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The ATLAS Collaboration

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¹Address(es) of author(s) should be given

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Keywords photon, Higgs boson, fermiophobic

Several extensions of the Standard Model (SM) have been proposed in which the Higgs field couplings to some or all fermion generations are substantially suppressed, for example two Higgs doublet models or Higgs triplet models [1–4]. A fermiophobic benchmark model, in which the Higgs field couplings to all fermions are set to zero while the couplings to bosons are kept at their SM values, has been introduced to allow a generic investigation of these scenarios [5].

In such a model, the production of the Higgs boson in hadron colliders and its decay properties are significantly altered compared to the SM. Fermiophobic Higgs bosons can only be produced via vector boson fusion (VBF) or associated production with vector bosons (VH, $V = W, Z$). Because Higgs boson decays to fermions are absent at tree level, the branching fractions for decays to gauge bosons are enhanced. In ad-

dition, the partial width of the decay to two photons is enhanced by the suppression of the destructive interference between the W -boson and top-quark loops. The resulting cross section times branching ratio for fermiophobic Higgs boson production with decay to two photons is larger than that of the SM for Higgs boson masses (m_H) below 125 GeV. Table 1 lists, for several values of m_H , the fermiophobic Higgs boson cross section multiplied by the decay branching ratio into two photons. The ratio of this quantity with respect to that of the SM Higgs boson and the enhancement of the diphoton branching ratio are also shown. In addition to the enhanced diphoton decay rates, the recoiling jets or vector bosons in the VBF or VH production modes, respectively, imply a high transverse momentum for the Higgs boson that can be exploited as a discriminating variable in the analysis. However, for increasing m_H the diphoton decay rate falls rapidly, making the search less sensitive at higher masses in this decay channel.

Searches for a fermiophobic Higgs boson have been performed at the LEP and Tevatron colliders. The combination of results from the LEP experiments [5] excludes a fermiophobic Higgs boson at 95% confidence level (CL) for masses below 109 GeV. When including both the WW and $\gamma\gamma$ decay modes, the Tevatron experiments exclude a fermiophobic Higgs boson with masses up to 119 GeV [6, 7].

This letter describes a search for a fermiophobic Higgs boson using diphoton events produced in proton-proton collisions at a centre-of-mass energy of $\sqrt{s} = 7$ TeV using data corresponding to an integrated luminosity of 4.9 fb^{-1} collected by the ATLAS experiment. This analysis follows exactly that of the related search for a SM Higgs boson with the same dataset [8], but the fermiophobic Higgs hypothesis is used to construct the signal model. The sensitivity to the fermiophobic

Table 1: Higgs boson production cross section multiplied by the branching ratio into two photons for the fermiophobic benchmark model (σ_f), the ratio of this value to the SM value ($\sigma_f/\sigma_{\text{SM}}$) and the two photon branching ratio enhancement compared to the SM ($\mathcal{B}_f/\mathcal{B}_{\text{SM}}$) for various fermiophobic Higgs boson masses. The expected number of signal events after candidate selection are also shown for 4.9 fb^{-1} of data as well as the overall signal selection efficiencies.

m_H [GeV]	110	115	120	125	130	135	140	145	150
σ_f [fb]	163	90	53	32	21	13	8.9	5.9	3.9
$\sigma_f/\sigma_{\text{SM}}$	3.7	2.1	1.2	0.8	0.6	0.4	0.3	0.3	0.2
$\mathcal{B}_f/\mathcal{B}_{\text{SM}}$	30.2	17.0	10.3	6.7	4.7	3.5	2.8	2.3	2.0
Signal events	255	149	91	58	38	25	17	12	7.9
Efficiency [%]	32	34	35	37	38	38	39	40	42

signal is larger than that for the SM Higgs due to the larger diphoton transverse momentum.

The ATLAS detector is described in detail in Ref. [9]. The most relevant subsystems for this analysis are the calorimeter, in particular the electromagnetic section, and the inner detector. The electromagnetic calorimeter is a lead-liquid-argon detector, finely segmented in the lateral and longitudinal directions. It is composed of a barrel part covering the pseudorapidity range $|\eta| < 1.475$ and two end-cap sections covering $1.375 < |\eta| < 3.2$. The barrel ($|\eta| < 0.8$) and extended barrel ($0.8 < |\eta| < 1.7$) hadron calorimeter sections consist of steel and scintillating tiles, while the end-cap sections ($1.5 < |\eta| < 3.2$) are composed of copper and liquid argon. The inner detector includes silicon-based pixel and micro-strip detectors in the range $|\eta| < 2.5$, and a transition radiation tracker with electron identification capability extending out to $|\eta| < 2.0$. It is surrounded by a superconducting solenoid that provides a 2 T axial magnetic field.

Data used in this analysis were recorded using a diphoton trigger with a 20 GeV transverse energy (E_T) threshold on each photon. This trigger is seeded by a first-level trigger, which requires two clusters in the electromagnetic calorimeter with $E_T > 14$ GeV or $E_T > 12$ GeV, depending on the data-taking period. This trigger has a signal efficiency close to 99% following the final event selection. After application of data-quality requirements the analysed data sample corresponds to a total integrated luminosity of $4.9 \pm 0.2 \text{ fb}^{-1}$ [10].

The events are required to have at least one reconstructed vertex with a minimum of three associated

tracks, where the transverse momentum of each track is required to be larger than 0.4 GeV. At least two photons within the fiducial region $|\eta| < 2.37$ (excluding the transition region between the barrel and the end-cap, $1.37 < |\eta| < 1.52$) satisfying tight identification criteria based on electromagnetic shower shapes [11] are required. The transverse momenta for the leading and sub-leading photons are required to be larger than 40 GeV and 25 GeV, respectively. The photon reconstruction and identification efficiency ranges typically from 65% to 95% for E_T in the range between 25 GeV and 80 GeV. The transverse energy deposited around each photon within a cone of $\Delta R = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2} = 0.4$, excluding the deposits of the photon itself, is required to be less than 5 GeV. Corrections for the small estimated energy leakage outside the excluded region, the underlying event and effects of additional minimum bias interactions occurring in the same or neighbouring bunch crossings (in-time and out-of-time pileup) are applied to this quantity on an event-by-event basis.

The invariant mass of each diphoton candidate ($m_{\gamma\gamma}$) is evaluated using the photon energies, the impact points measured in the calorimeter and the production vertex. The photon energy calibration is performed independently for converted and unconverted photons. Converted photons are defined to be those with a well-reconstructed conversion vertex in the inner detector. A detailed simulation of the detector geometry and response is used for the calibration. Additional corrections due to mis-modelling of the material in front of the calorimeter and of calorimeter non-uniformities are applied. These amount to about $\pm 1\%$ depending on the pseudorapidity of the photon and are obtained from studies of $Z \rightarrow e^+e^-$ decays in data [12]. The diphoton production vertex along the beam axis is determined by combining the trajectories of each photon, measured using the longitudinal segmentation of the calorimeter, with a constraint from the average beam spot position. The position of the conversion vertex is also used where the photons convert in the tracking region instrumented with silicon detectors. Conversion candidates with tracks reconstructed in inactive regions of the innermost pixel layer are rejected to reduce the contamination from misidentified electrons. The resolution of the diphoton mass reconstructed using this method is dominated by the photon energy resolution.

A total of 22,489 events were selected with a diphoton invariant mass between 100 GeV and 160 GeV. Although not used directly in the final result, the diphoton sample composition was studied using a two-dimensional side-band technique based on photon identification quality and isolation [8]. The fraction of true diphoton events was estimated to be $(71 \pm 5)\%$. The rest of the back-

ground is due to events with one or more misidentified jets, except for a small ($\sim 0.7\%$) contribution from Drell-Yan events where both electrons pass the photon selection.

To enhance the sensitivity of the analysis, the data sample is split into nine categories, each with different expected signal mass resolutions, signal yields and signal-to-background ratios (S/B). This categorisation depends on the impact point of the photons on the calorimeter, the presence of photon conversions and the value of the component of the diphoton transverse momentum orthogonal to the diphoton thrust-like axis in the transverse plane¹ (p_{Tt}) [13, 14].

Events in which both photons are unconverted are separated into the *unconverted central* (both photons in the central region of the barrel calorimeter, $|\eta| < 0.75$) and *unconverted rest* (all other events) categories. Events for which at least one photon is converted are separated into the *converted central* (both photons within $|\eta| < 0.75$), *converted transition* (at least one photon close to the barrel/end-cap transition region, $1.3 < |\eta| < 1.75$) and *converted rest* (the remaining events) categories.

With the exception of the *converted transition* category, all the events are further subdivided into *low* p_{Tt} ($p_{Tt} < 40$ GeV) and *high* p_{Tt} (all other events) categories. Monte Carlo (MC) simulation studies show that a fermiophobic Higgs boson signal has larger p_{Tt} on average than background events. This quantity is strongly correlated with the diphoton transverse momentum but offers several advantages. Higher values of p_{Tt} do not include kinematic configurations for which the two photons are back-to-back in the azimuthal plane with substantially different transverse momenta. This reduces biases on the identification and isolation (transverse energy deposited around the photon) of the sub-leading photon in the high p_{Tt} categories and retains a monotonically falling diphoton invariant mass distribution for the background events at the chosen cut values. The latter quality is advantageous for the background modelling and associated uncertainties discussed below.

A full **Geant4**-based [15] MC simulation [16] of Higgs boson events decaying into two photons is used to model the expected signal. The signal yields are normalised to next-to-next-to-leading-order production cross sections [17–22] and the branching ratios for the fermiophobic Higgs boson are calculated using **HDECAY** [23]. Higgs boson VBF production is simulated using **POWHEG** [24] interfaced with **PYTHIA** [25] for showering and hadro-

nisation, while **PYTHIA** is chosen for the VH processes. Pileup effects are simulated by overlaying each MC event with a variable number of simulated inelastic pp collisions, taking into account the LHC bunch-train structure [26].

A set of corrections is applied to the simulated events in order to match the data-taking conditions. The simulated events are re-weighted to reproduce the distribution of the average number of interactions per bunch crossing reconstructed in the data, which has a mean value of about nine for the data sample used in this analysis. The energies of the simulated photons are smeared to account for differences observed in studies of the calorimeter resolution with $Z \rightarrow e^+e^-$ decays. Calorimeter shower shapes used in the photon identification are slightly shifted to improve the agreement with the distributions observed with inclusive photons from data.

The number of fermiophobic Higgs bosons expected after candidate selection and the overall signal selection efficiency for various values of m_H are shown in Table 1. The signal selection efficiency increases from 32% to 42% as the Higgs boson mass increases from 110 GeV to 150 GeV.

Table 2: Expected signal mass resolution (σ_{CB} and FWHM in GeV, see text) and total number of signal events (N_S) for $m_H = 120$ GeV for each of the nine analysis categories and for the inclusive case. Also shown for each category are the number of observed events (N_D) in the diphoton mass range from 100 GeV to 160 GeV, and the expected signal-to-background ratio (S/B) in a mass window containing 90% of the signal.

Category	σ_{CB}	FWHM	N_S	N_D	S/B
Unconverted central, low p_{Tt}	1.4	3.3	6.2	1763	0.03
Unconverted central, high p_{Tt}	1.3	3.2	8.6	235	0.37
Unconverted rest, low p_{Tt}	1.7	3.9	12.1	6234	0.02
Unconverted rest, high p_{Tt}	1.6	3.8	16.0	1006	0.13
Converted central, low p_{Tt}	1.6	3.8	4.0	1318	0.02
Converted central, high p_{Tt}	1.5	3.5	5.8	184	0.26
Converted rest, low p_{Tt}	2.0	4.6	11.8	7311	0.01
Converted rest, high p_{Tt}	1.9	4.4	16.1	1072	0.09
Converted transition	2.3	5.8	10.8	3366	0.01
All categories	1.7	3.9	91.2	22489	0.03

¹ $p_{Tt} = |\mathbf{p}_T^{\gamma\gamma} \times \hat{t}|$, where $\hat{t} = \frac{\mathbf{p}_T^{\gamma 1} - \mathbf{p}_T^{\gamma 2}}{|\mathbf{p}_T^{\gamma 1} - \mathbf{p}_T^{\gamma 2}|}$ denotes the transverse thrust, $\mathbf{p}_T^{\gamma 1}$ and $\mathbf{p}_T^{\gamma 2}$ are the transverse momenta of the two photons, and $\mathbf{p}_T^{\gamma\gamma} = \mathbf{p}_T^{\gamma 1} + \mathbf{p}_T^{\gamma 2}$ is the transverse momentum of the diphoton system.

The signal is modelled as the sum of a core component, described by a *Crystal Ball* (CB) function [27], and a wider Gaussian component incorporating outly-

ing events. The latter component typically accounts for less than 5% of the signal. Table 2 lists the expected full-width-at-half-maximum (FWHM) and Gaussian width of the core component (σ_{CB}) for each of the nine event categories. The expected number of signal events for $m_H = 120$ GeV, the number of background events in the diphoton mass range of 100 GeV to 160 GeV, and the signal-to-background ratio in a mass window containing 90% of the signal are also shown. The main sensitivity to the fermiophobic production modes comes from the high p_{Tt} categories due to their enhanced signal yields and signal-to-background ratios. Figure 1 shows the signal diphoton mass distribution summed over the high p_{Tt} categories for a Higgs boson mass of 120 GeV.

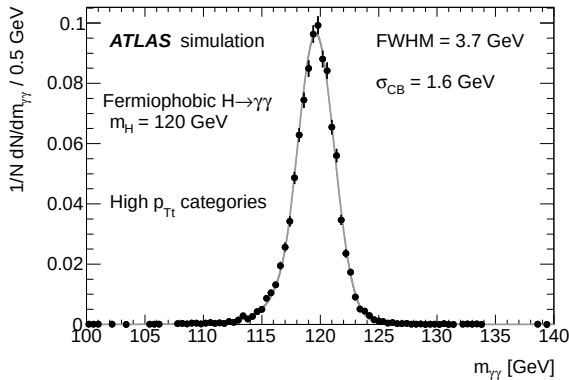


Fig. 1: Diphoton invariant mass spectrum from simulated signal samples (dots) with $m_H = 120$ GeV summed over the high p_{Tt} categories, superimposed with the signal model (line).

The observed diphoton invariant mass distribution in each category is modelled by an exponential function. A fit to the data is performed for which the slope and normalisation are unconstrained. Studies with large samples of simulated diphoton events show that this simple function gives a good description of the expected shape. The small systematic uncertainties associated with this assumption are discussed below. Figures 2(a) and 2(b) show the diphoton mass distributions of the selected data events summed over the low and high p_{Tt} categories, respectively. The *converted transition* category is included in the low p_{Tt} categories.

Systematic uncertainties affecting the signal significance arise from uncertainties on the predicted signal yields, the expected partition of the signal among the categories and the modelling of the signal and background shapes. The dominant experimental uncertainty on the signal yield is due to the imperfect knowledge

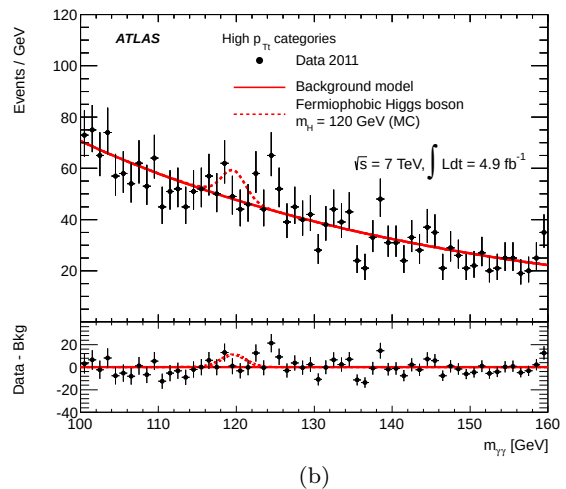
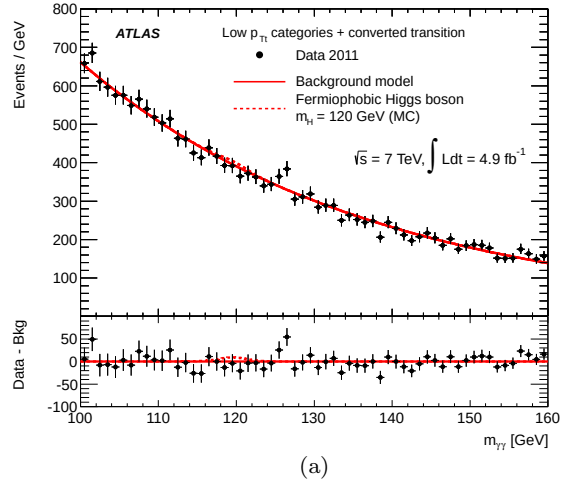


Fig. 2: Diphoton invariant mass spectra for the (a) low and (b) high p_{Tt} categories, overlaid with the sum of the background-only fits from the individual categories. The bottom plots show the residual of the data with respect to the fitted background. The signal expectation for a fermiophobic Higgs boson with a mass of 120 GeV superimposed on the background fit is also shown.

of the photon reconstruction and identification efficiencies, which is estimated to be $\pm 11\%$. This uncertainty is studied with electrons from W and Z boson decays in data, and photons from radiative decays of Z bosons to electron and muon pairs. In addition, the effect of pileup on photon identification gives a further contribution to the signal yield uncertainty of $\pm 4\%$. Uncertainties related to the trigger efficiency ($\pm 1\%$), isolation cut efficiency ($\pm 5\%$) and luminosity ($\pm 3.9\%$) are also included here.

Uncertainties on the signal cross section include a combination of the uncertainties on the parton distribution functions [28, 29] and α_s , and uncertainties on the

QCD scale. Combining the VBF and VH production modes this uncertainty is within $\pm 4\%$ over the considered mass range. To this uncertainty, that due to the $H \rightarrow \gamma\gamma$ branching ratio ($\pm 5\%$) is added linearly, based on the SM calculation [22]. This yields uncertainties of $\pm 9\%$ on the theoretical signal yield, leading to an overall uncertainty of $\pm 16\%$ on the total signal expectation. In addition, the uncertainty on the Higgs boson p_T modelling is estimated by comparing signal samples from alternative MC generators – HERWIG [30] for VBF and ResBos [31] for VH. The result is a $\pm 1\%$ signal migration between the low and high p_{Tt} categories with a negligible effect on the signal selection efficiency.

The dominant uncertainties on the signal mass resolution are due to the uncertainty on the calorimeter energy resolution ($\pm 12\%$) and photon calibration ($\pm 6\%$), which are both extrapolated from the uncertainty on the electron calibration determined using Z and J/ψ data [12]. The latter comes from the imperfect knowledge of the material in front of the active part of the calorimeter and is estimated using simulations with different amounts of material. This quantity also affects the fraction of expected events in the categories with converted photons; the maximal migration between *converted* and *unconverted* categories is estimated to be $\pm 4.5\%$. Other effects on the signal mass resolution are due to pileup fluctuations contributing to the cluster energy measurement ($\pm 3\%$) and to the uncertainty on the photon angular resolution ($\pm 1\%$) which is studied in $Z \rightarrow e^+e^-$ decays using the track-based direction measurement. The total relative uncertainty on the diphoton invariant mass resolution is thus $\pm 14\%$.

Systematic uncertainties on the background modelling arise from a possible deviation of the background mass distribution from the assumed exponential shape. This uncertainty is evaluated as the number of events that could be mistakenly attributed to the signal. It is estimated from the adequacy of the chosen background model's description of the mass distribution predicted by ResBos [32]. The residuals of the fit of the background model to the ResBos diphoton mass distribution are integrated over a sliding mass window of 4 GeV, the approximate FWHM of the expected signal. The largest deviations were found at small invariant masses and these uncertainties are then applied over the whole mass range. The resulting uncertainties range from ± 0.1 to ± 7.9 events in the individual analysis categories, where the magnitude of these uncertainties is roughly proportional to the number of background events in each category. These absolute uncertainties do not scale with the signal strength in the final likelihood fit. For a fermiophobic Higgs boson with $m_H = 120$ GeV the back-

ground modelling uncertainty in the high p_{Tt} categories is equivalent to up to 5% of the signal yield with nominal signal strength. The estimation of the uncertainties is cross-checked by fitting the data with different functional forms and comparing the result to the exponential fit.

The possible presence of a signal is investigated using a combined likelihood function constructed from the signal and background models for the diphoton invariant mass distribution in each of the nine categories. Unbinned maximum likelihood fits of the signal strength are performed, treating the systematic uncertainties as nuisance parameters – fourteen in total. These nuisance parameters are added to the signal likelihood function using a Gaussian term for the background modelling uncertainty, and log-normal terms for all other uncertainties.

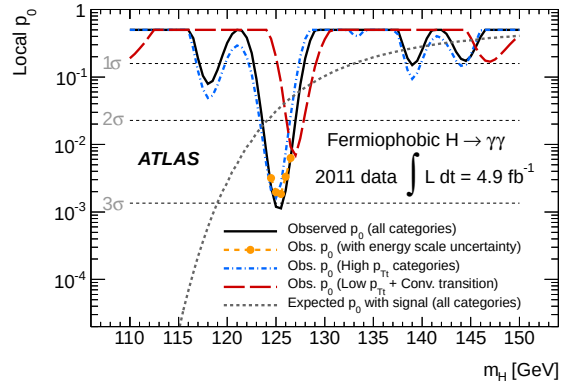


Fig. 3: Local observed p_0 as a function of the Higgs boson mass m_H (solid line) and the median expectation for a fermiophobic signal with the given m_H (dotted line). The five points near 125 GeV show the observed p_0 when the uncertainty on the photon energy scale is considered. The individual contributions of the low p_{Tt} and high p_{Tt} categories to the observed p_0 are also shown.

The compatibility of the data with the background-only hypothesis, relative to the hypothesis of background plus the fermiophobic model signal, is quantified by the local significance p_0 . Figure 3 shows the result for m_H ranging from 110 GeV to 150 GeV, where p_0 is computed in 0.5 GeV steps using asymptotic formulae [33]. The contributions to p_0 values from the high p_{Tt} and low p_{Tt} categories are shown separately. The high p_{Tt} contribution has a minimum p_0 at 125 GeV, while the low p_{Tt} contribution has a minimum at 127 GeV. The larger signal-to-background ratio as well as the larger expected signal yield in the high p_{Tt} category compared

to the low p_{Tt} category results in the high p_{Tt} contribution dominating in the final result. The combined p_0 has a minimum at 125.5 GeV corresponding to 3.0 standard deviations. The figure also shows the p_0 value expected for a fermiophobic Higgs boson signal, as a function of Higgs boson mass.

To obtain the final result, the impact of the uncertainties on the photon energy scale is considered for Higgs boson masses in the region of the minimum p_0 , as shown in Fig. 3. The corresponding effect on the measured p_0 value is estimated using pseudo-experiments, since asymptotic formulae were found not to yield accurate estimates of the probability in this case. The position of the minimum p_0 is almost unchanged and the significance is lowered to 2.9 standard deviations. Taking the look-elsewhere effect [34] into account in the range 110 – 150 GeV, the significance reduces to about 1.6 standard deviations, with $p_0 \approx 0.051$. This may be compared to the result of a search for the SM Higgs boson performed with the same dataset and candidate selection [8], yielding a minimum p_0 at a mass of 126.5 GeV with a global significance of 1.5 standard deviations. No statistically significant preference for either the SM or fermiophobic Higgs boson is observed.

Given the lack of evidence for a signal, mass-dependent exclusion limits on the fermiophobic benchmark model are calculated at the 95% confidence level (CL) with a profile likelihood ratio test statistic in the CL_s modified frequentist approach [33,35,36] and are shown in Fig. 4. Fermiophobic Higgs boson masses from 110.0 GeV to 118.0 GeV and from 119.5 GeV to 121.0 GeV are excluded, while the expected exclusion mass range is 110.0 – 123.5 GeV. These results give more stringent lower mass limits than the previous results from LEP (108.2 GeV) [5] and the Tevatron (112.9 GeV from D0, 114 GeV from CDF) [6,37] in the diphoton decay channel.

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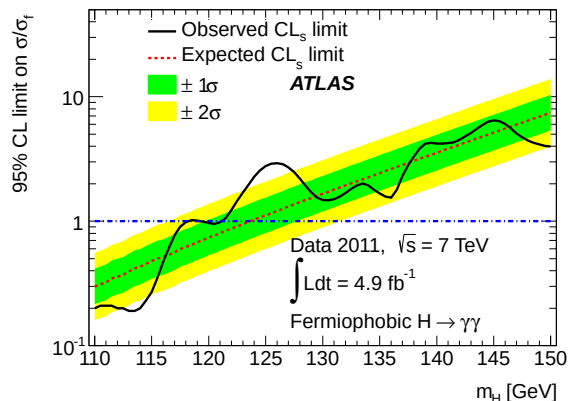


Fig. 4: Observed (solid line) and expected (dotted line) 95% CL exclusion limits for a fermiophobic Higgs boson normalised to the fermiophobic cross section times branching ratio expectation (σ_f) as a function of the Higgs boson mass hypothesis (m_H).

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The ATLAS Collaboration

G. Aad⁴⁸, B. Abbott¹¹¹, J. Abdallah¹¹,
 S. Abdel Khalek¹¹⁵, A.A. Abdelalim⁴⁹, O. Abdinov¹⁰,
 B. Abi¹¹², M. Abolins⁸⁸, O.S. AbouZeid¹⁵⁸,
 H. Abramowicz¹⁵³, H. Abreu¹³⁶, E. Acerbi^{89a,89b},
 B.S. Acharya^{164a,164b}, L. Adamczyk³⁷, D.L. Adams²⁴,
 T.N. Addy⁵⁶, J. Adelman¹⁷⁶, S. Adomeit⁹⁸,
 P. Adragna⁷⁵, T. Adye¹²⁹, S. Aefsky²²,
 J.A. Aguilar-Saavedra^{124b,a}, M. Aharrouche⁸¹,
 S.P. Ahlen²¹, F. Ahles⁴⁸, A. Ahmad¹⁴⁸, M. Ahsan⁴⁰,
 G. Aielli^{133a,133b}, T. Akdogan^{18a}, T.P.A. Åkesson⁷⁹,
 G. Akimoto¹⁵⁵, A.V. Akimov⁹⁴, A. Akiyama⁶⁶,
 M.S. Alam¹, M.A. Alam⁷⁶, J. Albert¹⁶⁹, S. Albrand⁵⁵,
 M. Aleksa²⁹, I.N. Aleksandrov⁶⁴, F. Alessandria^{89a},
 C. Alexa^{25a}, G. Alexander¹⁵³, G. Alexandre⁴⁹,
 T. Alexopoulos⁹, M. Alhroob^{164a,164c}, M. Aliev¹⁵,
 G. Alimonti^{89a}, J. Alison¹²⁰, B.M.M. Allbrooke¹⁷,
 P.P. Allport⁷³, S.E. Allwood-Spiers⁵³, J. Almond⁸²,
 A. Aloisio^{102a,102b}, R. Alon¹⁷², A. Alonso⁷⁹,
 B. Alvarez Gonzalez⁸⁸, M.G. Alviggi^{102a,102b},
 K. Amako⁶⁵, C. Amelung²², V.V. Ammosov¹²⁸,
 A. Amorim^{124a,b}, N. Amram¹⁵³, C. Anastopoulos²⁹,
 L.S. Ancu¹⁶, N. Andari¹¹⁵, T. Andeen³⁴,
 C.F. Anders^{58b}, G. Anders^{58a}, K.J. Anderson³⁰,
 A. Andreazza^{89a,89b}, V. Andrei^{58a}, X.S. Anduaga⁷⁰,
 P. Anger⁴³, A. Angerami³⁴, F. Anghinolfi²⁹,
 A. Anisenkov¹⁰⁷, N. Anjos^{124a}, A. Annovi⁴⁷,
 A. Antonaki⁸, M. Antonelli⁴⁷, A. Antonov⁹⁶,
 J. Antos^{144b}, F. Anulli^{132a}, S. Aoun⁸³,
 L. Aperio Bella⁴, R. Apolle^{118,c}, G. Arabidze⁸⁸,
 I. Aracena¹⁴³, Y. Arai⁶⁵, A.T.H. Arce⁴⁴, S. Arfaoui¹⁴⁸,
 J-F. Arguin¹⁴, E. Arik^{18a,*}, M. Arik^{18a},
 A.J. Armbruster⁸⁷, O. Arnaez⁸¹, V. Arnal⁸⁰,
 C. Arnault¹¹⁵, A. Artamonov⁹⁵, G. Artoni^{132a,132b},
 D. Arutinov²⁰, S. Asai¹⁵⁵, R. Asfandiyarov¹⁷³,
 S. Ask²⁷, B. Åsman^{146a,146b}, L. Asquith⁵,
 K. Assamagan²⁴, A. Astbury¹⁶⁹, B. Aubert⁴,
 E. Auge¹¹⁵, K. Augsten¹²⁷, M. Aourousseau^{145a},
 G. Avolio¹⁶³, R. Avramidou⁹, D. Axen¹⁶⁸,
 G. Azuelos^{93,d}, Y. Azuma¹⁵⁵, M.A. Baak²⁹,
 G. Baccaglioni^{89a}, C. Bacci^{134a,134b}, A.M. Bach¹⁴,
 H. Bachacou¹³⁶, K. Bachas²⁹, M. Backes⁴⁹,
 M. Backhaus²⁰, E. Badescu^{25a}, P. Bagnaia^{132a,132b},
 S. Bahinipati², Y. Bai^{32a}, D.C. Bailey¹⁵⁸, T. Bain¹⁵⁸,
 J.T. Baines¹²⁹, O.K. Baker¹⁷⁶, M.D. Baker²⁴,
 S. Baker⁷⁷, E. Banas³⁸, P. Banerjee⁹³,
 Sw. Banerjee¹⁷³, D. Banfi²⁹, A. Bangert¹⁵⁰,
 V. Bansal¹⁶⁹, H.S. Bansil¹⁷, L. Barak¹⁷²,
 S.P. Baranov⁹⁴, A. Barbaro Galtieri¹⁴, T. Barber⁴⁸,
 E.L. Barberio⁸⁶, D. Barberis^{50a,50b}, M. Barbero²⁰,
 D.Y. Bardin⁶⁴, T. Barillari⁹⁹, M. Barisonzi¹⁷⁵,
 T. Barklow¹⁴³, N. Barlow²⁷, B.M. Barnett¹²⁹,

R.M. Barnett¹⁴, A. Baroncelli^{134a}, G. Barone⁴⁹,
 A.J. Barr¹¹⁸, F. Barreiro⁸⁰, J. Barreiro Guimarães da
 Costa⁵⁷, P. Barrillon¹¹⁵, R. Bartoldus¹⁴³,
 A.E. Barton⁷¹, V. Bartsch¹⁴⁹, R.L. Bates⁵³,
 L. Batkova^{144a}, J.R. Batley²⁷, A. Battaglia¹⁶,
 M. Battistin²⁹, F. Bauer¹³⁶, H.S. Bawa^{143,e},
 S. Beale⁹⁸, T. Beau⁷⁸, P.H. Beauchemin¹⁶¹,
 R. Beccherle^{50a}, P. Bechtel²⁰, H.P. Beck¹⁶,
 A.K. Becker¹⁷⁵, S. Becker⁹⁸, M. Beckingham¹³⁸,
 K.H. Becks¹⁷⁵, A.J. Beddall^{18c}, A. Beddall^{18c},
 S. Bedikian¹⁷⁶, V.A. Bednyakov⁶⁴, C.P. Bee⁸³,
 M. Begel²⁴, S. Behar Harpaz¹⁵², M. Beimforde⁹⁹,
 C. Belanger-Champagne⁸⁵, P.J. Bell⁴⁹, W.H. Bell⁴⁹,
 G. Bella¹⁵³, L. Bellagamba^{19a}, F. Bellina²⁹,
 M. Bellomo²⁹, A. Belloni⁵⁷, O. Beloborodova^{107,f},
 K. Belotskiy⁹⁶, O. Beltramello²⁹, O. Benary¹⁵³,
 D. Benchekroun^{135a}, K. Bendtz^{146a,146b},
 N. Benekos¹⁶⁵, Y. Benhammou¹⁵³,
 E. Benhar Nocchioli⁴⁹, J.A. Benitez Garcia^{159b},
 D.P. Benjamin⁴⁴, M. Benoit¹¹⁵, J.R. Bensinger²²,
 K. Benslama¹³⁰, S. Bentvelsen¹⁰⁵, D. Berge²⁹,
 E. Bergeas Kuutmann⁴¹, N. Berger⁴, F. Berghaus¹⁶⁹,
 E. Berglund¹⁰⁵, J. Beringer¹⁴, P. Bernat⁷⁷,
 R. Bernhard⁴⁸, C. Bernius²⁴, T. Berry⁷⁶,
 C. Bertella⁸³, A. Bertin^{19a,19b}, F. Bertolucci^{122a,122b},
 M.I. Besana^{89a,89b}, G.J. Besjes¹⁰⁴, N. Besson¹³⁶,
 S. Bethke⁹⁹, W. Bhimji⁴⁵, R.M. Bianchi²⁹,
 M. Bianco^{72a,72b}, O. Biebel⁹⁸, S.P. Bieniek⁷⁷,
 K. Bierwagen⁵⁴, J. Biesiada¹⁴, M. Biglietti^{134a},
 H. Bilokon⁴⁷, M. Bindi^{19a,19b}, S. Binet¹¹⁵,
 A. Bingul^{18c}, C. Bini^{132a,132b}, C. Biscarat¹⁷⁸,
 U. Bitenc⁴⁸, K.M. Black²¹, R.E. Blair⁵,
 J.-B. Blanchard¹³⁶, G. Blanchot²⁹, T. Blazek^{144a},
 C. Blocker²², J. Blocki³⁸, A. Blondel⁴⁹, W. Blum⁸¹,
 U. Blumenschein⁵⁴, G.J. Bobbink¹⁰⁵,
 V.B. Bobrovnikov¹⁰⁷, S.S. Bocchetta⁷⁹, A. Bocci⁴⁴,
 C.R. Boddy¹¹⁸, M. Boehler⁴¹, J. Boek¹⁷⁵,
 N. Boelaert³⁵, J.A. Bogaerts²⁹, A. Bogdanchikov¹⁰⁷,
 A. Bogouch^{90,*}, C. Bohm^{146a}, J. Bohm¹²⁵,
 V. Boisvert⁷⁶, T. Bold³⁷, V. Boldea^{25a},
 N.M. Bolnet¹³⁶, M. Bomben⁷⁸, M. Bona⁷⁵,
 M. Bondioli¹⁶³, M. Boonekamp¹³⁶, C.N. Booth¹³⁹,
 S. Bordini⁷⁸, C. Borer¹⁶, A. Borisov¹²⁸, G. Borissov⁷¹,
 I. Borjanovic^{12a}, M. Borri⁸², S. Borroni⁸⁷,
 V. Bortolotto^{134a,134b}, K. Bos¹⁰⁵, D. Boscherini^{19a},
 M. Bosman¹¹, H. Boterenbrood¹⁰⁵, D. Botterill¹²⁹,
 J. Bouchami⁹³, J. Boudreau¹²³,
 E.V. Bouhova-Thacker⁷¹, D. Boumediene³³,
 C. Bourdarios¹¹⁵, N. Bousson⁸³, A. Boveia³⁰,
 J. Boyd²⁹, I.R. Boyko⁶⁴, I. Bozovic-Jelisavcic^{12b},
 J. Bracinik¹⁷, P. Branchini^{134a}, A. Brandt⁷,
 G. Brandt¹¹⁸, O. Brandt⁵⁴, U. Bratzler¹⁵⁶, B. Brau⁸⁴,
 J.E. Brau¹¹⁴, H.M. Braun¹⁷⁵, B. Breliev¹⁵⁸,

- J. Bremer²⁹, K. Brendlinger¹²⁰, R. Brenner¹⁶⁶,
S. Bressler¹⁷², D. Britton⁵³, F.M. Brochu²⁷,
I. Brock²⁰, R. Brock⁸⁸, E. Brodet¹⁵³, F. Broggi^{89a},
C. Bromberg⁸⁸, J. Bronner⁹⁹, G. Brooijmans³⁴,
T. Brooks⁷⁶, W.K. Brooks^{31b}, G. Brown⁸², H. Brown⁷,
P.A. Bruckman de Renstrom³⁸, D. Bruncko^{144b},
R. Bruneliere⁴⁸, S. Brunet⁶⁰, A. Bruni^{19a}, G. Bruni^{19a},
M. Bruschi^{19a}, T. Buanes¹³, Q. Buat⁵⁵, F. Bucci⁴⁹,
J. Buchanan¹¹⁸, P. Buchholz¹⁴¹, R.M. Buckingham¹¹⁸,
A.G. Buckley⁴⁵, S.I. Buda^{25a}, I.A. Budagov⁶⁴,
B. Budick¹⁰⁸, V. Büscher⁸¹, L. Bugge¹¹⁷,
O. Bulekov⁹⁶, A.C. Bundock⁷³, M. Bunse⁴²,
T. Buran¹¹⁷, H. Burckhart²⁹, S. Burdin⁷³,
T. Burgess¹³, S. Burke¹²⁹, E. Busato³³, P. Bussey⁵³,
C.P. Buszello¹⁶⁶, B. Butler¹⁴³, J.M. Butler²¹,
C.M. Buttar⁵³, J.M. Butterworth⁷⁷, W. Buttinger²⁷,
S. Cabrera Urbán¹⁶⁷, D. Caforio^{19a,19b}, O. Cakir^{3a},
P. Calafiura¹⁴, G. Calderini⁷⁸, P. Calfayan⁹⁸,
R. Calkins¹⁰⁶, L.P. Caloba^{23a}, R. Caloi^{132a,132b},
D. Calvet³³, S. Calvet³³, R. Camacho Toro³³,
P. Camarri^{133a,133b}, D. Cameron¹¹⁷,
L.M. Caminada¹⁴, S. Campana²⁹, M. Campanelli⁷⁷,
V. Canale^{102a,102b}, F. Canelli^{30,g}, A. Canepa^{159a},
J. Cantero⁸⁰, R. Cantrill⁷⁶, L. Capasso^{102a,102b},
M.D.M. Capeans Garrido²⁹, I. Caprini^{25a},
M. Caprini^{25a}, D. Capriotti⁹⁹, M. Capua^{36a,36b},
R. Caputo⁸¹, R. Cardarelli^{133a}, T. Carli²⁹,
G. Carlino^{102a}, L. Carminati^{89a,89b}, B. Caron⁸⁵,
S. Caron¹⁰⁴, E. Carquin^{31b}, G.D. Carrillo Montoya¹⁷³,
A.A. Carter⁷⁵, J.R. Carter²⁷, J. Carvalho^{124a,h},
D. Casadei¹⁰⁸, M.P. Casado¹¹, M. Cascella^{122a,122b},
C. Caso^{50a,50b,*}, A.M. Castaneda Hernandez^{173,i},
E. Castaneda-Miranda¹⁷³, V. Castillo Gimenez¹⁶⁷,
N.F. Castro^{124a}, G. Cataldi^{72a}, P. Catastini⁵⁷,
A. Catinaccio²⁹, J.R. Catmore²⁹, A. Cattai²⁹,
G. Cattani^{133a,133b}, S. Caughron⁸⁸, P. Cavalleri⁷⁸,
D. Cavalli^{89a}, M. Cavalli-Sforza¹¹,
V. Cavasinni^{122a,122b}, F. Ceradini^{134a,134b},
A.S. Cerqueira^{23b}, A. Cerri²⁹, L. Cerrito⁷⁵,
F. Cerutti⁴⁷, S.A. Cetin^{18b}, A. Chafaq^{135a},
D. Chakraborty¹⁰⁶, I. Chalupkova¹²⁶, K. Chan²,
B. Chapleau⁸⁵, J.D. Chapman²⁷, J.W. Chapman⁸⁷,
E. Chareyre⁷⁸, D.G. Charlton¹⁷, V. Chavda⁸²,
C.A. Chavez Barajas²⁹, S. Cheatham⁸⁵, S. Chekanov⁵,
S.V. Chekulaev^{159a}, G.A. Chelkov⁶⁴,
M.A. Chelstowska¹⁰⁴, C. Chen⁶³, H. Chen²⁴,
S. Chen^{32c}, X. Chen¹⁷³, A. Cheplakov⁶⁴,
R. Cherkaoui El Moursli^{135e}, V. Chernyatin²⁴,
E. Cheu⁶, S.L. Cheung¹⁵⁸, L. Chevalier¹³⁶,
G. Chiefari^{102a,102b}, L. Chikovani^{51a}, J.T. Childers²⁹,
A. Chilingarov⁷¹, G. Chiodini^{72a}, A.S. Chisholm¹⁷,
R.T. Chislett⁷⁷, M.V. Chizhov⁶⁴, G. Choudalakis³⁰,
S. Chouridou¹³⁷, I.A. Christidi⁷⁷, A. Christov⁴⁸,
D. Chromek-Burckhart²⁹, M.L. Chu¹⁵¹,
J. Chudoba¹²⁵, G. Ciapetti^{132a,132b}, A.K. Ciftci^{3a},
R. Ciftci^{3a}, D. Cinca³³, V. Cindro⁷⁴, C. Ciocca^{19a,19b},
A. Cicio¹⁴, M. Cirilli⁸⁷, P. Cirkovic^{12b},
M. Citterio^{89a}, M. Ciubancan^{25a}, A. Clark⁴⁹,
P.J. Clark⁴⁵, W. Cleland¹²³, J.C. Clemens⁸³,
B. Clement⁵⁵, C. Clement^{146a,146b}, Y. Coadou⁸³,
M. Cobal^{164a,164c}, A. Coccaro¹³⁸, J. Cochran⁶³,
J.G. Cogan¹⁴³, J. Coggeshall¹⁶⁵, E. Cogneras¹⁷⁸,
J. Colas⁴, A.P. Colijn¹⁰⁵, N.J. Collins¹⁷,
C. Collins-Tooth⁵³, J. Collot⁵⁵, T. Colombo^{119a,119b},
G. Colon⁸⁴, P. Conde Muiño^{124a}, E. Coniavitis¹¹⁸,
M.C. Conidi¹¹, S.M. Consonni^{89a,89b}, V. Consorti⁴⁸,
S. Constantinescu^{25a}, C. Conta^{119a,119b}, G. Conti⁵⁷,
F. Conventi^{102a,j}, M. Cooke¹⁴, B.D. Cooper⁷⁷,
A.M. Cooper-Sarkar¹¹⁸, K. Copic¹⁴, T. Cornelissen¹⁷⁵,
M. Corradi^{19a}, F. Corriveau^{85,k},
A. Cortes-Gonzalez¹⁶⁵, G. Cortiana⁹⁹, G. Costa^{89a},
M.J. Costa¹⁶⁷, D. Costanzo¹³⁹, T. Costin³⁰, D. Côté²⁹,
L. Courneyea¹⁶⁹, G. Cowan⁷⁶, C. Cowden²⁷,
B.E. Cox⁸², K. Cranmer¹⁰⁸, F. Crescioli^{122a,122b},
M. Cristinziani²⁰, G. Crosetti^{36a,36b}, R. Crupi^{72a,72b},
S. Crépe-Renaudin⁵⁵, C.-M. Cuciuc^{25a},
C. Cuenca Almenar¹⁷⁶, T. Cuhadar Donszelmann¹³⁹,
M. Curatolo⁴⁷, C.J. Curtis¹⁷, C. Cuthbert¹⁵⁰,
P. Cwetanski⁶⁰, H. Czirr¹⁴¹, P. Czodrowski⁴³,
Z. Czyczula¹⁷⁶, S. D'Auria⁵³, M. D'Onofrio⁷³,
A. D'Orazio^{132a,132b},
M.J. Da Cunha Sargedas De Sousa^{124a}, C. Da Via⁸²,
W. Dabrowski³⁷, A. Dafinca¹¹⁸, T. Dai⁸⁷,
C. Dallapiccola⁸⁴, M. Dam³⁵, M. Dameri^{50a,50b},
D.S. Damiani¹³⁷, H.O. Danielsson²⁹, V. Dao⁴⁹,
G. Darbo^{50a}, G.L. Darlea^{25b}, W. Davey²⁰,
T. Davidek¹²⁶, N. Davidson⁸⁶, R. Davidson⁷¹,
E. Davies^{118,c}, M. Davies⁹³, A.R. Davison⁷⁷,
Y. Davygora^{58a}, E. Dawe¹⁴², I. Dawson¹³⁹,
R.K. Daya-Ishmukhametova²², K. De⁷,
R. de Asmundis^{102a}, S. De Castro^{19a,19b},
S. De Cecco⁷⁸, J. de Graat⁹⁸, N. De Groot¹⁰⁴,
P. de Jong¹⁰⁵, C. De La Taille¹¹⁵, H. De la Torre⁸⁰,
F. De Lorenzi⁶³, L. de Mora⁷¹, L. De Nooij¹⁰⁵,
D. De Pedis^{132a}, A. De Salvo^{132a},
U. De Sanctis^{164a,164c}, A. De Santo¹⁴⁹,
J.B. De Vivie De Regie¹¹⁵, G. De Zorzi^{132a,132b},
W.J. Dearnaley⁷¹, R. Debbe²⁴, C. Debenedetti⁴⁵,
B. Dechenaux⁵⁵, D.V. Dedovich⁶⁴, J. Degenhardt¹²⁰,
C. Del Papa^{164a,164c}, J. Del Peso⁸⁰,
T. Del Prete^{122a,122b}, T. Delemontex⁵⁵,
M. Deliyergiyev⁷⁴, A. Dell'Acqua²⁹, L. Dell'Asta²¹,
M. Della Pietra^{102a,j}, D. della Volpe^{102a,102b},
M. Delmastro⁴, P.A. Delsart⁵⁵, C. Deluca¹⁰⁵,
S. Demers¹⁷⁶, M. Demichev⁶⁴, B. Demirkoz^{11,l},
J. Deng¹⁶³, S.P. Denisov¹²⁸, D. Derendarz³⁸,

- J.E. Derkaoui^{135d}, F. Derue⁷⁸, P. Dervan⁷³,
K. Desch²⁰, E. Devetak¹⁴⁸, P.O. Deviveiros¹⁰⁵,
A. Dewhurst¹²⁹, B. DeWilde¹⁴⁸, S. Dhaliwal¹⁵⁸,
R. Dhullipudi^{24,m}, A. Di Ciaccio^{133a,133b},
L. Di Ciaccio⁴, A. Di Girolamo²⁹, B. Di Girolamo²⁹,
S. Di Luise^{134a,134b}, A. Di Mattia¹⁷³, B. Di Micco²⁹,
R. Di Nardo⁴⁷, A. Di Simone^{133a,133b},
R. Di Sipio^{19a,19b}, M.A. Diaz^{31a}, E.B. Diehl⁸⁷,
J. Dietrich⁴¹, T.A. Dietzsch^{58a}, S. Diglio⁸⁶,
K. Dindar Yagci³⁹, J. Dingfelder²⁰, C. Dionisi^{132a,132b},
P. Dita^{25a}, S. Dita^{25a}, F. Dittus²⁹, F. Djama⁸³,
T. Djobava^{51b}, M.A.B. do Vale^{23c},
A. Do Valle Wemans^{124a,n}, T.K.O. Doan⁴,
M. Dobbs⁸⁵, R. Dobinson^{29,*}, D. Dobos²⁹,
E. Dobson^{29,o}, J. Dodd³⁴, C. Doglioni⁴⁹,
T. Doherty⁵³, Y. Doi^{65,*}, J. Dolejsi¹²⁶, I. Dolenc⁷⁴,
Z. Dolezal¹²⁶, B.A. Dolgoshein^{96,*}, T. Dohmae¹⁵⁵,
M. Donadelli^{23d}, M. Donega¹²⁰, J. Donini³³,
J. Dopke²⁹, A. Doria^{102a}, A. Dos Anjos¹⁷³,
A. Dotti^{122a,122b}, M.T. Dova⁷⁰, A.D. Doxiadis¹⁰⁵,
A.T. Doyle⁵³, M. Dris⁹, J. Dubbert⁹⁹, S. Dube¹⁴,
E. Duchovni¹⁷², G. Duckeck⁹⁸, A. Dudarev²⁹,
F. Dudziak⁶³, M. Dührssen²⁹, I.P. Duerdoth⁸²,
L. Duflo¹¹⁵, M-A. Dufour⁸⁵, M. Dunford²⁹,
H. Duran Yildiz^{3a}, R. Duxfield¹³⁹, M. Dwuznik³⁷,
F. Dydak²⁹, M. Düren⁵², J. Ebke⁹⁸, S. Eckweiler⁸¹,
K. Edmonds⁸¹, C.A. Edwards⁷⁶, N.C. Edwards⁵³,
W. Ehrenfeld⁴¹, T. Eifert¹⁴³, G. Eigen¹³,
K. Einsweiler¹⁴, E. Eisenhandler⁷⁵, T. Ekelof¹⁶⁶,
M. El Kacimi^{135c}, M. Ellert¹⁶⁶, S. Elles⁴,
F. Ellinghaus⁸¹, K. Ellis⁷⁵, N. Ellis²⁹, J. Elmsheuser⁹⁸,
M. Elsing²⁹, D. Emelianov¹²⁹, R. Engelmann¹⁴⁸,
A. Engl⁹⁸, B. Epp⁶¹, A. Eppig⁸⁷, J. Erdmann⁵⁴,
A. Ereditato¹⁶, D. Eriksson^{146a}, J. Ernst¹, M. Ernst²⁴,
J. Ernwein¹³⁶, D. Errede¹⁶⁵, S. Errede¹⁶⁵, E. Ertel⁸¹,
M. Escalier¹¹⁵, C. Escobar¹²³, X. Espinal Curull¹¹,
B. Esposito⁴⁷, F. Etienne⁸³, A.I. Etiennevire¹³⁶,
E. Etzion¹⁵³, D. Evangelakou⁵⁴, H. Evans⁶⁰,
L. Fabbri^{19a,19b}, C. Fabre²⁹, R.M. Fakhruddinov¹²⁸,
S. Falciano^{132a}, Y. Fang¹⁷³, M. Fanti^{89a,89b},
A. Farbin⁷, A. Farilla^{134a}, J. Farley¹⁴⁸,
T. Farooque¹⁵⁸, S. Farrell¹⁶³, S.M. Farrington¹¹⁸,
P. Farthouat²⁹, P. Fassnacht²⁹, D. Fassouliotis⁸,
B. Fathollahzadeh¹⁵⁸, A. Favareto^{89a,89b}, L. Fayard¹¹⁵,
S. Fazio^{36a,36b}, R. Febbraro³³, P. Federic^{144a},
O.L. Fedin¹²¹, W. Fedorko⁸⁸, M. Fehling-Kaschek⁴⁸,
L. Feligioni⁸³, D. Fellmann⁵, C. Feng^{32d}, E.J. Feng³⁰,
A.B. Fenyuk¹²⁸, J. Ferencei^{144b}, W. Fernando⁵,
S. Ferrag⁵³, J. Ferrando⁵³, V. Ferrara⁴¹, A. Ferrari¹⁶⁶,
P. Ferrari¹⁰⁵, R. Ferrari^{119a}, D.E. Ferreira de Lima⁵³,
A. Ferrer¹⁶⁷, D. Ferrere⁴⁹, C. Ferretti⁸⁷,
A. Ferretto Parodi^{50a,50b}, M. Fiassaric³⁰, F. Fiedler⁸¹,
A. Filipčić⁷⁴, F. Filthaut¹⁰⁴, M. Fincke-Keeler¹⁶⁹,
M.C.N. Fiolhais^{124a,h}, L. Fiorini¹⁶⁷, A. Firan³⁹,
G. Fischer⁴¹, M.J. Fisher¹⁰⁹, M. Flechl⁴⁸, I. Fleck¹⁴¹,
J. Fleckner⁸¹, P. Fleischmann¹⁷⁴, S. Fleischmann¹⁷⁵,
T. Flick¹⁷⁵, A. Floderus⁷⁹, L.R. Flores Castillo¹⁷³,
M.J. Flowerdew⁹⁹, T. Fonseca Martin¹⁶,
A. Formica¹³⁶, A. Forti⁸², D. Fortin^{159a},
D. Fournier¹¹⁵, H. Fox⁷¹, P. Francavilla¹¹,
S. Franchino^{119a,119b}, D. Francis²⁹, T. Frank¹⁷²,
S. Franz²⁹, M. Fraternali^{119a,119b}, S. Fratina¹²⁰,
S.T. French²⁷, C. Friedrich⁴¹, F. Friedrich⁴³,
R. Froeschl²⁹, D. Froidevaux²⁹, J.A. Frost²⁷,
C. Fukunaga¹⁵⁶, E. Fullana Torregrosa²⁹,
B.G. Fulsom¹⁴³, J. Fuster¹⁶⁷, C. Gabaldon²⁹,
O. Gabizon¹⁷², T. Gadfort²⁴, S. Gadomski⁴⁹,
G. Gagliardi^{50a,50b}, P. Gagnon⁶⁰, C. Galea⁹⁸,
E.J. Gallas¹¹⁸, V. Gallo¹⁶, B.J. Gallop¹²⁹,
P. Gallus¹²⁵, K.K. Gan¹⁰⁹, Y.S. Gao^{143,e},
A. Gaponenko¹⁴, F. Garbersson¹⁷⁶,
M. Garcia-Sciveres¹⁴, C. García¹⁶⁷, J.E. García
Navarro¹⁶⁷, R.W. Gardner³⁰, N. Garelli²⁹,
H. Garitaonandia¹⁰⁵, V. Garonne²⁹, J. Garvey¹⁷,
C. Gatti⁴⁷, G. Gaudio^{119a}, B. Gaur¹⁴¹, L. Gauthier¹³⁶,
P. Gauzzi^{132a,132b}, I.L. Gavrilenko⁹⁴, C. Gay¹⁶⁸,
G. Gaycken²⁰, E.N. Gazis⁹, P. Ge^{32d}, Z. Gecse¹⁶⁸,
C.N.P. Gee¹²⁹, D.A.A. Geerts¹⁰⁵, Ch. Geich-Gimbel²⁰,
K. Gellerstedt^{146a,146b}, C. Gemme^{50a}, A. Gemmell⁵³,
M.H. Genest⁵⁵, S. Gentile^{132a,132b}, M. George⁵⁴,
S. George⁷⁶, P. Gerlach¹⁷⁵, A. Gershon¹⁵³,
C. Geweniger^{58a}, H. Ghazlane^{135b}, N. Ghodbane³³,
B. Giacobbe^{19a}, S. Giagu^{132a,132b},
V. Giakoumopoulou⁸, V. Giangiobbe¹¹, F. Gianotti²⁹,
B. Gibbard²⁴, A. Gibson¹⁵⁸, S.M. Gibson²⁹,
D. Gillberg²⁸, A.R. Gillman¹²⁹, D.M. Gingrich^{2,d},
J. Ginzburg¹⁵³, N. Giokaris⁸, M.P. Giordani^{164c},
R. Giordano^{102a,102b}, F.M. Giorgi¹⁵, P. Giovannini⁹⁹,
P.F. Giraud¹³⁶, D. Giugni^{89a}, M. Giunta⁹³,
P. Giusti^{19a}, B.K. Gjelsten¹¹⁷, L.K. Gladilin⁹⁷,
C. Glasman⁸⁰, J. Glatzer⁴⁸, A. Glazov⁴¹,
K.W. Glitza¹⁷⁵, G.L. Glonti⁶⁴, J.R. Goddard⁷⁵,
J. Godfrey¹⁴², J. Godlewski²⁹, M. Goebel⁴¹,
T. Göpfert⁴³, C. Goeringer⁸¹, C. Gössling⁴²,
S. Goldfarb⁸⁷, T. Golling¹⁷⁶, A. Gomes^{124a,b},
L.S. Gomez Fajardo⁴¹, R. Gonçalves⁷⁶,
J. Goncalves Pinto Firmino Da Costa⁴¹, L. Gonella²⁰,
S. Gonzalez¹⁷³, S. González de la Hoz¹⁶⁷,
G. Gonzalez Parra¹¹, M.L. Gonzalez Silva²⁶,
S. Gonzalez-Sevilla⁴⁹, J.J. Goodson¹⁴⁸, L. Goossens²⁹,
P.A. Gorbounov⁹⁵, H.A. Gordon²⁴, I. Gorelov¹⁰³,
G. Gorfine¹⁷⁵, B. Gorini²⁹, E. Gorini^{72a,72b},
A. Gorišek⁷⁴, E. Gornicki³⁸, B. Gosdzik⁴¹,
A.T. Goshaw⁵, M. Gosselink¹⁰⁵, M.I. Gostkin⁶⁴,
I. Gough Eschrich¹⁶³, M. Goughri^{135a},
D. Goujdami^{135c}, M.P. Goulette⁴⁹, A.G. Goussiou¹³⁸,

- C. Goy⁴, S. Gozpınar²², I. Grabowska-Bold³⁷,
P. Grafström²⁹, K.-J. Grahm⁴¹, F. Grancagnolo^{72a},
S. Grancagnolo¹⁵, V. Grassi¹⁴⁸, V. Gratchev¹²¹,
N. Grau³⁴, H.M. Gray²⁹, J.A. Gray¹⁴⁸,
E. Graziani^{134a}, O.G. Grebenyuk¹²¹, T. Greenshaw⁷³,
Z.D. Greenwood^{24,m}, K. Gregersen³⁵, I.M. Gregor⁴¹,
P. Grenier¹⁴³, J. Griffiths¹³⁸, N. Grigalashvili⁶⁴,
A.A. Grillo¹³⁷, S. Grinstein¹¹, Y.V. Grishkevich⁹⁷,
J.-F. Grivaz¹¹⁵, E. Gross¹⁷², J. Grosse-Knetter⁵⁴,
J. Groth-Jensen¹⁷², K. Grybel¹⁴¹, D. Guest¹⁷⁶,
C. Guicheney³³, A. Guida^{72a,72b}, S. Guindon⁵⁴,
U. Gul⁵³, H. Guler^{85,p}, J. Gunther¹²⁵, B. Guo¹⁵⁸,
J. Guo³⁴, P. Gutierrez¹¹¹, N. Guttman¹⁵³,
O. Gutzwiller¹⁷³, C. Guyot¹³⁶, C. Gwenlan¹¹⁸,
C.B. Gwilliam⁷³, A. Haas¹⁴³, S. Haas²⁹, C. Haber¹⁴,
H.K. Hadavand³⁹, D.R. Hadley¹⁷, P. Haefner²⁰,
F. Hahn²⁹, S. Haider²⁹, Z. Hajduk³⁸, H. Hakobyan¹⁷⁷,
D. Hall¹¹⁸, J. Haller⁵⁴, K. Hamacher¹⁷⁵, P. Hamal¹¹³,
M. Hamer⁵⁴, A. Hamilton^{145b,q}, S. Hamilton¹⁶¹,
L. Han^{32b}, K. Hanagaki¹¹⁶, K. Hanawa¹⁶⁰,
M. Hance¹⁴, C. Handel⁸¹, P. Hanke^{58a}, J.R. Hansen³⁵,
J.B. Hansen³⁵, J.D. Hansen³⁵, P.H. Hansen³⁵,
P. Hansson¹⁴³, K. Hara¹⁶⁰, G.A. Hare¹³⁷,
T. Harenberg¹⁷⁵, S. Harkusha⁹⁰, D. Harper⁸⁷,
R.D. Harrington⁴⁵, O.M. Harris¹³⁸, K. Harrison¹⁷,
J. Hartert⁴⁸, F. Hartjes¹⁰⁵, T. Haruyama⁶⁵,
A. Harvey⁵⁶, S. Hasegawa¹⁰¹, Y. Hasegawa¹⁴⁰,
S. Hassani¹³⁶, S. Haug¹⁶, M. Hauschild²⁹,
R. Hauser⁸⁸, M. Havranek²⁰, C.M. Hawkes¹⁷,
R.J. Hawkings²⁹, A.D. Hawkins⁷⁹, D. Hawkins¹⁶³,
T. Hayakawa⁶⁶, T. Hayashi¹⁶⁰, D. Hayden⁷⁶,
C.P. Hays¹¹⁸, H.S. Hayward⁷³, S.J. Haywood¹²⁹,
M. He^{32d}, S.J. Head¹⁷, V. Hedberg⁷⁹, L. Heelan⁷,
S. Heim⁸⁸, B. Heinemann¹⁴, S. Heisterkamp³⁵,
L. Helary⁴, C. Heller⁹⁸, M. Heller²⁹,
S. Hellman^{146a,146b}, D. Hellmich²⁰, C. Helsens¹¹,
R.C.W. Henderson⁷¹, M. Henke^{58a}, A. Henrichs⁵⁴,
A.M. Henriques Correia²⁹, S. Henrot-Versille¹¹⁵,
C. Hensel⁵⁴, T. Henß¹⁷⁵, C.M. Hernandez⁷,
Y. Hernández Jiménez¹⁶⁷, R. Herrberg¹⁵, G. Herten⁴⁸,
R. Hertenberger⁹⁸, L. Hervas²⁹, G.G. Hesketh⁷⁷,
N.P. Hessey¹⁰⁵, E. Higón-Rodríguez¹⁶⁷, J.C. Hill²⁷,
K.H. Hiller⁴¹, S. Hillert²⁰, S.J. Hillier¹⁷,
I. Hinchliffe¹⁴, E. Hines¹²⁰, M. Hirose¹¹⁶, F. Hirsch⁴²,
D. Hirschbuehl¹⁷⁵, J. Hobbs¹⁴⁸, N. Hod¹⁵³,
M.C. Hodgkinson¹³⁹, P. Hodgson¹³⁹, A. Hoecker²⁹,
M.R. Hoefkamp¹⁰³, J. Hoffman³⁹, D. Hoffmann⁸³,
M. Hohlfeld⁸¹, M. Holder¹⁴¹, S.O. Holmgren^{146a},
T. Holy¹²⁷, J.L. Holzbauer⁸⁸, T.M. Hong¹²⁰,
L. Hooft van Huysduynen¹⁰⁸, C. Horn¹⁴³, S. Horner⁴⁸,
J.-Y. Hostachy⁵⁵, S. Hou¹⁵¹, A. Hoummada^{135a},
J. Howard¹¹⁸, J. Howarth⁸², I. Hristova¹⁵,
J. Hrivnac¹¹⁵, T. Hryn'ova⁴, P.J. Hsu⁸¹, S.-C. Hsu¹⁴,
Z. Hubacek¹²⁷, F. Hubaut⁸³, F. Huegging²⁰,
A. Huettmann⁴¹, T.B. Huffman¹¹⁸, E.W. Hughes³⁴,
G. Hughes⁷¹, M. Huhtinen²⁹, M. Hurwitz¹⁴,
U. Husemann⁴¹, N. Huseynov^{64,r}, J. Huston⁸⁸,
J. Huth⁵⁷, G. Iacobucci⁴⁹, G. Iakovidis⁹,
M. Ibbotson⁸², I. Ibragimov¹⁴¹,
L. Iconomidou-Fayard¹¹⁵, J. Idarraga¹¹⁵, P. Iengo^{102a},
O. Igonkina¹⁰⁵, Y. Ikegami⁶⁵, M. Ikeno⁶⁵,
D. Iliadis¹⁵⁴, N. Ilic¹⁵⁸, T. Ince²⁰, J. Inigo-Golfin²⁹,
P. Ioannou⁸, M. Iodice^{134a}, K. Iordanidou⁸,
V. Ippolito^{132a,132b}, A. Irles Quiles¹⁶⁷, C. Isaksson¹⁶⁶,
A. Ishikawa⁶⁶, M. Ishino⁶⁷, R. Ishmukhametov³⁹,
C. Issever¹¹⁸, S. Istina^{18a}, A.V. Ivashin¹²⁸,
W. Iwanski³⁸, H. Iwasaki⁶⁵, J.M. Izen⁴⁰, V. Izzo^{102a},
B. Jackson¹²⁰, J.N. Jackson⁷³, P. Jackson¹⁴³,
M.R. Jaekel²⁹, V. Jain⁶⁰, K. Jakobs⁴⁸, S. Jakobsen³⁵,
T. Jakoubek¹²⁵, J. Jakubek¹²⁷, D.K. Jana¹¹¹,
E. Jansen⁷⁷, H. Jansen²⁹, A. Jantsch⁹⁹, M. Janus⁴⁸,
G. Jarlskog⁷⁹, L. Jeanty⁵⁷, I. Jen-La Plante³⁰,
P. Jenni²⁹, A. Jeremie⁴, P. Jez³⁵, S. Jézéquel⁴,
M.K. Jha^{19a}, H. Ji¹⁷³, W. Ji⁸¹, J. Jia¹⁴⁸, Y. Jiang^{32b},
M. Jimenez Belenguer⁴¹, S. Jin^{32a}, O. Jinnouchi¹⁵⁷,
M.D. Joergensen³⁵, D. Joffe³⁹, M. Johansen^{146a,146b},
K.E. Johansson^{146a}, P. Johansson¹³⁹, S. Johnert⁴¹,
K.A. Johns⁶, K. Jon-And^{146a,146b}, G. Jones¹⁷⁰,
R.W.L. Jones⁷¹, T.J. Jones⁷³, C. Joram²⁹,
P.M. Jorge^{124a}, K.D. Joshi⁸², J. Jovicevic¹⁴⁷,
T. Jovin^{12b}, X. Ju¹⁷³, C.A. Jung⁴², R.M. Jungst²⁹,
V. Juranek¹²⁵, P. Jussel⁶¹, A. Juste Rozas¹¹,
S. Kabana¹⁶, M. Kaci¹⁶⁷, A. Kaczmarska³⁸,
P. Kadlecik³⁵, M. Kado¹¹⁵, H. Kagan¹⁰⁹, M. Kagan⁵⁷,
E. Kajomovitz¹⁵², S. Kalinin¹⁷⁵, L.V. Kalinovskaya⁶⁴,
S. Kama³⁹, N. Kanaya¹⁵⁵, M. Kaneda²⁹, S. Kaneti²⁷,
T. Kanno¹⁵⁷, V.A. Kantserov⁹⁶, J. Kanzaki⁶⁵,
B. Kaplan¹⁷⁶, A. Kapliy³⁰, J. Kaplon²⁹, D. Kar⁵³,
M. Karagounis²⁰, K. Karakostas⁹, M. Karnevskiy⁴¹,
V. Kartvelishvili⁷¹, A.N. Karyukhin¹²⁸, L. Kashif¹⁷³,
G. Kasieczka^{58b}, R.D. Kass¹⁰⁹, A. Kastanas¹³,
M. Kataoka⁴, Y. Kataoka¹⁵⁵, E. Katsoufis⁹,
J. Katzy⁴¹, V. Kaushik⁶, K. Kawagoe⁶⁹,
T. Kawamoto¹⁵⁵, G. Kawamura⁸¹, M.S. Kay¹⁰⁵,
V.A. Kazanin¹⁰⁷, M.Y. Kazarinov⁶⁴, R. Keeler¹⁶⁹,
R. Kehoe³⁹, M. Keil⁵⁴, G.D. Kekelidze⁶⁴,
J.S. Keller¹³⁸, M. Kenyon⁵³, O. Kepka¹²⁵,
N. Kerschen²⁹, B.P. Kerševan⁷⁴, S. Kersten¹⁷⁵,
K. Kessoku¹⁵⁵, J. Keung¹⁵⁸, F. Khalil-zada¹⁰,
H. Khandanyan¹⁶⁵, A. Khanov¹¹², D. Kharchenko⁶⁴,
A. Khodinov⁹⁶, A. Khomich^{58a}, T.J. Khoo²⁷,
G. Khorauli²⁰, A. Khoroshilov¹⁷⁵, V. Khovanskiy⁹⁵,
E. Khramov⁶⁴, J. Khubua^{51b}, H. Kim^{146a,146b},
M.S. Kim², S.H. Kim¹⁶⁰, N. Kimura¹⁷¹, O. Kind¹⁵,
B.T. King⁷³, M. King⁶⁶, R.S.B. King¹¹⁸, J. Kirk¹²⁹,
A.E. Kiryunin⁹⁹, T. Kishimoto⁶⁶, D. Kisielewska³⁷,

- T. Kittelmann¹²³, E. Kladiva^{144b}, M. Klein⁷³,
 U. Klein⁷³, K. Kleinknecht⁸¹, M. Klemetti⁸⁵,
 A. Klier¹⁷², P. Klimek^{146a,146b}, A. Klimentov²⁴,
 R. Klingenberg⁴², J.A. Klinger⁸², E.B. Klinkby³⁵,
 T. Klioutchnikova²⁹, P.F. Klok¹⁰⁴, S. Klous¹⁰⁵,
 E.-E. Kluge^{58a}, T. Kluge⁷³, P. Kluit¹⁰⁵, S. Kluth⁹⁹,
 N.S. Knecht¹⁵⁸, E. Kneringer⁶¹, E.B.F.G. Knoops⁸³,
 A. Knue⁵⁴, B.R. Ko⁴⁴, T. Kobayashi¹⁵⁵, M. Kobel⁴³,
 M. Kocian¹⁴³, P. Kodys¹²⁶, K. Köneke²⁹,
 A.C. König¹⁰⁴, S. Koenig⁸¹, L. Köpke⁸¹,
 F. Koetsveld¹⁰⁴, P. Koevesarki²⁰, T. Koffas²⁸,
 E. Koffeman¹⁰⁵, L.A. Kogan¹¹⁸, S. Kohlmann¹⁷⁵,
 F. Kohn⁵⁴, Z. Kohout¹²⁷, T. Kohriki⁶⁵, T. Koi¹⁴³,
 G.M. Kolachev¹⁰⁷, H. Kolanoski¹⁵, V. Kolesnikov⁶⁴,
 I. Koletsou^{89a}, J. Koll⁸⁸, M. Kollefrath⁴⁸,
 A.A. Komar⁹⁴, Y. Komori¹⁵⁵, T. Kondo⁶⁵,
 T. Kono^{41,s}, A.I. Kononov⁴⁸, R. Konoplich^{108,t},
 N. Konstantinidis⁷⁷, S. Koperny³⁷, K. Korcyl³⁸,
 K. Kordas¹⁵⁴, A. Korn¹¹⁸, A. Korol¹⁰⁷, I. Korolkov¹¹,
 E.V. Korolkova¹³⁹, V.A. Korotkov¹²⁸, O. Kortner⁹⁹,
 S. Kortner⁹⁹, V.V. Kostyukhin²⁰, S. Kotov⁹⁹,
 V.M. Kotov⁶⁴, A. Kotwal⁴⁴, C. Kourkoulis⁸,
 V. Kouskoura¹⁵⁴, A. Koutsman^{159a}, R. Kowalewski¹⁶⁹,
 T.Z. Kowalski³⁷, W. Kozanecki¹³⁶, A.S. Kozhin¹²⁸,
 V. Kral¹²⁷, V.A. Kramarenko⁹⁷, G. Kramberger⁷⁴,
 M.W. Krasny⁷⁸, A. Krasznahorkay¹⁰⁸, J. Kraus⁸⁸,
 J.K. Kraus²⁰, S. Kreiss¹⁰⁸, F. Krejci¹²⁷,
 J. Kretzschmar⁷³, N. Krieger⁵⁴, P. Krieger¹⁵⁸,
 K. Kroeninger⁵⁴, H. Kroha⁹⁹, J. Kroll¹²⁰,
 J. Kroseberg²⁰, J. Krstic^{12a}, U. Kruchonak⁶⁴,
 H. Krüger²⁰, T. Kruker¹⁶, N. Krumnack⁶³,
 Z.V. Krumshteyn⁶⁴, A. Kruth²⁰, T. Kubota⁸⁶,
 S. Kудay^{3a}, S. Kuehn⁴⁸, A. Kugel^{58c}, T. Kuhl⁴¹,
 D. Kuhn⁶¹, V. Kukhtin⁶⁴, Y. Kulchitsky⁹⁰,
 S. Kuleshov^{31b}, C. Kummer⁹⁸, M. Kuna⁷⁸,
 J. Kunkle¹²⁰, A. Kupco¹²⁵, H. Kurashige⁶⁶,
 M. Kurata¹⁶⁰, Y.A. Kurochkin⁹⁰, V. Kus¹²⁵,
 E.S. Kuwertz¹⁴⁷, M. Kuze¹⁵⁷, J. Kvita¹⁴², R. Kwee¹⁵,
 A. La Rosa⁴⁹, L. La Rotonda^{36a,36b}, L. Labarga⁸⁰,
 J. Labbe⁴, S. Lablak^{135a}, C. Lacasta¹⁶⁷,
 F. Lacava^{132a,132b}, H. Lacker¹⁵, D. Lacour⁷⁸,
 V.R. Lacuesta¹⁶⁷, E. Ladygin⁶⁴, R. Lafaye⁴,
 B. Laforge⁷⁸, T. Lagouri⁸⁰, S. Lai⁴⁸, E. Laisne⁵⁵,
 M. Lamanna²⁹, L. Lambourne⁷⁷, C.L. Lampen⁶,
 W. Lampl⁶, E. Lancon¹³⁶, U. Landgraf⁴⁸,
 M.P.J. Landon⁷⁵, J.L. Lane⁸², C. Lange⁴¹,
 A.J. Lankford¹⁶³, F. Lanni²⁴, K. Lantzsche¹⁷⁵,
 S. Laplace⁷⁸, C. Lapoire²⁰, J.F. Laporte¹³⁶,
 T. Lari^{89a}, A. Larnier¹¹⁸, M. Lassnig²⁹, P. Laurelli⁴⁷,
 V. Lavorini^{36a,36b}, W. Lavrijsen¹⁴, P. Laycock⁷³,
 O. Le Dortz⁷⁸, E. Le Guirrec⁸³, C. Le Maner¹⁵⁸,
 E. Le Menedeu¹¹, T. LeCompte⁵, F. Ledroit-Guillon⁵⁵,
 H. Lee¹⁰⁵, J.S.H. Lee¹¹⁶, S.C. Lee¹⁵¹, L. Lee¹⁷⁶,
 M. Lefebvre¹⁶⁹, M. Legendre¹³⁶, B.C. LeGeyt¹²⁰,
 F. Legger⁹⁸, C. Leggett¹⁴, M. Lehmacher²⁰,
 G. Lehmann Miotto²⁹, X. Lei⁶, M.A.L. Leite^{23d},
 R. Leitner¹²⁶, D. Lellouch¹⁷², B. Lemmer⁵⁴,
 V. Lendermann^{58a}, K.J.C. Leney^{145b}, T. Lenz¹⁰⁵,
 G. Lenzen¹⁷⁵, B. Lenzi²⁹, K. Leonhardt⁴³,
 S. Leontsinis⁹, F. Lepold^{58a}, C. Leroy⁹³,
 J.-R. Lessard¹⁶⁹, C.G. Lester²⁷, C.M. Lester¹²⁰,
 J. Levêque⁴, D. Levin⁸⁷, L.J. Levinson¹⁷²,
 A. Lewis¹¹⁸, G.H. Lewis¹⁰⁸, A.M. Leyko²⁰,
 M. Leyton¹⁵, B. Li⁸³, H. Li^{173,u}, S. Li^{32b,v}, X. Li⁸⁷,
 Z. Liang^{118,w}, H. Liao³³, B. Liberti^{133a}, P. Lichard²⁹,
 M. Lichtnecker⁹⁸, K. Lie¹⁶⁵, W. Liebig¹³,
 C. Limbach²⁰, A. Limosani⁸⁶, M. Limper⁶²,
 S.C. Lin^{151,x}, F. Linde¹⁰⁵, J.T. Linnemann⁸⁸,
 E. Lipeles¹²⁰, A. Lipniacka¹³, T.M. Liss¹⁶⁵,
 D. Lissauer²⁴, A. Lister⁴⁹, A.M. Litke¹³⁷, C. Liu²⁸,
 D. Liu¹⁵¹, H. Liu⁸⁷, J.B. Liu⁸⁷, M. Liu^{32b}, Y. Liu^{32b},
 M. Livan^{119a,119b}, S.S.A. Livermore¹¹⁸, A. Lleres⁵⁵,
 J. Llorente Merino⁸⁰, S.L. Lloyd⁷⁵, E. Lobodzinska⁴¹,
 P. Loch⁶, W.S. Lockman¹³⁷, T. Loddienkoetter²⁰,
 F.K. Loebinger⁸², A. Loginov¹⁷⁶, C.W. Loh¹⁶⁸,
 T. Lohse¹⁵, K. Lohwasser⁴⁸, M. Lokajicek¹²⁵,
 V.P. Lombardo⁴, R.E. Long⁷¹, L. Lopes^{124a},
 D. Lopez Mateos⁵⁷, J. Lorenz⁹⁸,
 N. Lorenzo Martinez¹¹⁵, M. Losada¹⁶², P. Loscutoff¹⁴,
 F. Lo Sterzo^{132a,132b}, M.J. Losty^{159a}, X. Lou⁴⁰,
 A. Lounis¹¹⁵, K.F. Loureiro¹⁶², J. Love²¹, P.A. Love⁷¹,
 A.J. Lowe^{143,e}, F. Lu^{32a}, H.J. Lubatti¹³⁸,
 C. Luci^{132a,132b}, A. Lucotte⁵⁵, A. Ludwig⁴³,
 D. Ludwig⁴¹, I. Ludwig⁴⁸, J. Ludwig⁴⁸, F. Luehring⁶⁰,
 G. Luijckx¹⁰⁵, W. Lukas⁶¹, D. Lumb⁴⁸,
 L. Luminari^{132a}, E. Lund¹¹⁷, B. Lund-Jensen¹⁴⁷,
 B. Lundberg⁷⁹, J. Lundberg^{146a,146b}, J. Lundquist³⁵,
 M. Lungwitz⁸¹, D. Lynn²⁴, E. Lytken⁷⁹, H. Ma²⁴,
 L.L. Ma¹⁷³, J.A. Macana Goia⁹³, G. Maccarrone⁴⁷,
 A. Macchiolo⁹⁹, B. Maček⁷⁴, J. Machado Miguens^{124a},
 R. Mackeprang³⁵, R.J. Madaras¹⁴, W.F. Mader⁴³,
 R. Maenner^{58c}, T. Maeno²⁴, P. Mättig¹⁷⁵, S. Mättig⁴¹,
 L. Magnoni²⁹, E. Magradze⁵⁴, K. Mahboubi⁴⁸,
 S. Mahmoud⁷³, G. Mahout¹⁷, C. Maiani¹³⁶,
 C. Maidantchik^{23a}, A. Maio^{124a,b}, S. Majewski²⁴,
 Y. Makida⁶⁵, N. Makovec¹¹⁵, P. Mal¹³⁶,
 B. Malaescu²⁹, Pa. Malecki³⁸, P. Malecki³⁸,
 V.P. Maleev¹²¹, F. Malek⁵⁵, U. Mallik⁶², D. Malon⁵,
 C. Malone¹⁴³, S. Maltezos⁹, V. Malyshev¹⁰⁷,
 S. Malyukov²⁹, R. Mameghani⁹⁸, J. Mamuzic^{12b},
 A. Manabe⁶⁵, L. Mandelli^{89a}, I. Mandić⁷⁴,
 R. Mandrysch¹⁵, J. Maneira^{124a}, P.S. Mangeard⁸⁸,
 L. Manhaes de Andrade Filho^{23a}, A. Mann⁵⁴,
 P.M. Manning¹³⁷, A. Manousakis-Katsikakis⁸,
 B. Mansoulie¹³⁶, A. Mapelli²⁹, L. Mapelli²⁹,
 L. March⁸⁰, J.F. Marchand²⁸, F. Marchese^{133a,133b},

- G. Marchiori⁷⁸, M. Marcisovsky¹²⁵, C.P. Marino¹⁶⁹,
 F. Marroquim^{23a}, Z. Marshall²⁹, F.K. Martens¹⁵⁸,
 S. Marti-Garcia¹⁶⁷, B. Martin²⁹, B. Martin⁸⁸,
 J.P. Martin⁹³, T.A. Martin¹⁷, V.J. Martin⁴⁵,
 B. Martin dit Latour⁴⁹, S. Martin-Haugh¹⁴⁹,
 M. Martinez¹¹, V. Martinez Outschoorn⁵⁷,
 A.C. Martyniuk¹⁶⁹, M. Marx⁸², F. Marzano^{132a},
 A. Marzin¹¹¹, L. Masetti⁸¹, T. Mashimo¹⁵⁵,
 R. Mashinistov⁹⁴, J. Masik⁸², A.L. Maslennikov¹⁰⁷,
 I. Massa^{19a,19b}, G. Massaro¹⁰⁵, N. Massol⁴,
 A. Mastroberardino^{36a,36b}, T. Masubuchi¹⁵⁵,
 P. Matricon¹¹⁵, H. Matsunaga¹⁵⁵, T. Matsushita⁶⁶,
 C. Mattravers^{118,c}, J. Maurer⁸³, S.J. Maxfield⁷³,
 A. Mayne¹³⁹, R. Mazini¹⁵¹, M. Mazur²⁰,
 L. Mazzaferro^{133a,133b}, M. Mazzanti^{89a},
 S.P. Mc Kee⁸⁷, A. McCarn¹⁶⁵, R.L. McCarthy¹⁴⁸,
 T.G. McCarthy²⁸, N.A. McCubbin¹²⁹,
 K.W. McFarlane⁵⁶, J.A. Mcfayden¹³⁹, H. McGlone⁵³,
 G. Mchedlidze^{51b}, T. McLaughlan¹⁷, S.J. McMahon¹²⁹,
 R.A. McPherson^{169,k}, A. Meade⁸⁴, J. Mechnich¹⁰⁵,
 M. Mechtel¹⁷⁵, M. Medinnis⁴¹, R. Meera-Lebbai¹¹¹,
 T. Meguro¹¹⁶, R. Mehdiyev⁹³, S. Mehlhase³⁵,
 A. Mehta⁷³, K. Meier^{58a}, B. Meirose⁷⁹,
 C. Melachrinou³⁰, B.R. Mellado Garcia¹⁷³,
 F. Meloni^{89a,89b}, L. Mendoza Navas¹⁶², Z. Meng^{151,u},
 A. Mengarelli^{19a,19b}, S. Menke⁹⁹, E. Meoni¹⁶¹,
 K.M. Mercurio⁵⁷, P. Mermoud⁴⁹, L. Merola^{102a,102b},
 C. Meroni^{89a}, F.S. Merritt³⁰, H. Merritt¹⁰⁹,
 A. Messina^{29,y}, J. Metcalfe¹⁰³, A.S. Mete¹⁶³,
 C. Meyer⁸¹, C. Meyer³⁰, J-P. Meyer¹³⁶, J. Meyer¹⁷⁴,
 J. Meyer⁵⁴, T.C. Meyer²⁹, W.T. Meyer⁶³, J. Miao^{32d},
 S. Michal²⁹, L. Micu^{25a}, R.P. Middleton¹²⁹,
 S. Migas⁷³, L. Mijović⁴¹, G. Mikenberg¹⁷²,
 M. Mikestikova¹²⁵, M. Mikuz⁷⁴, D.W. Miller³⁰,
 R.J. Miller⁸⁸, W.J. Mills¹⁶⁸, C. Mills⁵⁷, A. Milov¹⁷²,
 D.A. Milstead^{146a,146b}, D. Milstein¹⁷²,
 A.A. Minaenko¹²⁸, M. Miñano Moya¹⁶⁷,
 I.A. Minashvili⁶⁴, A.I. Mincer¹⁰⁸, B. Mindur³⁷,
 M. Mineev⁶⁴, Y. Ming¹⁷³, L.M. Mir¹¹,
 G. Mirabelli^{132a}, J. Mitrevski¹³⁷, V.A. Mitsou¹⁶⁷,
 S. Mitsui⁶⁵, P.S. Miyagawa¹³⁹, K. Miyazaki⁶⁶,
 J.U. Mjörnmark⁷⁹, T. Moa^{146a,146b}, V. Moeller²⁷,
 K. Mönig⁴¹, N. Möser²⁰, S. Mohapatra¹⁴⁸, W. Mohr⁴⁸,
 R. Moles-Valls¹⁶⁷, J. Molina-Perez²⁹, J. Monk⁷⁷,
 E. Monnier⁸³, S. Montesano^{89a,89b}, F. Monticelli⁷⁰,
 S. Monzani^{19a,19b}, R.W. Moore², G.F. Moorhead⁸⁶,
 C. Mora Herrera⁴⁹, A. Moraes⁵³, N. Morange¹³⁶,
 J. Morel⁵⁴, G. Morello^{36a,36b}, D. Moreno⁸¹,
 M. Moreno Llácer¹⁶⁷, P. Morettini^{50a},
 M. Morgenstern⁴³, M. Morii⁵⁷, A.K. Morley²⁹,
 G. Mornacchi²⁹, J.D. Morris⁷⁵, L. Morvaj¹⁰¹,
 H.G. Moser⁹⁹, M. Mosidze^{51b}, J. Moss¹⁰⁹,
 R. Mount¹⁴³, E. Mountricha^{9,z}, S.V. Mouraviev⁹⁴,
 E.J.W. Moyse⁸⁴, F. Mueller^{58a}, J. Mueller¹²³,
 K. Mueller²⁰, T.A. Müller⁹⁸, T. Mueller⁸¹,
 D. Muenstermann²⁹, Y. Munwes¹⁵³, W.J. Murray¹²⁹,
 I. Mussche¹⁰⁵, E. Musto^{102a,102b}, A.G. Myagkov¹²⁸,
 M. Myska¹²⁵, J. Nadal¹¹, K. Nagai¹⁶⁰, K. Nagano⁶⁵,
 A. Nagarkar¹⁰⁹, Y. Nagasaka⁵⁹, M. Nagel⁹⁹,
 A.M. Nairz²⁹, Y. Nakahama²⁹, K. Nakamura¹⁵⁵,
 T. Nakamura¹⁵⁵, I. Nakano¹¹⁰, G. Nanava²⁰,
 A. Napier¹⁶¹, R. Narayan^{58b}, M. Nash^{77,c},
 T. Nattermann²⁰, T. Naumann⁴¹, G. Navarro¹⁶²,
 H.A. Neal⁸⁷, P.Yu. Nechaeva⁹⁴, T.J. Neep⁸²,
 A. Negri^{119a,119b}, G. Negri²⁹, S. Nektarijevic⁴⁹,
 A. Nelson¹⁶³, T.K. Nelson¹⁴³, S. Nemecek¹²⁵,
 P. Nemethy¹⁰⁸, A.A. Nepomuceno^{23a}, M. Nessi^{29,aa},
 M.S. Neubauer¹⁶⁵, A. Neusiedl⁸¹, R.M. Neves¹⁰⁸,
 P. Nevski²⁴, P.R. Newman¹⁷, V. Nguyen Thi Hong¹³⁶,
 R.B. Nickerson¹¹⁸, R. Nicolaidou¹³⁶, B. Niquevert²⁹,
 F. Niedercorn¹¹⁵, J. Nielsen¹³⁷, N. Nikiforou³⁴,
 A. Nikiforov¹⁵, V. Nikolaenko¹²⁸, I. Nikolic-Audit⁷⁸,
 K. Nikolics⁴⁹, K. Nikolopoulos²⁴, H. Nilsen⁴⁸,
 P. Nilsson⁷, Y. Ninomiya¹⁵⁵, A. Nisati^{132a},
 T. Nishiyama⁶⁶, R. Nisius⁹⁹, L. Nodulman⁵,
 M. Nomachi¹¹⁶, I. Nomidis¹⁵⁴, M. Nordberg²⁹,
 P.R. Norton¹²⁹, J. Novakova¹²⁶, M. Nozaki⁶⁵,
 L. Nozka¹¹³, I.M. Nugent^{159a}, A.-E. Nuncio-Quiroz²⁰,
 G. Nunes Hanninger⁸⁶, T. Nunnemann⁹⁸, E. Nurse⁷⁷,
 B.J. O'Brien⁴⁵, S.W. O'Neale^{17,*}, D.C. O'Neil¹⁴²,
 V. O'Shea⁵³, L.B. Oakes⁹⁸, F.G. Oakham^{28,d},
 H. Oberlack⁹⁹, J. Ocariz⁷⁸, A. Ochi⁶⁶, S. Oda⁶⁹,
 S. Odaka⁶⁵, J. Odier⁸³, H. Ogren⁶⁰, A. Oh⁸²,
 S.H. Oh⁴⁴, C.C. Ohm^{146a,146b}, T. Ohshima¹⁰¹,
 S. Okada⁶⁶, H. Okawa¹⁶³, Y. Okumura¹⁰¹,
 T. Okuyama¹⁵⁵, A. Olariu^{25a}, A.G. Olchevski⁶⁴,
 S.A. Olivares Pino^{31a}, M. Oliveira^{124a,h},
 D. Oliveira Damazio²⁴, E. Oliver Garcia¹⁶⁷,
 D. Olivito¹²⁰, A. Olszewski³⁸, J. Olszowska³⁸,
 A. Onofre^{124a,ab}, P.U.E. Onyisi³⁰, C.J. Oram^{159a},
 M.J. Oreglia³⁰, Y. Oren¹⁵³, D. Orestano^{134a,134b},
 N. Orlando^{72a,72b}, I. Orlov¹⁰⁷, C. Oropeza Barrera⁵³,
 R.S. Orr¹⁵⁸, B. Osculati^{50a,50b}, R. Ospanov¹²⁰,
 C. Osuna¹¹, G. Otero y Garzon²⁶, J.P. Ottersbach¹⁰⁵,
 M. Ouchrif^{135d}, E.A. Ouellette¹⁶⁹, F. Ould-Saada¹¹⁷,
 A. Ouraou¹³⁶, Q. Ouyang^{32a}, A. Ovcharova¹⁴,
 M. Owen⁸², S. Owen¹³⁹, V.E. Ozcan^{18a}, N. Ozturk⁷,
 A. Pacheco Pages¹¹, C. Padilla Aranda¹¹,
 S. Pagan Griso¹⁴, E. Paganis¹³⁹, F. Paige²⁴, P. Pais⁸⁴,
 K. Pajchel¹¹⁷, G. Palacino^{159b}, C.P. Paleari⁶,
 S. Palestini²⁹, D. Pallin³³, A. Palma^{124a},
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 P. Pani¹⁰⁵, N. Panikashvili⁸⁷, S. Panitkin²⁴,
 D. Pantea^{25a}, A. Papadelis^{146a}, Th.D. Papadopoulou⁹,
 A. Paramonov⁵, D. Paredes Hernandez³³,
 W. Park^{24,ac}, M.A. Parker²⁷, F. Parodi^{50a,50b},

- J.A. Parsons³⁴, U. Parzefall⁴⁸, S. Pashapour⁵⁴,
 E. Pasqualucci^{132a}, S. Passaggio^{50a}, A. Passeri^{134a},
 F. Pastore^{134a,134b}, Fr. Pastore⁷⁶, G. Pásztor^{49,ad},
 S. Pataria¹⁷⁵, N. Patel¹⁵⁰, J.R. Pater⁸²,
 S. Patricelli^{102a,102b}, T. Pauly²⁹, M. Pecsý^{144a},
 M.I. Pedraza Morales¹⁷³, S.V. Peleganchuk¹⁰⁷,
 D. Pelikan¹⁶⁶, H. Peng^{32b}, B. Penning³⁰, A. Penson³⁴,
 J. Penwell⁶⁰, M. Perantoni^{23a}, K. Perez^{34,ae},
 T. Perez Cavalcanti⁴¹, E. Perez Codina^{159a},
 M.T. Pérez García-Están¹⁶⁷, V. Perez Reale³⁴,
 L. Perini^{89a,89b}, H. Pernegger²⁹, R. Perrino^{72a},
 P. Perrodo⁴, S. Persebe^{3a}, V.D. Peshekhonov⁶⁴,
 K. Peters²⁹, B.A. Petersen²⁹, J. Petersen²⁹,
 T.C. Petersen³⁵, E. Petit⁴, A. Petridis¹⁵⁴,
 C. Petridou¹⁵⁴, E. Petrolo^{132a}, F. Petrucci^{134a,134b},
 D. Petschull⁴¹, M. Petteni¹⁴², R. Pezoa^{31b}, A. Phan⁸⁶,
 P.W. Phillips¹²⁹, G. Piacquadio²⁹, A. Picazio⁴⁹,
 E. Piccaro⁷⁵, M. Piccinini^{19a,19b}, S.M. Piec⁴¹,
 R. Piegai²⁶, D.T. Pignotti¹⁰⁹, J.E. Pilcher³⁰,
 A.D. Pilkington⁸², J. Pina^{124a,b},
 M. Pinamonti^{164a,164c}, A. Pinder¹¹⁸, J.L. Pinfold²,
 B. Pinto^{124a}, C. Pizio^{89a,89b}, M. Plamondon¹⁶⁹,
 M.-A. Pleier²⁴, E. Plotnikova⁶⁴, A. Poblaguev²⁴,
 S. Poddar^{58a}, F. Podlyski³³, L. Poggioni¹¹⁵,
 T. Poghosyan²⁰, M. Pohl⁴⁹, F. Polci⁵⁵,
 G. Polesello^{119a}, A. Policicchio^{36a,36b}, A. Polini^{19a},
 J. Poll⁷⁵, V. Polychronakos²⁴, D. Pomeroy²²,
 K. Pommès²⁹, L. Pontecorvo^{132a}, B.G. Pope⁸⁸,
 G.A. Popeneciu^{25a}, D.S. Popovic^{12a}, A. Poppleton²⁹,
 X. Portell Bueso²⁹, G.E. Pospelov⁹⁹, S. Pospisil¹²⁷,
 I.N. Potrap⁹⁹, C.J. Potter¹⁴⁹, C.T. Potter¹¹⁴,
 G. Poulard²⁹, J. Poveda⁶⁰, V. Pozdnyakov⁶⁴,
 R. Prabhu⁷⁷, P. Pralavorio⁸³, A. Pranko¹⁴,
 S. Prasad²⁹, R. Pravahan²⁴, S. Prell⁶³, K. Pretzl¹⁶,
 D. Price⁶⁰, J. Price⁷³, L.E. Price⁵, D. Prieur¹²³,
 M. Primavera^{72a}, K. Prokofiev¹⁰⁸, F. Prokoshin^{31b},
 S. Protopopescu²⁴, J. Proudfoot⁵, X. Prudent⁴³,
 M. Przybycien³⁷, H. Przysiecki⁴, S. Psoroulas²⁰,
 E. Ptacek¹¹⁴, E. Pueschel⁸⁴, J. Purdham⁸⁷,
 M. Purohit^{24,ac}, P. Puze¹¹⁵, Y. Pylypchenko⁶²,
 J. Qian⁸⁷, A. Quadt⁵⁴, D.R. Quarrie¹⁴,
 W.B. Quayle¹⁷³, F. Quinonez^{31a}, M. Raas¹⁰⁴,
 V. Radescu⁴¹, P. Radloff¹¹⁴, T. Rador^{18a},
 F. Ragusa^{89a,89b}, G. Rahal¹⁷⁸, A.M. Rahimi¹⁰⁹,
 D. Rahm²⁴, S. Rajagopalan²⁴, M. Rammensee⁴⁸,
 M. Rammes¹⁴¹, A.S. Randle-Conde³⁹,
 K. Randrianarivony²⁸, F. Rauscher⁹⁸, T.C. Rave⁴⁸,
 M. Raymond²⁹, A.L. Read¹¹⁷, D.M. Rebuzzi^{119a,119b},
 A. Redelbach¹⁷⁴, G. Redlinger²⁴, R. Reece¹²⁰,
 K. Reeves⁴⁰, E. Reinherz-Aronis¹⁵³, A. Reinsch¹¹⁴,
 I. Reisinger⁴², C. Rembser²⁹, Z.L. Ren¹⁵¹,
 A. Renaud¹¹⁵, M. Rescigno^{132a}, S. Resconi^{89a},
 B. Resende¹³⁶, P. Reznicek⁹⁸, R. Rezvani¹⁵⁸,
 R. Richter⁹⁹, E. Richter-Was^{4,af}, M. Ridel⁷⁸,
 M. Rijpstra¹⁰⁵, M. Rijssenbeek¹⁴⁸, A. Rimoldi^{119a,119b},
 L. Rinaldi^{19a}, R.R. Rios³⁹, I. Riu¹¹,
 G. Rivoltella^{89a,89b}, F. Rizatdinova¹¹², E. Rizvi⁷⁵,
 S.H. Robertson^{85,k}, A. Robichaud-Veronneau¹¹⁸,
 D. Robinson²⁷, J.E.M. Robinson⁷⁷, A. Robson⁵³,
 J.G. Rocha de Lima¹⁰⁶, C. Roda^{122a,122b},
 D. Roda Dos Santos²⁹, A. Roe⁵⁴, S. Roe²⁹,
 O. Røhne¹¹⁷, S. Rolli¹⁶¹, A. Romaniouk⁹⁶,
 M. Romano^{19a,19b}, G. Romeo²⁶, E. Romero Adam¹⁶⁷,
 L. Roos⁷⁸, E. Ros¹⁶⁷, S. Rosati^{132a}, K. Rosbach⁴⁹,
 A. Rose¹⁴⁹, M. Rose⁷⁶, G.A. Rosenbaum¹⁵⁸,
 E.I. Rosenberg⁶³, P.L. Rosendahl¹³, O. Rosenthal¹⁴¹,
 L. Rosselet⁴⁹, V. Rossetti¹¹, E. Rossi^{132a,132b},
 L.P. Rossi^{50a}, M. Rotaru^{25a}, I. Roth¹⁷²,
 J. Rothberg¹³⁸, D. Rousseau¹¹⁵, C.R. Royon¹³⁶,
 A. Rozanov⁸³, Y. Rozen¹⁵², X. Ruan^{32a,ag},
 F. Rubbo¹¹, I. Rubinskiy⁴¹, B. Ruckert⁹⁸,
 N. Ruckstuhl¹⁰⁵, V.I. Rud⁹⁷, C. Rudolph⁴³,
 G. Rudolph⁶¹, F. Rühr⁶, F. Ruggieri^{134a,134b},
 A. Ruiz-Martinez⁶³, L. Rumyantsev⁶⁴, Z. Rurikova⁴⁸,
 N.A. Rusakovich⁶⁴, J.P. Rutherford⁶, C. Ruwiedel¹⁴,
 P. Ruzicka¹²⁵, Y.F. Ryabov¹²¹, P. Ryan⁸⁸,
 M. Rybar¹²⁶, G. Rybkin¹¹⁵, N.C. Ryder¹¹⁸,
 A.F. Saavedra¹⁵⁰, I. Sadeh¹⁵³, H.F.W. Sadrozinski¹³⁷,
 R. Sadykov⁶⁴, F. Safai Tehrani^{132a}, H. Sakamoto¹⁵⁵,
 G. Salamanna⁷⁵, A. Salamon^{133a}, M. Saleem¹¹¹,
 D. Salek²⁹, D. Salihagic⁹⁹, A. Salnikov¹⁴³, J. Salt¹⁶⁷,
 B.M. Salvachua Ferrando⁵, D. Salvatore^{36a,36b},
 F. Salvatore¹⁴⁹, A. Salvucci¹⁰⁴, A. Salzburger²⁹,
 D. Sampsonidis¹⁵⁴, B.H. Samset¹¹⁷,
 A. Sanchez^{102a,102b}, V. Sanchez Martinez¹⁶⁷,
 H. Sandaker¹³, H.G. Sander⁸¹, M.P. Sanders⁹⁸,
 M. Sandhoff¹⁷⁵, T. Sandoval²⁷, C. Sandoval¹⁶²,
 R. Sandstroem⁹⁹, D.P.C. Sankey¹²⁹, A. Sansoni⁴⁷,
 C. Santamarina Rios⁸⁵, C. Santoni³³,
 R. Santonico^{133a,133b}, H. Santos^{124a}, J.G. Saraiva^{124a},
 T. Sarangi¹⁷³, E. Sarkisyan-Grinbaum⁷,
 F. Sarri^{122a,122b}, G. Sartisohn¹⁷⁵, O. Sasaki⁶⁵,
 N. Sasao⁶⁷, I. Satsounkevitch⁹⁰, G. Sauvage⁴,
 E. Sauvan⁴, J.B. Sauvan¹¹⁵, P. Savard^{158,d},
 V. Savinov¹²³, D.O. Savu²⁹, L. Sawyer^{24,m},
 D.H. Saxon⁵³, J. Saxon¹²⁰, C. Sbarra^{19a},
 A. Sbrizzi^{19a,19b}, O. Scallan⁹³, D.A. Scannicchio¹⁶³,
 M. Scarcella¹⁵⁰, J. Schaarschmidt¹¹⁵, P. Schacht⁹⁹,
 D. Schaefer¹²⁰, U. Schäfer⁸¹, S. Schaepe²⁰,
 S. Schaetzel^{58b}, A.C. Schaffer¹¹⁵, D. Schaile⁹⁸,
 R.D. Schamberger¹⁴⁸, A.G. Schamov¹⁰⁷, V. Scharf^{58a},
 V.A. Schegelsky¹²¹, D. Scheirich⁸⁷, M. Schernau¹⁶³,
 M.I. Scherzer³⁴, C. Schiavi^{50a,50b}, J. Schieck⁹⁸,
 M. Schioppa^{36a,36b}, S. Schlenker²⁹, E. Schmidt⁴⁸,
 K. Schmieden²⁰, C. Schmitt⁸¹, S. Schmitt^{58b},
 M. Schmitz²⁰, B. Schneider¹⁶, U. Schnoor⁴³,

- A. Schöning^{58b}, A.L.S. Schorlemmer⁵⁴, M. Schott²⁹,
D. Schouten^{159a}, J. Schovancova¹²⁵, M. Schram⁸⁵,
C. Schroeder⁸¹, N. Schroer^{58c}, M.J. Schultens²⁰,
J. Schultes¹⁷⁵, H.-C. Schultz-Coulon^{58a}, H. Schulz¹⁵,
J.W. Schumacher²⁰, M. Schumacher⁴⁸,
B.A. Schumm¹³⁷, Ph. Schune¹³⁶,
C. Schwanenberger⁸², A. Schwartzman¹⁴³,
Ph. Schwemling⁷⁸, R. Schwienhorst⁸⁸, R. Schwierz⁴³,
J. Schwindling¹³⁶, T. Schwindt²⁰, M. Schwoerer⁴,
G. Sciolla²², W.G. Scott¹²⁹, J. Searcy¹¹⁴, G. Sedov⁴¹,
E. Sedykh¹²¹, S.C. Seidel¹⁰³, A. Seiden¹³⁷,
F. Seifert⁴³, J.M. Seixas^{23a}, G. Sekhniadze^{102a},
S.J. Sekula³⁹, K.E. Selbach⁴⁵, D.M. Seliverstov¹²¹,
B. Sellden^{146a}, G. Sellers⁷³, M. Seman^{144b},
N. Semprini-Cesari^{19a,19b}, C. Serfon⁹⁸, L. Serin¹¹⁵,
L. Serkin⁵⁴, R. Seuster⁹⁹, H. Severini¹¹¹, A. Sfyrila²⁹,
E. Shabalina⁵⁴, M. Shamim¹¹⁴, L.Y. Shan^{32a},
J.T. Shank²¹, Q.T. Shao⁸⁶, M. Shapiro¹⁴,
P.B. Shatalov⁹⁵, K. Shaw^{164a,164c}, D. Sherman¹⁷⁶,
P. Sherwood⁷⁷, A. Shibata¹⁰⁸, H. Shichi¹⁰¹,
S. Shimizu²⁹, M. Shimojima¹⁰⁰, T. Shin⁵⁶,
M. Shiyakova⁶⁴, A. Shmeleva⁹⁴, M.J. Shochet³⁰,
D. Short¹¹⁸, S. Shrestha⁶³, E. Shulga⁹⁶, M.A. Shupe⁶,
P. Sicho¹²⁵, A. Sidoti^{132a}, F. Siegert⁴⁸, Dj. Sijacki^{12a},
O. Silbert¹⁷², J. Silva^{124a}, Y. Silver¹⁵³,
D. Silverstein¹⁴³, S.B. Silverstein^{146a}, V. Simak¹²⁷,
O. Simard¹³⁶, Lj. Simic^{12a}, S. Simion¹¹⁵, E. Simioni⁸¹,
B. Simmons⁷⁷, R. Simoniello^{89a,89b}, M. Simonyan³⁵,
P. Sinervo¹⁵⁸, N.B. Sinev¹¹⁴, V. Sipica¹⁴¹,
G. Siragusa¹⁷⁴, A. Sircar²⁴, A.N. Sisakyan⁶⁴,
S.Yu. Sivoklov⁹⁷, J. Sjölin^{146a,146b}, T.B. Sjursen¹³,
L.A. Skinnari¹⁴, H.P. Skottowe⁵⁷, K. Skovpen¹⁰⁷,
P. Skubic¹¹¹, M. Slater¹⁷, T. Slavicek¹²⁷, K. Sliwa¹⁶¹,
V. Smakhtin¹⁷², B.H. Smart⁴⁵, S.Yu. Smirnov⁹⁶,
Y. Smirnov⁹⁶, L.N. Smirnova⁹⁷, O. Smirnova⁷⁹,
B.C. Smith⁵⁷, D. Smith¹⁴³, K.M. Smith⁵³,
M. Smizanska⁷¹, K. Smolek¹²⁷, A.A. Snesarev⁹⁴,
S.W. Snow⁸², J. Snow¹¹¹, S. Snyder²⁴, R. Sobie^{169,k},
J. Sodomka¹²⁷, A. Soffer¹⁵³, C.A. Solans¹⁶⁷,
M. Solar¹²⁷, J. Solc¹²⁷, E.Yu. Soldatov⁹⁶,
U. Soldevila¹⁶⁷, E. Solfaroli Camillocci^{132a,132b},
A.A. Solodkov¹²⁸, O.V. Solovyanov¹²⁸, N. Soni²,
V. Sopko¹²⁷, B. Sopko¹²⁷, M. Sosebee⁷,
R. Soualah^{164a,164c}, A. Soukharev¹⁰⁷,
S. Spagnolo^{72a,72b}, F. Spanò⁷⁶, R. Spighi^{19a},
G. Spigo²⁹, F. Spila^{132a,132b}, R. Spiwoks²⁹,
M. Spousta¹²⁶, T. Spreitzer¹⁵⁸, B. Spurlock⁷,
R.D. St. Denis⁵³, J. Stahlman¹²⁰, R. Stamen^{58a},
E. Stanecka³⁸, R.W. Stanek⁵, C. Stanescu^{134a},
M. Stanescu-Bellu⁴¹, S. Stapnes¹¹⁷,
E.A. Starchenko¹²⁸, J. Stark⁵⁵, P. Staroba¹²⁵,
P. Starovoitov⁴¹, A. Staude⁹⁸, P. Stavina^{144a},
G. Steele⁵³, P. Steinbach⁴³, P. Steinberg²⁴, I. Stekl¹²⁷,
B. Stelzer¹⁴², H.J. Stelzer⁸⁸, O. Stelzer-Chilton^{159a},
H. Stenzel⁵², S. Stern⁹⁹, G.A. Stewart²⁹,
J.A. Stillings²⁰, M.C. Stockton⁸⁵, K. Stoerig⁴⁸,
G. Stoicea^{25a}, S. Stonjek⁹⁹, P. Strachota¹²⁶,
A.R. Stradling⁷, A. Straessner⁴³, J. Strandberg¹⁴⁷,
S. Strandberg^{146a,146b}, A. Strandlie¹¹⁷, M. Strang¹⁰⁹,
E. Strauss¹⁴³, M. Strauss¹¹¹, P. Strizenec^{144b},
R. Ströhmer¹⁷⁴, D.M. Strom¹¹⁴, J.A. Strong^{76,*},
R. Stroynowski³⁹, J. Strube¹²⁹, B. Stugu¹³,
I. Stumer^{24,*}, J. Stupak¹⁴⁸, P. Sturm¹⁷⁵,
N.A. Styles⁴¹, D.A. Soh^{151,w}, D. Su¹⁴³,
H.S. Subramania², A. Succurro¹¹, Y. Sugaya¹¹⁶,
C. Suhr¹⁰⁶, K. Suita⁶⁶, M. Suk¹²⁶, V.V. Sulin⁹⁴,
S. Sultansoy^{3d}, T. Sumida⁶⁷, X. Sun⁵⁵,
J.E. Sundermann⁴⁸, K. Suruliz¹³⁹, G. Susinno^{36a,36b},
M.R. Sutton¹⁴⁹, Y. Suzuki⁶⁵, Y. Suzuki⁶⁶,
M. Svatos¹²⁵, S. Swedish¹⁶⁸, I. Sykora^{144a},
T. Sykora¹²⁶, J. Sánchez¹⁶⁷, D. Ta¹⁰⁵, K. Tackmann⁴¹,
A. Taffard¹⁶³, R. Tafirout^{159a}, N. Taiblum¹⁵³,
Y. Takahashi¹⁰¹, H. Takai²⁴, R. Takashima⁶⁸,
H. Takeda⁶⁶, T. Takeshita¹⁴⁰, Y. Takubo⁶⁵,
M. Talby⁸³, A. Talyshev^{107,f}, M.C. Tamsett²⁴,
J. Tanaka¹⁵⁵, R. Tanaka¹¹⁵, S. Tanaka¹³¹,
S. Tanaka⁶⁵, A.J. Tanasijczuk¹⁴², K. Tani⁶⁶,
N. Tannoury⁸³, S. Tapprogge⁸¹, D. Tardif¹⁵⁸,
S. Tarem¹⁵², F. Tarrade²⁸, G.F. Tartarelli^{89a},
P. Tas¹²⁶, M. Tasevsky¹²⁵, E. Tassi^{36a,36b},
M. Tatarkhanov¹⁴, Y. Tayalati^{135d}, C. Taylor⁷⁷,
F.E. Taylor⁹², G.N. Taylor⁸⁶, W. Taylor^{159b},
M. Teinturier¹¹⁵, M. Teixeira Dias Castanheira⁷⁵,
P. Teixeira-Dias⁷⁶, K.K. Temming⁴⁸, H. Ten Kate²⁹,
P.K. Teng¹⁵¹, S. Terada⁶⁵, K. Terashi¹⁵⁵, J. Terron⁸⁰,
M. Testa⁴⁷, R.J. Teuscher^{158,k}, J. Therhaag²⁰,
T. Theveneaux-Pelzer⁷⁸, S. Thoma⁴⁸, J.P. Thomas¹⁷,
E.N. Thompson³⁴, P.D. Thompson¹⁷,
P.D. Thompson¹⁵⁸, A.S. Thompson⁵³,
L.A. Thomsen³⁵, E. Thomson¹²⁰, M. Thomson²⁷,
R.P. Thun⁸⁷, F. Tian³⁴, M.J. Tibbetts¹⁴, T. Tic¹²⁵,
V.O. Tikhomirov⁹⁴, Y.A. Tikhonov^{107,f},
S. Timoshenko⁹⁶, P. Tipton¹⁷⁶,
F.J. Tique Aires Viegas²⁹, S. Tisserant⁸³,
T. Todorov⁴, S. Todorova-Nova¹⁶¹, B. Toggerson¹⁶³,
J. Tojo⁶⁹, S. Tokár^{144a}, K. Tokunaga⁶⁶,
K. Tokushuku⁶⁵, K. Tollefson⁸⁸, M. Tomoto¹⁰¹,
L. Tompkins³⁰, K. Toms¹⁰³, A. Tonoyan¹³,
C. Topfel¹⁶, N.D. Topilin⁶⁴, I. Torchiani²⁹,
E. Torrence¹¹⁴, H. Torres⁷⁸, E. Torró Pastor¹⁶⁷,
J. Toth^{83,ad}, F. Touchard⁸³, D.R. Tovey¹³⁹,
T. Trefzger¹⁷⁴, L. Tremblet²⁹, A. Tricoli²⁹,
I.M. Trigger^{159a}, S. Trincaz-Duvoid⁷⁸,
M.F. Tripiana⁷⁰, W. Trischuk¹⁵⁸, B. Trocmé⁵⁵,
C. Troncon^{89a}, M. Trottier-McDonald¹⁴²,
M. Trzebinski³⁸, A. Trzupek³⁸, C. Tsarouchas²⁹,

- J.C.-L. Tseng¹¹⁸, M. Tsiakiris¹⁰⁵, P.V. Tsireshka⁹⁰,
D. Tsionou^{4,ah}, G. Tsipolitis⁹, V. Tsiskaridze⁴⁸,
E.G. Tskhadadze^{51a}, I.I. Tsukerman⁹⁵, V. Tsulaia¹⁴,
J.-W. Tsung²⁰, S. Tsuno⁶⁵, D. Tsybychev¹⁴⁸,
A. Tua¹³⁹, A. Tudorache^{25a}, V. Tudorache^{25a},
J.M. Tuggle³⁰, M. Turala³⁸, D. Turecek¹²⁷,
I. Turk Cakir^{3e}, E. Turlay¹⁰⁵, R. Turra^{89a,89b},
P.M. Tuts³⁴, A. Tykhonov⁷⁴, M. Tylmad^{146a,146b},
M. Tyndel¹²⁹, G. Tzanakos⁸, K. Uchida²⁰, I. Ueda¹⁵⁵,
R. Ueno²⁸, M. Ugland¹³, M. Uhlenbrock²⁰,
M. Uhrmacher⁵⁴, F. Ukegawa¹⁶⁰, G. Unal²⁹,
A. Undrus²⁴, G. Unel¹⁶³, Y. Unno⁶⁵, D. Urbaniec³⁴,
G. Usai⁷, M. Uslenghi^{119a,119b}, L. Vacavant⁸³,
V. Vacek¹²⁷, B. Vachon⁸⁵, S. Vahsen¹⁴, J. Valenta¹²⁵,
P. Valente^{132a}, S. Valentinetti^{19a,19b}, S. Valkar¹²⁶,
E. Valladolid Gallego¹⁶⁷, S. Vallecorsa¹⁵²,
J.A. Valls Ferrer¹⁶⁷, H. van der Graaf¹⁰⁵,
E. van der Kraaij¹⁰⁵, R. Van Der Leeuw¹⁰⁵,
E. van der Poel¹⁰⁵, D. van der Ster²⁹, N. van Eldik²⁹,
P. van Gemmeren⁵, I. van Vulpen¹⁰⁵, M. Vanadia⁹⁹,
W. Vandelli²⁹, A. Vaniachine⁵, P. Vankov⁴¹,
F. Vannucci⁷⁸, R. Vari^{132a}, T. Varol⁸⁴,
D. Varouchas¹⁴, A. Vartapetian⁷, K.E. Varvell¹⁵⁰,
V.I. Vassilakopoulos⁵⁶, F. Vazeille³³,
T. Vazquez Schroeder⁵⁴, G. Vegni^{89a,89b},
J.J. Veillet¹¹⁵, F. Veloso^{124a}, R. Veness²⁹,
S. Veneziano^{132a}, A. Ventura^{72a,72b}, D. Ventura⁸⁴,
M. Venturi⁴⁸, N. Venturi¹⁵⁸, V. Vercesi^{119a},
M. Verducci¹³⁸, W. Verkerke¹⁰⁵, J.C. Vermeulen¹⁰⁵,
A. Vest⁴³, M.C. Vetterli^{142,d}, I. Vichou¹⁶⁵,
T. Vickey^{145b,ai}, O.E. Vickey Boeriu^{145b},
G.H.A. Viehhauser¹¹⁸, S. Viel¹⁶⁸, M. Villa^{19a,19b},
M. Villaplana Perez¹⁶⁷, E. Vilucchi⁴⁷, M.G. Vinciter²⁸,
E. Vinek²⁹, V.B. Vinogradov⁶⁴, M. Virchaux^{136,*},
J. Virzi¹⁴, O. Vitells¹⁷², M. Viti⁴¹, I. Vivarelli⁴⁸,
F. Vives Vaque², S. Vlachos⁹, D. Vladoiu⁹⁸,
M. Vlasak¹²⁷, A. Vogel²⁰, P. Vokac¹²⁷, G. Volpi⁴⁷,
M. Volpi⁸⁶, G. Volpini^{89a}, H. von der Schmitt⁹⁹,
J. von Loeben⁹⁹, H. von Radziewski⁴⁸,
E. von Toerne²⁰, V. Vorobel¹²⁶, V. Vorwerk¹¹,
M. Vos¹⁶⁷, R. Voss²⁹, T.T. Voss¹⁷⁵, J.H. Vossebeld⁷³,
N. Vranjes¹³⁶, M. Vranjes Milosavljevic¹⁰⁵, V. Vrba¹²⁵,
M. Vreeswijk¹⁰⁵, T. Vu Anh⁴⁸, R. Vuillemet²⁹,
I. Vukotic¹¹⁵, W. Wagner¹⁷⁵, P. Wagner¹²⁰,
H. Wahlen¹⁷⁵, S. Wahrmund⁴³, J. Wakabayashi¹⁰¹,
S. Walch⁸⁷, J. Walder⁷¹, R. Walker⁹⁸,
W. Walkowiak¹⁴¹, R. Wall¹⁷⁶, P. Waller⁷³, C. Wang⁴⁴,
H. Wang¹⁷³, H. Wang^{32b,aj}, J. Wang¹⁵¹, J. Wang⁵⁵,
R. Wang¹⁰³, S.M. Wang¹⁵¹, T. Wang²⁰,
A. Warburton⁸⁵, C.P. Ward²⁷, M. Warsinsky⁴⁸,
A. Washbrook⁴⁵, C. Wasicki⁴¹, P.M. Watkins¹⁷,
A.T. Watson¹⁷, I.J. Watson¹⁵⁰, M.F. Watson¹⁷,
G. Watts¹³⁸, S. Watts⁸², A.T. Waugh¹⁵⁰,
B.M. Waugh⁷⁷, M. Weber¹²⁹, M.S. Weber¹⁶,
P. Weber⁵⁴, A.R. Weidberg¹¹⁸, P. Weigell⁹⁹,
J. Weingarten⁵⁴, C. Weiser⁴⁸, H. Wellenstein²²,
P.S. Wells²⁹, T. Wenaus²⁴, D. Wendland¹⁵,
Z. Weng^{151,w}, T. Wengler²⁹, S. Wenig²⁹, N. Vermes²⁰,
M. Werner⁴⁸, P. Werner²⁹, M. Werth¹⁶³,
M. Wessels^{58a}, J. Wetter¹⁶¹, C. Weydert⁵⁵,
K. Whalen²⁸, S.J. Wheeler-Ellis¹⁶³, A. White⁷,
M.J. White⁸⁶, S. White^{122a,122b}, S.R. Whitehead¹¹⁸,
D. Whiteson¹⁶³, D. Whittington⁶⁰, F. Wicek¹¹⁵,
D. Wicke¹⁷⁵, F.J. Wickens¹²⁹, W. Wiedenmann¹⁷³,
M. Wielers¹²⁹, P. Wienemann²⁰, C. Wiglesworth⁷⁵,
L.A.M. Wiik-Fuchs⁴⁸, P.A. Wijeratne⁷⁷,
A. Wildauer¹⁶⁷, M.A. Wildt^{41,s}, I. Wilhelm¹²⁶,
H.G. Wilkens²⁹, J.Z. Will⁹⁸, E. Williams³⁴,
H.H. Williams¹²⁰, W. Willis³⁴, S. Willocq⁸⁴,
J.A. Wilson¹⁷, M.G. Wilson¹⁴³, A. Wilson⁸⁷,
I. Wingerter-Seez⁴, S. Winkelmann⁴⁸,
F. Winklmeier²⁹, M. Wittgen¹⁴³, M.W. Wolter³⁸,
H. Wolters^{124a,h}, W.C. Wong⁴⁰, G. Wooden⁸⁷,
B.K. Wosiek³⁸, J. Wotschack²⁹, M.J. Woudstra⁸²,
K.W. Wozniak³⁸, K. Wraight⁵³, C. Wright⁵³,
M. Wright⁵³, B. Wrona⁷³, S.L. Wu¹⁷³, X. Wu⁴⁹,
Y. Wu^{32b,ak}, E. Wulf³⁴, B.M. Wynne⁴⁵, S. Xella³⁵,
M. Xiao¹³⁶, S. Xie⁴⁸, C. Xu^{32b,z}, D. Xu¹³⁹,
B. Yabsley¹⁵⁰, S. Yacoob^{145b}, M. Yamada⁶⁵,
H. Yamaguchi¹⁵⁵, A. Yamamoto⁶⁵, K. Yamamoto⁶³,
S. Yamamoto¹⁵⁵, T. Yamamura¹⁵⁵, T. Yamanaka¹⁵⁵,
J. Yamaoka⁴⁴, T. Yamazaki¹⁵⁵, Y. Yamazaki⁶⁶,
Z. Yan²¹, H. Yang⁸⁷, U.K. Yang⁸², Y. Yang⁶⁰,
Z. Yang^{146a,146b}, S. Yanush⁹¹, L. Yao^{32a}, Y. Yao¹⁴,
Y. Yasu⁶⁵, G.V. Ybeles Smit¹³⁰, J. Ye³⁹, S. Ye²⁴,
M. Yilmaz^{3c}, R. Yoosoofmiya¹²³, K. Yorita¹⁷¹,
R. Yoshida⁵, C. Young¹⁴³, C.J. Young¹¹⁸,
S. Youssef²¹, D. Yu²⁴, J. Yu⁷, J. Yu¹¹², L. Yuan⁶⁶,
A. Yurkewicz¹⁰⁶, B. Zabinski³⁸, R. Zaidan⁶²,
A.M. Zaitsev¹²⁸, Z. Zajacova²⁹, L. Zanello^{132a,132b},
A. Zaytsev¹⁰⁷, C. Zeitnitz¹⁷⁵, M. Zeman¹²⁵,
A. Zemla³⁸, C. Zendler²⁰, O. Zenin¹²⁸, T. Ženiš^{144a},
Z. Zinonos^{122a,122b}, S. Zenz¹⁴, D. Zerwas¹¹⁵,
G. Zevi della Porta⁵⁷, Z. Zhan^{32d}, D. Zhang^{32b,aj},
H. Zhang⁸⁸, J. Zhang⁵, X. Zhang^{32d}, Z. Zhang¹¹⁵,
L. Zhao¹⁰⁸, T. Zhao¹³⁸, Z. Zhao^{32b}, A. Zhemchugov⁶⁴,
J. Zhong¹¹⁸, B. Zhou⁸⁷, N. Zhou¹⁶³, Y. Zhou¹⁵¹,
C.G. Zhu^{32d}, H. Zhu⁴¹, J. Zhu⁸⁷, Y. Zhu^{32b},
X. Zhuang⁹⁸, V. Zhuravlov⁹⁹, D. Zieminska⁶⁰,
N.I. Zimin⁶⁴, R. Zimmermann²⁰, S. Zimmermann²⁰,
S. Zimmermann⁴⁸, M. Ziolkowski¹⁴¹, R. Zitoun⁴,
L. Živković³⁴, V.V. Zmouchko^{128,*}, G. Zobernig¹⁷³,
A. Zoccoli^{19a,19b}, M. zur Nedden¹⁵, V. Zutshi¹⁰⁶,
L. Zwalinski²⁹.

¹ University at Albany, Albany NY, United States of America

² Department of Physics, University of Alberta, Edmonton AB, Canada

³ ^(a)Department of Physics, Ankara University, Ankara; ^(b)Department of Physics, Dumlupinar University, Kutahya; ^(c)Department of Physics, Gazi University, Ankara; ^(d)Division of Physics, TOBB University of Economics and Technology, Ankara; ^(e)Turkish Atomic Energy Authority, Ankara, Turkey

⁴ LAPP, CNRS/IN2P3 and Université de Savoie, Annecy-le-Vieux, France

⁵ High Energy Physics Division, Argonne National Laboratory, Argonne IL, United States of America

⁶ Department of Physics, University of Arizona, Tucson AZ, United States of America

⁷ Department of Physics, The University of Texas at Arlington, Arlington TX, United States of America

⁸ Physics Department, University of Athens, Athens, Greece

⁹ Physics Department, National Technical University of Athens, Zografou, Greece

¹⁰ Institute of Physics, Azerbaijan Academy of Sciences, Baku, Azerbaijan

¹¹ Institut de Física d'Altes Energies and Departament de Física de la Universitat Autònoma de Barcelona and ICREA, Barcelona, Spain

¹² ^(a)Institute of Physics, University of Belgrade, Belgrade; ^(b)Vinca Institute of Nuclear Sciences, University of Belgrade, Belgrade, Serbia

¹³ Department for Physics and Technology, University of Bergen, Bergen, Norway

¹⁴ Physics Division, Lawrence Berkeley National Laboratory and University of California, Berkeley CA, United States of America

¹⁵ Department of Physics, Humboldt University, Berlin, Germany

¹⁶ Albert Einstein Center for Fundamental Physics and Laboratory for High Energy Physics, University of Bern, Bern, Switzerland

¹⁷ School of Physics and Astronomy, University of Birmingham, Birmingham, United Kingdom

¹⁸ ^(a)Department of Physics, Bogazici University, Istanbul; ^(b)Division of Physics, Dogus University, Istanbul; ^(c)Department of Physics Engineering, Gaziantep University, Gaziantep; ^(d)Department of Physics, Istanbul Technical University, Istanbul, Turkey

¹⁹ ^(a)INFN Sezione di Bologna; ^(b)Dipartimento di Fisica, Università di Bologna, Bologna, Italy

²⁰ Physikalisches Institut, University of Bonn, Bonn, Germany

²¹ Department of Physics, Boston University, Boston MA, United States of America

²² Department of Physics, Brandeis University, Waltham MA, United States of America

²³ ^(a)Universidade Federal do Rio De Janeiro COPPE/EE/IF, Rio de Janeiro; ^(b)Federal University of Juiz de Fora (UFJF), Juiz de Fora; ^(c)Federal University of Sao Joao del Rei (UFSJ), Sao Joao del Rei; ^(d)Instituto de Fisica, Universidade de Sao Paulo, Sao Paulo, Brazil

²⁴ Physics Department, Brookhaven National Laboratory, Upton NY, United States of America

²⁵ ^(a)National Institute of Physics and Nuclear Engineering, Bucharest; ^(b)University Politehnica Bucharest, Bucharest; ^(c)West University in Timisoara, Timisoara, Romania

²⁶ Departamento de Física, Universidad de Buenos Aires, Buenos Aires, Argentina

²⁷ Cavendish Laboratory, University of Cambridge, Cambridge, United Kingdom

²⁸ Department of Physics, Carleton University, Ottawa ON, Canada

²⁹ CERN, Geneva, Switzerland

³⁰ Enrico Fermi Institute, University of Chicago, Chicago IL, United States of America

³¹ ^(a)Departamento de Física, Pontificia Universidad Católica de Chile, Santiago; ^(b)Departamento de Física, Universidad Técnica Federico Santa María, Valparaíso, Chile

³² ^(a)Institute of High Energy Physics, Chinese Academy of Sciences, Beijing; ^(b)Department of Modern Physics, University of Science and Technology of China, Anhui; ^(c)Department of Physics, Nanjing University, Jiangsu; ^(d)School of Physics, Shandong University, Shandong, China

³³ Laboratoire de Physique Corpusculaire, Clermont Université and Université Blaise Pascal and CNRS/IN2P3, Aubiere Cedex, France

³⁴ Nevis Laboratory, Columbia University, Irvington NY, United States of America

³⁵ Niels Bohr Institute, University of Copenhagen, Kobenhavn, Denmark

³⁶ ^(a)INFN Gruppo Collegato di Cosenza; ^(b)Dipartimento di Fisica, Università della Calabria, Arcavata di Rende, Italy

³⁷ AGH University of Science and Technology, Faculty of Physics and Applied Computer Science, Krakow, Poland

³⁸ The Henryk Niewodniczanski Institute of Nuclear Physics, Polish Academy of Sciences, Krakow, Poland

³⁹ Physics Department, Southern Methodist University, Dallas TX, United States of America

-
- ⁴⁰ Physics Department, University of Texas at Dallas, Richardson TX, United States of America
- ⁴¹ DESY, Hamburg and Zeuthen, Germany
- ⁴² Institut für Experimentelle Physik IV, Technische Universität Dortmund, Dortmund, Germany
- ⁴³ Institut für Kern- und Teilchenphysik, Technical University Dresden, Dresden, Germany
- ⁴⁴ Department of Physics, Duke University, Durham NC, United States of America
- ⁴⁵ SUPA - School of Physics and Astronomy, University of Edinburgh, Edinburgh, United Kingdom
- ⁴⁶ Fachhochschule Wiener Neustadt, Johannes Gutenbergstrasse 3 2700 Wiener Neustadt, Austria
- ⁴⁷ INFN Laboratori Nazionali di Frascati, Frascati, Italy
- ⁴⁸ Fakultät für Mathematik und Physik, Albert-Ludwigs-Universität, Freiburg i.Br., Germany
- ⁴⁹ Section de Physique, Université de Genève, Geneva, Switzerland
- ⁵⁰ ^(a)INFN Sezione di Genova; ^(b)Dipartimento di Fisica, Università di Genova, Genova, Italy
- ⁵¹ ^(a)E.Andronikashvili Institute of Physics, Tbilisi State University, Tbilisi; ^(b)High Energy Physics Institute, Tbilisi State University, Tbilisi, Georgia
- ⁵² II Physikalisches Institut, Justus-Liebig-Universität Giessen, Giessen, Germany
- ⁵³ SUPA - School of Physics and Astronomy, University of Glasgow, Glasgow, United Kingdom
- ⁵⁴ II Physikalisches Institut, Georg-August-Universität, Göttingen, Germany
- ⁵⁵ Laboratoire de Physique Subatomique et de Cosmologie, Université Joseph Fourier and CNRS/IN2P3 and Institut National Polytechnique de Grenoble, Grenoble, France
- ⁵⁶ Department of Physics, Hampton University, Hampton VA, United States of America
- ⁵⁷ Laboratory for Particle Physics and Cosmology, Harvard University, Cambridge MA, United States of America
- ⁵⁸ ^(a)Kirchhoff-Institut für Physik, Ruprecht-Karls-Universität Heidelberg, Heidelberg; ^(b)Physikalisches Institut, Ruprecht-Karls-Universität Heidelberg, Heidelberg; ^(c)ZITI Institut für technische Informatik, Ruprecht-Karls-Universität Heidelberg, Mannheim, Germany
- ⁵⁹ Faculty of Applied Information Science, Hiroshima Institute of Technology, Hiroshima, Japan
- ⁶⁰ Department of Physics, Indiana University, Bloomington IN, United States of America
- ⁶¹ Institut für Astro- und Teilchenphysik, Leopold-Franzens-Universität, Innsbruck, Austria
- ⁶² University of Iowa, Iowa City IA, United States of America
- ⁶³ Department of Physics and Astronomy, Iowa State University, Ames IA, United States of America
- ⁶⁴ Joint Institute for Nuclear Research, JINR Dubna, Dubna, Russia
- ⁶⁵ KEK, High Energy Accelerator Research Organization, Tsukuba, Japan
- ⁶⁶ Graduate School of Science, Kobe University, Kobe, Japan
- ⁶⁷ Faculty of Science, Kyoto University, Kyoto, Japan
- ⁶⁸ Kyoto University of Education, Kyoto, Japan
- ⁶⁹ Department of Physics, Kyushu University, Fukuoka, Japan
- ⁷⁰ Instituto de Física La Plata, Universidad Nacional de La Plata and CONICET, La Plata, Argentina
- ⁷¹ Physics Department, Lancaster University, Lancaster, United Kingdom
- ⁷² ^(a)INFN Sezione di Lecce; ^(b)Dipartimento di Matematica e Fisica, Università del Salento, Lecce, Italy
- ⁷³ Oliver Lodge Laboratory, University of Liverpool, Liverpool, United Kingdom
- ⁷⁴ Department of Physics, Jožef Stefan Institute and University of Ljubljana, Ljubljana, Slovenia
- ⁷⁵ School of Physics and Astronomy, Queen Mary University of London, London, United Kingdom
- ⁷⁶ Department of Physics, Royal Holloway University of London, Surrey, United Kingdom
- ⁷⁷ Department of Physics and Astronomy, University College London, London, United Kingdom
- ⁷⁸ Laboratoire de Physique Nucléaire et de Hautes Energies, UPMC and Université Paris-Diderot and CNRS/IN2P3, Paris, France
- ⁷⁹ Fysiska institutionen, Lunds universitet, Lund, Sweden
- ⁸⁰ Departamento de Física Teórica C-15, Universidad Autonoma de Madrid, Madrid, Spain
- ⁸¹ Institut für Physik, Universität Mainz, Mainz, Germany
- ⁸² School of Physics and Astronomy, University of Manchester, Manchester, United Kingdom
- ⁸³ CPPM, Aix-Marseille Université and CNRS/IN2P3, Marseille, France
- ⁸⁴ Department of Physics, University of Massachusetts, Amherst MA, United States of America
- ⁸⁵ Department of Physics, McGill University, Montreal QC, Canada
- ⁸⁶ School of Physics, University of Melbourne, Victoria, Australia
- ⁸⁷ Department of Physics, The University of Michigan, Ann Arbor MI, United States of America

-
- ⁸⁸ Department of Physics and Astronomy, Michigan State University, East Lansing MI, United States of America
- ⁸⁹ ^(a)INFN Sezione di Milano; ^(b)Dipartimento di Fisica, Università di Milano, Milano, Italy
- ⁹⁰ B.I. Stepanov Institute of Physics, National Academy of Sciences of Belarus, Minsk, Republic of Belarus
- ⁹¹ National Scientific and Educational Centre for Particle and High Energy Physics, Minsk, Republic of Belarus
- ⁹² Department of Physics, Massachusetts Institute of Technology, Cambridge MA, United States of America
- ⁹³ Group of Particle Physics, University of Montreal, Montreal QC, Canada
- ⁹⁴ P.N. Lebedev Institute of Physics, Academy of Sciences, Moscow, Russia
- ⁹⁵ Institute for Theoretical and Experimental Physics (ITEP), Moscow, Russia
- ⁹⁶ Moscow Engineering and Physics Institute (MEPhI), Moscow, Russia
- ⁹⁷ Skobeltsyn Institute of Nuclear Physics, Lomonosov Moscow State University, Moscow, Russia
- ⁹⁸ Fakultät für Physik, Ludwig-Maximilians-Universität München, München, Germany
- ⁹⁹ Max-Planck-Institut für Physik (Werner-Heisenberg-Institut), München, Germany
- ¹⁰⁰ Nagasaki Institute of Applied Science, Nagasaki, Japan
- ¹⁰¹ Graduate School of Science, Nagoya University, Nagoya, Japan
- ¹⁰² ^(a)INFN Sezione di Napoli; ^(b)Dipartimento di Scienze Fisiche, Università di Napoli, Napoli, Italy
- ¹⁰³ Department of Physics and Astronomy, University of New Mexico, Albuquerque NM, United States of America
- ¹⁰⁴ Institute for Mathematics, Astrophysics and Particle Physics, Radboud University Nijmegen/Nikhef, Nijmegen, Netherlands
- ¹⁰⁵ Nikhef National Institute for Subatomic Physics and University of Amsterdam, Amsterdam, Netherlands
- ¹⁰⁶ Department of Physics, Northern Illinois University, DeKalb IL, United States of America
- ¹⁰⁷ Budker Institute of Nuclear Physics, SB RAS, Novosibirsk, Russia
- ¹⁰⁸ Department of Physics, New York University, New York NY, United States of America
- ¹⁰⁹ Ohio State University, Columbus OH, United States of America
- ¹¹⁰ Faculty of Science, Okayama University, Okayama, Japan
- ¹¹¹ Homer L. Dodge Department of Physics and Astronomy, University of Oklahoma, Norman OK, United States of America
- ¹¹² Department of Physics, Oklahoma State University, Stillwater OK, United States of America
- ¹¹³ Palacký University, RCPTM, Olomouc, Czech Republic
- ¹¹⁴ Center for High Energy Physics, University of Oregon, Eugene OR, United States of America
- ¹¹⁵ LAL, Université Paris-Sud and CNRS/IN2P3, Orsay, France
- ¹¹⁶ Graduate School of Science, Osaka University, Osaka, Japan
- ¹¹⁷ Department of Physics, University of Oslo, Oslo, Norway
- ¹¹⁸ Department of Physics, Oxford University, Oxford, United Kingdom
- ¹¹⁹ ^(a)INFN Sezione di Pavia; ^(b)Dipartimento di Fisica, Università di Pavia, Pavia, Italy
- ¹²⁰ Department of Physics, University of Pennsylvania, Philadelphia PA, United States of America
- ¹²¹ Petersburg Nuclear Physics Institute, Gatchina, Russia
- ¹²² ^(a)INFN Sezione di Pisa; ^(b)Dipartimento di Fisica E. Fermi, Università di Pisa, Pisa, Italy
- ¹²³ Department of Physics and Astronomy, University of Pittsburgh, Pittsburgh PA, United States of America
- ¹²⁴ ^(a)Laboratorio de Instrumentacao e Fisica Experimental de Particulas - LIP, Lisboa, Portugal; ^(b)Departamento de Fisica Teorica y del Cosmos and CAFPE, Universidad de Granada, Granada, Spain
- ¹²⁵ Institute of Physics, Academy of Sciences of the Czech Republic, Praha, Czech Republic
- ¹²⁶ Faculty of Mathematics and Physics, Charles University in Prague, Praha, Czech Republic
- ¹²⁷ Czech Technical University in Prague, Praha, Czech Republic
- ¹²⁸ State Research Center Institute for High Energy Physics, Protvino, Russia
- ¹²⁹ Particle Physics Department, Rutherford Appleton Laboratory, Didcot, United Kingdom
- ¹³⁰ Physics Department, University of Regina, Regina SK, Canada
- ¹³¹ Ritsumeikan University, Kusatsu, Shiga, Japan
- ¹³² ^(a)INFN Sezione di Roma I; ^(b)Dipartimento di Fisica, Università La Sapienza, Roma, Italy
- ¹³³ ^(a)INFN Sezione di Roma Tor Vergata; ^(b)Dipartimento di Fisica, Università di Roma Tor Vergata, Roma, Italy
- ¹³⁴ ^(a)INFN Sezione di Roma Tre; ^(b)Dipartimento di Fisica, Università Roma Tre, Roma, Italy

- ¹³⁵ ^(a)Faculté des Sciences Ain Chock, Réseau Universitaire de Physique des Hautes Energies - Université Hassan II, Casablanca; ^(b)Centre National de l'Energie des Sciences Techniques Nucleaires, Rabat; ^(c)Faculté des Sciences Semlalia, Université Cadi Ayyad, LPHEA-Marrakech; ^(d)Faculté des Sciences, Université Mohamed Premier and LTPM, Oujda; ^(e)Faculté des sciences, Université Mohammed V-Agdal, Rabat, Morocco
- ¹³⁶ DSM/IRFU (Institut de Recherches sur les Lois Fondamentales de l'Univers), CEA Saclay (Commissariat a l'Energie Atomique), Gif-sur-Yvette, France
- ¹³⁷ Santa Cruz Institute for Particle Physics, University of California Santa Cruz, Santa Cruz CA, United States of America
- ¹³⁸ Department of Physics, University of Washington, Seattle WA, United States of America
- ¹³⁹ Department of Physics and Astronomy, University of Sheffield, Sheffield, United Kingdom
- ¹⁴⁰ Department of Physics, Shinshu University, Nagano, Japan
- ¹⁴¹ Fachbereich Physik, Universität Siegen, Siegen, Germany
- ¹⁴² Department of Physics, Simon Fraser University, Burnaby BC, Canada
- ¹⁴³ SLAC National Accelerator Laboratory, Stanford CA, United States of America
- ¹⁴⁴ ^(a)Faculty of Mathematics, Physics & Informatics, Comenius University, Bratislava; ^(b)Department of Subnuclear Physics, Institute of Experimental Physics of the Slovak Academy of Sciences, Kosice, Slovak Republic
- ¹⁴⁵ ^(a)Department of Physics, University of Johannesburg, Johannesburg; ^(b)School of Physics, University of the Witwatersrand, Johannesburg, South Africa
- ¹⁴⁶ ^(a)Department of Physics, Stockholm University; ^(b)The Oskar Klein Centre, Stockholm, Sweden
- ¹⁴⁷ Physics Department, Royal Institute of Technology, Stockholm, Sweden
- ¹⁴⁸ Departments of Physics & Astronomy and Chemistry, Stony Brook University, Stony Brook NY, United States of America
- ¹⁴⁹ Department of Physics and Astronomy, University of Sussex, Brighton, United Kingdom
- ¹⁵⁰ School of Physics, University of Sydney, Sydney, Australia
- ¹⁵¹ Institute of Physics, Academia Sinica, Taipei, Taiwan
- ¹⁵² Department of Physics, Technion: Israel Institute of Technology, Haifa, Israel
- ¹⁵³ Raymond and Beverly Sackler School of Physics and Astronomy, Tel Aviv University, Tel Aviv, Israel
- ¹⁵⁴ Department of Physics, Aristotle University of Thessaloniki, Thessaloniki, Greece
- ¹⁵⁵ International Center for Elementary Particle Physics and Department of Physics, The University of Tokyo, Tokyo, Japan
- ¹⁵⁶ Graduate School of Science and Technology, Tokyo Metropolitan University, Tokyo, Japan
- ¹⁵⁷ Department of Physics, Tokyo Institute of Technology, Tokyo, Japan
- ¹⁵⁸ Department of Physics, University of Toronto, Toronto ON, Canada
- ¹⁵⁹ ^(a)TRIUMF, Vancouver BC; ^(b)Department of Physics and Astronomy, York University, Toronto ON, Canada
- ¹⁶⁰ Institute of Pure and Applied Sciences, University of Tsukuba, 1-1-1 Tennodai, Tsukuba, Ibaraki 305-8571, Japan
- ¹⁶¹ Science and Technology Center, Tufts University, Medford MA, United States of America
- ¹⁶² Centro de Investigaciones, Universidad Antonio Narino, Bogota, Colombia
- ¹⁶³ Department of Physics and Astronomy, University of California Irvine, Irvine CA, United States of America
- ¹⁶⁴ ^(a)INFN Gruppo Collegato di Udine; ^(b)ICTP, Trieste; ^(c)Dipartimento di Chimica, Fisica e Ambiente, Università di Udine, Udine, Italy
- ¹⁶⁵ Department of Physics, University of Illinois, Urbana IL, United States of America
- ¹⁶⁶ Department of Physics and Astronomy, University of Uppsala, Uppsala, Sweden
- ¹⁶⁷ Instituto de Física Corpuscular (IFIC) and Departamento de Física Atómica, Molecular y Nuclear and Departamento de Ingeniería Electrónica and Instituto de Microelectrónica de Barcelona (IMB-CNM), University of Valencia and CSIC, Valencia, Spain
- ¹⁶⁸ Department of Physics, University of British Columbia, Vancouver BC, Canada
- ¹⁶⁹ Department of Physics and Astronomy, University of Victoria, Victoria BC, Canada
- ¹⁷⁰ Department of Physics, University of Warwick, Coventry, United Kingdom
- ¹⁷¹ Waseda University, Tokyo, Japan
- ¹⁷² Department of Particle Physics, The Weizmann Institute of Science, Rehovot, Israel
- ¹⁷³ Department of Physics, University of Wisconsin, Madison WI, United States of America
- ¹⁷⁴ Fakultät für Physik und Astronomie, Julius-Maximilians-Universität, Würzburg, Germany

¹⁷⁵ Fachbereich C Physik, Bergische Universität Wuppertal, Wuppertal, Germany

¹⁷⁶ Department of Physics, Yale University, New Haven CT, United States of America

¹⁷⁷ Yerevan Physics Institute, Yerevan, Armenia

¹⁷⁸ Domaine scientifique de la Doua, Centre de Calcul CNRS/IN2P3, Villeurbanne Cedex, France

^a Also at Laboratório de Instrumentação e Física Experimental de Partículas - LIP, Lisboa, Portugal

^b Also at Faculdade de Ciências and CFNUL, Universidade de Lisboa, Lisboa, Portugal

^c Also at Particle Physics Department, Rutherford Appleton Laboratory, Didcot, United Kingdom

^d Also at TRIUMF, Vancouver BC, Canada

^e Also at Department of Physics, California State University, Fresno CA, United States of America

^f Also at Novosibirsk State University, Novosibirsk, Russia

^g Also at Fermilab, Batavia IL, United States of America

^h Also at Department of Physics, University of Coimbra, Coimbra, Portugal

ⁱ Also at Department of Physics, UASLP, San Luis Potosi, Mexico

^j Also at Università di Napoli Parthenope, Napoli, Italy

^k Also at Institute of Particle Physics (IPP), Canada

^l Also at Department of Physics, Middle East Technical University, Ankara, Turkey

^m Also at Louisiana Tech University, Ruston LA, United States of America

ⁿ Also at Dep Física and CEFITEC of Faculdade de Ciências e Tecnologia, Universidade Nova de Lisboa, Caparica, Portugal

^o Also at Department of Physics and Astronomy, University College London, London, United Kingdom

^p Also at Group of Particle Physics, University of Montreal, Montreal QC, Canada

^q Also at Department of Physics, University of Cape Town, Cape Town, South Africa

^r Also at Institute of Physics, Azerbaijan Academy of Sciences, Baku, Azerbaijan

^s Also at Institut für Experimentalphysik, Universität Hamburg, Hamburg, Germany

^t Also at Manhattan College, New York NY, United States of America

^u Also at School of Physics, Shandong University, Shandong, China

^v Also at CPPM, Aix-Marseille Université and CNRS/IN2P3, Marseille, France

^w Also at School of Physics and Engineering, Sun Yat-sen University, Guanzhou, China

^x Also at Academia Sinica Grid Computing, Institute of Physics, Academia Sinica, Taipei, Taiwan

^y Also at Dipartimento di Fisica, Università La Sapienza, Roma, Italy

^z Also at DSM/IRFU (Institut de Recherches sur les Lois Fondamentales de l'Univers), CEA Saclay (Commissariat à l'Energie Atomique), Gif-sur-Yvette, France

^{aa} Also at Section de Physique, Université de Genève, Geneva, Switzerland

^{ab} Also at Departamento de Física, Universidade de Minho, Braga, Portugal

^{ac} Also at Department of Physics and Astronomy, University of South Carolina, Columbia SC, United States of America

^{ad} Also at Institute for Particle and Nuclear Physics, Wigner Research Centre for Physics, Budapest, Hungary

^{ae} Also at California Institute of Technology, Pasadena CA, United States of America

^{af} Also at Institute of Physics, Jagiellonian University, Krakow, Poland

^{ag} Also at LAL, Université Paris-Sud and CNRS/IN2P3, Orsay, France

^{ah} Also at Department of Physics and Astronomy, University of Sheffield, Sheffield, United Kingdom

^{ai} Also at Department of Physics, Oxford University, Oxford, United Kingdom

^{aj} Also at Institute of Physics, Academia Sinica, Taipei, Taiwan

^{ak} Also at Department of Physics, The University of Michigan, Ann Arbor MI, United States of America

* Deceased