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Search for charged Higgs bosons produced in association with a top quark and decaying via $H^\pm \rightarrow \tau \nu$ using pp collision data recorded at $\sqrt{s} = 13$ TeV by the ATLAS detector



The ATLAS Collaboration*

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ABSTRACT

Charged Higgs bosons produced in association with a single top quark and decaying via $H^\pm \rightarrow \tau \nu$ are searched for with the ATLAS experiment at the LHC, using proton–proton collision data at $\sqrt{s} = 13$ TeV corresponding to an integrated luminosity of 3.2 fb^{-1} . The final state is characterised by the presence of a hadronic τ decay and missing transverse momentum, as well as a hadronically decaying top quark, resulting in the absence of high-transverse-momentum electrons and muons. The data are found to be consistent with the expected background from Standard Model processes. A statistical analysis leads to 95% confidence-level upper limits on the production cross section times branching fraction, $\sigma(pp \rightarrow [b]tH^\pm) \times \text{BR}(H^\pm \rightarrow \tau \nu)$, between 1.9 pb and 15 fb, for charged Higgs boson masses ranging from 200 to 2000 GeV. The exclusion limits for this search surpass those obtained with the proton–proton collision data recorded at $\sqrt{s} = 8$ TeV.

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1. Introduction

Following the discovery of a neutral scalar particle at the Large Hadron Collider (LHC) in 2012 [1,2], an important question is whether this new particle is the Higgs boson of the Standard Model (SM) or part of an extended Higgs sector. Charged Higgs bosons¹ appear in several non-minimal scalar sectors, where a second doublet [3] or triplets [4–8] are added to the SM Higgs doublet. The observation of a charged Higgs boson would therefore clearly indicate physics beyond the SM.

The ATLAS and CMS collaborations have searched for light charged Higgs bosons, produced in top-quark decays, using proton–proton (pp) collisions at $\sqrt{s} = 7$ –8 TeV in the $\tau \nu$ [9–13] and cs [14, 15] decay modes. Using data collected at $\sqrt{s} = 8$ TeV, charged Higgs bosons heavier than the top quark were also searched for, using final states originating from both the $\tau \nu$ and tb decay modes [11,13,16]. Vector-boson-fusion H^\pm production was also searched for by ATLAS using the WZ final state [17]. No evidence of a charged Higgs boson was found in any of these searches.

For m_{H^\pm} greater than the top-quark mass m_{top} , which is the mass range of interest in this paper, the main production mode

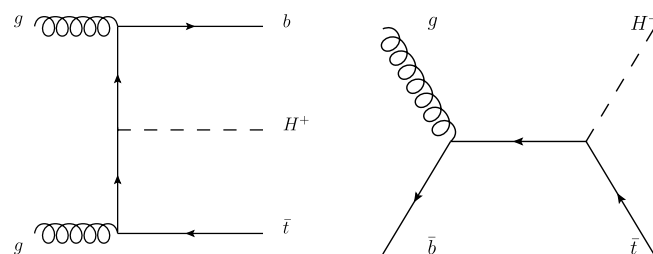


Fig. 1. Leading-order Feynman diagrams for the production of a charged Higgs boson with a mass $m_{H^\pm} > m_{\text{top}}$, in association with a single top quark (left in the 4FS, and right in the 5FS).

of a charged Higgs boson at the LHC is expected to be in association with a top quark [18–20]. The corresponding Feynman diagrams are shown in Fig. 1. When calculating the corresponding cross section in a four-flavour scheme (4FS), b -quarks are dynamically produced, whereas in a five-flavour scheme (5FS), the b -quark is also considered as an active flavour in the proton. For model-dependent interpretations, 4FS and 5FS cross sections are averaged according to Ref. [21]. In two-Higgs-doublet models (2HDMs), the production and decay of the charged Higgs boson also depend on the parameter $\tan \beta$, defined as the ratio of the vacuum expectation values of the two Higgs doublets, and the mixing angle α between the CP-even Higgs bosons. In the alignment limit, where $\cos(\beta - \alpha) \simeq 0$, the decay $H^\pm \rightarrow \tau \nu$ can have a substantial branch-

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

¹ In the following, charged Higgs bosons are denoted H^\pm , with the charge-conjugate H^\mp always implied. Similarly, generic symbols are used for their decay products.

ing fraction. In a type-II 2HDM, even when the decay $H^+ \rightarrow tb$ dominates, the branching fraction $\text{BR}(H^+ \rightarrow \tau\nu)$ can reach 10–15% at large values of $\tan\beta$ [22].

This paper describes a search for charged Higgs bosons in pp collisions at $\sqrt{s} = 13$ TeV using the ATLAS experiment. The production of a charged Higgs boson in association with a single top quark and its decay via $H^+ \rightarrow \tau\nu$ are explored in the mass range 200 to 2000 GeV, extending by 1000 GeV the mass range considered by the ATLAS collaboration during Run 1 of the LHC. The final state is characterised by the presence of a hadronic τ decay and missing transverse momentum arising from the H^+ decay, as well as a fully hadronic top-quark decay, resulting in the absence of high-transverse-momentum electrons and muons. The SM prediction is compared to the data, and results for the signal cross section times branching fraction $\sigma(pp \rightarrow [b]tH^\pm) \times \text{BR}(H^\pm \rightarrow \tau\nu)$ are presented, together with an interpretation in the hMSSM benchmark scenario [23,24], in which the light CP-even Higgs boson mass m_h is set to 125 GeV, without choosing explicitly the soft-supersymmetry-breaking parameters.

2. Data and simulated events

The ATLAS experiment [25] consists of an inner detector with coverage in pseudorapidity² up to $|\eta| = 2.5$, surrounded by a thin 2 T superconducting solenoid, a calorimeter system extending up to $|\eta| = 4.9$ and a muon spectrometer extending up to $|\eta| = 2.7$ that measures the deflection of muon trajectories in the field of three superconducting toroid magnets. The innermost pixel layer, the insertable B-layer (IBL), was added between the first and second runs of the LHC, around a new, narrower and thinner beam pipe [26]. A two-level trigger system is used to select events of interest [27]. The integrated luminosity, considering only the data-taking periods of 2015 in which all relevant detector subsystems were operational, is 3.2 fb^{-1} and has an uncertainty of 5%. It is derived following a methodology similar to that detailed in Ref. [28], from a calibration of the luminosity scale using x - y beam-separation scans performed in August 2015.

Simulated events of H^+ production in association with a single top quark are generated in the 4FS at the next-to-leading order (NLO) with MADGRAPH5_AMC@NLO v.2.2.2 [29] using the NNPDF23LO [30] parton distribution function (PDF) set, interfaced to PYTHIA v8.186 [31] with the A14 set of tuned parameters (tune) [32] for the underlying event.

The main backgrounds are the production of $t\bar{t}$ pairs, single top quarks, W +jets, Z/γ^* +jets and electroweak gauge boson pairs ($WW/WZ/ZZ$), as well as multi-jet events. For the generation of $t\bar{t}$ pairs and single top quarks in the Wt - and s -channels, the POWHEG-Box v2 [33,34] generator with the CT10 [35,36] PDF set in the matrix-element calculations is used. Electroweak t -channel single-top-quark events are generated using the POWHEG-Box v1 generator. This generator uses the 4FS for the NLO matrix-element calculations together with the fixed four-flavour PDF set CT10F4. For this process, the top quark is decayed using MADSPIN [37], thereby preserving all spin correlations. For all backgrounds above, the parton shower, the fragmentation and the underlying event are simulated using PYTHIA v6.428 [38] with the CTEQ6L1 [39] PDF set and the corresponding Perugia 2012 (P2012) tune [40].

The top-quark mass is set to 172.5 GeV for all relevant background and signal samples. The $t\bar{t}$ cross section is calculated at next-to-next-to-leading order (NNLO), including soft-gluon resummation to the next-to-next-to-leading logarithmic (NNLL) order, with Top++ v2.0 [41–47]. The single-top-quark samples are normalised to the approximate NNLO cross sections [48–50]. Events containing a W or Z boson with associated jets are simulated using MADGRAPH5_AMC@NLO v.2.2.2 at LO with the NNPDF23LO PDF set, interfaced to PYTHIA v8.186 with the A14 underlying-event tune. These samples are normalised to the NNLO cross sections calculated with FEWZ [51–53]. Finally, diboson processes are simulated using the POWHEG-Box v2 generator interfaced to the PYTHIA v8.186 parton shower model. The CT10 NLO set is used as the PDF for the hard-scatter process, while the CTEQ6L1 PDF set is used for the parton shower. The non-perturbative effects are modelled using the AZNLO tune [54]. The diboson samples are normalised to their NLO cross sections, as computed by the event generator.

Whenever applicable, PHOTOS++ v3.52 [55] is employed for photon radiation from charged leptons, and EVTGEN v1.2.0 [56] is used to simulate b - and c -hadron decays. Multiple overlaid pp collisions (pile-up, with 14 collisions per bunch-crossing on average) are simulated with the soft QCD processes of PYTHIA v8.186 using the MSTW2008LO [57–59] PDF set and the A2 underlying-event tune [60]. All simulated signal and background samples are processed through a simulation [61] of the detector geometry and response using GEANT4 [62]. Finally, they are processed through the same reconstruction software as the data.

In the following, the backgrounds are categorised based on the type of reconstructed objects identified as the visible decay products³ of the hadronically decaying τ candidate ($\tau_{\text{had-vis}}$). Only simulated events having a true hadronically decaying τ at generator level (τ_{had}) or with a charged lepton (electron or muon) misidentified as a $\tau_{\text{had-vis}}$ are kept. Backgrounds arising from a jet misidentified as a $\tau_{\text{had-vis}}$ are estimated with a data-driven method.

3. Object reconstruction and identification

In the ATLAS experiment, hadronic jets are reconstructed from energy deposits in the calorimeters, using the anti- k_t algorithm [63,64] with a radius parameter $R = 0.4$. In the following, jets are required to have a transverse momentum $p_T > 25$ GeV and $|\eta| < 2.5$. A multi-variate technique (Jet Vertex Tagger) relying on jet energy and tracking variables to determine the likelihood that a given jet originates from pile-up [65] is applied to jets with $p_T < 50$ GeV and $|\eta| < 2.4$. Jets arising from b -hadron decays are identified by using an algorithm that combines impact parameter information with the explicit identification of secondary and tertiary vertices within the jet into a b -tagging score [66,67]. The minimal requirement imposed on the b -tagging score in this analysis corresponds to a 70% efficiency to tag a b -quark-initiated jet in $t\bar{t}$ events, with rejection rates of 400 for light-quark-initiated jets, 27 for τ_{had} -initiated jets and 8 for c -quark-initiated jets, enhanced with respect to Run 1 by the use of the IBL and an improved algorithm. The tagging efficiencies from simulation are corrected based on the results of flavour-tagging calibrations performed with data [68].

Candidates for identification as $\tau_{\text{had-vis}}$ arise from jets that have $p_T > 10$ GeV and for which one or three charged-particle tracks are found within a cone of size⁴ $\Delta R = 0.2$ around the axis of

² 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 from the IP to the centre of the LHC ring, and the y -axis points upward. Cylindrical coordinates (r, ϕ) are used in the transverse plane, ϕ being the azimuthal angle around the z -axis. The pseudorapidity is defined in terms of the polar angle θ as $\eta = -\ln \tan(\theta/2)$.

³ This refers to all τ decay products except the neutrinos.

⁴ $\Delta R = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2}$, where $\Delta\eta$ and $\Delta\phi$ are differences in pseudorapidity and azimuthal angle, respectively.

the $\tau_{\text{had-vis}}$ candidate [69,70]. These objects are further required to have a visible transverse momentum (p_T^τ) of at least 40 GeV and to be within $|\eta| < 2.3$. The output of boosted decision tree (BDT) algorithms [71] is used in order to distinguish $\tau_{\text{had-vis}}$ candidates from jets not initiated by hadronically decaying τ -leptons. This is done separately for decays with one or three charged-particle tracks, and for varying values of the identification efficiency. In this analysis, a working point corresponding to a 55% (40%) efficiency for the identification of 1-prong (3-prong) $\tau_{\text{had-vis}}$ objects is used, with rejection rates of $\mathcal{O}(10^2)$ for jets.

In this analysis, events with isolated electron or muon candidates with a transverse energy or momentum above 20 GeV are rejected. Electron candidates [72] are reconstructed from energy deposits (clusters) in the electromagnetic calorimeter, associated with a reconstructed track in the inner detector. The pseudorapidity range for the electromagnetic clusters covers the fiducial volume of the detector, $|\eta| < 2.47$ (the transition region between the barrel and end-cap calorimeters, $1.37 < |\eta| < 1.52$, is excluded). Quality requirements on the electromagnetic clusters and the tracks, as well as isolation requirements in a cone around the electron candidate based on its transverse energy and the tracking information, are then applied in order to reduce contamination from jets. The muon candidates are reconstructed from track segments in the muon spectrometer, and matched with tracks found in the inner detector within $|\eta| < 2.5$ [73]. The final muon candidates are refitted using the complete track information from both detector systems. They must fulfil quality requirements including a p_T -dependent track-based isolation requirement in a cone of variable size around the muon, which has good performance under high pile-up conditions and/or when a muon is close to a jet.

When objects overlap geometrically, the following procedures are applied, in this order. Every $\tau_{\text{had-vis}}$ candidate that overlaps with a loosely identified electron or muon, within a cone of size ΔR of 0.4 or 0.2, respectively, is removed. Then, reconstructed jets are discarded if an electron or a $\tau_{\text{had-vis}}$ candidate fulfilling the selection criteria above is found within a cone of size $\Delta R = 0.2$.

The magnitude E_T^{miss} of the missing transverse momentum [74] is reconstructed from the negative vector sum of transverse momenta of reconstructed and fully calibrated objects (collected in the hard term), as well as from reconstructed tracks associated with the hard-scatter vertex which are not in the hard term (collected in the soft term). In order to mitigate the effects of pile-up, the E_T^{miss} is refined by using object-level corrections for the identified electrons, muons, jets and $\tau_{\text{had-vis}}$ candidates in the hard term. As the soft term contains only tracks associated with the hard-scatter vertex, it is robust against pile-up.

4. Event selection and background modelling

Charged Higgs bosons are searched for in the topology $pp \rightarrow [b]tH^+ \rightarrow [b](jjb)(\tau_{\text{had}}\nu)$. Events collected using an E_T^{miss} trigger with a threshold at 70 GeV are considered. After ensuring that no jets are consistent with having originated from instrumental effects or non-collision background, each event is required to contain one $\tau_{\text{had-vis}}$ with $p_T^\tau > 40$ GeV (only the highest- p_T^τ candidate must fulfil the identification criteria described in Section 3), three or more jets with $p_T > 25$ GeV, of which at least one is b -tagged, no electron or muon with a transverse energy or momentum above 20 GeV, and to have $E_T^{\text{miss}} > 150$ GeV. For the selected events, the transverse mass m_T of the $\tau_{\text{had-vis}}$ and E_T^{miss} system is defined as:

$$m_T = \sqrt{2p_T^\tau E_T^{\text{miss}}(1 - \cos \Delta\phi_{\tau, \text{miss}})}, \quad (1)$$

where $\Delta\phi_{\tau, \text{miss}}$ is the azimuthal angle between the $\tau_{\text{had-vis}}$ and the direction of the missing transverse momentum. This discrim-

inating variable takes values lower than the W boson mass for $W \rightarrow \tau\nu$ decays in background events and lower than the H^+ mass for signal events, in the absence of detector resolution effects. A requirement of $m_T > 50$ GeV is applied in order to reject events with mismeasured E_T^{miss} , where $\tau_{\text{had-vis}}$ is nearly aligned with the direction of the missing transverse momentum.

The E_T^{miss} trigger efficiency is measured in data and then used to reweight the simulated events, rather than relying on the E_T^{miss} trigger in the simulated samples. This measurement is performed in a control region of the data that is orthogonal to the signal region described above, while retaining as many similarities as possible. For this purpose, events passing a single-electron trigger with a transverse energy threshold at 24 GeV are considered and required to contain exactly one electron matched to the corresponding trigger object, exactly one $\tau_{\text{had-vis}}$ and two or more jets, of which at least one is b -tagged. Both the electron and the $\tau_{\text{had-vis}}$ fulfil loose identification criteria in order to improve the statistical precision, with little impact on the measured E_T^{miss} turn-on curve.

The “jet $\rightarrow \tau_{\text{had-vis}}$ ” background includes multi-jet events and other processes where a quark- or gluon-initiated jet is reconstructed and selected as the $\tau_{\text{had-vis}}$ candidate. This background is estimated with a data-driven method that relies on the measurement of the rate at which jets are misidentified as $\tau_{\text{had-vis}}$, hereafter referred to as the fake factor (FF). For this purpose, a control region populated primarily with misidentified $\tau_{\text{had-vis}}$ candidates is defined by using the same requirements as for the signal region, except that $E_T^{\text{miss}} < 80$ GeV and that the number of b -tagged jets is zero. The FF is defined as the ratio of the number of misidentified $\tau_{\text{had-vis}}$ candidates fulfilling the nominal object selection to the number of misidentified $\tau_{\text{had-vis}}$ candidates satisfying an “anti- $\tau_{\text{had-vis}}$ ” selection. This anti- $\tau_{\text{had-vis}}$ selection is defined by inverting the $\tau_{\text{had-vis}}$ identification criteria while maintaining a loose requirement on the BDT output score, which selects the same kind of objects mimicking $\tau_{\text{had-vis}}$ candidates as those fulfilling the identification criteria. In order to account for differences between gluon-, light-quark- and b -quark-initiated jets, FFs are parameterised as functions of p_T , the type of τ_{had} decay via the measured number of charged and neutral particles (π^0) [70], and the b -tagging score, as illustrated in Fig. 2. For each type of τ_{had} decay, the threshold value for the b -tagging score of the $\tau_{\text{had-vis}}$ candidate is optimised to keep enough entries in each of the two bins, below and above the threshold. After correcting for $\tau_{\text{had-vis}}$ candidates not fulfilling the identification criteria but matching a true τ_{had} at generator level, the number of events with a misidentified $\tau_{\text{had-vis}}$ in the signal region ($N_{\text{fakes}}^{\tau_{\text{had-vis}}}$) is derived from the subset of anti- $\tau_{\text{had-vis}}$ candidates as follows:

$$N_{\text{fakes}}^{\tau_{\text{had-vis}}} = \sum_i N_{\text{anti-}\tau_{\text{had-vis}}}(i) \times \text{FF}(i), \quad (2)$$

where the index i refers to each bin in terms of p_T , type of τ_{had} decay and b -tagging score, in which the FF is evaluated.

Backgrounds arising from events in which an electron or muon is misidentified as a $\tau_{\text{had-vis}}$ only contribute at the level of 5% to the total background, with misidentified muons contributing about one order of magnitude less than misidentified electrons. These backgrounds are estimated with simulation and include contributions from $t\bar{t}$, single-top-quark, W/Z + jets and diboson processes. If an electron is misidentified as a $\tau_{\text{had-vis}}$, a correction factor is applied to the event in order to account for the misidentification rate measured in a $Z \rightarrow ee$ control region in data, where one electron is reconstructed as a $\tau_{\text{had-vis}}$. Charged leptons from in-flight decays in multi-jet events are accounted for in the misidentified jet $\rightarrow \tau_{\text{had-vis}}$ background estimate.

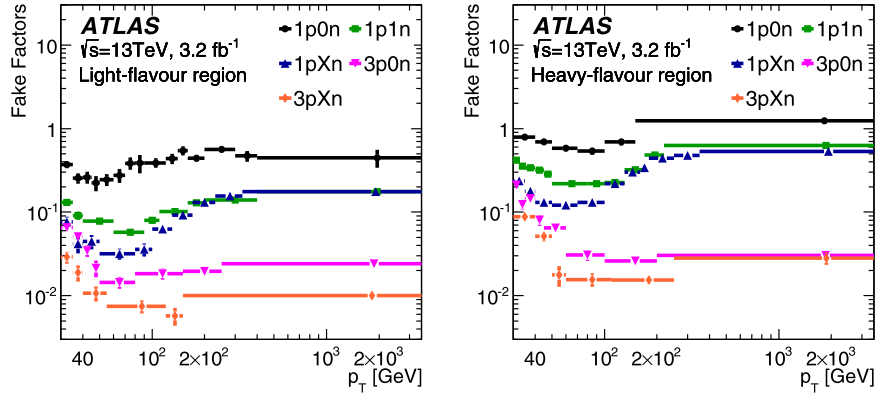


Fig. 2. Fake factors parameterised as a function of p_T and the reconstructed τ_{had} decay mode, for a b -tagging score of the $\tau_{\text{had-vis}}$ candidate below (left, light-flavour region) or above (right, heavy-flavour region) the chosen threshold. The τ_{had} decay mode is referred to as 1p0n, 1p1n, 1pXn, 3p0n or 3pXn, for a p -prong decay with n neutral particles (π^0), where $X \geq 2$ (1) for 1pXn (3pXn) decays. The threshold value for the b -tagging score is set to keep enough entries in each of the two bins, separately for each type of τ_{had} decay. The errors shown arise from the statistical uncertainty for a given p_T bin.

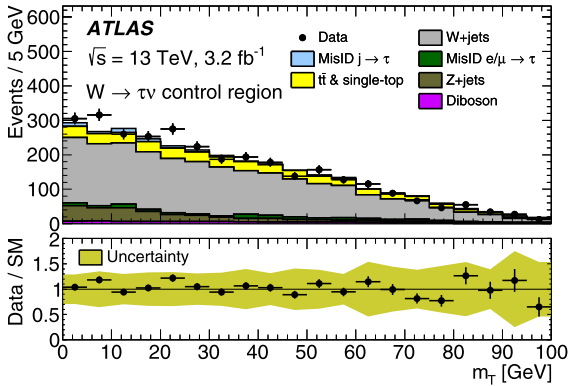


Fig. 3. Distribution of m_T in the control region enriched with $W \rightarrow \tau\nu$ events, which differs from the nominal event selection by the requirements that $m_T < 100$ GeV and that the number of b -tagged jets be zero. The $W \rightarrow \tau\nu$ background is normalised to the data through an overall scale factor. The total (statistical and systematic) uncertainties in the SM prediction are shown in the lower plot.

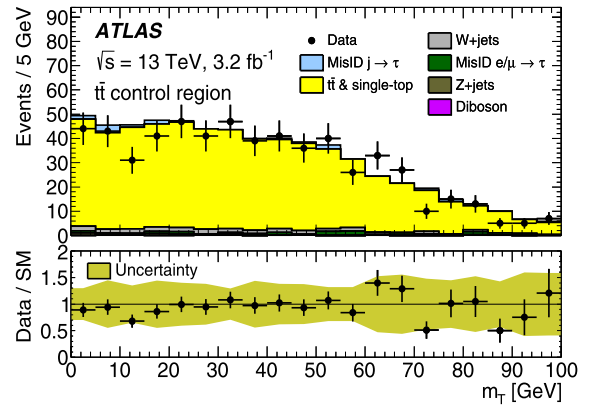


Fig. 4. Distribution of m_T in the control region enriched with $t\bar{t}$ events, which differs from the nominal event selection by the requirements that $m_T < 100$ GeV and that the number of b -tagged jets be at least two. The total (statistical and systematic) uncertainties in the SM prediction are shown in the lower plot.

The backgrounds with a true τ_{had} are estimated using simulation. The two dominant processes, $t\bar{t}$ and $W \rightarrow \tau\nu$, are validated in two dedicated control regions, which differ from the nominal event selection by the requirements that $m_T < 100$ GeV (instead of $m_T > 50$ GeV) and that the number of b -tagged jets be either at least two (for the control region enriched with $t\bar{t}$ events) or zero (for the control region enriched with $W \rightarrow \tau\nu$ events). The latter is also used to correct the overall normalisation of the simulated $W \rightarrow \tau\nu$ background. The m_T distributions that are predicted and measured in these two background-enriched control regions are displayed in Figs. 3 and 4. The relative signal contamination in the control region enriched in $W \rightarrow \tau\nu$ events is about two orders of magnitude smaller than the expected fraction of $H^+ \rightarrow \tau\nu$ events in the signal region. The control region enriched in $t\bar{t}$ events has a small overlap with the signal region, however the expected signal contamination is negligible, about one order of magnitude smaller than the expected fraction of $H^+ \rightarrow \tau\nu$ events in the signal region.

The expected number of background events in the signal region is shown in Table 1, together with the hypothetical contribution from charged Higgs bosons with a mass of 200 or 1000 GeV, and with $\sigma(pp \rightarrow [b]tH^\pm) \times \text{BR}(H^\pm \rightarrow \tau\nu)$ set to the prediction from the hMSSM scenario for $\tan\beta = 60$ (for a given mass, the expected signal yield increases quadratically with $\tan\beta$). The calculation of the production cross section is based on Refs. [22,75–78], while HDECAY [79] is used for computing the branching fraction. The sig-

Table 1

Expected event yields for the backgrounds and a hypothetical H^+ signal after all selection criteria, and comparison with 3.2 fb^{-1} of data. The values shown for the signal assume a charged Higgs boson mass of 200 or 1000 GeV, with a cross section times branching fraction $\sigma(pp \rightarrow [b]tH^\pm) \times \text{BR}(H^\pm \rightarrow \tau\nu)$ corresponding to $\tan\beta = 60$ in the hMSSM benchmark scenario. The uncertainties include statistical and systematic components.

Sample	Event yield
True τ_{had}	
$t\bar{t}$ & single-top-quark	590 ± 170
$W \rightarrow \tau\nu$	58 ± 14
$Z \rightarrow \tau\tau$	6.4 ± 2.0
diboson (WW, WZ, ZZ)	4.3 ± 1.3
Misidentified $e, \mu \rightarrow \tau_{\text{had-vis}}$	40 ± 6
Misidentified jet $\rightarrow \tau_{\text{had-vis}}$	196 ± 24
All backgrounds	900 ± 170
H^+ (200 GeV), hMSSM $\tan\beta = 60$	175 ± 28
H^+ (1000 GeV), hMSSM $\tan\beta = 60$	2.0 ± 0.2
Data	890

nal acceptance at 200 (1000) GeV is 1.5% (12%), as evaluated with respect to simulated samples where both the τ -lepton and the associated top quark decay inclusively. The event yield observed in 3.2 fb^{-1} of data is also shown in Table 1 and found to be consistent with the expectation for the background-only hypothesis.

5. Systematic uncertainties

Several sources of systematic uncertainty, affecting the normalisation of signal and background processes or the shape of their distributions, are considered. The individual sources of systematic uncertainty are assumed to be uncorrelated. However, when applicable, correlations of a given systematic uncertainty are maintained across all processes. All systematic uncertainties are symmetrised with respect to the nominal value.

In order to assess the impact of most detector-related systematic uncertainties, in particular those arising from the simulation of pile-up and object reconstruction, the event selection is re-applied after shifting a particular parameter to its ± 1 standard-deviation value. All instrumental systematic uncertainties arising from the reconstruction, identification and energy scale of electrons, muons, (b -tagged) jets and $\tau_{\text{had-vis}}$ candidates are considered. They are propagated to the reconstructed $E_{\text{T}}^{\text{miss}}$ and an additional uncertainty in its soft term is taken into account. The dominant detector-related systematic uncertainties for this search arise from the reconstruction and identification of $\tau_{\text{had-vis}}$ candidates, from the jet energy scale, from the $\tau_{\text{had-vis}}$ energy scale and from the b -tagging efficiency. Their impacts on the predicted event yield for the dominant background process ($t\bar{t}$) are, respectively, 12%, 11%, 3% and 2%. Systematic uncertainties arising from the reconstruction, identification and energy scale of electrons and muons are found to be negligible. The luminosity uncertainty of 5% is applied directly to the event yields of all simulated events.

The efficiency of the $E_{\text{T}}^{\text{miss}}$ trigger is measured in a control region of the data, as described in Section 4. The parameterisation of the efficiency shows a small dependence on the identification criteria (loose versus nominal) for the electron and the $\tau_{\text{had-vis}}$ candidate, as well as on the minimum number of jets chosen for the control region. This results in small variations of the measured fit function. These variations, as well as the limited statistical precision of the bins used for the fit function and the resulting parameterisation, are accounted for as systematic uncertainties. In the signal region, the total systematic uncertainty arising from the $E_{\text{T}}^{\text{miss}}$ trigger efficiency measurement is about 2%.

In the estimation of backgrounds with jets misidentified as $\tau_{\text{had-vis}}$, the dominant systematic uncertainties arise from the level of contamination of $\tau_{\text{had-vis}}$ objects matching a true τ_{had} decay at generator level and fulfilling the anti- $\tau_{\text{had-vis}}$ selection (varied by 50%), from the statistical limitation due to the control sample size and from the requirement on the BDT score in the anti- $\tau_{\text{had-vis}}$ control sample. When changing the latter, different fractions of gluon- and quark-initiated jets populate the anti- $\tau_{\text{had-vis}}$ control region. The event topology (in particular the shape of the $E_{\text{T}}^{\text{miss}}$ and $\Delta\phi_{\tau,\text{miss}}$ distributions) also depends on the requirement imposed on the BDT score. The corresponding systematic uncertainty is assessed by considering the shape of the m_{T} distribution obtained for two alternative cuts on the BDT score, which are symmetric around the nominal cut value. The impacts of the three systematic uncertainties listed above on the event yield of the background with jets misidentified as $\tau_{\text{had-vis}}$ are, respectively, 8%, 6% and 2%.

The dominant background process with a true τ_{had} is the production of $t\bar{t}$ pairs and single-top-quark events, for which an overall cross-section uncertainty of 6% is applied, incorporating scale, PDF+ α_s and top-quark mass uncertainties [47,80,81]. In addition, systematic uncertainties due to the choice of parton shower and hadronisation models are derived by comparing $t\bar{t}$ events generated with POWHEG-Box interfaced to either PYTHIA v8.210 or HERWIG++ v2.7.1 [82], which uses the UEEE5 [83] underlying-event tune. The systematic uncertainties arising from initial- and final-state parton radiation, which modify the jet production rate, are computed with the same packages as for the baseline $t\bar{t}$ event

generation, by setting the corresponding parameters in PYTHIA to a range of values not excluded by the experimental data. Finally, the uncertainty due to the choice of matrix-element generator is evaluated by comparing samples generated with MADGRAPH5_AMC@NLO or POWHEG-Box, both using the CTEQ6L1 PDF set and interfaced to HERWIG++. The impacts of the three systematic uncertainties listed above on the event yield of the $t\bar{t}$ background are, respectively, 16%, 7% and 15%.

For the sub-leading background process with a true τ_{had} , $W \rightarrow \tau\nu$, a systematic uncertainty of 3% is assigned to the overall renormalisation factor, as obtained by changing various selection criteria for the control region enriched with such background events. For Z +jets and diboson production, theoretical uncertainties of 5% and 6% are considered, respectively, combining PDF+ α_s and scale variation uncertainties in quadrature.

Systematic uncertainties in the H^+ signal generation are estimated as follows. The uncertainty arising from the QCD scale is obtained by varying the factorisation and renormalisation scale up and down by a factor of two. The largest variation of the signal acceptance is then symmetrised and taken as the scale uncertainty, 4–8% depending on the H^+ mass hypothesis. The variation of the signal acceptance with various PDF sets is estimated using LHAPDF [84], but is found to be negligible for all signal samples. Finally, the impact of A14 tune variations on the signal acceptance is estimated by adding in quadrature the positive and negative excursions from a subset of tune variations that cover underlying-event and jet-structure effects, as well as different aspects of extra jet production. This uncertainty amounts to 8–10% and is of the same order as the sum in quadrature of the detector-related systematic uncertainties for the H^+ signal samples.

6. Results

In order to test the compatibility of the data with the background-only and signal + background hypotheses, a profile likelihood ratio [85] is used, with m_{T} as the discriminating variable. The statistical analysis is based on a binned likelihood function for this distribution. All systematic uncertainties from theoretical or experimental sources are implemented as nuisance parameters. The parameter of interest (or signal strength) $\mu \equiv \sigma(pp \rightarrow [b]tH^\pm) \times \text{BR}(H^\pm \rightarrow \tau\nu)$, and the nuisance parameters are simultaneously fitted by means of a negative log-likelihood minimisation. Expected limits are derived using the asymptotic approximation of the distribution of the test statistic [86].

Fig. 5 shows the m_{T} distribution obtained after a fit with the background-only hypothesis, together with the m_{T} distributions corresponding to two H^+ mass hypotheses: 200 and 1000 GeV. The binning shown in Fig. 5 is also used in the statistical analysis. The SM predictions are found to be consistent with the data, and exclusion limits are set on $\sigma(pp \rightarrow [b]tH^\pm) \times \text{BR}(H^\pm \rightarrow \tau\nu)$ by rejecting the signal hypothesis at the 95% confidence level (CL) using the CL_s procedure [87]. Fig. 6 shows the observed and expected exclusion limits. They agree within the uncertainties over the explored H^+ mass range. The observed limits range from 1.9 pb to 15 fb in the mass range 200–2000 GeV. For the largest charged Higgs boson mass hypotheses, the exclusion limits show very little dependence on m_{H^+} , as there is only one bin entering the fit for $m_{\text{T}} > 500$ GeV. The impact from the various sources of systematic uncertainty on the expected 95% CL exclusion limits are summarised in Table 2, for H^+ mass hypotheses of 200 and 1000 GeV. The impact of the systematic uncertainties reported in Section 5 only represents the relative change in event yields. In the limit-setting procedure, however, m_{T} shape variations are also taken into account, leading to a different relative importance of the various systematic uncertainties. Those with a large impact over the ex-

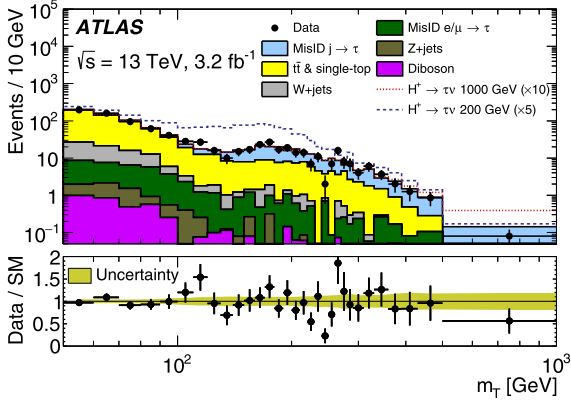


Fig. 5. Distribution of m_T after full event selection and a fit to the data with the background-only hypothesis. The horizontal axis starts at $m_T = 50$ GeV and is in logarithmic scale. Two H^+ signal hypotheses are included separately on the stack. The signal sample at 200 (1000) GeV is scaled to 5 (10) times the cross section predicted at $\tan\beta = 60$ in the hMSSM benchmark scenario. Bins are 10 GeV in width up to 310 GeV and then have a varying size. The last bin includes all overflow events. The total (statistical and systematic) uncertainties in the SM prediction are shown in the lower plot.

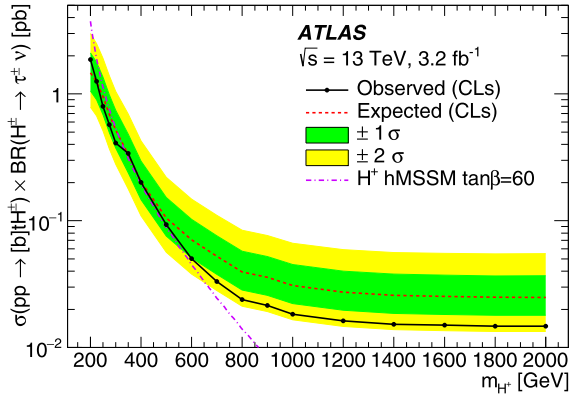


Fig. 6. Observed and expected 95% CL exclusion limits for heavy charged Higgs boson production as a function of m_{H^+} in 3.2 fb^{-1} of pp collision data. The prediction for $\sigma(pp \rightarrow [b]tH^\pm) \times \text{BR}(H^\pm \rightarrow \tau^\pm \nu)$ as a function of the charged Higgs boson mass is also shown as a dotted-dashed line, for $\tan\beta = 60$ in the hMSSM benchmark scenario.

ploded mass range are the $\tau_{\text{had-vis}}$ identification and energy-scale uncertainties, the $t\bar{t}$ background modelling uncertainties, and the statistical precision in the estimation of the background with a jet misidentified as a $\tau_{\text{had-vis}}$. For the larger H^+ mass hypotheses, the signal modelling uncertainties also have a significant impact. The total uncertainty is dominated by the statistical uncertainty.

The limits in Fig. 6 are presented together with an illustrative signal prediction in the hMSSM benchmark scenario. Fig. 7 shows the 95% CL exclusion limits on $\tan\beta$ as a function of m_{H^+} in the context of the hMSSM, compared with the Run 1 results. Values of $\tan\beta$ in the range 42–60 are excluded for a charged Higgs boson mass of 200 GeV. At $\tan\beta = 60$, above which no reliable theoretical calculations exist, the H^+ mass range from 200 to 340 GeV is excluded. The limits of this search surpass those obtained with the pp collision data at $\sqrt{s} = 8$ TeV [11].

7. Conclusion

A search for charged Higgs bosons produced in association with a single top quark and subsequently decaying via $H^+ \rightarrow \tau \nu$ is performed, based on fully hadronic final states. The dataset used for this analysis contains 3.2 fb^{-1} of pp collisions at $\sqrt{s} =$

Table 2

Impact of various sources of uncertainty on the expected 95% CL exclusion limit, for two H^+ mass hypotheses: 200 and 1000 GeV. The impact is obtained by comparing the nominal expected limit with the expected limit when a certain set of uncertainties is not included in the limit-setting procedure.

Source of systematic uncertainty	Impact on the expected limit (in %)	
	$m_{H^+} = 200$ GeV	$m_{H^+} = 1000$ GeV
Experimental		
luminosity	2.0	1.1
trigger	< 0.1	< 0.1
$\tau_{\text{had-vis}}$	2.7	1.1
jet	0.4	< 0.1
E_T^{miss}	0.3	< 0.1
Fake factors		
statistical limitation	4.5	0.7
true τ_{had} contamination	< 0.1	< 0.1
anti- $\tau_{\text{had-vis}}$ BDT score	0.2	0.6
Signal and background models		
$t\bar{t}$ cross section	0.2	< 0.1
$t\bar{t}$ modelling	7.5	1.0
H^+ signal modelling	1.4	1.3

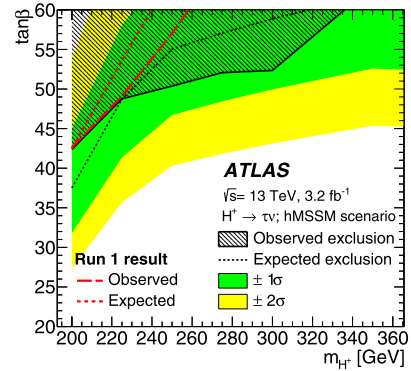


Fig. 7. 95% CL exclusion limits on $\tan\beta$ as a function of m_{H^+} , shown in the context of the hMSSM, for the regions in which reliable theoretical calculations exist ($\tan\beta \leq 60$). As a comparison, the two lighter dashed curves (in red in the web version of this article) in the upper-left corner show the observed and expected exclusion limits from Run 1 analyses of pp collisions measured at $\sqrt{s} = 8$ TeV by ATLAS [11].

13 TeV, recorded in 2015 by the ATLAS detector at the LHC. The background-only hypothesis is found to be in agreement with the data. Upper limits are set on the production cross section times branching fraction between 1.9 pb and 15 fb for a charged Higgs boson mass range of 200–2000 GeV. In the context of the hMSSM, values of $\tan\beta$ in the range 42–60 are excluded for a charged Higgs boson mass of 200 GeV. At $\tan\beta = 60$, above which no reliable theoretical calculations exist, the H^+ mass range from 200 to 340 GeV is excluded.

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The ATLAS Collaboration

M. Aaboud^{135d}, G. Aad⁸⁶, B. Abbott¹¹³, J. Abdallah⁶⁴, O. Abdinov¹¹, B. Abeloos¹¹⁷, R. Aben¹⁰⁷, O.S. AbouZeid¹³⁷, N.L. Abraham¹⁴⁹, H. Abramowicz¹⁵³, H. Abreu¹⁵², R. Abreu¹¹⁶, Y. Abulaiti^{146a,146b}, B.S. Acharya^{163a,163b,a}, L. Adamczyk^{39a}, D.L. Adams²⁶, J. Adelman¹⁰⁸, S. Adomeit¹⁰⁰, T. Adye¹³¹, A.A. Affolder⁷⁵, T. Agatonovic-Jovin¹³, J. Agricola⁵⁵, J.A. Aguilar-Saavedra^{126a,126f}, S.P. Ahlen²³, F. Ahmadov^{66,b}, G. Aielli^{133a,133b}, H. Akerstedt^{146a,146b}, T.P.A. Åkesson⁸², A.V. Akimov⁹⁶, G.L. Alberghi^{21a,21b}, J. Albert¹⁶⁸, S. Albrand⁵⁶, M.J. Alconada Verzini⁷², M. Aleksa³¹, I.N. Aleksandrov⁶⁶, C. Alexa^{27b}, G. Alexander¹⁵³, T. Alexopoulos¹⁰, M. Alhroob¹¹³, M. Aliev^{74a,74b}, G. Alimonti^{92a}, J. Alison³², S.P. Alkire³⁶, B.M.M. Allbrooke¹⁴⁹, B.W. Allen¹¹⁶, P.P. Allport¹⁸, A. Aloisio^{104a,104b}, A. Alonso³⁷, F. Alonso⁷², C. Alpigiani¹³⁸, M. Alstary⁸⁶, B. Alvarez Gonzalez³¹, D. Álvarez Piqueras¹⁶⁶, M.G. Alviggi^{104a,104b}, B.T. Amadio¹⁵, K. Amako⁶⁷, Y. Amaral Coutinho^{25a}, C. Amelung²⁴, D. Amidei⁹⁰, S.P. Amor Dos Santos^{126a,126c}, A. Amorim^{126a,126b}, S. Amoroso³¹, G. Amundsen²⁴, C. Anastopoulos¹³⁹, L.S. Ancu⁵⁰, N. Andari¹⁰⁸, T. Andeen³², C.F. Anders^{59b}, G. Anders³¹, J.K. Anders⁷⁵, K.J. Anderson³², A. Andreazza^{92a,92b}, V. Andrei^{59a}, S. Angelidakis⁹, I. Angelozzi¹⁰⁷, P. Anger⁴⁵, A. Angerami³⁶, F. Anghinolfi³¹, A.V. Anisenkov^{109,c}, N. Anjos¹², A. Annovi^{124a,124b}, M. Antonelli⁴⁸, A. Antonov⁹⁸, F. Anulli^{132a}, M. Aoki⁶⁷, L. Aperio Bella¹⁸, G. Arabidze⁹¹, Y. Arai⁶⁷, J.P. Araque^{126a}, A.T.H. Arce⁴⁶, F.A. Arduh⁷², J.-F. Arguin⁹⁵, S. Argyropoulos⁶⁴, M. Arik^{19a}, A.J. Armbruster¹⁴³, L.J. Armitage⁷⁷, O. Arnæz³¹, H. Arnold⁴⁹, M. Arratia²⁹, O. Arslan²², A. Artamonov⁹⁷, G. Artoni¹²⁰, S. Artz⁸⁴, S. Asai¹⁵⁵, N. Asbah⁴³, A. Ashkenazi¹⁵³, B. Åsman^{146a,146b}, L. Asquith¹⁴⁹, K. Assamagan²⁶, R. Astalos^{144a},

M. Atkinson¹⁶⁵, N.B. Atlay¹⁴¹, K. Augsten¹²⁸, G. Avolio³¹, B. Axen¹⁵, M.K. Ayoub¹¹⁷, G. Azuelos^{95,d},
 M.A. Baak³¹, A.E. Baas^{59a}, M.J. Baca¹⁸, H. Bachacou¹³⁶, K. Bachas^{74a,74b}, M. Backes³¹, M. Backhaus³¹,
 P. Bagiacchi^{132a,132b}, P. Bagnaia^{132a,132b}, Y. Bai^{34a}, J.T. Baines¹³¹, O.K. Baker¹⁷⁵, E.M. Baldin^{109,c},
 P. Balek¹²⁹, T. Balestri¹⁴⁸, F. Balli¹³⁶, W.K. Balunas¹²², E. Banas⁴⁰, Sw. Banerjee^{172,e}, A.A.E. Bannoura¹⁷⁴,
 L. Barak³¹, E.L. Barberio⁸⁹, D. Barberis^{51a,51b}, M. Barbero⁸⁶, T. Barillari¹⁰¹, M. Barisonzi^{163a,163b},
 T. Barklow¹⁴³, N. Barlow²⁹, S.L. Barnes⁸⁵, B.M. Barnett¹³¹, R.M. Barnett¹⁵, Z. Barnovska⁵,
 A. Baroncelli^{134a}, G. Barone²⁴, A.J. Barr¹²⁰, L. Barranco Navarro¹⁶⁶, F. Barreiro⁸³,
 J. Barreiro Guimarães da Costa^{34a}, R. Bartoldus¹⁴³, A.E. Barton⁷³, P. Bartos^{144a}, A. Basalae¹²³,
 A. Bassalat¹¹⁷, R.L. Bates⁵⁴, S.J. Batista¹⁵⁸, J.R. Batley²⁹, M. Battaglia¹³⁷, M. Bauc^{132a,132b}, F. Bauer¹³⁶,
 H.S. Bawa^{143,f}, J.B. Beacham¹¹¹, M.D. Beattie⁷³, T. Beau⁸¹, P.H. Beauchemin¹⁶¹, P. Bechtel²²,
 H.P. Beck^{17.g}, K. Becker¹²⁰, M. Becker⁸⁴, M. Beckingham¹⁶⁹, C. Becot¹¹⁰, A.J. Beddall^{19e}, A. Beddall^{19b},
 V.A. Bednyakov⁶⁶, M. Bedognetti¹⁰⁷, C.P. Bee¹⁴⁸, L.J. Beemster¹⁰⁷, T.A. Beermann³¹, M. Begel²⁶,
 J.K. Behr⁴³, C. Belanger-Champagne⁸⁸, A.S. Bell⁷⁹, G. Bella¹⁵³, L. Bellagamba^{21a}, A. Bellerive³⁰,
 M. Bellomo⁸⁷, K. Belotskiy⁹⁸, O. Beltramello³¹, N.L. Belyaev⁹⁸, O. Benary¹⁵³, D. Benchekroun^{135a},
 M. Bender¹⁰⁰, K. Bendtz^{146a,146b}, N. Benekos¹⁰, Y. Benhammou¹⁵³, E. Benhar Noccioli¹⁷⁵, J. Benitez⁶⁴,
 D.P. Benjamin⁴⁶, J.R. Bensinger²⁴, S. Bentvelsen¹⁰⁷, L. Beresford¹²⁰, M. Beretta⁴⁸, D. Berge¹⁰⁷,
 E. Bergeaas Kuutmann¹⁶⁴, N. Berger⁵, J. Beringer¹⁵, S. Berlendis⁵⁶, N.R. Bernard⁸⁷, C. Bernius¹¹⁰,
 F.U. Bernlochner²², T. Berry⁷⁸, P. Berta¹²⁹, C. Bertella⁸⁴, G. Bertoli^{146a,146b}, F. Bertolucci^{124a,124b},
 I.A. Bertram⁷³, C. Bertsche⁴³, D. Bertsche¹¹³, G.J. Besjes³⁷, O. Bessidskaia Bylund^{146a,146b}, M. Bessner⁴³,
 N. Besson¹³⁶, C. Betancourt⁴⁹, S. Bethke¹⁰¹, A.J. Bevan⁷⁷, W. Bhimji¹⁵, R.M. Bianchi¹²⁵, L. Bianchini²⁴,
 M. Bianco³¹, O. Biebel¹⁰⁰, D. Biedermann¹⁶, R. Bielski⁸⁵, N.V. Biesuz^{124a,124b}, M. Biglietti^{134a},
 J. Bilbao De Mendizabal⁵⁰, H. Bilokon⁴⁸, M. Bindi⁵⁵, S. Binet¹¹⁷, A. Bingul^{19b}, C. Bini^{132a,132b},
 S. Biondi^{21a,21b}, D.M. Bjergaard⁴⁶, C.W. Black¹⁵⁰, J.E. Black¹⁴³, K.M. Black²³, D. Blackburn¹³⁸,
 R.E. Blair⁶, J.-B. Blanchard¹³⁶, J.E. Blanco⁷⁸, T. Blazek^{144a}, I. Bloch⁴³, C. Blocker²⁴, W. Blum^{84,*},
 U. Blumenschein⁵⁵, S. Blunier^{33a}, G.J. Bobbink¹⁰⁷, V.S. Bobrovnikov^{109,c}, S.S. Bocchetta⁸², A. Bocci⁴⁶,
 C. Bock¹⁰⁰, M. Boehler⁴⁹, D. Boerner¹⁷⁴, J.A. Bogaerts³¹, D. Bogavac¹³, A.G. Bogdanchikov¹⁰⁹,
 C. Boehm^{146a}, V. Boisvert⁷⁸, P. Bokan¹³, T. Bold^{39a}, A.S. Boldyrev^{163a,163c}, M. Bomben⁸¹, M. Bona⁷⁷,
 M. Boonekamp¹³⁶, A. Borisov¹³⁰, G. Borissov⁷³, J. Bortfeldt¹⁰⁰, D. Bortoletto¹²⁰, V. Bortolotto^{61a,61b,61c},
 K. Bos¹⁰⁷, D. Boscherini^{21a}, M. Bosman¹², J.D. Bossio Sola²⁸, J. Boudreau¹²⁵, J. Bouffard²,
 E.V. Bouhova-Thacker⁷³, D. Boumediene³⁵, C. Bourdarios¹¹⁷, S.K. Boutle⁵⁴, A. Boveia³¹, J. Boyd³¹,
 I.R. Boyko⁶⁶, J. Bracinik¹⁸, A. Brandt⁸, G. Brandt⁵⁵, O. Brandt^{59a}, U. Bratzler¹⁵⁶, B. Brau⁸⁷, J.E. Brau¹¹⁶,
 H.M. Braun^{174,*}, W.D. Breaden Madden⁵⁴, K. Brendlinger¹²², A.J. Brennan⁸⁹, L. Brenner¹⁰⁷,
 R. Brenner¹⁶⁴, S. Bressler¹⁷¹, T.M. Bristow⁴⁷, D. Britton⁵⁴, D. Britzger⁴³, F.M. Brochu²⁹, I. Brock²²,
 R. Brock⁹¹, G. Brooijmans³⁶, T. Brooks⁷⁸, W.K. Brooks^{33b}, J. Brosamer¹⁵, E. Brost¹¹⁶, J.H. Broughton¹⁸,
 P.A. Bruckman de Renstrom⁴⁰, D. Bruncko^{144b}, R. Bruneliere⁴⁹, A. Bruni^{21a}, G. Bruni^{21a}, B.H. Brunt²⁹,
 M. Bruschi^{21a}, N. Bruscino²², P. Bryant³², L. Bryngemark⁸², T. Buanes¹⁴, Q. Buat¹⁴², P. Buchholz¹⁴¹,
 A.G. Buckley⁵⁴, I.A. Budagov⁶⁶, F. Buehrer⁴⁹, M.K. Bugge¹¹⁹, O. Bulekov⁹⁸, D. Bullock⁸, H. Burckhart³¹,
 S. Burdin⁷⁵, C.D. Burgard⁴⁹, B. Burghgrave¹⁰⁸, K. Burka⁴⁰, S. Burke¹³¹, I. Burmeister⁴⁴, E. Busato³⁵,
 D. Büscher⁴⁹, V. Büscher⁸⁴, P. Bussey⁵⁴, J.M. Butler²³, C.M. Buttar⁵⁴, J.M. Butterworth⁷⁹, P. Butti¹⁰⁷,
 W. Buttinger²⁶, A. Buzatu⁵⁴, A.R. Buzykaev^{109,c}, S. Cabrera Urbán¹⁶⁶, D. Caforio¹²⁸, V.M. Cairo^{38a,38b},
 O. Cakir^{4a}, N. Calace⁵⁰, P. Calafiura¹⁵, A. Calandri⁸⁶, G. Calderini⁸¹, P. Calfayan¹⁰⁰, L.P. Caloba^{25a},
 D. Calvet³⁵, S. Calvet³⁵, T.P. Calvet⁸⁶, R. Camacho Toro³², S. Camarda³¹, P. Camarri^{133a,133b},
 D. Cameron¹¹⁹, R. Caminal Armadans¹⁶⁵, C. Camincher⁵⁶, S. Campana³¹, M. Campanelli⁷⁹,
 A. Camplani^{92a,92b}, A. Campoverde¹⁴⁸, V. Canale^{104a,104b}, A. Canepa^{159a}, M. Cano Bret^{34e}, J. Cantero¹¹⁴,
 R. Cantrill^{126a}, T. Cao⁴¹, M.D.M. Capeans Garrido³¹, I. Caprini^{27b}, M. Caprini^{27b}, M. Capua^{38a,38b},
 R. Caputo⁸⁴, R.M. Carbone³⁶, R. Cardarelli^{133a}, F. Cardillo⁴⁹, T. Carli³¹, G. Carlino^{104a},
 L. Carminati^{92a,92b}, S. Caron¹⁰⁶, E. Carquin^{33b}, G.D. Carrillo-Montoya³¹, J.R. Carter²⁹, J. Carvalho^{126a,126c},
 D. Casadei¹⁸, M.P. Casado^{12,h}, M. Casolino¹², D.W. Casper¹⁶², E. Castaneda-Miranda^{145a}, R. Castelijns¹⁰⁷,
 A. Castelli¹⁰⁷, V. Castillo Gimenez¹⁶⁶, N.F. Castro^{126a,i}, A. Catinaccio³¹, J.R. Catmore¹¹⁹, A. Cattai³¹,
 J. Caudron⁸⁴, V. Cavaliere¹⁶⁵, E. Cavallaro¹², D. Cavalli^{92a}, M. Cavalli-Sforza¹², V. Cavasinni^{124a,124b},
 F. Ceradini^{134a,134b}, L. Cerda Alberich¹⁶⁶, B.C. Cerio⁴⁶, A.S. Cerqueira^{25b}, A. Cerri¹⁴⁹, L. Cerrito⁷⁷,
 F. Cerutti¹⁵, M. Cerv³¹, A. Cervelli¹⁷, S.A. Cetin^{19d}, A. Chafaq^{135a}, D. Chakraborty¹⁰⁸, I. Chalupkova¹²⁹,

S.K. Chan⁵⁸, Y.L. Chan^{61a}, P. Chang¹⁶⁵, J.D. Chapman²⁹, D.G. Charlton¹⁸, A. Chatterjee⁵⁰, C.C. Chau¹⁵⁸, C.A. Chavez Barajas¹⁴⁹, S. Che¹¹¹, S. Cheatham⁷³, A. Chegwidden⁹¹, S. Chekanov⁶, S.V. Chekulaev^{159a}, G.A. Chelkov^{66,j}, M.A. Chelstowska⁹⁰, C. Chen⁶⁵, H. Chen²⁶, K. Chen¹⁴⁸, S. Chen^{34c}, S. Chen¹⁵⁵, X. Chen^{34f}, Y. Chen⁶⁸, H.C. Cheng⁹⁰, H.J. Cheng^{34a}, Y. Cheng³², A. Cheplakov⁶⁶, E. Cheremushkina¹³⁰, R. Cherkaoui El Moursli^{135e}, V. Chernyatin^{26,*}, E. Cheu⁷, L. Chevalier¹³⁶, V. Chiarella⁴⁸, G. Chiarelli^{124a,124b}, G. Chiodini^{74a}, A.S. Chisholm¹⁸, A. Chitan^{27b}, M.V. Chizhov⁶⁶, K. Choi⁶², A.R. Chomont³⁵, S. Chouridou⁹, B.K.B. Chow¹⁰⁰, V. Christodoulou⁷⁹, D. Chromek-Burckhart³¹, J. Chudoba¹²⁷, A.J. Chuinard⁸⁸, J.J. Chwastowski⁴⁰, L. Chytka¹¹⁵, G. Ciapetti^{132a,132b}, A.K. Ciftci^{4a}, D. Cinca⁵⁴, V. Cindro⁷⁶, I.A. Cioara²², A. Ciochio¹⁵, F. Ciroto^{104a,104b}, Z.H. Citron¹⁷¹, M. Citterio^{92a}, M. Ciubancan^{27b}, A. Clark⁵⁰, B.L. Clark⁵⁸, M.R. Clark³⁶, P.J. Clark⁴⁷, R.N. Clarke¹⁵, C. Clement^{146a,146b}, Y. Coadou⁸⁶, M. Cobal^{163a,163c}, A. Coccaro⁵⁰, J. Cochran⁶⁵, L. Coffey²⁴, L. Colasurdo¹⁰⁶, B. Cole³⁶, A.P. Colijn¹⁰⁷, J. Collot⁵⁶, T. Colombo³¹, G. Compostella¹⁰¹, P. Conde Muiño^{126a,126b}, E. Coniavitis⁴⁹, S.H. Connell^{145b}, I.A. Connelly⁷⁸, V. Consorti⁴⁹, S. Constantinescu^{27b}, G. Conti³¹, F. Conventi^{104a,k}, M. Cooke¹⁵, B.D. Cooper⁷⁹, A.M. Cooper-Sarkar¹²⁰, K.J.R. Cormier¹⁵⁸, T. Cornelissen¹⁷⁴, M. Corradi^{132a,132b}, F. Corriveau^{88,l}, A. Corso-Radu¹⁶², A. Cortes-Gonzalez¹², G. Cortiana¹⁰¹, G. Costa^{92a}, M.J. Costa¹⁶⁶, D. Costanzo¹³⁹, G. Cottin²⁹, G. Cowan⁷⁸, B.E. Cox⁸⁵, K. Cranmer¹¹⁰, S.J. Crawley⁵⁴, G. Cree³⁰, S. Crépé-Renaudin⁵⁶, F. Crescioli⁸¹, W.A. Cribbs^{146a,146b}, M. Crispin Ortuzar¹²⁰, M. Cristinziani²², V. Croft¹⁰⁶, G. Crosetti^{38a,38b}, T. Cuhadar Donszelmann¹³⁹, J. Cummings¹⁷⁵, M. Curatolo⁴⁸, J. Cúth⁸⁴, C. Cuthbert¹⁵⁰, H. Czirr¹⁴¹, P. Czodrowski³, G. D'amen^{21a,21b}, S. D'Auria⁵⁴, M. D'Onofrio⁷⁵, M.J. Da Cunha Sargedas De Sousa^{126a,126b}, C. Da Via⁸⁵, W. Dabrowski^{39a}, T. Dado^{144a}, T. Dai⁹⁰, O. Dale¹⁴, F. Dallaire⁹⁵, C. Dallapiccola⁸⁷, M. Dam³⁷, J.R. Dandoy³², N.P. Dang⁴⁹, A.C. Daniells¹⁸, N.S. Dann⁸⁵, M. Danninger¹⁶⁷, M. Dano Hoffmann¹³⁶, V. Dao⁴⁹, G. Darbo^{51a}, S. Darmora⁸, J. Dassoulas³, A. Dattagupta⁶², W. Davey²², C. David¹⁶⁸, T. Davidek¹²⁹, M. Davies¹⁵³, P. Davison⁷⁹, E. Dawe⁸⁹, I. Dawson¹³⁹, R.K. Daya-Ishmukhametova⁸⁷, K. De⁸, R. de Asmundis^{104a}, A. De Benedetti¹¹³, S. De Castro^{21a,21b}, S. De Cecco⁸¹, N. De Groot¹⁰⁶, P. de Jong¹⁰⁷, H. De la Torre⁸³, F. De Lorenzi⁶⁵, A. De Maria⁵⁵, D. De Pedis^{132a}, A. De Salvo^{132a}, U. De Sanctis¹⁴⁹, A. De Santo¹⁴⁹, J.B. De Vivie De Regie¹¹⁷, W.J. Dearnaley⁷³, R. Debbé²⁶, C. Debenedetti¹³⁷, D.V. Dedovich⁶⁶, N. Dehghanian³, I. Deigaard¹⁰⁷, M. Del Gaudio^{38a,38b}, J. Del Peso⁸³, T. Del Prete^{124a,124b}, D. Delgove¹¹⁷, F. Deliot¹³⁶, C.M. Delitzsch⁵⁰, M. Deliyergiyev⁷⁶, A. Dell'Acqua³¹, L. Dell'Asta²³, M. Dell'Orso^{124a,124b}, M. Della Pietra^{104a,k}, D. della Volpe⁵⁰, M. Delmastro⁵, P.A. Delsart⁵⁶, C. Deluca¹⁰⁷, D.A. DeMarco¹⁵⁸, S. Demers¹⁷⁵, M. Demichev⁶⁶, A. Demilly⁸¹, S.P. Denisov¹³⁰, D. Denysiuk¹³⁶, D. Derendarz⁴⁰, J.E. Derkaoui^{135d}, F. Derue⁸¹, P. Dervan⁷⁵, K. Desch²², C. Deterre⁴³, K. Dette⁴⁴, P.O. Deviveiros³¹, A. Dewhurst¹³¹, S. Dhaliwal²⁴, A. Di Ciaccio^{133a,133b}, L. Di Ciaccio⁵, W.K. Di Clemente¹²², C. Di Donato^{132a,132b}, A. Di Girolamo³¹, B. Di Girolamo³¹, B. Di Micco^{134a,134b}, R. Di Nardo⁴⁸, A. Di Simone⁴⁹, R. Di Sipio¹⁵⁸, D. Di Valentino³⁰, C. Diaconu⁸⁶, M. Diamond¹⁵⁸, F.A. Dias⁴⁷, M.A. Diaz^{33a}, E.B. Diehl⁹⁰, J. Dietrich¹⁶, S. Diglio⁸⁶, A. Dimitrievska¹³, J. Dingfelder²², P. Dita^{27b}, S. Dita^{27b}, F. Dittus³¹, F. Djama⁸⁶, T. Djobava^{52b}, J.I. Djuvsland^{59a}, M.A.B. do Vale^{25c}, D. Dobos³¹, M. Dobre^{27b}, C. Doglioni⁸², T. Dohmae¹⁵⁵, J. Dolejsi¹²⁹, Z. Dolezal¹²⁹, B.A. Dolgoshein^{98,*}, M. Donadelli^{25d}, S. Donati^{124a,124b}, P. Dondero^{121a,121b}, J. Donini³⁵, J. Dopke¹³¹, A. Doria^{104a}, M.T. Dova⁷², A.T. Doyle⁵⁴, E. Drechsler⁵⁵, M. Dris¹⁰, Y. Du^{34d}, J. Duarte-Campderros¹⁵³, E. Duchovni¹⁷¹, G. Duckeck¹⁰⁰, O.A. Ducu^{95,m}, D. Duda¹⁰⁷, A. Dudarev³¹, E.M. Duffield¹⁵, L. Duflost¹¹⁷, L. Duguid⁷⁸, M. Dührssen³¹, M. Dumancic¹⁷¹, M. Dunford^{59a}, H. Duran Yildiz^{4a}, M. Düren⁵³, A. Durglishvili^{52b}, D. Duschinger⁴⁵, B. Dutta⁴³, M. Dyndal^{39a}, C. Eckardt⁴³, K.M. Ecker¹⁰¹, R.C. Edgar⁹⁰, N.C. Edwards⁴⁷, T. Eifert³¹, G. Eigen¹⁴, K. Einsweiler¹⁵, T. Ekelof¹⁶⁴, M. El Kacimi^{135c}, V. Ellajosyula⁸⁶, M. Ellert¹⁶⁴, S. Elles⁵, F. Ellinghaus¹⁷⁴, A.A. Elliot¹⁶⁸, N. Ellis³¹, J. Elmsheuser²⁶, M. Elsing³¹, D. Emelianov¹³¹, Y. Enari¹⁵⁵, O.C. Endner⁸⁴, M. Endo¹¹⁸, J.S. Ennis¹⁶⁹, J. Erdmann⁴⁴, A. Ereditato¹⁷, G. Ernis¹⁷⁴, J. Ernst², M. Ernst²⁶, S. Errede¹⁶⁵, E. Ertel⁸⁴, M. Escalier¹¹⁷, H. Esch⁴⁴, C. Escobar¹²⁵, B. Esposito⁴⁸, A.I. Etievre¹³⁶, E. Etzion¹⁵³, H. Evans⁶², A. Ezhilov¹²³, F. Fabbri^{21a,21b}, L. Fabbri^{21a,21b}, G. Facini³², R.M. Fakhruddinov¹³⁰, S. Falciano^{132a}, R.J. Falla⁷⁹, J. Faltova¹²⁹, Y. Fang^{34a}, M. Fanti^{92a,92b}, A. Farbin⁸, A. Farilla^{134a}, C. Farina¹²⁵, T. Farooque¹², S. Farrell¹⁵, S.M. Farrington¹⁶⁹, P. Farthouat³¹, F. Fassi^{135e}, P. Fassnacht³¹, D. Fassouliotis⁹, M. Fauci Giannelli⁷⁸, A. Favareto^{51a,51b}, W.J. Fawcett¹²⁰, L. Fayard¹¹⁷, O.L. Fedin^{123,n}, W. Fedorko¹⁶⁷, S. Feigl¹¹⁹, L. Felgioni⁸⁶, C. Feng^{34d}, E.J. Feng³¹, H. Feng⁹⁰,

A.B. Fenyuk¹³⁰, L. Feremenga⁸, P. Fernandez Martinez¹⁶⁶, S. Fernandez Perez¹², J. Ferrando⁵⁴,
 A. Ferrari¹⁶⁴, P. Ferrari¹⁰⁷, R. Ferrari^{121a}, D.E. Ferreira de Lima^{59b}, A. Ferrer¹⁶⁶, D. Ferrere⁵⁰,
 C. Ferretti⁹⁰, A. Ferretto Parodi^{51a,51b}, F. Fiedler⁸⁴, A. Filipčič⁷⁶, M. Filipuzzi⁴³, F. Filthaut¹⁰⁶,
 M. Fincke-Keeler¹⁶⁸, K.D. Finelli¹⁵⁰, M.C.N. Fiolhais^{126a,126c}, L. Fiorini¹⁶⁶, A. Firan⁴¹, A. Fischer²,
 C. Fischer¹², J. Fischer¹⁷⁴, W.C. Fisher⁹¹, N. Flaschel⁴³, I. Fleck¹⁴¹, P. Fleischmann⁹⁰, G.T. Fletcher¹³⁹,
 R.R.M. Fletcher¹²², T. Flick¹⁷⁴, A. Floderus⁸², L.R. Flores Castillo^{61a}, M.J. Flowerdew¹⁰¹, G.T. Forcolin⁸⁵,
 A. Formica¹³⁶, A. Forti⁸⁵, A.G. Foster¹⁸, D. Fournier¹¹⁷, H. Fox⁷³, S. Fracchia¹², P. Francavilla⁸¹,
 M. Franchini^{21a,21b}, D. Francis³¹, L. Franconi¹¹⁹, M. Franklin⁵⁸, M. Frate¹⁶², M. Fraternali^{121a,121b},
 D. Freeborn⁷⁹, S.M. Fressard-Batraneanu³¹, F. Friedrich⁴⁵, D. Froidevaux³¹, J.A. Frost¹²⁰, C. Fukunaga¹⁵⁶,
 E. Fullana Torregrosa⁸⁴, T. Fusayasu¹⁰², J. Fuster¹⁶⁶, C. Gabaldon⁵⁶, O. Gabizon¹⁷⁴, A. Gabrielli^{21a,21b},
 A. Gabrielli¹⁵, G.P. Gach^{39a}, S. Gadatsch³¹, S. Gadomski⁵⁰, G. Gagliardi^{51a,51b}, L.G. Gagnon⁹⁵,
 P. Gagnon⁶², C. Galea¹⁰⁶, B. Galhardo^{126a,126c}, E.J. Gallas¹²⁰, B.J. Gallop¹³¹, P. Gallus¹²⁸, G. Galster³⁷,
 K.K. Gan¹¹¹, J. Gao^{34b,86}, Y. Gao⁴⁷, Y.S. Gao^{143,f}, F.M. Garay Walls⁴⁷, C. García¹⁶⁶, J.E. García Navarro¹⁶⁶,
 M. Garcia-Sciveres¹⁵, R.W. Gardner³², N. Garelli¹⁴³, V. Garonne¹¹⁹, A. Gascon Bravo⁴³, C. Gatti⁴⁸,
 A. Gaudiello^{51a,51b}, G. Gaudio^{121a}, B. Gaur¹⁴¹, L. Gauthier⁹⁵, I.L. Gavrilenko⁹⁶, C. Gay¹⁶⁷, G. Gaycken²²,
 E.N. Gazis¹⁰, Z. Gece¹⁶⁷, C.N.P. Gee¹³¹, Ch. Geich-Gimbel²², M. Geisen⁸⁴, M.P. Geisler^{59a},
 C. Gemme^{51a}, M.H. Genest⁵⁶, C. Geng^{34b,o}, S. Gentile^{132a,132b}, S. George⁷⁸, D. Gerbaudo¹²,
 A. Gershon¹⁵³, S. Ghasemi¹⁴¹, H. Ghazlane^{135b}, M. Ghneimat²², B. Giacobbe^{21a}, S. Giagu^{132a,132b},
 P. Giannetti^{124a,124b}, B. Gibbard²⁶, S.M. Gibson⁷⁸, M. Gignac¹⁶⁷, M. Gilchriese¹⁵, T.P.S. Gillam²⁹,
 D. Gillberg³⁰, G. Gilles¹⁷⁴, D.M. Gingrich^{3,d}, N. Giokaris⁹, M.P. Giordani^{163a,163c}, F.M. Giorgi^{21a},
 F.M. Giorgi¹⁶, P.F. Giraud¹³⁶, P. Giromini⁵⁸, D. Giugni^{92a}, F. Giuli¹²⁰, C. Giuliani¹⁰¹, M. Giulini^{59b},
 B.K. Gjelsten¹¹⁹, S. Gkaitatzis¹⁵⁴, I. Gkialas¹⁵⁴, E.L. Gkoukousis¹¹⁷, L.K. Gladilin⁹⁹, C. Glasman⁸³,
 J. Glatzer³¹, P.C.F. Glaysher⁴⁷, A. Glazov⁴³, M. Goblirsch-Kolb¹⁰¹, J. Godlewski⁴⁰, S. Goldfarb⁹⁰,
 T. Golling⁵⁰, D. Golubkov¹³⁰, A. Gomes^{126a,126b,126d}, R. Gonçalo^{126a},
 J. Goncalves Pinto Firmino Da Costa¹³⁶, L. Gonella¹⁸, A. Gongadze⁶⁶, S. González de la Hoz¹⁶⁶,
 G. Gonzalez Parra¹², S. Gonzalez-Sevilla⁵⁰, L. Goossens³¹, P.A. Gorbounov⁹⁷, H.A. Gordon²⁶,
 I. Gorelov¹⁰⁵, B. Gorini³¹, E. Gorini^{74a,74b}, A. Gorišek⁷⁶, E. Gornicki⁴⁰, A.T. Goshaw⁴⁶, C. Gössling⁴⁴,
 M.I. Gostkin⁶⁶, C.R. Goudet¹¹⁷, D. Goujdami^{135c}, A.G. Goussiou¹³⁸, N. Govender^{145b}, E. Gozani¹⁵²,
 L. Graber⁵⁵, I. Grabowska-Bold^{39a}, P.O.J. Gradin⁵⁶, P. Grafström^{21a,21b}, J. Gramling⁵⁰, E. Gramstad¹¹⁹,
 S. Grancagnolo¹⁶, V. Gratchev¹²³, P.M. Gravila^{27e}, H.M. Gray³¹, E. Graziani^{134a}, Z.D. Greenwood^{80,p},
 C. Grefe²², K. Gregersen⁷⁹, I.M. Gregor⁴³, P. Grenier¹⁴³, K. Grevtsov⁵, J. Griffiths⁸, A.A. Grillo¹³⁷,
 K. Grimm⁷³, S. Grinstein^{12,q}, Ph. Gris³⁵, J.-F. Grivaz¹¹⁷, S. Groh⁸⁴, J.P. Grohs⁴⁵, E. Gross¹⁷¹,
 J. Grosse-Knetter⁵⁵, G.C. Grossi⁸⁰, Z.J. Grout¹⁴⁹, L. Guan⁹⁰, W. Guan¹⁷², J. Guenther¹²⁸, F. Guescini⁵⁰,
 D. Guest¹⁶², O. Gueta¹⁵³, E. Guido^{51a,51b}, T. Guillemin⁵, S. Guindon², U. Gul⁵⁴, C. Gumpert³¹, J. Guo^{34e},
 Y. Guo^{34b,o}, S. Gupta¹²⁰, G. Gustavino^{132a,132b}, P. Gutierrez¹¹³, N.G. Gutierrez Ortiz⁷⁹, C. Gutschow⁴⁵,
 C. Guyot¹³⁶, C. Gwenlan¹²⁰, C.B. Gwilliam⁷⁵, A. Haas¹¹⁰, C. Haber¹⁵, H.K. Hadavand⁸, N. Haddad^{135e},
 A. Hadeef⁸⁶, P. Haefner²², S. Hageböck²², Z. Hajduk⁴⁰, H. Hakobyan^{176,*}, M. Haleem⁴³, J. Haley¹¹⁴,
 G. Halladjian⁹¹, G.D. Hallewell⁸⁶, K. Hamacher¹⁷⁴, P. Hamal¹¹⁵, K. Hamano¹⁶⁸, A. Hamilton^{145a},
 G.N. Hamity¹³⁹, P.G. Hamnett⁴³, L. Han^{34b}, K. Hanagaki^{67,r}, K. Hanawa¹⁵⁵, M. Hance¹³⁷, B. Haney¹²²,
 P. Hanke^{59a}, R. Hanna¹³⁶, J.B. Hansen³⁷, J.D. Hansen³⁷, M.C. Hansen²², P.H. Hansen³⁷, K. Hara¹⁶⁰,
 A.S. Hard¹⁷², T. Harenberg¹⁷⁴, F. Hariri¹¹⁷, S. Harkusha⁹³, R.D. Harrington⁴⁷, P.F. Harrison¹⁶⁹,
 F. Hartjes¹⁰⁷, N.M. Hartmann¹⁰⁰, M. Hasegawa⁶⁸, Y. Hasegawa¹⁴⁰, A. Hasib¹¹³, S. Hassani¹³⁶, S. Haug¹⁷,
 R. Hauser⁹¹, L. Hauswald⁴⁵, M. Havranek¹²⁷, C.M. Hawkes¹⁸, R.J. Hawking³¹, D. Hayden⁹¹,
 C.P. Hays¹²⁰, J.M. Hays⁷⁷, H.S. Hayward⁷⁵, S.J. Haywood¹³¹, S.J. Head¹⁸, T. Heck⁸⁴, V. Hedberg⁸²,
 L. Heelan⁸, S. Heim¹²², T. Heim¹⁵, B. Heinemann¹⁵, J.J. Heinrich¹⁰⁰, L. Heinrich¹¹⁰, C. Heinz⁵³,
 J. Hejbal¹²⁷, L. Helary²³, S. Hellman^{146a,146b}, C. Helsen³¹, J. Henderson¹²⁰, R.C.W. Henderson⁷³,
 Y. Heng¹⁷², S. Henkelmann¹⁶⁷, A.M. Henriques Correia³¹, S. Henrot-Versille¹¹⁷, G.H. Herbert¹⁶,
 Y. Hernández Jiménez¹⁶⁶, G. Herten⁴⁹, R. Hertenberger¹⁰⁰, L. Hervas³¹, G.G. Hesketh⁷⁹, N.P. Hessey¹⁰⁷,
 J.W. Hetherly⁴¹, R. Hickling⁷⁷, E. Higón-Rodríguez¹⁶⁶, E. Hill¹⁶⁸, J.C. Hill²⁹, K.H. Hiller⁴³, S.J. Hillier¹⁸,
 I. Hinchliffe¹⁵, E. Hines¹²², R.R. Hinman¹⁵, M. Hirose¹⁵⁷, D. Hirschbuehl¹⁷⁴, J. Hobbs¹⁴⁸, N. Hod^{159a},
 M.C. Hodgkinson¹³⁹, P. Hodgson¹³⁹, A. Hoecker³¹, M.R. Hoferkamp¹⁰⁵, F. Hoenig¹⁰⁰, D. Hohn²²,
 T.R. Holmes¹⁵, M. Homann⁴⁴, T.M. Hong¹²⁵, B.H. Hooberman¹⁶⁵, W.H. Hopkins¹¹⁶, Y. Horii¹⁰³,

A.J. Horton¹⁴², J.-Y. Hostachy⁵⁶, S. Hou¹⁵¹, A. Hoummada^{135a}, J. Howarth⁴³, M. Hrabovsky¹¹⁵,
 I. Hristova¹⁶, J. Hrivnac¹¹⁷, T. Hryn'ova⁵, A. Hrynevich⁹⁴, C. Hsu^{145c}, P.J. Hsu^{151,s}, S.-C. Hsu¹³⁸, D. Hu³⁶,
 Q. Hu^{34b}, Y. Huang⁴³, Z. Hubacek¹²⁸, F. Hubaut⁸⁶, F. Huegging²², T.B. Huffman¹²⁰, E.W. Hughes³⁶,
 G. Hughes⁷³, M. Huhtinen³¹, T.A. Hülsing⁸⁴, P. Huo¹⁴⁸, N. Huseynov^{66,b}, J. Huston⁹¹, J. Huth⁵⁸,
 G. Iacobucci⁵⁰, G. Iakovidis²⁶, I. Ibragimov¹⁴¹, L. Iconomidou-Fayard¹¹⁷, E. Ideal¹⁷⁵, Z. Idrissi^{135e},
 P. Iengo³¹, O. Igonkina¹⁰⁷, T. Iizawa¹⁷⁰, Y. Ikegami⁶⁷, M. Ikeno⁶⁷, Y. Ilchenko^{32,t}, D. Iliadis¹⁵⁴, N. Ilic¹⁴³,
 T. Ince¹⁰¹, G. Introzzi^{121a,121b}, P. Ioannou^{9,*}, M. Iodice^{134a}, K. Iordanidou³⁶, V. Ippolito⁵⁸, M. Ishino⁶⁹,
 M. Ishitsuka¹⁵⁷, R. Ishmukhametov¹¹¹, C. Issever¹²⁰, S. Istin^{19a}, F. Ito¹⁶⁰, J.M. Iturbe Ponce⁸⁵,
 R. Iuppa^{133a,133b}, W. Iwanski⁴⁰, H. Iwasaki⁶⁷, J.M. Izen⁴², V. Izzo^{104a}, S. Jabbar³, B. Jackson¹²²,
 M. Jackson⁷⁵, P. Jackson¹, V. Jain², K.B. Jakobi⁸⁴, K. Jakobs⁴⁹, S. Jakobsen³¹, T. Jakoubek¹²⁷,
 D.O. Jamin¹¹⁴, D.K. Jana⁸⁰, E. Jansen⁷⁹, R. Jansky⁶³, J. Janssen²², M. Janus⁵⁵, G. Jarlskog⁸²,
 N. Javadov^{66,b}, T. Javurek⁴⁹, F. Jeanneau¹³⁶, L. Jeanty¹⁵, J. Jejelava^{52a,u}, G.-Y. Jeng¹⁵⁰, D. Jennens⁸⁹,
 P. Jenni^{49,v}, J. Jentsch⁴⁴, C. Jeske¹⁶⁹, S. Jézéquel⁵, H. Ji¹⁷², J. Jia¹⁴⁸, H. Jiang⁶⁵, Y. Jiang^{34b}, S. Jiggins⁷⁹,
 J. Jimenez Pena¹⁶⁶, S. Jin^{34a}, A. Jinaru^{27b}, O. Jinnouchi¹⁵⁷, P. Johansson¹³⁹, K.A. Johns⁷, W.J. Johnson¹³⁸,
 K. Jon-And^{146a,146b}, G. Jones¹⁶⁹, R.W.L. Jones⁷³, S. Jones⁷, T.J. Jones⁷⁵, J. Jongmanns^{59a},
 P.M. Jorge^{126a,126b}, J. Jovicevic^{159a}, X. Ju¹⁷², A. Juste Rozas^{12,q}, M.K. Köhler¹⁷¹, A. Kaczmarska⁴⁰,
 M. Kado¹¹⁷, H. Kagan¹¹¹, M. Kagan¹⁴³, S.J. Kahn⁸⁶, E. Kajomovitz⁴⁶, C.W. Kalderon¹²⁰, A. Kaluza⁸⁴,
 S. Kama⁴¹, A. Kamenshchikov¹³⁰, N. Kanaya¹⁵⁵, S. Kaneti²⁹, L. Kanjir⁷⁶, V.A. Kantserov⁹⁸, J. Kanzaki⁶⁷,
 B. Kaplan¹¹⁰, L.S. Kaplan¹⁷², A. Kapliy³², D. Kar^{145c}, K. Karakostas¹⁰, A. Karamaoun³, N. Karastathis¹⁰,
 M.J. Kareem⁵⁵, E. Karentzos¹⁰, M. Karnevskiy⁸⁴, S.N. Karpov⁶⁶, Z.M. Karpova⁶⁶, K. Karthik¹¹⁰,
 V. Kartvelishvili⁷³, A.N. Karyukhin¹³⁰, K. Kasahara¹⁶⁰, L. Kashif¹⁷², R.D. Kass¹¹¹, A. Kastanas¹⁴,
 Y. Kataoka¹⁵⁵, C. Kato¹⁵⁵, A. Katre⁵⁰, J. Katzy⁴³, K. Kawagoe⁷¹, T. Kawamoto¹⁵⁵, G. Kawamura⁵⁵,
 S. Kazama¹⁵⁵, V.F. Kazanin^{109,c}, R. Keeler¹⁶⁸, R. Kehoe⁴¹, J.S. Keller⁴³, J.J. Kempster⁷⁸, K. Kentaro¹⁰³,
 H. Keoshkerian¹⁵⁸, O. Kepka¹²⁷, B.P. Kerševan⁷⁶, S. Kersten¹⁷⁴, R.A. Keyes⁸⁸, F. Khalil-zada¹¹,
 A. Khanov¹¹⁴, A.G. Kharlamov^{109,c}, T.J. Khoo⁵⁰, V. Khovanskiy⁹⁷, E. Khramov⁶⁶, J. Khubua^{52b,w},
 S. Kido⁶⁸, H.Y. Kim⁸, S.H. Kim¹⁶⁰, Y.K. Kim³², N. Kimura¹⁵⁴, O.M. Kind¹⁶, B.T. King⁷⁵, M. King¹⁶⁶,
 S.B. King¹⁶⁷, J. Kirk¹³¹, A.E. Kiryunin¹⁰¹, T. Kishimoto⁶⁸, D. Kisielewska^{39a}, F. Kiss⁴⁹, K. Kiuchi¹⁶⁰,
 O. Kivernyk¹³⁶, E. Kladiva^{144b}, M.H. Klein³⁶, M. Klein⁷⁵, U. Klein⁷⁵, K. Kleinknecht⁸⁴, P. Klimek^{146a,146b},
 A. Klimentov²⁶, R. Klingenberg⁴⁴, J.A. Klinger¹³⁹, T. Klioutchnikova³¹, E.-E. Kluge^{59a}, P. Kluit¹⁰⁷,
 S. Kluth¹⁰¹, J. Knapik⁴⁰, E. Kneringer⁶³, E.B.F.G. Knoops⁸⁶, A. Knue⁵⁴, A. Kobayashi¹⁵⁵, D. Kobayashi¹⁵⁷,
 T. Kobayashi¹⁵⁵, M. Kobel⁴⁵, M. Kocian¹⁴³, P. Kodys¹²⁹, T. Koffas³⁰, E. Koffeman¹⁰⁷, T. Koi¹⁴³,
 H. Kolanoski¹⁶, M. Kolb^{59b}, I. Koletsou⁵, A.A. Komar^{96,*}, Y. Komori¹⁵⁵, T. Kondo⁶⁷, N. Kondrashova⁴³,
 K. Köneke⁴⁹, A.C. König¹⁰⁶, T. Kono^{67,x}, R. Konoplich^{110,y}, N. Konstantinidis⁷⁹, R. Kopeliansky⁶²,
 S. Koperny^{39a}, L. Köpke⁸⁴, A.K. Kopp⁴⁹, K. Korcyl⁴⁰, K. Kordas¹⁵⁴, A. Korn⁷⁹, A.A. Korol^{109,c},
 I. Korolkov¹², E.V. Korolkova¹³⁹, O. Kortner¹⁰¹, S. Kortner¹⁰¹, T. Kosek¹²⁹, V.V. Kostyukhin²²,
 A. Kotwal⁴⁶, A. Kourkouveli-Charalampidi¹⁵⁴, C. Kourkouvelis⁹, V. Kouskoura²⁶, A.B. Kowalewska⁴⁰,
 R. Kowalewski¹⁶⁸, T.Z. Kowalski^{39a}, C. Kozakai¹⁵⁵, W. Kozanecki¹³⁶, A.S. Kozhin¹³⁰, V.A. Kramarenko⁹⁹,
 G. Kramberger⁷⁶, D. Krasnopevtsev⁹⁸, M.W. Krasny⁸¹, A. Krasznahorkay³¹, J.K. Kraus²²,
 A. Kravchenko²⁶, M. Kretz^{59c}, J. Kretzschmar⁷⁵, K. Kreutzfeldt⁵³, P. Krieger¹⁵⁸, K. Krizka³²,
 K. Kroeninger⁴⁴, H. Kroha¹⁰¹, J. Kroll¹²², J. Kroseberg²², J. Krstic¹³, U. Kruchonak⁶⁶, H. Krüger²²,
 N. Krumnack⁶⁵, A. Kruse¹⁷², M.C. Kruse⁴⁶, M. Kruskal²³, T. Kubota⁸⁹, H. Kucuk⁷⁹, S. Kuday^{4b},
 J.T. Kuechler¹⁷⁴, S. Kuehn⁴⁹, A. Kugel^{59c}, F. Kuger¹⁷³, A. Kuhl¹³⁷, T. Kuhl⁴³, V. Kukhtin⁶⁶, R. Kukla¹³⁶,
 Y. Kulchitsky⁹³, S. Kuleshov^{33b}, M. Kuna^{132a,132b}, T. Kunigo⁶⁹, A. Kupco¹²⁷, H. Kurashige⁶⁸,
 Y.A. Kurochkin⁹³, V. Kus¹²⁷, E.S. Kuwertz¹⁶⁸, M. Kuze¹⁵⁷, J. Kvita¹¹⁵, T. Kwan¹⁶⁸, D. Kyriazopoulos¹³⁹,
 A. La Rosa¹⁰¹, J.L. La Rosa Navarro^{25d}, L. La Rotonda^{38a,38b}, C. Lacasta¹⁶⁶, F. Lacava^{132a,132b}, J. Lacey³⁰,
 H. Lacker¹⁶, D. Lacour⁸¹, V.R. Lacuesta¹⁶⁶, E. Ladygin⁶⁶, R. Lafaye⁵, B. Laforge⁸¹, T. Lagouri¹⁷⁵, S. Lai⁵⁵,
 S. Lammers⁶², W. Lampl⁷, E. Lançon¹³⁶, U. Landgraf⁴⁹, M.P.J. Landon⁷⁷, V.S. Lang^{59a}, J.C. Lange¹²,
 A.J. Lankford¹⁶², F. Lanni²⁶, K. Lantsch²², A. Lanza^{121a}, S. Laplace⁸¹, C. Lapoire³¹, J.F. Laporte¹³⁶,
 T. Lari^{92a}, F. Lasagni Manghi^{21a,21b}, M. Lassnig³¹, P. Laurelli⁴⁸, W. Lavrijsen¹⁵, A.T. Law¹³⁷, P. Laycock⁷⁵,
 T. Lazovich⁵⁸, M. Lazzaroni^{92a,92b}, B. Le⁸⁹, O. Le Dortz⁸¹, E. Le Guirriec⁸⁶, E.P. Le Quilleuc¹³⁶,
 M. LeBlanc¹⁶⁸, T. LeCompte⁶, F. Ledroit-Guillon⁵⁶, C.A. Lee²⁶, S.C. Lee¹⁵¹, L. Lee¹, G. Lefebvre⁸¹,
 M. Lefebvre¹⁶⁸, F. Legger¹⁰⁰, C. Leggett¹⁵, A. Lehan⁷⁵, G. Lehmann Miotto³¹, X. Lei⁷, W.A. Leight³⁰,

A. Leisos^{154,z}, A.G. Leister¹⁷⁵, M.A.L. Leite^{25d}, R. Leitner¹²⁹, D. Lellouch¹⁷¹, B. Lemmer⁵⁵, K.J.C. Leney⁷⁹,
 T. Lenz²², B. Lenzi³¹, R. Leone⁷, S. Leone^{124a,124b}, C. Leonidopoulos⁴⁷, S. Leontsinis¹⁰, G. Lerner¹⁴⁹,
 C. Leroy⁹⁵, A.A.J. Lesage¹³⁶, C.G. Lester²⁹, M. Levchenko¹²³, J. Levêque⁵, D. Levin⁹⁰, L.J. Levinson¹⁷¹,
 M. Levy¹⁸, D. Lewis⁷⁷, A.M. Leyko²², M. Leyton⁴², B. Li^{34b,aa}, H. Li¹⁴⁸, H.L. Li³², L. Li⁴⁶, L. Li^{34e},
 Q. Li^{34a}, S. Li⁴⁶, X. Li⁸⁵, Y. Li¹⁴¹, Z. Liang^{34a}, B. Liberti^{133a}, A. Liblong¹⁵⁸, P. Lichard³¹, K. Lie¹⁶⁵,
 J. Liebal²², W. Liebig¹⁴, A. Limosani¹⁵⁰, S.C. Lin^{151,ab}, T.H. Lin⁸⁴, B.E. Lindquist¹⁴⁸, A.E. Lioni⁵⁰,
 E. Lipeles¹²², A. Lipniacka¹⁴, M. Lisovsky^{59b}, T.M. Liss¹⁶⁵, A. Lister¹⁶⁷, A.M. Litke¹³⁷, B. Liu^{151,ac},
 D. Liu¹⁵¹, H. Liu⁹⁰, H. Liu²⁶, J. Liu⁸⁶, J.B. Liu^{34b}, K. Liu⁸⁶, L. Liu¹⁶⁵, M. Liu⁴⁶, M. Liu^{34b}, Y.L. Liu^{34b},
 Y. Liu^{34b}, M. Livan^{121a,121b}, A. Lleres⁵⁶, J. Llorente Merino^{34a}, S.L. Lloyd⁷⁷, F. Lo Sterzo¹⁵¹,
 E. Lobodzinska⁴³, P. Loch⁷, W.S. Lockman¹³⁷, F.K. Loebinger⁸⁵, A.E. Loevschall-Jensen³⁷, K.M. Loew²⁴,
 A. Loginov¹⁷⁵, T. Lohse¹⁶, K. Lohwasser⁴³, M. Lokajicek¹²⁷, B.A. Long²³, J.D. Long¹⁶⁵, R.E. Long⁷³,
 L. Longo^{74a,74b}, K.A. Looper¹¹¹, L. Lopes^{126a}, D. Lopez Mateos⁵⁸, B. Lopez Paredes¹³⁹, I. Lopez Paz¹²,
 A. Lopez Solis⁸¹, J. Lorenz¹⁰⁰, N. Lorenzo Martinez⁶², M. Losada²⁰, P.J. Lösel¹⁰⁰, X. Lou^{34a}, A. Lounis¹¹⁷,
 J. Love⁶, P.A. Love⁷³, H. Lu^{61a}, N. Lu⁹⁰, H.J. Lubatti¹³⁸, C. Luci^{132a,132b}, A. Lucotte⁵⁶, C. Luedtke⁴⁹,
 F. Luehring⁶², W. Lukas⁶³, L. Luminari^{132a}, O. Lundberg^{146a,146b}, B. Lund-Jensen¹⁴⁷, P.M. Luzi⁸¹,
 D. Lynn²⁶, R. Lysak¹²⁷, E. Lytken⁸², V. Lyubushkin⁶⁶, H. Ma²⁶, L.L. Ma^{34d}, Y. Ma^{34d}, G. Maccarrone⁴⁸,
 A. Macchiolo¹⁰¹, C.M. Macdonald¹³⁹, B. Maček⁷⁶, J. Machado Miguens^{122,126b}, D. Madaffari⁸⁶,
 R. Madar³⁵, H.J. Maddocks¹⁶⁴, W.F. Mader⁴⁵, A. Madsen⁴³, J. Maeda⁶⁸, S. Maeland¹⁴, T. Maeno²⁶,
 A. Maevskiy⁹⁹, E. Magradze⁵⁵, J. Mahlstedt¹⁰⁷, C. Maiani¹¹⁷, C. Maidantchik^{25a}, A.A. Maier¹⁰¹,
 T. Maier¹⁰⁰, A. Maio^{126a,126b,126d}, S. Majewski¹¹⁶, Y. Makida⁶⁷, N. Makovec¹¹⁷, B. Malaescu⁸¹,
 Pa. Malecki⁴⁰, V.P. Maleev¹²³, F. Malek⁵⁶, U. Mallik⁶⁴, D. Malon⁶, C. Malone¹⁴³, S. Maltezos¹⁰,
 V.M. Malyshev¹⁰⁹, S. Malyukov³¹, J. Mamuzic¹⁶⁶, G. Mancini⁴⁸, B. Mandelli³¹, L. Mandelli^{92a},
 I. Mandić⁷⁶, J. Maneira^{126a,126b}, L. Manhaes de Andrade Filho^{25b}, J. Manjarres Ramos^{159b}, A. Mann¹⁰⁰,
 A. Manousos³¹, B. Mansoulie¹³⁶, J.D. Mansour^{34a}, R. Mantifel⁸⁸, M. Mantoani⁵⁵, S. Manzoni^{92a,92b},
 L. Mapelli³¹, G. Marceca²⁸, L. March⁵⁰, G. Marchiori⁸¹, M. Marcisovsky¹²⁷, M. Marjanovic¹³,
 D.E. Marley⁹⁰, F. Marroquim^{25a}, S.P. Marsden⁸⁵, Z. Marshall¹⁵, S. Marti-Garcia¹⁶⁶, B. Martin⁹¹,
 T.A. Martin¹⁶⁹, V.J. Martin⁴⁷, B. Martin dit Latour¹⁴, M. Martinez^{12,q}, S. Martin-Haugh¹³¹,
 V.S. Martoiu^{27b}, A.C. Martyniuk⁷⁹, M. Marx¹³⁸, A. Marzin³¹, L. Masetti⁸⁴, T. Mashimo¹⁵⁵,
 R. Mashinistov⁹⁶, J. Masik⁸⁵, A.L. Maslennikov^{109,c}, I. Massa^{21a,21b}, L. Massa^{21a,21b}, P. Mastrandrea⁵,
 A. Mastroberardino^{38a,38b}, T. Masubuchi¹⁵⁵, P. Mättig¹⁷⁴, J. Mattmann⁸⁴, J. Maurer^{27b}, S.J. Maxfield⁷⁵,
 D.A. Maximov^{109,c}, R. Mazini¹⁵¹, S.M. Mazza^{92a,92b}, N.C. Mc Fadden¹⁰⁵, G. Mc Goldrick¹⁵⁸,
 S.P. Mc Kee⁹⁰, A. McCarn⁹⁰, R.L. McCarthy¹⁴⁸, T.G. McCarthy³⁰, L.I. McClymont⁷⁹, E.F. McDonald⁸⁹,
 K.W. McFarlane^{57,*}, J.A. MCFayden⁷⁹, G. Mchedlidze⁵⁵, S.J. McMahon¹³¹, R.A. McPherson^{168,l},
 M. Medinnis⁴³, S. Meehan¹³⁸, S. Mehlhase¹⁰⁰, A. Mehta⁷⁵, K. Meier^{59a}, C. Meineck¹⁰⁰, B. Meirose⁴²,
 D. Melini¹⁶⁶, B.R. Mellado Garcia^{145c}, M. Melo^{144a}, F. Meloni¹⁷, A. Mengarelli^{21a,21b}, S. Menke¹⁰¹,
 E. Meoni¹⁶¹, S. Mergelmeyer¹⁶, P. Mermod⁵⁰, L. Merola^{104a,104b}, C. Meroni^{92a}, F.S. Merritt³²,
 A. Messina^{132a,132b}, J. Metcalfe⁶, A.S. Mete¹⁶², C. Meyer⁸⁴, C. Meyer¹²², J-P. Meyer¹³⁶, J. Meyer¹⁰⁷,
 H. Meyer Zu Theenhausen^{59a}, R.P. Middleton¹³¹, S. Miglioranza^{51a,51b}, L. Mijović²², G. Mikenberg¹⁷¹,
 M. Mikesstikova¹²⁷, M. Mikuz⁷⁶, M. Milesi⁸⁹, A. Milic⁶³, D.W. Miller³², C. Mills⁴⁷, A. Milov¹⁷¹,
 D.A. Milstead^{146a,146b}, A.A. Minaenko¹³⁰, Y. Minami¹⁵⁵, I.A. Minashvili⁶⁶, A.I. Mincer¹¹⁰, B. Mindur^{39a},
 M. Mineev⁶⁶, Y. Ming¹⁷², L.M. Mir¹², K.P. Mistry¹²², T. Mitani¹⁷⁰, J. Mitrevski¹⁰⁰, V.A. Mitsou¹⁶⁶,
 A. Miucci⁵⁰, P.S. Miyagawa¹³⁹, J.U. Mjörnmark⁸², T. Moe^{146a,146b}, K. Mochizuki⁹⁵, S. Mohapatra³⁶,
 S. Molander^{146a,146b}, R. Moles-Valls²², R. Monden⁶⁹, M.C. Mondragon⁹¹, K. Mönig⁴³, J. Monk³⁷,
 E. Monnier⁸⁶, A. Montalbano¹⁴⁸, J. Montejo Berlingen³¹, F. Monticelli⁷², S. Monzani^{92a,92b},
 R.W. Moore³, N. Morange¹¹⁷, D. Moreno²⁰, M. Moreno Llácer⁵⁵, P. Morettini^{51a}, D. Mori¹⁴², T. Mori¹⁵⁵,
 M. Morii⁵⁸, M. Morinaga¹⁵⁵, V. Morisbak¹¹⁹, S. Moritz⁸⁴, A.K. Morley¹⁵⁰, G. Mornacchi³¹, J.D. Morris⁷⁷,
 S.S. Mortensen³⁷, L. Morvaj¹⁴⁸, M. Mosidze^{52b}, J. Moss¹⁴³, K. Motohashi¹⁵⁷, R. Mount¹⁴³,
 E. Mountricha²⁶, S.V. Mouraviev^{96,*}, E.J.W. Moyse⁸⁷, S. Muanza⁸⁶, R.D. Mudd¹⁸, F. Mueller¹⁰¹,
 J. Mueller¹²⁵, R.S.P. Mueller¹⁰⁰, T. Mueller²⁹, D. Muenstermann⁷³, P. Mullen⁵⁴, G.A. Mullier¹⁷,
 F.J. Munoz Sanchez⁸⁵, J.A. Murillo Quijada¹⁸, W.J. Murray^{169,131}, H. Musheghyan⁵⁵, M. Muskinja⁷⁶,
 A.G. Myagkov^{130,ad}, M. Myska¹²⁸, B.P. Nachman¹⁴³, O. Nackenhorst⁵⁰, K. Nagai¹²⁰, R. Nagai^{67,x},
 K. Nagano⁶⁷, Y. Nagasaka⁶⁰, K. Nagata¹⁶⁰, M. Nagel⁴⁹, E. Nagy⁸⁶, A.M. Nairz³¹, Y. Nakahama³¹,

K. Nakamura⁶⁷, T. Nakamura¹⁵⁵, I. Nakano¹¹², H. Namasivayam⁴², R.F. Naranjo Garcia⁴³, R. Narayan³²,
 D.I. Narrias Villar^{59a}, I. Naryshkin¹²³, T. Naumann⁴³, G. Navarro²⁰, R. Nayyar⁷, H.A. Neal⁹⁰,
 P.Yu. Nechaeva⁹⁶, T.J. Neep⁸⁵, P.D. Nef¹⁴³, A. Negri^{121a,121b}, M. Negrini^{21a}, S. Nektarijevic¹⁰⁶,
 C. Nellist¹¹⁷, A. Nelson¹⁶², S. Nemecek¹²⁷, P. Nemethy¹¹⁰, A.A. Nepomuceno^{25a}, M. Nessi^{31,ae},
 M.S. Neubauer¹⁶⁵, M. Neumann¹⁷⁴, R.M. Neves¹¹⁰, P. Nevski²⁶, P.R. Newman¹⁸, D.H. Nguyen⁶,
 T. Nguyen Manh⁹⁵, R.B. Nickerson¹²⁰, R. Nicolaidou¹³⁶, J. Nielsen¹³⁷, A. Nikiforov¹⁶,
 V. Nikolaenko^{130,ad}, I. Nikolic-Audit⁸¹, K. Nikolopoulos¹⁸, J.K. Nilsen¹¹⁹, P. Nilsson²⁶, Y. Ninomiya¹⁵⁵,
 A. Nisati^{132a}, R. Nisius¹⁰¹, T. Nobe¹⁵⁵, L. Nodulman⁶, M. Nomachi¹¹⁸, I. Nomidis³⁰, T. Nooney⁷⁷,
 S. Norberg¹¹³, M. Nordberg³¹, N. Norjoharuddeen¹²⁰, O. Novgorodova⁴⁵, S. Nowak¹⁰¹, M. Nozaki⁶⁷,
 L. Nozka¹¹⁵, K. Ntekas¹⁰, E. Nurse⁷⁹, F. Nuti⁸⁹, F. O'grady⁷, D.C. O'Neil¹⁴², A.A. O'Rourke⁴³, V. O'Shea⁵⁴,
 F.G. Oakham^{30,d}, H. Oberlack¹⁰¹, T. Obermann²², J. Ocariz⁸¹, A. Ochi⁶⁸, I. Ochoa³⁶, J.P. Ochoa-Ricoux^{33a},
 S. Oda⁷¹, S. Odaka⁶⁷, H. Ogren⁶², A. Oh⁸⁵, S.H. Oh⁴⁶, C.C. Ohm¹⁵, H. Ohman¹⁶⁴, H. Oide³¹,
 H. Okawa¹⁶⁰, Y. Okumura³², T. Okuyama⁶⁷, A. Olariu^{27b}, L.F. Oleiro Seabra^{126a}, S.A. Olivares Pino⁴⁷,
 D. Oliveira Damazio²⁶, A. Olszewski⁴⁰, J. Olszowska⁴⁰, A. Onofre^{126a,126e}, K. Onogi¹⁰³, P.U.E. Onyisi^{32,t},
 M.J. Oreglia³², Y. Oren¹⁵³, D. Orestano^{134a,134b}, N. Orlando^{61b}, R.S. Orr¹⁵⁸, B. Osculati^{51a,51b},
 R. Ospanov⁸⁵, G. Otero y Garzon²⁸, H. Otono⁷¹, M. Ouchrif^{135d}, F. Ould-Saada¹¹⁹, A. Ouraou¹³⁶,
 K.P. Oussoren¹⁰⁷, Q. Ouyang^{34a}, M. Owen⁵⁴, R.E. Owen¹⁸, V.E. Ozcan^{19a}, N. Ozturk⁸, K. Pachal¹⁴²,
 A. Pacheco Pages¹², C. Padilla Aranda¹², M. Pagáčová⁴⁹, S. Pagan Griso¹⁵, F. Paige²⁶, P. Pais⁸⁷,
 K. Pajchel¹¹⁹, G. Palacino^{159b}, S. Palestini³¹, M. Palka^{39b}, D. Pallin³⁵, A. Palma^{126a,126b},
 E.St. Panagiotopoulou¹⁰, C.E. Pandini⁸¹, J.G. Panduro Vazquez⁷⁸, P. Pani^{146a,146b}, S. Panitkin²⁶,
 D. Pantea^{27b}, L. Paolozzi⁵⁰, Th.D. Papadopoulou¹⁰, K. Papageorgiou¹⁵⁴, A. Paramonov⁶,
 D. Paredes Hernandez¹⁷⁵, A.J. Parker⁷³, M.A. Parker²⁹, K.A. Parker¹³⁹, F. Parodi^{51a,51b}, J.A. Parsons³⁶,
 U. Parzefall⁴⁹, V.R. Pascuzzi¹⁵⁸, E. Pasqualucci^{132a}, S. Passaggio^{51a}, Fr. Pastore⁷⁸, G. Pásztor^{30,af},
 S. Pataraja¹⁷⁴, J.R. Pater⁸⁵, T. Pauly³¹, J. Pearce¹⁶⁸, B. Pearson¹¹³, L.E. Pedersen³⁷, M. Pedersen¹¹⁹,
 S. Pedraza Lopez¹⁶⁶, R. Pedro^{126a,126b}, S.V. Peleganchuk^{109,c}, D. Pelikan¹⁶⁴, O. Penc¹²⁷, C. Peng^{34a},
 H. Peng^{34b}, J. Penwell⁶², B.S. Peralva^{25b}, M.M. Perego¹³⁶, D.V. Perepelitsa²⁶, E. Perez Codina^{159a},
 L. Perini^{92a,92b}, H. Pernegger³¹, S. Perrella^{104a,104b}, R. Peschke⁴³, V.D. Peshekhonov⁶⁶, K. Peters⁴³,
 R.F.Y. Peters⁸⁵, B.A. Petersen³¹, T.C. Petersen³⁷, E. Petit⁵⁶, A. Petridis¹, C. Petridou¹⁵⁴, P. Petroff¹¹⁷,
 E. Petrolo^{132a}, M. Petrov¹²⁰, F. Petrucci^{134a,134b}, N.E. Pettersson⁸⁷, A. Peyaud¹³⁶, R. Pezoa^{33b},
 P.W. Phillips¹³¹, G. Piacquadio¹⁴³, E. Pianori¹⁶⁹, A. Picazio⁸⁷, E. Piccaro⁷⁷, M. Piccinini^{21a,21b},
 M.A. Pickering¹²⁰, R. Piegaia²⁸, J.E. Pilcher³², A.D. Pilkington⁸⁵, A.W.J. Pin⁸⁵, M. Pinamonti^{163a,163c,ag},
 J.L. Pinfold³, A. Pingel³⁷, S. Pires⁸¹, H. Pirumov⁴³, M. Pitt¹⁷¹, L. Plazak^{144a}, M.-A. Pleier²⁶, V. Pleskot⁸⁴,
 E. Plotnikova⁶⁶, P. Plucinski⁹¹, D. Pluth⁶⁵, R. Poettgen^{146a,146b}, L. Poggioli¹¹⁷, D. Pohl²²,
 G. Polesello^{121a}, A. Poley⁴³, A. Policicchio^{38a,38b}, R. Polifka¹⁵⁸, A. Polini^{21a}, C.S. Pollard⁵⁴,
 V. Polychronakos²⁶, K. Pommès³¹, L. Pontecorvo^{132a}, B.G. Pope⁹¹, G.A. Popeneciu^{27c}, D.S. Popovic¹³,
 A. Poppleton³¹, S. Pospisil¹²⁸, K. Potamianos¹⁵, I.N. Potrap⁶⁶, C.J. Potter²⁹, C.T. Potter¹¹⁶, G. Poulard³¹,
 J. Poveda³¹, V. Pozdnyakov⁶⁶, M.E. Pozo Astigarraga³¹, P. Pralavorio⁸⁶, A. Pranko¹⁵, S. Prell⁶⁵,
 D. Price⁸⁵, L.E. Price⁶, M. Primavera^{74a}, S. Prince⁸⁸, M. Proissl⁴⁷, K. Prokofiev^{61c}, F. Prokoshin^{33b},
 S. Protopopescu²⁶, J. Proudfoot⁶, M. Przybycien^{39a}, D. Puddu^{134a,134b}, M. Purohit^{26,ah}, P. Puzo¹¹⁷,
 J. Qian⁹⁰, G. Qin⁵⁴, Y. Qin⁸⁵, A. Quadt⁵⁵, W.B. Quayle^{163a,163b}, M. Queitsch-Maitland⁸⁵, D. Quilty⁵⁴,
 S. Raddum¹¹⁹, V. Radeka²⁶, V. Radescu^{59b}, S.K. Radhakrishnan¹⁴⁸, P. Radloff¹¹⁶, P. Rados⁸⁹,
 F. Ragusa^{92a,92b}, G. Rahal¹⁷⁷, J.A. Raine⁸⁵, S. Rajagopalan²⁶, M. Rammensee³¹, C. Rangel-Smith¹⁶⁴,
 M.G. Ratti^{92a,92b}, F. Rauscher¹⁰⁰, S. Rave⁸⁴, T. Ravenscroft⁵⁴, M. Raymond³¹, A.L. Read¹¹⁹,
 N.P. Readoff⁷⁵, M. Reale^{74a,74b}, D.M. Rebuzzi^{121a,121b}, A. Redelbach¹⁷³, G. Redlinger²⁶, R. Reece¹³⁷,
 K. Reeves⁴², L. Rehnisch¹⁶, J. Reichert¹²², H. Reisin²⁸, C. Rembser³¹, H. Ren^{34a}, M. Rescigno^{132a},
 S. Resconi^{92a}, O.L. Rezanova^{109,c}, P. Reznicek¹²⁹, R. Rezvani⁹⁵, R. Richter¹⁰¹, S. Richter⁷⁹,
 E. Richter-Was^{39b}, O. Ricken²², M. Ridel⁸¹, P. Rieck¹⁶, C.J. Riegel¹⁷⁴, J. Rieger⁵⁵, O. Rifki¹¹³,
 M. Rijssenbeek¹⁴⁸, A. Rimoldi^{121a,121b}, M. Rimoldi¹⁷, L. Rinaldi^{21a}, B. Ristić⁵⁰, E. Ritsch³¹, I. Riu¹²,
 F. Rizatdinova¹¹⁴, E. Rizvi⁷⁷, C. Rizzi¹², S.H. Robertson^{88,l}, A. Robichaud-Veronneau⁸⁸, D. Robinson²⁹,
 J.E.M. Robinson⁴³, A. Robson⁵⁴, C. Roda^{124a,124b}, Y. Rodina⁸⁶, A. Rodriguez Perez¹²,
 D. Rodriguez Rodriguez¹⁶⁶, S. Roe³¹, C.S. Rogan⁵⁸, O. Røhne¹¹⁹, A. Romaniouk⁹⁸, M. Romano^{21a,21b},
 S.M. Romano Saez³⁵, E. Romero Adam¹⁶⁶, N. Rompotis¹³⁸, M. Ronzani⁴⁹, L. Roos⁸¹, E. Ros¹⁶⁶,

S. Rosati ^{132a}, K. Rosbach ⁴⁹, P. Rose ¹³⁷, O. Rosenthal ¹⁴¹, N.-A. Rosien ⁵⁵, V. Rossetti ^{146a,146b},
E. Rossi ^{104a,104b}, L.P. Rossi ^{51a}, J.H.N. Rosten ²⁹, R. Rosten ¹³⁸, M. Rotaru ^{27b}, I. Roth ¹⁷¹, J. Rothberg ¹³⁸,
D. Rousseau ¹¹⁷, C.R. Royon ¹³⁶, A. Rozanov ⁸⁶, Y. Rozen ¹⁵², X. Ruan ^{145c}, F. Rubbo ¹⁴³, M.S. Rudolph ¹⁵⁸,
F. Rühr ⁴⁹, A. Ruiz-Martinez ³⁰, Z. Rurikova ⁴⁹, N.A. Rusakovich ⁶⁶, A. Ruschke ¹⁰⁰, H.L. Russell ¹³⁸,
J.P. Rutherford ⁷, N. Ruthmann ³¹, Y.F. Ryabov ¹²³, M. Rybar ¹⁶⁵, G. Rybkin ¹¹⁷, S. Ryu ⁶, A. Ryzhov ¹³⁰,
G.F. Rzehorz ⁵⁵, A.F. Saavedra ¹⁵⁰, G. Sabato ¹⁰⁷, S. Sacerdoti ²⁸, H.F.-W. Sadrozinski ¹³⁷, R. Sadykov ⁶⁶,
F. Safai Tehrani ^{132a}, P. Saha ¹⁰⁸, M. Sahinsoy ^{59a}, M. Saimpert ¹³⁶, T. Saito ¹⁵⁵, H. Sakamoto ¹⁵⁵,
Y. Sakurai ¹⁷⁰, G. Salamanna ^{134a,134b}, A. Salamon ^{133a,133b}, J.E. Salazar Loyola ^{33b}, D. Salek ¹⁰⁷,
P.H. Sales De Bruin ¹³⁸, D. Salihagic ¹⁰¹, A. Salnikov ¹⁴³, J. Salt ¹⁶⁶, D. Salvatore ^{38a,38b}, F. Salvatore ¹⁴⁹,
A. Salvucci ^{61a}, A. Salzburger ³¹, D. Sammel ⁴⁹, D. Sampsonidis ¹⁵⁴, A. Sanchez ^{104a,104b}, J. Sánchez ¹⁶⁶,
V. Sanchez Martinez ¹⁶⁶, H. Sandaker ¹¹⁹, R.L. Sandbach ⁷⁷, H.G. Sander ⁸⁴, M. Sandhoff ¹⁷⁴, C. Sandoval ²⁰,
R. Sandstroem ¹⁰¹, D.P.C. Sankey ¹³¹, M. Sannino ^{51a,51b}, A. Sansoni ⁴⁸, C. Santoni ³⁵, R. Santonico ^{133a,133b},
H. Santos ^{126a}, I. Santoyo Castillo ¹⁴⁹, K. Sapp ¹²⁵, A. Sapronov ⁶⁶, J.G. Saraiva ^{126a,126d}, B. Sarrazin ²²,
O. Sasaki ⁶⁷, Y. Sasaki ¹⁵⁵, K. Sato ¹⁶⁰, G. Sauvage ^{5,*}, E. Sauvan ⁵, G. Savage ⁷⁸, P. Savard ^{158,d},
C. Sawyer ¹³¹, L. Sawyer ^{80,p}, J. Saxon ³², C. Sbarra ^{21a}, A. Sbrizzi ^{21a,21b}, T. Scanlon ⁷⁹, D.A. Scannicchio ¹⁶²,
M. Scarcella ¹⁵⁰, V. Scarfone ^{38a,38b}, J. Schaarschmidt ¹⁷¹, P. Schacht ¹⁰¹, B.M. Schachtner ¹⁰⁰,
D. Schaefer ³¹, R. Schaefer ⁴³, J. Schaeffer ⁸⁴, S. Schaepe ²², S. Schaezel ^{59b}, U. Schäfer ⁸⁴, A.C. Schaffer ¹¹⁷,
D. Schaile ¹⁰⁰, R.D. Schamberger ¹⁴⁸, V. Scharf ^{59a}, V.A. Schegelsky ¹²³, D. Scheirich ¹²⁹, M. Schernau ¹⁶²,
C. Schiavi ^{51a,51b}, S. Schier ¹³⁷, C. Schillo ⁴⁹, M. Schioppa ^{38a,38b}, S. Schlenker ³¹,
K.R. Schmidt-Sommerfeld ¹⁰¹, K. Schmieden ³¹, C. Schmitt ⁸⁴, S. Schmitt ⁴³, S. Schmitz ⁸⁴,
B. Schneider ^{159a}, U. Schnoor ⁴⁹, L. Schoeffel ¹³⁶, A. Schoening ^{59b}, B.D. Schoenrock ⁹¹, E. Schopf ²²,
M. Schott ⁸⁴, J. Schovancova ⁸, S. Schramm ⁵⁰, M. Schreyer ¹⁷³, N. Schuh ⁸⁴, M.J. Schultens ²²,
H.-C. Schultz-Coulon ^{59a}, H. Schulz ¹⁶, M. Schumacher ⁴⁹, B.A. Schumm ¹³⁷, Ph. Schune ¹³⁶,
A. Schwartzman ¹⁴³, T.A. Schwarz ⁹⁰, Ph. Schwegler ¹⁰¹, H. Schweiger ⁸⁵, Ph. Schwemling ¹³⁶,
R. Schwienhorst ⁹¹, J. Schwindling ¹³⁶, T. Schwindt ²², G. Sciolla ²⁴, F. Scuri ^{124a,124b}, F. Scutti ⁸⁹,
J. Searcy ⁹⁰, P. Seema ²², S.C. Seidel ¹⁰⁵, A. Seiden ¹³⁷, F. Seifert ¹²⁸, J.M. Seixas ^{25a}, G. Sekhniaidze ^{104a},
K. Sekhon ⁹⁰, S.J. Sekula ⁴¹, D.M. Seliverstov ^{123,*}, N. Semprini-Cesari ^{21a,21b}, C. Serfon ¹¹⁹, L. Serin ¹¹⁷,
L. Serkin ^{163a,163b}, M. Sessa ^{134a,134b}, R. Seuster ¹⁶⁸, H. Severini ¹¹³, T. Sfligoj ⁷⁶, F. Sforza ³¹, A. Sfyrla ⁵⁰,
E. Shabalina ⁵⁵, N.W. Shaikh ^{146a,146b}, L.Y. Shan ^{34a}, R. Shang ¹⁶⁵, J.T. Shank ²³, M. Shapiro ¹⁵,
P.B. Shatalov ⁹⁷, K. Shaw ^{163a,163b}, S.M. Shaw ⁸⁵, A. Shcherbakova ^{146a,146b}, C.Y. Shehu ¹⁴⁹, P. Sherwood ⁷⁹,
L. Shi ^{151,ai}, S. Shimizu ⁶⁸, C.O. Shimmin ¹⁶², M. Shimojima ¹⁰², M. Shiyakova ^{66,qj}, A. Shmeleva ⁹⁶,
D. Shoaleh Saadi ⁹⁵, M.J. Shochet ³², S. Shojaii ^{92a,92b}, S. Shrestha ¹¹¹, E. Shulga ⁹⁸, M.A. Shupe ⁷,
P. Sicho ¹²⁷, A.M. Sickles ¹⁶⁵, P.E. Sidebo ¹⁴⁷, O. Sidiropoulou ¹⁷³, D. Sidorov ¹¹⁴, A. Sidoti ^{21a,21b},
F. Siegert ⁴⁵, Dj. Sijacki ¹³, J. Silva ^{126a,126d}, S.B. Silverstein ^{146a}, V. Simak ¹²⁸, O. Simard ⁵, Lj. Simic ¹³,
S. Simion ¹¹⁷, E. Simioni ⁸⁴, B. Simmons ⁷⁹, D. Simon ³⁵, M. Simon ⁸⁴, P. Sinervo ¹⁵⁸, N.B. Sinev ¹¹⁶,
M. Sioli ^{21a,21b}, G. Siragusa ¹⁷³, S.Yu. Sivoklov ⁹⁹, J. Sjölin ^{146a,146b}, T.B. Sjursen ¹⁴, M.B. Skinner ⁷³,
H.P. Skottowe ⁵⁸, P. Skubic ¹¹³, M. Slater ¹⁸, T. Slavicek ¹²⁸, M. Slawinska ¹⁰⁷, K. Sliwa ¹⁶¹, R. Slovak ¹²⁹,
V. Smakhtin ¹⁷¹, B.H. Smart ⁵, L. Smestad ¹⁴, J. Smiesko ^{144a}, S.Yu. Smirnov ⁹⁸, Y. Smirnov ⁹⁸,
L.N. Smirnova ^{99,ak}, O. Smirnova ⁸², M.N.K. Smith ³⁶, R.W. Smith ³⁶, M. Smizanska ⁷³, K. Smolek ¹²⁸,
A.A. Snesarev ⁹⁶, S. Snyder ²⁶, R. Sobie ^{168,l}, F. Socher ⁴⁵, A. Soffer ¹⁵³, D.A. Soh ^{151,ai}, G. Sokhrannyi ⁷⁶,
C.A. Solans Sanchez ³¹, M. Solar ¹²⁸, E.Yu. Soldatov ⁹⁸, U. Soldevila ¹⁶⁶, A.A. Solodkov ¹³⁰, A. Soloshenko ⁶⁶,
O.V. Solovyanov ¹³⁰, V. Solovyev ¹²³, P. Sommer ⁴⁹, H. Son ¹⁶¹, H.Y. Song ^{34b,aa}, A. Sood ¹⁵, A. Sopczak ¹²⁸,
V. Sopko ¹²⁸, V. Sorin ¹², D. Sosa ^{59b}, C.L. Sotiropoulou ^{124a,124b}, R. Soualah ^{163a,163c}, A.M. Soukharev ^{109,c},
D. South ⁴³, B.C. Sowden ⁷⁸, S. Spagnolo ^{74a,74b}, M. Spalla ^{124a,124b}, M. Spangenberg ¹⁶⁹, F. Spanò ⁷⁸,
D. Sperlich ¹⁶, F. Spettel ¹⁰¹, R. Spighi ^{21a}, G. Spigo ³¹, L.A. Spiller ⁸⁹, M. Spousta ¹²⁹, R.D. St. Denis ^{54,*},
A. Stabile ^{92a}, R. Stamen ^{59a}, S. Stamm ¹⁶, E. Stanecka ⁴⁰, R.W. Stanek ⁶, C. Stanescu ^{134a},
M. Stanescu-Bellu ⁴³, M.M. Stanitzki ⁴³, S. Stapnes ¹¹⁹, E.A. Starchenko ¹³⁰, G.H. Stark ³², J. Stark ⁵⁶,
P. Staroba ¹²⁷, P. Starovoitov ^{59a}, S. Stärz ³¹, R. Staszewski ⁴⁰, P. Steinberg ²⁶, B. Stelzer ¹⁴², H.J. Stelzer ³¹,
O. Stelzer-Chilton ^{159a}, H. Stenzel ⁵³, G.A. Stewart ⁵⁴, J.A. Stillings ²², M.C. Stockton ⁸⁸, M. Stoebe ⁸⁸,
G. Stoica ^{27b}, P. Stolte ⁵⁵, S. Stonjek ¹⁰¹, A.R. Stradling ⁸, A. Straessner ⁴⁵, M.E. Stramaglia ¹⁷,
J. Strandberg ¹⁴⁷, S. Strandberg ^{146a,146b}, A. Strandlie ¹¹⁹, M. Strauss ¹¹³, P. Strizenec ^{144b}, R. Ströhmer ¹⁷³,
D.M. Strom ¹¹⁶, R. Stroynowski ⁴¹, A. Strubig ¹⁰⁶, S.A. Stucci ¹⁷, B. Stugu ¹⁴, N.A. Styles ⁴³, D. Su ¹⁴³,

J. Su¹²⁵, R. Subramaniam⁸⁰, S. Suchek^{59a}, Y. Sugaya¹¹⁸, M. Suk¹²⁸, V.V. Sulin⁹⁶, S. Sultansoy^{4c}, T. Sumida⁶⁹, S. Sun⁵⁸, X. Sun^{34a}, J.E. Sundermann⁴⁹, K. Suruliz¹⁴⁹, G. Susinno^{38a,38b}, M.R. Sutton¹⁴⁹, S. Suzuki⁶⁷, M. Svatos¹²⁷, M. Swiatlowski³², I. Sykora^{144a}, T. Sykora¹²⁹, D. Ta⁴⁹, C. Taccini^{134a,134b}, K. Tackmann⁴³, J. Taenzer¹⁵⁸, A. Taffard¹⁶², R. Tafirout^{159a}, N. Taiblum¹⁵³, H. Takai²⁶, R. Takashima⁷⁰, T. Takeshita¹⁴⁰, Y. Takubo⁶⁷, M. Talby⁸⁶, A.A. Talyshev^{109,c}, K.G. Tan⁸⁹, J. Tanaka¹⁵⁵, R. Tanaka¹¹⁷, S. Tanaka⁶⁷, B.B. Tannenwald¹¹¹, S. Tapia Araya^{33b}, S. Tapprogge⁸⁴, S. Tarem¹⁵², G.F. Tartarelli^{92a}, P. Tas¹²⁹, M. Tasevsky¹²⁷, T. Tashiro⁶⁹, E. Tassi^{38a,38b}, A. Tavares Delgado^{126a,126b}, Y. Tayalati^{135d}, A.C. Taylor¹⁰⁵, G.N. Taylor⁸⁹, P.T.E. Taylor⁸⁹, W. Taylor^{159b}, F.A. Teischinger³¹, P. Teixeira-Dias⁷⁸, K.K. Temming⁴⁹, D. Temple¹⁴², H. Ten Kate³¹, P.K. Teng¹⁵¹, J.J. Teoh¹¹⁸, F. Tepel¹⁷⁴, S. Terada⁶⁷, K. Terashi¹⁵⁵, J. Terron⁸³, S. Terzo¹⁰¹, M. Testa⁴⁸, R.J. Teuscher^{158,l}, T. Theveneaux-Pelzer⁸⁶, J.P. Thomas¹⁸, J. Thomas-Wilsker⁷⁸, E.N. Thompson³⁶, P.D. Thompson¹⁸, A.S. Thompson⁵⁴, L.A. Thomsen¹⁷⁵, E. Thomson¹²², M. Thomson²⁹, M.J. Tibbetts¹⁵, R.E. Ticse Torres⁸⁶, V.O. Tikhomirov^{96,al}, Yu.A. Tikhonov^{109,c}, S. Timoshenko⁹⁸, P. Tipton¹⁷⁵, S. Tisserant⁸⁶, K. Todome¹⁵⁷, T. Todorov^{5,*}, S. Todorova-Nova¹²⁹, J. Tojo⁷¹, S. Tokár^{144a}, K. Tokushuku⁶⁷, E. Tolley⁵⁸, L. Tomlinson⁸⁵, M. Tomoto¹⁰³, L. Tompkins^{143,am}, K. Toms¹⁰⁵, B. Tong⁵⁸, E. Torrence¹¹⁶, H. Torres¹⁴², E. Torr o Pastor¹³⁸, J. Toth^{86,an}, F. Touchard⁸⁶, D.R. Tovey¹³⁹, T. Trefzger¹⁷³, A. Tricoli²⁶, I.M. Trigger^{159a}, S. Trincaz-Duvoid⁸¹, M.F. Tripiana¹², W. Trischuk¹⁵⁸, B. Trocm e⁵⁶, A. Trofymov⁴³, C. Troncon^{92a}, M. Trotter-McDonald¹⁵, M. Trovatelli¹⁶⁸, L. Truong^{163a,163c}, M. Trzebinski⁴⁰, A. Trzupek⁴⁰, J.C.-L. Tseng¹²⁰, P.V. Tsiareshka⁹³, G. Tsipolitis¹⁰, N. Tsirintanis⁹, S. Tsiskaridze¹², V. Tsiskaridze⁴⁹, E.G. Tskhadadze^{52a}, K.M. Tsui^{61a}, I.I. Tsukerman⁹⁷, V. Tsulaia¹⁵, S. Tsuno⁶⁷, D. Tsybychev¹⁴⁸, A. Tudorache^{27b}, V. Tudorache^{27b}, A.N. Tuna⁵⁸, S.A. Tupputi^{21a,21b}, S. Turchikhin^{99,ak}, D. Turecek¹²⁸, D. Turgeman¹⁷¹, R. Turra^{92a,92b}, A.J. Turvey⁴¹, P.M. Tuts³⁶, M. Tyndel¹³¹, G. Uccielli^{21a,21b}, I. Ueda¹⁵⁵, R. Ueno³⁰, M. Ughetto^{146a,146b}, F. Ukegawa¹⁶⁰, G. Unal³¹, A. Undrus²⁶, G. Unel¹⁶², F.C. Ungaro⁸⁹, Y. Unno⁶⁷, C. Unverdorben¹⁰⁰, J. Urban^{144b}, P. Urquijo⁸⁹, P. Urrejola⁸⁴, G. Usai⁸, A. Usanova⁶³, L. Vacavant⁸⁶, V. Vacek¹²⁸, B. Vachon⁸⁸, C. Valderanis¹⁰⁰, E. Valdes Santurio^{146a,146b}, N. Valencic¹⁰⁷, S. Valentineti^{21a,21b}, A. Valero¹⁶⁶, L. Valery¹², S. Valkar¹²⁹, S. Vallecorsa⁵⁰, J.A. Valls Ferrer¹⁶⁶, W. Van Den Wollenberg¹⁰⁷, P.C. Van Der Deijl¹⁰⁷, R. van der Geer¹⁰⁷, H. van der Graaf¹⁰⁷, N. van Eldik¹⁵², P. van Gemmeren⁶, J. Van Nieuwkoop¹⁴², I. van Vulpen¹⁰⁷, M.C. van Woerden³¹, M. Vanadia^{132a,132b}, W. Vandelli³¹, R. Vanguri¹²², A. Vaniachine⁶, P. Vankov¹⁰⁷, G. Vardanyan¹⁷⁶, R. Vari^{132a}, E.W. Varnes⁷, T. Varol⁴¹, D. Varouchas⁸¹, A. Vartapetian⁸, K.E. Varvell¹⁵⁰, J.G. Vasquez¹⁷⁵, F. Vazeille³⁵, T. Vazquez Schroeder⁸⁸, J. Veatch⁵⁵, L.M. Veloce¹⁵⁸, F. Veloso^{126a,126c}, S. Veneziano^{132a}, A. Ventura^{74a,74b}, M. Venturi¹⁶⁸, N. Venturi¹⁵⁸, A. Venturini²⁴, V. Vercesi^{121a}, M. Verducci^{132a,132b}, W. Verkerke¹⁰⁷, J.C. Vermeulen¹⁰⁷, A. Vest^{45,ao}, M.C. Vetterli^{142,d}, O. Viazlo⁸², I. Vichou¹⁶⁵, T. Vickey¹³⁹, O.E. Vickey Boeriu¹³⁹, G.H.A. Viehhauser¹²⁰, S. Viel¹⁵, L. Vignani¹²⁰, R. Vigne⁶³, M. Villa^{21a,21b}, M. Villaplana Perez^{92a,92b}, E. Vilucchi⁴⁸, M.G. Vincker³⁰, V.B. Vinogradov⁶⁶, C. Vittori^{21a,21b}, I. Vivarelli¹⁴⁹, S. Vlachos¹⁰, M. Vlasak¹²⁸, M. Vogel¹⁷⁴, P. Vokac¹²⁸, G. Volpi^{124a,124b}, M. Volpi⁸⁹, H. von der Schmitt¹⁰¹, E. von Toerne²², V. Vorobel¹²⁹, K. Vorobev⁹⁸, M. Vos¹⁶⁶, R. Voss³¹, J.H. Vosseveld⁷⁵, N. Vranjes¹³, M. Vranjes Milosavljevic¹³, V. Vrba¹²⁷, M. Vreeswijk¹⁰⁷, R. Vuillemet³¹, I. Vukotic³², Z. Vykydal¹²⁸, P. Wagner²², W. Wagner¹⁷⁴, H. Wahlberg⁷², S. Wahrmund⁴⁵, J. Wakabayashi¹⁰³, J. Walder⁷³, R. Walker¹⁰⁰, W. Walkowiak¹⁴¹, V. Wallangen^{146a,146b}, C. Wang^{34c}, C. Wang^{34d,86}, F. Wang¹⁷², H. Wang¹⁵, H. Wang⁴¹, J. Wang⁴³, J. Wang¹⁵⁰, K. Wang⁸⁸, R. Wang⁶, S.M. Wang¹⁵¹, T. Wang²², T. Wang³⁶, W. Wang^{34b}, X. Wang¹⁷⁵, C. Wanotayaroj¹¹⁶, A. Warburton⁸⁸, C.P. Ward²⁹, D.R. Wardrope⁷⁹, A. Washbrook⁴⁷, P.M. Watkins¹⁸, A.T. Watson¹⁸, M.F. Watson¹⁸, G. Watts¹³⁸, S. Watts⁸⁵, B.M. Waugh⁷⁹, S. Webb⁸⁴, M.S. Weber¹⁷, S.W. Weber¹⁷³, J.S. Webster⁶, A.R. Weidberg¹²⁰, B. Weinert⁶², J. Weingarten⁵⁵, C. Weiser⁴⁹, H. Weits¹⁰⁷, P.S. Wells³¹, T. Wenaus²⁶, T. Wengler³¹, S. Wenig³¹, N. Wermes²², M. Werner⁴⁹, P. Werner³¹, M. Wessels^{59a}, J. Wetter¹⁶¹, K. Whalen¹¹⁶, N.L. Whallon¹³⁸, A.M. Wharton⁷³, A. White⁸, M.J. White¹, R. White^{33b}, D. Whiteson¹⁶², F.J. Wickens¹³¹, W. Wiedenmann¹⁷², M. Wielers¹³¹, P. Wienemann²², C. Wiglesworth³⁷, L.A.M. Wiik-Fuchs²², A. Wildauer¹⁰¹, F. Wilk⁸⁵, H.G. Wilkens³¹, H.H. Williams¹²², S. Williams¹⁰⁷, C. Willis⁹¹, S. Willocq⁸⁷, J.A. Wilson¹⁸, I. Wingarter-Seez⁵, F. Winklmeier¹¹⁶, O.J. Winston¹⁴⁹, B.T. Winter²², M. Wittgen¹⁴³, J. Wittkowski¹⁰⁰, S.J. Wollstadt⁸⁴, M.W. Wolter⁴⁰, H. Wolters^{126a,126c}, B.K. Wosiek⁴⁰, J. Wotschack³¹, M.J. Woudstra⁸⁵, K.W. Wozniak⁴⁰, M. Wu⁵⁶, M. Wu³², S.L. Wu¹⁷²,

X. Wu⁵⁰, Y. Wu⁹⁰, T.R. Wyatt⁸⁵, B.M. Wynne⁴⁷, S. Xella³⁷, D. Xu^{34a}, L. Xu²⁶, B. Yabsley¹⁵⁰, S. Yacoob^{145a}, R. Yakabe⁶⁸, D. Yamaguchi¹⁵⁷, Y. Yamaguchi¹¹⁸, A. Yamamoto⁶⁷, S. Yamamoto¹⁵⁵, T. Yamanaka¹⁵⁵, K. Yamauchi¹⁰³, Y. Yamazaki⁶⁸, Z. Yan²³, H. Yang^{34e}, H. Yang¹⁷², Y. Yang¹⁵¹, Z. Yang¹⁴, W.-M. Yao¹⁵, Y.C. Yap⁸¹, Y. Yasu⁶⁷, E. Yatsenko⁵, K.H. Yau Wong²², J. Ye⁴¹, S. Ye²⁶, I. Yeletsikh⁶⁶, A.L. Yen⁵⁸, E. Yildirim⁸⁴, K. Yorita¹⁷⁰, R. Yoshida⁶, K. Yoshihara¹²², C. Young¹⁴³, C.J.S. Young³¹, S. Youssef²³, D.R. Yu¹⁵, J. Yu⁸, J.M. Yu⁹⁰, J. Yu⁶⁵, L. Yuan⁶⁸, S.P.Y. Yuen²², I. Yusuff^{29,ap}, B. Zabinski⁴⁰, R. Zaidan^{34d}, A.M. Zaitsev^{130,ad}, N. Zakharchuk⁴³, J. Zalieckas¹⁴, A. Zaman¹⁴⁸, S. Zambito⁵⁸, L. Zanello^{132a,132b}, D. Zanzi⁸⁹, C. Zeitnitz¹⁷⁴, M. Zeman¹²⁸, A. Zemla^{39a}, J.C. Zeng¹⁶⁵, Q. Zeng¹⁴³, K. Zengel²⁴, O. Zenin¹³⁰, T. Ženiš^{144a}, D. Zerwas¹¹⁷, D. Zhang⁹⁰, F. Zhang¹⁷², G. Zhang^{34b,aa}, H. Zhang^{34c}, J. Zhang⁶, L. Zhang⁴⁹, R. Zhang²², R. Zhang^{34b,aq}, X. Zhang^{34d}, Z. Zhang¹¹⁷, X. Zhao⁴¹, Y. Zhao^{34d,117}, Z. Zhao^{34b}, A. Zhemchugov⁶⁶, J. Zhong¹²⁰, B. Zhou⁹⁰, C. Zhou⁴⁶, L. Zhou³⁶, L. Zhou⁴¹, M. Zhou¹⁴⁸, N. Zhou^{34f}, C.G. Zhu^{34d}, H. Zhu^{34a}, J. Zhu⁹⁰, Y. Zhu^{34b}, X. Zhuang^{34a}, K. Zhukov⁹⁶, A. Zibell¹⁷³, D. Zieminska⁶², N.I. Zimine⁶⁶, C. Zimmermann⁸⁴, S. Zimmermann⁴⁹, Z. Zinonos⁵⁵, M. Zinser⁸⁴, M. Ziolkowski¹⁴¹, L. Živković¹³, G. Zobernig¹⁷², A. Zoccoli^{21a,21b}, M. zur Nedden¹⁶, G. Zurzolo^{104a,104b}, L. Zwalinski³¹

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

¹² Institut de Física d'Altes Energies (IFAE), The Barcelona Institute of Science and Technology, Barcelona, Spain

¹³ Institute of Physics, University of Belgrade, Belgrade, Serbia

¹⁴ Department for Physics and Technology, University of Bergen, Bergen, Norway

¹⁵ Physics Division, Lawrence Berkeley National Laboratory and University of California, Berkeley, CA, United States

¹⁶ Department of Physics, Humboldt University, Berlin, Germany

¹⁷ Albert Einstein Center for Fundamental Physics and Laboratory for High Energy Physics, University of Bern, Bern, Switzerland

¹⁸ School of Physics and Astronomy, University of Birmingham, Birmingham, United Kingdom

¹⁹ (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

²⁰ Centro de Investigaciones, Universidad Antonio Narino, Bogota, Colombia

²¹ (a) INFN Sezione di Bologna; (b) Dipartimento di Fisica e Astronomia, Università di Bologna, Bologna, Italy

²² Physikalisches Institut, University of Bonn, Bonn, Germany

²³ Department of Physics, Boston University, Boston, MA, United States

²⁴ Department of Physics, Brandeis University, Waltham, MA, United States

²⁵ (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

²⁶ Physics Department, Brookhaven National Laboratory, Upton, NY, United States

²⁷ (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

²⁸ Departamento de Física, Universidad de Buenos Aires, Buenos Aires, Argentina

²⁹ Cavendish Laboratory, University of Cambridge, Cambridge, United Kingdom

³⁰ Department of Physics, Carleton University, Ottawa, ON, Canada

³¹ CERN, Geneva, Switzerland

³² Enrico Fermi Institute, University of Chicago, Chicago, IL, United States

³³ (a) Departamento de Física, Pontificia Universidad Católica de Chile, Santiago; (b) Departamento de Física, Universidad Técnica Federico Santa María, Valparaíso, Chile

³⁴ (a) Institute of High Energy Physics, Chinese Academy of Sciences, Beijing; (b) Department of Modern Physics, University of Science and Technology of China, Anhui; (c) Department of Physics, Nanjing University, Jiangsu; (d) School of Physics, Shandong University, Shandong; (e) Department of Physics and Astronomy, Shanghai Key Laboratory for Particle Physics and Cosmology, Shanghai Jiao Tong University, Shanghai; (f) Physics Department, Tsinghua University, Beijing 100084, China

³⁵ Laboratoire de Physique Corpusculaire, Clermont Université and Université Blaise Pascal and CNRS/IN2P3, Clermont-Ferrand, France

³⁶ Nevis Laboratory, Columbia University, Irvington, NY, United States

³⁷ Niels Bohr Institute, University of Copenhagen, Copenhagen, Denmark

³⁸ (a) INFN Gruppo Collegato di Cosenza, Laboratori Nazionali di Frascati; (b) Dipartimento di Fisica, Università della Calabria, Rende, Italy

³⁹ (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

⁴⁰ Institute of Nuclear Physics Polish Academy of Sciences, Krakow, Poland

⁴¹ Physics Department, Southern Methodist University, Dallas, TX, United States

⁴² Physics Department, University of Texas at Dallas, Richardson, TX, United States

⁴³ DESY, Hamburg and Zeuthen, Germany

⁴⁴ Institut für Experimentelle Physik IV, Technische Universität Dortmund, Dortmund, Germany

⁴⁵ Institut für Kern- und Teilchenphysik, Technische Universität Dresden, Dresden, Germany

⁴⁶ Department of Physics, Duke University, Durham, NC, United States

⁴⁷ SUPA – School of Physics and Astronomy, University of Edinburgh, Edinburgh, United Kingdom

⁴⁸ INFN Laboratori Nazionali di Frascati, Frascati, Italy

⁴⁹ Fakultät für Mathematik und Physik, Albert-Ludwigs-Universität, Freiburg, Germany

⁵⁰ Section de Physique, Université de Genève, Geneva, Switzerland

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

- 126 ^(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
- 127 Institute of Physics, Academy of Sciences of the Czech Republic, Praha, Czech Republic
- 128 Czech Technical University in Prague, Praha, Czech Republic
- 129 Faculty of Mathematics and Physics, Charles University in Prague, Praha, Czech Republic
- 130 State Research Center Institute for High Energy Physics (Protvino), NRC KI, Russia
- 131 Particle Physics Department, Rutherford Appleton Laboratory, Didcot, United Kingdom
- 132 ^(a) INFN Sezione di Roma; ^(b) Dipartimento di Fisica, Sapienza Università di Roma, Roma, Italy
- 133 ^(a) INFN Sezione di Roma Tor Vergata; ^(b) Dipartimento di Fisica, Università di Roma Tor Vergata, Roma, Italy
- 134 ^(a) INFN Sezione di Roma Tre; ^(b) Dipartimento di Matematica e Fisica, Università Roma Tre, Roma, Italy
- 135 ^(a) Faculté des Sciences Ain Chock, Réseau Universitaire de Physique des Hautes Energies – Université Hassan II, Casablanca; ^(b) Centre National de l’Energie des Sciences Techniques Nucleaires, Rabat; ^(c) Faculté des Sciences Semlalia, Université Cadi Ayyad, LPHEA, Marrakech; ^(d) Faculté des Sciences, Université Mohamed Premier and LPTPM, Oujda; ^(e) Faculté des sciences, Université Mohammed V, Rabat, Morocco
- 136 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
- 137 Santa Cruz Institute for Particle Physics, University of California Santa Cruz, Santa Cruz, CA, United States
- 138 Department of Physics, University of Washington, Seattle, WA, United States
- 139 Department of Physics and Astronomy, University of Sheffield, Sheffield, United Kingdom
- 140 Department of Physics, Shinshu University, Nagano, Japan
- 141 Fachbereich Physik, Universität Siegen, Siegen, Germany
- 142 Department of Physics, Simon Fraser University, Burnaby, BC, Canada
- 143 SLAC National Accelerator Laboratory, Stanford, CA, United States
- 144 ^(a) Faculty of Mathematics, Physics & Informatics, Comenius University, Bratislava; ^(b) Department of Subnuclear Physics, Institute of Experimental Physics of the Slovak Academy of Sciences, Kosice, Slovak Republic
- 145 ^(a) Department of Physics, University of Cape Town, Cape Town; ^(b) Department of Physics, University of Johannesburg, Johannesburg; ^(c) School of Physics, University of the Witwatersrand, Johannesburg, South Africa
- 146 ^(a) Department of Physics, Stockholm University; ^(b) The Oskar Klein Centre, Stockholm, Sweden
- 147 Physics Department, Royal Institute of Technology, Stockholm, Sweden
- 148 Departments of Physics & Astronomy and Chemistry, Stony Brook University, Stony Brook, NY, United States
- 149 Department of Physics and Astronomy, University of Sussex, Brighton, United Kingdom
- 150 School of Physics, University of Sydney, Sydney, Australia
- 151 Institute of Physics, Academia Sinica, Taipei, Taiwan
- 152 Department of Physics, Technion: Israel Institute of Technology, Haifa, Israel
- 153 Raymond and Beverly Sackler School of Physics and Astronomy, Tel Aviv University, Tel Aviv, Israel
- 154 Department of Physics, Aristotle University of Thessaloniki, Thessaloniki, Greece
- 155 International Center for Elementary Particle Physics and Department of Physics, The University of Tokyo, Tokyo, Japan
- 156 Graduate School of Science and Technology, Tokyo Metropolitan University, Tokyo, Japan
- 157 Department of Physics, Tokyo Institute of Technology, Tokyo, Japan
- 158 Department of Physics, University of Toronto, Toronto, ON, Canada
- 159 ^(a) TRIUMF, Vancouver, BC; ^(b) Department of Physics and Astronomy, York University, Toronto, ON, Canada
- 160 Faculty of Pure and Applied Sciences, and Center for Integrated Research in Fundamental Science and Engineering, University of Tsukuba, Tsukuba, Japan
- 161 Department of Physics and Astronomy, Tufts University, Medford, MA, United States
- 162 Department of Physics and Astronomy, University of California Irvine, Irvine, CA, United States
- 163 ^(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
- 164 Department of Physics and Astronomy, University of Uppsala, Uppsala, Sweden
- 165 Department of Physics, University of Illinois, Urbana, IL, United States
- 166 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
- 167 Department of Physics, University of British Columbia, Vancouver, BC, Canada
- 168 Department of Physics and Astronomy, University of Victoria, Victoria, BC, Canada
- 169 Department of Physics, University of Warwick, Coventry, United Kingdom
- 170 Waseda University, Tokyo, Japan
- 171 Department of Particle Physics, The Weizmann Institute of Science, Rehovot, Israel
- 172 Department of Physics, University of Wisconsin, Madison, WI, United States
- 173 Fakultät für Physik und Astronomie, Julius-Maximilians-Universität, Würzburg, Germany
- 174 Fakultät für Mathematik und Naturwissenschaften, Fachgruppe Physik, Bergische Universität Wuppertal, Wuppertal, Germany
- 175 Department of Physics, Yale University, New Haven, CT, United States
- 176 Yerevan Physics Institute, Yerevan, Armenia
- 177 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.

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

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

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

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

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

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

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

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

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

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

^p Also at Louisiana Tech University, Ruston, LA, United States.

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

- ^r Also at Graduate School of Science, Osaka University, Osaka, Japan.
- ^s Also at Department of Physics, National Tsing Hua University, Taiwan.
- ^t Also at Department of Physics, The University of Texas at Austin, Austin, TX, United States.
- ^u Also at Institute of Theoretical Physics, Iliia State University, Tbilisi, Georgia.
- ^v Also at CERN, Geneva, Switzerland.
- ^w Also at Georgian Technical University (GTU), Tbilisi, Georgia.
- ^x Also at Ochadai Academic Production, Ochanomizu University, Tokyo, Japan.
- ^y Also at Manhattan College, New York, NY, United States.
- ^z Also at Hellenic Open University, Patras, Greece.
- ^{aa} Also at Institute of Physics, Academia Sinica, Taipei, Taiwan.
- ^{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 Moscow Institute of Physics and Technology State University, Dolgoprudny, Russia.
- ^{ae} Also at Section de Physique, Université de Genève, Geneva, Switzerland.
- ^{af} Also at Eotvos Lorand University, Budapest, Hungary.
- ^{ag} Also at International School for Advanced Studies (SISSA), Trieste, Italy.
- ^{ah} Also at Department of Physics and Astronomy, University of South Carolina, Columbia, SC, United States.
- ^{ai} Also at School of Physics and Engineering, Sun Yat-sen University, Guangzhou, China.
- ^{aj} Also at Institute for Nuclear Research and Nuclear Energy (INRNE) of the Bulgarian Academy of Sciences, Sofia, Bulgaria.
- ^{ak} Also at Faculty of Physics, M.V. Lomonosov Moscow State University, Moscow, Russia.
- ^{al} Also at National Research Nuclear University MEPhI, Moscow, Russia.
- ^{am} Also at Department of Physics, Stanford University, Stanford, CA, United States.
- ^{an} Also at Institute for Particle and Nuclear Physics, Wigner Research Centre for Physics, Budapest, Hungary.
- ^{ao} Also at Flensburg University of Applied Sciences, Flensburg, Germany.
- ^{ap} Also at University of Malaya, Department of Physics, Kuala Lumpur, Malaysia.
- ^{aq} Also at CPPM, Aix-Marseille Université and CNRS/IN2P3, Marseille, France.
- ^{ar} Also affiliated with PKU-CHEP.
- * Deceased.