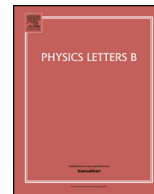




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Search for dark matter in association with a Higgs boson decaying to b -quarks in pp collisions at $\sqrt{s} = 13$ TeV with the ATLAS detector



The ATLAS Collaboration ^{*}

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ABSTRACT

A search for dark matter pair production in association with a Higgs boson decaying to a pair of bottom quarks is presented, using 3.2 fb^{-1} of pp collisions at a centre-of-mass energy of 13 TeV collected by the ATLAS detector at the LHC. The decay of the Higgs boson is reconstructed as a high-momentum $b\bar{b}$ system with either a pair of small-radius jets, or a single large-radius jet with substructure. The observed data are found to be consistent with the expected backgrounds. Results are interpreted using a simplified model with a Z' gauge boson mediating the interaction between dark matter and the Standard Model as well as a two-Higgs-doublet model containing an additional Z' boson which decays to a Standard Model Higgs boson and a new pseudoscalar Higgs boson, the latter decaying into a pair of dark matter particles.

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1. Introduction

Although dark matter (DM) constitutes the dominant component of matter in the universe, little is known about its properties and particle content [1]. The leading hypothesis suggests that most DM is in the form of stable, electrically neutral, massive particles with cosmological constraints indicating that DM interactions with Standard Model (SM) particles occur at a weak scale or below [2]. Collider-based searches for the particle content of DM provide important information complementary to that from direct and indirect detection experiments [3].

A traditional dark-matter signature at a proton–proton collider is one where one or more SM particles, X , are produced and detected, recoiling against missing transverse momentum – with magnitude $E_{\text{T}}^{\text{miss}}$ – associated with the non-interacting DM candidate. A number of searches at the Large Hadron Collider (LHC) [4] have been performed recently, where X is considered to be a hadronic jet [5,6], b - or t -quarks [7–9], a photon [10–13], or a W/Z boson [14–17]. The discovery of a Higgs boson, h [18,19], provides a new opportunity to search for DM production via the $h + E_{\text{T}}^{\text{miss}}$ signature [20–22]. In contrast to most of the aforementioned probes, Higgs boson radiation from an initial-state quark is Yukawa-suppressed. As a result, in a potential signal the Higgs boson would be part of the interaction producing the DM, providing unique insight into the structure of the DM coupling to SM particles. Recently, the ATLAS Collaboration has published such searches using 20.3 fb^{-1} of proton–proton collision data at $\sqrt{s} = 8 \text{ TeV}$, ex-

ploiting the Higgs boson decays to two photons or a pair of bottom quarks [23,24].

This Letter presents an update on the search for $h + E_{\text{T}}^{\text{miss}}$, where the Higgs boson decays to a pair of bottom quarks ($h \rightarrow b\bar{b}$), using 3.2 fb^{-1} of pp collision data collected by the ATLAS detector at a centre-of-mass energy of 13 TeV during 2015. The results are interpreted in the context of simplified models of DM, characterised by a minimal particle content and the corresponding renormalisable interactions [25].

Many simplified models of DM production contain a massive particle which can be a vector, an axial-vector, a scalar or a pseudoscalar, and mediates the interaction between DM and Standard Model particles. In this search, simplified models involving a vector mediator are considered following the recommendation in Ref. [26].

In the first model [21], a vector mediator, Z' , is exchanged in the s -channel, radiates the Higgs boson and decays into two DM particles. A diagram for this process is shown in Fig. 1(a). The vector mediator has an associated baryon number B , which is assumed to be gauge invariant under $U(1)_B$ thus allowing it to couple to quarks [27]. This symmetry is spontaneously broken to generate the Z' mass. However, there is no Z' coupling to leptons as such couplings are tightly constrained by dilepton searches. Finally, the dark-matter candidate carries a baryon number, which allows it to couple to quarks through the Z' . The parameters of this model are as follows: the coupling of Z' to dark matter (g_{χ}); the coupling of Z' to quarks (g_q); the coupling of Z' to the SM Higgs boson ($g_{Z'}$); the mixing angle between the baryonic Higgs boson, introduced in the model to generate the Z' mass, and the

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

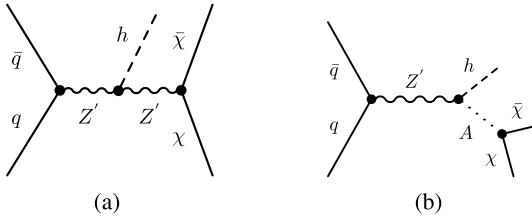


Fig. 1. Diagrams showing the simplified models where (a) a Z' decays to a pair of DM candidates $\chi\bar{\chi}$ after emitting a Higgs boson h , and where (b) a Z' decays to a Higgs boson h and the pseudoscalar A of a two-Higgs-doublet model, and the latter decays to a pair of DM candidates $\chi\bar{\chi}$.

SM Higgs boson ($\sin\theta$); the Z' mass ($m_{Z'}$); and the DM particle mass (m_χ).

In the second model, apart from the vector mediator, the SM is extended by an additional Higgs field doublet, resulting in five physical Higgs bosons [22]: a light scalar h associated with the observed Higgs boson, a heavy scalar H , a pseudoscalar A , and two charged scalars H^\pm . The vector mediator is produced resonantly and decays as $Z' \rightarrow hA$ in a Type-II two-Higgs-doublet model (2HDM) [28]. The pseudoscalar A subsequently decays into two DM particles with a large branching ratio. A diagram for this process is shown in Fig. 1(b). To define the model, the ratio of the up- and down-type vacuum expectation values, $\tan\beta$, must be specified along with the Z' gauge coupling, g_z , the DM particle mass, m_χ , and the Z' and A masses, $m_{Z'}$ and m_A , respectively. The results presented are for the alignment limit, in which the h - H mixing angle α is related to β by $\alpha = \beta - \pi/2$. Only regions of parameter space consistent with precision electroweak constraints [29] and with constraints from direct searches for dijet resonances [30–32] are considered. As the A boson is produced on-shell and decays into DM, the mass of the DM particle does not affect the kinematic properties or cross-section of the signal process if it is below half of the A boson mass. Hence, the Z' -2HDM model is interpreted in the parameter spaces of Z' mass ($m_{Z'}$), A mass (m_A) and $\tan\beta$.

2. ATLAS detector

ATLAS is a multi-purpose particle physics detector [33] at the LHC, with an approximately forward-backward symmetric and hermetic cylindrical geometry.¹ At its innermost part lies the inner detector (ID), immersed in a 2 T axial magnetic field provided by a thin superconducting solenoid, consisting of silicon pixel and microstrip detectors, which provide precision tracking in the pseudorapidity range $|\eta| < 2.5$. It is complemented by a transition radiation tracker providing tracking and particle identification information for $|\eta| < 2.0$. Between Run 1 and Run 2 of the LHC, the pixel detector was upgraded by the addition of a new innermost layer [34] that significantly improves the identification of heavy-flavour jets [35,36]. The solenoid is surrounded by sampling calorimeters: a lead/liquid-argon (LAr) electromagnetic calorimeter for $|\eta| < 3.2$ and a steel/scintillator tile hadronic calorimeter for $|\eta| < 1.7$. Additional LAr calorimeters with copper and tungsten absorbers provide coverage up to $|\eta| = 4.9$. In the outermost part, air-core toroids provide the magnetic field for the muon spec-

trometer. The latter consists of three layers of gaseous detectors: monitored drift tubes and cathode strip chambers for muon identification and momentum measurements for $|\eta| < 2.7$, and resistive-plate and thin-gap chambers for triggering up to $|\eta| = 2.4$. A two-level trigger system, custom hardware followed by a software-based level, is used to reduce the event rate to about 1 kHz for offline storage.

3. Data and simulation samples

The data sample used in this search, collected during normal operation of the detector, corresponds to an integrated luminosity of 3.2 fb^{-1} . The primary data sample is selected using a calorimeter-based E_T^{miss} trigger with a threshold of 70 GeV. The trigger efficiency for signal events selected by the offline analysis is about 90% for events with E_T^{miss} of 150 GeV and reaches 100% for events with E_T^{miss} larger than 200 GeV.

Signal samples are generated at tree level with MADGRAPH5_aMC@NLO 2.2.3 [37], interfaced to PYTHIA 8.186 [38] using the NNPDF2.3 parton distribution function (PDF) set [39] and the A14 parameter tune [40] for parton showering, hadronisation, underlying-event simulation, and for simulation of the Higgs boson decay to a pair of bottom quarks. For the vector-mediator simplified models, signals are generated with mediator mass between 10 and 2000 GeV and DM particle mass between 1 and 1000 GeV. The event kinematics are largely independent of the other parameters of the model, and thus the same values of these parameters are chosen following the recommendations in Ref. [26]: $g_\chi = 1.0$, $g_q = 1/3$, $g_{Z'} = m_{Z'}$, $\sin\theta = 0.3$. For the Z' -2HDM model, $pp \rightarrow Z' \rightarrow Ah \rightarrow \chi\bar{\chi}h$ samples are produced with Z' mass values between 600 and 1000 GeV, A mass values between 300 and 800 GeV (where kinematically allowed), and a DM mass value of 100 GeV. The other parameters chosen for this model are taken to be $\tan\beta = 1.0$ and $g_z = 0.8$.

Higgs boson production in association with a W or Z vector boson, Vh , is modelled using PYTHIA 8.186 and the NNPDF2.3 PDF set. The samples are normalised using the SM total cross-sections calculated at next-to-leading order (NLO) [41] and next-to-next-to-leading order (NNLO) [42] in QCD for Wh and Zh , respectively, and include NLO electroweak corrections [43]. In all cases, the Higgs boson mass is set to 125 GeV.

Simulated samples of vector boson production in association with jets, $W/Z + \text{jets}$, where the W or Z bosons decay in all leptonic decay modes, are generated using SHERPA2.1.1 [44], including b - and c -quark mass effects, and the CT10 PDF set [45]. Matrix elements are calculated for up to two partons at NLO and four partons at LO using the Comix [46] and OpenLoops [47] matrix element generators and merged with the SHERPA parton shower [48] using the ME + PS@NLO prescription [49]. The cross-sections are determined at NNLO [50] in QCD. Furthermore, these backgrounds are split into different components according to the true flavour of the two jets that are used to identify the flavor of the reconstructed Higgs boson candidate, as described in Section 5: l denotes a light quark (u, d, s) or a gluon and the heavy quarks are denoted by c and b . This division is performed to allow accurate modelling of the $W/Z + \text{heavy-flavour}$ backgrounds in the combined fit described in Section 8.

Diboson production modes, including ZZ , WW , and WZ processes, with one boson decaying hadronically and the other leptonically are simulated using the SHERPA2.1.1 generator with the CT10 PDF set. They are calculated for up to one (ZZ) or zero (WW/WZ) additional partons at NLO and up to three additional partons at LO using the Comix and OpenLoops matrix element generators and merged with the SHERPA parton shower using the ME + PS@NLO

¹ ATLAS uses a right-handed coordinate system with its origin at the nominal interaction point (IP) in the centre of the detector and the z -axis along the beam pipe. The x -axis points towards the centre of the LHC ring, and the y -axis points upwards. Cylindrical coordinates (r, ϕ) are used in the transverse plane, ϕ is the azimuthal angle around the beam pipe. The pseudorapidity η is defined as $\eta = -\ln|\tan(\theta/2)|$, where θ is the polar angle. Finally, the angular distance ΔR is defined as $\sqrt{(\Delta\phi)^2 + (\Delta\eta)^2}$.

prescription. Their cross-sections are determined by the generator at NLO.

The $t\bar{t}$ and single-top-quark backgrounds are generated with POWHEGBOX [51] using the CT10 PDF set. It is interfaced with PYTHIA 6.428 [52] to simulate parton showering, fragmentation, and the underlying event, for which the CTEQ6L1 PDF set [53] and the Perugia 2012 parameter tune [54] are used. The $t\bar{t}$ cross-section is determined at NNLO in QCD and next-to-next-to-leading logarithms (NNLL) for soft gluon radiation [55], while the single-top-quark cross-sections are fixed to those in Refs. [56–58]. A top-quark mass of 172.5 GeV is used throughout.

The simulated event samples are processed with the detailed ATLAS detector simulation [59] based on GEANT4 [60]. Effects of multiple proton–proton interactions (pile-up) as a function of the instantaneous luminosity are taken into account by overlaying simulated minimum-bias events generated with PYTHIA8.186 with the A2 tune [61] and MSTW2008LO PDF set [62] onto the hard-scattering process, such that the distribution of the average number of interactions per bunch crossing in the simulated event samples matches that in the data.

4. Object reconstruction

Proton–proton collision vertices are reconstructed using ID tracks with $p_T > 0.4$ GeV. The primary vertex is defined as the vertex with the highest $\Sigma(p_T^{\text{track}})^2$. Each event is required to have at least one vertex reconstructed from at least two tracks.

Muon candidates are identified by matching tracks found in the ID to either full tracks or track segments reconstructed in the muon spectrometer, and are required to satisfy the *loose* muon identification quality criteria [63]. Electron candidates are identified as ID tracks that are matched to a cluster of energy in the electromagnetic calorimeter. Electron candidates must satisfy a likelihood-based identification requirement [64] based on shower shape and track selection criteria, and are selected using the *loose* working point. Both the muons and electrons are required to originate from the primary vertex, to have $p_T > 7$ GeV, and to lie within $|\eta| < 2.5$ for muons and $|\eta| < 2.47$ for electrons. They are further required to be isolated using requirements on the sum of p_T of the tracks within a cone around the lepton direction. The cone size and the requirements are varied as a function of the lepton p_T to obtain an efficiency that is fixed as a function of p_T such that a 99% efficiency for prompt leptons is retained across a broad kinematic range.

Jets are reconstructed in two categories, small-radius (small- R) and large-radius (large- R) jets. In both cases, the jets are reconstructed from topological clusters of calorimeter cells using the anti- k_t jet clustering algorithm [65]. In the case of small- R jets, a radius parameter of $R = 0.4$ is used and the effects of pile-up are corrected for by a technique based on jet area [66]. In the case of large- R jets, a radius parameter of $R = 1.0$ is used and the jet trimming algorithm [67,68] is applied to minimise the impact of energy depositions due to pile-up and the underlying event. This algorithm reconstructs subjets within the large- R jet using the k_t algorithm [69] with radius parameter $R_{\text{sub}} = 0.2$ and removes any subjet with p_T less than 5% of the large- R jet p_T . The jet energy scale, and also in the case of large- R jets the jet mass scale, is calibrated using p_T - and η -dependent factors determined from simulation, with small- R jets receiving further calibrations using *in situ* measurements [70]. Small- R jets within the ID acceptance, $|\eta| < 2.5$, are called *central* in the following and are required to satisfy $p_T > 20$ GeV. Those with $2.5 < |\eta| < 4.5$ are called *forward* and are required to satisfy $p_T > 30$ GeV. To reduce the effects of pile-up in small- R jets with $p_T < 50$ GeV and $|\eta| < 2.5$, a significant fraction of the tracks associated with each jet must have an

origin compatible with the primary vertex, as defined by the jet vertex tagger [71]. Furthermore, small- R jets are removed if they are within a $\Delta R = 0.2$ cone around an electron candidate. Large- R jets are required to satisfy $p_T > 250$ GeV and $|\eta| < 2.0$.

Track jets are built from tracks using the anti- k_t algorithm with $R = 0.2$. Track jets with $p_T > 10$ GeV and $|\eta| < 2.5$ are selected and are matched by ghost-association [72] to large- R jets. Small- R jets and track jets containing b -hadrons are identified – “ b -tagged” – using a boosted decision tree that combines information about the impact parameter and reconstructed secondary vertices of the tracks associated with these jets [35,36,73]. A working point is used which achieves an average efficiency of 70% in identifying small- R calorimeter jet (track jet) containing a b -hadron with misidentification probabilities of ~ 12 (18)% for charm-quark jets and ~ 0.2 (0.6)% for light-flavour jets, as determined in a simulated sample of $t\bar{t}$ events. Track jets have higher misidentification probabilities due to the smaller radius parameter used.

The missing transverse momentum, \vec{E}_T^{miss} , is defined as the negative vector sum of the transverse momenta of the calibrated physics objects (electrons, muons, small- R jets), with unassociated energy depositions, referred to as the *soft-term*, accounted for using ID tracks with $p_T > 0.5$ GeV [74,75]. Furthermore, a track-based missing transverse momentum vector, \vec{p}_T^{miss} , is calculated as the negative vector sum of the transverse momenta of tracks with $|\eta| < 2.5$, consistent with originating from the primary vertex.²

5. Event selection

For an event to be considered in the search, it is required to have $E_T^{\text{miss}} > 150$ GeV, $p_T^{\text{miss}} > 30$ GeV, and no identified, isolated muons or electrons. This is referred to as the *zero-lepton region*.

Events with E_T^{miss} less than 500 GeV are considered in the *resolved region*. First, this set of events is required to have at least two central small- R jets. Following this selection, the reconstructed small- R jets are ranked as follows. First, the central jets are divided into two categories, those that are b -tagged and those that are not. Each of these samples of jets are ordered in decreasing p_T . The ordered set of b -tagged jets is considered with the highest priority, while those that are central but not b -tagged are considered with second priority, and finally any forward jets, ordered in decreasing p_T , are considered last. The two most highly ranked jets are used to reconstruct the Higgs boson candidate, h_r , and therefore cannot contain forward jets. Furthermore, at least one of the jets constituting h_r must satisfy $p_T > 45$ GeV. Finally, events are divided into three categories based on the number of central jets that are b -tagged being either zero, one, or two b -tagged central jets. To achieve a high E_T^{miss} trigger efficiency, events are retained if the scalar sum of the p_T of the three leading jets is greater than 150 GeV. This requirement is lowered to 120 GeV if only two central small- R jets are present.

Additional selections are applied to further suppress the multijet background. Specifically, to reject events with E_T^{miss} due to mismeasured jets a requirement is placed on the minimum azimuthal angle between the direction of the E_T^{miss} and each of the jets, $\min(\Delta\phi(\vec{E}_T^{\text{miss}}, \text{jets})) > 20^\circ$, for the three highest-ranked jets. Furthermore, the azimuthal angle between the \vec{E}_T^{miss} and the \vec{p}_T^{miss} , $\Delta\phi(\vec{E}_T^{\text{miss}}, \vec{p}_T^{\text{miss}})$, is required to be less than 90° , to suppress events with misreconstructed missing transverse momentum. The Higgs boson candidate is required to be well separated

² Throughout this search, the magnitude of \vec{E}_T^{miss} is referred to as E_T^{miss} and the magnitude of \vec{p}_T^{miss} is referred to as p_T^{miss} . Only when the directionality is necessary does the notation use the vector symbol.

in azimuth from the missing transverse momentum by requiring $\Delta\phi(\vec{E}_T^{\text{miss}}, h_r) > 120^\circ$. Finally, to reject back-to-back dijet production, the azimuthal opening angle of the two jets forming the Higgs boson candidate is required to be $\Delta\phi(j_{h_r}^1, j_{h_r}^2) < 140^\circ$.

The DM signal is expected to have large E_T^{miss} , whereas the background is expected to be most prominent at low E_T^{miss} . Therefore, to retain signal efficiency while preserving the increased sensitivity of the high E_T^{miss} region, events in the resolved region are separated into three categories based on the reconstructed E_T^{miss} : 150–200 GeV, 200–350 GeV, and 350–500 GeV.

In the *merged region* – composed of events with E_T^{miss} in excess of 500 GeV – the presence of at least one large- R jet is required, associated with at least two track jets [76], and the highest p_T large- R jet is taken as the reconstructed Higgs candidate. In an analogous way to the resolved region, the events are classified based on the number of b -tagged track jets associated with the large- R jet into three categories with zero, one, and two or more b -tags.

The combined selection of both the resolved and merged selections in the signal region with two or more b -tags yields a signal acceptance times efficiency ranging between 5 and 30%. The primary change in the signal acceptance is due to the choice of masses (e.g. $m_{Z'}$ and m_A) in the point of parameter space being probed.

The search is performed by implementing a shape fit of the reconstructed dijet mass (m_{jj}) or single large- R jet mass (m_j) distribution. After event selection, the energy calibration of the b -tagged jets is improved as follows. The invariant mass of the candidate is corrected [77] if a muon is identified within $\Delta R = 0.4$ of a b -tagged small- R jet, or within $\Delta R = 1.0$ of the large- R jet. The four-momentum of the closest muon in ΔR within a jet is added to the calorimeter-based jet energy after removing the energy deposited in the calorimeter by the muon (muon-in-jet correction). Additionally, a simulation-based jet- p_T -dependent correction [77] is applied in the case of b -tagged small- R jets to improve the signal resolution of the reconstructed Higgs mass peak. Events consistent with a DM signal would have a reconstructed mass near the Higgs boson mass, thereby allowing the sidebands to act as a natural control region to further constrain the backgrounds estimated from dedicated W/Z + jets and $t\bar{t}$ control regions and the multijet estimates described in Section 6.

6. Background estimation

The background is mainly composed of SM W/Z + jets and $t\bar{t}$ events, which constitute 15–65% and 45–80% of the total background, respectively, depending on the E_T^{miss} value. The model for these backgrounds is constrained using two dedicated control regions. Other backgrounds, including diboson, Vh , and single top-quark production, constitute less than 15% of the total background and the estimation is modelled using simulated event samples. The contribution from multijet events arises mainly from events containing jets containing semi-muonic decays of b -hadrons. It constitutes less than 2% of the background in the resolved region and is negligibly small in the merged region, and is estimated using a data-driven technique.

In addition to the zero-lepton region, which serves as a control region to constrain the Z + jets background in the zero- b -tag case and via the reconstructed mass sidebands that enter in the fit as described in Section 8, two dedicated control regions are used to constrain the main W/Z + jets and $t\bar{t}$ backgrounds. These control regions are defined based on the number of leptons and b -tags in the event and are orthogonal to each other and to the signal region.

The *one-muon control region* is designed to constrain the W + jets and $t\bar{t}$ backgrounds. Events are selected using the E_T^{miss} trigger and are required to have exactly one muon candidate and no electron candidates. Furthermore, the full signal region selection is applied after modifying the E_T^{miss} observable to mimic the behaviour of such events that contaminate the signal region by adding the p_T of the reconstructed muon to the E_T^{miss} . As in the signal region, these events are divided into exclusive regions based on the number of b -tags. This division naturally separates $t\bar{t}$ from W + jet events.

The *two-lepton control region* is used to constrain the Z + jets background contribution. Events are collected using a single-electron or single-muon trigger and selected by requiring exactly one electron pair or muon pair. Of these two leptons, one is required to have $p_T > 25$ GeV. The electron (muon) pair must have an invariant mass $83 < m_{\ell\ell} < 99$ GeV ($71 < m_{\ell\ell} < 106$ GeV). In the muon channel, where a larger mass window is used, an opposite-charge requirement is also applied. Furthermore, the missing transverse momentum significance, defined as the ratio of E_T^{miss} to the square root of the scalar sum of lepton and jet p_T in the event, is required to be less than $3.5\text{GeV}^{1/2}$ in order to reject $t\bar{t}$ background. In this control region, the transverse momentum of the dilepton system, p_T^V , is used – instead of E_T^{miss} – to match the division of the resolved and merged regions and the categorisation of the resolved events. Other than the above, the event selection and Higgs boson candidate requirements are the same as in the signal region.

The multijet background for the resolved analysis is determined using a data-driven method. A sample of events selected to satisfy the analysis trigger, p_T^{miss} requirement, and inverted $\min(\Delta\phi(\vec{E}_T^{\text{miss}}, \text{jets}))$ requirement, is used to provide multijet templates of all the distributions relevant to the analysis. These templates are normalised by a fit to the distribution of the number of small- R jets that contain a muon in the nominal selection. The fit is performed separately for each b -tag category. Since agreement is found between the categories the average normalisation scale factor is used. In the merged region, it was found that the requirement of high E_T^{miss} suppresses the multijet background to a negligible level. Therefore it is not included as a background in the search.

7. Systematic uncertainties

The most important experimental systematic uncertainties arise from the determination of the b -tagging efficiency and mistag rate, the luminosity determination and uncertainties associated with the calibration of the scale and resolution of the jet energy and mass. The uncertainties in the small- R jet energy scale have contributions from *in situ* calibration studies, from the dependence on pile-up activity and on flavour composition of jets, and from the changes of the detector and run conditions between Run 1 and Run 2 [78,79]. The uncertainty in the scale and resolution of large- R jet energy and mass are evaluated by comparing the ratio of calorimeter-based to track-based measurements in dijet data and simulation [80]. The b -tagging efficiency uncertainty arises mainly from the uncertainty in the measurement of the efficiency in $t\bar{t}$ events [73,81].

Other experimental systematic uncertainties with a smaller impact are those in the lepton energy and momentum scales, and lepton identification and trigger efficiencies [63,82,83]. An uncertainty in the E_T^{miss} soft-term resolution and scale is taken into account [74], and uncertainties due to the lepton energy scales and resolutions, as well as reconstruction and identification efficiencies, are also considered, although they are negligible. The uncertainty

in the integrated luminosity amounts to 2.1%, and is derived following a methodology similar to that detailed in Ref. [84].

Uncertainties are also taken into account for possible differences between data and the simulation modelling used for each process. The SHERPA $W + \text{jets}$ and $Z + \text{jets}$ background modelling is studied in the one and two lepton control regions, respectively, as a function of p_T of the vector boson, the mass m_{jj} or m_J and the azimuthal angle difference $\Delta\phi_{jj}$ between the small- R jets used to reconstruct the Higgs in the resolved region. The shape of the data distributions is described by the simulation with no indication that a correction is needed. A shape uncertainty in these variables is derived, encompassing the data/simulation differences. An uncertainty in the SHERPA description of the flavour composition of the jets in these backgrounds is derived by comparing to MadGraph. The top-quark background modelling is studied in the dedicated one lepton control region, and in a two lepton control region using $e\mu$ pairs. Both the p_T and mass of the two small- R jet system are studied. A systematic uncertainty is derived based on the data/simulation comparison in these regions.

The normalisations of the $W + b\bar{b}$, $Z + b\bar{b}$, and $t\bar{t}$ contributions are determined directly from the data by leaving them as free parameters in the combined fit. The normalisations of the other $W/Z + \text{jets}$ background contributions are obtained from theory predictions, with assigned normalisation uncertainties of 10% for $W/Z + l$, 30% for $W/Z + cl$ and a 30% uncertainty is applied to the relative normalisation between $W/Z + bc/bl/cc$ to $W/Z + b\bar{b}$. In addition, the following normalisation uncertainties are assigned to the background processes: 4% for single-top in the s - and t -channels, 7% for single-top in the Wt -channel [85,86], and 50% for associated $(W/Z)h$ [77,87] production. The sources of uncertainty considered for the cross-sections for the diboson production (WW , WZ and ZZ) are the renormalisation and factorisation scales, the choice of PDFs and parton-shower and hadronisation model. The multijet contribution is estimated from data and is assigned a 50% uncertainty. Uncertainties arising from the size of the simulated event sample are also taken into account.

Uncertainties in the signal acceptance from the choice of PDFs, from the choice of factorisation and renormalisation scales, and from the choice of parton-shower and underlying-event tune have been taken into account in the analysis. These are typically $<10\%$ each, although they can be larger for regions with low acceptance at either low or high E_T^{miss} depending on the model and the choice of masses. In addition, uncertainties arising from the limited number of simulated events have been taken into account.

The contribution of the various sources of uncertainty for an example production scenario is given in Table 1.

8. Results

Results are extracted by means of a profile likelihood fit to the reconstructed invariant mass distribution of the dijet system or single-large- R -jet simultaneously in all signal and control regions. The normalisations of the major backgrounds are constrained by the data in both the signal and control regions. The shapes of the background distributions are taken from Monte Carlo simulations but can be modified within the systematic errors listed in Section 7. The spectra entering the fit are those from the three selections associated with the number of leptons with each of these regions divided into three categories based on the number of b -tags and four kinematic regions. In the zero-lepton region, this division is based on E_T^{miss} while in the one- and two-lepton regions, it is based on $p_T(\mu, E_T^{\text{miss}})$ and $p_T(\ell, \ell)$, respectively. The shape information is not used in the zero- b -tag distributions in order to simplify the fit. This division is designed to isolate, and more effectively constrain, different backgrounds. In particular, the

Table 1

The percentage impact of the various sources of uncertainty on the expected production cross-section for the signal in the vector-mediator model with $m_{Z'} = 2000$ GeV and $m_\chi = 1$ GeV, normalised to a cross section of 0.1 pb.

Source of uncertainty	Impact [%]
Total	23.0
Statistical	20.5
Systematic	10.3
Experimental uncertainties	
b -tagging	6.6
Luminosity	4.4
Jets + E_T^{miss}	2.8
Leptons	0.4
Theoretical and modelling uncertainties	
Top	5.1
$Z + \text{jets}$	3.4
Signal	2.6
$W + \text{jets}$	1.5
Diboson	0.6
Multijet	0.5
$Vh (h \rightarrow b\bar{b})$	0.4

$Z + \text{jets}$ background normalisation is constrained both by the sample of events containing two leptons and those containing zero leptons and zero b -tags. In addition, the set of events containing one lepton and zero b -tags constrains the $W + \text{jets}$ normalisation while those containing one or two b -tags constrain both the $W + \text{jets}$ and $t\bar{t}$ normalisations. The parameter of interest in the fit is the signal yield, while all parameters describing the systematic uncertainties and their correlations are included in the likelihood function as nuisance parameters, with Gaussian constraints, implemented using the framework described in Refs. [88,89]. The nuisance parameters with the largest effect on the determination of the parameter of interest are the flavour-tagging and jet systematic uncertainties, together with the normalisation of the $t\bar{t}$ and $W + b\bar{b}$ backgrounds. The reconstructed Higgs boson candidate mass distribution is shown in Fig. 2 in each of the E_T^{miss} categories for the set of events with two b -tags with the integrated event yields shown in Table 2. Furthermore, shown in Fig. 3 is the E_T^{miss} distribution in the signal region, noting that in the two portions of the spectrum, below and above $E_T^{\text{miss}} = 500$ GeV, the requirements on the hadronic activity are taken from the small- R and large- R jets, respectively. No significant excess of events is observed above the background, with the global significance of the deviation of the data from the background-only prediction being 0.056.

Upper limits on the production cross-section for the process times branching ratio of the Higgs boson decaying to two bottom quarks ($\sigma(pp \rightarrow h\chi\chi) \times \text{BR}(h \rightarrow b\bar{b})$) are set at 95% confidence level using the CL_s modified frequentist formalism [90] with the profile-likelihood-ratio test statistic [91]. For the Z' -2HDM model, these limits range from 191.3 fb for a Z' mass of 600 GeV and an A mass of 300 GeV to 6.72 fb for a Z' mass of 1600 GeV and an A mass of 600 GeV. For the vector mediator model interpretation, the limits range from 1.01 pb for a mediator mass of 50 GeV and a dark matter mass of 1 GeV to 40.3 fb for a mediator mass of 800 GeV and a dark matter mass of 500 GeV. These are further interpreted as lower limits on the mass parameters of interest in the specific model. In Fig. 4(a) the Z' -2HDM exclusion contour in the $(m_{Z'}, m_A)$ plane for $\tan\beta = 1$, $m_\chi = 100$ GeV is presented, with limits more stringent than obtained in Run 1, excluding Z' masses up to 1950 GeV and A masses up to 500 GeV. In Fig. 4(b), the exclusion contour is shown in the $(m_{Z'}, m_\chi)$ plane for the vector mediator model described in Section 3. This interpretation was not performed in Run 1 and the mass reach for this choice of couplings excludes Z' masses below 700 GeV for low DM mass.

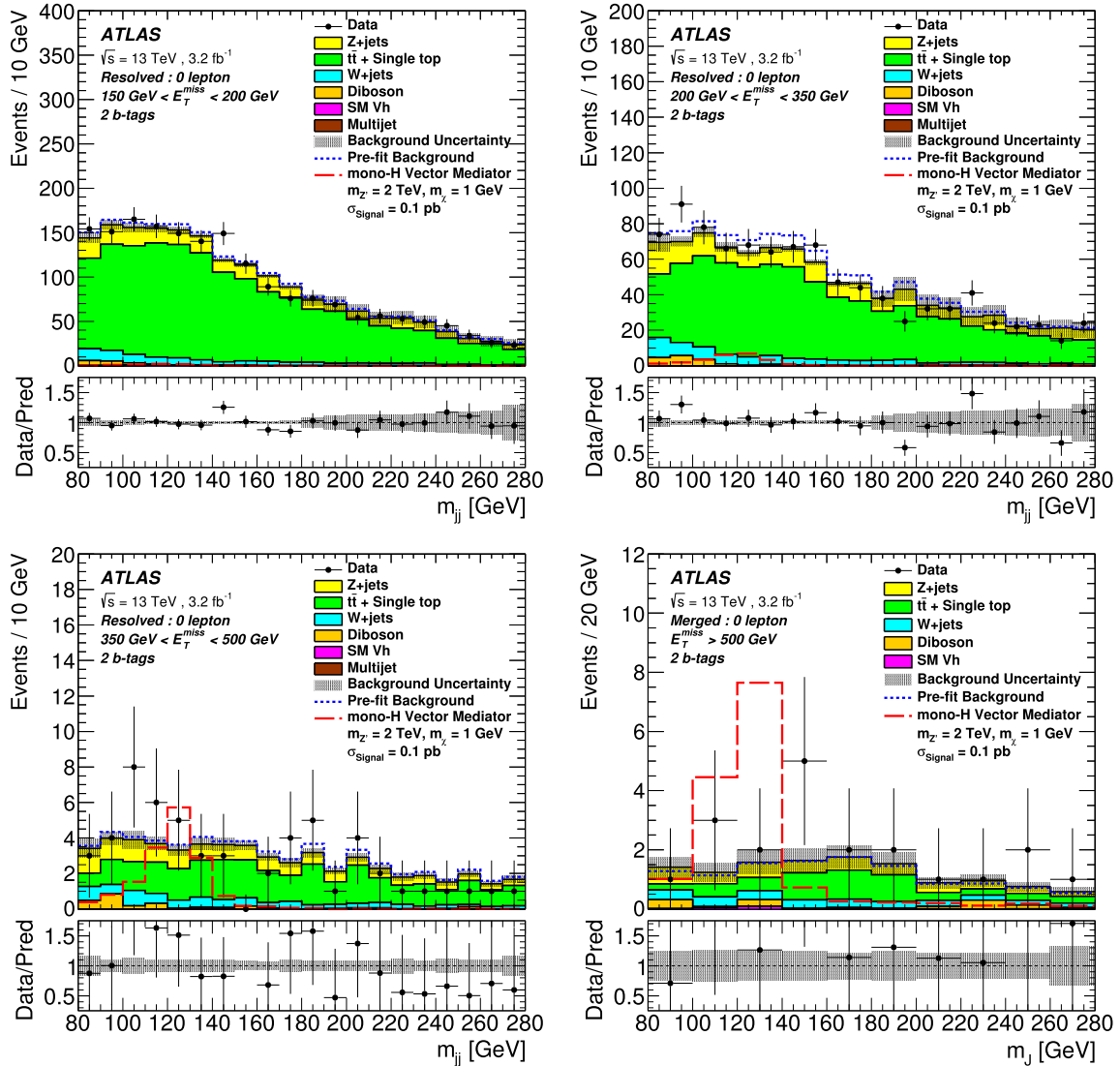


Fig. 2. The reconstructed dijet and single jet invariant mass distribution in the resolved and the merged signal regions for the case where two b -tags have been identified for the four kinematic regions. The Standard Model background expectation is shown before (after) the profile likelihood fit by the dashed blue line (solid histograms) with the bottom panel showing the ratio of the data to the predicted background after the combined fit with no signal included. For visual clarity the various components of the W/Z + jets ($b\bar{b}$, bc , bl , $c\bar{c}$, cl , ll) backgrounds have been merged and labelled W + jets and Z + jets. The expected signal in the vector-mediator model with $m_{Z'} = 2$ TeV and $m_\chi = 1$ GeV, normalised with a cross-section of 0.1 pb, is also shown. (For interpretation of the references to colour in this figure, the reader is referred to the web version of this article.)

Table 2

The numbers of predicted background events following the profile likelihood fit for each background process, the sum of all background components, and observed data yields in the two b -tag signal region of the resolved and merged channels for each E_T^{miss} region. Statistical and systematic uncertainties are combined. The uncertainties in the total background take into account the correlation of systematic uncertainties among different background processes. The expected signal in the vector-mediator model with $m_{Z'} = 2000$ GeV and $m_\chi = 1$ GeV.

E_T^{miss} [GeV]	Resolved			Merged
	150–200	200–350	350–500	>500
Z + jets	259 ± 27	171 ± 13	14.6 ± 1.2	3.80 ± 0.44
W + jets	95 ± 28	70 ± 22	7.5 ± 2.4	2.48 ± 0.71
$t\bar{t}$ & Single top	1444 ± 44	656 ± 25	30.8 ± 1.4	4.9 ± 0.9
Multijet	21 ± 10	11.0 ± 5.0	0.58 ± 0.27	–
Diboson	17.8 ± 1.6	18.7 ± 1.0	2.53 ± 0.22	1.20 ± 0.12
SM Vh	2.8 ± 1.3	2.8 ± 1.4	0.46 ± 0.23	0.15 ± 0.08
Total Bkg.	1840 ± 33	930 ± 20	56.5 ± 2.1	12.5 ± 1.3
Data	1830	942	56	20
Exp. Signal	8.0 ± 0.8	24.5 ± 1.8	16.1 ± 1.2	14.9 ± 3.4

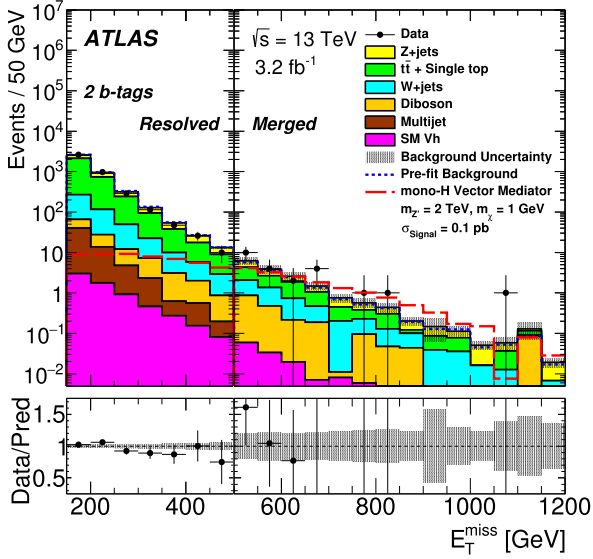


Fig. 3. The reconstructed E_T^{miss} distribution in the combined resolved and merged two- b -tag signal regions. The Standard Model prediction is shown before (after) the profile likelihood fit by the dashed blue line (solid histograms) with the bottom panel showing the ratio of the data to the predicted background after the combined fit with no signal included. For visual clarity the various components of the W/Z + jets (bb , bc , bl , cc , cl , ll) backgrounds have been merged and labelled W + jets and Z + jets. The multijet background is found to be negligible in the merged region. The expected signal in the vector-mediator model with $m_{Z'} = 2$ TeV and $m_\chi = 1$ GeV, normalised with a cross-section of 0.1 pb, is also shown.

9. Conclusion

A search is presented for dark-matter pair production in association with a Higgs boson decaying into two b -quarks, using 3.2 fb^{-1} of pp collisions collected at $\sqrt{s} = 13$ TeV by the ATLAS detector at the LHC. Two regions are considered, a low- E_T^{miss} region where the two b -quark jets from the Higgs boson decay are reconstructed separately and a high- E_T^{miss} region where they are reconstructed inside a single large-radius trimmed jet.

The data are found to be consistent with the background expectation and the results are interpreted for two simplified models involving a massive vector mediator. In the Z' -two-Higgs-doublet, constraints are placed on the $(m_{Z'}, m_A)$ space and found to exclude a wide range of Z' masses with the pseudo-scalar Higgs mass exclusion reaching up to 500 GeV. In the context of the vec-

tor mediator model, constraints are placed in the two-dimensional space of $(m_{Z'}, m_\chi)$ and found to exclude vector mediators with masses up to 700 GeV.

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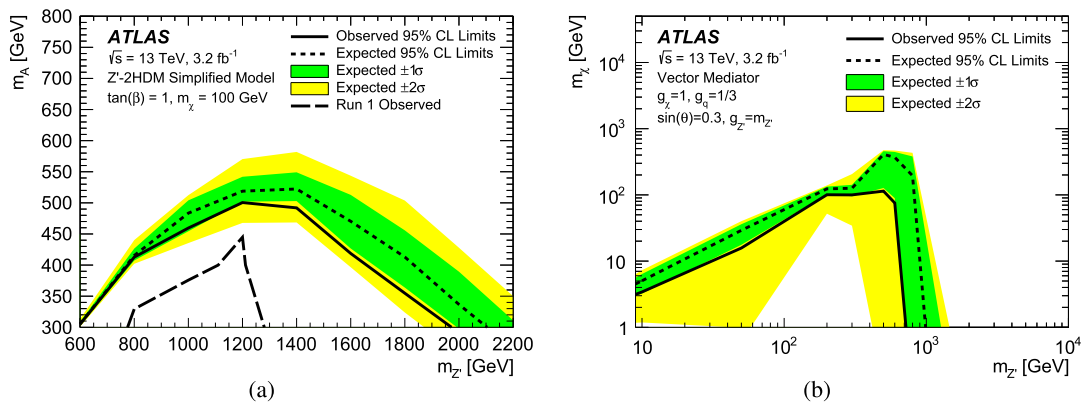


Fig. 4. Exclusion contours for (a) the Z' -2HDM in the $(m_{Z'}, m_A)$ plane for $\tan\beta = 1$ and $m_\chi = 100$ GeV and (b) the vector-mediator model in the $(m_{Z'}, m_\chi)$ plane for $\sin\theta = 0.3$, $g_\chi = 1$, $g_q = 1/3$ and $g_{Z'} = m_{Z'}$. The expected limits are given by the dashed lines, while the green and yellow bands indicate the $\pm 1\sigma$ and $\pm 2\sigma$ uncertainty bands, respectively. The observed limits are given by the solid lines. The parameter space below the limit contours are excluded at 95% confidence level. Shown for the Z' -2HDM exclusion is the observed limit from the Run 1 search while no such exclusion is shown from Run 1 for the vector-mediator model as it was not used for interpretation in the Run 1 ATLAS search. (For interpretation of the colours in this figure, the reader is referred to the web version of this article.)

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M. Aaboud^{136d}, G. Aad⁸⁷, B. Abbott¹¹⁴, J. Abdallah⁶⁵, O. Abdinov¹², B. Abeloos¹¹⁸, R. Aben¹⁰⁸, O.S. AbouZeid¹³⁸, N.L. Abraham¹⁵², H. Abramowicz¹⁵⁶, H. Abreu¹⁵⁵, R. Abreu¹¹⁷, Y. Abulaiti^{149a,149b}, B.S. Acharya^{167a,167b,a}, L. Adamczyk^{40a}, D.L. Adams²⁷, J. Adelman¹⁰⁹, S. Adomeit¹⁰¹, T. Adye¹³², A.A. Affolder⁷⁶, T. Agatonovic-Jovin¹⁴, J. Agricola⁵⁶, J.A. Aguilar-Saavedra^{127a,127f}, S.P. Ahlen²⁴, F. Ahmadov^{67,b}, G. Aielli^{134a,134b}, H. Akerstedt^{149a,149b}, T.P.A. Åkesson⁸³, A.V. Akimov⁹⁷, G.L. Alberghi^{22a,22b}, J. Albert¹⁷², S. Albrand⁵⁷, M.J. Alconada Verzini⁷³, M. Aleksa³², I.N. Aleksandrov⁶⁷, C. Alexa^{28b}, G. Alexander¹⁵⁶, T. Alexopoulos¹⁰, M. Alhroob¹¹⁴, B. Ali¹²⁹, M. Aliev^{75a,75b}, G. Alimonti^{93a}, J. Alison³³, S.P. Alkire³⁷, B.M.M. Allbrooke¹⁵², B.W. Allen¹¹⁷, P.P. Allport¹⁹, A. Aloisio^{105a,105b}, A. Alonso³⁸, F. Alonso⁷³, C. Alpigiani¹³⁹, M. Alstaty⁸⁷, B. Alvarez Gonzalez³², D. Álvarez Piqueras¹⁷⁰, M.G. Alviggi^{105a,105b}, B.T. Amadio¹⁶, K. Amako⁶⁸, Y. Amaral Coutinho^{26a}, C. Amelung²⁵, D. Amidei⁹¹, S.P. Amor Dos Santos^{127a,127c}, A. Amorim^{127a,127b}, S. Amoroso³², G. Amundsen²⁵, C. Anastopoulos¹⁴², L.S. Ancu⁵¹, N. Andari¹⁰⁹, T. Andeen¹¹, C.F. Anders^{60b}, G. Anders³², J.K. Anders⁷⁶, K.J. Anderson³³, A. Andreazza^{93a,93b}, V. Andrei^{60a}, S. Angelidakis⁹, I. Angelozzi¹⁰⁸, P. Anger⁴⁶, A. Angerami³⁷, F. Anghinolfi³², A.V. Anisenkov^{110,c}, N. Anjos¹³, A. Annovi^{125a,125b}, C. Antel^{60a}, M. Antonelli⁴⁹, A. Antonov^{99,*}, F. Anulli^{133a}, M. Aoki⁶⁸, L. Aperio Bella¹⁹, G. Arabidze⁹², Y. Arai⁶⁸, J.P. Araque^{127a}, A.T.H. Arce⁴⁷, F.A. Arduh⁷³, J-F. Arguin⁹⁶, S. Argyropoulos⁶⁵, M. Arik^{20a}, A.J. Armbruster¹⁴⁶, L.J. Armitage⁷⁸, O. Arnaez³², H. Arnold⁵⁰, M. Arratia³⁰, O. Arslan²³, A. Artamonov⁹⁸, G. Artoni¹²¹, S. Artz⁸⁵, S. Asai¹⁵⁸, N. Asbah⁴⁴, A. Ashkenazi¹⁵⁶, B. Åsman^{149a,149b}, L. Asquith¹⁵², K. Assamagan²⁷, R. Astalos^{147a}, M. Atkinson¹⁶⁹, N.B. Atlay¹⁴⁴, K. Augsten¹²⁹, G. Avolio³², B. Axen¹⁶, M.K. Ayoub¹¹⁸, G. Azuelos^{96,d}, M.A. Baak³², A.E. Baas^{60a}, M.J. Baca¹⁹, H. Bachacou¹³⁷, K. Bachas^{75a,75b}, M. Backes³², M. Backhaus³², P. Bagiachi^{133a,133b}, P. Bagnaia^{133a,133b}, Y. Bai^{35a}, J.T. Baines¹³², O.K. Baker¹⁷⁹, E.M. Baldin^{110,c}, P. Balek¹⁷⁵, T. Balestri¹⁵¹, F. Balli¹³⁷, W.K. Balunas¹²³, E. Banas⁴¹, Sw. Banerjee^{176,e}, A.A.E. Bannoura¹⁷⁸, L. Barak³², E.L. Barberio⁹⁰, D. Barberis^{52a,52b}, M. Barbero⁸⁷, T. Barillari¹⁰²,

M-S Barisits ³², T. Barklow ¹⁴⁶, N. Barlow ³⁰, S.L. Barnes ⁸⁶, B.M. Barnett ¹³², R.M. Barnett ¹⁶,
 Z. Barnovska-Blenessy ⁵, A. Baroncelli ^{135a}, G. Barone ²⁵, A.J. Barr ¹²¹, L. Barranco Navarro ¹⁷⁰,
 F. Barreiro ⁸⁴, J. Barreiro Guimarães da Costa ^{35a}, R. Bartoldus ¹⁴⁶, A.E. Barton ⁷⁴, P. Bartos ^{147a},
 A. Basalae ¹²⁴, A. Bassalat ^{118,f}, R.L. Bates ⁵⁵, S.J. Batista ¹⁶², J.R. Batley ³⁰, M. Battaglia ¹³⁸,
 M. Bauce ^{133a,133b}, F. Bauer ¹³⁷, H.S. Bawa ^{146.g}, J.B. Beacham ¹¹², M.D. Beattie ⁷⁴, T. Beau ⁸²,
 P.H. Beauchemin ¹⁶⁵, P. Bechtel ²³, H.P. Beck ^{18,h}, K. Becker ¹²¹, M. Becker ⁸⁵, M. Beckingham ¹⁷³,
 C. Becot ¹¹¹, A.J. Beddall ^{20e}, A. Beddall ^{20b}, V.A. Bednyakov ⁶⁷, M. Bedognetti ¹⁰⁸, C.P. Bee ¹⁵¹,
 L.J. Beemster ¹⁰⁸, T.A. Beermann ³², M. Begel ²⁷, J.K. Behr ⁴⁴, C. Belanger-Champagne ⁸⁹, A.S. Bell ⁸⁰,
 G. Bella ¹⁵⁶, L. Bellagamba ^{22a}, A. Bellerive ³¹, M. Bellomo ⁸⁸, K. Belotskiy ⁹⁹, O. Beltramello ³²,
 N.L. Belyaev ⁹⁹, O. Benary ^{156,*}, D. Bencheekroun ^{136a}, M. Bender ¹⁰¹, K. Bendtz ^{149a,149b}, N. Benekos ¹⁰,
 Y. Benhamou ¹⁵⁶, E. Benhar Nocchioli ¹⁷⁹, J. Benitez ⁶⁵, D.P. Benjamin ⁴⁷, J.R. Bensinger ²⁵,
 S. Bentvelsen ¹⁰⁸, L. Beresford ¹²¹, M. Beretta ⁴⁹, D. Berge ¹⁰⁸, E. Bergeaas Kuutmann ¹⁶⁸, N. Berger ⁵,
 J. Beringer ¹⁶, S. Berlendis ⁵⁷, N.R. Bernard ⁸⁸, C. Bernius ¹¹¹, F.U. Bernlochner ²³, T. Berry ⁷⁹, P. Berta ¹³⁰,
 C. Bertella ⁸⁵, G. Bertoli ^{149a,149b}, F. Bertolucci ^{125a,125b}, I.A. Bertram ⁷⁴, C. Bertsche ⁴⁴, D. Bertsche ¹¹⁴,
 G.J. Besjes ³⁸, O. Bessidskaia Bylund ^{149a,149b}, M. Bessner ⁴⁴, N. Besson ¹³⁷, C. Betancourt ⁵⁰, S. Bethke ¹⁰²,
 A.J. Bevan ⁷⁸, W. Bhimji ¹⁶, R.M. Bianchi ¹²⁶, L. Bianchini ²⁵, M. Bianco ³², O. Biebel ¹⁰¹, D. Biedermann ¹⁷,
 R. Bielski ⁸⁶, N.V. Biesuz ^{125a,125b}, M. Biglietti ^{135a}, J. Bilbao De Mendizabal ⁵¹, H. Bilokon ⁴⁹, M. Bindi ⁵⁶,
 S. Binet ¹¹⁸, A. Bingul ^{20b}, C. Bini ^{133a,133b}, S. Biondi ^{22a,22b}, D.M. Bjergaard ⁴⁷, C.W. Black ¹⁵³, J.E. Black ¹⁴⁶,
 K.M. Black ²⁴, D. Blackburn ¹³⁹, R.E. Blair ⁶, J.-B. Blanchard ¹³⁷, J.E. Blanco ⁷⁹, T. Blazek ^{147a}, I. Bloch ⁴⁴,
 C. Blocker ²⁵, W. Blum ^{85,*}, U. Blumenschein ⁵⁶, S. Blunier ^{34a}, G.J. Bobbink ¹⁰⁸, V.S. Bobrovnikov ^{110.c},
 S.S. Bocchetta ⁸³, A. Bocci ⁴⁷, C. Bock ¹⁰¹, M. Boehler ⁵⁰, D. Boerner ¹⁷⁸, J.A. Bogaerts ³², D. Bogavac ¹⁴,
 A.G. Bogdanchikov ¹¹⁰, C. Bohm ^{149a}, V. Boisvert ⁷⁹, P. Bokan ¹⁴, T. Bold ^{40a}, A.S. Boldyrev ^{167a,167c},
 M. Bomben ⁸², M. Bona ⁷⁸, M. Boonekamp ¹³⁷, A. Borisov ¹³¹, G. Borissov ⁷⁴, J. Bortfeldt ³²,
 D. Bortoletto ¹²¹, V. Bortolotto ^{62a,62b,62c}, K. Bos ¹⁰⁸, D. Boscherini ^{22a}, M. Bosman ¹³, J.D. Bossio Sola ²⁹,
 J. Boudreau ¹²⁶, J. Bouffard ², E.V. Bouhova-Thacker ⁷⁴, D. Boumediene ³⁶, C. Bourdarios ¹¹⁸, S.K. Boutle ⁵⁵,
 A. Boveia ³², J. Boyd ³², I.R. Boyko ⁶⁷, J. Bracinik ¹⁹, A. Brandt ⁸, G. Brandt ⁵⁶, O. Brandt ^{60a}, U. Bratzler ¹⁵⁹,
 B. Brau ⁸⁸, J.E. Brau ¹¹⁷, H.M. Braun ^{178,*}, W.D. Breaden Madden ⁵⁵, K. Brendlinger ¹²³, A.J. Brennan ⁹⁰,
 L. Brenner ¹⁰⁸, R. Brenner ¹⁶⁸, S. Bressler ¹⁷⁵, T.M. Bristow ⁴⁸, D. Britton ⁵⁵, D. Britzger ⁴⁴, F.M. Brochu ³⁰,
 I. Brock ²³, R. Brock ⁹², G. Brooijmans ³⁷, T. Brooks ⁷⁹, W.K. Brooks ^{34b}, J. Brosamer ¹⁶, E. Brost ¹⁰⁹,
 J.H. Broughton ¹⁹, P.A. Bruckman de Renstrom ⁴¹, D. Bruncko ^{147b}, R. Brunelieri ⁵⁰, A. Bruni ^{22a},
 G. Bruni ^{22a}, L.S. Bruni ¹⁰⁸, B.H. Brunt ³⁰, M. Bruschi ^{22a}, N. Bruscino ²³, P. Bryant ³³, L. Bryngemark ⁸³,
 T. Buanes ¹⁵, Q. Buat ¹⁴⁵, P. Buchholz ¹⁴⁴, A.G. Buckley ⁵⁵, I.A. Budagov ⁶⁷, F. Buehrer ⁵⁰, M.K. Bugge ¹²⁰,
 O. Bulekov ⁹⁹, D. Bullock ⁸, H. Burckhart ³², S. Burdin ⁷⁶, C.D. Burgard ⁵⁰, B. Burghgrave ¹⁰⁹, K. Burka ⁴¹,
 S. Burke ¹³², I. Burmeister ⁴⁵, J.T.P. Burr ¹²¹, E. Busato ³⁶, D. Büscher ⁵⁰, V. Büscher ⁸⁵, P. Bussey ⁵⁵,
 J.M. Butler ²⁴, C.M. Buttar ⁵⁵, J.M. Butterworth ⁸⁰, P. Butti ¹⁰⁸, W. Buttinger ²⁷, A. Buzatu ⁵⁵,
 A.R. Buzykaev ^{110.c}, S. Cabrera Urbán ¹⁷⁰, D. Caforio ¹²⁹, V.M. Cairo ^{39a,39b}, O. Cakir ^{4a}, N. Calace ⁵¹,
 P. Calafiura ¹⁶, A. Calandri ⁸⁷, G. Calderini ⁸², P. Calfayan ¹⁰¹, L.P. Caloba ^{26a}, S. Calvente Lopez ⁸⁴,
 D. Calvet ³⁶, S. Calvet ³⁶, T.P. Calvet ⁸⁷, R. Camacho Toro ³³, S. Camarda ³², P. Camarri ^{134a,134b},
 D. Cameron ¹²⁰, R. Caminal Armadans ¹⁶⁹, C. Camincher ⁵⁷, S. Campana ³², M. Campanelli ⁸⁰,
 A. Camplani ^{93a,93b}, A. Campoverde ¹⁴⁴, V. Canale ^{105a,105b}, A. Canepa ^{163a}, M. Cano Bret ¹⁴¹, J. Cantero ¹¹⁵,
 R. Cantrill ^{127a}, T. Cao ⁴², M.D.M. Capeans Garrido ³², I. Caprini ^{28b}, M. Caprini ^{28b}, M. Capua ^{39a,39b},
 R. Caputo ⁸⁵, R.M. Carbone ³⁷, R. Cardarelli ^{134a}, F. Cardillo ⁵⁰, I. Carli ¹³⁰, T. Carli ³², G. Carlino ^{105a},
 L. Carminati ^{93a,93b}, S. Caron ¹⁰⁷, E. Carquin ^{34b}, G.D. Carrillo-Montoya ³², J.R. Carter ³⁰,
 J. Carvalho ^{127a,127c}, D. Casadei ¹⁹, M.P. Casado ^{13,i}, M. Casolino ¹³, D.W. Casper ¹⁶⁶,
 E. Castaneda-Miranda ^{148a}, R. Castelijin ¹⁰⁸, A. Castelli ¹⁰⁸, V. Castillo Gimenez ¹⁷⁰, N.F. Castro ^{127a,j},
 A. Catinaccio ³², J.R. Catmore ¹²⁰, A. Cattai ³², J. Caudron ⁸⁵, V. Cavaliere ¹⁶⁹, E. Cavallaro ¹³, D. Cavalli ^{93a},
 M. Cavalli-Sforza ¹³, V. Cavasinni ^{125a,125b}, F. Ceradini ^{135a,135b}, L. Cerda Alberich ¹⁷⁰, B.C. Cerio ⁴⁷,
 A.S. Cerqueira ^{26b}, A. Cerri ¹⁵², L. Cerrito ⁷⁸, F. Cerutti ¹⁶, M. Cerv ³², A. Cervelli ¹⁸, S.A. Cetin ^{20d},
 A. Chafaq ^{136a}, D. Chakraborty ¹⁰⁹, S.K. Chan ⁵⁸, Y.L. Chan ^{62a}, P. Chang ¹⁶⁹, J.D. Chapman ³⁰,
 D.G. Charlton ¹⁹, A. Chatterjee ⁵¹, C.C. Chau ¹⁶², C.A. Chavez Barajas ¹⁵², S. Che ¹¹², S. Cheatham ⁷⁴,
 A. Chegwidden ⁹², S. Chekanov ⁶, S.V. Chekulaev ^{163a}, G.A. Chelkov ^{67,k}, M.A. Chelstowska ⁹¹, C. Chen ⁶⁶,
 H. Chen ²⁷, K. Chen ¹⁵¹, S. Chen ^{35b}, S. Chen ¹⁵⁸, X. Chen ^{35c}, Y. Chen ⁶⁹, H.C. Cheng ⁹¹, H.J. Cheng ^{35a},

Y. Cheng³³, A. Cheplakov⁶⁷, E. Cheremushkina¹³¹, R. Cherkaoui El Moursli^{136e}, V. Chernyatin^{27,*},
 E. Cheu⁷, L. Chevalier¹³⁷, V. Chiarella⁴⁹, G. Chiarelli^{125a,125b}, G. Chiodini^{75a}, A.S. Chisholm¹⁹,
 A. Chitan^{28b}, M.V. Chizhov⁶⁷, K. Choi⁶³, A.R. Chomont³⁶, S. Chouridou⁹, B.K.B. Chow¹⁰¹,
 V. Christodoulou⁸⁰, D. Chromek-Burckhart³², J. Chudoba¹²⁸, A.J. Chuinard⁸⁹, J.J. Chwastowski⁴¹,
 L. Chytka¹¹⁶, G. Ciapetti^{133a,133b}, A.K. Ciftci^{4a}, D. Cinca⁴⁵, V. Cindro⁷⁷, I.A. Cioara²³, C. Ciocca^{22a,22b},
 A. Ciocio¹⁶, F. Ciroto^{105a,105b}, Z.H. Citron¹⁷⁵, M. Citterio^{93a}, M. Ciubancan^{28b}, A. Clark⁵¹, B.L. Clark⁵⁸,
 M.R. Clark³⁷, P.J. Clark⁴⁸, R.N. Clarke¹⁶, C. Clement^{149a,149b}, Y. Coadou⁸⁷, M. Cobal^{167a,167c},
 A. Coccaro⁵¹, J. Cochran⁶⁶, L. Coffey²⁵, L. Colasurdo¹⁰⁷, B. Cole³⁷, A.P. Colijn¹⁰⁸, J. Collot⁵⁷,
 T. Colombo³², G. Compostella¹⁰², P. Conde Muiño^{127a,127b}, E. Coniavitis⁵⁰, S.H. Connell^{148b},
 I.A. Connelly⁷⁹, V. Consorti⁵⁰, S. Constantinescu^{28b}, G. Conti³², F. Conventi^{105a,l}, M. Cooke¹⁶,
 B.D. Cooper⁸⁰, A.M. Cooper-Sarkar¹²¹, K.J.R. Cormier¹⁶², T. Cornelissen¹⁷⁸, M. Corradi^{133a,133b},
 F. Corriveau^{89,m}, A. Corso-Radu¹⁶⁶, A. Cortes-Gonzalez¹³, G. Cortiana¹⁰², G. Costa^{93a}, M.J. Costa¹⁷⁰,
 D. Costanzo¹⁴², G. Cottin³⁰, G. Cowan⁷⁹, B.E. Cox⁸⁶, K. Cranmer¹¹¹, S.J. Crawley⁵⁵, G. Cree³¹,
 S. Crépe-Renaudin⁵⁷, F. Crescioli⁸², W.A. Cribbs^{149a,149b}, M. Crispin Ortuzar¹²¹, M. Cristinziani²³,
 V. Croft¹⁰⁷, G. Crosetti^{39a,39b}, T. Cuhadar Donszelmann¹⁴², J. Cummings¹⁷⁹, M. Curatolo⁴⁹, J. Cúth⁸⁵,
 C. Cuthbert¹⁵³, H. Czirr¹⁴⁴, P. Czodrowski³, G. D'amen^{22a,22b}, S. D'Auria⁵⁵, M. D'Onofrio⁷⁶,
 M.J. Da Cunha Sargedas De Sousa^{127a,127b}, C. Da Via⁸⁶, W. Dabrowski^{40a}, T. Dado^{147a}, T. Dai⁹¹,
 O. Dale¹⁵, F. Dallaire⁹⁶, C. Dallapiccola⁸⁸, M. Dam³⁸, J.R. Dandoy³³, N.P. Dang⁵⁰, A.C. Daniells¹⁹,
 N.S. Dann⁸⁶, M. Danninger¹⁷¹, M. Dano Hoffmann¹³⁷, V. Dao⁵⁰, G. Darbo^{52a}, S. Darmora⁸,
 J. Dassoulas³, A. Dattagupta⁶³, W. Davey²³, C. David¹⁷², T. Davidek¹³⁰, M. Davies¹⁵⁶, P. Davison⁸⁰,
 E. Dawe⁹⁰, I. Dawson¹⁴², R.K. Daya-Ishmukhametova⁸⁸, K. De⁸, R. de Asmundis^{105a}, A. De Benedetti¹¹⁴,
 S. De Castro^{22a,22b}, S. De Cecco⁸², N. De Groot¹⁰⁷, P. de Jong¹⁰⁸, H. De la Torre⁸⁴, F. De Lorenzi⁶⁶,
 A. De Maria⁵⁶, D. De Pedis^{133a}, A. De Salvo^{133a}, U. De Sanctis¹⁵², A. De Santo¹⁵²,
 J.B. De Vivie De Regie¹¹⁸, W.J. Dearnaley⁷⁴, R. Debebe²⁷, C. Debenedetti¹³⁸, D.V. Dedovich⁶⁷,
 N. Dehghanian³, I. Deigaard¹⁰⁸, M. Del Gaudio^{39a,39b}, J. Del Peso⁸⁴, T. Del Prete^{125a,125b}, D. Delgove¹¹⁸,
 F. Deliot¹³⁷, C.M. Delitzsch⁵¹, M. Deliyergiyev⁷⁷, A. Dell'Acqua³², L. Dell'Asta²⁴, M. Dell'Orso^{125a,125b},
 M. Della Pietra^{105a,l}, D. della Volpe⁵¹, M. Delmastro⁵, P.A. Delsart⁵⁷, D.A. DeMarco¹⁶², S. Demers¹⁷⁹,
 M. Demichev⁶⁷, A. Demilly⁸², S.P. Denisov¹³¹, D. Denysiuk¹³⁷, D. Derendarz⁴¹, J.E. Derkaoui^{136d},
 F. Derue⁸², P. Dervan⁷⁶, K. Desch²³, C. Deterre⁴⁴, K. Dette⁴⁵, P.O. Deviveiros³², A. Dewhurst¹³²,
 S. Dhaliwal²⁵, A. Di Ciaccio^{134a,134b}, L. Di Ciaccio⁵, W.K. Di Clemente¹²³, C. Di Donato^{133a,133b},
 A. Di Girolamo³², B. Di Girolamo³², B. Di Micco^{135a,135b}, R. Di Nardo³², A. Di Simone⁵⁰, R. Di Sipio¹⁶²,
 D. Di Valentino³¹, C. Diaconu⁸⁷, M. Diamond¹⁶², F.A. Dias⁴⁸, M.A. Diaz^{34a}, E.B. Diehl⁹¹, J. Dietrich¹⁷,
 S. Diglio⁸⁷, A. Dimitrievska¹⁴, J. Dingfelder²³, P. Dita^{28b}, S. Dita^{28b}, F. Dittus³², F. Djama⁸⁷,
 T. Djobava^{53b}, J.I. Djuvsland^{60a}, M.A.B. do Vale^{26c}, D. Dobos³², M. Dobre^{28b}, C. Doglioni⁸³,
 T. Dohmae¹⁵⁸, J. Dolejsi¹³⁰, Z. Dolezal¹³⁰, B.A. Dolgoshein^{99,*}, M. Donadelli^{26d}, S. Donati^{125a,125b},
 P. Dondero^{122a,122b}, J. Donini³⁶, J. Dopke¹³², A. Doria^{105a}, M.T. Dova⁷³, A.T. Doyle⁵⁵, E. Drechsler⁵⁶,
 M. Dris¹⁰, Y. Du¹⁴⁰, J. Duarte-Campderros¹⁵⁶, E. Duchovni¹⁷⁵, G. Duckeck¹⁰¹, O.A. Ducu^{96,n},
 D. Duda¹⁰⁸, A. Dudarev³², E.M. Duffield¹⁶, L. Duflot¹¹⁸, L. Duguid⁷⁹, M. Dührssen³², M. Dumancic¹⁷⁵,
 M. Dunford^{60a}, H. Duran Yildiz^{4a}, M. Düren⁵⁴, A. Durglishvili^{53b}, D. Duschinger⁴⁶, B. Dutta⁴⁴,
 M. Dyndal⁴⁴, C. Eckardt⁴⁴, K.M. Ecker¹⁰², R.C. Edgar⁹¹, N.C. Edwards⁴⁸, T. Eifert³², G. Eigen¹⁵,
 K. Einsweiler¹⁶, T. Ekelof¹⁶⁸, M. El Kacimi^{136c}, V. Ellajosyula⁸⁷, M. Ellert¹⁶⁸, S. Elles⁵, F. Ellinghaus¹⁷⁸,
 A.A. Elliot¹⁷², N. Ellis³², J. Elmsheuser²⁷, M. Elsing³², D. Emelianov¹³², Y. Enari¹⁵⁸, O.C. Endner⁸⁵,
 M. Endo¹¹⁹, J.S. Ennis¹⁷³, J. Erdmann⁴⁵, A. Ereditato¹⁸, G. Ernis¹⁷⁸, J. Ernst², M. Ernst²⁷, S. Errede¹⁶⁹,
 E. Ertel⁸⁵, M. Escalier¹¹⁸, H. Esch⁴⁵, C. Escobar¹²⁶, B. Esposito⁴⁹, A.I. Etienvre¹³⁷, E. Etzion¹⁵⁶,
 H. Evans⁶³, A. Ezhilov¹²⁴, F. Fabbri^{22a,22b}, L. Fabbri^{22a,22b}, G. Facini³³, R.M. Fakhruddinov¹³¹,
 S. Falciano^{133a}, R.J. Falla⁸⁰, J. Faltova³², Y. Fang^{35a}, M. Fanti^{93a,93b}, A. Farbin⁸, A. Farilla^{135a},
 C. Farina¹²⁶, E.M. Farina^{122a,122b}, T. Farooque¹³, S. Farrell¹⁶, S.M. Farrington¹⁷³, P. Farthouat³²,
 F. Fassi^{136e}, P. Fassnacht³², D. Fassouliotis⁹, M. Fauci Giannelli⁷⁹, A. Favareto^{52a,52b}, W.J. Fawcett¹²¹,
 L. Fayard¹¹⁸, O.L. Fedin^{124,o}, W. Fedorko¹⁷¹, S. Feigl¹²⁰, L. Feligioni⁸⁷, C. Feng¹⁴⁰, E.J. Feng³², H. Feng⁹¹,
 A.B. Fenyuk¹³¹, L. Feremenga⁸, P. Fernandez Martinez¹⁷⁰, S. Fernandez Perez¹³, J. Ferrando⁵⁵,
 A. Ferrari¹⁶⁸, P. Ferrari¹⁰⁸, R. Ferrari^{122a}, D.E. Ferreira de Lima^{60b}, A. Ferrer¹⁷⁰, D. Ferrere⁵¹,
 C. Ferretti⁹¹, A. Ferretto Parodi^{52a,52b}, F. Fiedler⁸⁵, A. Filipčič⁷⁷, M. Filipuzzi⁴⁴, F. Filthaut¹⁰⁷,

M. Fincke-Keeler¹⁷², K.D. Finelli¹⁵³, M.C.N. Fiolhais^{127a,127c}, L. Fiorini¹⁷⁰, A. Firan⁴², A. Fischer²,
 C. Fischer¹³, J. Fischer¹⁷⁸, W.C. Fisher⁹², N. Flaschel⁴⁴, I. Fleck¹⁴⁴, P. Fleischmann⁹¹, G.T. Fletcher¹⁴²,
 R.R.M. Fletcher¹²³, T. Flick¹⁷⁸, A. Floderus⁸³, L.R. Flores Castillo^{62a}, M.J. Flowerdew¹⁰², G.T. Forcolin⁸⁶,
 A. Formica¹³⁷, A. Forti⁸⁶, A.G. Foster¹⁹, D. Fournier¹¹⁸, H. Fox⁷⁴, S. Fracchia¹³, P. Francavilla⁸²,
 M. Franchini^{22a,22b}, D. Francis³², L. Franconi¹²⁰, M. Franklin⁵⁸, M. Frate¹⁶⁶, M. Fraternali^{122a,122b},
 D. Freeborn⁸⁰, S.M. Fressard-Batranceanu³², F. Friedrich⁴⁶, D. Froidevaux³², J.A. Frost¹²¹, C. Fukunaga¹⁵⁹,
 E. Fullana Torregrosa⁸⁵, T. Fusayasu¹⁰³, J. Fuster¹⁷⁰, C. Gabaldon⁵⁷, O. Gabizon¹⁷⁸, A. Gabrielli^{22a,22b},
 A. Gabrielli¹⁶, G.P. Gach^{40a}, S. Gadatsch³², S. Gadomski⁵¹, G. Gagliardi^{52a,52b}, L.G. Gagnon⁹⁶,
 P. Gagnon⁶³, C. Galea¹⁰⁷, B. Galhardo^{127a,127c}, E.J. Gallas¹²¹, B.J. Gallop¹³², P. Gallus¹²⁹, G. Galster³⁸,
 K.K. Gan¹¹², J. Gao⁵⁹, Y. Gao⁴⁸, Y.S. Gao^{146.g}, F.M. Garay Walls⁴⁸, C. García¹⁷⁰, J.E. García Navarro¹⁷⁰,
 M. Garcia-Sciveres¹⁶, R.W. Gardner³³, N. Garelli¹⁴⁶, V. Garonne¹²⁰, A. Gascon Bravo⁴⁴, C. Gatti⁴⁹,
 A. Gaudiello^{52a,52b}, G. Gaudio^{122a}, B. Gaur¹⁴⁴, L. Gauthier⁹⁶, I.L. Gavrilenko⁹⁷, C. Gay¹⁷¹, G. Gaycken²³,
 E.N. Gazis¹⁰, Z. Gecse¹⁷¹, C.N.P. Gee¹³², Ch. Geich-Gimbel²³, M. Geisen⁸⁵, M.P. Geisler^{60a},
 C. Gemme^{52a}, M.H. Genest⁵⁷, C. Geng^{59.p}, S. Gentile^{133a,133b}, C. Gentsos¹⁵⁷, S. George⁷⁹,
 D. Gerbaudo¹³, A. Gershon¹⁵⁶, S. Ghasemi¹⁴⁴, H. Ghazlane^{136b}, M. Ghneimat²³, B. Giacobbe^{22a},
 S. Giagu^{133a,133b}, P. Giannetti^{125a,125b}, B. Gibbard²⁷, S.M. Gibson⁷⁹, M. Gignac¹⁷¹, M. Gilchriese¹⁶,
 T.P.S. Gillam³⁰, D. Gillberg³¹, G. Gilles¹⁷⁸, D.M. Gingrich^{3.d}, N. Giokaris⁹, M.P. Giordani^{167a,167c},
 F.M. Giorgi^{22a}, F.M. Giorgi¹⁷, P.F. Giraud¹³⁷, P. Giromini⁵⁸, D. Giugni^{93a}, F. Giuli¹²¹, C. Giuliani¹⁰²,
 M. Giulini^{60b}, B.K. Gjelsten¹²⁰, S. Gkaitatzis¹⁵⁷, I. Gkialas¹⁵⁷, E.L. Gkougkousis¹¹⁸, L.K. Gladilin¹⁰⁰,
 C. Glasman⁸⁴, J. Glatzer⁵⁰, P.C.F. Glaysher⁴⁸, A. Glazov⁴⁴, M. Goblirsch-Kolb²⁵, J. Godlewski⁴¹,
 S. Goldfarb⁹⁰, T. Golling⁵¹, D. Golubkov¹³¹, A. Gomes^{127a,127b,127d}, R. Gonçalo^{127a},
 J. Goncalves Pinto Firmino Da Costa¹³⁷, G. Gonella⁵⁰, L. Gonella¹⁹, A. Gongadze⁶⁷,
 S. González de la Hoz¹⁷⁰, G. Gonzalez Parra¹³, S. Gonzalez-Sevilla⁵¹, L. Goossens³², P.A. Gorbounov⁹⁸,
 H.A. Gordon²⁷, I. Gorelov¹⁰⁶, B. Gorini³², E. Gorini^{75a,75b}, A. Gorišek⁷⁷, E. Gornicki⁴¹, A.T. Goshaw⁴⁷,
 C. Gössling⁴⁵, M.I. Gostkin⁶⁷, C.R. Goudet¹¹⁸, D. Goujdami^{136c}, A.G. Goussiou¹³⁹, N. Govender^{148b,q},
 E. Gozani¹⁵⁵, L. Graber⁵⁶, I. Grabowska-Bold^{40a}, P.O.J. Gradin⁵⁷, P. Grafström^{22a,22b}, J. Gramling⁵¹,
 E. Gramstad¹²⁰, S. Grancagnolo¹⁷, V. Gratchev¹²⁴, P.M. Gravila^{28e}, H.M. Gray³², E. Graziani^{135a},
 Z.D. Greenwood^{81.r}, C. Grefe²³, K. Gregersen⁸⁰, I.M. Gregor⁴⁴, P. Grenier¹⁴⁶, K. Grevtsov⁵, J. Griffiths⁸,
 A.A. Grillo¹³⁸, K. Grimm⁷⁴, S. Grinstein^{13.s}, Ph. Gris³⁶, J.-F. Grivaz¹¹⁸, S. Groh⁸⁵, J.P. Grohs⁴⁶,
 E. Gross¹⁷⁵, J. Grosse-Knetter⁵⁶, G.C. Grossi⁸¹, Z.J. Grout¹⁵², L. Guan⁹¹, W. Guan¹⁷⁶, J. Guenther⁶⁴,
 F. Guescini⁵¹, D. Guest¹⁶⁶, O. Gueta¹⁵⁶, E. Guido^{52a,52b}, T. Guillemin⁵, S. Guindon², U. Gul⁵⁵,
 C. Gumpert³², J. Guo¹⁴¹, Y. Guo^{59.p}, R. Gupta⁴², S. Gupta¹²¹, G. Gustavino^{133a,133b}, P. Gutierrez¹¹⁴,
 N.G. Gutierrez Ortiz⁸⁰, C. Gutsche⁴⁶, C. Guyot¹³⁷, C. Gwenlan¹²¹, C.B. Gwilliam⁷⁶, A. Haas¹¹¹,
 C. Haber¹⁶, H.K. Hadavand⁸, N. Haddad^{136e}, A. Hader⁸⁷, P. Haefner²³, S. Hageböck²³, Z. Hajduk⁴¹,
 H. Hakobyan^{180.*}, M. Haleem⁴⁴, J. Haley¹¹⁵, G. Halladjian⁹², G.D. Hallewell⁸⁷, K. Hamacher¹⁷⁸,
 P. Hamal¹¹⁶, K. Hamano¹⁷², A. Hamilton^{148a}, G.N. Hamity¹⁴², P.G. Hamnett⁴⁴, L. Han⁵⁹, K. Hanagaki^{68.t},
 K. Hanawa¹⁵⁸, M. Hance¹³⁸, B. Haney¹²³, P. Hanke^{60a}, R. Hanna¹³⁷, J.B. Hansen³⁸, J.D. Hansen³⁸,
 M.C. Hansen²³, P.H. Hansen³⁸, K. Hara¹⁶⁴, A.S. Hard¹⁷⁶, T. Harenberg¹⁷⁸, F. Hariri¹¹⁸, S. Harkusha⁹⁴,
 R.D. Harrington⁴⁸, P.F. Harrison¹⁷³, F. Hartjes¹⁰⁸, N.M. Hartmann¹⁰¹, M. Hasegawa⁶⁹, Y. Hasegawa¹⁴³,
 A. Hasib¹¹⁴, S. Hassani¹³⁷, S. Haug¹⁸, R. Hauser⁹², L. Hauswald⁴⁶, M. Havranek¹²⁸, C.M. Hawkes¹⁹,
 R.J. Hawkins³², D. Hayden⁹², C.P. Hays¹²¹, J.M. Hays⁷⁸, H.S. Hayward⁷⁶, S.J. Haywood¹³², S.J. Head¹⁹,
 T. Heck⁸⁵, V. Hedberg⁸³, L. Heelan⁸, S. Heim¹²³, T. Heim¹⁶, B. Heinemann¹⁶, J.J. Heinrich¹⁰¹,
 L. Heinrich¹¹¹, C. Heinz⁵⁴, J. Hejbal¹²⁸, L. Helary²⁴, S. Hellman^{149a,149b}, C. Hensens³², J. Henderson¹²¹,
 R.C.W. Henderson⁷⁴, Y. Heng¹⁷⁶, S. Henkelmann¹⁷¹, A.M. Henriques Correia³², S. Henrot-Versille¹¹⁸,
 G.H. Herbert¹⁷, Y. Hernández Jiménez¹⁷⁰, G. Herten⁵⁰, R. Hertenberger¹⁰¹, L. Hervas³², G.G. Hesketh⁸⁰,
 N.P. Hessey¹⁰⁸, J.W. Hetherly⁴², R. Hickling⁷⁸, E. Higón-Rodríguez¹⁷⁰, E. Hill¹⁷², J.C. Hill³⁰, K.H. Hiller⁴⁴,
 S.J. Hillier¹⁹, I. Hinchliffe¹⁶, E. Hines¹²³, R.R. Hinman¹⁶, M. Hirose⁵⁰, D. Hirschbuehl¹⁷⁸, J. Hobbs¹⁵¹,
 N. Hod^{163a}, M.C. Hodgkinson¹⁴², P. Hodgson¹⁴², A. Hoecker³², M.R. Hoefkamp¹⁰⁶, F. Hoenig¹⁰¹,
 D. Hohn²³, T.R. Holmes¹⁶, M. Homann⁴⁵, T.M. Hong¹²⁶, B.H. Hooberman¹⁶⁹, W.H. Hopkins¹¹⁷,
 Y. Horii¹⁰⁴, A.J. Horton¹⁴⁵, J.-Y. Hostachy⁵⁷, S. Hou¹⁵⁴, A. Hoummada^{136a}, J. Howarth⁴⁴,
 M. Hrabovsky¹¹⁶, I. Hristova¹⁷, J. Hrivnac¹¹⁸, T. Hryn'ova⁵, A. Hrynevich⁹⁵, C. Hsu^{148c}, P.J. Hsu^{154.u},
 S.-C. Hsu¹³⁹, D. Hu³⁷, Q. Hu⁵⁹, Y. Huang⁴⁴, Z. Hubacek¹²⁹, F. Hubaut⁸⁷, F. Huegging²³, T.B. Huffman¹²¹,

E.W. Hughes³⁷, G. Hughes⁷⁴, M. Huhtinen³², P. Huo¹⁵¹, N. Huseynov^{67,b}, J. Huston⁹², J. Huth⁵⁸,
 G. Iacobucci⁵¹, G. Iakovidis²⁷, I. Ibragimov¹⁴⁴, L. Iconomidou-Fayard¹¹⁸, E. Ideal¹⁷⁹, Z. Idrissi^{136e},
 P. Iengo³², O. Igonkina^{108,v}, T. Iizawa¹⁷⁴, Y. Ikegami⁶⁸, M. Ikeno⁶⁸, Y. Ilchenko^{11,w}, D. Iliadis¹⁵⁷,
 N. Ilic¹⁴⁶, T. Ince¹⁰², G. Introzzi^{122a,122b}, P. Ioannou^{9,*}, M. Iodice^{135a}, K. Iordanidou³⁷, V. Ippolito⁵⁸,
 N. Ishijima¹¹⁹, M. Ishino⁷⁰, M. Ishitsuka¹⁶⁰, R. Ishmukhametov¹¹², C. Issever¹²¹, S. Istin^{20a}, F. Ito¹⁶⁴,
 J.M. Iturbe Ponce⁸⁶, R. Iuppa^{134a,134b}, W. Iwanski⁶⁴, H. Iwasaki⁶⁸, J.M. Izen⁴³, V. Izzo^{105a}, S. Jabbar³,
 B. Jackson¹²³, M. Jackson⁷⁶, P. Jackson¹, V. Jain², K.B. Jakobi⁸⁵, K. Jakobs⁵⁰, S. Jakobsen³²,
 T. Jakoubek¹²⁸, D.O. Jamin¹¹⁵, D.K. Jana⁸¹, E. Jansen⁸⁰, R. Jansky⁶⁴, J. Janssen²³, M. Janus⁵⁶,
 G. Jarlskog⁸³, N. Javadov^{67,b}, T. Javůrek⁵⁰, F. Jeanneau¹³⁷, L. Jeanty¹⁶, G.-Y. Jeng¹⁵³, D. Jennens⁹⁰,
 P. Jenni^{50,x}, J. Jentsch⁴⁵, C. Jeske¹⁷³, S. Jézéquel⁵, H. Ji¹⁷⁶, J. Jia¹⁵¹, H. Jiang⁶⁶, Y. Jiang⁵⁹, S. Jiggins⁸⁰,
 J. Jimenez Pena¹⁷⁰, S. Jin^{35a}, A. Jinaru^{28b}, O. Jinnouchi¹⁶⁰, P. Johansson¹⁴², K.A. Johns⁷, W.J. Johnson¹³⁹,
 K. Jon-And^{149a,149b}, G. Jones¹⁷³, R.W.L. Jones⁷⁴, S. Jones⁷, T.J. Jones⁷⁶, J. Jongmanns^{60a},
 P.M. Jorge^{127a,127b}, J. Jovicevic^{163a}, X. Ju¹⁷⁶, A. Juste Rozas^{13,s}, M.K. Köhler¹⁷⁵, A. Kaczmarska⁴¹,
 M. Kado¹¹⁸, H. Kagan¹¹², M. Kagan¹⁴⁶, S.J. Kahn⁸⁷, E. Kajomovitz⁴⁷, C.W. Kalderon¹²¹, A. Kaluza⁸⁵,
 S. Kama⁴², A. Kamenshchikov¹³¹, N. Kanaya¹⁵⁸, S. Kaneti³⁰, L. Kanjir⁷⁷, V.A. Kantserov⁹⁹, J. Kanzaki⁶⁸,
 B. Kaplan¹¹¹, L.S. Kaplan¹⁷⁶, A. Kapliy³³, D. Kar^{148c}, K. Karakostas¹⁰, A. Karamaoun³, N. Karastathis¹⁰,
 M.J. Kareem⁵⁶, E. Karentzos¹⁰, M. Karnevskiy⁸⁵, S.N. Karpov⁶⁷, Z.M. Karpova⁶⁷, K. Karthik¹¹¹,
 V. Kartvelishvili⁷⁴, A.N. Karyukhin¹³¹, K. Kasahara¹⁶⁴, L. Kashif¹⁷⁶, R.D. Kass¹¹², A. Kastanas¹⁵,
 Y. Kataoka¹⁵⁸, C. Kato¹⁵⁸, A. Katre⁵¹, J. Katzy⁴⁴, K. Kawade¹⁰⁴, K. Kawagoe⁷², T. Kawamoto¹⁵⁸,
 G. Kawamura⁵⁶, S. Kazama¹⁵⁸, V.F. Kazanin^{110,c}, R. Keeler¹⁷², R. Kehoe⁴², J.S. Keller⁴⁴, J.J. Kempster⁷⁹,
 H. Keoshkerian¹⁶², O. Kepka¹²⁸, B.P. Kerševan⁷⁷, S. Kersten¹⁷⁸, R.A. Keyes⁸⁹, M. Khader¹⁶⁹,
 F. Khalil-zada¹², A. Khanov¹¹⁵, A.G. Kharlamov^{110,c}, T.J. Khoo⁵¹, V. Khovanskiy⁹⁸, E. Khramov⁶⁷,
 J. Khubua^{53b,y}, S. Kido⁶⁹, H.Y. Kim⁸, S.H. Kim¹⁶⁴, Y.K. Kim³³, N. Kimura¹⁵⁷, O.M. Kind¹⁷, B.T. King⁷⁶,
 M. King¹⁷⁰, S.B. King¹⁷¹, J. Kirk¹³², A.E. Kiryunin¹⁰², T. Kishimoto⁶⁹, D. Kisiielewska^{40a}, F. Kiss⁵⁰,
 K. Kiuchi¹⁶⁴, O. Kivernyk¹³⁷, E. Kladiva^{147b}, M.H. Klein³⁷, M. Klein⁷⁶, U. Klein⁷⁶, K. Kleinknecht⁸⁵,
 P. Klimek¹⁰⁹, A. Klimentov²⁷, R. Klingenberg⁴⁵, J.A. Klinger¹⁴², T. Klioutchnikova³², E.-E. Kluge^{60a},
 P. Kluit¹⁰⁸, S. Kluth¹⁰², J. Knapik⁴¹, E. Kneringer⁶⁴, E.B.F.G. Knoops⁸⁷, A. Knue⁵⁵, A. Kobayashi¹⁵⁸,
 D. Kobayashi¹⁶⁰, T. Kobayashi¹⁵⁸, M. Kobel⁴⁶, M. Kocian¹⁴⁶, P. Kodys¹³⁰, T. Koffas³¹, E. Koffeman¹⁰⁸,
 T. Koi¹⁴⁶, H. Kolanoski¹⁷, M. Kolb^{60b}, I. Koletsou⁵, A.A. Komar^{97,*}, Y. Komori¹⁵⁸, T. Kondo⁶⁸,
 N. Kondrashova⁴⁴, K. Köneke⁵⁰, A.C. König¹⁰⁷, T. Kono^{68,z}, R. Konoplich^{111,aa}, N. Konstantinidis⁸⁰,
 R. Kopeliansky⁶³, S. Koperny^{40a}, L. Köpke⁸⁵, A.K. Kopp⁵⁰, K. Korcyl⁴¹, K. Kordas¹⁵⁷, A. Korn⁸⁰,
 A.A. Korol^{110,c}, I. Korolkov¹³, E.V. Korolkova¹⁴², O. Kortner¹⁰², S. Kortner¹⁰², T. Kosek¹³⁰,
 V.V. Kostyukhin²³, A. Kotwal⁴⁷, A. Kourkoumeli-Charalampidi¹⁵⁷, C. Kourkoumelis⁹, V. Kouskoura²⁷,
 A.B. Kowalewska⁴¹, R. Kowalewski¹⁷², T.Z. Kowalski^{40a}, C. Kozakai¹⁵⁸, W. Kozanecki¹³⁷, A.S. Kozhin¹³¹,
 V.A. Kramarenko¹⁰⁰, G. Kramberger⁷⁷, D. Krasnopevtsev⁹⁹, M.W. Krasny⁸², A. Krasznahorkay³²,
 J.K. Kraus²³, A. Kravchenko²⁷, M. Kretz^{60c}, J. Kretzschmar⁷⁶, K. Kreutzfeldt⁵⁴, P. Krieger¹⁶², K. Krizka³³,
 K. Kroeninger⁴⁵, H. Kroha¹⁰², J. Kroll¹²³, J. Kroseberg²³, J. Krstic¹⁴, U. Kruchonak⁶⁷, H. Krüger²³,
 N. Krumnack⁶⁶, A. Kruse¹⁷⁶, M.C. Kruse⁴⁷, M. Kruskal²⁴, T. Kubota⁹⁰, H. Kucuk⁸⁰, S. Kuday^{4b},
 J.T. Kuechler¹⁷⁸, S. Kuehn⁵⁰, A. Kugel^{60c}, F. Kuger¹⁷⁷, A. Kuhl¹³⁸, T. Kuhl⁴⁴, V. Kukhtin⁶⁷, R. Kukla¹³⁷,
 Y. Kulchitsky⁹⁴, S. Kuleshov^{34b}, M. Kuna^{133a,133b}, T. Kunigo⁷⁰, A. Kupco¹²⁸, H. Kurashige⁶⁹,
 Y.A. Kurochkin⁹⁴, V. Kus¹²⁸, E.S. Kuwertz¹⁷², M. Kuze¹⁶⁰, J. Kvita¹¹⁶, T. Kwan¹⁷², D. Kyriazopoulos¹⁴²,
 A. La Rosa¹⁰², J.L. La Rosa Navarro^{26d}, L. La Rotonda^{39a,39b}, C. Lacasta¹⁷⁰, F. Lacava^{133a,133b}, J. Lacey³¹,
 H. Lacker¹⁷, D. Lacour⁸², V.R. Lacuesta¹⁷⁰, E. Ladygin⁶⁷, R. Lafaye⁵, B. Laforge⁸², T. Lagouri¹⁷⁹, S. Lai⁵⁶,
 S. Lammers⁶³, W. Lampl⁷, E. Lançon¹³⁷, U. Landgraf⁵⁰, M.P.J. Landon⁷⁸, V.S. Lang^{60a}, J.C. Lange¹³,
 A.J. Lankford¹⁶⁶, F. Lanni²⁷, K. Lantsch²³, A. Lanza^{122a}, S. Laplace⁸², C. Lapoire³², J.F. Laporte¹³⁷,
 T. Lari^{93a}, F. Lasagni Manghi^{22a,22b}, M. Lassnig³², P. Laurelli⁴⁹, W. Lavrijsen¹⁶, A.T. Law¹³⁸, P. Laycock⁷⁶,
 T. Lazovich⁵⁸, M. Lazzaroni^{93a,93b}, B. Le⁹⁰, O. Le Dortz⁸², E. Le Guirriec⁸⁷, E.P. Le Quilleuc¹³⁷,
 M. LeBlanc¹⁷², T. LeCompte⁶, F. Ledroit-Guillon⁵⁷, C.A. Lee²⁷, S.C. Lee¹⁵⁴, L. Lee¹, G. Lefebvre⁸²,
 M. Lefebvre¹⁷², F. Legger¹⁰¹, C. Leggett¹⁶, A. Lehan⁷⁶, G. Lehmann Miotto³², X. Lei⁷, W.A. Leight³¹,
 A.G. Leister¹⁷⁹, M.A.L. Leite^{26d}, R. Leitner¹³⁰, D. Lellouch¹⁷⁵, B. Lemmer⁵⁶, K.J.C. Leney⁸⁰, T. Lenz²³,
 B. Lenzi³², R. Leone⁷, S. Leone^{125a,125b}, C. Leonidopoulos⁴⁸, S. Leontsinis¹⁰, G. Lerner¹⁵², C. Leroy⁹⁶,
 A.A.J. Lesage¹³⁷, C.G. Lester³⁰, M. Levchenko¹²⁴, J. Levêque⁵, D. Levin⁹¹, L.J. Levinson¹⁷⁵, M. Levy¹⁹,

D. Lewis⁷⁸, A.M. Leyko²³, M. Leyton⁴³, B. Li^{59,p}, H. Li¹⁵¹, H.L. Li³³, L. Li⁴⁷, L. Li¹⁴¹, Q. Li^{35a}, S. Li⁴⁷, X. Li⁸⁶, Y. Li¹⁴⁴, Z. Liang^{35a}, B. Liberti^{134a}, A. Liblong¹⁶², P. Lichard³², K. Lie¹⁶⁹, J. Liebal²³, W. Liebig¹⁵, A. Limosani¹⁵³, S.C. Lin^{154,ab}, T.H. Lin⁸⁵, B.E. Lindquist¹⁵¹, A.E. Lioni⁵¹, E. Lipeles¹²³, A. Lipniacka¹⁵, M. Lisovyi^{60b}, T.M. Liss¹⁶⁹, A. Lister¹⁷¹, A.M. Litke¹³⁸, B. Liu^{154,ac}, D. Liu¹⁵⁴, H. Liu⁹¹, H. Liu²⁷, J. Liu⁸⁷, J.B. Liu⁵⁹, K. Liu⁸⁷, L. Liu¹⁶⁹, M. Liu⁴⁷, M. Liu⁵⁹, Y.L. Liu⁵⁹, Y. Liu⁵⁹, M. Livan^{122a,122b}, A. Lleres⁵⁷, J. Llorente Merino^{35a}, S.L. Lloyd⁷⁸, F. Lo Sterzo¹⁵⁴, E.M. Lobodzinska⁴⁴, P. Loch⁷, W.S. Lockman¹³⁸, F.K. Loebinger⁸⁶, A.E. Loevschall-Jensen³⁸, K.M. Loew²⁵, A. Loginov^{179,*}, T. Lohse¹⁷, K. Lohwasser⁴⁴, M. Lokajicek¹²⁸, B.A. Long²⁴, J.D. Long¹⁶⁹, R.E. Long⁷⁴, L. Longo^{75a,75b}, K.A.Looper¹¹², L. Lopes^{127a}, D. Lopez Mateos⁵⁸, B. Lopez Paredes¹⁴², I. Lopez Paz¹³, A. Lopez Solis⁸², J. Lorenz¹⁰¹, N. Lorenzo Martinez⁶³, M. Losada²¹, P.J. Lösel¹⁰¹, X. Lou^{35a}, A. Lounis¹¹⁸, J. Love⁶, P.A. Love⁷⁴, H. Lu^{62a}, N. Lu⁹¹, H.J. Lubatti¹³⁹, C. Luci^{133a,133b}, A. Lucotte⁵⁷, C. Luedtke⁵⁰, F. Luehring⁶³, W. Lukas⁶⁴, L. Luminari^{133a}, O. Lundberg^{149a,149b}, B. Lund-Jensen¹⁵⁰, P.M. Luzi⁸², D. Lynn²⁷, R. Lysak¹²⁸, E. Lytken⁸³, V. Lyubushkin⁶⁷, H. Ma²⁷, L.L. Ma¹⁴⁰, Y. Ma¹⁴⁰, G. Maccarrone⁴⁹, A. Macchiolo¹⁰², C.M. Macdonald¹⁴², B. Maček⁷⁷, J. Machado Miguens^{123,127b}, D. Madaffari⁸⁷, R. Madar³⁶, H.J. Maddocks¹⁶⁸, W.F. Mader⁴⁶, A. Madsen⁴⁴, J. Maeda⁶⁹, S. Maeland¹⁵, T. Maeno²⁷, A. Maevskiy¹⁰⁰, E. Magradze⁵⁶, J. Mahlstedt¹⁰⁸, C. Maiani¹¹⁸, C. Maidantchik^{26a}, A.A. Maier¹⁰², T. Maier¹⁰¹, A. Maio^{127a,127b,127d}, S. Majewski¹¹⁷, Y. Makida⁶⁸, N. Makovec¹¹⁸, B. Malaescu⁸², Pa. Malecki⁴¹, V.P. Maleev¹²⁴, F. Malek⁵⁷, U. Mallik⁶⁵, D. Malon⁶, C. Malone¹⁴⁶, S. Maltezos¹⁰, S. Malyukov³², J. Mamuzic¹⁷⁰, G. Mancini⁴⁹, B. Mandelli³², L. Mandelli^{93a}, I. Mandić⁷⁷, J. Maneira^{127a,127b}, L. Manhaes de Andrade Filho^{26b}, J. Manjarres Ramos^{163b}, A. Mann¹⁰¹, A. Manousos³², B. Mansoulie¹³⁷, J.D. Mansour^{35a}, R. Mantifel⁸⁹, M. Mantoani⁵⁶, S. Manzoni^{93a,93b}, L. Mapelli³², G. Marceca²⁹, L. March⁵¹, G. Marchiori⁸², M. Marcisovsky¹²⁸, M. Marjanovic¹⁴, D.E. Marley⁹¹, F. Marroquim^{26a}, S.P. Marsden⁸⁶, Z. Marshall¹⁶, S. Marti-Garcia¹⁷⁰, B. Martin⁹², T.A. Martin¹⁷³, V.J. Martin⁴⁸, B. Martin dit Latour¹⁵, M. Martinez^{13,s}, V.I. Martinez Outschoorn¹⁶⁹, S. Martin-Haugh¹³², V.S. Martoiu^{28b}, A.C. Martyniuk⁸⁰, M. Marx¹³⁹, A. Marzin³², L. Masetti⁸⁵, T. Mashimo¹⁵⁸, R. Mashinistov⁹⁷, J. Masik⁸⁶, A.L. Maslennikov^{110,c}, I. Massa^{22a,22b}, L. Massa^{22a,22b}, P. Mastrandrea⁵, A. Mastroberardino^{39a,39b}, T. Masubuchi¹⁵⁸, P. Mättig¹⁷⁸, J. Mattmann⁸⁵, J. Maurer^{28b}, S.J. Maxfield⁷⁶, D.A. Maximov^{110,c}, R. Mazini¹⁵⁴, S.M. Mazza^{93a,93b}, N.C. Mc Fadden¹⁰⁶, G. Mc Goldrick¹⁶², S.P. Mc Kee⁹¹, A. McCarn⁹¹, R.L. McCarthy¹⁵¹, T.G. McCarthy¹⁰², L.I. McClymont⁸⁰, E.F. McDonald⁹⁰, J.A. McFayden⁸⁰, G. Mchedlidze⁵⁶, S.J. McMahon¹³², R.A. McPherson^{172,m}, M. Medinnis⁴⁴, S. Meehan¹³⁹, S. Mehlhase¹⁰¹, A. Mehta⁷⁶, K. Meier^{60a}, C. Meineck¹⁰¹, B. Meirose⁴³, D. Melini¹⁷⁰, B.R. Mellado Garcia^{148c}, M. Melo^{147a}, F. Meloni¹⁸, A. Mengarelli^{22a,22b}, S. Menke¹⁰², E. Meoni¹⁶⁵, S. Mergelmeyer¹⁷, P. Mermoud⁵¹, L. Merola^{105a,105b}, C. Meroni^{93a}, F.S. Merritt³³, A. Messina^{133a,133b}, J. Metcalfe⁶, A.S. Mete¹⁶⁶, C. Meyer⁸⁵, C. Meyer¹²³, J.-P. Meyer¹³⁷, J. Meyer¹⁰⁸, H. Meyer Zu Theenhausen^{60a}, F. Miano¹⁵², R.P. Middleton¹³², S. Miglioranza^{52a,52b}, L. Mijović²³, G. Mikenberg¹⁷⁵, M. Mikestikova¹²⁸, M. Mikuž⁷⁷, M. Milesi⁹⁰, A. Milic⁶⁴, D.W. Miller³³, C. Mills⁴⁸, A. Milov¹⁷⁵, D.A. Milstead^{149a,149b}, A.A. Minaenko¹³¹, Y. Minami¹⁵⁸, I.A. Minashvili⁶⁷, A.I. Mincer¹¹¹, B. Mindur^{40a}, M. Mineev⁶⁷, Y. Ming¹⁷⁶, L.M. Mir¹³, K.P. Mistry¹²³, T. Mitani¹⁷⁴, J. Mitrevski¹⁰¹, V.A. Mitsou¹⁷⁰, A. Miucci⁵¹, P.S. Miyagawa¹⁴², J.U. Mjörnmark⁸³, T. Moa^{149a,149b}, K. Mochizuki⁹⁶, S. Mohapatra³⁷, S. Molander^{149a,149b}, R. Moles-Valls²³, R. Monden⁷⁰, M.C. Mondragon⁹², K. Mönig⁴⁴, J. Monk³⁸, E. Monnier⁸⁷, A. Montalbano¹⁵¹, J. Montejo Berlingen³², F. Monticelli⁷³, S. Monzani^{93a,93b}, R.W. Moore³, N. Morange¹¹⁸, D. Moreno²¹, M. Moreno Llácer⁵⁶, P. Morettini^{52a}, S. Morgenstern³², D. Mori¹⁴⁵, T. Mori¹⁵⁸, M. Morii⁵⁸, M. Morinaga¹⁵⁸, V. Morisbak¹²⁰, S. Moritz⁸⁵, A.K. Morley¹⁵³, G. Mornacchi³², J.D. Morris⁷⁸, S.S. Mortensen³⁸, L. Morvaj¹⁵¹, M. Mosidze^{53b}, J. Moss^{146,ad}, K. Motohashi¹⁶⁰, R. Mount¹⁴⁶, E. Mountricha²⁷, S.V. Mouraviev^{97,*}, E.J.W. Moyses⁸⁸, S. Muanza⁸⁷, R.D. Mudd¹⁹, F. Mueller¹⁰², J. Mueller¹²⁶, R.S.P. Mueller¹⁰¹, T. Mueller³⁰, D. Muenstermann⁷⁴, P. Mullen⁵⁵, G.A. Mullier¹⁸, F.J. Munoz Sanchez⁸⁶, J.A. Murillo Quijada¹⁹, W.J. Murray^{173,132}, H. Musheghyan⁵⁶, M. Muškinja⁷⁷, A.G. Myagkov^{131,ae}, M. Myska¹²⁹, B.P. Nachman¹⁴⁶, O. Nackenhorst⁵¹, K. Nagai¹²¹, R. Nagai^{68,z}, K. Nagano⁶⁸, Y. Nagasaka⁶¹, K. Nagata¹⁶⁴, M. Nagel⁵⁰, E. Nagy⁸⁷, A.M. Nairz³², Y. Nakahama³², K. Nakamura⁶⁸, T. Nakamura¹⁵⁸, I. Nakano¹¹³, H. Namasivayam⁴³, R.F. Naranjo Garcia⁴⁴, R. Narayan¹¹, D.I. Narrias Villar^{60a}, I. Naryshkin¹²⁴, T. Naumann⁴⁴, G. Navarro²¹, R. Nayyar⁷, H.A. Neal⁹¹, P.Yu. Nechaeva⁹⁷, T.J. Neep⁸⁶, P.D. Nef¹⁴⁶,

A. Negri ^{122a,122b}, M. Negrini ^{22a}, S. Nektarijevic ¹⁰⁷, C. Nellist ¹¹⁸, A. Nelson ¹⁶⁶, S. Nemecek ¹²⁸,
 P. Nemethy ¹¹¹, A.A. Nepomuceno ^{26a}, M. Nessi ^{32.af}, M.S. Neubauer ¹⁶⁹, M. Neumann ¹⁷⁸, R.M. Neves ¹¹¹,
 P. Nevski ²⁷, P.R. Newman ¹⁹, D.H. Nguyen ⁶, T. Nguyen Manh ⁹⁶, R.B. Nickerson ¹²¹, R. Nicolaidou ¹³⁷,
 J. Nielsen ¹³⁸, A. Nikiforov ¹⁷, V. Nikolaenko ^{131.ae}, I. Nikolic-Audit ⁸², K. Nikolopoulos ¹⁹, J.K. Nilsen ¹²⁰,
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 I. Nomidis ³¹, T. Nooney ⁷⁸, S. Norberg ¹¹⁴, M. Nordberg ³², N. Norjoharuddeen ¹²¹, O. Novgorodova ⁴⁶,
 S. Nowak ¹⁰², M. Nozaki ⁶⁸, L. Nozka ¹¹⁶, K. Ntekas ¹⁰, E. Nurse ⁸⁰, F. Nuti ⁹⁰, F. O'grady ⁷, D.C. O'Neil ¹⁴⁵,
 A.A. O'Rourke ⁴⁴, V. O'Shea ⁵⁵, F.G. Oakham ^{31.d}, H. Oberlack ¹⁰², T. Obermann ²³, J. Ocariz ⁸², A. Ochi ⁶⁹,
 I. Ochoa ³⁷, J.P. Ochoa-Ricoux ^{34a}, S. Oda ⁷², S. Odaka ⁶⁸, H. Ogren ⁶³, A. Oh ⁸⁶, S.H. Oh ⁴⁷, C.C. Ohm ¹⁶,
 H. Ohman ¹⁶⁸, H. Oide ³², H. Okawa ¹⁶⁴, Y. Okumura ³³, T. Okuyama ⁶⁸, A. Olariu ^{28b},
 L.F. Oleiro Seabra ^{127a}, S.A. Olivares Pino ⁴⁸, D. Oliveira Damazio ²⁷, A. Olszewski ⁴¹, J. Olszowska ⁴¹,
 A. Onofre ^{127a,127e}, K. Onogi ¹⁰⁴, P.U.E. Onyisi ^{11.w}, M.J. Oreglia ³³, Y. Oren ¹⁵⁶, D. Orestano ^{135a,135b},
 N. Orlando ^{62b}, R.S. Orr ¹⁶², B. Osculati ^{52a,52b,*}, R. Ospanov ⁸⁶, G. Otero y Garzon ²⁹, H. Otono ⁷²,
 M. Ouchrif ^{136d}, F. Ould-Saada ¹²⁰, A. Ouraou ¹³⁷, K.P. Oussoren ¹⁰⁸, Q. Ouyang ^{35a}, M. Owen ⁵⁵,
 R.E. Owen ¹⁹, V.E. Ozcan ^{20a}, N. Ozturk ⁸, K. Pachal ¹⁴⁵, A. Pacheco Pages ¹³, L. Pacheco Rodriguez ¹³⁷,
 C. Padilla Aranda ¹³, M. Pagáčová ⁵⁰, S. Pagan Griso ¹⁶, F. Paige ²⁷, P. Pais ⁸⁸, K. Pajchel ¹²⁰, G. Palacino ^{163b},
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 C.E. Pandini ⁸², J.G. Panduro Vazquez ⁷⁹, P. Pani ^{149a,149b}, S. Panitkin ²⁷, D. Pantea ^{28b}, L. Paolozzi ⁵¹,
 Th.D. Papadopoulou ¹⁰, K. Papageorgiou ¹⁵⁷, A. Paramonov ⁶, D. Paredes Hernandez ¹⁷⁹, A.J. Parker ⁷⁴,
 M.A. Parker ³⁰, K.A. Parker ¹⁴², F. Parodi ^{52a,52b}, J.A. Parsons ³⁷, U. Parzefall ⁵⁰, V.R. Pascuzzi ¹⁶²,
 E. Pasqualucci ^{133a}, S. Passaggio ^{52a}, Fr. Pastore ⁷⁹, G. Pásztor ^{31.ag}, S. Pataria ¹⁷⁸, J.R. Pater ⁸⁶, T. Pauly ³²,
 J. Pearce ¹⁷², B. Pearson ¹¹⁴, L.E. Pedersen ³⁸, M. Pedersen ¹²⁰, S. Pedraza Lopez ¹⁷⁰, R. Pedro ^{127a,127b},
 S.V. Peleganchuk ^{110.c}, D. Pelikan ¹⁶⁸, O. Penc ¹²⁸, C. Peng ^{35a}, H. Peng ⁵⁹, J. Penwell ⁶³, B.S. Peralva ^{26b},
 M.M. Perego ¹³⁷, D.V. Perepelitsa ²⁷, E. Perez Codina ^{163a}, L. Perini ^{93a,93b}, H. Pernegger ³²,
 S. Perrella ^{105a,105b}, R. Peschke ⁴⁴, V.D. Peshekhonov ⁶⁷, K. Peters ⁴⁴, R.F.Y. Peters ⁸⁶, B.A. Petersen ³²,
 T.C. Petersen ³⁸, E. Petit ⁵⁷, A. Petridis ¹, C. Petridou ¹⁵⁷, P. Petroff ¹¹⁸, E. Petrolo ^{133a}, M. Petrov ¹²¹,
 F. Petrucci ^{135a,135b}, N.E. Pettersson ⁸⁸, A. Peyaud ¹³⁷, R. Pezoa ^{34b}, P.W. Phillips ¹³², G. Piacquadio ^{146.ah},
 E. Pianori ¹⁷³, A. Picazio ⁸⁸, E. Piccaro ⁷⁸, M. Piccinini ^{22a,22b}, M.A. Pickering ¹²¹, R. Piegai ²⁹,
 J.E. Pilcher ³³, A.D. Pilkington ⁸⁶, A.W.J. Pin ⁸⁶, M. Pinamonti ^{167a,167c.ai}, J.L. Pinfold ³, A. Pingel ³⁸,
 S. Pires ⁸², H. Pirumov ⁴⁴, M. Pitt ¹⁷⁵, L. Plazak ^{147a}, M.-A. Pleier ²⁷, V. Pleskot ⁸⁵, E. Plotnikova ⁶⁷,
 P. Plucinski ⁹², D. Pluth ⁶⁶, R. Poettgen ^{149a,149b}, L. Poggioli ¹¹⁸, D. Pohl ²³, G. Polesello ^{122a}, A. Poley ⁴⁴,
 A. Policicchio ^{39a,39b}, R. Polifka ¹⁶², A. Polini ^{22a}, C.S. Pollard ⁵⁵, V. Polychronakos ²⁷, K. Pommès ³²,
 L. Pontecorvo ^{133a}, B.G. Pope ⁹², G.A. Popeneciu ^{28c}, D.S. Popovic ¹⁴, A. Poppleton ³², S. Pospisil ¹²⁹,
 K. Potamianos ¹⁶, I.N. Potrap ⁶⁷, C.J. Potter ³⁰, C.T. Potter ¹¹⁷, G. Poulard ³², J. Poveda ³², V. Pozdnyakov ⁶⁷,
 M.E. Pozo Astigarraga ³², P. Pralavorio ⁸⁷, A. Pranko ¹⁶, S. Prell ⁶⁶, D. Price ⁸⁶, L.E. Price ⁶, M. Primavera ^{75a},
 S. Prince ⁸⁹, M. Proissl ⁴⁸, K. Prokofiev ^{62c}, F. Prokoshin ^{34b}, S. Protopopescu ²⁷, J. Proudfoot ⁶,
 M. Przybycien ^{40a}, D. Puudu ^{135a,135b}, M. Purohit ^{27.aj}, P. Puzo ¹¹⁸, J. Qian ⁹¹, G. Qin ⁵⁵, Y. Qin ⁸⁶,
 A. Quadt ⁵⁶, W.B. Quayle ^{167a,167b}, M. Queitsch-Maitland ⁸⁶, D. Quilty ⁵⁵, S. Raddum ¹²⁰, V. Radeka ²⁷,
 V. Radescu ^{60b}, S.K. Radhakrishnan ¹⁵¹, P. Radloff ¹¹⁷, P. Rados ⁹⁰, F. Ragusa ^{93a,93b}, G. Rahal ¹⁸¹,
 J.A. Raine ⁸⁶, S. Rajagopalan ²⁷, M. Rammensee ³², C. Rangel-Smith ¹⁶⁸, M.G. Ratti ^{93a,93b}, F. Rauscher ¹⁰¹,
 S. Rave ⁸⁵, T. Ravenscroft ⁵⁵, I. Ravinovich ¹⁷⁵, M. Raymond ³², A.L. Read ¹²⁰, N.P. Readioff ⁷⁶,
 M. Reale ^{75a,75b}, D.M. Rebuffi ^{122a,122b}, A. Redelbach ¹⁷⁷, G. Redlinger ²⁷, R. Reece ¹³⁸, K. Reeves ⁴³,
 L. Rehnisch ¹⁷, J. Reichert ¹²³, H. Reisin ²⁹, C. Rembser ³², H. Ren ^{35a}, M. Rescigno ^{133a}, S. Resconi ^{93a},
 O.L. Rezanova ^{110.c}, P. Reznicek ¹³⁰, R. Rezvani ⁹⁶, R. Richter ¹⁰², S. Richter ⁸⁰, E. Richter-Was ^{40b},
 O. Ricken ²³, M. Ridel ⁸², P. Rieck ¹⁷, C.J. Riegel ¹⁷⁸, J. Rieger ⁵⁶, O. Rifki ¹¹⁴, M. Rijssenbeek ¹⁵¹,
 A. Rimoldi ^{122a,122b}, M. Rimoldi ¹⁸, L. Rinaldi ^{22a}, B. Ristić ⁵¹, E. Ritsch ³², I. Riu ¹³, F. Rizatdinova ¹¹⁵,
 E. Rizvi ⁷⁸, C. Rizzi ¹³, S.H. Robertson ^{89.m}, A. Robichaud-Veronneau ⁸⁹, D. Robinson ³⁰, J.E.M. Robinson ⁴⁴,
 A. Robson ⁵⁵, C. Roda ^{125a,125b}, Y. Rodina ^{87.ak}, A. Rodriguez Perez ¹³, D. Rodriguez Rodriguez ¹⁷⁰, S. Roe ³²,
 C.S. Rogan ⁵⁸, O. Røhne ¹²⁰, R. Röhrig ¹⁰², A. Romaniouk ⁹⁹, M. Romano ^{22a,22b}, S.M. Romano Saez ³⁶,
 E. Romero Adam ¹⁷⁰, N. Rompotis ¹³⁹, M. Ronzani ⁵⁰, L. Roos ⁸², E. Ros ¹⁷⁰, S. Rosati ^{133a}, K. Rosbach ⁵⁰,
 P. Rose ¹³⁸, O. Rosenthal ¹⁴⁴, N.-A. Rosien ⁵⁶, V. Rossetti ^{149a,149b}, E. Rossi ^{105a,105b}, L.P. Rossi ^{52a},
 J.H.N. Rosten ³⁰, R. Rosten ¹³⁹, M. Rotaru ^{28b}, I. Roth ¹⁷⁵, J. Rothberg ¹³⁹, D. Rousseau ¹¹⁸, C.R. Royon ¹³⁷,

A. Rozanov⁸⁷, Y. Rozen¹⁵⁵, X. Ruan^{148c}, F. Rubbo¹⁴⁶, M.S. Rudolph¹⁶², F. Rühr⁵⁰, A. Ruiz-Martinez³¹,
 Z. Rurikova⁵⁰, N.A. Rusakovich⁶⁷, A. Ruschke¹⁰¹, H.L. Russell¹³⁹, J.P. Rutherford⁷, N. Ruthmann³²,
 Y.F. Ryabov¹²⁴, M. Rybar¹⁶⁹, G. Rybkin¹¹⁸, S. Ryu⁶, A. Ryzhov¹³¹, G.F. Rzehorz⁵⁶, A.F. Saavedra¹⁵³,
 G. Sabato¹⁰⁸, S. Sacerdoti²⁹, H.F.-W. Sadrozinski¹³⁸, R. Sadykov⁶⁷, F. Safai Tehrani^{133a}, P. Saha¹⁰⁹,
 M. Sahinsoy^{60a}, M. Saimpert¹³⁷, T. Saito¹⁵⁸, H. Sakamoto¹⁵⁸, Y. Sakurai¹⁷⁴, G. Salamanna^{135a,135b},
 A. Salamon^{134a,134b}, J.E. Salazar Loyola^{34b}, D. Salek¹⁰⁸, P.H. Sales De Bruin¹³⁹, D. Saliagic¹⁰²,
 A. Salnikov¹⁴⁶, J. Salt¹⁷⁰, D. Salvatore^{39a,39b}, F. Salvatore¹⁵², A. Salvucci^{62a}, A. Salzburger³²,
 D. Sammel⁵⁰, D. Sampsonidis¹⁵⁷, J. Sánchez¹⁷⁰, V. Sanchez Martinez¹⁷⁰, A. Sanchez Pineda^{105a,105b},
 H. Sandaker¹²⁰, R.L. Sandbach⁷⁸, H.G. Sander⁸⁵, M. Sandhoff¹⁷⁸, C. Sandoval²¹, R. Sandstroem¹⁰²,
 D.P.C. Sankey¹³², M. Sannino^{52a,52b}, A. Sansoni⁴⁹, C. Santoni³⁶, R. Santonico^{134a,134b}, H. Santos^{127a},
 I. Santoyo Castillo¹⁵², K. Sapp¹²⁶, A. Saponov⁶⁷, J.G. Saraiva^{127a,127d}, B. Sarrazin²³, O. Sasaki⁶⁸,
 Y. Sasaki¹⁵⁸, K. Sato¹⁶⁴, G. Sauvage^{5,*}, E. Sauvan⁵, G. Savage⁷⁹, P. Savard^{162,d}, C. Sawyer¹³²,
 L. Sawyer^{81,r}, J. Saxon³³, C. Sbarra^{22a}, A. Sbrizzi^{22a,22b}, T. Scanlon⁸⁰, D.A. Scannicchio¹⁶⁶,
 M. Scarcella¹⁵³, V. Scarfone^{39a,39b}, J. Schaarschmidt¹⁷⁵, P. Schacht¹⁰², B.M. Schachtner¹⁰¹,
 D. Schaefer³², R. Schaefer⁴⁴, J. Schaeffer⁸⁵, S. Schaepe²³, S. Schaezel^{60b}, U. Schäfer⁸⁵, A.C. Schaffer¹¹⁸,
 D. Schaile¹⁰¹, R.D. Schamberger¹⁵¹, V. Scharf^{60a}, V.A. Schegelsky¹²⁴, D. Scheirich¹³⁰, M. Schernau¹⁶⁶,
 C. Schiavi^{52a,52b}, S. Schier¹³⁸, C. Schillo⁵⁰, M. Schioppa^{39a,39b}, S. Schlenker³²,
 K.R. Schmidt-Sommerfeld¹⁰², K. Schmieden³², C. Schmitt⁸⁵, S. Schmitt⁴⁴, S. Schmitz⁸⁵,
 B. Schneider^{163a}, U. Schnoor⁵⁰, L. Schoeffel¹³⁷, A. Schoening^{60b}, B.D. Schoenrock⁹², E. Schopf²³,
 M. Schott⁸⁵, J. Schovancova⁸, S. Schramm⁵¹, M. Schreyer¹⁷⁷, N. Schuh⁸⁵, A. Schulte⁸⁵, M.J. Schultens²³,
 H.-C. Schultz-Coulon^{60a}, H. Schulz¹⁷, M. Schumacher⁵⁰, B.A. Schumm¹³⁸, Ph. Schune¹³⁷,
 A. Schwartzman¹⁴⁶, T.A. Schwarz⁹¹, Ph. Schwegler¹⁰², H. Schweiger⁸⁶, Ph. Schwemling¹³⁷,
 R. Schwienhorst⁹², J. Schwindling¹³⁷, T. Schwindt²³, G. Sciolla²⁵, F. Scuri^{125a,125b}, F. Scutti⁹⁰,
 J. Searcy⁹¹, P. Seema²³, S.C. Seidel¹⁰⁶, A. Seiden¹³⁸, F. Seifert¹²⁹, J.M. Seixas^{26a}, G. Sekhniaidze^{105a},
 K. Sekhon⁹¹, S.J. Sekula⁴², D.M. Seliverstov^{124,*}, N. Semprini-Cesari^{22a,22b}, C. Serfon¹²⁰, L. Serin¹¹⁸,
 L. Serkin^{167a,167b}, M. Sessa^{135a,135b}, R. Seuster¹⁷², H. Severini¹¹⁴, T. Sfiligoi⁷⁷, F. Sforza³², A. Sfyrla⁵¹,
 E. Shabalina⁵⁶, N.W. Shaikh^{149a,149b}, L.Y. Shan^{35a}, R. Shang¹⁶⁹, J.T. Shank²⁴, M. Shapiro¹⁶,
 P.B. Shatalov⁹⁸, K. Shaw^{167a,167b}, S.M. Shaw⁸⁶, A. Shcherbakova^{149a,149b}, C.Y. Shehu¹⁵², P. Sherwood⁸⁰,
 L. Shi^{154,al}, S. Shimizu⁶⁹, C.O. Shimmin¹⁶⁶, M. Shimojima¹⁰³, M. Shiyakova^{67,am}, A. Shmeleva⁹⁷,
 D. Shoaleh Saadi⁹⁶, M.J. Shochet³³, S. Shojaii^{93a,93b}, S. Shrestha¹¹², E. Shulga⁹⁹, M.A. Shupe⁷,
 P. Sicho¹²⁸, A.M. Sickles¹⁶⁹, P.E. Sidebo¹⁵⁰, O. Sidiropoulou¹⁷⁷, D. Sidorov¹¹⁵, A. Sidoti^{22a,22b},
 F. Siegert⁴⁶, Dj. Sijacki¹⁴, J. Silva^{127a,127d}, S.B. Silverstein^{149a}, V. Simak¹²⁹, O. Simard⁵, Lj. Simic¹⁴,
 S. Simion¹¹⁸, E. Simioni⁸⁵, B. Simmons⁸⁰, D. Simon³⁶, M. Simon⁸⁵, P. Sinervo¹⁶², N.B. Sinev¹¹⁷,
 M. Sioli^{22a,22b}, G. Siragusa¹⁷⁷, S.Yu. Sivoklokov¹⁰⁰, J. Sjölin^{149a,149b}, M.B. Skinner⁷⁴, H.P. Skottowe⁵⁸,
 P. Skubic¹¹⁴, M. Slater¹⁹, T. Slavicek¹²⁹, M. Slawinska¹⁰⁸, K. Sliwa¹⁶⁵, R. Slovak¹³⁰, V. Smakhtin¹⁷⁵,
 B.H. Smart⁵, L. Smestad¹⁵, J. Smiesko^{147a}, S.Yu. Smirnov⁹⁹, Y. Smirnov⁹⁹, L.N. Smirnova^{100,an},
 O. Smirnova⁸³, M.N.K. Smith³⁷, R.W. Smith³⁷, M. Smizanska⁷⁴, K. Smolek¹²⁹, A.A. Snesarev⁹⁷,
 S. Snyder²⁷, R. Sobie^{172,m}, F. Socher⁴⁶, A. Soffer¹⁵⁶, D.A. Soh¹⁵⁴, G. Sokhrannyi⁷⁷,
 C.A. Solans Sanchez³², M. Solar¹²⁹, E.Yu. Soldatov⁹⁹, U. Soldevila¹⁷⁰, A.A. Solodkov¹³¹, A. Soloshenko⁶⁷,
 O.V. Solovyanov¹³¹, V. Solovyev¹²⁴, P. Sommer⁵⁰, H. Son¹⁶⁵, H.Y. Song^{59,ao}, A. Sood¹⁶, A. Sopczak¹²⁹,
 V. Sopko¹²⁹, V. Sorin¹³, D. Sosa^{60b}, C.L. Sotiropoulou^{125a,125b}, R. Soualah^{167a,167c}, A.M. Soukharev^{110,c},
 D. South⁴⁴, B.C. Sowden⁷⁹, S. Spagnolo^{75a,75b}, M. Spalla^{125a,125b}, M. Spangenberg¹⁷³, F. Spanò⁷⁹,
 D. Sperlich¹⁷, F. Spettel¹⁰², R. Spighi^{22a}, G. Spigo³², L.A. Spiller⁹⁰, M. Spousta¹³⁰, R.D. St. Denis^{55,*},
 A. Stabile^{93a}, R. Stamen^{60a}, S. Stamm¹⁷, E. Stanecka⁴¹, R.W. Stanek⁶, C. Stanescu^{135a},
 M. Stanescu-Bellu⁴⁴, M.M. Stanitzki⁴⁴, S. Stapnes¹²⁰, E.A. Starchenko¹³¹, G.H. Stark³³, J. Stark⁵⁷,
 P. Staroba¹²⁸, P. Starovoitov^{60a}, S. Stärz³², R. Staszewski⁴¹, P. Steinberg²⁷, B. Stelzer¹⁴⁵, H.J. Stelzer³²,
 O. Stelzer-Chilton^{163a}, H. Stenzel⁵⁴, G.A. Stewart⁵⁵, J.A. Stillings²³, M.C. Stockton⁸⁹, M. Stoebe⁸⁹,
 G. Stoicea^{28b}, P. Stolte⁵⁶, S. Stonjek¹⁰², A.R. Stradling⁸, A. Straessner⁴⁶, M.E. Stramaglia¹⁸,
 J. Strandberg¹⁵⁰, S. Strandberg^{149a,149b}, A. Strandlie¹²⁰, M. Strauss¹¹⁴, P. Strizenec^{147b}, R. Ströhmer¹⁷⁷,
 D.M. Strom¹¹⁷, R. Stroynowski⁴², A. Strubig¹⁰⁷, S.A. Stucci¹⁸, B. Stugu¹⁵, N.A. Styles⁴⁴, D. Su¹⁴⁶,
 J. Su¹²⁶, R. Subramaniam⁸¹, S. Suchek^{60a}, Y. Sugaya¹¹⁹, M. Suk¹²⁹, V.V. Sulin⁹⁷, S. Sultansoy^{4c},
 T. Sumida⁷⁰, S. Sun⁵⁸, X. Sun^{35a}, J.E. Sundermann⁵⁰, K. Suruliz¹⁵², G. Susinno^{39a,39b}, M.R. Sutton¹⁵²,

S. Suzuki⁶⁸, M. Svatos¹²⁸, M. Swiatlowski³³, I. Sykora^{147a}, T. Sykora¹³⁰, D. Ta⁵⁰, C. Taccini^{135a,135b}, K. Tackmann⁴⁴, J. Taenzer¹⁶², A. Taffard¹⁶⁶, R. Tafirout^{163a}, N. Taiblum¹⁵⁶, H. Takai²⁷, R. Takashima⁷¹, T. Takeshita¹⁴³, Y. Takubo⁶⁸, M. Talby⁸⁷, A.A. Talyshev^{110.c}, K.G. Tan⁹⁰, J. Tanaka¹⁵⁸, R. Tanaka¹¹⁸, S. Tanaka⁶⁸, B.B. Tannenwald¹¹², S. Tapia Araya^{34b}, S. Tapprogge⁸⁵, S. Tarem¹⁵⁵, G.F. Tartarelli^{93a}, P. Tas¹³⁰, M. Tasevsky¹²⁸, T. Tashiro⁷⁰, E. Tassi^{39a,39b}, A. Tavares Delgado^{127a,127b}, Y. Tayalati^{136d}, A.C. Taylor¹⁰⁶, G.N. Taylor⁹⁰, P.T.E. Taylor⁹⁰, W. Taylor^{163b}, F.A. Teischinger³², P. Teixeira-Dias⁷⁹, K.K. Temming⁵⁰, D. Temple¹⁴⁵, H. Ten Kate³², P.K. Teng¹⁵⁴, J.J. Teoh¹¹⁹, F. Tepel¹⁷⁸, S. Terada⁶⁸, K. Terashi¹⁵⁸, J. Terron⁸⁴, S. Terzo¹⁰², M. Testa⁴⁹, R.J. Teuscher^{162.m}, T. Theveneaux-Pelzer⁸⁷, J.P. Thomas¹⁹, J. Thomas-Wilsker⁷⁹, E.N. Thompson³⁷, P.D. Thompson¹⁹, A.S. Thompson⁵⁵, L.A. Thomsen¹⁷⁹, E. Thomson¹²³, M. Thomson³⁰, M.J. Tibbetts¹⁶, R.E. Ticse Torres⁸⁷, V.O. Tikhomirov^{97.ap}, Yu.A. Tikhonov^{110.c}, S. Timoshenko⁹⁹, P. Tipton¹⁷⁹, S. Tisserant⁸⁷, K. Todome¹⁶⁰, T. Todorov^{5,*}, S. Todorova-Nova¹³⁰, J. Tojo⁷², S. Tokár^{147a}, K. Tokushuku⁶⁸, E. Tolley⁵⁸, L. Tomlinson⁸⁶, M. Tomoto¹⁰⁴, L. Tompkins^{146.aq}, K. Toms¹⁰⁶, B. Tong⁵⁸, E. Torrence¹¹⁷, H. Torres¹⁴⁵, E. Torr  Pastor¹³⁹, J. Toth^{87.ar}, F. Touchard⁸⁷, D.R. Tovey¹⁴², T. Trefzger¹⁷⁷, A. Tricoli²⁷, I.M. Trigger^{163a}, S. Trincaz-Duvoid⁸², M.F. Tripiana¹³, W. Trischuk¹⁶², B. Trocme⁵⁷, A. Trofymov⁴⁴, C. Troncon^{93a}, M. Trottier-McDonald¹⁶, M. Trovatelli¹⁷², L. Truong^{167a,167c}, M. Trzebinski⁴¹, A. Trzupek⁴¹, J.C-L. Tseng¹²¹, P.V. Tsiareshka⁹⁴, G. Tsipolitis¹⁰, N. Tsirintanis⁹, S. Tsiskaridze¹³, V. Tsiskaridze⁵⁰, E.G. Tskhadadze^{53a}, K.M. Tsui^{62a}, I.I. Tsukerman⁹⁸, V. Tsulaia¹⁶, S. Tsuno⁶⁸, D. Tsybychev¹⁵¹, A. Tudorache^{28b}, V. Tudorache^{28b}, A.N. Tuna⁵⁸, S.A. Tupputi^{22a,22b}, S. Turchikhin^{100.an}, D. Turecek¹²⁹, D. Turgeman¹⁷⁵, R. Turra^{93a,93b}, A.J. Turvey⁴², P.M. Tuts³⁷, M. Tyndel¹³², G. Uccielli^{22a,22b}, I. Ueda¹⁵⁸, M. Ughetto^{149a,149b}, F. Ukegawa¹⁶⁴, G. Unal³², A. Undrus²⁷, G. Unel¹⁶⁶, F.C. Ungaro⁹⁰, Y. Unno⁶⁸, C. Unverdorben¹⁰¹, J. Urban^{147b}, P. Urquijo⁹⁰, P. Urrejola⁸⁵, G. Usai⁸, A. Usanova⁶⁴, L. Vacavant⁸⁷, V. Vacek¹²⁹, B. Vachon⁸⁹, C. Valderanis¹⁰¹, E. Valdes Santurio^{149a,149b}, N. Valencic¹⁰⁸, S. Valentinietti^{22a,22b}, A. Valero¹⁷⁰, L. Valery¹³, S. Valkar¹³⁰, S. Vallecorsa⁵¹, J.A. Valls Ferrer¹⁷⁰, W. Van Den Wollenberg¹⁰⁸, P.C. Van Der Deijl¹⁰⁸, R. van der Geer¹⁰⁸, H. van der Graaf¹⁰⁸, N. van Eldik¹⁵⁵, P. van Gemmeren⁶, J. Van Nieuwkoop¹⁴⁵, I. van Vulpen¹⁰⁸, M.C. van Woerden³², M. Vanadia^{133a,133b}, W. Vandelli³², R. Vanguri¹²³, A. Vaniachine¹⁶¹, P. Vankov¹⁰⁸, G. Vardanyan¹⁸⁰, R. Vari^{133a}, E.W. Varnes⁷, T. Varol⁴², D. Varouchas⁸², A. Vartapetian⁸, K.E. Varvell¹⁵³, J.G. Vasquez¹⁷⁹, F. Vazeille³⁶, T. Vazquez Schroeder⁸⁹, J. Veatch⁵⁶, L.M. Veloce¹⁶², F. Veloso^{127a,127c}, S. Veneziano^{133a}, A. Ventura^{75a,75b}, M. Venturi¹⁷², N. Venturi¹⁶², A. Venturini²⁵, V. Vercesi^{122a}, M. Verducci^{133a,133b}, W. Verkerke¹⁰⁸, J.C. Vermeulen¹⁰⁸, A. Vest^{46.as}, M.C. Vetterli^{145.d}, O. Viazlo⁸³, I. Vichou^{169,*}, T. Vickey¹⁴², O.E. Vickey Boeriu¹⁴², G.H.A. Viehhauser¹²¹, S. Viel¹⁶, L. Vigani¹²¹, R. Vigne⁶⁴, M. Villa^{22a,22b}, M. Villaplana Perez^{93a,93b}, E. Vilucchi⁴⁹, M.G. Vincter³¹, V.B. Vinogradov⁶⁷, C. Vittori^{22a,22b}, I. Vivarelli¹⁵², S. Vlachos¹⁰, M. Vlasak¹²⁹, M. Vogel¹⁷⁸, P. Vokac¹²⁹, G. Volpi^{125a,125b}, M. Volpi⁹⁰, H. von der Schmitt¹⁰², E. von Toerne²³, V. Vorobel¹³⁰, K. Vorobev⁹⁹, M. Vos¹⁷⁰, R. Voss³², J.H. Vossebeld⁷⁶, N. Vranjes¹⁴, M. Vranjes Milosavljevic¹⁴, V. Vrba¹²⁸, M. Vreeswijk¹⁰⁸, R. Vuillermet³², I. Vukotic³³, Z. Vykydal¹²⁹, P. Wagner²³, W. Wagner¹⁷⁸, H. Wahlberg⁷³, S. Wahrmund⁴⁶, J. Wakabayashi¹⁰⁴, J. Walder⁷⁴, R. Walker¹⁰¹, W. Walkowiak¹⁴⁴, V. Wallangen^{149a,149b}, C. Wang^{35b}, C. Wang^{140,87}, F. Wang¹⁷⁶, H. Wang¹⁶, H. Wang⁴², J. Wang⁴⁴, J. Wang¹⁵³, K. Wang⁸⁹, R. Wang⁶, S.M. Wang¹⁵⁴, T. Wang²³, T. Wang³⁷, W. Wang⁵⁹, X. Wang¹⁷⁹, C. Wanotayaraj¹¹⁷, A. Warburton⁸⁹, C.P. Ward³⁰, D.R. Wardrope⁸⁰, A. Washbrook⁴⁸, P.M. Watkins¹⁹, A.T. Watson¹⁹, M.F. Watson¹⁹, G. Watts¹³⁹, S. Watts⁸⁶, B.M. Waugh⁸⁰, S. Webb⁸⁵, M.S. Weber¹⁸, S.W. Weber¹⁷⁷, J.S. Webster⁶, A.R. Weidberg¹²¹, B. Weinert⁶³, J. Weingarten⁵⁶, C. Weiser⁵⁰, H. Weits¹⁰⁸, P.S. Wells³², T. Wenaus²⁷, T. Wengler³², S. Wenig³², N. Wermes²³, M. Werner⁵⁰, M.D. Werner⁶⁶, P. Werner³², M. Wessels^{60a}, J. Wetter¹⁶⁵, K. Whalen¹¹⁷, N.L. Whallon¹³⁹, A.M. Wharton⁷⁴, A. White⁸, M.J. White¹, R. White^{34b}, D. Whiteson¹⁶⁶, F.J. Wickens¹³², W. Wiedenmann¹⁷⁶, M. Wielers¹³², P. Wienemann²³, C. Wiglesworth³⁸, L.A.M. Wiik-Fuchs²³, A. Wildauer¹⁰², F. Wilk⁸⁶, H.G. Wilkens³², H.H. Williams¹²³, S. Williams¹⁰⁸, C. Willis⁹², S. Willocq⁸⁸, J.A. Wilson¹⁹, I. Wingerter-Seez⁵, F. Winklmeier¹¹⁷, O.J. Winston¹⁵², B.T. Winter²³, M. Wittgen¹⁴⁶, J. Wittkowski¹⁰¹, M.W. Wolter⁴¹, H. Wolters^{127a,127c}, S.D. Worm¹³², B.K. Wosiek⁴¹, J. Wotschack³², M.J. Woudstra⁸⁶, K.W. Wozniak⁴¹, M. Wu⁵⁷, M. Wu³³, S.L. Wu¹⁷⁶, X. Wu⁵¹, Y. Wu⁹¹, T.R. Wyatt⁸⁶, B.M. Wynne⁴⁸, S. Xella³⁸, D. Xu^{35a}, L. Xu²⁷, B. Yabsley¹⁵³, S. Yacoob^{148a}, R. Yakabe⁶⁹, D. Yamaguchi¹⁶⁰, Y. Yamaguchi¹¹⁹, A. Yamamoto⁶⁸, S. Yamamoto¹⁵⁸,

T. Yamanaka¹⁵⁸, K. Yamauchi¹⁰⁴, Y. Yamazaki⁶⁹, Z. Yan²⁴, H. Yang¹⁴¹, H. Yang¹⁷⁶, Y. Yang¹⁵⁴, Z. Yang¹⁵, W.-M. Yao¹⁶, Y.C. Yap⁸², Y. Yasu⁶⁸, E. Yatsenko⁵, K.H. Yau Wong²³, J. Ye⁴², S. Ye²⁷, I. Yeletsikh⁶⁷, A.L. Yen⁵⁸, E. Yildirim⁸⁵, K. Yorita¹⁷⁴, R. Yoshida⁶, K. Yoshihara¹²³, C. Young¹⁴⁶, C.J.S. Young³², S. Youssef²⁴, D.R. Yu¹⁶, J. Yu⁸, J.M. Yu⁹¹, J. Yu⁶⁶, L. Yuan⁶⁹, S.P.Y. Yuen²³, I. Yusuff^{30,at}, B. Zabinski⁴¹, R. Zaidan¹⁴⁰, A.M. Zaitsev^{131,ae}, N. Zakharchuk⁴⁴, J. Zalieckas¹⁵, A. Zaman¹⁵¹, S. Zambito⁵⁸, L. Zanello^{133a,133b}, D. Zanzi⁹⁰, C. Zeitnitz¹⁷⁸, M. Zeman¹²⁹, A. Zemla^{40a}, J.C. Zeng¹⁶⁹, Q. Zeng¹⁴⁶, K. Zengel²⁵, O. Zenin¹³¹, T. Ženiš^{147a}, D. Zerwas¹¹⁸, D. Zhang⁹¹, F. Zhang¹⁷⁶, G. Zhang^{59,ao}, H. Zhang^{35b}, J. Zhang⁶, L. Zhang⁵⁰, R. Zhang²³, R. Zhang^{59,au}, X. Zhang¹⁴⁰, Z. Zhang¹¹⁸, X. Zhao⁴², Y. Zhao¹⁴⁰, Z. Zhao⁵⁹, A. Zhemchugov⁶⁷, J. Zhong¹²¹, B. Zhou⁹¹, C. Zhou⁴⁷, L. Zhou³⁷, L. Zhou⁴², M. Zhou¹⁵¹, N. Zhou^{35c}, C.G. Zhu¹⁴⁰, H. Zhu^{35a}, J. Zhu⁹¹, Y. Zhu⁵⁹, X. Zhuang^{35a}, K. Zhukov⁹⁷, A. Zibell¹⁷⁷, D. Zieminska⁶³, N.I. Zimine⁶⁷, C. Zimmermann⁸⁵, S. Zimmermann⁵⁰, Z. Zinonos⁵⁶, M. Zinser⁸⁵, M. Ziolkowski¹⁴⁴, L. Živković¹⁴, G. Zobernig¹⁷⁶, A. Zoccoli^{22a,22b}, M. zur Nedden¹⁷, L. Zwalinski³²

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

² Physics Department, SUNY Albany, Albany NY, United States

³ Department 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

⁵ LAPP, CNRS/IN2P3 and Université Savoie Mont Blanc, Annecy-le-Vieux, France

⁶ High Energy Physics Division, Argonne National Laboratory, Argonne IL, United States

⁷ Department of Physics, University of Arizona, Tucson AZ, United States

⁸ Department of Physics, The University of Texas at Arlington, Arlington TX, United States

⁹ Physics Department, University of Athens, Athens, Greece

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

¹¹ Department of Physics, The University of Texas at Austin, Austin TX, United States

¹² Institute of Physics, Azerbaijan Academy of Sciences, Baku, Azerbaijan

¹³ Institut de Física d'Altes Energies (IFAE), The Barcelona Institute of Science and Technology, Barcelona, Spain

¹⁴ Institute of Physics, University of Belgrade, Belgrade, Serbia

¹⁵ Department for Physics and Technology, University of Bergen, Bergen, Norway

¹⁶ Physics Division, Lawrence Berkeley National Laboratory and University of California, Berkeley CA, United States

¹⁷ Department of Physics, Humboldt University, Berlin, Germany

¹⁸ Albert Einstein Center for Fundamental Physics and Laboratory for High Energy Physics, University of Bern, Bern, Switzerland

¹⁹ School of Physics and Astronomy, University of Birmingham, Birmingham, United Kingdom

²⁰ (a) Department of Physics, Bogazici University, Istanbul; (b) Department of Physics Engineering, Gaziantep University, Gaziantep; (d) Istanbul Bilgi University, Faculty of Engineering and Natural Sciences, Istanbul, Turkey; (e) Bahcesehir University, Faculty of Engineering and Natural Sciences, Istanbul, Turkey

²¹ Centro de Investigaciones, Universidad Antonio Narino, Bogota, Colombia

²² (a) INFN Sezione di Bologna; (b) Dipartimento di Fisica e Astronomia, Università di Bologna, Bologna, Italy

²³ Physikalisches Institut, University of Bonn, Bonn, Germany

²⁴ Department of Physics, Boston University, Boston MA, United States

²⁵ Department of Physics, Brandeis University, Waltham MA, United States

²⁶ (a) Universidade Federal do Rio De Janeiro, COPPE/EE/IF, Rio de Janeiro; (b) Electrical Circuits Department, 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

²⁷ Physics Department, Brookhaven National Laboratory, Upton NY, United States

²⁸ (a) Transilvania University of Brasov, Brasov, Romania; (b) National Institute of Physics and Nuclear Engineering, Bucharest; (c) National Institute for Research and Development of Isotopic and Molecular Technologies, Physics Department, Cluj Napoca; (d) University Politehnica Bucharest, Bucharest; (e) West University in Timisoara, Timisoara, Romania

²⁹ Departamento de Fisica, Universidad de Buenos Aires, Buenos Aires, Argentina

³⁰ Cavendish Laboratory, University of Cambridge, Cambridge, United Kingdom

³¹ Department of Physics, Carleton University, Ottawa ON, Canada

³² CERN, Geneva, Switzerland

³³ Enrico Fermi Institute, University of Chicago, Chicago IL, United States

³⁴ (a) Departamento de Fisica, Pontificia Universidad Católica de Chile, Santiago; (b) Departamento de Fisica, Universidad Técnica Federico Santa María, Valparaíso, Chile

³⁵ (a) Institute of High Energy Physics, Chinese Academy of Sciences, Beijing; (b) Department of Physics, Nanjing University, Jiangsu; (c) Physics Department, Tsinghua University, Beijing 100084, China

³⁶ Laboratoire de Physique Corpusculaire, Clermont Université and Université Blaise Pascal and CNRS/IN2P3, Clermont-Ferrand, France

³⁷ Nevis Laboratory, Columbia University, Irvington NY, United States

³⁸ Niels Bohr Institute, University of Copenhagen, Kobenhavn, Denmark

³⁹ (a) INFN Gruppo Collegato di Cosenza, Laboratori Nazionali di Frascati; (b) Dipartimento di Fisica, Università della Calabria, Rende, Italy

⁴⁰ (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

⁴¹ Institute of Nuclear Physics Polish Academy of Sciences, Krakow, Poland

⁴² Physics Department, Southern Methodist University, Dallas TX, United States

⁴³ Physics Department, University of Texas at Dallas, Richardson TX, United States

⁴⁴ DESY, Hamburg and Zeuthen, Germany

⁴⁵ Lehrstuhl für Experimentelle Physik IV, Technische Universität Dortmund, Dortmund, Germany

⁴⁶ Institut für Kern- und Teilchenphysik, Technische Universität Dresden, Dresden, Germany

⁴⁷ Department of Physics, Duke University, Durham NC, United States

⁴⁸ SUPA – School of Physics and Astronomy, University of Edinburgh, Edinburgh, United Kingdom

⁴⁹ INFN Laboratori Nazionali di Frascati, Frascati, Italy

⁵⁰ Fakultät für Mathematik und Physik, Albert-Ludwigs-Universität, Freiburg, Germany

⁵¹ Section de Physique, Université de Genève, Geneva, Switzerland

⁵² (a) INFN Sezione di Genova; (b) Dipartimento di Fisica, Università di Genova, Genova, Italy

⁵³ (a) E. Andronikashvili Institute of Physics, Iv. Javakishvili Tbilisi State University, Tbilisi; (b) High Energy Physics Institute, Tbilisi State University, Tbilisi, Georgia

⁵⁴ II Physikalisches Institut, Justus-Liebig-Universität Giessen, Giessen, Germany

- ⁵⁵ SUPA – School of Physics and Astronomy, University of Glasgow, Glasgow, United Kingdom
- ⁵⁶ II Physikalisches Institut, Georg-August-Universität, Göttingen, Germany
- ⁵⁷ Laboratoire de Physique Subatomique et de Cosmologie, Université Grenoble-Alpes, CNRS/IN2P3, Grenoble, France
- ⁵⁸ Laboratory for Particle Physics and Cosmology, Harvard University, Cambridge MA, United States
- ⁵⁹ Department of Modern Physics, University of Science and Technology of China, Anhui, China
- ⁶⁰ ^(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
- ⁶¹ Faculty of Applied Information Science, Hiroshima Institute of Technology, Hiroshima, Japan
- ⁶² ^(a) Department of Physics, The Chinese University of Hong Kong, Shatin, N.T., Hong Kong; ^(b) Department of Physics, The University of Hong Kong, Hong Kong; ^(c) Department of Physics, The Hong Kong University of Science and Technology, Clear Water Bay, Kowloon, Hong Kong, China
- ⁶³ Department of Physics, Indiana University, Bloomington IN, United States
- ⁶⁴ Institut für Astro- und Teilchenphysik, Leopold-Franzens-Universität, Innsbruck, Austria
- ⁶⁵ University of Iowa, Iowa City IA, United States
- ⁶⁶ Department of Physics and Astronomy, Iowa State University, Ames IA, United States
- ⁶⁷ Joint Institute for Nuclear Research, JINR Dubna, Dubna, Russia
- ⁶⁸ KEK, High Energy Accelerator Research Organization, Tsukuba, Japan
- ⁶⁹ Graduate School of Science, Kobe University, Kobe, Japan
- ⁷⁰ Faculty of Science, Kyoto University, Kyoto, Japan
- ⁷¹ Kyoto University of Education, Kyoto, Japan
- ⁷² Department of Physics, Kyushu University, Fukuoka, Japan
- ⁷³ Instituto de Física La Plata, Universidad Nacional de La Plata and CONICET, La Plata, Argentina
- ⁷⁴ Physics Department, Lancaster University, Lancaster, United Kingdom
- ⁷⁵ ^(a) INFN Sezione di Lecce; ^(b) Dipartimento di Matematica e Fisica, Università del Salento, Lecce, Italy
- ⁷⁶ Oliver Lodge Laboratory, University of Liverpool, Liverpool, United Kingdom
- ⁷⁷ Department of Physics, Jožef Stefan Institute and University of Ljubljana, Ljubljana, Slovenia
- ⁷⁸ School of Physics and Astronomy, Queen Mary University of London, London, United Kingdom
- ⁷⁹ Department of Physics, Royal Holloway University of London, Surrey, United Kingdom
- ⁸⁰ Department of Physics and Astronomy, University College London, London, United Kingdom
- ⁸¹ Louisiana Tech University, Ruston LA, United States
- ⁸² Laboratoire de Physique Nucléaire et de Hautes Energies, UPMC and Université Paris-Diderot and CNRS/IN2P3, Paris, France
- ⁸³ Fysiska institutionen, Lunds universitet, Lund, Sweden
- ⁸⁴ Departamento de Física Teórica C-15, Universidad Autónoma de Madrid, Madrid, Spain
- ⁸⁵ Institut für Physik, Universität Mainz, Mainz, Germany
- ⁸⁶ School of Physics and Astronomy, University of Manchester, Manchester, United Kingdom
- ⁸⁷ CPPM, Aix-Marseille Université and CNRS/IN2P3, Marseille, France
- ⁸⁸ Department of Physics, University of Massachusetts, Amherst MA, United States
- ⁸⁹ Department of Physics, McGill University, Montreal QC, Canada
- ⁹⁰ School of Physics, University of Melbourne, Victoria, Australia
- ⁹¹ Department of Physics, The University of Michigan, Ann Arbor MI, United States
- ⁹² Department of Physics and Astronomy, Michigan State University, East Lansing MI, United States
- ⁹³ ^(a) INFN Sezione di Milano; ^(b) Dipartimento di Fisica, Università di Milano, Milano, Italy
- ⁹⁴ B.I. Stepanov Institute of Physics, National Academy of Sciences of Belarus, Minsk, Belarus
- ⁹⁵ National Scientific and Educational Centre for Particle and High Energy Physics, Minsk, Belarus
- ⁹⁶ Group of Particle Physics, University of Montreal, Montreal QC, Canada
- ⁹⁷ P.N. Lebedev Physical Institute of the Russian Academy of Sciences, Moscow, Russia
- ⁹⁸ Institute for Theoretical and Experimental Physics (ITEP), Moscow, Russia
- ⁹⁹ National Research Nuclear University MEPhI, Moscow, Russia
- ¹⁰⁰ D.V. Skobeltsyn Institute of Nuclear Physics, M.V. Lomonosov Moscow State University, Moscow, Russia
- ¹⁰¹ Fakultät für Physik, Ludwig-Maximilians-Universität München, München, Germany
- ¹⁰² Max-Planck-Institut für Physik (Werner-Heisenberg-Institut), München, Germany
- ¹⁰³ Nagasaki Institute of Applied Science, Nagasaki, Japan
- ¹⁰⁴ Graduate School of Science and Kobayashi-Maskawa Institute, Nagoya University, Nagoya, Japan
- ¹⁰⁵ ^(a) INFN Sezione di Napoli; ^(b) Dipartimento di Fisica, Università di Napoli, Napoli, Italy
- ¹⁰⁶ Department of Physics and Astronomy, University of New Mexico, Albuquerque NM, United States
- ¹⁰⁷ Institute for Mathematics, Astrophysics and Particle Physics, Radboud University Nijmegen/Nikhef, Nijmegen, Netherlands
- ¹⁰⁸ Nikhef National Institute for Subatomic Physics and University of Amsterdam, Amsterdam, Netherlands
- ¹⁰⁹ Department of Physics, Northern Illinois University, DeKalb IL, United States
- ¹¹⁰ Budker Institute of Nuclear Physics, SB RAS, Novosibirsk, Russia
- ¹¹¹ Department of Physics, New York University, New York NY, United States
- ¹¹² Ohio State University, Columbus OH, United States
- ¹¹³ Faculty of Science, Okayama University, Okayama, Japan
- ¹¹⁴ Homer L. Dodge Department of Physics and Astronomy, University of Oklahoma, Norman OK, United States
- ¹¹⁵ Department of Physics, Oklahoma State University, Stillwater OK, United States
- ¹¹⁶ Palacký University, RCPTM, Olomouc, Czechia
- ¹¹⁷ Center for High Energy Physics, University of Oregon, Eugene OR, United States
- ¹¹⁸ LAL, Univ. Paris-Sud, CNRS/IN2P3, Université Paris-Saclay, Orsay, France
- ¹¹⁹ Graduate School of Science, Osaka University, Osaka, Japan
- ¹²⁰ Department of Physics, University of Oslo, Oslo, Norway
- ¹²¹ Department of Physics, Oxford University, Oxford, United Kingdom
- ¹²² ^(a) INFN Sezione di Pavia; ^(b) Dipartimento di Fisica, Università di Pavia, Pavia, Italy
- ¹²³ Department of Physics, University of Pennsylvania, Philadelphia PA, United States
- ¹²⁴ National Research Centre “Kurchatov Institute”, B.P. Konstantinov Petersburg Nuclear Physics Institute, St. Petersburg, Russia
- ¹²⁵ ^(a) INFN Sezione di Pisa; ^(b) Dipartimento di Fisica E. Fermi, Università di Pisa, Pisa, Italy
- ¹²⁶ Department of Physics and Astronomy, University of Pittsburgh, Pittsburgh PA, United States
- ¹²⁷ ^(a) Laboratório de Instrumentação e Física Experimental de Partículas – LIP, Lisboa; ^(b) Faculdade de Ciências, Universidade de Lisboa, Lisboa; ^(c) Department of Physics, University of Coimbra, Coimbra; ^(d) Centro de Física Nuclear da Universidade de Lisboa, Lisboa; ^(e) Departamento de Física, Universidade do Minho, Braga; ^(f) Departamento de Física Teórica y del Cosmos and CAFPE, Universidad de Granada, Granada (Spain); ^(g) Dep Física and CEFITEC of Faculdade de Ciências e Tecnologia, Universidade Nova de Lisboa, Caparica, Portugal
- ¹²⁸ Institute of Physics, Academy of Sciences of the Czech Republic, Praha, Czechia
- ¹²⁹ Czech Technical University in Prague, Praha, Czechia

- ¹³⁰ Faculty of Mathematics and Physics, Charles University in Prague, Praha, Czechia
¹³¹ State Research Center Institute for High Energy Physics (Protvino), NRC KI, Russia
¹³² Particle Physics Department, Rutherford Appleton Laboratory, Didcot, United Kingdom
¹³³ ^(a) INFN Sezione di Roma; ^(b) Dipartimento di Fisica, Sapienza Università di Roma, Roma, Italy
¹³⁴ ^(a) INFN Sezione di Roma Tor Vergata; ^(b) Dipartimento di Fisica, Università di Roma Tor Vergata, Roma, Italy
¹³⁵ ^(a) INFN Sezione di Roma Tre; ^(b) Dipartimento di Matematica e Fisica, Università Roma Tre, Roma, Italy
¹³⁶ ^(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 LPTPM, Oujda; ^(e) Faculté des Sciences, Université Mohammed V, Rabat, Morocco
¹³⁷ DSM/IRFU (Institut de Recherches sur les Lois Fondamentales de l'Univers), CEA Saclay (Commissariat à l'Energie Atomique et aux Energies Alternatives), Gif-sur-Yvette, France
¹³⁸ Santa Cruz Institute for Particle Physics, University of California Santa Cruz, Santa Cruz CA, United States
¹³⁹ Department of Physics, University of Washington, Seattle WA, United States
¹⁴⁰ School of Physics, Shandong University, Shandong, China
¹⁴¹ Department of Physics and Astronomy, Shanghai Key Laboratory for Particle Physics and Cosmology, Shanghai Jiao Tong University, Shanghai, China ^{av}
¹⁴² Department of Physics and Astronomy, University of Sheffield, Sheffield, United Kingdom
¹⁴³ Department of Physics, Shinshu University, Nagano, Japan
¹⁴⁴ Fachbereich Physik, Universität Siegen, Siegen, Germany
¹⁴⁵ Department of Physics, Simon Fraser University, Burnaby BC, Canada
¹⁴⁶ SLAC National Accelerator Laboratory, Stanford CA, United States
¹⁴⁷ ^(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
¹⁴⁸ ^(a) Department of Physics, University of Cape Town, Cape Town; ^(b) Department of Physics, University of Johannesburg, Johannesburg; ^(c) School of Physics, University of the Witwatersrand, Johannesburg, South Africa
¹⁴⁹ ^(a) Department of Physics, Stockholm University; ^(b) The Oskar Klein Centre, Stockholm, Sweden
¹⁵⁰ Physics Department, Royal Institute of Technology, Stockholm, Sweden
¹⁵¹ Departments of Physics & Astronomy and Chemistry, Stony Brook University, Stony Brook NY, United States
¹⁵² Department of Physics and Astronomy, University of Sussex, Brighton, United Kingdom
¹⁵³ School of Physics, University of Sydney, Sydney, Australia
¹⁵⁴ Institute of Physics, Academia Sinica, Taipei, Taiwan
¹⁵⁵ Department of Physics, Technion: Israel Institute of Technology, Haifa, Israel
¹⁵⁶ Raymond and Beverly Sackler School of Physics and Astronomy, Tel Aviv University, Tel Aviv, Israel
¹⁵⁷ Department of Physics, Aristotle University of Thessaloniki, Thessaloniki, Greece
¹⁵⁸ International Center for Elementary Particle Physics and Department of Physics, The University of Tokyo, Tokyo, Japan
¹⁵⁹ Graduate School of Science and Technology, Tokyo Metropolitan University, Tokyo, Japan
¹⁶⁰ Department of Physics, Tokyo Institute of Technology, Tokyo, Japan
¹⁶¹ Tomsk State University, Tomsk, Russia
¹⁶² Department of Physics, University of Toronto, Toronto ON, Canada
¹⁶³ ^(a) TRIUMF, Vancouver BC; ^(b) Department of Physics and Astronomy, York University, Toronto ON, Canada
¹⁶⁴ Faculty of Pure and Applied Sciences, and Center for Integrated Research in Fundamental Science and Engineering, University of Tsukuba, Tsukuba, Japan
¹⁶⁵ Department of Physics and Astronomy, Tufts University, Medford MA, United States
¹⁶⁶ Department of Physics and Astronomy, University of California Irvine, Irvine CA, United States
¹⁶⁷ ^(a) INFN Gruppo Collegato di Udine, Sezione di Trieste, Udine; ^(b) ICTP, Trieste; ^(c) Dipartimento di Chimica, Fisica e Ambiente, Università di Udine, Udine, Italy
¹⁶⁸ Department of Physics and Astronomy, University of Uppsala, Uppsala, Sweden
¹⁶⁹ Department of Physics, University of Illinois, Urbana IL, United States
¹⁷⁰ Instituto de Física Corpuscular (IFIC) and Departamento de Física Atomica, Molecular y Nuclear and Departamento de Ingeniería Electrónica and Instituto de Microelectrónica de Barcelona (IMB-CNM), University of Valencia and CSIC, Valencia, Spain
¹⁷¹ Department of Physics, University of British Columbia, Vancouver BC, Canada
¹⁷² Department of Physics and Astronomy, University of Victoria, Victoria BC, Canada
¹⁷³ Department of Physics, University of Warwick, Coventry, United Kingdom
¹⁷⁴ Waseda University, Tokyo, Japan
¹⁷⁵ Department of Particle Physics, The Weizmann Institute of Science, Rehovot, Israel
¹⁷⁶ Department of Physics, University of Wisconsin, Madison WI, United States
¹⁷⁷ Fakultät für Physik und Astronomie, Julius-Maximilians-Universität, Würzburg, Germany
¹⁷⁸ Fakultät für Mathematik und Naturwissenschaften, Fachgruppe Physik, Bergische Universität Wuppertal, Wuppertal, Germany
¹⁷⁹ Department of Physics, Yale University, New Haven CT, United States
¹⁸⁰ Yerevan Physics Institute, Yerevan, Armenia
¹⁸¹ Centre de Calcul de l'Institut National de Physique Nucléaire et de Physique des Particules (IN2P3), Villeurbanne, France

^a Also at Department of Physics, King's College London, London, United Kingdom.

^b Also at Institute of Physics, Azerbaijan Academy of Sciences, Baku, Azerbaijan.

^c Also at Novosibirsk State University, Novosibirsk, Russia.

^d Also at TRIUMF, Vancouver BC, Canada.

^e Also at Department of Physics & Astronomy, University of Louisville, Louisville, KY, United States of America.

^f Also at Physics Department, An-Najah National University, Nablus, Palestine.

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

^h Also at Department of Physics, University of Fribourg, Fribourg, Switzerland.

ⁱ Also at Departament de Física de la Universitat Autònoma de Barcelona, Barcelona, Spain.

^j Also at Departamento de Física e Astronomia, Faculdade de Ciências, Universidade do Porto, Portugal.

^k Also at Tomsk State University, Tomsk, Russia.

^l Also at Università di Napoli Parthenope, Napoli, Italy.

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

ⁿ Also at National Institute of Physics and Nuclear Engineering, Bucharest, Romania.

^o Also at Department of Physics, St. Petersburg State Polytechnical University, St. Petersburg, Russia.

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

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

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

^s Also at Institutio Catalana de Recerca i Estudis Avancats, ICREA, Barcelona, Spain.

- ^t Also at Graduate School of Science, Osaka University, Osaka, Japan.
- ^u Also at Department of Physics, National Tsing Hua University, Taiwan.
- ^v Also at Institute for Mathematics, Astrophysics and Particle Physics, Radboud University Nijmegen/Nikhef, Nijmegen, Netherlands.
- ^w Also at Department of Physics, The University of Texas at Austin, Austin TX, United States of America.
- ^x Also at CERN, Geneva, Switzerland.
- ^y Also at Georgian Technical University (GTU), Tbilisi, Georgia.
- ^z Also at O Chadai Academic Production, Ochanomizu University, Tokyo, Japan.
- ^{aa} Also at Manhattan College, New York NY, United States of America.
- ^{ab} Also at Academia Sinica Grid Computing, Institute of Physics, Academia Sinica, Taipei, Taiwan.
- ^{ac} Also at School of Physics, Shandong University, Shandong, China.
- ^{ad} Also at Department of Physics, California State University, Sacramento CA, United States of America.
- ^{ae} Also at Moscow Institute of Physics and Technology State University, Dolgoprudny, Russia.
- ^{af} Also at Section de Physique, Université de Genève, Geneva, Switzerland.
- ^{ag} Also at Eotvos Lorand University, Budapest, Hungary.
- ^{ah} Also at Departments of Physics & Astronomy and Chemistry, Stony Brook University, Stony Brook NY, United States of America.
- ^{ai} Also at International School for Advanced Studies (SISSA), Trieste, Italy.
- ^{aj} Also at Department of Physics and Astronomy, University of South Carolina, Columbia SC, United States of America.
- ^{ak} Also at Institut de Física d'Altes Energies (IFAE), The Barcelona Institute of Science and Technology, Barcelona, Spain.
- ^{al} Also at School of Physics and Engineering, Sun Yat-sen University, Guangzhou, China.
- ^{am} Also at Institute for Nuclear Research and Nuclear Energy (INRNE) of the Bulgarian Academy of Sciences, Sofia, Bulgaria.
- ^{an} Also at Faculty of Physics, M.V. Lomonosov Moscow State University, Moscow, Russia.
- ^{ao} Also at Institute of Physics, Academia Sinica, Taipei, Taiwan.
- ^{ap} Also at National Research Nuclear University MEPhI, Moscow, Russia.
- ^{aq} Also at Department of Physics, Stanford University, Stanford CA, United States of America.
- ^{ar} Also at Institute for Particle and Nuclear Physics, Wigner Research Centre for Physics, Budapest, Hungary.
- ^{as} Also at Flensburg University of Applied Sciences, Flensburg, Germany.
- ^{at} Also at University of Malaya, Department of Physics, Kuala Lumpur, Malaysia.
- ^{au} Also at CPPM, Aix-Marseille Université and CNRS/IN2P3, Marseille, France.
- ^{av} Also affiliated with PKU-CHEP.
- * Deceased.