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Combination of searches for invisible Higgs boson decays with the ATLAS experiment

The ATLAS Collaboration

Dark matter particles, if sufficiently light, may be produced in decays of the Higgs boson. This Letter presents a statistical combination of searches for $H \rightarrow$ invisible decays where H is produced according to the Standard Model via vector boson fusion, $Z(\ell\ell)H$, and $W/Z(\text{had})H$, all performed with the ATLAS detector using 36.1 fb^{-1} of pp collisions at a center-of-mass energy of $\sqrt{s} = 13 \text{ TeV}$ at the LHC. In combination with the results at $\sqrt{s} = 7$ and 8 TeV , an exclusion limit on the $H \rightarrow$ invisible branching ratio of $0.26 (0.17^{+0.07}_{-0.05})$ at 95% confidence level is observed (expected).

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One of the central open questions in physics today is the nature of dark matter (DM) that is found to comprise most of the matter in the universe [1–4]. A compelling candidate for DM is a stable electrically neutral particle χ whose non-gravitational interactions with Standard Model (SM) particles are weak. Such a particle with a mass comparable to the mass scale of the electroweak sector particles could be detectable [5–7] and accommodate the observed DM relic density [8, 9]. Numerous models predict detectable production rates of such DM particles at the Large Hadron Collider (LHC) [10–12]. In a wide class of those models, the 125 GeV Higgs boson H [13, 14] acts as a portal between a dark sector and the SM sector, either through Yukawa-type couplings to fermionic dark matter, or other mechanisms [15–28]. If kinematically allowed, decays of the Higgs boson to DM particles represent a distinct signature in such models. Higgs boson decays to DM particles can only be indirectly inferred through missing transverse momentum¹ $E_{\text{T}}^{\text{miss}}$ due to DM particles escaping detection, and are therefore termed “invisible” (inv).

Direct searches for invisible Higgs boson decays have been carried out with the ATLAS detector [29–31] in Run 1 of the LHC, using up to 4.7 fb^{-1} of pp collision data at a center-of-mass energy of $\sqrt{s} = 7 \text{ TeV}$ and up to 20.3 fb^{-1} at 8 TeV. Different event topologies were considered, assuming SM production rates: vector boson fusion (VBF) [32], Higgsstrahlung from a Z boson decaying into a pair of electrons or muons ($Z(\text{lep})H$) [33], and Higgsstrahlung from a W or Z boson decaying into hadrons ($V(\text{had})H$) [34]. These searches for invisible Higgs boson decays have been statistically combined, and an upper limit at 95% confidence level (CL) on the invisible Higgs boson branching ratio of $\mathcal{B}_{H \rightarrow \text{inv}} < 0.25$ ($0.27_{-0.08}^{+0.10}$) [35] was observed (expected). In combination with visible decay modes of the Higgs boson, the upper observed (expected) limit improved to 0.23 (0.24) [35]. Direct searches for invisible Higgs decays were performed using up to 36.1 fb^{-1} of pp collision data at $\sqrt{s} = 13 \text{ TeV}$ recorded in 2015 and 2016 in the VBF [36], $Z(\text{lep})H$ [37], and $V(\text{had})H$ [38] topologies at ATLAS. The aforementioned results at $\sqrt{s} = 13 \text{ TeV}$ will be referred to as “Run 2 results” in the following. Similar searches were performed by the CMS Collaboration [39–43].

This Letter presents the statistical combination of the Run 2 searches with 36.1 fb^{-1} of data for invisible decays of the Higgs boson using the ATLAS detector. Subsequently, a statistical combination with the combined Run 1 result [35] from ATLAS is performed. An overview of all results used as inputs in this combination is given in Table 1. The analysis is performed under the assumption of SM Higgs boson production. Visible decay modes of the Higgs boson are not considered.

A brief overview of the Run 2 searches for $H \rightarrow \text{inv}$ is given below.

- **VBF topology [36]:** The analysis of the VBF production mode employs a $E_{\text{T}}^{\text{miss}}$ trigger that is 98% efficient or better in the considered region of phase space. The event selection requires $E_{\text{T}}^{\text{miss}} > 180 \text{ GeV}$. Jets (j) are reconstructed up to $|\eta(j)| < 4.5$ from energy clusters in the calorimeter using the anti- k_r algorithm [44] with a radius parameter $R = 0.4$. The two jets leading in p_{T} are required to be separated by $|\Delta\eta_{jj}| > 4.8$. There should be no additional jets with $p_{\text{T}} > 25 \text{ GeV}$ and no isolated electron or muon candidate with $p_{\text{T}} > 7 \text{ GeV}$. These requirements serve to reduce the contribution from W/Z production in association with jets ($V + \text{jets}$). In the search signal region (SR) the m_{jj} distribution of the background falls more rapidly than the signal, where m_{jj} represents the invariant mass of the two selected leading jets. Thus the SR is divided into three m_{jj} regions ($1 < m_{jj}/\text{TeV} < 1.5$, $1.5 < m_{jj}/\text{TeV} < 2$, and $m_{jj}/\text{TeV} > 2$) to improve the

¹ ATLAS uses a right-handed coordinate system with its origin at the nominal interaction point (IP) in the center of the detector and the z -axis along the beam pipe. The x -axis points to the center of the LHC ring, and the y -axis points upward. 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 $\eta = -\ln \tan(\theta/2)$. The distance between two objects in η - ϕ space is $\Delta R = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2}$. Transverse momentum is defined by $p_{\text{T}} = p \sin \theta$.

search sensitivity. The dominant background sources are $Z(\nu\nu) + \text{jets}$ and $W(\ell\nu) + \text{jets}$ production, where the charged lepton ℓ is not detected. Control regions (CR) enriched in $Z(\ell\ell) + \text{jets}$ and $W(\ell\nu) + \text{jets}$ processes with $\ell = e, \mu$ are defined to determine the respective normalization factors in the SR. The main contributions to uncertainties are from the finite number of simulated Monte Carlo (MC) events, the modelling of $V + \text{jets}$ production, and accuracy of the jet energy scale (JES). The final discriminant is the number of events in the three m_{jj} regions.

- **$Z(\text{lep})H$ topology [37]:** This search is conducted in the Higgsstrahlung channel where the Z boson decays into a pair of electrons or muons. A selected candidate event must pass at least one of the various single-lepton triggers, fulfill $E_T^{\text{miss}} > 90$ GeV and $E_T^{\text{miss}}/H_T > 0.6$, where H_T is calculated as the scalar sum of the p_T of the selected leptons and jets, and have exactly one pair of isolated electrons or muons with an invariant mass that is consistent with that of the Z boson. The transverse momentum requirement on the leading (subleading) charged lepton is $p_T > 30$ (20) GeV. To reduce the $Z + \text{jets}$ background, the dilepton system must be aligned back-to-back relative to the E_T^{miss} vector in the transverse plane. Events with jets originating from b -quarks (b -jets) are vetoed to suppress backgrounds from top quark pair ($t\bar{t}$) production and W boson production in association with a single top quark (Wt). The irreducible $Z(\nu\nu)Z(\ell\ell)$ background is estimated from MC simulations and its production yield is normalized to the theoretical prediction of Ref. [45, 46]. The $W(\ell\nu)Z(\ell\ell)$ background contribution is also predicted with MC simulations and is normalized by a scale factor that is obtained from a CR enriched in WZ events. The $Z + \text{jets}$ background is estimated with a data-driven method that uses Z -enriched CRs. The final discriminant is E_T^{miss} .
- **$V(\text{had})H$ topology [38]:** This analysis considers the Higgsstrahlung channel where the associated W or Z boson decays into hadrons. The final state signature of large E_T^{miss} and jets also receives contributions from Higgs boson production via gluon fusion with jets originating from initial state radiation, and production via the VBF process. Selected events must pass a E_T^{miss} trigger and must not contain an isolated electron or muon with $p_T > 7$ GeV. As a V is boosted, the two jets from its decay become increasingly collimated and are eventually merged into one single reconstructed jet. Thus, this search is conducted in two topological channels. In the “merged” topology, the SR is defined with $E_T^{\text{miss}} > 250$ GeV and has at least one trimmed [47, 48] large- R jet (J) that is reconstructed using the anti- k_r algorithm with $R = 1.0$. The signal large- R jet is the one with the highest p_T . For the “resolved” topology, the selected event should have $E_T^{\text{miss}} > 150$ GeV and at least two small- R jets (j) with $R = 0.4$. Each event is first passed through the merged topology selection and, if it fails, it is passed through the resolved topology selection. To improve the search sensitivity, the selected events are further split into categories with zero, one, and two identified b -jets, and into two mass regions of the invariant mass of the signal large- R jet (two signal small- R jets) for the merged (resolved) topology. The low mass region ($70 \lesssim m_J, m_{jj}/\text{GeV} \lesssim 100$) targets the hadronic W/Z boson decays of the associated production, whereas the high mass region ($100 \lesssim m_J, m_{jj}/\text{GeV} < 250$) is sensitive to gluon fusion and VBF production. The main background contributions are from the $V + \text{jets}$ and $t\bar{t}$ processes. The predictions from MC simulations are constrained with CRs that contained one or two leptons, and are kinematically similar to the SR. The final discriminant is E_T^{miss} .

The SRs and CRs of the individual input analyses are either orthogonal by construction, or were shown to have an overlap below 1%, which is neglected in the following.

The statistical combination of the analyses is performed by constructing the product of their likelihoods and maximizing the resulting likelihood ratio $\Lambda(\mathcal{B}_{H \rightarrow \text{inv}}; \theta)$ [49]. This is done following the implementation described in Ref. [50, 51], with $\mathcal{B}_{H \rightarrow \text{inv}}$ as the parameter of interest. Systematic uncertainties are modeled in the likelihood function as nuisance parameters θ constrained by Gaussian or log-normal probability density functions [35]. Expected results are obtained using the Asimov dataset technique [49].

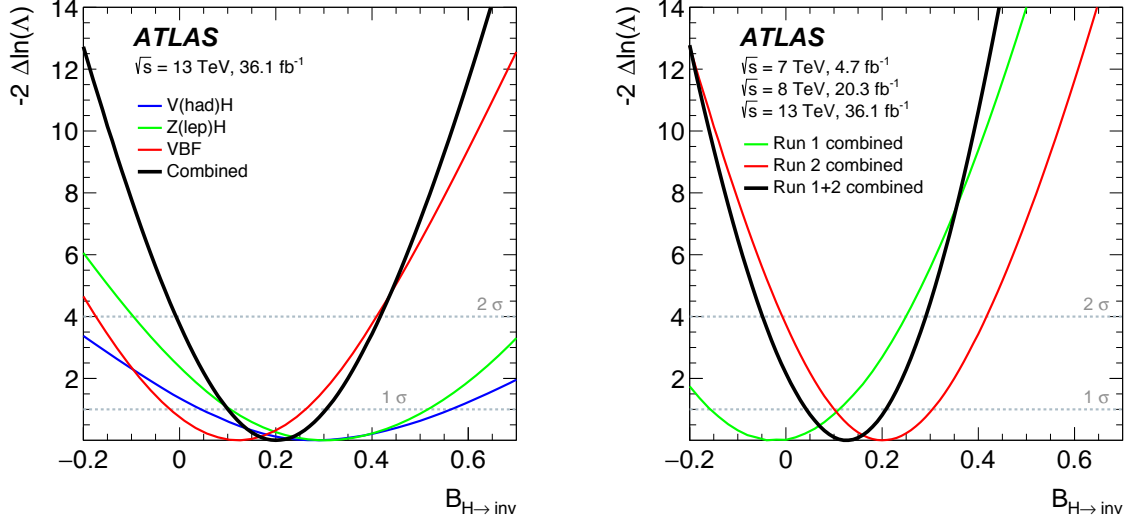


Figure 1: The observed negative logarithmic profile likelihood ratios $-2 \Delta \ln(\Lambda)$ as a function of $\mathcal{B}_{H \rightarrow \text{inv}}$ of the $V(\text{had})H$, $Z(\text{lep})H$, and VBF topologies using Run 2 data only and their statistical combination (left). The $-2 \Delta \ln(\Lambda)$ functions for the Run 2 combination together with the Run 1 combination and the total Run 1+2 combination (right).

In the combination of Run 2 results, most experimental systematic uncertainties as well as the uncertainty on the integrated luminosity and the modeling of additional pp collisions in the same and neighboring bunch crossings (pile-up) are correlated across all search channels. Some experimental uncertainties related to flavor tagging and the JES are represented through different parameterizations in the input analyses and are therefore treated as uncorrelated. The impact of this assumption on the combined result is estimated using alternative correlation models where the leading sources of systematic uncertainty in the respective parameterizations are treated as correlated, and found to have an absolute effect on the $\mathcal{B}_{H \rightarrow \text{inv}}$ limit of the order of 0.01. The systematic uncertainties on the total $H \rightarrow \text{inv}$ signal cross section due to the choice of parton distribution functions (PDF) are considered correlated among all channels. By contrast, uncertainties due to missing higher order corrections are estimated through variations of factorization and renormalisation scales and treated as correlated between the $Z(\text{lep})H$ and $V(\text{had})H$ processes. This is not done for VBF, which represents a distinct topology. The impact of the corresponding uncertainties on the acceptance rather than the total cross section of $V(\text{had})H$ production is evaluated and found negligible. Few systematic uncertainties that are tightly constrained in a given analysis are left uncorrelated in order not to introduce any potential phase space specific biases.

The negative logarithmic profile likelihood ratios $-2 \Delta \ln(\Lambda)(\mathcal{B}_{H \rightarrow \text{inv}}; \theta)$ as a function of $\mathcal{B}_{H \rightarrow \text{inv}}$ of the individual analyses and of the combined Run 2 result are shown in Fig. 1, corresponding to a best-fit combined value of $\mathcal{B}_{H \rightarrow \text{inv}} = 0.20 \pm 0.10$. The dominant uncertainty sources are finite event yields in data and MC, reconstruction of jets and leptons, and modelling of diboson and $W/Z + \text{jets}$ production. In absence of a significant excess, an upper limit at 95% CL of $\mathcal{B}_{H \rightarrow \text{inv}} < 0.38$ ($0.21^{+0.08}_{-0.06}$) is observed (expected) with the CL_s formalism [52] using the profile likelihood ratio as a test statistic. The excess in data corresponds to a p_{SM} -value of 3% under the SM hypothesis of $\mathcal{B}_{H \rightarrow \text{inv}} \simeq 10^{-3}$, and is a consequence of the excesses present in each of the three input analyses.

Subsequently, the above Run 2 result is combined with the Run 1 searches for $H \rightarrow \text{inv}$ decays [35]. Due to the differences between the detector layouts and data-taking conditions, reconstruction algorithms and their

Table 1: Observed and expected upper limits on $\mathcal{B}_{H \rightarrow \text{inv}}$ at 95% CL from direct searches for invisible decays of the 125 GeV Higgs boson and statistical combinations. Also given are the observed p -values under the SM hypothesis.

Analysis	\sqrt{s}	Int. luminosity	Observed	Expected	p_{SM} -value	Reference
Run 2 VBF	13 TeV	36.1 fb ⁻¹	0.37	0.28 ^{+0.11} _{-0.08}	0.19	[36]
Run 2 $Z(\text{lep})H$	13 TeV	36.1 fb ⁻¹	0.67	0.39 ^{+0.17} _{-0.11}	0.06	[37]
Run 2 $V(\text{had})H$	13 TeV	36.1 fb ⁻¹	0.83	0.58 ^{+0.23} _{-0.16}	0.12	[38]
Run 2 Comb.	13 TeV	36.1 fb ⁻¹	0.38	0.21 ^{+0.08} _{-0.06}	0.03	this Letter
Run 1 Comb.	7, 8 TeV	4.7, 20.3 fb ⁻¹	0.25	0.27 ^{+0.10} _{-0.08}	—	[35]
Run 1+2 Comb.	7, 8, 13 TeV	4.7, 20.3, 36.1 fb ⁻¹	0.26	0.17 ^{+0.07} _{-0.05}	0.10	this Letter

calibrations, and treatment of systematic uncertainties, the correlations between the runs are not clearly identifiable. Hence, no correlations between Run 1 and 2 are assumed for most instrumental uncertainties. The uncertainties related to the modeling of the calorimeter response dependence on jet flavor and pile-up are taken as either correlated or uncorrelated between the runs, and the choice which results in a weaker expected exclusion limit on $\mathcal{B}_{H \rightarrow \text{inv}}$ is adopted. The uncertainty on the JES of b -quark jets was estimated using MC simulations [53, 54] and is therefore considered correlated. For the signal modeling, the parton shower uncertainty in the $V(\text{had})H$ channel, the uncertainty from missing higher order corrections in the $Z(\text{lep})H$ analysis, and the uncertainty on the jet multiplicity in the VBF channel [55] are each taken as correlated between the runs since the estimated uncertainties stem from the same source. For the same reason, the uncertainty from missing higher order corrections on the dominant background from diboson production in the $Z(\text{lep})H$ search is treated as correlated. All other background modeling uncertainties are considered uncorrelated. The impact of these correlation assumptions on the combined $\mathcal{B}_{H \rightarrow \text{inv}}$ limit is found to be at most 0.005. In addition, scenarios ranging from full anti-correlation to full correlation were studied using BLUE [56] for the components of the JES uncertainty, the V +jets background, and diboson production that are nominally not correlated due to different parameterisations in Run 1 and 2. Their absolute effect on the $\mathcal{B}_{H \rightarrow \text{inv}}$ limit is at most 0.01.

The observed $-2 \Delta \ln(\Lambda)(\mathcal{B}_{H \rightarrow \text{inv}}; \theta)$ ratio of the combined Run 1+2 result is represented in Fig. 1, alongside the individual Run 1 and Run 2 combinations. A best-fit value of $\mathcal{B}_{H \rightarrow \text{inv}} = 0.13 \pm 0.08$ is obtained, corresponding to an observed (expected) upper limit of $\mathcal{B}_{H \rightarrow \text{inv}} < 0.26$ ($0.17^{+0.07}_{-0.05}$) at 95% CL. The p_{SM} -value under the SM hypothesis is 10%, and the compatibility between the Run 1 and Run 2 results is 1.5 standard deviations. The final result, together with the results in the individual Run 2 analyses as well as the Run 2-only and the Run 1-only combinations, are summarized in Table 1, and the upper limits on $\mathcal{B}_{H \rightarrow \text{inv}}$ are graphically represented in Fig. 2.

The constraint from the combined observed Run 1+2 exclusion limit of $\mathcal{B}_{H \rightarrow \text{inv}} < 0.24$ at 90% CL is compared to the results from representative direct DM detection experiments [57–61] in Fig. 3. This comparison is performed in the context of Higgs portal models [62]. The translation of the $H \rightarrow \text{inv}$ result into a weak interacting massive particle–nucleon scattering cross section $\sigma_{\text{WIMP-N}}$ relies on an effective field theory approach [32] under the assumption that invisible Higgs decays to a pair of WIMPs are kinematically possible and that the WIMP is a scalar or a fermion [23, 63, 64], using the nuclear form

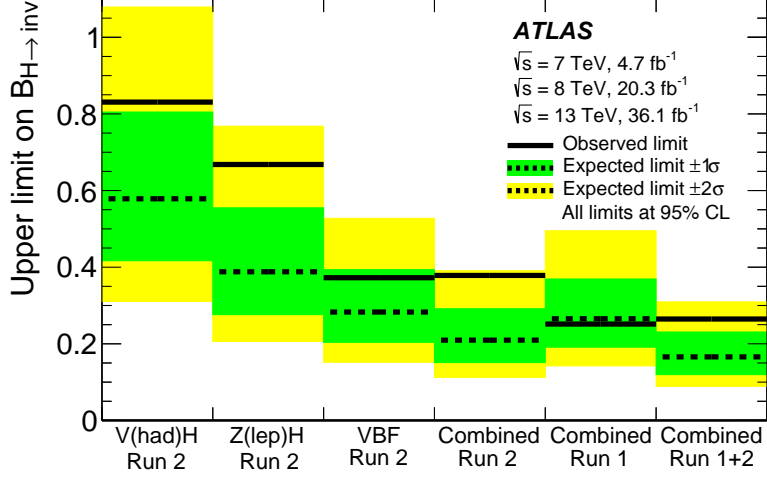


Figure 2: The observed and expected upper limits on $\mathcal{B}_{H \rightarrow \text{inv}}$ at 95% CL from direct searches for invisible decays of the 125 GeV Higgs boson and their statistical combinations in Run 1 and 2.

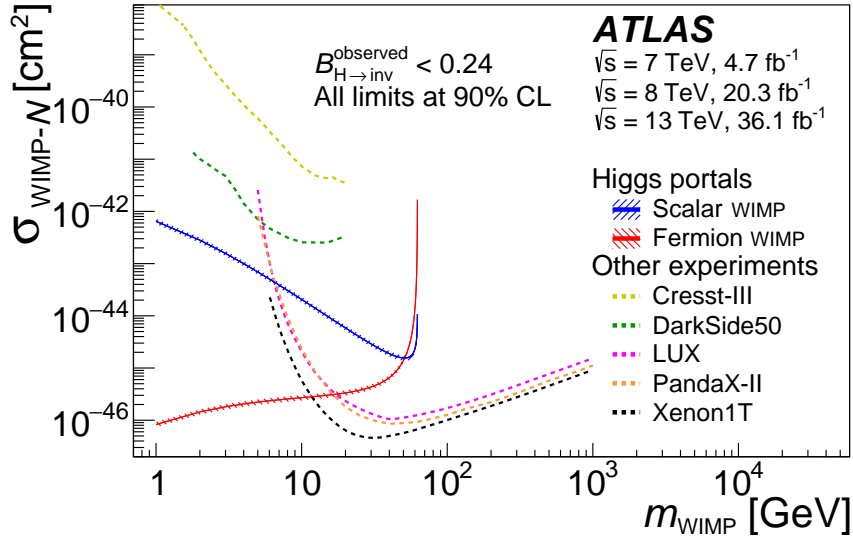


Figure 3: Comparison of the upper limits at 90% CL from direct detection experiments [57–61] on the spin-independent WIMP-nucleon scattering cross section to the observed exclusion limits from this analysis, assuming Higgs portal scenarios where the 125 GeV Higgs boson decays to a pair of DM particles [32, 62]. The regions above the limit contours are excluded in the range shown in the plot.

factor $f_N = 0.308 \pm 0.018$ [65]. The excluded $\sigma_{\text{WIMP-N}}$ values range down to $2 \times 10^{-45} \text{ cm}^2$ in the scalar WIMP scenario. In the fermion WIMP case, the effective coupling is reduced by m_H^2 [32], excluding $\sigma_{\text{WIMP-N}}$ values down to 10^{-46} cm^2 . While the ATLAS exclusion limits extend to $m_{\text{WIMP}} < 1 \text{ GeV}$, that region is subject to uncertainties in modelling of the nuclear recoil and is therefore not included in Figure 3.

In summary, direct searches for invisible Higgs boson decays using 36.1 fb^{-1} of pp collision data at $\sqrt{s} = 13 \text{ TeV}$ recorded in 2015 and 2016 in the VBF, $Z(\text{lep})H$, and $V(\text{had})H$ topologies are statistically

combined assuming SM-like Higgs boson production. An upper limit on the invisible Higgs branching ratio of $\mathcal{B}_{H \rightarrow \text{inv}} < 0.38$ ($0.21^{+0.08}_{-0.06}$) is observed (expected) at 95% CL. A statistical combination of this result with the combination of direct $H \rightarrow \text{inv}$ searches using up to 4.7 fb^{-1} of pp collision data at $\sqrt{s} = 7 \text{ TeV}$ and up to 20.3 fb^{-1} at 8 TeV collected in Run 1 of the LHC yields an observed (expected) upper limit of $\mathcal{B}_{H \rightarrow \text{inv}} < 0.26$ ($0.17^{+0.07}_{-0.05}$) at 95% CL. The combined Run 1+2 result is translated into upper limits on the WIMP–nucleon scattering cross section for Higgs portal models. The derived limits range down to $2 \times 10^{-45} \text{ cm}^2$ in the scalar and 10^{-46} cm^2 in the fermion WIMP scenarios, highlighting the complementarity of DM searches at the LHC and direct detection experiments.

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The ATLAS Collaboration

M. Aaboud^{35d}, G. Aad¹⁰¹, B. Abbott¹²⁸, D.C. Abbott¹⁰², O. Abidinov^{13,*}, A. Abed Abud^{70a,70b}, D.K. Abhayasinghe⁹³, S.H. Abidi¹⁶⁷, O.S. AbouZeid⁴⁰, N.L. Abraham¹⁵⁶, H. Abramowicz¹⁶¹, H. Abreu¹⁶⁰, Y. Abulaiti⁶, B.S. Acharya^{66a,66b,n}, S. Adachi¹⁶³, L. Adam⁹⁹, L. Adamczyk^{83a}, L. Adamek¹⁶⁷, J. Adelman¹²¹, M. Adersberger¹¹⁴, A. Adiguzel^{12c,ah}, S. Adorni⁵⁴, T. Adye¹⁴⁴, A.A. Affolder¹⁴⁶, Y. Afik¹⁶⁰, C. Agapopoulou¹³², M.N. Agaras³⁸, A. Aggarwal¹¹⁹, C. Agheorghiesei^{27c}, J.A. Aguilar-Saavedra^{140f,140a,ag}, F. Ahmadov⁷⁹, G. Aielli^{73a,73b}, S. Akatsuka⁸⁵, T.P.A. Åkesson⁹⁶, E. Akilli⁵⁴, A.V. Akimov¹¹⁰, K. Al Khoury¹³², G.L. Alberghi^{23b,23a}, J. Albert¹⁷⁶, M.J. Alconada Verzini⁸⁸, S. Alderweireldt¹¹⁹, M. Aleksa³⁶, I.N. Aleksandrov⁷⁹, C. Alexa^{27b}, D. Alexandre¹⁹, T. Alexopoulos¹⁰, A. Alfonsi¹²⁰, M. Alhroob¹²⁸, B. Ali¹⁴², G. Alimonti^{68a}, J. Alison³⁷, S.P. Alkire¹⁴⁸, C. Allaire¹³², B.M.M. Allbrooke¹⁵⁶, B.W. Allen¹³¹, P.P. Allport²¹, A. Aloisio^{69a,69b}, A. Alonso⁴⁰, F. Alonso⁸⁸, C. Alpigiani¹⁴⁸, A.A. Alshehri⁵⁷, M.I. Alstaty¹⁰¹, M. Alvarez Estevez⁹⁸, B. Alvarez Gonzalez³⁶, D. Álvarez Piqueras¹⁷⁴, M.G. Alviggi^{69a,69b}, Y. Amaral Coutinho^{80b}, A. Ambler¹⁰³, L. Ambroz¹³⁵, C. Amelung²⁶, D. Amidei¹⁰⁵, S.P. Amor Dos Santos^{140a,140c}, S. Amoroso⁴⁶, C.S. Amrouche⁵⁴, F. An⁷⁸, C. Anastopoulos¹⁴⁹, N. Andari¹⁴⁵, T. Andeen¹¹, C.F. Anders^{61b}, J.K. Anders²⁰, A. Andreazza^{68a,68b}, V. Andrei^{61a}, C.R. Anelli¹⁷⁶, S. Angelidakis³⁸, I. Angelozzi¹²⁰, A. Angerami³⁹, A.V. Anisenkov^{122b,122a}, A. Annovi^{71a}, C. Antel^{61a}, M.T. Anthony¹⁴⁹, M. Antonelli⁵¹, D.J.A. Antrim¹⁷¹, F. Anulli^{72a}, M. Aoki⁸¹, J.A. Aparisi Pozo¹⁷⁴, L. Aperio Bella³⁶, G. Arabidze¹⁰⁶, J.P. Araque^{140a}, V. Araujo Ferraz^{80b}, R. Araujo Pereira^{80b}, A.T.H. Arce⁴⁹, F.A. Arduh⁸⁸, J-F. Arguin¹⁰⁹, S. Argyropoulos⁷⁷, J.-H. Arling⁴⁶, A.J. Armbruster³⁶, L.J. Armitage⁹², A. Armstrong¹⁷¹, O. Arnaez¹⁶⁷, H. Arnold¹²⁰, A. Artamonov^{111,*}, G. Artoni¹³⁵, S. Artz⁹⁹, S. Asai¹⁶³, N. Asbah⁵⁹, E.M. Asimakopoulou¹⁷², L. Asquith¹⁵⁶, K. Assamagan²⁹, R. Astalos^{28a}, R.J. Atkin^{33a}, M. Atkinson¹⁷³, N.B. Atlay¹⁵¹, H. Atmani¹³², K. Augsten¹⁴², G. Avolio³⁶, R. Avramidou^{60a}, M.K. Ayoub^{15a}, A.M. Azoulay^{168b}, G. Azuelos^{109,au}, A.E. Baas^{61a}, M.J. Baca²¹, H. Bachacou¹⁴⁵, K. Bachas^{67a,67b}, M. Backes¹³⁵, F. Backman^{45a,45b}, P. Bagnaia^{72a,72b}, M. Bahmani⁸⁴, H. Bahrasemani¹⁵², A.J. Bailey¹⁷⁴, V.R. Bailey¹⁷³, J.T. Baines¹⁴⁴, M. Bajic⁴⁰, C. Bakalis¹⁰, O.K. Baker¹⁸³, P.J. Bakker¹²⁰, D. Bakshi Gupta⁸, S. Balaji¹⁵⁷, E.M. Baldin^{122b,122a}, P. Balek¹⁸⁰, F. Balli¹⁴⁵, W.K. Balunas¹³⁵, J. Balz⁹⁹, E. Banas⁸⁴, A. Bandyopadhyay²⁴, S. Banerjee^{181,i}, A.A.E. Bannoura¹⁸², L. Barak¹⁶¹, W.M. Barbe³⁸, E.L. Barberio¹⁰⁴, D. Barberis^{55b,55a}, M. Barbero¹⁰¹, T. Barillari¹¹⁵, M-S. Barisits³⁶, J. Barkeloo¹³¹, T. Barklow¹⁵³, R. Barnea¹⁶⁰, S.L. Barnes^{60c}, B.M. Barnett¹⁴⁴, R.M. Barnett¹⁸, Z. Barnovska-Blenessy^{60a}, A. Baroncelli^{60a}, G. Barone²⁹, A.J. Barr¹³⁵, L. Barranco Navarro¹⁷⁴, F. Barreiro⁹⁸, J. Barreiro Guimarães da Costa^{15a}, R. Bartoldus¹⁵³, G. Bartolini¹⁰¹, A.E. Barton⁸⁹, P. Bartos^{28a}, A. Basalae⁴⁶, A. Bassalat¹³², R.L. Bates⁵⁷, S.J. Batista¹⁶⁷, S. Batlamous^{35e}, J.R. Batley³², B. Batool¹⁵¹, M. Battaglia¹⁴⁶, M. Baucé^{72a,72b}, F. Bauer¹⁴⁵, K.T. Bauer¹⁷¹, H.S. Bawa^{31,1}, J.B. Beacham¹²⁶, T. Beau¹³⁶, P.H. Beauchemin¹⁷⁰, P. Bechtel²⁴, H.C. Beck⁵³, H.P. Beck^{20,q}, K. Becker⁵², M. Becker⁹⁹, C. Becot⁴⁶, A. Beddall^{12d}, A.J. Beddall^{12a}, V.A. Bednyakov⁷⁹, M. Bedognetti¹²⁰, C.P. Bee¹⁵⁵, T.A. Beermann⁷⁶, M. Begalli^{80b}, M. Biegel²⁹, A. Behera¹⁵⁵, J.K. Behr⁴⁶, F. Beisiegel²⁴, A.S. Bell⁹⁴, G. Bella¹⁶¹, L. Bellagamba^{23b}, A. Bellerive³⁴, P. Bellos⁹, K. Beloborodov^{122b,122a}, K. Belotskiy¹¹², N.L. Belyaev¹¹², O. Benary^{161,*}, D. Benchekroun^{35a}, N. Benekos¹⁰, Y. Benhammou¹⁶¹, D.P. Benjamin⁶, M. Benoit⁵⁴, J.R. Bensinger²⁶, S. Bentvelsen¹²⁰, L. Beresford¹³⁵, M. Beretta⁵¹, D. Berge⁴⁶, E. Bergeaas Kuutmann¹⁷², N. Berger⁵, B. Bergmann¹⁴², L.J. Bergsten²⁶, J. Beringer¹⁸, S. Berlendis⁷, N.R. Bernard¹⁰², G. Bernardi¹³⁶, C. Bernius¹⁵³, F.U. Bernlochner²⁴, T. Berry⁹³, P. Berta⁹⁹, C. Bertella^{15a}, G. Bertoli^{45a,45b}, I.A. Bertram⁸⁹, G.J. Besjes⁴⁰, O. Bessidskaia Bylund¹⁸², N. Besson¹⁴⁵, A. Bethani¹⁰⁰, S. Bethke¹¹⁵, A. Betti²⁴, A.J. Bevan⁹², J. Beyer¹¹⁵, R. Bi¹³⁹, R.M. Bianchi¹³⁹, O. Biebel¹¹⁴, D. Biedermann¹⁹, R. Bielski³⁶, K. Bierwagen⁹⁹, N.V. Biesuz^{71a,71b}, M. Biglietti^{74a},

T.R.V. Billoud¹⁰⁹, M. Bindi⁵³, A. Bingul^{12d}, C. Bini^{72a,72b}, S. Biondi^{23b,23a}, M. Birman¹⁸⁰, T. Bisanz⁵³, J.P. Biswal¹⁶¹, A. Bitadze¹⁰⁰, C. Bittrich⁴⁸, D.M. Bjergaard⁴⁹, J.E. Black¹⁵³, K.M. Black²⁵, T. Blazek^{28a}, I. Bloch⁴⁶, C. Blocker²⁶, A. Blue⁵⁷, U. Blumenschein⁹², G.J. Bobbink¹²⁰, V.S. Bobrovnikov^{122b,122a}, S.S. Bocchetta⁹⁶, A. Bocci⁴⁹, D. Boerner⁴⁶, D. Bogavac¹¹⁴, A.G. Bogdanchikov^{122b,122a}, C. Bohm^{45a}, V. Boisvert⁹³, P. Bokan^{53,172}, T. Bold^{83a}, A.S. Boldyrev¹¹³, A.E. Bolz^{61b}, M. Bomben¹³⁶, M. Bona⁹², J.S. Bonilla¹³¹, M. Boonekamp¹⁴⁵, H.M. Borecka-Bielska⁹⁰, A. Borisov¹²³, G. Borissov⁸⁹, J. Bortfeldt³⁶, D. Bortoletto¹³⁵, V. Bortolotto^{73a,73b}, D. Boscherini^{23b}, M. Bosman¹⁴, J.D. Bossio Sola³⁰, K. Bouaouda^{35a}, J. Boudreau¹³⁹, E.V. Bouhova-Thacker⁸⁹, D. Boumediene³⁸, C. Bourdarios¹³², S.K. Boutle⁵⁷, A. Boveia¹²⁶, J. Boyd³⁶, D. Boye^{33b}, I.R. Boyko⁷⁹, A.J. Bozson⁹³, J. Bracinik²¹, N. Brahim¹⁰¹, G. Brandt¹⁸², O. Brandt^{61a}, F. Braren⁴⁶, U. Bratzler¹⁶⁴, B. Brau¹⁰², J.E. Brau¹³¹, W.D. Breaden Madden⁵⁷, K. Brendlinger⁴⁶, L. Brenner⁴⁶, R. Brenner¹⁷², S. Bressler¹⁸⁰, B. Brickwedde⁹⁹, D.L. Briglin²¹, D. Britton⁵⁷, D. Britzger¹¹⁵, I. Brock²⁴, R. Brock¹⁰⁶, G. Brooijmans³⁹, T. Brooks⁹³, W.K. Brooks^{147b}, E. Brost¹²¹, J.H. Broughton²¹, P.A. Bruckman de Renstrom⁸⁴, D. Bruncko^{28b}, A. Bruni^{23b}, G. Bruni^{23b}, L.S. Bruni¹²⁰, S. Bruno^{73a,73b}, B.H. Brunt³², M. Bruschi^{23b}, N. Bruscinò¹³⁹, P. Bryant³⁷, L. Bryngemark⁹⁶, T. Buanes¹⁷, Q. Buat³⁶, P. Buchholz¹⁵¹, A.G. Buckley⁵⁷, I.A. Budagov⁷⁹, M.K. Bugge¹³⁴, F. Bühner⁵², O. Bulekov¹¹², T.J. Burch¹²¹, S. Burdin⁹⁰, C.D. Burgard¹²⁰, A.M. Burger¹²⁹, B. Burghgrave⁸, K. Burka⁸⁴, J.T.P. Burr⁴⁶, V. Büscher⁹⁹, E. Buschmann⁵³, P.J. Bussey⁵⁷, J.M. Butler²⁵, C.M. Buttar⁵⁷, J.M. Butterworth⁹⁴, P. Butti³⁶, W. Buttinger³⁶, A. Buzatu¹⁵⁸, A.R. Buzykaev^{122b,122a}, G. Cabras^{23b,23a}, S. Cabrera Urbán¹⁷⁴, D. Caforio¹⁴², H. Cai¹⁷³, V.M.M. Cairo¹⁵³, O. Cakir^{4a}, N. Calace³⁶, P. Calafura¹⁸, A. Calandri¹⁰¹, G. Calderini¹³⁶, P. Calfayan⁶⁵, G. Callea⁵⁷, L.P. Caloba^{80b}, 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.C. Cardillo¹⁴⁹, I. Carli¹⁴³, T. Carli³⁶, G. Carlino^{69a}, B.T. Carlson¹³⁹, L. Carminati^{68a,68b}, R.M.D. Carney^{45a,45b}, S. Caron¹¹⁹, E. Carquin^{147b}, S. Carrá^{68a,68b}, J.W.S. Carter¹⁶⁷, M.P. Casado^{14,e}, A.F. Casha¹⁶⁷, D.W. Casper¹⁷¹, R. Castelijin¹²⁰, F.L. Castillo¹⁷⁴, V. Castillo Gimenez¹⁷⁴, N.F. Castro^{140a,140e}, A. Catinaccio³⁶, J.R. Catmore¹³⁴, A. Cattai³⁶, J. Caudron²⁴, V. Cavaliere²⁹, E. Cavallaro¹⁴, D. Cavalli^{68a}, M. Cavalli-Sforza¹⁴, V. Cavasinni^{71a,71b}, E. Celebi^{12b}, L. Cerda Alberich¹⁷⁴, A.S. Cerqueira^{80a}, A. Cerri¹⁵⁶, L. Cerrito^{73a,73b}, F. Cerutti¹⁸, A. Cervelli^{23b,23a}, S.A. Cetin^{12b}, A. Chafaq^{35a}, D. Chakraborty¹²¹, S.K. Chan⁵⁹, W.S. Chan¹²⁰, W.Y. Chan⁹⁰, J.D. Chapman³², B. Chargeishvili^{159b}, D.G. Charlton²¹, C.C. Chau³⁴, C.A. Chavez Barajas¹⁵⁶, S. Che¹²⁶, A. Chegwiddden¹⁰⁶, S. Chekanov⁶, S.V. Chekulaev^{168a}, G.A. Chelkov^{79,at}, 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,as}, Y. Chen⁸², Y-H. Chen⁴⁶, H.C. Cheng^{63a}, H.J. Cheng^{15a,15d}, A. Cheplakov⁷⁹, E. Cheremushkina¹²³, R. Cherkaoui El Moursli^{35e}, E. Cheu⁷, K. Cheung⁶⁴, T.J.A. Chevalérias¹⁴⁵, L. Chevalier¹⁴⁵, V. Chiarella⁵¹, G. Chiarelli^{71a}, G. Chiodini^{67a}, A.S. Chisholm^{36,21}, A. Chitan^{27b}, I. Chiu¹⁶³, Y.H. Chiu¹⁷⁶, M.V. Chizhov⁷⁹, K. Choi⁶⁵, A.R. Chomont¹³², S. Chouridou¹⁶², Y.S. Chow¹²⁰, M.C. Chu^{63a}, J. Chudoba¹⁴¹, A.J. Chuinard¹⁰³, J.J. Chwastowski⁸⁴, L. Chytka¹³⁰, D. Cinca⁴⁷, V. Cindro⁹¹, I.A. Cioară^{27b}, A. Ciocio¹⁸, F. Cirotto^{69a,69b}, Z.H. Citron¹⁸⁰, M. Citterio^{68a}, 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. Coimbra¹⁸⁰, L. Colasurdo¹¹⁹, B. Cole³⁹, A.P. Colijn¹²⁰, J. Collot⁵⁸, P. Conde Muiño^{140a,f}, E. Coniavitis⁵², S.H. Connell^{33b}, I.A. Connelly⁵⁷, S. Constantinescu^{27b}, F. Conventi^{69a,av}, A.M. Cooper-Sarkar¹³⁵, F. Cormier¹⁷⁵, K.J.R. Cormier¹⁶⁷, L.D. Corpe⁹⁴, M. Corradi^{72a,72b}, E.E. Corrigan⁹⁶, F. Corriveau^{103,ac}, 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. Croft¹²⁰, G. Crosetti^{41b,41a}, A. Cueto⁵, T. Cuhadar Donszelmann¹⁴⁹,
A.R. Cukierman¹⁵³, S. Czekierda⁸⁴, P. Czodrowski³⁶, M.J. Da Cunha Sargedas De Sousa^{60b},
J.V. Da Fonseca Pinto^{80b}, C. Da Via¹⁰⁰, W. Dabrowski^{83a}, T. Dado^{28a}, S. Dahbi^{35e}, T. Dai¹⁰⁵,
C. Dallapiccola¹⁰², M. Dam⁴⁰, G. D'amen^{23b,23a}, J. Damp⁹⁹, J.R. Dandoy¹³⁷, M.F. Daneri³⁰,
N.P. Dang^{181,i}, N.D. Dann¹⁰⁰, M. Danninger¹⁷⁵, V. Dao³⁶, G. Darbo^{55b}, O. Dartsis⁵, A. Dattagupta¹³¹,
T. Daubney⁴⁶, S. D'Auria^{68a,68b}, W. Davey²⁴, C. David⁴⁶, T. Davidek¹⁴³, D.R. Davis⁴⁹, E. Dawe¹⁰⁴,
I. Dawson¹⁴⁹, K. De⁸, R. De Asmundis^{69a}, A. De Benedetti¹²⁸, M. De Beurs¹²⁰, S. De Castro^{23b,23a},
S. De Cecco^{72a,72b}, N. De Groot¹¹⁹, P. de Jong¹²⁰, 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, M. Del Gaudio^{41b,41a},
J. Del Peso⁹⁸, Y. Delabat Diaz⁴⁶, D. Delgove¹³², F. Deliot¹⁴⁵, C.M. Delitzsch⁷, M. Della Pietra^{69a,69b},
D. Della Volpe⁵⁴, A. Dell'Acqua³⁶, L. Dell'Asta²⁵, M. Delmastro⁵, C. Delporte¹³², P.A. Delsart⁵⁸,
D.A. DeMarco¹⁶⁷, S. Demers¹⁸³, M. Demichev⁷⁹, G. Demontigny¹⁰⁹, S.P. Denisov¹²³, D. Denysiuk¹²⁰,
L. D'Eramo¹³⁶, D. Derendarz⁸⁴, J.E. Derkaoui^{35d}, F. Derue¹³⁶, P. Dervan⁹⁰, K. Desch²⁴, C. Deterre⁴⁶,
K. Dette¹⁶⁷, M.R. Devesa³⁰, P.O. Deviveiros³⁶, A. Dewhurst¹⁴⁴, S. Dhaliwal²⁶, 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,140e}, 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}, J. Donini³⁸,
A. D'onofrio⁹², M. D'Onofrio⁹⁰, J. Dopke¹⁴⁴, A. Doria^{69a}, M.T. Dova⁸⁸, A.T. Doyle⁵⁷, E. Drechsler¹⁵²,
E. Dreyer¹⁵², S.S. Dreyer^{61a}, T. Dreyer⁵³, Y. Du^{60b}, Y. Duan^{60b}, F. Dubinin¹¹⁰, M. Dubovsky^{28a},
A. Dubreuil⁵⁴, E. Duchovni¹⁸⁰, G. Duckeck¹¹⁴, A. Ducourthial¹³⁶, O.A. Ducu^{109,w}, D. Duda¹¹⁵,
A. Dudarev³⁶, A.C. Dudder⁹⁹, E.M. Duffield¹⁸, L. Dufflot¹³², 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. Dyndal⁴⁶, S. Dysch¹⁰⁰, B.S. Dziedzic⁸⁴, K.M. Ecker¹¹⁵, R.C. Edgar¹⁰⁵, T. Eifert³⁶, G. Eigen¹⁷,
K. Einsweiler¹⁸, T. Ekelof¹⁷², M. El Kacimi^{35c}, R. El Kosseifi¹⁰¹, V. Ellajosyula¹⁷², M. Ellert¹⁷²,
F. Ellinghaus¹⁸², A.A. Elliot⁹², N. Ellis³⁶, J. Elmsheuser²⁹, M. Elsing³⁶, D. Emeliyanov¹⁴⁴,
A. Emerman³⁹, Y. Enari¹⁶³, J.S. Ennis¹⁷⁸, M.B. Epland⁴⁹, J. Erdmann⁴⁷, A. Ereditato²⁰, M. Escalier¹³²,
C. Escobar¹⁷⁴, O. Estrada Pastor¹⁷⁴, A.I. Etievre¹⁴⁵, E. Etzion¹⁶¹, H. Evans⁶⁵, A. Ezhilov¹³⁸,
M. Ezzi^{35e}, F. Fabbri⁵⁷, L. Fabbri^{23b,23a}, V. Fabiani¹¹⁹, G. Facini⁹⁴, R.M. Faisca Rodrigues Pereira^{140a},
R.M. Fakhruddinov¹²³, S. Falciano^{72a}, P.J. Falke⁵, S. Falke⁵, J. Faltova¹⁴³, Y. Fang^{15a}, Y. Fang^{15a},
G. Fanourakis⁴⁴, M. Fanti^{68a,68b}, A. Farbin⁸, A. Farilla^{74a}, E.M. Farina^{70a,70b}, T. Farooque¹⁰⁶, S. Farrell¹⁸,
S.M. Farrington¹⁷⁸, P. Farthouat³⁶, F. Fassi^{35e}, P. Fassnacht³⁶, D. Fassouliotis⁹, M. Fauci Giannelli⁵⁰,
W.J. Fawcett³², L. Fayard¹³², O.L. Fedin^{138,o}, W. Fedorko¹⁷⁵, M. Feickert⁴², S. Feigl¹³⁴, L. Felgioni¹⁰¹,
A. Fell¹⁴⁹, C. Feng^{60b}, E.J. Feng³⁶, M. Feng⁴⁹, M.J. Fenton⁵⁷, A.B. Fenyuk¹²³, J. Ferrando⁴⁶,
A. Ferrari¹⁷², P. Ferrari¹²⁰, R. Ferrari^{70a}, D.E. Ferreira de Lima^{61b}, A. Ferrer¹⁷⁴, D. Ferrere⁵⁴,
C. Ferretti¹⁰⁵, F. Fiedler⁹⁹, A. Filipčič⁹¹, F. Filthaut¹¹⁹, K.D. Finelli²⁵, M.C.N. Fiolhais^{140a}, L. Fiorini¹⁷⁴,
C. Fischer¹⁴, F. Fischer¹¹⁴, W.C. Fisher¹⁰⁶, I. Fleck¹⁵¹, P. Fleischmann¹⁰⁵, R.R.M. Fletcher¹³⁷,
T. Flick¹⁸², B.M. Flierl¹¹⁴, L.M. Flores¹³⁷, L.R. Flores Castillo^{63a}, F.M. Follega^{75a,75b}, N. Fomin¹⁷,
G.T. Forcolin^{75a,75b}, A. Formica¹⁴⁵, F.A. Förster¹⁴, A.C. Forti¹⁰⁰, A.G. Foster²¹, D. Fournier¹³²,
H. Fox⁸⁹, S. Fracchia¹⁴⁹, P. Francavilla^{71a,71b}, M. Franchini^{23b,23a}, S. Franchino^{61a}, D. Francis³⁶,
L. Franconi²⁰, M. Franklin⁵⁹, M. Frate¹⁷¹, A.N. Fray⁹², 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. Fusayasu¹¹⁶, J. Fuster¹⁷⁴, A. Gabrielli^{23b,23a},

A. Gabrielli¹⁸, G.P. Gach^{83a}, S. Gadatsch⁵⁴, P. Gadow¹¹⁵, G. Gagliardi^{55b,55a}, L.G. Gagnon¹⁰⁹,
 C. Galea^{27b}, B. Galhardo^{140a,140c}, E.J. Gallas¹³⁵, B.J. Gallop¹⁴⁴, P. Gallus¹⁴², G. Galster⁴⁰,
 R. Gamboa Goni⁹², K.K. Gan¹²⁶, S. Ganguly¹⁸⁰, J. Gao^{60a}, Y. Gao⁹⁰, Y.S. Gao^{31,1}, C. García¹⁷⁴,
 J.E. García Navarro¹⁷⁴, J.A. García Pascual^{15a}, C. Garcia-Argos⁵², M. Garcia-Sciveres¹⁸,
 R.W. Gardner³⁷, N. Garelli¹⁵³, S. Gargiulo⁵², V. Garonne¹³⁴, A. Gaudiello^{55b,55a}, G. Gaudio^{70a},
 I.L. Gavrilenko¹¹⁰, A. Gavriyuk¹¹¹, C. Gay¹⁷⁵, G. Gaycken²⁴, E.N. Gazis¹⁰, C.N.P. Gee¹⁴⁴, J. Geisen⁵³,
 M. Geisen⁹⁹, M.P. Geisler^{61a}, C. Gemme^{55b}, M.H. Genest⁵⁸, C. Geng¹⁰⁵, S. Gentile^{72a,72b}, S. George⁹³,
 T. Geralis⁴⁴, D. Gerbaudo¹⁴, L.O. Gerlach⁵³, G. Gessner⁴⁷, S. Ghasemi¹⁵¹, M. Ghasemi Bostanabad¹⁷⁶,
 M. Ghneimat²⁴, A. Ghosh⁷⁷, B. Giacobbe^{23b}, S. Giagu^{72a,72b}, N. Giangiacomi^{23b,23a}, P. Giannetti^{71a},
 A. Giannini^{69a,69b}, S.M. Gibson⁹³, M. Gignac¹⁴⁶, D. Gillberg³⁴, G. Gilles¹⁸², D.M. Gingrich^{3,au},
 M.P. Giordani^{66a,66c}, F.M. Giorgi^{23b}, P.F. Giraud¹⁴⁵, G. Giugliarelli^{66a,66c}, D. Giugni^{68a}, F. Giuli¹³⁵,
 M. Giulini^{61b}, S. Gkaitatzis¹⁶², I. Gkialas^{9,h}, E.L. Gkoukousis¹⁴, P. Gkoutoumis¹⁰, L.K. Gladilin¹¹³,
 C. Glasman⁹⁸, J. Glatzer¹⁴, P.C.F. Glaysher⁴⁶, A. Glazov⁴⁶, M. Goblirsch-Kolb²⁶, S. Goldfarb¹⁰⁴,
 T. Golling⁵⁴, D. Golubkov¹²³, A. Gomes^{140a,140b}, R. Goncalves Gama⁵³, R. Gonçalo^{140a,140b},
 G. Gonella⁵², L. Gonella²¹, A. Gongadze⁷⁹, F. Gonnella²¹, J.L. Gonski⁵⁹, S. González de la Hoz¹⁷⁴,
 S. Gonzalez-Sevilla⁵⁴, G.R. Gonzalvo Rodriguez¹⁷⁴, L. Goossens³⁶, P.A. Gorbounov¹¹¹, H.A. Gordon²⁹,
 B. Gorini³⁶, E. Gorini^{67a,67b}, A. Gorišek⁹¹, A.T. Goshaw⁴⁹, C. Gössling⁴⁷, M.I. Gostkin⁷⁹,
 C.A. Gottardo²⁴, C.R. Goudet¹³², D. Goudami^{35c}, A.G. Goussiou¹⁴⁸, N. Govender^{33b,a}, C. Goy⁵,
 E. Gozani¹⁶⁰, I. Grabowska-Bold^{83a}, P.O.J. Gradin¹⁷², 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, N.A. Grieser¹²⁸,
 J. Griffiths⁸, A.A. Grillo¹⁴⁶, K. Grimm^{31,k}, S. Grinstein^{14,x}, J.-F. Grivaz¹³², S. Groh⁹⁹, E. Gross¹⁸⁰,
 J. Grosse-Knetter⁵³, Z.J. Grout⁹⁴, C. Grud¹⁰⁵, A. Grummer¹¹⁸, L. Guan¹⁰⁵, W. Guan¹⁸¹, J. Guenther³⁶,
 A. Guerguichon¹³², F. Guescini^{168a}, D. Guest¹⁷¹, R. Gugel⁵², B. Gui¹²⁶, T. Guillemin⁵, S. Guindon³⁶,
 U. Gul⁵⁷, J. Guo^{60c}, W. Guo¹⁰⁵, Y. Guo^{60a,r}, Z. Guo¹⁰¹, R. Gupta⁴⁶, S. Gurbuz^{12c}, G. Gustavino¹²⁸,
 P. Gutierrez¹²⁸, C. Gutschow⁹⁴, C. Guyot¹⁴⁵, M.P. Guzik^{83a}, C. Gwenlan¹³⁵, C.B. Gwilliam⁹⁰,
 A. Haas¹²⁴, C. Haber¹⁸, H.K. Hadavand⁸, N. Haddad^{35e}, A. Hader^{60a}, S. Hageböck³⁶, M. Hagihara¹⁶⁹,
 M. Haleem¹⁷⁷, J. Haley¹²⁹, G. Halladjian¹⁰⁶, G.D. Hallewell¹⁰¹, K. Hamacher¹⁸², P. Hamal¹³⁰,
 K. Hamano¹⁷⁶, H. Hamdaoui^{35e}, G.N. Hamity¹⁴⁹, K. Han^{60a,aj}, L. Han^{60a}, S. Han^{15a,15d}, K. Hanagaki^{81,u},
 M. Hance¹⁴⁶, D.M. Handl¹¹⁴, B. Haney¹³⁷, R. Hankache¹³⁶, P. Hanke^{61a}, E. Hansen⁹⁶, J.B. Hansen⁴⁰,
 J.D. Hansen⁴⁰, M.C. Hansen²⁴, P.H. Hansen⁴⁰, E.C. Hanson¹⁰⁰, K. Hara¹⁶⁹, A.S. Hard¹⁸¹,
 T. Harenberg¹⁸², S. Harkusha¹⁰⁷, P.F. Harrison¹⁷⁸, N.M. Hartmann¹¹⁴, Y. Hasegawa¹⁵⁰, A. Hasib⁵⁰,
 S. Hassani¹⁴⁵, S. Haug²⁰, R. Hauser¹⁰⁶, L. Hauswald⁴⁸, L.B. Havener³⁹, M. Havranek¹⁴²,
 C.M. Hawkes²¹, R.J. Hawkins³⁶, D. Hayden¹⁰⁶, C. Hayes¹⁵⁵, 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, J. Heilman³⁴, S. Heim⁴⁶, T. Heim¹⁸, B. Heinemann^{46,ap}, J.J. Heinrich¹³¹,
 L. Heinrich³⁶, C. Heinz⁵⁶, J. Hejbal¹⁴¹, L. Helary^{61b}, A. Held¹⁷⁵, S. Hellesund¹³⁴, C.M. Helling¹⁴⁶,
 S. Hellman^{45a,45b}, C. Hensens³⁶, R.C.W. Henderson⁸⁹, Y. Heng¹⁸¹, S. Henkelmann¹⁷⁵,
 A.M. Henriques Correia³⁶, G.H. Herbert¹⁹, H. Herde²⁶, V. Herget¹⁷⁷, Y. Hernández Jiménez^{33c},
 H. Herr⁹⁹, M.G. Herrmann¹¹⁴, T. Herrmann⁴⁸, G. Herten⁵², R. Hertenberger¹¹⁴, 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,
 F. Hoenig¹¹⁴, D. Hohn⁵², D. Hohov¹³², T.R. Holmes³⁷, M. Holzbock¹¹⁴, L.B.A.H. Hommels³²,
 S. Honda¹⁶⁹, T. Honda⁸¹, T.M. Hong¹³⁹, A. Hönle¹¹⁵, B.H. Hooberman¹⁷³, W.H. Hopkins⁶, Y. Horii¹¹⁷,
 P. Horn⁴⁸, A.J. Horton¹⁵², L.A. Horyn³⁷, J.-Y. Hostachy⁵⁸, A. Hostiuc¹⁴⁸, 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. 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^{35c}, P.I. Iengo³⁶, R. Ignazzi⁴⁰, O. Igonkina^{120,z}, R. Iguchi¹⁶³, T. Iizawa⁵⁴, Y. Ikegami⁸¹, M. Ikeno⁸¹, D. Iliadis¹⁶², N. Ilic¹¹⁹, F. Iltzsche⁴⁸, G. Introzzi^{70a,70b}, M. Iodice^{74a}, K. Iordanidou³⁹, V. Ippolito^{72a,72b}, M.F. Isacson¹⁷², N. Ishijima¹³³, M. Ishino¹⁶³, M. Ishitsuka¹⁶⁵, W. Islam¹²⁹, C. Issever¹³⁵, 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, V. Jain², G. Jäkel¹⁸², K.B. Jakobi⁹⁹, K. Jakobs⁵², S. Jakobsen⁷⁶, T. Jakoubek¹⁴¹, J. Jamieson⁵⁷, D.O. Jamin¹²⁹, R. Jansky⁵⁴, J. Janssen²⁴, M. Janus⁵³, P.A. Janus^{83a}, G. Jarlskog⁹⁶, N. Javadov^{79,ae}, T. Javůrek³⁶, M. Javurkova⁵², F. Jeanneau¹⁴⁵, L. Jeanty¹³¹, J. Jejelava^{159a,af}, 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 Pena¹⁷⁴, 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,140b}, J. Jovicevic^{168a}, X. Ju¹⁸, J.J. Junggeburth¹¹⁵, A. Juste Rozas^{14,x}, A. Kaczmarska⁸⁴, M. Kado¹³², H. Kagan¹²⁶, M. Kagan¹⁵³, T. Kaji¹⁷⁹, E. Kajomovitz¹⁶⁰, C.W. Kalderon⁹⁶, A. Kaluza⁹⁹, A. Kamenshchikov¹²³, L. Kanjir⁹¹, Y. Kano¹⁶³, V.A. Kantserov¹¹², J. Kanzaki⁸¹, L.S. Kaplan¹⁸¹, D. Kar^{33c}, M.J. Kareem^{168b}, E. Karentzos¹⁰, S.N. Karpov⁷⁹, Z.M. Karpova⁷⁹, V. Kartvelishvili⁸⁹, A.N. Karyukhin¹²³, L. Kashif¹⁸¹, R.D. Kass¹²⁶, A. Kastanas^{45a,45b}, Y. Kataoka¹⁶³, C. Kato^{60d,60c}, J. Katzy⁴⁶, K. Kawade⁸², K. Kawagoe⁸⁷, T. Kawaguchi¹¹⁷, T. Kawamoto¹⁶³, G. Kawamura⁵³, E.F. Kay¹⁷⁶, V.F. Kazanin^{122b,122a}, R. Keeler¹⁷⁶, R. Kehoe⁴², J.S. Keller³⁴, E. Kellermann⁹⁶, J.J. Kempster²¹, J. Kendrick²¹, O. Kepka¹⁴¹, S. Kersten¹⁸², B.P. Kerševan⁹¹, S. Ketabchi Haghighat¹⁶⁷, R.A. Keyes¹⁰³, M. Khader¹⁷³, F. Khalil-Zada¹³, A. Khanov¹²⁹, A.G. Kharlamov^{122b,122a}, T. Kharlamova^{122b,122a}, E.E. Khoda¹⁷⁵, A. Khodinov¹⁶⁶, T.J. Khoo⁵⁴, E. Khramov⁷⁹, J. Khubua^{159b}, S. Kido⁸², M. Kiehn⁵⁴, C.R. Kilby⁹³, Y.K. Kim³⁷, N. Kimura^{66a,66c}, O.M. Kind¹⁹, B.T. King^{90,*}, D. Kirchmeier⁴⁸, J. Kirk¹⁴⁴, A.E. Kiryunin¹¹⁵, T. Kishimoto¹⁶³, V. Kitali⁴⁶, O. Kivernyk⁵, E. Kladiva^{28b,*}, T. Klapdor-Kleingrothaus⁵², M.H. Klein¹⁰⁵, M. Klein⁹⁰, U. Klein⁹⁰, K. Kleinknecht⁹⁹, P. Klimek¹²¹, A. Klimentov²⁹, T. Klingl²⁴, T. Klioutchnikova³⁶, F.F. Klitzner¹¹⁴, P. Kluit¹²⁰, S. Kluth¹¹⁵, 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. Köhler¹¹⁵, T. Koi¹⁵³, M. Kolb^{61b}, I. Koletsou⁵, T. Kondo⁸¹, N. Kondrashova^{60c}, K. Köneke⁵², A.C. König¹¹⁹, T. Kono¹²⁵, R. Konoplich^{124,am}, 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. Korotkova¹¹³, O. Kortner¹¹⁵, S. Kortner¹¹⁵, T. Kosek¹⁴³, V.V. Kostyukhin²⁴, 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. Kozhin¹²³, V.A. Kramarenko¹¹³, G. Kramberger⁹¹, D. Krasnopevtsev^{60a}, M.W. Krasny¹³⁶, A. Krasznahorkay³⁶, D. Krauss¹¹⁵, J.A. Kremer^{83a}, J. Kretschmar⁹⁰, P. Krieger¹⁶⁷, A. Krishnan^{61b}, K. Krizka¹⁸, K. Kroeninger⁴⁷, H. Kroha¹¹⁵, J. Kroll¹⁴¹, J. Kroll¹³⁷, J. Krstic¹⁶, U. Kruchonak⁷⁹, H. Krüger²⁴, N. Krumnack⁷⁸, M.C. Kruse⁴⁹, T. Kubota¹⁰⁴, S. Kuday^{4b}, J.T. Kuechler⁴⁶, S. Kuehn³⁶, A. Kugel^{61a}, T. Kuhl⁴⁶, V. Kukhtin⁷⁹, R. Kukla¹⁰¹, Y. Kulchitsky^{107,ai}, S. Kuleshov^{147b}, Y.P. Kulinich¹⁷³, M. Kuna⁵⁸, T. Kunigo⁸⁵, A. Kupco¹⁴¹, T. Kupfer⁴⁷, O. Kuprash⁵², H. Kurashige⁸², L.L. Kurchaninov^{168a}, Y.A. Kurochkin¹⁰⁷, A. Kurova¹¹², M.G. Kurth^{15a,15d}, E.S. Kuwertz³⁶, M. Kuze¹⁶⁵, A.K. Kvam¹⁴⁸, J. Kvita¹³⁰, T. Kwan¹⁰³, A. La Rosa¹¹⁵, J.L. La Rosa Navarro^{80d}, 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, S. Lammers⁶⁵, W. Lampl⁷, E. Lançon²⁹, U. Landgraf⁵²,
 M.P.J. Landon⁹², M.C. Lanfermann⁵⁴, V.S. Lang⁴⁶, J.C. Lange⁵³, R.J. Langenberg³⁶, 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. Lavorgna^{69a,69b},
 M. Lazzaroni^{68a,68b}, B. Le¹⁰⁴, O. Le Dortz¹³⁶, E. Le Guirriec¹⁰¹, M. LeBlanc⁷, T. LeCompte⁶,
 F. Ledroit-Guillon⁵⁸, C.A. Lee²⁹, G.R. Lee^{147a}, L. Lee⁵⁹, S.C. Lee¹⁵⁸, S.J. Lee³⁴, B. Lefebvre^{168a},
 M. Lefebvre¹⁷⁶, F. Legger¹¹⁴, C. Leggett¹⁸, K. Lehmann¹⁵², N. Lehmann¹⁸², G. Lehmann Miotto³⁶,
 W.A. Leight⁴⁶, A. Leisos^{162,v}, M.A.L. Leite^{80d}, R. Leitner¹⁴³, D. Lellouch^{180,*}, K.J.C. Leney⁴²,
 T. Lenz²⁴, B. Lenzi³⁶, R. Leone⁷, S. Leone^{71a}, C. Leonidopoulos⁵⁰, A. Leopold¹³⁶, G. Lerner¹⁵⁶,
 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,al}, 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. Liang^{15a}, B. Liberti^{73a}, A. Liblong¹⁶⁷,
 K. Lie^{63c}, S. Liem¹²⁰, C.Y. Lin³², K. Lin¹⁰⁶, T.H. Lin⁹⁹, R.A. Linck⁶⁵, J.H. Lindon²¹, A.L. Lioni⁵⁴,
 E. Lipeles¹³⁷, A. Lipniacka¹⁷, M. Lisovsky^{61b}, T.M. Liss^{173,ar}, 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 Merino^{15a}, 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^{147b}, I. Lopez Paz¹⁰⁰, A. Lopez Solis¹⁴⁹, J. Lorenz¹¹⁴, N. Lorenzo Martinez⁵, M. Losada²²,
 P.J. Lösel¹¹⁴, A. Lösle⁵², X. Lou⁴⁶, X. Lou^{15a}, A. Lounis¹³², J. Love⁶, P.A. Love⁸⁹,
 J.J. Lozano Bahilo¹⁷⁴, H. Lu^{63a}, 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,
 R. Lysak¹⁴¹, E. Lytken⁹⁶, F. Lyu^{15a}, V. Lyubushkin⁷⁹, T. Lyubushkina⁷⁹, H. Ma²⁹, L.L. Ma^{60b}, Y. Ma^{60b},
 G. Maccarrone⁵¹, A. Macchiolo¹¹⁵, C.M. Macdonald¹⁴⁹, J. Machado Miguens^{137,140b}, D. Madaffari¹⁷⁴,
 R. Madar³⁸, W.F. Mader⁴⁸, N. Madysa⁴⁸, J. Maeda⁸², K. Maekawa¹⁶³, S. Maeland¹⁷, T. Maeno²⁹,
 M. Maerker⁴⁸, A.S. Maevskiy¹¹³, V. Magerl⁵², N. Magini⁷⁸, D.J. Mahon³⁹, C. Maidantchik^{80b},
 T. Maier¹¹⁴, A. Maio^{140a,140b,140d}, 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. Malyukov³⁶, J. Mamuzic¹⁷⁴, G. Mancini⁵¹, I. Mandić⁹¹,
 L. Manhaes de Andrade Filho^{80a}, I.M. Maniatis¹⁶², J. Manjarres Ramos⁴⁸, K.H. Mankinen⁹⁶,
 A. Mann¹¹⁴, A. Manousos⁷⁶, B. Mansoulie¹⁴⁵, I. Manthos¹⁶², S. Manzoni¹²⁰, A. Marantis¹⁶²,
 G. Marceca³⁰, L. Marchese¹³⁵, G. Marchiori¹³⁶, M. Marcisovsky¹⁴¹, C. Marcon⁹⁶, C.A. Marin Tobon³⁶,
 M. Marjanovic³⁸, F. Marroquim^{80b}, Z. Marshall¹⁸, M.U.F. Martensson¹⁷², S. Marti-Garcia¹⁷⁴,
 C.B. Martin¹²⁶, T.A. Martin¹⁷⁸, V.J. Martin⁵⁰, B. Martin dit Latour¹⁷, M. Martinez^{14,x},
 V.I. Martinez Outschoorn¹⁰², S. Martin-Haugh¹⁴⁴, V.S. Martoiu^{27b}, A.C. Martyniuk⁹⁴, A. Marzin³⁶,
 L. Masetti⁹⁹, T. Mashimo¹⁶³, R. Mashinistov¹¹⁰, J. Masik¹⁰⁰, A.L. Maslennikov^{122b,122a}, L.H. Mason¹⁰⁴,
 L. Massa^{73a,73b}, P. Massarotti^{69a,69b}, P. Mastrandrea^{71a,71b}, A. Mastroberardino^{41b,41a}, T. Masubuchi¹⁶³,
 A. Matic¹¹⁴, P. Mättig²⁴, J. Maurer^{27b}, B. Maček⁹¹, S.J. Maxfield⁹⁰, D.A. Maximov^{122b,122a},
 R. Mazini¹⁵⁸, I. Maznas¹⁶², S.M. Mazza¹⁴⁶, S.P. Mc Kee¹⁰⁵, T.G. McCarthy¹¹⁵, L.I. McClymont⁹⁴,
 W.P. McCormack¹⁸, E.F. McDonald¹⁰⁴, J.A. Mcfayden³⁶, G. Mchedlidze⁵³, M.A. McKay⁴²,
 K.D. McLean¹⁷⁶, S.J. McMahan¹⁴⁴, P.C. McNamara¹⁰⁴, C.J. McNicol¹⁷⁸, R.A. McPherson^{176,ac},
 J.E. Mdhluli^{33c}, Z.A. Meadows¹⁰², S. Meehan¹⁴⁸, T. Megy⁵², S. Mehlhase¹¹⁴, A. Mehta⁹⁰, T. Meideck⁵⁸,
 B. Meirose⁴³, D. Melini¹⁷⁴, 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. Menke¹¹⁵,
 E. Meoni^{41b,41a}, S. Mergelmeyer¹⁹, S.A.M. Merkt¹³⁹, C. Merlassino²⁰, P. Mermod⁵⁴, L. Merola^{69a,69b},
 C. Meroni^{68a}, O. Meshkov¹¹³, J.K.R. Meshreki¹⁵¹, A. Messina^{72a,72b}, J. Metcalfe⁶, A.S. Mete¹⁷¹,
 C. Meyer⁶⁵, J. Meyer¹⁶⁰, J-P. Meyer¹⁴⁵, H. Meyer Zu Theenhausen^{61a}, F. Miano¹⁵⁶, R.P. Middleton¹⁴⁴,

L. Mijović⁵⁰, G. Mikenberg¹⁸⁰, M. Mikestikova¹⁴¹, M. Mikuž⁹¹, H. Mildner¹⁴⁹, M. Milesi¹⁰⁴, A. Milic¹⁶⁷, D.A. Millar⁹², D.W. Miller³⁷, A. Milov¹⁸⁰, D.A. Milstead^{45a,45b}, R.A. Mina^{153,p}, A.A. Minaenko¹²³, M. Miñano Moya¹⁷⁴, I.A. Minashvili^{159b}, A.I. Mincer¹²⁴, B. Mindur^{83a}, M. Mineev⁷⁹, Y. Minegishi¹⁶³, Y. Ming¹⁸¹, L.M. Mir¹⁴, A. Mirto^{67a,67b}, K.P. Mistry¹³⁷, T. Mitani¹⁷⁹, J. Mitrevski¹¹⁴, V.A. Mitsou¹⁷⁴, M. Mittal^{60c}, A. Miucci²⁰, P.S. Miyagawa¹⁴⁹, A. Mizukami⁸¹, J.U. Mjörnmark⁹⁶, T. Mkrtchyan¹⁸⁴, 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 Llácer³⁶, P. Moretini^{55b}, M. Morgenstern¹²⁰, S. Morgenstern⁴⁸, D. Mori¹⁵², M. Morii⁵⁹, M. Morinaga¹⁷⁹, V. Morisbak¹³⁴, A.K. Morley³⁶, G. Mornacchi³⁶, A.P. Morris⁹⁴, L. Morvaj¹⁵⁵, P. Moschovakos¹⁰, B. Moser¹²⁰, M. Mosidze^{159b}, H.J. Moss¹⁴⁹, J. Moss^{31,m}, K. Motohashi¹⁶⁵, E. Mountricha³⁶, E.J.W. Moyse¹⁰², S. Muanza¹⁰¹, F. Mueller¹¹⁵, J. Mueller¹³⁹, R.S.P. Mueller¹¹⁴, D. Muenstermann⁸⁹, G.A. Mullier⁹⁶, 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^{123,an}, J. Myers¹³¹, M. Myska¹⁴², B.P. Nachman¹⁸, O. Nackenhorst⁴⁷, A. Nag Nag⁴⁸, K. Nagai¹³⁵, K. Nagano⁸¹, Y. Nagasaka⁶², M. Nagel¹⁵², E. Nagy¹⁰¹, A.M. Nairz³⁶, Y. Nakahama¹¹⁷, K. Nakamura⁸¹, T. Nakamura¹⁶³, I. Nakano¹²⁷, H. Nanjo¹³³, F. Napolitano^{61a}, R.F. Naranjo Garcia⁴⁶, R. Narayan¹¹, D.I. Narrias Villar^{61a}, I. Naryshkin¹³⁸, T. Naumann⁴⁶, G. Navarro²², H.A. Neal^{105,*}, P.Y. Nechaeva¹¹⁰, F. Nechansky⁴⁶, T.J. Neep¹⁴⁵, A. Negri^{70a,70b}, M. Negrini^{23b}, S. Nektarijevic¹¹⁹, C. Nellist⁵³, M.E. Nelson¹³⁵, S. Nemecek¹⁴¹, P. Nemethy¹²⁴, M. Nessi^{36,d}, M.S. Neubauer¹⁷³, M. Neumann¹⁸², P.R. Newman²¹, T.Y. Ng^{63c}, Y.S. Ng¹⁹, Y.W.Y. Ng¹⁷¹, H.D.N. Nguyen¹⁰¹, T. Nguyen Manh¹⁰⁹, E. Nibigira³⁸, R.B. Nickerson¹³⁵, R. Nicolaidou¹⁴⁵, D.S. Nielsen⁴⁰, J. Nielsen¹⁴⁶, N. Nikiforou¹¹, V. Nikolaenko^{123,an}, I. Nikolic-Audit¹³⁶, K. Nikolopoulos²¹, P. Nilsson²⁹, H.R. Nindhito⁵⁴, Y. Ninomiya⁸¹, A. Nisati^{72a}, N. Nishu^{60c}, R. Nisius¹¹⁵, I. Nitsche⁴⁷, T. Nitta¹⁷⁹, T. Nobe¹⁶³, Y. Noguchi⁸⁵, M. Nomachi¹³³, I. Nomidis¹³⁶, M.A. Nomura²⁹, M. Nordberg³⁶, N. Norjoharuddeen¹³⁵, T. Novak⁹¹, O. Novgorodova⁴⁸, R. Novotny¹⁴², L. Nozka¹³⁰, K. Ntekas¹⁷¹, E. Nurse⁹⁴, F. Nuti¹⁰⁴, F.G. Oakham^{34,au}, H. Oberlack¹¹⁵, 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. Oide^{55b,55a}, M.L. Ojeda¹⁶⁷, H. Okawa¹⁶⁹, Y. Okazaki⁸⁵, 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. Onofre^{140a,140e}, K. Onogi¹¹⁷, P.U.E. Onyisi¹¹, H. Oppen¹³⁴, M.J. Oreglia³⁷, G.E. Orellana⁸⁸, Y. Oren¹⁶¹, D. Orestano^{74a,74b}, N. Orlando¹⁴, R.S. Orr¹⁶⁷, B. Osculati^{55b,55a,*}, V. O'Shea⁵⁷, R. Ospanov^{60a}, G. Otero y Garzon³⁰, H. Otono⁸⁷, M. Ouchrif^{35d}, 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,h}, A. Paramonov⁶, D. Paredes Hernandez^{63b}, S.R. Paredes Saenz¹³⁵, B. Parida¹⁶⁶, T.H. Park¹⁶⁷, A.J. Parker⁸⁹, M.A. Parker³², F. Parodi^{55b,55a}, E.W.P. Parrish¹²¹, J.A. Parsons³⁹, U. Parzefall⁵², L. Pascual Dominguez¹³⁶, V.R. Pascuzzi¹⁶⁷, J.M.P. Pasner¹⁴⁶, E. Pasqualucci^{72a}, S. Passaggio^{55b}, F. Pastore⁹³, P. Pasuwan^{45a,45b}, S. Pataria⁹⁹, J.R. Pater¹⁰⁰, A. Pathak^{181,i}, T. Pauly³⁶, B. Pearson¹¹⁵, M. Pedersen¹³⁴, L. Pedraza Diaz¹¹⁹, R. Pedro^{140a,140b}, S.V. Peleganchuk^{122b,122a}, O. Penc¹⁴¹, C. Peng^{15a}, H. Peng^{60a}, B.S. Peralva^{80a}, M.M. Perego¹³², A.P. Pereira Peixoto^{140a,140e}, D.V. Perepelitsa²⁹, F. Peri¹⁹, L. Perini^{68a,68b}, H. Pernegger³⁶, S. Perrella^{69a,69b}, V.D. Peshekhonov^{79,*}, K. Peters⁴⁶, R.F.Y. Peters¹⁰⁰, B.A. Petersen³⁶, T.C. Petersen⁴⁰, E. Petit⁵⁸, A. Petridis¹, C. Petridou¹⁶², P. Petroff¹³², M. Petrov¹³⁵, F. Petrucci^{74a,74b}, M. Pettee¹⁸³, N.E. Pettersson¹⁰², K. Petukhova¹⁴³, A. Peyaud¹⁴⁵, R. Pezoa^{147b}, 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^{73a,73b}, J.L. Pinfeld³, M. Pitt¹⁸⁰, L. Pizzimento^{73a,73b}, M.-A. Pleier²⁹, V. Pleskot¹⁴³, E. Plotnikova⁷⁹, D. Pluth⁷⁸, P. Podberezko^{122b,122a}, R. Poettgen⁹⁶, R. Poggi⁵⁴, L. Poggioli¹³², I. Pogrebnyak¹⁰⁶, D. Pohl²⁴, I. Pokharel⁵³, G. Polesello^{70a}, A. Poley¹⁸, A. Policicchio^{72a,72b}, R. Polifka³⁶, A. Polini^{23b}, C.S. Pollard⁴⁶, V. Polychronakos²⁹, D. Ponomarenko¹¹², L. Pontecorvo³⁶, S. Popa^{27a}, G.A. Popeneciu^{27d}, D.M. Portillo Quintero¹³⁶, 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. Proklova¹¹², K. Prokofiev^{63c}, F. Prokoshin^{147b}, S. Protopopescu²⁹, J. Proudfoot⁶, M. Przybycien^{83a}, A. Puri¹⁷³, P. Puzo¹³², J. Qian¹⁰⁵, Y. Qin¹⁰⁰, A. Quadl⁵³, M. Queitsch-Maitland⁴⁶, A. Qureshi¹, P. Rados¹⁰⁴, F. Ragusa^{68a,68b}, G. Rahal⁹⁷, J.A. Raine⁵⁴, S. Rajagopalan²⁹, A. Ramirez Morales⁹², K. Ran^{15a,15d}, T. Rashid¹³², S. Raspopov⁵, M.G. Ratti^{68a,68b}, D.M. Rauch⁴⁶, F. Rauscher¹¹⁴, S. Rave⁹⁹, B. Ravina¹⁴⁹, I. Ravinovich¹⁸⁰, J.H. Rawling¹⁰⁰, M. Raymond³⁶, A.L. Read¹³⁴, N.P. Readioff⁵⁸, M. Reale^{67a,67b}, D.M. Rebuffi^{70a,70b}, A. Redelbach¹⁷⁷, G. Redlinger²⁹, R.G. Reed^{33c}, K. Reeves⁴³, L. Rehnisch¹⁹, J. Reichert¹³⁷, D. Reikher¹⁶¹, A. Reiss⁹⁹, A. Rej¹⁵¹, C. Rembser³⁶, H. Ren^{15a}, M. Rescigno^{72a}, S. Resconi^{68a}, E.D. Resseguie¹³⁷, S. Rettie¹⁷⁵, E. Reynolds²¹, O.L. Rezanova^{122b,122a}, P. Reznicek¹⁴³, E. Ricci^{75a,75b}, R. Richter¹¹⁵, S. Richter⁴⁶, E. Richter-Was^{83b}, O. Ricken²⁴, M. Ridel¹³⁶, P. Rieck¹¹⁵, C.J. Riegel¹⁸², O. Rifki⁴⁶, M. Rijssenbeek¹⁵⁵, A. Rimoldi^{70a,70b}, M. Rimoldi²⁰, L. Rinaldi^{23b}, G. Ripellino¹⁵⁴, B. Ristić⁸⁹, E. Ritsch³⁶, I. Riu¹⁴, J.C. Rivera Vergara^{147a}, F. Rizatdinova¹²⁹, E. Rizvi⁹², C. Rizzi³⁶, R.T. Roberts¹⁰⁰, S.H. Robertson^{103,ac}, D. Robinson³², J.E.M. Robinson⁴⁶, A. Robson⁵⁷, E. Rocco⁹⁹, C. Roda^{71a,71b}, Y. Rodina¹⁰¹, S. Rodriguez Bosca¹⁷⁴, A. Rodriguez Perez¹⁴, D. Rodriguez Rodriguez¹⁷⁴, A.M. Rodríguez Vera^{168b}, S. Roe³⁶, O. Røhne¹³⁴, R. Röhrig¹¹⁵, C.P.A. Roland⁶⁵, J. Roloff⁵⁹, A. Romaniouk¹¹², M. Romano^{23b,23a}, N. Rompotis⁹⁰, M. Ronzani¹²⁴, L. Roos¹³⁶, S. Rosati^{72a}, K. Rosbach⁵², N-A. Rosien⁵³, G. Rosin¹⁰², B.J. Rosser¹³⁷, E. Rossi⁴⁶, E. Rossi^{74a,74b}, E. Rossi^{69a,69b}, L.P. Rossi^{55b}, L. Rossini^{68a,68b}, J.H.N. Rosten³², R. Rosten¹⁴, M. Rotaru^{27b}, J. Rothberg¹⁴⁸, D. Rousseau¹³², D. Roy^{33c}, A. Rozanov¹⁰¹, Y. Rozen¹⁶⁰, X. Ruan^{33c}, F. Rubbo¹⁵³, F. Rühr⁵², A. Ruiz-Martinez¹⁷⁴, A. Rummeler³⁶, Z. Rurikova⁵², N.A. Rusakovich⁷⁹, H.L. Russell¹⁰³, L. Rustige^{38,47}, J.P. Rutherford⁷, E.M. Rüttinger^{46,j}, Y.F. Ryabov¹³⁸, M. Rybar³⁹, G. Rybkin¹³², S. Ryu⁶, A. Ryzhov¹²³, G.F. Rzehorz⁵³, P. Sabatini⁵³, G. Sabato¹²⁰, S. Sacerdoti¹³², H.F-W. Sadrozinski¹⁴⁶, R. Sadykov⁷⁹, F. Safai Tehrani^{72a}, P. Saha¹²¹, S. Saha¹⁰³, M. Sahinsoy^{61a}, A. Sahu¹⁸², M. Saimpert⁴⁶, M. Saito¹⁶³, T. Saito¹⁶³, H. Sakamoto¹⁶³, A. Sakharov^{124,am}, D. Salamani⁵⁴, G. Salamanna^{74a,74b}, J.E. Salazar Loyola^{147b}, P.H. Sales De Bruin¹⁷², D. Salihagic^{115,*}, 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,66c}, H. Sandaker¹³⁴, C.O. Sander⁴⁶, M. Sandhoff¹⁸², C. Sandoval²², D.P.C. Sankey¹⁴⁴, M. Sannino^{55b,55a}, Y. Sano¹¹⁷, A. Sansoni⁵¹, C. Santoni³⁸, H. Santos^{140a,140b}, S.N. Santpur¹⁸, A. Santra¹⁷⁴, A. Saponov⁷⁹, J.G. Saraiva^{140a,140d}, O. Sasaki⁸¹, K. Sato¹⁶⁹, E. Sauvan⁵, P. Savard^{167,au}, N. Savic¹¹⁵, R. Sawada¹⁶³, C. Sawyer¹⁴⁴, L. Sawyer^{95,ak}, C. Sbarra^{23b}, A. Sbrizzi^{23a}, T. Scanlon⁹⁴, J. Schaarschmidt¹⁴⁸, P. Schacht¹¹⁵, B.M. Schachtner¹¹⁴, D. Schaefer³⁷, L. Schaefer¹³⁷, J. Schaeffer⁹⁹, S. Schaepe³⁶, U. Schäfer⁹⁹, A.C. Schaffer¹³², D. Schaile¹¹⁴, 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-Sommerfeld¹¹⁵, K. Schmieden³⁶, C. Schmitt⁹⁹, S. Schmitt⁴⁶, S. Schmitz⁹⁹, J.C. Schmoedel⁴⁶, U. Schnoor⁵², L. Schoeffel¹⁴⁵, A. Schoening^{61b}, E. Schopf¹³⁵, M. Schott⁹⁹, J.F.P. Schouwenberg¹¹⁹, J. Schovancova³⁶, S. Schramm⁵⁴, A. Schulte⁹⁹, H-C. Schultz-Coulon^{61a}, M. Schumacher⁵², B.A. Schumm¹⁴⁶, Ph. Schune¹⁴⁵, A. Schwartzman¹⁵³, T.A. Schwarz¹⁰⁵, Ph. Schwemling¹⁴⁵, R. Schwienhorst¹⁰⁶, A. Sciandra²⁴, G. Sciolla²⁶, M. Scornajenghi^{41b,41a}, F. Scuri^{71a},

F. Scutti¹⁰⁴, L.M. Scyboz¹¹⁵, C.D. Sebastiani^{72a,72b}, P. Seema¹⁹, S.C. Seidel¹¹⁸, A. Seiden¹⁴⁶, T. Seiss³⁷, J.M. Seixas^{80b}, G. Sekhniaidze^{69a}, K. Sekhon¹⁰⁵, S.J. Sekula⁴², N. Semprini-Cesari^{23b,23a}, S. Sen⁴⁹, S. Senkin³⁸, C. Serfon⁷⁶, L. Serin¹³², L. Serkin^{66a,66b}, M. Sessa^{60a}, H. Severini¹²⁸, F. Sforza¹⁷⁰, A. Sfyrla⁵⁴, E. Shabalina⁵³, J.D. Shahinian¹⁴⁶, N.W. Shaikh^{45a,45b}, D. Shaked Renous¹⁸⁰, L.Y. Shan^{15a}, R. Shang¹⁷³, J.T. Shank²⁵, M. Shapiro¹⁸, A.S. Sharma¹, A. Sharma¹³⁵, P.B. Shatalov¹¹¹, K. Shaw¹⁵⁶, S.M. Shaw¹⁰⁰, A. Shcherbakova¹³⁸, Y. Shen¹²⁸, N. Sherafati³⁴, A.D. Sherman²⁵, P. Sherwood⁹⁴, L. Shi^{158,aq}, S. Shimizu⁸¹, C.O. Shimmin¹⁸³, Y. Shimogama¹⁷⁹, M. Shimojima¹¹⁶, I.P.J. Shipsey¹³⁵, S. Shirabe⁸⁷, M. Shiyakova^{79,aa}, J. Shlomi¹⁸⁰, A. Shmeleva¹¹⁰, M.J. Shochet³⁷, S. Shojaii¹⁰⁴, D.R. Shope¹²⁸, S. Shrestha¹²⁶, E. Shulga¹¹², P. Sicho¹⁴¹, A.M. Sickles¹⁷³, P.E. Sidebo¹⁵⁴, E. Sideras Haddad^{33c}, O. Sidiropoulou³⁶, A. Sidoti^{23b,23a}, F. Siegert⁴⁸, Dj. Sijacki¹⁶, M. Silva Jr.¹⁸¹, M.V. Silva Oliveira^{80a}, S.B. Silverstein^{45a}, S. Simion¹³², E. Simioni⁹⁹, M. Simon⁹⁹, R. Simoniello⁹⁹, P. Sinervo¹⁶⁷, N.B. Sinev¹³¹, M. Sioli^{23b,23a}, I. Siral¹⁰⁵, S.Yu. Sivoklov¹¹³, J. Sjölin^{45a,45b}, E. Skorda⁹⁶, P. Skubic¹²⁸, M. Slawinska⁸⁴, K. Sliwa¹⁷⁰, R. Slovak¹⁴³, V. Smakhtin¹⁸⁰, B.H. Smart¹⁴⁴, J. Smiesko^{28a}, N. Smirnov¹¹², S.Yu. Smirnov¹¹², Y. Smirnov¹¹², L.N. Smirnova^{113,s}, O. Smirnova⁹⁶, J.W. Smith⁵³, M. Smizanska⁸⁹, K. Smolek¹⁴², A. Smykiewicz⁸⁴, A.A. Snesarev¹¹⁰, I.M. Snyder¹³¹, S. Snyder²⁹, R. Sobie^{176,ac}, A.M. Soffa¹⁷¹, A. Soffer¹⁶¹, A. Søggaard⁵⁰, F. Sohns⁵³, G. Sokhrany⁹¹, C.A. Solans Sanchez³⁶, E.Yu. Soldatov¹¹², U. Soldevila¹⁷⁴, A.A. Solodkov¹²³, A. Soloshenko⁷⁹, O.V. Solovyanov¹²³, V. Solovye¹³⁸, P. Sommer¹⁴⁹, H. Son¹⁷⁰, W. Song¹⁴⁴, W.Y. Song^{168b}, A. Sopczak¹⁴², F. Sopkova^{28b}, C.L. Sotiropoulou^{71a,71b}, S. Sottocornola^{70a,70b}, R. Soualah^{66a,66c,g}, A.M. Soukharev^{122b,122a}, D. South⁴⁶, S. Spagnolo^{67a,67b}, M. Spalla¹¹⁵, M. Spangenberg¹⁷⁸, F. Spanò⁹³, D. Sperlich¹⁹, T.M. Spieker^{61a}, R. Spighi^{23b}, G. Spigo³⁶, L.A. Spiller¹⁰⁴, M. Spina¹⁵⁶, D.P. Spiteri⁵⁷, M. Spousta¹⁴³, A. Stabile^{68a,68b}, B.L. Stamas¹²¹, R. Stamen^{61a}, M. Stamenkovic¹²⁰, S. Stamm¹⁹, E. Stanecka⁸⁴, R.W. Stanek⁶, B. Stanislaus¹³⁵, M.M. Stanitzki⁴⁶, M. Stankaityte¹³⁵, B. Stapf¹²⁰, E.A. Starchenko¹²³, G.H. Stark¹⁴⁶, J. Stark⁵⁸, S.H. Stark⁴⁰, P. Staroba¹⁴¹, P. Starovoitov^{61a}, S. Stärz¹⁰³, R. Staszewski⁸⁴, G. Stavropoulos⁴⁴, M. Stegler⁴⁶, P. Steinberg²⁹, B. Stelzer¹⁵², H.J. Stelzer³⁶, O. Stelzer-Chilton^{168a}, H. Stenzel⁵⁶, T.J. Stevenson¹⁵⁶, G.A. Stewart³⁶, M.C. Stockton³⁶, G. Stoicea^{27b}, M. Stolarski^{140a}, P. Stolte⁵³, S. Stonjek¹¹⁵, 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}, Y. Sugaya¹³³, 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, A. Sydorenko⁹⁹, I. Sykora^{28a}, M. Sykora¹⁴³, T. Sykora¹⁴³, D. Ta⁹⁹, K. Tackmann^{46,y}, J. Taenzer¹⁶¹, A. Taffard¹⁷¹, R. Tafirout^{168a}, E. Tahirovic⁹², H. Takai²⁹, R. Takashima⁸⁶, K. Takeda⁸², T. Takeshita¹⁵⁰, E.P. Takeva⁵⁰, Y. Takubo⁸¹, M. Talby¹⁰¹, A.A. Talyshev^{122b,122a}, J. Tanaka¹⁶³, M. Tanaka¹⁶⁵, R. Tanaka¹³², B.B. Tannenwald¹²⁶, S. Tapia Araya¹⁷³, S. Tapprogge⁹⁹, A. Tarek Abouelfadl Mohamed¹³⁶, S. Tarem¹⁶⁰, G. Tarna^{27b,c}, G.F. Tartarelli^{68a}, P. Tas¹⁴³, M. Tasevsky¹⁴¹, T. Tashiro⁸⁵, E. Tassi^{41b,41a}, A. Tavares Delgado^{140a,140b}, Y. Tayalati^{35e}, A.J. Taylor⁵⁰, G.N. Taylor¹⁰⁴, P.T.E. Taylor¹⁰⁴, W. Taylor^{168b}, A.S. Tee⁸⁹, R. Teixeira De Lima¹⁵³, P. Teixeira-Dias⁹³, H. Ten Kate³⁶, J.J. Teoh¹²⁰, S. Terada⁸¹, K. Terashi¹⁶³, J. Terron⁹⁸, S. Terzo¹⁴, M. Testa⁵¹, R.J. Teuscher^{167,ac}, 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, Y. Tian³⁹, R.E. Ticse Torres⁵³, V.O. Tikhomirov^{110,ao}, Yu.A. Tikhonov^{122b,122a}, S. Timoshenko¹¹², 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. Tomoto¹¹⁷, L. Tompkins^{153,p}, K. Toms¹¹⁸, B. Tong⁵⁹, P. Tornambe¹⁰², E. Torrence¹³¹, H. Torres⁴⁸, E. Torró Pastor¹⁴⁸, C. Toscirì¹³⁵, J. Toth^{101,ab}, D.R. Tovey¹⁴⁹, C.J. Treado¹²⁴, T. Trefzger¹⁷⁷, F. Tresoldi¹⁵⁶, A. Tricoli²⁹, I.M. Trigger^{168a}, S. Trincaz-Duvoid¹³⁶, W. Trischuk¹⁶⁷, B. Trocme⁵⁸, A. Trofymov¹³², C. Troncon^{68a}, M. Trovatelli¹⁷⁶, F. Trovato¹⁵⁶, L. Truong^{33b},

M. Trzebinski⁸⁴, A. Trzupek⁸⁴, F. Tsai⁴⁶, J.C-L. Tseng¹³⁵, P.V. Tsiarehka^{107,ai}, A. Tsirigotis¹⁶²,
N. Tsirintanis⁹, V. Tsiskaridze¹⁵⁵, E.G. Tskhadadze^{159a}, M. Tsopoulou¹⁶², I.I. Tsukerman¹¹¹,
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,t}, R.J. Turner²¹, R.T. Turra^{68a}, P.M. Tuts³⁹,
S. Tzamarias¹⁶², E. Tzovara⁹⁹, G. Uccielli⁴⁷, I. Ueda⁸¹, M. Ughetto^{45a,45b}, F. Ukegawa¹⁶⁹, G. Unal³⁶,
A. Undrus²⁹, G. Unel¹⁷¹, F.C. Ungaro¹⁰⁴, Y. Unno⁸¹, K. Uno¹⁶³, J. Urban^{28b}, P. Urquijo¹⁰⁴, G. Usai⁸,
J. Usui⁸¹, L. Vacavant¹⁰¹, V. Vacek¹⁴², B. Vachon¹⁰³, K.O.H. Vadla¹³⁴, A. Vaidya⁹⁴, C. Valderanis¹¹⁴,
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 Vulpen¹²⁰,
M. Vanadia^{73a,73b}, W. Vandelli³⁶, A. Vaniachine¹⁶⁶, R. Vari^{72a}, E.W. Varnes⁷, C. Varni^{55b,55a}, T. Varol⁴²,
D. Varouchas¹³², K.E. Varvell¹⁵⁷, M.E. Vasile^{27b}, G.A. Vasquez¹⁷⁶, J.G. Vasquez¹⁸³, F. Vazeille³⁸,
D. Vazquez Furelos¹⁴, T. Vazquez Schroeder³⁶, J. Veatch⁵³, V. Vecchio^{74a,74b}, L.M. Veloce¹⁶⁷,
F. Veloso^{140a,140c}, S. Veneziano^{72a}, A. Ventura^{67a,67b}, N. Venturi³⁶, A. Verbytskyi¹¹⁵, V. Vercesi^{70a},
M. Verducci^{74a,74b}, C.M. Vergel Infante⁷⁸, C. Vergis²⁴, W. Verkerke¹²⁰, A.T. Vermeulen¹²⁰,
J.C. Vermeulen¹²⁰, M.C. Vetterli^{152,au}, N. Viaux Maira^{147b}, M. Vicente Barreto Pinto⁵⁴, I. Vichou^{173,*},
T. Vickey¹⁴⁹, O.E. Vickey Boeriu¹⁴⁹, G.H.A. Viehhauser¹³⁵, L. Vigani¹³⁵, M. Villa^{23b,23a},
M. Villaplana Perez^{68a,68b}, E. Vilucchi⁵¹, M.G. Vincter³⁴, V.B. Vinogradov⁷⁹, A. Vishwakarma⁴⁶,
C. Vittori^{23b,23a}, I. Vivarelli¹⁵⁶, M. Vogel¹⁸², P. Vokac¹⁴², G. Volpi¹⁴, S.E. von Buddenbrock^{33c},
E. Von Toerne²⁴, V. Vorobel¹⁴³, K. Vorobev¹¹², M. Vos¹⁷⁴, J.H. Vosseveld⁹⁰, N. Vranjes¹⁶,
M. Vranjes Milosavljevic¹⁶, V. Vrba¹⁴², M. Vreeswijk¹²⁰, T. Šfiligoj⁹¹, R. Vuillermet³⁶, I. Vukotic³⁷,
T. Ženiš^{28a}, L. Živković¹⁶, P. Wagner²⁴, W. Wagner¹⁸², J. Wagner-Kuhr¹¹⁴, H. Wahlberg⁸⁸,
S. Wahrenmund⁴⁸, K. Wakamiya⁸², V.M. Walbrecht¹¹⁵, J. Walder⁸⁹, R. Walker¹¹⁴, S.D. Walker⁹³,
W. Walkowiak¹⁵¹, V. Wallangen^{45a,45b}, A.M. Wang⁵⁹, C. Wang^{60b}, F. Wang¹⁸¹, H. Wang¹⁸, H. Wang³,
J. Wang¹⁵⁷, J. Wang^{61b}, P. Wang⁴², Q. Wang¹²⁸, R.-J. Wang¹³⁶, R. Wang^{60a}, R. Wang⁶, S.M. Wang¹⁵⁸,
W.T. Wang^{60a}, W. Wang^{15c,ad}, W.X. Wang^{60a,ad}, Y. Wang^{60a,al}, Z. Wang^{60c}, C. Wanotayaroj⁴⁶,
A. Warburton¹⁰³, C.P. Ward³², D.R. Wardrope⁹⁴, 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. Wermes²⁴, M.D. Werner⁷⁸, P. Werner³⁶, M. Wessels^{61a},
T.D. Weston²⁰, K. Whalen¹³¹, N.L. Whallon¹⁴⁸, A.M. Wharton⁸⁹, A.S. White¹⁰⁵, A. White⁸,
M.J. White¹, R. White^{147b}, D. Whiteson¹⁷¹, B.W. Whitmore⁸⁹, F.J. Wickens¹⁴⁴, W. Wiedenmann¹⁸¹,
M. Wielers¹⁴⁴, 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. Wolf¹²⁰, 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, D. Xu^{15a}, H. Xu^{60a,c}, L. Xu²⁹, T. Xu¹⁴⁵, W. Xu¹⁰⁵, Z. Xu^{60b}, Z. Xu¹⁵³, B. Yabsley¹⁵⁷,
S. Yacoob^{33a}, K. Yajima¹³³, D.P. Yallup⁹⁴, D. Yamaguchi¹⁶⁵, Y. Yamaguchi¹⁶⁵, A. Yamamoto⁸¹,
T. Yamanaka¹⁶³, F. Yamane⁸², M. Yamatani¹⁶³, T. Yamazaki¹⁶³, Y. Yamazaki⁸², Z. Yan²⁵,
H.J. Yang^{60c,60d}, H.T. Yang¹⁸, S. Yang⁷⁷, X. Yang^{60b,58}, Y. Yang¹⁶³, Z. Yang¹⁷, W-M. Yao¹⁸, Y.C. Yap⁴⁶,
Y. Yasu⁸¹, E. Yatsenko^{60c,60d}, J. Ye⁴², S. Ye²⁹, I. Yeletsikh⁷⁹, E. Yigitbasi²⁵, E. Yildirim⁹⁹, K. Yorita¹⁷⁹,
K. Yoshihara¹³⁷, C.J.S. Young³⁶, C. Young¹⁵³, J. Yu⁷⁸, X. Yue^{61a}, S.P.Y. Yuen²⁴, B. Zabinski⁸⁴,
G. Zacharis¹⁰, E. Zaffaroni⁵⁴, J. Zahreddine¹³⁶, R. Zaidan¹⁴, A.M. Zaitsev^{123,an}, T. Zakareishvili^{159b},
N. Zakharchuk³⁴, S. Zambito⁵⁹, D. Zanzi³⁶, D.R. Zaripovas⁵⁷, S.V. Zeißner⁴⁷, C. Zeitnitz¹⁸²,
G. Zemaityte¹³⁵, J.C. Zeng¹⁷³, O. Zenin¹²³, D. Zerwas¹³², M. Zgubić¹³⁵, D.F. Zhang^{15b}, F. Zhang¹⁸¹,
G. Zhang^{60a}, G. Zhang^{15b}, H. Zhang^{15c}, J. Zhang⁶, L. Zhang^{15c}, L. Zhang^{60a}, M. Zhang¹⁷³, R. Zhang^{60a},

R. Zhang²⁴, 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}, H.L. Zhu^{60a}, H. Zhu^{15a}, J. Zhu¹⁰⁵, Y. Zhu^{60a}, X. Zhuang^{15a}, K. Zhukov¹¹⁰, V. Zhulanov^{122b,122a}, D. Zieminska⁶⁵, N.I. Zimine⁷⁹, S. Zimmermann⁵², Z. Zinonos¹¹⁵, M. Ziolkowski¹⁵¹, G. Zobernig¹⁸¹, A. Zoccoli^{23b,23a}, K. Zoch⁵³, T.G. Zorbas¹⁴⁹, R. Zou³⁷, L. Zwalinski³⁶.

¹Department of Physics, University of Adelaide, Adelaide; Australia.

²Physics Department, SUNY Albany, Albany NY; United States of America.

³Department of Physics, University of Alberta, Edmonton AB; Canada.

⁴(^a)Department of Physics, Ankara University, Ankara; (^b)Istanbul Aydin University, Istanbul; (^c)Division of Physics, TOBB University of Economics and Technology, Ankara; Turkey.

⁵LAPP, Université Grenoble Alpes, Université Savoie Mont Blanc, CNRS/IN2P3, Annecy; France.

⁶High Energy Physics Division, Argonne National Laboratory, Argonne IL; United States of America.

⁷Department of Physics, University of Arizona, Tucson AZ; United States of America.

⁸Department of Physics, University of Texas at Arlington, Arlington TX; United States of America.

⁹Physics Department, National and Kapodistrian University of Athens, Athens; Greece.

¹⁰Physics Department, National Technical University of Athens, Zografou; Greece.

¹¹Department 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.

¹³Institute of Physics, Azerbaijan Academy of Sciences, Baku; Azerbaijan.

¹⁴Institut 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.

¹⁶Institute of Physics, University of Belgrade, Belgrade; Serbia.

¹⁷Department for Physics and Technology, University of Bergen, Bergen; Norway.

¹⁸Physics Division, Lawrence Berkeley National Laboratory and University of California, Berkeley CA; United States of America.

¹⁹Institut für Physik, Humboldt Universität zu Berlin, Berlin; Germany.

²⁰Albert Einstein Center for Fundamental Physics and Laboratory for High Energy Physics, University of Bern, Bern; Switzerland.

²¹School of Physics and Astronomy, University of Birmingham, Birmingham; United Kingdom.

²²Facultad 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.

²⁴Physikalisches Institut, Universität Bonn, Bonn; Germany.

²⁵Department of Physics, Boston University, Boston MA; United States of America.

²⁶Department 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.
- ²⁹Physics Department, Brookhaven National Laboratory, Upton NY; United States of America.
- ³⁰Departamento de Física, Universidad de Buenos Aires, Buenos Aires; Argentina.
- ³¹California State University, CA; United States of America.
- ³²Cavendish 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.
- ³⁴Department 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.
- ³⁶CERN, Geneva; Switzerland.
- ³⁷Enrico Fermi Institute, University of Chicago, Chicago IL; United States of America.
- ³⁸LPC, Université Clermont Auvergne, CNRS/IN2P3, Clermont-Ferrand; France.
- ³⁹Nevis Laboratory, Columbia University, Irvington NY; United States of America.
- ⁴⁰Niels 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.
- ⁴²Physics Department, Southern Methodist University, Dallas TX; United States of America.
- ⁴³Physics Department, University of Texas at Dallas, Richardson TX; United States of America.
- ⁴⁴National Centre for Scientific Research "Demokritos", Agia Paraskevi; Greece.
- ^{45(a)}Department of Physics, Stockholm University;^(b)Oskar Klein Centre, Stockholm; Sweden.
- ⁴⁶Deutsches Elektronen-Synchrotron DESY, Hamburg and Zeuthen; Germany.
- ⁴⁷Lehrstuhl für Experimentelle Physik IV, Technische Universität Dortmund, Dortmund; Germany.
- ⁴⁸Institut für Kern- und Teilchenphysik, Technische Universität Dresden, Dresden; Germany.
- ⁴⁹Department of Physics, Duke University, Durham NC; United States of America.
- ⁵⁰SUPA - School of Physics and Astronomy, University of Edinburgh, Edinburgh; United Kingdom.
- ⁵¹INFN e Laboratori Nazionali di Frascati, Frascati; Italy.
- ⁵²Physikalisches Institut, Albert-Ludwigs-Universität Freiburg, Freiburg; Germany.
- ⁵³II. Physikalisches Institut, Georg-August-Universität Göttingen, Göttingen; Germany.
- ⁵⁴Département 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.
- ⁵⁶II. Physikalisches Institut, Justus-Liebig-Universität Giessen, Giessen; Germany.
- ⁵⁷SUPA - School of Physics and Astronomy, University of Glasgow, Glasgow; United Kingdom.
- ⁵⁸LPSC, Université Grenoble Alpes, CNRS/IN2P3, Grenoble INP, Grenoble; France.
- ⁵⁹Laboratory 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.

⁶²Faculty 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.

⁶⁴Department of Physics, National Tsing Hua University, Hsinchu; Taiwan.

⁶⁵Department 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.

⁷⁶Institut für Astro- und Teilchenphysik, Leopold-Franzens-Universität, Innsbruck; Austria.

⁷⁷University of Iowa, Iowa City IA; United States of America.

⁷⁸Department of Physics and Astronomy, Iowa State University, Ames IA; United States of America.

⁷⁹Joint 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.

⁸¹KEK, High Energy Accelerator Research Organization, Tsukuba; Japan.

⁸²Graduate 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.

⁸⁴Institute of Nuclear Physics Polish Academy of Sciences, Krakow; Poland.

⁸⁵Faculty of Science, Kyoto University, Kyoto; Japan.

⁸⁶Kyoto University of Education, Kyoto; Japan.

⁸⁷Research Center for Advanced Particle Physics and Department of Physics, Kyushu University, Fukuoka ; Japan.

⁸⁸Instituto de Física La Plata, Universidad Nacional de La Plata and CONICET, La Plata; Argentina.

⁸⁹Physics Department, Lancaster University, Lancaster; United Kingdom.

⁹⁰Oliver Lodge Laboratory, University of Liverpool, Liverpool; United Kingdom.

⁹¹Department of Experimental Particle Physics, Jožef Stefan Institute and Department of Physics, University of Ljubljana, Ljubljana; Slovenia.

⁹²School of Physics and Astronomy, Queen Mary University of London, London; United Kingdom.

⁹³Department of Physics, Royal Holloway University of London, Egham; United Kingdom.

⁹⁴Department of Physics and Astronomy, University College London, London; United Kingdom.

⁹⁵Louisiana Tech University, Ruston LA; United States of America.

- ⁹⁶Fysiska institutionen, Lunds universitet, Lund; Sweden.
- ⁹⁷Centre de Calcul de l'Institut National de Physique Nucléaire et de Physique des Particules (IN2P3), Villeurbanne; France.
- ⁹⁸Departamento de Física Teórica C-15 and CIAFF, Universidad Autónoma de Madrid, Madrid; Spain.
- ⁹⁹Institut für Physik, Universität Mainz, Mainz; Germany.
- ¹⁰⁰School of Physics and Astronomy, University of Manchester, Manchester; United Kingdom.
- ¹⁰¹CPPM, Aix-Marseille Université, CNRS/IN2P3, Marseille; France.
- ¹⁰²Department of Physics, University of Massachusetts, Amherst MA; United States of America.
- ¹⁰³Department of Physics, McGill University, Montreal QC; Canada.
- ¹⁰⁴School of Physics, University of Melbourne, Victoria; Australia.
- ¹⁰⁵Department of Physics, University of Michigan, Ann Arbor MI; United States of America.
- ¹⁰⁶Department of Physics and Astronomy, Michigan State University, East Lansing MI; United States of America.
- ¹⁰⁷B.I. Stepanov Institute of Physics, National Academy of Sciences of Belarus, Minsk; Belarus.
- ¹⁰⁸Research Institute for Nuclear Problems of Byelorussian State University, Minsk; Belarus.
- ¹⁰⁹Group of Particle Physics, University of Montreal, Montreal QC; Canada.
- ¹¹⁰P.N. Lebedev Physical Institute of the Russian Academy of Sciences, Moscow; Russia.
- ¹¹¹Institute for Theoretical and Experimental Physics of the National Research Centre Kurchatov Institute, Moscow; Russia.
- ¹¹²National Research Nuclear University MEPhI, Moscow; Russia.
- ¹¹³D.V. Skobel'syn Institute of Nuclear Physics, M.V. Lomonosov Moscow State University, Moscow; Russia.
- ¹¹⁴Fakultät für Physik, Ludwig-Maximilians-Universität München, München; Germany.
- ¹¹⁵Max-Planck-Institut für Physik (Werner-Heisenberg-Institut), München; Germany.
- ¹¹⁶Nagasaki Institute of Applied Science, Nagasaki; Japan.
- ¹¹⁷Graduate School of Science and Kobayashi-Maskawa Institute, Nagoya University, Nagoya; Japan.
- ¹¹⁸Department of Physics and Astronomy, University of New Mexico, Albuquerque NM; United States of America.
- ¹¹⁹Institute for Mathematics, Astrophysics and Particle Physics, Radboud University Nijmegen/Nikhef, Nijmegen; Netherlands.
- ¹²⁰Nikhef National Institute for Subatomic Physics and University of Amsterdam, Amsterdam; Netherlands.
- ¹²¹Department of Physics, Northern Illinois University, DeKalb IL; United States of America.
- ¹²²(^a)Budker Institute of Nuclear Physics and NSU, SB RAS, Novosibirsk; (^b)Novosibirsk State University Novosibirsk; Russia.
- ¹²³Institute for High Energy Physics of the National Research Centre Kurchatov Institute, Protvino; Russia.
- ¹²⁴Department of Physics, New York University, New York NY; United States of America.
- ¹²⁵Ochanomizu University, Otsuka, Bunkyo-ku, Tokyo; Japan.
- ¹²⁶Ohio State University, Columbus OH; United States of America.
- ¹²⁷Faculty of Science, Okayama University, Okayama; Japan.
- ¹²⁸Homer L. Dodge Department of Physics and Astronomy, University of Oklahoma, Norman OK; United States of America.
- ¹²⁹Department of Physics, Oklahoma State University, Stillwater OK; United States of America.
- ¹³⁰Palacký University, RCPTM, Joint Laboratory of Optics, Olomouc; Czech Republic.
- ¹³¹Center for High Energy Physics, University of Oregon, Eugene OR; United States of America.
- ¹³²LAL, Université Paris-Sud, CNRS/IN2P3, Université Paris-Saclay, Orsay; France.

- ¹³³Graduate School of Science, Osaka University, Osaka; Japan.
- ¹³⁴Department of Physics, University of Oslo, Oslo; Norway.
- ¹³⁵Department of Physics, Oxford University, Oxford; United Kingdom.
- ¹³⁶LPNHE, Sorbonne Université, Paris Diderot Sorbonne Paris Cité, CNRS/IN2P3, Paris; France.
- ¹³⁷Department of Physics, University of Pennsylvania, Philadelphia PA; United States of America.
- ¹³⁸Konstantinov Nuclear Physics Institute of National Research Centre "Kurchatov Institute", PNPI, St. Petersburg; Russia.
- ¹³⁹Department of Physics and Astronomy, University of Pittsburgh, Pittsburgh PA; United States of America.
- ¹⁴⁰(^a)Laboratório de Instrumentação e Física Experimental de Partículas - LIP;(^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)Universidad de Granada, Granada (Spain);(^g)Dep Física and CEFITEC of Faculdade de Ciências e Tecnologia, Universidade Nova de Lisboa, Caparica; Portugal.
- ¹⁴¹Institute of Physics of the Czech Academy of Sciences, Prague; Czech Republic.
- ¹⁴²Czech Technical University in Prague, Prague; Czech Republic.
- ¹⁴³Charles University, Faculty of Mathematics and Physics, Prague; Czech Republic.
- ¹⁴⁴Particle Physics Department, Rutherford Appleton Laboratory, Didcot; United Kingdom.
- ¹⁴⁵IRFU, CEA, Université Paris-Saclay, Gif-sur-Yvette; France.
- ¹⁴⁶Santa 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)Departamento de Física, Universidad Técnica Federico Santa María, Valparaíso; Chile.
- ¹⁴⁸Department of Physics, University of Washington, Seattle WA; United States of America.
- ¹⁴⁹Department of Physics and Astronomy, University of Sheffield, Sheffield; United Kingdom.
- ¹⁵⁰Department of Physics, Shinshu University, Nagano; Japan.
- ¹⁵¹Department Physik, Universität Siegen, Siegen; Germany.
- ¹⁵²Department of Physics, Simon Fraser University, Burnaby BC; Canada.
- ¹⁵³SLAC National Accelerator Laboratory, Stanford CA; United States of America.
- ¹⁵⁴Physics Department, Royal Institute of Technology, Stockholm; Sweden.
- ¹⁵⁵Departments of Physics and Astronomy, Stony Brook University, Stony Brook NY; United States of America.
- ¹⁵⁶Department of Physics and Astronomy, University of Sussex, Brighton; United Kingdom.
- ¹⁵⁷School of Physics, University of Sydney, Sydney; Australia.
- ¹⁵⁸Institute of Physics, Academia Sinica, Taipei; Taiwan.
- ¹⁵⁹(^a)E. Andronikashvili Institute of Physics, Iv. Javakhishvili Tbilisi State University, Tbilisi;(^b)High Energy Physics Institute, Tbilisi State University, Tbilisi; Georgia.
- ¹⁶⁰Department of Physics, Technion, Israel Institute of Technology, Haifa; Israel.
- ¹⁶¹Raymond and Beverly Sackler School of Physics and Astronomy, Tel Aviv University, Tel Aviv; Israel.
- ¹⁶²Department of Physics, Aristotle University of Thessaloniki, Thessaloniki; Greece.
- ¹⁶³International Center for Elementary Particle Physics and Department of Physics, University of Tokyo, Tokyo; Japan.
- ¹⁶⁴Graduate School of Science and Technology, Tokyo Metropolitan University, Tokyo; Japan.
- ¹⁶⁵Department of Physics, Tokyo Institute of Technology, Tokyo; Japan.
- ¹⁶⁶Tomsk State University, Tomsk; Russia.
- ¹⁶⁷Department of Physics, University of Toronto, Toronto ON; Canada.
- ¹⁶⁸(^a)TRIUMF, Vancouver BC;(^b)Department of Physics and Astronomy, York University, Toronto ON;

Canada.

¹⁶⁹Division of Physics and Tomonaga Center for the History of the Universe, Faculty of Pure and Applied Sciences, University of Tsukuba, Tsukuba; Japan.

¹⁷⁰Department of Physics and Astronomy, Tufts University, Medford MA; United States of America.

¹⁷¹Department of Physics and Astronomy, University of California Irvine, Irvine CA; United States of America.

¹⁷²Department of Physics and Astronomy, University of Uppsala, Uppsala; Sweden.

¹⁷³Department of Physics, University of Illinois, Urbana IL; United States of America.

¹⁷⁴Instituto de Física Corpuscular (IFIC), Centro Mixto Universidad de Valencia - CSIC, Valencia; Spain.

¹⁷⁵Department of Physics, University of British Columbia, Vancouver BC; Canada.

¹⁷⁶Department of Physics and Astronomy, University of Victoria, Victoria BC; Canada.

¹⁷⁷Fakultät für Physik und Astronomie, Julius-Maximilians-Universität Würzburg, Würzburg; Germany.

¹⁷⁸Department of Physics, University of Warwick, Coventry; United Kingdom.

¹⁷⁹Waseda University, Tokyo; Japan.

¹⁸⁰Department of Particle Physics, Weizmann Institute of Science, Rehovot; Israel.

¹⁸¹Department of Physics, University of Wisconsin, Madison WI; United States of America.

¹⁸²Fakultät für Mathematik und Naturwissenschaften, Fachgruppe Physik, Bergische Universität Wuppertal, Wuppertal; Germany.

¹⁸³Department of Physics, Yale University, New Haven CT; United States of America.

¹⁸⁴Yerevan Physics Institute, Yerevan; Armenia.

^a Also at Centre for High Performance Computing, CSIR Campus, Rosebank, Cape Town; South Africa.

^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 Departamento de Física, Instituto Superior Técnico, Universidade de Lisboa, Lisboa; Portugal.

^g Also at Department of Applied Physics and Astronomy, University of Sharjah, Sharjah; United Arab Emirates.

^h Also at Department of Financial and Management Engineering, University of the Aegean, Chios; Greece.

ⁱ Also at Department of Physics and Astronomy, University of Louisville, Louisville, KY; United States of America.

^j Also at Department of Physics and Astronomy, University of Sheffield, Sheffield; United Kingdom.

^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 Fribourg, Fribourg; Switzerland.

^r Also at Department of Physics, University of Michigan, Ann Arbor MI; United States of America.

^s Also at Faculty of Physics, M.V. Lomonosov Moscow State University, Moscow; Russia.

^t Also at Giresun University, Faculty of Engineering, Giresun; Turkey.

^u Also at Graduate School of Science, Osaka University, Osaka; Japan.

^v Also at Hellenic Open University, Patras; Greece.

^w Also at Horia Hulubei National Institute of Physics and Nuclear Engineering, Bucharest; Romania.

- ^x Also at Institutio Catalana de Recerca i Estudis Avancats, ICREA, Barcelona; Spain.
- ^y Also at Institut für Experimentalphysik, Universität Hamburg, Hamburg; Germany.
- ^z Also at Institute for Mathematics, Astrophysics and Particle Physics, Radboud University Nijmegen/Nikhef, Nijmegen; Netherlands.
- ^{aa} Also at Institute for Nuclear Research and Nuclear Energy (INRNE) of the Bulgarian Academy of Sciences, Sofia; Bulgaria.
- ^{ab} Also at Institute for Particle and Nuclear Physics, Wigner Research Centre for Physics, Budapest; Hungary.
- ^{ac} Also at Institute of Particle Physics (IPP); Canada.
- ^{ad} Also at Institute of Physics, Academia Sinica, Taipei; Taiwan.
- ^{ae} Also at Institute of Physics, Azerbaijan Academy of Sciences, Baku; Azerbaijan.
- ^{af} Also at Institute of Theoretical Physics, Ilia State University, Tbilisi; Georgia.
- ^{ag} Also at Instituto de Fisica Teorica, IFT-UAM/CSIC, Madrid; Spain.
- ^{ah} Also at Istanbul University, Dept. of Physics, Istanbul; Turkey.
- ^{ai} Also at Joint Institute for Nuclear Research, Dubna; Russia.
- ^{aj} Also at LAL, Université Paris-Sud, CNRS/IN2P3, Université Paris-Saclay, Orsay; France.
- ^{ak} Also at Louisiana Tech University, Ruston LA; United States of America.
- ^{al} Also at LPNHE, Sorbonne Université, Paris Diderot Sorbonne Paris Cité, CNRS/IN2P3, Paris; France.
- ^{am} Also at Manhattan College, New York NY; United States of America.
- ^{an} Also at Moscow Institute of Physics and Technology State University, Dolgoprudny; Russia.
- ^{ao} Also at National Research Nuclear University MEPhI, Moscow; Russia.
- ^{ap} Also at Physikalisches Institut, Albert-Ludwigs-Universität Freiburg, Freiburg; Germany.
- ^{aq} Also at School of Physics, Sun Yat-sen University, Guangzhou; China.
- ^{ar} Also at The City College of New York, New York NY; United States of America.
- ^{as} Also at The Collaborative Innovation Center of Quantum Matter (CICQM), Beijing; China.
- ^{at} Also at Tomsk State University, Tomsk, and Moscow Institute of Physics and Technology State University, Dolgoprudny; Russia.
- ^{au} Also at TRIUMF, Vancouver BC; Canada.
- ^{av} Also at Università di Napoli Parthenope, Napoli; Italy.
- * Deceased