



Search for the Higgs boson decays $H \rightarrow ee$ and $H \rightarrow e\mu$ in pp collisions at $\sqrt{s} = 13$ TeV with the ATLAS detector

The ATLAS Collaboration ^{*}



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ABSTRACT

Searches for the Higgs boson decays $H \rightarrow ee$ and $H \rightarrow e\mu$ are performed using data corresponding to an integrated luminosity of 139 fb^{-1} collected with the ATLAS detector in pp collisions at $\sqrt{s} = 13$ TeV at the LHC. No significant signals are observed, in agreement with the Standard Model expectation. For a Higgs boson mass of 125 GeV, the observed (expected) upper limit at the 95% confidence level on the branching fraction $\mathcal{B}(H \rightarrow ee)$ is 3.6×10^{-4} (3.5×10^{-4}) and on $\mathcal{B}(H \rightarrow e\mu)$ is 6.2×10^{-5} (5.9×10^{-5}). These results represent improvements by factors of about five and six on the previous best limits on $\mathcal{B}(H \rightarrow ee)$ and $\mathcal{B}(H \rightarrow e\mu)$ respectively.

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1. Introduction

The discovery of a heavy scalar particle by ATLAS and CMS [1, 2] provided experimental confirmation of the Englert–Brout–Higgs mechanism [3–8], which spontaneously breaks electroweak (EW) gauge symmetry and generates mass terms for the W and Z gauge bosons. In the Standard Model (SM) the fermion masses are generated via Yukawa interactions. The Yukawa couplings to third-generation fermions were determined by measurements of Higgs boson production and decays [9–15], and found to be in agreement with the expectations of the SM. However, there is currently no evidence of Higgs boson decays into first- or second-generation quarks or leptons.

This Letter presents the first ATLAS searches for $H \rightarrow ee$ and for the lepton-flavour-violating decay $H \rightarrow e\mu$ using the full Run 2 dataset of proton–proton (pp) collisions at a centre-of-mass energy of $\sqrt{s} = 13$ TeV, with an integrated luminosity of 139 fb^{-1} . The CMS Collaboration has previously performed searches for $H \rightarrow ee$ [16] and $H \rightarrow e\mu$ [17] using LHC Run 1 pp data at $\sqrt{s} = 8$ TeV corresponding to an integrated luminosity of 19.7 fb^{-1} .

In the SM the $H \rightarrow ee$ branching fraction is given by $G_F m_H m_e^2 / (4\sqrt{2}\pi\Gamma_H) \simeq 5 \times 10^{-9}$, where m_H and Γ_H are the Higgs mass and width respectively. This branching fraction is far below the sensitivity of the LHC experiments. Contributions from diagrams that do not depend on the electron Yukawa coupling Y_{ee} and are non-resonant e.g. $H \rightarrow ee\gamma$, are expected to be significantly larger, although still much smaller than present sensitivity.

The LHC offers the best constraint on Y_{ee} [18], which may be larger than predicted by the SM. The SM forbids lepton-flavour-number-violating Higgs boson decays. There are strong indirect constraints on the off-diagonal $Y_{e\mu}$ coupling, the strongest derived from limits on the branching fraction of $\mu \rightarrow e\gamma$ and the electric dipole moment of the electron [19]. However, these indirect constraints assume SM values for the as yet unmeasured Y_{ee} and $Y_{\mu\mu}$ Yukawa couplings. Searching for $H \rightarrow e\mu$ allows $Y_{e\mu}$ to be constrained directly.

Both analyses presented in this Letter closely follow the search for the SM Higgs boson decay $H \rightarrow \mu\mu$ [20]. The signal is separated from the background primarily by identifying a narrow peak in the distribution of the invariant mass of the two leptons $m_{\ell\ell}$ corresponding to the mass of the Higgs boson of 125 GeV [21]. The background in the ee search is dominated by Drell–Yan (DY) Z/γ^* production, with smaller contributions from top-quark pair ($t\bar{t}$) and diboson production (ZZ , WZ and WW). In the $e\mu$ search, a much smaller yield of SM background events is expected. The DY background only contributes through decays of $Z/\gamma^* \rightarrow \tau\tau \rightarrow e\nu_\tau \nu_e \mu\nu_\tau \nu_\mu$. Thus the production of top quarks, dibosons (mainly through $WW \rightarrow e\nu_e \mu\nu_\mu$), W +jets and multijet events, with jets misidentified as leptons, are more important than in the ee search.

2. ATLAS detector

The ATLAS experiment [22–24] at the LHC is a multipurpose particle detector with a forward–backward symmetric cylindrical geometry and a near 4π coverage in solid angle.¹ It consists of an

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

¹ ATLAS uses a right-handed coordinate system with its origin at the nominal interaction point (IP) in the centre of the detector and the z -axis along the beam

inner tracking detector (ID) surrounded by a thin superconducting solenoid providing a 2 T axial magnetic field, electromagnetic and hadron calorimeters, and a muon spectrometer.

The ID covers the pseudorapidity range $|\eta| < 2.5$. It consists of silicon pixel, silicon microstrip, and transition radiation tracking detectors. Lead/liquid-argon (LAr) sampling calorimeters provide electromagnetic (EM) energy measurements with high granularity. A steel/scintillator-tile calorimeter in the central pseudorapidity range $|\eta| < 1.7$ measures the energies of hadrons. The endcap and forward regions are instrumented with LAr calorimeters for both the EM and hadronic energy measurements up to $|\eta| = 4.9$. The muon spectrometer (MS) surrounds the calorimeters up to $|\eta| = 2.7$ and is based on three large air-core toroidal superconducting magnets with eight coils each. The field integral of the toroids ranges between 2.0 and 6.0 Tm across most of the detector. The muon spectrometer includes a system of precision tracking chambers and fast detectors for triggering.

A two-level trigger system is used to select events [25]. It consists of a first-level trigger implemented in hardware and using a subset of the detector information to reduce the event rate to 100 kHz. This is followed by a software-based high-level trigger that employs algorithms similar to those used offline and reduces the rate of accepted events to 1 kHz.

3. Simulated event samples

Samples of simulated signal events with a Higgs boson mass of $m_H = 125$ GeV were generated as described below and processed through the full ATLAS detector simulation [26] based on GEANT4 [27]. Higgs boson production via the gluon–gluon fusion (ggF) process was simulated using the POWHEG NNLOPS program [28–35] with the PDF4LHC15 set of parton distribution functions (PDFs) [36]. The Higgs boson rapidity in the simulation was reweighted to achieve next-to-next-to-leading-order (NNLO) accuracy in QCD [37]. Higgs boson production via vector-boson fusion (VBF) and with an associated vector boson (VH) were generated at next-to-leading-order (NLO) accuracy in QCD using the POWHEG-BOX program [38–40]. The ZH samples were simulated for processes with quark–quark initial states, and the small contribution from gluon–gluon initial states is accounted for in the normalisation of the ZH cross section. The parton-level events were processed with PYTHIA8 [41] for the decay of the Higgs bosons into the ee or $e\mu$ final states and to simulate parton showering, hadronisation and the underlying event, using the AZNLO set of tuned parameters [42]. All samples were normalised to state-of-the-art predictions using higher-order QCD and electroweak corrections [43–66]. The effects arising from multiple pp collisions in the same or neighbouring bunch crossings (pile-up) were included in the simulation by overlaying inelastic pp interactions generated with PYTHIA8 using the NNPDF2.3LO set of PDFs [67] and the A3 set of tuned parameters [68]. Events were reweighted such that the distribution of the average number of interactions per bunch crossing matches that observed in data. Simulated events were corrected to reflect the lepton energy scale and resolution, and trigger, reconstruction, identification and isolation efficiencies measured in data.

To evaluate the uncertainty in the background modelling in the ee channel, a dedicated fast simulation for the dominant DY background was used to produce a sample of 10^9 events, equivalent

pipe. The x -axis points from the IP to the centre of the LHC ring, and the y -axis points upwards. Cylindrical coordinates (r, ϕ) are used in the transverse plane, ϕ being the azimuthal angle around the z -axis. The pseudorapidity is defined in terms of the polar angle θ as $\eta = -\ln \tan(\theta/2)$. Angular distance is measured in units of $\Delta R \equiv \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2}$.

to 40 times the integrated luminosity of the data. For this sample, $Z/\gamma^* + (0, 1)$ -jet events were generated inclusively at NLO accuracy using POWHEG-BOX [69] with the CT10 PDF set [70]. Additional $Z/\gamma^* + 2$ -jet events were generated with ALPGEN [71] at leading-order accuracy with the CTEQ6L1 PDF set [72]. The events were interfaced to PHOTOS [73] to simulate QED final-state radiation. The effects of pile-up and a fast parameterisation of the response of the detector to electrons and jets, using simple smearing functions, was then applied to the generated events.

4. Event selection

Events are recorded using triggers that require either an isolated electron or an isolated muon above a transverse momentum (p_T) threshold of 26 GeV [25,74]. Electrons are reconstructed in the range $|\eta| < 2.47$ from clusters of energy deposits in the calorimeter matched to a track in the ID [75]. Muons are reconstructed in the range $|\eta| < 2.5$ by combining tracks in the ID either with tracks in the MS or, for $|\eta| < 0.1$, with calorimeter energy deposits consistent with a muon [76]. The electrons and muons are required to be associated with the primary pp collision vertex, which is defined as the collision vertex with largest sum of p_T^2 of tracks, and to be isolated from other tracks [75,76]. Each event must contain either exactly two electrons or an electron and a muon. One lepton must have $p_T > 27$ GeV to ensure a high trigger efficiency and the other must be of opposite charge and have $p_T > 15$ GeV.

Requirements on jets are used in this analysis to suppress background and define a category that has a high sensitivity to signal produced in the VBF production mode. Jets in the range $|\eta| < 4.5$ and $p_T > 30$ GeV are reconstructed from energy deposits in the calorimeter [77], using the anti- k_r algorithm [78,79] with a radius parameter of 0.4. Tracking information is combined using a multivariate likelihood to suppressed jets from pile-up interactions [80].

Backgrounds with top quarks are suppressed by identifying b -hadrons and neutrinos in the final state. Jets in the range $|\eta| < 2.5$ containing b -hadrons are identified as b -jets using a multivariate algorithm that uses calorimeter and tracking information [81]. Events are rejected if there is at least one identified b -jet. Different working points are used for the ee and $e\mu$ channels because the latter has a larger top-quark background. For the ee ($e\mu$) channel the b -jet identification efficiency is about 60% (85%) with a rejection factor of about 1200 (25) for light-flavour jets [82]. Neutrinos produced in semileptonic top-quark decays escape detection and lead to missing transverse momentum E_T^{miss} , reconstructed as the magnitude of the vector sum of the transverse momenta of all calibrated leptons and jets and additional ID tracks associated with the primary vertex (soft term) [83]. Backgrounds with significant E_T^{miss} are suppressed by requiring $E_T^{\text{miss}}/\sqrt{H_T} < 3.5$ (1.75) $\text{GeV}^{1/2}$ for the ee ($e\mu$) channel, where H_T is the scalar sum of the transverse momenta of leptons and jets and $\sqrt{H_T}$ is proportional to the E_T^{miss} resolution.

Background from the process $H \rightarrow \gamma\gamma$, where the photons are misreconstructed as electrons, is studied with simulated events and found to contribute about 0.07% in the ee channel for a $H \rightarrow ee$ branching fraction at the expected limit. It is therefore neglected in the rest of the analysis.

The search is performed in the range of dilepton invariant mass $110 < m_{\ell\ell} < 160$ GeV, which allows the background to be determined with analytic functions constrained by the sidebands to either side of the potential signal.

The event sample passing the basic lepton selection is divided into seven (eight) categories for the ee ($e\mu$) channel that differ in their expected signal-to-background ratios, to improve the overall sensitivity of the search. These categories are based on those

used in Ref. [20], and are found to provide good sensitivity in the present analyses.

First, a low- p_T lepton category ‘Low $p_T^{\ell'}$ ’ is defined in the $e\mu$ channel with events in which the subleading lepton has $p_T < 27$ GeV. This region has a significant fraction of events in which either reconstructed lepton is of non-prompt origin or is a misidentified photon or hadron, hereafter called a fake lepton. These events are not separated out in the ee channel because the relative contribution from fake leptons is smaller. A category enriched in events from VBF production is defined from the remaining events by selecting those containing two jets with pseudorapidities of opposite signs, a pseudorapidity separation $|\Delta\eta_{jj}| > 3$ and a dijet invariant mass $m_{jj} > 500$ GeV.

Events that fail to meet the criteria of the ‘Low $p_T^{\ell'}$ ’ and VBF categories are classified as ‘Central’ if the pseudorapidities of both leptons are $|\eta^{\ell}| < 1$ or as ‘Non-central’ otherwise. For each of these two categories, three ranges in the dilepton transverse momentum $p_T^{\ell\ell}$ are considered: ‘Low $p_T^{\ell\ell}$ ’, ($p_T^{\ell\ell} \leq 15$ GeV), ‘Mid $p_T^{\ell\ell}$ ’, ($15 < p_T^{\ell\ell} \leq 50$ GeV), and ‘High $p_T^{\ell\ell}$ ’, ($p_T^{\ell\ell} > 50$ GeV). These categories exploit differences in the dilepton mass resolution, which is better for more central leptons, as well as differences in the expected signal-to-background ratio between the signal and the background processes as function of dilepton transverse momentum and rapidity.

5. Signal and background parameterisation

Analytic functions are used to describe the $m_{\ell\ell}$ distributions for both the signal and the background. The $H \rightarrow ee$ and $H \rightarrow e\mu$ signals considered are narrow resonances with a mass and a width set to the SM values of $m_H = 125$ GeV and 4.1 MeV respectively. The observed signal shapes are thus determined by detector resolution effects and are parameterised as a sum of a Crystal Ball function (F_{CB}) [84] and a Gaussian function (F_{GS}) following Ref. [20]:

$$P_S(m_{\ell\ell}) = f_{CB} \times F_{CB}(m_{\ell\ell}|m_{CB}, \sigma_{CB}, \alpha, n) + (1 - f_{CB}) \times F_{GS}(m_{\ell\ell}|m_{GS}, \sigma_{GS}^S).$$

The parameters α and n define the power-law tail of the F_{CB} distribution, while m_{CB} , m_{GS} , σ_{CB} , and σ_{GS}^S denote the F_{CB} mean value, F_{GS} mean value, F_{CB} width, and F_{GS} width respectively. The relative normalisation between the terms is governed by the parameter f_{CB} . These parameters are determined by fitting the simulated signal $m_{\ell\ell}$ distribution in each category. In the ee ($e\mu$) channel the signal mass resolution varies between about 2.0 GeV (2.3 GeV) for the central and 2.9 GeV (3.0 GeV) for the non-central categories.

The background parameterisation for the ee channel follows Ref. [20] as the background is very similar. The m_{ee} distributions in each category are described by a sum of a Breit-Wigner function (F_{BW}) convolved with a F_{GS} , and an exponential function divided by a cubic function:

$$P_B(m_{ee}) = f \times [F_{BW}(m_{ee}|m_{BW}, \Gamma_{BW}) \otimes F_{GS}(m_{ee}|\sigma_{GS}^B)] + (1 - f) \times C e^{A \cdot m_{ee}} / m_{ee}^3,$$

where f represents the fraction of the F_{BW} component when each individual component is normalised to unity and C is a normalisation coefficient. The σ_{GS}^B parameter in each category is fixed to the corresponding average $m_{\ell\ell}$ resolution as determined from simulated signal events. For all the categories, the F_{BW} parameters are fixed to $m_{BW} = 91.2$ GeV and $\Gamma_{BW} = 2.49$ GeV [85]. The pa-

rameters f and A and the overall normalisation are left free to be determined in the fit and uncorrelated between different categories.

A Bernstein polynomial of degree two is used to parameterise the $m_{e\mu}$ distribution of the background in each of the eight categories in the $e\mu$ channel, with parameters uncorrelated across categories. The choice of background function is validated by an F-test considering Bernstein polynomials of first, second and third degree.

The signal yield, which is allowed to be positive or negative, is constrained using separate binned maximum-likelihood fits to the observed $m_{\ell\ell}$ distributions in the range $110 < m_{\ell\ell} < 160$ GeV in the two channels. The fits are performed using the sum of the signal and background models (‘S + B model’) and are performed simultaneously in all the categories. In addition to the background-model parameters described earlier, the background normalisation in each category and the branching fraction of the signal are free parameters in the fit.

6. Systematic uncertainties

The signal expectation is subject to experimental and theoretical uncertainties, which are correlated across the categories.

The uncertainty in the combined 2015–2018 integrated luminosity is 1.7% [86], obtained using the LUCID-2 detector [87] for the primary luminosity measurements. Other sources of experimental uncertainty include the electron and muon trigger, reconstruction, identification and isolation efficiencies [75,76], the b -jet identification efficiency [81], the pile-up modelling [88], the determination of the E_T^{miss} soft term [83], and the jet energy scale and resolution [89]. The uncertainties in the electron energy scale and resolution [75] and in the muon momentum scale and resolution [76] affect the shape of the signal distribution as well as the signal acceptance.

The total experimental uncertainty in the predicted signal yield in each ggF category is between 2% and 3% for the ee channel and between 4% and 6% for the $e\mu$ channel. It is dominated by the luminosity, E_T^{miss} soft term and pile-up effects, and the last two contributions are larger in the $e\mu$ analysis due to the tighter $E_T^{\text{miss}}/\sqrt{H_T}$ requirement. The experimental uncertainty in the VBF category is between 7% and 15% for the ee channel and between 6% and 22% for the $e\mu$ channel, due to larger contributions from the jet energy scale and resolution.

The theoretical uncertainties in the production cross section of the Higgs boson are taken from Ref. [43]. In addition, theoretical modelling uncertainties affecting the acceptance for the signals are calculated separately for the ggF and VBF Higgs boson production processes in each analysis category. The uncertainty in the acceptance for the VH process is neglected. The effects of missing higher-order terms in the perturbative QCD calculations are estimated by varying the renormalisation and factorisation scales. For the ggF process the uncertainties are approximated as two correlated sources that range from around 1% to 11% for the different analysis categories in both channels. For the VBF process the uncertainties in the acceptance due to the QCD scales are found to be small. The effects of uncertainties in the parton distribution functions and the value of α_S are estimated using the PDF4LHC15 recommendations [36] and found to be very small. The uncertainty in the modelling of the parton shower, underlying event, and hadronisation is assessed by comparing the acceptance of signal events showered by PYTHIA with that of events showered by HERWIG [90, 91]. The total variations due to these uncertainties range from less than 1% to 11% for the ggF signal process and from 1% to 8% for the VBF signal process depending on the analysis category.

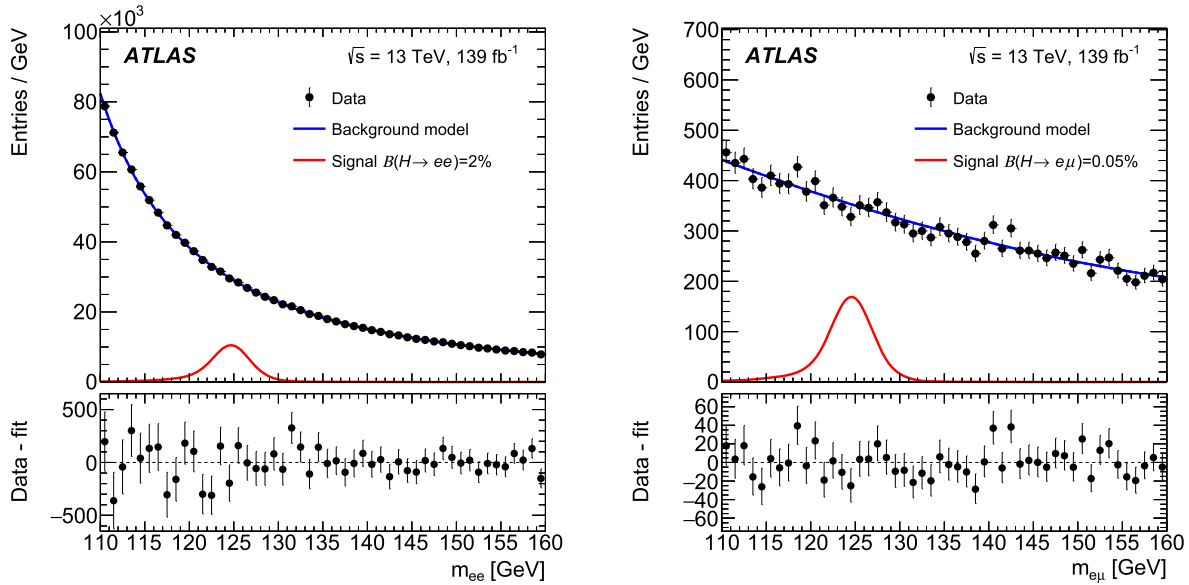


Fig. 1. Dilepton invariant mass $m_{\ell\ell}$ for all categories summed together for the ee channel (left) and the $e\mu$ channel (right) compared with the background-only model. The signal parameterisations with branching fractions set to $\mathcal{B}(H \rightarrow ee) = 2\%$ and $\mathcal{B}(H \rightarrow e\mu) = 0.05\%$ are also shown (red line). The bottom panels show the difference between data and the background-only fit.

Due to the very different yields and composition of the backgrounds in the ee and $e\mu$ channels, the potential bias on the measured signal from the choice of background function is assessed in different ways. In the ee channel the $S + B$ fit is repeated using the high-statistics DY-background fast simulation instead of the data. The number of signal events in each category obtained from the fit is used as a systematic uncertainty following the method of Ref. [1]. To be conservative, the maximum absolute deviation from zero for a signal mass between 120 and 130 GeV is taken. The uncertainty is treated as uncorrelated between categories. The background modelling uncertainty is implemented as a set of additional nuisance parameters acting on the signal normalisation in each category. The effect of this uncertainty on the expected limit is about 8%. In the $e\mu$ channel the background modelling uncertainty is estimated by changing the fit function to an exponential and evaluating the difference in signal yield compared with the default fit to a sample of simulated background events [92–94]. The effect of this uncertainty on the expected limit is about 1%.

7. Results

In the ee channel, the observed dielectron mass spectra are divided into 200 m_{ee} bins in each of the seven categories and signal yields are obtained in a simultaneous maximum-likelihood fit. Confidence intervals are based on the profile-likelihood-ratio test statistics [95], assuming asymptotic distributions for the test statistics. The systematic uncertainties affecting the signal normalisation and shape across categories are parameterised by making the likelihood function depend on dedicated nuisance parameters, constrained by additional Gaussian or log-normal probability terms. The Higgs boson production cross sections are assumed to be as predicted in the Standard Model. The data and expectation for all categories summed together are shown in Fig. 1. No evidence of the decay $H \rightarrow ee$ is observed. The best-fit value of the branching fraction is $(0.0 \pm 1.7(\text{stat.}) \pm 0.6(\text{syst.})) \times 10^{-4}$. The uncertainty is dominated by the statistical uncertainty in the data, while the largest systematic contribution is from the background modelling uncertainty. The observed (expected) upper limit on the branching fraction, computed using a modified frequentist

CL_s method [95,96], at the 95% confidence level, is found to be 3.6×10^{-4} (3.5×10^{-4}). This result is a significant improvement on the previous limit by CMS of 1.9×10^{-3} based on the Run 1 dataset [16].

In the $e\mu$ channel, a similar fit is performed to the observed electron–muon mass spectra divided into 50 $m_{e\mu}$ bins in each of the eight categories. The data and expectation for all categories summed together are shown in Fig. 1. No evidence of the decay $H \rightarrow e\mu$ is observed, with a best-fit value of the branching fraction of $(0.4 \pm 2.9(\text{stat.}) \pm 0.3(\text{syst.})) \times 10^{-5}$. The uncertainty is dominated by the statistical uncertainty in the data, while the largest systematic contribution is from the Higgs boson production cross-section uncertainty. The observed (expected) upper limit at the 95% confidence level is found to be 6.2×10^{-5} (5.9×10^{-5}). This result is a significant improvement on the previous limit by CMS of 3.5×10^{-4} based on the Run 1 dataset [17].

8. Conclusion

Searches are performed for the Higgs boson decays $H \rightarrow ee$ and $H \rightarrow e\mu$ using 139 fb $^{-1}$ of data collected with the ATLAS detector in pp collisions at $\sqrt{s} = 13$ TeV at the LHC. No evidence of either decay is found and observed (expected) upper limits at the 95% confidence level on the branching fractions of 3.6×10^{-4} (3.5×10^{-4}) for $\mathcal{B}(H \rightarrow ee)$ and 6.2×10^{-5} (5.9×10^{-5}) for $\mathcal{B}(H \rightarrow e\mu)$ are obtained for a Higgs boson with mass 125 GeV. These are the first such searches made by the ATLAS Collaboration and are considerable improvements on previous measurements.

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The ATLAS Collaboration

G. Aad¹⁰¹, B. Abbott¹²⁸, D.C. Abbott¹⁰², A. Abed Abud^{70a,70b}, K. Abeling⁵³, D.K. Abhayasinghe⁹³, S.H. Abidi¹⁶⁷, O.S. AbouZeid⁴⁰, N.L. Abraham¹⁵⁶, H. Abramowicz¹⁶¹, H. Abreu¹⁶⁰, Y. Abulaiti⁶, B.S. Acharya^{66a,66b,n}, B. Achkar⁵³, S. Adachi¹⁶³, L. Adam⁹⁹, C. Adam Bourdarios⁵, L. Adamczyk^{83a}, L. Adamek¹⁶⁷, J. Adelman¹²⁰, M. Adersberger¹¹³, A. Adiguzel^{12c}, S. Adorni⁵⁴, T. Adye¹⁴⁴,

A.A. Affolder ¹⁴⁶, Y. Afik ¹⁶⁰, C. Agapopoulou ¹³², M.N. Agaras ³⁸, A. Aggarwal ¹¹⁸, C. Agheorghiesei ^{27c},
 J.A. Aguilar-Saavedra ^{140f,140a,af}, F. Ahmadov ⁷⁹, W.S. Ahmed ¹⁰³, X. Ai ¹⁸, G. Aielli ^{73a,73b}, S. Akatsuka ⁸⁵,
 T.P.A. Åkesson ⁹⁶, E. Akilli ⁵⁴, A.V. Akimov ¹¹⁰, K. Al Khoury ¹³², G.L. Alberghi ^{23b,23a}, J. Albert ¹⁷⁶,
 M.J. Alconada Verzini ¹⁶¹, S. Alderweireldt ³⁶, M. Aleksa ³⁶, I.N. Aleksandrov ⁷⁹, C. Alexa ^{27b},
 T. Alexopoulos ¹⁰, A. Alfonsi ¹¹⁹, F. Alfonsi ^{23b,23a}, M. Alhroob ¹²⁸, B. Ali ¹⁴², M. Aliev ¹⁶⁶, G. Alimonti ^{68a},
 S.P. Alkire ¹⁴⁸, C. Allaire ¹³², B.M.M. Allbrooke ¹⁵⁶, B.W. Allen ¹³¹, P.P. Allport ²¹, A. Aloisio ^{69a,69b},
 A. Alonso ⁴⁰, F. Alonso ⁸⁸, C. Alpigiani ¹⁴⁸, A.A. Alshehri ⁵⁷, M. Alvarez Estevez ⁹⁸, D. Álvarez Piqueras ¹⁷⁴,
 M.G. Alviggi ^{69a,69b}, Y. Amaral Coutinho ^{80b}, A. Ambler ¹⁰³, L. Ambroz ¹³⁵, C. Amelung ²⁶, D. Amidei ¹⁰⁵,
 S.P. Amor Dos Santos ^{140a}, S. Amoroso ⁴⁶, C.S. Amrouche ⁵⁴, F. An ⁷⁸, C. Anastopoulos ¹⁴⁹, N. Andari ¹⁴⁵,
 T. Andeen ¹¹, C.F. Anders ^{61b}, J.K. Anders ²⁰, A. Andreazza ^{68a,68b}, V. Andrei ^{61a}, C.R. Anelli ¹⁷⁶,
 S. Angelidakis ³⁸, A. Angerami ³⁹, A.V. Anisenkov ^{121b,121a}, A. Annovi ^{71a}, C. Antel ⁵⁴, M.T. Anthony ¹⁴⁹,
 E. Antipov ¹²⁹, M. Antonelli ⁵¹, D.J.A. Antrim ¹⁷¹, F. Anulli ^{72a}, M. Aoki ⁸¹, J.A. Aparisi Pozo ¹⁷⁴,
 L. Aperio Bella ^{15a}, J.P. Araque ^{140a}, V. Araujo Ferraz ^{80b}, R. Araujo Pereira ^{80b}, C. Arcangeletti ⁵¹,
 A.T.H. Arce ⁴⁹, F.A. Arduh ⁸⁸, J-F. Arguin ¹⁰⁹, S. Argyropoulos ⁷⁷, J.-H. Arling ⁴⁶, A.J. Armbruster ³⁶,
 A. Armstrong ¹⁷¹, O. Arnaez ¹⁶⁷, H. Arnold ¹¹⁹, Z.P. Arrubarrena Tame ¹¹³, G. Artoni ¹³⁵, S. Artz ⁹⁹,
 S. Asai ¹⁶³, T. Asawatavonvanich ¹⁶⁵, N. Asbah ⁵⁹, E.M. Asimakopoulou ¹⁷², L. Asquith ¹⁵⁶, J. Assahsah ^{35d},
 K. Assamagan ²⁹, R. Astalos ^{28a}, R.J. Atkin ^{33a}, M. Atkinson ¹⁷³, N.B. Atlay ¹⁹, H. Atmani ¹³², K. Augsten ¹⁴²,
 G. Avolio ³⁶, R. Avramidou ^{60a}, M.K. Ayoub ^{15a}, A.M. Azoulay ^{168b}, G. Azuelos ^{109,as}, H. Bachacou ¹⁴⁵,
 K. Bachas ^{67a,67b}, M. Backes ¹³⁵, F. Backman ^{45a,45b}, P. Bagnaia ^{72a,72b}, M. Bahmani ⁸⁴, H. Bahrasemani ¹⁵²,
 A.J. Bailey ¹⁷⁴, V.R. Bailey ¹⁷³, J.T. Baines ¹⁴⁴, M. Bajic ⁴⁰, C. Bakalis ¹⁰, O.K. Baker ¹⁸³, P.J. Bakker ¹¹⁹,
 D. Bakshi Gupta ⁸, S. Balaji ¹⁵⁷, E.M. Baldin ^{121b,121a}, P. Balek ¹⁸⁰, F. Balli ¹⁴⁵, W.K. Balunas ¹³⁵, J. Balz ⁹⁹,
 E. Banas ⁸⁴, A. Bandyopadhyay ²⁴, Sw. Banerjee ^{181,i}, A.A.E. Bannoura ¹⁸², L. Barak ¹⁶¹, W.M. Barbe ³⁸,
 E.L. Barberio ¹⁰⁴, D. Barberis ^{55b,55a}, M. Barbero ¹⁰¹, G. Barbour ⁹⁴, T. Barillari ¹¹⁴, M-S. Barisits ³⁶,
 J. Barkeloo ¹³¹, T. Barklow ¹⁵³, R. Barnea ¹⁶⁰, S.L. Barnes ^{60c}, B.M. Barnett ¹⁴⁴, R.M. Barnett ¹⁸,
 Z. Barnovska-Blenessy ^{60a}, A. Baroncelli ^{60a}, G. Barone ²⁹, A.J. Barr ¹³⁵, L. Barranco Navarro ^{45a,45b},
 F. Barreiro ⁹⁸, J. Barreiro Guimarães da Costa ^{15a}, S. Barsov ¹³⁸, R. Bartoldus ¹⁵³, G. Bartolini ¹⁰¹,
 A.E. Barton ⁸⁹, P. Bartos ^{28a}, A. Basalae ⁴⁶, A. Basan ⁹⁹, A. Bassalat ^{132,am}, M.J. Basso ¹⁶⁷, R.L. Bates ⁵⁷,
 S. Batlamous ^{35e}, J.R. Batley ³², B. Batool ¹⁵¹, M. Battaglia ¹⁴⁶, M. Bauce ^{72a,72b}, F. Bauer ¹⁴⁵, K.T. Bauer ¹⁷¹,
 H.S. Bawa ^{31,l}, J.B. Beacham ⁴⁹, T. Beau ¹³⁶, P.H. Beauchemin ¹⁷⁰, F. Becherer ⁵², P. Bechtel ²⁴, H.C. Beck ⁵³,
 H.P. Beck ^{20,r}, K. Becker ⁵², M. Becker ⁹⁹, C. Becot ⁴⁶, A. Beddall ^{12d}, A.J. Beddall ^{12a}, V.A. Bednyakov ⁷⁹,
 M. Bedognetti ¹¹⁹, C.P. Bee ¹⁵⁵, T.A. Beermann ¹⁸², M. Begalli ^{80b}, M. Begel ²⁹, A. Behera ¹⁵⁵, J.K. Behr ⁴⁶,
 F. Beisiegel ²⁴, A.S. Bell ⁹⁴, G. Bella ¹⁶¹, L. Bellagamba ^{23b}, A. Bellerive ³⁴, P. Bellos ⁹,
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 Y. Benhammou ¹⁶¹, D.P. Benjamin ⁶, M. Benoit ⁵⁴, J.R. Bensinger ²⁶, S. Bentvelsen ¹¹⁹, L. Beresford ¹³⁵,
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 I.A. Bertram ⁸⁹, O. Bessidskaia Bylund ¹⁸², N. Besson ¹⁴⁵, A. Bethani ¹⁰⁰, S. Bethke ¹¹⁴, A. Betti ⁴²,
 A.J. Bevan ⁹², J. Beyer ¹¹⁴, D.S. Bhattacharya ¹⁷⁷, P. Bhattarai ²⁶, R. Bi ¹³⁹, R.M. Bianchi ¹³⁹, O. Biebel ¹¹³,
 D. Biedermann ¹⁹, R. Bielski ³⁶, K. Bierwagen ⁹⁹, N.V. Biesuz ^{71a,71b}, M. Biglietti ^{74a}, T.R.V. Billoud ¹⁰⁹,
 M. Bindi ⁵³, A. Bingul ^{12d}, C. Bini ^{72a,72b}, S. Biondi ^{23b,23a}, M. Birman ¹⁸⁰, T. Bisanz ⁵³, J.P. Biswal ¹⁶¹,
 D. Biswas ^{181,i}, A. Bitadze ¹⁰⁰, C. Bittrich ⁴⁸, K. Bjørke ¹³⁴, K.M. Black ²⁵, T. Blazek ^{28a}, I. Bloch ⁴⁶,
 C. Blocker ²⁶, A. Blue ⁵⁷, U. Blumenschein ⁹², G.J. Bobbink ¹¹⁹, V.S. Bobrovnikov ^{121b,121a}, S.S. Bocchetta ⁹⁶,
 A. Bocci ⁴⁹, D. Boerner ⁴⁶, D. Bogavac ¹⁴, A.G. Bogdanchikov ^{121b,121a}, C. Böhm ^{45a}, V. Boisvert ⁹³,
 P. Bokan ^{53,172}, T. Bold ^{83a}, A.S. Boldyrev ¹¹², A.E. Bolz ^{61b}, M. Bomben ¹³⁶, M. Bona ⁹², J.S. Bonilla ¹³¹,
 M. Boonekamp ¹⁴⁵, C.D. Booth ⁹³, H.M. Borecka-Bielska ⁹⁰, A. Borisov ¹²², G. Borissov ⁸⁹, J. Bortfeldt ³⁶,
 D. Bortoletto ¹³⁵, D. Boscherini ^{23b}, M. Bosman ¹⁴, J.D. Bossio Sola ¹⁰³, K. Bouaouda ^{35a}, J. Boudreau ¹³⁹,
 E.V. Bouhova-Thacker ⁸⁹, D. Boumediene ³⁸, S.K. Boutle ⁵⁷, A. Boveia ¹²⁶, J. Boyd ³⁶, D. Boye ^{33b,an},
 I.R. Boyko ⁷⁹, A.J. Bozson ⁹³, J. Bracinik ²¹, N. Brahimi ¹⁰¹, G. Brandt ¹⁸², O. Brandt ³², F. Braren ⁴⁶,
 B. Brau ¹⁰², J.E. Brau ¹³¹, W.D. Breaden Madden ⁵⁷, K. Brendlinger ⁴⁶, L. Brenner ⁴⁶, R. Brenner ¹⁷²,
 S. Bressler ¹⁸⁰, B. Brickwedde ⁹⁹, D.L. Briglin ²¹, D. Britton ⁵⁷, D. Britzger ¹¹⁴, I. Brock ²⁴, R. Brock ¹⁰⁶,
 G. Brooijmans ³⁹, W.K. Brooks ^{147c}, E. Brost ¹²⁰, J.H. Broughton ²¹, P.A. Bruckman de Renstrom ⁸⁴,
 D. Bruncko ^{28b}, A. Bruni ^{23b}, G. Bruni ^{23b}, L.S. Bruni ¹¹⁹, S. Bruno ^{73a,73b}, M. Bruschi ^{23b}, N. Brusino ^{72a,72b},

P. Bryant³⁷, L. Bryngemark⁹⁶, T. Buanes¹⁷, Q. Buat³⁶, P. Buchholz¹⁵¹, A.G. Buckley⁵⁷, I.A. Budagov⁷⁹, M.K. Bugge¹³⁴, F. Bühner⁵², O. Bulekov¹¹¹, T.J. Burch¹²⁰, S. Burdin⁹⁰, C.D. Burgard¹¹⁹, A.M. Burger¹²⁹, B. Burghgrave⁸, J.T.P. Burr⁴⁶, C.D. Burton¹¹, J.C. Burzynski¹⁰², V. Büscher⁹⁹, E. Buschmann⁵³, P.J. Bussey⁵⁷, J.M. Butler²⁵, C.M. Buttar⁵⁷, J.M. Butterworth⁹⁴, P. Butti³⁶, W. Buttinger³⁶, C.J. Buxo Vazquez¹⁰⁶, A. Buzatu¹⁵⁸, A.R. Buzykaev^{121b,121a}, G. Cabras^{23b,23a}, S. Cabrera Urbán¹⁷⁴, D. Caforio⁵⁶, H. Cai¹⁷³, V.M.M. Cairo¹⁵³, O. Cakir^{4a}, N. Calace³⁶, P. Calafiura¹⁸, A. Calandri¹⁰¹, G. Calderini¹³⁶, P. Calfayan⁶⁵, G. Callea⁵⁷, L.P. Caloba^{80b}, A. Caltabiano^{73a,73b}, S. Calvente Lopez⁹⁸, D. Calvet³⁸, S. Calvet³⁸, T.P. Calvet¹⁵⁵, M. Calvetti^{71a,71b}, R. Camacho Toro¹³⁶, S. Camarda³⁶, D. Camarero Munoz⁹⁸, P. Camarri^{73a,73b}, D. Cameron¹³⁴, R. Caminal Armadans¹⁰², C. Camincher³⁶, S. Campana³⁶, M. Campanelli⁹⁴, A. Camplani⁴⁰, A. Campoverde¹⁵¹, V. Canale^{69a,69b}, A. Canesse¹⁰³, M. Cano Bret^{60c}, J. Cantero¹²⁹, T. Cao¹⁶¹, Y. Cao¹⁷³, M.D.M. Capeans Garrido³⁶, M. Capua^{41b,41a}, R. Cardarelli^{73a}, F. Cardillo¹⁴⁹, G. Carducci^{41b,41a}, I. Carli¹⁴³, T. Carli³⁶, G. Carlino^{69a}, B.T. Carlson¹³⁹, L. Carminati^{68a,68b}, R.M.D. Carney^{45a,45b}, S. Caron¹¹⁸, E. Carquin^{147c}, S. Carrá⁴⁶, J.W.S. Carter¹⁶⁷, M.P. Casado^{14,e}, A.F. Casha¹⁶⁷, D.W. Casper¹⁷¹, R. Castelijm¹¹⁹, F.L. Castillo¹⁷⁴, V. Castillo Gimenez¹⁷⁴, N.F. Castro^{140a,140e}, A. Catinaccio³⁶, J.R. Catmore¹³⁴, A. Cattai³⁶, V. Cavaliere²⁹, E. Cavallaro¹⁴, M. Cavalli-Sforza¹⁴, V. Cavasinni^{71a,71b}, E. Celebi^{12b}, F. Ceradini^{74a,74b}, L. Cerda Alberich¹⁷⁴, K. Cerny¹³⁰, A.S. Cerqueira^{80a}, A. Cerri¹⁵⁶, L. Cerrito^{73a,73b}, F. Cerutti¹⁸, A. Cervelli^{23b,23a}, S.A. Cetin^{12b}, Z. Chadi^{35a}, D. Chakraborty¹²⁰, W.S. Chan¹¹⁹, W.Y. Chan⁹⁰, J.D. Chapman³², B. Chargeishvili^{159b}, D.G. Charlton²¹, T.P. Charman⁹², C.C. Chau³⁴, S. Che¹²⁶, S. Chekanov⁶, S.V. Chekulaev^{168a}, G.A. Chelkov^{79,ar}, M.A. Chelstowska³⁶, B. Chen⁷⁸, C. Chen^{60a}, C.H. Chen⁷⁸, H. Chen²⁹, J. Chen^{60a}, J. Chen³⁹, S. Chen¹³⁷, S.J. Chen^{15c}, X. Chen^{15b}, Y-H. Chen⁴⁶, H.C. Cheng^{63a}, H.J. Cheng^{15a,15d}, A. Cheplakov⁷⁹, E. Cheremushkina¹²², R. Cherkaoui El Moursli^{35e}, E. Cheu⁷, K. Cheung⁶⁴, T.J.A. Chevaléras¹⁴⁵, L. Chevalier¹⁴⁵, V. Chiarella⁵¹, G. Chiarelli^{71a}, G. Chiodini^{67a}, A.S. Chisholm²¹, A. Chitan^{27b}, I. Chiu¹⁶³, Y.H. Chiu¹⁷⁶, M.V. Chizhov⁷⁹, K. Choi⁶⁵, A.R. Chomont^{72a,72b}, S. Chouridou¹⁶², Y.S. Chow¹¹⁹, M.C. Chu^{63a}, X. Chu^{15a}, J. Chudoba¹⁴¹, A.J. Chuinard¹⁰³, J.J. Chwastowski⁸⁴, L. Chytka¹³⁰, D. Cieri¹¹⁴, K.M. Ciesla⁸⁴, D. Cinca⁴⁷, V. Cindro⁹¹, I.A. Cioară^{27b}, A. Ciocio¹⁸, F. Ciotto^{69a,69b}, Z.H. Citron^{180,j}, M. Citterio^{68a}, D.A. Ciubotaru^{27b}, B.M. Ciungu¹⁶⁷, A. Clark⁵⁴, M.R. Clark³⁹, P.J. Clark⁵⁰, C. Clement^{45a,45b}, Y. Coadou¹⁰¹, M. Cobal^{66a,66c}, A. Coccaro^{55b}, J. Cochran⁷⁸, H. Cohen¹⁶¹, A.E.C. Coimbra³⁶, L. Colasurdo¹¹⁸, B. Cole³⁹, A.P. Colijn¹¹⁹, J. Collot⁵⁸, P. Conde Muiño^{140a,140h}, S.H. Connell^{33b}, I.A. Connelly⁵⁷, S. Constantinescu^{27b}, F. Conventi^{69a,at}, A.M. Cooper-Sarkar¹³⁵, F. Cormier¹⁷⁵, K.J.R. Cormier¹⁶⁷, L.D. Corpe⁹⁴, M. Corradi^{72a,72b}, E.E. Corrigan⁹⁶, F. Corriveau^{103,ad}, A. Cortes-Gonzalez³⁶, M.J. Costa¹⁷⁴, F. Costanza⁵, D. Costanzo¹⁴⁹, G. Cowan⁹³, J.W. Cowley³², J. Crane¹⁰⁰, K. Cranmer¹²⁴, S.J. Crawley⁵⁷, R.A. Creager¹³⁷, S. Crépe-Renaudin⁵⁸, F. Crescioli¹³⁶, M. Cristinziani²⁴, V. Croft¹¹⁹, G. Crosetti^{41b,41a}, A. Cueto⁵, T. Cuhadar Donszelmann¹⁴⁹, A.R. Cukierman¹⁵³, W.R. Cunningham⁵⁷, S. Czekierda⁸⁴, P. Czodrowski³⁶, M.J. Da Cunha Sargedas De Sousa^{60b}, J.V. Da Fonseca Pinto^{80b}, C. Da Via¹⁰⁰, W. Dabrowski^{83a}, F. Dachs³⁶, T. Dado^{28a}, S. Dahbi^{35e}, T. Dai¹⁰⁵, C. Dallapiccola¹⁰², M. Dam⁴⁰, G. D'amen²⁹, V. D'Amico^{74a,74b}, J. Damp⁹⁹, J.R. Dandoy¹³⁷, M.F. Daneri³⁰, N.P. Dang^{181,i}, N.S. Dann¹⁰⁰, M. Danninger¹⁷⁵, V. Dao³⁶, G. Darbo^{55b}, O. Dartsis⁵, A. Dattagupta¹³¹, T. Daubney⁴⁶, S. D'Auria^{68a,68b}, C. David⁴⁶, T. Davidek¹⁴³, D.R. Davis⁴⁹, I. Dawson¹⁴⁹, K. De⁸, R. De Asmundis^{69a}, M. De Beurs¹¹⁹, S. De Castro^{23b,23a}, S. De Cecco^{72a,72b}, N. De Groot¹¹⁸, P. de Jong¹¹⁹, H. De la Torre¹⁰⁶, A. De Maria^{15c}, D. De Pedis^{72a}, A. De Salvo^{72a}, U. De Sanctis^{73a,73b}, M. De Santis^{73a,73b}, A. De Santo¹⁵⁶, K. De Vasconcelos Corga¹⁰¹, J.B. De Vivie De Regie¹³², C. Debenedetti¹⁴⁶, D.V. Dedovich⁷⁹, A.M. Deiana⁴², J. Del Peso⁹⁸, Y. Delabat Diaz⁴⁶, D. Delgove¹³², F. Deliot^{145,q}, C.M. Delitzsch⁷, M. Della Pietra^{69a,69b}, D. Della Volpe⁵⁴, A. Dell'Acqua³⁶, L. Dell'Asta^{73a,73b}, M. Delmastro⁵, C. Delporte¹³², P.A. Delsart⁵⁸, D.A. DeMarco¹⁶⁷, S. Demers¹⁸³, M. Demichev⁷⁹, G. Demontigny¹⁰⁹, S.P. Denisov¹²², L. D'Eramo¹³⁶, D. Derendarz⁸⁴, J.E. Derkaoui^{35d}, F. Derue¹³⁶, P. Dervan⁹⁰, K. Desch²⁴, C. Deterre⁴⁶, K. Dette¹⁶⁷, C. Deutsch²⁴, M.R. Devesa³⁰, P.O. Deviveiros³⁶, A. Dewhurst¹⁴⁴, F.A. Di Bello⁵⁴, A. Di Ciaccio^{73a,73b}, L. Di Ciaccio⁵, W.K. Di Clemente¹³⁷, C. Di Donato^{69a,69b}, A. Di Girolamo³⁶, G. Di Gregorio^{71a,71b}, B. Di Micco^{74a,74b}, R. Di Nardo¹⁰², K.F. Di Petrillo⁵⁹, R. Di Sipio¹⁶⁷, D. Di Valentino³⁴, C. Diaconu¹⁰¹, F.A. Dias⁴⁰, T. Dias Do Vale^{140a}, M.A. Diaz^{147a}, J. Dickinson¹⁸, E.B. Diehl¹⁰⁵, J. Dietrich¹⁹, S. Díez Cornell⁴⁶, A. Dimitrievska¹⁸, W. Ding^{15b},

J. Dingfelder²⁴, F. Dittus³⁶, F. Djama¹⁰¹, T. Djobava^{159b}, J.I. Djuvsland¹⁷, M.A.B. Do Vale^{80c}, M. Dobre^{27b}, D. Dodsworth²⁶, C. Doglioni⁹⁶, J. Dolejsi¹⁴³, Z. Dolezal¹⁴³, M. Donadelli^{80d}, B. Dong^{60c}, J. Donini³⁸, A. D'Onofrio^{15c}, M. D'Onofrio⁹⁰, J. Dopke¹⁴⁴, A. Doria^{69a}, M.T. Dova⁸⁸, A.T. Doyle⁵⁷, E. Drechsler¹⁵², E. Dreyer¹⁵², T. Dreyer⁵³, A.S. Drobac¹⁷⁰, D. Du^{60b}, Y. Duan^{60b}, F. Dubinin¹¹⁰, M. Dubovsky^{28a}, A. Dubreuil⁵⁴, E. Duchovni¹⁸⁰, G. Duckeck¹¹³, A. Ducourthial¹³⁶, O.A. Ducu¹⁰⁹, D. Duda¹¹⁴, A. Dudarev³⁶, A.C. Dudder⁹⁹, E.M. Duffield¹⁸, L. Duflot¹³², M. Dührssen³⁶, C. Dülsen¹⁸², M. Dumancic¹⁸⁰, A.E. Dumitriu^{27b}, A.K. Duncan⁵⁷, M. Dunford^{61a}, A. Duperrin¹⁰¹, H. Duran Yildiz^{4a}, M. Düren⁵⁶, A. Durglishvili^{159b}, D. Duschinger⁴⁸, B. Dutta⁴⁶, D. Duvnjak¹, G.I. Dyckes¹³⁷, M. Dyndal³⁶, S. Dysch¹⁰⁰, B.S. Dziedzic⁸⁴, K.M. Ecker¹¹⁴, R.C. Edgar¹⁰⁵, M.G. Eggleston⁴⁹, T. Eifert³⁶, G. Eigen¹⁷, K. Einsweiler¹⁸, T. Ekelof¹⁷², H. El Jarrari^{35e}, M. El Kacimi^{35c}, R. El Kosseifi¹⁰¹, V. Ellajosyula¹⁷², M. Ellert¹⁷², F. Ellinghaus¹⁸², A.A. Elliot⁹², N. Ellis³⁶, J. Elmsheuser²⁹, M. Elsing³⁶, D. Emelianov¹⁴⁴, A. Emerman³⁹, Y. Enari¹⁶³, M.B. Epland⁴⁹, J. Erdmann⁴⁷, A. Ereditato²⁰, M. Errenst³⁶, M. Escalier¹³², C. Escobar¹⁷⁴, O. Estrada Pastor¹⁷⁴, E. Etzion¹⁶¹, H. Evans⁶⁵, A. Ezhilov¹³⁸, F. Fabbri⁵⁷, L. Fabbri^{23b,23a}, V. Fabiani¹¹⁸, G. Facini⁹⁴, R.M. Faisca Rodrigues Pereira^{140a}, R.M. Fakhruddinov¹²², S. Falciano^{72a}, P.J. Falke⁵, S. Falke⁵, J. Faltova¹⁴³, Y. Fang^{15a}, Y. Fang^{15a}, G. Fanourakis⁴⁴, M. Fanti^{68a,68b}, M. Faraj^{66a,66c,t}, A. Farbin⁸, A. Farilla^{74a}, E.M. Farina^{70a,70b}, T. Farooque¹⁰⁶, S. Farrell¹⁸, S.M. Farrington⁵⁰, P. Farthouat³⁶, F. Fassi^{35e}, P. Fassnacht³⁶, D. Fassouliotis⁹, M. Fauci Giannelli⁵⁰, W.J. Fawcett³², L. Fayard¹³², O.L. Fedin^{138,o}, W. Fedorko¹⁷⁵, A. Fehr²⁰, M. Feickert⁴², L. Feligioni¹⁰¹, A. Fell¹⁴⁹, C. Feng^{60b}, M. Feng⁴⁹, M.J. Fenton⁵⁷, A.B. Fenyuk¹²², S.W. Ferguson⁴³, J. Ferrando⁴⁶, A. Ferrante¹⁷³, A. Ferrari¹⁷², P. Ferrari¹¹⁹, R. Ferrari^{70a}, D.E. Ferreira de Lima^{61b}, A. Ferrer¹⁷⁴, D. Ferrere⁵⁴, C. Ferretti¹⁰⁵, F. Fiedler⁹⁹, A. Filipčič⁹¹, F. Filthaut¹¹⁸, K.D. Finelli²⁵, M.C.N. Fiolhais^{140a,140c,a}, L. Fiorini¹⁷⁴, F. Fischer¹¹³, W.C. Fisher¹⁰⁶, I. Fleck¹⁵¹, P. Fleischmann¹⁰⁵, R.R.M. Fletcher¹³⁷, T. Flick¹⁸², B.M. Flierl¹¹³, L. Flores¹³⁷, L.R. Flores Castillo^{63a}, F.M. Follega^{75a,75b}, N. Fomin¹⁷, J.H. Foo¹⁶⁷, G.T. Forcolin^{75a,75b}, A. Formica¹⁴⁵, F.A. Förster¹⁴, A.C. Forti¹⁰⁰, A.G. Foster²¹, M.G. Foti¹³⁵, D. Fournier¹³², H. Fox⁸⁹, P. Francavilla^{71a,71b}, S. Francescato^{72a,72b}, M. Franchini^{23b,23a}, S. Franchino^{61a}, D. Francis³⁶, L. Franconi²⁰, M. Franklin⁵⁹, A.N. Fray⁹², P.M. Freeman²¹, B. Freund¹⁰⁹, W.S. Freund^{80b}, E.M. Freundlich⁴⁷, D.C. Frizzell¹²⁸, D. Froidevaux³⁶, J.A. Frost¹³⁵, C. Fukunaga¹⁶⁴, E. Fullana Torregrosa¹⁷⁴, E. Fumagalli^{55b,55a}, T. Fusayasu¹¹⁵, J. Fuster¹⁷⁴, A. Gabrielli^{23b,23a}, A. Gabrielli¹⁸, S. Gadatsch⁵⁴, P. Gadow¹¹⁴, G. Gagliardi^{55b,55a}, L.G. Gagnon¹⁰⁹, C. Galea^{27b}, B. Galhardo^{140a}, G.E. Gallardo¹³⁵, E.J. Gallas¹³⁵, B.J. Gallop¹⁴⁴, G. Galster⁴⁰, R. Gamboa Goni⁹², K.K. Gan¹²⁶, S. Ganguly¹⁸⁰, J. Gao^{60a}, Y. Gao⁵⁰, Y.S. Gao^{31,l}, C. García¹⁷⁴, J.E. García Navarro¹⁷⁴, J.A. García Pascual^{15a}, C. Garcia-Argos⁵², M. Garcia-Sciveres¹⁸, R.W. Gardner³⁷, N. Garelli¹⁵³, S. Gargiulo⁵², C.A. Garner¹⁶⁷, V. Garonne¹³⁴, S.J. Gasiorowski¹⁴⁸, P. Gaspar^{80b}, A. Gaudiello^{55b,55a}, G. Gaudio^{70a}, I.L. Gavrilenko¹¹⁰, A. Gavrilyuk¹²³, C. Gay¹⁷⁵, G. Gaycken⁴⁶, E.N. Gazis¹⁰, A.A. Geanta^{27b}, C.M. Gee¹⁴⁶, C.N.P. Gee¹⁴⁴, J. Geisen⁵³, M. Geisen⁹⁹, C. Gemme^{55b}, M.H. Genest⁵⁸, C. Geng¹⁰⁵, S. Gentile^{72a,72b}, S. George⁹³, T. Gerialis⁴⁴, L.O. Gerlach⁵³, P. Gessinger-Befurt⁹⁹, G. Gessner⁴⁷, S. Ghasemi¹⁵¹, M. Ghasemi Bostanabad¹⁷⁶, M. Ghneimat¹⁵¹, A. Ghosh¹³², A. Ghosh⁷⁷, B. Giacobbe^{23b}, S. Giagu^{72a,72b}, N. Giangiacomi^{23b,23a}, P. Giannetti^{71a}, A. Giannini^{69a,69b}, G. Giannini¹⁴, S.M. Gibson⁹³, M. Gignac¹⁴⁶, D. Gillberg³⁴, G. Gilles¹⁸², D.M. Gingrich^{3,as}, M.P. Giordani^{66a,66c}, F.M. Giorgi^{23b}, P.F. Giraud¹⁴⁵, G. Giugliarelli^{66a,66c}, D. Giugni^{68a}, F. Giuli^{73a,73b}, S. Gkaitatzis¹⁶², I. Gkialas^{9,g}, E.L. Gkougkousis¹⁴, P. Gkoutoumis¹⁰, L.K. Gladilin¹¹², C. Glasman⁹⁸, J. Glatzer¹⁴, P.C.F. Glaysheer⁴⁶, A. Glazov⁴⁶, G.R. Gledhill¹³¹, M. Goblirsch-Kolb²⁶, D. Godin¹⁰⁹, S. Goldfarb¹⁰⁴, T. Golling⁵⁴, D. Golubkov¹²², A. Gomes^{140a,140b}, R. Goncalves Gama⁵³, R. Gonçalves^{140a,140b}, G. Gonella⁵², L. Gonella²¹, A. Gongadze⁷⁹, F. Gonnella²¹, J.L. Gonski³⁹, S. González de la Hoz¹⁷⁴, S. Gonzalez-Sevilla⁵⁴, G.R. Gonzalvo Rodriguez¹⁷⁴, L. Goossens³⁶, N.A. Gorasia²¹, P.A. Gorbounov¹²³, H.A. Gordon²⁹, B. Gorini³⁶, E. Gorini^{67a,67b}, A. Gorišek⁹¹, A.T. Goshaw⁴⁹, M.I. Gostkin⁷⁹, C.A. Gottardo¹¹⁸, M. Gouighri^{35b}, D. Goujdami^{35c}, A.G. Goussiou¹⁴⁸, N. Govender^{33b}, C. Goy⁵, E. Gozani¹⁶⁰, I. Grabowska-Bold^{83a}, E.C. Graham⁹⁰, J. Gramling¹⁷¹, E. Gramstad¹³⁴, S. Grancagnolo¹⁹, M. Grandi¹⁵⁶, V. Gratchev¹³⁸, P.M. Gravila^{27f}, F.G. Gravili^{67a,67b}, C. Gray⁵⁷, H.M. Gray¹⁸, C. Grefe²⁴, K. Gregersen⁹⁶, I.M. Gregor⁴⁶, P. Grenier¹⁵³, K. Grevtsov⁴⁶, C. Grieco¹⁴, N.A. Grieser¹²⁸, A.A. Grillo¹⁴⁶, K. Grimm^{31,k}, S. Grinstein^{14,y}, J.-F. Grivaz¹³², S. Groh⁹⁹, E. Gross¹⁸⁰, J. Grosse-Knetter⁵³, Z.J. Grout⁹⁴, C. Grud¹⁰⁵, A. Grummer¹¹⁷, L. Guan¹⁰⁵, W. Guan¹⁸¹, C. Gubbels¹⁷⁵, J. Guenther³⁶, A. Guerguichon¹³²

J.G.R. Guerrero Rojas¹⁷⁴, F. Guescini¹¹⁴, D. Guest¹⁷¹, R. Gugel⁵², T. Guillemin⁵, S. Guindon³⁶, U. Gul⁵⁷, J. Guo^{60c}, W. Guo¹⁰⁵, Y. Guo^{60a,s}, Z. Guo¹⁰¹, R. Gupta⁴⁶, S. Gurbuz^{12c}, G. Gustavino¹²⁸, M. Guth⁵², P. Gutierrez¹²⁸, C. Gutsche⁹⁴, C. Guyot¹⁴⁵, C. Gwenlan¹³⁵, C.B. Gwilliam⁹⁰, A. Haas¹²⁴, C. Haber¹⁸, H.K. Hadavand⁸, N. Haddad^{35e}, A. Hadeef^{60a}, S. Hageböck³⁶, M. Haleem¹⁷⁷, J. Haley¹²⁹, G. Halladjian¹⁰⁶, G.D. Hallewell¹⁰¹, K. Hamacher¹⁸², P. Hamal¹³⁰, K. Hamano¹⁷⁶, H. Hamdaoui^{35e}, M. Hamer²⁴, G.N. Hamity⁵⁰, K. Han^{60a,ah}, L. Han^{60a}, S. Han^{15a,15d}, Y.F. Han¹⁶⁷, K. Hanagaki^{81,w}, M. Hance¹⁴⁶, D.M. Handl¹¹³, B. Haney¹³⁷, R. Hankache¹³⁶, E. Hansen⁹⁶, J.B. Hansen⁴⁰, J.D. Hansen⁴⁰, M.C. Hansen²⁴, P.H. Hansen⁴⁰, E.C. Hanson¹⁰⁰, K. Hara¹⁶⁹, T. Harenberg¹⁸², S. Harkusha¹⁰⁷, P.F. Harrison¹⁷⁸, N.M. Hartmann¹¹³, Y. Hasegawa¹⁵⁰, A. Hasib⁵⁰, S. Hassani¹⁴⁵, S. Haug²⁰, R. Hauser¹⁰⁶, L.B. Havener³⁹, M. Havranek¹⁴², C.M. Hawkes²¹, R.J. Hawkins³⁶, D. Hayden¹⁰⁶, C. Hayes¹⁰⁵, R.L. Hayes¹⁷⁵, C.P. Hays¹³⁵, J.M. Hays⁹², H.S. Hayward⁹⁰, S.J. Haywood¹⁴⁴, F. He^{60a}, M.P. Heath⁵⁰, V. Hedberg⁹⁶, L. Heelan⁸, S. Heer²⁴, K.K. Heidegger⁵², W.D. Heidorn⁷⁸, J. Heilman³⁴, S. Heim⁴⁶, T. Heim¹⁸, B. Heinemann^{46,ao}, J.J. Heinrich¹³¹, L. Heinrich³⁶, J. Hejbal¹⁴¹, L. Helary^{61b}, A. Held¹⁷⁵, S. Hellesund¹³⁴, C.M. Helling¹⁴⁶, S. Hellman^{45a,45b}, C. Hensens³⁶, R.C.W. Henderson⁸⁹, Y. Heng¹⁸¹, L. Henkelmann^{61a}, S. Henkelmann¹⁷⁵, A.M. Henriques Correia³⁶, G.H. Herbert¹⁹, H. Herde²⁶, V. Herget¹⁷⁷, Y. Hernández Jiménez^{33c}, H. Herr⁹⁹, M.G. Herrmann¹¹³, T. Herrmann⁴⁸, G. Herten⁵², R. Hertenberger¹¹³, L. Hervas³⁶, T.C. Herwig¹³⁷, G.G. Hesketh⁹⁴, N.P. Hessey^{168a}, A. Higashida¹⁶³, S. Higashino⁸¹, E. Higón-Rodríguez¹⁷⁴, K. Hildebrand³⁷, E. Hill¹⁷⁶, J.C. Hill³², K.K. Hill²⁹, K.H. Hiller⁴⁶, S.J. Hillier²¹, M. Hils⁴⁸, I. Hinchliffe¹⁸, F. Hinterkeuser²⁴, M. Hirose¹³³, S. Hirose⁵², D. Hirschbuehl¹⁸², B. Hiti⁹¹, O. Hladik¹⁴¹, D.R. Hlaluku^{33c}, X. Hoad⁵⁰, J. Hobbs¹⁵⁵, N. Hod¹⁸⁰, M.C. Hodgkinson¹⁴⁹, A. Hoecker³⁶, D. Hohn⁵², D. Hohov¹³², T. Holm²⁴, T.R. Holmes³⁷, M. Holzbock¹¹³, L.B.A.H. Hommels³², S. Honda¹⁶⁹, T.M. Hong¹³⁹, J.C. Honig⁵², A. Hönle¹¹⁴, B.H. Hooberman¹⁷³, W.H. Hopkins⁶, Y. Horii¹¹⁶, P. Horn⁴⁸, L.A. Horyn³⁷, S. Hou¹⁵⁸, A. Hoummada^{35a}, J. Howarth¹⁰⁰, J. Hoya⁸⁸, M. Hrabovsky¹³⁰, J. Hrdinka⁷⁶, I. Hristova¹⁹, J. Hrivnac¹³², A. Hrynevich¹⁰⁸, T. Hryn'ova⁵, P.J. Hsu⁶⁴, S.-C. Hsu¹⁴⁸, Q. Hu²⁹, S. Hu^{60c}, Y.F. Hu^{15a}, D.P. Huang⁹⁴, Y. Huang^{60a}, Y. Huang^{15a}, Z. Hubacek¹⁴², F. Hubaut¹⁰¹, M. Huebner²⁴, F. Huegging²⁴, T.B. Huffman¹³⁵, M. Huhtinen³⁶, R.F.H. Hunter³⁴, P. Huo¹⁵⁵, A.M. Hupe³⁴, N. Huseynov^{79,ae}, J. Huston¹⁰⁶, J. Huth⁵⁹, R. Hyneman¹⁰⁵, S. Hyrych^{28a}, G. Iacobucci⁵⁴, G. Iakovidis²⁹, I. Ibragimov¹⁵¹, L. Iconomidou-Fayard¹³², Z. Idrissi^{35e}, P. Iengo³⁶, R. Ignazzi⁴⁰, O. Igonkina^{119,aa,*}, R. Iguchi¹⁶³, T. Iizawa⁵⁴, Y. Ikegami⁸¹, M. Ikeno⁸¹, D. Iliadis¹⁶², N. Ilic^{118,167,ad}, F. Iltzsche⁴⁸, G. Introzzi^{70a,70b}, M. Iodice^{74a}, K. Iordanidou^{168a}, V. Ippolito^{72a,72b}, M.F. Isacson¹⁷², M. Ishino¹⁶³, W. Islam¹²⁹, C. Issever^{19,46}, S. Istin¹⁶⁰, F. Ito¹⁶⁹, J.M. Iturbe Ponce^{63a}, R. Iuppa^{75a,75b}, A. Ivina¹⁸⁰, H. Iwasaki⁸¹, J.M. Izen⁴³, V. Izzo^{69a}, P. Jacka¹⁴¹, P. Jackson¹, R.M. Jacobs²⁴, B.P. Jaeger¹⁵², V. Jain², G. Jäkel¹⁸², K.B. Jakobi⁹⁹, K. Jakobs⁵², T. Jakoubek¹⁴¹, J. Jamieson⁵⁷, K.W. Janas^{83a}, R. Jansky⁵⁴, J. Janssen²⁴, M. Janus⁵³, P.A. Janus^{83a}, G. Jarlskog⁹⁶, N. Javadov^{79,ae}, T. Javůrek³⁶, M. Javůrkova¹⁰², F. Jeanneau¹⁴⁵, L. Jeanty¹³¹, J. Jejelava^{159a}, A. Jelinskas¹⁷⁸, P. Jenni^{52,b}, J. Jeong⁴⁶, N. Jeong⁴⁶, S. Jézéquel⁵, H. Ji¹⁸¹, J. Jia¹⁵⁵, H. Jiang⁷⁸, Y. Jiang^{60a}, Z. Jiang^{153,p}, S. Jiggins⁵², F.A. Jimenez Morales³⁸, J. Jimenez Pena¹¹⁴, S. Jin^{15c}, A. Jinaru^{27b}, O. Jinnouchi¹⁶⁵, H. Jivan^{33c}, P. Johansson¹⁴⁹, K.A. Johns⁷, C.A. Johnson⁶⁵, K. Jon-And^{45a,45b}, R.W.L. Jones⁸⁹, S.D. Jones¹⁵⁶, S. Jones⁷, T.J. Jones⁹⁰, J. Jongmanns^{61a}, P.M. Jorge^{140a}, J. Jovicevic³⁶, X. Ju¹⁸, J.J. Junggeburth¹¹⁴, A. Juste Rozas^{14,y}, A. Kaczmarska⁸⁴, M. Kado^{72a,72b}, H. Kagan¹²⁶, M. Kagan¹⁵³, A. Kahn³⁹, C. Kahra⁹⁹, T. Kaji¹⁷⁹, E. Kajomovitz¹⁶⁰, C.W. Kalderon⁹⁶, A. Kaluza⁹⁹, A. Kamenshchikov¹²², M. Kaneda¹⁶³, N.J. Kang¹⁴⁶, L. Kanjir⁹¹, Y. Kano¹¹⁶, V.A. Kantserov¹¹¹, J. Kanzaki⁸¹, L.S. Kaplan¹⁸¹, D. Kar^{33c}, K. Karava¹³⁵, M.J. Kareem^{168b}, S.N. Karpov⁷⁹, Z.M. Karpova⁷⁹, V. Kartvelishvili⁸⁹, A.N. Karyukhin¹²², L. Kashif¹⁸¹, R.D. Kass¹²⁶, A. Kastanas^{45a,45b}, C. Kato^{60d,60c}, J. Katzy⁴⁶, K. Kawade¹⁵⁰, K. Kawagoe⁸⁷, T. Kawaguchi¹¹⁶, T. Kawamoto¹⁶³, G. Kawamura⁵³, E.F. Kay¹⁷⁶, V.F. Kazanin^{121b,121a}, R. Keeler¹⁷⁶, R. Kehoe⁴², J.S. Keller³⁴, E. Kellermann⁹⁶, D. Kelsey¹⁵⁶, J.J. Kempster²¹, J. Kendrick²¹, K.E. Kennedy³⁹, O. Kepka¹⁴¹, S. Kersten¹⁸², B.P. Kerševan⁹¹, S. Ketabchi Haghighat¹⁶⁷, M. Khader¹⁷³, F. Khalil-Zada¹³, M. Khandoga¹⁴⁵, A. Khanov¹²⁹, A.G. Kharlamov^{121b,121a}, T. Kharlamova^{121b,121a}, E.E. Khoda¹⁷⁵, A. Khodinov¹⁶⁶, T.J. Khoo⁵⁴, E. Khramov⁷⁹, J. Khubua^{159b}, S. Kido⁸², M. Kiehn⁵⁴, C.R. Kilby⁹³, Y.K. Kim³⁷, N. Kimura⁹⁴, O.M. Kind¹⁹, B.T. King^{90,*}, D. Kirchmeier⁴⁸, J. Kirk¹⁴⁴, A.E. Kiryunin¹¹⁴, T. Kishimoto¹⁶³, D.P. Kisliuk¹⁶⁷, V. Kitali⁴⁶, O. Kivernyk⁵, T. Klapdor-Kleingrothaus⁵², M. Klassen^{61a}, M.H. Klein¹⁰⁵, M. Klein⁹⁰, U. Klein⁹⁰, K. Kleinknecht⁹⁹, P. Klimek¹²⁰, A. Klimentov²⁹, T. Klingl²⁴, T. Klioutchnikova³⁶,

F.F. Klitzner¹¹³, P. Kluit¹¹⁹, S. Kluth¹¹⁴, E. Kneringer⁷⁶, E.B.F.G. Knoops¹⁰¹, A. Knue⁵², D. Kobayashi⁸⁷, T. Kobayashi¹⁶³, M. Kobel⁴⁸, M. Kocian¹⁵³, P. Kodys¹⁴³, P.T. Koenig²⁴, T. Koffas³⁴, N.M. Köhler³⁶, T. Koi¹⁵³, M. Kolb¹⁴⁵, I. Koletsou⁵, T. Komarek¹³⁰, T. Kondo⁸¹, K. Köneke⁵², A.X.Y. Kong¹, A.C. König¹¹⁸, T. Kono¹²⁵, R. Konoplich^{124.aj}, V. Konstantinides⁹⁴, N. Konstantinidis⁹⁴, B. Konya⁹⁶, R. Kopeliansky⁶⁵, S. Koperny^{83a}, K. Korcyl⁸⁴, K. Kordas¹⁶², G. Koren¹⁶¹, A. Korn⁹⁴, I. Korolkov¹⁴, E.V. Korolkova¹⁴⁹, N. Korotkova¹¹², O. Kortner¹¹⁴, S. Kortner¹¹⁴, T. Kosek¹⁴³, V.V. Kostyukhin¹⁶⁶, A. Kotsokechagia¹³², A. Kotwal⁴⁹, A. Koulouris¹⁰, A. Kourkoumeli-Charalampidi^{70a,70b}, C. Kourkoumelis⁹, E. Kourlitis¹⁴⁹, V. Kouskoura²⁹, A.B. Kowalewska⁸⁴, R. Kowalewski¹⁷⁶, C. Kozakai¹⁶³, W. Kozanecki¹⁴⁵, A.S. Kozhin¹²², V.A. Kramarenko¹¹², G. Kramberger⁹¹, D. Krasnopevtsev^{60a}, M.W. Krasny¹³⁶, A. Krasznahorkay³⁶, D. Krauss¹¹⁴, J.A. Kremer^{83a}, J. Kretzschmar⁹⁰, P. Krieger¹⁶⁷, F. Krieter¹¹³, A. Krishnan^{61b}, K. Krizka¹⁸, K. Kroeninger⁴⁷, H. Kroha¹¹⁴, J. Kroll¹⁴¹, J. Kroll¹³⁷, K.S. Krowpman¹⁰⁶, J. Krstic¹⁶, U. Kruchonak⁷⁹, H. Krüger²⁴, N. Krumnack⁷⁸, M.C. Kruse⁴⁹, J.A. Krzysiak⁸⁴, T. Kubota¹⁰⁴, O. Kuchinskaia¹⁶⁶, S. Kuday^{4b}, J.T. Kuechler⁴⁶, S. Kuehn³⁶, A. Kugel^{61a}, T. Kuhl⁴⁶, V. Kukhtin⁷⁹, R. Kukla¹⁰¹, Y. Kulchitsky^{107.ag}, S. Kuleshov^{147c}, Y.P. Kulinich¹⁷³, M. Kuna⁵⁸, T. Kunigo⁸⁵, A. Kupco¹⁴¹, T. Kupfer⁴⁷, O. Kuprash⁵², H. Kurashige⁸², L.L. Kurchaninov^{168a}, Y.A. Kurochkin¹⁰⁷, A. Kurova¹¹¹, M.G. Kurth^{15a,15d}, E.S. Kuwertz³⁶, M. Kuze¹⁶⁵, A.K. Kvam¹⁴⁸, J. Kvita¹³⁰, T. Kwan¹⁰³, A. La Rosa¹¹⁴, L. La Rotonda^{41b,41a}, F. La Ruffa^{41b,41a}, C. Lacasta¹⁷⁴, F. Lacava^{72a,72b}, D.P.J. Lack¹⁰⁰, H. Lacker¹⁹, D. Lacour¹³⁶, E. Ladygin⁷⁹, R. Lafaye⁵, B. Laforge¹³⁶, T. Lagouri^{33c}, S. Lai⁵³, I.K. Lakomic^{83a}, S. Lammers⁶⁵, W. Lampl⁷, C. Lampoudis¹⁶², E. Lançon²⁹, U. Landgraf⁵², M.P.J. Landon⁹², M.C. Lanfermann⁵⁴, V.S. Lang⁴⁶, J.C. Lange⁵³, R.J. Langenberg¹⁰², A.J. Lankford¹⁷¹, F. Lanni²⁹, K. Lantzsch²⁴, A. Lanza^{70a}, A. Lapertosa^{55b,55a}, S. Laplace¹³⁶, J.F. Laporte¹⁴⁵, T. Lari^{68a}, F. Lasagni Manghi^{23b,23a}, M. Lassnig³⁶, T.S. Lau^{63a}, A. Laudrain¹³², A. Laurier³⁴, M. Lavourga^{69a,69b}, S.D. Lawlor⁹³, M. Lazzaroni^{68a,68b}, B. Le¹⁰⁴, E. Le Guirriec¹⁰¹, M. LeBlanc⁷, T. LeCompte⁶, F. Ledroit-Guillon⁵⁸, A.C.A. Lee⁹⁴, C.A. Lee²⁹, G.R. Lee¹⁷, L. Lee⁵⁹, S.C. Lee¹⁵⁸, S.J. Lee³⁴, S. Lee⁷⁸, B. Lefebvre^{168a}, H.P. Lefebvre⁹³, M. Lefebvre¹⁷⁶, F. Legger¹¹³, C. Leggett¹⁸, K. Lehmann¹⁵², N. Lehmann¹⁸², G. Lehmann Miotto³⁶, W.A. Leight⁴⁶, A. Leisos^{162,x}, M.A.L. Leite^{80d}, C.E. Leitgeb¹¹³, R. Leitner¹⁴³, D. Lellouch^{180,*}, K.J.C. Leney⁴², T. Lenz²⁴, R. Leone⁷, S. Leone^{71a}, C. Leonidopoulos⁵⁰, A. Leopold¹³⁶, C. Leroy¹⁰⁹, R. Les¹⁶⁷, C.G. Lester³², M. Levchenko¹³⁸, J. Levêque⁵, D. Levin¹⁰⁵, L.J. Levinson¹⁸⁰, D.J. Lewis²¹, B. Li^{15b}, B. Li¹⁰⁵, C-Q. Li^{60a}, F. Li^{60c}, H. Li^{60a}, H. Li^{60b}, J. Li^{60c}, K. Li¹⁵³, L. Li^{60c}, M. Li^{15a}, Q. Li^{15a,15d}, Q.Y. Li^{60a}, S. Li^{60d,60c}, X. Li⁴⁶, Y. Li⁴⁶, Z. Li^{60b}, Z. Liang^{15a}, B. Liberti^{73a}, A. Liblong¹⁶⁷, K. Lie^{63c}, S. Lim²⁹, C.Y. Lin³², K. Lin¹⁰⁶, T.H. Lin⁹⁹, R.A. Linck⁶⁵, J.H. Lindon²¹, A.L. Lioni⁵⁴, E. Lipeles¹³⁷, A. Lipniacka¹⁷, T.M. Liss^{173,ag}, A. Lister¹⁷⁵, A.M. Litke¹⁴⁶, J.D. Little⁸, B. Liu⁷⁸, B.L. Liu⁶, H.B. Liu²⁹, H. Liu¹⁰⁵, J.B. Liu^{60a}, J.K.K. Liu¹³⁵, K. Liu¹³⁶, M. Liu^{60a}, P. Liu¹⁸, Y. Liu^{15a,15d}, Y.L. Liu¹⁰⁵, Y.W. Liu^{60a}, M. Livan^{70a,70b}, A. Lleres⁵⁸, J. Llorente Merino¹⁵², S.L. Lloyd⁹², C.Y. Lo^{63b}, F. Lo Sterzo⁴², E.M. Lobodzinska⁴⁶, P. Loch⁷, S. Loffredo^{73a,73b}, T. Lohse¹⁹, K. Lohwasser¹⁴⁹, M. Lokajicek¹⁴¹, J.D. Long¹⁷³, R.E. Long⁸⁹, L. Longo³⁶, K.A. Looper¹²⁶, J.A. Lopez^{147c}, I. Lopez Paz¹⁰⁰, A. Lopez Solis¹⁴⁹, J. Lorenz¹¹³, N. Lorenzo Martinez⁵, A.M. Lory¹¹³, M. Losada²², P.J. Lösel¹¹³, A. Lösle⁵², X. Lou⁴⁶, X. Lou^{15a}, A. Lounis¹³², J. Love⁶, P.A. Love⁸⁹, J.J. Lozano Bahilo¹⁷⁴, M. Lu^{60a}, Y.J. Lu⁶⁴, H.J. Lubatti¹⁴⁸, C. Luci^{72a,72b}, A. Lucotte⁵⁸, C. Luedtke⁵², F. Luehring⁶⁵, I. Luise¹³⁶, L. Luminari^{72a}, B. Lund-Jensen¹⁵⁴, M.S. Lutz¹⁰², D. Lynn²⁹, H. Lyons⁹⁰, R. Lysak¹⁴¹, E. Lytken⁹⁶, F. Lyu^{15a}, V. Lyubushkin⁷⁹, T. Lyubushkina⁷⁹, H. Ma²⁹, L.L. Ma^{60b}, Y. Ma^{60b}, G. Maccarrone⁵¹, A. Macchiolo¹¹⁴, C.M. Macdonald¹⁴⁹, J. Machado Miguens¹³⁷, D. Madaffari¹⁷⁴, R. Madar³⁸, W.F. Mader⁴⁸, M. Madugoda Ralalage Don¹²⁹, N. Madysa⁴⁸, J. Maeda⁸², T. Maeno²⁹, M. Maerker⁴⁸, A.S. Maevskiy¹¹², V. Magerl⁵², N. Magini⁷⁸, D.J. Mahon³⁹, C. Maidantchik^{80b}, T. Maier¹¹³, A. Maio^{140a,140b,140d}, K. Maj^{83a}, O. Majersky^{28a}, S. Majewski¹³¹, Y. Makida⁸¹, N. Makovec¹³², B. Malaescu¹³⁶, Pa. Malecki⁸⁴, V.P. Maleev¹³⁸, F. Malek⁵⁸, U. Mallik⁷⁷, D. Malon⁶, C. Malone³², S. Maltezos¹⁰, S. Malyukov⁷⁹, J. Mamuzic¹⁷⁴, G. Mancini⁵¹, I. Mandić⁹¹, L. Manhaes de Andrade Filho^{80a}, I.M. Maniatis¹⁶², J. Manjarres Ramos⁴⁸, K.H. Mankinen⁹⁶, A. Mann¹¹³, A. Manousos⁷⁶, B. Mansoulie¹⁴⁵, I. Manthos¹⁶², S. Manzoni¹¹⁹, A. Marantis¹⁶², G. Marceca³⁰, L. Marchese¹³⁵, G. Marchiori¹³⁶, M. Marcisovsky¹⁴¹, L. Marcocchia^{73a,73b}, C. Marcon⁹⁶, C.A. Marin Tobon³⁶, M. Marjanovic¹²⁸, Z. Marshall¹⁸, M.U.F. Martensson¹⁷², S. Marti-Garcia¹⁷⁴, C.B. Martin¹²⁶, T.A. Martin¹⁷⁸, V.J. Martin⁵⁰, B. Martin dit Latour¹⁷, L. Martinelli^{74a,74b}, M. Martinez^{14.y}, V.I. Martinez Outschoorn¹⁰², S. Martin-Haugh¹⁴⁴, V.S. Martoiu^{27b}, A.C. Martyniuk⁹⁴,

A. Marzin³⁶, S.R. Maschek¹¹⁴, L. Masetti⁹⁹, T. Mashimo¹⁶³, R. Mashinistov¹¹⁰, J. Masik¹⁰⁰,
 A.L. Maslennikov^{121b,121a}, L. Massa^{73a,73b}, P. Massarotti^{69a,69b}, P. Mastrandrea^{71a,71b},
 A. Mastroberardino^{41b,41a}, T. Masubuchi¹⁶³, D. Matakias¹⁰, A. Matic¹¹³, N. Matsuzawa¹⁶³, P. Mättig²⁴,
 J. Maurer^{27b}, B. Maček⁹¹, D.A. Maximov^{121b,121a}, R. Mazini¹⁵⁸, I. Maznas¹⁶², S.M. Mazza¹⁴⁶,
 S.P. Mc Kee¹⁰⁵, T.G. McCarthy¹¹⁴, W.P. McCormack¹⁸, E.F. McDonald¹⁰⁴, J.A. MCFayden³⁶,
 G. Mchedlidze^{159b}, M.A. McKay⁴², K.D. McLean¹⁷⁶, S.J. McMahon¹⁴⁴, P.C. McNamara¹⁰⁴, C.J. McNicol¹⁷⁸,
 R.A. McPherson^{176,ad}, J.E. Mdhlluli^{33c}, Z.A. Meadows¹⁰², S. Meehan³⁶, T. Megy⁵², S. Mehlhase¹¹³,
 A. Mehta⁹⁰, T. Meideck⁵⁸, B. Meirose⁴³, D. Melini¹⁶⁰, B.R. Mellado Garcia^{33c}, J.D. Mellenthin⁵³,
 M. Melo^{28a}, F. Meloni⁴⁶, A. Melzer²⁴, S.B. Menary¹⁰⁰, E.D. Mendes Gouveia^{140a,140e}, L. Meng³⁶,
 X.T. Meng¹⁰⁵, S. Menke¹¹⁴, E. Meoni^{41b,41a}, S. Mergelmeyer¹⁹, S.A.M. Merkt¹³⁹, C. Merlassino²⁰,
 P. Mermod⁵⁴, L. Merola^{69a,69b}, C. Meroni^{68a}, G. Merz¹⁰⁵, O. Meshkov^{112,110}, J.K.R. Meshreki¹⁵¹,
 A. Messina^{72a,72b}, J. Metcalfe⁶, A.S. Mete¹⁷¹, C. Meyer⁶⁵, J-P. Meyer¹⁴⁵, H. Meyer Zu Theenhausen^{61a},
 F. Miano¹⁵⁶, M. Michetti¹⁹, R.P. Middleton¹⁴⁴, L. Mijović⁵⁰, G. Mikenberg¹⁸⁰, M. Mikesikova¹⁴¹,
 M. Mikuž⁹¹, H. Mildner¹⁴⁹, M. Milesi¹⁰⁴, A. Milic¹⁶⁷, D.A. Millar⁹², D.W. Miller³⁷, A. Milov¹⁸⁰,
 D.A. Milstead^{45a,45b}, R.A. Mina¹⁵³, A.A. Minaenko¹²², M. Miñano Moya¹⁷⁴, I.A. Minashvili^{159b},
 A.I. Mincer¹²⁴, B. Mindur^{83a}, M. Mineev⁷⁹, Y. Minegishi¹⁶³, L.M. Mir¹⁴, A. Mirto^{67a,67b}, K.P. Mistry¹³⁷,
 T. Mitani¹⁷⁹, J. Mitrevski¹¹³, V.A. Mitsou¹⁷⁴, M. Mittal^{60c}, O. Miu¹⁶⁷, A. Miucci²⁰, P.S. Miyagawa¹⁴⁹,
 A. Mizukami⁸¹, J.U. Mjörnmark⁹⁶, T. Mkrtchyan^{61a}, M. Mlynarikova¹⁴³, T. Moa^{45a,45b}, K. Mochizuki¹⁰⁹,
 P. Mogg⁵², S. Mohapatra³⁹, R. Moles-Valls²⁴, M.C. Mondragon¹⁰⁶, K. Mönig⁴⁶, J. Monk⁴⁰,
 E. Monnier¹⁰¹, A. Montalbano¹⁵², J. Montejo Berlingen³⁶, M. Montella⁹⁴, F. Monticelli⁸⁸, S. Monzani^{68a},
 N. Morange¹³², D. Moreno²², M. Moreno Llácer¹⁷⁴, C. Moreno Martinez¹⁴, P. Morettini^{55b},
 M. Morgenstern¹¹⁹, S. Morgenstern⁴⁸, D. Mori¹⁵², M. Morii⁵⁹, M. Morinaga¹⁷⁹, V. Morisbak¹³⁴,
 A.K. Morley³⁶, G. Mornacchi³⁶, A.P. Morris⁹⁴, L. Morvaj¹⁵⁵, P. Moschovakos³⁶, B. Moser¹¹⁹,
 M. Mosidze^{159b}, T. Moskalets¹⁴⁵, H.J. Moss¹⁴⁹, J. Moss^{31,m}, E.J.W. Moyses¹⁰², S. Muanza¹⁰¹,
 J. Mueller¹³⁹, R.S.P. Mueller¹¹³, D. Muenstermann⁸⁹, G.A. Mullier⁹⁶, D.P. Mungo^{68a,68b},
 J.L. Munoz Martinez¹⁴, F.J. Munoz Sanchez¹⁰⁰, P. Murin^{28b}, W.J. Murray^{178,144}, A. Murrone^{68a,68b},
 M. Muškinja¹⁸, C. Mwewa^{33a}, A.G. Myagkov^{122,ak}, A.A. Myers¹³⁹, J. Myers¹³¹, M. Myska¹⁴²,
 B.P. Nachman¹⁸, O. Nackenhorst⁴⁷, A. Nag Nag⁴⁸, K. Nagai¹³⁵, K. Nagano⁸¹, Y. Nagasaka⁶², J.L. Nagle²⁹,
 E. Nagy¹⁰¹, A.M. Nairz³⁶, Y. Nakahama¹¹⁶, K. Nakamura⁸¹, T. Nakamura¹⁶³, I. Nakano¹²⁷, H. Nanjo¹³³,
 F. Napolitano^{61a}, R.F. Naranjo Garcia⁴⁶, R. Narayan⁴², I. Naryshkin¹³⁸, T. Naumann⁴⁶, G. Navarro²²,
 P.Y. Nechaeva¹¹⁰, F. Nechansky⁴⁶, T.J. Neep²¹, A. Negri^{70a,70b}, M. Negrini^{23b}, C. Nellist⁵³,
 M.E. Nelson^{45a,45b}, S. Nemecek¹⁴¹, P. Nemethy¹²⁴, M. Nessi^{36,d}, M.S. Neubauer¹⁷³, M. Neumann¹⁸²,
 R. Newhouse¹⁷⁵, P.R. Newman²¹, Y.S. Ng¹⁹, Y.W.Y. Ng¹⁷¹, B. Ngair^{35e}, H.D.N. Nguyen¹⁰¹,
 T. Nguyen Manh¹⁰⁹, E. Nibigira³⁸, R.B. Nickerson¹³⁵, R. Nicolaidou¹⁴⁵, D.S. Nielsen⁴⁰, J. Nielsen¹⁴⁶,
 N. Nikiforou¹¹, V. Nikolaenko^{122,ak}, I. Nikolic-Audit¹³⁶, K. Nikolopoulos²¹, P. Nilsson²⁹, H.R. Nindhito⁵⁴,
 Y. Ninomiya⁸¹, A. Nisati^{72a}, N. Nishu^{60c}, R. Nisius¹¹⁴, I. Nitsche⁴⁷, T. Nitta¹⁷⁹, T. Nobe¹⁶³, Y. Noguchi⁸⁵,
 I. Nomidis¹³⁶, M.A. Nomura²⁹, M. Nordberg³⁶, N. Norjoharuddeen¹³⁵, T. Novak⁹¹, O. Novgorodova⁴⁸,
 R. Novotny¹⁴², L. Nozka¹³⁰, K. Ntekas¹⁷¹, E. Nurse⁹⁴, F.G. Oakham^{34,as}, H. Oberlack¹¹⁴, J. Ocariz¹³⁶,
 A. Ochi⁸², I. Ochoa³⁹, J.P. Ochoa-Ricoux^{147a}, K. O'Connor²⁶, S. Oda⁸⁷, S. Odaka⁸¹, S. Oerdek⁵³,
 A. Ogrodnik^{83a}, A. Oh¹⁰⁰, S.H. Oh⁴⁹, C.C. Ohm¹⁵⁴, H. Oide¹⁶⁵, M.L. Ojeda¹⁶⁷, H. Okawa¹⁶⁹,
 Y. Okazaki⁸⁵, M.W. O'Keefe⁹⁰, Y. Okumura¹⁶³, T. Okuyama⁸¹, A. Olariu^{27b}, L.F. Oleiro Seabra^{140a},
 S.A. Olivares Pino^{147a}, D. Oliveira Damazio²⁹, J.L. Oliver¹, M.J.R. Olsson¹⁷¹, A. Olszewski⁸⁴,
 J. Olszowska⁸⁴, D.C. O'Neil¹⁵², A.P. O'Neill¹³⁵, A. Onofre^{140a,140e}, P.U.E. Onyisi¹¹, H. Oppen¹³⁴,
 M.J. Oreglia³⁷, G.E. Orellana⁸⁸, D. Orestano^{74a,74b}, N. Orlando¹⁴, R.S. Orr¹⁶⁷, V. O'Shea⁵⁷, R. Ospanov^{60a},
 G. Otero y Garzon³⁰, H. Otono⁸⁷, P.S. Ott^{61a}, M. Ouchrif^{35d}, J. Ouellette²⁹, F. Ould-Saada¹³⁴,
 A. Ouraou¹⁴⁵, Q. Ouyang^{15a}, M. Owen⁵⁷, R.E. Owen²¹, V.E. Ozcan^{12c}, N. Ozturk⁸, J. Pacalt¹³⁰,
 H.A. Pacey³², K. Pachal⁴⁹, A. Pacheco Pages¹⁴, C. Padilla Aranda¹⁴, S. Pagan Griso¹⁸, M. Paganini¹⁸³,
 G. Palacino⁶⁵, S. Palazzo⁵⁰, S. Palestini³⁶, M. Palka^{83b}, D. Pallin³⁸, I. Panagoulas¹⁰, C.E. Pandini³⁶,
 J.G. Panduro Vazquez⁹³, P. Pani⁴⁶, G. Panizzo^{66a,66c}, L. Paolozzi⁵⁴, C. Papadatos¹⁰⁹, K. Papageorgiou^{9,g},
 S. Parajuli⁴³, A. Paramonov⁶, D. Paredes Hernandez^{63b}, S.R. Paredes Saenz¹³⁵, B. Parida¹⁶⁶, T.H. Park¹⁶⁷,
 A.J. Parker³¹, M.A. Parker³², F. Parodi^{55b,55a}, E.W. Parrish¹²⁰, J.A. Parsons³⁹, U. Parzefall⁵²,
 L. Pascual Dominguez¹³⁶, V.R. Pascuzzi¹⁶⁷, J.M.P. Pasner¹⁴⁶, F. Pasquali¹¹⁹, E. Pasqualucci^{72a},

S. Passaggio^{55b}, F. Pastore⁹³, P. Pasuwan^{45a,45b}, S. Patarraia⁹⁹, J.R. Pater¹⁰⁰, A. Pathak^{181,i}, T. Pauly³⁶, J. Pearkes¹⁵³, B. Pearson¹¹⁴, M. Pedersen¹³⁴, L. Pedraza Diaz¹¹⁸, R. Pedro^{140a}, T. Peiffer⁵³, S.V. Peleganchuk^{121b,121a}, O. Penc¹⁴¹, H. Peng^{60a}, B.S. Peralva^{80a}, M.M. Perego¹³², A.P. Pereira Peixoto^{140a}, D.V. Perepelitsa²⁹, F. Peri¹⁹, L. Perini^{68a,68b}, H. Pernegger³⁶, S. Perrella^{69a,69b}, A. Perrevoort¹¹⁹, K. Peters⁴⁶, R.F.Y. Peters¹⁰⁰, B.A. Petersen³⁶, T.C. Petersen⁴⁰, E. Petit¹⁰¹, A. Petridis¹, C. Petridou¹⁶², P. Petroff¹³², M. Petrov¹³⁵, F. Petrucci^{74a,74b}, M. Pettee¹⁸³, N.E. Pettersson¹⁰², K. Petukhova¹⁴³, A. Peyaud¹⁴⁵, R. Pezoa^{147c}, L. Pezzotti^{70a,70b}, T. Pham¹⁰⁴, F.H. Phillips¹⁰⁶, P.W. Phillips¹⁴⁴, M.W. Phipps¹⁷³, G. Piacquadio¹⁵⁵, E. Pianori¹⁸, A. Picazio¹⁰², R.H. Pickles¹⁰⁰, R. Piegaia³⁰, D. Pietreanu^{27b}, J.E. Pilcher³⁷, A.D. Pilkington¹⁰⁰, M. Pinamonti^{66a,66c}, J.L. Pinfold³, M. Pitt¹⁶¹, L. Pizzimento^{73a,73b}, M.-A. Pleier²⁹, V. Pleskot¹⁴³, E. Plotnikova⁷⁹, P. Podberezko^{121b,121a}, R. Poettgen⁹⁶, R. Poggi⁵⁴, L. Poggioli¹³², I. Pogrebnyak¹⁰⁶, D. Pohl²⁴, I. Pokharel⁵³, G. Polesello^{70a}, A. Poley¹⁸, A. Policicchio^{72a,72b}, R. Polifka¹⁴³, A. Polini^{23b}, C.S. Pollard⁴⁶, V. Polychronakos²⁹, D. Ponomarenko¹¹¹, L. Pontecorvo³⁶, S. Popa^{27a}, G.A. Popeneciu^{27d}, L. Portales⁵, D.M. Portillo Quintero⁵⁸, S. Pospisil¹⁴², K. Potamianos⁴⁶, I.N. Potrap⁷⁹, C.J. Potter³², H. Potti¹¹, T. Poulsen⁹⁶, J. Poveda³⁶, T.D. Powell¹⁴⁹, G. Pownall⁴⁶, M.E. Pozo Astigarraga³⁶, P. Pralavorio¹⁰¹, S. Prell⁷⁸, D. Price¹⁰⁰, M. Primavera^{67a}, S. Prince¹⁰³, M.L. Proffitt¹⁴⁸, N. Proklova¹¹¹, K. Prokofiev^{63c}, F. Prokoshin⁷⁹, S. Protopopescu²⁹, J. Proudfoot⁶, M. Przybycien^{83a}, D. Pudzha¹³⁸, A. Puri¹⁷³, P. Puzo¹³², J. Qian¹⁰⁵, Y. Qin¹⁰⁰, A. Quadt⁵³, M. Queitsch-Maitland³⁶, A. Qureshi¹, M. Racko^{28a}, F. Ragusa^{68a,68b}, G. Rahal⁹⁷, J.A. Raine⁵⁴, S. Rajagopalan²⁹, A. Ramirez Morales⁹², K. Ran^{15a,15d}, T. Rashid¹³², S. Raspopov⁵, D.M. Rauch⁴⁶, F. Rauscher¹¹³, S. Rave⁹⁹, B. Ravina¹⁴⁹, I. Ravinovich¹⁸⁰, J.H. Rawling¹⁰⁰, M. Raymond³⁶, A.L. Read¹³⁴, N.P. Readioff⁵⁸, M. Reale^{67a,67b}, D.M. Rebuszi^{70a,70b}, A. Redelbach¹⁷⁷, G. Redlinger²⁹, K. Reeves⁴³, L. Rehnisch¹⁹, J. Reichert¹³⁷, D. Reikher¹⁶¹, A. Reiss⁹⁹, A. Rej¹⁵¹, C. Rembser³⁶, M. Renda^{27b}, M. Rescigno^{72a}, S. Resconi^{68a}, E.D. Resseguie¹³⁷, S. Rettie¹⁷⁵, B. Reynolds¹²⁶, E. Reynolds²¹, O.L. Rezanova^{121b,121a}, P. Reznicek¹⁴³, E. Ricci^{75a,75b}, R. Richter¹¹⁴, S. Richter⁴⁶, E. Richter-Was^{83b}, O. Ricken²⁴, M. Ridel¹³⁶, P. Rieck¹¹⁴, O. Rifki⁴⁶, M. Rijssenbeek¹⁵⁵, A. Rimoldi^{70a,70b}, M. Rimoldi⁴⁶, L. Rinaldi^{23b}, G. Ripellino¹⁵⁴, I. Riu¹⁴, J.C. Rivera Vergara¹⁷⁶, F. Rizatdinova¹²⁹, E. Rizvi⁹², C. Rizzi³⁶, R.T. Roberts¹⁰⁰, S.H. Robertson^{103,ad}, M. Robin⁴⁶, D. Robinson³², J.E.M. Robinson⁴⁶, C.M. Robles Gajardo^{147c}, A. Robson⁵⁷, A. Rocchi^{73a,73b}, E. Rocco⁹⁹, C. Roda^{71a,71b}, S. Rodriguez Bosca¹⁷⁴, A. Rodriguez Perez¹⁴, D. Rodriguez Rodriguez¹⁷⁴, A.M. Rodríguez Vera^{168b}, S. Roe³⁶, O. Røhne¹³⁴, R. Röhrig¹¹⁴, R.A. Rojas^{147c}, C.P.A. Roland⁶⁵, J. Roloff²⁹, A. Romaniouk¹¹¹, M. Romano^{23b,23a}, N. Rompotis⁹⁰, M. Ronzani¹²⁴, L. Roos¹³⁶, S. Rosati^{72a}, G. Rosin¹⁰², B.J. Rosser¹³⁷, E. Rossi⁴⁶, E. Rossi^{74a,74b}, E. Rossi^{69a,69b}, L.P. Rossi^{55b}, L. Rossini^{68a,68b}, R. Rosten¹⁴, M. Rotaru^{27b}, J. Rothberg¹⁴⁸, D. Rousseau¹³², G. Rovelli^{70a,70b}, A. Roy¹¹, D. Roy^{33c}, A. Rozanov¹⁰¹, Y. Rozen¹⁶⁰, X. Ruan^{33c}, F. Rühr⁵², A. Ruiz-Martinez¹⁷⁴, A. Rummler³⁶, Z. Rurikova⁵², N.A. Rusakovich⁷⁹, H.L. Russell¹⁰³, L. Rustige^{38,47}, J.P. Rutherford⁷, E.M. Rüttinger¹⁴⁹, M. Rybar³⁹, G. Rybkin¹³², E.B. Rye¹³⁴, A. Ryzhov¹²², J.A. Sabater Iglesias⁴⁶, P. Sabatini⁵³, G. Sabato¹¹⁹, S. Sacerdoti¹³², H.F.-W. Sadrozinski¹⁴⁶, R. Sadykov⁷⁹, F. Safai Tehrani^{72a}, B. Safarzadeh Samani¹⁵⁶, P. Saha¹²⁰, S. Saha¹⁰³, M. Sahinsoy^{61a}, A. Sahu¹⁸², M. Saimpert⁴⁶, M. Saito¹⁶³, T. Saito¹⁶³, H. Sakamoto¹⁶³, A. Sakharov^{124,aj}, D. Salamani⁵⁴, G. Salamanna^{74a,74b}, J.E. Salazar Loyola^{147c}, A. Salnikov¹⁵³, J. Salt¹⁷⁴, D. Salvatore^{41b,41a}, F. Salvatore¹⁵⁶, A. Salvucci^{63a,63b,63c}, A. Salzburger³⁶, J. Samarati³⁶, D. Sammel⁵², D. Sampsonidis¹⁶², D. Sampsonidou¹⁶², J. Sánchez¹⁷⁴, A. Sanchez Pineda^{66a,36,66c}, H. Sandaker¹³⁴, C.O. Sander⁴⁶, I.G. Sanderswood⁸⁹, M. Sandhoff¹⁸², C. Sandoval²², D.P.C. Sankey¹⁴⁴, M. Sannino^{55b,55a}, Y. Sano¹¹⁶, A. Sansoni⁵¹, C. Santoni³⁸, H. Santos^{140a,140b}, S.N. Santpur¹⁸, A. Santra¹⁷⁴, A. Saponov⁷⁹, J.G. Saraiva^{140a,140d}, O. Sasaki⁸¹, K. Sato¹⁶⁹, F. Sauerburger⁵², E. Sauvan⁵, P. Savard^{167,as}, R. Sawada¹⁶³, C. Sawyer¹⁴⁴, L. Sawyer^{95,ai}, C. Sbarra^{23b}, A. Sbrizzi^{23a}, T. Scanlon⁹⁴, J. Schaarschmidt¹⁴⁸, P. Schacht¹¹⁴, B.M. Schachtner¹¹³, D. Schaefer³⁷, L. Schaefer¹³⁷, J. Schaeffer⁹⁹, S. Schaepe³⁶, U. Schäfer⁹⁹, A.C. Schaffer¹³², D. Schaile¹¹³, R.D. Schamberger¹⁵⁵, N. Scharmberg¹⁰⁰, V.A. Schegelsky¹³⁸, D. Scheirich¹⁴³, F. Schenck¹⁹, M. Schernau¹⁷¹, C. Schiavi^{55b,55a}, S. Schier¹⁴⁶, L.K. Schildgen²⁴, Z.M. Schillaci²⁶, E.J. Schioppa³⁶, M. Schioppa^{41b,41a}, K.E. Schleicher⁵², S. Schlenker³⁶, K.R. Schmidt-Sommerfeld¹¹⁴, K. Schmieden³⁶, C. Schmitt⁹⁹, S. Schmitt⁴⁶, S. Schmitz⁹⁹, J.C. Schmoekel⁴⁶, U. Schnoor⁵², L. Schoeffel¹⁴⁵, A. Schoening^{61b}, P.G. Scholer⁵², E. Schopf¹³⁵, M. Schott⁹⁹, J.F.P. Schouwenberg¹¹⁸, J. Schovancova³⁶, S. Schramm⁵⁴, F. Schroeder¹⁸², A. Schulte⁹⁹,

H.-C. Schultz-Coulon^{61a}, M. Schumacher⁵², B.A. Schumm¹⁴⁶, Ph. Schune¹⁴⁵, A. Schwartzman¹⁵³, T.A. Schwarz¹⁰⁵, Ph. Schwemling¹⁴⁵, R. Schwienhorst¹⁰⁶, A. Sciandra¹⁴⁶, G. Sciolla²⁶, M. Scodeggio⁴⁶, M. Scornajenghi^{41b,41a}, F. Scuri^{71a}, F. Scutti¹⁰⁴, L.M. Scyboz¹¹⁴, C.D. Sebastiani^{72a,72b}, P. Seema¹⁹, S.C. Seidel¹¹⁷, A. Seiden¹⁴⁶, B.D. Seidlitz²⁹, T. Seiss³⁷, J.M. Seixas^{80b}, G. Sekhniaidze^{69a}, K. Sekhon¹⁰⁵, S.J. Sekula⁴², N. Semprini-Cesari^{23b,23a}, S. Sen⁴⁹, C. Serfon⁷⁶, L. Serin¹³², L. Serkin^{66a,66b}, M. Sessa^{60a}, H. Severini¹²⁸, S. Sevova¹⁵³, T. Šfiligoj⁹¹, F. Sforza^{55b,55a}, A. Sfyrla⁵⁴, E. Shabalina⁵³, J.D. Shahinian¹⁴⁶, N.W. Shaikh^{45a,45b}, D. Shaked Renous¹⁸⁰, L.Y. Shan^{15a}, J.T. Shank²⁵, M. Shapiro¹⁸, A. Sharma¹³⁵, A.S. Sharma¹, P.B. Shatalov¹²³, K. Shaw¹⁵⁶, S.M. Shaw¹⁰⁰, M. Shehade¹⁸⁰, Y. Shen¹²⁸, A.D. Sherman²⁵, P. Sherwood⁹⁴, L. Shi^{158,ap}, S. Shimizu⁸¹, C.O. Shimmin¹⁸³, Y. Shimogama¹⁷⁹, M. Shimojima¹¹⁵, I.P.J. Shipsey¹³⁵, S. Shirabe¹⁶⁵, M. Shiyakova^{79,ab}, J. Shlomi¹⁸⁰, A. Shmeleva¹¹⁰, M.J. Shochet³⁷, J. Shojaii¹⁰⁴, D.R. Shope¹²⁸, S. Shrestha¹²⁶, E.M. Shrif^{33c}, E. Shulga¹⁸⁰, P. Sicho¹⁴¹, A.M. Sickles¹⁷³, P.E. Sidebo¹⁵⁴, E. Sideras Haddad^{33c}, O. Sidiropoulou³⁶, A. Sidoti^{23b,23a}, F. Siegert⁴⁸, Dj. Sijacki¹⁶, M.Jr. Silva¹⁸¹, M.V. Silva Oliveira^{80a}, S.B. Silverstein^{45a}, S. Simion¹³², R. Simoniello⁹⁹, S. Simsek^{12b}, P. Sinervo¹⁶⁷, V. Sinetckii¹¹², N.B. Sinev¹³¹, S. Singh¹⁵², M. Sioli^{23b,23a}, I. Siral¹³¹, S.Yu. Sivoklov¹¹², J. Sjölin^{45a,45b}, E. Skorda⁹⁶, P. Skubic¹²⁸, M. Slawinska⁸⁴, K. Sliwa¹⁷⁰, R. Slovak¹⁴³, V. Smakhtin¹⁸⁰, B.H. Smart¹⁴⁴, J. Smiesko^{28a}, N. Smirnov¹¹¹, S.Yu. Smirnov¹¹¹, Y. Smirnov¹¹¹, L.N. Smirnova^{112,u}, O. Smirnova⁹⁶, J.W. Smith⁵³, M. Smizanska⁸⁹, K. Smolek¹⁴², A. Smykiewicz⁸⁴, A.A. Snesarev¹¹⁰, H.L. Snoek¹¹⁹, I.M. Snyder¹³¹, S. Snyder²⁹, R. Sobie^{176,ad}, A. Soffer¹⁶¹, A. Søgaard⁵⁰, F. Sohns⁵³, C.A. Solans Sanchez³⁶, E.Yu. Soldatov¹¹¹, U. Soldevila¹⁷⁴, A.A. Solodkov¹²², A. Soloshenko⁷⁹, O.V. Solovyanov¹²², V. Solovyev¹³⁸, P. Sommer¹⁴⁹, H. Son¹⁷⁰, W. Song¹⁴⁴, W.Y. Song^{168b}, A. Sopczak¹⁴², A.L. Sopio⁹⁴, F. Sopkova^{28b}, C.L. Sotiropoulou^{71a,71b}, S. Sottocornola^{70a,70b}, R. Soualah^{66a,66c,f}, A.M. Soukharev^{121b,121a}, D. South⁴⁶, S. Spagnolo^{67a,67b}, M. Spalla¹¹⁴, M. Spangenberg¹⁷⁸, F. Spanò⁹³, D. Sperlich⁵², T.M. Spieker^{61a}, R. Spighi^{23b}, G. Spigo³⁶, M. Spina¹⁵⁶, D.P. Spiteri⁵⁷, M. Spousta¹⁴³, A. Stabile^{68a,68b}, B.L. Stamas¹²⁰, R. Stamen^{61a}, M. Stamenkovic¹¹⁹, E. Stanecka⁸⁴, B. Stanislaus¹³⁵, M.M. Stanitzki⁴⁶, M. Stankaityte¹³⁵, B. Stapf¹¹⁹, E.A. Starchenko¹²², G.H. Stark¹⁴⁶, J. Stark⁵⁸, S.H. Stark⁴⁰, P. Staroba¹⁴¹, P. Starovoitov^{61a}, S. Stärz¹⁰³, R. Staszewski⁸⁴, G. Stavropoulos⁴⁴, M. Stegler⁴⁶, P. Steinberg²⁹, A.L. Steinhebel¹³¹, B. Stelzer¹⁵², H.J. Stelzer¹³⁹, O. Stelzer-Chilton^{168a}, H. Stenzel⁵⁶, T.J. Stevenson¹⁵⁶, G.A. Stewart³⁶, M.C. Stockton³⁶, G. Stoicea^{27b}, M. Stolarski^{140a}, S. Stonjek¹¹⁴, A. Straessner⁴⁸, J. Strandberg¹⁵⁴, S. Strandberg^{45a,45b}, M. Strauss¹²⁸, P. Strizenec^{28b}, R. Ströhmer¹⁷⁷, D.M. Strom¹³¹, R. Stroynowski⁴², A. Strubig⁵⁰, S.A. Stucci²⁹, B. Stugu¹⁷, J. Stupak¹²⁸, N.A. Styles⁴⁶, D. Su¹⁵³, S. Suchek^{61a}, V.V. Sulin¹¹⁰, M.J. Sullivan⁹⁰, D.M.S. Sultan⁵⁴, S. Sultansoy^{4c}, T. Sumida⁸⁵, S. Sun¹⁰⁵, X. Sun³, K. Suruliz¹⁵⁶, C.J.E. Suster¹⁵⁷, M.R. Sutton¹⁵⁶, S. Suzuki⁸¹, M. Svatos¹⁴¹, M. Swiatlowski³⁷, S.P. Swift², T. Swirski¹⁷⁷, A. Sydorenko⁹⁹, I. Sykora^{28a}, M. Sykora¹⁴³, T. Sykora¹⁴³, D. Ta⁹⁹, K. Tackmann^{46,z}, J. Taenzer¹⁶¹, A. Taffard¹⁷¹, R. Tafirout^{168a}, H. Takai²⁹, R. Takashima⁸⁶, K. Takeda⁸², T. Takeshita¹⁵⁰, E.P. Takeva⁵⁰, Y. Takubo⁸¹, M. Talby¹⁰¹, A.A. Talyshv^{121b,121a}, N.M. Tamir¹⁶¹, J. Tanaka¹⁶³, M. Tanaka¹⁶⁵, R. Tanaka¹³², S. Tapia Araya¹⁷³, S. Tapprogge⁹⁹, A. Tarek Abouelfadl Mohamed¹³⁶, S. Tarem¹⁶⁰, K. Tariq^{60b}, G. Tarna^{27b,c}, G.F. Tartarelli^{68a}, P. Tas¹⁴³, M. Tasevsky¹⁴¹, T. Tashiro⁸⁵, E. Tassi^{41b,41a}, A. Tavares Delgado^{140a}, Y. Tayalati^{35e}, A.J. Taylor⁵⁰, G.N. Taylor¹⁰⁴, W. Taylor^{168b}, A.S. Tee⁸⁹, R. Teixeira De Lima¹⁵³, P. Teixeira-Dias⁹³, H. Ten Kate³⁶, J.J. Teoh¹¹⁹, S. Terada⁸¹, K. Terashi¹⁶³, J. Terron⁹⁸, S. Terzo¹⁴, M. Testa⁵¹, R.J. Teuscher^{167,ad}, S.J. Thais¹⁸³, T. Theveneaux-Pelzer⁴⁶, F. Thiele⁴⁰, D.W. Thomas⁹³, J.O. Thomas⁴², J.P. Thomas²¹, A.S. Thompson⁵⁷, P.D. Thompson²¹, L.A. Thomsen¹⁸³, E. Thomson¹³⁷, E.J. Thorpe⁹², R.E. Ticse Torres⁵³, V.O. Tikhomirov^{110,al}, Yu.A. Tikhonov^{121b,121a}, S. Timoshenko¹¹¹, P. Tipton¹⁸³, S. Tisserant¹⁰¹, K. Todome^{23b,23a}, S. Todorova-Nova⁵, S. Todt⁴⁸, J. Tojo⁸⁷, S. Tokár^{28a}, K. Tokushuku⁸¹, E. Tolley¹²⁶, K.G. Tomiwa^{33c}, M. Tomoto¹¹⁶, L. Tompkins^{153,p}, B. Tong⁵⁹, P. Tornambe¹⁰², E. Torrence¹³¹, H. Torres⁴⁸, E. Torrón Pastor¹⁴⁸, C. Toscirì¹³⁵, J. Toth^{101,ac}, D.R. Tovey¹⁴⁹, A. Traet¹⁷, C.J. Treado¹²⁴, T. Trefzger¹⁷⁷, F. Tresoldi¹⁵⁶, A. Tricoli²⁹, I.M. Trigger^{168a}, S. Trincaz-Duvoid¹³⁶, D.T. Trischuk¹⁷⁵, W. Trischuk¹⁶⁷, B. Trocmé⁵⁸, A. Trofymov¹⁴⁵, C. Troncon^{68a}, M. Trovatelli¹⁷⁶, F. Trovato¹⁵⁶, L. Truong^{33b}, M. Trzebinski⁸⁴, A. Trzupek⁸⁴, F. Tsai⁴⁶, J.C.-L. Tseng¹³⁵, P.V. Tsiareshka^{107,ag}, A. Tsirigotis^{162,x}, V. Tsiskaridze¹⁵⁵, E.G. Tskhadadze^{159a}, M. Tsopoulou¹⁶², I.I. Tsukerman¹²³, V. Tsulaia¹⁸, S. Tsuno⁸¹, D. Tsybychev¹⁵⁵, Y. Tu^{63b}, A. Tudorache^{27b}, V. Tudorache^{27b}, T.T. Tulbure^{27a}, A.N. Tuna⁵⁹, S. Turchikhin⁷⁹, D. Turgeman¹⁸⁰, I. Turk Cakir^{4b,v}, R.J. Turner²¹,

R.T. Turra^{68a}, P.M. Tuts³⁹, S. Tzamarias¹⁶², E. Tzovara⁹⁹, G. Ucchielli⁴⁷, K. Uchida¹⁶³, I. Ueda⁸¹, F. Ukegawa¹⁶⁹, G. Unal³⁶, A. Undrus²⁹, G. Unel¹⁷¹, F.C. Ungaro¹⁰⁴, Y. Unno⁸¹, K. Uno¹⁶³, J. Urban^{28b}, P. Urquijo¹⁰⁴, G. Usai⁸, Z. Uysal^{12d}, V. Vacek¹⁴², B. Vachon¹⁰³, K.O.H. Vadla¹³⁴, A. Vaidya⁹⁴, C. Valderanis¹¹³, E. Valdes Santurio^{45a,45b}, M. Valente⁵⁴, S. Valentinetti^{23b,23a}, A. Valero¹⁷⁴, L. Valéry⁴⁶, R.A. Vallance²¹, A. Vallier³⁶, J.A. Valls Ferrer¹⁷⁴, T.R. Van Daalen¹⁴, P. Van Gemmeren⁶, I. Van Vulpen¹¹⁹, M. Vanadia^{73a,73b}, W. Vandelli³⁶, M. Vandenbroucke¹⁴⁵, E.R. Vandewall¹²⁹, A. Vaniachine¹⁶⁶, D. Vannicola^{72a,72b}, R. Vari^{72a}, E.W. Varnes⁷, C. Varni^{55b,55a}, T. Varol¹⁵⁸, D. Varouchas¹³², K.E. Varvell¹⁵⁷, M.E. Vasile^{27b}, G.A. Vasquez¹⁷⁶, F. Vazeille³⁸, D. Vazquez Furelos¹⁴, T. Vazquez Schroeder³⁶, J. Veatch⁵³, V. Vecchio^{74a,74b}, M.J. Veen¹¹⁹, L.M. Veloce¹⁶⁷, F. Veloso^{140a,140c}, S. Veneziano^{72a}, A. Ventura^{67a,67b}, N. Venturi³⁶, A. Verbitskyi¹¹⁴, V. Vercesi^{70a}, M. Verducci^{71a,71b}, C.M. Vergel Infante⁷⁸, C. Vergis²⁴, W. Verkerke¹¹⁹, A.T. Vermeulen¹¹⁹, J.C. Vermeulen¹¹⁹, M.C. Vetterli^{152,as}, N. Viaux Maira^{147c}, M. Vicente Barreto Pinto⁵⁴, T. Vickey¹⁴⁹, O.E. Vickey Boeriu¹⁴⁹, G.H.A. Viehhauser¹³⁵, L. Vigani^{61b}, M. Villa^{23b,23a}, M. Villaplana Perez^{68a,68b}, E. Vilucchi⁵¹, M.G. Vincter³⁴, G.S. Virdee²¹, A. Vishwakarma⁴⁶, C. Vittori^{23b,23a}, I. Vivarelli¹⁵⁶, M. Vogel¹⁸², P. Vokac¹⁴², S.E. von Buddenbrock^{33c}, E. Von Toerne²⁴, V. Vorobel¹⁴³, K. Vorobev¹¹¹, M. Vos¹⁷⁴, J.H. Vosseveld⁹⁰, M. Vozak¹⁰⁰, N. Vranjes¹⁶, M. Vranjes Milosavljevic¹⁶, V. Vrba¹⁴², M. Vreeswijk¹¹⁹, R. Vuillermet³⁶, I. Vukotic³⁷, P. Wagner²⁴, W. Wagner¹⁸², J. Wagner-Kuhr¹¹³, S. Wahdan¹⁸², H. Wahlberg⁸⁸, V.M. Walbrecht¹¹⁴, J. Walder⁸⁹, R. Walker¹¹³, S.D. Walker⁹³, W. Walkowiak¹⁵¹, V. Wallangen^{45a,45b}, A.M. Wang⁵⁹, C. Wang^{60c}, F. Wang¹⁸¹, H. Wang¹⁸, H. Wang³, J. Wang^{63a}, J. Wang¹⁵⁷, J. Wang^{61b}, P. Wang⁴², Q. Wang¹²⁸, R.-J. Wang⁹⁹, R. Wang^{60a}, R. Wang⁶, S.M. Wang¹⁵⁸, W.T. Wang^{60a}, W. Wang^{15c}, W.X. Wang^{60a}, Y. Wang^{60a}, Z. Wang^{60c}, C. Wanotayaroj⁴⁶, A. Warburton¹⁰³, C.P. Ward³², D.R. Wardrope⁹⁴, N. Warrack⁵⁷, A. Washbrook⁵⁰, A.T. Watson²¹, M.F. Watson²¹, G. Watts¹⁴⁸, B.M. Waugh⁹⁴, A.F. Webb¹¹, S. Webb⁹⁹, C. Weber¹⁸³, M.S. Weber²⁰, S.A. Weber³⁴, S.M. Weber^{61a}, A.R. Weidberg¹³⁵, J. Weingarten⁴⁷, M. Weirich⁹⁹, C. Weiser⁵², P.S. Wells³⁶, T. Wenaus²⁹, T. Wengler³⁶, S. Wenig³⁶, N. Vermes²⁴, M.D. Werner⁷⁸, M. Wessels^{61a}, T.D. Weston²⁰, K. Whalen¹³¹, N.L. Whallon¹⁴⁸, A.M. Wharton⁸⁹, A.S. White¹⁰⁵, A. White⁸, M.J. White¹, D. Whiteson¹⁷¹, B.W. Whitmore⁸⁹, W. Wiedenmann¹⁸¹, C. Wiel⁴⁸, M. Wielers¹⁴⁴, N. Wieseotte⁹⁹, C. Wiglesworth⁴⁰, L.A.M. Wiik-Fuchs⁵², F. Wilk¹⁰⁰, H.G. Wilkens³⁶, L.J. Wilkins⁹³, H.H. Williams¹³⁷, S. Williams³², C. Willis¹⁰⁶, S. Willocq¹⁰², J.A. Wilson²¹, I. Wingerter-Seez⁵, E. Winkels¹⁵⁶, F. Winklmeier¹³¹, O.J. Winston¹⁵⁶, B.T. Winter⁵², M. Wittgen¹⁵³, M. Wobisch⁹⁵, A. Wolf⁹⁹, T.M.H. Wolf¹¹⁹, R. Wolff¹⁰¹, R.W. Wölker¹³⁵, J. Wollrath⁵², M.W. Wolter⁸⁴, H. Wolters^{140a,140c}, V.W.S. Wong¹⁷⁵, N.L. Woods¹⁴⁶, S.D. Worm²¹, B.K. Wosiek⁸⁴, K.W. Woźniak⁸⁴, K. Wraight⁵⁷, S.L. Wu¹⁸¹, X. Wu⁵⁴, Y. Wu^{60a}, T.R. Wyatt¹⁰⁰, B.M. Wynne⁵⁰, S. Xella⁴⁰, Z. Xi¹⁰⁵, L. Xia¹⁷⁸, X. Xiao¹⁰⁵, I. Xiotidis¹⁵⁶, D. Xu^{15a}, H. Xu^{60a}, L. Xu²⁹, T. Xu¹⁴⁵, W. Xu¹⁰⁵, Z. Xu^{60b}, Z. Xu¹⁵³, B. Yabsley¹⁵⁷, S. Yacoob^{33a}, K. Yajima¹³³, D.P. Yallup⁹⁴, N. Yamaguchi⁸⁷, Y. Yamaguchi¹⁶⁵, A. Yamamoto⁸¹, M. Yamatani¹⁶³, T. Yamazaki¹⁶³, Y. Yamazaki⁸², Z. Yan²⁵, H.J. Yang^{60c,60d}, H.T. Yang¹⁸, S. Yang⁷⁷, X. Yang^{60b,58}, Y. Yang¹⁶³, W.-M. Yao¹⁸, Y.C. Yap⁴⁶, Y. Yasu⁸¹, E. Yatsenko^{60c,60d}, H. Ye^{15c}, J. Ye⁴², S. Ye²⁹, I. Yeletsikh⁷⁹, M.R. Yexley⁸⁹, E. Yigitbasi²⁵, K. Yorita¹⁷⁹, K. Yoshihara¹³⁷, C.J.S. Young³⁶, C. Young¹⁵³, J. Yu⁷⁸, R. Yuan^{60b,h}, X. Yue^{61a}, S.P.Y. Yuen²⁴, M. Zaazoua^{35e}, B. Zabinski⁸⁴, G. Zacharis¹⁰, E. Zaffaroni⁵⁴, J. Zahreddine¹³⁶, A.M. Zaitsev^{122,ak}, T. Zakareishvili^{159b}, N. Zakharchuk³⁴, S. Zambito⁵⁹, D. Zanzi³⁶, D.R. Zaripovas⁵⁷, S.V. Zeiřner⁴⁷, C. Zeitnitz¹⁸², G. Zemaityte¹³⁵, J.C. Zeng¹⁷³, O. Zenin¹²², T. Ženiř^{28a}, D. Zerwas¹³², M. Zgubić¹³⁵, B. Zhang^{15c}, D.F. Zhang^{15b}, G. Zhang^{15b}, H. Zhang^{15c}, J. Zhang⁶, L. Zhang^{15c}, L. Zhang^{60a}, M. Zhang¹⁷³, R. Zhang¹⁸¹, S. Zhang¹⁰⁵, X. Zhang^{60b}, Y. Zhang^{15a,15d}, Z. Zhang^{63a}, Z. Zhang¹³², P. Zhao⁴⁹, Y. Zhao^{60b}, Z. Zhao^{60a}, A. Zhemchugov⁷⁹, Z. Zheng¹⁰⁵, D. Zhong¹⁷³, B. Zhou¹⁰⁵, C. Zhou¹⁸¹, M.S. Zhou^{15a,15d}, M. Zhou¹⁵⁵, N. Zhou^{60c}, Y. Zhou⁷, C.G. Zhu^{60b}, C. Zhu^{15a}, H.L. Zhu^{60a}, H. Zhu^{15a}, J. Zhu¹⁰⁵, Y. Zhu^{60a}, X. Zhuang^{15a}, K. Zhukov¹¹⁰, V. Zhulanov^{121b,121a}, D. Ziemska⁶⁵, N.I. Zimine⁷⁹, S. Zimmermann⁵², Z. Zinonos¹¹⁴, M. Ziolkowski¹⁵¹, L. Živković¹⁶, G. Zobernig¹⁸¹, A. Zoccoli^{23b,23a}, K. Zoch⁵³, T.G. Zorbass¹⁴⁹, R. Zou³⁷, L. Zwalinski³⁶

¹ Department of Physics, University of Adelaide, Adelaide, Australia² Physics Department, SUNY Albany, Albany, NY, United States of America³ Department of Physics, University of Alberta, Edmonton, AB, Canada⁴ (^a) Department of Physics, Ankara University, Ankara; (^b) Istanbul Aydin University, Istanbul; (^c) Division of Physics, TOBB University of Economics and Technology, Ankara, Turkey⁵ LAPP, Université Grenoble Alpes, Université Savoie Mont Blanc, CNRS/IN2P3, Annecy, France⁶ High Energy Physics Division, Argonne National Laboratory, Argonne, IL, United States of America

- ⁷ Department of Physics, University of Arizona, Tucson, AZ, United States of America
- ⁸ Department of Physics, University of Texas at Arlington, Arlington, TX, United States of America
- ⁹ Physics Department, National and Kapodistrian University of Athens, Athens, Greece
- ¹⁰ Physics Department, National Technical University of Athens, Zografou, Greece
- ¹¹ Department of Physics, University of Texas at Austin, Austin, TX, United States of America
- ¹² ^(a) Bahcesehir University, Faculty of Engineering and Natural Sciences, Istanbul; ^(b) Istanbul Bilgi University, Faculty of Engineering and Natural Sciences, Istanbul; ^(c) Department of Physics, Bogazici University, Istanbul; ^(d) Department of Physics Engineering, Gaziantep University, Gaziantep, Turkey
- ¹³ Institute of Physics, Azerbaijan Academy of Sciences, Baku, Azerbaijan
- ¹⁴ Institut de Física d'Altes Energies (IFAE), Barcelona Institute of Science and Technology, Barcelona, Spain
- ¹⁵ ^(a) Institute of High Energy Physics, Chinese Academy of Sciences, Beijing; ^(b) Physics Department, Tsinghua University, Beijing; ^(c) Department of Physics, Nanjing University, Nanjing; ^(d) University of Chinese Academy of Science (UCAS), Beijing, China
- ¹⁶ Institute of Physics, University of Belgrade, Belgrade, Serbia
- ¹⁷ Department for Physics and Technology, University of Bergen, Bergen, Norway
- ¹⁸ Physics Division, Lawrence Berkeley National Laboratory and University of California, Berkeley, CA, United States of America
- ¹⁹ Institut für Physik, Humboldt Universität zu Berlin, Berlin, Germany
- ²⁰ Albert Einstein Center for Fundamental Physics and Laboratory for High Energy Physics, University of Bern, Bern, Switzerland
- ²¹ School of Physics and Astronomy, University of Birmingham, Birmingham, United Kingdom
- ²² Facultad de Ciencias y Centro de Investigaciones, Universidad Antonio Nariño, Bogota, Colombia
- ²³ ^(a) INFN Bologna and Università di Bologna, Dipartimento di Fisica; ^(b) INFN Sezione di Bologna, Italy
- ²⁴ Physikalisches Institut, Universität Bonn, Bonn, Germany
- ²⁵ Department of Physics, Boston University, Boston, MA, United States of America
- ²⁶ Department of Physics, Brandeis University, Waltham, MA, United States of America
- ²⁷ ^(a) Transilvania University of Brasov, Brasov; ^(b) Horia Hulubei National Institute of Physics and Nuclear Engineering, Bucharest; ^(c) Department of Physics, Alexandru Ioan Cuza University of Iasi, Iasi; ^(d) National Institute for Research and Development of Isotopic and Molecular Technologies, Physics Department, Cluj-Napoca; ^(e) University Politehnica Bucharest, Bucharest; ^(f) West University in Timisoara, Timisoara, Romania
- ²⁸ ^(a) Faculty of Mathematics, Physics and Informatics, Comenius University, Bratislava; ^(b) Department of Subnuclear Physics, Institute of Experimental Physics of the Slovak Academy of Sciences, Kosice, Slovak Republic
- ²⁹ Physics Department, Brookhaven National Laboratory, Upton, NY, United States of America
- ³⁰ Departamento de Física, Universidad de Buenos Aires, Buenos Aires, Argentina
- ³¹ California State University, CA, United States of America
- ³² Cavendish Laboratory, University of Cambridge, Cambridge, United Kingdom
- ³³ ^(a) Department of Physics, University of Cape Town, Cape Town; ^(b) Department of Mechanical Engineering Science, University of Johannesburg, Johannesburg; ^(c) School of Physics, University of the Witwatersrand, Johannesburg, South Africa
- ³⁴ Department of Physics, Carleton University, Ottawa, ON, Canada
- ³⁵ ^(a) Faculté des Sciences Ain Chock, Réseau Universitaire de Physique des Hautes Energies – Université Hassan II, Casablanca; ^(b) Faculté des Sciences, Université Ibn-Tofail, Kénitra; ^(c) Faculté des Sciences Semlalia, Université Cadi Ayyad, LPHEA, Marrakech; ^(d) Faculté des Sciences, Université Mohamed Premier and LPTPM, Oujda; ^(e) Faculté des sciences, Université Mohammed V, Rabat, Morocco
- ³⁶ CERN, Geneva, Switzerland
- ³⁷ Enrico Fermi Institute, University of Chicago, Chicago, IL, United States of America
- ³⁸ LPC, Université Clermont Auvergne, CNRS/IN2P3, Clermont-Ferrand, France
- ³⁹ Nevis Laboratory, Columbia University, Irvington, NY, United States of America
- ⁴⁰ Niels Bohr Institute, University of Copenhagen, Copenhagen, Denmark
- ⁴¹ ^(a) Dipartimento di Fisica, Università della Calabria, Rende; ^(b) INFN Gruppo Collegato di Cosenza, Laboratori Nazionali di Frascati, Italy
- ⁴² Physics Department, Southern Methodist University, Dallas, TX, United States of America
- ⁴³ Physics Department, University of Texas at Dallas, Richardson, TX, United States of America
- ⁴⁴ National Centre for Scientific Research "Demokritos", Agia Paraskevi, Greece
- ⁴⁵ ^(a) Department of Physics, Stockholm University; ^(b) Oskar Klein Centre, Stockholm, Sweden
- ⁴⁶ Deutsches Elektronen-Synchrotron DESY, Hamburg and Zeuthen, Germany
- ⁴⁷ Lehrstuhl für Experimentelle Physik IV, Technische Universität Dortmund, Dortmund, Germany
- ⁴⁸ Institut für Kern- und Teilchenphysik, Technische Universität Dresden, Dresden, Germany
- ⁴⁹ Department of Physics, Duke University, Durham, NC, United States of America
- ⁵⁰ SUPA – School of Physics and Astronomy, University of Edinburgh, Edinburgh, United Kingdom
- ⁵¹ INFN e Laboratori Nazionali di Frascati, Frascati, Italy
- ⁵² Physikalisches Institut, Albert-Ludwigs-Universität Freiburg, Freiburg, Germany
- ⁵³ II. Physikalisches Institut, Georg-August-Universität Göttingen, Göttingen, Germany
- ⁵⁴ Département de Physique Nucléaire et Corpusculaire, Université de Genève, Genève, Switzerland
- ⁵⁵ ^(a) Dipartimento di Fisica, Università di Genova, Genova; ^(b) INFN Sezione di Genova, Italy
- ⁵⁶ II. Physikalisches Institut, Justus-Liebig-Universität Giessen, Giessen, Germany
- ⁵⁷ SUPA – School of Physics and Astronomy, University of Glasgow, Glasgow, United Kingdom
- ⁵⁸ LPSC, Université Grenoble Alpes, CNRS/IN2P3, Grenoble INP, Grenoble, France
- ⁵⁹ Laboratory for Particle Physics and Cosmology, Harvard University, Cambridge, MA, United States of America
- ⁶⁰ ^(a) Department of Modern Physics and State Key Laboratory of Particle Detection and Electronics, University of Science and Technology of China, Hefei; ^(b) Institute of Frontier and Interdisciplinary Science and Key Laboratory of Particle Physics and Particle Irradiation (MOE), Shandong University, Qingdao; ^(c) School of Physics and Astronomy, Shanghai Jiao Tong University, KLPPAC-MoE, SKLPPC, Shanghai; ^(d) Tsung-Dao Lee Institute, Shanghai, China
- ⁶¹ ^(a) Kirchhoff-Institut für Physik, Ruprecht-Karls-Universität Heidelberg, Heidelberg; ^(b) Physikalisches Institut, Ruprecht-Karls-Universität Heidelberg, Heidelberg, Germany
- ⁶² Faculty of Applied Information Science, Hiroshima Institute of Technology, Hiroshima, Japan
- ⁶³ ^(a) Department of Physics, Chinese University of Hong Kong, Shatin, N.T., Hong Kong; ^(b) Department of Physics, University of Hong Kong, Hong Kong; ^(c) Department of Physics and Institute for Advanced Study, Hong Kong University of Science and Technology, Clear Water Bay, Kowloon, Hong Kong, China
- ⁶⁴ Department of Physics, National Tsing Hua University, Hsinchu, Taiwan
- ⁶⁵ Department of Physics, Indiana University, Bloomington, IN, United States of America
- ⁶⁶ ^(a) INFN Gruppo Collegato di Udine, Sezione di Trieste, Udine; ^(b) ICTP, Trieste; ^(c) Dipartimento Politecnico di Ingegneria e Architettura, Università di Udine, Udine, Italy
- ⁶⁷ ^(a) INFN Sezione di Lecce; ^(b) Dipartimento di Matematica e Fisica, Università del Salento, Lecce, Italy
- ⁶⁸ ^(a) INFN Sezione di Milano; ^(b) Dipartimento di Fisica, Università di Milano, Milano, Italy
- ⁶⁹ ^(a) INFN Sezione di Napoli; ^(b) Dipartimento di Fisica, Università di Napoli, Napoli, Italy
- ⁷⁰ ^(a) INFN Sezione di Pavia; ^(b) Dipartimento di Fisica, Università di Pavia, Pavia, Italy
- ⁷¹ ^(a) INFN Sezione di Pisa; ^(b) Dipartimento di Fisica E. Fermi, Università di Pisa, Pisa, Italy
- ⁷² ^(a) INFN Sezione di Roma; ^(b) Dipartimento di Fisica, Sapienza Università di Roma, Roma, Italy
- ⁷³ ^(a) INFN Sezione di Roma Tor Vergata; ^(b) Dipartimento di Fisica, Università di Roma Tor Vergata, Roma, Italy
- ⁷⁴ ^(a) INFN Sezione di Roma Tre; ^(b) Dipartimento di Matematica e Fisica, Università Roma Tre, Roma, Italy

- 75 ^(a) INFN-TIFPA; ^(b) Università degli Studi di Trento, Trento, Italy
- 76 Institut für Astro- und Teilchenphysik, Leopold-Franzens-Universität, Innsbruck, Austria
- 77 University of Iowa, Iowa City, IA, United States of America
- 78 Department of Physics and Astronomy, Iowa State University, Ames, IA, United States of America
- 79 Joint Institute for Nuclear Research, Dubna, Russia
- 80 ^(a) Departamento de Engenharia Elétrica, Universidade Federal de Juiz de Fora (UFJF), Juiz de Fora; ^(b) Universidade Federal do Rio De Janeiro COPPE/EE/IF, Rio de Janeiro;
- ^(c) Universidade Federal de São João del Rei (UFSJ), São João del Rei; ^(d) Instituto de Física, Universidade de São Paulo, São Paulo, Brazil
- 81 KEK, High Energy Accelerator Research Organization, Tsukuba, Japan
- 82 Graduate School of Science, Kobe University, Kobe, Japan
- 83 ^(a) AGH University of Science and Technology, Faculty of Physics and Applied Computer Science, Krakow; ^(b) Marian Smoluchowski Institute of Physics, Jagiellonian University, Krakow, Poland
- 84 Institute of Nuclear Physics Polish Academy of Sciences, Krakow, Poland
- 85 Faculty of Science, Kyoto University, Kyoto, Japan
- 86 Kyoto University of Education, Kyoto, Japan
- 87 Research Center for Advanced Particle Physics and Department of Physics, Kyushu University, Fukuoka, Japan
- 88 Instituto de Física La Plata, Universidad Nacional de La Plata and CONICET, La Plata, Argentina
- 89 Physics Department, Lancaster University, Lancaster, United Kingdom
- 90 Oliver Lodge Laboratory, University of Liverpool, Liverpool, United Kingdom
- 91 Department of Experimental Particle Physics, Jožef Stefan Institute and Department of Physics, University of Ljubljana, Ljubljana, Slovenia
- 92 School of Physics and Astronomy, Queen Mary University of London, London, United Kingdom
- 93 Department of Physics, Royal Holloway University of London, Egham, United Kingdom
- 94 Department of Physics and Astronomy, University College London, London, United Kingdom
- 95 Louisiana Tech University, Ruston, LA, United States of America
- 96 Fysiska institutionen, Lunds universitet, Lund, Sweden
- 97 Centre de Calcul de l'Institut National de Physique Nucléaire et de Physique des Particules (IN2P3), Villeurbanne, France
- 98 Departamento de Física Teórica C-15 and CIAFF, Universidad Autónoma de Madrid, Madrid, Spain
- 99 Institut für Physik, Universität Mainz, Mainz, Germany
- 100 School of Physics and Astronomy, University of Manchester, Manchester, United Kingdom
- 101 CPPM, Aix-Marseille Université, CNRS/IN2P3, Marseille, France
- 102 Department of Physics, University of Massachusetts, Amherst, MA, United States of America
- 103 Department of Physics, McGill University, Montreal, QC, Canada
- 104 School of Physics, University of Melbourne, Victoria, Australia
- 105 Department of Physics, University of Michigan, Ann Arbor, MI, United States of America
- 106 Department of Physics and Astronomy, Michigan State University, East Lansing, MI, United States of America
- 107 B.I. Stepanov Institute of Physics, National Academy of Sciences of Belarus, Minsk, Belarus
- 108 Research Institute for Nuclear Problems of Byelorussian State University, Minsk, Belarus
- 109 Group of Particle Physics, University of Montreal, Montreal, QC, Canada
- 110 P.N. Lebedev Physical Institute of the Russian Academy of Sciences, Moscow, Russia
- 111 National Research Nuclear University MEPhI, Moscow, Russia
- 112 D.V. Skobel'syn Institute of Nuclear Physics, M.V. Lomonosov Moscow State University, Moscow, Russia
- 113 Fakultät für Physik, Ludwig-Maximilians-Universität München, München, Germany
- 114 Max-Planck-Institut für Physik (Werner-Heisenberg-Institut), München, Germany
- 115 Nagasaki Institute of Applied Science, Nagasaki, Japan
- 116 Graduate School of Science and Kobayashi-Maskawa Institute, Nagoya University, Nagoya, Japan
- 117 Department of Physics and Astronomy, University of New Mexico, Albuquerque, NM, United States of America
- 118 Institute for Mathematics, Astrophysics and Particle Physics, Radboud University Nijmegen/Nikhef, Nijmegen, Netherlands
- 119 Nikhef National Institute for Subatomic Physics and University of Amsterdam, Amsterdam, Netherlands
- 120 Department of Physics, Northern Illinois University, DeKalb, IL, United States of America
- 121 ^(a) Budker Institute of Nuclear Physics and NSU, SB RAS, Novosibirsk; ^(b) Novosibirsk State University Novosibirsk, Russia
- 122 Institute for High Energy Physics of the National Research Centre Kurchatov Institute, Protvino, Russia
- 123 Institute for Theoretical and Experimental Physics named by A.I. Alikhanov of National Research Centre "Kurchatov Institute", Moscow, Russia
- 124 Department of Physics, New York University, New York, NY, United States of America
- 125 Ochanomizu University, Otsuka, Bunkyo-ku, Tokyo, Japan
- 126 Ohio State University, Columbus, OH, United States of America
- 127 Faculty of Science, Okayama University, Okayama, Japan
- 128 Homer L. Dodge Department of Physics and Astronomy, University of Oklahoma, Norman, OK, United States of America
- 129 Department of Physics, Oklahoma State University, Stillwater, OK, United States of America
- 130 Palacký University, RCPTM, Joint Laboratory of Optics, Olomouc, Czech Republic
- 131 Center for High Energy Physics, University of Oregon, Eugene, OR, United States of America
- 132 LAL, Université Paris-Sud, CNRS/IN2P3, Université Paris-Saclay, Orsay, France
- 133 Graduate School of Science, Osaka University, Osaka, Japan
- 134 Department of Physics, University of Oslo, Oslo, Norway
- 135 Department of Physics, Oxford University, Oxford, United Kingdom
- 136 LPNHE, Sorbonne Université, Université de Paris, CNRS/IN2P3, Paris, France
- 137 Department of Physics, University of Pennsylvania, Philadelphia, PA, United States of America
- 138 Konstantinov Nuclear Physics Institute of National Research Centre "Kurchatov Institute", PNPI, St. Petersburg, Russia
- 139 Department of Physics and Astronomy, University of Pittsburgh, Pittsburgh, PA, United States of America
- 140 ^(a) Laboratório de Instrumentação e Física Experimental de Partículas – LIP, Lisboa; ^(b) Departamento de Física, Faculdade de Ciências, Universidade de Lisboa, Lisboa; ^(c) Departamento de Física, Universidade de Coimbra, Coimbra; ^(d) Centro de Física Nuclear da Universidade de Lisboa, Lisboa; ^(e) Departamento de Física, Universidade do Minho, Braga; ^(f) Departamento de Física Teórica y del Cosmos, Universidad de Granada, Granada (Spain); ^(g) Dep Física and CEFITEC of Faculdade de Ciências e Tecnologia, Universidade Nova de Lisboa, Caparica; ^(h) Instituto Superior Técnico, Universidade de Lisboa, Lisboa, Portugal
- 141 Institute of Physics of the Czech Academy of Sciences, Prague, Czech Republic
- 142 Czech Technical University in Prague, Prague, Czech Republic
- 143 Charles University, Faculty of Mathematics and Physics, Prague, Czech Republic
- 144 Particle Physics Department, Rutherford Appleton Laboratory, Didcot, United Kingdom
- 145 IRFU, CEA, Université Paris-Saclay, Gif-sur-Yvette, France
- 146 Santa Cruz Institute for Particle Physics, University of California Santa Cruz, Santa Cruz, CA, United States of America
- 147 ^(a) Departamento de Física, Pontificia Universidad Católica de Chile, Santiago; ^(b) Universidad Andres Bello, Department of Physics, Santiago; ^(c) Departamento de Física, Universidad Técnica Federico Santa María, Valparaíso, Chile

- ¹⁴⁸ Department of Physics, University of Washington, Seattle, WA, United States of America
¹⁴⁹ Department of Physics and Astronomy, University of Sheffield, Sheffield, United Kingdom
¹⁵⁰ Department of Physics, Shinshu University, Nagano, Japan
¹⁵¹ Department Physik, Universität Siegen, Siegen, Germany
¹⁵² Department of Physics, Simon Fraser University, Burnaby, BC, Canada
¹⁵³ SLAC National Accelerator Laboratory, Stanford, CA, United States of America
¹⁵⁴ Physics Department, Royal Institute of Technology, Stockholm, Sweden
¹⁵⁵ Departments of Physics and Astronomy, Stony Brook University, Stony Brook, NY, United States of America
¹⁵⁶ Department of Physics and Astronomy, University of Sussex, Brighton, United Kingdom
¹⁵⁷ School of Physics, University of Sydney, Sydney, Australia
¹⁵⁸ Institute of Physics, Academia Sinica, Taipei, Taiwan
¹⁵⁹ ^(a) E. Andronikashvili Institute of Physics, Iv. Javakishvili Tbilisi State University, Tbilisi; ^(b) High Energy Physics Institute, Tbilisi State University, Tbilisi, Georgia
¹⁶⁰ Department of Physics, Technion, Israel Institute of Technology, Haifa, Israel
¹⁶¹ Raymond and Beverly Sackler School of Physics and Astronomy, Tel Aviv University, Tel Aviv, Israel
¹⁶² Department of Physics, Aristotle University of Thessaloniki, Thessaloniki, Greece
¹⁶³ International Center for Elementary Particle Physics and Department of Physics, University of Tokyo, Tokyo, Japan
¹⁶⁴ Graduate School of Science and Technology, Tokyo Metropolitan University, Tokyo, Japan
¹⁶⁵ Department of Physics, Tokyo Institute of Technology, Tokyo, Japan
¹⁶⁶ Tomsk State University, Tomsk, Russia
¹⁶⁷ Department of Physics, University of Toronto, Toronto, ON, Canada
¹⁶⁸ ^(a) TRIUMF, Vancouver, BC; ^(b) Department of Physics and Astronomy, York University, Toronto, ON, Canada
¹⁶⁹ Division of Physics and Tomonaga Center for the History of the Universe, Faculty of Pure and Applied Sciences, University of Tsukuba, Tsukuba, Japan
¹⁷⁰ Department of Physics and Astronomy, Tufts University, Medford, MA, United States of America
¹⁷¹ Department of Physics and Astronomy, University of California Irvine, Irvine, CA, United States of America
¹⁷² Department of Physics and Astronomy, University of Uppsala, Uppsala, Sweden
¹⁷³ Department of Physics, University of Illinois, Urbana, IL, United States of America
¹⁷⁴ Instituto de Física Corpuscular (IFIC), Centro Mixto Universidad de Valencia – CSIC, Valencia, Spain
¹⁷⁵ Department of Physics, University of British Columbia, Vancouver, BC, Canada
¹⁷⁶ Department of Physics and Astronomy, University of Victoria, Victoria, BC, Canada
¹⁷⁷ Fakultät für Physik und Astronomie, Julius-Maximilians-Universität Würzburg, Würzburg, Germany
¹⁷⁸ Department of Physics, University of Warwick, Coventry, United Kingdom
¹⁷⁹ Waseda University, Tokyo, Japan
¹⁸⁰ Department of Particle Physics, Weizmann Institute of Science, Rehovot, Israel
¹⁸¹ Department of Physics, University of Wisconsin, Madison, WI, United States of America
¹⁸² Fakultät für Mathematik und Naturwissenschaften, Fachgruppe Physik, Bergische Universität Wuppertal, Wuppertal, Germany
¹⁸³ Department of Physics, Yale University, New Haven, CT, United States of America

- ^a Also at Borough of Manhattan Community College, City University of New York, New York, NY; United States of America.
^b Also at CERN, Geneva; Switzerland.
^c Also at CPPM, Aix-Marseille Université, CNRS/IN2P3, Marseille; France.
^d Also at Département de Physique Nucléaire et Corpusculaire, Université de Genève, Genève; Switzerland.
^e Also at Departament de Física de la Universitat Autònoma de Barcelona, Barcelona; Spain.
^f Also at Department of Applied Physics and Astronomy, University of Sharjah, Sharjah; United Arab Emirates.
^g Also at Department of Financial and Management Engineering, University of the Aegean, Chios; Greece.
^h Also at Department of Physics and Astronomy, Michigan State University, East Lansing, MI; United States of America.
ⁱ Also at Department of Physics and Astronomy, University of Louisville, Louisville, KY; United States of America.
^j Also at Department of Physics, Ben Gurion University of the Negev, Beer Sheva; Israel.
^k Also at Department of Physics, California State University, East Bay; United States of America.
^l Also at Department of Physics, California State University, Fresno; United States of America.
^m Also at Department of Physics, California State University, Sacramento; United States of America.
ⁿ Also at Department of Physics, King's College London, London; United Kingdom.
^o Also at Department of Physics, St. Petersburg State Polytechnical University, St. Petersburg; Russia.
^p Also at Department of Physics, Stanford University, Stanford, CA; United States of America.
^q Also at Department of Physics, University of Adelaide, Adelaide; Australia.
^r Also at Department of Physics, University of Fribourg, Fribourg; Switzerland.
^s Also at Department of Physics, University of Michigan, Ann Arbor, MI; United States of America.
^t Also at Dipartimento di Matematica, Informatica e Fisica, Università di Udine, Udine; Italy.
^u Also at Faculty of Physics, M.V. Lomonosov Moscow State University, Moscow; Russia.
^v Also at Giresun University, Faculty of Engineering, Giresun; Turkey.
^w Also at Graduate School of Science, Osaka University, Osaka; Japan.
^x Also at Hellenic Open University, Patras; Greece.
^y Also at Institutio Catalana de Recerca i Estudis Avancats, ICREA, Barcelona; Spain.
^z Also at Institut für Experimentalphysik, Universität Hamburg, Hamburg; Germany.
^{aa} Also at Institute for Mathematics, Astrophysics and Particle Physics, Radboud University Nijmegen/Nikhef, Nijmegen; Netherlands.
^{ab} Also at Institute for Nuclear Research and Nuclear Energy (INRNE) of the Bulgarian Academy of Sciences, Sofia; Bulgaria.
^{ac} Also at Institute for Particle and Nuclear Physics, Wigner Research Centre for Physics, Budapest; Hungary.
^{ad} Also at Institute of Particle Physics (IPP), Vancouver; Canada.
^{ae} Also at Institute of Physics, Azerbaijan Academy of Sciences, Baku; Azerbaijan.
^{af} Also at Instituto de Física Teórica, IFT-UAM/CSIC, Madrid; Spain.
^{ag} Also at Joint Institute for Nuclear Research, Dubna; Russia.
^{ah} Also at LAL, Université Paris-Sud, CNRS/IN2P3, Université Paris-Saclay, Orsay; France.
^{ai} Also at Louisiana Tech University, Ruston, LA; United States of America.
^{aj} Also at Manhattan College, New York, NY; United States of America.
^{ak} Also at Moscow Institute of Physics and Technology State University, Dolgoprudny; Russia.
^{al} Also at National Research Nuclear University MEPhI, Moscow; Russia.
^{am} Also at Physics Department, An-Najah National University, Nablus; Palestine.

^{an} Also at Physics Dept, University of South Africa, Pretoria; South Africa.

^{ao} Also at Physikalisches Institut, Albert-Ludwigs-Universität Freiburg, Freiburg; Germany.

^{ap} Also at School of Physics, Sun Yat-sen University, Guangzhou; China.

^{aq} Also at The City College of New York, New York, NY; United States of America.

^{ar} Also at Tomsk State University, Tomsk, and Moscow Institute of Physics and Technology State University, Dolgoprudny; Russia.

^{as} Also at TRIUMF, Vancouver BC; Canada.

^{at} Also at Università di Napoli Parthenope, Napoli; Italy.

* Deceased.