151,f</sup>, G. Koren<sup>150</sup>, A. Korn<sup>95</sup>,  
 S. Korn<sup>55</sup>, I. Korolkov<sup>13</sup>, N. Korotkova<sup>37</sup>, B. Kortman<sup>113</sup>, O. Kortner<sup>109</sup>, S. Kortner<sup>109</sup>, W.H. Kostecka<sup>114</sup>,  
 V.V. Kostyukhin<sup>140</sup>, A. Kotskechagia<sup>134</sup>, A. Kotwal<sup>51</sup>, A. Koulouris<sup>36</sup>,  
 A. Kourkoumeli-Charalampidi<sup>72a,72b</sup>, C. Kourkoumelis<sup>9</sup>, E. Kourlitis<sup>6</sup>, O. Kovanda<sup>145</sup>, R. Kowalewski<sup>164</sup>,  
 W. Kozanecki<sup>134</sup>, A.S. Kozhin<sup>37</sup>, V.A. Kramarenko<sup>37</sup>, G. Kramberger<sup>92</sup>, P. Kramer<sup>99</sup>, M.W. Krasny<sup>126</sup>,  
 A. Krasznahorkay<sup>36</sup>, J.A. Kremer<sup>99</sup>, T. Kresse<sup>50</sup>, J. Kretzschmar<sup>91</sup>, K. Kreul<sup>18</sup>, P. Krieger<sup>154</sup>, F. Krieter<sup>108</sup>,  
 S. Krishnamurthy<sup>102</sup>, A. Krishnan<sup>63b</sup>, M. Krivos<sup>132</sup>, K. Krizka<sup>17a</sup>, K. Kroeninger<sup>49</sup>, H. Kroha<sup>109</sup>,  
 J. Kroll<sup>130</sup>, J. Kroll<sup>127</sup>, K.S. Krowpman<sup>106</sup>, U. Kruchonak<sup>38</sup>, H. Krüger<sup>24</sup>, N. Krumnack<sup>80</sup>, M.C. Kruse<sup>51</sup>,  
 J.A. Krzysiak<sup>85</sup>, O. Kuchinskaia<sup>37</sup>, S. Kuday<sup>3a</sup>, D. Kuechler<sup>48</sup>, J.T. Kuechler<sup>48</sup>, S. Kuehn<sup>36</sup>, T. Kuhl<sup>48</sup>,  
 V. Kukhtin<sup>38</sup>, Y. Kulchitsky<sup>37,a</sup>, S. Kuleshov<sup>136d,136b</sup>, M. Kumar<sup>33g</sup>, N. Kumari<sup>101</sup>, A. Kupco<sup>130</sup>,  
 T. Kupfer<sup>49</sup>, A. Kupich<sup>37</sup>, O. Kuprash<sup>54</sup>, H. Kurashige<sup>83</sup>, L.L. Kurchaninov<sup>155a</sup>, Y.A. Kurochkin<sup>37</sup>,  
 A. Kurova<sup>37</sup>, M. Kuze<sup>153</sup>, A.K. Kvam<sup>102</sup>, J. Kvita<sup>121</sup>, T. Kwan<sup>103</sup>, K.W. Kwok<sup>64a</sup>, N.G. Kyriacou<sup>105</sup>,  
 L.A.O. Laatu<sup>101</sup>, C. Lacasta<sup>162</sup>, F. Lacava<sup>74a,74b</sup>, H. Lacker<sup>18</sup>, D. Lacour<sup>126</sup>, N.N. Lad<sup>95</sup>, E. Ladygin<sup>38</sup>,  
 B. Laforge<sup>126</sup>, T. Lagouri<sup>136e</sup>, S. Lai<sup>55</sup>, I.K. Lakomic<sup>84a</sup>, N. Lalloue<sup>60</sup>, J.E. Lambert<sup>119</sup>, S. Lammers<sup>67</sup>,  
 W. Lampl<sup>7</sup>, C. Lampoudis<sup>151,f</sup>, A.N. Lancaster<sup>114</sup>, E. Lançon<sup>29</sup>, U. Landgraf<sup>54</sup>, M.P.J. Landon<sup>93</sup>,  
 V.S. Lang<sup>54</sup>, R.J. Langenberg<sup>102</sup>, A.J. Lankford<sup>159</sup>, F. Lanni<sup>36</sup>, K. Lantzsch<sup>24</sup>, A. Lanza<sup>72a</sup>,  
 A. Lapertosa<sup>57b,57a</sup>, J.F. Laporte<sup>134</sup>, T. Lari<sup>70a</sup>, F. Lasagni Manghi<sup>23b</sup>, M. Lassnig<sup>36</sup>, V. Latonova<sup>130</sup>,  
 T.S. Lau<sup>64a</sup>, A. Laudrain<sup>99</sup>, A. Laurier<sup>34</sup>, S.D. Lawlor<sup>94</sup>, Z. Lawrence<sup>100</sup>, M. Lazzaroni<sup>70a,70b</sup>, B. Le<sup>100</sup>,  
 B. Leban<sup>92</sup>, A. Lebedev<sup>80</sup>, M. LeBlanc<sup>36</sup>, T. LeCompte<sup>6</sup>, F. Ledroit-Guillon<sup>60</sup>, A.C.A. Lee<sup>95</sup>, G.R. Lee<sup>16</sup>,  
 L. Lee<sup>61</sup>, S.C. Lee<sup>147</sup>, S. Lee<sup>47a,47b</sup>, T.F. Lee<sup>91</sup>, L.L. Leeuw<sup>33c</sup>, H.P. Lefebvre<sup>94</sup>, M. Lefebvre<sup>164</sup>,  
 C. Leggett<sup>17a</sup>, K. Lehmann<sup>141</sup>, G. Lehmann Miotto<sup>36</sup>, M. Leigh<sup>56</sup>, W.A. Leight<sup>102</sup>, A. Leisos<sup>151,u</sup>,  
 M.A.L. Leite<sup>81c</sup>, C.E. Leitgeb<sup>48</sup>, R. Leitner<sup>132</sup>, K.J.C. Leney<sup>44</sup>, T. Lenz<sup>24</sup>, S. Leone<sup>73a</sup>,  
 C. Leonidopoulos<sup>52</sup>, A. Leopold<sup>143</sup>, C. Leroy<sup>107</sup>, R. Les<sup>106</sup>, C.G. Lester<sup>32</sup>, M. Levchenko<sup>37</sup>, J. Levêque<sup>4</sup>,

D. Levin<sup>105</sup>, L.J. Levinson<sup>168</sup>, M.P. Lewicki<sup>85</sup>, D.J. Lewis<sup>4</sup>, A. Li<sup>5</sup>, B. Li<sup>14b</sup>, B. Li<sup>62b</sup>, C. Li<sup>62a</sup>, C-Q. Li<sup>62c</sup>,  
 H. Li<sup>62a</sup>, H. Li<sup>62b</sup>, H. Li<sup>14c</sup>, H. Li<sup>62b</sup>, J. Li<sup>62c</sup>, K. Li<sup>137</sup>, L. Li<sup>62c</sup>, M. Li<sup>14a,14d</sup>, Q.Y. Li<sup>62a</sup>, S. Li<sup>14a,14d</sup>,  
 S. Li<sup>62d,62c,e</sup>, T. Li<sup>62b</sup>, X. Li<sup>103</sup>, Z. Li<sup>62b</sup>, Z. Li<sup>125</sup>, Z. Li<sup>103</sup>, Z. Li<sup>91</sup>, Z. Li<sup>14a,14d</sup>, Z. Liang<sup>14a</sup>,  
 M. Liberatore<sup>48</sup>, B. Liberti<sup>75a</sup>, K. Lie<sup>64c</sup>, J. Lieber Marin<sup>81b</sup>, K. Lin<sup>106</sup>, R.A. Linck<sup>67</sup>, R.E. Lindley<sup>7</sup>,  
 J.H. Lindon<sup>2</sup>, A. Lins<sup>48</sup>, E. Lipeles<sup>127</sup>, A. Lipniacka<sup>16</sup>, A. Lister<sup>163</sup>, J.D. Little<sup>4</sup>, B. Liu<sup>14a</sup>, B.X. Liu<sup>141</sup>,  
 D. Liu<sup>62d,62c</sup>, J.B. Liu<sup>62a</sup>, J.K.K. Liu<sup>32</sup>, K. Liu<sup>62d,62c</sup>, M. Liu<sup>62a</sup>, M.Y. Liu<sup>62a</sup>, P. Liu<sup>14a</sup>, Q. Liu<sup>62d,137,62c</sup>,  
 X. Liu<sup>62a</sup>, Y. Liu<sup>48</sup>, Y. Liu<sup>14c,14d</sup>, Y.L. Liu<sup>105</sup>, Y.W. Liu<sup>62a</sup>, M. Livan<sup>72a,72b</sup>, J. Llorente Merino<sup>141</sup>,  
 S.L. Lloyd<sup>93</sup>, E.M. Lobodzinska<sup>48</sup>, P. Loch<sup>7</sup>, S. Loffredo<sup>75a,75b</sup>, T. Lohse<sup>18</sup>, K. Lohwasser<sup>138</sup>,  
 M. Lokajicek<sup>130</sup>, J.D. Long<sup>161</sup>, I. Longarini<sup>74a,74b</sup>, L. Longo<sup>69a,69b</sup>, R. Longo<sup>161</sup>, I. Lopez Paz<sup>36</sup>,  
 A. Lopez Solis<sup>48</sup>, J. Lorenz<sup>108</sup>, N. Lorenzo Martinez<sup>4</sup>, A.M. Lory<sup>108</sup>, A. Lösle<sup>54</sup>, X. Lou<sup>47a,47b</sup>,  
 X. Lou<sup>14a,14d</sup>, A. Lounis<sup>66</sup>, J. Love<sup>6</sup>, P.A. Love<sup>90</sup>, J.J. Lozano Bahilo<sup>162</sup>, G. Lu<sup>14a,14d</sup>, M. Lu<sup>79</sup>, S. Lu<sup>127</sup>,  
 Y.J. Lu<sup>65</sup>, H.J. Lubatti<sup>137</sup>, C. Luci<sup>74a,74b</sup>, F.L. Lucio Alves<sup>14c</sup>, A. Lucotte<sup>60</sup>, F. Luehring<sup>67</sup>, I. Luise<sup>144</sup>,  
 O. Lukianchuk<sup>66</sup>, O. Lundberg<sup>143</sup>, B. Lund-Jensen<sup>143</sup>, N.A. Luongo<sup>122</sup>, M.S. Lutz<sup>150</sup>, D. Lynn<sup>29</sup>,  
 H. Lyons<sup>91</sup>, R. Lysak<sup>130</sup>, E. Lytken<sup>97</sup>, F. Lyu<sup>14a</sup>, V. Lyubushkin<sup>38</sup>, T. Lyubushkina<sup>38</sup>, H. Ma<sup>29</sup>, L.L. Ma<sup>62b</sup>,  
 Y. Ma<sup>95</sup>, D.M. Mac Donell<sup>164</sup>, G. Maccarrone<sup>53</sup>, J.C. MacDonald<sup>138</sup>, R. Madar<sup>40</sup>, W.F. Mader<sup>50</sup>,  
 J. Maeda<sup>83</sup>, T. Maeno<sup>29</sup>, M. Maerker<sup>50</sup>, V. Magerl<sup>54</sup>, H. Maguire<sup>138</sup>, D.J. Mahon<sup>41</sup>, C. Maidantchik<sup>81b</sup>,  
 A. Maio<sup>129a,129b,129d</sup>, K. Maj<sup>84a</sup>, O. Majersky<sup>28a</sup>, S. Majewski<sup>122</sup>, N. Makovec<sup>66</sup>, V. Maksimovic<sup>15</sup>,  
 B. Malaescu<sup>126</sup>, Pa. Malecki<sup>85</sup>, V.P. Maleev<sup>37</sup>, F. Malek<sup>60</sup>, D. Malito<sup>43b,43a</sup>, U. Mallik<sup>79</sup>, C. Malone<sup>32</sup>,  
 S. Maltezos<sup>10</sup>, S. Malyukov<sup>38</sup>, J. Mamuzic<sup>13</sup>, G. Mancini<sup>53</sup>, G. Manco<sup>72a,72b</sup>, J.P. Mandalia<sup>93</sup>, I. Mandić<sup>92</sup>,  
 L. Manhaes de Andrade Filho<sup>81a</sup>, I.M. Maniatis<sup>151,f</sup>, M. Manisha<sup>134</sup>, J. Manjarres Ramos<sup>50</sup>,  
 D.C. Mankad<sup>168</sup>, A. Mann<sup>108</sup>, B. Mansoulie<sup>134</sup>, S. Manzoni<sup>36</sup>, A. Marantis<sup>151</sup>, G. Marchiori<sup>5</sup>,  
 M. Marcisovsky<sup>130</sup>, L. Marcoccia<sup>75a,75b</sup>, C. Marcon<sup>70a,70b</sup>, M. Marinescu<sup>20</sup>, M. Marjanovic<sup>119</sup>,  
 E.J. Marshall<sup>90</sup>, Z. Marshall<sup>17a</sup>, S. Marti-Garcia<sup>162</sup>, T.A. Martin<sup>166</sup>, V.J. Martin<sup>52</sup>, B. Martin dit Latour<sup>16</sup>,  
 L. Martinelli<sup>74a,74b</sup>, M. Martinez<sup>13,v</sup>, P. Martinez Agullo<sup>162</sup>, V.I. Martinez Outschoorn<sup>102</sup>,  
 P. Martinez Suarez<sup>13</sup>, S. Martin-Haugh<sup>133</sup>, V.S. Martoiu<sup>27b</sup>, A.C. Martyniuk<sup>95</sup>, A. Marzin<sup>36</sup>,  
 S.R. Maschek<sup>109</sup>, L. Masetti<sup>99</sup>, T. Mashimo<sup>152</sup>, J. Masik<sup>100</sup>, A.L. Maslennikov<sup>37</sup>, L. Massa<sup>23b</sup>,  
 P. Massarotti<sup>71a,71b</sup>, P. Mastrandrea<sup>73a,73b</sup>, A. Mastroberardino<sup>43b,43a</sup>, T. Masubuchi<sup>152</sup>, T. Mathisen<sup>160</sup>,  
 N. Matsuzawa<sup>152</sup>, J. Maurer<sup>27b</sup>, B. Maček<sup>92</sup>, D.A. Maximov<sup>37</sup>, R. Mazini<sup>147</sup>, I. Maznas<sup>151,f</sup>, M. Mazza<sup>106</sup>,  
 S.M. Mazza<sup>135</sup>, C. Mc Ginn<sup>29,ah</sup>, J.P. Mc Gowan<sup>103</sup>, S.P. Mc Kee<sup>105</sup>, W.P. McCormack<sup>17a</sup>,  
 E.F. McDonald<sup>104</sup>, A.E. McDougall<sup>113</sup>, J.A. Mcfayden<sup>145</sup>, G. Mchedlidze<sup>148b</sup>, R.P. Mckenzie<sup>33g</sup>,  
 T.C. McLachlan<sup>48</sup>, D.J. McLaughlin<sup>95</sup>, K.D. McLean<sup>164</sup>, S.J. McMahon<sup>133</sup>, P.C. McNamara<sup>104</sup>,  
 C.M. Mcpartland<sup>91</sup>, R.A. McPherson<sup>164,x</sup>, T. Megy<sup>40</sup>, S. Mehlhase<sup>108</sup>, A. Mehta<sup>91</sup>, B. Meirose<sup>45</sup>,  
 D. Melini<sup>149</sup>, B.R. Mellado Garcia<sup>33g</sup>, A.H. Melo<sup>55</sup>, F. Meloni<sup>48</sup>, E.D. Mendes Gouveia<sup>129a</sup>,  
 A.M. Mendes Jacques Da Costa<sup>20</sup>, H.Y. Meng<sup>154</sup>, L. Meng<sup>90</sup>, S. Menke<sup>109</sup>, M. Mentink<sup>36</sup>, E. Meoni<sup>43b,43a</sup>,  
 C. Merlassino<sup>125</sup>, L. Merola<sup>71a,71b</sup>, C. Meroni<sup>70a</sup>, G. Merz<sup>105</sup>, O. Meshkov<sup>37</sup>, J.K.R. Meshreki<sup>140</sup>,  
 J. Metcalfe<sup>6</sup>, A.S. Mete<sup>6</sup>, C. Meyer<sup>67</sup>, J-P. Meyer<sup>134</sup>, M. Michetti<sup>18</sup>, R.P. Middleton<sup>133</sup>, L. Mijović<sup>52</sup>,  
 G. Mikenberg<sup>168</sup>, M. Mikesikova<sup>130</sup>, M. Mikuž<sup>92</sup>, H. Mildner<sup>138</sup>, A. Milic<sup>36</sup>, C.D. Milke<sup>44</sup>, D.W. Miller<sup>39</sup>,  
 L.S. Miller<sup>34</sup>, A. Milov<sup>168</sup>, D.A. Milstead<sup>47a,47b</sup>, T. Min<sup>14c</sup>, A.A. Minaenko<sup>37</sup>, I.A. Minashvili<sup>148b</sup>,  
 L. Mince<sup>59</sup>, A.I. Mincer<sup>116</sup>, B. Mindur<sup>84a</sup>, M. Mineev<sup>38</sup>, Y. Mino<sup>86</sup>, L.M. Mir<sup>13</sup>, M. Miralles Lopez<sup>162</sup>,  
 M. Mironova<sup>125</sup>, M.C. Missio<sup>112</sup>, T. Mitani<sup>167</sup>, A. Mitra<sup>166</sup>, V.A. Mitsou<sup>162</sup>, O. Miu<sup>154</sup>, P.S. Miyagawa<sup>93</sup>,  
 Y. Miyazaki<sup>88</sup>, A. Mizukami<sup>82</sup>, J.U. Mjörnmark<sup>97</sup>, T. Mkrtychyan<sup>63a</sup>, T. Mlinarevic<sup>95</sup>, M. Mlynarikova<sup>36</sup>,  
 T. Moa<sup>47a,47b</sup>, S. Mobius<sup>55</sup>, K. Mochizuki<sup>107</sup>, P. Moder<sup>48</sup>, P. Mogg<sup>108</sup>, A.F. Mohammed<sup>14a,14d</sup>,  
 S. Mohapatra<sup>41</sup>, G. Mokgatitswane<sup>33g</sup>, B. Mondal<sup>140</sup>, S. Mondal<sup>131</sup>, K. Mönig<sup>48</sup>, E. Monnier<sup>101</sup>,  
 L. Monsonis Romero<sup>162</sup>, J. Montejo Berlingen<sup>36</sup>, M. Montella<sup>118</sup>, F. Monticelli<sup>89</sup>, N. Morange<sup>66</sup>,  
 A.L. Moreira De Carvalho<sup>129a</sup>, M. Moreno Llácer<sup>162</sup>, C. Moreno Martinez<sup>56</sup>, P. Morettini<sup>57b</sup>,  
 S. Morgenstern<sup>166</sup>, M. Morii<sup>61</sup>, M. Morinaga<sup>152</sup>, A.K. Morley<sup>36</sup>, F. Morodei<sup>74a,74b</sup>, L. Morvaj<sup>36</sup>,  
 P. Moschovakos<sup>36</sup>, B. Moser<sup>36</sup>, M. Mosidze<sup>148b</sup>, T. Moskalets<sup>54</sup>, P. Moskvitina<sup>112</sup>, J. Moss<sup>31,p</sup>,

E.J.W. Moyse<sup>102</sup>, O. Mtintsilana<sup>33g</sup>, S. Muanza<sup>101</sup>, J. Mueller<sup>128</sup>, D. Muenstermann<sup>90</sup>, R. Müller<sup>19</sup>, G.A. Mullier<sup>160</sup>, J.J. Mullin<sup>127</sup>, D.P. Mungo<sup>154</sup>, J.L. Munoz Martinez<sup>13</sup>, D. Munoz Perez<sup>162</sup>, F.J. Munoz Sanchez<sup>100</sup>, M. Murin<sup>100</sup>, W.J. Murray<sup>166,133</sup>, A. Murrone<sup>70a,70b</sup>, J.M. Muse<sup>119</sup>, M. Muškinja<sup>17a</sup>, C. Mwewa<sup>29</sup>, A.G. Myagkov<sup>37,a</sup>, A.J. Myers<sup>8</sup>, A.A. Myers<sup>128</sup>, G. Myers<sup>67</sup>, M. Myska<sup>131</sup>, B.P. Nachman<sup>17a</sup>, O. Nackenhorst<sup>49</sup>, A. Nag<sup>50</sup>, K. Nagai<sup>125</sup>, K. Nagano<sup>82</sup>, J.L. Nagle<sup>29,ah</sup>, E. Nagy<sup>101</sup>, A.M. Nairz<sup>36</sup>, Y. Nakahama<sup>82</sup>, K. Nakamura<sup>82</sup>, H. Nanjo<sup>123</sup>, R. Narayan<sup>44</sup>, E.A. Narayanan<sup>111</sup>, I. Naryshkin<sup>37</sup>, M. Naseri<sup>34</sup>, C. Nass<sup>24</sup>, G. Navarro<sup>22a</sup>, J. Navarro-Gonzalez<sup>162</sup>, R. Nayak<sup>150</sup>, A. Nayaz<sup>18</sup>, P.Y. Nechaeva<sup>37</sup>, F. Nechansky<sup>48</sup>, L. Nedic<sup>125</sup>, T.J. Neep<sup>20</sup>, A. Negri<sup>72a,72b</sup>, M. Negrini<sup>23b</sup>, C. Nellist<sup>112</sup>, C. Nelson<sup>103</sup>, K. Nelson<sup>105</sup>, S. Nemecek<sup>130</sup>, M. Nessi<sup>36,i</sup>, M.S. Neubauer<sup>161</sup>, F. Neuhaus<sup>99</sup>, J. Neundorff<sup>48</sup>, R. Newhouse<sup>163</sup>, P.R. Newman<sup>20</sup>, C.W. Ng<sup>128</sup>, Y.S. Ng<sup>18</sup>, Y.W.Y. Ng<sup>48</sup>, B. Ngair<sup>35e</sup>, H.D.N. Nguyen<sup>107</sup>, R.B. Nickerson<sup>125</sup>, R. Nicolaidou<sup>134</sup>, J. Nielsen<sup>135</sup>, M. Niemeyer<sup>55</sup>, N. Nikiforou<sup>36</sup>, V. Nikolaenko<sup>37,a</sup>, I. Nikolic-Audit<sup>126</sup>, K. Nikolopoulos<sup>20</sup>, P. Nilsson<sup>29</sup>, H.R. Nindhito<sup>56</sup>, A. Nisati<sup>74a</sup>, N. Nishu<sup>2</sup>, R. Nisius<sup>109</sup>, J-E. Nitschke<sup>50</sup>, E.K. Nkadimeng<sup>33g</sup>, S.J. Noacco Rosende<sup>89</sup>, T. Nobe<sup>152</sup>, D.L. Noel<sup>32</sup>, Y. Noguchi<sup>86</sup>, T. Nommensen<sup>146</sup>, M.A. Nomura<sup>29</sup>, M.B. Norfolk<sup>138</sup>, R.R.B. Norisam<sup>95</sup>, B.J. Norman<sup>34</sup>, J. Novak<sup>92</sup>, T. Novak<sup>48</sup>, O. Novgorodova<sup>50</sup>, L. Novotny<sup>131</sup>, R. Novotny<sup>111</sup>, L. Nozka<sup>121</sup>, K. Ntekas<sup>159</sup>, N.M.J. Nunes De Moura Junior<sup>81b</sup>, E. Nurse<sup>95</sup>, F.G. Oakham<sup>34,ae</sup>, J. Ocariz<sup>126</sup>, A. Ochi<sup>83</sup>, I. Ochoa<sup>129a</sup>, S. Oerdek<sup>160</sup>, A. Ogrodnik<sup>84a</sup>, A. Oh<sup>100</sup>, C.C. Ohm<sup>143</sup>, H. Oide<sup>82</sup>, R. Oishi<sup>152</sup>, M.L. Ojeda<sup>48</sup>, Y. Okazaki<sup>86</sup>, M.W. O'Keefe<sup>91</sup>, Y. Okumura<sup>152</sup>, A. Olariu<sup>27b</sup>, L.F. Oleiro Seabra<sup>129a</sup>, S.A. Olivares Pino<sup>136e</sup>, D. Oliveira Damazio<sup>29</sup>, D. Oliveira Goncalves<sup>81a</sup>, J.L. Oliver<sup>159</sup>, M.J.R. Olsson<sup>159</sup>, A. Olszewski<sup>85</sup>, J. Olszowska<sup>85,\*</sup>, Ö.O. Öncel<sup>54</sup>, D.C. O'Neil<sup>141</sup>, A.P. O'Neill<sup>19</sup>, A. Onofre<sup>129a,129e</sup>, P.U.E. Onyisi<sup>11</sup>, M.J. Oreglia<sup>39</sup>, G.E. Orellana<sup>89</sup>, D. Orestano<sup>76a,76b</sup>, N. Orlando<sup>13</sup>, R.S. Orr<sup>154</sup>, V. O'Shea<sup>59</sup>, R. Ospanov<sup>62a</sup>, G. Otero y Garzon<sup>30</sup>, H. Otono<sup>88</sup>, P.S. Ott<sup>63a</sup>, G.J. Ottino<sup>17a</sup>, M. Ouchrif<sup>35d</sup>, J. Ouellette<sup>29,ah</sup>, F. Ould-Saada<sup>124</sup>, M. Owen<sup>59</sup>, R.E. Owen<sup>133</sup>, K.Y. Oyulmaz<sup>21a</sup>, V.E. Ozcan<sup>21a</sup>, N. Ozturk<sup>8</sup>, S. Ozturk<sup>21d</sup>, J. Pacalt<sup>121</sup>, H.A. Pacey<sup>32</sup>, K. Pachal<sup>51</sup>, A. Pacheco Pages<sup>13</sup>, C. Padilla Aranda<sup>13</sup>, G. Padovano<sup>74a,74b</sup>, S. Pagan Griso<sup>17a</sup>, G. Palacino<sup>67</sup>, A. Palazzo<sup>69a,69b</sup>, S. Palestini<sup>36</sup>, M. Palka<sup>84b</sup>, J. Pan<sup>171</sup>, T. Pan<sup>64a</sup>, D.K. Panchal<sup>11</sup>, C.E. Pandini<sup>113</sup>, J.G. Panduro Vazquez<sup>94</sup>, H. Pang<sup>14b</sup>, P. Pani<sup>48</sup>, G. Panizzo<sup>68a,68c</sup>, L. Paolozzi<sup>56</sup>, C. Papadatos<sup>107</sup>, S. Parajuli<sup>44</sup>, A. Paramonov<sup>6</sup>, C. Paraskevopoulos<sup>10</sup>, D. Paredes Hernandez<sup>64b</sup>, T.H. Park<sup>154</sup>, M.A. Parker<sup>32</sup>, F. Parodi<sup>57b,57a</sup>, E.W. Parrish<sup>114</sup>, V.A. Parrish<sup>52</sup>, J.A. Parsons<sup>41</sup>, U. Parzefall<sup>54</sup>, B. Pascual Dias<sup>107</sup>, L. Pascual Dominguez<sup>150</sup>, V.R. Pascuzzi<sup>17a</sup>, F. Pasquali<sup>113</sup>, E. Pasqualucci<sup>74a</sup>, S. Passaggio<sup>57b</sup>, F. Pastore<sup>94</sup>, P. Pasuwan<sup>47a,47b</sup>, P. Patel<sup>85</sup>, J.R. Pater<sup>100</sup>, T. Pauly<sup>36</sup>, J. Pearkes<sup>142</sup>, M. Pedersen<sup>124</sup>, R. Pedro<sup>129a</sup>, S.V. Peleganchuk<sup>37</sup>, O. Penc<sup>36</sup>, E.A. Pender<sup>52</sup>, C. Peng<sup>64b</sup>, H. Peng<sup>62a</sup>, K.E. Pensi<sup>108</sup>, M. Penzin<sup>37</sup>, B.S. Peralva<sup>81d,81d</sup>, A.P. Pereira Peixoto<sup>60</sup>, L. Pereira Sanchez<sup>47a,47b</sup>, D.V. Perepelitsa<sup>29,ah</sup>, E. Perez Codina<sup>155a</sup>, M. Perganti<sup>10</sup>, L. Perini<sup>70a,70b,\*</sup>, H. Pernegger<sup>36</sup>, S. Perrella<sup>36</sup>, A. Perrevoort<sup>112</sup>, O. Perrin<sup>40</sup>, K. Peters<sup>48</sup>, R.F.Y. Peters<sup>100</sup>, B.A. Petersen<sup>36</sup>, T.C. Petersen<sup>42</sup>, E. Petit<sup>101</sup>, V. Petousis<sup>131</sup>, C. Petridou<sup>151,f</sup>, A. Petrukhin<sup>140</sup>, M. Pettee<sup>17a</sup>, N.E. Pettersson<sup>36</sup>, A. Petukhov<sup>37</sup>, K. Petukhova<sup>132</sup>, A. Peyaud<sup>134</sup>, R. Pezoa<sup>136f</sup>, L. Pezzotti<sup>36</sup>, G. Pezzullo<sup>171</sup>, T.M. Pham<sup>169</sup>, T. Pham<sup>104</sup>, P.W. Phillips<sup>133</sup>, M.W. Phipps<sup>161</sup>, G. Piacquadio<sup>144</sup>, E. Pianori<sup>17a</sup>, F. Piazza<sup>70a,70b</sup>, R. Piegai<sup>30</sup>, D. Pietreanu<sup>27b</sup>, A.D. Pilkington<sup>100</sup>, M. Pinamonti<sup>68a,68c</sup>, J.L. Pinfeld<sup>2</sup>, B.C. Pinheiro Pereira<sup>129a</sup>, C. Pitman Donaldson<sup>95</sup>, D.A. Pizzi<sup>34</sup>, L. Pizzimento<sup>75a,75b</sup>, A. Pizzini<sup>113</sup>, M.-A. Pleier<sup>29</sup>, V. Plesanovs<sup>54</sup>, V. Pleskot<sup>132</sup>, E. Plotnikova<sup>38</sup>, G. Poddar<sup>4</sup>, R. Poettgen<sup>97</sup>, L. Poggioli<sup>126</sup>, I. Pogrebnyak<sup>106</sup>, D. Pohl<sup>24</sup>, I. Pokharel<sup>55</sup>, S. Polacek<sup>132</sup>, G. Polesello<sup>72a</sup>, A. Poley<sup>141,155a</sup>, R. Polifka<sup>131</sup>, A. Polini<sup>23b</sup>, C.S. Pollard<sup>125</sup>, Z.B. Pollock<sup>118</sup>, V. Polychronakos<sup>29</sup>, E. Pompa Pacchi<sup>74a,74b</sup>, D. Ponomarenko<sup>37</sup>, L. Pontecorvo<sup>36</sup>, S. Popa<sup>27a</sup>, G.A. Popeneciu<sup>27d</sup>, D.M. Portillo Quintero<sup>155a</sup>, S. Pospisil<sup>131</sup>, P. Postolache<sup>27c</sup>, K. Potamianos<sup>125</sup>, I.N. Potrap<sup>38</sup>, C.J. Potter<sup>32</sup>, H. Potti<sup>1</sup>, T. Poulsen<sup>48</sup>, J. Poveda<sup>162</sup>, M.E. Pozo Astigarraga<sup>36</sup>, A. Prades Ibanez<sup>162</sup>, M.M. Prapa<sup>46</sup>, J. Pretel<sup>54</sup>, D. Price<sup>100</sup>, M. Primavera<sup>69a</sup>, M.A. Principe Martin<sup>98</sup>, R. Privara<sup>121</sup>, M.L. Proffitt<sup>137</sup>, N. Proklova<sup>127</sup>, K. Prokofiev<sup>64c</sup>, G. Proto<sup>75a,75b</sup>, S. Protopopescu<sup>29</sup>, J. Proudfoot<sup>6</sup>, M. Przybycien<sup>84a</sup>, J.E. Puddefoot<sup>138</sup>, D. Pudzha<sup>37</sup>,

P. Puzo<sup>66</sup>, D. Pyatiizbyantseva<sup>37</sup>, J. Qian<sup>105</sup>, D. Qichen<sup>100</sup>, Y. Qin<sup>100</sup>, T. Qiu<sup>93</sup>, A. Quadt<sup>55</sup>,  
 M. Queitsch-Maitland<sup>100</sup>, G. Quetant<sup>56</sup>, G. Rabanal Bolanos<sup>61</sup>, D. Rafanoharana<sup>54</sup>, F. Ragusa<sup>70a,70b</sup>,  
 J.L. Rainbolt<sup>39</sup>, J.A. Raine<sup>56</sup>, S. Rajagopalan<sup>29</sup>, E. Ramakoti<sup>37</sup>, K. Ran<sup>48,14d</sup>, N.P. Rapheeha<sup>33g</sup>,  
 V. Raskina<sup>126</sup>, D.F. Rassloff<sup>63a</sup>, S. Rave<sup>99</sup>, B. Ravina<sup>55</sup>, I. Ravinovich<sup>168</sup>, M. Raymond<sup>36</sup>, A.L. Read<sup>124</sup>,  
 N.P. Readioff<sup>138</sup>, D.M. Rebuzzi<sup>72a,72b</sup>, G. Redlinger<sup>29</sup>, K. Reeves<sup>45</sup>, J.A. Reidelsturz<sup>170</sup>, D. Reikher<sup>150</sup>,  
 A. Reiss<sup>99</sup>, A. Rej<sup>140</sup>, C. Rembser<sup>36</sup>, A. Renardi<sup>48</sup>, M. Renda<sup>27b</sup>, M.B. Rendel<sup>109</sup>, F. Renner<sup>48</sup>,  
 A.G. Rennie<sup>59</sup>, S. Resconi<sup>70a</sup>, M. Ressegotti<sup>57b,57a</sup>, E.D. Resseguie<sup>17a</sup>, S. Rettie<sup>36</sup>, J.G. Reyes Rivera<sup>106</sup>,  
 B. Reynolds<sup>118</sup>, E. Reynolds<sup>17a</sup>, M. Rezaei Estabragh<sup>170</sup>, O.L. Rezanova<sup>37</sup>, P. Reznicek<sup>132</sup>, E. Ricci<sup>77a,77b</sup>,  
 R. Richter<sup>109</sup>, S. Richter<sup>47a,47b</sup>, E. Richter-Was<sup>84b</sup>, M. Ridel<sup>126</sup>, P. Rieck<sup>116</sup>, P. Riedler<sup>36</sup>,  
 M. Rijssenbeek<sup>144</sup>, A. Rimoldi<sup>72a,72b</sup>, M. Rimoldi<sup>48</sup>, L. Rinaldi<sup>23b,23a</sup>, T.T. Rinn<sup>29</sup>, M.P. Rinnagel<sup>108</sup>,  
 G. Ripellino<sup>143</sup>, I. Riu<sup>13</sup>, P. Rivadeneira<sup>48</sup>, J.C. Rivera Vergara<sup>164</sup>, F. Rizatdinova<sup>120</sup>, E. Rizvi<sup>93</sup>,  
 C. Rizzi<sup>56</sup>, B.A. Roberts<sup>166</sup>, B.R. Roberts<sup>17a</sup>, S.H. Robertson<sup>103,x</sup>, M. Robin<sup>48</sup>, D. Robinson<sup>32</sup>,  
 C.M. Robles Gajardo<sup>136f</sup>, M. Robles Manzano<sup>99</sup>, A. Robson<sup>59</sup>, A. Rocchi<sup>75a,75b</sup>, C. Roda<sup>73a,73b</sup>,  
 S. Rodriguez Bosca<sup>63a</sup>, Y. Rodriguez Garcia<sup>22a</sup>, A. Rodriguez Rodriguez<sup>54</sup>, A.M. Rodríguez Vera<sup>155b</sup>,  
 S. Roe<sup>36</sup>, J.T. Roemer<sup>159</sup>, A.R. Roepe-Gier<sup>119</sup>, J. Roggel<sup>170</sup>, O. Røhne<sup>124</sup>, R.A. Rojas<sup>164</sup>, B. Roland<sup>54</sup>,  
 C.P.A. Roland<sup>67</sup>, J. Roloff<sup>29</sup>, A. Romaniouk<sup>37</sup>, E. Romano<sup>72a,72b</sup>, M. Romano<sup>23b</sup>,  
 A.C. Romero Hernandez<sup>161</sup>, N. Rompotis<sup>91</sup>, L. Roos<sup>126</sup>, S. Rosati<sup>74a</sup>, B.J. Rosser<sup>39</sup>, E. Rossi<sup>4</sup>,  
 E. Rossi<sup>71a,71b</sup>, L.P. Rossi<sup>57b</sup>, L. Rossini<sup>48</sup>, R. Rosten<sup>118</sup>, M. Rotaru<sup>27b</sup>, B. Rottler<sup>54</sup>, D. Rousseau<sup>66</sup>,  
 D. Rousso<sup>32</sup>, G. Rovelli<sup>72a,72b</sup>, A. Roy<sup>161</sup>, A. Rozanov<sup>101</sup>, Y. Rozen<sup>149</sup>, X. Ruan<sup>33g</sup>, A. Rubio Jimenez<sup>162</sup>,  
 A.J. Ruby<sup>91</sup>, V.H. Ruelas Rivera<sup>18</sup>, T.A. Ruggeri<sup>1</sup>, F. Rühr<sup>54</sup>, A. Ruiz-Martinez<sup>162</sup>, A. Rummler<sup>36</sup>,  
 Z. Rurikova<sup>54</sup>, N.A. Rusakovich<sup>38</sup>, H.L. Russell<sup>164</sup>, J.P. Rutherford<sup>7</sup>, K. Rybacki<sup>90</sup>, M. Rybar<sup>132</sup>,  
 E.B. Rye<sup>124</sup>, A. Ryzhov<sup>37</sup>, J.A. Sabater Iglesias<sup>56</sup>, P. Sabatini<sup>162</sup>, L. Sabetta<sup>74a,74b</sup>, H.F.W. Sadrozinski<sup>135</sup>,  
 F. Safai Tehrani<sup>74a</sup>, B. Safarzadeh Samani<sup>145</sup>, M. Safdari<sup>142</sup>, S. Saha<sup>103</sup>, M. Sahinsoy<sup>109</sup>, M. Saimpert<sup>134</sup>,  
 M. Saito<sup>152</sup>, T. Saito<sup>152</sup>, D. Salamani<sup>36</sup>, G. Salamanna<sup>76a,76b</sup>, A. Salnikov<sup>142</sup>, J. Salt<sup>162</sup>,  
 A. Salvador Salas<sup>13</sup>, D. Salvatore<sup>43b,43a</sup>, F. Salvatore<sup>145</sup>, A. Salzburger<sup>36</sup>, D. Sammel<sup>54</sup>,  
 D. Sampsonidis<sup>151,f</sup>, D. Sampsonidou<sup>62d,62c</sup>, J. Sánchez<sup>162</sup>, A. Sanchez Pineda<sup>4</sup>, V. Sanchez Sebastian<sup>162</sup>,  
 H. Sandaker<sup>124</sup>, C.O. Sander<sup>48</sup>, J.A. Sandesara<sup>102</sup>, M. Sandhoff<sup>170</sup>, C. Sandoval<sup>22b</sup>, D.P.C. Sankey<sup>133</sup>,  
 A. Sansoni<sup>53</sup>, L. Santi<sup>74a,74b</sup>, C. Santoni<sup>40</sup>, H. Santos<sup>129a,129b</sup>, S.N. Santpur<sup>17a</sup>, A. Santra<sup>168</sup>,  
 K.A. Saoucha<sup>138</sup>, J.G. Saraiva<sup>129a,129d</sup>, J. Sardain<sup>7</sup>, O. Sasaki<sup>82</sup>, K. Sato<sup>156</sup>, C. Sauer<sup>63b</sup>, F. Sauerburger<sup>54</sup>,  
 E. Sauvan<sup>4</sup>, P. Savard<sup>154,ae</sup>, R. Sawada<sup>152</sup>, C. Sawyer<sup>133</sup>, L. Sawyer<sup>96</sup>, I. Sayago Galvan<sup>162</sup>, C. Sbarra<sup>23b</sup>,  
 A. Sbrizzi<sup>23b,23a</sup>, T. Scanlon<sup>95</sup>, J. Schaarschmidt<sup>137</sup>, P. Schacht<sup>109</sup>, D. Schaefer<sup>39</sup>, U. Schäfer<sup>99</sup>,  
 A.C. Schaffer<sup>66</sup>, D. Schaile<sup>108</sup>, R.D. Schamberger<sup>144</sup>, E. Schanet<sup>108</sup>, C. Scharf<sup>18</sup>, M.M. Schefer<sup>19</sup>,  
 V.A. Schegelsky<sup>37</sup>, D. Scheirich<sup>132</sup>, F. Schenck<sup>18</sup>, M. Schernau<sup>159</sup>, C. Scheulen<sup>55</sup>, C. Schiavi<sup>57b,57a</sup>,  
 Z.M. Schillaci<sup>26</sup>, E.J. Schioppa<sup>69a,69b</sup>, M. Schioppa<sup>43b,43a</sup>, B. Schlag<sup>99</sup>, K.E. Schleicher<sup>54</sup>, S. Schlenker<sup>36</sup>,  
 J. Schmeing<sup>170</sup>, M.A. Schmidt<sup>170</sup>, K. Schmieden<sup>99</sup>, C. Schmitt<sup>99</sup>, S. Schmitt<sup>48</sup>, L. Schoeffel<sup>134</sup>,  
 A. Schoening<sup>63b</sup>, P.G. Scholer<sup>54</sup>, E. Schopf<sup>125</sup>, M. Schott<sup>99</sup>, J. Schovancova<sup>36</sup>, S. Schramm<sup>56</sup>,  
 F. Schroeder<sup>170</sup>, H-C. Schultz-Coulon<sup>63a</sup>, M. Schumacher<sup>54</sup>, B.A. Schumm<sup>135</sup>, Ph. Schune<sup>134</sup>,  
 A. Schwartzman<sup>142</sup>, T.A. Schwarz<sup>105</sup>, Ph. Schwemling<sup>134</sup>, R. Schwienhorst<sup>106</sup>, A. Sciandra<sup>135</sup>,  
 G. Sciolla<sup>26</sup>, F. Scuri<sup>73a</sup>, F. Scutti<sup>104</sup>, C.D. Sebastiani<sup>91</sup>, K. Sedlaczek<sup>49</sup>, P. Seema<sup>18</sup>, S.C. Seidel<sup>111</sup>,  
 A. Seiden<sup>135</sup>, B.D. Seidlitz<sup>41</sup>, T. Seiss<sup>39</sup>, C. Seitz<sup>48</sup>, J.M. Seixas<sup>81b</sup>, G. Sekhniaidze<sup>71a</sup>, S.J. Sekula<sup>44</sup>,  
 L. Selem<sup>4</sup>, N. Semprini-Cesari<sup>23b,23a</sup>, S. Sen<sup>51</sup>, D. Sengupta<sup>56</sup>, V. Senthilkumar<sup>162</sup>, L. Serin<sup>66</sup>,  
 L. Serkin<sup>68a,68b</sup>, M. Sessa<sup>76a,76b</sup>, H. Severini<sup>119</sup>, S. Sevova<sup>142</sup>, F. Sforza<sup>57b,57a</sup>, A. Sfyrla<sup>56</sup>, E. Shabalina<sup>55</sup>,  
 R. Shaheen<sup>143</sup>, J.D. Shahinian<sup>127</sup>, D. Shaked Renous<sup>168</sup>, L.Y. Shan<sup>14a</sup>, M. Shapiro<sup>17a</sup>, A. Sharma<sup>36</sup>,  
 A.S. Sharma<sup>163</sup>, P. Sharma<sup>79</sup>, S. Sharma<sup>48</sup>, P.B. Shatalov<sup>37</sup>, K. Shaw<sup>145</sup>, S.M. Shaw<sup>100</sup>, Q. Shen<sup>62c,5</sup>,  
 P. Sherwood<sup>95</sup>, L. Shi<sup>95</sup>, C.O. Shimmin<sup>171</sup>, Y. Shimogama<sup>167</sup>, J.D. Shinner<sup>94</sup>, I.P.J. Shipsey<sup>125</sup>,  
 S. Shirabe<sup>60</sup>, M. Shiyakova<sup>38</sup>, J. Shlomi<sup>168</sup>, M.J. Shochet<sup>39</sup>, J. Shojaii<sup>104</sup>, D.R. Shope<sup>124</sup>, S. Shrestha<sup>118,ai</sup>,  
 E.M. Shrif<sup>33g</sup>, M.J. Shroff<sup>164</sup>, P. Sicho<sup>130</sup>, A.M. Sickles<sup>161</sup>, E. Sideras Haddad<sup>33g</sup>, A. Sidoti<sup>23b</sup>, F. Siegert<sup>50</sup>,

Dj. Sijacki<sup>15</sup>, R. Sikora<sup>84a</sup>, F. Sili<sup>89</sup>, J.M. Silva<sup>20</sup>, M.V. Silva Oliveira<sup>36</sup>, S.B. Silverstein<sup>47a</sup>, S. Simion<sup>66</sup>, R. Simoniello<sup>36</sup>, E.L. Simpson<sup>59</sup>, N.D. Simpson<sup>97</sup>, S. Simsek<sup>21d</sup>, S. Sindhu<sup>55</sup>, P. Sinervo<sup>154</sup>, V. Sinetckii<sup>37</sup>, S. Singh<sup>141</sup>, S. Singh<sup>154</sup>, S. Sinha<sup>48</sup>, S. Sinha<sup>33g</sup>, M. Sioli<sup>23b,23a</sup>, I. Siral<sup>36</sup>, S.Yu. Sivoklokov<sup>37,\*</sup>, J. Sjölin<sup>47a,47b</sup>, A. Skaf<sup>55</sup>, E. Skorda<sup>97</sup>, P. Skubic<sup>119</sup>, M. Slawinska<sup>85</sup>, V. Smakhtin<sup>168</sup>, B.H. Smart<sup>133</sup>, J. Smiesko<sup>36</sup>, S.Yu. Smirnov<sup>37</sup>, Y. Smirnov<sup>37</sup>, L.N. Smirnova<sup>37,a</sup>, O. Smirnova<sup>97</sup>, A.C. Smith<sup>41</sup>, E.A. Smith<sup>39</sup>, H.A. Smith<sup>125</sup>, J.L. Smith<sup>91</sup>, R. Smith<sup>142</sup>, M. Smizanska<sup>90</sup>, K. Smolek<sup>131</sup>, A. Smykiewicz<sup>85</sup>, A.A. Snesarev<sup>37</sup>, H.L. Snoek<sup>113</sup>, S. Snyder<sup>29</sup>, R. Sobie<sup>164,x</sup>, A. Soffer<sup>150</sup>, C.A. Solans Sanchez<sup>36</sup>, E.Yu. Soldatov<sup>37</sup>, U. Soldevila<sup>162</sup>, A.A. Solodkov<sup>37</sup>, S. Solomon<sup>54</sup>, A. Soloshenko<sup>38</sup>, K. Solovieva<sup>54</sup>, O.V. Solovyanov<sup>37</sup>, V. Solovyev<sup>37</sup>, P. Sommer<sup>36</sup>, A. Sonay<sup>13</sup>, W.Y. Song<sup>155b</sup>, A. Sopczak<sup>131</sup>, A.L. Sopio<sup>95</sup>, F. Sopkova<sup>28b</sup>, V. Sothilingam<sup>63a</sup>, S. Sottocornola<sup>72a,72b</sup>, R. Soualah<sup>115b</sup>, Z. Soumami<sup>35e</sup>, D. South<sup>48</sup>, S. Spagnolo<sup>69a,69b</sup>, M. Spalla<sup>109</sup>, F. Spano<sup>94</sup>, D. Sperlich<sup>54</sup>, G. Spigo<sup>36</sup>, M. Spina<sup>145</sup>, S. Spinali<sup>90</sup>, D.P. Spiteri<sup>59</sup>, M. Spousta<sup>132</sup>, E.J. Staats<sup>34</sup>, A. Stabile<sup>70a,70b</sup>, R. Stamen<sup>63a</sup>, M. Stamenkovic<sup>113</sup>, A. Stampekis<sup>20</sup>, M. Standke<sup>24</sup>, E. Stanecka<sup>85</sup>, M.V. Stange<sup>50</sup>, B. Stanislaus<sup>17a</sup>, M.M. Stanitzki<sup>48</sup>, M. Stankaityte<sup>125</sup>, B. Stapf<sup>48</sup>, E.A. Starchenko<sup>37</sup>, G.H. Stark<sup>135</sup>, J. Stark<sup>101</sup>, D.M. Starke<sup>155b</sup>, P. Staroba<sup>130</sup>, P. Starovoitov<sup>63a</sup>, S. Stärz<sup>103</sup>, R. Staszewski<sup>85</sup>, G. Stavropoulos<sup>46</sup>, J. Steentoft<sup>160</sup>, P. Steinberg<sup>29</sup>, A.L. Steinhebel<sup>122</sup>, B. Stelzer<sup>141,155a</sup>, H.J. Stelzer<sup>128</sup>, O. Stelzer-Chilton<sup>155a</sup>, H. Stenzel<sup>58</sup>, T.J. Stevenson<sup>145</sup>, G.A. Stewart<sup>36</sup>, M.C. Stockton<sup>36</sup>, G. Stoicea<sup>27b</sup>, M. Stolarski<sup>129a</sup>, S. Stonjek<sup>109</sup>, A. Straessner<sup>50</sup>, J. Strandberg<sup>143</sup>, S. Strandberg<sup>47a,47b</sup>, M. Strauss<sup>119</sup>, T. Strebler<sup>101</sup>, P. Strizenec<sup>28b</sup>, R. Ströhmer<sup>165</sup>, D.M. Strom<sup>122</sup>, L.R. Strom<sup>48</sup>, R. Stroynowski<sup>44</sup>, A. Strubig<sup>47a,47b</sup>, S.A. Stucci<sup>29</sup>, B. Stugu<sup>16</sup>, J. Stupak<sup>119</sup>, N.A. Styles<sup>48</sup>, D. Su<sup>142</sup>, S. Su<sup>62a</sup>, W. Su<sup>62d,137,62c</sup>, X. Su<sup>62a,66</sup>, K. Sugizaki<sup>152</sup>, V.V. Sulin<sup>37</sup>, M.J. Sullivan<sup>91</sup>, D.M.S. Sultan<sup>77a,77b</sup>, L. Sultanaliyeva<sup>37</sup>, S. Sultansoy<sup>3b</sup>, T. Sumida<sup>86</sup>, S. Sun<sup>105</sup>, S. Sun<sup>169</sup>, O. Sunneborn Gudnadottir<sup>160</sup>, M.R. Sutton<sup>145</sup>, M. Svatos<sup>130</sup>, M. Swiatlowski<sup>155a</sup>, T. Swirski<sup>165</sup>, I. Sykora<sup>28a</sup>, M. Sykora<sup>132</sup>, T. Sykora<sup>132</sup>, D. Ta<sup>99</sup>, K. Tackmann<sup>48,w</sup>, A. Taffard<sup>159</sup>, R. Tafirout<sup>155a</sup>, J.S. Tafoya Vargas<sup>66</sup>, R.H.M. Taibah<sup>126</sup>, R. Takashima<sup>87</sup>, K. Takeda<sup>83</sup>, E.P. Takeva<sup>52</sup>, Y. Takubo<sup>82</sup>, M. Talby<sup>101</sup>, A.A. Talyshv<sup>37</sup>, K.C. Tam<sup>64b</sup>, N.M. Tamir<sup>150</sup>, A. Tanaka<sup>152</sup>, J. Tanaka<sup>152</sup>, R. Tanaka<sup>66</sup>, M. Tanasini<sup>57b,57a</sup>, J. Tang<sup>62c</sup>, Z. Tao<sup>163</sup>, S. Tapia Araya<sup>80</sup>, S. Tapprogge<sup>99</sup>, A. Tarek Abouelfadl Mohamed<sup>106</sup>, S. Tarem<sup>149</sup>, K. Tariq<sup>62b</sup>, G. Tarna<sup>101,27b</sup>, G.F. Tartarelli<sup>70a</sup>, P. Tas<sup>132</sup>, M. Tasevsky<sup>130</sup>, E. Tassi<sup>43b,43a</sup>, A.C. Tate<sup>161</sup>, G. Tateno<sup>152</sup>, Y. Tayalati<sup>35e</sup>, G.N. Taylor<sup>104</sup>, W. Taylor<sup>155b</sup>, H. Teagle<sup>91</sup>, A.S. Tee<sup>169</sup>, R. Teixeira De Lima<sup>142</sup>, P. Teixeira-Dias<sup>94</sup>, J.J. Teoh<sup>154</sup>, K. Terashi<sup>152</sup>, J. Terron<sup>98</sup>, S. Terzo<sup>13</sup>, M. Testa<sup>53</sup>, R.J. Teuscher<sup>154,x</sup>, A. Thaler<sup>78</sup>, O. Theiner<sup>56</sup>, N. Themistokleous<sup>52</sup>, T. Theveneaux-Pelzer<sup>18</sup>, O. Thielmann<sup>170</sup>, D.W. Thomas<sup>94</sup>, J.P. Thomas<sup>20</sup>, E.A. Thompson<sup>48</sup>, P.D. Thompson<sup>20</sup>, E. Thomson<sup>127</sup>, E.J. Thorpe<sup>93</sup>, Y. Tian<sup>55</sup>, V. Tikhomirov<sup>37,a</sup>, Yu.A. Tikhonov<sup>37</sup>, S. Timoshenko<sup>37</sup>, E.X.L. Ting<sup>1</sup>, P. Tipton<sup>171</sup>, S. Tisserant<sup>101</sup>, S.H. Tlou<sup>33g</sup>, A. Tnourji<sup>40</sup>, K. Todome<sup>23b,23a</sup>, S. Todorova-Nova<sup>132</sup>, S. Todt<sup>50</sup>, M. Togawa<sup>82</sup>, J. Tojo<sup>88</sup>, S. Tokár<sup>28a</sup>, K. Tokushuku<sup>82</sup>, R. Tombs<sup>32</sup>, M. Tomoto<sup>82,110</sup>, L. Tompkins<sup>142</sup>, K.W. Topolnicki<sup>84b</sup>, P. Tornambe<sup>102</sup>, E. Torrence<sup>122</sup>, H. Torres<sup>50</sup>, E. Torró Pastor<sup>162</sup>, M. Toscani<sup>30</sup>, C. Toscirri<sup>39</sup>, M. Tost<sup>11</sup>, D.R. Tovey<sup>138</sup>, A. Traet<sup>16</sup>, I.S. Trandafir<sup>27b</sup>, T. Trefzger<sup>165</sup>, A. Tricoli<sup>29</sup>, I.M. Trigger<sup>155a</sup>, S. Trincaz-Duvoid<sup>126</sup>, D.A. Trischuk<sup>26</sup>, B. Trocmé<sup>60</sup>, A. Trofymov<sup>66</sup>, C. Troncon<sup>70a</sup>, L. Truong<sup>33c</sup>, M. Trzebinski<sup>85</sup>, A. Trzupek<sup>85</sup>, F. Tsai<sup>144</sup>, M. Tsai<sup>105</sup>, A. Tsiamis<sup>151,f</sup>, P.V. Tsiarehka<sup>37</sup>, S. Tsigaridas<sup>155a</sup>, A. Tsirigotis<sup>151,u</sup>, V. Tsiskaridze<sup>144</sup>, E.G. Tskhadadze<sup>148a</sup>, M. Tsopoulou<sup>151,f</sup>, Y. Tsujikawa<sup>86</sup>, I.I. Tsukerman<sup>37</sup>, V. Tsulaia<sup>17a</sup>, S. Tsuno<sup>82</sup>, O. Tsur<sup>149</sup>, D. Tsybychev<sup>144</sup>, Y. Tu<sup>64b</sup>, A. Tudorache<sup>27b</sup>, V. Tudorache<sup>27b</sup>, A.N. Tuna<sup>36</sup>, S. Turchikhin<sup>38</sup>, I. Turk Cakir<sup>3a</sup>, R. Turra<sup>70a</sup>, T. Turtuvshin<sup>38,y</sup>, P.M. Tuts<sup>41</sup>, S. Tzamarias<sup>151,f</sup>, P. Tzani<sup>10</sup>, E. Tzovara<sup>99</sup>, K. Uchida<sup>152</sup>, F. Ukegawa<sup>156</sup>, P.A. Ulloa Poblete<sup>136c</sup>, E.N. Umaka<sup>80</sup>, G. Unal<sup>36</sup>, M. Unal<sup>11</sup>, A. Undrus<sup>29</sup>, G. Unel<sup>159</sup>, J. Urban<sup>28b</sup>, P. Urquijo<sup>104</sup>, G. Usai<sup>8</sup>, R. Ushioda<sup>153</sup>, M. Usman<sup>107</sup>, Z. Uysal<sup>21b</sup>, L. Vacavant<sup>101</sup>, V. Vacek<sup>131</sup>, B. Vachon<sup>103</sup>, K.O.H. Vadla<sup>124</sup>, T. Vafeiadis<sup>36</sup>, A. Vaitkus<sup>95</sup>, C. Valderanis<sup>108</sup>, E. Valdes Santurio<sup>47a,47b</sup>, M. Valente<sup>155a</sup>, S. Valentineti<sup>23b,23a</sup>, A. Valero<sup>162</sup>, A. Vallier<sup>101</sup>, J.A. Valls Ferrer<sup>162</sup>, T.R. Van Daalen<sup>137</sup>, P. Van Gemmeren<sup>6</sup>, M. Van Rijnbach<sup>124,36</sup>, S. Van Stroud<sup>95</sup>,



I. Van Vulpen<sup>113</sup>, M. Vanadia<sup>75a,75b</sup>, W. Vandelli<sup>36</sup>, M. Vandenbroucke<sup>134</sup>, E.R. Vandewall<sup>120</sup>, D. Vannicola<sup>150</sup>, L. Vannoli<sup>57b,57a</sup>, R. Vari<sup>74a</sup>, E.W. Varnes<sup>7</sup>, C. Varni<sup>17a</sup>, T. Varol<sup>147</sup>, D. Varouchas<sup>66</sup>, L. Varriale<sup>162</sup>, K.E. Varvell<sup>146</sup>, M.E. Vasile<sup>27b</sup>, L. Vaslin<sup>40</sup>, G.A. Vasquez<sup>164</sup>, F. Vazeille<sup>40</sup>, T. Vazquez Schroeder<sup>36</sup>, J. Veatch<sup>31</sup>, V. Vecchio<sup>100</sup>, M.J. Veen<sup>102</sup>, I. Veliscek<sup>125</sup>, L.M. Veloce<sup>154</sup>, F. Veloso<sup>129a,129c</sup>, S. Veneziano<sup>74a</sup>, A. Ventura<sup>69a,69b</sup>, A. Verbytskyi<sup>109</sup>, M. Verducci<sup>73a,73b</sup>, C. Vergis<sup>24</sup>, M. Verissimo De Araujo<sup>81b</sup>, W. Verkerke<sup>113</sup>, J.C. Vermeulen<sup>113</sup>, C. Vernieri<sup>142</sup>, P.J. Verschuuren<sup>94</sup>, M. Vessella<sup>102</sup>, M.C. Vetterli<sup>141,ae</sup>, A. Vgenopoulos<sup>151,f</sup>, N. Viaux Maira<sup>136f</sup>, T. Vickey<sup>138</sup>, O.E. Vickey Boeriu<sup>138</sup>, G.H.A. Viehhauser<sup>125</sup>, L. Vigani<sup>63b</sup>, M. Villa<sup>23b,23a</sup>, M. Villaplana Perez<sup>162</sup>, E.M. Villhauer<sup>52</sup>, E. Vilucchi<sup>53</sup>, M.G. Vinciter<sup>34</sup>, G.S. Virdee<sup>20</sup>, A. Vishwakarma<sup>52</sup>, C. Vittori<sup>23b,23a</sup>, I. Vivarelli<sup>145</sup>, V. Vladimirov<sup>166</sup>, E. Voevodina<sup>109</sup>, F. Vogel<sup>108</sup>, P. Vokac<sup>131</sup>, J. Von Ahnen<sup>48</sup>, E. Von Toerne<sup>24</sup>, B. Vormwald<sup>36</sup>, V. Vorobel<sup>132</sup>, K. Vorobev<sup>37</sup>, M. Vos<sup>162</sup>, J.H. Vosseveld<sup>91</sup>, M. Vozak<sup>113</sup>, L. Vozdecky<sup>93</sup>, N. Vranjes<sup>15</sup>, M. Vranjes Milosavljevic<sup>15</sup>, M. Vreeswijk<sup>113</sup>, R. Vuillermet<sup>36</sup>, O. Vujanovic<sup>99</sup>, I. Vukotic<sup>39</sup>, S. Wada<sup>156</sup>, C. Wagner<sup>102</sup>, W. Wagner<sup>170</sup>, S. Wahdan<sup>170</sup>, H. Wahlberg<sup>89</sup>, R. Wakasa<sup>156</sup>, M. Wakida<sup>110</sup>, V.M. Walbrecht<sup>109</sup>, J. Walder<sup>133</sup>, R. Walker<sup>108</sup>, W. Walkowiak<sup>140</sup>, A.M. Wang<sup>61</sup>, A.Z. Wang<sup>169</sup>, C. Wang<sup>62a</sup>, C. Wang<sup>62c</sup>, H. Wang<sup>17a</sup>, J. Wang<sup>64a</sup>, R.-J. Wang<sup>99</sup>, R. Wang<sup>61</sup>, R. Wang<sup>6</sup>, S.M. Wang<sup>147</sup>, S. Wang<sup>62b</sup>, T. Wang<sup>62a</sup>, W.T. Wang<sup>79</sup>, X. Wang<sup>14c</sup>, X. Wang<sup>161</sup>, X. Wang<sup>62c</sup>, Y. Wang<sup>62d</sup>, Y. Wang<sup>14c</sup>, Z. Wang<sup>105</sup>, Z. Wang<sup>62d,51,62c</sup>, Z. Wang<sup>105</sup>, A. Warburton<sup>103</sup>, R.J. Ward<sup>20</sup>, N. Warrack<sup>59</sup>, A.T. Watson<sup>20</sup>, H. Watson<sup>59</sup>, M.F. Watson<sup>20</sup>, G. Watts<sup>137</sup>, B.M. Waugh<sup>95</sup>, A.F. Webb<sup>11</sup>, C. Weber<sup>29</sup>, H.A. Weber<sup>18</sup>, M.S. Weber<sup>19</sup>, S.M. Weber<sup>63a</sup>, C. Wei<sup>62a</sup>, Y. Wei<sup>125</sup>, A.R. Weidberg<sup>125</sup>, J. Weingarten<sup>49</sup>, M. Weirich<sup>99</sup>, C. Weiser<sup>54</sup>, C.J. Wells<sup>48</sup>, T. Wenaus<sup>29</sup>, B. Wendland<sup>49</sup>, T. Wengler<sup>36</sup>, N.S. Wenke<sup>109</sup>, N. Wermes<sup>24</sup>, M. Wessels<sup>63a</sup>, K. Whalen<sup>122</sup>, A.M. Wharton<sup>90</sup>, A.S. White<sup>61</sup>, A. White<sup>8</sup>, M.J. White<sup>1</sup>, D. Whiteson<sup>159</sup>, L. Wickremasinghe<sup>123</sup>, W. Wiedenmann<sup>169</sup>, C. Wiel<sup>50</sup>, M. Wielers<sup>133</sup>, N. Wieseotte<sup>99</sup>, C. Wiglesworth<sup>42</sup>, L.A.M. Wiik-Fuchs<sup>54</sup>, D.J. Wilbern<sup>119</sup>, H.G. Wilkens<sup>36</sup>, D.M. Williams<sup>41</sup>, H.H. Williams<sup>127</sup>, S. Williams<sup>32</sup>, S. Willocq<sup>102</sup>, P.J. Windischhofer<sup>125</sup>, F. Winklmeier<sup>122</sup>, B.T. Winter<sup>54</sup>, J.K. Winter<sup>100</sup>, M. Wittgen<sup>142</sup>, M. Wobisch<sup>96</sup>, R. Wölker<sup>125</sup>, J. Wollrath<sup>159</sup>, M.W. Wolter<sup>85</sup>, H. Wolters<sup>129a,129c</sup>, V.W.S. Wong<sup>163</sup>, A.F. Wongel<sup>48</sup>, S.D. Worm<sup>48</sup>, B.K. Wosiek<sup>85</sup>, K.W. Woźniak<sup>85</sup>, K. Wraight<sup>59</sup>, J. Wu<sup>14a,14d</sup>, M. Wu<sup>64a</sup>, M. Wu<sup>112</sup>, S.L. Wu<sup>169</sup>, X. Wu<sup>56</sup>, Y. Wu<sup>62a</sup>, Z. Wu<sup>134,62a</sup>, J. Wuerzinger<sup>125</sup>, T.R. Wyatt<sup>100</sup>, B.M. Wynne<sup>52</sup>, S. Xella<sup>42</sup>, L. Xia<sup>14c</sup>, M. Xia<sup>14b</sup>, J. Xiang<sup>64c</sup>, X. Xiao<sup>105</sup>, M. Xie<sup>62a</sup>, X. Xie<sup>62a</sup>, S. Xin<sup>14a,14d</sup>, J. Xiong<sup>17a</sup>, I. Xiotidis<sup>145</sup>, D. Xu<sup>14a</sup>, H. Xu<sup>62a</sup>, H. Xu<sup>62a</sup>, L. Xu<sup>62a</sup>, R. Xu<sup>127</sup>, T. Xu<sup>105</sup>, W. Xu<sup>105</sup>, Y. Xu<sup>14b</sup>, Z. Xu<sup>62b</sup>, Z. Xu<sup>14a</sup>, B. Yabsley<sup>146</sup>, S. Yacoob<sup>33a</sup>, N. Yamaguchi<sup>88</sup>, Y. Yamaguchi<sup>153</sup>, H. Yamauchi<sup>156</sup>, T. Yamazaki<sup>17a</sup>, Y. Yamazaki<sup>83</sup>, J. Yan<sup>62c</sup>, S. Yan<sup>125</sup>, Z. Yan<sup>25</sup>, H.J. Yang<sup>62c,62d</sup>, H.T. Yang<sup>62a</sup>, S. Yang<sup>62a</sup>, T. Yang<sup>64c</sup>, X. Yang<sup>62a</sup>, X. Yang<sup>14a</sup>, Y. Yang<sup>44</sup>, Z. Yang<sup>62a,105</sup>, W.-M. Yao<sup>17a</sup>, Y.C. Yap<sup>48</sup>, H. Ye<sup>14c</sup>, H. Ye<sup>55</sup>, J. Ye<sup>44</sup>, S. Ye<sup>29</sup>, X. Ye<sup>62a</sup>, Y. Yeh<sup>95</sup>, I. Yeletsikh<sup>38</sup>, B.K. Yeo<sup>17a</sup>, M.R. Yexley<sup>90</sup>, P. Yin<sup>41</sup>, K. Yorita<sup>167</sup>, S. Younas<sup>27b</sup>, C.J.S. Young<sup>54</sup>, C. Young<sup>142</sup>, M. Yuan<sup>105</sup>, R. Yuan<sup>62b,1</sup>, L. Yue<sup>95</sup>, X. Yue<sup>63a</sup>, M. Zaazoua<sup>35e</sup>, B. Zabinski<sup>85</sup>, E. Zaid<sup>52</sup>, T. Zakareishvili<sup>148b</sup>, N. Zakharchuk<sup>34</sup>, S. Zambito<sup>56</sup>, J.A. Zamora Saa<sup>136d,136b</sup>, J. Zang<sup>152</sup>, D. Zanzi<sup>54</sup>, O. Zaplatilek<sup>131</sup>, S.V. Zeiβner<sup>49</sup>, C. Zeitnitz<sup>170</sup>, J.C. Zeng<sup>161</sup>, D.T. Zenger Jr<sup>26</sup>, O. Zenin<sup>37</sup>, T. Ženiš<sup>28a</sup>, S. Zenz<sup>93</sup>, S. Zerradi<sup>35a</sup>, D. Zerwas<sup>66</sup>, B. Zhang<sup>14c</sup>, D.F. Zhang<sup>138</sup>, G. Zhang<sup>14b</sup>, J. Zhang<sup>62b</sup>, J. Zhang<sup>6</sup>, K. Zhang<sup>14a,14d</sup>, L. Zhang<sup>14c</sup>, P. Zhang<sup>14a,14d</sup>, R. Zhang<sup>169</sup>, S. Zhang<sup>105</sup>, T. Zhang<sup>152</sup>, X. Zhang<sup>62c</sup>, X. Zhang<sup>62b</sup>, Y. Zhang<sup>62c,5</sup>, Z. Zhang<sup>17a</sup>, Z. Zhang<sup>66</sup>, H. Zhao<sup>137</sup>, P. Zhao<sup>51</sup>, T. Zhao<sup>62b</sup>, Y. Zhao<sup>135</sup>, Z. Zhao<sup>62a</sup>, A. Zhemchugov<sup>38</sup>, X. Zheng<sup>62a</sup>, Z. Zheng<sup>142</sup>, D. Zhong<sup>161</sup>, B. Zhou<sup>105</sup>, C. Zhou<sup>169</sup>, H. Zhou<sup>7</sup>, N. Zhou<sup>62c</sup>, Y. Zhou<sup>7</sup>, C.G. Zhu<sup>62b</sup>, C. Zhu<sup>14a,14d</sup>, H.L. Zhu<sup>62a</sup>, H. Zhu<sup>14a</sup>, J. Zhu<sup>105</sup>, Y. Zhu<sup>62c</sup>, Y. Zhu<sup>62a</sup>, X. Zhuang<sup>14a</sup>, K. Zhukov<sup>37</sup>, V. Zhulanov<sup>37</sup>, N.I. Zimine<sup>38</sup>, J. Zinsser<sup>63b</sup>, M. Ziolkowski<sup>140</sup>, L. Živković<sup>15</sup>, A. Zoccoli<sup>23b,23a</sup>, K. Zoch<sup>56</sup>, T.G. Zorbas<sup>138</sup>, O. Zormpa<sup>46</sup>, W. Zou<sup>41</sup>, L. Zwalinski<sup>36</sup>.

<sup>1</sup>Department of Physics, University of Adelaide, Adelaide; Australia.

<sup>2</sup>Department of Physics, University of Alberta, Edmonton AB; Canada.

- <sup>3(a)</sup>Department of Physics, Ankara University, Ankara;<sup>(b)</sup>Division of Physics, TOBB University of Economics and Technology, Ankara; Türkiye.
- <sup>4</sup>LAPP, Univ. Savoie Mont Blanc, CNRS/IN2P3, Annecy; France.
- <sup>5</sup>APC, Université Paris Cité, CNRS/IN2P3, Paris; France.
- <sup>6</sup>High Energy Physics Division, Argonne National Laboratory, Argonne IL; United States of America.
- <sup>7</sup>Department of Physics, University of Arizona, Tucson AZ; United States of America.
- <sup>8</sup>Department of Physics, University of Texas at Arlington, Arlington TX; United States of America.
- <sup>9</sup>Physics Department, National and Kapodistrian University of Athens, Athens; Greece.
- <sup>10</sup>Physics Department, National Technical University of Athens, Zografou; Greece.
- <sup>11</sup>Department of Physics, University of Texas at Austin, Austin TX; United States of America.
- <sup>12</sup>Institute of Physics, Azerbaijan Academy of Sciences, Baku; Azerbaijan.
- <sup>13</sup>Institut de Física d'Altes Energies (IFAE), Barcelona Institute of Science and Technology, Barcelona; Spain.
- <sup>14(a)</sup>Institute of High Energy Physics, Chinese Academy of Sciences, Beijing;<sup>(b)</sup>Physics Department, Tsinghua University, Beijing;<sup>(c)</sup>Department of Physics, Nanjing University, Nanjing;<sup>(d)</sup>University of Chinese Academy of Science (UCAS), Beijing; China.
- <sup>15</sup>Institute of Physics, University of Belgrade, Belgrade; Serbia.
- <sup>16</sup>Department for Physics and Technology, University of Bergen, Bergen; Norway.
- <sup>17(a)</sup>Physics Division, Lawrence Berkeley National Laboratory, Berkeley CA;<sup>(b)</sup>University of California, Berkeley CA; United States of America.
- <sup>18</sup>Institut für Physik, Humboldt Universität zu Berlin, Berlin; Germany.
- <sup>19</sup>Albert Einstein Center for Fundamental Physics and Laboratory for High Energy Physics, University of Bern, Bern; Switzerland.
- <sup>20</sup>School of Physics and Astronomy, University of Birmingham, Birmingham; United Kingdom.
- <sup>21(a)</sup>Department of Physics, Bogazici University, Istanbul;<sup>(b)</sup>Department of Physics Engineering, Gaziantep University, Gaziantep;<sup>(c)</sup>Department of Physics, Istanbul University, Istanbul;<sup>(d)</sup>Istinye University, Sariyer, Istanbul; Türkiye.
- <sup>22(a)</sup>Facultad de Ciencias y Centro de Investigaciones, Universidad Antonio Nariño, Bogotá;<sup>(b)</sup>Departamento de Física, Universidad Nacional de Colombia, Bogotá; Colombia.
- <sup>23(a)</sup>Dipartimento di Fisica e Astronomia A. Righi, Università di Bologna, Bologna;<sup>(b)</sup>INFN Sezione di Bologna; Italy.
- <sup>24</sup>Physikalisches Institut, Universität Bonn, Bonn; Germany.
- <sup>25</sup>Department of Physics, Boston University, Boston MA; United States of America.
- <sup>26</sup>Department of Physics, Brandeis University, Waltham MA; United States of America.
- <sup>27(a)</sup>Transilvania University of Brasov, Brasov;<sup>(b)</sup>Horia Hulubei National Institute of Physics and Nuclear Engineering, Bucharest;<sup>(c)</sup>Department of Physics, Alexandru Ioan Cuza University of Iasi, Iasi;<sup>(d)</sup>National Institute for Research and Development of Isotopic and Molecular Technologies, Physics Department, Cluj-Napoca;<sup>(e)</sup>University Politehnica Bucharest, Bucharest;<sup>(f)</sup>West University in Timisoara, Timisoara;<sup>(g)</sup>Faculty of Physics, University of Bucharest, Bucharest; Romania.
- <sup>28(a)</sup>Faculty of Mathematics, Physics and Informatics, Comenius University, Bratislava;<sup>(b)</sup>Department of Subnuclear Physics, Institute of Experimental Physics of the Slovak Academy of Sciences, Kosice; Slovak Republic.
- <sup>29</sup>Physics Department, Brookhaven National Laboratory, Upton NY; United States of America.
- <sup>30</sup>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.
- <sup>31</sup>California State University, CA; United States of America.
- <sup>32</sup>Cavendish Laboratory, University of Cambridge, Cambridge; United Kingdom.

- <sup>33(a)</sup>Department of Physics, University of Cape Town, Cape Town;<sup>(b)</sup>iThemba Labs, Western Cape;<sup>(c)</sup>Department of Mechanical Engineering Science, University of Johannesburg, Johannesburg;<sup>(d)</sup>National Institute of Physics, University of the Philippines Diliman (Philippines);<sup>(e)</sup>University of South Africa, Department of Physics, Pretoria;<sup>(f)</sup>University of Zululand, KwaDlangezwa;<sup>(g)</sup>School of Physics, University of the Witwatersrand, Johannesburg; South Africa.
- <sup>34</sup>Department of Physics, Carleton University, Ottawa ON; Canada.
- <sup>35(a)</sup>Faculté des Sciences Ain Chock, Réseau Universitaire de Physique des Hautes Energies - Université Hassan II, Casablanca;<sup>(b)</sup>Faculté des Sciences, Université Ibn-Tofail, Kénitra;<sup>(c)</sup>Faculté des Sciences Semlalia, Université Cadi Ayyad, LPHEA-Marrakech;<sup>(d)</sup>LPMR, Faculté des Sciences, Université Mohamed Premier, Oujda;<sup>(e)</sup>Faculté des sciences, Université Mohammed V, Rabat;<sup>(f)</sup>Institute of Applied Physics, Mohammed VI Polytechnic University, Ben Guerir; Morocco.
- <sup>36</sup>CERN, Geneva; Switzerland.
- <sup>37</sup>Affiliated with an institute covered by a cooperation agreement with CERN.
- <sup>38</sup>Affiliated with an international laboratory covered by a cooperation agreement with CERN.
- <sup>39</sup>Enrico Fermi Institute, University of Chicago, Chicago IL; United States of America.
- <sup>40</sup>LPC, Université Clermont Auvergne, CNRS/IN2P3, Clermont-Ferrand; France.
- <sup>41</sup>Nevis Laboratory, Columbia University, Irvington NY; United States of America.
- <sup>42</sup>Niels Bohr Institute, University of Copenhagen, Copenhagen; Denmark.
- <sup>43(a)</sup>Dipartimento di Fisica, Università della Calabria, Rende;<sup>(b)</sup>INFN Gruppo Collegato di Cosenza, Laboratori Nazionali di Frascati; Italy.
- <sup>44</sup>Physics Department, Southern Methodist University, Dallas TX; United States of America.
- <sup>45</sup>Physics Department, University of Texas at Dallas, Richardson TX; United States of America.
- <sup>46</sup>National Centre for Scientific Research "Demokritos", Agia Paraskevi; Greece.
- <sup>47(a)</sup>Department of Physics, Stockholm University;<sup>(b)</sup>Oskar Klein Centre, Stockholm; Sweden.
- <sup>48</sup>Deutsches Elektronen-Synchrotron DESY, Hamburg and Zeuthen; Germany.
- <sup>49</sup>Fakultät Physik, Technische Universität Dortmund, Dortmund; Germany.
- <sup>50</sup>Institut für Kern- und Teilchenphysik, Technische Universität Dresden, Dresden; Germany.
- <sup>51</sup>Department of Physics, Duke University, Durham NC; United States of America.
- <sup>52</sup>SUPA - School of Physics and Astronomy, University of Edinburgh, Edinburgh; United Kingdom.
- <sup>53</sup>INFN e Laboratori Nazionali di Frascati, Frascati; Italy.
- <sup>54</sup>Physikalisches Institut, Albert-Ludwigs-Universität Freiburg, Freiburg; Germany.
- <sup>55</sup>II. Physikalisches Institut, Georg-August-Universität Göttingen, Göttingen; Germany.
- <sup>56</sup>Département de Physique Nucléaire et Corpusculaire, Université de Genève, Genève; Switzerland.
- <sup>57(a)</sup>Dipartimento di Fisica, Università di Genova, Genova;<sup>(b)</sup>INFN Sezione di Genova; Italy.
- <sup>58</sup>II. Physikalisches Institut, Justus-Liebig-Universität Giessen, Giessen; Germany.
- <sup>59</sup>SUPA - School of Physics and Astronomy, University of Glasgow, Glasgow; United Kingdom.
- <sup>60</sup>LPSC, Université Grenoble Alpes, CNRS/IN2P3, Grenoble INP, Grenoble; France.
- <sup>61</sup>Laboratory for Particle Physics and Cosmology, Harvard University, Cambridge MA; United States of America.
- <sup>62(a)</sup>Department of Modern Physics and State Key Laboratory of Particle Detection and Electronics, University of Science and Technology of China, Hefei;<sup>(b)</sup>Institute of Frontier and Interdisciplinary Science and Key Laboratory of Particle Physics and Particle Irradiation (MOE), Shandong University, Qingdao;<sup>(c)</sup>School of Physics and Astronomy, Shanghai Jiao Tong University, Key Laboratory for Particle Astrophysics and Cosmology (MOE), SKLPPC, Shanghai;<sup>(d)</sup>Tsung-Dao Lee Institute, Shanghai; China.
- <sup>63(a)</sup>Kirchhoff-Institut für Physik, Ruprecht-Karls-Universität Heidelberg, Heidelberg;<sup>(b)</sup>Physikalisches Institut, Ruprecht-Karls-Universität Heidelberg, Heidelberg; Germany.
- <sup>64(a)</sup>Department of Physics, Chinese University of Hong Kong, Shatin, N.T., Hong Kong;<sup>(b)</sup>Department of

- Physics, University of Hong Kong, Hong Kong;<sup>(c)</sup>Department of Physics and Institute for Advanced Study, Hong Kong University of Science and Technology, Clear Water Bay, Kowloon, Hong Kong; China.
- <sup>65</sup>Department of Physics, National Tsing Hua University, Hsinchu; Taiwan.
- <sup>66</sup>IJCLab, Université Paris-Saclay, CNRS/IN2P3, 91405, Orsay; France.
- <sup>67</sup>Department of Physics, Indiana University, Bloomington IN; United States of America.
- <sup>68(a)</sup>INFN Gruppo Collegato di Udine, Sezione di Trieste, Udine;<sup>(b)</sup>ICTP, Trieste;<sup>(c)</sup>Dipartimento Politecnico di Ingegneria e Architettura, Università di Udine, Udine; Italy.
- <sup>69(a)</sup>INFN Sezione di Lecce;<sup>(b)</sup>Dipartimento di Matematica e Fisica, Università del Salento, Lecce; Italy.
- <sup>70(a)</sup>INFN Sezione di Milano;<sup>(b)</sup>Dipartimento di Fisica, Università di Milano, Milano; Italy.
- <sup>71(a)</sup>INFN Sezione di Napoli;<sup>(b)</sup>Dipartimento di Fisica, Università di Napoli, Napoli; Italy.
- <sup>72(a)</sup>INFN Sezione di Pavia;<sup>(b)</sup>Dipartimento di Fisica, Università di Pavia, Pavia; Italy.
- <sup>73(a)</sup>INFN Sezione di Pisa;<sup>(b)</sup>Dipartimento di Fisica E. Fermi, Università di Pisa, Pisa; Italy.
- <sup>74(a)</sup>INFN Sezione di Roma;<sup>(b)</sup>Dipartimento di Fisica, Sapienza Università di Roma, Roma; Italy.
- <sup>75(a)</sup>INFN Sezione di Roma Tor Vergata;<sup>(b)</sup>Dipartimento di Fisica, Università di Roma Tor Vergata, Roma; Italy.
- <sup>76(a)</sup>INFN Sezione di Roma Tre;<sup>(b)</sup>Dipartimento di Matematica e Fisica, Università Roma Tre, Roma; Italy.
- <sup>77(a)</sup>INFN-TIFPA;<sup>(b)</sup>Università degli Studi di Trento, Trento; Italy.
- <sup>78</sup>Universität Innsbruck, Department of Astro and Particle Physics, Innsbruck; Austria.
- <sup>79</sup>University of Iowa, Iowa City IA; United States of America.
- <sup>80</sup>Department of Physics and Astronomy, Iowa State University, Ames IA; United States of America.
- <sup>81(a)</sup>Departamento de Engenharia Elétrica, Universidade Federal de Juiz de Fora (UFJF), Juiz de Fora;<sup>(b)</sup>Universidade Federal do Rio De Janeiro COPPE/EE/IF, Rio de Janeiro;<sup>(c)</sup>Instituto de Física, Universidade de São Paulo, São Paulo;<sup>(d)</sup>Rio de Janeiro State University, Rio de Janeiro; Brazil.
- <sup>82</sup>KEK, High Energy Accelerator Research Organization, Tsukuba; Japan.
- <sup>83</sup>Graduate School of Science, Kobe University, Kobe; Japan.
- <sup>84(a)</sup>AGH University of Science and Technology, Faculty of Physics and Applied Computer Science, Krakow;<sup>(b)</sup>Marian Smoluchowski Institute of Physics, Jagiellonian University, Krakow; Poland.
- <sup>85</sup>Institute of Nuclear Physics Polish Academy of Sciences, Krakow; Poland.
- <sup>86</sup>Faculty of Science, Kyoto University, Kyoto; Japan.
- <sup>87</sup>Kyoto University of Education, Kyoto; Japan.
- <sup>88</sup>Research Center for Advanced Particle Physics and Department of Physics, Kyushu University, Fukuoka ; Japan.
- <sup>89</sup>Instituto de Física La Plata, Universidad Nacional de La Plata and CONICET, La Plata; Argentina.
- <sup>90</sup>Physics Department, Lancaster University, Lancaster; United Kingdom.
- <sup>91</sup>Oliver Lodge Laboratory, University of Liverpool, Liverpool; United Kingdom.
- <sup>92</sup>Department of Experimental Particle Physics, Jožef Stefan Institute and Department of Physics, University of Ljubljana, Ljubljana; Slovenia.
- <sup>93</sup>School of Physics and Astronomy, Queen Mary University of London, London; United Kingdom.
- <sup>94</sup>Department of Physics, Royal Holloway University of London, Egham; United Kingdom.
- <sup>95</sup>Department of Physics and Astronomy, University College London, London; United Kingdom.
- <sup>96</sup>Louisiana Tech University, Ruston LA; United States of America.
- <sup>97</sup>Fysiska institutionen, Lunds universitet, Lund; Sweden.
- <sup>98</sup>Departamento de Física Teórica C-15 and CIAFF, Universidad Autónoma de Madrid, Madrid; Spain.
- <sup>99</sup>Institut für Physik, Universität Mainz, Mainz; Germany.
- <sup>100</sup>School of Physics and Astronomy, University of Manchester, Manchester; United Kingdom.
- <sup>101</sup>CPPM, Aix-Marseille Université, CNRS/IN2P3, Marseille; France.
- <sup>102</sup>Department of Physics, University of Massachusetts, Amherst MA; United States of America.

- <sup>103</sup>Department of Physics, McGill University, Montreal QC; Canada.
- <sup>104</sup>School of Physics, University of Melbourne, Victoria; Australia.
- <sup>105</sup>Department of Physics, University of Michigan, Ann Arbor MI; United States of America.
- <sup>106</sup>Department of Physics and Astronomy, Michigan State University, East Lansing MI; United States of America.
- <sup>107</sup>Group of Particle Physics, University of Montreal, Montreal QC; Canada.
- <sup>108</sup>Fakultät für Physik, Ludwig-Maximilians-Universität München, München; Germany.
- <sup>109</sup>Max-Planck-Institut für Physik (Werner-Heisenberg-Institut), München; Germany.
- <sup>110</sup>Graduate School of Science and Kobayashi-Maskawa Institute, Nagoya University, Nagoya; Japan.
- <sup>111</sup>Department of Physics and Astronomy, University of New Mexico, Albuquerque NM; United States of America.
- <sup>112</sup>Institute for Mathematics, Astrophysics and Particle Physics, Radboud University/Nikhef, Nijmegen; Netherlands.
- <sup>113</sup>Nikhef National Institute for Subatomic Physics and University of Amsterdam, Amsterdam; Netherlands.
- <sup>114</sup>Department of Physics, Northern Illinois University, DeKalb IL; United States of America.
- <sup>115</sup><sup>(a)</sup>New York University Abu Dhabi, Abu Dhabi; <sup>(b)</sup>University of Sharjah, Sharjah; United Arab Emirates.
- <sup>116</sup>Department of Physics, New York University, New York NY; United States of America.
- <sup>117</sup>Ochanomizu University, Otsuka, Bunkyo-ku, Tokyo; Japan.
- <sup>118</sup>Ohio State University, Columbus OH; United States of America.
- <sup>119</sup>Homer L. Dodge Department of Physics and Astronomy, University of Oklahoma, Norman OK; United States of America.
- <sup>120</sup>Department of Physics, Oklahoma State University, Stillwater OK; United States of America.
- <sup>121</sup>Palacký University, Joint Laboratory of Optics, Olomouc; Czech Republic.
- <sup>122</sup>Institute for Fundamental Science, University of Oregon, Eugene, OR; United States of America.
- <sup>123</sup>Graduate School of Science, Osaka University, Osaka; Japan.
- <sup>124</sup>Department of Physics, University of Oslo, Oslo; Norway.
- <sup>125</sup>Department of Physics, Oxford University, Oxford; United Kingdom.
- <sup>126</sup>LPNHE, Sorbonne Université, Université Paris Cité, CNRS/IN2P3, Paris; France.
- <sup>127</sup>Department of Physics, University of Pennsylvania, Philadelphia PA; United States of America.
- <sup>128</sup>Department of Physics and Astronomy, University of Pittsburgh, Pittsburgh PA; United States of America.
- <sup>129</sup><sup>(a)</sup>Laboratório de Instrumentação e Física Experimental de Partículas - LIP, Lisboa; <sup>(b)</sup>Departamento de Física, Faculdade de Ciências, Universidade de Lisboa, Lisboa; <sup>(c)</sup>Departamento de Física, Universidade de Coimbra, Coimbra; <sup>(d)</sup>Centro de Física Nuclear da Universidade de Lisboa, Lisboa; <sup>(e)</sup>Departamento de Física, Universidade do Minho, Braga; <sup>(f)</sup>Departamento de Física Teórica y del Cosmos, Universidad de Granada, Granada (Spain); <sup>(g)</sup>Departamento de Física, Instituto Superior Técnico, Universidade de Lisboa, Lisboa; Portugal.
- <sup>130</sup>Institute of Physics of the Czech Academy of Sciences, Prague; Czech Republic.
- <sup>131</sup>Czech Technical University in Prague, Prague; Czech Republic.
- <sup>132</sup>Charles University, Faculty of Mathematics and Physics, Prague; Czech Republic.
- <sup>133</sup>Particle Physics Department, Rutherford Appleton Laboratory, Didcot; United Kingdom.
- <sup>134</sup>IRFU, CEA, Université Paris-Saclay, Gif-sur-Yvette; France.
- <sup>135</sup>Santa Cruz Institute for Particle Physics, University of California Santa Cruz, Santa Cruz CA; United States of America.
- <sup>136</sup><sup>(a)</sup>Departamento de Física, Pontificia Universidad Católica de Chile, Santiago; <sup>(b)</sup>Millennium Institute

for Subatomic physics at high energy frontier (SAPHIR), Santiago;<sup>(c)</sup>Instituto de Investigación Multidisciplinario en Ciencia y Tecnología, y Departamento de Física, Universidad de La Serena;<sup>(d)</sup>Universidad Andres Bello, Department of Physics, Santiago;<sup>(e)</sup>Instituto de Alta Investigación, Universidad de Tarapacá, Arica;<sup>(f)</sup>Departamento de Física, Universidad Técnica Federico Santa María, Valparaíso; Chile.

<sup>137</sup>Department of Physics, University of Washington, Seattle WA; United States of America.

<sup>138</sup>Department of Physics and Astronomy, University of Sheffield, Sheffield; United Kingdom.

<sup>139</sup>Department of Physics, Shinshu University, Nagano; Japan.

<sup>140</sup>Department Physik, Universität Siegen, Siegen; Germany.

<sup>141</sup>Department of Physics, Simon Fraser University, Burnaby BC; Canada.

<sup>142</sup>SLAC National Accelerator Laboratory, Stanford CA; United States of America.

<sup>143</sup>Department of Physics, Royal Institute of Technology, Stockholm; Sweden.

<sup>144</sup>Departments of Physics and Astronomy, Stony Brook University, Stony Brook NY; United States of America.

<sup>145</sup>Department of Physics and Astronomy, University of Sussex, Brighton; United Kingdom.

<sup>146</sup>School of Physics, University of Sydney, Sydney; Australia.

<sup>147</sup>Institute of Physics, Academia Sinica, Taipei; Taiwan.

<sup>148</sup><sup>(a)</sup>E. Andronikashvili Institute of Physics, Iv. Javakhishvili Tbilisi State University, Tbilisi;<sup>(b)</sup>High Energy Physics Institute, Tbilisi State University, Tbilisi;<sup>(c)</sup>University of Georgia, Tbilisi; Georgia.

<sup>149</sup>Department of Physics, Technion, Israel Institute of Technology, Haifa; Israel.

<sup>150</sup>Raymond and Beverly Sackler School of Physics and Astronomy, Tel Aviv University, Tel Aviv; Israel.

<sup>151</sup>Department of Physics, Aristotle University of Thessaloniki, Thessaloniki; Greece.

<sup>152</sup>International Center for Elementary Particle Physics and Department of Physics, University of Tokyo, Tokyo; Japan.

<sup>153</sup>Department of Physics, Tokyo Institute of Technology, Tokyo; Japan.

<sup>154</sup>Department of Physics, University of Toronto, Toronto ON; Canada.

<sup>155</sup><sup>(a)</sup>TRIUMF, Vancouver BC;<sup>(b)</sup>Department of Physics and Astronomy, York University, Toronto ON; Canada.

<sup>156</sup>Division of Physics and Tomonaga Center for the History of the Universe, Faculty of Pure and Applied Sciences, University of Tsukuba, Tsukuba; Japan.

<sup>157</sup>Department of Physics and Astronomy, Tufts University, Medford MA; United States of America.

<sup>158</sup>United Arab Emirates University, Al Ain; United Arab Emirates.

<sup>159</sup>Department of Physics and Astronomy, University of California Irvine, Irvine CA; United States of America.

<sup>160</sup>Department of Physics and Astronomy, University of Uppsala, Uppsala; Sweden.

<sup>161</sup>Department of Physics, University of Illinois, Urbana IL; United States of America.

<sup>162</sup>Instituto de Física Corpuscular (IFIC), Centro Mixto Universidad de Valencia - CSIC, Valencia; Spain.

<sup>163</sup>Department of Physics, University of British Columbia, Vancouver BC; Canada.

<sup>164</sup>Department of Physics and Astronomy, University of Victoria, Victoria BC; Canada.

<sup>165</sup>Fakultät für Physik und Astronomie, Julius-Maximilians-Universität Würzburg, Würzburg; Germany.

<sup>166</sup>Department of Physics, University of Warwick, Coventry; United Kingdom.

<sup>167</sup>Waseda University, Tokyo; Japan.

<sup>168</sup>Department of Particle Physics and Astrophysics, Weizmann Institute of Science, Rehovot; Israel.

<sup>169</sup>Department of Physics, University of Wisconsin, Madison WI; United States of America.

<sup>170</sup>Fakultät für Mathematik und Naturwissenschaften, Fachgruppe Physik, Bergische Universität Wuppertal, Wuppertal; Germany.

<sup>171</sup>Department of Physics, Yale University, New Haven CT; United States of America.

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



**Declaration of interests**

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

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.